By acceptance of this article, the publisher or recipient acknowledges the U.S. Government's right to retain a nonexclusive, royalty-free license in and to any copyright covering the article.

MASTER

CONF-830406--65

CONF-830406--65

DE83 012351

EBT REACTOR CHARACTERISTICS CONSISTENT WITH STABILITY AND POWER BALANCE REQUIREMENTS*

N. A. Uckan and R. T. Santoro
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830
(615) 574-1354

ABSTRACT

This paper summarizes the results of a recent EBT reactor study that includes both ring and core plasma properties and consistent treatment of coupled ring-core stability criteria and power balance requirements. The principal finding is that constraints imposed by these coupling and other physics and technology considerations permit a broad operating window for reactor design optimization. A number of concept improvements are also proposed that are found to offer the potential for further improvement of the reactor size and parameters.

1. INTRODUCTION

Present ELMO Bumpy Torus (EBT) reactor studies differ from earlier ones primarily by including theoretical stability criteria developed in the past several years [particularly the Lee-Van Dam-Nelson (LVN) limit^{2,3}] and their coupling to the ring power requirements. The principal result is that these criteria and other physics and technology constraints permit a broad operating window for reactor optimization. Within this operating window, physics and engineering systems analysis and cost sensitivity studies indicate that reactors with $\langle \beta_{\text{core}} \rangle \sim 6-10\%$, $P \sim 1200-1700$ MW(e), wall loading $\sim 1.5-2.5$ MW/m², and recirculating power fraction (including ring sustaining power and all other reactor auxiliaries) $\sim 10-15\%$ are possible.

The physics rationale for this recent study includes: (1) equilibrium, particle orbits, and magnetics optimization; (2) confinement/transport scaling; (3) stability (beta limits); (4) electron and ion ring power requirements; (5) optimal pressure profiles; and (6) coupling of ring and core plasma properties. In addition, the EBT systems code¹ has been developed to integrate physics, engineering, and cost constraints to establish a macrostable, steady-state operating window for a family of EBT reactors that are competitive with other fusion reactors.

Whereas most of the discussions are centered on stability, ring power requirements, optimal pressure profiles, and their impact on reactor operating space, we consider briefly some of the other highlights from the study. Also, a number of concept improvements are introduced that could offer the potential for further improvement of the reactor parameters (such as size, recirculating power fraction, etc.).

II. COUPLED CORE AND RING STABILITY LIMITS

The basic EBT operation requires the use of high beta, hot electron rings for the stability of the overall

*Research sponsored by the Office of Fusion Energy, U. S. Department of Energy, under contract W-7405-eng-26 with the Union Carbide Corporation.

plasma. These rings form near contours of constant mod-B in the midplane of each mirror section and produce a local magnetic well near the edge of a toroidally confined plasma. Typical profiles of the magnetic field, toroidal core and ring pressure profiles, and $U = \oint d\ell/B$ are shown in Fig. 1.

Fig. 1. Typical profiles of $U = \oint d\ell/B$, the magnetic field B , and pressures (core and ring) as a function of midplane radius.

In EBT, the stability requirements of core and energetic ring plasmas are closely coupled,^{4,5} and their interaction defines the stable operating regimes of both plasmas and determines core beta (β_c) limits, as well as the allowable upper and lower limits of the ratio of the core to the hot plasma densities (n_c/n_h).

NOTICE
PORTIONS OF THIS REPORT ARE ILLEGIBLE.

It has been reproduced from the best available copy to permit the broadest possible availability.

mlp
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

The role of high beta, hot electron rings in maintaining the stability of the toroidal core plasma against flute and interchange modes may be seen from Fig. 1 and the simple stability criterion given by⁶

$$(p'U + \gamma pU') [U' - p' \frac{d\Delta}{B^3}] > 0, \quad (1)$$

where $U = \oint d\Delta/B$, p is the core plasma pressure, γ is the ratio of specific heats, and the derivative is with respect to the flux ψ ($' = d/d\psi$). In the central region and at the inside edge of the ring (regions I and II in Fig. 1), stability is attained if $p' = 0$ or

$$p'/p > -\gamma U'/U. \quad (2)$$

At the outer edge (region III), stability is possible if

$$|p'| \leq |U'| / \frac{d\Delta}{B^3}. \quad (3)$$

Thus, the electron ring modifies B and $\oint d\Delta/B$ in such a way as to stably support core plasma pressure gradients in the regions in which they are largest. The stability threshold is then related to the critical value of ring beta, β_{crit} , necessary to reverse the gradients at the outer edge of the plasma, which is given by

$$\beta_{crit} = 2\Delta / \langle R_C \rangle, \quad (4)$$

where Δ = ring half-width, and $\langle R_C \rangle$ = average magnetic field radius of curvature.

Although the hot electron rings provide a local minimum in B and stabilize low beta interchange modes of the toroidal core plasma, a number of instabilities (curvature-driven modes) may still persist because of electromagnetic coupling between ring and core plasmas. Among them is the core pressure-driven interchange mode, which is stable if

$$\beta_C < \frac{2\Delta}{R_C} \left(1 + \frac{p_{\perp h}}{p_{\parallel h}} \right), \quad (5)$$

where R_C is the local radius of curvature in the midplane and $p_{\perp h}$ and $p_{\parallel h}$ are the hot electron ring pressures parallel and perpendicular, respectively, to the B field. This is the core beta limit^{2,3} (so-called LVN limit) near the outside edge of the core plasma (see Fig. 1, region III), which is typically on the order of 10-15% for a reactor. Volume-averaged core beta depends on the core pressure profiles in the core plasma (regions I and II in Fig. 1).

Because the hot electron rings are localized in the region near the outside edge of the core plasma (see Fig. 1), the radial structure of the instability eigenmodes is assumed to be more significant near the rings on the outside edge, and almost all of the theoretical calculations to date that are carried out for region III assume core pressure gradient $p' = 0$ in regions I and II. As will be discussed later, this assumption (made for convenience of calculations) is neither realistic nor favorable for reactor applications.

Summaries of the various modes that may be relevant to a reactor and approximate analytic expressions^{1,5} for their respective stability criteria are listed in Table 1.

Table 1. Summary of stability conditions

MODE	STABILITY CONDITION
CORE PLASMA INTERCHANGE	$\beta_{hot} \geq 4\Delta / \langle R_C \rangle$
HOT ELECTRON INTERCHANGE	$\frac{n_{core}}{n_{hot}} > \frac{4}{(k_{\perp} \Delta)^2} \frac{1}{q_0} \frac{1}{(1 - \beta_C R_C / 2\Delta)^2}$
COMPRESSIONAL ALFVÉN	$\frac{n_{core}}{n_{hot}} < \frac{(q_0 (1 - \beta_C) (k_{\theta} / k_{\perp})^2 - 1)^2}{(k_{\theta} / k_{\perp})^2 q_0 (2\Delta / R_C)^2 \beta_{hot} (\beta_{hot} - 1) (1 - \beta_C)}$
INTERACTING RING-CORE INTERCHANGE	$\beta_{core} < \frac{2\Delta}{R_C} \left(1 + \frac{p_{\perp h}}{p_{\parallel h}} \right)$
DEFINITIONS: $q_0 = \frac{v_{cv1}}{\Delta \omega_c}$, $\beta = \frac{R_C}{2\Delta}$, $k_{\theta} = \frac{m}{a}$, $k_{\perp}^2 = k_z^2 + k_{\theta}^2$, $k_r \sim \frac{2}{\Delta}$	

These are the core interchange, hot electron interchange, and interacting ring-core interchange (LVN) modes. The compressional Alfvén does not pose any problem for reactor-like devices. Typically, these modes impose restrictions on upper and lower limits of n_{core}/n_{hot} , an upper limit on β_{hot} , a lower limit on β_{hot} , etc.; these restrictions are determined by ring scale length Δ , radius of curvature R_C (local and/or field line averaged), $q_0 = v_{cv1}/\omega_{ci} \Delta$, (= ratio of curvature drift frequency to ion cyclotron frequency), anisotropy, radial and poloidal wave numbers, etc.

Although core beta values on the order of 10-15% have been estimated, the coupling of beta limits with ring dimensions (through Δ) and power balance (through n_{core}/n_{hot}) is a concern for a reactor. Boundaries of a reactor plasma operating window as a function of n_{core}/n_{hot} and q_0 are shown in Fig. 2. Within the constraints (1) that reactor parameters lie within the possible operating window shown in Fig. 2 for stability and (2) that the core pressure profile inside the ring (regions I and II in Fig. 1) satisfies core interchange criteria (see next section) for profile considerations, we find that a favorable reactor design can be formulated in regard to both the recirculated power fraction and the total fusion power produced.¹

III. OPTIMAL PRESSURE PROFILES

The economic viability of an EBT reactor improves noticeably if the average core beta $\langle \beta_C \rangle$ significantly exceeds ~5%. The radial profiles of core pressure (which, for simplicity, are assumed to be constant in most of the stability calculations discussed in Sect. I) are found to play an important role in both fusion and ring power balance.¹ Since the magnetic fields in EBT vary both radially and axially (along the field lines), for constant pressure profiles, the volume-averaged core beta $\langle \beta_C \rangle$ is much smaller than the theoretically calculated core beta β_C value near the outside edge of the ring (region III in Fig. 1):

$$\langle \beta_C \rangle \leq \frac{1}{4} \beta_C. \quad (6)$$

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Fig. 2. Boundaries of stable operating window in $n_{\text{core}}/n_{\text{hot}}$ ($=n_c/n_h$) vs q_0 ($\sim T_{\text{hot}}/B^2 R_c \Delta$) space in a reactor. Various boundaries are indicated.

where the limit on β_c is given by Eq. (5). This imposes a serious economic penalty for a reactor. However, if pressure gradients in the core plasma (in regions I and II of Fig. 1) are allowed, $\langle \beta_c \rangle$ is found to be comparable to local core beta at the outer edge of the ring:

$$\langle \beta_c \rangle = (0.5-1.0) \beta_c. \quad (7)$$

This permits fusion power density to be high enough for a sufficiently small ring width and, in turn, an allowable recirculating power fraction for ring-sustaining power.

In the absence of detailed kinetic derivations, stable pressure profiles are derived from the MHD criterion⁶ given by Eq. (1) for the core plasma (regions I and II in Fig. 1), where ∇B is not reversed, and from kinetically derived relations⁵ for the outer edge (region III).

In regions I and II the stability condition is given by Eq. (2), and marginal stability is achieved if

$$p'/p = -\gamma U'/U = -\gamma/\langle R_g \rangle, \quad (8)$$

where $U = \oint d\ell/B$, $1/\langle R_g \rangle = U'/U$, and

$$U' = \partial U / \partial \psi = -\oint (\partial B / \partial \psi + \kappa/r) d\ell / B^2, \quad (9)$$

with $\kappa = -1/R_c$ the curvature. Equilibrium relations are used in Eq. (9) to calculate $\langle R_g \rangle$.

In region III, the corresponding expression for Eq. (8) is

$$p'/p = -1/\Delta. \quad (10)$$

Combining Eqs. (8) and (10), the stable core pressure profile can be derived from

$$p'(r) + \alpha(r)p(r) = 0 \quad (11)$$

to give

$$p(r) = C \exp[-\int \alpha(r) dr], \quad (12)$$

where C is constant and expressions for $\alpha(r)$ are given by¹

$$\alpha(r) = \begin{cases} \frac{2\gamma r}{\langle r_0 R_c(r_0) \rangle}, & 0 < r < r_0 - \Delta \\ \frac{2\gamma r}{\langle r_0 R_c(r_0) \rangle} \left(1 + \frac{\beta_h \langle R_c \rangle}{4\Delta} \right), & r_0 - \Delta < r < r_0 \\ \frac{1}{\Delta}, & r_0 < r < r_0 + \Delta \end{cases}$$

where the angle brackets represents field line average, r_0 is the ring radius, β_h is the ring beta, and $\gamma = 5/3$ is the ratio of specific heats (see Fig. 1 for geometry).

Considering, for example, the central core plasma region in Fig. 1, $0 < r < r_0 - \Delta$,

$$p(r) = p(0) \exp[-\gamma r^2 / r_0 R_c(r_0)]. \quad (13)$$

For a representative set of reactor parameters [$\Delta/r_0 = 0.1$, $r_0/R_c(r_0) = 1/2-1/3$] one finds $p(r_0 - \Delta)/p(0) = 0.6 \pm 0.1$ and $p(r_0)/p(0) = 0.3 \pm 0.1$. This implies that $\beta_c(0) = (1-2) \beta_c(r_0)$ and $\langle \beta_c \rangle \sim 0[\beta_c(r_0)]$, where $\beta_c(r_0)$ is the core beta value that enters in theoretical stability calculations. It should be noted that the radial pressure profiles obtained from one-and-one-half-dimensional (1-1/2-D) transport calculations¹ are found to be similar to those required for stability.

IV. STEADY-STATE RING POWER REQUIREMENTS

In present EBT experiments hot electron rings (formed by electron cyclotron heating (ECH)) are used to achieve gross plasma stability. Power losses from these hot electron rings are observed to scale classically,^{4,7,8} primarily determined by drag cooling, pitch angle scattering, and synchrotron radiation. Ring temperature is observed to be limited by $\rho/L = 5 \times 10^{-2}$ scaling,⁹ corresponding to the nonadiabatic limit (where ρ = average hot electron gyroradius and L = magnetic field radius of curvature).

The use of ion rings^{1,10} that could be formed by ion cyclotron heating (ICH) is also proposed. The properties of ion rings are compared with those of electron rings to determine the potential physics and/or technology advantages. It is found that (1) ion rings would require devices with reactor-like size and magnetic field strengths for stable, adiabatic confinement if the criterion $\rho/L = 5 \times 10^{-2}$ limits the ion ring temperature

(as it appears to do for hot electron rings); (2) stability conditions for curvature-driven modes (discussed in Sect. II) are the same for ion and electron rings, although additional diamagnetic drift and anisotropy driven modes may be present; and (3) power requirements for ion rings can be qualitatively lower than those for electron rings, provided the ion ring volume does not greatly exceed the electron ring volume.

A. Electron Ring Power Losses

The power absorbed in the ring $P_{ring,e}$ is balanced by losses due to drag cooling of hot electrons on core electrons, pitch angle scattering of the ring electrons on core ions and electrons, and synchrotron radiation. The power loss is given (in mks units with temperature in keV and power in MW) by ⁹

$$P_{ring,e} \text{ (MW)} = 0.16 \delta_{h,e} B_R^2 V_{ring,e} G(\gamma, \beta_h, n_c/n_h), \quad (14)$$

where $V_{ring,e} = 2\pi a \cdot \Delta_e \cdot (NL_{ring})$ is the ring volume, with $a = r_0$ = plasma radius, Δ_e = electron ring half-width, L_{ring} = ring length ($=a$) and N = number of rings (sectors); β_h is the ring beta ($\beta_h = n_h T_h / B_R^2$ with n_h and T_h the density and temperature of the ring); and B_R is the magnetic field at the ring location. Here,

$$G(\gamma, \beta_h, n_c/n_h) = 1 + 2.5(\gamma - 1) + 7.4 \delta_h \left(\frac{n_c}{n_h} \right) \frac{\gamma(\gamma - 1)^2}{(\gamma^2 - 1)^{1/2}} \left(1 + \frac{4}{\gamma + 1} \right), \quad (15)$$

where $\gamma = 1 + T_h/511$ is the relativistic factor and n_c/n_h is the ratio of the core to ring plasma density at the ring location.

B. Ion Ring Power Losses

Power loss from the ion rings is found to be dominated by Coulomb drag cooling of energetic ions on background core electrons, although drag and scattering by background core ions are not entirely negligible.¹⁰ At the ion ring energies (on the order of megaelectron volts, MeV) required for stable reactor operation, charge-exchange losses have a small effect on the power balance. The total power required for ion rings can then be approximated as¹⁰

$$P_{ring,i} \text{ (MW)} = 10^3 \frac{e^2 \delta_h B_R^2}{4\pi T_{ec}^{5/2}} V_{ring,i} [1 + f(T_{ec}/T_h)], \quad (16)$$

where $V_{ring,i} = 2\pi a \cdot \Delta_i \cdot (NL_{ring})$ is the ion ring volume of half-width Δ_i , T_{ec} is the core plasma electron temperature at the ring location, $\delta_h = m_e/m_p$ is the ratio of the hot ion mass to the proton mass, δ_c is the core beta at the ring location, and the function f is small and on the order of $\sim 10^{-1}$.

C. Comparison of Electron and Ion Rings

The power required to sustain an ion ring ($P_{ring,i} = P_i$) relative to that required for an electron ring ($P_{ring,e} = P_e$) can be calculated from Eqs. (14) and (16) to give

$$P_i/P_e = 2 \delta_h^{-1} \delta_c (10/T_{ec})^{5/2} V_{ring,i}/V_{ring,e}, \quad (17)$$

where it is assumed that ion and electron ring betas are the same ($\beta_{h,i} = \beta_{h,e}$) with equal ring temperatures of $T_h \sim 1-2$ MeV. The temperature scaling of Eq. (17) favors a large core electron temperature in the ring region. Considering comparable ion and electron ring volumes with $\delta_c \sim 0.1$ and $T_{ec} \sim 5-10$ keV, one has

$$\frac{P_i}{P_e} \sim \begin{cases} 0.1-0.5 & \text{for D}^+ \text{ ion ring} \\ 0.2-1.0 & \text{for H}^+ \text{ ion ring} \end{cases}. \quad (18)$$

Thus, one sees that ion ring power requirements can be quantitatively favorable, provided that (1) the ion ring volume is not much larger than the electron ring volume and (2) the core electron temperature is not much smaller than about 5 keV near the vicinity of the ring. One would expect $\Delta_i = \rho_i$ to be a minimum ring thickness. For ion rings of $T_h \sim 1-2$ MeV and $B_R \sim 2$ T, $\rho_i \sim 10$ cm [corresponding gyroradius for electron ring is $\rho_e < 0.5$ cm with $\Delta_e \sim (10-30)\rho_e$]. Thus, the ion rings must be sufficiently localized so that Δ_i is not much larger than ρ_i .

V. COUPLING OF STABILITY AND RING POWER BALANCE

Limitations imposed on core beta and pressure profiles, ring scale lengths, and power balance by stability constraints are critical in EBT in determining the operating windows of future experiments and in assessing the desirability of a reactor.

Coupling of core beta with ring volume (through the ring thickness Δ) and with ring power losses (through the relative core/ring density ratio n_c/n_h) affects reactor power balance. Minimizing ring power requires thin (small Δ) rings whereas high beta (high fusion power density) requires thick (large Δ) rings; this implies opposing constraints. Taking into account the various stability constraints (LVN limit, etc.), profile effects, and other physics and technology constraints, the results of system studies¹ indicate the existence of a comfortable operating window with acceptable ring power losses (recirculating power fraction) in a reactor. One such operating window is shown in Fig. 2. Boundaries of this window are determined from the stability constraints, microwave cutoff, beta limit, and net power production requirements.

For a typical reactor of ~ 1500 MW(e), required sustaining powers are¹ $P_{ring,e} = 50-60$ MW and $P_{ring,i} = 5-6$ MW. Here, $T_h \sim 2$ MeV, $\delta_h \sim 0.15$, $\delta_c \sim 0.1$, $B_R \sim 2$ T, the average plasma radius $\langle a \rangle \sim 1.5$ m, and the average core plasma temperature $\langle T_{ec} \rangle = \langle T_{ic} \rangle = 25$ keV. (Note that the core plasma temperature near the ring location

depends on profiles; it is roughly one-half to one-third of the central value.) For this reactor case, the difference in cost of electricity is about 8-12% (in favor of ion rings) depending on the absorption efficiencies of ECR (for electron rings) and ICH (for ion rings).

VI. MAGNETICS

The spatial position of hot electron rings (formed near contours of constant $|B|$ in the midplane) is critical to efficient utilization of the magnetic volume within the vacuum chamber because it determines the boundary of the toroidally confined core plasma. Recent studies^{1,11} indicate that centering of mod-B (centering of ring) through symmetrizing (SYM) or inverse D (ID) magnetic configurations can be more efficient than coil configurations assumed in previous studies [i.e., axis-encircling aspect ratio enhancement (ARE) coils¹²].

One of the critical parameters in the assessment of any ECR reactor magnetics configuration is the radial distance $\Delta r = \delta$ between the first wall and the mirror coil winding with $\delta =$ blanket and shield thickness plus various gaps, dewar, etc., under the coil. Typically, $\delta = 1.0-1.5$ m for adequate shielding and tritium breeding and $\delta/r_{\text{coil}} = 1/3$ to $1/2$ for a reactor in comparison to $\delta/r_{\text{coil}} = 1/8$ in the present experiments (where r_{coil} is the mean coil radius). A primary consideration is to optimize δ/r_{coil} in a reasonably sized device while modifying the vacuum magnetic fields to improve single-particle confinement and centering of mod-B either with supplementary (i.e., SYM) coils or with noncircular (i.e., ID) coils.

Owen and Uckan¹² have shown that the use of SYM coils, with circular mirror coils and with $\delta = 1.5$ m, resulted in a magnetic field geometry within the reactor chamber in which the midplane mod-B was symmetric across the minor axis at the ring location. The corresponding magnetic ARE factors were approximately 2 (1.5) for trapped (passing) particles. Similar results were obtained with axis-encircling ARE coils. Both ARE and SYM coils improve volume utilization and single-particle confinement by lengthening the magnetic field lines inside the torus relative to those outside, with SYM coils being more efficient in terms of magnetic field utilization in a reactor.

Reactor applications of noncircular ID coils have also been examined.^{1,11} The parameters describing the noncircularity are similar to those of typical tokamak D-shaped toroidal field (TF) coils. In a bumpy torus, however, the vertical "straight" leg is optimally located on the outside of the torus rather than on the inside; that is, the coil is reversed from the tokamak configuration. In a toroidal array of these coils, this orientation results in a partial cancellation of the vertical drift that arises from the toroidicity. A finite aspect ratio torus with ID coils has a mod-B in the midplane almost perfectly symmetric about the magnetic axis.

The ratio of the area of the largest confined passing particle ($V_z = V$) drift orbit to that for trapped particles ($V_z = 0$) is compared in Fig. 3 for ID coils and for circular mirror coils (with and without SYM coils) as a function of δ for various reactor sizes. In all cases, ID coils are superior to simple circular coils. However, for $\delta \geq 1.0-1.2$ m in the example shown in Fig. 3, the improvement obtained with ID coils is not as large as that obtained with SYM coils. With nonuniform distribution of blanket and shield thickness under and between the coils, if future detailed engineering and neutronics calculations indicate that $\delta \leq 1.0-1.2$ m gives adequate neutron shielding and a minimal breeding ratio under the coil, then ID coils will certainly compare favorably with systems utilizing SYM coils. The ID coil magnetics system is significantly less complicated; hence, assembly, maintenance, and access should not be adversely affected, as they are with configurations in which there are two supplementary coils per sector. Configurations with noncircular tori (square, racetrack, etc.) are also under consideration.

VII. CONFINEMENT SCALING

The operating parameter space of a reactor is investigated by using both time-dependent zero-dimensional (0-D) and 1-1/2-D transport calculations.^{1,13} The 0-D model is used for parametric burn studies to examine the global plasma performance and the sensitivity of these performance parameters to various transport assumptions and operational scenarios. The 1-1/2-D radial transport code, on the other hand, is used for determination of density, temperature, and ambipolar potential profiles and the effect of these profiles in energy confinement scaling.

Fig. 3. The ratio of the area of the largest confined passing particle ($V_z = V$) drift orbit to that for trapped ($V_z = 0$) particles is shown for circular coils [without (a) and with (b) SYM coils] and for ID coils (c) as a function of blanket-shield thickness ($\Delta_{B-S} = \delta$) under the coils for various reactor sizes.

In EBT, a simple neoclassical electron transport scaling is given by¹⁴

$$n\tau \sim A^2 T^{3/2} \left(1 + \frac{R_B}{R_E} \frac{e\phi}{T_e}\right)^2 f(\text{profiles}), \quad (19)$$

where $A = R_T/R_B$ is the magnetic aspect ratio; R_T , R_B , and R_P are the major radius of the torus, magnetic field scale length, and electric field scale length, respectively; and $e\phi$ is the ambipolar potential. Because the neoclassical electron losses dominate the experimental behavior, it is difficult to make comparisons between the theoretical ion losses and experimental observations. Scaling laws governing ion behavior are important in a reactor. At present, ion transport principally determines the radial electric field ($E = \nabla\phi$) needed to maintain ambipolarity. $E_r < 0$ in the experiments; however, $E_r > 0$ is also possible, which could yield to enhanced confinement.

In a global analysis with $E_r < 0$ [which leads to the simple scaling given by Eq. (19)], it is observed that large devices ($A > 20$) are required for ignition. Analysis with the 1-1/2-D transport simulation code, however, provides an important new insight into confinement scaling of EBT in going from present experiments (EBT-S) to a reactor (EBT-R). It is observed that in the EBT-S to EBT-R sequence profile effects near the outer edge of the hot electron ring lead to enhanced confinement beyond the simple scaling obtained from the global analysis (which omits these profile effects). In Fig. 4 the dashed curves represent the values of $n\tau$ calculated from Eq. (19) for the sequence of EBT devices: EBT-S, -P, -Q, and -R. The solid curves show the results of 1-1/2-D transport simulations (for $E_r < 0$) of these increasingly larger devices. Note that the confinement is better than predicted by the simple $A^2 T^{3/2}$ scaling of Eq. (19). Profile effects suggest that confinement exceeds the simple scaling by at least a factor of 3-5. A similar enhancement factor is also observed as possible with $E_r > 0$.

VIII. SYSTEMS INTEGRATION

The EBT systems code¹ is used to carry out parametric studies. Considered in this code are the coupling of the ring and core plasma properties, the consistent treatment of the stability and power balance requirements, and preliminary cost calculations. A reactor operating space obtained from the systems code is similar to one shown in Fig. 2. Within this operating window, a representative set of reactor parameters, though not optimized, is given in Table 2.

Table 2. Representative EBT reactor parameters

Thermal power	5000 MW(t)
Net electric power	
with electron ring	1550 MW(e)
with ion ring	1650 MW(e)
Major radius	38 m
Average plasma radius	1.5 m
Number of sectors	34
Average magnetic field	4 T
Neutron wall loading	1.4 MW/m ²
Average core density	$8 \times 10^{19} \text{ m}^{-3}$
Average core temperature	25 keV
Core/ring beta	10%/15%
Ring temperature	2 MeV
Ring power losses	
Electron ring	60 MW
Ion ring	5 MW

Fig. 4. Confinement parameter $n\tau$ vs collisionality $\nu_e = \nu_e/\Omega_e$ for sequence of EBT devices. Dashed curves represent values of $n\tau$ calculated from Eq. (19). Solid curves (solid circles) are results from 1-1/2-D transport calculations.

REFERENCES

1. N. A. UCKAN et al., ORNL/TM-8712, Oak Ridge National Laboratory (1983).
2. J. W. VAN DAM and Y. C. LEE, *EBT Ring Physics, Proceedings of the Workshop*, Oak Ridge National Laboratory (1980), p. 471.
3. D. B. NELSON, *Phys. Fluids*, **23**, 1850 (1980).
4. N. A. UCKAN, ed., *EBT Ring Physics: Proceedings of Workshop*, Oak Ridge, Tenn. (1980), papers published therein; *EBT Stability Theory: Proceedings of Workshop*, Oak Ridge, Tenn. (1981), papers published therein; *Hot Electron Ring Physics: Proceedings 2nd Workshop*, Vols. I and II, San Diego, Calif. (1981), papers published therein.
5. H. L. BERK et al., *Phys. Fluids*, **26**, 201 (1983).
6. D. G. NELSON and C. L. HEDRICK, *Nucl. Fusion*, **19**, 283 (1979).
7. N. A. UCKAN et al., in *Plasma Physics and Controlled Nuclear Fusion Research 1980*, Vol. I, IAEA, Vienna (1981), p. 831.
8. N. A. UCKAN and EBT Group, *Plasma Phys.*, **25**, 129 (1983).
9. N. A. UCKAN, *Phys. Fluids*, **25**, 238 (1982).
10. J. B. MCBRIDE, N. A. UCKAN, and R. J. KASHUBA, "Assessment of Energetic Ion Rings Versus Electron Rings for an EBT Reactor," these proceedings.
11. L. W. OWEN and N. A. UCKAN, "Particle Confinement in EBT Reactors with Noncircular Mirror Coils," these proceedings.
12. L. W. OWEN and N. A. UCKAN, *J. Fusion Energy*, **1**, 341 (1981).
13. T. UCKAN, E. F. JAEGER, and N. A. UCKAN, "Transport Scaling Studies for EBT Reactor," these proceedings.
14. L. A. BERRY, C. L. HEDRICK, and N. A. UCKAN, ORNL/TM-6743, Oak Ridge National Laboratory (1979).