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**EBT - P PROPOSED REFERENCE
DESIGN REPORT**

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ORNL/TM-7191

FUSION ENERGY DIVISION

EBT-P PROPOSED REFERENCE DESIGN REPORT

A. L. Boch
Project Manager

This report was prepared by the ORNL EBT project staff based on information derived from ORNL studies; Phase I Preconceptual Design Reports for EBT-P submitted by EBASCO Services, Inc., Grumman Aerospace, Inc., McDonnell-Douglas Astronautics Company, and Westinghouse Electric Corporation, each in conjunction with their subcontractors; and extensive discussions with the participants throughout the month of November 1979. Oak Ridge National Laboratory would like to acknowledge their support and contribution to the overall EBT-P project effort.

January 1980

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ABSTRACT

This report describes the proposed reference design for the EBT-P "proof-of-principle" test device. The device described is a result of broad studies by many participating organizations from industry and from Department of Energy-sponsored fusion research groups, some working together and some in competitive studies, but all with the goal of defining a device at minimum cost and with maximum probability of meeting its goals. This design work is based upon advances in experimental and theoretical understanding of EBT achieved at Oak Ridge National Laboratory. The strategy adopted permits an initial test and validation of the key scaling properties of the ELMO Bumpy Torus concept, with a degree of built-in flexibility to extend the performance parameters toward the condition for containing a fusion reactor plasma. This will lead the way, then, to determination of a later power "break-even" demonstration and an eventual fusion reactor that can exploit the special high power-density and steady-state properties of the EBT concept.

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EXECUTIVE SUMMARY

This report describes EBT-P, a device designed to advance the EBT concept to the proof-of-principle level. The advances made by EBT-P should be sufficient, with optimistic assumptions made about device operation, to give confidence to proceed to the next step, a D-T burning device (designated EBT-Q in this report). The roles of EBT-P and EBT-Q may be taken as analogous to those of PLT and TFTR in the tokamak program. However, the present EBT-I, EBT-P, and EBT-Q are steady-state devices ($\geq 10^4$ sec), and for comparable plasma parameters to a given tokamak, they are a significant step nearer a reactor.

Important objectives for EBT-P are to:

- Determine whether energy confinement of the core plasma is sufficient to make a viable D-T burning device.
- Determine whether there is a favorable power balance in the relativistic electron annuli at betas that are sufficient, when extrapolated to a reaction, to stabilize the core plasma.
- Advance technology in the area of high power microwave tubes toward the higher frequencies that will be required by a reactor.

PLASMA PARAMETERS

EBT-P should represent first a significant scale up from the current experiment EBT-I/S. Second, it should be capable of achieving PLT-like parameters. This, as in the case of the PLT, will be accomplished by improvements. In the case of EBT, the improvements include:

- Direct ion heating.
- Operation over an expanded range of collisionality and density, by the use of improved heating control and particle control.
- Modifications of the magnetic field, which should lead to better energy confinement.
- Operation at higher frequency.

The basic improvements over EBT-I may be obtained from simple scaling formulas; these are listed below. Their predictions are confirmed by 1-D code calculations.

$$(n\tau)_p = (n\tau)_1 \cdot \left(\frac{R_p}{R_1}\right)^2 \left(\frac{R_{B1}}{R_{Bp}}\right)^{1.4} \left(\frac{a_p}{a_1}\right)^{0.6} \left(\frac{f_{\mu p}}{f_{\mu 1}}\right)^{1.8} \frac{(\nu/\Omega)_1^{0.6}}{(\nu/\Omega)_p} \cdot \frac{[1 + C(T_i/T_e)]_p^2}{[1 + C(T_i/T_e)]_1^2} \cdot f_A^2 \cdot \left(\frac{n_{cp}}{n_{c1}}\right)^{0.6} \cdot \left(\frac{f_{\mu p I}}{f_{\mu 1}}\right)^{1.8},$$

$$\langle T_i \rangle_p = \langle T_i \rangle_1 \cdot \left(\frac{f_{\mu p}}{f_{\mu 1}}\right)^{1.2} \cdot \left(\frac{R_{Bp} a_p}{R_{B1} a_1}\right)^{0.4},$$

and

$$\langle \beta \rangle_p = \langle \beta \rangle_1 \cdot \frac{(1 + T_i/T_e)_p}{(1 + T_i/T_e)_1} \cdot \frac{(\nu/\Omega)_1^{0.4}}{(\nu/\Omega)_p} \cdot \left(\frac{R_{Bp} a_p}{R_{B1} a_1}\right)^{1.8} \cdot \left(\frac{f_{\mu p}}{f_{\mu 1}}\right)^{1.2}.$$

A significant scale up over EBT-I/S is taken to be ≥ 2 times the increase. The parameters of EBT-I and the projected parameters for EBT-P, EBT-PI, and a reference EBT-Q are given in Table 1.3.

The design of EBT-P has evolved from the reference design established during Phase I of the EBT-P task by Oak Ridge National Laboratory, Ebasco, Grumman, McDonnell Douglas, and Westinghouse. The reference design is subject to the constraints discussed in Sect. 1.4.

To achieve the goals, EBT-P will start with microwave power at 60 GHz initially [4 x 200-kW gyrotrons + (2 x 200-kW, 28-GHz profile heating systems)]. The power will be increased in stages by adding further gyrotrons — 8 x 200 kW and 12 x 200 kW. In addition, direct ion heating will be provided by ion cyclotron heating, initially 100 kW. Other methods of heating that may be applied are lower hybrid heating, neutral beam heating, and molecular ion heating. The latter system is also proposed for modifying the potential.

Further device improvements planned are the addition of pellet fueling and a divertor and finally the increase of the magnetic field to allow operation of ~ 90 GHz.

The device parameters are a compromise set by meeting the objectives under budgetary constraints. In particular, the plasma minor radius is only about a factor of two larger than in EBT-I, though the major radius has increased by a factor of three. This reflects the need to improve confinement [$n\tau \propto (R/R_B)^2$, $R_B \propto R_C \propto a$] while minimizing the plasma volume to keep auxiliary heating requirements low. At constant collisionality, fold and density $P \propto a^{3.6}/R$. The coils are overlarge to accommodate a divertor scrape-off layer between the plasma and the coil throat.

RELATIVISTIC ELECTRON RING PARAMETERS

A primary physics objective of EBT-P is the study of relativistic electron ring power balance. When scaled up from EBT-I, the ring power requirements for a reactor may be viewed as favorable or unfavorable depending upon the scaling assumption made. Favorable scaling depends upon operation of higher energy (>0.1 MeV, the present level) on the ring having a relatively smaller volume with respect to the core plasma and on a greater efficiency of power coupled to the ring. The ring energy and volume depend on a number of factors. Among these are: background plasma density, the ratios of electron gyroradius to plasma radius and magnetic field scale lengths, scale lengths of resonant frequencies along field lines, and microwave distribution at the annulus. To help determine the ring power usage, a separate heating source is needed for the core plasma. It is proposed to accomplish this by direct ion heating (ICH, LHH, beams — molecular and neutral) and by ultimately feeding polarized ECH power separately to the ring and core plasma.

The proposed EBT-P device can operate with frequencies from $f_u = 28\text{--}90$ GHz, $B_r = 1.0\text{--}3.1$ T, and $n_c = 0.4\text{--}10 \times 10^{13} \text{ cm}^{-3}$. With this capability and with the flexibility given by the improvements, it should be possible to accomplish the objective of establishing whether the ring power balance is favorable for a reactor.

TECHNOLOGY

The device uses two systems that require development. The superconducting NbTi coils are likely to take advantage of relatively new construction techniques that will allow them to operate at high current density ($\sim 10 \text{ kA}\cdot\text{cm}^{-2}$ at ~ 7 T). A development program is in hand to construct prototype coils.

The high frequency, steady-state (60 GHz, ~ 90 GHz) gyrotrons do not exist, and a development program has started to develop 200-kW steady-state 60-GHz gyrotrons. Note that a 60-kW, 28-GHz gyrotron has operated for 10 hours and that high power pulsed tubes have operated in the Soviet Union at ~ 80 GHz.

1. INTRODUCTION

1.1 THE REASON FOR EBT-P

1.1.1 Background

During 1978 an ad hoc committee was convened by the U.S. Department of Energy (DOE) with John Foster (TRW) as chairman to examine the fusion effort in the U.S. One of their recommendations was to broaden the research effort to include alternatives to the leading concepts. To implement their recommendation, the DOE Office of Fusion Energy (ETM) held a review of various alternate concepts in October 1978. The Oak Ridge National Laboratory's (ORNL's) ELMO Bumpy Torus (EBT) concept was selected by ETM's Concept Review Committee as one of the alternate concepts to be pursued to proof-of-principle level. A quote from the DOE, "Report on the Concept Review Committee Recommendations for Proof-of-Principle Alternate Concept Programs," DOE/ET-0085,¹ summarizes the current DOE policy and the basis for this project.

"The recently announced DOE policy statement on the development of fusion energy places increased emphasis on the testing of promising alternate concepts. More specifically, this policy suggests comparisons of promising alternatives with tokamaks and mirrors in the mid-1980's. In order to make these concept comparisons, it is necessary to extend greatly the scientific data base for the alternate concepts toward the reactor regime to provide significant experimental tests. These significant tests have been designated as proof-of-principle (POP) experiments and are to have most of the important dimensionless parameters in or near the reactor regime. A proof-of-principle experiment may be considered the scientific equivalent of PLT in the tokamak program."

The proof-of-principle device has been designated EBT-P. It is intended that the experiment be conducted by DOE with the Union Carbide Corporation-Nuclear Division (UCC-ND) as the program manager and technical advisor on the project. In turn, UCC-ND will subcontract the detailed design and fabrication of the device to a major industrial participant (IP) and other subcontractors as required. It is also intended that the IP should play a major role in the operation phase. The procedure for accomplishing the initiation phase of the EBT-P project is indicated schematically in Fig. 1.1. To date Phase I of the project has been completed and reference designs have been prepared by each of four candidate IP's (Ebasco, Grumman, McDonnell-Douglas, and Westinghouse), one of which will be selected ultimately to be the IP. In addition, at ORNL work continued on refining the reference design first presented in 1978 to the Concept Evaluation Committee as EBT-II.² Following the completion of the reference designs, presentations were made at ORNL by each of the IP's and by ORNL which reviewed the work (November 1-2, 1979). Following these presentations, ORNL has had the responsibility for assessing the proposals and establishing the single reference design, which represents the subject of this report. The time to accomplish this work was approximately five weeks (11/5-12/7). To achieve this goal, ORNL held two discussion sessions during November 1979 with the IP's to establish common ground on the technical and physics constraints for the device. In addition, discussions were held involving DOE, ORNL, and the IP's to establish the goals of the device and the experimental schedule and strategy which would meet the perceived schedule and budget requirements. This proposal incorporates many good ideas and analyses that were promulgated by the various participants during the Phase I studies and discussions and will form the basis for the Request for Proposals that will be issued to the four IPs. This document presupposes an Oak Ridge site for EBT-P, but it is the intent of DOE and ORNL that IPs also may optionally propose construction elsewhere, with the ultimate site decision to be made by DOE after proposal evaluation.

It is a credit to all parties involved that it was possible to arrive, in such a short time, at the effective reference design presented here which offers such exciting possibilities for the EBT and fusion programs.

Fig. 1.1. EBR-P Project Initiation phase schedule.

1.1.2 EBT Experiments

An EBT is a toroidal magnetic trap consisting of a set of linked magnetic mirrors. A simple bumpy torus with only vacuum magnetic fields is magnetohydrodynamically (MHD) unstable. In the EBT³ at ORNL, this problem has been circumvented by the application of electron cyclotron heating (ECH), which, as discovered in mirror research at ORNL, creates high beta (β), energetic electron annuli that modify the toroidal magnetic field in such a way as to prevent MHD instabilities. The primary motivation for EBT confinement research is the fusion reactor goal which, for EBT, could be accomplished in a high β , steady-state operation, high accessibility configuration.

The EBT concept as embodied in the EBT-I device is illustrated in Fig. 1.2. The main parameters are given in Table 1.1. In EBT-I it has been demonstrated that energetic electron annuli stabilize the toroidally confined plasma, which is also produced by ECH. Even in the low magnetic field, 6 kG of EBT-I, the stable toroidal plasma attains significant density ($\bar{n}_e \sim 10^{12} \text{ cm}^{-3}$), temperature ($T_e \sim 300 \text{ eV}$, $T_i \sim 100 \text{ eV}$), and confinement time ($\tau_E \sim 5 \text{ msec}$) with $\sim 50 \text{ kW}$ of microwave power at 18 GHz. The parameters compare favorably with predictions of a diffusive neoclassical transport model. With these encouraging results as a baseline, a new experiment, EBT-Scale (EBT-S), is presently under way to provide deeper insight into the scaling of plasma parameters with high microwave frequency (28 GHz), magnetic field (10 kG), and heating power ($\leq 200 \text{ kW}$).

The EBT-I device has experimentally confirmed the fundamental premise macroscopic stability by demonstrating the smooth transition from the typical MHD-unstable bumpy torus regime (when the annulus beta β_{an} is low) into a macrostable, hot plasma regime. This regime extends over a significant range of operating conditions provided β_{an} exceeds a minimum value for stability. In the six years since EBT-I began operating, work has progressed from a demonstration of this macrostability to an increasingly detailed understanding of the plasma properties. This work is now complemented and confirmed by studies in a second EBT, the Nagoya Bumpy Torus (NBT) in Nagoya, Japan.⁴

Stability calculations have shown that the annuli and the toroidal plasma in EBT serve to stabilize each other and that unstable coupling of the two plasmas need not occur,⁵ a fact verified in EBT-I at low β . Theoretically, ballooning modes in the toroidal core plasma lead to upper limits on the containable amount of core plasma. Magnetohydrodynamic (MHD) calculations indicate that β_{core} cannot greatly exceed β_{an} , but since β_{an} may be $\gtrsim 40\%$ this leads to a plasma which is attractive for a reactor. Recent kinetic calculations⁶ have been carried out for similar modes in slab geometry. These initial simplified calculations indicate a lower bound on β_{core} than did the MHD calculations. Calculations based on MHD theory led to early concern about the ballooning instability of the annulus, but MHD theory provides an inadequate description of annulus behavior, and a kinetic treatment demonstrates that ballooning modes are stabilized. Also, a number of microinstabilities that could conceivably occur in this system have been studied and are found to be stable for the expected field and plasma gradients.⁷

So far, theoretical studies have provided no significant indication that the toroidal plasma will be other than stable in interesting regimes. The EBT-I experiment has demonstrated nearly quiescent toroidal mode (T-mode) operation with very low density fluctuation levels.³ In experiments, collisionless scaling (energy confinement time τ increases with temperature) has been observed, and the magnitude of τ is consistent with neoclassical theory.⁸⁻¹¹ The results of a comparison between the experimentally observed plasma parameters (ion and electron temperatures, plasma density, and confinement time) and the values and behavior predicted by neoclassical theory are very encouraging: in the T-mode, the EBT-I plasma parameters seem entirely consistent with neoclassical transport predictions. The correspondence is limited at present to a small range of each parameter and has a coarse nature as a result of the small size of the experiments, and by diagnostic limitations associated with operation at low microwave frequency, low magnetic field, and low plasma density. The quality of the measurements is being improved

Fig. 1.2. EBT.

by the addition of better diagnostics, and the parameter range will be extended with the application on EBT-S of more power for extended periods at higher frequency (28 GHz). The confirmatory and complementary work on the Nagoya Bumpy Torus is making a major contribution to establishing a sound data base.

Table 1.1. Main parameters of the EBT concept as embodied in the EBT-I design

Characteristic	Value
Magnetic field (maximum)	0.65 T (midplane), 1.3 T (mirror)
Magnetic field power	10 MW supplied by motor-generator sets
Major radius	150 cm
Aspect ratio (major to mean coil radius)	9:1
Torus volume	1350 liters
Microwave power (evenly distributed among 24 cavities)	200 kW at 28 GHz, 60 kW at 18 GHz, 30 kW at 10.6 GHz

Plasma parameters and diagnostics

Parameter	Diagnostics
T_e	Si(Li) x-rays, Thomson scattering (corroborative)
n_e	Microwave interferometer, probes, bremsstrahlung
T_i	Charge exchange
n_o	Spectroscopy, charge exchange
ϕ	Heavy ion beam
n_z	VUV spectroscopy
B	Probes, loops, etc.

Typical steady-state EBT-I toroidal parameters

$n \sim 0.5\text{--}2 \times 10^{12} \text{ cm}^{-3}$
 $T_e \sim 200\text{--}600 \text{ eV}$
 $T_i \sim 50 \text{ eV}$
 ϕ Positive at rings, well depth of 100-300 V, electric field points radially inward
 $n_z/n_e \sim 10^{-3}\text{--}10^{-4}$
 $(C, Al: Z_{eff} \sim 1.01\text{--}1.001)$
 $\beta \sim 0.2\text{--}0.5\%$

1.2 THE ROLE OF EBT-P

1.2.1 Definition of Proof-of-Principle

To summarize the statement in the DOE Concept Review Committee Report DOE/ET-0085,¹ the purpose of a proof-of-principle device is: to provide a test in the mid-1980's of promising alternatives to tokamaks and mirrors and to extend the scientific data base for an alternate concept towards the reactor regime and provide significant experimental tests. The device may be considered the scientific equivalent of PLT in the tokamak program. Thus, the identified goals of the device may be quantified in terms of dimensionless parameters such as ν/Ω and β ; and dimensional parameters such as T_e , T_i , n_e , n_i , Z_{eff} , plasma pulse length t_p , and for EBT's, electron ring parameters. In turn, the level required of these parameters must be related to a scale which stretches from the present experiments to a reactor. Finally, the composite of all the projected parameters should be normalized to PLT to ensure that in a more absolute sense the device is a significant step.

The consensus of the groups working on EBT-P is that, given the realities of budget and construction and experimental schedules, a device should be constructed to offer the greatest possible flexibility for improvements which optimistically we may expect to work. In its initial phase it should satisfy mainly the constraint of significant scale up from EBT-I/S and NBT towards the next device (EBT-Q?).

In addition, there is complete agreement that the device should be steady state. This latter constraint, coupled with the minimum performance objectives ($n_i \sim \text{few} \times 10^{11} \text{ cm}^{-3}$, $T_e \sim 2 \text{ keV}$, $T_i \sim 0.5 \text{ keV}$), leads to a device with superconducting coils, and a minimum device size which is set in part by the additional constraints imposed by such coils. A more detailed logic for the design is given below; for the present we will concentrate on comparing the projected performance of the proposed design with the proof-of-principle guidelines.

1.2.2 EBT Scaling

The performance is determined by scaling up from the performance of EBT-I in the T-mode using a 1-D code (this is described in detail in Sect. 3). For several years EBT scaling has been a fundamental element in design studies; it is based upon theoretical scaling laws with coefficients determined from experimental measurements on EBT-I/S. The more detailed code calculations compare favorably with experimental results in the T-mode of operation of EBT and confirm that the gross behavior of the toroidal core density and temperatures is dominated by the neoclassical electron transport coefficients, leading to EBT scaling of (see Sect. 3)

$$n_i \sim A^2 T_e^{3/2} \left(1 + \frac{e\phi}{T_i} \right)^2$$

for small collisionality

$$\left(\frac{\nu}{\Omega} < 1 \right)$$

where $\nu/\Omega \sim n (BR_B a)/T_e^{5/2}$. Here a is the mean plasma radius, A is the magnetic aspect ratio defined as R/R_B , and R and R_B are the major radius of the torus and the magnetic radius of curvature, respectively.

Since the potential ϕ is approximately proportional to the ion temperature T_i , the factor

$$\frac{e\phi}{T_e} \rightarrow C \frac{T_i}{T_e}$$

where typically $C \sim 1.5-2$. Constraints on the application of the formula for $n\tau$ include a limitation on v/Ω , on the mirror ratio (M) of each sector, and on single particle confinement. Namely, v/Ω is approximately the value in EBT-I for initial operation, $M \sim 2$, and single particle confinement as good as that in EBT-I (see Appendix A.3.1).

It is possible to modify the aspect ratio by shaping the coils (wedging) and with coils additional to the basic toroidal coil set; such coils are known as aspect ratio enhancement (ARE) coils. Additional coils may also be used to vary the mirror ratio (trim coils). The effective aspect ratio with ARE coils may be written as $A_{\text{eff}} = (R/R_B) f_{\text{ARE}} \cong A f_A$. Such coils on EBT-P might lead to an enhancement factor as high as $f_A \sim 1.4$ (see Appendix A.3.1).

Finally, note that the cutoff for microwave propagation (electron plasma frequency $\omega_{pe} \leq$ electron cyclotron frequency ω_{ce}) imposes an upper limit on density n , which scales as the square of the magnetic field, i.e., $n_{\text{max}} \sim f_{\mu}^2 \sim B_r^2$ where f_{μ} is the applied microwave frequency and B_r is the resonant magnetic field. The resonance occurs in the region between the coils, and for mirror $M \sim 2$, the maximum field at the coil $B_M \sim 2 B_r$. Combining all of these formulae and constraints it is possible to arrive at the following formulation:

$$(n\tau)_{\text{EBT-P}} \cong (n\tau)_{\text{EBT-I}} \cdot \left(\frac{R_p}{R_1}\right)^2 \cdot \left(\frac{R_{B1}}{R_{Bp}}\right)^{1.4} \left(\frac{a_p}{a_1}\right)^{0.6} \times \left(\frac{f_{\mu p}}{f_{\mu 1}}\right)^{1.8} \\ \times \frac{(v/\Omega)_1^{0.6}}{(v/\Omega)_p^{0.6}} \cdot \frac{(1 + CT_i/T_e)_p^2}{(1 + CT_i/T_e)_1^2} \cdot f_A^2 \cdot \left(\frac{n_{cp}}{n_{c1}}\right)^{0.6}.$$

On the first line is the gain in $n\tau$ assuming operation under the same conditions as presently explored in EBT-I. On the second line are improvements coming from:

- Operation at lower collisionality due to better control of the plasma; for example, from the use of microwave feed from the high field side and from particle control.
- Direct ion heating leading to a larger potential well and better confinement.
- Aspect ratio enhancement leading to better single particle orbits and to better confinement.
- Operation nearer the cutoff density, achieved by better core heating techniques and higher power densities.

It is proposed that EBT-P should start operation at 60 GHz, but the coils should have the capability to accommodate ~ 90 -GHz frequencies. This increase in frequency should lead to a factor of ~ 2 improvement in $n\tau$, though it will require additional ring power and heating power. It is in fact the importance of determining the scaling of ring power¹² with field and plasma conditions that is a main driver for this upgrade capability. The parameters of the phase 1 reference EBT-P design are summarized in Table 1.2. As can be seen there was broad agreement on the major device parameters, initial operating frequency (50-60 GHz), major radius (4-5.6 m), minor plasma radius (0.14-0.22 m), number of sectors (36-40), mechanical aspect ratio (15-20), mirror ratio ~ 2 . The new reference design falls within the envelope of parameters discussed in phase I with the exception that it is on the average slightly less conservative a design at the highest field (frequency ~ 90 GHz) level. This is justified by recent advances in the state of the art.

The parameters of the proposed design for EBT-P are given in Table 1.3 and are compared with EBT-I. The results of some 1-D code calculations for $n\tau$, T_e , T_i , and ϕ are given in Figs. 1.3 and 1.4.

Table 1.2. Summary of Phase 1 reference design parameters

	ORNL	Ebasco	Grumman	McDonnell Douglas	Westinghouse
Maximum frequency f_μ (GHz)	110	60	94	110	110
Initial frequency f_μ (GHz)	60	60	50	56	60
Major radius R (m)	5.6	4.0	5.25	5.5	4.2
Mean plasma radius $\bar{a}$ (m)	~ 0.19	~ 0.17	~ 0.14	~ 0.22	~ 0.15
Number of sections	36	40	36	36	36
Mechanical aspect ratio A	16	20	15	15	18
Mirror ratio M	1.9-2.3	2	2.26	2	1.9-3.8

Table 1.3. Comparison of EBT-P reference design and EBT-I/S

	EBT-I	EBT-S	EBT-P	EBT-P maximum	
Gyrotron frequencies f_μ (GHz)	18/10.6	28	60/28	90	
Resonant field B_r (T)	0.64	1.0	2.1	3.2	
Major radius R (m)	1.5	1.5	4.5	4.5	
Mean plasma radius a (m)	0.11	0.11	0.18	0.18	
Mean coil radius R_c (m)	0.16	0.16	0.29	0.29	
Mechanical aspect ratio A	9.3	9.3	15.5	15.5	
Number of coils	24	24	36	36	
Mirror ratio M	2.0	2.0	2.2	2.2	
ARE coils	YES I/S.A		Possible	Possible	
					with improvements
Plasma density n_c ($\times 10^{13}$ cm $^{-3}$)	0.15	0.36	1.7	3.8	~ 5
Cutoff density n_c ($\times 10^{13}$ cm $^{-3}$)	0.40	0.96	4.4	10.0	10
Typical T_e (keV)	0.3	0.5	2.0	3.3	~ 5
Typical T_i (keV)	0.06	0.1	0.4	0.7	~ 2
Midplane, axis β (q)	~ 0.1	~ 0.1	~ 0.5	~ 0.9	~ 2
$(\nu/\Omega)_e$	$\gtrsim 0.3$				
Confinement time τ (sec)	$\sim 6 \times 10^{-3}$	$\sim 6 \times 10^{-3}$	$\sim 3 \times 10^{-2}$	$\sim 3 \times 10^{-2}$	$\sim 10^{-1}$
$n\tau$ (cm $^{-3}$ sec)	$\sim 10^{10}$	$\sim 2 \times 10^{10}$	$\sim 5 \times 10^{11}$	$\sim 1 \times 10^{12}$	$\sim 5 \times 10^{12}$
Estimates scaled from EBT-I at constant collisionalities and constant fraction of cutoff					
Field at ring B_{ring} (T)	0.32	0.50	1.07	1.6	
Ring temperature T_R (MeV)	0.15	0.2	$\gtrsim 0.5$	> 0.5	
β_R (%)	15 $\rightarrow$ 30	15 $\rightarrow$ 30	$\gtrsim 30$	$\gtrsim 30$	
Ring density n_r ($\times 10^{13}$ cm $^{-3}$)	0.02 $\rightarrow$ 0.05	0.03 $\rightarrow$ 0.05	~ 0.2	~ 0.3	
Electron gyroradius ρ_{ER} (mm)	~ 4.5	~ 3.3	$\gtrsim 3.0$	$\gtrsim 2.0$

Fig. 1.3. Calculated T_e , T_i , τ_e , and ϕ vs n_e for EBT-I and EBT-P. (See Sect. 3.1 for definitions.)

Fig. 1.4. Calculated values of $n\tau$ vs electron collisionality. (See Sect. 3.1 for definitions.)

The conclusion is that in initial operation the device should have at 60 GHz, $n_i \sim \text{few} \times 10^{11} \text{ cm}^{-3}$ at $n \geq 10^{13} \text{ cm}^{-3}$ with $T_e \sim 2 \text{ keV}$ and $T_i \sim 0.5 \text{ keV}$. Following a staged experimental program, these parameters may be raised by a number of potential improvements. Ultimately at $\sim 90 \text{ GHz}$ with ion heating, aspect ratio enhancement, and operating at lower collisionality and near cutoff, the device has the potential to achieve $n_i \sim 5 \times 10^{12} \text{ cm}^{-3}$, at $n \sim 5 \times 10^{13} \text{ cm}^{-3}$ with $T_e \sim 5 \text{ keV}$ and $T_i \sim 2 \text{ keV}$.

These points should be emphasized:

- The density and temperature profiles in EBT are essentially flat in the central regions so the above numbers are volume average values.
- The experimental program committed on EBT-I/S (Fig. 1.5) will study mirror ratio variation (ARE), ion heating, higher frequency electron cyclotron heating, particle control (divertor) in a staged manner which will lead on a reasonable schedule into the EBT-P program.
- The results are for steady state operation.

1.2.3 EBT Hierarchy

A device (EBT-Q) to follow EBT-P has been indicated by ORNL and by the IP's. This device has broadly the parameters indicated in Table 1.4, where the sequence of EBT's is indicated. The device EBT-Q could be a D-T burning device with $Q \geq 1$. It is somewhat more ambitious than TFTR by virtue of its steady-state operation. In fact, this feature of EBT's leads to a leap-frogging program in which each device with plasma parameters comparable to a tokamak is in fact more ambitious and further down the route to a fusion reactor.

It is the combination of a large number of parameters that characterize a fusion device which makes difficult the comparison of the status of one device with another type of device. Nevertheless, we will attempt to relate the parameters of EBT-P and EBT-Q to ATC, PLT, TFTR, ETF, and a reactor.

Some preliminary comments are appropriate. While singular advances in one parameter (n , n_i , T_i , T_p , β ...) are important and strengthen the program, it is the combination of parameters which matters, for example, nT_i , etc. Thus, major steps in the program are the high nT_i ($>10^{13} \text{ cm}^{-3} \text{ sec}$) of Alcator at low temperatures ($T < 1 \text{ keV}$) and low β ($\sim 0.5\%$) for $\leq 1 \text{ sec}$; the high T_i ($\sim 6-7 \text{ keV}$) of PLT at $nT_i \sim 10^{12} \text{ cm}^{-3} \text{ sec}$ and low β ($\sim 0.5\%$) for $\sim 0.1 \text{ sec}$; and the high β (2-3%) of ISX-B at low temperature ($T < 1 \text{ keV}$) and for $\sim 0.03 \text{ sec}$. The combined values are, however, substantially short of the combination of best values: $nT_i \approx 5 \times 10^{12} \text{ cm}^{-3} \text{ keV sec}$ (compared to $nT_i \sim 3 \times 10^{13} \text{ cm}^{-3} \text{ keV sec}$).

For EBT-P we view the achievement singly of any of these plasma levels as significant (viz. $T_i \geq 1 \text{ keV}$, $nT_i \geq 10^{12} \text{ cm}^{-3} \text{ sec}$, $\beta \geq 1\%$), given that it will be steady state. In Fig. 1.6 the EBT devices are compared with tokamak devices using the standard nT_i vs T_i plot. However, as indicated above, this diagram does not adequately represent the role of plasma pulse length T_p . Figure 1.7 is an attempt to do justice to the significance of this parameter and to place EBT achievements in perspective. Present tokamaks operate for not more than 1.0 sec, TFTR will operate initially for 1.5 sec, but has the capability for ~ 10 -sec operation. The ETF, as a tokamak, is projected to have a pulse length of about 100 sec. The tokamak reactor, however, may be expected to operate for at least 1000 sec, and more probably $\geq 10,000 \text{ sec}$. (For large tokamaks with $T_e \sim 10 \text{ keV}$, it is straight forward to provide volt-second capability for such pulse lengths). Similarly mirror reactors would operate for times $\geq 10,000 \text{ sec}$. The present EBT-I does operate for $>10,000 \text{ sec}$ ($\geq 4 \text{ hours}$), limited mainly by operator fatigue.

That EBT-P has, in its improved state, the potential capability of achieving, by a number of routes, parameters such as $nT_i \geq 10^{12} \text{ cm}^{-3} \text{ sec}$, $T_i > 1 \text{ keV}$ at $n > 1 \times 10^{13} \text{ cm}^{-3}$ with $\beta \geq 1\%$ in steady state is remarkably significant even when compared with the achievements and projections of other devices.

Fig. 1.5. EBT program.

Table 1.4. Hierarchy of EBT's

	EBT-1	EBT-S	EBT-P	EBT-PI	EBT-Q
B_{res} (T)	0.64	1.0	2.1	~3.2	~4.0
R (m)	1.5	1.5	4.5	4.5	17.0
f_E^a	1.0	1.0	1.0	≤2.0	≤2.0
A	9.3	9.3	16	16	14
$\bar{a}$ (m)	0.11	0.11	0.18	0.18	0.55
N_{coils}	24	24	36	36	36
n (cm ⁻³)	1.5×10^{12}	4×10^{12}	1.7×10^{13}	$\sim 5 \times 10^{13}$	$\sim 8 \times 10^{13}$
T_e (keV)	0.3	0.5	2	~5	~15
T_i (keV)	0.06	0.1	~0.4	~2	~10
$n\tau$ (cm ⁻³)/sec)	1×10^{10}	2×10^{10}	5×10^{11}	$\sim 5 \times 10^{12}$	$\sim 1 \times 10^{14}$

^a f_E contains f_A as well as all the other enhancement factors in the second line of the expression given for $n\tau$ in Sect. 1.2.2.

Fig. 1.6. Plot of $\langle n\tau \rangle$ vs $\langle T_i \rangle$ for tokamaks and EBT's.

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Fig. 1.7. Plot of $\langle n\tau \rangle$ vs $\langle T_i \rangle$ and pulse length t_p for tokamaks and EBT's.

1.3 THE LOGIC OF THE EBT-P DESIGN

1.3.1 Scaling and Goals

Simple scaling arguments are presented below to indicate why high frequency microwave power (≥ 60 GHz) and large major radius (≥ 4.5 m) are required to achieve POP-like parameters. These simple calculations are confirmed by 1-D code calculations.

As discussed above theoretical analyses of EBT performance give a scaling for $n\tau$ that predicts that for EBT-P

$$(n\tau)_{\text{EBT-P}} \cong (n\tau)_{\text{EBT-I}} \cdot \left(\frac{R_p}{R_1}\right)^2 \cdot \left(\frac{R_{B1}}{R_{Bp}}\right)^{1.4} \left(\frac{a_p}{a_1}\right)^{0.6} \times \left(\frac{f_{\mu p}}{f_{\mu 1}}\right)^{1.8} \\ \times \frac{(\nu/\Omega)_1^{0.6}}{(\nu/\Omega)_p^{0.6}} \cdot \frac{(1 + C T_i/T_e)_p^2}{(1 + C T_i/T_e)_1^2} \cdot f_A^2 \left(\frac{n_{cp}}{n_{c1}}\right)^{0.6},$$

where the first line assumes operation under similar conditions (as in EBT-I of collisionality), T_i/T_e , and density normalized to cut-off. The second line indicates possible improvements, that come from geometry and optimization of heat and particle deposition outside the range already investigated in

In discussion with the IPs it was agreed that EBT-P should be able to achieve a significant advance over EBT-I to satisfy the scaling requirements of proof-of-principle and that this should be achieved without invoking the improvements. To satisfy a comparison with PLT, then, it should have the capability, with improvements, of studying comparable conditions to PLT (i.e., $n\tau \geq 10^{12}$ cm⁻³ sec, $T_i > 1$ keV). (Temperatures are volume average values.)

At constant collisionality $T_e \propto (n B R_B a)^{0.4} \propto T_i$ for constant T_i/T_e , or $T_i \propto (f_{\mu})^{1.2} (R_B a)^{0.4}$. Representative of the best EBT-I parameters are $n\tau \cong 10^{10}$ cm⁻³ sec and $T_i \cong 0.1$ keV. There is a requirement that the plasma radius should scale up significantly from EBT-I. Because the cost of the device scales rapidly with size we are restricted to $a_p/a_1 \sim 2$. From a knowledge of the way EBTs scale, we take $M \sim 2$, constant collisionality, T_i/T_e , and n/n_c . Further, in order to preserve single particle confinement comparable with that of EBT-I we use a coil radius roughly proportional to the plasma radius. So,

$$R_{Bp}/R_{B1} \cong 1.5 \rightarrow 2.$$

Then,

$$(n\tau)_p \cong 0.57 \rightarrow 0.96 \times 10^{10} \left(\frac{R_p}{1.5}\right)^2 \left(\frac{f_{\mu p}}{18}\right)^{1.8} \text{ cm}^{-3} \text{ sec} \\ T_{ip} \cong 0.17 \rightarrow 0.16 \left(\frac{f_{\mu p}}{18}\right)^{1.2} \text{ keV}.$$

To achieve $T_{ip} \geq 1.0$ keV with this simple formulation requires $f_{\mu p} \geq 90$ GHz. To achieve $(n\tau)_p \geq 10^{12}$ cm⁻³ sec at 90 GHz requires $R_p \geq 4.5$ m.

In the reference designs presented in November the goals of $(n\tau)_p \geq 10^{12}$ cm⁻³ sec and $T_i \geq 1$ keV were achieved either by the use of frequencies in the range of 94-110 GHz or by invoking aspect ratio

enhancement effects at 60 GHz. Following discussions, where it was agreed that it was likely that 60 GHz gyrotrons would be developed (and should be developed) first and that it was reasonable to assume that some improvements would work, a design has been pursued that has $R \cong 4.5$ m and initial operation at 60 GHz, but that has toroidal coils capable of going to higher fields to utilize $f_{\mu} \approx 90$ GHz. Thus the design in its initial form has the capability of $(n\tau)_p \cong 5 \times 10^{11} \text{ cm}^{-3} \text{ sec}$ and $T_{ip} \cong 0.7 \text{ keV}$.

1.3.2 Improvements

To take advantage of all the possible improvements, the device should have the capability of accommodating techniques for improving performance. The suggestions given in design studies were:

- Ion heating techniques, by ion cyclotron heating (ICH), lower hybrid heating (LHH), and by beams, both neutral and molecular ion. The use of ion heating to supplement ECH is analogous to the use of ion heating in PLT to supplement ohmic heating and raise the value of T_i/T_e .
- The use of separate ECH launching positions, in the main cavity to drive the electron ring, and in the coil throat to heat the toroidal core plasma. This should give better control of the ring and toroidal core plasma which should ensure a good operating range of plasma parameters.
- The use of aspect ratio enhancement (ARE) to improve single particle orbits and energy confinement, by the use of either or both of wedging and additional ARE coils, to vary plasma centering and the mirror ratio.
- The use of a divertor to give control of the plasma edge and to permit the use of neutral beams.

In the initial phase of the device, heating will be with a minimum number of gyrotrons (4 x 200 kW at 60 GHz) for ring production and ECH consistent with the budget and a credible schedule to bring them in to operation. Modest amounts, initially, of ICH (~100 kW) are proposed for ion heating. Further, ECH power will be added during the first phase of machine operation to a total, possibly, of 2.4 MW. In initial operation profile heating power may be available at 28 GHz (2 x 200 kW) using EBT-S systems. The areas for improving performance are discussed in the appendices. More detailed design is needed to tie down the "optimum" design. Some brief comments are made below.

The question of the benefits of wedging the toroidal coils is discussed in Appendix 3. A design with modest wedging is being studied and is indicated. However, there has not been time to work out an "optimum" design and this trade-off is left to the chosen IP. In any case, ARE coils may be added at a later time. Given that such coils generate only modest field they could be demountable and therefore added relatively easily during the first phase of operation.

To provide throat launching of ECH there are essentially two possibilities, launch through the coil and launch around the coil. Both techniques were proposed by IPs, and each has its own problems. Wedging has been proposed both for improving confinement and because the split coil might be used for throat launching. Again, there has been no time to determine the "optimum" technique, and the option is left open to the chosen IP. In any case some techniques require the use of polarized μ -wave power, and in the opinion of experts this may not be available economically until later phases of the machine operation. (Note that the mode structure of the successful 60 GHz gyrotron is not known at the present time.) Electron cyclotron heating is discussed in Sect. 3 and Appendix 4.

The use of neutral beam heating and molecular ion beam heating and potential control are discussed in Appendices 6 and 7. The application of these systems apparently does not make any great demands on the design of the device, and each could be applied provided reasonable access through the activities is allowed. Similarly it should be possible to add a divertor by replacing a few sectors of the device.

The majority of the improvement techniques are scheduled for testing on the EBT-I/S device as indicated in Fig. 1.5. The testing of molecular ion beam injection and throat launching is under discussion.

With improvements it is projected that EBT-P will achieve the parameters given in Table 1.3 and shown in Figs. 1.3 and 1.4.

1.3.3 Superconducting Coils

In comparison with EBT-I, which has 24 water-cooled copper coils, $R = 1.5$ m, and uses 5 MW of dc power to produce a resonant field $B_r \sim 0.65$ T, EBT-P will have $R \cong 4.5$ m and 36 coils of similar geometry, but proportionally larger dimensions, producing a resonant field of $B_r \geq 2.0$ T. For water-cooled copper coils, the power required would exceed 50 MW. Because the steady-state operation of EBT-P is an important consideration and because further power is required for the production of the rings and plasma, all participants followed the logic of the EBT II design in using superconducting coils to minimize the total power requirements. The use of superconducting coils does, however, place significant constraints on design because of the need for x-ray shielding and for dewars and thermal shields. The x-radiation is produced when energetic ring electrons impinge on the limiters (or walls). A criterion for the design of EBT-P has been that the single-particle confinement in the vacuum magnetic fields should be comparable with that in EBT-I. To a first approximation this requires that the coil plasma geometry be "photographically" increased in size from EBT-I to EBT-P. To maintain the geometry, given the greater distance from plasma to coil, because of shielding needed in addition to the coil supports, it is necessary to increase the coil radius and to minimize machine size to go to higher current densities. In the design presented here the coil is approximately 1.7 times larger than that in EBT-I, and it has a capability of a current density 1.5 times higher. These dimensions taken together with the goals of the device lead to a major radius $R \sim 4.5$ m. Approximately, the magnetic curvature $R_B \propto R_C$, the minor radius of the coils, and in the scaling formula above, $n\tau \propto (R/T_C)^2$. Consequently a similar performance could be obtained in a device of smaller major radius (R), if the coil minor radius (R_C) could be decreased. Two proposals were made that lead to smaller R_C . First, by restricting the maximum frequency to 60 GHz it is possible to lower the field on the coil and consequently to raise the current density for comparable coil stability and decrease the coil cross section. In addition, since ring power should scale as B^4 , less x-rays are produced and less shielding is needed. Both factors lead to a smaller value for $R_C \sim 1.5$ times larger than EBT-I, and $R \sim 3.6$ -4.0 m. This option still remains open to the chosen IP. If budgetary restrictions become more stringent, however, there is general agreement that it would be advisable to maintain the higher field option to give increased upgrade potential and to permit more extensive scaling of both plasma and ring physics within the same device. A second proposal involved the use of hybrid coils where the x-ray shielding was replaced by a thicker water-cooled copper coil that also would provide shielding. This design leads to an effectively smaller coil radius by placing current carriers closer to the plasma and by reducing the requirements of field production on the superconducting coil. The design proposed had $R_A = 4.2$ m for operation at up to 100 GHz. There has not been time to evaluate such a design in detail and again it remains an option open to the chosen IP. One difficulty is to make a copper coil with adequate cooling. A solution is to use, as in EBT-I, a number of individually cooled windings; a problem is then routing the leads and minimizing field errors. A discussion of magnetic design is given in Appendix 3.

1.4 CONSTRAINTS ON THE EBT-P DESIGNS

During meetings on November 8, 1979, and November 29-30, 1979, discussions were held with the candidate IP'S to determine the physics and technological constraints which were considered to represent a reasonable balance between conservatism and optimism. These discussions were remarkably constructive and productive. The results are itemized below.

1.4.1 Relativistic Electron Rings

A discussion of relativistic electron rings and a summary of a workshop on this topic held December 3-5, 1979, are presented in Appendix 1.

For the design of EBT-P it was agreed that the following conservative numbers should be assumed:

- The ring volume is ~10% of the toroidal plasma volume.
- As a base case, the ring energy is chosen to be $T_{\text{RING}} \approx 500 \text{ keV}$, or better, $500 \text{ keV} < T_{\text{RING}} < 1\text{-}2 \text{ MeV}$.
- Based on experimental results and theoretical calculations, the ring power is $P_{\text{RING}} \approx 0.5 \text{ W cm}^{-3}$ for 60-GHz bulk heating and 1 T at the ring.
- It was pointed out that this is a conservative estimate and improvements are possible in the area of microwave feeding, operating, controlling, and so on.
- For shielding purposes the following specifications are given: for the ring power, 0.5 W cm^{-3} at 1 MeV energy with a Maxwellian distribution out to 10 MeV for operation at 60 GHz (1 T at the ring). At higher fields the power scales as $P_{\text{RING}} \propto B^4$.

1.4.2 X-ray Shielding

This topic is discussed in Appendix 2. For the purpose of design, the shielding requirements are taken to be:

- Shield material unspecified, except no uranium. Tungsten is favored in most of the designs.
- Personnel shielding: 2.5 mr/hr at the outer shield wall and vicinity, 0.25 mr/hr in noncontrolled areas.
- Coil shielding: 10 W per coil; for split-wedged coils, 10 W per coil pair.
- The source of x-rays is the energetic electrons leaving the ring and striking the limiter. The power striking the limiter is 0.5 W cm^{-3} times the ring volume times the scattering fraction (see Appendices 1 and 2). The ring volume is taken to be one-tenth the plasma volume.
- The energy distribution of electrons striking the limiter is a temperature of 1 MeV with maximum energy 10 MeV and the particle loss rate varies as $E^{-3/2}$.
- The source of the x-rays is uniform over an area of 10 cm^2 on each side of each coil. Thus, for a 36-coil set there are 72 localized sources of x-rays.

1.4.3 Superconducting Magnets

These are discussed in Appendix 3. The agreed design constraints are that:

- The maximum resonant frequency will be ~90 GHz and maximum field on the coil ~8 T. The maximum current at the high field operating point will be $\leq 2,000 \text{ A}$.
- NbTi will be the superconducting material and it will be cooled by pool boiling. The maximum bath temperature will be 4.4°K . The x-ray heat load will be 10 W per coil or 10 W per coil pair for split wedged coils.

- The maximum current density of the winding as a fraction of maximum field on the winding will be:

Maximum winding	9 kA cm ⁻² at 8T
Current density	11 kA cm ⁻² at 7T
	13.5 kA cm ⁻² at 6T
	17.5 kA cm ⁻² at 5T

1.4.4 Microwave Systems

The theory and technology of microwave systems are discussed in Sect. 3 and Appendix 4.

Systems

- The frequency chosen for initial operation is 60 GHz. This represents a good balance between advancing gyrotron development and the needs of the whole fusion program. It is a reasonable step for the EBT program, which presently uses frequencies up to 28 GHz.
- Mode-controlled transmission and launching systems, while highly desirable, are not absolutely essential to EBT-P goals. Multimode systems have a higher probability of being realized on schedule.
- Disadvantages of multimode systems include: additional constraints on gyrotron development that will impact the schedule; lower transmission efficiency; and requirement of significant additional development, which will increase the technical risk.
- Nevertheless, it is very desirable that mode controlled systems be developed for added flexibility and degree of control in later experiments.

Throat launching

- Provision for launching microwave power in the coil throats is desirable. Single mode operation is preferred.
- Provision for waveguide windows on the high field side of the outer resonance, suitably shielded from the plasma, is prudent. For a multimode system it is essential.
- The ECH power density at the launch ports should not exceed 3-5 kW cm⁻².
- There are impedance matching concerns owing to the close proximity of plasma in the throat region.
- As few as four throat launchers may be sufficient for initial experiments, but the design of EBT-P should be sufficiently flexible to permit future ECH application in all coil throats.

Cost

- Gyrotron power supplies are one of the major items determining cost (given the gyrotron efficiency of ~20%).
- It is prudent to limit the numbers of tubes to one or two per supply for initial EBT-P construction. Later upgrades may realize cost savings from the simplification of supply systems as gyrotrons are refined.
- The ECH transmission and distribution efficiency is likely to range from ~50% for a mode-controlled system to 70-80% for a multimode system.
- Estimates have been made for the cost per watt delivered to the transmission system by a single tube (~\$5/W) and the cost per watt delivered to the plasma (~\$10/W). It must be fully recognized that these estimates are extremely primitive, because neither the 200-W, 60-GHz tube nor the

distribution exist. Furthermore, the estimates are based on the design presented in this document.

1.4.5 Ion Cyclotron Heating

This is discussed in Appendix 5.

- ICH should be included in the EBT-P design. It is attractive as an auxiliary heating technique and should cost ~\$1 per watt. This is discussed in detail in Appendix 3.

1.4.6 Theory

The theory of EBT's is discussed in numerous published papers⁴⁻¹² and in Sect. 3 and for magnetics design in Appendix 3. An issue is the definition and calculation of aspect ratio enhancement, and specifically the factor f_A where $A_{eff} = f_A A$.

- It was agreed that for minimum (initial) performance $f_A = 1$, but that $f_A > 1$ could be considered among the EBT-P improvements.
- For calculating f_A from single particle orbits in the vacuum magnetic fields there were various proposals. It was agreed that in computing single particle orbits the ring (outer radius) should be used as a virtual limiter.
- It was agreed that maximizing volumetric efficiency over all $v_{||}/v$ was desirable.

1.4.7 Startup Diagnostics

Three categories of diagnostics were identified.

- Startup diagnostics:
 - Thomson scattering (single point)
 - Microwave interferometer (single chord)
 - Closed-circuit television monitor (not computer interfaced)
 - Toroidal current sensor
 - Ring current sensor
 - Hard x-ray detectors (NaI)
 - Ionization gauges
- Basic EBT diagnostics:
 - Thomson scattering (multipoint)
 - Microwave interferometer (multipoint)
 - Heavy ion beam probe
 - Spectroscopy (multichord) visible → VUV
 - Soft x-ray (multichord)
 - Charge exchange (multichord)
 - Bolometers
- Desired EBT diagnostics:
 - Surface physics
 - Synchrotron radiation
 - Laser Faraday rotation
 - Barium beam
 - Neutral beam — charge exchange
 - Crystal x-ray spectrometer

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2. THE ELMO BUMPY TORUS EXPERIMENT AND RESULTS

2.1 INTRODUCTION

EBT-I was constructed to investigate the ability to create diamagnetic electron annuli by high power microwave heating in toroidal geometry and to study the effect of these annuli on the toroidal plasma equilibrium. Experiments began in 1973 and quickly confirmed the existence of stable annuli and their stabilizing effect on the toroidal plasma. The effort then shifted to documenting the toroidal plasma. What follows is a brief synopsis of EBT experimental results through the recent shutdown in November, 1979.

The physical dimensions and operational parameters of EBT-I/S are listed in Table 2.1. The magnetic field is produced by 24 magnet coils arranged about a torus, each pair producing a 2:1 magnetic mirror ratio on the axis. Each mirror sector is fed with steady-state microwave power at 10.6 GHz and 18 GHz. It should be noted that EBT-Scale (EBT-S) is an upgrade of the EBT-I machine consisting of an increased magnetic field (to 1.0 T midplane) and the addition of microwave power at 28 GHz. In its present configuration the EBT device can operate in either the I or S mode, hence the reference EBT-I/S.

Table 2.1. Physical characteristics and operational parameters of EBT-I/S

Characteristic	Value
Magnetic field (maximum)	0.65 T (midplane), 1.3 T (mirror)
Magnetic field power	10 MW supplied by motor-generator sets
Major radius	150 cm
Aspect ratio (major to mean coil radius)	9:1
Torus volume	1350 liters
Microwave power (evenly distributed among 24 cavities)	200 kW at 28 GHz, 60 kW at 18 GHz, 30 kW at 10.6 GHz

2.2 EBT OPERATIONS

EBT is generally operated steady state (~ 4 hours, limited by operator fatigue). To operate the device the magnetic field is adjusted to the desired level, and the operating gas, usually hydrogen (although deuterium, helium, nitrogen, argon, and even air have all been used as operating gases), is fed into only one of the toroidal bumps so that the pressure rises to 10^{-5} torr. As the microwave power is introduced a plasma is formed, and the particles recirculate between the walls and plasma until an equilibrium is reached between atoms returning from the walls and losses out of the plasma. The fast servo-controlled gas-feed input is just a "makeup" gas for the small fraction of recirculated atoms that manage to be pumped out of the device. The desired plasma conditions are then established by first adjusting the bulk heating power at 18 GHz, the profile power at 10.6 GHz, and then the ambient gas pressure.

Plasma parameters at the experimental operating point critically depend on a symbiotic relationship between the toroidal plasma and the energetic annuli. The toroidal plasma requires stable electron annuli with a minimum energy density ($W_{\perp}$, hence β_{annulus}) to establish the minimum average B configuration. In turn, the annuli require a cool electron component in the toroidal plasma for their stability.¹ The ultimate source of the toroidal plasma is the cold gas recirculating from the walls.

Experimentally, the operating point is controlled with the background neutral pressure and the microwave power. At high background neutral pressure (10^{-5} torr) and modest microwave power (tens of kilowatts), the rings cannot form with sufficient $W_{\perp}$ to stabilize the toroidal plasma because of collisional loading by the cold gas. However, a significant average toroidal plasma line density ($n_{e\ell}$) is observed using a 70-GHz interferometer (Fig. 2.1). The rings are stable as monitored by $W_{\perp}$, but the toroidal plasma density fluctuation level under these conditions is high [$\Delta(n\ell)/(n\ell) > 1$] in the bandwidth of the interferometer (10 Hz - 30 kHz).

This regime of operation is designated as the C-mode for cold plasma operation. As the neutral pressure is lowered (at fixed microwave power as shown in Fig. 2.1), the stored energy in each sector increases and $\bar{n}_e$ falls slightly. Depending on experimental conditions (i.e., power and pressure), a point is reached where the fluctuation level falls dramatically to almost thermal levels in optimum cases [$\Delta(n\ell)/(n\ell) \sim 10^{-3}$]. The drop in fluctuation level marks the beginning of the T-mode (for toroidally confined mode) and the existence of minimum average B stabilization. The regime is the fusion-relevant condition since fluctuation-free confinement is observed and the density and ion electron temperatures are relatively high. Parameters continue to improve as the pressure decreases over a moderate range (typically $3-10 \times 10^{-6}$ torr). This can be understood by noting that as the pressure drops ($n_{e\ell}$ also drops slowly; see Fig. 2.1), the input ECH power is shared by fewer electrons in the cavity. The toroidal plasma electrons become hotter, and thus their collision frequency ($\nu_e \sim T^{-3/2}$) and collisionality ($\nu_e/\Omega_e \sim T^{-5/2}$) decrease. A drop in collisionality implies a longer residence along a precessional orbit, hence a longer confinement time. In essence, the bumpy torus geometry provides a volume equilibrium in which to make a plasma, and once a minimum critical annulus beta has been achieved (T-mode), the rings allow the volume to be filled stably with warm plasma at nonzero beta.

The pressure cannot be lowered indefinitely, however, because the source of cold electrons required to keep the rings stable decreases with pressure. At a certain point the plasma undergoes an abrupt transition to a mode in which the annuli are no longer macroscopically stable. In this mode, designated the M-mode (for mirror mode), steady-state operation is not possible. The critical pressure at which this transition occurs is reduced by extended operation; this indicates that wall conditioning plays a role. For pressures slightly higher than the critical value, instability activity is observed on the microwave interferometer, which indicates that instabilities, perhaps drift waves, play a role.

2.3 MEASUREMENTS OF PLASMA PARAMETERS IN T-MODE

The EBT-I diagnostic array is, in principle, no different from the standard diagnostic array that is installed on all tokamaks, an excellent compilation of which has been done by the TFR group.² The steady-state nature of the plasma also appears to be ideal for plasma measurements. The distinction, however, lies in the magnitude of the basic plasma parameters, i.e., low densities (10^{12} cm^{-3}) and relatively moderate temperatures ($T_e \approx 400 \text{ eV}$, $T_i \approx 100 \text{ eV}$). As a consequence, diagnostics that count events require long counting times ($\sim 10 \text{ min}$) or multiple counting intervals (e.g., Thomson scattering) to improve the statistics. The low temperatures imply detection in ranges where standard techniques suffer from a disastrous loss in sensitivity. Long times and low sensitivity imply slow data taking and, in some cases, loss of transient physics. Furthermore, all diagnostics must be isolated from the high levels of microwave and x-ray radiation inherent to EBT operation. The present diagnostic array and typical plasma parameters in T-mode are listed in Table 2.2. The details are reported elsewhere.³

Fig. 2.1 Plasma parameters measured in EBT-I as a function of observed stored energy W_1 : (•) neutral pressure, (o) density fluctuation level, $[(\cup) n_e l]$ line density.

Table 2.2. Diagnostic array and typical plasma parameters in T-mode

Parameter	Diagnostics
T_e	Si(Li) x-rays, Thomson scattering (corroborative)
n_e	Microwave interferometer, probes, bremsstrahlung
T_i	Charge exchange
n_o	Spectroscopy, charge exchange
ϕ	Heavy ion beam
n_z	VUV spectroscopy
B	Probes, loops, etc.

Typical steady-state EBT-I toroidal parameters

$n \sim 1-2 \times 10^{12} \text{ cm}^{-3}$
$T_e \sim 200-600 \text{ eV}$
$T_i \sim 50-150 \text{ eV}$
ϕ Positive at rings, well depth of 100-300 V, electric field points radially inward
$n_z/n_e \sim 10^{-3} - 10^{-4}$
(C,Al: $Z_{\text{eff}} \sim 1.01-1.001$)
$\beta \sim 0.2-0.5\%$

The line density of electrons was measured using a 70-GHz microwave interferometer. The plasma diameter was taken from Langmuir probe data, which indicated $\ell \approx 20-30 \text{ cm}$. From the observed interferometer phase shifts in T-mode, $\bar{n}\ell = 1.5 \times 10^{13} \text{ cm}^{-2}$.

The density was also deduced from bremsstrahlung measurements. These measurements were, in general, lower than those observed with the interferometer measurements. This is not surprising, since the phase shift is sensitive to all electrons along the plasma arm of the interferometer and the x-ray signal is due only to the electrons above some threshold energy, in this case above about 500 eV. In particular, the interferometer is sensitive to the surface plasma outside the hotter core; the x-ray detector is not. At the lowest neutral pressure consistent with T-mode, the densities differ by less than a factor of 2. As the pressure is increased, the relative contribution of the surface plasma increases and the difference between the two density measurements also increases. In discussing the behavior of the toroidal plasma as a function of power or pressure, we have used the bremsstrahlung observations.

Several techniques have been used to establish T_e in the closed drift surface region during T-mode operation. These include spectroscopic measurements of impurity intensity ratios, heavy ion beam probing, Thomson scattering, and soft x-ray spectroscopy. Each has its own set of difficulties, and generally data are not available for comparison. However, all four have served to corroborate the existence of a warm electron component while using soft x-ray measurements as the principle diagnostic tool.

Vacuum ultraviolet experiments on emission lines of CIV make use of the temperature dependences of excitation cross sections to determine core temperatures. From spatial scans of the plasma over a

variety of operating conditions, ratios of intensities of these transitions indicate T-mode temperature in the range 40-300 eV. Uncertainties in excitation cross sections are the major sources of error in these calculations.

The ion beam probe is capable of obtaining a spatially resolved indication of electron temperature by similarly making use of the temperature dependence of beam ionization cross sections. Through spatially resolved detection of 2, 3, and 4 times ionized reaction products from Rb and Cs beams, a lower bound $T_e > 50$ eV across the plasma cross section has been established. However, despite the sensitivity of this technique, accurate determination of electron temperature has to date proven impossible due to beam distortion as well as numerous difficulties in calibration.

Thomson scattering experiments have used a 1-J and more recently a 14-J, Q-switched ruby laser. At the limited plasma density ($n_e \sim 10^{12} \text{ cm}^{-3}$) and in the presence of relatively high plasma light background signal, it was difficult to obtain data over a broad range of operation. Under modest operating conditions, T_e ranged between 50 and 250 eV with probable error the order of a factor 1.5. To date only limited Thomson scattering data are available for standard T-mode operation of EBT.

The principal diagnostic tool used for electron temperature determinations was a "windowless" lithium-drifted, silicon [Si(Li)] barrier detector. From observations at various operating conditions, the range of electron temperatures in the T-mode is between 150 and 600 eV with confidence levels about a factor of 2.

As noted earlier the EBT plasma depends strongly on the pressure equilibrium. A scan of density (n_e), stored ring energy (W_L), and well depth (ΔV_p) is plotted vs gage pressure in Fig. 2.2 for 40 kW of input power. The onset of T-mode conditions is clearly seen as the rapid increase of W_L and the existence of a potential well. The approach of the T-M transition, however, is seen as the rapid fall off of n_e and ΔV_p . A systematic scan of this behavior for n_e as a function of various combinations of 18 GHz + 10.6 power is seen in Fig. 2.3. A map of the stable equilibrium found in T-mode can be seen. Further, it is seen that density does not vary significantly with changes in pressure at a particular value of microwave power when operating in the T-mode. However, both the electron and ion temperatures increase with a decrease in pressure, again indicating that the confinement increases. A scan of electron temperature obtained from Thomson scattering vs pressure is shown in Fig. 2.4.

Typical measurements of plasma space potential made with a heavy ion beam probe show a symmetric well and hence a radially inward pointing electric field as shown on Fig. 2.5. A pressure scan in Fig. 2.6 shows that the well depth and peak potential increase as pressure decreases and that the density measurement $nf(T_e)$ supplied by the heavy ion beam probe decreases, consistent with the microwave interferometer. A scan of the magnetic field demonstrates that as the resonance region moves toward the axis, the rings move inward and hence the plasma radius decreases, as shown, for example, by the space potential in Fig. 2.7. Recent experiments have indicated the ability to extract more details of the temperature, density, and potential in the neighborhood of the rings with the beam probe. Preliminary indications are that a very hot electron component is located radially just outside the peak potential. Quantitative information must await further experiments.

Spectroscopic measurements of impurity lines indicate that impurities are kept from entering the toroidal plasma, yielding a Z_{eff} approaching unity in the toroidal plasma. Evidence of a natural diverter action can be seen in isometric projections of reconstructed emission distributions of impurity line radiation. As shown in Fig. 2.8 the impurity density profile for neutral aluminum is hollow, indicating that neutral aluminum does not get into the core. Aluminum is a natural impurity because the cavity walls are aluminum.

Table 2.3 indicates the average impurity density for the major impurities found in the experiment. It is also seen experimentally that the temperature of the impurities is quite high. For the first two charge states of aluminum, the temperature is 80 eV and 40 eV, respectively, and may explain why there is no impurity buildup.

Fig. 2.2 A scan of density ($n_e \ell$), stored ring energy (W_1), and well depth (ΔV_p) vs gage pressure for 40 kW of 18 GHz power.

Fig. 2.3 A scan of $n_e \ell$ vs gage pressure for various combinations of 18 GHz + 10.6 GHz power.

Fig. 2.4 T_e vs gage pressure obtained by Thomson scattering.

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Fig. 2.5 Space potential measured in EBT-I as a function of position in the midplane (T-mode conditions). The computer-generated perspective view includes data taken at various energies and angles of beam incidence and then "spline-fits" the data to present the smoothed display. No data are taken outside the points at which the maximum potentials are found.

Fig. 2.6 Space potential (well depth and peak) and $nf(T_e)$ (a measure of density) vs gage pressure.

Fig. 2.7 Space potential vs radius for toroidal magnet field current 4000 A, 4500 A, and 5000 A. The centerline field is approximately 1 G/A.

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Fig. 2.8 Isometric projection of the reconstructed emission distributions of Al I λ 2151.

Table 2.3. Impurity concentrations

Species	Density at $r = 0$ (cm^{-3})
C II	6×10^7
C III	4×10^7
C IV	1×10^7
Al II	5×10^7
Al III	1×10^8

This technique was also used to estimate the value of the neutral hydrogen density in the core. Under typical conditions the neutral hydrogen density is the order of 10^{10} cm^{-3} . A Fabry-Perot scan of the H^0 line indicates that the energy of the bulk neutrals is bi-Maxwellian with temperatures of the order of 1/2 eV and 5 eV. Furthermore, the two energy groups are approximately equal in concentration.

The EBT-I experiment has demonstrated nearly "quiescent" T-mode operation with very low density fluctuation levels. A comparison can therefore be made between the experimentally observed plasma parameters (e.g., ion and electron temperatures, plasma density and potential, and energy confinement time) and the values predicted by neoclassical transport theory for a stable bumpy torus with ordinary particle collisions and charge exchange as the only loss mechanisms. Parametric studies of the electron energy confinement time (normalized as $T_e \tau_e / B$) vs the collisionality parameter (ν/r) (Fig. 2.9) show remarkable agreement with the electron energy confinement times derived by Kovrizhnykh and extrapolated to the experimentally observed value of electric field (i.e., $e\phi_s/kT_e \approx 1$).

Fig. 2.9 Normalized relative average energy confinement time ($T_e \tau_e / B$) as a function of collisionality parameter (ν / Ω) for a wide range of operating parameters of EBT-I. The solid curves indicate neoclassical predictions assuming $e\phi_s/kT_e = 1$ and either a linear or parabolic spatial profile of T_e . Preliminary data for EBT-S is also shown.

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3. THEORY

Here theoretical projections for the toroidal core plasma (n , τ , T_e , T_i) are discussed for initial phases of operation of EBT-P, as are methods for enhancing performance through optimization of heat and particle deposition. In Sect. 3.1, plasma performance is projected using a one-dimensional (1-D) transport code which includes some of the effects produced by the hot electron rings. The results from this code are in reasonable agreement with experimental observations from EBT-I/S as well as the simple scaling discussed in Sect. 1.2. In addition to pure ECH, Sect. 3.1 includes one-dimensional calculations assuming direct heating of ions (ICRH or neutral beams). These calculations indicate that direct ion heating significantly raises the ion temperature.

Section 3.2 includes brief discussions of ECH in EBT-I and differences expected in EBT-P. Also included is a discussion of some of the methods for varying the ECH deposition profiles in phase space. (There are five distinct ways of controlling the deposition of heat and/or particles in EBT-P, some of which are only discussed in the appendix.) The motivation for each of the five ways of providing different heat and particle deposition in phase space is to improve plasma performance through control of core and ring densities and temperatures, ambipolar electric field, and finite beta magnetic field profiles. Each specific technique aims at controlling a few specific quantities to improve plasma performance through more efficient use of power.

A central theme of several of the heat deposition methods is separate control of the hot electron ring and toroidal core plasmas. One motivation for this is that it should permit lower collisionality operation with its attendant improved plasma performance. Experiments on EBT-I and NBT show that a lower bound on collisionality exists — the T-M transition. It has been observed that the lower bound on collisionality imposed by the T-M transition can be effected by techniques such as profile heating (a second, lower frequency component of microwave heating). The present theoretical and experimental evidence suggests that three mechanisms play a role in the T-M transition and that controlling any one of them tends to permit lower collisionality. The mechanisms involved appear to be: neoclassical and atomic physics process; thermal runaway of the hot electron rings; and instabilities (e.g., drift waves).

Learning to control instabilities is also a longer term goal of the EBT program since it affects the maximum core beta which can be achieved. Most of the stability criteria for EBT involve profiles of both toroidal core and hot electron ring plasmas (often translated into requirements on core or ring betas and densities). The five methods for controlling heat and particle deposition coupled with the methods for controlling single particle losses through magnetic field shaping (Appendix 3) should permit comparison of experiment at higher betas with more highly evolved theoretical descriptions of the stability boundaries. Many of the longer term issues of the EBT program hinge on ring/core interaction at higher beta (see Appendix A.1). These issues include stability, ring scaling, and hot ion transport in the ring region. The six distinct methods of controlling and improving plasma performance suggested in this document hold out the possibility of not only achieving minimum requirements in the initial phases of EBT-P operation but also addressing in later phases the additional physics and technology issues which are central to the development of the EBT reactor concept.

3.1 TRANSPORT CALCULATIONS FOR EBT-P DESIGN STUDIES

Encouraging results from the ELMO Bumpy Torus (EBT-I) experiment¹ have prompted interest in scaling to larger experiments (EBT-P) with confinement parameters in the range $\bar{n}\tau_E \sim 10^{12} \text{ cm}^{-3} \text{ sec}$ and $T_i \sim 1 \text{ keV}$. In projecting to these larger machines, it is important to use the most realistic magnetic geometry possible in transport calculations. The calculations given here represent an advance over previous calculations of EBT transport²⁻⁴ in that the transport equations are averaged along magnetic field lines

computed from a 2-D solution to the magnetic equilibrium equation in mirror geometry.⁵ An isotropic pressure peaked off axis approximates the finite beta, hot electron ring plasma. Toroidal plasma pressure is neglected due to low toroidal beta. Previous transport calculations²⁻⁴ have assumed cylindrical geometry with ad hoc magnetic field profiles. As in the previous calculations, the present work assumes neoclassical transport including approximate lowest order effects of velocity space regions where poloidal drift frequencies are small. In the moderate collisionality regime with radially inward pointing electric fields, this leads to so called "plateau" ion transport, which is approximately independent of collisionality^{3,6} [we use Eq. (14) of Ref. 3], and to electron transport as derived by Kovrizhnykh.⁷

Assuming isotropic pressure ($P \equiv P_\perp = P_\parallel$) and poloidal symmetry, the magnetic equilibrium equation can be written

$$\nabla^2 \psi_p \equiv \frac{\partial^2 \psi_p}{\partial r^2} - \frac{1}{r} \frac{\partial \psi_p}{\partial r} + \frac{\partial^2 \psi_p}{\partial z^2} = -\mu_0 r^2 \frac{\partial p}{\partial \psi}, \quad (1)$$

where r and z are the radial and longitudinal coordinates, respectively.⁵ The flux function ψ is proportional to the magnetic flux in the z direction.

$$\psi(r) = \int_0^r r dr B_z, \quad (2)$$

and can be separated into two components such that $\psi = \psi_p + \psi_c$, where ψ_c is due to external currents in the coils and ψ_p is due to diamagnetic currents in the plasma. The isotropic pressure P can also be divided into two parts such that $P = p(\psi) + \hat{p} \cdot g(\psi)$, where $p(\psi)$ is due to the low beta toroidal plasma and here will be neglected in comparison with the second term $\hat{p} \cdot g(\psi)$, which is due to the high beta electron rings. The function $g(\psi)$ is chosen as

$$g(\psi) = \begin{cases} 0, & \text{if } \psi < \psi_1 \\ \frac{(\psi - \psi_1)^2(\psi - \psi_a)^2}{(\psi_2 - \psi_1)^2(\psi_2 - \psi_a)^2}, & \text{if } \psi_1 \leq \psi \leq \psi_2 \\ \frac{(\psi - \psi_b)^2(\psi - \psi_3)^2}{(\psi_2 - \psi_b)^2(\psi_2 - \psi_3)^2}, & \text{if } \psi_2 \leq \psi \leq \psi_3 \\ 0, & \text{if } \psi_3 < \psi \end{cases}, \quad (3)$$

where $\psi_a = 2\psi_2 - \psi_1$ and $\psi_b = 2\psi_2 - \psi_3$.⁵ The values of ψ_1 , ψ_2 , and ψ_3 are adjusted during the solution of Eq. (1) to keep the maximum and zeroes of the pressure profile at fixed radii in the midplane.

Figure 3.1.4 shows typical solutions to Eq. (1) for EBT-I and EBT-P parameters, respectively. For both cases, the electron ring pressure is chosen so that $\beta_A = \hat{p}/(B_{00}^2/2\mu_0) = 40\%$, where $B_{00} = B(r=0, z=0)$. The figure shows contours of constant $|B|$ and magnetic field lines (contours of constant ψ) for a 24-sector 18-GHz EBT-I device with a major radius (R) of 1.5 m; the annulus pressure is assumed to

Fig. 3.1. Contours of constant B and constant ψ from Eq. (1) for EBT-I (a) and EBT-P (b).

peak at $a = 0.10$ m in the midplane with a half-width (δ) of 0.02 m. Similar contours are shown for a 36-sector, 60-GHz EBT-P device with $R = 4.5$ m, $a = 0.20$ m and $\delta = 0.04$ m. The magnetic well formed by the ring pressure is clearly evident in the $|B|$ contours in Fig. 3.1, and deformations of the $|B|$ contours extend all the way into the mirror throat. This result is clearly sensitive to the isotropic pressure assumption. The magnetic field lines in the figure are relatively unaffected by the ring.

The plasma transport equations reflect conservation of particles, energy, and charge in three dimensions and can be written

$$\begin{aligned}
 \frac{\partial n}{\partial t} &= S_i - \nabla \cdot \vec{\Gamma} \\
 \frac{3}{2} \frac{\partial p_e}{\partial t} &= P_\mu - \nabla \cdot \vec{Q}_e - Q_{ei} - e \vec{\Gamma}_e \cdot \vec{E} \\
 \frac{3}{2} \frac{\partial p_i}{\partial t} &= P_i - \nabla \cdot \vec{Q}_i + Q_{ei} + e \vec{\Gamma}_e \cdot \vec{E} - Q_{cx} \\
 \nabla \cdot (\vec{\Gamma}_e - \vec{\Gamma}_i) &= 0,
 \end{aligned} \tag{4}$$

where S_i is the source of particles due to ionization; P_μ and P_i are the sources of power to electrons and ions, respectively; and $\vec{E}$ is the electric field. The energy densities p_e and p_i and heat fluxes $\vec{Q}_e$ and $\vec{Q}_i$ are defined to include the ordered flow as well as random motion. The energy transfer rate between ions and electrons is denoted by Q_{ei} , and the ion energy loss rate due to charge exchange is denoted by Q_{cx} .

Averaging Eq. (4) over surfaces of constant ψ as shown in Fig. 3.1.1, we obtain the one-dimensional (1-D) equations

$$\begin{aligned}
 \frac{\partial n}{\partial t} &= \langle S_i \rangle - \frac{U_1}{\rho} \frac{\partial}{\partial \rho} (\rho U_2 \Gamma_\rho) \\
 \frac{3}{2} \frac{\partial p_e}{\partial t} &= \langle P_\mu \rangle - \frac{U_1}{\rho} \frac{\partial}{\partial \rho} (\rho U_2 Q_{\rho e}) - U_1 U_2 e \Gamma_\rho E_\rho - \langle Q_{ei} \rangle \\
 \frac{3}{2} \frac{\partial p_i}{\partial t} &= \langle P_i \rangle - \frac{U_1}{\rho} \frac{\partial}{\partial \rho} (\rho U_2 Q_{\rho i}) + U_1 U_2 e \Gamma_\rho E_\rho + \langle Q_{ei} \rangle - \langle Q_{cx} \rangle \\
 \Gamma_{i,\rho} &= \Gamma_{e,\rho},
 \end{aligned} \tag{5}$$

where $\langle \rangle$ denotes the ψ surface average

$$\langle f \rangle = \frac{\partial}{\partial V} \int_V f d^3x,$$

and V is the volume enclosed by the constant ψ surface. In Eq. (5), the density and temperatures are assumed constant along field lines, and the ψ surface label ρ has been chosen to be the radius r in the midplane. The 1-D equations in Eq. (5) differ from those solved previously²⁻⁴ in simple cylindrical

geometry by the geometric form factors U_1 and U_2 , which are defined by

$$U_1 = \left(\frac{B_{z, \text{midplane}}}{L} \int_0^L \frac{d\ell}{B} \right)^{-1}$$

$$U_2 = \int_0^L \frac{r^2}{\rho^2} \frac{B}{B_{z, \text{midplane}}} d\ell ,$$
(6)

where L is the length of a mirror sector. Particle and energy fluxes perpendicular to the ψ surface are given by

$$\Gamma_\rho = -D_n \frac{\partial n}{\partial \rho} - D_T \frac{\partial T}{\partial \rho} + n\mu_n E_\rho$$

$$Q_\rho = -K_n \frac{\partial n}{\partial \rho} - K_T \frac{\partial T}{\partial \rho} + n\mu_T E_\rho ,$$

where the transport coefficients D , K , and μ are evaluated at the mirror midplane.

Figure 3.2 compares steady-state solutions of Eq. (5) for EBT-I in a 2-D mirror geometry (dashed) with previous calculations² in 1-D cylindrical geometry (solid). Steady-state values of electron temperature T_e , ion temperature T_i , energy containment time τ_E , and ambipolar potential well depth ϕ are plotted versus plasma density n as edge neutral pressure is varied. The collisional ($\tau_E \propto T_e^{-7/2}$) and collisionless ($\tau_E \propto T_e^{3/2}$) behavior exhibited by the characteristic "nose"-shaped curves in Fig. 3.2 is similar to that observed in recent Thomson scattering measurements⁸ on EBT-I as shown by Fig. 3.3.

Results in Fig. 3.1.2 are sensitive to the parameter β_A . For example, Fig. 3.4 compares results for $\beta_A = 40\%$ (solid) and $\beta_A = 50\%$ (dashed). The deeper magnetic well in the $\beta_A = 50\%$ case gives relatively better ion energy confinement, higher potentials, and longer confinement times.

In Fig. 3.5, these results are extended to the operating regime of the proposed 36-sector, 60-GHz EBT-P experiment, with $R = 4.5$ m, $a = 0.2$ m, $\beta_A = 40\%$, $P_\mu = 500$ kW, and $P_i = 0$ kW. The characteristic "nose"-shaped curves persist for EBT-P parameters where both densities and lifetimes exceed those of EBT-I by slightly less than one order of magnitude. Values of $\bar{n}\tau_E$ versus electron collisionality for this 36-sector case are shown in Fig. 3.6 along with similar calculations for a smaller, 32-sector device with major radius $R = 3.75$ m. For 500 kW of microwave power absorbed by the toroidal plasma electrons, results show $\bar{n}\tau_E \sim 0.3 \rightarrow 0.6 \times 10^{12}$ cm⁻³ sec with $T_i \sim 0.5 \rightarrow 0.6$ keV for electron collisionalities $\nu_e/\Omega_{0,e} \sim 0.3 \rightarrow 0.1$ (i.e., minimum collisionalities observed in EBT-I). Obtaining confinement parameters in the range $\bar{n}\tau_E \sim 0.6 \rightarrow 1.0 \times 10^{12}$ cm⁻³ sec without direct ion heating requires operating in a lower collisionality range $\nu_e/\Omega_{0,e} \sim 0.1 \rightarrow 0.04$. With 100 kW of direct ion heating and 400 kW of microwave power, the dashed curve in Fig. 3.6 shows $\bar{n}\tau_E \sim 0.5 \rightarrow 0.9 \times 10^{12}$ cm⁻³ sec with $T_i \sim 0.8 \rightarrow 1.1$ keV for $\nu_e/\Omega_{0,e} \sim 0.3 \rightarrow 0.1$. Plasma densities for all these results are in the range of $n \sim 1.0 \rightarrow 1.3 \times 10^{13}$ cm⁻³, which is approximately 25% of the cutoff density (as observed in EBT-I).

Fig. 3.2. Steady-state transport results for EBT-I (Fig. 3.1a) with $P_{\mu} = 6 \text{ kW}$ and $P_i = 0 \text{ kW}$ for 2-D mirror geometry (dashed) and 1-D cylindrical geometry (solid).

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EXPERIMENTAL RESULTS (THOMPSON SCATTERING)

Fig. 3.3. Thomson scattering measurements from EBT-I experiment.
 [From: J. A. Cobble et al., Proceedings of the 21st Annual Meeting of
 the Division of Plasma Physics of the American Physical Society, Boston,
 Massachusetts (1979).]

Fig. 3.4. Steady-state transport results for EBT-I in 2-D mirror geometry with $\beta_A = 40\%$ (solid) and $\beta_A = 50\%$ (dashed).

Fig. 3.5. Steady-state transport results for EBT-I (Fig. 3.1a) with $P_u = 6 \text{ kW}$ and $P_i = 0 \text{ kW}$ and EBT-P (Fig. 3.1b) with $P_u = 500 \text{ kW}$ and $P_i = 0 \text{ kW}$.

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Fig. 3.6. Confinement scaling with electron collisionality for the cases of Fig. 3.5 and for a 32-sector EBT-P device with $R = 3.75 \text{ m}$, $P_\mu = 500 \text{ kW}$, $P_i = 0 \text{ kW}$. Dashed curve shows the effect of ion heating for the case of Fig. 3.1b.

3.2 ELECTRON CYCLOTRON HEATING

3.2.1 Electron Cyclotron Heating in EBT-I

The theory of electron cyclotron heating in EBT devices is reviewed in some detail in Appendix 1. In this subsection we simply outline the dominant processes involved in the heating of EBT-I. Figure 3.7 shows a cross section in the equatorial plane of a sector of EBT-I with a finite beta ($\beta \approx 40\%$) magnetic field configuration calculated using the Oak Ridge 3-D equilibrium code. An ad hoc density profile model was used for the low beta core plasma component, in which the density is constant along field lines, decreases slowly out to the vicinity of the annulus, and then drops rapidly to a constant value outside the annulus. Also shown in Fig. 3.7 are the fundamental cyclotron resonance surface [$\Omega_e(\underline{x})/2\pi = 18$ GHz], the second harmonic resonance surface [$\Omega_e(\underline{x})/2\pi = 9$ GHz], and the extraordinary mode right-hand cutoff surface, $\omega = \Omega_e/2 + (\Omega_e^2/4 + \omega_{pe}^2)^{1/2}$. At the right-hand cutoff, the extraordinary mode does not propagate at any angle. Therefore, the extraordinary mode energy launched near the mirror midplane is reflected before reaching the cutoff surface and in particular before reaching the fundamental resonance. The topology of the cutoff surface depends upon the peak plasma density. Figure 3.7 was plotted such that $\omega_{pe}^2 = \omega^2/2$ (i.e., $n_e = 2 \times 10^{12}/\text{cm}^3$) at the second harmonic resonance, the maximum density for which the entire second harmonic resonance is accessible for the extraordinary mode. The entire plasma is accessible to the ordinary mode since $\omega_{pe} < \omega$ everywhere.

The degree of cyclotron absorption which a wave experiences depends upon the plasma density and temperature and depends very sensitively upon the angle between $\underline{k}$ and $\underline{B}$ at resonance and the angle between $\underline{v}_g$ and the normal to the resonant surface. For the complicated geometry of EBT, details of the wave propagation characteristics and absorption must be determined by ray tracing. However, a number of general statements can be made:

- The density and temperature of the core plasma in EBT-I are sufficiently small that heating of the core plasma by the ordinary mode is negligible both at fundamental and second harmonic resonance.
- Heating of the core plasma by the extraordinary mode is negligible at the second harmonic resonance.
- Because of strong gradients in $|\underline{B}|$ along field lines, any extraordinary mode energy propagating from the high field side (mirror throat region) is totally absorbed at the fundamental resonance. This is true even for the low density surface plasma.
- Both ordinary and extraordinary mode are absorbed by the hot electron annuli. Experimental measurements of the annulus lifetime indicate that one-fourth to one-third of the total injected power is absorbed by the annuli.
- Plasma resonance occurs at the upper hybrid frequency only for perpendicularly stratified plasmas. Because of the geometry of EBT, the upper hybrid resonance plays no role.

Since the core plasma in EBT-I is observed to be strongly heated, some mechanism must exist whereby extraordinary mode energy reaches the high magnetic field region from which it can be efficiently absorbed at the fundamental cyclotron resonance. A number of mechanisms have been considered in this regard, including Budden tunnelling, destruction of the cutoff by finite temperature effects, and depolarization of ordinary mode energy into extraordinary mode in the high field region upon wall reflection. Of these, the dominant process appears to be conversion of ordinary mode energy to extraordinary mode in the high field region. Considering a low density, magnetized plasma having parameters characteristic of the surface plasma in EBT-I in contact with a perfectly conducting wall, it is found that a

Fig. 3.7. Location of first and second harmonic cyclotron resonance zones and the right hand cutoff surface for 18 GHz radiation in a model EBT-I equilibrium.

fraction of ordinary mode power approaching 100% is converted to extraordinary mode for certain angles of incidence on the wall. Averaging over a uniform distribution in angle of incidence gives average conversion efficiencies in the range 10% to 50% for parameters characteristic of the mirror throat region in EBT-I.

The core heating of EBT-I can be summarized as follows. Extraordinary mode energy injected at the midplane is partially absorbed by the annulus, partially depolarized into ordinary mode upon wall reflection, and weakly absorbed and transmitted to the high field region by Budden tunnelling. Aside from these sinks, extraordinary mode energy is trapped in the region outside the right-hand cutoff. Ordinary mode energy launched from the midplane is partially absorbed by the annulus and is partially depolarized into extraordinary mode at all wall surfaces. Because the production of extraordinary mode energy in the high field region is such an indirect process, it is quite difficult to calculate the radial distribution of extraordinary mode power flux into the fundamental resonance surface. However, if one makes the reasonable assumption that this power flux is uniform across the resonance surface, then the power deposited directly into the core plasma as opposed to the surface plasma is just proportional to the fraction of surface area of the resonant zone which lies in the core plasma as compared to the fraction of the resonant zone which lies in the surface plasma. A simple geometric model embodying the above ideas indicates that in EBT-I the microwave power is ~30% deposited in the annuli, ~20% deposited in the core, and ~50% deposited in the surface plasma.

3.2.2 Electron Cyclotron Heating in EBT-P

In scaling the EBT concept to a proof-of-principle device, the plasma parameters change in such a way as to modify the above view of heating. Increasing density, temperature, scale lengths, and microwave frequency all tend to increase local cyclotron absorption rates. In particular, assuming $n_e \approx 1.5 \times 10^{13}$, $T_e \approx 2.5$ keV, $\omega/2\pi = 60$ GHz, and a plasma radius at the midplane of 20 cm, one obtains fractional absorption rates of 50% to 80% at the fundamental resonance for ordinary mode waves launched near the midplane. This is advantageous since the ordinary mode is preferentially absorbed in the hot, dense core plasma rather than the surface plasma. In addition, direct absorption of the ordinary mode reduces the production of extraordinary mode energy in the high field region which tends to be equally partitioned between core and surface plasma. Ordinary mode absorption at the second harmonic resonance is still small (fractional absorption $\lesssim 3\%$).

Because of the increased annulus density and temperature, the extraordinary mode is quite heavily damped at the second harmonic resonance. Indeed, the annulus should be virtually opaque to extraordinary mode radiation propagating perpendicular to the field lines.

3.2.3 Techniques for Independent Control of Core and Annulus Heating

A difficulty which must be considered in scaling to EBT-P is that as the density and temperature of the annulus increase, the penetration of microwaves into the core plasma decreases. Unless some method is provided by which the core plasma can be heated independently of the annulus, it is possible that the core density and temperature will be limited by annulus absorption regardless of the amount of microwave power available. Since the annulus relies on the presence of a high density, warm plasma for stabilization of instabilities, this raises questions concerning stable operation at higher microwave power levels. Even if desirable operating conditions can be achieved without separate core heating, it would nevertheless be advantageous to have some control over the core/annulus heating ratio. For example, a prime physics objective of the EBT-P experiment is to delineate the stable regions of $\beta_{\text{core}}/\beta_{\text{annulus}}$. In addition, flexibility in heating may permit tailoring of temperature and density profiles for optimal transport and stability.

If the microwaves are to be launched from the midplane region, some control of core/annulus heating can be exercised by adjusting the polarization of the incoming waves or the radiation pattern of the antenna, or both. Launching predominantly ordinary mode waves enhances core heating. Similarly, steering a null in the antenna radiation pattern toward the midplane tends to avoid direct illumination of the annulus and causes the waves reflected from the cavity wall and right-hand cutoff to propagate to the annulus at an oblique angle with respect to the magnetic field ($\theta \neq \pi/2$). Since absorption of the extraordinary mode at the second harmonic resonance is strongest at $\theta = \pi/2$, the effect is to reduce annulus heating. Control from the midplane has the technical advantage of easy access, and only one microwave distribution system is required. However, the generation and distribution of polarized microwave power at these frequencies is itself a significant technical problem and inevitably results in loss of efficiency.

More direct control of core heating can be achieved by launching microwaves in the high magnetic field region. The ordinary mode component is strongly absorbed in the core region, whereas any ordinary mode energy incident on the fundamental resonance in the surface plasma region will pass on to the midplane and serve to heat the annulus as well as the core. As in EBT-I, extraordinary mode energy propagating to resonance on the high field side is totally absorbed by either core or surface plasma. To the extent that power launched from the mirror throat can be directed into the central core region, heating of the core plasma is enhanced over annulus or surface heating.

If a wedged coil design is adopted, it may be possible to insert a waveguide through the dewar between coil windings and install an antenna in the mirror throat. Another approach would be to insert a waveguide into the high field region at the side of the coil casing and in the shadow of a limiter. Serious technical problems are associated with either approach, since a cyclotron resonant surface must pass through the power carrying waveguide, and a microwave window may be required in close proximity to a hot, dense plasma. A disadvantage of launching from the throat is that a separate microwave source and distribution system is required.

It should be mentioned that any plasma heating technique can be used to provide the desired independent core heating. Two such techniques, ion cyclotron heating and neutral beam injection, are discussed in the appendices.

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4. PROJECT DESIGN DESCRIPTION

4.1 DESIGN SUMMARY

This design report is based on installation of the EBT-P experiment in Building 9201-2 at the Y-12 plant. The device and its enclosure will be located on the second floor high bay area immediately west of the existing EBT-I/S experiment. Figure 4.1 shows the physical layout of the equipment required for EBT-P. Plan and elevation views of the device are shown in engineering drawings X2D-14270-0012 and X2E-14270-0013. (Engineering drawings referred to in this section are included in Appendix 10.) The physical characteristics of the device are presented in Table 4.1.

EBT-P is a toroidal device with a 4.5-m major radius and 36 sectors. The aluminum toroidal vessel is composed of 36 mirror cavity sectors alternating with 36 dewar vacuum liner sectors. The vacuum liner is located in the bore of each coil vacuum dewar with a radial clearance that results in the vacuum torus being nonintegral with the mirror coil assembly. The sidewall of each vacuum liner contains a thin membrane that acts as a flex joint to accommodate thermal expansion and misalignment of the torus. Access ports are provided in each mirror cavity sector, which is located between each dewar vacuum liner.

The steady-state EBT-P plasma is contained by the magnetic field generated by the 36 mirror coils. Each coil consists of a liquid-helium-cooled (pool boiling) NbTi winding enclosed in a stainless steel case. The coils are mounted inside the vacuum dewar via an orthogonal system of struts that carries the magnetic loads from the coils, to the dewar outer ring, and then to the device support structure. A tungsten alloy shield, located at the bore and sides of the vacuum dewar external to the evacuated area, protects the superconducting winding from excessive x-radiation. Power is supplied to the mirror coils from a high current dc power supply through helium-vapor-cooled leads arranged in a series fashion.

Stabilization and heating of the plasma are provided by the injection of 1.2 MW of microwave power at 28 and 60 GHz into the toroidal vessel. Microwave power is transmitted from the six gyrotron power sources to the toroidal vessel via an overmoded, segmented manifold system having symmetrical connections to each mirror cavity.

Primary pumping of the toroidal vacuum vessel is accomplished through the use of nine 3000-liter/sec cryosorption pumps, located on every fourth mirror cavity. A roughing system, composed of a mechanical pump, two nitrogen cryosorption pumps, and a turbomolecular pump, is utilized for initial pumpdown of the vacuum vessel, coil dewars, and for regeneration of the primary cryosorption pumps. Primary pumping of the coil vacuum dewars is accomplished with a 1000-liter/sec cryosorption pump on each dewar. The torus cryosorption pumps will be shielded from scattered microwave power by a water-cooled, perforated copper plate in each pumping port.

The entire torus structure is cantilevered from a structural "bucking" ring at its inner bore. This ring is in the form of a spoked wheel and is designed to structurally restrain the magnetic and dead-weight loading of the torus. The bucking ring is supported from the floor via structural members.

The entire device will be surrounded by a 40-in.-thick concrete biological radiation shield designed to limit radiation outside the enclosure to 2.5 mr/hr. Entrance to the device will be through a labyrinth designed to attenuate reflected radiation. Gyrotron assemblies, the regulator and crowbar portion of the gyrotron power supplies, and coil power supplies will be located at the first floor level directly below the device in an enclosed area.

A control room, located adjacent to the shielded enclosure, will be an upgrade of the existing EBT-I/S control room.

Equipment associated with device operation will be as near the device as possible. The cold box and liquid helium storage dewar portion of the helium refrigerator/liquefier will be located on the north low-bay roof, and the compressor will be located on a concrete pad at the west end of the building. Gyrotron power supplies will be located in two areas adjacent to the experiment site. The high voltage

Fig. 4.1. The physical location of EBT-P and associated equipment and their locations relative to other experiments in Bldg. 9201-2.

switchgear will be located on an open, fenced concrete pad on the south side of Building 9201-2, and the remainder of the power supply equipment will be sheltered in a building addition for the west end of the building.

Table 4.1. Physical characteristics

Toroidal vessel		
Material construction	Aluminum, nonintegral	
Major radius	4.5 m	
Number of sectors	36	
Clear bore radius	17 cm	
Volume	7.3 m ³	
Surface area	71 m ²	
Magnetic system		
Type	Pool boiling NbTi	
Number of coils	36	
Winding dimensions (IR x OR x W)	24 x 34.1 x 21.2 cm	
Current density	10,000 A/cm ²	
Design maximum field @ winding	7.4 T	
X-ray shielding	3/4-in. tungsten alloy	
Microwave heating system		
	<u>Bulk</u>	<u>Profile</u>
Number of gyrotrons	4	2
Frequency	60 GHz	28 GHz
Power	800 kW	400 GHz
Vacuum system		
Torus primary system	9 3000-liter/sec cryosorption pumps	
Roughing system	1 mechanical pump, 2 cryosorption pumps, and 1 1500-liter/sec turbomolecular pump	
Pumping speed/port	1000-liter/sec	
Microwave shield	Perforated copper plate (50-dB attenuation)	
Ultimate pressure	10 ⁻⁷ torr	
Dewar vacuum	36 1000-liter/sec cryosorption pumps	
Utilities		
Cooling water requirements	4800 gal/min.	
Refrigeration requirements	1500 W + 210 liter/hr	
Electrical load	10 MVA	

4.1.1 Building Additions and Modifications

Demolition and site preparation

General criteria. The available space for the EBT-P experiments in Building 9201-2 is as outlined in Table 4.2.

Table 4.2

Facility/equipment	Location (column line boundaries)	Floor	Comments
Device enclosure	3, 7, f, k	basement, 1st, 2nd	~5400 ft ² per floor
Control room	2 1/2, 5 1/2, k, m	2nd	~1550 ft ² existing floor space ^a
HVAC equipment	5 1/2, 7, k, m	Roof	
	1, 2, k, l	1st	South 1/2 of existing fan room for chiller and pumps
Cryogenics — cold box	3, 5, k, m	Roof	

^aExpansion of the existing EBT-S control room may also be considered.

Building 9201-2 is a reinforced concrete frame structure with stepped spread footings and integral one-way floor slabs. Demolition within the building will be as required to accommodate the new facility within the basic existing structure. Outside of Building 9201-2, there is ample space for support equipment (power supplies, the compressors, the storage tanks, liquid nitrogen trailers, etc.) at grade, as shown in engineering drawing S2E-8945B-SK1. In addition, there is some available space on the south bank of Poplar Creek. It should be noted that excavation at the west end of Building 9201-2 will probably involve substantial rock removal.

Design description. Demolition for the EBT-P device enclosure will include complete removal of the existing first and second floors of Building 9201-2 within the area outlined in engineering drawing S2E-8945-SK11. Only the principal high bay building columns will remain within the outlined area. The existing 1-MW power supply vault for EBT-S will be temporarily relocated during the demolition. A dust screen will be provided around the entire area for the duration of the demolition work. Demolition for the new power supply and compressor building additions will include the removal of Building 9732-2, relocation of an existing fan, and rerouting an existing storm sewer and several sidewalks (see engineering drawing S2E-8945B-SK1).

Power supply enclosures

General criteria. The new power supply building will be an insulated preengineered metal frame structure with corrugated sheet metal siding and roofing. The floor system will be a reinforced concrete slab on grade. The building will include a designated service bay for equipment maintenance. An environmental control system will be provided in the building to maintain a maximum 110°F during the summer and a minimum of 40°F in the winter. An automatic deluge sprinkler system will be provided for fire protection inside the building. The sprinkler system will be supplied through a new valve house from a nearby 10-in. main. A diked equipment pad will be provided on existing grade in the vicinity for the more reliable electrical components in the device power supply system. The oil-cooled components will be provided with an automatic deluge sprinkler fire protection system.

Design description. The new power supply building addition will be 70 ft long x 42 ft wide x 20 ft high in accordance with the above criteria. The building will be located between existing Buildings 9201-2 and 9105. The new power supply equipment pad will be located on grade at the southwest corner of Building 9201-2. The pad will be 21 ft wide x 90 ft long. Pedestrian access to the diked pad will be controlled with a 7-ft-high security fence. For maintenance, equipment will be installed and removed with a mobile crane.

Cryogenic mounts and enclosures

The cryogenic system components will be protected from the elements by the new helium compressor and cold box building additions.

General criteria. An insulated sheet metal and steel frame enclosure will be provided for the helium refrigerator, which will be 9 ft diam. x 18 ft high. Support must also be provided for a new helium dewar for the cryogenic system. A nominal steel frame enclosure will be provided for the two helium compressors for the cryogenic system. Fire protection systems for the two enclosures above will be provided in accordance with current NFPA standards.

Design description. The cold box building addition will be located on the low-bay roof 1A between column lines 3, 5, k, and m (see engineering drawing S2E-8945A-SK10). The new helium dewar will be supported on the same roof immediately (1 bay) east of the cold box building addition. The helium compressor building addition will be 26.5 ft high x 40 ft wide x 44 ft long and will be located just off of the existing northwest fan room for Building 9201-2 between column lines k and n. The two compressors, mounted on independent structurally isolated concrete foundations, will be maintained with a 3-ton hoist and monorail (see engineering drawing S2E-8945A-SK8).

Control room

General criteria. The control room will be an insulated, environmentally controlled enclosure on the second floor of Building 9201-2. Cable tray and conduit access to the device will be provided through appropriate radiation shielding. The control room will be provided with an appropriate "system compatible" fire protection system in accordance with current NFPA standards.

Design description. The new EBT-P control room will be an extension of the existing EBT-S control room. The steel frame structure will be enclosed with metal stud and sheet rock walls carrying a minimum 1-hr fire rating in accordance with Underwriter's Laboratories specifications. The room will be protected against fire damage with smoke detectors and a preaction sprinkler system. The control room environment will be controlled at 78°F $\pm$ 2°F, with a relative humidity of 50% $\pm$ 10%. The HVAC units for the control room and device enclosure will be located on the low-bay roof 1A between column lines 5^{1/2}, 7, k, and m (see engineering drawing S2E-8945A-SK10).

Device enclosure and structure support

General criteria. The device enclosure must provide adequate x-radiation shielding to reduce the maximum exposure to 2.5 mr/hr outside of the device enclosure in Building 9201-2 and the 0.25 mr/hr in uncontrolled access areas and outside of Building 9201-2. The device enclosure will be environmentally controlled. Fire protection will be provided in accordance with current NFPA standards. The enclosure structure height will not exceed elevation 972.0 ft, so that overhead clearance for the high bay bridge crane will be maintained.

ORNL reference design. The device enclosure and support structure will be located between column lines 3, 7, g, and k in the high bay area of Building 9201-2 as shown in engineering drawing S2E-8945-SK11. The structure will consist of high density concrete ring walls 40 in. thick supported at the existing building basement level (elev. 919.0 ft) extending up to elevation 969.0 ft and covered with a 3-ft thick modular, precast, prestressed concrete roof system. There will be two intermediate floor levels inside the structure; one at each of the existing first and second floor elevations of Building 9201-2. The device will be supported from, and 6 ft above, the second floor level. The device support structure will extend down to the building foundations. The first floor level (929.0 ft) will be used to support the gyrotrons, magnet power supplies, and other support equipment. Outside access to the

area will be provided through the two existing overhead rollup doors in the northwest corner of Building 9201-2. Personnel access to the device will be through mazed x-ray shielding, with appropriate administrative controls. The device enclosure will be thermally controlled to $75^{\circ} \pm 2^{\circ}\text{F}$ with a positive internal pressure of 0.05 in. w.g. with respect to the surrounding area. The device will be fire protected with a preaction sprinkler system at each of the interior floor levels.

Building electrical service

Design criteria. Approximately 50 MVA of electrical power is presently available at Building 9201-2. An additional 80 MVA could be made available with additional overhead distribution equipment (~200 ft) and a 13.8 kV, 750 MVA tie breaker. Of the 50 MVA presently connected to Building 9201-2, 17 MVA are required for existing steady-state experiments and building utilities, and about 50 MVA are required on a pulsed basis (200 msec) for remaining experiments. With judicious scheduling of the other experiments, the immediate availability of 34 MVA may be assumed. The additional 80 MVA source is used to full capacity on the same pulsed basis (200 msec) but is available with scheduling and additional distribution equipment.

Design description. Existing 13.8-kV power will supply all of the high voltage microwave power supplies for the experiment. Also required are 1500 kVA of 2.4-kV power (for the helium compressor) and 3000 kVA of 480-V power for various magnet supplies, cooling fans, vacuum pumps, and air conditioning. Control room 120-V power will be derived from a 480/120-V transformer located in the control room. A separate 1500-kVA, 13.8/2.4-kV transformer and switchgear and two 1500-kVA, 13.8/480-V transformers and switchgear will be installed on the east end of the new power supply pad to meet power needs at these voltages. All 480-V circuit breakers will be located on the north end of the power supply building addition in order to minimize the total length of 480-V conduit, which is considerable. (See engineering drawing E2E-14270-00001.)

The estimated electrical power demand loads for EBT-P, including future expansion, are summarized in Table 4.3..

Helium tanks and pad

A reinforced concrete support slab will be provided for the high pressure helium storage tanks located approximately 100 ft southwest of Building 9201-2. In addition, steel tube pipe supports will be provided for the helium supply line from the tanks to Building 9201-2.

4.1.2 Toroidal Vessel

Design criteria

The toroidal vessel is designed to operate at base pressures in the range of 10^{-7} to 10^{-6} torr and to maintain structural integrity at steady state proof-of-principle plasma requirements. Since the plasma interactions with the vessel at the upper limits of operation are not fully predicted at this point, the vessel should have the capability of being extended beyond the original design operating conditions. The toroidal vessel should have a major radius within the limits of 3.75 to 4.5 m and a clear bore radius of approximately 17 cm.

Design description

The ORNL toroidal vessel design has a 4.5-m major radius with a 17-cm clear bore radius. The design consists of 36 sectors. Each sector is made up of a vacuum liner and a mirror cavity. The

Table 4.3. Required electrical power for EBT-P

	Ratings	kVA
Microwave power supplies		
Beam power	100 kV, 10 A x 6	6,000
Gun anode	40 kV, 0.2 A x 6	48
Gyrotron magnet (SC)	10 V, 2400 A x 6	144
Mirror coil power supplies (SC)	50 V, 1800 A	100
Global field error correction power supplies	65 V, 500 A x 4	130
Utilities		
Helium refrigerator	1500	
Vacuum pumps	50	
Control room power	100	
Lighting	70	2,000
Air conditioning	125	
Power supply cooling fans	105	
Miscellaneous power	50	
Subtotal		8,450
Future expansion		
Neutral beams		
Accel power	20 kV, 12.5 A x 4	1,000
Decel power	5 kV, 1 A x 4	20
Source table		
Arc supply	150 V, 400 A x 4	
Filament supply	12 V, 200 A x 4	250
Beam magnet	6 V, 75 A x 4	
Arc coil power (available from existing motor-generator sets)	23.4 V, 6408 A x 96	14,400
Six additional microwave power supplies		6,200
ICRH		400
Additional utilities		1,000
Subtotal		23,300
Total		31,750

vacuum liner is the portion of the vessel which is extended through the coil bore, joining with the two adjacent mirror cavities. The vessel material consists of high-strength aluminum alloys (2217 T87 for the vacuum liner and 6061 for the mirror cavity). An aluminum vessel material was chosen over a stainless steel material because of the more favorable heat transfer and thermal growth characteristics of aluminum. Engineering Drawing X2E-14270-0014 shows a typical vessel sector cross section.

The coolant flow requirements for the vessel are established for a 3-MW power loss from the plasma to the walls of the vessel. The coolant flow (demineralized water) is distributed to the vessel in

anticipation of absorbing the primary portion of the plasma energy at the throat locations. Thermal growth is to be absorbed by the membrane walls of each vacuum liner.

The construction of the vessel is such that the vessel and mirror coil dewars are not rigidly attached. This characteristic allows more flexibility in coil adjustments and vessel machining tolerances. A total of eight flanged ports are provided in each mirror cavity. The vessel uses Viton O-ring seals for all flanges. The vessel is rigidly supported at each sector flange. Although the concept of a freely expanding vessel is more desirable from an engineering standpoint (also due to higher heat loads expected in a reactor), the coil performance requirements could not tolerate clearance requirements needed for this concept.

4.1.3 Magnetics System

Mirror coils

Design criteria. The mirror coil design criteria are as follows:

1. Conductor
 - A. Superconducting material — NbTi.
 - B. Matrix material — copper.
 - C. Shape — rectangular.
 - D. Monolithic conductor with twisted filaments each no larger than 50 μm in diameter.
 - E. Operating current ≤ 2000 A at maximum field at the conductor of 7.5 T.
2. Winding
 - A. $\langle j \rangle_{\text{winding}} \cong 10,000$ A/cm² at 7.4 T.
 - B. Conductor grading — optional.
 - C. Number of joints or crossovers — optional.
 - D. The error field, $\Delta B/B$, in the vertical plane halfway between two mirror coils on the minor axis should be less than 6×10^{-4} , where ΔB is the deviation of the field from an ideal solenoid, and B is the field due to an array of ideal solenoids. The sources of ΔB should include the nonsolenoidal currents in the windings, the current leads, the bus work, and any ferromagnetic materials present.
 - E. Insulation scheme — optional.
 - F. Coil position to be adjustable after the dewar is put in place and the coil is cold.
3. Cooling
 - A. Pool boiling helium I at 4.2 to 4.4 K.
 - B. The magnet design must be capable of withstanding the nonuniform steady state x-ray heat load at the 90-GHz operating point.
4. Protection system
 - A. Verify by analysis that the coil is not damaged in the event of a quench.
 - B. Identify the various fault modes of the protection system and their possible consequences.
5. Structural
 - A. The conductor shall be designed to accommodate stresses owing to winding tension, cooldown, and magnetic forces during normal operation, and fault conditions.
 - B. The insulation to be used should be compatible with the stresses expected for both the normal operation and fault conditions.
 - C. The bobbin shall be designed to resist the stresses expected in both the normal operation and in fault conditions.
 - D. The motion of the conductor when energized shall not be excessive (i.e., will not cause the coil to quench) and the stresses shall not be over two-thirds minimum yield.

Design description. The EBT-P device will have a major radius of 4.5 m and 36 mirror magnets. The size, shape, mirror ratio, maximum field, and maximum current density were set in a series of tradeoffs between plasma physics requirements and reasonable goals for a moderate-risk magnet system. The magnet parameters are listed in Table 4.4 and engineering drawing X2E-14270-0015 and refer to the magnet system.

The rationale for the choice of a NbTi pool boiling system is discussed in Appendix 3. The conductor and conductor insulation scheme, the rationale for the winding scheme, steps in winding the coil, bobbin design, and the protection system are discussed below.

As pointed out in Appendix 3, the copper-to-superconductor ratio and the operating current should be kept low with respect to the critical current. The conductor size and the operating and critical currents are given in Table 4.1.4. The conductor will be monolithic or built up of a superconducting element and a copper element.

Table 4.4. Magnet parameters

Winding dimensions	
Inner radius (cm)	24.0
Outer radius (cm)	34.0
Axial length (cm)	21.1
Number of turns per coil	1,280
Current density in winding (A/m ²)	10,000
Mirror ratio (MR)	2.26
Operating current (A)	1,641
Peak operating field (T)	7.4
Winding type ^a	Hybrid
Cooling type	Pool boiling
Conductor size ^b (mm)	2.9 × 5.0
Number of grades	2
Insulation turn to turn	50% covered barber pole wrap 0.127 mm thick
Minimum copper-to-superconductor ratio ^c	3
Critical current (both grades) (A)	3,400
Stored energy (total all magnets) (MJ)	52
Peak discharge voltage (V)	120
Peak discharge coil temperature (K)	100

^aA hybrid winding is a particular combination of pancake and layer winding; see text for explanation.

^bBecause of dimensional tolerance and strength requirements, a cable or a braid will not be used.

^cThe copper-to-superconductor ratio will change from one grade of conductor to another. The final ratio will be determined by the conductor manufacturer after the other conductor parameters are met.

The turn-to-turn insulation is a 50% covering of the conductor surface with a barber pole wrap of 0.127-mm thick Nomex lacing tape. The voltage per turn in the inner coil during a system dump is 0.1 V; the maximum voltage between adjacent turns is, then, approximately 7.8 V. Hence, the minimum distance between turns can easily insulate this voltage.

The winding scheme for the mirror coils must be chosen carefully to keep the field errors low. These errors are introduced by crossovers, by layer-to-layer transitions in the magnet, and by leads. The largest potential error is the result of the large separation of the leads as they leave the winding. The choice of the winding scheme strongly influences the lead placement. Two common winding types are layer winding and pancake winding. An inappropriate layer winding scheme would feed the conductor onto the bobbin through a hole in a side plate and then wind each layer and bring the other lead off the outside diameter. The bad feature of this scheme is that there is an uncompensated current lead the length of the coil build. It is possible to design a layer winding that eliminates this problem, but it requires conductor joints at one end of the magnet. One can also make a design of a pancake winding with uncompensated leads on each end of the coil. Pancake-wound coils for this application have another disadvantage. If the conductor is graded, there must be two joints in each pancake to make the change of grade and two more joints to connect the pancakes electrically. All joints take considerable time to make, thus increasing the overall winding cost. But as in the layer-wound case, proper designs of pancake-wound coils are also possible (e.g., the mirror magnets for EBT-S).

A hybrid winding scheme has been chosen for the EBT-P coils. Basically, this design consists of a layer-wound coil with a pie (one-half of a pancake) wound on one end to bring the conductor next to the bobbin to the outside diameter as a lead. There will be an even number of layers and the same number of turns in the pie so that the two leads end up on the outside diameter on the same end of the coil. The leads can then be brought out close together for good field error compensation. The lead spacing will be set by helium breakdown voltages during a possible dump.

There will be two grades of conductor. A conductor with a 3:1 Cu:SC ratio will be used in the high field areas. A conductor with the same dimensions and less superconductor will be used in the low field regions to help reduce costs. The hybrid scheme requires only one joint between the two conductor grades. The actual number of joints in the magnet depends on a number of things, such as the maximum length of conductor that can be manufactured, but in any case there should be many fewer joints than in a pancake-wound coil.

The insulation between the bobbin and the windings will be slotted G-10 sheets covered with a solid sheet to electrically insulate the winding cavity from the bobbin. The helium circulation next to the bobbin is designed to keep the x-ray heat deposited in the bobbin and to keep heat conducted from the structure through the support struts away from the magnet turns. During steady-state operation, the helium in the windings will cool only the superconductor heated by the x-rays.

The motivation for the winding scheme and a general description of it were given earlier; the following is a description of the winding sequence. After the bobbin insulation is installed, enough high field conductor for the entire high field, layer-wound portion of the coil will be wound (uninsulated) on one end of the bobbin. Then the pie (one-half of a pancake) section of the coil will be wound on the other end. The lead will be bent into an insulated slot in the bobbin and the banding needed for the pie will be wound on. As the conductor is wound, with the proper winding tension being maintained, a 50% barber pole wrap of Nomex tape is applied. The high field conductor will then be unwound from the bobbin and transferred to another spool. The 2.2 mm of insulation between the pie and the layer-wound section will be put in place. This insulation is a sandwich of two slotted sections on each side of a solid piece of G-10. While it is being layer wound, the high field conductor will be held in tension and insulated in the same way as the conductor for the pie. The number of turns per layer will be monitored, and when the proper number has been wound on (in this design 39 turns), a

polycarbonate wedge will be placed between the last turn and its neighbor to hold the last turn tightly against the insulation on the end plate. The winding cavity width is determined by adding 1.5 mm to the maximum width of a layer, given the acceptable tolerances of the conductor and the insulation dimension. After the wedge is inserted, the transition to the next layer is made and that layer is wound. After the proper number of layers has been wound, the joint to the low field conductor is made on the end of the coil away from the pie. The low field conductor will then be wound the same way as the high field conductor.

Banding will be required on the outside radius for both the single pie and the layer wound region. One scheme has been devised for bringing both leads out from under the bonding while maintaining the separation needed for insulation. The ends of the leads are insulated and brought out as close together as possible through a radial slot in the bobbin.

The bobbin will be welded together in a "U" shape and then a final machining done on the inner surface prior to winding. Final closure will be accomplished by bolting two "C" rings to the "U" bobbin and then seal welding.

Mirror vacuum dewar

Design criteria. The magnet vacuum dewar encloses the superconducting coil and bobbin assembly. It must perform the following functions:

1. Provide an insulating vacuum for the superconducting coil to permit long-term steady-state magnet operation. Allowable leak rates will be determined in the detailed design phase.
2. Withstand an external pressure of 1 atm.
3. Transmit normal magnet centering forces and worst-case fault loads from the 4.2-K structure to warm support structure.
4. Allow for magnet coil adjustment about all axes to achieve desired field accuracy while the coil is at 4.2 K.
5. Minimize heat input to the refrigeration system.

Design description. As shown in engineering drawing X2E-14270-0015, the dewar is cylindrical. The outer cylindrical piece is fabricated from stainless steel 1 in. thick, and all structural loads are transmitted through it to the base. The side walls are 1/4 in. thick and the cylindrical surface on the inner radius is 1/8 in. thick. These surfaces only see the 1 atm load.

Gravity loads are transmitted through a thin titanium compressor member at the bottom of the coil case to the dewar. Centering force loads (~15,000 lb) are transmitted through one titanium horizontal compression member to the dewar. The length of these struts is fixed after initial fabrication. Adjustments are made by moving the entire dewar.

The coil is centered axially in the dewar by Belleville washers mounted from the outer ring at four locations. Out-of-plane fault loads (~65,000 lb) are taken by snubber pins located inside the washers. This arrangement should provide low heat conduction during normal operation.

The coil-dewar assembly is mounted from a central bucking ring. The support and adjustment system for the dewar is similar to the design proposed by Grumman et al.¹ There is a separate adjustable support plate that allows 6° freedom of movement for coil adjustment. This motion is not coupled to either the vacuum torus or the support ring.

Vapor-cooled conductor leads and liquid helium are brought through the dewar case at top center location.

The superconducting mirror coils are maintained at 4.2 K in a bath of liquid helium; the magnet is suspended in a vacuum for thermal insulation. The supports transmit all loads on the magnet from the

coil case at 4.2 K to the vacuum dewar outer ring, which is at 300 K. Between the temperature extremes of 300 K and 4.2 K, there is a cold wall that is cooled to 80 K by liquid nitrogen. This intermediate temperature surface is thermally attached to each support member. Thus, the cold wall reduces the conductive heat leak through the supports in addition to reducing the radiation heat transfer to the coil. Layers of aluminized mylar superinsulation further reduce radiation heat leak by creating isothermal layers with low emissivity.

The structural supports can be thermally optimized to reduce heat leak by taking advantage of the thermally dependent mechanical properties of titanium alloys. One alloy considered, Ti-5 Al-2.5 Sn, is 16% stronger at 4.2 K than at 80 K and is 60% stronger at 80 K than at 300 K. The cross-sectional area of the support can decrease by the same percentage as the strength increases, thus reducing the area available for conductive heat transfer.

The vacuum in the dewar will be initially provided by a commercial cryopump or turbomolecular pumping while the coil is warm. After the coil has cooled down, the case can be valved off and the cold surfaces will act as a huge cryopump with many times the effective pumping speed of the commercial pump. A molecular sieve will be attached to either the coil case or the cold wall to further increase pumping speed and capacity.

Magnet shielding

Design criteria. The primary purpose of the mirror coil shielding is to attenuate x-ray emissions resulting from high energy electron collisions with a limiting surface in the coil throat. The primary source of these electrons is the electron annuli.

Owing to the magnitude of scaling from the EBT-S to the proof-of-principle, there is presently little information available for shielding design requirements. Based on a combination of existing theory and available data from EBT-S experiments, the following shielding design criteria were established:

1. Ring temperature for POP will be in the 1-MeV range.
2. A Maxwellian electron energy distribution is assumed for ring electrons with a maximum energy of 10 MeV being present.
3. The ring power density should be expected to be in the range of 0.5 W/cm³.
4. Total ring power for shielding and coil design purposes is expected to be in the range of 0.2-1.0 MW.
5. Total bremsstrahlung energy deposition rate into the coil should be limited to 10 W/coil.
6. The source of the bremsstrahlung emission is to be assumed over a concentrated 10-cm² surface area patch at each throat leading edge.

The radiation level that will be experienced at the upper operating range is a critical factor in sizing coils and cryogenic systems. The final design requires a detailed analysis with as much flexibility as possible to allow for shielding modifications without limiting plasma confinement.

Design description. The coil shielding used in the reference design consists of a tungsten powder alloy (97% tungsten). A uniform shielding thickness of 3/4 in. around the bore of the coil dewar and the dewar sidewalls is used. Water cooling is provided in the shielding material to remove converted x-ray energy. If shielding modifications should be required, there is limited additional space between the outer coil dewar surface and the vacuum liner to increase effective shielding thickness. Another possibility if further shielding is required is to install a localized limiter-shield combination located upstream of the throat.

Mirror coil protection system

Design criteria. In the event that energy must be rapidly removed from the mirror coils, specialized circuitry will be required. The basic idea involves electrically isolating each coil with switches and then allowing each coil to discharge into a resistive element. Each of the 36 coils shall have its own dump circuit capable of absorbing 1.5 MJ. The discharge voltage shall be 120 V or less.

Design description. The electrical details for the mirror coil protection system are shown schematically in Fig. 4.2. During steady-state operation, current flows through the SCR's and the mirror coils. The dc contactor is open, and the dump resistor is effectively shorted out by the superconducting coil. When the decision to dump is made, all dc contactors will be closed; then all SCR's will be commutated open, leaving all mirror coils free to discharge into their respective dump resistors. The use of the contactors will preclude any potential problems with commutating all SCR's simultaneously.

The SCR-forced commutation circuitry includes a capacitor bank to force the SCR current to zero, a power supply to maintain the capacitor bank, and a saturable reactor to prolong the current zero crossing. In the detailed design, use can be made of circuits similar to these, designed for experiments at Los Alamos Scientific Laboratory (except in that case vacuum circuit breakers were used). In this instance, solid-state switches are preferable to vacuum circuit breakers because the interrupting voltage is only 120 V and space is a factor.

The switches and dump resistor will be packaged as a unit for each coil and suspended from the ceiling of the experiment enclosure. Connections to the coils will be made with rigid copper bus. Internal connections and some of the interconnections between switch/dump resistor units will be braided copper cable.

Structural supports

Design criteria. Supports are to be constructed from nonmagnetic materials. They must be capable of withstanding magnetically induced coil centering force and fault load and the gravity loads of the mirror coil assemblies and toroidal vessel.

Design description. The structural support system consists of a bucking ring and intercoil structural supports. The central bucking ring is a room temperature structure that (1) transfers the gravity forces of the mirror coil assemblies and toroidal vessel to the concrete support base, (2) supports the magnetically induced mirror coil centering force (15,000 lb each), and (3) supports a portion of the fault induced out-of-plane load (65,000 lb) on the mirror coils. The intercoil structural supports assume the remaining portion of the fault load.

The stainless steel central bucking ring is in the form of a spoked wheel, with the mirror coil assemblies and toroidal vessel cantilevered from the outer ring as shown in engineering drawings X2D-14270-0012 and X2E-14270-0013. The bucking ring is supported from the concrete support base, with vertical structural members on both the inside and outside diameter of the ring. The intercoil structural supports are located between adjacent coils and are mechanically fastened to the mirror coil vacuum dewar outer ring both above and below the torus midplane.

4.1.4 Microwave Heating System

The microwave heating system provides energy to heat and stabilize the plasma and comprises the following subsystems:

1. profile heating gyrotrons and bulk heating gyrotrons,
2. the gyrotron mounting tanks and support equipment,

Fig. 4.2. Mirror coil protection scheme.

3. bulk and profile power distribution systems, and
4. power supplies.

A detailed description of each of these subsystems is given below.

Gyrotron

Design criteria. Design criteria for the gyrotron are as follows:

1. Profile heating frequency shall be 28 GHz.
2. Bulk heating frequency shall be 60 GHz.
3. Four bulk heating and two profile heating tubes shall be used to provide rf heating.
4. Each tube must deliver 200 kW.

Design description. Cyclotron resonance devices are considered the most promising type of microwave tube for development to the power and frequency levels required by EBT-P. An exact physical description of the EBT-P gyrotrons is not possible at this time, primarily because of the uncertainty in the output coupler design. However, work performed under a Varian Associates subcontract indicates that the tubes required for EBT-P bulk heating should have about the same microwave power conversion efficiency as the tubes now being used on EBT-S and will therefore require the same amount of water cooling. The EBT-P bulk heating gyrotron's cathode design should also be very similar to that used on the 28-GHz EBT-S tube and will, therefore, require the same type of oil bath for high voltage insulation and cooling. An output window design is currently being developed for the 28-GHz gyrotron that uses a fluorinated hydrocarbon as a forced-convection coolant, and the higher frequency gyrotron will probably use an output window that is almost identical. The size of the 60-GHz gyrotrons is, however, not known; therefore, a liberal amount of head space has been left in the containment structure to accommodate very long tube designs.

Gyrotron mount and support

Design criteria. Each tube must be rigidly mounted in the basement of the containment building in a manner that facilitates installation and removal and provides for isolation and cooling of the high voltage cathode. A water manifold must also be provided that will meet the tube cooling requirements, and auxiliary systems (such as a circulating and heat removal system for the FC-75 window coolant) must be provided as their need develops.

Design description. Each EBT-P gyrotron used in the ORNL reference design will be mounted on the lid of an oil tank containing transformer oil so that the high voltage cathode can be both cooled and isolated electrically. A small centrifugal pump will be used to circulate cooling oil through the gyrotron gun, and the system will be completely contained in the tank to prevent any possibility of oil leakage. Each of the six tanks will be movable so that the gyrotrons can be installed and replaced through the access hatch on the west side of the containment building. Estimates of the heat load in the oil tank have been made and indicate that free convection cooling of the tank's surface will be sufficient to maintain the oil temperature at an acceptable level.

This support concept will allow the operation of all six tubes simultaneously for plasma physics experiments or one tube at a time for the tube and distribution system development work. The fluorocarbon coolant circulation system currently in use on EBT-S is considered prototypical of those required for EBT-P. Six separate systems will be used to facilitate the operation of individual tubes. The six water manifolds for the separate systems will be installed in the torus enclosure basement and will provide cooling water for each gyrotron and one section of the microwave distribution system.

Microwave power distribution system

Design criteria. The power distribution system must divide the total power output from all six tubes evenly between the 36 torus cavities and must also provide for isolating each gyrotron from the others. In addition, the power losses must be kept as low as possible to avoid excessive microwave power system cost.

Design description. Conventional microwave systems use dominant-mode waveguide in which power propagation is possible in only one mode. The EBT-P gyrotrons, however, will be coupled to the torus with a power distribution system that utilizes a waveguide many wavelengths in diameter. This is because the required diameters of dominant-mode systems at 28 and 60 GHz would be much too small to handle the proposed power levels and because the transmission losses of dominant-mode systems are, in general, much too high for practical power transmission networks.

Power is coupled from the EBT-S gyrotron to the torus through a system that consists of several straight sections of waveguide and a toroidal distribution manifold that couples power to the plasma through a series of waveguide links. A similar system will be used on EBT-P because the feasibility of this approach has now been experimentally verified. In addition, the EBT-S device will be readily available to aid in component development.

The microwave power distribution network for EBT-P is shown schematically in Fig. 4.3. The detailed design of the system will be based on criteria generated by both the gyrotron development subcontracts and by component research conducted on the EBT-S facility.

Both the toroidal distribution manifolds and the 72 waveguide links that connect them to each of the 36 torus cavities are sized so that the average power density in each manifold and link is the same as in the gyrotron output waveguides. The bulk heating power manifold is divided into four segments with flat copper plates so that each of the high frequency gyrotrons is electrically isolated from the others; the profile heating manifold is divided into two segments for the same reason. Each manifold will also be equipped with a scattering wedge at the input waveguide feed point.

The waveguides and power distribution manifolds will be initially purged with dry nitrogen gas to remove all traces of water vapor and a small over-pressure will be maintained in this part of the system during operation. Each of the 72 waveguide sections that connect the toroidal power distribution manifolds to the plasma vessel will contain an edge cooled ceramic window to isolate the distribution system from the high vacuum torus. These windows will be located behind right angle miter bends to prevent sputtered aluminum from being deposited on their surface. Each connecting link will also contain an iris to aid in achieving power balance among the cavities fed by each gyrotron.

Either free convection or water cooling will be used to cool the entire distribution system, but a decision on which type to use cannot be made until the mode distribution at the gyrotron output flange is known. A probable mode distribution assumption has been made, however, and the resulting power losses were determined to be easily compatible with water cooling; the conceptual design of the distribution system includes the components necessary to accomplish this.

Gyrotron power supplies

Design criteria. High voltage dc power supplies will be used to power the six gyrotron microwave tubes to be used for bulk and profile heating on EBT-P. Each supply will be variable and regulated and will consist of a beam supply having a nominal rating of 100 kV at 10 A and a gun anode supply nominally rated at 40 kV at 0.2 A. Two of these will have been procured for EBT-S by the time they are required for EBT-P.

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Fig. 4.3. The microwave power distribution network for EBT-P with 2-28 GHz and 4-60 GHz sources feeding 36 cavities.

Design description. The design and configuration of these power supplies will be based on the prototype power supply developed for EBT-S. A one-line schematic of the gyrotron power supplies is included in engineering drawing E2E-14270-0001. Nearly all major components of these high voltage power supplies will be accommodated by a new building addition adjacent to the west wall of Building 9201-2 and by a new power supply pad south of Building 9201-2. Details of the building itself are discussed in Sect. 4.1.1.

Also required for gyrotron operation will be low voltage, high current gyrotron magnet power supplies. These magnets will be superconducting and will require approximately 10 V at 2400 A. These supplies and the regulators for the 40-kV gun anode power supplies should be near the microwave tubes. They will be located on the first floor in Building 9201-2 directly under the experiment.

Design description. The torus vacuum system includes the roughing system, the primary system, and cryopump microwave isolation.

Roughing system. The roughing system is designed with a cryogenic primary system to initially evacuate the torus from 1 atm to 10^{-4} torr and to regenerate cryosorption pumps while the device is operating. The proposed system is shown schematically in Fig. 4.4. The principal components are: one 50-cfm mechanical pump, two Varian Megasorb modules, and one 1500-liter/sec turbomolecular pump. On one mirror cavity a microwave isolation plate and a 10-in. gate valve are installed on a lower port. A 10-in. pipe connects this to a 6-in. gate valve and the turbomolecular pump. Also mounted below are the two Megasorb modules (which are connected to the 10-in. pipe) and the 50-cfm mechanical pump.

Approximately 1 hr is required to pump from 1 atm to 10^{-4} torr. Below 10^{-4} torr the pressure is determined by the outgassing rate, which is a function of time and the pumping speed. Crossover to the cryosorption pumps can occur as high as 0.5 torr. Going down to 10^{-4} to 10^{-5} torr, however, avoids preloading the pumping surfaces. In addition, the turbopump allows pressure on the order of 10^{-5} torr to be maintained with the primary vacuum system down for maintenance.

Primary system. Commercially available cryosorption pumps were selected for the primary vacuum system. At this time they appear capable of meeting the design requirements at the lowest cost. Nine CTI CRYO-TORR 10 pumps can achieve the desired base pressure of 10^{-7} torr with the assumed outgassing load and the microwave isolation system described below.

The cryosorption pumps use a closed-cycle refrigerator with a small motor and permanent magnet. The refrigeration unit is 53 in. from the centerline, where the stray field is 100 G or less. Magnetic shielding, if required, appears feasible. The resulting error fields ($\Delta B/B$) on the plasma centerline in the radial direction are estimated to be on the order of 10^{-7} .

The hydrogen capacity of the CRYO-TORR 10 pump is 6 standard liters. The net H_2 pumping speed is 19.5 liter/sec. Under an up-to-air accident with all 9 pumps holding 6 standard liters, the net volume fraction of H_2 in the torus would be 1%, which is well below the 4.6% explosive mixture. Sixteen hours of pumping at 5×10^{-6} torr would produce a 2.5% mixture of H_2 in the pump unit itself with the gate valve closed at 1 atm.

There is no separate high vacuum distribution system. The torus and plasma provide a very high conductance from a cavity that is not pumped to a neighboring cavity that is pumped.

Cryopump microwave isolation. Microwave power needs to be kept out of the vacuum system to prevent arcing and damage to components, to increase the power absorbed by the plasma, and to keep cryogenic systems from exceeding the refrigeration capacity or evolving previously pumped gases.

A perforated copper plate followed by a pipe coated with a microwave-absorbent material is proposed. The plate is 1/16 in. thick with 45-mil-diam holes set in a triangular pitch with a spacing of 55 mil center to center. Using Chen's theory,² the attenuation at 60 GHz for normal incidence is 50 dB and at 110 GHz it is 34 dB. The absorbent coated section prevents the region behind the plate from being a high-Q cavity for leakage radiation. It is estimated that <1 W of microwave radiation would

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Fig. 4.4. Proposed torus vacuum system for EBT-P.

enter the cryopump. Testing should be performed, however, to determine the isolation system and vacuum pump performance under anticipated conditions.

Cooling the plate for heat loads on the order of 2 W/cm^2 appears feasible with tubes brazed or soldered to the rear surface.

The net molecular gas flow transmission probability for particles incident on the 11.5-in.-diam port to the cryopump was estimated to be 0.195. This results in a net pumping speed of 1000 liters/sec/pump for air, 1600 liters/sec for water vapor, and 1975 liters/sec for H_2 .

4.1.5 Vacuum Pumping System

The torus vacuum system initially evacuates the torus, removes impurities released by surface outgassing during operation, and provides sufficient hydrogen pumping speed for pressure control. A separate system is provided for coil magnet dewar evacuation prior to cooldown.

The torus is constructed of unbaked aluminum and assembled using Viton O-rings. The following are the assumed system parameters used for calculating pumping requirements:

Surface area	100 m^2
Volume	7.3 m^3
Outgassing rate (assumed rate after 16 hours)	10^{-9} torr-liter/sec/ cm^2
O-ring gas throughput	4×10^{-4} torr-liter/sec
Base pressure	10^{-7} torr

Torus vacuum system

Design criteria. The high vacuum and roughing system for the torus will be designed to fulfill the following criteria:

1. Base pressure — $\leq 10^{-7}$ torr.
2. Pumpdown time ambient to base pressure — ≤ 16 hour.
3. Operating pressure in the wall region will be variable between 10^{-6} torr and 10^{-5} torr.
4. The design base pressure will be provided for the start of normal plasma operation within 16 hours of the last shutdown.
5. The vacuum system shall be capable of 16 hours of continuous plasma operation at any desired wall pressure between 10^{-6} torr and 10^{-5} torr.
6. The pumpdown time is for a system that has undergone wall conditioning and that is then exposed for 16 hours to atmosphere.

Additional constraints to be met:

1. Within the anticipated range of plasma parameters, the wall pressure in different cavities shall not differ by more than $\pm 10\%$ from the mean for all cavities.
2. Microwave power isolation will be provided so that the above criteria are met with no long-term damage to vacuum system components from microwave power. Isolation systems for the lower initial frequency (~ 60 GHz) may be installed, but there must also be a design for operation at 90 GHz.
3. No catastrophic, single pump failure (e.g., turbine overheat, helium leak, vacuum lead, etc.) shall require a shutdown of plasma operation.
4. Stray magnetic fields generated by electrical components in the vacuum system or magnetic materials will be estimated and included in evaluating the magnetic geometry error field in the plasma region. ($\Delta B_{\text{radial}}/B$)
5. Diffusion pumps or Zr-Al getter pumps will not be used.

Magnet dewar vacuum system

Design criteria. The vacuum system for the mirror magnet dewars and, if required, for the gyrotron magnet dewars will be designed to fulfill the following criteria:

1. A separate vacuum system distinct from the torus system will be provided.
2. The base pressure will be $<10^{-4}$ torr prior to cooldown.
3. A capability for pumping small He leaks will be provided. The amount of pumping and response time will be determined in the detailed design phase.

Design description. A separate vacuum system is provided for the magnet dewars. A 50-ft³/min pump is used to rough down to 0.2 torr through a 4-in.-ID manifold. Individual CTI CRYO-TORR 7 pumps on each dewar are then used to evacuate the dewars to 10^{-5} torr prior to cooldown. The same system is also used in evacuating and flushing the helium lines. A possible alternative is to replace the cryosorption pumps with a few turbomolecular pumps and a dedicated high vacuum manifold.

Hydrogen injection system

Design criteria. The hydrogen injection system will be designed to fulfill the following criteria:

1. Inject H₂ gas continuously or intermittently as required for startup and steady state operation.
2. Impurity level — ≤ 1.0 ppm (total oxygen).
3. Meet criteria 3, 4, and 5 as given for the torus vacuum system and additional constraints 1, 2, and 4.

Design description. Assuming all pumps have a net H₂ pumping speed of 1975 liters/sec, the H₂ throughput would range from 0.18 torr-liter/sec at 10^{-5} torr to 0.018 torr-liter/sec at 10^{-6} torr. Pressure can be controlled by one VEECO PV-10 piezoelectric valve and APC-110 automatic pressure controller. Maximum throughput for this system is 1 torr-liter/sec at 1-atm pressure differential. The valve response time is <2 msec full open to full close.

4.1.6 Utilities

Demineralized cooling water system

Design criteria. The demineralized cooling water system in Building 9201-2 can supply to EBT-P up to 2500 gal/min at 100 psig and 2500 gal/min at 210 psig with a range of 18°F. The piping modifications shall include installation of the EBT-P device and microwave system cooling water manifolds with connections to the existing building supply and connection of secondary devices (i.e., helium liquefaction/refrigeration systems and HVAC equipment) to the building cooling water system.

All demineralized cooling water pipe shall be 304 SS in sizes below 6-in.-diam. Six-inch and larger pipe shall be carbon steel painted in accordance with UCC-ND Interim Piping Specification 100, Paragraph 3b, using DuPont No. 759 Submarine Metal Primer.

Design description. The demineralized cooling water flow scheme will be as shown in engineering drawing P2D-57700-0001. There will be a main supply that connects to the building supply. Pipe to the HVAC equipment and to the helium compressor(s) will branch from the main supply. The main supply will terminate at the torus and microwave generators' manifolds. All water flow control valves will be remotely actuated from the EBT-P control room to allow flow control while the device is running.

Helium liquefaction/refrigeration system

Design criteria. The existing helium system in Building 9201-2 is an order of magnitude too small for this device. Therefore, a separate helium system will be required to support the superconducting magnets in the torus and the microwave system. It will be installed within exterior building additions to Building 9201-2. The helium system will consist of a refrigerator/liquefier module, refrigerator/liquefier supply compressors, a cryogenic helium storage dewar, warm and cryogenic helium piping, and warm helium storage tanks. The location of the helium system components is shown in engineering drawing P2E-95306-0001.

Design description. The ORNL design requires a 1500-W, 210-liter/hr refrigerator/liquefier that operates at 1 atm; a 15,000-liter atmospheric helium storage dewar; three 2500-ft³ warm helium storage tanks; superinsulated cryogenic piping for both liquid and cryogenic gaseous helium; and welded steel pipe for the warm helium service. The equipment will be located as shown in engineering drawing P2E-95306-0001. The piping from the compressor(s) to the cold box will be welded, schedule 10 stainless steel, which will help maintain helium system integrity and helium purity. The 2500-ft³ tanks and the pipe to connect them to the cold box will be carbon steel. Carbon steel will be used because of its lower cost and the anticipated lower use of the storage tank part of the system.

The piping from the cold box to the storage dewar and from the storage dewar to the torus manifolds will be heavily superinsulated, vacuum jacketed cryogenic pipe. The storage dewar will be superinsulated and vacuum jacketed and will have a liquid nitrogen heat shield.

The refrigerator/liquefier will consist of two or three modules. It will have a cold box module where all the refrigeration, liquefaction, and process control is performed. The other module(s) will be helium compressors that supply high pressure helium to the cold box. An additional requirement of the compressor(s) will be to supply high pressure helium to nine cryocondensation vacuum pumps at a rate of 6 ft³/min at 275 psig.

All helium control valves will be remotely actuated from the EBT-P control room to allow flow control while the device is running.

Cryogenic distribution system

Design criteria and constraints. The cryogenic distribution system shall provide liquid nitrogen and liquid helium to the EBT-P facility. Cryogens are required by the mirror coils around the toroidal cavity and by the gyrotron coils located below the mirror coil ring. Vacuum jacketed, superinsulated components shall be used for all liquid helium lines and cold gaseous helium lines. Field welded joints are to be employed in the liquid helium system to reduce heat leaks unless frequent disassembly is anticipated, in which case bayonet joints are to be used. The liquid nitrogen transfer lines and components are also to be vacuum jacketed and superinsulated.

All lines inside the building that may potentially carry cold gas are to be insulated or have thermally controlled heaters to ensure that no exposed surface will have a temperature lower than the dew point of ambient air.

The liquid helium bath in the coils shall be between 1.0 atm and 2.0 atm, and shall not exceed 4.4 K. All vent lines are to exit outside of the building.

Cooldown of the facility from ambient conditions shall take less than seven days. Helium shall be the only fluid used to cool the helium system. In the event of a facility warmup, the distribution system shall accommodate use of the refrigerator to minimize the time required to reach ambient temperature.

Design description. A schematic of the cryogenic distribution system is included in engineering drawing P2D-57700-0002, which illustrates the components and basic operation of the distribution system. Liquid helium lines connect the storage dewar to the gyrotron supply header and to the dewar supply header. Cold gaseous helium lines carry gas from the gyrotron return header and from the dewar return header back to the cold box. These lines can also be vented to the compressor suction through a heater during cooldown. Liquid nitrogen is also supplied to each dewar, providing cold wall cooling for the magnet dewar. Nitrogen vent gas will be vented outside the building. The cold nitrogen vent lines will be vacuum insulated within the facility area to prevent icing or condensation and to meet critical dimensional constraints. Outside the facility area, these lines can use larger foam insulation. The warm gaseous helium lines that vent the mirror coil and gyrotron coil vapor-cooled leads will be uninsulated and have a temperature-controlled heater to heat the vent gas above the dew point as necessary.

The liquid in the dewars provides coolant for the vapor-cooled leads; the liquid level will be controlled by a level control valve. To ensure proper cooling for the vapor-cooled leads, a blower will be used to maintain 0.5-atm suction on the warm gas lead return line. Each lead will have a remotely actuated flow control valve so that proper cooling can be ensured on each of the 82 (41 pairs) vapor-cooled leads. All control valves that are necessary to equalize He or N₂ flows throughout the system will be remotely actuated.

High voltage electrical system

Primary electrical power for the EBT-P project will be provided through new 15-kV metal-clad switchgear added to the existing switchgear line-up. The new switchgear will be located on the second floor of Building 9201-2 directly above the existing switchgear room. The 13.8-kV feeders from the new switchgear to the EBT-P power supplies and utilities will consist of 15-kV shielded cable enclosed in rigid steel conduit. Total capacity is discussed in Sect. 4.1.1.

Other utilities

Design criteria. The other utilities available within or immediately next to Building 9201-2 are summarized below:

Service	Pressure (psig)	Flow rate
Steam	235	500 lb/hr
Process water	55-85	350 gal/min
Plant air	100	100 scfm
Instrument air	100	100 scfm
Hydrogen	50	100 scfm
Nitrogen	115	75 scfm
Helium	110	200 scfm

In addition to the above utilities, a dedicated liquid nitrogen system will be required. It will supply superconducting magnet precooling refrigeration. During operation, liquid nitrogen will be required for the storage dewar's and superconducting magnet's radiation heat shields. It will also be required for the helium refrigerator/liquefier.

ORNL reference design. The utilities required by the ORNL design are steam, instrument air, helium, and liquid nitrogen. Steam will be needed for unit heaters in the power supply building and

for the device enclosure air handling units. Instrument air will be required to operate remotely actuated flow control valves in water, helium, and nitrogen piping. Helium will be required to supply the liquid helium system with an initial charge and to provide makeup gas in the event of a leak. All of these services will be installed according to UCC-ND Technical Specifications.

The liquid nitrogen supply system will consist of two storage/transport trailers, an unloading station, a pressurizing pump, vacuum insulated pipe, and a gaseous helium cooldown heat exchanger. The flow scheme for the liquid nitrogen is shown on engineering drawing P2D-57700-0002.

4.1.7 Instrumentation and Control

The EBT-P facility is composed of a series of subsystems having interdependent operations. These systems shall be monitored and controlled by facility transducers and interlocks. The general criteria shall be to provide sequential and orderly startup and operation of the EBT-P device and to furnish adequate data to verify the operation. In addition, the facility shall be configured to minimize the personnel required for a successful operation (engineering drawing I2E-14270A-006). The instrumentation and controls shall be divided into the following subsections: vacuum system, cryogenic system, magnet system, auxiliary system, microwave systems, interlocks, data acquisition, master control console, grounding and shielding, personnel safety, and machine diagnostics. A block diagram of the system is shown on engineering drawing I2E-14270-A010; Table 4.5 summarizes the proposed instrumentation. The instrumentation shall be selected to provide personnel and equipment safety, and data accuracy and reliability. The output of the signal conditioning shall be compatible with both a computer and strip chart recorder.

Vacuum system

The EBT-P vacuum shall be established and maintained by a system of mechanical, turbomolecular, and cryosorption pumps. The vacuum system instrumentation and controls shall include all the transducers and circuits to monitor and control the torus and magnet system vacuum levels. The instrumentation shall include Pirani gauges, ion gauges, a residual gas analyzer, and vendor-furnished instrumentation required for the monitoring, control, and regeneration of the cryosorption pumps. The operation of the vacuum system shall be controlled by a programmable logic controller, and all operations shall be performed at the vacuum system location on the Master Control Console (MCC).

The Pirani gauges shall monitor and control the system pumpdown. This gauge was chosen for its wide range and its compatibility with magnetic fields. A questionable area with this type of gauge is microwave effects. If this becomes a problem, thermocouple gauges shall be used, with a corresponding decrease in usable range. The Pirani gauges shall provide the control points for the required pump operations. The gauge controllers shall have set points that can be set over the range of the instrument and shall provide contact closure inputs to a programmable logic controller (PLC). The PLC shall provide an operator-assisted operation to ensure safe and logical operation from the MCC. The Pirani gauge set points shall be input to the PLC through isolated input cards and the remote vacuum valves controlled through isolated output cards. The display and controls for the vacuum system on the MCC will give the operator control and system status information at all times. In addition to digital meters furnished with the Pirani gauge controllers, an analog output shall be input to a digital computer and be available for patching onto a strip chart recorder.

The system operating vacuum shall be monitored and controlled by a series of ion gauges and ion gauge controllers. Ion gauges shall be provided on each torus cavity for diagnostics, on each magnet dewar to monitor and indicate insulating vacuum, and in the piping system for indication and control. The dewar ion gauges shall also act as an input to the superconducting coil control and protection

Table 4.5. Proposed EBT-P instrumentation

System	Parameter	Sensor	Quantity	Location
Vacuum	Low vacuum	Pirani gauge	82	Torus Piping Dewars
	High vacuum	Ion gauge	76	Torus Piping Dewars
Cryogenic	Gas composition	Residual gas analyzer	1	Piping
	LN ₂ flow	Orifice	1	LN ₂ piping
	LN ₂ temperature	Type E thermocouple	50	LN ₂ piping
	LHe temperature	Type E thermocouple	50	LHe piping
		Carbon glass thermometer	36	LHe magnet piping
		Silicon thermometer	15	
	LHe level	Superconducting probe	37	Dewars
Magnet	Differential voltage	Voltage taps	180	Coils Vapor-cooled leads
	Temperature	Type E thermocouple	216	Structure
		Carbon glass thermometer	149	Coils
		PRT	72	Coils
	Pressure	Strain gauge pressure transducer	36	Dewars
Cooling water	Flow	Flow switches	TBD	Piping
		Flow meters	TBD	Piping
	Temperature	Differential temperature	TBD	
		Transducers	TBD	Piping
		Thermocouples	TBD	Piping
Microwave	Temperature	Differential temperature transducer	108	Piping
		Type T thermocouples	6	Piping
	Pressure	Indicating pressure transducer	12	Piping
		Indicating pressure switch	6	Piping
	Flow	Flow switch	125	Piping
	Vacuum (low)	Thermocouple gauge	6	Waveguides
	Vacuum (high)	Ion gauge	6	Waveguides
	Radiation	Microwave detectors	4	Torus enclosure
	Microwave arcing	ARC detector	TBD	Waveguide and gyrotron tube

circuitry. The ion gauge controller outputs shall be input to a computer and be available for patching to a strip chart recorder. In addition, any ion gauges required for control shall act as an input to the PLC.

In addition to the magnetic shielding, a microwave shield will be provided on each of the torus ion gauges. The effects of this shield on response time will be evaluated during detailed design. A piezoelectric valve shall be provided on one torus cavity for hydrogen injection. The piezoelectric valve throttling is controlled by a dc power supply setting, and the time the valve is open shall be controlled by preset pulses.

There shall be a residual gas analyzer (RGA) provided for evaluating the operation of the EBT-P vacuum system. The RGA shall be of the quadrupole type with a cathode ray tube (CRT) display; in addition, the output of the unit shall be input to a digital computer to provide an ongoing record.

Cryogenic system

The cryogenic system for EBT-P shall furnish the liquid helium and liquid nitrogen required for the operation of the device. The liquid nitrogen, to be supplied from an exterior trailer system, shall be monitored by a series of Type E thermocouples, a flow meter, or a load cell at the supply. The thermocouples shall be mounted in separate sections of the transfer lines and switched to common read-outs. The supply of liquid nitrogen shall be monitored at all times with an alarm for low liquid nitrogen supply.

The liquid helium system shall be composed of all components supplying or requiring liquid helium. The temperatures shall be monitored by silicon thermometers, carbon glass thermometers, and platinum resistance thermometers. The liquid helium levels shall be monitored by superconducting level probes and pressures are to be monitored by cryogenically rated strain gauge transducers. As presently conceived, all liquid helium transfer shall be controlled by remote-operated valves with the valve operators mounted at room temperature. The liquid helium shall be supplied by a closed-loop liquefier/refrigerator controlled by instrumentation supplied by the vendor. An existing large refrigerator is controlled by a vendor-supplied PLC and three mode controllers designed for direct digital control. The size and complexity of the proposed system indicate that digital computer control will be required. The cryogenic system shall be controlled by a PLC, and required operator functions shall be from the MCC.

Magnet system

The EBT-P coils shall be superconducting pool boiling. The instrumentation for the magnet system shall be divided into two sections: coil monitoring and coil protection. The liquid level of the dewar shall be continuously monitored, indicated, and alarmed by a superconducting level probe. In addition, the rate of liquid helium use shall be calculated and stored to indicate any potential problems with the coils. This level shall have a dual set point and shall act as an input to the coil dump circuitry. The dewar pressure shall be continuously monitored by strain gauge pressure transducers, burst disks, and pressure relief valves that protect the dewar. The temperature sensors furnished with the coils shall be kept to a minimum because of the difficulty of installing instruments on the coils. As a minimum, Type E thermocouples shall be installed on the coil support structure to observe cooldown, and carbon glass thermometers shall be installed to monitor operational temperatures. These sensors were chosen for their wide range, and the thermometers shall be conditioned and input to a digital computer. The coil vapor-cooled leads shall be purchased with a thermocouple and carbon glass thermometer. The thermocouple shall monitor the gaseous temperatures, and the carbon glass thermometers shall be mounted at liquid helium temperatures. These transducers shall be continuously monitored and alarmed. The

thermocouple shall have a dual set point and act as an input to the dump circuitry. All power supplies shall be procured with the required control options to control the power supply from the MCC. The expected control modes shall be a rampup and rampdown for the current with operator-selected rates. A magnet control microcomputer shall continuously monitor the voltage taps and temperature transducers on the coils and leads and, in the event of a discrepancy between coils, initiate a current level hold. If the coils equalize, the current will automatically start ramping again toward the final current set point; however, if the coils remain unmatched, the operator will have the option of continuing to charge or to deenergize the coils. This shall be performed from the MCC, and the operator shall be able to display all coil signals on a CRT. The coil quench detection shall be based on signals from voltage taps installed across each coil and subtracted from the voltage tap signals from two adjacent coils. These signals shall be conditioned with isolation and differential amplifiers to a level of -10 to +10 V. These high level signals shall act as inputs to hard-wired quench detectors, which shall have a high level and low level comparator. A quench signal is produced when the input exceeds the high level set point or when the input exceeds the low level set point and remains above it for a length of time presettable from 1 to 99 sec. The output from the quench detector shall act as an input to the coil dump signal. Sensors providing input signals to the dump circuitry measure dewar level, vapor-cooled lead temperature, dewar vacuum, and ground fault detector output. The coil dump or protection circuit shall be a dedicated PLC or, if required during design, a hard-wired system. All magnet signals shall be scanned and stored by the magnet system microcomputer, but no portion of the coil protection circuitry shall be scanned or sampled. When a coil dump signal is generated, all coils shall dump at the same time. Each coil has a normally open switch across its terminals and a normally closed switch in series with the positive coil lead. The dump signal first closes all the normally open switches and then opens the normally closed switches, causing the coils to discharge through the parallel dump resistors across each coil. The present design assumes that any dump signal discharges all coils.

Auxiliary systems

Instrumentation for auxiliary systems shall comprise all the transducers required to monitor plant services supplied to the EBT-P. All cooling water lines shall be monitored by flow switches and, if applicable, flow meters. In critical areas of the system, thermocouples and differential temperature transducers shall be installed. The instrument air system shall be controlled by air sets and filter regulators, and all valving dependent on instrument air shall be designed for safe operation in the event of loss of instrument air. The auxiliary systems shall be controlled by and provide input to the system interlock PLC.

Microwave system

The basic microwave power input system shall consist of six gyrotron microwave power tubes and related support equipment listed as follows: power supplies, mounts, microwave distribution system (wave guide), utility services (fluids and electrical power), personnel protection, monitoring and control instrumentation, and installation hardware (cables, conduits, cabinets, etc.).

Instrumentation for monitoring and controlling the microwave power system shall be located in the control room (see engineering drawing IZE-19270-A0006). The bulk of the equipment, programmable controllers, analog/ digital readouts, analog recorders, audiovisual alarm panels, and so on, shall be mounted in equipment cabinets located around the perimeter of the control room. Gyrotron control panels, CRT displays, printouts, and so on, for operator interface shall be located at the MCC in the

control room. Field mounted sensors for measuring the machine parameters (temperature, pressure, etc.) shall provide input signals to read-out devices, recorders, and the programmable controllers (PC's), located in the equipment cabinets. An interface between the equipment cabinets and the MCC shall be provided through programmable controllers, where practical, for direct operator monitoring and control. A supply of demineralized water, oil, FC-75 coolant, nitrogen gas, and liquid helium is required for microwave system operation. Each gyrotron and related microwave distribution system will require approximately 16 demineralized water inputs, two FC-75 coolant inputs, one oil input, one nitrogen gas input, and one liquid helium input for a total of 21 fluid inputs. The demineralized water shall be supplied from a 4-in. header through a pressure control valve. Flow control and monitoring for each input shall be provided by individual rotameters and flow switches. The differential temperature of each water input shall be monitored continuously. Set flow rates and differential temperature measurements will allow the PC to calculate and display heat dissipation values. The FC-75 coolant inputs shall be monitored and controlled in a similar manner. Cooling oil to the gyrotron gun is provided by recirculating oil in a closed loop configuration and requires only pressure and flow monitoring. Dry nitrogen gas shall be supplied to a portion of the wave guide and vented to the atmosphere. The nitrogen gas shall be controlled with a pressure switch and a solenoid on the upstream side of the nitrogen feed line. The set-point pressure shall be approximately 0.1 psig. In addition, a pressure relief valve is required on the downstream side of the nitrogen line to prevent overpressure if the pressure switch should fail. Liquid helium shall be supplied to the gyrotron magnets and recovered as a gas. A liquid level indicator/ controller shall be provided to assure an adequate supply of liquid helium. Each gyrotron will require an ion vacuum pump that shall be monitored and controlled with a combination thermocouple/ion gauge controller interlocked with the gyrotron power supplies through the PC. The gyrotron requires three power supplies for operation. The power supplies shall be provided with automatic and manual controls through a dedicated programmable controller. The gyrotron manufacturer will supply at least two types of detectors; microwave arc detectors mounted in the microwave distribution system and/or in the gyrotron itself, and temperature elements mounted at the ceramic window interface between the gyrotron and the microwave distribution system. Both the arc detectors and temperature elements, supplied by the gyrotron, shall be control interlocked through the PC.

One programmable controller (PC) shall be provided for each gyrotron and microwave distribution system. The programmable controller shall be used to monitor and control the gyrotron power supplies during startup, operation, and shutdown. The programmable controllers shall provide a data acquisition system (DAS), CRT display, and control interface for operating personnel in the MCC. All system parameters (temperature, pressure, vacuum, etc.) shall be interfaced through the PCs, to the MCC, and then to an audiovisual alarm panel mounted in control cabinets located in the control room. The PCs shall provide automatic gyrotron shutdown for selected out-of-tolerance conditions, identify and store fault conditions and their sequence of occurrence, monitor all parameters, and display the information automatically on operator command. In general, each PC shall be used as the primary monitor and control device for microwave power system operation.

Because microwaves present a health hazard, microwave monitoring and audiovisual alarm devices shall be mounted in strategic locations around the device to protect personnel from exposure.

Interlocks

The EBT-P devices shall be interlocked to provide for safe, sequential, and orderly operation. The inputs of the interlock system shall be contact closures, limit switches, instrument set points, push buttons, flow switch outputs, and other process variables required. For a system as complex as

EBT-P, traditional relay logic is not practical. The size and complexity of the system necessitates the use of Program Logic Controller (PLC) to control the system. The PLC is a solid-state, programmable device designed to operate in an industrial environment and to perform control functions formerly performed by relays. The most obvious advantage of the PLC in a complex system is that it is programmable and thus can be incorporated in large systems with relative ease. The PLC basically consists of four parts: processor, input/output, power supply, and programmer. These are furnished as a package with all required interface and interconnecting cables. The only user wiring required is field wiring to the input/output cards. The PLC programming consists of a series of user oriented commands to duplicate relay implementation of a ladder diagram. The present design plan is based on using optically isolated input/output cards with a common mode voltage rating of 1500 V for 10 msec. These cards are optically isolated from the controller for noise elimination. The PLCs shall be programmed for control from the MCC. The first consideration in the system interlock scheme shall be personnel safety; the expected interlock scheme contains personnel safety interlocks on the auxiliary systems, vacuum system, cryogenic system, magnet system, and microwave system, in addition to the operational interlocks. The required programming shall be performed to allow supervised overrides for testing and trouble-shooting. All systems and subsystems affecting the operation of the interlocks shall be designed for fail-safe operation.

Data acquisition

The EBT-P shall be provided a computer-based digital data acquisition system. The system consists of two 16-bit microcomputers controlling various EBT-P subsystems and communicating with a 16-bit minicomputer that shall record and store data, control peripherals, provide supervisory control to the liquifier/ refrigerator, and communicate with the MCC. The vacuum system, facility variables, and cryogenic system are instrumented with relatively slow-speed transducers, but the total number of signals to be monitored and displayed is large. From an operational standpoint, it is practical to provide a method of displaying all these signals at one location. In EBT-P, this location shall be either the data acquisition cabinets and/or the MCC. In addition, a means of storing data to provide time histories of selected variables shall be required, especially during facility startup. The slow-speed signals shall be scanned by a slow-speed scanner supplied with an automatic thermocouple reference junction. The output of the scanner shall be input to a DEC-11/23 microcomputer. The memory requirements for the DEC-11/23 shall be determined during detailed design, but the present concept calls for providing 64 K of solid-state memory and a video terminal. A data link shall be provided to the 11/60 minicomputer for long-term storage data output.

The magnet system shall have a DEC-11/23 to monitor the coils and to provide control of the power supplies. The decision was made to dedicate a microcomputer to the superconducting coils because of the number of variables and the sampling speed required during a coil quench. This system shall also use a DEC 11/23 with 64 K of solid-state memory, but a high-speed scanner shall also be provided in addition to a slow-speed scanner for variables such as temperature and level. The sampled signals shall not affect the coil protection circuitry. This PDP-11/03 shall also communicate with the central PDP-11/60.

The central PDP-11/60 shall have 128 K of solid-state memory, a printer/plotter, a moving head disk, a video terminal, and DMA interface to the 11/23's. This computer shall serve three primary functions: to store data from the LSI-11/23's, to provide total system supervision, and to provide operator-requested output to the MCC. The main operator access to all facility data shall be through the PDP-11/60. In addition to these functions, any required control algorithms for the liquefier/ refrigerator controller shall be generated in the 11/60.

Master control console

A master control console (MCC) shall be furnished as a centralized facility control location. The MCC shall be divided according to the various systems to be controlled. The panel shall be designed with a semigraphic representation of each subsystem. There shall be a set of lighted flat pack push buttons and LED lamps for control and status indication. The operation of all system PLC's shall be from the MCC. In addition, CRT display shall be provided to allow the operator to call up and display data from the PDP-11/60. Also, all critical variables displayed 100% of the time shall be read at the MCC's digital panel meters. The present design calls for inclusion of a system annunciator at the MCC.

Grounding and shielding

The first grounding consideration shall be personnel safety and the second the elimination or reduction of electromagnetic interference. The basic concept requires the design of a low-impedance ground bus to which all control room cabinets and control room ends of the signal cables are connected. This ground bus is extended into the cable trays, and all low level signal cables are run in these trays. The cables to be used shall be shielded coaxial or twisted shielded pairs. The termination of cable shields shall be evaluated for each sensor during the detailed design phase and installed, where possible, in the best fashion to guarantee data quality.

Personnel safety

A system of interlocks shall be provided to prevent personnel from entering any hazardous area during an experiment. A series of Kirk key-type interlocks will regulate the operation of all hazardous subsystems. These shall be the first set of permissives to be satisfied for the PLCs, and unless they are satisfied, the systems will not be operable. The microwave monitors provided for personnel safety are discussed earlier.

Machine diagnostics

The diagnostics to be furnished shall consist of only those required for machine startup. These shall include an ion gauge in each cavity (covered in the description of the vacuum system), a microwave interferometer, a single point Thomson scattering diagnostic, diamagnetic loops, toroidal current coils, field correction coils, hard x-ray detectors (NaI), and a color television monitor. The applicable diagnostics shall be input to a PDP-11/34 computer through a CAMAC crate. The present concept calls for transferring startup diagnostics from EBT-S to EBT-P at the required time. This will not be possible with the magnetic coils and loops, but their required electronics can be exchanged. Any additional diagnostics shall be added to the machine as required by operations.

4.2 ESTIMATED COST

The EBT-P Project cost estimate summary for the proposed reference design is shown in Table 4.6. The estimate was prepared using fourth-quarter FY 1979 pricing data as a base, with approved DOE escalation factors applied. All numbers were escalated to the midpoint of the fiscal year by the following factors:

FY 80 — 10%	FY 83 — 9%
FY 81 — 9%	FY 84 — 9%
FY 82 — 9%	

Table 4.6. EBT-P proposed reference design project budget summary
(Dollars in thousands)

	Obligations					Costs					Total
	FY 80	FY 81	FY 82	FY 83	FY 84	FY 80	FY 81	FY 82	FY 83	FY 84	
Engineering	(1,600)	(3,300)	(5,680)	(4,960)	(2,460)	(1,600)	(3,300)	(5,680)	(4,960)	(2,460)	(18,000)
Project management ^a	500	600	700	800	700	500	600	700	800	700	3,300
Engineering Title I	1,100	420	0	0	0	1,100	420	0	0	0	1,520
Engineering Title II	0	2,140	3,180	800	0	0	2,140	3,180	800	0	6,120
Engineering Title III	0	140	1,800	3,360	1,760	0	140	1,800	3,360	1,760	7,060
Construction	(0)	(3,000)	(21,720)	(14,640)	(3,540)	(0)	(1,500)	(8,820)	(19,440)	(13,140)	(42,900)
1.2.0 Building mod.	0	200	3,740	990	0	0	200	3,530	1,200	0	4,930
1.3.0 Toroidal vessel	0	0	2,130	0	0	0	0	300	1,830	0	2,130
1.4.0 Magnet system	0	1,300	6,000	5,100	1,550	0	800	1,000	6,200	5,950	13,950
1.5.0 Microwave system	0	0	3,000	3,000	1,300	0	0	1,090	2,500	3,710	7,300
1.6.0 Vacuum system	0	0	850	0	0	0	0	400	450	0	850
1.7.0 Utilities	0	1,500	3,500	3,050	0	0	500	2,200	5,350	0	8,050
1.8.0 Instrumentation	0	0	2,500	2,500	690	0	0	300	1,910	3,480	5,690
Subtotal	1,600	6,300	27,400	19,600	6,000	1,600	4,800	14,500	24,400	15,600	60,900
Contingency ≈30%	400	1,600	8,400	6,100	1,800	400	1,200	4,400	7,500	4,800	18,300
Total	2,000	7,900	35,800	25,700	7,800	2,000	6,000	18,900	31,900	20,400	79,200

^aUCC-ND project management team.

The estimate encompasses only the capital line item funds required for project management engineering, construction, and installation of the EBT-P device and support facilities. No funds for maintenance, operation, or future upgrading of the device are included within the scope of the cost estimate. The estimate was organized around the EBT-P work breakdown structure (WBS) shown in Fig. 4.5 and defined below. The standard WBS was organized to facilitate cost accumulation in accordance with established DOE reporting categories as established in the DOE Cost Code Manual for Construction Projects (May 1979).

Facility WBS

Land improvements. These include site preparation grading; storm drainage; exterior demolition; paving; and landscaping, if required.

Building modifications. These include modifications to building 9201-2 to make it suitable for the EBT-P experiment, including interior demolition, control room modification, shield construction, utility modifications, and cold box installation.

Building additions. These include construction of new buildings or building additions and related utilities, including foundations, concrete pads, power supply, building enclosure, transformer pads, the compressor building shelter, and utilities within the building.

Outside utilities. These include new or modified utilities outside the building, such as electrical, water, steam, and helium storage tanks.

Device WBS

Toroidal vessel. This includes the basic toroidal vacuum structure, which consists of the mirror cavity and the nonintegral dewar vacuum lines, including access ports for pumps, microwaves, and diagnostics.

Magnetic system. This system includes all magnet and magnet-related components, such as mirror coils, power supplies, x-ray shielding, dewar assembly, magnet protection system, and device support structure.

Fig. 4.5. EBT-P work breakdown structure.

Microwave system. This system includes all microwave related components, such as tubes, power supplies, tube mounts, microwave distribution system, etc.

Vacuum system. This system includes all pumping and vacuum-system-related components except the toroidal vacuum vessel and the magnet vacuum dewar. It also includes the hydrogen gas injection system.

Instrumentation. This includes all items necessary to monitor and control operation of the device, a basic complement of experimental diagnostics, and the required safety interlocks.

Device utilities. These include all utilities necessary and peculiar to the operation of the device, such as the cryogenics system, cooling water manifold, and electrical service independent of building electrical.

4.3 PROPOSED SCHEDULE

The proposed schedule (Fig. 4.6) was developed based on the following assumptions:

1. Contract award to the successful subcontractor will take place before June 1980.
2. Budget restraints limit work in FY 1980 and 1981.
3. Development activities on the magnets and the gyrotrons permit procurement of components no later than the times shown.

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Fig. 4.6. Proposed EBT-P project schedule.

REFERENCES

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APPENDIX 1

RELATIVISTIC ELECTRON RINGS

BACKGROUND

A workshop on EBT Ring Physics was held at Oak Ridge, Tennessee on December 3-5, 1979, under the sponsorship of the Oak Ridge National Laboratory. About 70 U.S. and Japanese participants attended the workshop representing various U.S. industries, universities, national laboratories, and DOE; and Japan Ministry of Education (MOE) and Nagoya University.

The workshop organizing committee were:

N. A. Uckan, chairman, Oak Ridge National Laboratory
W. B. Ard, McDonnell Douglas Research Laboratories
R. A. Dandl, Consultant
A. Favale, Grumman Aerospace Corporation
G. C. Guest, General Atomic Company
G. R. Haste, Oak Ridge National Laboratory
C. L. Hedrick, Oak Ridge National Laboratory
H. Ikegami, Nagoya University, Japan

The purpose of the workshop was:

- to evaluate the status of the current (experimental and theoretical) understanding of the hot electron ring properties,
- to identify dominant physical processes which influence ring formation and scaling and their optimal behavior, and
- to determine critical areas for near-term research.

The proceedings of the workshop containing the consensus summary of the workshop participants as well as the full-length papers presented and the technical discussions that took place are in preparation and will be published as soon as all the necessary inputs are available.

The workshop summary and collection of abstracts are appended to this report under separate cover.

This appendix reflects the summary discussions that took place during November 1979 with candidate IP's on the ring power balance.

INTRODUCTION

An essential feature of EBT is the presence of a relativistic electron annulus in each of the toroidal mirror sectors. These high beta annuli are formed and sustained by microwave heating and are of sufficient density and temperature for diamagnetic currents to produce the necessary minimum in the magnetic field required for the MHD stability of the toroidal core plasma. The stability of the electron ring itself requires the presence of an appreciable cold electron density component, $n_{\text{cold}}/n_{\text{hot}} > 1$.¹

Because electron rings play an important role in the confinement characteristics and performance of EBT, the tradeoff between the quality of the confinement afforded by the rings and the power required to sustain them represents an important physics question for EBT-P and in scaling the EBT to a reactor.

Recent studies of the ring power balance² in EBT-I have indicated that the energy transfer between the relativistic annulus electrons and the core electrons via Coulomb collisions (drag cooling) is the dominant loss mechanism. Experimental measurements of the annulus decay time³ are within a factor of ~ 2 of the theoretical drag time, indicating the importance of this loss mechanism in future EBT devices.

While disagreement is seen in the details, the models developed by ORNL^{2,4} and McDonnell Douglas⁵ are in qualitative agreement within 10-15% for typical annulus parameter ranges of interest.

ANNULUS POWER REQUIREMENTS

Because the core-stabilizing electron annulus must be continuously driven by the microwave sources during steady-state operation, the question of power drain from the annulus is extremely important in scaling the microwave power requirements. If the annulus can be stabilized against drift instabilities, as is the case in simple mirrors and EBT-I, classical losses should dominate the power requirements. In its most basic form the annulus power balance is given by

$$P_{\mu A} = P_{\text{synch}} + P_{\text{brems}} + P_{\text{scatt}} + P_{\text{drag}}, \quad (1)$$

where P_{synch} and P_{brems} represent power lost by synchrotron and bremsstrahlung radiation, P_{scatt} is the 90° pitch angle scattering of the ring electrons on the core plasma ions, P_{drag} represents the power lost from the relativistic electrons due to drag on the toroidal core electrons, and $P_{\mu A}$ is the microwave power required to sustain the annulus. In terms of plasma and machine parameters, Eq. (1) can be expressed in mks units with I in keV as follows (see Refs. 2, 4, and 5 for details):

$$\begin{aligned} P_{\mu A} (\text{mW}) = & \underbrace{\left\{ 3.2 \times 10^{-20} B_A^2 n_A (\gamma - 1) [1 + 2.5(\gamma - 1)] \right\}}_{P_{\text{synch}}} \\ & + \underbrace{8 \times 10^{-43} n_A n_{ep} \sqrt{\gamma^2 - 1}}_{P_{\text{brems}}} \\ & + \underbrace{1.0 \times 10^{-39} n_A n_{ip} \frac{\gamma(\gamma - 1)}{(\gamma^2 - 1)^{3/2}} \ln \Lambda_{ei}}_{P_{\text{scatt}}} \\ & + 2.5 \times 10^{-39} \left\{ \frac{\gamma^\alpha \ln \Lambda_\alpha}{\sqrt{\gamma^2 - 1}} n_A n_{ep} \right\} V_A \end{aligned} \quad (2)$$

where

$$\gamma = 1 + T_A/511;$$

$$\ln \Lambda_{ei} \cong 38 - \ln (\sqrt{n_A}/T_A);$$

n_A , T_A , and B_A are the density, kinetic energy, and magnetic field strength at the annulus, respectively; $n_p \cong n_{ip} \cong n_{ep}$ is the toroidal core plasma (ion/electron) density near the vicinity of the annulus; V_A is the total annulus volume; $\alpha = 1$ or 2 depending on the model chosen^{2,4,5,6}; and $\ln \Lambda_\alpha$ is the Coulomb logarithm with slight differences in definition for $\alpha = 1$ or $\alpha = 2$ ($\ln \Lambda_1 \sim 25-30$; $\ln \Lambda_2 \sim 16$ for typical parameter ranges of annulus). It should be noted that the difference of the effect of the two assumed drag models ($\alpha = 1$ or 2) on the total power loss is small ($\sim 10-15\%$). Drag losses dominate a significant range of the ring energy and are large for small energies. At high ring energies, $T_A \geq 1$ MeV, accelerated ring cooling occurs due to the synchrotron radiation.

The stability of hot electron rings requires an appreciable cold electron density component near the vicinity of the rings, $n_p/n_A > 1$.¹ An experimental examination of the annulus stability boundaries is planned for EBT-S and will help to establish the acceptable range for the ratio of cold-to-hot plasma density for ring stabilization. Defining the ring stability ratio as

$$f_R = \frac{n_{\text{cold}}}{n_{\text{hot}}} = \frac{n_p}{n_A},$$

one can write

$$P_{\mu A}(\text{MW}) = \left\{ 3.2 \times 10^{-20} B_A^2 n_A (\gamma - 1) [1 + 2.5(\gamma - 1)] + \frac{10^{-39}}{\sqrt{\gamma^2 - 1}} f_R n_A^2 \left[\frac{\gamma}{\gamma + 1} \ln \Lambda_{ei} + 2.5 \gamma^\alpha \ln \Lambda_\alpha \right] \right\} V_A. \quad (3)$$

Bremsstrahlung radiation is smaller than the least of the other losses by better than two orders of magnitude and is therefore neglected in Eq. (3).

One can also express the microwave power loss from the annulus in terms of magnetic field B_A and annulus beta β_A . The cutoff for microwave propagation (electron plasma frequency $\omega_{pe} \leq$ electron cyclotron frequency ω_{ce}) imposes an upper limit on core density n_p , which scales as the square of the magnetic field. Defining a fraction f_c of the microwave cutoff as

$$n_p = f_c n_{\text{cutoff}} = f_c n_c,$$

where

$$n_c \cong 10^{19} B_A^2,$$

and defining annulus density n_A in terms of β_A and B_A as

$$n_A = \frac{5 \times 10^{18} \beta_A B_A^2}{(T_A/511)},$$

Eq. (3) can be rewritten as

$$P_{\mu A}(\text{MW}) = \frac{5 \times 10^{-2} \beta_A B_A^4}{(T_A/511)} \left\{ 3.2(\gamma - 1) [1 + 2.5(\gamma - 1)] + \frac{f_c}{\sqrt{\gamma^2 - 1}} \left[\frac{\gamma}{(\gamma + 1)} \ln \Lambda_{ei} + 2.5 \gamma^\alpha \ln \Lambda_\alpha \right] \right\} V_A. \quad (4)$$

As indicated before, the terms in brackets represent the energy loss due to synchrotron radiation, scattering, and drag, respectively. This can be averaged over the annulus electron energy distribution as is done in Ref. 5.

An accurate determination of $P_{\mu A}$ requires detailed knowledge of ring parameters and volume. The modest parameter range accessible in the past mirror and EBT experiments, which all have similar sizes,

is not sufficiently broad to allow a credible straightforward extrapolation to future larger devices, especially to a reactor. However, based on the theoretical calculations and the experience gained from earlier experiments, it is possible to determine the dominant mechanisms that influence the ring formation and power balance and their scaling for the proposed EBT-P experiment.

One of the primary physics objectives of EBT-P is the study of hot electron ring power balance. When scaled up from ELMO and EBT-I, the ring power requirements for a reactor can become favorable or unfavorable depending on the scaling assumptions made as well as on the completeness and/or self-consistency of the models used. The proposed EBT-P device has the capability to operate with frequencies in the range of $\sim 28-90$ GHz, which correspond to $B_{\text{resonance}} \sim 1-3.1$ T ($B_A \sim 0.5-1.5$ T). With this capability and with the flexibility given by various possible improvements in the area of microwave feeding and separate control of annulus, it should be possible to accomplish the objective of establishing the ring power balance scaling.

SCALING PROJECTIONS FOR EBT-P

The microwave power required to sustain the annulus in EBT-I is modest and reasonably well estimated by the theoretical models discussed here.² Good agreement between the experimental and theoretical estimates of $P_{\mu A}$ for EBT-I provides a level of confidence in the predicted annulus power requirements for EBT-P. Such an assessment is necessary for EBT-P and future machines. In the near term, it can provide valuable sizing information pertaining to the fraction of the system power necessary to drive the microwave sources. Such information will benefit the ongoing development program for millimeter wavelength, cw microwave sources by ensuring tube procurement at sufficiently high power levels. On the longer time scales envisioned for a reactor (EBTR), the continuous microwave power required to sustain the annulus during steady-state operation may become the determining factor for overall reactor efficiency. This is to be expected because following ignition, the bulk heating (either ECH or neutral beams) will be terminated and the plasma temperature maintained by alpha particle heating and collisional energy gains from the annulus.

Scaling curves for initial EBT-P operation are shown in Fig. A.1.1. These curves enable us to determine the microwave power required to sustain the rings at a given annular beta for increasing (or decreasing) levels of core plasma density. In Fig. A.1.1 is plotted f_R (ring stability ratio $= n_p/n_A$) versus annulus energy for various microwave power levels (MW/m^3) and is based on the annular power balance given by Eq. (3). It assumes $f_c = 1$ [$= (n_p/n_{\text{cutoff}})$], $n_{\text{cutoff}} \approx 10^{19} \text{ m}^{-3}$ @ $B_A = 1$ T].

Also shown in Fig. A.1.1 is the correlation between values of annular beta (β_A) and the various modes of EBT operation (C-, T-, and M-modes).³ The C-mode corresponds to the noisy operation when insufficient microwave power is supplied to produce enough β_A ($\beta_A \leq 10\%$). At $\beta_A \geq \beta_{\text{crit}}$ ($\sim 10\%$) there is a transition from the C-mode to the quiet, macrostable T-mode, where the stable steady-state operation occurs. For β_A values much larger than $\sim 50\%$, abrupt transition into an M-mode occurs.³

For a range of annular beta values $\beta_A \sim 10-50\%$, the stability of the hot electron ring itself requires the presence of an appreciable cold electron density component.¹ Stability curves derived in Ref. 1 are also superimposed on Fig. A.1.1 in order to show possible stable operating regime for the hot electrons. For $f_c = 1$, i.e., $n_p = n_{\text{cutoff}} = 10^{19} \text{ m}^{-3}$ at $B_A = 1$ T leads to $T_A \geq 500$ keV, $f_R \geq 10$, and $P_{\mu A} \leq 1 \text{ MW}/\text{m}^3$. Similar curves for $f_c = 0.5$ give $P_{\mu A} \leq 0.5 \text{ MW}/\text{m}^3$.

Table A.1.1 summarizes $P_{\mu A}/\beta_A B_A^4 V_A$ for various annulus energies and for $f_c = 0.5$ and 1.0. Table A.1.1 is based on Eq. (4) and is averaged over relativistic two-dimensional Maxwellian distribution function assuming $\alpha = 1$.⁵

Fig. A.1.1. The fraction of cold-to-hot electrons, $f_R = n_{\text{cold}}/n_{\text{hot}} = n_p/n_A$ vs annulus electron energy, T_A , for $P_{\mu A}/V_A = 0.5, 1.0$, and 2.0 MW/m³. $f_c = 1$ (i.e., $n_p = n_{\text{cutoff}}$) and $B_A = 1$ T. C-, T-, M-mode boundaries are indicated with $\beta_A \approx 10\%$ and 50% curves. Marginal stability curves (from Ref. 1) for $\delta = 0.5$ and 1.0 ($\delta = 1/kr_p$, $r_p^{-1} = n^{-1} dn/dr$) are also shown. Stable operating regimes for annulus electrons are bounded by the β_A curves from the sides (T-mode) and $\delta = 0.5$ and 1.0 curve from the below.

Table A.1.1

T_A (keV)	$P_{\mu A} / B_A^4 V_A$	
	$f_c = 1.0$	$f_c = 0.5$
100	39	19.6
200	14.2	7.27
300	8.14	4.27
400	5.65	3.06
500	4.38	2.47
600	3.64	2.14
700	3.18	1.96
800	2.89	1.86
900	2.70	1.80
1000	2.57	1.79
1200	2.45	1.82
1400	2.42	1.90
1600	2.46	2.02
1800	2.54	2.15
2000	2.64	2.30

↑ Probable C-mode
limit for
EBT-P

↓ Probable M-mode
limit for
EBT-P

Source: McDonnell Douglas Astronautics Company Report
MDC E2160, Saint Louis, Missouri (October 1979).

The total loss rate has a minimum that is bounded by collisional drag and scattering from one side and synchrotron radiation from the other end of the energy spectrum. While scattering and drag dominate at very low energies, drag dominates over a significant portion of the energy range, decreasing as $\sim 1/v$ until v is comparable to c . At these high energies, the model with $\alpha = 2$ shows a strong dependence on the relativistic term, which scales as γ for very relativistic electrons. In comparison, the classical model with $\alpha = 1$ reaches a minimum when the kinetic energy of the electron is of the order of its rest mass, although it depends on f_c . It then increases logarithmically. Accelerated ring cooling occurs at high energies due to synchrotron radiation, and this effect masks the difference between $\alpha = 1$ and $\alpha = 2$ drag models.

Because of the uncertainty associated with the annulus volume, our scaling projections thus far have not included any assumptions regarding ring size. Based on experimental measurements and theoretical estimates, it appears that a range exists for the annulus thickness which varies between a minimum of the relativistic gyrodiameter and a maximum value of ~ 3 -4 cm as measured on ELMO. It also appears that the annulus length in those experiments are comparable to the plasma size, but all are within the ~ 10 cm range. Since all the experiments during the past twenty years with mirrors and EBT's (NBT as well) had similar device and plasma parameters, it is difficult to make a definitive estimate for the ring volume scaling. Given the uncertainties, it was agreed by all the candidate IP's to make the following conservative assumptions for the design of EBT-P:

- The ring volume is assumed to be 10% of the toroidal plasma volume, as in the case of EBT-I. It was the belief of the majority of the participants that this ratio will be much smaller when it is extrapolated to future devices with higher magnetic fields.
- As a base case, the ring energy is chosen to be $T_A \geq 500$ keV ($500 \leq T_A \leq 1.5$ MeV).
- Based on experimental results and theoretical calculations, the microwave power required to sustain the rings is $P_{\mu A} \approx 0.5$ W/cm³ (or 0.5 MW/m³) for 60-GHz bulk heating with $B_A = 1$ T at the ring and $f_c \approx 0.5$.

It was pointed out that above assumptions and estimates are conservative ones and improvements and optimizations are possible in the area of microwave feeding, operating, formation, and separate control of hot electron rings as well as in efficient coupling of microwave power.

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3. R. A. Dandl et al., Oak Ridge National Laboratory Report ORNL/TM-6457, Oak Ridge, Tennessee (1978).
4. See Appendix A.3 in Oak Ridge National Laboratory Report ORNL/TM-7066 (October 1979).
5. See Appendix B in McDonnell Douglas Astronautics Company Report MDCE2160 (October 1979).
6. J. D. Jackson, Classical Electrodynamics, 2d ed., p. 618 (New York: John Wiley and Sons, Inc., 1975).

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APPENDIX 2

X-RAY HEATING

INTRODUCTION

The latter portion of this Appendix was written for and attached to the EBT-P Preliminary Conceptual Design Report prepared in October 1979 (TM-7066). A number of developments have occurred since then. These developments have resulted from discussions with the Phase I subcontractors and have led to a more extensive specification of the x-ray source expected. These changes are as follows:

1. Although the shielding effectiveness of depleted uranium was widely recognized, it was agreed that, because of other considerations, it was not a desirable material. As such it will no longer be considered in subsequent designs.
2. Production of the x-rays in a nonuniform manner has led to more stringent requirements on the gamma-ray heating in the superconducting coils. The energetic electrons strike the coil perferentially near the vertical midplane on the inboard side of the coil throat. For design purposes, the impact area of the energetic electrons is taken to be 10 cm^2 . When this area is chosen to be on the coil case itself, the peaking factor of the gamma heating is high. By removing this source from the coil case, as with a movable limiter, the peaking factor can be reduced. The applicability of this concept to a specific coil design depends on the geometry of the cavity, case, and coil.
3. The ring parameters, which will determine the shielding necessary, have been agreed upon. These include: a temperature of 1 meV, a particle scattering loss rate term that varies inversely as the $3/2$ power of the energy, and a scattering loss power equivalent to 0.5 W/cm^3 of ring volume for a frequency of 60 GHz. At other frequencies, this power scales as the fourth power of the frequency.
4. One quantity that could limit the usable life of the coils is the radiation damage in the insulation. Although a quantitative appreciation of this problem was lacking, it was agreed that a design goal would be a 10-year life when operating 8 hours a day continuously.

SHIELDING ANALYSIS

Because of the expected large loss of electrons on the magnetic coil assemblies and other components of the proposed EBT-P plasma device, the induced gamma field from bremsstrahlung will be very intense. These gammas will yield increased heating loads on the superconducting cryogenic coils as well as producing a significant biological hazard. In this section the results from a series of one-dimensional (1-D) calculations in which the gamma heating loads were determined are presented for several coil shield configurations. Also given are 1-D results that indicate the level of biological dose for varying thicknesses of either lead or concrete that have been proposed for the primary shielding. The calculational methods and results are presented and discussed below.

Method of Calculation

The transport of electrons, positrons, and gammas through the magnet assembly was carried out using the EGS-PEGS code system.¹ This Monte Carlo code package takes into account all physical processes that are important in the energy range of interest, i.e., $\leq 10 \text{ MeV}$. These processes include Compton scattering, pair production, photoelectric effect, Moller scattering, Bhabha scattering, electron-positron annihilation, bremsstrahlung, and, through the use of the continuous slowing-down approximation, the energy loss of the charged particles.

The EGS-PEGS code system could have been used for the entire set of calculations except for the large statistical uncertainties associated with the calculated results at large shielded distances from the radiation source. To circumvent this problem, the EGS-PEGS code system was used to generate only photon spectra. These spectra were then input to the 1-D discrete ordinates transport code ANISN.² This code has been used extensively for 1-D shielding calculations and is very applicable to deep penetration problems.

With the photon spectra from EGS-PEGS, the ANISN calculations were carried out using an S_8 angular quadrature and a 21-photon energy group cross-section set containing a P_3 Legendre approximation of the transfer cross sections. These cross sections, which cover the energy range 0.01-14 MeV, were stripped from the DLC-31³ few-group 37-neutron/21-gamma group microscopic cross-section library using the AXMIX code.⁴ This code was also utilized to obtain the macroscopic cross sections by folding the microscopic data with the theoretical atom densities of aluminum, tungsten, ^{238}U , and copper, and lead and with the elemental atom densities of the concrete used in the Tower Shielding Facility.⁵

The photon-heating kerma factors for aluminum, ^{238}U , and copper were obtained from the Evaluate Photon Interaction Library⁶ and were processed into the DLC-31 photon energy group structure using the SMUG module in the AMPX code system.⁷ The photon flux-to-dose conversion factors were taken from the DLC-31 library.

Geometry

The 1-D geometries employed in EGS-PEGS and ANISN and in both the coil-heating and biological dose calculations consisted of a series of infinitely long concentric cylinders as shown in Fig. A.2.1. In the heating calculations (Fig. A.2.1a), electrons were assumed to be isotropically incident on the front face of the 1-cm-thick aluminum liner for the transport utilizing the EGS-PEGS code system. Although the bremsstrahlung gammas produced by the electrons were somewhat smeared radially throughout the aluminum, the photon source was placed at a radius of 21.3 cm for the ANISN calculations. The angular distribution associated with these gammas is isotropic because the electron source was assumed to be isotropic. However, some calculations were performed for normally incident gammas to determine angular sensitivity. Coil shield thicknesses of 0.5, 1.0, and 1.5 in. were considered for both the ^{238}U and tungsten shields.

The biological dose calculations were performed using the geometry illustrated in Fig. A.2.1(b). In these calculations the biological dose rates for up to 1 ft of lead and 6 ft of concrete were obtained with and without 1.25 in. of ^{238}U coil shielding. The bremsstrahlung spectra used in the heating calculations were again used for these calculations. These photon sources were assumed to be isotropically incident on the inner face of the ^{238}U (or voided) region.

Electron loss distribution

The rate at which electrons are lost from the plasma was assumed to be proportional to a Maxwellian distribution weighted by $E^{-3/2}$, i.e.,

$$\text{Loss} = A \times \exp(-E/kT)/E^{3/2},$$

where E is the electron energy and T represents the plasma temperature. This distribution was normalized to a maximum power loss of 1 MW, yielding a normalization constant of $A = 6.242 \times 10^{18}/kT$.

Because very low energy electrons do not contribute significantly to either the photon heating or the biological dose, only electrons with energies >0.239 MeV were considered. For kT values of 1.0,

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Fig. A.2.1. One-dimensional geometric models:
 (a) geometric model for coil-heating calculations;
 (b) geometric model for biological dose calculations.

1.5, and 2.0 MeV, the number of electrons lost from the system per second with energies >0.239 MeV is 5.99×10^{10} , 5.37×10^{18} , and 4.80×10^{18} , respectively. These numbers were obtained by integrating the loss distribution of electrons with energies of up to 10 MeV. For a kT of 2.0 MeV, the integration was also carried out up to 20 MeV, which produced a loss rate of 4.81×10^{18} electrons/sec.

The cumulative bremsstrahlung spectra for the various kT values were obtained from the following expression:

$$h(E_\gamma) = \frac{\int_{0.239}^{10 \text{ MeV}} g(E_\gamma, E_e) \exp(-E_e/kT) / E_e dE_e}{\int_{0.239}^{10 \text{ MeV}} \exp(-E_e/kT) / E_e dE_e},$$

where $g(E_\gamma, E_e)$ represents the bremsstrahlung spectrum produced from electrons of energy E_e . In a similar fashion the heating and dose rates can be obtained. As stated above, for $kT = 2.0$ MeV (hereafter referred to as 2.0^* MeV), the integral was also extended to 20 MeV, assuming the bremsstrahlung spectra from electrons with energies greater than 10 MeV were the same as those produced by 10-MeV electrons.

RESULTS

Energy deposition in superconducting coils

The bremsstrahlung spectra obtained from the EGS-PEGS calculations are given in Table A.2.1 for a large range of electron energies. The photon energy group structure used in this study is also given in Table A.2.1. This group structure corresponds to the 21-photon energy group structure in the DLC-31 cross-section library.

The importance of electron energy to the total photon energy deposition rate in the superconducting coils is illustrated in Fig. A.2.2 for several ^{238}U shield thicknesses. These results are normalized per incident electron per second and were obtained by performing separate ANISN calculations for each of the spectra in Table A.2.1. The increased energy deposition rate with increasing electron energy is the result of both the increased number of photons and the increased photon energies associated with the higher energy electrons.

To obtain the actual total energy deposition rate, the data in Fig. A.2.2 must be weighted with the electron loss distribution. Energy deposition rates obtained with the loss distribution given above are presented in Fig. A.2.3 for electron temperatures of 1.0, 1.5, 2.0, and 2.0^* MeV as a function of coil shield thickness. As explained, 2.0^* MeV represents extending the integration to 20 MeV. These results have been normalized to a 1-MW electron power loss. The energy deposition rate for the tungsten shield was calculated only for the $kT = 2.0^*$ -MeV electron temperature because this temperature yields the greatest heating.

The total energy deposition rates in the aluminum liner, ^{238}U shield, and copper coil for these same electron temperatures and three ^{238}U shield thicknesses are given in Table A.2.2. These results have also been normalized to a 1 MW-electron power loss. The energy deposition rates represent only the heating due to bremsstrahlung. The remainder of the heating associated with the incident electrons amounts to $\sim 98\%$ of the total power loss. This portion of the power loss is deposited almost entirely in the aluminum liner because only some of the higher energy electrons are able to penetrate into the ^{238}U shield.

Table A.2.1. Bremsstrahlung spectra for photons above 0.01 MeV (photons/electron)

Photon upper energy (MeV)	Electron energy (MeV)						
	0.489(1.0) ^a	0.989(1.5)	1.489(2.0)	1.989(2.5)	2.489(3.0)	2.989(3.5)	3.489(4.0)
14	0	0	0	0	0	0	0
10	↑	↑	↑	↑	↑	↑	↑
8	↑	↑	↑	↑	↑	↑	↑
7	↑	↑	↑	↑	↑	↑	↑
6	↑	↑	↑	↑	↑	↑	↑
5	↑	↑	↑	↑	↑	↑	↑
4	↑	↑	↑	↑	↑	↑	↑
3	↑	↑	↑	↑	↑	↑	↑
2.5	↑	↑	↑	↑	↑	↑	↑
2.0	↑	↑	↑	↑	↑	↑	↑
1.5	↑	↑	↑	↑	↑	↑	↑
1.0	↑	↑	↑	↑	↑	↑	↑
0.7	↑	↑	↑	↑	↑	↑	↑
0.45	↑	↑	↑	↑	↑	↑	↑
0.3	↑	↑	↑	↑	↑	↑	↑
0.15	↑	↑	↑	↑	↑	↑	↑
0.1	↑	↑	↑	↑	↑	↑	↑
0.07	↑	↑	↑	↑	↑	↑	↑
0.045	↑	↑	↑	↑	↑	↑	↑
0.03	↑	↑	↑	↑	↑	↑	↑
0.02	↑	↑	↑	↑	↑	↑	↑
Total γ's/e ⁻	3.92-2	1.00-1	1.78-1	2.58-1	3.46-1	4.43-1	5.24-1

	3.989(4.0)	4.489(5.0)	4.989(5.5)	5.489(6.0)	5.989(6.5)	6.989(7.0)	6.989(7.5)
14	0	0	0	0	0	0	0
10	↑	↑	↑	↑	↑	0	0
8	↑	↑	↑	↑	↑	0	0
7	↑	↑	↑	↑	↑	1.11-4	4.00-4
6	↑	↑	↑	↑	↑	1.11-3	1.60-3
5	0	0	4.44-4	1.67-3	2.00-3	3.33-3	6.00-3
4	1.00-3	2.44-3	2.89-3	5.33-3	8.22-3	9.44-3	1.28-2
3	2.22-3	3.22-3	4.22-3	5.33-3	6.78-3	8.78-3	9.00-3
2.5	4.11-3	4.78-3	6.44-3	1.02-2	1.08-2	1.42-2	1.46-2
2.0	7.00-3	1.06-2	1.49-2	1.56-2	1.91-2	2.14-2	2.62-2
1.5	1.51-2	2.04-2	2.50-2	2.81-2	3.43-2	4.17-2	5.22-2
1.0	2.09-2	2.53-2	3.08-2	3.18-2	4.18-2	4.36-2	5.08-2
0.7	3.26-2	3.73-2	4.39-2	5.47-2	5.53-2	6.71-2	8.30-2
0.45	3.80-2	4.40-2	4.99-2	5.62-2	5.88-2	7.18-2	7.78-2
0.3	7.91-2	9.02-2	1.02-1	1.13-1	1.30-1	1.45-1	1.64-1
0.15	5.38-2	6.26-2	6.78-2	7.87-2	7.97-2	9.46-2	1.02-1
0.1	5.34-2	5.77-2	6.54-2	6.89-2	7.90-2	8.74-2	9.12-2

Table A.2.1 (continued)

Photon upper energy (MeV)	Electron energy (MeV)						
	3.989(4.0)	4.489(5.0)	4.989(5.5)	5.489(6.0)	5.989(6.5)	6.989(7.0)	6.989(7.5)
0.07	6.64-2	7.59-2	8.32-2	9.74-2	1.00-1	1.12-1	1.31-1
0.045	6.21-2	7.56-2	8.22-2	8.46-2	9.61-2	1.07-1	1.21-1
0.03	6.77-2	6.94-2	8.51-2	8.83-2	9.93-2	1.09-1	1.27-1
0.02	1.09-1	1.21-1	1.30-1	1.45-1	1.59-1	1.71-1	2.07-1
Total γ 's/e ⁻	6.12-1	7.00-1	7.94-1	8.85-1	9.80-1	1.109	1.329
	7.489(8.0)	7.989(8.5)	8.489(9.0)	8.989(9.5)	9.489(10.0)		
14	0	0	0	0	0		
10	0	0	0	4.00-4	6.00-4		
8	1.11-4	4.00-4	1.20-3	1.20-3	2.00-3		
7	1.11-3	1.20-3	1.80-3	4.20-3	3.80-3		
6	3.00-3	4.40-3	5.60-3	5.60-3	7.60-3		
5	5.78-3	7.40-3	8.60-3	1.04-2	1.32-2		
4	1.10-2	1.74-2	1.70-2	2.08-2	2.68-2		
3	1.16-2	1.38-2	1.82-2	1.80-2	2.12-2		
2.5	1.59-2	2.14-2	2.68-2	2.54-2	3.22-2		
2.0	2.92-2	3.52-2	4.02-2	4.06-2	5.10-2		
1.5	5.24-2	5.46-2	6.86-2	8.42-2	8.74-2		
1.0	5.53-2	5.98-2	7.74-2	9.00-2	9.90-2		
0.7	8.44-2	1.02-1	1.10-1	1.25-1	1.43-1		
0.45	9.40-2	1.01-1	1.17-1	1.24-1	1.45-1		
0.3	1.84-1	2.06-1	2.50-1	2.55-1	2.88-1		
0.15	1.21-1	1.33-1	1.51-1	1.74-1	1.96-1		
0.1	1.16-1	1.26-1	1.39-1	1.61-1	1.84-1		
0.07	1.46-1	1.53-1	1.85-1	2.12-1	2.22-1		
0.045	1.39-1	1.54-1	1.79-1	2.05-1	2.24-1		
0.03	1.41-1	1.62-1	1.95-1	2.13-1	2.17-1		
0.02	2.29-1	2.68-1	2.91-1	3.16-1	3.51-1		
Total γ 's/e ⁻	1.440	1.621	1.882	2.086	2.315		

^aNumbers in parentheses denote total electron energy.

^bRead as 1.20×10^{-3} .

The energy deposition rate density profiles across the copper coils for an electron temperature of 2.0* MeV are given in Fig. A.2.4. To obtain the absolute power density for a 1-MW electron power loss, these results must be multiplied by 4.81×10^{18} electrons/sec and divided by $2\pi R_{\text{major}}$, where R_{major} is the major radius of the torus. For a major radius of 5.67 m, the maximum power density with the 1-in.-thick ²³⁸U shield is 0.135 mW/cm³.

Some of the above calculations were carried out for a maximum possible condition, i.e., normal incident photons. The results increased only by ~ 2 .

Fig. A.2.2. Normalized bremsstrahlung energy deposition rate in copper coils vs electron energy for uranium shield thicknesses of 0.5, 1.0, and 1.5 in.

Fig. A.2.3. Total energy deposition rate in copper coils vs coil shield thickness for several electron temperatures.

Table A.2.2. Energy deposition rate in coil materials (W)

Material	^{238}U thickness (in.)	Electron temperature (MeV)			
		1.0	1.5	2.0	2.0*
Al^a	0.5	2530	3,260	3,840	3,930
	1.0	2520	3,250	3,840	3,930
	1.5	2520	3,250	3,830	3,920
^{238}U	0.5	6590	9,670	12,400	12,800
	1.0	6830	10,200	13,200	13,700
	1.5	6830	10,300	13,400	13,900
Cu	0.5	260	644	1,080	1,170
	1.0	54	148	260	285
	1.5	13	38	68	75

^aEnergy deposition rate in aluminum is due to photons only. The total energy deposition rate in aluminum can be obtained simply by subtracting the combined energy deposition rate in ^{238}U and copper from the total power loss of 1 MW.

Biological dose rates

The calculated biological dose rates as a function of lead and concrete shield thickness are presented in Figs. A.2.5 and A.2.6, respectively. These results were obtained with and without 1.25 in. of ^{238}U coil shielding for the electron temperatures of interest. The isotropic photon sources used in these calculations were the same as those used in the heating calculations and again correspond to a 1-MW electron power loss. For a kT value of 2.0* MeV in the absence of any ^{238}U coil shielding, 12.5 in. of lead or 6.3 ft of concrete is required to reduce the biological dose rate to 2.5 mrem/hr, the maximum occupational radiation level currently accepted. However, because no reduction of the photon spectra was assumed to occur due to shielding by the components of the machine, these results should represent the maximum required shielding to obtain a 2.5 mrem/hr radiation level.

Fig. A.2.4. Normalized energy deposition rate density profiles in copper coils for uranium shield thicknesses of 0.5, 1.0, and 1.5 in.

Fig. A.2.5. Biological dose rate vs lead shield thickness with and without $1\frac{1}{4}$ in. of ^{238}U coil shield for several electron temperatures.

Fig. A.2.6. Biological dose rate vs concrete shield thickness with and without 1 1/4 in. of ^{238}U coil shield for several electron temperatures.

APPENDIX 3 MAGNETICS DESIGN

MAGNETIC FIELD AND PARTICLE ORBIT CALCULATIONS

The logic of the choice of the EBT-P reference design parameters is discussed in Sect. 2.3. The constraints on the design of the superconducting coils are discussed in Sect. 1.4. The reference design uses simple superconducting coils mounted in a dewar and surrounded by tungsten shielding. In turn these components are mounted in a water-cooled jacket that acts as a part of the main torus vacuum wall. The device has 36 sectors on a major radius of 4.5 m. The mirror ratio is $m = 2.2$. The details of the coil design are given in Sect. 4.1.3 and Appendix 3. The design of a sector is shown in Fig. A.3.1, with field lines and mod-B contours superimposed. This section discusses single particle orbits in the vacuum magnetic field, the effects of wedging the coils, and the effects of adding Aspect Ratio Enhancement (ARE) coils. The conclusions are that (1) a simple coil set appears to be the logical design for EBT-P; (2) wedging, when subject to consistent constraints, does not significantly improve the particle orbits, though modest wedging is not ruled out; and (3) additional ARE coils improve the particle orbits and the symmetry of the field but they do this at the expense of added current in the main coils. The latter option, while it is ruled out for the maximum coil field (for ~ 90 GHz), could be met with the lower field for 60 GHz operation and is an interesting physics test.

Particle Orbits and Volumetric Efficiency for the Reference 36 Coil Design

In EBT two types of particle losses are associated with drift motion: diffusive losses at low energies and direct losses at high energies caused by particles drifting to the wall or the shadow of the limiter. For the toroidal core plasma the dominant particle loss mechanism is diffusion, which will be discussed later in this section. For the hot electron rings, direct particle losses are the potentially more dangerous loss mechanism. As indicated in Appendix 1, the energy loss associated with direct particle losses is usually small compared to that associated with Coulomb drag and radiation from the hot electron rings. However, since the ring/core interaction is not presently understood in detail, it is prudent to demand that single particle confinement be better in EBT-P than in EBT-I/S.

To carry out a detailed evaluation of particle drift orbits, it is convenient to introduce the longitudinal adiabatic invariant J :

$$J = \oint v_{\parallel} d\ell ,$$

where $1/2 m v_{\parallel}^2 = E - \mu B - e\phi$. E is the total energy, μ is the magnetic moment, e is the charge, ϕ is the ambipolar potential, and $d\ell$ is the arc length along the field line. The integration is over a complete period of the particle motion. Because E , μ , and J are conserved quantities (adiabatically), the particle must lie on a surface of constant J for fixed E and μ . Particle drift surfaces may be determined by calculating J on a grid in the midplane for fixed E and μ , and plotting contours of constant J . For the high energy particles associated with the hot electron rings, $E \gg e\phi$, and the geometry of the drift surfaces depends only upon the pitch angle like variable,

$$\frac{v_{\parallel}}{v} = \sqrt{1 - \frac{\mu B_{00}}{E}}$$

Here B_{00} is the magnetic field evaluated in the center of the midplane.

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Fig. A.3.1. Mod-B contours and field lines in the equatorial plane for reference design. The position of the superconducting windings and the shape of the vacuum lines are noted.

A sensitive measure of direct particle losses is afforded by the volumetric efficiency, defined in Fig. A.3.2. The last closed drift orbit is the largest surface of constant J that is contained within the "limiter," which taken to be a circle in the midplane centered on the minor axis. The volumetric efficiency is a sensitive function not only of the inward shift of the drift surfaces but also of the limiter radius. The $J(x)$ curve in Fig. A.3.3 illustrates this point. The combined effects of the toroidal curvature of the magnetic field lines and increased bumpiness at larger minor radius cause $J(x)$ to be steeper on the inside of the torus than on the outside; hence a small change in the limiter radius can lead to a large change in volumetric efficiency. As mentioned in Sect. 1.4, the limiter is assumed to be outside but close to the energetic electron ring. For these calculations it is taken as a circle centered on the minor axis that intersects the point in the midplane at which the magnetic field on the inside of the torus has dropped to 0.6 of the value at the midplane center.

In Fig. A.3.4 the volumetric efficiency for EBT-P is compared to that of EBT-1/S; it shows an overall improvement and satisfies this design constraint. Studies by ORNL and the industrial participants concerned the use of trim coils to vary the mirror ratio and wedging, and ARE coils to improve the particle orbits. The use of superconducting trim coils is ruled out by budgetary restrictions that encourage economy in the basic design. The use of water-cooled, demountable ARE or trim coils, which may be added at a later stage, remains an option and is discussed below. The question of wedging, since it does impact the cost of the basic device, is discussed first.

The Effects of Wedge Coils on Volumetric Efficiency

Analyses have been made of the effect on field lines, mod-B surfaces, particle orbits, and volumetric efficiency of wedging the mirror coils. These calculations follow those presented in the Phase I studies of Ebasco, McDonnell-Douglas, and Westinghouse, with the agreed constraint that there would be in fact or in effect a limiter just outside the hot electron ring. Consistent with the previous limiter definition for the reference design, the limiter is taken to be a circle centered on the minor axis in the midplane that intersects the point where B has fallen to 0.6 of the value at the midplane center. The calculations assume a constant mirror ratio, constant shield and dewar thickness, constant coil minor radius, and total coil conductor cross-sectional area. With these restrictions it is necessary to increase the coil major radius with increasing wedge angle. The change in the coil design is illustrated in Fig. A.3.5.

In Fig. A.3.6 the volumetric efficiency is shown as a function of $V_{||}/V$ for wedge angles of 0° , 5° , 10° , and 15° , for $M = 2.2$ and major radii of 4.5, 4.8, 5.0 and 5.2 m, respectively. Unfortunately, for the larger wedge angles the picture becomes more complicated because a subsidiary mirror region forms in the coil throat. This is illustrated in Fig. A.3.7. As can be seen for the larger wedge angles, this subsidiary mirror has moved in to the limiting field line region. Thus, at the larger wedge angles, the region bounded by the "limiter" contains a new class of particles — those trapped in the subsidiary mirror in the coil throat. This situation is further complicated by the fact that these particles tend to drift (nearly vertically) out of the subsidiary mirror region and become passing particles. (If they stay in the machine, they can eventually become trapped in the main mirror.) While these complications make it difficult to assess the precise effect of the subsidiary mirror on direct particle losses, upper and lower bounds can be given.

The most striking feature of Fig. A.3.6 is the apparent improvement in confinement for transitional particles ($V_{||}/V \approx 0.8$) achieved at the larger wedge angles. However, the new class of transitional particles introduced by the subsidiary mirror is completely ignored in the calculations leading to Fig. A.3.6, and it should be regarded as an upper bound on single particle confinement. To obtain a lower bound, we make the drastic assumption that the edge of the subsidiary mirror region acts as a

Fig. A.3.2. Last closed drift orbit in the midplane (solid curve) that does not intercept the limiter (dashed curve). The limiter is defined by projecting the inside of the vacuum lines along flux lines to the midplane.

Fig. A.3.3. J vs distance from the minor axis x . Changing the limiter position (from x_1 to x'_1) causes the equatorial crossing of the last closed contour on the outside of the torus to be increased from x_2 to x'_2 . Because of the steeper slope of J for negative x , $x'_2 = x_2 > |x'_1 = x_1|$, and a small change in the limiter position can lead to a large change in the volumetric efficiency.

NOTE: The volumetric efficiency F is the ratio of the largest closed drift orbit contained within the limiter to the area intercepted by the limiter.

Fig. A.3.4. Comparison of the volumetric efficiency for the EBT-P reference design with that of EBT-I/S. The limiter is defined by projecting the inside of the vacuum liner along flux lines to the midplane.

Fig. A.3.5. Mod-B contours and field lines in the equatorial plane for split-wedge mirror coils ($\theta_w = 10^\circ$). Coil halves and vacuum lines are shown, as is the formation of the subsidiary "mirror" near the coil plane.

Fig. A.3.6. Volumetric efficiency as a function of wedge angle for split-wedge mirror coils. A constant mirror ratio of 2.2 is maintained by increasing the major radius as the wedge angle is increased.

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Fig. A.3.7. The magnetic field is plotted as a function of arc length along the field line that passes through the outer edge of the annulus defined as that point in the midplane at which $B/B_{00} = 0.6$. A subsidiary "mirror" is observed to form as the wedge angle is increased.

limiter. The effect on volumetric efficiency for a 10° wedge is shown in Fig. A.3.8. It should be made clear that this is a pessimistic view for completely trapped or passing particles, but it does indicate the level of effect to be expected in the transition region. For this reason the high values of volumetric efficiency shown in Fig. A.3.6 are suspect for large wedge angle, particularly in the transition region ($V_{||}/V \approx 0.8$).

Estimates of the Effect of Wedge Coils on Aspect Ratio Enhancement

As mentioned earlier in this section, the toroidal core plasma losses are dominated by neoclassical diffusive processes. Fundamentally, these diffusive losses occur because of differences in the guiding center drift surfaces for particles in different parts of velocity space (and Coulomb scattering from one orbit to another). In the limit of an infinitely large number of sectors in a bumpy torus (infinite aspect ratio) these differences (dispersion) in drift orbits vanish and the step size for neoclassical diffusion becomes zero. It is this fact that leads to the toroidal core plasma scaling law $n\tau \sim A^2 T^{3/2}$, where A is the magnetic aspect ratio. However, there are other ways to decrease the dispersion in the drift orbits that can lead to similar, if not identical, reductions in these losses. Wedging the main coils and/or adding ARE coils or trim coils can change the basic magnetic geometry so that the dispersion in drift orbits and hence diffusive losses are reduced. Because of the obvious analogy, methods of reducing dispersion in the particle orbits by modifying the vacuum magnetic geometry without increasing the number of sectors are called aspect ratio enhancement.

However, the guiding center orbits in the vacuum magnetic field of EBT are altered by two mechanisms: The hot electron ring modification of the magnetic field and the ambipolar electric field. The finite beta magnetic field of the hot electron rings affects trapped particles most strongly. The ambipolar electric field affects low to modest energy particles most strongly. The emphasis for the various vacuum magnetic field modifications is upon those particles that are least affected by the rings and ambipolar electric field, i.e., high energy passing particles.

The problem, then, is to assess the effect of various means of modifying the vacuum magnetic field. Clearly, any method that improves high energy passing particle confinement without interfering with other classes of particles is good. However, because the formation of the hot electron rings and ambipolar electric field is coupled to the vacuum field, it is difficult to make a quantitative assessment. Below, several alternate means of assessment are discussed, starting with the method generally agreed to be the most meaningful by ORNL and the industrial participants at meetings in October 1979.

The prime method for assessment is based on several observations.¹⁻³ Toroidal core plasma losses are governed principally by electron diffusion. For electrons, high and modest energy passing and transitional particle orbits deviate most from the average orbit. Assuming a reasonable distribution in energy (e.g., approximately Maxwellian), the modest energy passing electrons ($V_{||} = V$) are far more numerous and contribute most to the neoclassical step size. Low energy and trapped electrons, on the other hand, all have approximately the same orbits and contribute least to the neoclassical step size. To lowest order, then, we may assume that there are only two classes of orbits, passing ($V_{||} = V$) and trapped ($V_{||} = 0$). Either class of orbits is a set of approximately concentric circles shifted inward from the minor axis. The shift for the trapped particles S_t can be obtained from the maximum of mod-B in the midplane, while the shift for the passing particles S_p can be obtained from the minimum of adiabatic invariant J , which is proportional to the field line length for $V_{||} = V$. The neoclassical step size is, then,

$$\Delta x = |S_t - S_p|$$

as depicted in Fig. A.3.9.

Fig. A.3.8. Volumetric efficiency for split-wedge mirror coils ($\theta_w = 10^\circ$) showing the effect of limiter radius. The larger limiter corresponds to the radius of the point at which $B/B_{00} = 0.6$ in the midplane and the smaller one to that radius at which the subsidiary "mirror" just begins to form.

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Fig. A.3.9. The neoclassical step size is estimated from $\Delta x = |S_t - S_p|$. The shift for passing particles, S_p , is determined from the minimum in J for $v_{||}/v = 1$. The shift for trapped particles, S_t , is determined from the maximum of B in the midplane.

As indicated in Sect. 1.2.2, the effect of aspect ratio enhancement is expressed in the form

$$n\tau = f_A^2 (n\tau)_0 .$$

Since diffusive losses scale as the square of the step size, the life time scales as the inverse square of the step size, and the prime definition of the aspect ratio enhancement factor f_A is

$$f_A = (\Delta x)_{\text{ref}} / \Delta x ,$$

where $(\Delta x)_{\text{ref}}$ is taken from the reference design discussed earlier in this section. Table A.3.1 gives the shifts, step size, and f_A for the reference design as well as for three wedge angles, θ_W . For the purpose of comparison, the same quantities are shown for the reference design with ARE coils added (see next section, Aspect Ratio Enhancement Coils).

Table A.3.1. Shifts, step size, and f_A for the reference design and three wedge angles

	Reference design	$\theta_W = 5^\circ$	$\theta_W = 10^\circ$	$\theta_W = 15^\circ$	Reference with $I_{\text{ARE}} = 5\%$
$S_t(\text{cm})$	3.05	2.41	1.77	0.963	2.41
$S_p(\text{cm})$	15.26	15.06	14.26	13.27	13.08
$\Delta_x(\text{cm})$	12.21	12.65	12.49	12.31	10.67
f_A	1.0	0.965	0.978	0.992	1.14

From Table A.3.1 we see that the prime measure of f_A indicates that wedge coils interfered with rather than improved $n\tau$. This is caused by the fact that wedging improves the centering of trapped particles faster than it improves the centering of passing particles. Acknowledging that this definition of f_A may be too severe because it may not incorporate nuances of formation of the hot electron rings and an ambipolar electric field, we consider some alternate definitions. A simple alternative, which has been used at ORNL from time to time, is

$$f_{A,1} = S_{p,\text{ref}} / S_p .$$

During the Phase 1 Design Studies for EBT-P, ORNL and the industrial participants used a variety of definitions for f_A based on volumetric efficiency. In each case it was necessary to compare volumetric efficiency of our model with that from a configuration of simple coils having the same mirror ratio but larger major radius (and number of sectors). For this purpose, Fig. A.3.10 shows plots of volumetric efficiency for major radii (and number of sectors): 4.5 m (36), 6.75 m (54), and 9.00 m (72). Ideally, one would look for a wedged coil set (or ARE coil design) and a simple set of coils that have identical volumetric efficiencies. The wedged set would then be classified as having the same value of $A = R/R_B$ as the larger simple set. The aspect ratio enhancement factor f_A could then be defined as

Fig. A.3.10. Variation of volumetric efficiency with aspect ratio (number of sectors) using the reference design magnets.

$$f_A = \left(\frac{R}{R_B}\right) \left(\frac{R_B}{R}\right)_0 \times \left(\frac{R_0}{R_W}\right),$$

where the first factor is a measure of the gain over the simple unwedged coil set of the original radius ($R_0 = 4.5$ m) and the second factor allows for the fact that some of the gain has come from the increased major radius of the wedged system ($R_W > R_0$).

In practice the volumetric efficiency curves $F(V_{||}/V)$ are not identical, and therefore one must pick some feature of $F(V_{||}/V)$ in making the comparison. Three examples are used to illustrate this point:

- $f_{A,2}$ based on $F(0)-F(1)$ as a measure of dispersion in drift orbit centering;
- $f_{A,3}$ based on $F(1)$ as a measure of passing particle confinement; and
- $f_{A,4}$ based on $[F(y + \Delta) + F(y - \Delta)]/2$ as a measure of transitional particle confinement, where $y = V_{||}/V$ at the minimum in F . For this illustration we take $\Delta = 0.1$.

The values of the prime and four alternate definitions of f_A are given in Table A.3.2 for the same case listed in Table A.3.1. For large wedge angle, the values of $f_{A,4}$ are surrounded by parentheses to indicate the complications in interpretation caused by the subsidiary mirror.

Table A.3.2. Values of the prime and four alternate definitions of f_A

	Reference design	$\theta_W = 5^\circ$	$\theta_W = 10^\circ$	$\theta_W = 15^\circ$	Reference with $I_{ARE} = 5\%$
f_A	1.0	0.966	0.977	0.993	1.14
$f_{A,1}$	1.0	1.01	1.07	1.15	1.17
$f_{A,2}$	1.0	0.85	0.80	0.77	1.25
$f_{A,3}$	1.0	0.94	1.00	1.11	1.41
$f_{A,4}$	1.0	1.03	(1.30)	(1.65)	1.41

One final comment should be made. The above calculations for wedge coils used a constant radius and cross-section coil, while R was increased with wedging. Since $\oint \mathbf{B} \cdot d\mathbf{x} = \mu_0 N_C I_C$ is approximately constant for fixed frequency, the coil current (I_C) must be essentially proportional to R . Calculated coil design parameters are given in Table A.3.3.

Table A.3.3. Calculated coil design parameters

θ_W	Magnetic field at coil, T	Coil current density, A cm ⁻²
0	7.4	10,000
5°	7.4	11,400
10°	7.7	12,000
15°	8.0	12,600

Given that the unwedged coils are operating at maximum field and current densities, the wedged coils exceed the constraints and would have to be altered to lower frequency or increased in size. The conclusion of this analysis is that wedging does not offer any obvious advantages in improving particle orbits, though small wedging to give slightly better centering of the plasma cannot be ruled out.

Aspect Ratio Enhancement Coils

Vacuum field particle confinement in EBT-P can be improved through the addition of low current supplementary toroidal field coils called aspect ratio enhancement (ARE) coils. By varying the current in these coils, the plasma geometry and effective aspect ratio can be changed with the result of either spoiling or enhancing plasma confinement.

Figure A.3.11 shows the position in the equatorial plane of the ARE coils (two per sector). This position is optimum for confinement enhancement and at the same time has the least impact on vacuum chamber access. The coils are D-shaped to minimize their circumference in the canted configuration shown in Fig. A.3.11. The effects of ARE coils on vacuum field geometry are illustrated in Fig. A.3.12, where mod-B contours and field lines in the equatorial plane are plotted for $I_{ARF} = 5\%$ and where I_{ARF} is the ratio of the current in the ARE coils to the current in the mirror coils. An important effect of ARE coils is to lengthen the magnetic field lines on the inside of the torus relative to those on the outside, resulting in improvement in the confinement of transitional and passing particles, as well as improved centering of trapped particle drift orbits.

Volumetric efficiency curves for $I_{ARE} = 0$ (no aspect ratio enhancement) and $I_{ARE} = 5\%$ are presented in Fig. A.3.13. Improved centering of the drift orbits of mirror-trapped particles and a decrease in the width of the velocity space loss cone near $V_{||}/V = 0.8$ are seen. As shown in Table A.3.2, the aspect ratio enhancement factor is $f_A \cong 1.14-1.41$ for all the definitions considered. Thus, ARE coils do appear to improve particle orbits; however, again there is a price to pay. These coils improve orbits by cancelling some of the field generated by the mirror coils. To maintain the same resonant frequency and plasma scale, the mirror coil current must be increased, typically by $\sim 12\%$ for a 5% ARE coil current. Consequently, for EBT-P this option may be applied at 60 GHz but probably not at the maximum frequency (dependent on safety margins). Nevertheless, it does represent an attractive physics option, and it is an add-on that may be relatively inexpensive in schedule time if demountable ARE coils are used and if it does not have much impact on the initial device costs. Finally, similar coils may be used for mirror ratio variation tests similar to those to be installed on EBT-SA and similar in spirit to the "trim" coils of the earlier ORNL and Westinghouse EBT-P designs. This type of "trim coil" provides most of the improvement obtainable from ARE coils, particularly if confinement in the basic device (without aspect ratio enhancement) is already quite good, as is the case with the reference design. Trim coils have the added advantage of minimal impact upon toroidal vacuum vessel access as well as having circular instead of D-shaped coils.

MAGNETICS DESIGN RATIONALE

At the outset of any magnet design project, the most important things to establish are the real constraints and the significance of small deviations from the desired objectives. Only in this manner can one establish the design parameters with the confidence that unnecessary advances in the state of the art and development have been avoided. Of course, constant communication between the plasma physicists who establish the EBT-P machine goals and parameters and the magnet technologists who must assess what can be accomplished within a realistic time schedule is necessary to establish the constraints. Our understanding of the constraints is a direct result of working on various EBT designs and carrying out this constant dialogue over a number of years.

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Fig. A.3.11. Sector of EBT-P in the equatorial plane displaying position of the superconducting mirror coils and ARE coils. Dots and crosses indicate polarity of currents when in the enhancement mode.

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Fig. A.3.12. Mod-B contours and field lines in the equatorial plane for the reference design with ARE coils ($I_{ARE} = 5\%$).

Fig. A.3.13. The effect on volumetric efficiency of adding ARE coils to the reference design is shown for $I_{ARE} = 5\%$. The ARE current opposes that in the mirror coils.

In other sections, the justification and value of the desired magnet field, the minimum working bore (warm bore in the case of superconducting magnets), and the mirror ratio are given. Taken together, these three constraints in effect specify the average current density of the magnet. For a superconducting magnet it can be shown that the maximum field (which is related to the central field by geometry factors and is an important parameter in the selection of conductor and magnet type) is given by the product of winding current density $\langle j \rangle$; inside radius of the windings r ; and F , a factor containing a numerical constant and all the normalized geometry variables:

$$B_{\max} = \langle j \rangle r F. \quad (1)$$

Because the magnitude of field, the radius, the mirror ratio, and the quality of field distribution establish the coil geometry within a small range of variables, the current density is not a free choice as it is in most magnet design projects. The final design values chosen in order to meet all of the desired goals for the inner magnet are (1) $B_{\max} = 7.4$ T, (2) $2r = 48$ cm, and (3) mirror ratio = 2.2. These values require an average winding current density of $\langle j \rangle = 10,000$ A/cm². These are the operating parameters for the eventual extrapolation corresponding to microwave power at 90 GHz. The design of the EBT-P mirror magnets for the initial operation at 60 GHz will of necessity be conservative, and therefore trouble-free operation in this regime is assured.

With these parameters, we established the magnet design without any preconceived preferences for magnet type, conductor, or cooling mode. Our desire is to select the choice that provides the most assurance of success (i.e., the least cost, least development, and simplicity of fabrication and operation) and the best chance to complete the proposal within a reasonable time schedule. Table A.3.4 shows the matrix of possibilities. Before discussing these possibilities, we should point out that in the past ORNL has had extensive experience in testing both superconducting material and magnets. We have made magnets using both NbTi and Nb₃Sn. We have made cryostable, metastable, and adiabatically stabilized magnets. We have not made any forced-flow magnets using the cable-in-conduit conductor, nor have we designed magnets specifically for superfluid operation, although we have some testing experience. Our experience with Nb₃Sn tape conductor is extensive; in fact, the largest and most complicated Nb₃Sn magnet ever built originated in the Magnetics Section at ORNL.

Table A.3.4. Type of stabilization and cooling mode

Material	1	2	3	4
	Pool-boiling, 1-atm, 4.2-K helium	Forced-flow, 4.2-K helium	Forced-flow, pressurized, subcooled helium	Pool-boiling, pressurized, superfluid helium
A NbTi	Metastable (cryostability not possible)	Cryostability not possible	Cryostability may be possible	Cryostability may be possible
B Nb ₃ Sn	Metastable (cryostability not possible)	Cryostable	Not needed	Cryostable

In Table A.3.4 all of the feasible superconducting materials (V₃Ga is too expensive and presents no advantage over Nb₃Sn until fields of 13 T are exceeded) and cooling schemes (subcooled pool-boiling He I is no advantage over 4.2-K helium because cryostability cannot be accomplished unless one uses the superfluid state) for constructing EBT-P superconducting magnets are tabulated. Column 4 may be quickly discounted because cryostability can be achieved by other means and because there is no experience with

the use of large amounts of superfluid helium cooling in the United States. Indeed, one system, the Pion magnet project at Stanford University, had to abandon the superfluid cooling mode after persistently failing to reach the low temperature necessary to establish the He II phase transition. Superfluid temperatures do have great advantages for either extending the operating field range of NbTi and Nb₃Sn or raising the current density of a completely cryostabilized design. With more knowledge of the behavior of superfluid systems, these advantages may be realized sometime in the future. The French TORE II Project (a superconducting tokamak) will provide valuable insight into the practical problems associated with the use of He II cooling. Columns 2 and 3 taken together provide one good choice, namely, row B in column 2, a Nb₃Sn forced-flow conductor operated at 4.2 K. We feel this choice of a forced-flow conductor utilizes the high critical temperature of Nb₃Sn while avoiding the extra refrigeration complexity of a pressurized, subcooled, forced-flow system for which no experience exists. Furthermore, the choice attempts to capitalize on the Westinghouse Large Coil Program experience and conductor development. Finally, in column 1 the clear choice is row A because the advantage of working with a ductile alloy, NbTi, outweighs the higher critical temperature T_c and hence higher current-sharing temperature T_s of a brittle material, Nb₃Sn, particularly in the case where cryostability cannot be achieved by the material substitution. Perhaps a further word on the cryostabilization of a conductor in pool-boiling helium is in order here. To a first approximation, the type of superconducting material does not influence the overall current density that can be cryostabilized at a particular field. Full cryostability is determined by assuming that a length of conductor in the high field zone has gone normal and that the Joule heating in the copper stabilizer (sometimes aluminum is used) is smaller than the helium heat transfer to the helium at the transition from film boiling back to nucleate boiling. Therefore, to stabilize at a high current density, the controllable variables are a high conductivity matrix and a conductor of small dimension, which result in a large cooling surface. However, a small conductor is not compatible with a high value of current, which is needed for the proper protection of magnets with high stored energy (in the present case, $E_s \sim 1.4$ MJ/coil). In addition, the conductivity of copper decreases as the field increases (magnetoresistance), making it harder to stabilize a conductor at high fields. Therefore, pool-boiling stabilization at high winding current densities can be achieved only in relatively small magnets at low field. Existing cryostabilized magnets have overall winding current densities much less than the needed 10,000 A/cm², with most having values below 2500 A/cm². In summary, we conclude that the best choices for an EBT-P magnet lie in either a metastable, pool-boiling NbTi design or a cryostabilized, forced-flow Nb₃Sn design. Both systems use nominal 4.2-K helium. Considering cost, schedule, minimum development, and simplicity of fabrication and operation, the pool-boiling NbTi design is the preferred choice. There is still too little experience with multifilamentary Nb₃Sn to select it for the main approach for a major facility, especially because the maximum required field is 7.4 T, which is in the acceptable range for NbTi (see Table A.3.5 for practical field limitations on commercial superconducting material). We should also point out that no large magnet has yet been fabricated with a cabled conductor that is the configuration for the force-cooled Nb₃Sn conductor. Although cables are easier to stabilize than monolithic or built-up conductors because of the large surface areas available for cooling, even cables of NbTi have not been used in any

Table A.3.5. Commercial superconducting material

	T_c (K) at zero field	B_{max} (T)	Practical maximum field B_{max} (T) at 4.2K
Alloy (ductile) NbTi	9	10-12	8.5
Compound (brittle) Nb ₃ Sn	18	20-22	15

large magnets principally because of their inherent structural deficiencies. Outside of the cable-in-conduit configuration, it is difficult to envision a scheme for containing the movement of cables while simultaneously providing sufficient means for helium cooling.

EXAMPLES OF METASTABLE MAGNETS

Although high energy physicists have had great difficulty with low copper-to-superconductor volume ratio (Cu:SC of 1:1-2:1) adiabatic conductor (also incorrectly known as intrinsic) operated at high current density and in pulsed magnets, there has been considerable success with metastable magnets wound with an intermediate range of Cu:SC ratio (3-8) conductor and operated in dc mode. In fact, one could survey the literature and conclude that few cryostabilized magnets have operated as reliably as most metastable magnets. A metastable design is therefore proposed for the EBT-P project, but we reiterate that it is only because the constraints do not permit us to achieve a pool-boiling cryostable design. A metastable magnet is one that will undergo a quench if a large region is driven normal by some disturbance, in contrast to a cryostable design that should recover even if many meters of the windings are driven normal. A metastable magnet if properly designed can recover from a local normalcy and can withstand fairly high energy inputs on a transient basis.

It is important to consider the experience to date of all large metastable magnets or magnets wound from conductors with intermediate values of Cu:SC ratio. By intermediate values, deliberate avoidance is implied of the low values (Cu:SC < 3) associated with the adiabatically stabilized conductors used in high energy physics experiments and known for their unpredictable behavior (training) and failure to make design values (degradation). Most of the magnets being developed in the high energy labs are pulse coils, which are more difficult to develop. By definition, a large magnet or magnet system is one with stored energy of at least 1 MJ. At this level some means of protection is generally necessary to avoid damage on a quench. Often the intrinsic strength of the composite conductor is not sufficient at stored energies of many megajoules to contain the magnetic forces, and some means of structural reinforcement is required for safe, reliable operation. Generally, magnets in this range are not completely cryo-stabilized (i.e., a normal zone collapses and the current returns completely to the superconductor). Some magnets in this range can tolerate normal zones but only if they are sufficiently localized.

All of the magnets in Table A.3.6 operated without training or degradation. Also, in each case the design value was met.⁴ In some of the cases shown, the conductor was cooled by conduction and was not even in intimate contact with helium. Therefore, if such a conductor were also well cooled, one would expect it to perform in a cryostable or partially cryostable mode. Large pool-boiling cryostabilized

Table A.3.6. Parameters of large metastable magnets
(Cu:SC > 3 and $E_s > 1$ MJ)

Magnet	E_s (MJ)	Size (m) (bore x length)	B_{max} (T)	$\langle j \rangle$ (kA/cm ²)	Cu:SC ratio
Muon channel	2	0.13 x 8	5	17.6	3.5
HYRUC	1.7	0.18 x 0.6	8	10	3
BIM	10.5	1 x 1	5.5	5.3	8
Rutherford	>1	~0.5 x 0.5	7.5	>5	6
W7	1.6	0.85 x 0.2	6	~12	2.5
CGE	2	0.4 x 0.3	7.8	8.4	~5

magnets have average current densities over the windings (excluding structure and bobbin) of between 1.3 and 2.5 kA/cm². One magnet not listed in Table A.3.6 but presently under design is the MHD magnet for Stanford. The project is being managed by MIT and the coil is being designed and fabricated by General Dynamics, Convair Division. It will also be a metastable design and not a cryostable design.

DESIGN CONSIDERATIONS FOR THE EBT-P MAGNET

In the previous sections we established the conductor material (NbTi), cooling mode, pool boiling, and the stabilization technique (metastable), which are our first choices to satisfy the design parameters because a pool-boiling cryostable design is precluded. The actual dimensions for the winding are established after consideration of structural requirements. Although no structure is required in the windings to keep within reasonable stress limits, one has to make a careful assessment of whether some structure is required in the form of banding on the outer turns. The bobbin thickness and end flanges must be calculated to take care of not only the winding stresses but also the loads arising under full field and possible fault conditions. At this point in the design we are ready to decide on the conductor and winding details. Is the coil to be potted or ventilated? What is the conductor configuration — monolithic, built up, or cable? What is the appropriate Cu:SC ratio for maximum stability against perturbations, and what dimensional shape is preferred? This latter point must go along with considerations of the winding mode — pancake, layer, or hybrid. One must decide the insulation scheme in conjunction with the winding mode. In general, there is no one choice among these alternatives. Each specific application must be analyzed, and as mentioned in the introduction to this summary of magnet design considerations for EBT-P, the constraints must be carefully considered and fully understood. The important aspect in selecting the specifics of the winding is to make the choices compatible and arrive at a self-consistent design.

Cooling Design

Our clear preference in magnet designs that are subjected to external heat, in this case radiation, is a ventilated design rather than potted windings in an epoxy. Helium heat capacity is enormous compared to the metals NbTi and copper that comprise the superconductor, even if only 20% of the winding volume is accessible for helium. It is preferable to have heat transfer directly from the surface of the conductor to liquid helium rather than via conduction through a poor thermal conductor, as is the case for all potting compounds.

Conductor and Filament Configuration

In the specification for the purchase of the conductor, the choice of either monolithic or built-up conductor remained open. Only the plain cable configuration was specifically eliminated from consideration. This is because there are no ac losses anticipated and the need to have accurate field quality translates into the need for close dimensional tolerance, which is difficult to achieve reliably in a Rutherford cable. Whether a straight monolithic conductor is cheaper than a built-up conductor remains for the commercial vendors to decide.

The size of the filaments is not particularly critical in this application. It is necessary to have the filaments much less than about $\ll 200 \mu\text{m}$ to ensure that each filament itself is adiabatically stabilized. It is not necessary to reduce the filaments down to the state-of-the-art limit, as is often required for applications in pulse field magnets. A size of $\sim 50 \mu\text{m}$ in diameter is easily obtainable and avoids the problems associated with the defects inherent in much smaller sizes.

Optimum Copper to Superconductor Ratio

When we build a superconducting magnet, we want it to work; that is, we want it to reach design field without quenching. We try to build strong, rigid magnets that do not experience perturbations substantial enough to quench them when they are energized. This task is rendered difficult by our lack of knowledge of the perturbations that quench magnets. The magnets of EBT cannot be cryostable and are in the metastable regime, which means that a large enough perturbation will quench them. In the absence of any clear knowledge about the perturbations they will suffer during operation, we must prefer conductors that require large perturbations to quench them to conductors that can be quenched by small perturbations. Comparison by the size of the perturbation required to quench the conductor gives us the opportunity to select the best conductor of a class of conductors. For example, we may ask whether all other things being held constant, there is a best Cu:SC ratio that maximizes the perturbation from which the conductor can just recover. Using this best conductor should afford us the greatest chance that the magnet will work.

A straightforward approach to determining the best Cu:SC ratio would be to assume some canonical form of perturbation and calculate the Cu:SC ratio that makes the size of the perturbation greatest. Alternatively, we can say, following Wilson and Iwasa,⁵ that the more stable of two conductors differing only in Cu:SC ratio is the one with the larger minimum propagating zone. Another possibility is to define as the more stable of the two conductors the one with the smaller normal-zone propagation velocity. Implicit in the use of these alternatives is the assumption that the more stable conductor they define will truly have the larger maximum permissible perturbation.

These alternatives can be studied with a minimum of labor if we assume constant thermo-physical properties. First we consider canonical perturbations consisting of an instantaneous deposition of energy E at a point in the conductor. The larger E is, the more stable the conductor is. How does E vary with the Cu:SC ratio?

Shown in Fig. A.3.14 are curves of constant dimensionless energy ϵ_δ in the plane of the Stekly parameter α and the dimensionless current i . Consider a candidate EBT conductor intended for service at 8 T, 4.2 K, and 9000 A cm⁻². We assume that the conductor is a composite of NbTi, which has a critical current density of 5.6×10^4 A cm⁻² at 8 T and 4.2 K, and copper, which has a residual resistivity ratio of 160. With these data fixed we find that

$$\alpha = \frac{1.2 \times 10^8}{Ph/A} \cdot \frac{(1-f)^2}{f} \quad (Ph/A \text{ in } W \text{ m}^{-3} \text{ K}^{-1})$$

and

$$i = \frac{0.16}{1-f},$$

(2)

where f is the volume fraction of copper in the composite.

The quantity Ph/A is not very well known in the early stages of design, but the values that occur in practice range from $\sim 2 \times 10^5$ – $\sim 5 \times 10^6$. As we shall see, the uncertainty in Ph/A will not affect our conclusions about the Cu:SC ratio.

Figure A.3.15 shows curves obtained from Eq. (2) by fixing Ph/A and letting f vary (f -loci). If we superimpose one of these f -loci on the curves of Fig. A.3.4, the intersections will give ϵ_δ as a function of f . Let us consider the f -locus for which $Ph/A = 1 \times 10^6$ W m⁻³ K⁻¹ (shown dotted in Fig. A.3.4). When $f = 0.84$, the operating current equals the critical current and $\epsilon_\delta = 0$. Near the right-hand side of the graph, the f -locus cuts the curves of constant ϵ_δ at a steep angle so that we start out moving rapidly from curve to curve as f decreases. However, as f continues to decrease, the f -locus becomes

Fig. A.3.14. In the plane of the Stekly parameter α and the dimensionless current i are shown curves of constant dimensionless energy ϵ_δ .

Fig. A.3.15. In the α - i plane the value of f , the volume fraction of copper in the conductor, has been allowed to vary for a specific value of Ph/A .

nearly parallel to the curves of constant ϵ_δ so that a point is quickly reached at which further reduction of f brings little increase in stability. In the example under discussion, the point of diminishing returns occurs at $i \sim 0.6$, for which $f = 0.73$ and $\text{Cu:SC} = 2.75$. When $\text{Cu:SC} = 5$, $i = 0.96$ and ϵ_δ (which measures stability) is about six times smaller than for $\text{Cu:SC} = 2.75$. Thus, the lower Cu:SC ratio is clearly preferable.

We reach the same conclusion no matter which of the f -loci we consider, up to values of $\text{Ph/A} = 5 \times 10^6 \text{ W m}^{-3} \text{ K}^{-1}$. For this value of Ph/A we see that it is possible to achieve cryostability (both cold-end stability and full stability, depending on the choice of f). Paradoxically, to achieve cryostability when Ph/A is large, we need large Cu:SC ratios. But for EBT, Ph/A will probably be in the range $2\text{--}5 \times 10^5 \text{ W m}^{-3} \text{ K}^{-1}$ so that cryostability is unattainable for any choice of f . This being the case, we must prefer low Cu:SC ratios. Note well that all of these conclusions are based on a conductor of constant current density. It is always preferable to add copper if it leads to a corresponding reduction in current density.

Figures A.3.16 and A.3.17 show curves of constant dimensionless minimum-propagation-zone energy ϵ_{MPZ} and dimensionless normal-zone propagation velocity m , respectively, in the α i plane. These families of curves strongly resemble the curves of constant ϵ_δ in Fig. A.3.14. If we superimpose the f -loci on them rather than on the curves of Fig. A.3.14, we get the same conclusion as before, namely, that for candidate EBT conductors, a Cu:SC ratio of ~ 3 (with operating current at 60% of critical current) is preferable to one of ~ 5 (with operating current at 90% of critical current).

A simplified way of understanding this result is to consider the change in both the current-sharing temperature and the heat capacity as superconductor is substituted for copper in a conductor of fixed dimensions. Since the dimensions and operating current are fixed, lowering the Cu:SC ratio means that the critical current is increased and the operating current becomes a smaller fraction of the critical current. The current-sharing temperature is thereby increased according to Eq. (3):

$$T_{\text{CS}} = T_{\text{cr}} \left(1 - \frac{I_{\text{op}}}{I_{\text{c}}} \right). \quad (3)$$

Since the heat capacity of NbTi is almost an order of magnitude larger than copper at 8 T, decreasing the Cu:SC ratio leads to an increase in the overall heat capacity of the conductor. The enthalpy of a conductor at Cu:SC ratio of 3:1 therefore is much higher than one of similar dimensions at 5:1.

Winding Current Density

Practical values of overall average current density for different field values can be derived in a relatively straightforward fashion. We start with the most likely upper limit for the current density of the superconductor itself as a function of field:

$$\begin{aligned} j_{\text{SC}} (8 \text{ T}) &= 80 \text{ kA/cm}^2 \\ j_{\text{SC}} (6 \text{ T}) &= 139 \text{ kA/cm}^2 \\ j_{\text{SC}} (5 \text{ T}) &= 150 \text{ kA/cm}^2 \end{aligned} \quad (4)$$

Fig. A.3.16. In the α - i plane the minimum-propagation-zone energy ϵ_{MPZ} has been allowed to vary.

Fig. A.3.17. In the $\alpha=i$ plane the normal-zone propagation velocity m has been allowed to vary.

The critical current density of the conductor is by definition

$$j_c (\text{cond}) = \frac{j_{SC}}{(Cu:SC) + 1} . \quad (5)$$

In the previous section we discussed the operating value relative to the critical value and showed that it is prudent to leave a reasonable margin (i.e., $v = 0.6$ is better than $v = 0.9$):

$$j_{op} (\text{cond}) = v j_c (\text{cond}) . \quad (6)$$

By definition

$$\langle j \rangle_{\text{winding}} = \lambda j_{op} (\text{cond}) ,$$

where λ is the packing factor which includes the insulation, helium space, and lost space at the ends of the winding region where the crossovers occur. In Fig. A.3.18 the calculated value for $\langle j \rangle_{\text{winding}}$ is shown assuming a Cu:SC ratio of 3:1, a packing factor $\lambda = 0.7$, and an operating current at $v = 0.6$ the critical current. This fraction ($j_{op} = 0.6 j_c$ for $B = 7.4$ T) is consistent with the critical current margin theory recently proposed by Iwasa.³ The reference design is indicated by the solid-filled circle, and the dashed line indicates the load line from the initial 60-GHz operation field value. The five open circles are the design points initially proposed by the four subcontractors and ORNL.

In Fig. A.3.19 the load line for the reference design is shown relative to the short sample critical current to provide some visual means for the operating margin that this design provides at its maximum field value.

Winding Method

There are advantages and disadvantages to both layer and pancake winding. Below is a tabulation of the principal advantages offered by either scheme:

1. Pancake
 - a. good surface for transmitting large radial compressive forces (easier to prevent conductor motion),
 - b. solid insulation between pancakes,
 - c. better packing factor,
 - d. grading of conductor that can be optimized, and
 - e. good bubble clearance and helium replenishment between pancakes.
2. Layer
 - a. joints that are kept to a minimum,
 - b. grading joints that can be kept out of the winding pack,
 - c. easier layer winding for edge winding of large aspect conductor (no saucer or trapezoid effects), and
 - d. better winding tightness in axial direction for U-shaped bobbin.

For the EBT-P application the need for minimizing errors introduced by joints and the shorter winding time offered by layer winding both lead to the choice of a layer-wound coil. Actually we should

Fig. A.3.18. The calculated value for $\langle j \rangle$ winding, assuming a Cu/Sc ratio of 3:1, a packing factor λ of 0.7, and an operating current at $v = 0.6$ the critical current.

Fig. A.3.19. The load line for the reference design relative to the short sample critical current.

call it a hybrid (or "layercake") because one pancake will be wound on the end and the remainder of the coil will be layer wound. In this manner there is no need to make an entrance through the end flange; furthermore, the input and output leads can be placed in close proximity, making the cancellation of field errors due to the current leads a relatively easy task. A layer winding in conjunction with a rectangular-shaped conductor leads to a tight, well-packed winding.

SUMMARY

Because the constraints on the magnet design (7.4 T and 10,000 A/cm²) preclude the possibility of a cryostabilized pool-boiling magnet, we have selected a NbTi pool-boiling metastable design as our preference over a force-cooled Nb₃Sn cryostabilized design. A critical review of the existing literature shows that magnets of the type being proposed have all worked to full operating design value without training. No degradation has been observed in this class of magnet. A stability analysis has shown that the conductor will be more stable against energy perturbations if the Cu:SC ratio is closer to 3:1 than to 5:1. The conductor will be rectangular and flat wound in a hybrid-type winding that consists of one pancake wound next to the end flange with the remainder of the coil wound in layers.

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Appendix 4

MICROWAVE HEATING

MICROWAVE HEATING THEORY

In the ELMO Bumpy Torus (EBT) device,^{1,2} all heating is provided by microwaves through the electron-cyclotron resonance interaction. In addition, the microwaves play an essential role by producing the high beta, hot electron annuli which provide macroscopic stability for the toroidal plasma component. A knowledge of the microwave field distribution and heating profile is crucial to the understanding of EBT physics.

EBT-I consists of 24 toroidally linked mirror sectors having a 2:1 mirror ratio and a peak field strength on axis at the mirror throat of 13 kG. The magnetic geometry is illustrated in Fig. A.4.1, which shows the vacuum field lines (solid) and contours of constant $|B|$ in the equatorial plane for a sector of EBT. Steady-state plasma is formed and heated by an ECH microwave source providing up to 60 kW at a frequency of 18 GHz and a lower, off-resonance heating source providing up to 30 kW at 10.6 GHz. The current in the mirror coils is adjusted so as to produce cyclotron resonance zones $\omega = \Omega_e(x) = e|B(x)|/m_e c$ as indicated in Fig. A.4.1. High beta annuli consisting of relativistic electrons ($T_{e\text{Annulus}} \sim 200$ keV) form at the midplane of each mirror sector in the vicinity of the second harmonic resonance for the 18-GHz microwaves. In addition to the high beta annuli, the EBT plasma contains a toroidal core component of much higher density ($n_{e\text{Core}} \gtrsim 10 n_{e\text{Annulus}}$) and lower temperature ($T_{e\text{Core}} \sim 150\text{--}600$ eV) confined by the bumpy torus magnetic field configuration.³ There is now great interest in the transport and scaling properties of the toroidal core plasma in EBT to assess its potential as a fusion reactor.^{4,5} In this paper, therefore, we will concentrate on the cyclotron damping of the 18-GHz microwaves by the higher density toroidal core plasma. Relativistic calculations of absorption by the hot electron annuli are currently under way and will be reported separately.

A number of previous studies have dealt with the theory of electron-cyclotron heating in axisymmetric mirror machines⁶⁻¹⁰ where the heating was calculated from single particle orbits or from a Fokker-Planck-type equation. The microwave field was assumed to be a cavity normal mode or some arbitrarily specified field structure, and the plasma density was assumed to be sufficiently low that plasma currents produce only small perturbations in the wave fields. However, the volume of the EBT vacuum vessel is so large ($V = 1.3 \text{ m}^3 \sim 10^5 \lambda^3$, where λ = microwave free space wavelength) that cavity modes cannot be expected to play any role, and the unperturbed field structure is certainly not known. In addition, the plasma density is sufficiently high ($\omega_{pe}^2/c\Omega_e^2 v_e \gg 1$) that plasma currents strongly affect wave propagation throughout the machine. Indeed, in EBT plasma resonances and cutoffs dominate the propagation characteristics of the microwave power.

Other studies have investigated electron-cyclotron heating in tokamak geometry.¹¹⁻¹⁶ Usually these studies have made simplifying assumptions on the geometry, such as plane stratification. In EBT, however, the plasma and cavity have a very complicated and unsymmetrical structure (refer to Fig. A.4.1); thus, the assumption of plane stratification is inadequate, and more detailed calculations are necessary in order to determine the spatial heating profiles. A large-scale computational effort is now in progress to trace the microwave energy flow and heating characteristics of EBT using geometrical optics;¹⁷ some preliminary results of this work are reported here.

In this section of this Appendix, we first will discuss the wave propagation properties of the ordinary and extraordinary modes in EBT geometry. A dominant feature is the presence of the right-hand cutoff, which prevents the extraordinary mode from propagating directly to the cyclotron resonance layer from the mirror midplane, where the waves are injected. This unavoidable cutoff and the presence of strong gradients in magnetic field strength along the field lines make the electron-cyclotron heating of

Fig. A.4.1. Configuration of magnetic field in EBT. Two microwave frequencies (10.6 GHz and 18 GHz) are fed from the opening on the inside wall of the cavity. The wave mode at the injection port is ordinary rather than extraordinary. The hot electron ring (runaway electrons) is observed to be a narrow belt encircling the local second harmonic resonance (for 18 GHz) in the midplane. The maximum microwave heating takes place at the cyclotron resonance zone (hatched area).

EBT entirely different from that of tokamaks. We consider in some detail two cases of plane-stratified plasma: (1) perpendicular stratified plasma (gradients perpendicular to $\underline{B}$, characteristic of tokamaks) and (2) parallel stratified plasma (gradients purely along $\underline{B}$, characteristic of fundamental resonance in EBT). For extraordinary mode propagation in a parallel stratified plasma, the wave vector $\underline{k}$ turns parallel to $\underline{B}$ as the wave approaches cyclotron resonance. This results in enormous absorption in a dense plasma.

The energy deposition is evaluated by integrating the imaginary part of the refractive index k_i along geometrical optics ray paths. We will discuss the finite temperature dispersion relation used and indicate some of the complications which arise when the gradients in plasma parameters are not perpendicular to $\underline{B}$ or when the plasma is not plane stratified. It is shown that when the waves are not too heavily damped, the absorption predicted by integrating k_i along the ray is independent of the direction chosen for $\underline{k}_i$.

Calculations are then presented showing damping rates and fractional power absorption at the cyclotron and second harmonic resonances in plane-stratified plasmas typical of EBT-I and projected parameters for EBT-II. We find that absorption of the ordinary mode by the core plasma of EBT-I is negligible throughout. On the other hand, the extraordinary mode is strongly damped at the cyclotron resonance but weakly damped at the second harmonic. For plasma parameters expected in EBT-II, the situation is entirely different. The ordinary mode is heavily damped in the hot, dense core region. Also, the extraordinary mode is significantly damped by the core plasma in the region of the second harmonic resonance. These results for plane-stratified geometry are borne out by calculations in a more realistic magnetic mirror geometry. We also will discuss fractional absorption calculations made with a geometrical optics code using a bumpy cylinder equilibrium model.

Finally, we will summarize the results and construct a qualitative picture of the electron-cyclotron heating of the core plasma in EBT. Because the extraordinary mode energy injected near the mirror midplane is cut off before reaching the cyclotron resonance and the ordinary mode does not significantly heat the core plasma in EBT-I, some mechanism must exist outside the geometrical optics model whereby extraordinary mode energy is transmitted to the high field region. The most likely candidate appears to be the conversion of ordinary mode to extraordinary mode in the high field region.

Energy Transport Considerations

The transport of energy throughout the EBT plasma, as distinguished from the actual deposition of energy, can adequately be understood using cold plasma wave theory. The cold plasma dispersion relation in the electron-cyclotron frequency regime $\omega \sim \Omega_e \gg \Omega_i$, ω_{pi} is conveniently expressed in the Appleton-Hartree form¹⁸

$$n^2 = 1 - \frac{2\alpha(1 - \alpha)}{2(1 - \alpha) - \beta \sin^2 \theta \pm \Gamma}, \quad (1)$$

where

$n = ck/\omega$ = wave refractive index;

$$\alpha = \frac{\omega_{pe}^2}{\omega^2} = \frac{4\pi n_e e^2}{m_e \omega^2}, \quad \beta = \frac{\Omega_e^2}{\omega^2};$$

$$r = [\beta^2 \sin^4 \theta + 4\beta(1 - \alpha)^2 \cos^2 \theta]^{1/2};$$

$$\theta = \cos^{-1}(\mathbf{k} \cdot \mathbf{B}/|\mathbf{k}| |\mathbf{B}|);$$

and the $+$ ($-$) signs refer to ordinary (extraordinary) mode propagation. A resonance, $n \rightarrow \infty$, occurs in the extraordinary mode branch at a magnetic field strength β_R which depends on the density and angle of propagation, $\beta_R = (1 - \alpha)(1 - \alpha \cos^2 \theta)^{-1}$. The extraordinary mode cutoff or right-hand cutoff, $n \rightarrow 0$, occurs at the magnetic field strength $\beta_C = (1 - \alpha)^2$, for which the extraordinary mode does not propagate at any angle θ . Thus an extraordinary mode wave propagating toward the cyclotron resonance from a low magnetic field region ($\beta < \beta_C < \beta_R$) will be reflected at or before it reaches the right-hand cutoff layer.

Since EBT operates in a density regime such that $\alpha < 1$, there are no resonances or cutoffs for the ordinary mode. In fact, ray tracing studies show that ordinary mode waves are barely refracted in EBT plasmas. It is anticipated that future devices will also operate in this $\alpha < 1$ regime.

Figure A.4.2 shows a cross section of an EBT sector with a high beta ($\beta = 40\%$) annulus plasma calculated using a 3-D tensor-pressure equilibrium code. An ad hoc model was adopted for the low beta core plasma density profile. In this model, the density is constant along magnetic field lines, is maximum on axis, decreases slowly with radius out to the high beta annulus, and then drops sharply to a constant value outside the annulus. The peak electron density is known experimentally to be $1\text{--}2 \times 10^{12} \text{ cm}^{-3}$, whereas the density near the surface is $n_e \sim 2 \times 10^{11} \text{ cm}^{-3}$. Shown in Fig. A.4.2 are magnetic field lines, 18-GHz first and second harmonic cyclotron resonant zones, and the right-hand cutoff. The resonance and cutoff surfaces are distorted by the presence of the magnetic well. It is clear that extraordinary mode energy, propagating from the midplane region (where the microwaves are injected), is reflected from the right-hand cutoff before reaching the fundamental cyclotron resonant surface.

For the case shown in Fig. A.4.2, the peak density was chosen to be $n_e = 2 \times 10^{12} \text{ cm}^{-3}$ [i.e., $\alpha(r=0) = 1/2$]. For this or lower density, the second harmonic resonance is accessible to the extraordinary mode. In a sequence of experiments with electron-cyclotron heated mirror plasmas having high beta rings, a maximum density limit was observed at about half the ordinary mode cutoff density. We conjecture that this is related to the condition for extraordinary mode accessibility to the second harmonic resonance, i.e., $\alpha < 1/2$. At higher density, extraordinary mode heating of the annulus would be reduced and annulus beta could not be maintained.

Although the fundamental cyclotron resonance is inaccessible to the injected extraordinary mode waves, it is observed experimentally that significant heating of the core plasma does, in fact, occur. The cyclotron resonant surface is accessible to the ordinary mode, but, as shown later, the ordinary mode is not absorbed. Therefore, a mechanism must exist for extraordinary mode energy to propagate to the resonant surface. Later in this Appendix ("Qualitative Picture of ECH in EBT"), it is argued that this mechanism is the conversion of ordinary mode energy to extraordinary mode in the high field region by means of wall reflections.

The amount of cyclotron damping which a wave experiences in passing through cyclotron resonance is strongly dependent on θ , the angle between $\mathbf{k}$ and $\mathbf{B}$ at the resonance layer. This angle is not actually under the experimenters' control, but is sensitively dependent on the plasma geometry as well as on the $\mathbf{k}$ spectrum of injected waves. For complicated plasma geometry it is necessary to use the methods of ray tracing to determine the direction of $\mathbf{k}$ throughout the plasma. Considerable simplification is obtained if one assumes that the plasma has a plane-stratified geometry (i.e., all gradients are in a fixed direction). In that case, the refractive index in any direction perpendicular to the gradients is constant as a consequence of Snell's law. We will consider two examples of plane-stratified plasmas

Fig. A.4.2. Location of first and second harmonic cyclotron resonance zones and the right-hand cutoff zones for 18-GHz extraordinary mode radiation in a model EBT-I equilibrium.

which serve to illustrate some of the important differences between wave propagation and absorption in tokamaks vs EBT.

For many purposes the plasma in a tokamak is adequately modeled as a slab with straight magnetic field lines $\underline{B}$ along the z direction and all gradients of $|B|$ and density, n_e , being perpendicular to $\underline{B}$ in the x direction (Fig. A.4.3a). A similar situation is seen for waves propagating perpendicular to $\underline{B}$ near the midplane of EBT. In such a plasma, stratified perpendicular to $\underline{B}$, the refractive indices in the z and y directions ($n_z = k_z c/\omega$, $n_y = k_y c/\omega$) are constant; and for $n_y = 0$, the refractive index along the gradients satisfies a dispersion relation of the form

$$An_x^4 + Bn_x^2 + C = 0, \quad (2)$$

where

$$A = 1 - \alpha - \beta,$$

$$B = [(1 - \alpha)(1 - \beta) + (1 - \alpha - \beta)]n_z^2 - [(1 - \alpha)(1 - \alpha - \beta) + (1 - \alpha)^2 - \beta], \text{ and}$$

$$C = (1 - \alpha)[(1 - \beta)n_z^4 - 2(1 - \alpha - \beta)n_z^2 + (1 - \alpha)^2 - \beta].$$

A resonance ($n_x^2 \rightarrow \infty$) occurs in the extraordinary mode branch at the upper hybrid frequency ($\alpha + \beta = 1$) for arbitrary values of n_z^2 . Cutoffs ($n_x \rightarrow 0$) occur at the values of density such that $\alpha = 1$ and at $\alpha = (1 \pm \sqrt{\beta})(1 - n_z^2)$. The cutoff $\alpha = 1$ is associated with the ordinary mode, the cutoff $\alpha = (1 - \sqrt{\beta})(1 - n_z^2)$ is associated with the extraordinary mode, whereas the cutoff at $\alpha = (1 + \sqrt{\beta})(1 - n_z^2)$ is in the ordinary or extraordinary mode branch according to whether $\alpha < 1$ or $\alpha > 1$, respectively. Figure A.4.3a shows typical extraordinary mode rays injected from the low and high magnetic field region. In the cold plasma theory, a wave propagating toward the cyclotron resonance from the high field side passes without impediment through the cyclotron resonance to the upper hybrid resonance, where it must be absorbed or mode converted. Cyclotron absorption in a perpendicularly stratified plasma is entirely a finite temperature effect.

In other devices such as bumpy tori, mirror machines, or multipoles, the variations in B and n_e along the magnetic field are very important and in some regions can dominate variations perpendicular to $\underline{B}$. For example, near the fundamental cyclotron resonance in EBT, particularly at the magnetic axis, the magnetic field varies strongly along the field lines (magnetic beach). As a simple model of this type of geometry, consider a plasma slab which is stratified parallel to the magnetic field (Fig. A.4.3b). The magnetic field is taken along z , and the field strength and possibly the density are assumed to vary only with z [$B = B(z)\hat{z}$].

In this geometry the components of the refractive index in the x and y directions are fixed and we can, without loss of generality, choose $n_y = 0$. Using cold plasma wave theory, one finds that the parallel index of refraction n_z satisfies a dispersion relation of the form

$$An_z^4 + Bn_z^2 + C = 0, \quad (3)$$

where

$$A = (1 - \alpha)(1 - \beta),$$

$$B = -2(1 - \alpha)(1 - \alpha - \beta) - [(1 - \alpha)(1 - \beta) + 1 - \alpha - \beta]n_x^2,$$

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Fig. A.4.3. Geometry and ray propagation for parallel and perpendicularly plane-stratified plasmas. Arrows on rays indicate direction of $\vec{k}$.

$$C = (1 - \alpha - \beta)n_X^4 - [(1 - \alpha)(1 - \alpha - \beta) + (1 - \alpha)^2 - \beta]n_X^2 + (1 - \alpha)[(1 - \alpha)^2 - \beta] .$$

Here the extraordinary mode resonance ($A \rightarrow 0$) occurs at the cyclotron layer $\beta = \Omega_e^2/\omega^2 = 1$ independent of n_X , and the extraordinary mode cutoff ($C \rightarrow 0$) occurs at

$$(1 - \alpha)^2 - \beta - (1 - \alpha - \beta)n_X^2 = 0 . \quad (4)$$

Figure A.4.3b shows typical extraordinary mode rays launched toward the cyclotron resonance in a parallel stratified plasma from both the low and high magnetic field sides. As the ray approaches the resonance from the high field side, the wave vector $\underline{k}$ turns parallel to $\underline{B}$, the parallel phase velocity c/n_z becomes slow, and the large numbers of resonant particles produce very strong cyclotron damping.

The Finite Temperature Dispersion Relation and Properties of the Solutions

In the present work, the energy deposition was calculated by integrating the imaginary part of the refractive index along a ray path:

$$P(s) = P_0 \exp \left\{ - \int_{s_0}^s ds' \underline{k}_i \cdot \underline{v}_g / |\underline{v}_g| \right\} , \quad (5)$$

where

$P(s)$ = power flux density along the ray,

P_0 = initial power flux density,

s = path length along the ray,

$\underline{k}_i$ = imaginary part of the wave vector, and

$\underline{v}_g$ = group velocity.

The imaginary part of $\underline{k}$ is obtained by solving a finite temperature dispersion relation of the form

$$D[\underline{k}, \omega, \omega_{pe}(\underline{x}), \Omega_e(\underline{x}), v_e] = \det[\underline{D}] = 0 , \quad (6)$$

where

$$\underline{D} = \left(1 - \frac{c^2 k^2}{\omega^2} \right) \underline{I} + \frac{c^2}{\omega^2} \underline{k} \underline{k} + \frac{4\pi i}{\omega} \underline{\sigma} \quad \text{and}$$

$\underline{\sigma}$ = warm plasma conductivity tensor.

General expressions for the conductivity tensor can be found in the literature.^{18,19} However, for the present purposes the electron distribution function can be taken to be an isotropic, nonrelativistic Maxwellian and the ion contribution can be neglected entirely. A typical element of the conductivity tensor is of the form

$$\sigma_{11} = - \frac{i}{4\pi} \frac{\omega_{pe}^2}{k_z v_e} \sum_{\ell=-N}^N \frac{\ell^2}{b} I_{\ell}(b) e^{-b} Z(\xi_{\ell}) , \quad (7)$$

where

$$Z(\xi_\ell) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} dx \frac{e^{-x^2}}{x - \xi_\ell} = \text{plasma dispersion function ,}$$

$$\xi_\ell = \frac{\omega - \ell \Omega_e}{k_z v_e} ,$$

$$v_e = (2T_e/m_e)^{1/2} ,$$

$$b = k_x^2 v_e^2 / 2 \Omega_e^2 = k_x^2 \rho_e^2 / 2 , \quad \text{and}$$

$$I_\ell(b) = \text{modified Bessel function of order } \ell.$$

No small argument expansion is made on the $I_\ell(b)$, and the sum is taken over all cyclotron harmonics of interest (typically $N = 2$). For the plasma parameters found in EBT, the energy confinement time $\tau_E \sim 2\text{-}5$ msec is much longer than the electron-electron collision time $\nu_{ee}^{-1} \sim 10^{-4}$ sec, and each particle spends only a short time in the resonance zone. Therefore, the assumption of an isotropic Maxwellian distribution for the toroidal core electrons is justified.

In many cases, useful approximation to k_i can be obtained by expanding the dispersion relation about the cold plasma roots.^{14,19} Assuming $k_x^2 \rho_e^2 \ll 1$, $\xi_\ell \gg 1$ for $\ell \neq 1$ and taking the large argument limit of $Z(\xi_\ell)$ for $\ell \neq 0$ give a dispersion relation valid near the fundamental cyclotron resonance ($\omega \sim \Omega_e$) of the form

$$D = \sigma D_0(\omega, \underline{n}, \omega_{pe}, \Omega_e) + D_1(\omega, \underline{n}, \omega_{pe}, \Omega_e) + \xi_1 Z(\xi_1) D_2(\omega, \underline{n}, \omega_{pe}, \Omega_e) , \quad (8)$$

where

$$\sigma = -\frac{1}{2} \frac{\omega_{pe}^2}{\omega^2} \frac{1}{n_z} \frac{c}{v_e} Z(\xi_1)$$

and D_0 , D_1 , D_2 are fourth degree polynomials in $\underline{n} = c\mathbf{k}/\omega$. For propagation not along field lines ($n_z \lesssim 1$) in nonrelativistic plasma ($v_e/c \ll 1$) of sufficiently high density, the quantity σ is large near $\omega = \Omega_e$:

$$|\sigma(\omega = \Omega_e)| = \frac{\sqrt{\pi}}{2} \frac{\omega_{pe}^2}{\Omega_e^2} \frac{c}{v_e} \frac{1}{n_z} \gg 1 . \quad (9)$$

To lowest order, n is given by

$$D_0(\omega = \Omega_e, \underline{n}^0) = n_x^2 n^2 - [2(1 - \alpha) n^2 + n_x^2] + (1 - \alpha)(2 - \alpha) = 0 , \quad (10)$$

where $n^2 = n_x^2 + n_z^2$. Equation (10) coincides exactly with the cold plasma dispersion relation [Eq. (2) or (3)] evaluated at $\omega = \Omega_e$ and can be solved either for $n_x^2(\alpha, n_z)$, $n_z^2(\alpha, n_x)$, or $n^2(\alpha, \theta)$. In any case, a quadratic equation is obtained that yields two roots corresponding to the cold plasma ordinary

and extraordinary modes. The first order correction is obtained by regarding D_0, D_1, D_2 , as slowly varying functions of Ω_e near the resonance and expanding Eq. (9) about n^0 :

$$D(\tilde{n}^0 + \tilde{n}^1) = \sigma \left[D_0(\tilde{n}^0) + \tilde{n}^1 \cdot \frac{\partial}{\partial \tilde{n}} \cdot D_0(\tilde{n}^0) \right] + D_1(\tilde{n}^0) + \epsilon_1 Z(\epsilon_1) D_2(\tilde{n}^0) = 0. \quad (11)$$

Finally we get an expression for $\tilde{n}_i$ of the form

$$\tilde{n}_i \cdot \frac{\partial D_0}{\partial n_0} = -2 \frac{\Omega_e^2}{\omega_{pe}^2} n_z \frac{v_e}{c} D_1(\tilde{n}^0) \text{Im} \left\{ \frac{1}{Z \left(\frac{\omega - \Omega_e}{k_z^0 v_e} \right)} \right\}. \quad (12)$$

This approximation or similar ones have been used in a number of previous papers to evaluate cyclotron damping in tokamaks. The qualitative properties of cyclotron absorption can be summarized as follows: near the fundamental resonance, damping of the extraordinary mode is very heavy ($k_i/k_r \sim 1$) for propagation nearly parallel to the magnetic field ($\theta \sim 0$), but then decreases with increasing θ . The damping increases with increasing temperature, but decreases as the density is increased. The ordinary mode is weakly damped ($k_i/k_r \sim T_e/mc^2$) in comparison to the extraordinary mode, but the damping increases with increasing θ , with increasing temperature, and with increasing density. Near the second harmonic ($\omega \sim 2\Omega_e$) both modes are weakly damped [$k_i/k_r \sim T_e/mc^2$ for extraordinary mode, $k_i/k_r \sim (T_e/mc^2)^2$ for ordinary mode], with absorption increasing as temperature and density increase. The damping of the extraordinary mode increases with θ , whereas damping of the ordinary mode peaks at an oblique angle $0 < \theta < \pi/2$.

The approximate method described above is usually adequate for high density tokamaks or other nearly perpendicularly stratified plasmas. In such cases, the cold plasma extraordinary mode resonance is in n_x (rather than n_z) and occurs at a value of Ω_e well separated from $\Omega_e = \omega$. At the cyclotron resonance n_z remains small ($n_z \lesssim 1$) so that the inequality in Eq. (9) is satisfied. However, in EBT or a nearly parallel stratified plasma, n_z becomes large at the cold plasma resonance (in this case $\Omega_e \sim \omega$ at the cold plasma resonance) and Eq. (9) fails. Application of the weak damping expansion in such cases gives incorrect damping rates, including nonphysical absorption on the low field side of the right-hand cutoff. In order to deal with these difficulties, we use the full finite temperature dispersion tensor in our studies and obtain solutions of the dispersion relation by numerical root finding techniques.

The formulation of cyclotron absorption in terms of a homogeneous plasma, nonrelativistic dispersion relation also breaks down for waves propagating nearly perpendicular to the magnetic field ($\theta \approx \pi/2$). In that case, resonance broadening processes other than the thermal Doppler broadening described by $Z(\xi)$ must be included. Relativistic broadening is important for $n_z \lesssim v_e/c$,^{14,20} and broadening owing to magnetic field inhomogeneity becomes important for $n_z < (c/v)(k_\perp L)^{-1}$, where $L = (d \ln B/dx)^{-1}$ is the magnetic field scale length.¹⁵ In either case, the effect is to give nonzero absorption of the extraordinary mode and to limit the local damping rate of the ordinary mode at perpendicular propagation. We have not included these corrections in our calculations because the geometry of the cyclotron resonant surface in EBT is such that propagation perpendicular to B at resonance is very difficult to achieve (Fig. A.4.2), and the absorption of such waves is not expected to play an important role.

A difficulty that arises in our method of calculating the power absorption (i.e., integrating k_i along a ray) is that the direction of k_i is not determined by the ray equations for arbitrary plasma geometry. For example, in a uniform plasma the direction of k_i is determined by the boundary conditions

or the geometry of the wave launching structure and is not, in general, parallel to $\underline{k}_r$. However, using Poynting's theorem for a time invariant, anisotropic medium,²¹

$$\underline{\Delta} \cdot (\underline{u} \underline{v}_g) = -\underline{E}^* \cdot \underline{\sigma}^H \cdot \underline{E}, \quad (13)$$

where

$$u = \frac{1}{8\pi} \underline{E}^* \cdot \frac{\partial}{\partial \omega} (\omega \underline{D}^H) \cdot \underline{E} = \text{wave energy density and}$$

$$\underline{\sigma}^H = \frac{1}{2} (\underline{\sigma} + \underline{\sigma}^\dagger) = \text{Hermitian part of } \underline{\sigma}^H,$$

and making the ansatz $\underline{E}(\underline{x}, t) = \underline{E}_0 \exp [i(\underline{k} \cdot \underline{x} - \omega t)]$, where $\underline{k} = \underline{k}_r + i\underline{k}_i$ ($\underline{k}_i$ is not necessarily parallel to $\underline{k}_r$), we obtain

$$\underline{k}_i \cdot \underline{v}_g = \frac{\underline{E}_0^* \cdot \underline{\sigma}^H \cdot \underline{E}_0}{\underline{E}_0^* \cdot \frac{\partial}{\partial \omega} (\omega \underline{D}^H) \cdot \underline{E}_0}. \quad (14)$$

This indicates that the component of $\underline{k}_i$ along the group velocity is independent of the direction chosen for $\underline{k}_i$. Of course, this breaks down if $\underline{k}_i$ is exactly perpendicular to $\underline{v}_g$.

For the particular problem of interest here, Poynting's theorem in the form of Eq. (13) is not valid. This is because derivation of Eq. (13)²¹ for a dissipative medium requires that $|\underline{\sigma}^H| \ll |\underline{\sigma}^A|$, whereas near a cyclotron harmonic in a dense plasma, we have $|\underline{\sigma}^H| \gg |\underline{\sigma}^A|$. However, even near a cyclotron harmonic a result similar to Eq. (14) can be obtained from the dispersion relation, Eq. (8), provided the absorption is not too large. Noting that in Eq. (8) $D_0(n, \omega = \Omega_e) = 0$ is the cold plasma dispersion relation evaluated at $\omega = \Omega_e$, we see that

$$\left. \frac{\partial D_0}{\partial n_0} = \frac{\omega}{c} \frac{\partial D_0}{\partial k} \right]_{\underline{k} = \omega \underline{n}_0 / c} = - \left. \frac{\omega}{c} \frac{\partial D_0}{\partial \omega} \right]_{\underline{k} = \omega \underline{n}_0 / c} \underline{v}_g, \quad (15)$$

where $\underline{v}_g$ is the group velocity at resonance as determined from cold plasma theory. Therefore, Eq. (12) becomes

$$\underline{k}_i \cdot \underline{v}_g = 2 \frac{\Omega_e^2}{\omega_{pe}^2} \frac{k_z^0 v_e}{c} \frac{D_1(n^0)}{\frac{\partial D_0}{\partial \omega}} \text{Im} \left\{ \frac{1}{Z \left(\frac{\omega - \Omega_e}{k_z^0 v_e} \right)} \right\}, \quad (16)$$

which again shows that the component of $\underline{k}_i$ along $\underline{v}_g$ is independent of the choice of direction for $\underline{k}_i$.

In order to study this situation in somewhat more detail, we have obtained numerical solutions of the full dispersion relation Eq. (6) with $\underline{k}_i$ at an arbitrary angle with respect to $\underline{k}_r$. We find that $\underline{k}_i \cos \psi$, where ψ is the angle between $\underline{k}_i$ and $\underline{v}_g$, is independent of ψ even for fairly heavily damped waves. Figure A.4.4 shows the magnitude of $\underline{k}_i$ and $\underline{k}_i \cos \psi$ plotted for the extraordinary mode as a function of ψ at the cyclotron resonance, $\Omega_e / \omega = 1$. For the case shown, the parameters were $\omega / 2\pi = 18$ GHz, $\omega_{pe}^2 / \omega^2 = 0.7$, and $v_e / c = 0.034$. The angle θ between $\underline{k}_r$ and $\underline{B}$ was 27.7° , and the angle ϕ between $\underline{v}_g$ and $\underline{B}$ was 83.7° . Despite the heavy damping [$k_i(\psi = 0) = 0.32/\text{cm}$], we see that $\underline{k}_i \cos \psi$ is virtually constant.

Fig. A.4.4. Dependence of $|k_i|$ and the projection of k_i along $\hat{v}_g$ upon the direction chosen for k_i . The parameters are typical of EBT-I.

For fixed ω , the shape of the absorption line (i.e., k_z considered as a function of Ω_e) depends strongly on the plasma geometry. In a perpendicularly stratified plasma, k_z is fixed and real. The resonance absorption line is approximately Gaussian shaped and is described accurately by the approximation given by Eq. (12) provided $\omega_{pe}^2 c / \Omega_e^2 v_e \gg 1$. Absorption line calculations for parameters typical of tokamaks are presented in Ref. 14.

However, if the geometry is such that k_z develops a finite imaginary part in the resonance region, the extraordinary mode line shape will be distorted from Gaussian. In particular, for a parallel-stratified plasma, k_x is fixed and real, whereas $\text{Im}\{k_z\}$ becomes large near $\omega \cong \Omega_e$ so that the plasma dispersion function becomes highly oscillatory $Z(\xi) \sim i\sqrt{\pi} \exp(-\xi^2)$. Also, since $|k_z| \rightarrow 0$ at the cutoff region and $k_z = 0$ is an essential singularity of the plasma dispersion function, the dispersion relation is found to have an infinite number of roots distributed throughout the complex k_z plane in the frequency region between the right-hand cutoff and the cyclotron resonance.²² Figure A.4.5 shows extraordinary mode $\text{Re}\{k_z\}$ and $\text{Im}\{k_z\}$ plotted as a function of Ω_e/ω for $n_x = 0.6$ with plasma parameters typical of EBT-I [i.e., $\omega = 2\pi(18 \text{ GHz})$, $v_e/c = 0.034$, $\omega_{pe}^2/\omega^2 = 0.3$]. Far from the fundamental cyclotron resonance, $\text{Re}\{k_z\}$ agrees with cold plasma results obtained from Eq. (3) except for a small perturbation at the second harmonic resonance. When approaching resonance from the high field side, $\text{Re}\{k_z\}$ peaks at $\Omega_e/\omega = 1.025$ and remains finite at $\Omega_e/\omega = 1.0$. The damping rate, $\text{Im}\{k_z\}$, becomes quite large near resonance, and clearly the wave approaching from the high magnetic field side is totally absorbed. This result is virtually independent of the plasma density or the value of n_x . The relative weakness of second harmonic absorption is indicated by the magnitude of $\text{Im}\{k_z\}$ at the second harmonic resonance. Between the cutoff $\Omega_e/\omega = 0.61$ and resonance, the dispersion relation has multiple solutions. The roots shown in this range in Fig. A.4.5 were obtained by continuity, following the root from the high field side.

Fractional Absorption Calculations for Plane-Stratified Plasmas

Because of the complicated EBT geometry, the fraction of power absorbed from a propagating ray depends sensitively on the initial position of the ray and injection angle. In order to obtain a qualitative understanding of the relative importance of the different modes, geometrical characteristics, and plasma parameters, we have compiled a compendium of calculations of fractional absorbed power as rays pass through fundamental and second harmonic cyclotron resonances in plane-stratified plasmas having parameters appropriate for EBT devices. For consideration of EBT-I the parameters are taken to be $\omega/2\pi = 18 \text{ GHz}$, $T_e = 300 \text{ eV}$ [this corresponds to $v_e/c = (2T_e/mc^2)^{1/2} = 0.034$], and $\omega_{pe}^2/\omega^2 = 0.3, 0.5, 0.7$ (this corresponds to $n_e = 1.2, 2.0, 2.8 \times 10^{12} \text{ cm}^{-3}$, respectively). In order to gain some understanding of the implications for hotter, denser devices, we have also performed calculations for a projected EBT-II device²³ with parameters $\omega/2\pi = 120 \text{ GHz}$, $T_e = 2 \text{ keV}$ (corresponding to $v_e/c = 0.09$), and $\omega_{pe}^2/\omega^2 = 0.3, 0.5, 0.7$ (corresponding to $n_e = 5.4 \times 10^{13} \text{ cm}^{-3}, 8.9 \times 10^{13} \text{ cm}^{-3}$, and $1.25 \times 10^{14} \text{ cm}^{-3}$, respectively).

Calculations were performed for the ordinary mode in a parallel-stratified plasma with linearly increasing magnetic field, $B(x) = B_0(1 + x/L)^2$. As mentioned previously, the extraordinary mode is completely absorbed in this geometry when launched from the high magnetic field side. The magnetic scale length L was taken to be 10 cm in the calculations for both EBT-I and EBT-II. This value is typical of, or slightly longer than, magnetic gradient scale lengths at the fundamental cyclotron resonance in EBT-I (Fig. A.4.1). For EBT-II, scale lengths may be somewhat larger, so that these results represent minimum absorption for EBT-II. For comparison, we also evaluated ordinary and extraordinary modes in a perpendicularly stratified plasma with linearly increasing magnetic field, $B(x) = B_0(1 + x/L)^2$. Again, L was taken to be 10 cm. The fraction of power absorbed, f , is calculated by actually tracing rays in the appropriate plasma geometry and integrating k_z :

Fig. A.4.5. Extraordinary mode $\text{Re}\{k_z\}$ and $\text{Im}\{k_z\}$ vs Ω_e/ω for typical EBT-I parameters.

$$f = 1 - \exp \left[-2 \int_{s_1}^{s_2} ds k_i(s) \right], \quad (17)$$

where $k_i(s)$ is chosen to be parallel to the local group velocity $v_g(s)$, and s is the arc length along a ray.

Figure A.4.6 shows the fraction of power absorbed for typical EBT-I parameters. Figure A.4.6a is for the ordinary mode in a parallel-stratified plasma as a function of the perpendicular index of refraction n_x with which the ray is injected. It can be seen that the fractional absorption increases with density and with angle of propagation relative to the magnetic field. The absorption increases rapidly with n_x because the magnitude of k_i increases with n_x , and increasing n_x causes the ray to spend a longer time in the resonant zone. However, the finite radial size of EBT-I and the curvature of the resonant zone (i.e., deviation from plane stratification) limit the per pass fractional absorption for ordinary mode radiation to $<1\%$, even for nearly perpendicularly propagating rays in the actual device. Over most of the spectrum in n_x , f is less than 10^{-3} . Figures A.4.6b and A.4.6c, respectively, show ordinary mode absorption and extraordinary mode absorption in perpendicularly stratified plasma as a function of the parallel index of refraction n_z with which the ray is injected. This type of geometry does not actually occur for the 18-GHz fundamental resonance in EBT, although the 10.6 GHz resonance might be modeled as perpendicularly stratified near the midplane. The ordinary mode (Fig. A.4.6b) absorption is quite small and decreases with increasing n_z . The extraordinary mode absorption (Fig. A.4.6c) decreases with density and increases rapidly with increasing n_z . In this case, the magnitude of k_i increases as the wave vector becomes more nearly parallel to B , and the ray stays longer in the resonant zone as n_z increases.

Figure A.4.7 shows similar plots of fractional power absorption for the projected EBT-II parameters. The important point here is that for a hotter, denser plasma such as EBT-II, the ordinary mode is quite heavily absorbed for both directions of stratification.

Figure A.4.8 shows fractional absorption at the second harmonic resonance for parameters characteristic of the toroidal core plasma in EBT-I. In Figs. A.4.8a and A.4.8b is plotted the second harmonic absorption for the ordinary mode in parallel and perpendicularly stratified geometry, respectively; Figs. A.4.8c and A.4.8d have similar plots for the extraordinary mode. For fixed density in parallel stratification, the fractional absorption f increases with n_x . The obtainable absorption is bounded, however, because the waves do not propagate for n_x above the limiting values

$$n_x^2 = 1 - \alpha \quad (\text{ordinary mode}) \text{ and}$$

$$n_x^2 = \frac{(1 - \alpha)^2 - \beta}{1 - \alpha - \beta} \quad (\text{extraordinary mode}).$$

From the figures we see that second harmonic absorption of the ordinary mode for these EBT-I parameters is less than $\sim 2 \times 10^{-3}$, and absorption of the extraordinary mode is less than a few percent. These results, which are confirmed by calculations in mirror geometry (Sect. 4), show that wave absorption at the second harmonic resonance does not play a role in heating of the core plasma in EBT-I. Figure A.4.9 shows second harmonic absorption calculations similar to those in Fig. A.4.8 but for the parameters characteristic of EBT-II used in Fig. A.4.7. The results are qualitatively like those shown in Fig. A.4.8, but the absorption is much stronger. The results for extraordinary mode (Figs. A.4.9c and A.4.9d) showing tens of percents wave absorption over a broad spectrum of n_x and n_z indicate that second harmonic heating of the core plasma will be important in the next generation of EBT devices.

Fig. A.4.6. Fraction of power absorbed from a ray passing through cyclotron resonance vs refractive index in direction perpendicular to gradients. Plasma parameters are characteristic of EBT-I.

Fig. A.4.7. Fraction of power absorbed in passing through cyclotron resonance for plasma parameters characteristic of EBT-II.

Fig. A.4.8. Fraction of power absorbed from a ray passing through second harmonic cyclotron resonance vs refractive index in direction perpendicular to gradient. Plasma parameters are characteristic of EBI-1.

Fig. A.4.9. Fraction of power absorbed from a ray passing through second harmonic resonance for plasma parameters characteristic of EBT-II.

Cyclotron Damping in EBT Geometry

We now present cyclotron damping calculations for nonstratified plasma geometry more representative of the actual EBT configuration. In particular we consider a bumpy cylinder magnetic field $\underline{B}(\underline{x}) = B_z(r,z)\hat{z} + B_r(r,z)\hat{r}$ given analytically as the field owing to a set of coaxial current loops spaced uniformly along the z axis.¹⁷ A non-self-consistent density model for the low beta core plasma was adopted in which $n_e(\underline{x})$ is constant along magnetic field lines and is an explicit function of the toroidal magnetic flux $\psi(r,z)$:

$$n_e(\underline{x}) = n_0 \frac{1 - \tanh \left[\frac{\psi(\underline{x}) - \psi(r_0, z=0)}{\delta^2} \right]}{1 + \tanh [\psi(r_0, z=0)/\delta^2]}, \quad (18)$$

where

$$\psi(r,z) = \int_0^r dr' r' B_z(r', z).$$

Here r_0 plays the role of a plasma radius (typically $r_0 = 10$ cm for the EBT-I calculations, which is approximately the radius of the annulus), and δ is a gradient scale length (typically $\delta \sim 3$ cm).

The ray paths are traced using the Hamiltonian form of the geometrical optics equations^{17,21}

$$\frac{d\underline{x}}{ds} = \frac{1}{|\underline{v}_g|} \frac{d\underline{x}}{dt} = -\text{sgn} \left(\frac{\partial D}{\partial \omega} \right) \frac{\partial D / \partial \underline{k}}{|\partial D / \partial \underline{k}|} \quad (19)$$

and

$$\frac{d\underline{k}}{ds} = \frac{1}{|\underline{v}_g|} \frac{d\underline{k}}{dt} = \text{sgn} \left(\frac{\partial D}{\partial \omega} \right) \frac{\partial D / \partial \underline{x}}{|\partial D / \partial \underline{k}|}; \quad (20)$$

using the Appleton-Hartree dispersion relation $D[\underline{k}, \omega_{pe}(\underline{x}), n_e(\underline{x})] = 0$, Eq. (1). The parameter s is the arc length along the ray. The ray equations Eqs. (19) and (20), as well as the wave damping equation Eq. (5), are integrated numerically from given initial conditions $\underline{x}_0, \underline{k}_0$.

Figure A.4.10 shows the results of injecting extraordinary mode rays into the bumpy cylinder equilibrium at varying angles from two points located in the equatorial plane ($y = 0$). The plasma parameters were chosen to be representative of EBT-I: $\omega/2\pi = 18$ GHz, $(\omega_{pe}/\omega)_{\max} = 0.4$, and $v_e/c = 0.034$. Also shown in Fig. A.4.10 are the magnetic field lines and equatorial cross sections of the first and second harmonic resonant surfaces and the right-hand cutoff. The fraction of power absorbed in passing through resonance is indicated by each ray. A group of rays was injected from the low field region at the mirror midplane ($z = 0$) and outside the core plasma $x = -18$ cm. It can be seen that these rays do not penetrate to the cyclotron resonant surface but are reflected at the right-hand cutoff. Absorption at the second harmonic resonance, which is accessible, is negligible ($<2\%$ for the most heavily damped ray).

Fig. A.4.10. Extraordinary mode propagation in EBT-I. Numbers by rays indicate fraction of power absorbed.

It is of interest to examine the fate of an extraordinary mode ray originating near the mirror throat, which, for example, might arise from depolarization of an ordinary mode ray on reflection. Figure A.4.10 also shows ray paths and wave vectors for extraordinary mode rays injected at varying angles from a point near the mirror coil. On this side, the cyclotron resonance zone is accessible. It can be seen that the rays approach the cyclotron resonance layer with $\underline{v}_g$ nearly perpendicular to $\underline{B}$ and $\underline{k}$ nearly parallel to $\underline{B}$. This is characteristic of parallel-stratified media in the cold plasma model. The rays are terminated at the point at which 99% of the wave power has been absorbed. For the EBT-I parameters used in the calculation, the waves are completely damped well before reaching the resonant layer.

The situation is much less complicated for the ordinary mode. As long as the microwave frequency is higher than the plasma frequency, the entire plasma is accessible to the ordinary mode. Figure A.4.11 shows ordinary mode rays for the same equilibrium and injection geometry as shown in Fig. A.4.10. The rays are virtually straight, with slight curvature owing to density gradients. For the EBT-I parameters used, only rays within a narrow cone have more than 1% of the wave energy absorbed in passing through the fundamental cyclotron resonance. Absorption of the ordinary mode at the second harmonic resonance is entirely negligible ($f \leq 10^{-4}$).

Similar calculations have been performed for plasmas having parameters projected for EBT-P: $\omega/2\pi = 60$ GHz, $(\omega_{pe}/\omega)_{\max} = 0.5$, and $v_e/c = 0.1$. These parameters correspond to a peak density of $n_e = 1.1 \times 10^{13}/\text{cm}^3$ and an electron temperature $T_e = 2.5$ keV. The magnetic field was modeled as a bumpy cylinder with a 74-cm coil separation and a coil radius so as to give a 2:1 mirror ratio on axis. The plasma radius was taken as 20 cm in the midplane. Figure A.4.12 shows the result of injecting extraordinary mode rays at varying angles from the midplane and mirror throat.

In this case there is significant absorption ($f \sim 60\%$) at the second harmonic resonance of rays injected near the midplane. The rays injected from the high field side are again completely absorbed. Figure A.4.13 shows the propagation and absorption of ordinary mode energy in EBT-P. At this density and temperature the ordinary mode is heavily absorbed by the core plasma ($f \leq 80\%$). Absorption of the ordinary mode at the second harmonic resonance is again quite small ($f \leq 2\%$).

Qualitative Picture of ECH in EBT

From the cyclotron damping calculations discussed in the previous sections, certain important features of the microwave heating process in EBT can be clearly discerned. The density, temperature, and geometry of the core plasma in EBT-I are such that the direct absorption of the ordinary mode is negligibly weak. Although the extraordinary mode is totally absorbed at the fundamental cyclotron resonance if it can propagate from the high magnetic field side, this resonance is inaccessible to waves propagating from the low field (midplane) side. Heating of the core plasma at the second harmonic resonance, which is accessible, can be neglected for both ordinary and extraordinary modes.

One possibility that has been considered to explain the strong heating of the core plasma experimentally observed in EBT-I is to include finite temperature effects in the calculation of the extraordinary mode cutoff. In a finite temperature treatment, the right-hand cutoff disappears if the density is sufficiently low and the temperature high. Physically this occurs if the resonance is thermally broadened so that large numbers of resonant particles are present at the cold plasma cutoff:

$$\left. \frac{\omega - \Omega_e}{k_{\parallel} v_e} \right|_{\Omega_e \text{ cutoff}} = \frac{1 - \sqrt{\beta_c}}{n_{\parallel} v_e / c} = \frac{\alpha}{n_{\parallel} v_e / c} \sim \frac{\omega_{pe}^2}{\Omega_e^2} \frac{c}{v_e} \lesssim 1. \quad (21)$$

Fig. A.4.11. Ordinary mode propagation in EBT-I. Numbers by rays indicate fraction of power absorbed.

Fig. A.4.12. Extraordinary mode propagation
in EBT-P.

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Fig. A.4.13. Ordinary mode propagation in EBT-P.

In the surface plasma of EBT-I ($n_e \sim 2 \times 10^{11}$, $T_e \sim 20$ eV) this parameter is $\Omega_{pe}^2 c / \Omega_e^2 v_e \sim 6$, and in the core plasma it is ~ 15 . Thus the cutoff is also present in the finite temperature theory even for the surface plasma, where the density is low and the evanescent region is thin.

The thinness of the evanescent layer in the surface plasma (see Fig. A.4.2) suggests that extraordinary mode energy might be absorbed and penetrate to the high field region by means of Budden tunneling.²⁴ This possibility was examined in detail in Ref. 25, where the Budden tunneling transmission and absorption coefficients were extended to allow an arbitrary angle of propagation in a parallel-stratified plasma. For extraordinary mode waves propagating exactly along a linearly increasing magnetic field, the Budden power and absorption and transmission coefficients $|A|^2$ and $|T|^2$ are

$$\begin{aligned} |A|^2 &= e^{-\pi k_0 z_0} (1 - e^{-\pi k_z z_0}) \\ |T|^2 &= e^{-\pi k_0 z_0} \end{aligned} \quad (22)$$

where

$$k_0 = \frac{\omega}{c} = \text{free space wave number,}$$

$$z_0 = \frac{\omega_{pe}^2}{\omega^2} L = \text{width of evanescent region, and}$$

$$L = \text{magnetic field gradient scale length.}$$

Using parameters appropriate for the surface plasma in EBT-I ($n_e \sim 1-2 \times 10^{11}/\text{cm}^3$, $L \cong 6.5$ cm), one obtains absorption and transmission coefficients in the range $|A|^2 \sim 0.02$ to 0.125 and $|T|^2 \cong 0.02$ to 0.15 . Only small deviations from these results are obtained for oblique angles of propagation up to $n_x \sim 0.5$.²⁵ Budden tunneling can, therefore, make some contribution to the flow of extraordinary mode energy to the high magnetic field region and to the heating of the surface plasma.

It appears, however, that the most important mechanism by which extraordinary mode waves reach the high field region in EBT is depolarization of the ordinary mode upon reflection or scattering by a conducting wall surface.²⁶ When, for example, an ordinary mode wave in a magnetized plasma is incident on a perfectly conducting surface in contact with the plasma, a significant amount of power in the reflected wave is in the extraordinary mode depending on plasma density, magnetic field, and angle of incidence.

The wave depolarization situation diagrammed in Fig. A.4.14 has been investigated in detail.²⁶ A perfectly conducting surface is in the x-y plane, and a uniform magnetic field B is in the x-z plane making angle ψ with respect to the z axis. An incident wave of pure characteristic mode (for example, ordinary mode) is incident from above with refractive index n^0 where n_x, n_y are specified and n_z^0 is determined from the Booker quartic equation.²⁴ For the reflected ordinary wave, n_x, n_y are conserved but $n_z = n_z^0$ is, in general, different from n_z^0 of the incident wave, and the electric field eigenvector $\underline{E}^0$ is different from the electric field of the incident ordinary mode wave $\underline{E}^0$. In order to enforce the boundary condition that the transverse component of the electric field vanish at the surface, it is necessary that a component of extraordinary mode $\underline{E}^{X'}$ be included in the reflected wave:

Fig. A.4.14. Geometry for wave depolarization upon wall reflection.

$$(\underline{E}^0 + c_{00}\underline{E}^0 + c_{0X}\underline{E}^{X'}) \times \hat{z} = 0. \quad (23)$$

A similar constraint holds if the incident wave is purely extraordinary:

$$(\underline{E}^X + c_{X0}\underline{E}^0 + c_{XX}\underline{E}^{X'}) \times \hat{z} = 0. \quad (24)$$

The conversion of power between modes can be described by a matrix T of the form

$$[T] = \begin{bmatrix} |c_{00}|^2 \frac{s'_0}{s_0} & |c_{0X}|^2 \frac{s'_0}{s_X} \\ |c_{X0}|^2 \frac{s'_X}{s_0} & |c_{XX}|^2 \frac{s'_X}{s_X} \end{bmatrix}, \quad (25)$$

where s_0 , s_X , s'_0 , s'_X are the power fluxes in the z direction for the ordinary and extraordinary mode incident and reflected wave eigenvectors,

$$\underline{s} = \frac{1}{8\pi} \text{Re}(\underline{E} \times (\underline{n} \times \underline{E}^*)) . \quad (26)$$

The matrix T is symmetric by virtue of a reciprocity relation.

It was found that for plasma parameters characteristic of the surface plasma in EBT-I, a fraction approaching 1.0 of the energy in an incident wave can be mode-converted at certain angles. Figure A.4.15 shows T_{0X} (fraction of incident ordinary mode energy converted to extraordinary mode) as a function of the polar angles of incidence $\phi = \tan^{-1}(n_y/n_x)$, $\theta = \tan^{-1}(n_z/\sqrt{n_x^2+n_y^2})$ for the case $\alpha = 0.05$, $\beta = 2.0$, $\psi = 90^\circ$. These parameters would be appropriate near the mirror throat of EBT-I. Because the ordinary mode is so weakly damped in EBT-I, we may assume that the ordinary mode energy makes several wall bounces and the incident flux is nearly isotropic with respect to angle of arrival. If the mode conversion coefficient shown in Fig. A.4.15 is averaged over a uniform, uncorrelated distribution of incident waves, one obtains $\langle T_{0X} \rangle = 0.403$ for the average fraction of ordinary mode power converted to extraordinary mode. Values of $\langle T_{0X} \rangle$ ranging from ~ 0.1 to ~ 0.5 are found throughout the α, β range to be expected in the high field part of the surface plasma. It should also be mentioned that this wall reflection process gives the minimum rate of mode conversion. Plasma inhomogeneities and turbulent fluctuations, particularly in the low density regions where n^0 and n^X are nearly equal, will cause additional coupling between modes within the plasma. The extraordinary mode energy born in the high field region is rapidly absorbed upon propagating to the cyclotron resonance. Calculations of gross energy balance performed in Ref. 26 indicate that this process — propagation of ordinary mode to the high field region, conversion to extraordinary mode, and absorption of the extraordinary mode at the cyclotron resonance — is the dominant mechanism for heating of the core plasma in EBT-I. This view is supported by the experimental observation that the reflected power is lower and the plasma parameters are better when the dominant mode waveguides used to inject the microwaves are oriented so that the wave electric field is parallel to the magnetic field (ordinary mode) rather than perpendicular to it (extraordinary mode).

A simple model for microwave power balance in EBT devices has been developed along the ideas discussed above.²⁶ The plasma is assumed to consist of three components: core plasma, low density

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Fig. A.4.15. Power conversion coefficient T_{0X} from ordinary to extraordinary mode vs angle of incidence. The plasma parameters are characteristic of the mirror throat region of EBT-I. $\langle T_{0X} \rangle = 0.403$.

surface plasma, and annulus. For consideration of microwave propagation, the interior is divided into two regions: region I, lying outside the extraordinary mode cutoff, and region II, which includes the remainder of the volume (Fig. A.4.16). For any region V bounded by surface S, energy conservation for the j^{th} mode can be written

$$P_j - A_j - \sum_k T_{jk} + \sum_k T_{kj} = 0, \quad (27)$$

where

$$P_j = \int_S d\vec{\omega} \cdot \vec{S}^j = \text{net } j^{\text{th}} \text{ mode power flowing into } V,$$

$$A_j = \int_V d^3x \int d^3k \vec{E}_j(\underline{x}, \underline{k}) \cdot \vec{\sigma}^H(\underline{x}, \underline{k}) \cdot \vec{E}_j(\underline{x}, \underline{k}) = \text{power dissipated from } j^{\text{th}} \text{ mode throughout } V,$$

$$T_{jk} = \int_{S_\omega} d\vec{\omega} \cdot \int_{\underline{k}_{\text{incident}}} r_{jk}(\underline{k}, \underline{x}) \vec{S}^j(\underline{x}, \underline{k}) = \text{power in } j^{\text{th}} \text{ mode converted to } k^{\text{th}} \text{ mode at conversion surface } S_\omega,$$

$$\vec{S}^j(\underline{k}) = \text{Poynting flux},$$

$$\vec{\sigma}^H = \text{Hermitian part of plasma conductivity tensor, and}$$

$$r_{jk} = \text{mode conversion coefficient.}$$

In order to proceed, highly simplified models are adopted for the wave absorption and mode conversion processes. Since each ray undergoes a number of reflections on the average before being absorbed, we assume that the microwave field consists of an isotropic superposition of propagating waves and that the wave energy density in each mode is uniform throughout a given region. With this simplification, the dissipation terms can be modeled just as the product of a decay rate and the constant energy density; for example,

$$A_X^I = \alpha_X^I W_X^I = \text{extraordinary mode power dissipated in region I}, \quad (28)$$

where W_X^I = extraordinary mode energy density in region I and α_X^I = decay rate. In our calculations, we assumed that any extraordinary mode power approaching resonance from the high field side (region II) is totally absorbed. Since this is the only dissipation mechanism for extraordinary mode in region II, the decay rate is just $\alpha_X^{II} = c/2 S_R$, where S_R is the area of the cyclotron resonant surface (see Fig. A.4.16), and the group velocity of the waves is taken as $v_g = c$. For EBT-I, absorption of the ordinary mode in region II is negligible ($\alpha_0^{II} = 0$).

In EBT-I the only dissipation mechanism in region I is absorption by the annulus. Unfortunately, we do not as yet have a reliable independent model for the annulus decay rate. Therefore, we have regarded α_X^I and α_0^I as unknowns to be determined by the requirement that $P_{\text{annulus}} = \alpha_X^I W_X^I + \alpha_0^I W_0^I$ be equal to 25% to 30% of the total injected power as indicated by experimental observations of annulus lifetime.

Simple models have also been devised for the mode conversion rates. Since the Poynting flux can be expressed $\vec{S}^j = w_j \vec{v}_g = \text{constant}$, where $\vec{v}_g$ is the group velocity, the mode conversion terms can be averaged over angle of incidence and over the conversion surface to give, for example,

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Fig. A.4.16. Cross section of a sector of EBT-I showing the three plasma components (core, surface, annulus) and the two microwave propagation regions (I and II) defined in the power balance model. S_{R-core} and $S_{r-surface}$ are the surface areas of the fundamental cyclotron resonance zone lying in the core and surface plasma components respectively.

$$T_{jk} = t_{jk} W_j, \quad (29)$$

where t_{jk} is an average conversion coefficient. To model conversion of extraordinary mode to ordinary mode owing to wall reflection in region I, we assume a constant (in space) isotropic flux of incident extraordinary mode energy $S_x^I(\hat{r}) = c W_x^I \hat{r}$, where we have taken $v_g = c \hat{r}$. Averaging over angle and over the wall surface of region I gives

$$T_{x0}^I = c W_x^I \int_{S_{\text{wall}}^I} d\Omega \hat{n} \cdot \hat{r}_{x0}(\hat{x}, \hat{r}) \equiv \beta^I W_x^I. \quad (30)$$

For our calculations we have assumed $\beta^I = c r_{0x} S_I$, where r_{0x} is a constant $r_{0x} \leq 0.5$ and S_I = surface area of the wall in region I.

In this way we obtain equations for the ordinary and extraordinary mode power densities in each of the two regions. For example the equation for extraordinary mode energy density in region I can be written

$$P_x - \alpha_x^I W_x^I - \beta^I W_x^I + \beta^I W_0^I - (\gamma_A + \gamma_T) W_x^I = 0, \quad (31)$$

where

P_x = extraordinary mode power injected from waveguide,

W_x^I = extraordinary mode energy density in region I,

W_0^I = ordinary mode energy density in region I,

$\alpha_x^I W_x^I$ = extraordinary mode power absorbed in region I (i.e., annulus absorption in EBT-I),

$\beta^I W_x^I$ = extraordinary mode power converted to ordinary mode,

$\beta^I W_0^I$ = ordinary mode power converted to extraordinary mode,

$\gamma_A W_x^I$ = extraordinary mode power absorbed by Budden tunnelling,

$\gamma_T W_x^I$ = extraordinary mode power transmitted to region II by Budden tunnelling.

This model has been used to estimate the stored energy densities in the different modes to evaluate the sensitivity of core heating to Budden tunnelling, ratio of injected ordinary to extraordinary mode power and the like. The results can be summarized as follows. Extraordinary mode energy injected at the midplane is partially absorbed by the annulus and partially depolarized into ordinary mode upon wall reflection. Budden tunnelling has a comparatively small effect on the overall power deposition. In EBT-I the only microwave power sink other than absorption by the annulus is absorption of the extraordinary mode from region II at the fundamental cyclotron resonance. Because the production of extraordinary mode energy in the high field region is such an indirect process, it is quite difficult to calculate the radial distribution of extraordinary mode energy into the fundamental resonance. However,

if one makes the reasonable assumption that this power flux is uniform across the resonance surface, then the power deposited in the core is $P_{\text{core}} = c/2 S_{\text{R-core}} W_x^{\text{II}}$, whereas the power deposited directly in the surface plasma is $P_{\text{surface}} = c/2 S_{\text{R-surface}} W_x^{\text{II}}$. Here, $S_{\text{R-core}}$ is the area of the fundamental resonance lying in the core plasma, $S_{\text{R-surface}}$ is the area of the fundamental resonance lying in the surface plasma, and $S_{\text{R-surface}} + S_{\text{R-core}} = S_{\text{R}}$. Geometrical estimates of the respective areas give $P_{\text{core}}/P_{\text{surface}} \cong 2.6$. Assuming that 25% of the total injected power P_{TOT} is deposited in the annulus, the partitioning of power is

$$P_{\text{annulus}} = 0.25 P_{\text{TOT}}, \quad P_{\text{core}} = 0.21 P_{\text{TOT}}, \quad P_{\text{surface}} = 0.54 P_{\text{TOT}}. \quad (32)$$

The results presented in the previous sections also have important implications for future EBT devices, such as EBT-II. In hotter, denser devices the ordinary mode can do significant heating (Figs. A.4.7b and A.4.13). This is advantageous because the dense plasma center is preferentially heated by the ordinary mode in contrast to the extraordinary mode which, when propagating from the high field side, is efficiently absorbed even in the cold, surface plasma. It is clear from Figs. A.4.9c, A.4.9d, and A.4.12 that the extraordinary mode will be heavily absorbed by the toroidal core plasma at the second harmonic resonance. The associated heating at the plasma edge may have deleterious effects on energy transport and impurity behavior. In addition, the effects which the presence of a hot, dissipative plasma at the second harmonic resonance will have on the formation and maintenance of the annulus are not at all understood.

MICROWAVE HEATING TECHNOLOGY

The Microwave Development and Technology Program is an outgrowth of support activities conducted for many years as an integral part of the ORNL High Beta Plasma Program. Its broad purpose is to develop microwave and millimeter wave methods, techniques, components, and systems for plasma heating relevant to the controlled fusion effort. Emphasis upon the development of high power, high frequency (short wavelength) systems is thus implicit. The continuation of this program in close collaboration with the EBT effort is considered essential because of the inherent "applied" nature of technology programs and the resulting aspects of mutual dependence.

Significant past accomplishments of the Microwave Development and Technology Program are exemplified by the microwave power systems presently used on EBT. These systems demonstrate (1) the practicality of the assembly, management, and control of large microwave power sources employing multiple plasma device inputs with both conventional and oversized waveguide transmission lines; (2) the efficient coupling and matching of these transmission lines to the plasma device; (3) compatible design criteria for the utilization of large power microwave inputs in plasma devices; (4) the advance in the state of the art of conventional microwave tubes; and (5) control and monitoring systems integrated into the experimental facility to provide for operational simplicity and flexibility, equipment safety, and personnel safety. Therefore, these systems model the areas of effort required in the comprehensive future program.

By 1984 the millimeter wave power requirements for EBT-P are expected to be of the order of a megawatt at a frequency of 60 GHz. This frequency corresponds to electron cyclotron resonance of approximately 21 kG and is consistent with existing superconducting magnet development.

High power microwave systems for EBT-P are composed of three basic elements:

1. a multiple array of active devices for conversion of dc power;
2. microwave transmission networks for efficient transfer and coupling of energy to the fusion device;
3. supporting electrical and electronic subsystems for overall system control and monitoring, operation of active devices, and safety.

For realization of multimegawatt capability at 60 GHz, an intensive complementary development effort is required in each of these categories. The key element is the development of active devices, whereas the microwave transmission networks and supporting subsystems involve the characteristics of both the active devices and the plasma confinement experiment. Also, the gyrotron development has been identified as the key pacing item in determining the earliest possible operation of EBT-P.

Development of Microwave Active Devices

Multimegawatt, continuous wave (cw) electron cyclotron heating (ECH) systems operating at 60 GHz are required by the EBT-P program and by subsequent programs. Clearly, this power generation capability is beyond the present state of the art for microwave linear beam tubes. Hence, an intensive development program has been undertaken through subcontract with private industry. This development effort began in 1974 when Varian Associates was commissioned by means of an ORNL subcontract to perform a study to determine the best approach for realization of a microwave power device capable of producing 200 kW of cw power at millimeter wavelengths. This study identified the gyrotron, a form of cyclotron resonance maser, as the most promising device for development of this objective. Then in April 1976 ORNL initiated a subcontract with Varian for the development of a 200-kW, cw 28-GHz device for use in EBT-S. A further stipulation in the subcontract was that the device be scalable to 120 GHz. Progress to date on this program has been significant. In May 1978 a gyrotron was operated at 105 kW of cw power, and in September 1978 a 28-GHz gyrotron was operated into the EBT-S device at the 50-kW level with encouraging plasma physics results. At this time it is expected that the 28-GHz, 200-kW, cw development program will be successfully completed by September 1980. Although several challenging design problems remain in this development program, the progress made to date in the 28-GHz program indicates that the gyrotron is the correct choice for this application at higher frequencies.

In view of the encouraging results from the 28-GHz development program and the anticipated need for higher frequency devices at the earliest possible date for EBT-P operation, ORNL awarded two industry subcontracts in mid-1979. Successful completion of these development contracts is expected by 1983. Both subcontractors will pursue the gyrotron as the device most likely to achieve the goal of 200 kW of cw power at 60 GHz.

The required characteristics of these gyrotrons, namely, that each gyrotron produce about 200 kW of cw power at millimeter wavelengths, result from the unique plasma heating application for EBT-P. This high power level requires good tube efficiency to keep power supply costs reasonable. The gyrotron realizes high efficiency and high power by (1) having an interaction region many wavelengths long, (2) utilizing the entire electron beam cross section in the interaction region, and (3) keeping the microwave power dissipated in the interaction region low by use of circular electric cavity modes.

The theoretical basis for operation of the gyrotron, or electron cyclotron maser, is well known. This device employs a cloud of monoenergetic electrons in a fast-wave structure. Electron velocity is primarily transverse to the applied axial magnetic field. Phase bunching of the electrons occurs because of the relativistic mass change of the electrons. As these phase-bunched electrons radiate coherently, energy is transferred to the electromagnetic wave. To date, applications of these principles have been limited by the technologies and design detail necessary to incorporate the theory into useful devices. Key elements of the gyrotron include the electron gun, interaction cavity, collector and output system, window, and magnet system. All of these design issues are being addressed by the subcontract developers.

Auxiliary Systems

The gyrotron power supply, control systems, and instrumentation currently in operation on EBT-S are considered prototypical for the EBT-P gyrotron system. Gyrotron power supplies are the major item determining ECH system costs. The operation of multiple gyrotrons on EBT-P will require an extension of this effort in terms of control, suitable operation for the application, overall performance, reliability, and economics. Specifically, it is expected that the operating parameters of these gyrotrons will not be identical and will thus require a sophisticated supervisory control system for uniform output control as well as careful monitoring for abnormal conditions. In addition, there is the possibility of locking and/or beating problems associated with oscillator operation. These problems are being addressed in the EBT-P design, and it is expected that multiple gyrotron operation will be demonstrated on EBT-S.

It is unlikely that precise gyrotron power supply requirements will be defined in sufficient time to permit tailored power supplies in initial EBT-P operation, which implies a need for highly flexible power supply systems. The greatest flexibility is expected to result from operation of a single tube per power supply, and this is the recommended approach for initial operation. Any cost savings that may result from multitube operation from a single supply will be applied to ECH system upgrades as the gyrotrons are refined and operating experience is gained.

Components and Transmission

As a direct consequence of using a circular electric cavity mode in the interaction region, the axisymmetric gyrotron produces most of its output power in a few TE_{0n}^0 circular electric waveguide modes. Although these modes have the advantages of very low transmission losses and superior power handling capability compared to most other waveguide modes, they suffer from the fact that they are not the modes with the lowest cutoff frequency; therefore, they must always be used in a waveguide capable of propagating a number of modes. To achieve the very low transmission losses and high power-handling capability, the operating frequency must be well above cutoff so that many more modes are in the propagating range.

The practical problems raised by the multimode character are several. First, one must prevent spurious modes from being excited in the waveguide system by irregularities. Spurious mode conversion is caused by either mechanical or electrical imperfections in the waveguide, such as cross-section distortion, surface roughness, departure from axial straightness, and changes in surface conductivity. Once excited, these modes may become cut off somewhere else in the system at other irregularities. These spurious modes can then become trapped between irregularities, and at a particular frequency one of the spurious modes can absorb a large fraction of power from the main mode, causing localized waveguide heating or even breakdown. This situation can be prevented in three ways. The first is to avoid exciting the spurious modes by carefully controlling the waveguide shape. Second, if spurious mode excitation cannot be avoided, as in the case of a waveguide bend, then loss must be provided for the trapped (spurious) modes by the use of mode filters; this reduces the stored energy (Q) of these modes. Thirdly, if higher order mode power is useful for plasma heating, then any spurious modes, once excited, are allowed to propagate toward the load, thus avoiding trapping.

In the past, mode filters consisting of waveguide sections of lossy material such as stainless steel have proved to be reliable high power mode filters. They work on the principle that the lower order circular electric modes (TE_{01}^0 , TE_{02}^0 , TE_{03}^0) have lower losses than most other modes in the system; thus, if a certain amount of loss for the circular electric modes can be tolerated, then the other spurious modes will have even higher fractional power losses in the stainless steel waveguide.

To achieve higher spurious mode losses relative to the circular electric modes, a mode filter consisting of alternating rings of conducting and lossy material sandwiched together in a waveguide section can be utilized. This filter has very low loss for the circular electric modes because the modes produce only circumferential wall currents that travel around the conducting rings. The wall currents of all other modes, however, have axial components that suffer attenuation through the lossy rings. To handle the high average power, these lossy rings must be cooled and made of high temperature material, such as ceramic loaded with carbon.

An abrupt quasi-optical bend for the waveguide system consists of two circular waveguides intersecting at 90° with a reflecting, elliptical miter surface at 45° to both waveguides. Such a bend is referred to as a miter bend and to a first approximation behaves as an optical mirror if the waveguide diameter is much greater than a wavelength. Some mode conversion will invariably be present; therefore, mode filters will be required on either side of the bend to absorb spurious modes.

One of the most important measurements in the microwave heating system is the forward and reflected power measured by directional couplers. Two general types of couplers can be used in the oversized waveguide system. The first is a "cross-guide" directional coupler consisting of two 90° miter bends placed back to back on the mitered plane, forming a waveguide cross with a 45° junction. The 45° junction consists of a metal plate perforated with a large number of very small holes in cutoff at the design frequency. The holes transmit an attenuated sample of the incident mode pattern on the high power side of the plate to the forward power arm on the low power side of the plate. The reflected mode pattern on the high power side is similarly coupled to the low power reflected arm of the coupler. Both low power sampling arms are terminated in matched calorimetric loads for total mode power measurements.

Another approach for forward and reflected power monitoring is a coupled mode transducer consisting of a low power dominant mode waveguide that is phase matched to the desired circular electric mode in the high power oversized waveguide. The coupling between waveguides is achieved by an array of small apertures in cutoff spaced by a one-quarter guide wavelength and tapered in size to preferentially couple to the desired mode pattern in the oversized waveguide.

Microwave-Plasma Coupling

In EBT-S the ECH power feed into the plasma chamber at the cavity midplane undergoes multiple low loss reflections with accompanying changes in polarization and direction. Therefore, the Q of the plasma chamber without the plasma present is very large. However, electron cyclotron resonance surfaces present in the chamber, the extraordinary wave is heavily damped during transit through a resonance region. Because polarization and directional changes accompany successive reflections (resulting in reflected waves comprising both ordinary and extraordinary waves), the total input wave is soon converted to extraordinary waves and is rapidly damped by coupling to the plasma. The resulting loaded Q of the chamber is then very low.

Because the effective loaded Q of the ECH multimode cavity is very low under normal conditions ($\omega > \omega_{pe}$), the impedance presented to the input wave is nearly equal to the impedance of free space. Impedance matching considerations for the design of the coupling aperture are then similar to those for a radiating antenna. The simplest such aperture suitable for high power use is an oversized waveguide terminating flush with the interior wall of the cavity. The complex electromagnetic field patterns associated with higher mode propagation in such multimode transmission lines obviously do not permit the launching of a linearly polarized wave with high purity.

Because of efficient absorption and plasma shielding effects, microwave power fed into one mirror confinement region of EBT-P does not readily propagate into adjacent regions. Accordingly, it has been necessary to provide a discrete ECH input to each of the 36 mirror confinement regions in order to form

and maintain the high beta, hot electron annuli as well as to provide uniform heating of the entire volume. The approach is to feed several mirror confinement regions through a large external reflecting manifold via identical oversized waveguides entering along the minor radius at the midplane of each cavity. No spurious cyclotron resonant regions are involved with this arrangement of entry, and no such regions are likely to interfere with the external reflecting manifold because the magnetic fields everywhere outside the torus are quite small. In this way ECH power fed from the source into the external reflecting manifold via an oversized waveguide is coupled into several regions simultaneously. Some degree of balance between power inputs to individual regions is provided by the large Q of the reflecting manifold and by symmetry in the connections. An additional degree of balance and an increase in overall efficiency result because power reflected from one region is available for absorption in another. Additional control of power distribution may be obtained by the use of irises, or "stops," to limit the power fed to selected regions or to remove it entirely.

Control of the polarization of the input power implies a high degree of mode control of the gyrotron output and the microwave distribution system. While polarization control is highly desirable, it is not essential for initial EBT-P goals. Also, the increased constraints placed upon the gyrotron development program will have an adverse impact upon initial EBT-P operation since the gyrotron is now the key pacing item. Lower overall transmission efficiency of mode controlled microwave distribution systems means increased cost of power delivered to the plasma compared to mixed mode systems. Also, significantly higher costs and technical risks are associated with the development of mode-controlled microwave distribution systems. Therefore, a mixed mode microwave distribution is preferred for initial EBT-P operation; polarization control for later ECH system upgrades remains a possibility.

Access to the high field side of the fundamental resonance zone is highly desirable, and this capability should be available in the initial design. The preference is for entry around the coils in the shadow of the limiter, rather than a warm penetration of dewar and shield between split mirror coils. Good practice dictates that ECH power density in the transmission system and at launch ports be limited to 3-5 kW/cm² for reliable operation.

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APPENDIX 5

ION CYCLOTRON HEATING EXPERIMENTS

INTRODUCTION

Auxiliary ion heating in an EBT device is essential in order to achieve fusion-relevant ion temperatures. Without auxiliary heating, the only source of energy for plasma ions is collisional transfer from electron cyclotron-heated electrons. The rate of collisional ion heating decreases with plasma temperature, and although it increases with density, the plasma density in EBT devices is limited by the ordinary mode microwave cutoff (for EBT-P with $f = 60$ GHz, $n_e(\text{max}) \cong 4 \times 10^{13}/\text{cm}^3$). Experimental results with ion cyclotron heating in other devices, although perhaps not as definitive as with neutral beam injection, are certainly promising. In addition, for the next generations of EBT devices (EBT-S and EBT-P), ion cyclotron resonance heating (ICRH) appears to have a number of advantages over neutral beam injection:

1. The technology of rf power sources in the ion cyclotron range of frequencies is well established so that no additional development program is required and long lead times are not required for procurement.
2. The cost of rf power in this frequency range is low. Realistic estimates of the cost of the entire rf system are \$1.00/W for a total power in the range of hundreds of kilowatts.
3. A rf system can be operated in steady state without difficulty and is not in any way limited by the particle removal speed of the vacuum system.
4. Much of the antenna development and optimization work can be done on EBT-S. In addition, experience with heating strategies, diagnostics, and ECRH/ICRH system compatibility can be obtained on EBT-S using the slow wave.

In view of these considerations we recommend that ICRH be adopted as an auxiliary heating technique in EBT-P and that a vigorous program be carried out on antenna development, preliminary experiments on EBT-S, and theoretical work.

Two types of cold plasma waves propagate in the ion cyclotron range of frequencies: (1) the fast wave (compressional Alfvén wave or magnetosonic wave), which is only weakly cyclotron damped at $\omega = \omega_{ci}$; (2) the slow wave (shear Alfvén wave or ion cyclotron wave), which is resonant and heavily damped at $\omega = \omega_{ci}$. In this appendix, we give a brief overview of the physics involved in the propagation and absorption of these waves, the results of heating experiments on other devices, and the applicability to EBT. We also discuss some considerations of antenna design and placement, and we outline the requirements for an ICRH system for EBT-P.

FAST WAVE

Most recent experimental and theoretical work has concentrated on the fast, or magnetosonic, wave,¹ including successful heating experiments on ST,² TFR,³ ATC,⁴ and PLT,⁵ all tokamaks.

In a vacuum cavity the fast wave corresponds to the TE mode, with transverse electric fields and a wave magnetic field along the axis. The dispersion relation is

$$N = c/V_A(1 + \cos^2 \theta)^{1/2}, \quad (1)$$

where $N = kc/\omega$ is the index of refraction, V_A is the Alfvén velocity with $c/V_A = f_{pi}/f_{ci}$, and θ is the angle between the wave vector and the static magnetic field.¹ This dispersion relation is valid over

the entire frequency range of interest. Because the wavelength increases as the density decreases ($\lambda \cong c f_{ci} / f f_{pi}$), in a cavity of fixed size there exists a minimum density below which the fast wave cannot be excited. The following table shows the index of refraction and wavelength for the range of densities expected in EBT-P. The frequency is taken to be $f = 33$ MHz (the proton cyclotron frequency for $B = 21.4$ kG), and the angle of propagation is $\theta = 90^\circ$.

Density (cm^{-3})	N_1	$\lambda(\text{cm})$	$2\pi r_p / \lambda$
5×10^{12}	14.4	63.1	1.9
1×10^{13}	20.3	44.8	2.7
2.5×10^{13}	32.1	28.3	4.2

Here the plasma radius for EBT-P is taken to be $r_p = 19$ cm; the expected densities are large enough for excitation of the lower cavity modes. In a cylindrical cavity the modes have the form $B_z \sim J_m(k_\perp r) e^{im\theta + in\phi - i\omega t}$, where we have approximated a torus of major radius R by introducing a toroidal mode number $n = k_z R$ (k_z is the wave vector in the axial direction). In this case the criterion for the existence of cavity modes¹ is

$$J'_m(k_\perp r_p) = J'_m(2\pi r_p / \lambda) = 0. \quad (2)$$

The first few roots of J'_0 are 3.83, 7.02, and 10.2, the roots of J'_1 are 1.84, 5.33, 8.54, One sees that the $m = \pm 1$ mode is the only one which will propagate at the lowest density, but at higher densities several modes are possible. This, of course, neglects such features as the toroidal curvature, the segmentation of the cavity, and the magnetic field variation. By including a vacuum layer near the wall, one finds that this rough criterion is modified somewhat,^{1,6} but the conclusion is the same: the excitation of the fast wave depends critically upon the density. However, the use of He^4 as the majority species with hydrogen as a minority species would increase N by a factor of 1.4 for the same electron density.

Because the electric field of the fast wave is polarized such that it does not effectively accelerate ions, its damping at cyclotron resonance is weak. With the local magnetic field in the z direction, the electric field combination that accelerates ions is $E^+ = E_x + iE_y$ (left-circular polarization). However, because the perpendicular dielectric constant is singular at $\omega = \omega_{ci}$, this component vanishes at resonance.¹ The fast mode does exhibit weak absorption in a single ion species plasma at the fundamental of the ion cyclotron frequency because of the Doppler shift of ions streaming along field lines, $\Delta\omega = k_\parallel v_\parallel \cong k_\parallel \sqrt{T/M}$. The theoretical heating rate is similar in form to the rate calculated for electrons and is proportional to $LT/\lambda MC^2$, where $L = B/|\nabla B|$ and λ is the free space wavelength. The long wavelength and large ion mass make the heating rate small. The spatial width of the resonance is $\Delta = n\lambda\sqrt{T/MC^2} L/R$, where n is the toroidal mode number. For $f = 33$ MHz, $T = 100$ eV, and $n = 1$, one finds that $\Delta = 3$ mm. There is, however, little experimental evidence for fast wave heating at the ion cyclotron frequency with a single species plasma.

Heating at the second ion gyroharmonic is also small, although the electric field rotating with the ions is larger. The heating is a finite cyclotron radius effect and is proportional to $k_\perp^2 T / M \omega_c^2 = N_1^2 T / MC^2$.

Ion Mixtures and the Ion-Ion Hybrid Resonance

If two ion species are present, the absorption of the fast mode is considerably modified. When the plasma has two ion species, a plasma hybrid resonance occurs between the two cyclotron frequencies. For fixed $N_{\parallel}$, the perpendicular index of refraction is singular for a cold plasma, just as it is for the lower hybrid and upper hybrid resonances. Although heating at this resonance was first reported for the TFR³ experiment, it probably occurred in earlier experiments in which small amounts of other gases were always present.

At the hybrid resonance, the component of the electric field perpendicular to the resonant surface becomes very large, but the parallel components do not. The electric field has equal amounts of the components E^{+} and E^{-} and is far more effective for accelerating ions. In addition, the large field amplitude opens the possibility of various nonlinear heating mechanisms.⁴

The presence of two plasma components also tends to modify the linear absorption at the fundamental cyclotron resonance. If the plasma consists of a heavy majority species (such as D^{+} or He^{3}) as well as a light impurity species (such as H^{+}), the wave polarization is largely determined by the majority so that the left-circular-polarized electric field component remains finite at the fundamental cyclotron frequency of the minority species. In this case, heating of the minority species is considerably enhanced.

Recent experiments on PLT⁵ with hydrogen as a minority species in a background of deuterium have shown strong minority heating with some electron heating. The coincidence of the second cyclotron harmonic of deuterium with the fundamental of hydrogen is apparently not important. A minority hydrogen plasma in a background of He^{3} is also strongly heated. This heating seems to be the result of cyclotron damping, the simplest of the heating mechanisms. The quasi-linear theory of Stix⁷ has been applied to explain the experiment and seems to fit fairly well.

Toroidal Eigenmodes

As a consequence of the weak damping of the fast mode in a single species plasma, it is possible to excite and identify high-Q toroidal eigenmodes. By properly selecting the modes, it may be possible to peak the wave fields in the center of the device, thereby tailoring the heating profile. Toroidal modes have been seen in the ST² and PLT⁵ tokamaks but were not nearly so prominent in ATC⁴ and TFR.³ The probable reason is that the ion-ion hybrid resonance in these tokamaks was present with damping sufficient to wash out the toroidal eigenmodes.

Conclusions

The plasma density in EBT-S is not anticipated to be high enough to permit fast-mode heating, whereas in EBT-P the fast mode should propagate. The technique of heating a minority hydrogen species in a deuterium plasma that has been employed successfully in tokamaks appears possible in EBT-P. However, the cyclotron heating of a moderate fraction of hydrogen in a helium plasma in EBT-P is an attractive possibility.

In addition to the technological and experimental questions to be solved, there are several areas where theoretical work is necessary to assess the potential of fast-wave heating in EBT-P. Calculations should be done to predict the structure of toroidal modes in a segmented cavity with a strong variation in the magnetic field. The quasi-linear calculation of Stix⁷ should be extended to include the mirror field geometry. Also, for finite ion temperature (and a large minority species fraction), a linear turning point occurs on the low magnetic field side of the ion-ion resonance. Linear conversion to hot plasma modes occurs with both ion and electron damping.⁸ At this time the importance of these processes is not understood.

THE SLOW WAVE

The slow wave is essentially a shear Alfvén wave at low frequencies that changes into an ion cyclotron wave near the cyclotron frequency. The dispersion relation for a single species cold plasma is¹

$$N_{\parallel}^2 = N^2 \cos^2 \theta = \frac{c^2}{c_A^2} (1 + \cos^2 \theta) \frac{\omega_{ci}^2}{\omega_{ci}^2 - \omega^2}. \quad (3)$$

In contrast to the fast wave, the slow wave has not received much attention recently. It was used more than ten years ago for early experiments on the B-65 stellarator⁹ and the B-66 mirror.¹⁰ This is the mode for which the concept of ion heating by waves breaking on a magnetic beach was developed.

The slow wave propagates at frequencies below the ion cyclotron frequency and is cut off at higher frequencies. In geometry such as that of EBT, where the magnetic field strength varies along the field lines, the wave propagates on the high field side of resonance (i.e., near the mirror coils) and is cut off on the low field side (i.e., near the midplane). As a slow-mode wave approaches the cyclotron resonant surface from the high field side, $N_{\parallel}$ becomes very large, the group velocity turns parallel to the resonant surface, and the wave is strongly damped. The polarization is given by¹

$$E_x/E_y = 1 \frac{\omega_{ci}}{\omega} (1 + k_{\perp}^2/k_{\parallel}^2). \quad (4)$$

Therefore, the wave is predominantly left-circular polarized.

Because the refractive index of the slow mode is quite large ($N_{\parallel}^2 \sim c^2/V_A^2 = m_i/m_e \omega_e^2/\omega_{pe}^2$), a high density is not required to "fit" the waves into the EBT cavity. Indeed, the slow mode should be usable on EBT-S as well as on EBT-P.

The boundary conditions for the wave fields can easily be satisfied for short parallel wavelengths (large $N_{\parallel}$). Several techniques exist for exciting waves with large $N_{\parallel}$, for example the use of Stix coils as antennas. Although the slow wave is evanescent in the low field region, in one relevant experiment the slow wave has been launched near the edge of a plasma column in a region of low magnetic field. Coupling to the high field region probably occurred in the boundary layer between the plasma and the wall.¹¹ For EBT-P, it is difficult to put an antenna in the mirror throat. It may be possible to launch the slow wave with two coils in the midplane of adjacent cavities, adjusting $N_{\parallel}$ by varying the phase of the two coils. This possibility can be tested on EBT-S.

Because of the strong damping, slow-wave toroidal eigenmodes do not exist, and one can expect appreciable ion heating even with weak coupling between the antenna and the region where the slow wave can propagate. Because of strong field gradients and relatively low density, the slow wave can be more efficient than the fast wave for EBT-P.

Multiple Ion Species

With two ion species the cold plasma dispersion relation is

$$N^2 = 1 - \frac{\omega_{pe}^2}{\omega \omega_{ce}} - \frac{\omega_{p1}^2}{\omega(\omega - \omega_{c1})} - \frac{\omega_{p2}^2}{\omega(\omega - \omega_{c2})}, \quad (5)$$

where the subscripts 1 and 2 refer to the two ion species.

This dispersion relation is plotted in Fig. A.5.1 for varying magnetic field and constant frequency $f = 60$ GHz. The electron density is $1.3 \times 10^{13} \text{ cm}^{-3}$, and the two species are H and He^4 in equal concentration. Cyclotron resonance occurs at $B = 40$ kG for hydrogen and at 80 kG for doubly ionized helium. The cutoff region extends over the entire center portion of the plasma. Two antennas in phase with a spacing of 30 cm would excite waves with $N_{||} = 17$ by coupling to the plasma on the surface where $B = 43$ kG.

The second cutoff at $B = 48$ kG is caused by the admixture of helium. The region where the slow mode can propagate becomes narrower with increasing helium concentration. As a consequence, the contribution of the slow wave to ion heating is expected to be negligible when attempting fundamental resonant heating of a large fraction of a minority species.

Conclusion

The slow wave should be very important for heating EBT-P, with its revised specifications. The propagation of this wave and its efficiency for ion heating should be carefully studied as an alternative to fast-wave heating, because the density of the plasma is relatively low and the large variation in magnetic field is well suited for damping on a magnetic beach.

ANTENNAS

Oscillators in this frequency range are readily available and relatively inexpensive. They may be located some tens of meters away from the machine, with the rf power carried in coaxial cables. A matching network is required for each antenna for a radiation resistance of the order $R \sim 0.1\text{--}0.5 \Omega$ and an inductive reactance $X_L \sim 100\text{--}200 \Omega$.

The fast-wave antennas currently used in tokamaks should be readily adaptable for use in EBT. Because the fast-wave antennas need not be located in the high field region, a simple water-cooled half-turn loop, located close to the wall at a cavity midplane, may suffice. There are a number of design problems associated with the antenna feedthrough insulators. First, the insulators must be shielded from direct exposure to plasma ultraviolet radiation. Second, careful placement will be required so that a cyclotron resonant surface of the 110-GHz microwave power does not come in contact with the insulator material. Finally, leakage of microwave power through the insulator must be prevented either by a microwave choke structure or by a jacket of deionized water. Although Faraday shields may be necessary, bare antennas should be carefully considered because they are easier to fabricate and much less vulnerable to the plasma environment.

In tokamaks these antennas are sometimes used in pairs, with a pair located in the same plane or spaced along the toroidal axis. For EBT-P a pair of antennas in adjacent cavities will provide some control on the spectrum in $N_{||}$. The half-turn loop will launch a wide spectrum of azimuthal modes.

The broad-band antennas for the fast wave may radiate useful amounts of the slow wave in EBT-P, with a strong magnetic field variation and relatively low density. To preferably excite the slow wave, a pair of single-loop antennas may be located in either end of a single cavity, where the magnetic field is large. It is probably not desirable to locate the antennas in the mirror throat but in a location where the metallic wall would shield the antenna from direct exposure to the hot plasma. It seems desirable to use a phased pair of single conductors rather than a Stix coil because extremely high $N_{||}$ is not required. These coils can encircle the plasma because the azimuthal mode number is not critical.

It is very important that antennas be fabricated and tested on EBT-I/S before the final design for EBT-P. More experimental information is critically needed, particularly data on the mode structure and

Fig. A.5.1. A plot of the dispersion relation for a varying magnetic field at a frequency of $f = 60 \text{ GHz}$.

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heating mechanisms with relatively low density plasma. This testing can be done at low power levels, with relatively simple antenna structures and arrays of rf probes.

IRCH SYSTEM SPECIFICATIONS

The IRCH system for EBT-P will evolve from the results of preliminary fast-wave experiments performed on EBT-P and from experiments on slow-wave heating on EBT-S. Initial experiments will be aimed at determining the optimum ICRH scheme and antenna design for plasma ion heating. One constraint regarding fast-wave minority species heating is that deuterium may not be usable in EBT-P. Because the technology of rf generation is well developed, lead times for procurement of the high power supplies are relatively short; therefore, the actual specification of power can await the initial results of heating efficiency measurements. By consensus, 100-200 kW of ICRH power in the plasma is reasonable during the early stages of the experiment.

Initial experiments on slow-wave heating in a hydrogen plasma will be modeled after similar experiments on EBT-S. Access to the high field region is very limited, but antennas could be placed next to the mirror coil dewar. If experiments on EBT-S show that the slow wave can be launched efficiently in the low field region, then antennas can be placed in the center of cavity sections, where access is plentiful. Should the amount of power coupled to the plasma from one antenna be limited, up to 36 antennas (one per sector) could be used.

Fast-wave minority species heating experiments in a helium plasma with a minority concentration of hydrogen will be considered. Because of the higher density of EBT-P, several toroidal eigenmodes will fit in the machine whereas on EBT-S definitive fast-wave experiments are not possible.

The ICRH control system must be capable of dynamic feedback control because ICRH, ECH, and neutral beam systems may be operated simultaneously in a steady state. In particular, the interplay between ECH and ICRH systems is important. The ECH system will be used for plasma startup, and as the plasma density builds up, the ICRH system can be turned up. As the ion density and confinement time become longer, the ECH system may be turned down or adjusted so as to maintain only the hot electron ring. The relative amounts of the two types of heating will allow control of the plasma potential and, thus, of plasma confinement. Neutral beams and pellets may be used for fueling of the plasma in later phases of the EBT-P program; therefore, the ICRH system should be capable of fairly fast time response in order to maintain a steady-state equilibrium. Neutral beams may also be used for heating ions, so some combination of ICRH minority species heating and neutral beam majority species heating may be used on gas mixtures.

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Appendix 6

TAKEN FROM THE EBASCO EBT-P PROJECT DEFINITION STUDY*

MOLECULAR ION INJECTION

Energetic molecular ion injection into an EBT plasma is an attractive technique for controlling the ambipolar potential and for heating the plasma ions and electrons provided the injected molecular ions remain inside the plasma for times exceeding the mean time for dissociative ionization by electron impact:

Computational studies of single particle trajectories in EBT-P encompassing a wide range of injection energies and angles have identified suitable orbits for D_2^+ ions in the energy range around 180 keV. The 90-keV deuterons resulting from the dissociative ionization are well-confined in EBT-P and have long lifetimes against charge exchange. The net positive charge introduced by D_2^+ injection will, therefore, partially neutralize the negative space charge characteristic of EBT-I/S operation. And since the technology for producing high-power D_2^+ beams in this energy range and at moderate cost is well-established, this approach has been adopted as a principal element of the auxiliary heating stage of the EBT-P research program.

We show the major results of this single particle orbit calculations in this Appendix. Very favorable orbits have been found for which the path length in the plasma region can be many times the mean free path for dissociative ionization. Thus, the trapping efficiency is expected to be very high. Moreover, as shown by these calculations, such orbits can be obtained over a wide enough range of injection angles to significantly relax the restrictions on acceptable beam divergence.

The efficiency with which the trapped power is absorbed by the plasma ions and electrons depends mainly on the rates at which the deuterons slow down on electrons and ions relative to the rate at which they are lost by charge exchange. These rates have been evaluated numerically and are discussed later in this Appendix. For the neutral atom densities predicted for EBT-P operation, a significant fraction of the injected power is deposited directly in plasma ions.

In addition to auxiliary heating, and of potentially greater importance to the EBT-P research program, the molecular-ion injection technique results in a significant deposition of the positive charge in the plasma, providing a mechanism for modifying and possibly controlling the ambipolar plasma potential. As discussed under "Molecular Ion Heating Dynamics" below, it appears likely, based on the neoclassical formulas for particle fluxes, the proper choice of D_2^+ beam current turn-on feedback scenarios can permit experimental operation in either the present-day negative potential or the long lifetime positive potential regime predicted by neoclassical theory. Since confinement time in the positive potential regime is increased by almost two orders of magnitude, great significance is attached to achieving experimental operation in that regime.

MOLECULAR ION INJECTION ORBIT STUDIES

In order to efficiently heat an EBT plasma by H_2^+ or D_2^+ molecular ion beam injection, it is necessary that the energetic molecular ions be injected from the outside of EBT and remain inside the plasma

*This Appendix is taken directly from the Ebasco study. Its inclusion is intended to bring to the attention of the Review Committee this interesting technique. There has been insufficient time to reference it to the present EBT-P design.

region for a sufficiently long period; namely, the plasma path lengths of the injected molecular ions inside the plasma must exceed the dissociation length, which is about 2 m in EBT-P.

The single particle trajectory code, TIBRO-X, which is used for this purpose, calculates the exact orbit (not the guiding center drift orbit) of a charged particle in a magnetic field without assuming any adiabatic invariants. The equations of motion are

$$\begin{aligned}\frac{d\vec{x}}{dt} &= \vec{v} , \\ \frac{d\vec{v}}{dt} &= \frac{q}{m} (\vec{v} \times \vec{B}) .\end{aligned}\tag{2}$$

The magnetic field configuration used in this study is that of a full 40-mirror-sector EBT-P torus including limiters. The critical dimensions are:

major radius = 359 cm, corresponding to simple coils,
coil radius = 23 cm (of zero thickness),
coil current = 1 MA,
magnetic induction = 3.0 T at the throat center,
 = 1.5 T at the midplane center,
limiter size = 13.7 cm x 13.7 cm around the coil center.

The effects of electron rings, wedge coils, aspect ratio enhancement (ARE) coils, the target plasma, and ambipolar electric potential were not included in this calculation, but such effects are not expected to alter the results significantly.

The TIBRO-X code in the 40-sector EBT-P configuration has been used to study orbit shape versus injection parameters, i.e., with different components of initial position and velocity, $\vec{x}_0$ and $\vec{v}_0$. Figure A.6.1 indicates the coordinate system with the injection position at $\vec{x}_0 = (320, 15, -25)$ cm. Some typically favorable orbits are shown in Figs. A.6.2-A.6.4 with the injection energy $E(H_2^+) = 360$ keV (or equivalently 180 keV of D_2^+) and with varying angles θ and ϕ . Figure A.6.5 summarizes the path length results of about 150 runs with this same injection energy, $E(H_2^+) = 360$ keV, to illustrate the injection angle insensitivity. These data show the possibility of choosing injection parameters, $\vec{v} = (E, \theta, \phi)$, to permit the employment of beams having half angles ($\pm 1/2 \sim 1^\circ$). One possible choice is

$$E(H_2^+) = 360 \text{ keV } (\pm 5) ,$$

$$\theta = 241^\circ (\pm 1^\circ) ,$$

$$\phi = 260^\circ (\pm 1^\circ) ,$$

where all path lengths are longer than the mean free path for ionization trapping.

We find similar results with the other injection energies; in particular, it seems to be possible to find other injection parameters with tolerable angular sensitivity. In this regard, $E(H_2^+) = 325, 400, \text{ and } 450$ keV have been calculated and the first case shown in Figs. A.6.6 and A.6.7. Injection from outside (rather than inside) of the EBT torus has also been studied, but the trajectories often intersect the coils, thus yielding results inferior to those obtained from inside injection.

Fig. A.6.1. Injection geometry

Fig. A.6.2. Molecular ion orbits in the minor cross section and the equatorial plane for $(\theta, \phi) = (241^\circ, 261^\circ)$ at $EH_2^+ = 360 \text{ keV}$ ($EN_2^+ = 180 \text{ keV}$).

Fig. A.6.3. Molecular ion orbits in the minor cross section and the equatorial plane for $(\theta, \phi) = (236^\circ, 262^\circ)$ at $EH_2^+ = 360$ keV ($ED_2^+ = 180$ keV).

Fig. A.6.4. Molecular ion orbits in the minor cross section and the equatorial plane for $(\theta, \phi) = (241^\circ, 259^\circ)$ at $EH_2^+ = 360$ keV ($ED_2^+ = 180$ keV).

Fig. A.6.5. Path lengths (in meters) for 180-keV D_2^+ ions as a function of angle of injection. Dots correspond to path lengths less than 1.5 m.

Fig. A.6.6. Molecular ion orbits in the minor cross section and the equatorial plane for $(\theta, \phi) = (247^\circ, 262^\circ)$ at $EH_2^+ = 325$ keV ($ED_2^+ = 162.5$ keV).

Fig. A.6.7. Molecular ion orbits in the minor cross section and the equatorial plane for $(\theta, \phi) = (249^\circ, 263^\circ)$ at $EH_2^+ = 325$ keV ($ED_2^+ = 162.5$ keV).

THERMALIZATION OF THE TRAPPED IONS

The rate of thermalization of deuterons (with energy E_0) through Coulomb collisions with the plasma electrons (with temperature T_e) and the plasma deuterium ions (with temperature T_i) is readily evaluated with the assumptions, $E_0/T_e \gg 1$ and $\sqrt{(E_0/T_e)(m_e/M_D)} \ll 1$:

$$\left(\frac{dE}{dt}\right)_i = -\frac{1}{4\pi} \left(\frac{e^2}{\epsilon_0}\right)^2 \frac{N_i}{M_D} \frac{\ln \Lambda}{v}, \quad (3)$$

$$\left(\frac{dE}{dt}\right)_e = -\frac{1}{4\pi} \left(\frac{e^2}{\epsilon_0}\right)^2 \frac{N_i}{M_D} \frac{\ln \Lambda}{v} \left[\frac{4}{3\sqrt{\pi}} \sqrt{\frac{m_e}{M_D}} \left(\frac{E_0}{T_e}\right)^{3/2} \right],$$

from which we obtain

$$E(t) = E_0 e^{-2t/3\tau} \left[1 - \left(\frac{E_c}{E_0}\right)^{3/2} (e^{t/\tau} - 1) \right]^{2/3}, \quad (4)$$

which is plotted in Fig. A.6.8. Here,

$$E_c = \left(\frac{3\sqrt{\pi}}{4} \sqrt{\frac{M_D}{m_e}}\right)^{2/3} T_e \quad (T_e = 2 \text{ keV})$$

$$\tau^{-1} = \frac{3}{8\pi} \frac{e^4}{\epsilon_0^2} \frac{N_i}{\sqrt{2} M_D} \frac{\ln \Lambda}{E_c^{3/2}} \quad (N_i = 2 \times 10^{13} \text{ cm}^{-3}).$$

Since the fraction of the injection energy going to the plasma ions is

$$\frac{\delta E_i}{E_0} = \frac{1}{E_0} \int_0^{\tau_{cx}} \left(-\frac{dE}{dt}\right)_i dt, \quad (5)$$

we must compare the charge exchange time τ_{cx} with the cooling time. For the injection energy, $40 \lesssim E_0$ (keV) $\lesssim 100$, we may use the following analytic form for the charge exchange cross section:

$$\sigma_{cx}(\text{cm}^2) = e^{-25} E_0^{-3} (\text{keV}). \quad (6)$$

Thus, the charge exchange time varies with the neutral density as plotted in Fig. A.6.9, showing that $\tau_{cx} \approx 0.2$ sec for $n_N \approx 10^9 \text{ cm}^{-3}$, which suggests the straight line variation for $0 \lesssim t \lesssim \tau_{cx}$ in Fig. A.6.10. Hence, with this simplifying assumption,

$$\frac{\delta E_i}{E_0} = \frac{4}{3} \left(\frac{E_c}{E_0}\right)^{3/2} \ln \left[1 + \left(\frac{E_0}{E_c}\right)^{3/2} \right] \left(1 - \sqrt{1 - \frac{\tau_{cx}}{t_s}} \right), \quad (7)$$

Fig. A.6.8. Cooling of the injected beam by both plasma species.

Fig. A.6.9. Charge exchange time for $E_0 = 90$ keV.

Fig. A.6.10. Fraction of injection energy going to plasma ions.

where

$$\frac{\tau_{cx}}{t_s} = \begin{cases} 3.376 \times 10^{-7} \frac{N_i}{n_N} \frac{E_0(\text{keV})(E_0/E_c)^{3/2}}{\ln[1 + (E_0/E_c)^{3/2}]} & \text{for } \frac{\tau_{cx}}{t_s} < 1 \\ 1 & \text{otherwise} \end{cases} \quad (8)$$

This is plotted in Fig. A.6.10 for various injection energies and neutral densities, showing that up to 50% of the injection energy can go to heat the plasma ions when the neutral density is held below around 10^9 cm^{-3} for $40 \lesssim E_0 (\text{keV}) \lesssim 100$.

MOLECULAR ION HEATING DYNAMICS

Molecular ion injection heating has favorable cost and operating convenience factors and permits positive charge to be injected as a way of controlling the ambipolar potential.

There follows in this section a relatively simple treatment of EBT plateau diffusion to illustrate the application of molecular ion beam heating to sustain equilibria in both the electron transport dominated, negative potential case and in the ion dominated, positive potential branch. Despite the embryonic nature of the following arguments, the possible confinement advantages are so striking that we are justified in discussing them here in a preliminary fashion prior to more detailed spatial modeling.

Beam Heating in a Negative Ambipolar Potential Well

The following calculation estimates the effect on ion and electron temperature of ion beam heating of an ECH EBT-P plasma in the negative potential electron transport region A of Fig. A.6.11. This is accomplished in the face of positive charge introduction by turning the beam current on very slowly at a rate determined by feedback on the ambipolar potential setpoint, V_s . Then $I_B = AK(\phi - V_s)$ is signed in the direction to drive the potential to a negative equilibrium. The optimization of V_s will permit maximization of injected current. The positive charge flow into the plasma as beam particles is easily balanced by the slightly increased transport (over the electron transport) of the background ions, since the maximum ion beam current is only about 5% of the plasma ion loss current. Fortunately, ion temperature-enhanced plateau ion diffusion is in the direction for sustaining this equilibrium, i.e., $D_{pi} \propto T_i$.

The resulting beam heating of ions is estimated as follows. The particle conservation equation yields

$$\frac{1}{\tau} = n_0 \langle \sigma v \rangle_i \quad (9)$$

For simplicity, we assume that the neutral density is constant throughout the heating process, so that the confinement time is also approximately constant (note that $\langle \sigma v \rangle_i$ is almost constant). Thus the ion and electron heating may be written as

$$\begin{aligned} E_{\text{crit}} j &= \Delta T_i / \tau, \\ (E - E_{\text{crit}}) j &= \Delta T_e / \tau, \end{aligned} \quad (10)$$

where E is the energy of the trapped beam and

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Fig. A.6.11. Solutions to the ambipolarity condition. Region A is the negative-potential, electron-transport-dominated regime, and region B is the positive-potential, ion-transport-dominated regime.

$$E_{\text{crit}} = 18.7 (T_e + \Delta T_e) ,$$

$$j \approx \frac{I_B}{(n + \Delta n) V e} ,$$

with I_B representing the beam current and V representing the plasma volume. Using the collisionless scaling, we have the relation

$$n + \Delta n = n \left(1 + \frac{\Delta T_e}{T_e} \right)^{3/2} . \quad (11)$$

The j can be written as

$$j = j_0 \left(1 + \frac{\Delta T_e}{T_e} \right)^{-3/2} \quad (12)$$

where

$$j_0 = \frac{I_B}{n V e} .$$

The electron and ion heating equations, then, become

$$18.7 j_0 \tau (T_e + \Delta T_e)^{-1/2} = \Delta T_i , \quad (13)$$

$$j_0 \tau [E - K(T_e + \Delta T_e)] \left(1 + \frac{\Delta T_e}{T_e} \right)^{-3/2} = \Delta T_e .$$

Assume ECH plasma with the plasma parameters given by the transport theory,

$$T_e = 1.8 \text{ keV} , \quad T_i = 1.2 \text{ keV}$$

$$\tau = 50 \times 10^{-3} \text{ sec} , \quad n = 2 \times 10^{13} \text{ cm}^{-3}$$

and

$$V = 1.1 \times 10^6 \text{ cm}^3 , \quad R = 4 \text{ m} , \quad r = 12 \text{ cm}$$

$$E = 90 \text{ keV} , \quad I_B = 2 \text{ A} .$$

The solutions to the above equations can be easily shown to be

$$\frac{\Delta T_e}{T_e} \approx 0.42 \text{ and } \frac{\Delta T_i}{T_e} \approx 0.44, \quad (14)$$

showing comparable amounts of beam heating to electrons and ions.

D₂⁺ Beam Heating in a Positive Ambipolar Potential Well.

Although the equilibria resulting from positive potential beam heating are very much less predictable at this stage of transport simulation, we emphasize the experimental tools to examine such heating because of the potential importance of this regime.

The B region in Fig. A.6.11 should be accessible by pulsing in enough positive charge to transfer the operating point to this positive potential, in a time short compared to either an ion or electron transport time.

For EBT parameters, the potential variation due to beam injection is roughly $\phi = 4.5 \times 10^7 I_B \tau$ ($I = \text{amps}$, τ in sec). Thus, positive potentials around 5 kV can be achieved with beam currents of 2 A, if the beam is on for 50 msec, a time much shorter than a transport time. Then the beam current would be controlled by feedback on a positive space potential setpoint. This control function should also behave well since, as indicated in Fig. A.6.11, a small positive increase confines electrons better than cold ions, thereby permitting an equilibrium. We assume $E_r > 0$ and express ion flux Γ_i and electron flux Γ_e simply as follows:

$$\begin{aligned} \Gamma_i &= -D_{ni} \left(\frac{\partial n}{\partial r} - a_i \frac{\partial T_i}{\partial r} + \frac{ne E_r}{T_i} \right), \\ \Gamma_e &= -D_{ne} \left(\frac{\partial n}{\partial r} - a_e \frac{\partial T_e}{\partial r} - \frac{ne E_r}{T_e} \right). \end{aligned} \quad (15)$$

For all the practical cases with $E_r > 0$, D_{ne} is much larger than D_{ni} ; thus the solution for positive ambipolar electric field should satisfy

$$\frac{e E_r}{T_e} \approx \frac{1}{n} \frac{\partial n}{\partial r} - \frac{a_e}{n} \frac{\partial T_e}{\partial r} > 0. \quad (16)$$

This solution is shown in Fig. A.6.11 inside of the B region.

The stability of the positive E_r solution can be checked by imagining a small positive charge disturbance: E_r is increased and Γ_i becomes larger than Γ_e ; thus, the ions are lost faster than the electrons and the system comes back to its original state. This solution is, therefore, stable.

Again the significant feature of this positive E_r solution is that the electron diffusion adjusts to the ion diffusion in order to satisfy the ambipolarity condition.

The scaling law in this regime therefore is ion diffusion dominated rather than electron diffusion dominated.

Experimentally, we require the ion pulse to be injected in a time short compared with collision times to make a rapid jump from the $E_r < 0$ solution to $E_r > 0$ solution. Then the necessary beam current $I_B = (\phi^+ - V_s)kA$ will, because of better confinement, gradually increase to full value, while holding the potential constant.

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Appendix 7

NEUTRAL BEAMS FOR EBT

INTRODUCTION

This section of the appendix is a brief progress report of a recently begun, long-term study to determine the compatibility and possible configuration of particle beam heating in a steady-state, microwave-heated (ECH) EBT plasma. This section will include a rationale for the choice of neutral beam heating, a brief review of the accomplishments of a previous study, and the goals and status of the ongoing work. Because this effort is in its infancy, only preliminary results are available.

Calculations mentioned in the Grumman Aerospace Corporation's EBT-P Project Definition Study indicate that losses of the trapped beam ions by charge exchange make the use of neutral injection at modest energies (~ 20 keV) unattractive. The particular problem is the presence of the neutrals left when the beam is trapped (halo neutrals) coupled with the fact that the beam ions remain in the same region (cavity) in which they are trapped. Further calculations are required to confirm whether neutral injection has any application in EBT-P (for fueling or heating diagnostics).

RATIONALE

The rationale for attempting to use particle beam heating, in particular neutral beam heating, is simple: Neutral beam heating is an effective, modestly efficient method for massive ion heating in tokamaks. The success in PLT is the obvious example.¹ A cursory comparison of tokamaks and EBT from a geometrical point of view indicates that the EBT beam line energy can be significantly lower than that for a tokamak, and consequently, technology already exists for pulsed injectors. However, it is not at all clear that such injectors are compatible with the EBT plasma. It must be demonstrated that a neutral beam injection system can effectively deliver the massive heat flux to the plasma in the microwave ECH environment of EBT. Furthermore, a lower beam energy implies a larger particle fluence for the same power. Again, it is not clear that this is compatible with the EBT plasma, particularly when long pulse or steady-state injection is called for.

PREVIOUS WORK

An earlier study, completed for the EBT-II Conceptual Design Study,² was an attempt to identify the problem areas. A target plasma conceivably attainable ($5 \times 10^{13} \text{ cm}^{-3}$) and a moderate beam energy (20 keV) were chosen to see what beam power was necessary to bring the plasma to a reactor-relevant regime. It was determined that 1 MW extracted and approximately 300 kW trapped would satisfy the goal. Problems of microwave isolation, particle control, realistic energy deposition and losses, and the steady-state nature of EBT were ignored, however.

GOAL OF THE PRESENT STUDY

The ultimate goal is an operational particle beam injection system on an EBT device compatible with all the nuances of an EBT plasma. The beam sources must either work in a microwave environment or be isolated from the microwave energy. Low energy, high fluence beams can easily swamp the vacuum system; therefore, particle control, possibly through a divertor, must be considered. In the short term, these systems are to be installed on EBT-I/S using ELMO as a test stand. Information learned in the short term should be applicable to later stages of EBT, e.g., EBT-P, although there is a danger in simply extrapolating because the microwave frequency increases dramatically from EBT-S (28 GHz) to EBT-P

(110 GHz). A solution at 28 GHz may not work at 110 GHz. In any event, any solution will be reached only with a well-coordinated mix of theory, experiment, and development.

STATUS

Theory

Present theoretical effort is directed toward determining the injection geometry, the beam energy and power, and the beam deposition profile for an EBT-P device. For tokamaks, neutral beam heating has proven to be an effective method for auxiliary heating. It is described well by classical physics processes, and almost all of the deposited neutral beam power is actually absorbed by the plasma. Accordingly, we must consider neutral beam injection as a prime candidate for heating EBT-P.

The physics of an EBT is, of course, different from that of a tokamak, causing the regime of injection parameters to be different. Confinement in an EBT improves with aspect ratio instead of with minor radius as it does in a tokamak. Thus, for a given class of device, the minor radius in an EBT tends to be much smaller than in a tokamak. Furthermore, there is little tangential injection access in a large aspect ratio EBT because of the mirror coils. These two facts make the path length for beam absorption much less in an EBT than in a tokamak.

To alleviate this problem, there are several things that may be done in the design of an optimal injection system.

(1) Lower the beam energy: To increase the beam-trapping cross section, the injection energy can be lowered from the 40 keV typical of PLT and ISX to 20 keV. This is only of limited effectiveness, however, because in this energy range the total cross section for beam trapping goes roughly as $E^{-2/5}$. Lowering the energy also gives a modest gain in the neutralization efficiency of the beam line.

(2) Increase the plasma density: An increased density leads to improved trapping because the beam deposition goes as $\exp(-n_e \sigma_T \lambda)$. For Stage I of EBT-P the density will probably be restricted to $\lesssim 3 \times 10^{13} \text{ cm}^{-3}$, which leads to a relatively thin target, $n\lambda \lesssim 10^{15} \text{ cm}^{-2}$.

(3) Decrease the beam radius: Although the access port on EBT-P can be up to 15 cm in radius, a 15-cm beam gives a very flat beam deposition profile. Reducing the radius to 10 cm increases the normalized central fast ion density by 50%. However, this also reduces the power per source. If we assume that (1) $\sim 0.3 \text{ A/cm}^2$ is extracted from the source, (2) the grid transparency is 50%, (3) the beam line transmission efficiency is 70%, and (4) the neutralization efficiency is 80%, then we may also assume that a 20-keV beam will deliver about 530 kW to the plasma, assuming 100% beam absorption. A 15-cm source will deliver about 2.25 times the power of a 10-cm source, thus delivering more power on axis, but it also will deliver much more power to the edge.

To try to resolve these tradeoffs, we developed a new beam deposition code for vertical injection into EBT along the lines of Ref. 3. Because the injection direction is perpendicular to the B field, the fast ion orbits are almost circles characterized by their radius z . The circles are slightly nested inward so that the major radius of the center is a function of ρ , $R_c(\rho)$. Any function $R_c(\rho)$ can be used, but in this case we assumed that the mod B contours were subject to a $1/R$ shift so that $R_c(\rho) = \sqrt{R_0^2 - a^2 + \rho^2}$, where R_0 and a are the major and minor radii of the plasma in the midplane. Also, it was assumed that, in good agreement with the EBT-S experimental data, the density and temperature profiles were flat.

For the 36-coil EBT-P configuration, we used $R_0 = 560 \text{ cm}$ and $a = 23.2 \text{ cm}$ and injected the beam vertically down. The fast ion density is represented by a function $H(\rho)$, which is normalized so that the fraction absorbed $= \frac{1}{\text{volume}} \int H(\rho) d(\text{volume})$. Each deposition curve plots both $H(\rho)$ (squares) together with the above integral (circles) taken from the center to $\rho(0)$.

Figures A.7.1-A.7.4 show $\langle \rho \rangle$ for a 10-cm, 20-keV beam for plasma densities of 1.7, 2.4, 3.0, and $5.0 \times 10^{13} \text{ cm}^{-3}$. The $n_e = 3 \times 10^{13} \text{ cm}^{-3}$ density is the highest expected in the first stage of EBT-P and yields only 70% beam absorption. The problem with this case is that 30% of the beam power is wasted and that it must be handled by a beam dump, a severe and possibly costly engineering problem. A density of 10^{14} cm^{-3} is needed to completely absorb the beam.

Figure A.7.5 shows the effect of a larger beam radius (15 cm) on $H(\rho)$ for the $3 \times 10^{13} \text{ cm}^{-3}$ case. As a general rule, the deposition profile is flat from the center out to the beam radius, as can be seen clearly in this plot. The deposition profile is quite broad, and slightly less of the beam is absorbed than for the 10-cm case.

Finally, we examined the effect of lowering the beam energy to 15 keV and 10 keV, as seen in Figs. A.7.6 and A.7.7. Halving the beam energy gives only a 10% increase in beam absorption, as expected, so that this is not a good course to take.

If the low beam absorption problem can be solved, a proper Fokker-Planck calculation for EBT that includes the fast particle loss regions must also be done. Although this can lead to further heating inefficiency, it will probably not be intolerable.

Experimental

Experimental work with microwave compatibility and particle control can presently be done on two machines, ELMO and EBT-I/S. A gas puffing and a gas-flow matching experiment⁴ has been done on EBT-I to test the EBT plasma tolerance to massive, pulsed cold gas fluences and the disruptive influence such pulses have on microwave power flow. Flow-matching experiments with and without plasma have given preliminary indications of the particle-handling capabilities of the EBT-I machine ($\sim 100 \text{ mA}$ under typical T-mode conditions). The gas puffing experiment indicated that cold gas pulses up to 7 A equivalent for 0.5 sec are tolerated by the EBT plasma. To be sure, plasma parameters do degrade because the 7-A pulse pushed the plasma into C-mode. However, when the pulse ended, the plasma recovered and there were no massive disruptions during the experiment. The next step will be the installation of a low fluence, 20-keV diagnostic neutral beam with the intention of obtaining spatially resolved ion temperatures. Microwave compatibility will apply only to EBT-I/S, however. Finally, a lower energy ($\sim 5 \text{ keV}$), modest fluence ($\sim 1 \text{ A}$) beam will be installed on ELMO and then on EBT-I/S to test both microwave compatibility and utility of particle control. Again, microwave compatibility can be demonstrated for the highest frequency available, which in this case is 28 GHz. Particle control will be achieved initially through pulse length; however, as the pulse length becomes longer, a divertor will be required.

Development

Massive, pulsed heating beams exist; however, providing steady-state neutral beam heating power in a microwave ECH environment is another question. Initially such beams will have to be developed for EBT-I/S ($\sim 5 \text{ kV}$, 1 A) and scaled up to EBT-P ($\sim 20 \text{ kV}$, 10 A) and beyond. At these power levels and steady-state operation, the question of pumping and particle control arises. It must be remembered that the stable operation of EBT is very sensitive to the particle inventory. Aside from adding massive cryopumps (where compatibility with high power microwave fluence is presently unknown), a conceivable method of particle control is through a divertor. DITE and the Poloidal Divertor Experiment (PDX) are only beginning to examine divertors on tokamaks, and their utility on an EBT device must also be examined. Plans call for this to be done initially on EBT-I/S and later on an upgraded version of EBT-P. The question of whether low energy beams may be used other than for diagnostics needs further study.

Fig. A.7.1. $H(\rho)$ and volume-integrated efficiency vs ρ for $n_e = 1.7 \times 10^{13} \text{ cm}^{-3}$, $E_B = 20 \text{ keV}$, $r_B = 10 \text{ cm}$, and $T_e = 3.5 \text{ keV}$; total absorbed = 49%.

Fig. A.7.2. $H(\rho)$ and volume-integrated efficiency vs ρ for $n_e = 2.4 \times 10^{13} \text{ cm}^{-3}$, $E_B = 20 \text{ keV}$, $r_B = 10 \text{ cm}$, and $T_e = 4.1 \text{ keV}$; total absorbed = 61%.

Fig. A.7.3. $H(\rho)$ and volume-integrated efficiency vs ρ for $n_e = 3 \times 10^{13} \text{ cm}^{-3}$, $E_B = 20 \text{ keV}$, $r_B = 10 \text{ cm}$, and $T_e = 4.4 \text{ keV}$; total absorbed = 69%.

Fig. A.7.4. $H(\rho)$ and volume-integrated efficiency vs ρ for $n_e = 5 \times 10^{13} \text{ cm}^{-3}$, $E_B = 20 \text{ keV}$, $r_B = 10 \text{ cm}$, and $T_e = 4.4 \text{ keV}$; total absorbed = 86%.

Fig. A.7.5. $H(\rho)$ and volume-integrated efficiency vs ρ for $n_e = 3 \times 10^{13} \text{ cm}^{-3}$, $E_B = 20 \text{ keV}$, $r_B = 15 \text{ cm}$, and $T_e = 4.4 \text{ keV}$; total absorbed = 68%.

Fig. A.7.6. $H(\rho)$ and volume-integrated efficiency vs ρ for $n_e = 3 \times 10^{13} \text{ cm}^{-3}$, $E_B = 15 \text{ keV}$, $r_B = 10 \text{ cm}$, and $T_e = 4.4 \text{ keV}$; total absorbed = 75%.

Fig. A.7.7. $H(\rho)$ and volume-integrated efficiency vs ρ for $n_e = 3 \times 10^{13} \text{ cm}^{-3}$, $E_B = 10 \text{ keV}$, $r_B = 10 \text{ cm}$, and $T_e = 4.4 \text{ keV}$; total absorbed = 80%.

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4. K. H. Carpenter and J. C. Glowienka, "Gas Injection in EBT-S for Assessment of Particle Loading Effects of Neutral Beam Injection," paper 253 presented at the 1979 IEEE Int. Conf. on Plasma Science, Montreal, Canada, June 4-6, 1979.

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Appendix 8

DIVERTORS, PELLET FUELING, AND LIMITERS

DIVERTORS FOR EBT-P

Recent calculations suggest that the EBT plasmas are sensitive to the conditions of particle recycling at the walls.¹ In addition, because of limitations in the pumping speed of the primary pumping system, the rate of particle removal in steady-state operation is very constrained. Consequently, there is little flexibility to add and subtract any great amount of particles, whether they are at low energies (gas recycling or pellets) or at high energies (neutral or molecular ion beams). An obvious solution is the addition of a divertor. This has been discussed previously for an EBT reactor² and is proposed for the EBT-I/S device.³ The gain in particle removal rate is readily calculated.

The pumping speed in EBT-P will be $\sim 2 \times 10^4$ liters sec^{-1} maximum. With a pressure outside the device of 10^{-6} - 10^{-5} torr, this leads to a particle flux of 0.02 - 0.1 torr-liters $\cdot\text{sec}^{-1}$ of H_2^0 , which amounts to 0.2 - 1 ampere equivalent of H_1^0 .

For a divertor, the amount of ions removed is $I_D = \alpha n_{es} c_s A_{se}$ (in amperes), where A_s is the area of the divertor throat, n_{es} is the electron density in the scrape-off layer, $c_s \propto (2T_{es}/m_i)^{1/2}$ is sound speed, and α is a measure of the transfer efficiency from the scrape-off layer to the divertor chamber ($\alpha \sim 0.1$).

For a full toroidal divertor, one could have $A_s \sim 10^3 \text{ cm}^2$, $n_{es} \cong 0.1$, $n_e \cong 1.5 \times 10^{12} \text{ cm}^{-3}$, and $C_s \cong 1.5 \times 10^7 \text{ cm}^{-1}$ for $T_{es} \sim 100 \text{ eV}$ ($e = 1.6 \times 10^{-19}$ Coulombs). These figures yield $I_D \sim 320$ amperes equivalent of H_1^0 .

The particle flux expected from the plasma core is given by $I_p \leq en_e V / \tau_E$ (amperes equivalent), where the particle confinement time (τ_p) is greater than or equal to the energy confinement time (τ_E). For $n_e = 1.5 \times 10^{13} \text{ cm}^{-3}$, $V = 3 \times 10^6 \text{ cm}^3$, and $\tau_E = 3 \times 10^{-2} \text{ sec}$, the particle flux from the core (I_p) is less than or equal to 240 amperes equivalent of H_1^0 .

A key issue for the divertor is power handling. The situation is more complicated than, for example, in the case of tokamaks because of the energetic ring electrons, some of which may well enter the divertor chamber. Calculations of this have not been made, but it is interesting to see whether the total power reaching the divertor targets would cause a problem. The divertor throat power for the area above would amount to $1 \text{ kW}\cdot\text{cm}^{-2}$ per MW of power, leaving the plasma to the divertor. It is possible to spread out the field lines in the divertor chamber and to angle the target to reduce target power density, and it should be possible to reduce this to $\sim 100 \text{ W}\cdot\text{cm}^{-2}$, which is an acceptable level. The problem of x-ray production owing to energetic electrons striking the walls and target has not been studied.

No detailed power balance has been made; therefore, we do not know what percentage of the power in the torus will reach the divertor. It is possible to estimate the power for given scrape-off layer conditions. By analogy with the DIVA divertor experiment,⁴ we may expect $P_D \cong \gamma T_{es} I_D$, where $\gamma \sim 7$; for $T_{es} \sim 100 \text{ eV}$ and $I_D \sim 320 \text{ A}$, $P_D \cong 220 \text{ kW}$.

These ad hoc numbers are intended only to give an indication of a divertor's properties. In reality, the edge temperature will sit at the level needed to balance simultaneously the heat and particle output to the input.

The particle flow (I_D) and heat flow (P_D) to the divertor are proportional to $(T_{es})^{1/2}$ and $(I_{es})^{3/2}$, respectively.

A further reason for analyzing a divertor is for impurity control, though in the case of an EBT the potential gradients set up in the plasma edge do act to repel wall-generated impurities. Nevertheless, in a steady-state D-T burning device, such as EBT-Q or a reactor, it will be necessary to remove helium ash. A demonstration of this capability is an important test for EBT-P.

The detailed design of a divertor has not been worked out, though toroidal devices and bundle divertors have been considered. Studies under way for EBT-I/S should help decide on designs.

FUELING

Pellet injectors developed at ORNL have been used successfully on the ORNL ISX-A⁵ and ISX-B⁶ tokamaks. Pellet fueling is an attractive prospect for EBT-P because it is a fueling method that does not lead to a large number of neutrals in the plasma, which can lead to charge exchange losses.⁶

ORNL pellet injectors have been developed that have characteristics well suited to the plasma parameters and dimensions of EBT-P. Injection between the limiter and the coil throat should minimize ablation by the outer cold plasma and energetic electrons. The rotating pellet injector has the following characteristics: pellets 0.5-0.8 mm in diameter, 150 pellets per second at $\sim 300 \text{ m}\cdot\text{s}^{-1}$. This system's can deliver up to 100-400 amperes equivalent of H_1^0 .

Some preliminary tests of a single shot pellet injector may be attempted on EBT-I/S.

LIMITERS

Prior to installation of a divertor, the power and recycling will be taken on the limiters. It is proposed to have water-cooled aluminum limiters, though other low Z materials which minimize x-ray production will be studied. These limiters will probably be installed on the smaller major radius side of the cavities on each side of the coil throat. They will project $\sim 1 \text{ cm}$ inside the coil throat so that this does not become a major sink for power. It is anticipated that some of the ring power will be deposited on an area $\sim 10 \text{ cm}^2$ per limiter, normal to the field. This number is obtained from thick target bremsstrahlung radiation pictures taken on EBT-I. Given that the limiters may be extended along the field and that there will be 72 limiters, this leads to a target area $\sim 1000 \text{ cm}^2$ for the energetic electrons that leave the plasma.

Roughly a third or less of the ring power should hit the limiter as energetic electrons. For 300 kW of power in the ring, the power density on the limiter is, then, $\leq 100 \text{ W}\cdot\text{cm}^{-2}$. The plasma power should be distributed over a wider area, and an analysis is required of the various plasma losses and their distribution.

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APPENDIX 9

TECHNOLOGY DEVELOPMENT REQUIREMENTS

Successful realization of EBT-P requires significant advances in some areas of technology. The ongoing EBT-S experimental program will have an essential role in extending the technology by providing important operating experience and serving as a test bed for subsystems and components; other needs will require development efforts specifically for EBT-P.

Two major subsystems, the superconducting mirror magnets and the microwave sources, were identified early as requiring intensive development efforts; development tasks for these components have been initiated. The microwave distribution and supporting subsystems also require technological advances, and a development program is being formulated to focus on specific needs for EBT-P. Consistent and vigorous efforts are clearly required in these areas to support a credible design for EBT-P in a time frame consistent with scheduled goals. In addition, it is recognized that as the design proceeds, other components and subsystems will require fabrication development or confirmatory testing.

EBT-P will be constructed with provisions for future improvements, including additional microwave power, higher microwave frequency, microwave feed from the high-field side, direct ion heating, aspect ratio enhancement (ARE) coils, particle control (divertor), and alternate fueling methods. The research and development needs for these improvements will be addressed in part by proposed experiments on EBT-S and will be further considered in specific planning for EBT-P upgrades.

MAGNET DEVELOPMENT

A development effort for the mirror magnets has been initiated at ORNL to reduce the risk of proceeding with the final design and manufacture of a full complement of EBT-P magnets. Specific objectives are (1) to demonstrate design features and fabrication techniques that will produce the required field accuracy and eliminate systematic (cumulative) field errors; (2) to solve the problems of structural containment and of maintaining proper alignment in the dewar after cooldown and energizing; (3) to evaluate thermal design features and determine heat removal capability; and (4) to develop techniques, facilities, and criteria for acceptance testing of the coils manufactured for EBT-P.

Magnet development presently planned consists of designing, fabricating, and testing two instrumented test magnets of the NbTi pool-boiling type as proposed for the EBT-P reference design. The coils will include heaters embedded in portions of the conductor for simulating heat input from gamma rays and other sources. The magnets will first be tested separately and then in a two-magnet array as they would be installed on EBT-P. This task is estimated to cost \$1.7 million and is to be completed by January 1982.

The NbTi superconductor for the test magnets was specified in FY 1979 based on ORNL's proposed design for EBT-P, and sufficient superconductor was ordered for two test magnets. Delivery is expected in June 1980. Detailed design of the test magnets will proceed when the EBT-P reference design is selected.

A parallel development effort was considered to preserve an option for a Nb₃Sn, cryostable design that would offer possible advantages but is less developed than NbTi designs. Sufficient Nb₃Sn superconductor for one test magnet was purchased and stored in the form of oversized wire. However, no further work on this concept is contemplated at this time.

The development schedule as now proposed is intended to make significant test results available early enough (estimate April 1981) to impact the detailed design for EBT-P and prior to ordering the

superconductor for all magnets. Essentially complete test results will be available prior to the start of magnet manufacture (estimate April 1982). Once the industrial participant who will direct the final design and manufacture of the mirror magnets is selected, he will interact with the development activity, assist in determining appropriate acceptance tests, monitor or participate in performing the tests, and apply the results and experience to his efforts on the EBT-P magnets.

MICROWAVE DEVELOPMENT

The microwave heating capability planned for EBT-P in its initial phase will provide substantial cw power (~ 800 kW) at a frequency of 60 GHz for bulk heating and lower cw power (~ 400 kW) at a frequency of 28 GHz for profile heating.

The microwave system consists of three basic elements: (1) a multiple array of microwave sources (gyrotrons); (2) a microwave distribution system for the efficient transfer of energy to the plasma; and (3) supporting electrical and electronic subsystems for monitoring, control, and safety. These basic elements require an intensive, complementary development effort that is being performed by ORNL as a continuation of the microwave heating support activities conducted for many years by the ORNL EBT program.

Microwave Sources

The time required to develop the microwave sources is the principal uncertainty affecting the EBT-P schedule. Much of the technology needed is being developed under a program started in April 1976 to develop a 28-GHz, 200-kW cw gyrotron for EBT-S. This work is being done by Varian Associates (Palo Alto, California) under subcontract to ORNL. At the time the work started, available tubes were capable of no more than a few kW steady state. Accomplishments include the attainment of 105 kW for several minutes in May 1978 and the successful operation of EBT-S with 50 kW of microwave heating (cw) in September 1978. However, despite significant progress, the experience indicates that the development of a reliable 200-kW cw tube is a difficult task. A second tube capable of sustained operation at 50-60 kW cw was not achieved until late 1979. An intensified effort is being made to reach the 28-GHz, 200-kW cw goal in 1980.

Parallel programs were initiated in mid-1979 to develop higher frequency 200-kW cw gyrotrons for EBT-P. Two industrial firms, Varian Associates and Hughes Aircraft Company (Torrance, California), began work under ORNL subcontracts with identical work statements aimed at developing 110-GHz, 200-kW cw gyrotrons in approximately three and one-half years. Subsequently, this goal was judged to be overly optimistic, and the consensus of the Project Definition Study teams was that EBT-P should be planned for initial operation with a lower-frequency microwave source, which will be less difficult to develop.

Both Varian and Hughes were instructed late in 1979 to redirect their 110-GHz programs to concentrate on developing 60-GHz microwave sources for EBT-P and to fill needs for tokamak and mirror applications. Development of a higher frequency (90- to 110-GHz) microwave source is now a lower-priority objective for a future improvement of EBT-P.

The development of microwave sources for EBT-P is being carried out as part of the DOE National Gyrotron Program, which is managed by the Office of Fusion Energy (D&T).

Microwave Distribution

The microwave distribution systems will require extensive component development and integrated system tests. Much of the experience gained in developing and operating the 28-GHz system on EBT-S

will be applicable to EBT-P; however, an additional development effort will be required that takes into account specific characteristics of EBT-P and of the microwave sources being developed for it. A dedicated test facility is desirable for this task and for the task described under "Microwave Supporting Subsystems" below.

Components that require testing either individually or in conjunction with others include: wave guides, directional couplers and bends, junctions, transitions, distribution manifolds, launch ports, windows, waterloads, antenna, mode filters, power monitors, and microwave isolation and shielding provisions. The results of tests will provide guidance and verification for the EBT-P design. Integrated system tests will demonstrate the functional capability, operating limits, fault detection, control and safety requirements, and so on, and provide qualification of the overall system.

ORNL is formulating a development plan based on the the proposed reference design.

Microwave Supporting Subsystems

These subsystems include the dc power supplies, automatic control networks for component protection, operational and performance monitoring, controls for operating multiple microwave sources, and personnel safety systems. Experience on EBT-S will be applicable; however, a supplementary development effort will be required to address the complex control aspects of EBT-P operation using multiple microwave sources.

Power supplies are the major item determining the cost of microwave heating systems. Significant cost savings would result from operating more than one gyrotron tube from a single power supply. A development and test plan is being formulated to be carried out on EBT-S initially and on EBT-P later to investigate the operation and controllability of two gyrotrons from one power supply. Results will not be available for the initial EBT-P installation but, if favorable, could reduce the cost of subsequent increases in microwave power.

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APPENDIX 10

ENGINEERING DRAWINGS

Engineering drawings prepared for EBT-P are included in this Appendix. A drawing list follows:

Drawing Number	Drawing Title	Series Number
S2E-8945B-SK1	EBT-P Reference Design General Layout	1
S2E-8945A-SK8	EBT-P Reference Design Compressor Building Addition	2
S2E-8945A-SK10	EBT-P Reference Design Roof Equipment Plan	3
S2E-8945-SK11	EBT-P Reference Design Device Enclosure 2nd Floor Plan	4
S2E-8945-SK12	EBT-P Reference Design First Floor Plan	5
X2D-14270-0012	EBT-P Reference Design Device Plan and Elevation	6
X2E-14270-0013	EBT-P Reference Design Device Details	7
X2E-14270-0014	EBT-P Reference Design Toroidal Vessel Details	8
X2E-14270-0015	EBT-P Reference Design Mirror Coil Assembly	9
P2D-57700-0001	EBT-P Reference Design Demineralized Water Flow Sheet	10
P2D-57700-0002	EBT-P Reference Design Cryogenics Flow Sheet	11
P2E-95306-0001	EBT-P Reference Design He Refrigerator Plan and Sections	12
E2E-14270-0001	EBT-P Reference Design Electrical One Line Diagram	13
I2E-14270A-006	EBT-P Reference Design Control Room Layout	14
I2E-14270A-010	EBT-P Reference Design System Instrumentation Block Diagram	15

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REV	DESCRIPTION	BY	CHK	RECT	DEPT	DATE	PE	REQ	DATE	UCCNO	DATE	ERDA	DATE	CA	EC	EE	EM	IE	M	PD	SE	XAD
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TOLERANCES UNLESS OTHERWISE SPECIFIED	DET. D. S. CAMPBELL R. 114
FRACTIONS	DET. P. D. DICKY R. 114
EX DECIMALS	DET. P. D. DICKY R. 114
XXX DECIMALS	DET. P. D. DICKY R. 114
ANGLES	DET. P. D. DICKY R. 114
BREAK SHARP EDGES	DET. P. D. DICKY R. 114
FIGURE	DET. P. D. DICKY R. 114
A. E.	DET. P. D. DICKY R. 114
UCC. NO.	DET. P. D. DICKY R. 114
ERDA	DET. P. D. DICKY R. 114

UNION CARBIDE CORPORATION - NUCLEAR DIVISION	
GENERAL LAYOUT	
S2E-8945A-SK1

PLAN
3/16" = 1'-0"

CONCEPTUAL

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ROOF EQUIPMENT PLAN

$\frac{1}{4}" = 1'-0"$ (ELEV. 967'-4")

NORTH ELEVATION
 $\frac{1}{4}'' = 1'-0''$

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															FRACTIONS 1/2 XX DECIMALS 2 XXX DECIMALS 3 APPROX 4 BREAK SHARP EDGES 5 MAX. FINISH 6										DRAWN L.VINARD 12/76				CHECK DEPT & PLANT					
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1st Fl. Pipe Below EBT-P
All Other New Pipe
MWS & MWR Demineralized Cooling
Water Supply & Return

[illegible]

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<u>CABINET NO.</u>	<u>EQUIPMENT</u>
1-21	MICROWAVE CONTROLS
22-27	CRYOGENICS AND FACILITY
28-30	MAGNET INSTRUMENTATION
31-35	DATA ACQUISITION
36-41	MAGNET INSTRUMENTATION
42-48	VACUUM SYSTEM
49-67	FIVE MACHINE DIAGNOSTICS
68-69	MCC VACUUM AND FACILITY CONTROLS
71	MCC CRYOGENICS
71-72	MCC MAGNET CONTROLLER
73-75	MCC MICROWAVE CONTROLS
76-80	INTERLOCKS AND ELECTRICAL
81-85	INTERLOCKS AND ELECTRICAL
MEZZANINE CABINETS	MACHINE DIAGNOSTICS BY EXPERIMENTERS

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