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This document is the final report for the Physics Modeling Support contract between TRW, Inc. and the Lawrence Livermore National Laboratory for fiscal year 1987. It is organized into five independent parts. Persons contributing to the tasks are noted on a separate cover page for each part. Each part has its own numbering system for pages, figures, and tables. Part 1 pertains to the TIBER Physics Modeling and Systems Code Development task and the Part 2 to the Advanced Blanket Modeling task. These two parts comprise the original Physics Modeling Support contract. Parts 3, 4, and 4a describe results from the tasks performed in support of the add-on to the original contract. Work on these latter tasks began in March 1987. The tasks are Time Dependent Studies (Part 3) and the Free Electron Maser (FEM) for TIBER II (Parts 4 and 4a). Part 4 is the main FEM section, and 4a is an addendum. This addendum describes the energy recovery system for the electron beam. An overview of each part will be presented in this summary.

1 TIBER Physics Modeling and Systems Code Development - M.E. Fenstermacher

For the 1987 fiscal year, tasks in the general category TIBER Physics Modeling and Systems Code Development were organized in twelve areas. Results from work in nine of these areas (numbers 2-8,11,12 in our proposal) are summarized in Part 1. Time dependent physics modeling calculations (tasks 1,9,10) have been done by D. T. Blackfield, and are reported under the heading Time Dependent Modeling below in Part 3. In Part 1, the time independent modeling work has been re-organized into five main categories: 1) TIBER physics modeling, 2) TETRA systems code module development, 3) MUMAK code development, 4) cognizance with the CIT community and ETOC recommendations, and 5) comparisons with the European ETR design, NET, the Japanese design, FER, and the Soviet design, OTR.

1.1 TIBER Physics Modeling

The following physics models have been developed in 1987 for the TIBER study:

- The loop voltage during pulsed inductive operation has been modeled including a detailed neo-classical resistivity calculation. Finite aspect ratio effects and radial profiles of plasma density and temperature are taken into account.

- A scaling formula for the bootstrap fraction of the total toroidal current has been developed through a collaboration with R. S. Devoto (LLNL) and A. A. Mirin (MFECC). The functional dependences of bootstrap current on the thermal component of the poloidal beta, the inverse aspect ratio, and the plasma effective charge are included in the model.
- A model has been developed for the pressure of the fast alphas and hot beam ions based on work done at the University of Wisconsin. Radial profiles of plasma density and temperature are included.
- A neutral beam attenuation and power deposition model has been developed for a monoenergetic pencil beam. Cross sections for electron and ion impact ionization and charge exchange are included.

All of these models have been used in determining the baseline steady state operating point described in Part 1.

1.2 TETRA Systems Code Module Development

Several modules have been developed and incorporated in the TETRA systems code during FY87. Some of these include adaptations of models which were developed for the MUMAK code during FY86. The modules which have been delivered to the FEDC systems code group are the following:

- A current drive efficiency module which calculates Amps/Watt conversion efficiencies for electron cyclotron resonance harmonic, lower hybrid slow wave, ion cyclotron harmonic fast wave, and neutral beam current drive has been delivered. Simplified versions of the MUMAK models have been developed for this systems code module.
- The fusion power from neutral beam-bulk plasma reactions is calculated as part of the plasma physics module based on models from the MUMAK code. Subroutines from MUMAK were adapted for the systems code for this case.
- A model for the partitioning of the non-inductive current in the core and edge plasma regions has been developed for the systems code. This calculation, when integrated, will be done as part of the physics module.

Final integration and testing of these modules will continue in FY88.

1.3 MUMAK Code Development

Several upgrades of the MUMAK code have been made this year. Subroutines corresponding to the physics models described above have been added to the code. In addition, several new types of MUMAK calculations have been developed including:

- Plasma Operating CONtour (POPCON) analysis for pulsed ignited operation has been developed. Comparisons of ignition capability for various devices can now be done with MUMAK.
- Steady state current drive calculations with the neutron wall loading constrained to a user specified value are now possible.
- Average surface heat load estimates on the first wall have been added.

MUMAK has also been made available to other users in the TIBER community this year. Global access files containing the source, sample input and output files, files needed for compiling and loading the source, and instructions have been created on the MFECC computer system. The instructions give enough detail that first time users of MUMAK can begin doing parametric analysis without additional references.

1.4 Cognizance with CIT and ETOC

POPCON analysis with MUMAK was developed to maintain cognizance with the CIT community in which pulsed ignited operation is the first priority. The MUMAK calculations have been benchmarked against independent POPCON results for CIT. The ignition capabilities of TIBER with the physics assumptions used for CIT are presented in Section III of Part 1. The recommendations of the ETOC have been incorporated in the calculation of the steady state baseline operating point. Specifications of beta limit scaling formulas, wall loading and plasma Q (=fusion power/input power) goals, and plasma profiles have been used for the baseline.

1.5 Comparisons with NET, FER and OTR

Finally, comparisons of TIBER pulsed ignited performance with that of NET, FER and OTR have been made using POPCON analysis. The major difference between the physics assumptions of TIBER and FER or OTR is the energy confinement scaling law used. Results for TIBER using the scaling laws from the FER and OTR

designs are given in Section III of Part 1. Comparison with NET involves differences in the assumed beta limits, plasma profiles and energy confinement scaling law. TIBER results using the NET assumptions are also presented in Section III.

1.6 Conclusions

In conclusion, all tasks relating to time independent power balance modeling for TIBER have been completed as described above. Tasks involving time dependent analysis were addressed by D. T. Blackfield with the Tokamak Time-Dependent Systems Code (TTSC) and are reported below. Results from this work have been reported at several plasma physics conferences including the American Physical Society Plasma Physics meeting, November 1986 in Baltimore MD and the Sherwood Plasma Theory meeting, April 1987 in San Diego CA. Results are also documented in the MUMAK report, LLNL UCID-21038, April 1987, Sections 2.4, 2.5 and Appendix A of the TIBER-II Final Design Report, LLNL UCID-21150 October 1987, and the TETRA systems code report ORNL/FEDC-87/7 (1987).

2 Advanced Blanket Modeling - R.B. Campbell

2.1 Description of Concept

The *microwave superheater* is a concept which can use the synchrotron radiation from a thermonuclear plasma to heat gas seeded with an alkali metal to temperatures far above the temperature of material walls. The idea is used in the innovative Compact Fusion Advanced Rankine (CFAR) cycle, although other blanket configurations could be substituted. Because of the need for copious amounts of synchrotron radiation, the microwave superheater is best suited for use with plasmas burning an advanced fuel such as $D-^3He$.

An advanced blanket such as CFAR is important to future tokamak reactor designs because it has the potential to eliminate the costly balance-of-plant. It is able to do this because the CFAR concept converts the fusion power directly into electricity within the confines of the reactor vault, eliminating the need for large turbines and associated buildings and equipment, and long runs of nuclear-grade piping.

Figure 1 in Part 2 shows a schematic diagram of the CFAR cycle using a microwave superheater. In its simplest form, the microwave superheater is a cylin-

dricl tube made of high temperature ceramic. The ceramic is transparent to the microwaves and serves as a window. The wall is maintained at a temperature which keeps microwave losses low, and may require transpiration cooling. Transpiration cooling involves the passage of a slip- stream of unseeded working fluid through tiny pores in the wall.

2.2 Scope of the Superheater Study

The present study is concerned with the description and modeling of the microwave superheater. We perform a detailed examination of heaters in the laminar flow regime, appropriate for a small scale demonstration experiment, although scaling to larger superheaters appears possible. Through parametric analysis, we determine the sensitivity of heater performance to changes in key parameters, such as gas pressure, seed fraction, and microwave intensity. Figures 6 through 9 in Part 2 show these results.

We have developed two steady-state codes which couple fluid dynamics, radiation transport, and plasma physics to predict the performance of the microwave superheater. A relatively simple 1-D code calculates the axial profiles of the bulk gas properties. Contour plots in parameter space obtained from this code are shown on Figure 4 of this part.

A more detailed 2-D code calculates both the radial and axial profiles of gas properties. Since issues of radial uniformity of the microwave heating are important, Part 2 will primarily concentrate on results of the 2-D model. The complete set of equations used in the model are described in detail in Section 3 of Part 2.

2.3 Important Results

We have considered experimental-sized superheaters operating in the laminar flow regime using helium seeded with lithium. The gas is heated by a monochromatic spectrum at 56GHz produced by a gyrotron. At reasonable pressures (0.1 to 1 atmospheres) and seed fractions ($\leq 10^{-4}$) we have found that the radial uniformity of the heating is sufficient to allow the bulk outlet temperatures to reach nearly 3000°K, when the inlet temperature is about 1200°K and the wall temperature is 1000°K. The seed concentration and intensity of the microwave radiation must be carefully controlled to avoid either overheating or underheating. Table 1 shows some parameters of the baseline superheater. The column "Without" is the same

case, but ignoring the radial energy loss channel for electrons. Without realistic radial losses, the amount of undesirable edge absorption increases dramatically, and the efficiency of the superheater is decreased.

2.4 Conclusions

Our conclusions from this study are that high bulk outlet temperatures can be achieved with microwave superheating in small proof-of-principle experiments. Quick scans of parameter space are accomplished with a radially averaged set of moment equations. The issue of radial non-uniformity of the heating is addressed with a radially resolved 2-D code.

In the range of operation we have studied, the microwave heating is sufficiently uniform that bulk gas temperatures above 3000°K are possible when the wall temperature is at 1000°K. Parametric studies indicate that the heating becomes more non-uniform when either the pressure, seed fraction, or radiation intensity is increased. It is particularly important to be able to control the radiation intensity to avoid overheating or underheating the gas. For superheaters with modest operating parameters, transpiration cooling will not be necessary. More work is needed to find out if reactor-sized superheaters will need it.

Simple scaling arguments indicate that superheaters for reactors can be built with microwave absorption properties similar to the smaller sizes. This scaling must be verified by detailed calculations using the 2-D code before anything definite can be claimed.

3 Time Dependent Modeling - D.T. Blackfield

3.1 Code Description and Capabilities

To perform this task, the Time-dependent Tokamak Systems Code (TTSC) was developed. TTSC solves radially-averaged time-dependent particle and energy balance equations together with various engineering constraints. The physics and engineering modules are time-dependent versions of the MUMAK and TETRA codes as they existed in early 1987. Models from these two codes were incorporated, made time-dependent, and combined with an MHD equilibrium scaling routine. The MHD scaling routine determines the required poloidal field and transformer coil currents to provide equilibrium and the necessary volt-seconds.

TTSC uses the steady-state plasma data from a TETRA output file and finds a reasonable startup scenario. TTSC determines auxiliary heating and fueling requirements, volt-second capability and startup time. These are features which MUMAK and TETRA, by their time-independent nature, cannot readily address. In addition, TTSC provides an initial assessment of the required OH and PF coil waveforms and checks to see if JB_{max} , B_{max} , and stress limits are exceeded.

TTSC has three basic modes of operation. In the fully time-dependent mode, time-varying particle sources for each ion species and heating sources for all species (including electrons) are known and the density and energy equations are solved. On the other hand, the desired density and temperature behavior may be prescribed and the required particle source is calculated. Finally, a realistic power source and density may be specified and the time-varying species temperatures determined.

3.2 Results

Part 3 in this document describes the model in more detail, specifically Sections 2.12.2 through 2.12.4. Figures 1-23 show various plasma engineering parameters as a function of time for a possible startup scenario for TIBER.

3.3 Conclusions

We have developed a 0-D time-dependent physics-engineering code which can quickly examine various startup scenarios and when coupled to the steady state non-linear optimization code TETRA, ascertain if the "optimal" steady-state operating conditions are achievable. TTSC can estimate volt-second requirements and capabilities and auxiliary heating and fueling requirements. In addition, TTSC can address potential magnet stress problems by examining B_{max} and JB_{max} at various coil locations.

TTSC has shown the effectiveness of auxiliary power in reducing the volt-seconds requirement during startup and has found a reasonable startup scenario for the pulsed-operation mode of TIBER. In addition, TTSC can estimate the burn time and volt-second capability of the magnet set.

The next version of the TTSC will include the most up-to-date physics and engineering routines from MUMAK and TETRA. We also hope to address the effect of rf current drive (in particular lower-hybrid) on the volt-second requirement and on the equilibrium scaling. We also intend calculating stresses in the OH and

PF coils to determine the burn time and volt-seconds capability. We will also use TTSC to examine expanding radius startup scenarios, since presumably at very low densities the plasma will be smaller and more circular. Finally, we will examine the effect of changing Z_{eff} from approximately 5 to the steady state value of 1.32 on the volt-seconds consumed during startup.

4 Free Electron Maser (FEM) for TIBER II - H. Böhmer, et. al.

4.1 Scope of Study

As part of the TIBER-II development program, a conceptual design of a C.W. Free Electron Maser (FEM) was performed. The FEM is intended as a source of microwaves for suppression of disruption in the Tokamak reactor via ECRH. Units with 2 megawatt power output at 450 and 225 GHz were considered. The requirements for the FEM systems are shown on Table I of Part 4. The operating parameters for a suitable FEM we have designed are listed in Table II.

Although all system requirements are met by the FEM parameters of Table I, it would be desirable to increase the gain bandwidth. For example, this could be done by increasing the interaction strength by increasing the beam current which also increase efficiency and output power. A previous conceptual design of a FEM for TIBER-I demonstrates this. Figure 4 of part 4 shows efficiency and gain bandwidth using a 2.36MV, 40A beam together with $\lambda_w = 5cm$, $B_w = 2kG$ wiggler resulting in 5.7 MW output power at 240 GHz. The gain curve for this case is 10% wide at 75% of peak gain.

4.2 Conclusions

The FEM design detailed in Parts 4 and 4a shows that a C.W. microwave source based on the FEM principle with electrostatic acceleration and a depressed voltage beam collector is a feasible choice for ECH in TIBER-II. Both second harmonic and fundamental heating are considered. Only standard technology is used in the design. With a total efficiency of 55% at 450 GHz and 2.9 MW of output power, the FEM should be a cost effective component of the TIBER-II reactor.

Apart from the modeling of the FEM interactions which will determine the

baseline parameters of the system, the most critical and time consuming part is the proper design of the electron beam line. Because of the late start of the FEM part of the TIBER-II program not all beam line calculations, particularly the design of the high power depressed voltage electron beam collector, could be done in time for the preparation of the final report. This necessitated the addendum to the FEM report, which we call Part 4a in this report.

PART 1

TIBER PHYSICS MODELING AND SYSTEMS CODE DEVELOPMENT

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TIBER PHYSICS MODELING AND SYSTEMS CODE DEVELOPMENT

FINAL REPORT

M. E. FENSTERMACHER

OCTOBER 15, 1987

TIBER PHYSICS MODELING AND SYSTEMS CODE DEVELOPMENT FINAL REPORT

M. E. Fenstermacher
October 15, 1987

I. TIBER PHYSICS MODELING

The following sections describe some of the results from the TIBER Physics Modeling and Systems Code Development tasks performed during FY87. The majority of the effort was spent in improving the models in the MUMAK tokamak power balance code and using the code for parametric analysis of TIBER-II. Several of these models were also adapted for and incorporated in the Tokamak Engineering Test Reactor Analysis (TETRA) systems code developed during FY87 at the Fusion Engineering Design Center (FEDC).

The remainder of this documentation is organized as follows. A description of the baseline operating point for TIBER-II which was generated with MUMAK is given in Section II. References are also given to more detailed descriptions of the models in MUMAK and the physics basis for the baseline operating point. Section III describes parameters of alternate operating points for TIBER-II generated by MUMAK. The capabilities of the code for Plasma OPERating CONTour (POPCON) analysis of pulsed operating points and parametric analysis of steady state burn operation are described. Section IV gives a brief description of the MUMAK code architecture with references to more detailed documentation of the code models. Section V describes the steady state current drive models which were developed for the TETRA code as part of this overall physics support effort. A summary of the work is given in Section VI.

II. TIBER-II BASELINE OPERATING POINT

II.1 Introduction

Plasma parameters for the baseline operating point of TIBER-II are described in this section. The baseline operating mode is steady state with non-inductive current drive by neutral beam injection (NBI), and lower hybrid (LH) current drive. Bootstrap current is included. The baseline parameters are summarized in Table II-1. The physics assumptions which are used in calculating these parameters are described in Ref. 1. Conservative physics assumptions have been used in the baseline

calculations in order to achieve high machine availability for nuclear testing under baseline conditions. Alternate operating points with more optimistic physics assumptions are presented in Section III.

II.2 Baseline Power Balance

The detailed power balance parameters for the baseline operating point are given in Table II-2. All terms in the power balance take into account the radial profiles of the density and temperature by integrating numerically the expressions for the powers using the assumed profiles (see Ref. 1).

Kaye-Goldston² energy confinement scaling is used with the power degradation term taken to be the sum of the alpha power and the current drive power minus the total radiation power (see Ref. 1). The radiation power includes bremsstrahlung and synchrotron radiation. The impurity is assumed to be oxygen with concentration $n_{\text{oxygen}}/(n_e + n_i) = C_{\text{oxygen}} = 0.024$. The concentration of thermal alpha ash is taken to be $C_\alpha = 0.05$. This results in an effective plasma charge $Z_{\text{eff}} = 2.1$. The wall reflectivity for the synchrotron power calculation is assumed to be 90%.

The thermal diffusivity for ions is taken to be equal to that for electrons so that $\tau_{E,e} = \tau_{E,i} = \tau_E$ (see Ref. 1). The H-mode energy confinement enhancement factor, defined by $H = \tau_E / \tau_E(L\text{-mode})$, has been selected to be $H = 1.14$. For the baseline beta constraint (0.75 times the ballooning beta limit) and the H-mode enhancement factor constraint, $1 \leq H \leq 2$, (see Ref. 1), this value optimizes both the wall loading and plasma Q value (fusion power/total input power) for the operating point. The average neutron wall loading is $\langle \Gamma \rangle = 1.3 \text{ MW/m}^2$, which produces nuclear heating in the inner leg of the toroidal field (TF) coils equal to the maximum set by the baseline assumptions for the magnet design including safety factors (see Ref. 1). The plasma Q value is 5.0 in this case. Higher values of H produce higher plasma Q value at lower wall loading for fixed beta; lower values of H give higher wall loading and lower Q.

The plasma shape is evaluated using the parameters for the 95% flux surface (see Ref. 1). The average neutron wall loading is estimated using an average scrapeoff thickness $\Delta r_s = 0.117 \text{ m}$. The model for the first wall assumes that this scrapeoff layer is uniform around the plasma periphery, although it is actually thinner on the inside than on the outside (see Ref. 1).

The partitioning of fast beam ion and fast alpha power to bulk electrons and ions during slowing down is calculated using a test particle formalism^{3,4}. Following Ref. 2, the equation for the test particle energy, E, assuming $v_i \ll v_{\text{test}} \ll v_e$ where v_i and v_e are the thermal velocities of the background ions and electrons respectively, is

$$dE/dt = -2E [1 + (E/E_c)^{1.5}] / \tau_E \quad (\text{II-1})$$

where the critical energy is (see also Ref. 5)

$$E_c = \left[\frac{3/\pi}{4} \frac{M^{3/2}}{n_e/m_e} \frac{n_j Z_j^2}{m_j} \Sigma \left(\frac{\ln \Lambda_j}{\ln \Lambda_e} \right)^{2/3} kT_e \right] \quad (\text{II-2})$$

and the slowing down time is

$$\tau_s = \frac{3 (kT_e)^{3/2}}{4 (2\pi m_e)^{1/2} Z^2} \left(\frac{4\pi\epsilon_0}{e^2} \right)^2 M / (n_e \ln \Lambda_e) \quad (\text{II-3})$$

The fraction of the test particle energy given to bulk ions then follows from

$$f_i = 2 V_c^2 / V_o^2 \int_0^X \frac{x}{(1+x^3)} dx \quad (\text{II-4})$$

where

$$V_c = 6k2Sc^2 = 2E_c/M, \quad V_o^2 = 2E_o/M, \quad X_c = V_o/V_c \quad (\text{II-5})$$

E_o is the birth energy, and M is the test particle mass. For the baseline operating point, all of the alpha power and neutral beam power is assumed to couple to the bulk plasma electrons and ions. Alpha and hot ion ripple losses have been computed and are found to be negligible⁶. All of the LH power is assumed to couple to the bulk plasma electrons since the fast tail electron slowing down time is much shorter than the electron energy confinement time.

Finally, the beam hot ion - bulk plasma fusion power is determined using reaction rate parameters calculated by the SIGV code⁷. The fast ion density is obtained from⁵

$$n_{\text{hot}} = I_b \tau_{s,\text{eff}} / V_p \quad (\text{II-6})$$

where the effective slowing down time is

$$\tau_{s,\text{eff}} = (\tau_s/3) \ln [1 + (E_b/E_c)^{1.5}] \quad (\text{II-7})$$

τ_s is the classical slowing down time, and V_p is the plasma volume. The fast ion pressure, p_{hot} , is calculated from the formalism in Ref. 2 (see Section II.3) and the average fast ion energy is

$$E_{\text{hot}} = 1.5 p_{\text{hot}} / n_{\text{hot}} \quad (\text{II-8})$$

This energy is used in the SIGV calculation to obtain the fusion reaction rate for hot ion-bulk Maxwellian reactions. The fusion power is calculated using average densities; no radial distribution

of fast ions has been calculated.

II.3 Fast Ion Beta

The finite pressure of fast alphas and fast beam ions is calculated from a slowing down distribution^{3,4}. Following Ref. 4, the distribution function for fast ions, neglecting up-scattering, satisfies the equation

$$\partial/\partial E [g(E) dE/dt] = S(E) \quad (II-9)$$

where dE/dt is given by Eq. II-1. For a monoenergetic and isotropic source,

$$S(E) = S_0 \delta(E - E_0) \quad (II-10)$$

the solution to Eq. II-6 is

$$g(E) = S_0 r_s / (2E [1 + (E_c/E)^{1.5}]) \quad \text{for } E < E_0 \quad (II-11)$$

and $g(E > E_0) = 0$. The pressure of the hot ion distribution is obtained from

$$p = MS_0 r_s^2 V_c^2 / 3 \int_0^{x_c} dx \frac{x^4}{(1+x^3)} \quad (II-12)$$

where the definition of V_c is given in Eq. II-5. The fast ion pressure is included in the MHD beta limit for the baseline operating point.

II.4 Current Drive Parameters

Detailed parameters for the NBI and LH current drive systems are given in Table II-2. The total non-inductive current requirement is given by $I_{cd} = I_p - I_{bs}$ where I_{bs} is the bootstrap current. The scaling relation for the bootstrap current is given in Ref. 1. Neutral beams of sufficient energy to penetrate to the plasma axis are used for core current drive; lower hybrid slow waves are used on the outer flux surfaces. The radius within which the LH waves do not penetrate, r_{max} , is determined by combining the conditions for wave accessibility and avoidance of strong quasi-linear electron Landau damping (see Ref. 1).

The partitioning of the total non-inductive current between the NBI and LH systems is done using model current density profiles. The current density profile for the total plasma current, $j_p(r)$, is consistent with the equilibrium solution (see Ref. 1). A model current density profile for the bootstrap current, $j_{bs}(r)$, is obtained from Fokker-Planck analysis⁵ (see Appendix C). The remaining current density profile, $j_{cd}(r) = j_p(r) - j_{bs}(r)$ is integrated out to the radius of maximum penetration for the LH waves, r_{max} , to give the core current fraction f_c . The neutral beam and lower hybrid currents are then

$I_{nb} = f_c I_{cd}$ and $I_{lh} = I_{cd} - I_{nb}$ respectively. The current drive efficiency calculations are described in Ref. 1.

II.5 Fueling Requirements and Alpha Ash Removal

The fueling requirements for steady state operation of TIBER are given in Table II-4. The total deuterium (tritium, assuming a 50:50 mixture) current which must be replenished in steady state is 121.8 A. This includes 17.8 A of fuel ion burn-up and 104 A of direct particle loss. To estimate particle lifetimes for steady state operation, the alpha particle balance equation is solved for the thermal alpha confinement time, $\tau_{p,\alpha}$, assuming a thermal alpha concentration, $C_\alpha = 0.05$. The thermal fuel ion confinement time, $\tau_{p,i}$, is then assumed to be equal to the thermal alpha confinement time. The neutral beams supply 87.3 A of deuterium in steady state, assuming the fast ion confinement time is long compared with its slowing down time. The remainder of the required current must be supplied by the fueling system (see Ref. 1).

Note that for the baseline parameters, $\tau_{p,\alpha} \approx 10 \tau_E$ to be consistent with the assumption that $C_\alpha = 0.05$. Experimental results typically indicate that $\tau_{p,i} \approx 3-5 \tau_E$. If this were the case for TIBER in steady state, the thermal alpha concentration would be reduced but the fueling requirements would increase.

III. ALTERNATE OPERATING POINTS

III.1. Introduction

Parameters for operating points of TIBER-II, different from the baseline operation described in Section II, are described here. This section also serves as an introduction to the description of pulsed operating scenarios given in Ref. 1. All of the calculations described below were made with the MUMAK time-independent, zero-dimensional power balance code⁹ (see Appendix A). Results of time dependent calculations, which produce scenarios for evolving the plasma from initiation through current rampup, densification and heating, and ultimately to the baseline and alternate operating points calculated with MUMAK, are given in Ref. 1.

III.1.1 Motivation. The baseline operating mode for TIBER-II is steady state operation with neutral beam injection (NBI), lower hybrid (LH) current drive, and bootstrap current. Other operating modes are of interest, however, especially in the context of comparing the capabilities of the TIBER design with other national designs such as the Next European Torus (NET), the Fusion Engineering Reactor (FER) and the Soviet design (OTR). There are three reasons for exploring alternate operation points for TIBER-II. First, the potential of the design for reaching an ignited operating point must be assessed so that comparisons

with other tokamak reactor studies, in which ignition is the driving factor in the design decisions, can be made. Second, the ranges of advanced steady state physics experiments and advanced engineering tests which are possible without making major modifications to the device, must be assessed. These results have an impact on plans for the operation of the machine toward the end of its operating lifetime. Finally, results from studies of both pulsed ignited and advanced steady state operating points provide targets for time dependent analysis of TIBER-II, in which the time history of the plasma build-up to the steady state or ignition conditions must be determined.

The general framework for the studies presented in this section is summarized in Table III-1. The scope of parameters for each study is described below followed by the results.

III.1.2 Scope of the Pulsed Operating Points. Pulsed operation, with the goal of achieving ignition, has been studied for the TIBER-II design using a range of toroidal currents and with a variety of energy confinement scaling laws. Cases will be presented using a set of assumptions which are consistent with those used in the CIT¹⁰ studies (see Ref. 1 for discussion of the physics basis for TIBER). The currents used range from 8MA to 12.5MA. In addition, cases at toroidal current of 8MA have been run with the four energy confinement scaling laws used by the ETR design teams in the U.S.^{1,11}, Europe¹², Japan¹³, and the Soviet Union¹⁴.

The results are presented in all cases in the form of Plasma Operating CONtour (POPCON)¹⁵ plots. These are contour plots of the auxiliary power required to sustain the power balance at points in a density versus temperature space. Density limits, from either the Murakami¹⁶ or Greenwald¹⁷ formulas, and beta limits, from either the Troyon¹⁸ or the Yamazaki¹⁹ formulas, tend to produce boundaries for an "operating window" in density vs. temperature space in which the required auxiliary power is less than or equal to zero. Zero auxiliary power requirement means that the plasma power losses are balanced by the alpha heating and the Joule dissipation (ohmic heating) alone. Negative auxiliary power requirement indicates that some additional degradation of confinement or enhanced radiation power loss, which has not been accounted for in the modeling, can be tolerated during operation. This is often referred to as an "ignition margin".

The final step is to estimate the loop voltage for conditions in the operating window. Combining this with the available flux swing (Volt-seconds) from the magnet set allows an estimate of the ignited burn time to be made. Combining this with the neutron wall loading during the burn allows estimates of the fluence from ignited operation to be determined. These calculations will be presented in Ref. 1

III.1.3 Scope of the Steady State High Performance Operating Points High performance steady state operation has been investigated with the assumption that NBI and LH would be used

for current drive in the core and edge plasma regions, respectively, as in the baseline operating point. Cases operating at the limits set by physics constraints, without the margin incorporated in the baseline operating point, have been generated. High plasma Q value ($Q = \text{fusion power} / \text{total power input to the plasma} \approx 20$) and high peak neutron wall loading $\Gamma \approx 3.5 \text{ MW/m}^2$ have been calculated.

High performance operation of TIBER-II with NBI and LH current drive has been achieved at lower toroidal current than in the baseline scenario. Scoping studies have shown that the plasma Q value for NBI + LH scenarios tends to maximize for intermediate values of toroidal current with large bootstrap current fraction. The bootstrap current fraction I_{bs}/I_p , where I_p is the toroidal current, scales linearly with the thermal component of the poloidal beta (see Ref. 1). This implies that the toroidal current must be as low as possible (for fixed toroidal beta given by a beta limit) to give low poloidal magnetic field and hence high poloidal beta. However, the energy confinement time and the toroidal beta limit decrease with decreasing current (see Ref. 1) so an intermediate current of 8 MA for TIBER-II seems to produce the best performance.

Other characteristics of the high performance cases include: 1) operation at the full ballooning beta limit given by the Yamazaki formula, 2) full H-mode energy confinement enhancement (factor of two increase in confinement time over Kaye-Goldston L-mode) for the high Q cases, 3) pure deuterium neutral beams with 1 MeV energy, and 4) lower hybrid waves with 90% of the power launched in the direction of the toroidal current. The corresponding baseline assumptions were (see Section II): 1) operation at a more conservative kink beta limit, 2) partial H-mode enhancement (factor of 1.14 increase in confinement time) 3) 500 keV neutral beams and 4) LH waves with only 80% of the power launched in the direction of the toroidal current.

The bootstrap current fraction scaling used in these cases includes the dependence on the thermal component of the poloidal beta, the inverse aspect ratio, and the plasma effective charge (see Ref. 1). Finally, the assumption has been made that only 60% of the beam hot ion beta is included in the toroidal beta limit. This value has been used to reflect preliminary theoretical estimates of the bulk plasma stabilization due to hot beam ion finite Larmor radius effects²⁰.

In the sections below, high performance physics operating points and advanced engineering operating points will be contrasted and the device modifications, if any, required to achieve each scenario will be described.

III.2 Pulsed Operating Points

Scoping studies have been made to determine the capability of the TIBER-II design for achieving ignition under various physics assumptions. The calculations are grouped into two study areas: 1) effects of various energy confinement scaling

laws and, 2) consequences of operation at various toroidal currents, I_p . The results are presented in the form of POPCON plots. A typical POPCON plot is shown in Fig. III-1. The capability for achieving ignition is evaluated from these plots by the existence and size of an operating window in which the plasma power losses are sustained by the alpha heating and the ohmic heating alone. The operating window boundaries (outlined in Fig. III-1) are the contour of zero auxiliary power, the density limit and the MHD beta limit.

III.2.1 Effect of Toroidal Current Variations. Cases which have been run in the study of toroidal current effects include plasmas with 8, 10, and 12.5 MA toroidal current. The assumptions made in all of these cases are summarized in Table III-2. The energy confinement scaling law used will be denoted the Kaye-Goldston plus Neo-Alcator (KG+NA) scaling. For this scaling, the gross energy confinement time τ_E is the quadrature sum (as proposed by Goldston²¹) of the Kaye-Goldston time², τ_{KG} , and the Neo-Alcator time²², τ_{NA} , (see Ref. 1) as

$$\tau_E = [(\tau_{KG})^2 + (\tau_{NA})^2]^{1/2} \quad (\text{III-1})$$

where H is the H-mode enhancement factor taken to be in the range $1 \leq H \leq 2$. Cases with full H-mode (H=2) are shown in Figs. III-1 - III-3 for TIBER operated with 8, 10, and 12.5 MA respectively. A case at $I_p=12.5$ MA using L-mode (H=1.0) confinement is shown in Fig. III-4. The density limits shown in these figures correspond to the Murakami formula¹⁶ with leading coefficient 1.5 (hereafter referred to as the Murakami limit) and 0.75 times the Greenwald formula¹⁷ (hereafter referred to as the Greenwald limit). The beta limit which is highlighted in the figures corresponds to the Troyon kink formula¹⁸ with leading coefficient 2.8%. As expected, the increase in energy confinement and Troyon beta limit as the current increases tends to open the ignition operating window. The following conclusions can be drawn from these results:

- $I_p=8$ MA, H=2 : No ignition window exists for densities below the Murakami limit. A narrow window exists for densities below the Greenwald limit for temperatures in the range $7 < T < 12$ keV. The power required to get through the saddle point is 9 MW.
- $I_p=10$ MA, H=2 : Ignition is marginal below the Murakami limit and a window exists only for high temperatures $T > 12$ keV. A substantial ignition window exists for densities below the Greenwald limit for temperatures in the range $6 < T < 15$ keV. The power required to get through the saddle point is 9 MW.
- $I_p=12.5$ MA, H=2 : An ignition window exists below the Murakami

limit for temperatures in the range $8 < T < 15$ keV. The beta limit is not important in this case. The power required to get through the saddle point is 9 MW.

H=1 : A narrow ignition window exists below the Greenwald limit for temperatures in the range $8 < T < 10$ keV. The power required to get through the saddle point is 18 MW.

These results are summarized in Table III-3.

III.2.2 Effect of Energy Confinement Scaling Law. Cases which have been run in the study of energy confinement scaling include calculations with KG + NA (Eq. III-1), Mirnov²³ scaling

$$\tau_{Mir} = 0.15 I_p (A_p/\pi)^{0.5} \quad (III-2)$$

and Mereshkin scaling²⁴

$$\tau_{Mer} = 4.43 \times 10^{-3} n_{e20} (a/R_0)^{-2.5} R_0^{3.0} q_{NET} A_i^{0.5} T_{e10}^{-0.5} \quad (III-3)$$

using the assumptions listed in Table III-2. In Eqs. III-2 and III-3, A_p is the plasma cross sectional area (m^2), and the equivalent atomic mass is taken to be $A_i = A_p A_T / 2 = 3$. Additional calculations have been done with the assumptions given in Table III-2 modified as shown in Table III-4 and using the Asdex H-mode energy confinement scaling²⁵,

$$\tau_{As} = 0.065 I_p R_0 (A_p + A_T)^{0.5} \quad (III-4)$$

This last set of calculations shows the performance of TIBER-II under the physics assumptions used to evaluate the ignition capability of NET¹². In all cases, the toroidal current is $I_p = 8$ MA. Results are shown in Figs. III-5 - III-7. The beta limit outlined in these figures corresponds to the Troyon value with leading coefficient $g = 2.8\%$. Note that the assumption used for NET is $g = 3.5\%$, corresponding to the dashed curve labelled 0.059 in Fig. III-7. The operating window for ignition is substantially larger with this assumption. Conclusions which can be drawn from these figures are the following:

KG + NA scaling : No ignition window exists below the Murakami
H-mode density limit. A narrow ignition window exists
for densities below the Greenwald limit for
temperatures in the range $7 < T < 12$ keV.
The power required to get through the saddle
point is 9 MW.

Mereshkin scaling : No ignition window exists below the Murakami limit. A narrow ignition window exists for densities below the Greenwald limit for temperatures in the range $7 < T < 10$ keV. The power required to get through the saddle point is 14 MW.

Mirnov scaling : No ignition window exists below the Murakami limit. A narrow ignition window exists for densities below the Greenwald limit for temperatures in the range $8 < T < 13$ keV. The power required to get through the saddle point is 11 MW. High temperature, $T > 10$ keV, is required at the saddle point.

NET assumptions : Ignition is marginal for densities below the Murakami limit at high temperatures, $T > 15$ keV. A narrow ignition window exists for densities below the Greenwald limit for temperatures in the range $9 < T < 17$ keV. The power required to get through the saddle point is 8 MW. High temperature, $T > 15$ keV, is required at the saddle point.

These conclusions are summarized in Table III-5.

III.3 Steady State High Performance Operating Points

The baseline steady state operating point for TIBER-II incorporates conservative physics and engineering assumptions in a number of areas. In this section, alternate steady state operating points are presented, using NBI and LH current drive systems as in the baseline device, in which several of the conservative physics and engineering limits are removed.

The most important of the physics limits is the MHD beta limit. In the baseline scenario the operating beta is taken to be the conservative kink limit given by the Troyon formula with coefficient $g=2.8\%$. For the cases below, the full ballooning beta limit given by the Yamazaki formula is used. For TIBER-II parameters $B_0=5.55$ T, $\kappa=2.4$, $\delta=0.4$, using a toroidal current of 8 MA, and the full minor radius to the separatrix $a=.855$ m, this means that the operating beta increases from $\beta_{op}(\text{Troyon})=4.7\%$ to $\beta_{op}(\text{Yamazaki})=6.6\%$.

Other physics parameters have been changed for the high performance calculations. The plasma effective charge Z_{eff} has been reduced from 2.1 to 1.5 because the scaling of the bootstrap current fraction with Z_{eff} produces higher values as Z_{eff} decreases (see Ref. 1). The beam energy has been increased to $E_b=1$ MeV for higher current drive efficiency. This would require an upgrade of the accelerator technology in the neutral beam system (see Ref. 1). Finally, it has been assumed that

improvements to launching grill designs for the LH waves could increase the fraction of the LH power launched in the direction of the toroidal current from the 80% assumed in the baseline to 90%. These characteristics are summarized in Table III-6.

Another physics constraint which becomes important when maximum wall loading cases are calculated is the density limit. High wall loading cases with densities up to the full Greenwald value have been explored. In the baseline calculation it is assumed that the density limit is 75% of the Greenwald value. The baseline operating point is actually well below this limit even with the 25% margin because the maximum achievable wall loading (and therefore the required density to achieve this wall loading) is limited by conservative limits on neutron heating in the inner leg of the toroidal field (TF) coils (see Ref. 1) The TF coil system has been designed to operate with nearly a factor of two higher heat load than is produced by the baseline operating point. High performance operating points have been investigated which produce up to a factor of two higher wall loading ($\langle \Gamma \rangle \approx 2.6 \text{ MW/m}^2$) compared with the baseline ($\langle \Gamma \rangle = 1.3 \text{ MW/m}^2$). In principle these operating points could be achieved without modifications to the coils or shield. With improvements in the forced flow cooling capabilities in the TF coils, even higher wall loading might be possible in TIBER-II.

To identify optimum operating points for both high Q and high neutron wall loading, scans of power balance solutions have been made using values of the H-mode enhancement factor in the range $1.0 < H < 2.0$ and using an operating beta fraction normalized to the full Yamazaki ballooning beta limit, $f_b = \beta_{op}/\beta(\text{Yamazaki})$, in the range $0.7 < f_b < 1.1$. The results are given in Fig. III-8. Contours of the plasma Q value (solid lines) and the average neutron wall loading (MW/m^2 - dashed lines) are shown. For fixed beta equal to the ballooning limit ($f_b = 1.0$), the Q value maximizes at $Q=21$ for $H=2.0$. The wall loading is maximum for $f_b=1.0$ at $H=1.45$ where $\langle \Gamma \rangle = 2.4 \text{ MW/m}^2$. The peak-to-average wall loading ratio for TIBER-II geometry is approximately 1.5 so this corresponds to peak wall loading of $\Gamma = 3.6 \text{ MW/m}^2$.

Parameters from the individual cases corresponding to the maximum Q and Γ values in Fig. III-8 are given in Table III-7. These cases have been refined somewhat compared with the corresponding points in Fig. III-8 particularly in the calculation of the radius of maximum penetration for the LH waves. This refinement also affects the partitioning of the neutral beam and lower hybrid driven currents.

III.4 Summary

Two classes of alternative operating points have been examined for TIBER-II. Pulsed ignited operating points have been studied with POPCON analysis. High performance steady state operating points have been found which give high plasma Q value and alternately high neutron wall loading.

The consequences of operation at various toroidal currents have been determined for pulsed scenarios. As expected, the ignition window becomes larger as the current increases because both the density limit and the beta limit increase with current. In addition, the ohmic power contribution to the power balance increases with current (at each point in density vs. temperature space) which further widens the operating window for ignition. These results are summarized in Table III-3. Also, the effects of various energy confinement scaling laws have been studied including KG + NA, Mereshkin, and Mirnov scalings. Studies using the NET assumptions (including Asdex H-mode scaling) have also been done. Ignition is marginal for all four of these scalings for densities below the Greenwald limit and beta less than the Troyon kink limit with a leading coefficient of 2.8%. The temperatures in the ignition windows and at the saddle points of the POPCON plots are higher for the cases with Mirnov scaling and with the NET assumptions than for the KG + NA and Mereshkin scalings. For fixed inductive volt-seconds available during the burn, higher temperature means longer burn time because the loop voltage decreases with temperature. These results are summarized in Table III-5.

It has been found that with NBI + LH current drive, optimum steady state performance occurs in TIBER-II at an intermediate value of toroidal current, $I_p = 8$ MA. This results from a balance between the performance advantages of high bootstrap current fraction (ie. low toroidal current) and high beta and confinement time (ie. high toroidal current). Calculations using this current and physics assumptions which are less conservative than those incorporated in the baseline operating point have found operating points with high $Q \sim 20$ and high neutron wall loading $\Gamma \sim 3.7$ MW/m². The most important assumptions used in these scenarios are : 1) operation at the ballooning beta limit and 2) use of 1 MeV neutral beams for good penetration to the axis at higher densities than in the baseline operating point. These high performance points can be sustained in steady state with no more current drive power than is specified in the baseline scenario.

IV. A BRIEF DESCRIPTION OF MUMAK

IV.1 Introduction

MUMAK⁹ is a zero-dimensional (volume averaged), time independent power balance code for modeling plasma particle and energy flow in tokamaks. The equations describing the steady-state power balance include terms for alpha power from D-T burning plasmas, inductive (ohmic) as well as non-inductive current drive power, conduction power losses described by empirical energy confinement scaling laws, and radiation power losses. Radial profiles of plasma density and temperature are controlled by input parameters and are assumed fixed for the power balance calculations.

MUMAK also performs calculations of non-inductive current drive efficiencies for electron cyclotron harmonic (ECH), neutral beam injection (NBI), lower hybrid (LH) slow wave, and fast wave (FW) current drive. The ECH models include relativistic effects and degradation of the efficiency due to electron trapping effects. The NBI models also include the effects of electron trapping as well as the beam energy dependence. The LH models take into account both the accessibility limit and the condition for avoiding strong electron Landau damping of the wave to determine the radius of maximum penetration for the waves.

Ancillary calculations performed by MUMAK include the determination of volumetric neutron source strength from D-T burning plasmas, thermal stability analysis of the steady-state burn operating point, and numerous graphical diagnostics. Radial plots of cyclotron and plasma frequencies, optical depth for ECH waves of various polarizations and the volumetric neutron source strength can be generated. Results from one and two dimensional scans of parameter space can also be plotted.

MUMAK also contains several models which address issues that are unique to steady-state tokamak operation. The first one is the particle balance of fusion alpha particles. This particle balance is computed at the solution (operating) point and the required alpha particle confinement time necessary to maintain the steady-state thermal alpha concentration (user specified) is determined. Tokamak designs with burn pulses much longer than this time must specify some mechanism by which the alphas are removed or the accumulation of alpha ash will eventually choke off the burn.

Another unique feature of steady state tokamak burn modeled by MUMAK is that the current drive power P_{CD} is comparable to the alpha power. For fixed toroidal current, P_{CD} is also sensitive to the plasma density and temperature at the operating point. The overall power balance is therefore quite sensitive to the current drive efficiency scaling and to the partitioning of the current drive power between bulk electrons

and ions.

IV.2 Method of Solution

The power balance equations in MUMAK are formulated as a set of N non-linear equations in N unknowns (N = 3 or 4). The non-linear equation solver COSNCF from the NAG mathematics library²⁶ is used to obtain a solution (a zero) to these equations to a specified accuracy. Routines are also available to search for multiple solutions to the equations. This is done by renormalizing the power balance equations after the first solution is found so that a new set of equations is generated for which the first solution is no longer acceptable. This renormalization is done in such a way that if a solution to the new set of renormalized equations is found it will satisfy the original power balance.

Power balance solutions are found by varying plasma temperatures, densities, energy confinement time, and operating beta. A two-fluid model is used with separate power balance equations for electrons and ions including electron-ion drag. The electron power balance equation takes the form

$$P_{\alpha e} + P_{ie} + P_{OH} + P_{CD,e} + P_{aux,e} = P_{c,e} + P_{rad} \quad (IV-1)$$

where

$P_{\alpha e}$	= alpha power deposited in bulk electrons
P_{ie}	= ion-electron drag power
P_{OH}	= ohmic heating power
$P_{CD,e}$	= non-inductive current drive power to bulk electrons
$P_{aux,e}$	= auxiliary bulk electron heating power
$P_{c,e}$	= bulk electron transport power
P_{rad}	= bulk electron radiation power

The electron radiation term includes bremsstrahlung and synchrotron power losses. The ion power balance equation is

$$P_{\alpha i} - P_{ie} + P_{CD,i} + P_{aux,i} = P_{c,i} \quad (IV-2)$$

where

$P_{\alpha i}$	= alpha power deposited in bulk ions
$P_{CD,i}$	= non-inductive current drive power to bulk ions
$P_{aux,i}$	= auxiliary bulk ion heating power
$P_{c,i}$	= bulk ion transport power

Detailed expressions for the terms in Eqs. (IV-1) and (IV-2) are given in Ref. 9.

The independent variable corresponding to the electron power balance equation is the density weighted volume averaged electron temperature, $T_e = \langle n_e T_e \rangle / \langle n_e \rangle$ (angle brackets denote volume averaging). Temperature and density profiles are taken to be of the form

$$X(r) = X(0) [1 - (r^2/a^2)]^{\alpha_X} \quad (IV-3)$$

where $X = n, T$. Volume averaging over these profiles is done using a circular flux surface model. For the ion power balance the ion temperature $T_i = \langle n_i T_i \rangle / \langle n_i \rangle$ or the gross energy confinement time, τ_E , parametrized by an H-mode enhancement factor, $H = \tau_E / \tau_E(\text{L-mode})$, can be varied. The third equation is a gross pressure balance constraint which requires that the total plasma pressure normalized to magnetic field squared be equal to a user specified operating beta. Typically this equation is used to determine the volume averaged electron density $n_e = \langle n_e(r) \rangle$. For solutions with user specified n_e , this equation can also be used to specify the operating beta. Finally a fourth equation is available which constrains the solution to a user specified value of average neutron wall loading $\langle \Gamma \rangle$. In this case, either the operating beta or the energy confinement enhancement factor, H , can be varied providing it is not being used as the independent variable for one of the other equations.

Typically, the user specifies the total toroidal current, the empirical scaling law for energy confinement, and the type of current drive to be used. From the current and the plasma shape MUMAK derives the beta limit either from the Troyon¹⁸ expression or the Yamazaki¹⁹ formulas and the density limit from the Murakami¹⁶ or Greenwald¹⁷ expressions. The user also specifies either the H-mode energy confinement enhancement factor, H , or the fraction $f_{\text{crit}} = \beta_{\text{(operating)}} / \beta_{\text{(critical)}}$ (or both if $\langle \Gamma \rangle$ is allowed to vary). Scenarios without current drive power, in which the plasma current is assumed frozen (long L/R decay time) can also be modeled. For some special cases, the current drive power may be input and the models will calculate the resulting toroidal current.

MUMAK can also perform Plasma OPERating CONtour (POPCON) analysis. The user specifies NEQ-2 and sets the density and temperature to the desired values. The auxiliary power required to satisfy power balance for the electrons and for the ions is calculated separately. The sum of the electron and ion powers can easily be plotted for each density and temperature in a density versus temperature space to generate a POPCON plot.

IV.3 Future Upgrades

Though MUMAK contains all of the basic components for a complete zero-dimensional description of steady-state tokamak power balance, several improvements can still be made. The model which determines the core current fraction, in cases using multiple current drive schemes simultaneously, will be upgraded so that the current density profile data can be read in from external files. This will allow results from 2-D MHD calculations to be read by MUMAK without changing the source and recompiling. Results from Fokker-Planck and transport calculations which predict the bootstrap current density profile

will be accessible by MUMAK in the same way. This should increase the accuracy of the partitioning of toroidal current into bootstrap and multiple current drive components calculated by MUMAK.

The NB current drive models will be improved to include ion trapping effects and the degradation of the efficiency due to toroidal plasma rotation. Preliminary estimates indicate these two effects may decrease the A/W conversion efficiency for NBI current drive by 10-30%. For NBI calculations, improvements are also required in the hot ion model. Particular attention will be given to improving the calculation of the average hot ion energy. This may have an appreciable effect on the hot ion fraction of the operating beta. This is an important calculation since the performance of many ETR class tokamaks may be limited by achievable beta more than other factors.

The deleterious effects of beam ion instabilities on the NBI current drive efficiency must be modeled in MUMAK. For beams with particle velocities above the Alfvén speed in the plasma, instabilities may increase the beam ion slowing down²⁷ thereby significantly reducing the current drive efficiency. The beneficial effects of bulk plasma stabilization by beam ions must also be modeled. Preliminary theoretical estimates²⁰ indicate that the toroidal beta limit may be increased with beam injection.

Finally, the MUMAK power balance models may be expanded to treat the core and edge power balances separately. This upgrade would require models for energy transfer between regions, separate energy transport scaling for each region and accurate partitioning of the current drive and auxiliary power to the regions in which the power is absorbed. This kind of calculation may be required to more accurately treat scenarios in which LH power is absorbed in the edge and heats electrons there while another form of current drive power is absorbed in the core.

IV.4 Documentation

A report⁹ exists which is intended to serve both as a reference to the physics models incorporated in MUMAK and as a user's guide to running MUMAK. Since MUMAK is presently configured as a BASIS package²⁸⁻³⁰, users will need to become somewhat familiar with BASIS to appreciate the full capability of the MUMAK package for parametric analysis. The user's guide in this document will give enough information on running MUMAK under BASIS to generate individual cases and simple parametrics. Readers interested only in using MUMAK as a "black-box" can skip Secs. 3-6 in the report without loss of continuity.

The report is organized as follows. Section 2 presents an overview to the mathematical approach for solving the power balance equations, including a description of some of the unique features of steady-state tokamak operation which are modeled. The detailed power balance equations are described in Sec. 3.

The steady state current drive efficiency models are presented in Sec. 4. Several additional calculations performed by MUMAK such as the volumetric neutron source calculation and the thermal stability analysis are described in Sec. 5. Sample results for the TIBER-II configuration are given in Sec. 6. A self contained user's guide is given in Sec. 7. A summary, including the present status of the MUMAK modeling effort and future plans, is presented in Sec. 8.

V. NON-INDUCTIVE CURRENT DRIVE MODELS IN THE TETRA CODE

The models used in the TETRA code to calculate amps-per-watt conversion efficiencies for various non-inductive current drive schemes are described below. These models are found in subroutine CURDRIV of the TETRA code. This subroutine is modular so that modifications can be made to any of these models without affecting the others. Models of current drive schemes which are not presently included can be added easily.

As in all modules of the TETRA code, a balance has been struck here between the need for accuracy in the computations and the requirement that the models be simple enough for use in a systems code environment. References will be made below to areas where more work is required to develop systems code compatible adaptations of more detailed calculations which can be installed in the TETRA code next year.

V.1 Neutral Beam Injection Current Drive

The conversion efficiency for current drive by neutral beam injection, η_{nb} , is calculated in a subroutine ETANB which is called by CURDRIV. The modeling equations in ETANB are described in detail in Refs. 31-35. The equation for the efficiency is

$$\eta_{nb}(A/W) = f_d T_e J(x,y) F_{nb} [1 - e^{-\tau_{nb}}] / (R_0 n_{e20} \ln A) \quad (V-1)$$

where f_d is a coefficient which calibrates this scaling formula to Fokker-Planck results ($f_d=2.65$ is used at present), T_e is the electron temperature (keV), $J(x,y)$ is a function⁵ of the beam energy ($x^2 = E_{beam}/E_{critical}$) and the plasma effective charge [$y = f(Z_{eff})$], F_{nb} is a degradation factor^{32,33} to take account for electron spin-up effects ($F_{nb}=0.76$ is used at present), τ_{nb} is the effective optical depth for the beam ions⁵ [ie. the shine-through fraction is $f_s = \exp(-\tau_{nb})$], R_0 is the plasma major radius (m), n_{e20} is the electron density (10^{20} m^{-3}) and $\ln A$ is the Coulomb logarithm. For typical TIBER-II parameters, $T_e \approx 13$ -20 keV, $n_{e20} \approx 1.0$, $R_0 = 3.0\text{m}$ the efficiency is $\eta_{nb} \approx .08 \text{-.} .10 \text{ (A/W)}$.

The required neutral beam power for current drive, P_{nb} , is calculated as $P_{nb} = I_{nb}/\eta_{nb}$ where I_{nb} is the current to be driven by the beams. At this writing, the models in the code assume that all of the neutral beam power is eventually transferred to the background plasma ions as the beam ions slow down. Models

for calculating the partitioning of the beam power between background electrons and ions, which are described in Refs. 31-35, will be adapted for use in the TETRA code next year. This partitioning is important for the power balance calculation when solutions are computed for the electron and ion power balances separately.

V.2 Lower Hybrid Current Drive

The scaling formula used in the TETRA code for calculating lower hybrid current drive efficiencies is a fit by Logan³⁵ to efficiencies calculated by Karney and Fisch³⁶. For parallel indices of refraction, $N_{||}$, of the lower hybrid waves in the range $1.5 \leq N_{||} \leq 2.0$ the efficiency is approximated well by

$$\eta_{lh}(A/W) = 0.36 [1 + (T_e/25)^{1.16}] / (R_0 n_{e20}) \quad (V-2)$$

where T_e , n_{e20} , and R_0 have been defined previously. An option also exists in the code to use a scaling recommended for the INTOR studies³⁷

$$\eta_{lh}^{INTOR}(A/W) = 0.3 / (R_0 n_{e20}) \quad (V-3)$$

Equation (2) tends to over estimate the efficiency at high T_e (>25 keV) because it does not include the effect of relativistic mass increase of the current carrying electrons in the tail of the distribution as T_e increases. Equation (3) represents present experimental results but tends to give lower efficiencies than detailed theoretical calculations for TIBER-like parameters. Neither formula takes into account trapped electron effects which reduce the efficiency, nor do they take into account any lower hybrid wave power which may be launched in a direction opposite to the current. Detailed models for some of these effects (given in Ref. 1) will be adapted for use in the TETRA code soon. Finally, the required lower hybrid power is calculated from $P_{lh} = I_{lh}^2 / \eta_{lh}$ where I_{lh} is the lower hybrid driven current. The code models assume that all of this power eventually couples from the fast current carrying electrons to the bulk plasma electrons.

V.3 Electron Cyclotron Resonance Current Drive

The efficiency of current drive by electron cyclotron resonance (ECR) waves is calculated in the TETRA code from the formula

$$\eta_{ecr}(A/W) = 0.21 T_e / (R_0 n_{e20} \ln \Lambda) \quad (V-4)$$

This scaling reproduces the result by Karney and Fisch³⁶ for a narrow spectrum of cyclotron waves, fundamental frequency, in the non-relativistic limit, for a background plasma with $Z_{eff} = 1$. When the resonance parallel velocity of the current carrying electrons is approximately 2.5 times the thermal velocity of the bulk

electrons. Linear theory (see Refs. 9, 38, 39) indicates that for TIBER-like parameters ($T_e=20\text{keV}$, $R_0=3\text{m}$, $\omega_{pe}^2/\omega_{ce}^2 \approx 5$) the optical depth for ECR waves at the fundamental is in the range $100 \leq \tau \leq 500$ so that the resonance parallel velocity is in the range $2 \leq v_{||} \leq 3$. For the systems code we have chosen an intermediate value. Equation(4) does not include degradation of the efficiency due to electron trapping effects, relativistic detuning of the resonance, or the phenomenon of higher harmonic overlap⁴⁰ when ECR waves with high $N_{||}$ (for efficient current drive) are injected into a plasma with high T_e ($>10\text{keV}$). Models for some of these effects (see Ref. 9) will be adapted for use in the TETRA code in the next year. Simple models for the harmonic overlap effect have yet to be developed. It should be stressed at this point that Eq.(4) should be used with caution in systems studies of configurations for which the electron temperature exceeds 10keV (harmonic overlap effect) and/or the aspect ratio of the tokamak is less than 4.0 (electron trapping effect). Finally, the ECR power is calculated from $P_{\text{ecr}} = I_{\text{ecr}}/\eta_{\text{ecr}}$ where I_{ecr} is the current to be driven by ECR waves. The model assumes that all of this power eventually couples to the bulk electrons.

V.4 Lower Hybrid Fast Wave Current Drive

The models for lower hybrid fast wave current drive in the TETRA code have been formulated by Ehst⁴¹. The conversion efficiency formula is

$$\eta_{\text{fw}}(A/W) = Z_c(0.034 + 0.196\beta_t)T_e^{0.77}/(R_0 n_{e20}) \quad (V-5)$$

where

$$Z_c = 0.08[32/(5+Z_{\text{eff}}) + 2 + Z_t] \quad (V-6)$$

$$Z_t = 12(6+Z_{\text{eff}})/[(5+Z_{\text{eff}})(3+Z_{\text{eff}})] + 3.76/Z_{\text{eff}} \quad (V-7)$$

where Z_{eff} is the bulk plasma effective charge, and β_t is the total beta. This parametrization was derived from a series of rf current drive and MHD equilibria calculations. Linear Landau damping was assumed and the effects of transit time magnetic pumping were not included. In addition, the parasitic damping of the fast waves by high energy fusion alphas was not considered in obtaining Eq. (V-5).

IV.5 Bootstrap Current

Neo-classical bootstrap current effects are modeled in the TETRA code with a scaling formula which includes the dependence on poloidal beta, aspect ratio and plasma effective charge. The bootstrap current is calculated as

$$I_{\text{bc}} = I_p \beta_{p, \text{th}} / \epsilon (1 + 0.94/Z_{\text{eff}} + 0.43/Z_{\text{eff}}^2) \quad (V-8)$$

where I_p is the total toroidal current, $\beta_{p,th}$ is the thermal component of the poloidal beta, $\epsilon = a/R_0$ is the inverse aspect ratio and Z_{eff} is the plasma effective charge. The total current which must be driven by the current drive system(s) is $I_{cd} = I_p - I_{be}$. Equation (V-8) was developed from a series of Fokker-Planck and power balance calculations⁵ for TIBER-like conditions.

IV.6 Combinations of Current Drive Systems

For some configurations it may be advantageous to use two or more current drive systems to drive the total current. For systems analysis this requires that the partitioning of the required current for each system be calculated. At present the only option implemented in the TETRA code is a combination of NBI and LH current drive with $I_{nb} = f I_{lh}$. The value $f=1.13$ corresponds roughly to the results of more detailed calculations for TIBER-like conditions (see Ref. 1). Simplified calculations of this partitioning have been adapted from the detailed calculations in Ref. 1 and are in the process of being added to the TETRA code.

IV.7 Summary

At present, simplified models of current drive by neutral beam injection, lower hybrid slow and fast waves, and electron cyclotron waves are available in the TETRA code. Lower hybrid slow waves and neutral beam current drive may be combined in a rudimentary way. Simplified models of more detailed calculations for each current drive method are under development and will be included in the systems code as soon as they are available.

Limitations on the parameter ranges over which the models are valid vary from one current drive method to another. The neutral beam model is valid except in cases with very high plasma density ($n_e \geq 4 \times 10^{20} \text{ m}^{-3}$) or low beam energy ($E_{beam} \leq 200 \text{ keV}$) for which a more detailed penetration calculation is required to assure that the beams reach the core of the plasma. The lower hybrid model is valid providing the bulk electron temperature in the region of lower hybrid wave propagation satisfies $T_e \leq 15 \text{ keV}$. At higher temperatures the model over-estimates the current drive efficiency. The ECR model is valid only for low temperature $T_e < 10 \text{ keV}$ plasmas in devices with large aspect ratio, $R_0/a > 4$. Electron trapping effects and the phenomenon of higher harmonic overlap must be included in the model to remove these limitations. Finally, the lower hybrid fast wave model is valid only for the outer radial regions of the plasma where alpha particle damping of the waves will not be important. Work continues to develop algorithms which extend the ranges of validity for each of these models.

VI. SUMMARY OF TIBER PHYSICS SUPPORT

Physics support for the TIBER study has been provided during FY87 in a number of areas. Baseline operating points have been generated with the MUMAK tokamak power balance code⁹. The models used in this code for steady state operation have been developed with full cognizance of the recommendations on physics from the CIT community, including the Ignition Physics Study Group (IPSG), and the ETR Technical Oversight Committee (ETOC). Though not reported here, several of the models now in MUMAK reflect results of more detailed calculations using Fokker-Planck and ray tracing codes for neutral beam injection (NBI) and lower hybrid (LH) current drive and bootstrap current effects⁸. MUMAK models of steady state current drive have also been adapted for inclusion in the TETRA systems code.

These models have also been extended to include pulsed ignited operation and POPCON¹⁵ analysis. Alternate pulsed ignited operating points for TIBER-II have been generated including cases with the physics assumptions recommended by the CIT community¹⁰, and those of the NET¹², FER¹³, and OTR¹⁴ designs. Comparisons of the ignition capability of TIBER under these different assumptions have been made.

REFERENCES

1. TIBER Team, "TIBER-II/ETR Final Design Report," Lawrence Livermore National Laboratory report UCID-21150, October 1987.
2. S. M. Kaye and R. J. Goldston, Nuclear Fusion, 25, 65 (1985).
3. B. Q. Deng and G. A. Emmert, "Fast Ion Pressure in Fusion Plasmas," University of Wisconsin report UWFD-718 (1987)
4. J. G. Cordey and M. J. Houghton, Nuclear Fusion, 13, 215 (1973).
5. D. R. Mikkelsen and C. E. Singer, Nuclear Technology/Fusion, 4, 237 (1983).
6. R. B. White, Princeton Plasma Physics Laboratory, Princeton, NJ, private communication (1987).
7. R. S. Devoto and J. D. Hanson, "SIGV - A Code to Evaluate Plasma Reaction Rates to a Specified Accuracy," Lawrence Livermore National Laboratory report UCRL-52559 (1978).
8. R. S. Devoto, M. E. Fenstermacher, and A. A. Mirin, to be published; Bulletin of the American Physical Society 31, 1519 (1986); see also J. Killeen, A. A. Mirin, and M. G. McCoy, Modern Plasma Physics (IAEA, Vienna, 1981) p. 395.
9. M. E. Fenstermacher, "MUMAK - A Computer Code for Modeling Plasma Power Balance and Current Drive in Tokamaks," Lawrence Livermore National Laboratory report UCID-21038 (1987).
10. J. Sheffield, et al., "Physics Guidelines for the Compact Ignition Tokamak," Proceedings of the Seventh Topical on the Technology of Fusion Energy, Reno, in Fusion Technology, 10, 481 (1986).
11. C. D. Henning and B. C. Logan eds., "TIBER-II Tokamak Ignition/Burn Experimental Reactor - 1986 Status Report," Lawrence Livermore National Laboratory report UCID-20863, (1986).
12. NET Team, "Next European Torus (NET) 1985 Status Report," report EUR-FU/XII-80/86-51, December 1985.
13. T. Tone, et al., "Fusion Experimental Reactor (FER) Design Concept," IAEA Technical Committee Meeting and Workshop on

Fusion Reactor Design and Technology, Yalta, U.S.S.R.,
26 May - 6 June, 1986, IAEA-TC-392.3 (1986).

14. B. Kadomtsev, et al., "OTR -- Experimental Fusion-Fission Tokamak Reactor Concept," IAEA Technical Committee Meeting and Workshop on Fusion Reactor Design and Technology, Yalta, U.S.S.R., 26 May - 6 June, 1986, IAEA-TC-392.3 (1986).
15. W.A. Houlberg et al., Nuclear Fusion 22, 935 (1982).
16. M. Murakami et al., Nuclear Fusion 16, 347 (1976).
17. M. Greenwald, "A New Look at Density Limits in Tokamaks," MIT report PFC-JA-86-22 (1986).
18. F. Troyon et al., Plasma Physics and Controlled Fusion 26, 209 (1984).
19. K. Yamazaki et al., Nuclear Fusion 25, 1543 (1985).
20. J. W. Connor and R. J. Hastie, Physics of Fluids, 19, 1727 (1976).
21. R. J. Goldston, Plasma Physics and Controlled Fusion 26, 98 (1984).
22. R. Parker, Nuclear Fusion 25, 1127 (1985).
23. E. P. Gorbunov, S. V. Mirnov, and V. S. Strelkov, Nuclear Fusion 10, 43 (1970).
24. V. G. Mereshkin and V. S. Mukhovatov, Soviet JETP Letters 33, 446 (1981).
25. F. Wagner et al., Physical Review Letters 49, 1408 (1982).
26. NAG FORTRAN Library Manual - Mark 11, Numerical Algorithms Group, 1101 31st Street, Downers Grove IL (1986).
27. H. L. Berk, W. Horton Jr., M. N. Rosenbluth, and P. H. Rutherford, Nuclear Fusion, 15, 819 (1975).
28. P. F. DuBois, "Basis Users Manual," Lawrence Livermore National Laboratory, Livermore, CA, Report M-189, June 1987.
29. P. F. DuBois, "Writing Basis Packages," Lawrence Livermore National Laboratory, Livermore, CA, Report M-194, February 1987.
30. P. F. DuBois, "MPPL User's Manual," Lawrence Livermore National Laboratory, Livermore, CA, Report M-187, October 1986.

31. R.S. Devoto, "Neutral-Beam Current Drive in Tokamaks," Lawrence Livermore National Laboratory report UCRL-95799, October 1986.
32. D.F.H. Start, J.G. Cordey, and E.M. Jones, Plasma Phys. 22, 303 (1980).
33. D.F.H. Start and J.G. Cordey, Phys. Fluids 23, 1477 (1980).
34. J.D. Gaffey, J. Plasma Phys. 16, 149 (1979).
35. C.D. Henning, B.G. Logan et al., "TIBER-Tokamak Ignition/Burn Experimental Research, Final Design Report," Lawrence Livermore National Laboratory report UCID-20589, November 1985.
36. C.F.F. Karney and N.J. Fisch, Phys. Fluids 28, 116 (1985).
37. "International Tokamak Reactor - Phase Two A, Part 1," International Atomic Energy Agency report ISBN 92-0-131283-0, (1983).
38. K.I. Thomassen ed., "Free-Electron Laser Experiments in Alcator C," Lawrence Livermore National Laboratory report LLL-PROP-00202, July 1986.
39. M. Bornatici et al., Nuc. Fus. 23, 1153 (1983).
40. G.R. Smith, R.H. Cohen, and T.K. Mau, "Harmonic Overlap in Electron-Cyclotron Current Drive at High T_e ," Lawrence Livermore National Laboratory report UCRL-96364 preprint, March 1987 (to be published in Physics of Fluids).
41. D. Ehst, "TIBER-II, Tokamak Ignition/Burn Experimental Reactor, 1986 Status Report - Appendix C," C.D. Henning and B.G. Logan Eds., Lawrence Livermore National Laboratory report UCID-20863, October 1986.

Table II-1 Baseline Parameters

Parameter	Description	Value
R_0 (m)	plasma major radius	3.0
a (m)	plasma minor radius*	0.834
κ	elongation*	2.4
δ	triangularity*	0.4
V_p (m ³)	plasma volume	96
S_p (m ²)	plasma surface area*	170
B_0 (T)	toroidal field at R_0	5.55
P_{fus} (MW)	fusion power	314
Q	fusion power/input power	5.0
$\langle \Gamma \rangle; \Gamma$ (MW/m ²)	average (peak) wall loading	1.3 ; 2.0
P_{NB} (MW)	neutral beam power	44
P_{LH} (MW)	lower hybrid power	19
I_p (MA)	total plasma current	10.0
I_{bs} (MA)	bootstrap current	2.7
I_{LH} (MA)	lower hybrid driven current	3.9
I_{NB} (MA)	neutral beam driven current	3.4
γ_{LH} (10 ²⁰ m ⁻² A/W)	lower hybrid efficiency	0.47
γ_{NB} (10 ²⁰ m ⁻² A/W)	neutral beam efficiency	0.25
γ_{CD} (10 ²⁰ m ⁻² A/W)	overall current drive efficiency (NBI + LH + bootstrap currents)	0.52
$\langle T_e \rangle; T_e$ (keV)	average (peak) electron temperature	19 ; 25
$\langle T_i \rangle; T_i$ (keV)	average (peak) ion temperature	20 ; 26
$\langle n_e \rangle; n_e$ (10 ²⁰ m ⁻³)	average (peak) electron density	1.1 ; 2.1
$n_{Greenwald}$ (10 ²⁰ m ⁻³)	Greenwald density limit	2.57
$n_{Murakami}$ (10 ²⁰ m ⁻³)	Murakami density limit	1.35
C_α	thermal alpha concentration	0.05
C_{oxygen}	thermal impurity concentration	0.024
Z_{eff}	plasma effective charge	2.1
τ_E (s)	gross energy confinement time	0.68

* Values on the 95% flux surface (see Ref. 1)

Table II-2 Baseline Power Balance Parameters

Parameter	Description	Value
P_{fus} (MW)	total fusion power	314.0
$P_{fus,beam}$ (MW)	beam-bulk fusion power	44.5
P_{α} (MW)	alpha power	62.8
$P_{\alpha,e}; P_{\alpha,i}$ (MW)	alpha power to electrons (ions)	42 ; 21
P_{LH} (MW)	lower hybrid power	18.7
P_{NB} (MW)	neutral beam power	43.7
$P_{NB,e}; P_{NB,i}$ (MW)	neutral beam power to electrons (ions)	12 ; 32
P_{brem} (MW)	bremsstrahlung power	7.3
P_{sync} (MW)	synchrotron power lost*	2.0
$P_{c,e}$ (MW)	electron conduction power lost	63.5
$P_{c,i}$ (MW)	ion conduction power lost	52.3
$P_{i,e}$ (MW)	ion-electron drag power	0.91
τ_E (s)	gross energy confinement time	0.68
H_{mode}/τ_E (L-mode)	H-mode energy confinement enhancement	1.14

* Assuming 90% wall reflectivity

Table II-3 Baseline Current Drive Parameters

Parameter	Description	Value
P_{NB} (MW)	neutral beam power	43.7
P_{LH} (MW)	lower hybrid power	18.7
I_{NB} (MA)	neutral beam driven current	3.43
I_{LH} (MA)	lower hybrid driven current	3.87
I_{GS} (MA)	bootstrap current	2.70
$N_{ ,LH}$	lower hybrid parallel refractive index	1.60
$N_{ ,ac}$	accessible parallel refractive index (high field side)	1.55
$E_{ }/\langle T_e \rangle$	normalized tail parallel energy	8.0
r_{max} (m)	radius of maximum penetration (LH)	0.45
$\langle T_e \rangle_{LH}$ (keV)	average electron temperature (LH)	5.5
$\langle n_e \rangle_{LH}$ ($10^{20} m^{-3}$)	average electron density (LH)	0.75
ω_{pe}/ω_{ce} at r_{max}	dielectric constant at r_{max}	0.33
$E_{c,hot}$ (keV)	hot deuterium critical energy	393
n_{hot} ($10^{20} m^{-3}$)	hot ion density	0.031
E_{hot} (keV)	hot ion average energy	2.64

Table II-4 Baseline Fueling Parameters

Parameter	Description	Value
$I_{c,d}=I_{c,t}$ (A)	deuterium (tritium) loss current	104
I_{burn} (A)	deuterium (tritium) burn-up current	18
$I_{c,beam}$ (A)	deuterium current from NBI	87
$I_{d,fuel}$ (A)	deuterium fueling current required	35
$I_{t,fuel}$ (A)	tritium fueling current required	122
$\tau_{p,\alpha}=\tau_{p,i}$ (s)	thermal alpha (ion) confinement time	5.9
τ_E (s)	thermal energy confinement time	0.68

Table III-1 Framework for Studies of Alternating Operating Points for TIBER-II.

Pulsed Operation	Effect of Toroidal Current Variations (Section III.2.1)
	Effect of Energy Confinement Scaling Law Assumptions (Section III.2.2)
High Performance Steady State Operation	High Plasma Q = Fusion Power/Input Power (Section III.3)
	High Neutron Wall Loading (Section III.3)

TABLE III-2 Assumptions Used for Ignition POPCONS with Various Toroidal Currents.

Geometry	: $R_0=3\text{m}$, $a=.83\text{m}$, $a_{\text{well}}=.95\text{m}$, $\kappa=2.4$, $\delta=0.4$, $B_0=5.55\text{T}$
Impurities	: $n_\alpha/(n_p+n_t)=.05$, $Z_{\text{eff}}=1.5$, Oxygen impurity, $n_p=n_t$
Profiles	: $X(r)=X(0)(1-r^2/a^2)^{.5}$, $X=n,T$; $\alpha_n=0.5$, $\alpha_T=1.0$
Safety Factor	: $q_{\text{NET}}=5a^2B_0K^2/R_0I_p$; $K=\int dl/2\pi a$
Power Degradation	: Power P used in the Kaye-Goldston energy confinement scaling $P=P_\alpha+P_{\text{aux}}-P_{\text{brem}}-P_{\text{sync}}$
Neo-Alcator	
Scaling	: $\tau_{\text{NA}}=0.071 \langle n_{e20} \rangle R_0^2 (A_p/\pi)^{.5} q_{\text{NET}}$

Table III-3 Summary of Results from Ignition Studies at Various Toroidal Currents.

Current, H	Ignition Murakami	Ignition Greenwald	Beta Limited	Power Required
8 MA, 2.0	no	marginal	yes	9 MW
10 MA, 2.0	no	yes	yes	9 MW
12.5 MA, 2.0	yes	yes	marginal	9 MW
12.5 MA, 1.0	no	marginal	yes	18 MW

TABLE III-4 Assumptions Used to Simulate NET Design Constraints

Geometry	: $R_0=3m$, $a=.855m$, $a_{wall}=.95m$, $\kappa=2.74$, $\delta=0.77$, $B_0=5.55T$
Impurities	: $n_\alpha/(n_p+n_T)=.08$, $Z_{eff}=1.5$, Oxygen impurity, $n_p=n_T$
Profiles	: $X(r)=X(0)(1-r^2/a^2)^{\alpha_X}$, $X=n,T$; $\alpha_n=.0.3$, $\alpha_T=.0.3$

Table III-5 Summary of Results from Ignition Studies with Various Energy Confinement Scaling Laws

Scaling	Ignition Murakami	Ignition Greenwald	Window Temperature	Saddle Point Temperature	Power Required
KG + NA, H	no	marginal	7 - 12 keV	5 keV	9 MW
Mereshkin, H	no	marginal	7 - 10 keV	5 keV	14 MW
Mirnov	no	marginal	8 - 13 keV	10 keV	11 MW
NET Assumptions (Asdex H-mode)	marginal ($T>15$ keV)	marginal	9 - 17 keV	13 keV	8 MW

Table III-6 Parameters and Physics Assumptions Used for the High Performance Cases.

Geometry	: $R_0=3m$, $a=.855m$, $a_{wall}=.971m$, $\kappa=2.4$, $\delta=0.4$, $B_0=5.55T$
Impurities	: $n_\alpha/(n_p+n_T)=.05$, $Z_{eff}=1.5$, Oxygen impurity, $n_p=n_T$
Profiles	: $X(r)=X(0)(1-r^2/a^2)^{\alpha_X}$, $X=n,T$; $\alpha_n=1.17$, $\alpha_T=0.66$
Energy Confinement	: Kaye-Goldston, H-mode ($1 < H < 2$)
Power Degradation	: Power P used in the Kaye-Goldston energy confinement scaling $P=P_\alpha+P_{aux}-P_{brem}-P_{sync}$
LH Forward Launch	: 90%
Beam Energy	: 1.0 MeV

Table III-7 Plasma Parameters for the High Q and High Wall Loading Cases.

Parameter	Description	High Q	High Γ
P_{fus} (MW)	fusion power	340	590
Q	$P_{fus}/\text{input power}$	21.6	13.1
$\langle \Gamma \rangle$; Γ (MW/m ²)	wall loading	1.4 ; 2.1	2.4 ; 3.7
P_{nb} (MW)	NBI power	11.5	31.3
P_{lh} (MW)	LH power	4.1	13.9
$T_e; T_i$ (keV)	e-ion temperature	22.2 ; 20.8	11.4 ; 10.5
$n_e; n_{DT}$ (10^{20} m^{-3})	e-DT density	0.96 ; 0.80	2.2 ; 1.88
$n_{Greenwald}$	density limit	2.51	2.51
Z_{eff}	effective charge	1.50	1.50
β_{op} ; $\beta_{Yamazaki}$		6.6 ; 6.6	6.6 ; 6.6
$\beta_{fast \alpha}$ (%)		1.32	0.48
H	$h=r_E/r_E(\text{L-mode})$	2.0	1.45
τ_E (s)	confinement time	1.1	0.70
I_p (MA)	plasma current	8.0	8.0
I_{nb} (MA)	NBI current	2.0	1.5
I_{lh} (MA)	LH current	1.4	1.0
I_{bs} (MA)	bootstrap current	4.6	5.5
E_{beam} (MeV)	NBI energy	1.0	1.0
$N_{ ,lh}$; $N_{ ,ac}$	refractive index	1.53 ; 1.52	2.1 ; 2.0
$\gamma_{lh}(10^{20} \text{ m}^{-2} \text{ A/W})$	LH efficiency	0.61	0.35
$\gamma_{nb}(10^{20} \text{ m}^{-2} \text{ A/W})$	NBI efficiency	0.50	0.31

Figure Captions (III)

- Fig. III-1 POPCON for TIBER using KG + NA scaling, $I_p=8$ MA, $H=2.0$. The Murakami density limit is $n_{Mu20}=1.1$; the Greenwald limit is $n_{Gr20}=2.3$. The beta limit is $\beta_{lim}=4.8\%$.
- Fig. III-2 POPCON for TIBER using KG + NA scaling, $I_p=10$ MA, $H=2.0$. The Murakami density limit is $n_{Mu20}=1.35$; the Greenwald limit is $n_{Gr20}=2.9$. The beta limit is $\beta_{lim}=6.0\%$.
- Fig. III-3 POPCON for TIBER using KG + NA scaling, $I_p=12.5$ MA, $H=2.0$. The Murakami density limit is $n_{Mu20}=1.7$; the Greenwald limit is $n_{Gr20}=3.6$. The beta limit is $\beta_{lim}=7.6\%$.
- Fig. III-4 POPCON for TIBER using KG + NA scaling, $I_p=12.5$ MA, $H=1.0$. The Murakami density limit is $n_{Mu20}=1.7$; the Greenwald limit is $n_{Gr20}=3.6$. The beta limit is $\beta_{lim}=7.6\%$.
- Fig. III-5 POPCON for TIBER using Mereshkin scaling, $I_p=8$ MA, $H=2.0$. The Murakami density limit is $n_{Mu20}=1.1$; the Greenwald limit is $n_{Gr20}=2.3$. The beta limit is $\beta_{lim}=4.8\%$.
- Fig. III-6 POPCON for TIBER using Mirnov scaling, $I_p=8$ MA, $H=1.0$. The Murakami density limit is $n_{Mu20}=1.1$; the Greenwald limit is $n_{Gr20}=2.3$. The beta limit is $\beta_{lim}=4.8\%$.
- Fig. III-7 POPCON for TIBER using NET assumptions including Asdex H-mode scaling, $I_p=8$ MA. The Murakami density limit is $n_{Mu20}=1.1$; the Greenwald limit is $n_{Gr20}=2.5$. Note that the beta limit outlined ($\beta_{lim}=4.8\%$) corresponds to the Troyon value with $g=2.8\%$. The NET assumption, $g=3.5\%$ corresponds to the dashed curve labelled 0.059.
- Fig. III-8 Contours of Q (solid lines) and $\langle T \rangle$ (MW/m² - dashed lines) for TIBER using the high performance assumptions (see Table III-6).

Fig. 1

Fig. 2

Temperature, $T_e - T_i$ (keV)

Fig. 4

Fig. 5

Fig. 6

H-mode Enhancement Factor, $H = \tau_E / \tau_E(L\text{-mode})$

PART 2

ADVANCED BLANKET MODELING
(THE MICROWAVE SUPERHEATER)

CONTRIBUTOR(S): R.B. CAMPBELL

Advanced Blanket Modeling- The Microwave Superheater

Robert B. Campbell

October 6, 1987

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1 Introduction

The *microwave superheater* is a concept which can use the synchrotron radiation from a thermonuclear plasma to heat gas seeded with an alkali metal to temperatures far above the temperature of material walls. The idea is used in the innovative Compact Fusion Advanced Rankine (CFAR) cycle[1], although other blanket configurations could be substituted. Because of the need for copious amounts of synchrotron radiation, the microwave superheater is best suited for use with plasmas burning an advanced fuel such as D-³He.

The present report is concerned with the description and modeling of the microwave superheater. We perform a detailed examination of heaters in the laminar flow regime, appropriate for a small scale demonstration experiment. Section 4.3 suggests that scaling to larger superheaters is possible. Through parametric analysis, discussed in Section 4, we determine the sensitivity of heater performance to changes in key parameters, such as gas pressure, seed fraction, and microwave intensity.

We have developed two steady-state codes which couple fluid dynamics, radiation transport, and plasma physics to predict the performance of the microwave superheater. A relatively simple 1-D code calculates the axial profiles of the bulk gas properties. A more detailed 2-D code calculates both the radial and axial profiles of gas properties. Since issues of radial uniformity of the microwave heating are important, this report will primarily concentrate on results of the 2-D model. The complete set of equations used in the model are described in detail in Section 3.

We have considered experimental-sized superheaters operating in the laminar flow regime using helium seeded with lithium. The gas is heated by a monochromatic spectrum at 56GHz produced by a gyrotron. At reasonable pressures (0.1 to 1 atmospheres) and seed fractions ($\leq 10^{-4}$) we have found that the radial uniformity of the heating is sufficient to allow the bulk outlet temperatures to reach nearly 3000°K, when the inlet temperature is about 1200°K and the wall temperature is 1000°K. The seed concentration and intensity of the microwave radiation must be carefully controlled to avoid either overheating or underheating.

2 Superheater Description and Design Issues

In its simplest form, the microwave superheater is a cylindrical tube made of high temperature ceramic. The ceramic is transparent to the microwaves and serves as a window. The wall is maintained at a temperature which keeps microwave losses low, and may require transpiration cooling. Transpiration cooling involves the passage of a slip-stream of unseeded working fluid through tiny pores in the wall. Figure 1 is a schematic diagram of the CFAR energy conversion system utilizing

Figure 1: An Energy Conversion System Utilizing a Microwave Superheater

a microwave superheater. Our present plan is to employ a Rankine cycle using mercury as the working fluid. The fusion fuel cycle would probably be D-³He. Liquid mercury is boiled and partially superheated within a two-zone fusion blanket and enters the superheater at two locations. The majority of the vapor is seeded and is superheated conventionally by a high temperature pebble bed in the rear of the blanket to about 2000°K and enters the microwave superheater for additional

heating to about 3000°K. Another stream of unseeded working fluid is heated in the front of the blanket to about 800°K and is used to cool the porous ceramic wall. It is desirable that the wall temperature not exceed 1000-1500°K to avoid microwave absorption. The synchrotron radiation is piped through overmoded waveguides with small losses to a resonance cavity surrounding the superheater structure. The microwaves pass through the ceramic wall, and heat the vapor.

The microwave superheater is attractive because the heating is volumetric, allowing the gas to be heated to temperatures considerably higher than the wall temperature. However, the volumetric heat source during strong heating can be peaked near the wall. Power deposited near the wall would be lost in the form of an enhanced heat flux and will not contribute to a change in the bulk enthalpy of the gas. These concerns have motivated the development of a two-dimensional model which self-consistently calculates the radial and axial variation of the microwave heating source and the gas properties. This model will be described in more detail in Section 3.

The issue of radial uniformity must be addressed in the reactor-relevant regime. The working fluid would be mercury vapor seeded with cesium, at pressures of several atmospheres and mass flow rates which would place it in the turbulent flow regime. The spectrum would be characteristic of synchrotron radiation with a peak at approximately 1000GHz for an advanced fuel (D-³He) tokamak. Section 4.3 presents some simple arguments which are used to scale to reactor-relevant superheaters.

3 Physical Model

3.1 Overview of Model

The model we have developed for the study of microwave superheating is comprised of the moment equations for the gas and electrons, the equation of mass transfer to describe the seed atom "impurity" density, and the radiation transport equation. The continuity equation, momentum equation, and energy equation[2] are solved for the main working fluid. The continuity and energy equations are solved for the electron fluid[3]. In the two-dimensional model when transpiration cooling with pure gas is used, the radial and axial evolution of the seed atom concentration is found by solving the mass transfer equation[2].

The volumetric heating term from the microwaves is calculated as a function of electron and gas fluid properties by two-dimensional ray-tracing. The inwardly-directed radiation intensity at the tube surface, I_0 , is assumed isotropic and is treated as a parameter. For the reactor, I_0 can be adjusted by controlling the plasma chamber wall reflectivity of the synchrotron radiation and the number of superheaters. In the experimental superheater, the power level of the gyrotron output determines I_0 .

The boundary conditions are specified as follows. Symmetry dictates that the radial derivative of all properties vanish at the tube centerline. The gas temperature at the wall must be equal to the wall temperature which can be specified externally or calculated using some model (such as a energy balance for the wall material). The axial velocity at the wall is zero, and the radial velocity is that value consistent with the transpiration cooling mass flux. The concentration gradient of seed material is determined by relating it to the flux of pure gas flowing through the wall. The equivalence between the macroscopic Fourier heat flux and the microscopic heat flux for electrons including the effects of a wall sheath potential places a boundary condition on the electron temperature gradient at the wall[4]. The electron density gradient boundary condition is obtained in a similar manner relating particle fluxes[3].

We have considered both a one and two dimensional model for the microwave superheater. The two dimensional model retains the radial and axial dependence of the properties, whereas the one dimensional model includes only the axial variations. The one dimensional model is obtained formally by a radial average of the two dimensional model equations over an assumed set of property profiles. The property profiles for this particular model are assumed uniform in radius. The volumetric heating term is evaluated with the average properties.

The one dimensional model, because of its relative simplicity, is useful in mapping out large regions of parameter space. The model suffers however, because it cannot address the important issue of radial uniformity of the heating. The two dimensional model, on the other hand, is much more complex and considerably more computing is required to examine a given configuration. However, it has the capability to answer critical questions related to the radial aspects of the problem.

Figure 2 shows the power flow through a differential slice of the superheater tube. Mass and enthalpy flows into the volume through the entering main tube flow and through transpiration cooling of the walls. Power is deposited in the volume by heating due to the microwaves. Power can be lost from the volume by surface

conduction and convection from the gas and electrons, and volumetrically from line radiation from electrons. The useful part of the microwave power, deposited by electron-neutral collisions, leaves the volume as increased enthalpy of the gas.

3.2 Gas Moment Equations

The gas is described by the equations of conservation of mass, momentum, and energy[2]. The radially resolved equations are written in the boundary layer approximation, which requires that velocities (axial, u and radial, v) and pressure, P , satisfy certain orderings. These are $u \gg v$, $\partial u / \partial r \gg \partial(u, v) / \partial x$, $\partial v / \partial r$; the stress tensor, $\vec{\sigma}$, is diagonal, with $\sigma_{xx} = -P$, and $\partial P / \partial r \approx 0$.

The continuity equation may be written:

$$\frac{\partial}{\partial x}(\rho u) + \frac{1}{r} \frac{\partial}{\partial r}(r \rho v) = 0, \quad (1)$$

where ρ is the gas mass density.

The gas momentum balance in an axisymmetric tube is given by:

$$\rho u \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial r} + \frac{\partial P}{\partial x} = \frac{1}{r} \frac{\partial}{\partial r} \left(r \mu \frac{\partial u}{\partial r} \right), \quad (2)$$

where the new variable is the viscosity, μ . We use for μ the relationship appropriate for an ideal gas:

$$\begin{aligned} \mu &= \frac{2}{5} \mathcal{M} \left(\frac{\gamma - 1}{R} \right) k, \\ k &= \frac{1}{3} \rho \bar{w} \lambda_{gas} \frac{R}{\mathcal{M}(\gamma - 1)}, \\ \bar{w} &= \sqrt{\frac{8RT_{gas}}{\pi \mathcal{M}}}, \\ \lambda_{gas} &= \frac{m_{gas}}{\rho \pi \tau_0^2}. \end{aligned} \quad (3)$$

The parameter γ is the ratio of specific heats, $\mathcal{M}$ is the molecular weight of the gas, R is the universal gas constant, and k the thermal conductivity. In the relation for k , $\bar{w}$ is the mean thermal speed of the gas molecules, and λ_{gas} is the mean free path

of the gas molecules. In λ_{gas} , m_{gas} is the mass of the gas molecule, and r_0 is the collision radius of the gas atom.

The energy equation for the gas can be written:

$$\begin{aligned} \rho u \frac{\partial \mathcal{H}}{\partial x} + \rho v \frac{\partial \mathcal{H}}{\partial r} - \frac{1}{r} \frac{\partial}{\partial r} \left(kr \frac{\partial T_{gas}}{\partial r} \right) \\ - \mu \left(\frac{\partial u}{\partial r} \right)^2 - u \frac{dP}{dx} - q_{coll}''' = 0, \end{aligned} \quad (4)$$

where $\mathcal{H}$ is the gas enthalpy, and q_{coll}''' is the source term from collisional heating of the gas by microwave heated electrons, given by Eq. 12.

When transpiration cooling using unseeded gas is employed, a mass diffusion equation is solved for the radial profile of the seed material mass concentration, $\mathcal{G}_{seed}$. This equation is:

$$\rho u \frac{\partial \mathcal{G}_{seed}}{\partial x} + \rho v \frac{\partial \mathcal{G}_{seed}}{\partial r} - \frac{1}{r} \frac{\partial}{\partial r} \left(r \Lambda_{seed} \frac{\partial \mathcal{G}_{seed}}{\partial r} \right) = 0 \quad (5)$$

The form of this equation is appropriate when $\mathcal{G}_{gas} \gg \mathcal{G}_{seed}$. The mass diffusion coefficient, Λ_{seed} , is related to the viscosity, μ , in the ideal gas and unity Lewis number (Prandtl # = Schmidt #) limit by $\Lambda_{seed} = \mu/Pr$, with $Pr = \frac{2}{3}$ for an ideal gas.

We now consider the boundary and inlet conditions for the gas in the super-heater:

$$\begin{aligned} \rho v(r_w, x) &= \frac{\dot{m}_{wall}(x)}{2\pi r_w}, \\ u(r_w, x) &= 0, \\ u(r, 0) &= u_0(r), \\ T_{gas}(r, 0) &= T_0(r), \\ T_{gas}(r_w, x) &= T_{wall}(x), \\ P(r, 0) &= P_0, \\ \Lambda_{gas} \frac{\partial \mathcal{G}_{seed}}{\partial r} \Big|_{r_w} &= \rho v(r_w, x) \mathcal{G}_{seed}, \end{aligned} \quad (6)$$

where $\dot{m}_{\text{wall}}(x)$ is the radial mass flux per unit length emitted from the wall during transpiration cooling, u_0 and T_0 are specified inlet radial profiles of u and T_{gas} , respectively. Note that wall mass flux into the flow is considered negative.

3.3 Electron Moment Equations

Collisions are strong in this weakly-ionized plasma so the electron distribution function remains Maxwellian, even during microwave heating. This justifies the use of moment equations derived from the electron Fokker-Planck equation. Equations which describe the particle and energy balance for electrons are solved. These equations apply outside the very thin sheath region near the wall. The effect of the sheath potential drop at the wall, ϕ_w , is included as a boundary condition on the electron heat and particle flux.

The electron particle balance outside the sheath region uses the assumption that the radial flow is ambipolar and is given by [3]:

$$-\frac{1}{r} \frac{\partial}{\partial r} \left[r n_e \left(\frac{D_{\text{amb}}}{2p_i} \frac{\partial}{\partial r} (p_e + p_i) \right) \right] + \frac{\partial (u n_e)}{\partial x} + \frac{1}{r} \frac{\partial}{\partial r} (r v n_e) = \alpha(T_e) [(n_e^*)^2 - n_e^2]. \quad (7)$$

In this equation, D_{amb} is the ambipolar diffusion coefficient, $p_e = n_e k_B T_e$, are the electron and ion pressures, $\alpha(T_e)$ is the recombination coefficient. Our modeling so far has included the two-electron three body collisional recombination process. In the density and temperature range of the experimental-sized superheater, radiative recombination may not be negligible, but the complexity of the calculation for general parent and seed gases prevents us from including it. For the three body process, α is given by (in MKS):

$$\alpha(T_e) = 1.09 \times 10^{-20} n_e T_e^{-\frac{9}{2}}. \quad (8)$$

The term $(n_e^*)^2$ is related to the Saha equilibrium relation, and is given by:

$$(n_e^*)^2 = 2(1 - \alpha_0) f_s n_{\text{gas}} \frac{Z_i}{Z} \left(\frac{2\pi m_e k_B T_e}{h^2} \right)^{\frac{3}{2}} e^{-\epsilon_i / k_B T_e}. \quad (9)$$

In this equation, Z and Z_i are the partition functions for the neutral and singly-ionized atom, respectively. The variable f_s is the seed fraction, m_e is the electron mass, ϵ_i is the ionization potential of the seed atom, h is Planck's constant, and

α_0 is the degree of ionization of the seed. The limit when the diffusion losses are negligible, Eq. 7 reduces to $(n_e^*)^2 = n_e^2$ which is the familiar Saha relationship. We have found that including the diffusion terms in the electron particle balance is important to properly model the penetration of the microwaves into the core region of the gas flow. The Saha relation overestimates the electron density near the wall and hence the amount of absorption there.

The electron energy balance forms the core of the plasma physics model of the microwave superheater. It balances the input from microwave heating with collisional heating of the gas, radiation losses, and conduction and convection losses to the walls. This equation can be written[3]:

$$\begin{aligned} u \frac{\partial}{\partial x} \left[n_e \left(\frac{3}{2} k_B T_e + \epsilon_i \right) \right] + v \frac{\partial}{\partial r} \left[n_e \left(\frac{3}{2} k_B T_e + \epsilon_i \right) \right] = \\ + n_e \left(\frac{5}{2} k_B T_e + \epsilon_i \right) \frac{1}{\rho} \left(u \frac{\partial \rho}{\partial x} + v \frac{\partial \rho}{\partial r} \right) \\ - \frac{1}{r} \frac{\partial}{\partial r} \left[r \left((\tilde{q}_e)_r - \frac{\epsilon_i}{e} (\tilde{J}_e)_r \right) \right] - q_{rad}''' - q_{con}''' - q_u''' \end{aligned} \quad (10)$$

The term q_{rad}''' is the loss due to radiation. For the heaters using helium seeded with cesium or lithium, radiation is about a 10% effect. We use the work of Gregory[5], Lutz[6], and Holstein[7] to compute this term. The assumption of a Lorentzian shape of the radiation emission line is made for both the seed element and the parent gas. The general form for this term for a given species, j , for each emission line is[6]:

$$\begin{aligned} q_{rad,j}''' &= \frac{3.71}{\sqrt{r - r_w}} \Delta \nu_j \sqrt{\zeta_0} [B_0(\lambda_j, T_e) - B_0(\lambda_j, T_{gas})], \\ \Delta \nu_j &= \Delta \nu_{press,j} + \Delta \nu_{dopp,j}, \\ \zeta_0 &= \frac{\mathcal{A} f_{osc,j} n_{gas}}{\Delta \nu_j}, \\ B_0(\lambda, T) &= \frac{2hc}{\lambda^5} \left[\exp \left(\frac{hc}{\lambda k_B T} \right) - 1 \right]^{-1}. \end{aligned} \quad (11)$$

The parameter λ is the wavelength of the line, ζ_0 is the inverse absorption length of the line evaluated at the line center, $\mathcal{A} = \frac{e^2}{2\pi m_e c}$, and $f_{osc,j}$ is the absorption

oscillator strength of the line. $B_0(\lambda, T)$ is the Planck function. The line width $\Delta\nu$ has important contributions due to both Doppler and pressure broadening[8].

The collisional power term, q_{coll}'' , couples the electrons to the gas, and provides the power input to heat the gas. It is evaluated for the case where elastic collisions are dominant. This is a good approximation for parent gasses which are monoatomic, such as helium or mercury. This term is of the form:

$$q_{coll}''' = \sum_h \frac{2m_e}{m_h} \nu_{eff} n_e \frac{3}{2} k_B (T_e - T_{gas}),$$

$$\nu_{eff} = n_0 Q_0 v_e.$$
(12)

The parameter ν_{eff} is the effective electron collision frequency. In ν_{eff} , n_0 is the neutral density, Q_0 is the collision cross section for electron-neutral interactions, and $v_e = \sqrt{\frac{8k_B T_e}{m_e \pi}}$ is the mean thermal speed of electrons. The sum over the heavy species reduces to a single term for our model, as long as the seed fraction is not too large.

The electron heat flux vector, $\vec{q}_e$, is given by a Fourier law:

$$(\vec{q}_e)_r = -\lambda_e \frac{\partial T_e}{\partial r},$$
(13)

where λ_e is the electron thermal conductivity, which includes collisions with both neutral and charged particles. It can be written[3]:

$$\lambda_e = \frac{2.4}{\left(1 + \frac{\nu_{ei}}{\sqrt{2}\nu_{eff}}\right)} \frac{k_B^2 n_e T_e}{m_e \nu_{eff}},$$
(14)

where ν_{ei} is the electron-ion momentum transfer collision frequency. The electron current is $\vec{J}_e$ related to the electron diffusion velocity, $\vec{U}_e$ by:

$$\vec{J}_e = en_e \vec{U}_e,$$
(15)

and, in the ambipolar approximation, $\vec{U}_e$ is given by:

$$(\vec{U}_e)_r = -\frac{D_{amb}}{2p_i} \frac{\partial}{\partial r} (p_e + p_i).$$
(16)

We conclude this subsection by describing the boundary conditions used for the electron balance equations. These relationships involve the specification of the flux

of particles or heat lost to the wall. From kinetic theory, including the effects of a sheath potential, an expression can be derived for the particle and heat flux. From the fluid description of the electrons, these fluxes are related to the gradients of density and temperature at the wall through Fick's and Fourier's laws. The boundary conditions are obtained by realizing that these two descriptions must be equivalent for the fluid model to be valid. The conditions are:

$$\begin{aligned} -n_e \frac{D_{amb}}{2p_i} \frac{\partial}{\partial r} (p_e + p_i) &= \frac{1}{4} F n_e v_e \\ -\lambda_e \frac{\partial T_e}{\partial r} &= \frac{1}{4} F n_e v_e \cdot 2k_B T_e \end{aligned} \quad (17)$$

at $r = r_w$. The function F takes into account the sheath potential. The form of F we use assumes that the ceramic wall is not an electron emitter. This is a good assumption for the wall temperature range we are considering. For this case, F can be written:

$$F = \sqrt{\frac{\pi\beta}{8}} \left[5 + \ln \left(\frac{1}{2\pi\beta} \right) \right], \quad (18)$$

where β is the ratio of electron to ion mass.

3.4 Heat Source from Microwave Absorption

The absorption process which is dominant at these frequencies and temperatures is collisional damping. The directed motion of the electrons oscillating in the electric field of the wave is converted to random thermal energy of the electrons by collisions with all species in the plasma. The randomization is caused by the loss of coherence between particle and wave phases when the electron's velocity vector changes due to a collision. The microwave power absorbed by the electrons can be transferred to the gas through electron-neutral collisions, lost by line radiation, or electron thermal conduction and convection. Fortunately, for the experimental-sized superheaters operating in the laminar regime using helium working fluid seeded with lithium, we have found that most of the power goes into the gas.

The equation of radiative transfer in the absence of scattering and re-emission is given by[9]:

$$dI_\nu = -\kappa_\nu \rho I_\nu d\ell, \quad (19)$$

where in Chandrasekhar's notation I_ν is the intensity of the radiation at a given frequency, ℓ is the path length along a ray pointed in a given direction, ρ is the material mass density, and the quantity κ_ν is known as the mass absorption coefficient. We ignore scattering in this treatment of the microwave absorption problem, and the re-emission of radiation is treated in a separate term given by Eq. 11. The neglect of scattering is justified for plasmas near thermodynamic equilibrium.

In the notation which will be used in this report, the product $\kappa\rho$ will be replaced by $\frac{\sqrt{\epsilon}}{\ell_D}$ where ϵ is the dielectric function and ℓ_D is the damping length based on collisional damping. Note that our treatment could be used to investigate heating of ionized gases by radiation in other frequency ranges just by supplying the proper damping length valid for that type of absorption mechanism. For our problem here, ℓ_D is given by [10]:

$$\ell_D = \frac{c}{2\omega} \left[-\frac{1}{2}\epsilon + \sqrt{\left(\frac{1}{2}\epsilon\right)^2 + \left(\frac{2\pi\sigma}{\omega}\right)^2} \right]^{-\frac{1}{2}} \quad (20)$$

where c is the speed of light, ω is the wave angular frequency, and σ is the conductivity:

$$\sigma = \frac{e^2 n_e \nu_{eff}}{m_e (\omega^2 + \nu_{eff}^2)} \quad (21)$$

For the weakly ionized gas in the magnetic field-free experimental-sized superheater the dielectric function for the ordinary mode is used:

$$\epsilon = 1 - \frac{\omega_{pe}^2}{(\omega^2 + \nu_{eff}^2)} \quad (22)$$

Here, e is the electron's charge, and ν_{eff} is the effective collision frequency for the electrons. The parameter $\omega_{pe}^2 = \frac{4\pi e^2 n_e}{m_e}$ is the electron plasma frequency. The largest contribution to ν_{eff} in this parameter range is due to electron-neutral collisions.

The solution of Eq. (19) with the initial condition that the intensity at the tube surface at an angle θ be $I_0 \frac{d\theta}{\pi}$ is straightforward and is given by:

$$I(\ell, x) = \frac{I_0 d\theta \sqrt{\epsilon}}{\pi \ell_D} \exp\left(-\int_0^\ell \frac{d\ell}{\ell_D}\right) \quad (23)$$

Evaluation of this term will give the intensity of radiation along the ray path. The distribution of rays will be isotropic in angle because the microwaves have

wavelengths much smaller than the dimensions of the cavity walls, and each ray bounces several times in the cavity before being absorbed or lost. To calculate the volumetric source of microwave power, the amount of power absorbed from a ray in a given direction when passing through a differential annular volume is determined, and divided by the differential volume. An integration over all ray directions and all locations around the tube circumference yields the expression for the volumetric source term, q_μ''' :

$$q_\mu'''(r, x) = \frac{2I_0 r_w}{\pi \ell_D} \int_{\theta_{cr}(r)}^{\frac{\pi}{2}} \frac{d\theta \sqrt{\epsilon}}{\sqrt{r^2 - r_w^2 \cos^2 \theta}} \exp \left(- \int_0^{\ell(r, \theta)} \frac{d\ell}{\ell_D} \right),$$

$$\theta_{cr} = \arccos \left(\frac{r}{r_w} \right),$$

$$\ell(r, \theta) = r_w \sin(\theta) \pm \sqrt{r^2 - r_w^2 \cos^2 \theta},$$

$$d\ell = \pm \frac{r' dr'}{\sqrt{(r')^2 - r_w^2 \cos^2 \theta}}.$$
(24)

The geometry of the ray tracing and variable definitions are shown on Figure 3. The $\pm$ in the Jacobian and the ℓ expression is determined by whether a positive differential change in r corresponds to a positive or negative change in ℓ . The point along the ray where this transition occurs is when $r = r_{min} = r_w \cos \theta$.

This term for the volumetric source strength is local in the axial coordinate, x , because only rays which lie in a plane of constant x are considered. This is an approximation to the actual situation where rays originating from $x' < x$ and $x' > x$ can be absorbed at x . Including these additional rays would couple all the axial locations in the moment equations and would add significant complication to the model. We feel the present local model gives a conservative first estimate of the absorption of microwaves in the gas and also contains all of the important physics required to address the radial uniformity questions.

The q_μ''' expression can be evaluated in the limit of $\epsilon \approx 1$, $\omega \gg \nu_{eff}$, and a radiation intensity incident only in one direction, $I = I_0 \pi \delta(\theta - \frac{\pi}{2})$. The result is:

$$q_\mu''' \approx I_0 \frac{r_w}{r \ell_D} \left[\exp \left(- \int_r^{r_w} \frac{dr'}{\ell_D} \right) + \exp \left(- \int_0^r \frac{dr'}{\ell_D} - \int_0^{\frac{dr'}{\ell_D}} \right) \right] \quad (25)$$

where in this limit the damping length takes the simple form:

$$\ell_D = \frac{c}{\nu_{eff}} \left(\frac{\omega}{\omega_{pe}} \right)^2 \quad (26)$$

By examining Eqns. 25 and 26, some qualitative features of the heating can be established. Notice first that the source can be decomposed into two factors: (1) a local absorption term $\propto 1/\ell_D$ and (2) a term which describes the decay of the power flux $\propto \exp()$ along a ray path. To have efficient heating of the core flow, not only does the local term have to be strong in the core, but the absorption along the ray path must not be too large. These two factors compete with each other in that short damping lengths correspond to strong local heating, but also to strong damping of the radiation intensity. If we could somehow keep the damping length long at the edge and shorten it toward the center, we could to achieve reasonably uniform heating.

The radial profiles of electron temperature and density we self-consistently calculate with the two-dimensional code yield radial profiles of damping length which exhibit this tendency for a range of the incident radiation intensity. Two elements of the modeling which are important to properly calculate the temperature and density profiles are the heat and particle flux boundary conditions at the wall for the electron temperature and density respectively, and the treatment of diffusion losses in the electron particle balance. Both effects tend to lower the electron temperature and density in the vicinity of the wall. Section 4 will give some illustrations.

By examining Eq. 26, we can identify some of the parameters which are important to describe the strength of the microwave heating. We substitute the expressions for ν_{eff} , ω_{pe} , $P = n_{gas} k_B T_{gas}$ and normalize the damping length with the tube radius, r_w :

$$\frac{\ell_D}{r_w} \propto \frac{(\omega T_{gas}(0))^2}{r_w \alpha_0 f_s Q_0 \sqrt{T_e} P^2} \quad (27)$$

The heating will become stronger by increasing the gas pressure, P , seed fraction f_s , degree of ionization, α_0 , or the collision cross section, Q_0 . Higher frequencies will result in weaker heating, unless other parameters are adjusted. Section 4.3 illustrates the use of this law to scale to a reactor-grade superheater system.

4 Results of Calculations

4.1 One-Dimensional Model

Figure 4 shows a plot of contours of constant outlet temperature as a function of gas pressure and seed fraction as predicted by the one dimensional superheater model. The gas is helium, with cesium seed material. The tube length is two meters, and its radius is fixed at 5cm. The inlet temperature was constant at 1100°K. The ℓ_D varies over a large range in this figure. The 1-D model cannot be expected to be correct when the damping length becomes much less than the tube radius. Therefore, we have drawn a contour of constant $\ell_D = 0.05m$ on the figure to show the maximum outlet temperature which can be believed. The main point of this plot is that outlet temperatures of nearly 3000°K can be obtained for a range of seed fraction-pressure combinations. The 1-D model can scan rapidly over parameter space but cannot investigate the radial uniformity issues. We therefore concentrate on results generated from the more complete 2-D code.

4.2 Two-Dimensional Model

Table 1 shows the characteristics of an experimental sized microwave superheater. The case labeled without will be discussed later. The choice of the length and radius of the tube is somewhat arbitrary, but seemed reasonable for a small sized proof of principle experiment. We changed the seed material from cesium to lithium because the ionization potential for lithium is larger than for cesium, allowing operation at a higher pressure for the same degree of heating non-uniformity. In a real configuration there would not be enough unheated entrance region for the profiles to approach fully-developed ones, hence radially uniform initial conditions of gas velocity and gas temperature are imposed. The mass flow rate is just under 1 gram/sec, a value which can be easily delivered by a canister of helium. There is no transpiration cooling of the wall for the baseline case. For waves at 56GHz, there is no problem in keeping the wall at 1000°K, based on the results of the one-dimensional model which has a simple energy balance for the wall.

The outlet gas temperature of 2750°K is obtained for an inlet temperature of 1200°K using 10kW of power. The pressure drops are negligible both axially and radially. The seed fraction, f_s , is on the same order which is required for an MHD generator, a necessary condition for compatibility with the rest of the cycle.

The single pass absorption fraction is about 33%. The multiple-pass absorption efficiency will approach unity, as long as the cavity wall remains highly reflective and the ceramic walls transparent. The efficiency for conversion of microwave energy absorbed to enthalpy of the gas is 66%. The remaining 34% is lost by line radiation and conduction and convection losses to the walls. To maintain a constant wall temperature, this lost heat must eventually be transferred to the chamber wall coolant.

Figure 5 shows some typical profiles of important calculated quantities for the base case. The first six subfigures are radial profiles at the tube exit, and the last two show axial profiles of the mean gas and electron temperatures, respectively. Figures 5b,e and f illustrate the fact that for modeling the central region of the gas flow, a point model for the electrons would have been adequate, but for the edge region, the thermal conductivity and diffusion terms are important. Subfigure e is the radial profile of the ratio of the electron density obtained by the Saha relation (ideal ∞ medium) to the actual electron density obtained by the electron particle balance. Subfigure f is the degree of ionization of the seed, α_0 .

The reduced temperature and electron density due to these finite geometry boundary conditions improve the penetration of the microwaves to the center by increasing the damping length near the wall. (cf. Eqn. 25) The Figures 5c and d show the non-uniformity of the volumetric heating term and the radiation emission term. The heating term is peaked because of the tradeoff discussed in Section 3.4. The radiation loss term is peaked at the edge because the plasma is optically thick to the helium and lithium line radiation except for a fairly thin layer near the wall.

To demonstrate that the electron conduction and convection terms improve the gas heating, we considered the baseline case using a version of the 2-D code which did not include them. The results are shown on Table 1. For this case, the electrons were hotter at the edge by about a factor of two, and the heating non-uniformity was 10:1 compared to 1.7:1 for the base case including the finite geometry terms. The efficiency of converting the microwaves to heat was dramatically reduced from 66% to 38%, since steeper gas temperature profiles increased the conduction heat losses. The single pass absorption was increased to over 50% due to the stronger edge heating.

Parametrics around the baseline will now be considered. The figures of merit in most of the plots are the superheat ΔT_{gas} achievable and the ratio of the maximum to centerline volumetric heating source term $q'''_{\mu,max}/q'''_{\mu}(0)$. The latter quantity gives a measure of the uniformity of the heating.

Figure 6 illustrates the effect of varying the seed fraction, f_s . By changing the

seed fraction only $\pm 25\%$ around the baseline can result in a difference of 400° in the outlet temperature. There appears to be a saturation in the improvement of the temperature rise at higher seed fraction. Notice that the non-uniformity increases as f_s is increased, although it too seems to saturate.

Figure 7 shows the pressure scaling of the baseline with the velocity changed to keep a constant Reynolds' number. The seed fraction was also scaled to keep the seed density constant in the parametric. For variations of $\pm 30\%$ around the baseline pressure, the ΔT_{gas} can change by 550° . The degree of non-uniformity of the heating is enhanced as the pressure increases, because the damping length gets shorter due to the higher electron-neutral collision frequency.

Figure 8 is a parametric of transpiration cooling mass flux. The heat flux, q''_{cond} , from gas conduction losses is reduced substantially, but the dilution of the heated gas with cooler gas from the wall reduces the superheat temperature. Transpiration cooling for heaters of this smaller size and modest parameter range does not appear to be necessary. If larger heaters have a heat flux which is higher than for these cases or the microwaves heat the wall to a greater degree than we estimate here, transpiration cooling may be necessary. The answer to this question must wait for a detailed study of the larger superheater.

Figure 9 shows a scaling of the superheat temperature, q''_{cond} , and the $q''_{\mu,max}/q''_{\mu}(0)$ uniformity parameter when the incident radiation flux is varied. When I_0 is varied by $\pm 20\%$, the superheat temperatures are changed dramatically. Outlet temperatures of well over 3000°K are possible. Notice however that the conduction heat flux and the degree of non-uniformity of the heating are increasing dramatically as I_0 rises. Both these effects tend to reduce the rate of rise of ΔT_{gas} as I_0 is changed. One might expect as the radiation intensity is increased further, the gain in the outlet temperature per unit intensity increase will be reduced. Calculations at higher intensity are difficult because of numerical problems in dealing with the very steep gradients at the wall.

The I_0 scaling illustrates the fact that careful adjustment of the power source will be necessary to avoid either underheating or overheating the gas.

4.3 Scaling to Reactor Grade Systems

An experimental-sized superheater as we have considered must scale to a larger, reactor-relevant system. We have found that ℓ_D scales with important microwave and thermodynamic variables in a manner which is favorable to larger sizes. The

reactor system would use mercury working fluid, operate at pressures of several atmospheres and mass flow rates of several kilograms/sec in tubes of radii of about half a meter. The radiation would have an intensity about an order of magnitude higher, produced by a plasma burning D-³He and be emitted in a synchrotron frequency spectrum. The dependence of the source term and damping length on the microwave frequency, collision frequency, and electron density is central to understanding the prospects for scaling. An important scaling criterion is that the radially averaged damping length normalized by the tube radius be kept constant. This quantity is given in Eq. 27. Going to the higher pressures in mercury will reduce non-equilibrium effects present in helium because of the higher Q_0 ($\times 3.7$) and pressure ($\times 8.3$). The inlet gas temperatures will typically be higher for the mercury channel ($\times 1.6$). The average frequency for the reactor heater will be much higher ($\times 18$). The $\alpha_0 f_s$ product is the adjustable parameter to preserve $\frac{\omega_p}{\omega}$. For the scaling ratios, we find that $\alpha_0 f_s$ for the reactor should be about half the value for the present experimental-sized heater, well within values compatible with an MHD generator. From this analysis it appears that the superheater may be scaled to the full sized system. More work must be done to demonstrate this rigorously using the 2-D code in the turbulent flow regime using mercury.

5 Conclusions

In this report, we have presented calculations which suggest that high bulk outlet temperatures can be achieved with microwave superheating in small proof-of-principle experiments. Quick scans of parameter space are accomplished with a radially averaged set of moment equations. The issue of radial non-uniformity of the heating is addressed with a radially resolved 2-D code.

In the range of operation we have studied, the microwave heating is sufficiently uniform that bulk gas temperatures above 3000°K are possible when the wall temperature is at 1000°K. Parametric studies indicate that the heating becomes more non-uniform when either the pressure, seed fraction, or radiation intensity is increased. It is particularly important to be able to control the radiation intensity to avoid overheating or underheating the gas. For superheaters with modest operating parameters, transpiration cooling will not be necessary. More work is needed to find out if reactor-sized superheaters will need it.

Simple scaling arguments indicate that superheaters for reactors can be built

with microwave absorption properties similar to the smaller sizes. This scaling must be verified by detailed calculations using the 2-D code before anything definite can be claimed.

References

- [1] B.G. Logan, R.B. Campbell, M.A. Hoffman, W.L. Barr, K. Yoshikawa, Y. Inui, M. Ishikawa, and J. Umoto. "The Compact Fusion Advanced Rankine (CFAR) Cycle Concept". *IEEE 12th Symposium on Fusion Engineering*, October 12-16, 1987.
- [2] W.M. Kays and M.E. Crawford. *Convective Heat and Mass Transfer*. McGraw-Hill, New York, 2nd edition, 1980.
- [3] M. Mitchner and C.H. Kruger Jr. *Partially Ionized Gases*. Wiley Interscience, New York, 1973.
- [4] G.D. Hobbs and J.A. Wesson. "Heat Transmission Through a Langmuir Sheath in the Presence of Electron Emission". *Plasma Physics*, 9:p85, 1967.
- [5] Chris Gregory. "Resonance Broadening of Cæsium". *Physical Review*, 61:p465, 1942.
- [6] Michael A. Lutz. "Radiation and Its Effect on the Nonequilibrium Properties of a Seeded Plasma". *AIAA Journal*, 5:p1416, 1967.
- [7] T. Holstein. "Imprisonment of Radiation in Gases. II". *Physical Review*, 83:p1159, 1951.
- [8] A.E. White. *Introduction to Atomic Spectra*. McGraw-Hill, New York, 1934. Chapter XXI.
- [9] S. Chandrasekhar. *Radiative Transfer*. Dover Books Inc., New York, 1960.
- [10] V.L. Ginzberg. *The Propagation of Electromagnetic Waves in Plasmas*. Pergamon Press, Oxford, 2nd edition, 1970.

Figure 2: Power Balance in the Microwave Superheater

Figure 3: Ray Tracing Geometry

Figure 4: Contour Plot of Outlet Temperatures from 1-D Code

Parameter(unit)	Baseline	Without
Working Gas	helium	helium
Seed Material	lithium	lithium
Length(m)	1.0	1.0
Radius(m)	0.05	0.05
Microwave Frequency(GHz)	56.	56.
Radiation Intensity(10^5W/m^2)	1.0	1.0
Mass Flow Rate(gm/sec)	0.86	0.86
Inlet Gas Temperature($^{\circ}\text{K}$)	1200.	1200.
Inlet Gas Velocity(m/sec)	9.0	9.0
Gas Pressure(atm)	0.3	0.3
Reynolds' Number	960.	960.
Seed Fraction(10^{-5})	0.8	0.8
Outlet Gas Temperature($^{\circ}\text{K}$)	2750.	2600.
Power Absorbed(kW)	10.4	16.2
Heating Non-Uniformity	1.7:1	10:1
Conversion Efficiency(%)	66	38
One Pass Absorption(%)	33	51

Table 1: Characteristics of the baseline case with and without radial electron losses

Figure 5: Radial and Axial Profiles for the Base Case

Figure 6: Seed Fraction Parametric

Figure 7: Gas Pressure Parametric

Figure 8: Transpiration Cooling Mass Flux Parametric

Figure 9: Microwave Radiation Intensity Parametric

PART 3

TIME DEPENDENT MODELING

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TIME-DEPENDENT STUDIES

2.12.1 INTRODUCTION - The Time-Dependent Systems Code (TTSC)

The Time-dependent Tokamak Systems Code (TTSC) solves radially averaged time-dependent particle and energy balance equations together with various engineering constraints. The physics and engineering modules are time-dependent versions of the MUMAK [1] and TETRA [2] codes as they existed in early 1987. These two codes were merged, made time-dependent and combined with an MHD equilibrium scaling routine [3]. The MHD scaling routine determines the required poloidal field (PF) and transformer coil currents (OH) to provide equilibrium and the necessary volts-seconds.

TTSC uses the steady-state plasma data from a TETRA output file and finds a reasonable startup scenario. TTSC determines auxiliary heating and fueling requirements, volts-seconds capability and startup time, all features which MUMAK and TETRA, by their time-independent nature cannot readily address. In addition, TTSC provides an initial assessment of the required OH and PF coil waveforms and checks to see if $J_{B_{max}}$, B_{max} and stress limits are exceeded.

TTSC has three basic modes of operations. In the fully time-dependent mode, time-varying particle sources for each ion species and heating sources for all species (including electrons) are known and the density and energy equations are solved. On the other hand, the desired density and temperature behavior may be specified so the required time-varying particle and energy sources determined. Finally, the density behavior may be prescribed and the required particle source is calculated while a realistic power source is specified and the time-varying species temperatures determined.

2.12.2 PHYSICS

The basic form of the time-dependent equations is

$$\frac{dF^\beta}{dt} = \left[S_a^\beta - \left[L_b^\beta \right] \right] \quad \beta = e, D, T, \alpha, H, O \quad (1)$$

where F is either the density n or the energy $\frac{3}{2} n_p kT_p$ and S_a are sources and L_b sinks. The S_a and L_b terms are modules from the MUMAK physics code which is described briefly in the appendices at the end of this chapter.

TTSC can solve particle and energy equations for each ion species. However, to save computer time since the ion-ion collision time is short, we assume that all ion species temperatures are the same and solve a global ion energy equation. In addition, since TTSC does not contain a wall model or an impurity transport model, we assume that the impurities (including thermalized alphas) are a percentage of the total ion density. The percentage for each species may be time-varying if specified. Hence the density equations for the impurities are not solved. In addition we also assume that the ratio of deuterium to tritium is fixed (normally this ratio is 1). Therefore, only a global ion density and ion and electron energy balance equations are solved. The impurity densities are determined from the density of the deuterium-tritium mixture while all ion species temperatures are the same.

The deuterium-tritium density equation is as follows

$$\frac{dn}{dt} = R_{\text{fueling}} - n_D n_T \langle \sigma v \rangle_{DT} - \frac{n}{\tau_p^i} \quad (2)$$

where R is a particle source term and

$$\tau_p^i = C \times \tau_E^i \quad (3)$$

where C is a constant and τ_E^i is the global energy confinement time calculated from the MUMAK transport routines.

The electron energy balance equation is

$$\frac{3}{2} \frac{dn_e T_e}{dt} = P_{ohmic} + P_{aux} + P_{\alpha}^e - \frac{n_e T_e}{\tau_E^e} - \frac{n_e (T_e - T_i)}{\tau_{EQ}} - P_{rad} + P_{source} \quad (4)$$

where P_{ohmic} is the ohmic heating source, P_{aux} is an auxiliary heating term (usually RF), P_{α} is the fraction of fast alpha power deposited in the electrons as they slow down, τ_E^e is a global electron energy confinement time, τ_{EQ} is the electron-ion equilibration time and P_{rad} is a radiation loss term (Bremsstrahlung and Synchrotron). The modules which calculate these terms come from the MUMAK code and are documented in Ref. [1]. The electron and ion densities are related through charge neutrality

$$n_e = \sum_{\beta} Z_{\beta} n_{\beta} \quad \text{where } \beta = D, T, \alpha, H, O \quad (5)$$

If the electron density, $n_e(t)$, is prescribed as either an analytic function or a set of data points, then the ion species densities are

$$n_{\beta} = \frac{f_{\beta} n_e}{Z_{\beta}} \quad \text{where } \beta = D, T, \alpha, H, O \quad (6)$$

where f_{β} are the concentrations of the ion species such that

$$\sum_{\beta} f_{\beta} = 1 \quad (7)$$

In this first version of TTSC, these concentrations are constant in time. The f_{β} can be adjusted so that the steady-state value of Z_{eff} used by MUMAK and TETRA is obtained

$$Z_{eff} = \frac{\sum_{\beta} Z_{\beta}^2 n_{\beta}}{n_e} = \sum_{\beta} Z_{\beta} f_{\beta} \quad (8)$$

Knowing the electron density and ion species mix, the required ion particle source terms can be obtained from Eq. (2)

$$R_{\text{fuel}}^{\beta} = \frac{dn_{\beta}}{dt} + \frac{n_{\beta}}{\tau_{\beta}} + R_{\alpha} \quad \text{for D, T, } \alpha, \text{ O, H} \quad (9)$$

where

$$\begin{aligned} R_{\alpha} &= n_D n_T \langle \sigma v \rangle_{DT} \quad \text{for D and T} \\ &= - n_D n_T \langle \sigma v \rangle_{DT} \quad \text{for alphas} \\ &= 0 \quad \text{for impurities} \end{aligned} \quad (10)$$

and $\frac{dn}{dt}$ is determined from the specified analytic expression for $n_e(t)$ or by fitting $n_e(t)$ data points to cubic splines.

Assuming that all the ion species have the same temperature, a global ion energy balance equation can be solved to obtain the ion temperature

$$\int_{\beta} \frac{3}{2} \frac{dn_{\beta} T_i}{dt} = \int_{\beta} P_{\text{aux}}^{\beta} T \int_{\beta} \frac{n_{\beta} (T_e - T_i)}{\tau_{ei}^{\beta}} - \int_{\beta} \frac{n_{\beta} T_{\beta}}{\tau_E^{\beta}} + P_{\alpha} + \int P_s^{\beta} \quad (11)$$

where P_{aux} is an auxiliary heating source (usually RF), τ_{EI}^{β} is the ion-electron equilibration term for ion species β , τ_E^{β} is the global energy confinement time for species β , P_{α} is the fraction of alpha power deposited in the ions and P_s^{β} is an additional energy (source or sink) which is used when the ion temperature is prescribed.

If $T_e(t)$ and the ratio of T_e to T_i prescribed, then Equations (4, 11) may be solved to obtain the required energy sources

$$P_{\text{source}}^e = \frac{3}{2} \frac{dn_e T_e}{dt} - P_{\text{ohmic}} - P_{\text{aux}} - P_{\alpha}^e + \frac{n_e T_e}{\tau_E^e} + \frac{n_e (T_e - T_i)}{\tau_{ei}} + P_{\text{rad}}$$

$$P_{\text{source}}^{\beta} = \frac{3}{2} \frac{dn_{\beta} T_i}{dt} - P_{\text{aux}}^{\beta} - P_{\alpha}^{\beta} + \frac{n_{\beta} (T_e - T_i)}{\tau_{ei}^{\beta}} + \frac{n_{\beta} T_{\beta}}{\tau_E^{\beta}}$$

where $\frac{dn}{dt}$ is determined from the analytic expressions for $n(t)$ and $T(t)$ or by using cubic splines.

2.12.3 INITIAL CONDITIONS

The initial plasma current is specified (typically 200 kA). The initial density is taken to be a fraction of the Greenwald density limit given as

$$n_e = \frac{1 \times 10^{14} f_e I_p}{\pi a^2} \quad (13)$$

where $f_e < 1$ (typically 0.2). Using Eq. (13) and the user supplied f_β from Eq. (6) the initial ion densities are determined. To find the ion and electron densities, the ion and electron energy balance equations are solved assuming

$$\frac{dn_{\beta} T_{\beta}}{dt} = 0 \quad \beta = D, T, \alpha, H, O, e \quad (14)$$

We also force the ratio $\frac{T_i}{T_e}$ to be a user supplied initial ratio

$$R_{ATTITE} = \frac{T_i}{T_e} \quad (15)$$

We also allow n_e to adjust somewhat and solve the charge balance equation

$$n_e = \sum_{\beta} Z_{\beta} n_{\beta} \quad \beta = D, T, \alpha, H, O \quad (16)$$

For these four equations, the corresponding four variables are T_e , T_i , n_e and τ_{MIN} where τ_{MIN} is the minimum energy confinement time used in the energy balance equations. The radial transport routines come from the MUMAK code which assumes a steady-state full-sized plasma. The τ_E^{β} calculated from these routines for the initial plasma is usually quite small and greatly increases the amount of computer time needed to reach steady-state. Therefore, TTSC assumes that

$$\tau_E^\beta \geq \tau_{\text{MIN}} \quad (17)$$

where τ_{MIN} is adjusted to solve the initial energy balance equations. A nonlinear equation solver HYBRID [4] is used to solve the four equations (12, 15, 16). The initial value for n_e comes from Eq. (13) while those for T_e and T_i come from Eq. (15) and the following equation

$$\beta = f \beta_{\text{LIM}} \quad (18)$$

where f is a user supplied number ≤ 1 (initially 0.005) and β_{LIM} is the Yamazaki beta limit with a coefficient of 0.047. When external energy and/or particle sources are prescribed, we assume that the global particle and energy confinement times obtained from the MUMAK model degrade exponentially when either the beta or density limits are exceeded. This prevents thermal runaway when the fusion power becomes significant. When either the density or temperature time-profiles are specified and the required sources calculated, at steady-state, the sources may be negative. This can be interpreted as an enhancement in radial transport required to prevent thermal runaway.

12.4 MHD EQUILIBRIUM SCALING

Having obtained the initial T_i , T_e , n_i , n_e and plasma current, the PF and OH coil currents need to be adjusted to provide MHD equilibrium and the proper amount of flux linkage. A unique feature of TTSC is the capability of linking the PF and OH coil waveforms with plasma performance. At each point in time, the OH and PF coil currents are adjusted to provide MHD equilibrium and correct amount of volts-seconds. The number, sizes, and locations of the PF and OH coils come from the output of the TETRA steady-state nonlinear optimization systems code discussed in Chapter .

Before the plasma is initiated, for a given OH current, the remaining PF coils currents are adjusted to produce (in a least squared sense) a zero

vertical magnetic field at a number of equally spaced grid points along the midplane (from 3 to 32). To determine the OH current, a guess for the initial OH current is supplied and the resulting PF coil currents determined. $B_{\max}$ and $JB_{\max}$ are calculated at the top and bottom of each PF coil and at the top, bottom and center of the transformer stack. The initial guess is then scaled so that the currents in the OH and PF coils do not exceed the $B_{\max}$ and $JB_{\max}$ limits (typically 14 T and 500 MAT) while being as large as possible. This will allow the OH coil swing to produce the largest amount of volts-seconds. Starting from these initiation coil currents, when the plasma is present, the coil currents are then adjusted to provide MHD equilibrium and the required volts-seconds. To obtain these currents, first the vertical field at the midplane grid points (from 3 to 32) is calculated using the plasma conditions (size, position, poloidal beta, current, elongation and inductivity) and the PF and OH coil currents and locations from a separate 2-D MHD equilibrium calculation. These reference set values are obtained from TETRA or directly from the 2-D MHD code NEQ [5]. This reference set provides the vertical field which the TTSC MHD routine then uses to scale the coil currents. For a given OH current, the PF coil currents are adjusted so that the vertical field at the grid points on the midplane match in a least-squared sense those values obtained from scaling the reference set vertical field for the new set of plasma conditions generated by TTSC. The OH current is adjusted so that the complete PF and OH coil sets provide the amount of volts-seconds required by the plasma at that point in time. At each time step, the new plasma conditions and volts-seconds requirement are given to the MHD scaling routine which then returns the required OH and PF coil currents.

In addition, at each time step, $B_{\max}$ and $JB_{\max}$ are determined at the top and bottom of each PF coil and at the top, bottom and center of the transformer stack. The max: $B_{\max}$ and $JB_{\max}$ for the entire coil set over

the entire simulation is recorded as well as the coil location where this occurs in order to pinpoint a possible stress problem. In addition, at the end of the simulation, usually 2-3 seconds into the current flat-top, and presumably, but not necessarily, when the plasma is at steady-state operating conditions, the PF and OH coil currents are linearly extrapolated to the time where either the $B_{\max}$ or $JB_{\max}$ limit (whichever comes first) is met. This then determines the maximum burn time and volts-seconds capability of the given magnet set for the assumed startup scenario. If either the $B_{\max}$ or $JB_{\max}$ limit is exceeded at some point during the startup, this is noted along with the coil location and current value. The burn time and volts-seconds capability is then given as the values obtained by TTSC at the end of the simulation.

2.12.5 ENGINEERING

The radial build and PF and OH coil locations and sizes come from the TETRA code. Given the PF and OH coil currents, an estimate of the actual coil stresses can be obtained. This will be done when the new version of TETRA is incorporated into TTSC.

The auxiliary power inputs can be adjusted to minimize the amount of volts-seconds used in startup without exceeding the beta limit or the capability of the auxiliary heating power supplies.

2.12.6 POSSIBLE STARTUP SCENARIOS

For this first version of TTSC we have examined various startup scenarios for pulsed operation where RF is used as a heating source but not as a current drive source. We have also assumed that the plasma density ramp is

prescribed while the auxiliary power (presumably RF) source to the electrons is specified. The resulting particle sources (or sinks) and electron and ion temperatures are determined. The plasma current is assumed to be a piecewise continuous linear ramp based on DIII-D data [5] and shown in Figure 1. The electron density is prescribed to follow the plasma current as displayed in Figure 2 where we have fixed Z_{eff} at 1.32. The general TIBER pulsed-mode parameters are given in TABLE I while TABLE II shows the assumed initial plasma conditions.

Figure 3 shows the prescribed RF auxiliary heating power waveform, in this case a maximum of 20 MW to the electrons. TABLE III shows the effects of varying the maximum amount of RF power. For RF powers less than 8 MW, the plasma does not ignite. For RF powers from 8-10 MW the plasma ignites but well after the current flattops. To ignite the plasma and reach steady-state when the current flattops requires at least 15 MW of RF power. Increasing the RF power from 10 MW to 20 MW saves over 1 volt-seconds which translates to 14 s of increased burn time.

To get a feeling for the capabilities of TTSC we examine in detail a possible start-up scenario assuming a maximum of 20 MW of RF power deposited in the electrons with the heating profile shown in Figure 3. Figures 4 and 5 show the resulting electron and ion temperatures. The initial change in slope in the temperature curves near 4 seconds corresponds to a change in confinement due to a change in the assumed slope in the current rampup. The second change in the temperature slopes near 9 seconds follows the exponential enhancement in radial losses when the beta limit is exceeded. The plasma beta and beta limit (dashed curve) are shown in Figure 6. The final change in slope occurring near 17 seconds results from the assumed change in slope in the plasma current due to flattopping. The energy confinement time is a function of density, temperature, plasma current and auxiliary power

(including alpha power) and is plotted for the electrons in Figure 7. There are several competing effects. As the density, temperature and plasma current increase, τ_E^e increases. However, as these increase, P_α increases, which decreases τ_E^e . Also P_{ohmic} decreases in time which tends to decrease the rate at which the electron energy increases. These effects, together with the exponential enhancement in losses when the beta limit is exceeded produces the temperature curves shown in Figures 4-5.

The reference magnet set which provides a 2-D MHD equilibrium during steady-state is shown in Figure 8. TTSC represents this case as 7 sets of PF coils and an OH stack made up of 4 coils all programmed with the same current. The numbering system for the coils can also be seen in Figure 8. Point 16 corresponds to the top of the OH stack while 16 is at the center. Figure 9 shows the volts-seconds required by the plasma. This volts-seconds requirement can be divided into an inductive part, primarily a function of plasma size and current (Figure 10), and a resistive part (Figure 11), a function of plasma density and temperature. Assuming a full sized plasma startup, the inductive part of the total volts-seconds requirement is independent of the startup scenario. The startup scenario can greatly affect the resistive part. The less auxiliary heating, the longer the plasma takes to reach steady-state and the greater the resistive volts-seconds consumed, as shown in TABLE III. However, in a reasonable startup scenario, the resistive part may amount to less than 10% of the total volts-seconds consumed so there reaches a point of diminishing return as far as increasing the amount of auxiliary heating. To provide this volts-seconds, the PF and OH coils are charged so as to swing from a -27.66 V-s to 22.79 V-s shown in Figure 12. The OH and PF coils are swung so as to prevent B_{max} and $J_{B_{max}}$ limits from being exceeded. The OH coil stack current waveform is shown in Figure 12 while the B_{max} and $J_{B_{max}}$ at the end of the OH stack is shown in Figures 13-14.

Figures 15-21 show the current waveforms for the other PF coil sets identified in Figure 8. The rather strange shape in many of the current waveforms between 4 and 8 seconds is a result of changes in beta poloidal, shown in Figure 22. For fixed plasma size, the scaling is a sensitive function of poloidal beta.

In addition to examining $B_{\max}$ and $JB_{\max}$ for the OH stack, we also examine them for each PF coil set. In this particular case, the $B_{\max}$ at point 16 limited the burn time. When the slope of $B_{\max}$ for the steady-state conditions in Figure 13 was extrapolated then the $B_{\max}$ limit of 14 T was reached for a burn time of 321 seconds with a total volts-seconds consumed of 74.8 V-s. These numbers are somewhat larger than the baseline parameters because we do not look at the stresses in the OH stack which may be exceeded before the $B_{\max}$ limit is met. In the next version of TTSC we hope to incorporate some analytic stress models. During steady-state, the plasma has a loop voltage of 0.072 V. Therefore, for each volts-seconds saved during startup, the burn time can be extended approximately 14 seconds. In addition, if $JB_{\max}$ was the limit, then this limit would be reached for a burn time of 30617 seconds. In charging the coils to zero out the vertical field at plasma initiation, the largest $B_{\max}$ is at the top of coil 4. However, as the coil currents change to follow the changing plasma conditions, the highest $B_{\max}$ point quickly switches to center of the transformer stack.

2.12.7 CONCLUSIONS

We have developed a 0-D time-dependent physics-engineering code which can quickly examine various startup scenarios and, when coupled to the steady-state nonlinear optimization tokamak systems code TETRA, ascertain if the "optimal" steady-state operating conditions are "achievable". TTSC can

estimate volts-seconds requirements and capabilities and auxiliary heating and fueling requirements. In addition, TTSC can address potential magnet stress problems by examining $B_{\max}$ and $JB_{\max}$ at various coil locations. TTSC has shown the effectiveness of auxiliary power in reducing the volts-seconds requirement during startup and has found a reasonable startup scenario for the pulsed-operation mode of TIBER. In addition, TTSC can estimate the burn time and volts-seconds capability of the magnet set.

The next version of TTSC will include the most up-to-date physics and engineering routines from MUMAK and TETRA. We also hope to address the effect of RF current drive (in particular, lower-hybrid) on the volts-seconds requirement and on the MHD equilibrium scaling. We also intend calculating stresses in the OH and PF coils to determine the burn time and volts-seconds capability. We will also use TTSC to examine expanding radius startup scenarios, since presumably, at very low densities the plasma will be smaller and more circular. Finally we will examine the effect of changing Z_{eff} from approximately 5 to the steady-state value of 1.32 on volts-seconds consumed during startup.

References for Section 2.12

- [1] M.E. Fenstermacher LLNL Report UCID-21038 (April 22, 1987); Section 2.4 of this report
- [2] L. Reid et al, Section 7 of this report
- [3] D. Strickler FEDC/ORNL Private communication (1986)
- [4] B.S. Garbow, K.E. Hillstrom and J.J. More, Argonne National Laboratory, Argonne, Il, Minpack Project (March 1980)
- [5] S. Ejima, L. Lao, J. Luxon, T.H. Osborne, R.D. Stav, T.S. Taylor, APS paper 6P2, Bull. of Am. Phys. Soc. Vol. 31, No. 9 (Oct. 1986) p. 1532

Table 1 shows the initial plasma conditions.

TABLE I

TIBER PARAMETERS

R_o (m)	3.0
a_o (m)	0.833
κ	2.4
B_T (T)	5.55
I_T (MA)	8.0
n_p ($\times 10^{20} \text{ m}^{-3}$)	1.78
z_e	1.32
β_{lim}^{eff} (75% of β_{Ham})	.050
$\frac{d}{dt}$ (V-S)	.072
$t_{startup}$ (s)	17

TABLE II

AT PLASMA INITIATION ($t = 3 \text{ s}$)

I (MA)	0.200
n^p ($\times 10^{20} \text{ m}^{-3}$)	.018
T^e (keV)	.13
T_i (keV)	.08

TABLE III

TIBER WITH CW RF HEATING

At $t \sim 27s$ ($\tau_{\text{flattop}} + 10s$)

CASE	RF POWER (MW)	T_e (keV)	T_i (keV)	β	P_{FUS} (MW)	Γ_{WALL} (MW/m ²)	V-S (VS)	V-S _{RES} (VS)	τ_E^e (S)
30.00	~ 0	1.49	1.49	.0083	1.27	.005	56.8	12.78	13.9
30.08	8	6.14	5.81	.0343	150	.621	47.9	3.98	3.7
30.10	10	8.78	7.83	.0492	297	1.23	47.0	3.00	2.94
30.15	15	9.20	8.05	.0515	314	1.30	46.1	2.05	1.97
30.20	20	9.82	8.04	.0519	313	1.30	45.7	1.71	1.07

LIST OF FIGURES

- (1) Assumed plasma current waveform. Initial value of 200 kA. Initial slope is 1 MA/s changing to $\frac{4}{9}$ MA/s after reaching 1 MA
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- (4) Radially-averaged electron temperature assuming the auxiliary power source in Figure 3.
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- (8) Reference PF and OH coil set used by TTSC and TETRA. This plot is generated by the FEDC/ORNL 2-D MHD equilibrium code NEQ. The numbers by the coils corresponds to the TTSC numbering system.
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- (12) Volts-seconds provided by the PF and OH coils. At each time-step, the volts-seconds provided by the coils equals that required by the plasma.

- (13) OH transformer stack current waveform. Initial peak limited by $B_{\max}$ limit.
- (14) $B_{\max}$ at point 16, the center of the OH transformer stack at an r location of 0.6 m.
- (15) $JB_{\max}$ at point 16, the center of the OH transformer stack at an r location of 0.6 m.
- (16) Current waveform in PF coil 1 located at $r = 0.8$ m and $z = \pm 1.2$ m
- (17) Current waveform in PF coil 3 located at $r = 0.8$ m and $z = \pm 2.0$ m
- (18) Current waveform in PF coil 5 located at $r = 0.8$ m and $z = \pm 2.8$ m
- (19) Current waveform in PF coil 7 located at $r = 1.8$ m and $z = \pm 4.25$ m
- (20) Current waveform in PF coil 9 located at $r = 4.1$ m and $z = \pm 4.25$ m
- (21) Current waveform in PF coil 11 located at $r = 6.2$ m and $z = \pm 3.2$ m
- (22) Current waveform in PF coil 13 located at $r = 6.2$ m and $z = \pm 1.5$ m
- (23) Poloidal beta

PLASMA I

- (1) Assumed plasma current waveform. Initial value of 200 kA. Initial slope is 1 MA/s changing to $\frac{4}{9}$ MA/s after reaching 1 MA

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DENSITY

(2) Assumed radially-averaged electron density ramp

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RF

RF INPUTS

- (3) Assumed auxiliary power source waveform (RF with all the power deposited in the electrons)

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- (4) Radially-averaged electron temperature assuming the auxiliary power source in Figure 3.

TEMP.

DEUTERIUM

0.000

8.043

- (5) Radially-averaged ion temperature assuming the auxiliary power source in Figure 3 with all ion species having the same value.

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BETA LIMIT

0.0000 5.1860×10^{-2} DOT - LIMIT

- (6) Plasma beta including fast alphas (solid line) and 75% of the Yamazaki beta limit (dashed line). Energy confinement time is exponentially degraded when the solid curve is above the dashed line.

TAUEE

(7) Global electron energy confinement time.

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- (8) Reference PF and OH coil set used by TTSC and TETRA. This plot is generated by the FEDC/ORNL 2-D MHD equilibrium code NEQ. The numbers by the coils corresponds to the TTSC numbering system.

VPLASM

(9) Volts-seconds consumed by the plasma.

(10) Inductive volts-seconds consumed by the plasma, a function of plasma current.

VSRES

0.000 6.428

- (11) Resistive volts-seconds consumed. This is may vary greatly with differing startup scenarios. Is a function of changing plasma conditions.

RVOLTS2

- (12) Volts-seconds provided by the PF and OH coils. At each time-step, the volts-seconds provided by the coils equals that required by the plasma.

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CURSTOT

(13) OH transformer stack current waveform. Initial peak limited by $R_{\max}$ limit.

PF COIL-16 2.661×10^{-1} 1.270×10^1
 RADH 0.600 ZH0H 0.000

- (14) $B_{\max}$ at point 16, the center of the OH transformer stack at an r location of 0.6 m.

JB_{MAX}

PF COIL-16 3.974×10^{-1} 3.309×10^2
 RROH 0.600 ZROH 0.000

- (15) JB_{max} at point 16, the center of the OH transformer stack at an r location of 0.6 m.

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WAVEFORM

WAVE-1 0.000 9.072 $\times 10^0$

RPF- 0.800 ZPF- 1.196 RICO--6.310

(16) Current waveform in PF coil 1 located at $r = 0.8$ m and $z = \pm 1.2$ m

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WAVEFORM

WAVE-3 0.000 1.254x10'
RPF- 0.800 ZPF- 1.996 RICO--11.15

(17) Current waveform in PF coil 3 located at $r = 0.8$ m and $z = \pm 2.0$ m

WAVEFORM

WAVE-5 0.000 6.709×10^0

RPF- 0.800 ZPF- 2.796 RICO--6.131

(18) Current waveform in PF coil 5 located at $r = 0.8$ m and $z = \pm 2.8$ m

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WAVEFORM

WAVE-7 0.000 6.116x10⁰
RPF- 1.800 ZPF- 4.246 RICO--4.727

(19) Current waveform in PF coil 7 located at r = 1.8 m and z = ± 4.25 m

WAVEFORM

WAVE-9 0.000 4.967×10^0

RPF- 4.095 ZPF- 4.246 RICO--1.172

(20) Current waveform in PF coil 9 located at $r = 4.1$ m and $z = \pm 4.25$ m

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WAVEFORM

WAVE-11 -1.443x10⁰ 0.000

RPF- 6.195 ZPF- 3.196 RICO- 0.490

(21) Current waveform in PF coil 11 located at r = 6.2 m and z = ± 3.2 m

WAVEFORM

WAVE-13 -5.802×10^0 6.777×10^{-1}

RPF- 6.195 ZPF- 1.496 RICO--0.312

(22) Current waveform in PF coil 13 located at $r = 6.2$ m and $z = \pm 1.5$ m

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BETA P

0.000

3.663

(23) Poloidal beta

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PART 4

FREE ELECTRON MASER (FEM) FOR TIBER II

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FINAL REPORT

FREE ELECTRON MASER FOR TIBER-II

1. Electron Cyclotron Heating Requirements in the TIBER-II Reactor.

The electron cyclotron heating (ECH) requirements are based on a scenario discussed by Smith, Logan, and Kritz¹. They show, that the same launching geometry can help the reactor operation in two ways: 1) Facilitating the initiation of burn by localized core heating during reactor startup and 2) suppression of the disruptions and decrease of transport by controlling radial electron temperature and current distribution. Second harmonic absorption is preferred over fundamental ECH because of the better accessibility of the resonance layer at high densities and because targeting of a specific heating area is less affected by density fluctuations which can scatter the microwave beam into an appreciable solid angle. The authors of Ref. 1 show that in the TIBER-II configuration, an extraordinary mode signal at 450 GHz launched at a polar angle of $\theta \approx 50^\circ$ and azimuthal angle of $\phi = 285^\circ$ (cylindrical coordinate system coaxial with the tokamak axis of symmetry) 99% of the incident power is absorbed in the region outside the $q = 2$ flux surface. The code calculations show that now power reaches the center of the plasma.

The less desirable choice of fundamental absorption of a 225 GHz signal, launched in the ordinary mode polarization, is also considered. Calculations of the toroidal current profile with and without ECH shows that a 10 MW power level at 450 GHz reduces the radial current gradient near the $q = 2$ surface to an extent that is expected to positively influence disruptions and plasma transport. Because of fluctuations in the current profile, the radial point for optimum profile control with ECH can vary on a timescale of several msec. Therefore, the microwave source should be fast tunable over 5-10% in frequency in order to be able to move the point of absorption to another cyclotron resonance layer.

The 10 MW microwave power considered above can be subdivided in a number of ways between several individual sources. Using one single source is undesirable because of high local power loading both in the source and transmission system but also because of lack of redundancy. A set of 6 sources, one of which a spare, would limit the individual power to a convenient 2 MW and would guarantee continuous operation in case of a failure in one unit.

Both fundamental and harmonic operation are an option in the ECH scenario considered above. It is highly desirable that both frequencies can be generated with the same sources with only minor modifications.

In conclusion, the design requirements for the microwave sources for ECH in TIBER-II can be listed as shown in Table I.

TABLE I

Frequency: 450 GHz (harmonic heating)
225 GHz (fundamental heating)
both frequencies should be generated
with the same sources with only minor
modifications.

Total Power: 10 MW

Power/Module: 2 MW

Dynamic frequency tuning range: 5-10%

Polarization: Linear

Mode: gaussian

Duty Cycle: C.W.

2. ECH Source Design Philosophy and Beam Layout

The Free Electron Maser (FEM) is ideally suited as a source for ECH in TIBER-II and other Tokamaks². Since no frequency determining cavities and/or magnet fields are necessary, the FEM does not have the frequency and power limitation of other devices. The approximate wavelength scaling law of

$$\lambda = \frac{\lambda_w}{2\gamma^2}$$

where λ_w is the wiggler wavelength and $\gamma = (1 + E_b/mc^2)^2$, shows that the output wavelength can be varied with the electron beam energy E_b . This makes it possible to operate a given FEM at different output frequencies. Furthermore, since the beam energy is high, the FEM is inherently a high power device. The beam extraction efficiency depends critically on the beam quality (energy spread $\Delta\gamma/\gamma$ and emittance ϵ). High quality beams can be generated optimally with electrostatic accelerators which operate in the D.C. mode. They also allow beam energy recovery of the spent beam which results in a high total efficiency, low power loading of the beam collector and allow the use of a low current; low cost high voltage power supply.

The FEM interaction is broad band. The device, therefore, can either be operated as a broad band amplifier or, with a frequency selective feedback loop, as a fast tunable amplifier. The latter option is important for fusion relevant frequencies, since no broadband tunable oscillators are available at any power level.

Figure 1 gives a schematic description of a high power, high frequency FEM for TIBER-II. The electron beam, generated by the electron gun, is accelerated to the required high voltage deflected into and out of the interaction region, represented by the magnetic wiggler, by achromatic bends which can deflect the beam independently of energy within the required limits. The highly overmoded interaction waveguide is straight. Frequency tuning over the gain bandwidth of the FEM is accomplished with a tunable longitudinal laser like cavity.

3. FEM parameter selection and interaction modeling.

Equation 1 shows that it is desirable to choose a short wavelength wiggler in order to limit the beam voltage. On the other hand, the wiggler field scales with $\exp(-g/\lambda_w)$, where g is the gap width between wiggler pole faces. This gap has to

accommodate the electron beam and microwave transport tube, usually a rectangular overmoded waveguide. It is then understandable that the gap and therefore the wiggler wavelength can not be made arbitrarily small both because of the finite electron beam size and the microwave power loading of the waveguide wall.

Other constraints that enter the parameter selection are current limitations due to space charge blow-up of the propagating beam, equilibrium radius in the wiggler section due to finite beam emittance and electron to microwave beam filling factor.

The operational parameters selected for the TIBER-II FEM are listed in Table II. As will be shown below, all parameters are conservative and well within the limit of present technology limits. For the input power level it is assumed that about - 30 dB of the output power enters the system through a feedback loop.

The TRW FEM interaction code was used to predict system performance for the conditions listed in Table II. The left panel in Figure 2a demonstrates for the 450 GHz case the axial wave growth in terms of the beam extraction efficiency. Nonlinear wave saturation and therefore maximum interaction occurs at $L = 160$ cm. The beam extraction efficiency at that point is 3.5%. The right panel of figure 2a shows the single pass gain as a function of frequency. Peak gain is 1400 which means that less than 30 dB of the output power needs to be recycled in a feedback loop for oscillator operation. Fast tunability can be achieved for constant beam parameters since the 3 dB width of the gain curve is 7.2%. By lowering the beam voltage to 1,88 MV, the system can be operated at 225 GHz while leaving the other system parameters constant. Figure 2b) shows, compared to the 450 GHz case, that the beam extraction efficiency is slightly enhanced to 3.8%. Since simultaneously the beam power decreased, the output power is reduced to 2.4 MW compared to 2.8 MW for the 450 GHz. Gain and 3 dB bandwidth are found to be quite similar for both operating conditions.

The FEM interaction code also predicts the electron beam energy distribution at the end of the interaction region. This is shown for the 450 GHz case at peak gain in Figure 3 which also lists the initial and final average beam energy $\langle V_i \rangle$ and $\langle V_f \rangle$. This distribution can be used to estimate the ideal system efficiency of a multi-stage depressed voltage collector. Arranging 5 collectors between 0 and 200 kV, as shown in Figure 3, one calculates the current collected and power dissipated for each collector. With a total power lost in the collector of $P_{\text{lost}} = 0.78$ MW and an microwave output power of $P_{\text{out}} = 2.8$ MW one finds the ideal total system efficiency

$$\eta_T = \frac{P_{out}}{P_{out} + P_{lost}} = 7.8\%.$$

The efficiency of an actual system will, of course, be smaller.

Although all system requirements are met for the FEM parameters of Table I, it would be desirable to increase the gain bandwidth. This could be done by increasing the interaction strength for example by increasing the beam current which also increase efficiency and output power. A previous conceptual design of a FEM for TIBER-I demonstrates this. Figure 4 shows efficiency and gain bandwidth using a 2.36 MV, 40A beam together with $\lambda_w = 5$ cm, $B_w = 2.0$ kG wiggler resulting in 5.7 MW output power at 240 GHz. Evidently the gain curve is now 10% wide at 75% of peak gain.

TABLE II

TIBER-II FEM parameters

Electron Beam:

$V = 2.7$ MV (harmonic operation at 450 GHz)

$V = 1.9$ MV (fundamental operation at 225 GHz)

$I = 30$ A

$r = 2.0$ mm

$\epsilon = 40$ mm mrad

Wiggler:

$\lambda_w = 2$ cm

$B_w = 2$ kG

linear polarized, untapered.

Waveguide:

2x6 cm

TE_{01} mode

Input power: 2 kW

Output Power: 2.8 MW (450 GHz)

2.4 MW (225 GHz)

Expected total efficiency with beam energy recovery: 44%

4. Electron Beam Line

As shown schematically in Figure 1, the electron beam is generated in an electron gun, accelerated to full high voltage in an acceleration column, deflected into and out of the interaction region with achromatic bends, decelerated to maximum collector voltage and collected in a multi-stage collector. The two most important aspects in the design of the electron beam line are:

- Beam Emittance
- Current loss at high voltage.

Electrons entering the wiggler with a finite angle or radius will perform betatron oscillations due to the alternating gradient focusing force of the wiggler field³. Consequently, the electron beam will have 1) an equilibrium radius given by the beam divergence (emittance) and the wiggler field and 2) an increased effective longitudinal energy spread. Since both beam density and energy spread influence the FEM gain and efficiency, the beam emittance is a crucial parameter which should be as small as possible. It is, therefore, essential to design a high quality electron gun and to keep the emittance growth in the beam transmission system small.

The current loss at high voltage should be kept small since it influences directly the current and therefore cost of the high voltage power supply. It will also generate the largest fraction of the power deposited in the high voltage components.

4.1 Electron Gun

The electron gun is modeled after the gun presently in operation at the TRW FEM, which was designed by a TRW consultant Dr. R. Hechtel, Redwood City. The electrode configuration, beam orbit, phase space and normalized current density at the gun exit are shown in Figure 5. The gun has two stages, the first, the actual gun, determines the operational current from the voltage applied to its anode, the second accelerates the beam to 300 kV in a relatively short gap in order to limit the space charge blow-up of the beam while still at low energy. A control electrode is placed between cathode and first anode which allows the beam to be pulsed on a microsecond time scale. This feature will facilitate electron beam line tune-up at the beginning of the system operation, since short beam pulses will limit

the power deposition in the beam line by an untuned beam. The control electrode does not intercept the beam with a grid because both of power loading and emittance growth due to the potential distribution surrounding the wires. Pulsing the voltage of the electrode from - 10 kV to +10 kV (w.r.t. cathode) will turn the gun from the "off" to the "on" stage. The sum of geometrical and thermal emittance at the gun exit is 10.7 mm mrad, considerably better than the minimum requirement of 40 mm mrad for the FEM interaction.

4.2 Accelerator Column

The transport of the high current, relativistic beam through the acceleration/deceleration columns was modeled with the EBQ code. EBQ is a particle simulation code for the steady-state transport of high current, charged particle beams in axisymmetric systems possessing external electric and/or magnetic fields. It includes the self-fields of the particles so as to obtain self-consistent charge and current distributions. In addition, because of the codes' unique method of handling the cancellation that occurs between radial electric and magnetic self-forces, the high current electron beam can be accurately tracked in its long distance flight through the accelerating/decelerating structures.

The external solenoidal focusing fields used in the simulations are those of an iron-shielded solenoid with a bore diameter of 2.5" and a gap width-to-bore diameter ratio of 1. A table of vector potentials for this coil geometry were generated using POISSON and input to the EBQ code.

Commercial accelerator sections like those built by the National Electrostatics Corporation can be used for the 120 cm long acceleration section. The beam modeling showed that additional magnetic focusing is necessary between the gun and accelerator column in order to focus the beam to a 5 mm radius at the entrance of the first achromatic bend. Electrode and magnetic field configuration as well as beam orbit and phase space at the first and last accelerator sections are shown in Figure 6. To within the fluctuations of the code output, no emittance growth is observed. Also, the current intercepted by the accelerating structure is zero.

4.3 Achromatic Bend

While the input beam at the first bend is cold, it obtains a sizable energy spread (see Figure 3) during the FEM interaction. Deflection of the beam with a

simple magnetic dipole, therefore, is not feasible for the output beam. A magnetic dipole - quadrupole - dipole combination can serve as an achromatic bend. The design of such a system for the 2.69 MV beam of TIBER-II is reproduced in Figure 7. The focusing action of both the quadrupole and the dipole pole faces is used in this design. The pole faces facing the quadrupole are rotated by 17.6° from the normal with respect to the beam orbit. Since this achromatic bend, in addition to the energy independency also has excellent focusing and transport properties, it is used both at the wiggler input and output side.

4.4 Wiggler Beam Transport

See Section 5.

4.5 Deceleration Column

In the deceleration column, which is constructed from the same components as the accelerator column, the beam energy is decreased to the lowest energy of the beam distribution. Since space charge forces become important as the beam is decelerated it was found to be necessary to include solenoidal magnetic focusing elements in the design.

4.6 Multi-Stage depressed Voltage Collector

Depressed voltage collectors are used extensively by the microwave tube manufacturing industry to boost the efficiency of space borne traveling wave tubes. One particular design, developed by Dr. R. Hechtel, Redwood City, for linear beam tubes has demonstrated high efficiency and has shown excellent agreement between predicted and actual performance⁴. The design features spherical collector surfaces in a configuration that spreads the collected beam elements over large areas to decrease local power loading and increase collectors efficiency. It also shows an excellent suppression of back streaming electrons. Recently, such a collector was built for the Free Electron Laser operated at the Quantum Institute of the University of California at Santa Barbara⁵.

The collector the the TIBER-II FEM, whose design will be discussed in an addendum to this report, is similar to that of the present TRW FEM collector (Figure 8) which was designed specifically to simulate the conditions of a high power FEM like the TIBER-II design discussed in this report. Specifically, it can

accommodate the total beam energy spread of $\Delta V/V = 15\%$ of the TIBER-II FEM beam. From the design calculations a collector efficiency of 97.3% is predicted. From experience obtained with prediction and measurements it is expected that the actual collector efficiency will be $\eta_R = 95 - 96\%$. With a predicted beam extraction efficiency $\eta_E = 3.7\%$ for the TIBER-II FEM one calculates from

$$\eta_T = \frac{\eta_E}{1 - \eta_R(1 - \eta_E)}$$

a total efficiency of $\eta_T = 44-49\%$.

Of concern is the power dissipation in the collector plates. In the example of Figure 3, a maximum of 230 kW is dissipated per stage. Assuming an average power loading of 250 W/cm^2 , the collector plate radius should be 20 cm. The required coolant flow is 17 gal/min for a water temperature increase of 100°F .

5. Magnetic Wiggler

The design parameters for the magnetic wiggler are:

Wavelength $\lambda_w = 4.0 \text{ cm}$

Field $B_w = 2.0 \text{ kG}$

Gap Width $g = 3 \text{ cm}$

Length $L = 160 \text{ cm}$

Number of wavelength $N = 40$

Field Error $\Delta B/B < 1\%$

Machining tolerance 0.004 inch.

Because the FEM is a C.W. device and because the wiggler is operated at high voltage it is advantageous to use a permanent magnet rather than a power consuming electromagnetic device.

The technology of magnetic wigglers powered by permanent magnets has been advanced to a second generation. A hybrid wiggler concept using high permeability material as pole faces and either Samarium-Cobalt or Neodymium-Iron permanent magnets has been developed by K. Halbach, Berkeley⁶. Such wigglers have been built at LBL and TRW. The magnetic design is schematically illustrated in Figure 9a). Soft iron poles which can be machined to high accuracy

define the distribution of the field in the interaction region. Slabs of transversely magnetized permanent magnets fill the space between adjacent poles. One pole with two magnets form individual pole modules that are attached via locating pins and screws to two parallel mounting plates as shown in Figure 10. Iron screws that are inserted into the back of each pole module can divert a fraction of the magnetic flux allowing individual pole tuning by 7%. This feature is important because field errors can cause the beam to deviate from an exact sinusoidal orbit inside the wiggler and consequently be deflected to the waveguide wall. Random beam walk-off for the TIBER-II wiggler can be limited to 10% of the beam radius by keeping the field error $\Delta B/B < 1\%$. This requires for $\lambda_w = 4$ cm, $g = 3$ cm and $B = 2$ kG a mechanical machining tolerance of 0.004 inch.

Confined transport of the electron beam in the interaction region is accomplished by the wiggler field. The radial field gradient in the B-Z plane indicated in Figure 9a provides a radial restoring force on any electron propagating not on-axis. Consequently, the beam electrons perform betatron orbits and the equilibrium radius of the beam in the field direction is

$$r^2 = \frac{\sqrt{2} \epsilon_N}{b_w}$$

Where ϵ_N is the normalized emittance and b_w the normalized wiggler field amplitude.

Focusing of the beam in the plane perpendicular to B can be achieved by obtaining a transverse field gradient with canted pole faces as indicated in Figure 9b. For the condition of the TIBER-II wiggler, a canting angle of 1° is required.

6. Microwave System

With a single pass gain of 1400 and a 3 dB width of 7% as discussed in section 3, the TIBER-II FEM could operate as a broadband amplifier if a suitable tunable input oscillator would be available. Also, a two stage FEM as proposed for TIBER-I that would use an input oscillator with a power level of several watts seem to be unadvisable because no uni-directional transmission line components are available at the operating frequencies of 225 and 450 GHz. Such elements would be necessary to attenuate reflected power between stages in the high gain system and therefore to prevent unwanted oscillations.

For these reasons it is recommended to operate the FEM as a single stage tunable oscillator by reflecting a small fraction of the output power with a broadband reflector and re-reflecting that power back into the interaction region using a frequency selective rotatable grating. The addition of the grating, rather than the use of an ordinary laser cavity, is necessary since the longitudinal modes of a 4m long cavity are separated by only 37.5 MHz which is small compared to the system gain width of about 15 GHz (Figure 2).

For a retro-reflecting grating at which the power is reflected back into the source, power maxima occur for

$$\cos \theta = \frac{n\lambda}{2d} \quad n = 0, \pm 1, \pm 2,$$

θ and d are defined in Figure 11a. From

$$\frac{d\theta}{d\lambda} = \frac{n}{2d \sin \theta}$$

it can be seen that θ should be small for high resolution, but this would increase the necessary rotating angle for frequency tuning. For $\theta_0 = 25^\circ$, the wavelength selection can be changed by $\Delta\lambda/\lambda = 5\%$ by rotating the grating over $\Delta\theta = 15^\circ$. Using the formalism for array antenna pattern one can maximize the grating configuration which is shown in Figure 11b) for 450 GHz and reflection into first order. For these grating dimensions and assuming a distance of 50 cm between the waveguide end and the grating, a frequency resolution of 1% can be obtained if the grating contains 72 rulings. With the ruling dimensions shown in Figure 11b this translates in the minimum grating size of only 3 cm.

The power balance of the system was estimated. Specifically, the following values were found:

Grating Efficiency	0.5
Overlap of returned beam and waveguide	0.6
Coupling from free space to waveguide mode	0.7
Mirror Reflectivity	0.98
Total Throughput	0.21

In order to find the fraction of the power that needs to be reflected at the broadband output reflector one can consider the oscillator condition

$$T_O T_i T_g C G > 1.$$

With

T_O = output reflector efficiency

T_i = Input reflector efficiency = 0.2

T_g = Waveguide transmission efficiency = 0.94

C = Coupling efficiency to FEM mode = 0.25

G = Power Gain

the oscillator condition is reduced to

$$T_O G > 21.$$

It was shown in section 3 that the power gain is 1400 for the 450 GHz FEM. Consequently, $T_O = 0.015$, or 1.5% of the output power needs to be reflected for oscillator operation. No startup power is needed to initiate oscillations. It was shown in a previous TRW FEM experiment⁷, that spontaneously radiated power is sufficient for that purpose.

The microwave power incident on the grating is $T_O P_{out} = 40$ kW. For 450 GHz and copper the mirror losses are 1×10^{-3} which means that the total mirror loading will be 40 Watt, or 1.6 W/cm^2 for a $5 \times 5 \text{ cm}^2$ mirror.

Finally, in order to make the FEM consistent with TIBER-II tuning requirements, it will be necessary to rotate the grating by 30° (.524 rad) within $t=6$ msec. This motion can be generated by a computer controlled motor drive built by Parker. The model KS/KSx22 "compumotor" has the following specifications:

Peak Torque = 1.29 N-M

Speed = 3000 rpm

Rotor Inertia = $13.2 \times 10^{-6} \text{ kg-m}^2$

Acceleration = $9.8 \times 10^{-4} \text{ rad/sec}^2$

During the 6 msec time interval of frequency tuning, the mirror has to be accelerated, rotated and decelerated, requiring an estimated acceleration of $6 \times 10^4 \text{ rad/sec}^2$. This, together with a mirror inertia of $8 \times 10^{-6} \text{ kg-m}^2$ and a rotor inertia of $13 \times 10^{-6} \text{ kg-m}^2$, results in a torque of 1.3 N-m. Both torque and acceleration

requirements, therefore, are within the specification of the motor drive described above.

Since the interaction region is operated at high voltage, the microwaves have to be transmitted to ground potential. For windowless operation, this can be accomplished by free radiation from the waveguide as a radiator through a standard accelerator tubing like those used for accelerating the electron beam. A cross-section is shown in Figure 12. The maximal allowable electric field at the outside of the tubing determines the length of 120 cm.

In Figure 12, the radiation pattern of a 450 GHz signal from a 2x6 cm waveguide at a distance of 120 cm is also plotted. Because the waveguide is operated in the TE_{01} mode, the pattern width is similar in both transverse directions. From the integrated power transmission it can be seen that 20 cm diameter tubing will allow 98% of the power to be transmitted.

7. Power Supplies

Figure 13a demonstrates schematically the arrangement of the FEM power supplies and the potential distribution in the beam line. The voltage of the anode power supply determines the beam current. For a well designed beam line, only a small fraction of the electrons is intercepted by the anode and the high voltage beam line. Consequently, both the anode and high voltage power supplies can be low current, low cost supplies. Regulation requirements are also minimal, 2% for the anode supply to keep current variations within 3% and 1% for the high voltage supply. Voltage changes in the latter will shift the peak of the broad gain curve (Figure 2) but will not change the operating frequency which is given by the setting of the grating of the oscillator.

For the beam to be collected, the energy lost to radiation has to be made up by the collector power supply. In this arrangement therefore, it is the collector supply, which also has to accommodate the full beam current, who delivers the power converted into radiation. Operating in the multi-megawatt range, it is the most costly part of the FEM. Compared to power supplies of other microwave sources operating at similar power levels it is actually more cost effective because the regulation requirements are again low. Its voltage needs to be constant to within 1.0% of the high voltage of 2.69 MV only, or to 27 kV, so that 10% regulation is sufficient.

Figure 13b demonstrates the arrangement of the collector power supply if a multi-stage collector for the example of Figure 3 is used.

High voltage power supplies in the multi-megavolt range are commercially available. The Pelletron, manufactured by National Electrostatics Corporation, and used in the UCSB FEL⁵ has insufficient current ratings. The optimum choice for the TIBER-II FEM is the Dynamitron, built for electron beam systems used in materials processing and manufactured by Radiation Dynamics. It uses a cascading circuit operating at 10 kHz as illustrated in Figure 14. The high voltage rating depends simply on the number of stages and the current by the shield-to-electrode capacitance. 3 MV, 50 mA supplies are catalog items. The current rating can, without any design changes, be increased to 100 mA, which could make simultaneous operation of two electron beam lines with one high voltage power supply possible, reducing the cost of the system.

Figure 15 shows the layout of the main power supplies together with the SF₆ pressure vessel containing the FEM. Because of internal structural constraints, the Dynamitron is operated preferentially in the upright position. The main power supplies and the FEM with the microwave transport and diagnostic facilities could then be positioned on separate floors. The magnetic wiggler of the FEM will be positioned in the center of the FEM pressure vessel. As indicated in Figure 15, one could add a second electron beam line, with the wigglers located parallel to each other and the acceleration and deceleration columns directed to opposite sides. With an increase of the shield-to-electrode capacitance of the dynamitron (Figure 14), the current can be boosted from the standard 50 mA to 100 mA. Two electron beam lines located in one high voltage tank could then be operated from the same high voltage power supply, greatly reducing the system cost.

References

1. Gary R. Smith, B. G. Logan, and A. H. Kritz: "Localized Electron Cyclotron Heating and Current Drive in the TIBER-II Reactor Study." LLNL Internal Report 1987.
2. D. Arnush, H. Boehmer, M. Zales Caponi, and C.C. Shih: "Design of a High Power C.W. Free Electron Maser." *Int. J. Electronics*, 53, 605 (1982).
3. E.T. Scharlemann: "Wiggler Plane Focusing in Linear Wigglers." LLNL Report #UCRL-92429 (1985).
4. J. R. Hechtel: "A Novel Electrostatic Focusing Depressed Collector for Linear Beam Tubes." *IEEE Trans. Electr. Devices*, ED-24, 45, 1977.
5. L. R. Elias and G. Ramien: "Design of the UCSB FEL Electron Beam System." *Physics of Quantum Electronics*, 9, 577 (1981). L. R. Elias, G. Rausian, J. Hu, and A. Amir: "Observation of Single Mode Observation in a Free Electron Laser." *Phys. Rev. Letters*, 57, 424 (1986).
6. K. Halbach, et al.: "CSEM-Steel Hybrid Wiggler/Undulator Magnetic Field Studies." *IEEE Trans. Nucl. Se.*, NS-32, 364 (1985).
7. H. Boehmer, M. Zales Caponi, and J. Munch: "A Free Electron Laser Experiment", in *Free Electron Lasers*, S. Martellucci and Arthur N. Chester, Ed., Plenum Press, New York, 1983, p. 541.

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Figure 1. Schematic of a 2 MW Free Electron Maser Module for TIBER-II

Figure 2. Modeling Results for TIBER-II FEM

a) Operation at 450 GHz with 2.69 MV beam,

b) Operation at 225 GHz with 1.88 MV beam, all other parameters as in Table II

Figure 3. Energy Distribution of the Spent Electron Beam for the Case of Figure 2a). Also Indicated Are Voltages, Currents and Power Dissipated in the Plates of an Assumed 5 Stage Depressed Voltage Collector

Figure 4. Efficiency and Bandwidth of the High Power FEM for TIBER-I Operating at 240 GHz

Figure 5. Electron Gun of the TRW FEM Showing Electrode Configuration, Beam Orbits, As Well As Phase Space and Radial Current Density Distributions at the Gun Exit

**FIRST FOCUSING SECTION ($B = 515$ G) AND
ADJACENT ACCELERATOR STAGE**

**INTERMEDIATE FOCUSING SECTION
($B = 675$ G) AND ADJACENT ACCELERATOR**

FINAL ACCELERATION SECTION

**Figure 6a). Electron Beam Orbits In Acceleration Column. No Beam Current is Lost
in Transit**

Figure 6b). Initial (Left) and Final (Right) Phase Space

Figure 7. 180° Achromatic Bend. a) Configuration b) Beam Envelope in Bend and Non-Bend Planes of a 2.69 MV Beam With 5 mm Initial Radius

Figure 8. Cross-Sectional View of the Multi-Stage Depressed Voltage Collector for the TRW FEM. Design: R. Hechtel

Figure 9. a) Schematic of a Hybrid Wiggler
 b) Wiggler Cross-Section with Waveguide
 c) Alternate Canting of Pole Faces for Transverse Focusing

Figure 10. Schematic of Wiggler Assembly

Figure 11a). Tunable Oscillator Operation With Broadband Output Reflector and Input Grating

Figure 11b). Grating Dimensions for 450 GHz. Power Optimized Into First Order

Figure 12. Radiation Pattern of the 450 GHz Microwave Signal From a 2 x 6 cm Waveguide Operated at the TE_{01} Mode, Observed at a Distance of 120 cm. Standard Accelerator Tubing Can Be Used for Power Transmission from High Voltage to Ground

Figure 13a). Principle of Operation and Potential Distribution of Electron Beam Line With Energy Recovery

Anode power supply:

$V_A = 100 \text{ kV}$, $I \leq 10 \text{ ma}$

regulation: $\leq 2\%$ (for $\Delta I/I \leq 3\%$)

Figure 13b). Operation with Multi-Stage Collector

SYM.	CAPACITANCE
(CSE)	SHIELD TO ELECTRODE
(CAC)	ANODE TO CATHODE
(CEG)	ELECTRODE TO GRD.

Figure 14. Schematic Diagram of a Dynamitron Cascade Circuit

Figure 15. Layout of the 2 MW TIBER-II FEM Showing the High Voltage Tank, High Voltage and Collector Power Supplies. Two FEM Beam Lines Could be Operated in One High Voltage Tank

PART 4A

ADDENDUM TO FREE ELECTRON LASER REPORT

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FREE ELECTRON MASER FOR TIBER-II

ADDENDUM TO FINAL REPORT

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1. Introduction

As part of the TIBER-II development program, a conceptual design of a C.W. Free Electron Maser (FEM) was performed. The FEM is intended as a source of microwaves for suppression of disruption in the Tokamak reactor via ECRH. 2 MW units at 450 and 225 GHz were considered. Apart from the modeling of the FEM interactions which will determine the baseline parameters of the system, the most critical and time consuming part is the proper design of the electron beam line. Because of a late start of the FEM part of the TIBER-II program not all beam line calculation, particularly the design of the high power depressed voltage electron beam collector, could be done in time for the preparation of the final report, necessitating this addendum to the main report.

2. Acceleration Column

The acceleration and deceleration columns were designed and the electron beam trajectories and the phase space distribution of the electrons were calculated using the EBQ-code. As discussed in Section 4.2 and Figure 6 of the final report, two solenoidal focusing lenses, one at the beginning and one in the center of the acceleration column were necessary to overcome the defocusing space charge forces. During further investigations it was found, that the number of mesh-points used for the EBQ-code in the acceleration modules was not quite sufficient for a correct calculation of the space charge forces. To remedy this, the accelerator module size was reduced from 8 to 4 acceleration apertures. For the same reason, the radial scale of the printout of the beam orbit in the solenoid (Figure 1a & c) and acceleration section (Figure 1b & d) are now different. The beam shows an excellent laminar flow, the beam density distribution at the end of the acceleration column is flat (Figure 1g) and the phase space (Figure 1h) is improved over the previous calculation.

3. Achromatic Bend

The geometry of and the beam envelope in the achromatic bends was shown in Figure 7 of the final report. In Figure 2 of this addendum the microscopic beam behavior is illustrated by the output of PARMELA-code calculations. The particle density in phase and real space can be seen to remain uniform throughout the system. the output beam diameter remains about 1 cm which means that the assumed gap spacing of 2.5 cm of the dipole magnets is sufficient. The transverse emittance growth is $\epsilon_x=16.5\pi$ mm mrad and $\epsilon_y=5.3\pi$ mm mrad.

4. Deceleration Column

In the deceleration column, the electron energy is changed from the initial 2.69 MV to 400 kV at the input of the multi-stage beam collector. As seen from Figure 3 of this addendum, this column is the mirror image of the acceleration column, with solenoidal focusing fields halfway through and at the end of the column. The positioning of the magnetic lenses at low and intermediate energies in both columns reflect the fact that at these points space charge is more important compared to high energies. Again, the beam flow is laminar, the output density distribution flat and the angular divergence small remaining between -21 and +1 mrad.

5. Multi-Stage Depressed Voltage Collector

The depressed voltage beam collector is an essential element in the design of a C.W. FEM as detailed in the TIBER-II FEM report. Its design will impact the capital cost via the high power power supplies necessary to operate the collector and operating expenses via the total system efficiency.

Depressed voltage beam collectors have been used extensively to boost the total efficiency of microwave tubes. Linear beam tubes, like the traveling wave tube (TWT) and the FEM are particularly adaptable to beam energy recovery. The importance of efficiency in satellite borne TWT's has matured the technology to routine applications of the

concept. In the mid 70th, R. Hechtel⁽¹⁾ developed a new multi-stage collector configuration that used hyperbolic focusing surfaces for beam trajectory shaping and electron collecting. This collector type has been proven to 1) have a far superior collection efficiency over uniform focusing and parabolic defocusing types of retarding fields and 2) successfully suppresses secondary electrons from propagating back in the retarding field. The collector design has become reliable to a degree that manufactured collectors deviate in their collection efficiency by at most 1-2% from the design value.

It should be noted that the task of designing a multi-stage collector is considerably simpler and the resulting efficiency higher for a FEM beam in comparison to a TWT beam since the beam energy spread of 15% and angular beam divergence of 1.6° (21 mrad) is much smaller than the energy spread of a TWT beam which can be as large as 50% and 20° (300 mrad) respectively.

The multi-stage collector design was performed by R. Hechtel while a TRW consultant. The following system parameters were used, corresponding to the FEM code calculations detailed in Table II and Figure 2 of the TIBER-II final report:

Beam Current	30.0A
Initial Beam Voltage	2.69 MV
Extraction Efficiency	3.6%
RF Power Output	2.92 MW

Longitudinal beam energy distribution see Figure 3 of the original report.

The geometrical configuration of the collector, equipotential lines and electron orbits belonging to selected energy bins are shown in Figure 4. The ideally hyperbolic collector plates are approximated by spherical surfaces to facilitate fabrication of the device. The beam enters the collector off the axis of symmetry to force the beam into a favorable orbit. Evidently, most of the electrons are collected at the back side of the collector plates eliminating backstreaming of secondary electrons.

Like in any tube generating microwave power with electron beams, a

Fraction of the electrons is accelerated beyond the initial energy of, in this case, 2.69 MV. In the low power case of the TRW FEM collector detailed in Figure 10 of the original report these electrons were simply allowed to dissipate their energy at ground potential. In the high power case of the TIBER-II FEM, a fraction of this energy is retrieved by two collector plates biased -30 kV and -65 kV below the cathode potentials.

The current collected, power recovered and dissipated on each plate is tabulated in Figure 5. From these numbers one calculates the collector efficiency to be 99.6%. From past experience with manufactured collectors, the actual recovery efficiency (η_R) is estimated to be 97%. With a predicted extraction efficiency of $\eta_E = 3.6\%$ one calculates from

$$\eta_T = \frac{\eta_E}{1 - \eta_R(1 - \eta_E)}$$

a total FEM efficiency of $\eta_T = 55\%$.

The total electron beam power dissipated in the collector plates is 298 kW. While this a small fraction of the microwave output power of 2.9 MW, it represents still an engineering problem to supply sufficient cooling. The design code calculations showed that the peak power deposition density is about 1 kW/cm². While this, compared to power loading in neutral beam dumps, is still a manageable value, it can be reduced by the following modifications:

1. Substitute the cylindrical, 2-dimensional plates for the at present spherical plates. As a result, the beam will be focused in the x-z plane only and expand in the y-direction.

2. Convert the present circular cross-section of the beam into a elliptical one. This can be done by substituting a quadrupole focusing magnet for the solenoidal magnetic lens at the end of the deceleration column.

While the multi-stage collector for the TRW FEM described in

Figure 10 of the original report is the final design that can be used for mechanical design and construction, the design of the collector shown on Figure 4 of this addendum is preliminary. As discussed above, a change in the cross-sectional shape of the beam can decrease the density of power deposition. Furthermore, engineering requirements related to vacuum housing and cooling might require design changes.

6. Conclusion

The FEM design detailed in the TIBER-II and in this addendum to the final report shows that a c.w. microwave source based on the FEM principle with electrostatic accelerator and depressed voltage beam collector is a feasible choice for ECH in TIBER-II. Both second harmonic and fundamental heating are considered. Only standard technology is used in the design. With a total efficiency of 55% at 450 GHz and 2.9 MW output power, the FEM should be a cost effective component of the TIBER-II reactor.

7. References

1. Hechtel, J.R., IEEE Trans. Electr. Dev., ED24, 45 (1977)

Figure 1. Electron Beam in Acceleration Column. Beam Orbits are Shown in a) Initial Focusing Solenoid, b) Intermediate Acceleration Module, c) Intermediate Focusing Solenoid, d) Final Acceleration Module. A Total of 24 Acceleration Modules are Used. The Radial Scales are Difficult for the Solenoid and Acceleration Sections. e) and f) Initial and g) and h) Final Current Density Distribution and Phase Space.

Figure 2. Beam Transport Through Achromatic Bend. Transverse Phase Space and Spatial Particle Distribution at End of First Dipole (Upper Three Panels) and at End of System (Lower Three Panels)

0.00 Z TIMES 0.5878 $\times 10^3$
TITLE
FEM DECELERATION MODULE

0.00 Z TIMES 0.5878
TITLE
SOLENOID MAGNET DRIFT MID-DECEL 518 GAUSS

0.00 Z TIMES 0.5878 $\times 10^3$
TITLE
CONTINUE TWENTYFOURTH MODULE

0.00 Z TIMES 0.5878
TITLE
SOLENOID MAGNET DRIFT END-DECEL 518 GAUSS

RAY GROUP 1 CURRENT DENSITY 1/2PI-R
Z= 10.0000
CELL 0.0409 $\times$ 0.1578
I= 3.1311E-01
1.00 $\times 10^2$

TITLE
SOLENOID MAGNET DRIFT AT START OF DECEL 0 GAUSS

RAY GROUP 1 CURRENT DENSITY 1/2PI-R
Z= 15.0000
CELL 0.2577 $\times$ 0.2561
I= 3.1311E-01
1.00 $\times 10^2$

TITLE
SOLENOID MAGNET DRIFT END-DECEL 518 GAUSS

RAY GROUP 1 PR/PZ VS R PHASE PLOT
Z= 5.0000
CELL 0.0409 $\times$ 0.1578
I= 3.1311E-01
7.95 $\times 10^{-4}$

TITLE
SOLENOID MAGNET DRIFT AT START OF DECEL 0 GAUSS

RAY GROUP 1 PR/PZ VS R PHASE PLOT
Z= 15.0000
CELL 0.2577 $\times$ 0.2561
I= 3.1311E-01
1.03 $\times 10^{-3}$

TITLE
SOLENOID MAGNET DRIFT END-DECEL 518 GAUSS

Figure 3. Electron Beam in Deceleration Column. Beam Orbits are Shown in a) Initial Deceleration Module, b) Intermediate Focusing Solenoid, c) Intermediate Deceleration Module, d) Final Focusing Solenoid. A Total of 24 Deceleration Modules are Used. The Radial Scales are Different for the Deceleration and Solenoid Sections. e) and f) Initial and g) and h) Final Current Density Distribution and Phase Space.

Figure 4. Schematic Cross-Sectional View of High Power Multistage Depressed Voltage Collector for the TIBER-II FEM. Maximum Power Dissipation is 1 kw/cm^2 . Design by R.Hechtel, Redwood City, CA

Stage	Vd/kvolts	Ip/amps	Prec/kVA	Pdiss/kVA
1	2485	1.6	3976	25
2	2507	2.9	7270	25
3	2525	3.1	3828	25
4	2541	3.1	7877	25
5	2557	3.1	7929	25
6	2573	3.0	7719	25
7	2590	2.8	7252	25
8	2608	2.4	6259	24
9	2628	2.1	5519	25
10	2652	1.7	4508	24
11	2680	1.5	4020	26
12	2715	1.5	4073	26
13	2750	1.2	3300	18
14	2785	—	—	—
All		30.0	77540	298

Vd = Voltage depression below circuit (wiggler)

Ip = Plate current for an individual stage

Prec = Beam power recovered in an individual stage

Pdiss = Beam power dissipated in an individual stage

The initial beam power is given by

$$P_o = I_o \cdot V_o = 30 \cdot 2.692 = 80.76 \text{ MVA}$$

The generated RF-power is

$$P_{rf} = 0.036 \cdot P_o = 2.92 \text{ MVA}$$

The beam power entering the collector is

$$P_{ent} = P_o - P_{rf} = 77.84 \text{ MVA}$$

The collector efficiency is defined as

$$(\eta)_{coll} = P_{rec}/P_{ent} = 77.54/77.84 = 0.996$$

Figure 5. Predicted Performance of High Power multistage Collector.
Design by R. Hechtel, Redwood City, CA