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9/17/76

CONF-760935--23

THE ELMO BUMPY TORUS REACTOR*

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ABSTRACT

In the Elmo Bumpy Torus Reactor (EBTR) study the feasibility of achieving a fusion power plant based on the EBT confinement concept was evaluated. If the present understanding of the physics can be extrapolated to reactor scale devices the reactor could operate at high beta, high power density, and at steady state. The high aspect ratio of the device eases the accessibility, structural design and remote maintenance problems which are common to low aspect ratio machines. A version of the EBTR reference design described here could be constructed with only minor extrapolations in available technology.

INTRODUCTION

Fusion reactor system studies to date primarily have dealt with the tokamak confinement concept. Results from these studies show that criteria necessitated by the physics lead to difficult engineering problems. Specifically, a low beta plasma which is confined in a low aspect ratio torus, results in a low power density, nonuniform structural loadings due to the strong curvature, accessibility problems, and requires the use of pulsed magnetic fields which

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*Research sponsored by the Energy Research and Development Administration under contract with Union Carbide Corporation.

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complicates the structural design. Although recent theoretical advances in tokamak plasma physics suggest that some of the problems may be alleviated,[1,2] it is prudent to examine alternate systems which hold promise.

A summary of the first reactor study based on the Elmo Bumpy Torus (EBT) confinement concept[3] is presented here. An EBT reactor plant could obviate many of the usual difficulties. It is assumed that the physics will extrapolate favorably to the reactor regime. If this is realized, the EBT reactor could operate at high beta, high power density and at steady state. No pulsed magnetic fields are required. EBT is a high aspect ratio device so that the accessibility problem is virtually eliminated, the remote maintenance difficulties are eased, and relatively uniform stuctural loadings due to weak curvature which lead to reduced design problems. The present EBT experiment has demonstrated stable plasma operaton and obtained results[4] which provide further motivation for the study. The major theoretical physics aspects related to the reactor plasma are summarized in the Appendix.

A uniform and self-consistent treatment of the EBT reactor concept has been completed in the plasma engineering, plasma physics, magnetics, neutronics and photonics, and design engineering areas. Plasma engineering parameters such as power density, neutron wall loading, and thermal output were used in tradeoff studies to determine the reactor operating conditions. Plasma physic analyses ensured that the reactor plasma characteristics are consistent with projections based on present day theory. Technology and engineering considerations were used to develop specific component designs and an overall framework for the development of feasible structural concepts and remote maintenance procedures. The neutronics analysses were an assessment of the nuclear performance of the blanket and shield designs. Specific reference designs have been developed to provide a focus for all of these analyses and to examine how they are related.

EBT REACTOR (EBTR) REFERENCE DESIGN PARAMETERS

An EBTR reference design has been developed. Preliminary power balance calculations suggest that the background or toroidal plasma should be heated to ignition conditions using neutral beam injection and that the stabilizing relativistic electron rings should be sustained during operation by microwaves. A plan view of the system is shown in Fig. 1. Table 1 shows the fundamental parameters for the system. The power output and neutron wall loading in EBTR have been taken to be similar to the values of the same parameters typically assumed in low beta system studies. This facilitates comparisons.

The reactor is fueled by deuterium and tritium and operates in the ignited mode. It produces 4000 MW(th), exclusive of blanket multiplications. This is consistent with a source neutron wall loading of 1.1 MW/m^2 and a fusion power density of 3.4 MW/m^3. The confining magnetic field at the midplane is about 2.5 T which results in a beta of 0.25. The magnetic field is produced by 48-6 m bore superconducting coils. The mirror ratio is 1.8 so that the field strength in a magnet throat is 4.5 T. The major radius of the device is 60 m, the plasma radius is 1 m, so that the plasma aspect ratio is 60. The self-consistent relationships between the geometrical and power production parameters are shown in Fig. 2.

The entire torus is enclosed in a concrete moat which provides a structural foundation for the reactor components and remote maintenance equipment as well as a biological shield. Figure 3 shows a cross section view of the torus and moat. The figure shows the system at an early stage of disassembly.

The high aspect ratio EBTR configuration affords several design options in the remaining areas. Two blanket and magnet shield concepts have been developed. The first blanket uses stainless steel structure, natural lithium for breeding, and is cooled by a eutectic nitrate salt. The associated shield materials are stainless steel and borated water. The shield is cooled by

circulating the borated water. The second design includes a Nb-1% Zr first wall, stainless steel structure, and natural lithium both for breeding and as the coolant. Electromagnetic pumps are used to circulate the lithium. The magnet shield in this case is composed of concrete loaded with (40$ by volume) austenitic iron shot. The shield is cooled by CO_2.

Preliminary neutronics analyses of the blanket options have been carried out using the one-dimensional discrete ordinates code ANISN[5] to assess the nuclear performance of the two proposed blanket-shield conceptual designs. The nuclear performance was evaluated in terms of the capability of the blanket assemblies for recovering the kinetic energy of the fusion neutrons and secondary gamma rays in the form of heat and for breeding tritium and of the capability of the blanket and shield in reducing the radiation incident on the toroidal magnet coils.

The eutectic nitrate salt cooled stainless steel blanket assembly consists of alternating layers of lithium and graphite followed by a gamma ray shield. The total thickness of the lithium is 41.9 cm and the graphite moderator-reflectors have a combined thickness of 15 cm. The magnet shield is composed of 35% borated water and 65% stainless steel spheres. A 12 cm thick lead liner surrounds the shield and reduces the gamma radiation which is incident on the magnet coils.

The lithium cooled niobium-stainless steel blanket assembly has a total thickness of lithium of 54.5 cm. A 15 cm thickn graphite reflector-moderator is adjacent to the lithium region. In this design, the main constituent of the shield is "heavy concrete" which consists of 40% iron and 60% ordinary concrete. A lead liner 5 cm thick surrounds the assembly.

In both designs, natural lithium (7.4% of ^6Li, 92.6% of ^7Li) is the tritium breeding material.

Some of the calculated results are given in Table 2. In the design utilizing niobium as the first wall, the tritium breeding ratio is 1.614 compared to 1.353 for the design utilizing stainless steel as the first wall. However, the tritium breeding ratio is essentially the same in both designs. The energy deposition rate in the first winding of the magnet coil is also given. The concrete shield option is more effective in reducing the nuclear heating in the first winding of the magnet coil. The heavy concrete shield is 86-cm thick compared to 53.5 cm for the borated water and stainless steel shield.

There are two structural arrangement options. In both of them the torus is constructed of modules to facilitate assembly and remote maintenance. In the movable magnet concept, the number of magnets and the number of modules are equal. The module then includes the first wall, blanket, magnet shield and magnet itself. The entire unit, which weights about 600 tons, is removed to a hot cell for maintenance. In the fixed magnet concept the number of modules is twice the number of coils. The modules, which include the first wall, blanket and magnet shield, located under the magnets are not identical to those located between the magnets. Thus there are two sets of 24 identical modules in the reactor. The fixed magnet concept permits any module to be removed for maintenance without disturbing the coils. The magnet is removed only if it fails. It is important to realize that both of these approaches allow standardization of the major EBTR components. That is, standard magnets and modules can be fabricated a d assembled into toroidal configurations of different major radii. Forth-eight coils are needed when the major radius is 60 m. The minimum size device which is compatible with the standard module concept has a major radius of 30 m and requires 24 coils. The power output in this case is 1180 MW(th) for a neutron wall loading of 1 MW/m^2 and can be

3540 MW(th) if 3 MW/m^2 can be tolerated. Standardization has broad implications from a commercialization point of view.

Two superconducting magnet alternatives have been examined. In both cases the magnetic field and coil loading are nearly symmetrical. There is no need to use D-shaped or oval-shaped coils to minimize the bending moment so tha' coils with a circular shape are used. The first option includes 48-NbTi superconducting magnets which are operated under pool-boiling conditions. The average current density in the windings is 1550 amp/cm^2 which results in a peak field strength in the winding of 7.3 T and 4.5 T at the magnet throat. The second option includes 48-NbTi-Nb_3Sn composite superconducting coils which are cooled by supercritical helium under forced-flow conditions. The peak fields in the Nb_3Sn and NbTi windings are 100 kG and 52kG, respectively. The average current density in the high field windings is 2000 $amps/cm^2$ and in the lower field windings it is 4000 $amps/cm^2$. Both options are fully stabilized and include current dump protection circuitry in case of a magnet failure.

Since impurity production and behavior in the reactor cannot be predicted with certainty and since it will be critical to achieving steady-state operation, it was decided to treat this area conservatively. In one case a system was studied that included a toroidal divertor. Energy and particle fluxes then are accommodated by the divertor system. Alternatively, a case was studied where impurity control was assumed but the full energy flux produced by a transported from the plasma must be tolerated by the first wall. This system, without the divertor, has significantly more stringent design criteria associated with the first wall thermal hydraulic system since it must handle 20% of the thermal output power and ~ 8% of the neutron energy produced.

CONCLUSIONS

An EBTR reference design has been developed. If the present understanding of the physics can be extrapolated to the reactor regime, the system could operate at high beta, high power density, and at steady state. The high aspect ratio of the machine and the fact that there are no pulsed magnet fields required for operation ease considerably the accessibility, structural design, and remote maintenance problems encountered in designing low aspect ratio devices.

The flexibility afforded by the EBTR configuration leads to several options in the areas of materials, primary coolant, blanket and shield arrangements, superconducting magnets, and maintenance procedures. When an EBTR reference design is envisioned which uses the more conventional options, it is found that the reactor could be constructed using techniques and technologies which exist or are the objectives of present development programs. The other more advanced design options require longer range development but would lead potentially to a more attractive reactor plant.

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APPENDIX – PLASMA PHYSICS

The plasma physics areas which ahve been evaluated in order to determine the operating characteristics are: (1) particle orbits and their effect on efficient use of the plasma chamber volume, (2) plasma stability and equilibrium, and (3) scaling, transport and modeling.

For a high beta, steady-state system, the plasma equilibrium, particle orbits, ambipolar electric field, and transport phenomena are closely coupled to one another and an adequate treatment of any one requires consideration of the others. Specifically, the interrelations are: (1) equilibrium magnetic fields depend on the plasma pressure profile, (2) guidinger center drift orbits depend on the equilibrium magnetic field and ambipolar electric fields, and (3) transport rates, which together with sources and sinks determine the profile, depend on the guiding center drift orbits. A self-consistent treatment of this coupled set of problems for a large-scale EBT reactor while being vigorously pursued, is as yet unavailable. Here intermediate and/or partial answers are obtained in order to proceed progressively into the full self-consistent treatment.

EQUILIBRIUM AND DRIFT SURFACES

Efficient use of the volume of an EBT reactor is proving to have a greater impact upon the design assessment than was expected. The shielding and blanket which surround the chamber in the reactor make the problem more difficult than that in EBT-I.[A-1]

Finite beta and ambipolar electric fields make considerable differences in the particle orbits. For the reference design, a detailed calculation was carried out for a sample equilibrium which was guided by the experimental observation that the ambipolar electric field is strongest in the vicinity of the annuli. The spatial position of the hot electron annuli is critical to efficient

utilization of the volume within the vacuum chamber. Macroscopic stability demands that the toroidal core plasma pressure be relatively constant near the minor axis and fall rather rapidly in the region of the annuli. Thus the annuli form a set of "guard rings" surround the toroidal core. Experimental observation and numerical computation show that the annuli form near contours of constant $|\vec{B}_{vacuum}|$ in the midplane of the device. Th toroidal effects cause these contours to be shifted inward toward the major axis. To the lowest order plasma follows the field lines, and for the present inner wall design some of the field lines which pass through the coil aperture intercept th dateral wall of the chamber. Hence, the present wall design limits the diameter of the annuli; consequently, limits the diameter of the plasma. By "bulging" the inner wall in the midplane (nonuniform layer of shield and blanket within the coil throat) or increasing the outer leg of the coil by about 25 cm while keeping teh plasm location and the thickness of blanket and shield constant. Either method would lead to the plasma size required for EBTR-48 which corresponds to the usable volume of about 100%.

There are three features which are relatively independent of the details of the inner wall design as well as the magnetic equilibrium and ambipolar electric field: (1) low energy particles are well confined, (2) well trapped particles are well confined, and (3) high energy partticles with high $v_{\parallel}/v$ are the worst confined. By using supplementary coils, the confinement of this last class of particles can be improved.

MACROSCOPIC STABILITY

The viability of EBT as a reactor requires the stable confinement of a plasma with densities about 10^{20} m^{-3} and temperatures on the order of 10 — 15 keV. Crucial to the stability of the EBT plasma is the presence of a relativistic hot electron population (annuli), with $T_e \sim 100$ keV, but with a required density of only about 10^{18} m^{-3}, or a small fraction of the total electron

density. This hot electron population is immune to the macroscopic flute-like drift instabilities because of the fast drift velocities and large Larmor radii of its particles. By modifying the magnetic field, it also provides stability for the rest of the plasma, composed of warm ions and electrons. Thus the simplest model for discussing the stability of the EBT plasma is one with three components: hot electrons, warm electrons, and warm ions. One can treat first the instabilities of the hot electrons, and then the instabilitie of the warm species. The effort to date has been concentrated on macroscopic instabilities, those which produce large particle transport and would be fatal to a reactor.

STABILITY OF THE HOT ELECTRON ANNULI

The requirement for the stability is that hog electrons temperature be high enough and the magnetic field gradient produced by their diamagnetism be large enough to achieve a ∇B drift frequency which exceeds the ion cyclotron frequency. When this condition is reached, analysis of the Vlasov-Maxwell equations show that hot electron drift waves are stabilized, apparently by interference between the responses of the fast drifting electrons and the slowly drifting ions.[A-2] As the hot electron density or temperature is reduced, these waves become unstable, and at still lower temperature, where the MHD and guiding center theories are applicable, they become the unstable flutes and ballooning interchanges predicted by these theories. Thus, stable operation of a reactor will require that the hot electrons achieve a temperature comparable to that in the present device (EBT-I) and a pressure profile of sufficient steepness to produce large ∇B drifts. Near the outer edges of the annuli, the hot electron temperature is not high enough to stabilize these instabilities. However, the outer edge of the plasma can be line tied, and line-typing effectively stabilizes the mechanism, but present theory does not

allow a definitive answer as to how large the line-tied region must be. It should be noted that the divertor system, included for impurity control, may well facilitate line typing since it provides a connection path to the boundary region.

STABILITY AND BETA LIMITATIONS OF THE BULK PLASMA

In vacuum field of EBT the bulk plasma is likewise subject to unstable drift and MHD modes at frequencies characteristic of their ∇B drift. The hot electron annuli stabilize these modes by a very interesting mechanism. The hot electron diamagnetic currents act as "invisible coils" colocated with the bulk plasma and create a region of minimum average B in which $\emptyset d\ell/B$ decreases with radius. In this region a stable bulk plasma can be established and then stably extended to the magnetic axis, even though the minimum average B region does not extend to the magnetic axis. Figure A-1 shows the location of the hot electron plasma, the region of decreasing $\emptyset d\ell/B$, and the stably confined bulk plasma. In general, one finds that the bulk plasma β can approximate that of the annuli before instability occurs.

To justify these results, several steps of analysis are required. It is shown that once a well has been established by the annuli (at annuli $\beta \sim 5 - 15\%$) a β of the bulk plasma comparable to, or higher than, the β of the annuli can be achieved which is stable to all modes encompassed by the guiding center or ideal MHD theories. These modes which limit bulk β are pressure-driven ballooning interchanges.

Experimental confirmation of these optimistic β predictions is not possible in the present device because there β is limited by heating and transport considerations. However, the threshold for stable confinement at annuli $\beta \sim 8\%$ is observed, where it marks the boundary between the C and T modes.[A-1]

SCALING, TRANSPORT, AND MODELING

The present state of knowledge requires that the design of fusion reactors be based on scaling laws which have not been fully verified by experiments. The observed macrostable regime of operaton in EBT-I[A-1] gives a reasonable agreement between experiment and a simplified neoclassical point model. The EBT-S and EBT-II[A-3] are designed to study further transport and scaling properties, especially in the collisionless regime (which is an interest to reactor operation). The theoretical supports for these experiments will yield refinement of present day transport theories.

In view of the uncertainties in the theoretical coefficients and the present lack of experimental evidence in this area; the plasma was modeled using both neoclassical and classical theory with appropriate density and temperature scaling. Model is consistent with the physics model: a toroidal core with nearly uniform density and determined by the stabilizing annuli. Flexibility was retained in the simulation models to permit updated data to be incorporated as they become available.

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Table 1. EBT REACTOR REFERENCE PARAMETERS

	EBTR-48[1]	EBTR-24[2]		
PLASMA RADIUS, A(M)	1.0	0.8		
ASPECT RACTIO, A(-)	60	30		
MAJOR RADIUS, R_0(M)	60	24		
MIRROR RATIO, M(-)	1.78	1.45		
ION TEMPERATURE	15	15		
ION DENSITY, $N_I \times 10^{-20}$	1.2	1.43	2.02	2.48
BETA, β(%)	24	18	25	31
MAGNETIC FIELD, B_T(ON AXIS)(T)	2.5 – 4.5	3.1 – 4.5		
NUMBER OF COILS, N_C(-)	48	24		
POWER, P_{TH}(MW)	4000	1180	2360	3540
POWER DENSITY, P_{TH}/V_P(MW/M^3)	3.37	3.9	7.8	11.7
NEUTRON WALL LOADING, L_W(MW/M^2)	1.13	1	2	3
COLD ZONE, δ(M)	0.2	0.2		
BLANKET AND SHIELD THICKNESS, T_{SB}(M)	1.75	1.75		
COIL INNER RADIUS, R_C(M)	2.95	2.75		
CURRENT DENSITY, J_C(A/CM^2)	1500	1500		
COIL RADIAL THICKNESS, T_C(M)	0.71	0.65		
COIL HALF LENGTH, L/2 (M)	1.30	1.05		

[1] EMPHASIS TO DATE HAS BEEN FOCUSSED ON EBTR-48.

[2] ALTERNATIVE SMALLER SIZE REACTORS WITH INCREASED NEUTRON WALL LOADING ARE PRESENTLY UNDER STUDY.

Table 2. Calculated Nuclear Performance for Two EBTR Reference Options

Tritium Breeding Ratio (tritium nuclei/incident neutron)	Stainless Steel Salt Coolant	Nb-1%Zr-Stainless Steel Lithium Coolant
^{6}Li	0.855	0.881
^{7}Li	0.498	0.733
Total	1.353	1.614
Nuclear Heating in the First Magnet Coil Winding $(W/cm^3)/(n/s/cm)$		
neutron	1.00×10^{-23}	2.96×10^{-25}
gamma-ray	5.61×10^{-23}	2.52×10^{-24}
Total	6.62×10^{-23}	2.78×10^{-24}
Radiation Damage to the First Wall		
Displacements per Atom/Year[a]	10.71	13.14
Hydrogen gas production (appm/yr)	444.38	
Helium gas production (appm/yr)	131.21	

[a]Based on effective displacement energies 40 eV for SS-316, 60 eV for Nb.