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Plasma Simulation and Modeling for ELMO Bumpy Torus Reactor

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FUSION ENERGY DIVISION

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ABSTRACT

A simple model (time-dependent deuterium-tritium point model) has been formulated to assess the energy balance in an ELMO Bumpy Torus Reactor (EBTR) plasma. The effects of the different scaling assumptions on EBTR performance and operating point have been analyzed. Although in the present EBT device (EBT-I) plasma transport seems to be governed largely by neoclassical processes, hypothesized anomalous transport losses are included in the plasma simulation model in addition to neoclassical and/or classical transport in order to test the sensitivity of EBTR parameters. For the particular case studied, it is shown that the reference EBTR can accommodate anomalous losses one to two orders of magnitude greater than the present neoclassical losses at the operating point (steady state). Results are discussed.

1. INTRODUCTION

The ELMO Bumpy Torus (EBT) [1] is a large aspect ratio, specific bumpy torus device which was designed to circumvent the bumpy torus MHD stability problem by using the "minimum-B" properties of annular high-beta, hot-electron plasmas formed by microwave heating.

Results from experiments carried out in the EBT-I [2] during the past few years have strongly supported the basic EBT premise: plasma currents produced by the high-beta, hot-electron annuli produce changes in the vacuum magnetic field gradients which provide macrostable plasma confinement in a steady-state bumpy torus. In addition to achieving this primary objective, the EBT experimental program has generated a considerable amount of interesting plasma data which prove to be consistent with theoretical "neoclassical" predictions [1-2].

The present EBT [pioneered at the Oak Ridge National Laboratory (ORNL)] is a first-generation device and the first of its kind, but the existing physics evidence suggests that the EBT approach can be extended to confine steady-state, high-beta plasmas. If this extension is demonstrated, then the EBT concept offers an attractive alternative to the tokamak and magnetic-mirror approaches to controlled thermonuclear fusion. Inspired by the exciting potential of EBT, a uniform and self-consistent treatment of EBT reactor (EBTR) scaling and design has been conducted and a reference design has been selected [3].

Two important parameters in designing and determining the feasibility of an EBTR are the plasma particle and energy lifetimes. In the present EBT device, plasma transport seems to be governed largely by neoclassical processes, provided proper treatment is given to the ambipolar electric

field and the presence of a non-Maxwellian electron population. Both theoretically and experimentally, a radial ambipolar electric field, E , arises to equalize electron and ion diffusion losses. The motion of particles with energies below the ambipolar potential energy is dominated by $E \times B$ drifts. The drift motion of high energy particles is dominated by gradient B and curvature drifts. Experimentally, the electric field appears to be strongest in the vicinity of the annulus. Exterior to the annuli, the losses are dominated by particles moving directly to the wall due to the toroidal curvature drifts of particles, while interior to the annuli, diffusive transport losses dominate. For this central toroidal core, a simple neoclassical point model of transport and scaling yields results which are in reasonable agreement with earlier and recent experimental observations [4]. A radially resolved fluid transport code, based upon refined neoclassical coefficients, also gives similar results [5]. Even though experimental observations and theoretical predictions represent significant agreement and advances in achievement during this past year, the information necessary to design an EBTR is not at hand. Here it should be noted that the applicability and extrapolation of present results to larger, hotter systems are in question not only for EBT but for all of the confinement systems.

The EBT-S and EBT-II devices [6] will provide further information on transport and scaling properties, especially in the collisionless regime (of interest to reactor operation). Theoretical work in support of these experiments will refine the existing transport theories. In view of the uncertainties in the theoretical coefficients and the present lack of experimental evidence in the reactor regime and conditions, it is necessary

to make plausible estimates of the parameters and to retain flexibility so the simulation models can incorporate refined data from experimental and theoretical programs.

The studies discussed here demonstrate the sensitivity of the EBTR design features to the scaling laws assumed. The models are suitable for simulating the energy and particle balances in a bumpy torus plasma. The success of this model in predicting energy balance consistent with present experimental observations and future theoretical expectations indicates the validity of the assumptions.

2. EBT PHYSICS MODEL

In order to evaluate EBTR characteristics, it is necessary to compute the expected plasma parameters under reasonable assumptions. A rigorous description of plasma dynamics is exceedingly complex and well beyond the needs of a study such as this. Thus, a simple model which retains the essential physics of the phenomena has been developed to assess the energy balance in an EBT reactor plasma. In this model, the toroidal plasma is characterized by simple energy and particle containment times with appropriate density and temperature scaling. The reactor plasma is consistent with the physics model: a toroidal core with nearly uniform density and temperature within the plasma radius, which is determined by the stabilizing hot electron annuli [1-6]. Two reactor models are studied, both with microwave heating and neutral beam heating. The resulting particle and energy balance equations are:

$$\frac{dn_D}{dt} = n_e n_o \langle \sigma v \rangle_{ion} + S_{DCOLD} + S_{DBEAM}(1 - f) - n_D n_T \langle \sigma v \rangle_{DT} - \frac{n_D}{\tau_{p,D}} \quad (2.1)$$

$$\frac{dn_T}{dt} = n_e n_{o_T} \langle \sigma v \rangle_{ion} + S_{TCOLD} - S_{DBEAM} f - n_D n_T \langle \sigma v \rangle_{DT} - \frac{n_T}{\tau_{p,T}} \quad (2.2)$$

$$\frac{dn_\alpha}{dt} = S_{DBEAM} f + n_D n_T \langle \sigma v \rangle_{DT} - \frac{n_\alpha}{\tau_{p,\alpha}} \quad (2.3)$$

$$n_e = n_D + n_T + 2n_\alpha \quad (2.4)$$

$$n_o = n_{o_D} + n_{o_T} \quad (2.5)$$

$$\begin{aligned} \frac{d}{dt} \left(\frac{3}{2} n_e T_e \right) &= S_{DBEAM} (U_{DDEAM} G_e + f U_\alpha f_{\alpha e}) + P_\mu \\ &+ n_D n_T \langle \sigma v \rangle_{DT} (U_\alpha f_{\alpha e} - 3T_e) - P_{RAD} \\ &- 1.5 \times 10^{-19} \frac{n_e}{T_e^{3/2}} \ln \Lambda (T_e - T_i) \left(\frac{n_D}{2} + \frac{n_T}{3} \right) \\ &- \frac{3}{2} \frac{n_e T_e}{\tau_{E,e}} \end{aligned} \quad (2.6)$$

$$\begin{aligned} \frac{d}{dt} \left(\frac{3}{2} n_i T_i \right) &= S_{DBEAM} (U_{DDEAM} G_i + f U_\alpha f_{\alpha i}) \\ &+ n_D n_T \langle \sigma v \rangle_{DT} (U_\alpha f_{\alpha i} - 3T_i) - \frac{3}{2} \frac{n_i T_i}{\tau_{E,i}} \\ &+ 1.5 \times 10^{-19} \frac{n_e}{T_e^{3/2}} \ln \Lambda (T_e - T_i) \left(\frac{n_D}{2} + \frac{n_T}{3} \right) \end{aligned} \quad (2.7)$$

Equations (2.1) and (2.2) represent a balance among an injected deuterium and tritium ion source (actually neutrals which are ionized, cold fueling, and loss or gain due to the injected beam which undergoes suprathermal fusion), fusion loss, and diffusion loss. Equation (2.3) represents a balance between fusion production and diffusion loss of alpha particles. The electron density, Eq. (2.4), is determined from the

requirement of charge neutrality. The neutral particle density, Eq. (2.5), is the sum of the neutral densities of deuterium and tritium. The terms in the electron energy balance, Eq. (2.6), represent heating by injected neutral beams and/or microwaves, heating by fusion alphas, cooling by radiation losses (bremsstrahlung and cyclotron radiation), cooling (or heating) by Coulomb interaction with ions, and cooling by transport loss, respectively. The terms in the ion energy balance, Eq. (2.7), represent heating by injected neutral beams, heating by fusion alphas, cooling by transport loss, and heating (or cooling) by Coulomb interaction with electrons, respectively. The symbols are defined in the glossary, and a somewhat expanded discussion of the model and computational method is presented in Ref. [7]. All quantities are in mks units except T , which is in kiloelectron volts.

In the model it is assumed that the time scale of interest for the variation of the average particle and energy densities in the plasma is long with respect to the self-equilibration times for ions and electrons and the alpha slowing-down times. It is envisioned that the ions or electrons which are injected into the plasma instantaneously equilibrate in energy with like particles in the plasma through collisions. Also, it is assumed that the alpha particles produced in the deuterium-tritium (D-T) fusion reaction and the injected neutral beam instantaneously distribute their energy to the ions and electrons.

A brief description of the key terms in Eqs. (2.1)-(2.7) is given below.

2.1 CONTAINMENT TIMES

The particle and energy containment times are critical in determining the detailed energy balance for a system. Because at present the scaling laws appropriate to large, hot plasmas in the EBT configuration (and in other confinement configurations as well) are not known, theoretical and empirical estimates have been used. The absolute numerical values of confinement times and limiting beta are important design determinants and must be approached if the EBT concept is to prove feasible. The detailed scaling of these parameters is less critical; this is the same approach which is used in tokamak reactor studies. For the purposes of this paper, it is sufficient to know the relative magnitudes of $\tau_{p,j}$ ($j = D, T, \alpha$), $\tau_{E,i}$, and $\tau_{E,e}$ and how each of them scales with particle density and temperatures. Several different models for confinement time scaling have been considered. From appropriate transport coefficients, particle confinement times for the j^{th} thermal species are given by

$$\text{Classical:} \quad : \quad C_C n_j^{-1} T_j^{1/2} \quad (2.8a)$$

$$\tau_{p,j} \propto \text{Neoclassical:} \quad : \quad \frac{C_{NC}}{v_j} \left(1 + \frac{v_j^2}{\Omega_j^2} \right) \quad (2.8b)$$

$$\text{Others} \quad : \quad \tau_{\text{Anomalous}} \quad (2.8c)$$

where C_C is a constant which is adjusted so that $\tau_{p,j}$ has a desired value at the steady-state operating conditions. Also,

$$v_j = 3.8 \times 10^{-17} \frac{Z_j^2 n_j}{\sqrt{A_j} T_j^{3/2}} \quad (2.9)$$

$$\Omega_j = 10^3 \frac{T_j}{Z_j B R_c a} (1 + Z_j \eta) \quad \text{with} \quad \eta = 10^{-3} \frac{E_R R_c}{T_j} \quad (2.10)$$

$$C_{NC} = \frac{3}{4} \left[\frac{R_T}{R_c} (1 + Z_j \eta) \right]^2 \quad (2.11)$$

R_T and R_c are the toroidal and mirror radii of curvature and E_r is the radial electric field. Notice that Ω_j , Eq. (2.10), incorporates the gradient B and curvature drifts through the mirror radius of curvature, R_c , and the $E \times B$ drift through the parameter η . From quasi-neutrality

$$\tau_{p,e} = \tau_{p,i} \quad (2.12)$$

where

$$\tau_{p,i}^{-1} \cong \sum_{j=D,T} \frac{n_j}{n_i} \tau_{p,j}^{-1} \quad (2.13)$$

and

$$\tau_{p,j}^{-1} = \gamma_{NC/C} \tau_{NC/C}^{-1} + \gamma_A \tau_A^{-1} \quad (2.14)$$

The γ factors permit consideration of different ion containment times, where the subscript "NC/C" corresponds to neoclassical or classical and "A" corresponds to anomalous processes. For alpha particles, $\tau_{p,\alpha} = C_\alpha \tau_{p,i}$ with C_α being constant.

The electron and ion energy containment times, $\tau_{E,e}$ and $\tau_{E,i}$, may be different. For electrons

$$\tau_{E,e} \approx C \tau_{p,i} \quad (2.15)$$

and for ions

$$\tau_{E,i}^{-1} \propto \tau_{E,e}^{-1} + \tau_{cx}^{-1} \quad (2.16)$$

In general,

$$\tau_{E,i}^{-1} = \gamma_{cx} \tau_{cx}^{-1} + \gamma_{NC/C} \tau_{NC/C}^{-1} + \gamma_A \tau_A^{-1} \quad (2.17)$$

C is a constant and τ_{cx} is the time for charge exchange between hot ions and cold neutral atoms.

2.2 RADIATION LOSSES

$$P_{RAD} = P_{BREM} + P_{LINE} + P_{RECOMBINATION} + P_{CYCLOTRON} \quad (2.18)$$

where

$$P_{BREM} + P_{LINE} + P_{RECOMBINATION} \approx n_e Z_{eff} \left(3 \times 10^{-21} T_e^{1/2} + 1.14 \times 10^{-22} T_e^{1/2} + 2.58 \times 10^{-24} T_e^{-3/2} \right) \quad (2.19)$$

and $P_{CYCLOTRON}$ is discussed in detail in Appendix C of Ref. [3].

2.3 ALPHA ENERGY DEPOSITION

The fraction of the alpha energy produced by fusion which is delivered to the electrons, $f_{\alpha e}$, is

$$f_{\alpha e} \approx 1 - \frac{2}{X} \left[\frac{1}{6} \ln \left(\frac{1 - \sqrt{X} + X}{1 + \sqrt{X}} \right) + \frac{1}{\sqrt{3}} \tan^{-1} \left(\frac{2\sqrt{X} - 1}{\sqrt{3}} \right) + 0.3023 \right] \quad (2.20)$$

where $X \equiv U_\alpha / U_{acr}$, and U_{acr} is the critical energy, i.e., the energy at which alpha particle energy is transferred to the electrons and ions at equal rates. The fraction delivered to the ions, $f_{\alpha i}$, is $(1 - f_{\alpha e})$.

2.4 NEUTRAL BEAM INJECTION HEATING

In the beam heated case, the energy delivered to the background plasma electrons and ions from injection of fast deuterium atoms is given by the functions G_e and G_i [8]. G_e and G_i can be found (neglecting charge

exchange) by using Eq. (2.20) for f_{ae} and letting $X \equiv U_{\text{DBEAM}}/U_{\text{cr}}$, where U_{cr} is the critical energy as defined above but for the fast injected ions.

When charge exchange is included, an approximate fit to the G_e and G_i curves given in Ref. [8] yields

$$G_i \approx 0.5 \exp \left[-0.1 \frac{U_{\text{DBEAM}}}{U_{\text{cr}}} \left(1 + 0.5 \frac{\tau_s}{\tau_{\text{cx}}} \right) \right] + 0.5 \exp \left[-0.6 \frac{U_{\text{DBEAM}}}{U_{\text{cr}}} \left(1 + 0.5 \frac{\tau_s}{\tau_{\text{cx}}} \right) \right] \quad (2.21)$$

$$G_e = 1 - G_i - G_{\text{cx}} \quad (2.22)$$

where

$$\begin{aligned} &\approx 1 - \exp \left[-0.121 \frac{U_{\text{DBEAM}}}{U_{\text{cr}}} \left(\frac{\tau_s}{\tau_{\text{cx}}} \right) \right], \quad \frac{U_{\text{DBEAM}}}{U_{\text{cr}}} \leq 1 \\ G_{\text{cx}} &\approx 1 - \exp \left[-0.121 \left(\frac{U_{\text{DBEAM}}}{U_{\text{cr}}} \right)^{1/2} \left(\frac{\tau_s}{\tau_{\text{cx}}} \right) \right], \quad \frac{U_{\text{DBEAM}}}{U_{\text{cr}}} > 1 \end{aligned} \quad (2.23)$$

τ_s is the Spitzer ion-electron momentum exchange time.

2.5 FURTHER COMMENTS ON THE MODEL

Two distinct models have been studied. Both models include microwave heating and neutral beam heating as options. It was of interest to determine the characteristics of the microwave/neutral beam system which can be used to start up and ignite the reactor plasma. The critical assumptions and approximations included in these models are described below.

2.5.1 Model A: Classical Scaling

The temperature and density behavior of the thermalized electrons, deuterons, and tritons has been examined by assuming classical scaling for both the particle and energy confinement times. In addition to the classical assumptions, some form of Bohm diffusion has been incorporated as a loss mechanism. Further assumptions included in this model are [3]:

- 1) The energy confinement time is taken to be ~ 2.5 sec at the reference operating point (i.e., $n \sim 1.2 \times 10^{20} \text{ m}^{-3}$ and $T \sim 15 \text{ keV}$; see Table I for reference parameters) and the ratio of particle lifetime to energy confinement time is assumed to be 3. Here it is assumed that the absolute numerical values of confinement times and limiting beta (see assumption 4) are important design determinants and must be approached if the EBTR concept as developed in Ref. [3] is to prove feasible.
- 2) The effects of a background neutral density are neglected.
- 3) Thermal alpha particles are assumed to diffuse out of the plasma at approximately the same rate as the other ion species, which results in a very small thermal alpha particle population [Eq. (3) is not used].
- 4) The plasma beta limit is chosen to be consistent with the limiting beta for stability [9]. When the value is exceeded, the particle confinement is modified so as to maintain constant plasma energy density. When the β limit is exceeded, the particle loss rate is assumed to increase (Bohm diffusion); as a result, the plasma reactivity decreases and limits the thermal excursion which otherwise occurs due to the variation of confinement time with temperature.

5) Z_{eff} is taken as unity. In the present EBT-I experiments, particle dynamics of transport processes do lead to this result naturally because of the short confinement of impurities on the surface plasma and the shielding by the electric field near the electron rings (annuli) [2,10]. Future experiments [6] will either validate EBT-I results or show that the reactor will require an impurity control mechanism. In either case, this assumption is probably valid. Z_{eff} considerably larger than unity would have a deleterious effect on both start-up and steady-state requirements.

6) The electron annulus is energetically separated from the bulk plasma, and power transfer between the electron ring and the toroidal plasma is included in the synchrotron radiation term. Details of this model and possible start-up scenarios are discussed in Ref. [3].

2.5.2 Model B: Neoclassical Scaling

Early comparisons between simple point models [4-5] and the experimentally observed ion and electron temperatures, plasma density, and energy confinement time in EBT-I indicated that in the toroidal or T-mode of operation, the EBT-I plasma has parameters entirely consistent with neoclassical predictions. The containment times in bumpy torus type geometries were originally calculated by Kovrizhnykh [11] for the case of a strong radial electric field. The ORNL work [12] has attempted to remove this limitation to include arbitrary values of the ambipolar electric field. Because the transport calculations of the ORNL group are still being developed for large D-T systems and will include the effects of

finite plasma pressure, for this study the radial electric field and the microwave power (in the case of microwave heating) are treated as parameters rather than self-consistently. This approach permits many unknowns to be lumped together in these parameters. In addition to the usual neo-classical transport losses, this model also includes the presence of an anomalous dissipative transport loss to study the possible effects of collisional drift waves on the performance of an EBTR. It should be pointed out that drift wave instabilities have not been found in EBT, but it should be emphasized that very little is known about the drift wave stability and transport for EBT compared to other confinement systems (e.g., tokamaks).

At this time there is no basis to believe that drift wave instabilities will exist in EBT as in tokamaks, and even if they do no one knows what their nonlinear limit and hence the resulting transport will be. Thus, this area is regarded as a critical one and sensitivity studies have been conducted to learn the level of anomalous losses that can be tolerated in an EBTR without disturbing the ignition conditions. The scaling of confinement time with density and temperature for anomalous loss rate is taken to be

$$\tau_A \propto n^s / T^r \quad (2.24)$$

where s and r are constants ($s = 1$, $r = 7/2$ correspond to the trapped ion mode [13] in tokamaks). From Eq. (2.17), for the j^{th} species one can arrange to have

$$\left(\frac{\gamma_A}{\tau_A} \right)_j = \frac{T_j^r}{n_j^s} \left[\left(\frac{n_j^s}{T_j^r} \right)_o \left(\frac{\gamma_{NC}}{\tau_{NC}} \right)_o F \right] \quad (2.25)$$

where the subscript "o" corresponds to the operating point values (steady state) and F (anomaly factor) is an adjustable constant which is chosen to yield physically plausible solutions. The results of the calculations for various values of F ($\equiv$ FAC) are discussed in Section 3.

For this model, the full set of equations (2.1)-(2.7) has been used. In addition to the above considerations, Z_{eff} is taken as unity (see assumption 5 for Model A and Section 2.5.4).

2.5.3 Start-up Procedures

Start-up scenarios consistent with microwave cutoff (120 GHz) or neutral beam penetration (150 keV) requirements have been derived to take advantage of high beta operation in EBT. At $T = 15$ keV, a beta of ≤ 0.35 is required for 120-GHz microwave penetration. Similarly, neutral beam attenuation, which is proportional to $\exp(-N\sigma\chi)$, also places a restriction on maximum density if hollow density profiles are to be avoided.

The power requirements for start-up and recirculating power for auxiliary functions and plasma sustenance will dictate power supply criteria and demand from the grid. For the purposes of the study, it is assumed that the beam and/or microwave power is held at a constant value until steady state is reached, at which point the beam and/or microwave is turned off. The beam/microwave power used is 0.2 MW/m^3 with an initial beam energy of 150 keV and/or a microwave frequency of 120 GHz. For the stabilizing annuli, the required microwave power is less than 0.5 MW per sector and the microwave frequency is about 60-80 GHz [3]. All of these values are consistent with the recognized objectives of long-range beam/microwave development [6] programs. The value of 0.2 MW/m^3 (or $\sim 200 \text{ MW}$

total for EBTR-48 [3] and ~ 100 MW total for EBTR-24 [3]) is an overestimate because of an unoptimized start-up and ignition scenario. Two possible techniques have been suggested to minimize the power required for start-up [2]: the "low density start-up," which relies on plasma losses scaling as N^2 , and the "restricted cross section or large aspect ratio (A) procedure." In the first case the maximum power requirement can be reduced by about 75% ($200 \rightarrow 50$ MW) if the start-up is accomplished at a density of half of the operating point value. In the latter case, volume $\sim Aa^3$ (where a is the plasma radius) and the power requirement can be reduced by 80-90% if the plasma cross section is limited to $a/3$ so that A increases by a factor of three. Detailed analyses of these possible start-up scenarios, means of controlling density, restriction of the cross section, and the basic plasma stability during the processes are under consideration.

For the purpose of this study, unoptimized start-up and ignition scenario results are presented in order to test the plausibility of microwave/beam heating and to demonstrate feasibility.

2.5.4 Maintaining Steady State

Fueling of the EBT reactor is required to take advantage of steady-state operation; however, this requirement is not unique because it applies to all large systems where the burn time will exceed the particle containment time. In present EBT experiments, particle density is maintained by introducing neutral gas into the chamber. The EBTR plasma is too large to permit adequate neutral penetration, so the particle density will be maintained by some other means, such as pellet fueling [S_{DCOLD} and S_{TCOLD} in Eqs (2.1) and (2.2)].

A method for removing residues (fusion products) and impurities may be necessary if particle dynamics of transport processes do not lead to this result naturally. In EBT-I impurities do not accumulate in the central region of the plasma due to short confinement of impurities on the surface plasma and shielding by the ring electric field [10]. Future experiments [6] will either validate EBT-I results or show that EBTR will require residue removal and impurity control mechanisms.

Power requirements to sustain the stabilizing annuli need to be examined in detail, although preliminary calculations show that this is not a problem because the ring plasma occupies a relatively small volume. In steady state the annulus power balance is

$$P_{\mu A} = P_{TA} + P_{BA} + P_{CA} \quad (2.26)$$

where P_{TA} is the thermal conduction and convection, P_{BA} is bremsstrahlung losses, P_{CA} is synchrotron (cyclotron) radiation, and $P_{\mu A}$ is the microwave power required to sustain the annulus. The emission of synchrotron radiation from the hot electron annulus in EBT and in a large-scale EBTR was estimated in the initial EBT proposal [1,2]. More detailed calculations have been carried out for the EBTR reference design and reported in Ref. [3]. In the later work, the synchrotron emission, P_{CA} , amounted to a few tens of kilowatts per sector at worst, compared to a few tens to a few hundreds of kilowatts of transport losses, P_{TA} , for the data chosen. It is important, however, that this subject be reviewed frequently as more information becomes available about the annuli and their scaling laws from future experiments.

As is done in Refs [2,5], the electron annulus is energetically separated from the toroidal plasma and power transfer between the electron

ring and the toroidal plasma is included in the synchrotron radiation term (P_C) which has a very small effect on the power balance.

3. ANALYSIS

A range of self-consistent plasma and engineering parameters within which an EBT reactor is expected to operate has been analyzed [3]. To do this, a reference set of fixed design parameters is specified, and a range of plasma parameters and reactor sizes which satisfy the design constraints is established. The operating point is obtained and the effects of different choices of scaling assumptions on reactor performance and operating point are examined.

The reference case presented here should be viewed as a representative system, not an optimum one, because there is no unique solution to the overall design problem. The "optimum design" is strongly dependent on the weight given to the constraints.

The following set of design parameters is specified in order to select the reference design.

- 1) From the utilities point of view, power output is limited to 2000-6000 MW(th).
- 2) Neutron wall loading is in the range of 1-2 MW/m².
- 3) The mirror ratio required for annulus formation is typically 2:1 [1-2].
- 4) The limiting plasma (toroidal core) pressure is in the range of 25-50% [10].
- 5) The ignition device, if possible, should use 150-keV neutral beams (TFTR neutral beams)/120-GHz microwave (EBT-II microwave) sources.

Within the above specifications and with the tools developed in Ref. [3] and Eqs (2.1)-(2.7), reference parameters in Table I are obtained.

Although details of Model A have been discussed in Ref. [3], for completeness density and temperature time histories during start-up are shown in Figs. 1 and 2. The reader can refer to Ref. [3] for more information.

For Model B (neoclassical scaling), the results of the calculations for various values of the anomaly factor, $F(\equiv \text{FAC})$ and η (the electric field parameter) are displayed in Figs. 3-5 for the reference case. In all cases shown, ignition occurs in less than 5 sec. Typical initial conditions and input parameters are given in Table II.

Figure 3 shows particle densities (n_e, n_i, n_α) vs time. When ion and electron densities reach the operating values, they are held constant by external fueling. Because of the feedback on the particle densities, the effects of F and η on these parameters are less pronounced.

Figure 4 is for temperatures (T_e, T_i) vs time for different values of the anomaly factor, F ($= 0, 1, 10, 20, \dots$) and η ($= 0, 0.1, 0.5, 1.0$). Thermal excursion to high temperatures occurs for $F = 0$ (pure neoclassical for all values of η) due to the favorable scaling. Temperatures are about 30 keV ($\eta = 0$) to 40 keV ($\eta = 1$) for $F = 1$, 16 keV ($\eta = 0$) to 22 keV ($\eta = 1$) for $F = 10$, 14 keV ($\eta = 0$) to 20 keV ($\eta = 1$) for $F = 20$, and about 14 keV for $\eta = 1$ and $F = 50$.

Figure 5 is for $N\tau$ vs ion temperature T_i . Ignition occurs when $P_\alpha > P_{\text{LOSS}}$, where

$$P_\alpha = n_D n_T \langle \sigma v \rangle_{DT} U_\alpha \quad (3.1)$$

$$P_{\text{LOSS}} = \frac{3}{2} \frac{n_e T_e}{\tau_{E,e}} + \frac{3}{2} \frac{n_i T_i}{\tau_{E,i}} + 3n_D n_T \langle \sigma v \rangle_{DT} (T_e + T_i) + P_{\text{RAD}} \quad (3.2)$$

$(N\tau)_{\text{ignition}}$ (dark solid curve) has been obtained from Eqs (3.1) and (3.2). Dashed curves are for $(N\tau)_{\text{global}}$, where global confinement time is defined as

$$\tau_{\text{global}} = \frac{\frac{3}{2} n_e T_e + \frac{3}{2} n_i T_i}{P_{\text{LOSS}}} \quad (3.3)$$

From the figure, one can see that with the values of $F > 50$ for $\eta = 1$ and $F > 20$ for $\eta = 0$, the possibility of achieving ignition (without changing any design parameters) becomes questionable. As pointed out earlier, none of the cases presented has been optimized. Different optimization schemes and start-up scenarios might apply to different upper limits for F . For the particular case studied here, it is shown that the reference EBTR can accommodate anomalous losses twenty to fifty times greater than the neoclassical losses at the operating point (steady state). For $F = 30$, $\eta = 0$ or $F = 75$, $\eta = 1$ the plasma temperatures are about 10-12 keV and a little below ignition. A 5-10% increase in plasma radius can help in this situation. Here it should be pointed out that the results presented were obtained for a straight cylindrical first wall design. In order to insure efficient use of the magnetic fields, the displaced aperture-inner wall design has been adopted recently. Figure 6 shows the moderate-B contours and field lines in the equatorial plane for one sector of EBTR for two wall designs. In the latter case, the plasma radius at the midplane is about the square root of the mirror ratio larger than the plasma radius at the coil throat. This improves the confinement properties and increases the F limit.

4. CONCLUSION

The effects of the different scaling assumptions on the EBTR performance and operating point have been analyzed. A simple model, which retains the essential physics of the phenomena, has been developed to assess the energy in an EBTR plasma. Although in the present EBT device (EBT-I) plasma transport seems to be governed largely by neoclassical processes, hypothesized anomalous transport losses are included in the plasma dynamics simulation model in addition to the neoclassical and/or classical transport in order to test the sensitivity of EBTR parameters. The selected scaling parameters are shown to be flexible enough to permit any physically acceptable departures, in reactor operating regimes and conditions, from neoclassical and/or classical confinement. For example, it is shown that the reference EBTR can accommodate anomalous losses one to two orders of magnitude greater than the neoclassical and/or classical losses at the operating point (steady state). Radial electric fields and the displaced aperture-inner wall design further improve the confinement properties.

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GLOSSARY

n_D, n_T, n_α, n_o	Average deuterium, tritium, alpha, and neutral densities.
n_e, n_i	Average electron and ion densities.
T_e, T_i	Average electron and ion temperatures.
S_{DBEAM}	Deuterium source from fast ions.
S_{DCOLD}, S_{TCOLD}	Deuterium, tritium cold fueling rate.
$\tau_{p,D}, \tau_{p,T}, \tau_{p,\alpha}$	Particle confinement times of deuterium, tritium, and alphas.
$\tau_{E,e}, \tau_{E,i}$	Energy confinement times of electrons and ions.
$\langle \sigma v \rangle_{DT}$	D-T fusion reaction rate.
$\langle \sigma v \rangle_{ion}$	Ionization rate.
f	Fraction of injected deuterium beam which undergoes suprathermal fusion [14].
$f_{\alpha e}, f_{\alpha i}$	Fraction of fusion produced alpha energy delivered to the electrons and ions.
G_e, G_i	Fraction of injected deuterium beam power delivered to the electrons and ions.
U_{DBEAM}	Neutral beam injection energy.
P_μ	Microwave power delivered to background electrons.
P_{RAD}	Total power loss from radiation (bremsstrahlung, cyclotron, etc.).

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TABLE I. EBTR REFERENCE PARAMETERS

Plasma radius (m)	1.0
Aspect ratio	30-60
Magnetic field (midplane/mirror)(T)	2.5/4.5
Number of sectors	24-48
Power output [MW(e)]	750-1500
Particle density (m^{-3})	1.2×10^{20}
Particle temperature (keV)	15
Toroidal beta (%)	27
Bulk heating ^a	
Neutral beam energy (keV)	150
Neutral beam power density (MW/m^3)	$0.05-0.2^b$
Microwave frequency (GHz)	120
Microwave power density (MW/m^3)	$0.05-0.2^b$
Profile heating	
Microwave frequency (GHz)	70-90
Microwave power (total) (MW)	5-10

^aToroidal plasma is heated to ignition conditions using either microwaves or neutral beam injection.

^bPower density required for ignition. "Low density" or "restricted cross-section" procedures for start-up minimize the power requirements.

TABLE II. TYPICAL INITIAL CONDITIONS AND INPUT PARAMETERS

Plasma radius, $a(m)$	1.0
Major radius, $R(m)$	60.0
Radius of curvature, $R_c(m)$	2.7
Electric field parameter, η	0.0, 0.1, 0.5, 1.0
Anomaly factor, F	0, 5, 10, 20, 30, 50, ...
Magnetic field, $B(T)$	2.5
Microwave power, $P_\mu (MW/m^3)$	0.2^a
Neutral beam power, $P_{BEAM} (MW/m^3)$	0.2^a
Neutral beam energy, $U_{DBEAM} (keV)$	150
Initial particle density, $(n_D + n_T)_0 (m^{-3})$	5×10^{19}
Initial neutral density, $(n_{oD} + n_{oT})_0 (m^{-3})$	2×10^{14}
Initial alpha density, $(n_\alpha)_0 (m^{-3})$	1×10^{15}
Initial particle temperatures, $(T_e)_0 = (T_i)_0 (keV)$	1.0

^aEither microwaves or neutral beams are used.

FIGURE CAPTIONS

- Fig. 1. Fueling rate and density vs time (for Model A).
- Fig. 2. Temperature vs time (for Model A).
- Fig. 3. Particle densities vs time. Shaded region represents the variation of densities for $0 \leq \eta \leq 1$ and $0 \leq F \leq 50$ (Model B).
- Fig. 4. Temperatures vs time for different values of the anomaly factor F and the electric field parameter η (Model B).
- Fig. 5. N_T vs ion temperature T_i for different values of the anomaly factor F and the electric field parameter η (Model B).
- Fig. 6. Mod-B contours (solid lines) and field lines (dashed lines) in the equatorial plane for one sector of EBTR for straight cylindrical (upper curve) and displaced aperture (lower curve) inner wall design. In the upper curve the boundary is the inner wall (and the coil planes). In the lower curve the aperture has been moved toward the major axis so that its projection along field lines into the midplane lies on mod-B contours.

Fig. 1. Fueling rate and density vs time (for Model A).

Fig. 2. Temperature vs time (for Model A).

Fig. 3. Particle densities vs time. Shaded region represents the variation of densities for $0 \leq \eta \leq 1$ and $0 \leq F \leq 50$ (Model B).

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Fig. 4. Temperatures vs time for different values of the anomaly factor F and the electric field parameter η (Model B).

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Fig. 6. Mod-B contours (solid lines) and field lines (dashed lines) in the equatorial plane for one sector of EBTR for straight cylindrical (upper curve) and displaced aperture (lower curve) inner wall design. In the upper curve the boundary is the inner wall (and the coil planes). In the lower curve the aperture has been moved toward the major axis so that its projection along field lines into the midplane lies on mod-B contours.

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