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The ELMO Bumpy Torus Program

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THERMONUCLEAR DIVISION

THE ELMO BUMPY TORUS PROGRAM

R.A. Dandl, R.A. Dory, H.O. Eason, E.G. Harris, G.R. Haste,
C.L. Hedrick, H. Ikegami, E.F. Jaeger, N.H. Lazar, J.N. Luton,
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APRIL 1976

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THE ELMO BUMPY TORUS PROGRAM

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THE ELMO BUMPY TORUS PROGRAM*

R.A. Dandl, R.A. Dory, H.O. Eason, E.G. Harris,† G.R. Haste, C.L. Hedrick, H. Ikegami,‡ E.F. Jaeger, N.H. Lazar, J.N. Luton, D.G. McAlees, D.H. McNeill, D.A. Spong, and N.A. Uckan.

ABSTRACT

Experiments in ELMO Bumpy Torus (EBT) have shown the validity of the premise that plasma currents produced by microwave-heated, hot-electron annuli can provide macroscopically stable plasma confinement in a steady state bumpy torus. If, as expected theoretically, the EBT approach can be extended to confine steady state, high beta (toroidal) plasmas, it will offer an attractive alternative to the tokamak, theta-pinch, and magnetic-mirror approaches to controlled thermonuclear fusion.

Our present understanding of equilibrium, stability, and transport in EBT suggests a sequence of experimental devices and related research activities which leads progressively toward an attractive full-scale reactor. The implementation of the steps in this sequence hinges on the development of microwave power sources, with high specific power levels, at millimeter wavelengths.

In this program plan we describe a sequence of programs and related research objectives. The achievement of each of these objectives then permits a rational choice of design parameters for successive devices. The first step proposed here, denoted EBT-S, requires increasing the EBT magnetic field to permit microwave heating at 18 and 28 GHz, as compared to the present 10.6- and 18-GHz configuration. We anticipate a three-fold increase in plasma density, some increase in the temperatures, and an opportunity to test the validity of the transport models presently used to predict the plasma parameters. This step will provide important operating experience with the 28-GHz power supplies, which are prototype tubes for millimeter sources at 120 GHz.

In the second step a new, superconducting bumpy torus, EBT-II, would be fabricated to permit microwave heating at 90 and 120 GHz. This device would be designed to produce plasma densities and temperatures comparable to those of present-day tokamaks and to test the plasma physics scaling of EBT confinement.

The third and less well-defined step is EBT-T, which would be designed to test the technology scaling of a very high-power microwave-heated device. This would be followed by EBT-IT, which would be aimed at ignition, the logical goal for a steady state toroidal device.

This report reviews the experimental and theoretical research on EBT that has been carried out to date or formulated for the near future, and provides a status report as well as a research program plan.

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

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1. DISCUSSION OF PROGRAM CHART

The future progress of the EBT* programs depends upon a large number of factors and decisions so that it is not reasonable to provide a full chart with all significant alternatives. Consequently, the program chart on page 4 represents our best projection for the future.

1.1 Main Elements of the EBT Program Chart

1.1.1 Sequence of Experimental Devices Relative to Plasma Parameters n_e, T_e, T_i, and β_{max} vs Magnetic Field and Total Microwave Power

Active Time Interval	Device	B_{res}, kG	$P_{\mu w}$, kG	Plasma Volume, L	Principal Experimental Parameters
1974-77	EBT-I	6.4	90	400	n, T, Ring Stability
1977-80	EBT-S	10	290	400	n, T, $\beta_{max} \cong 1\%$
1980-85	EBT-II	43	2400	800	n, T, $\beta_{min} \cong 10\%$
1982- ?	EBT-T	43	To be determined.		

1.1.2 Sequence of Technological Developments

Active Time Interval	Subject	Result
1976-79	EBT-II SC coil design and test	Reliability assured prototype coils for EBT-II
1976-77	200-kW, 28-GHz CW Gyroklystron and microwave circuit development	High-power multifeed oversize waveguide heating system for EBT-S
1977-79	200-kW, 120-GHz CW Gyroklystron and microwave coupling circuit development	Prototype modules for EBT-II
1979-81	2000-kW, 120-GHz heating system	EBT-II plasma heating source

*EBT is used in this report to refer to the ELMO Bumpy Torus Program as a whole, or the EBT concept. The first experimental device is referred to as EBT-I.

1.1.3 Sequence of Systems Engineering Activities

Active Time Interval	Subject Area
1976-83	Reactor technology studies relevant to the EBT confinement system, including shielding, fueling, impurities, and residue removal.
1976-83	Development of EBT startup and ignition program.

1.2 Basic Assumptions Underlying This Chart

1.2.1 EBT-S Starting Date

Timely approval is given for the EBT-S modification of the basic EBT-I configuration and for the new EBT-II device.

1.2.2 EBT Relevancy

There is a need for an EBT program because of the obvious advisability of vigorous alternative approaches to fusion.

1.2.3 Contingency Results from EBT-S

Favorable results are forthcoming from the EBT-S by mid-1978 so that detailed design of the EBT-T (Technology/Test Phase) can be initiated in December 1978. This device should provide tests of technological factors (startup, fueling, residue removal, etc.) and, if neoclassical scaling has held true, should provide ignition-grade hydrogen plasma. From the present vantage point, this feasibility test device would probably not be engineered for actual DT burn.

1.2.4 Contingency Results from EBT-II

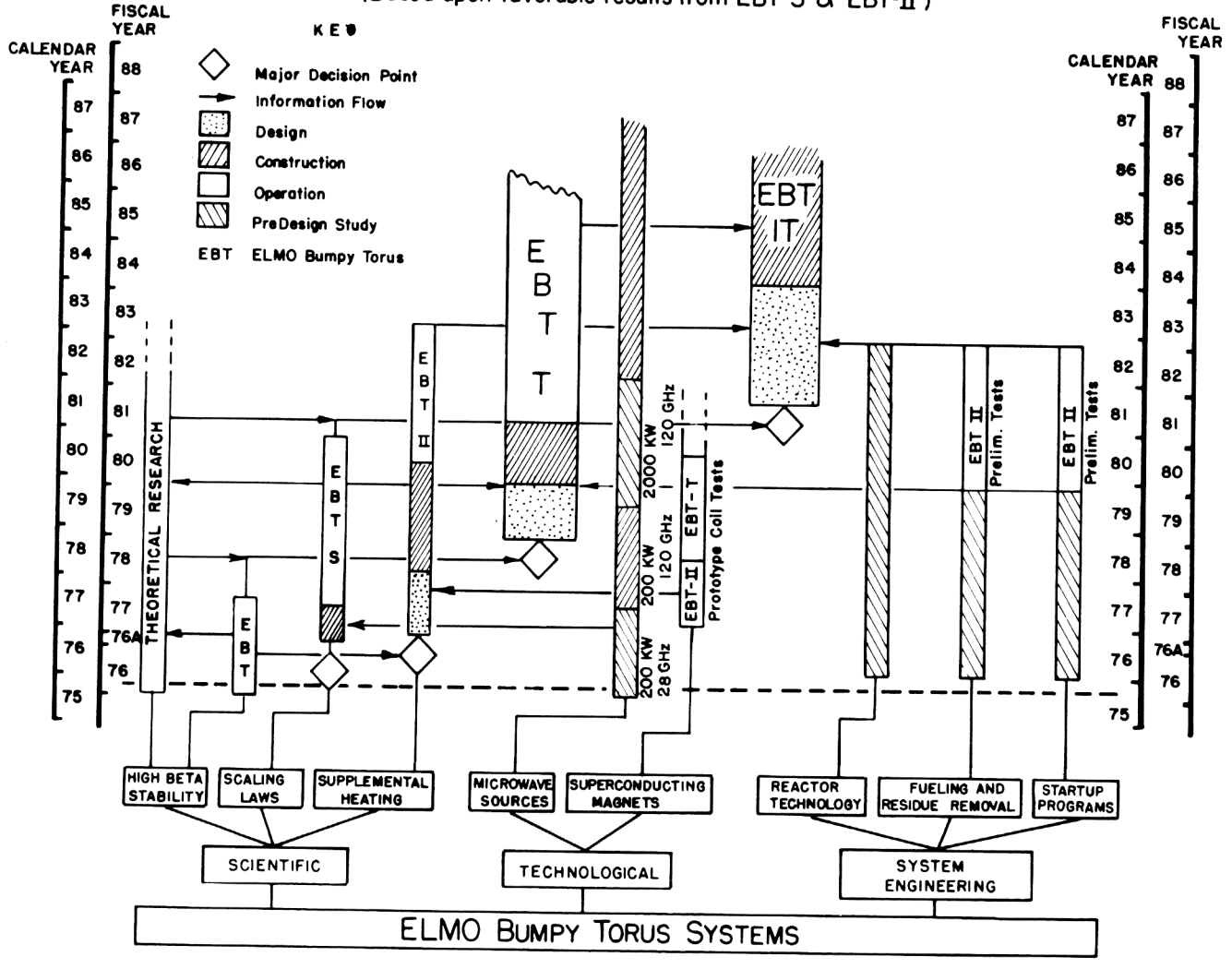
Favorable results from EBT-II about 1981 would motivate a decision to proceed with design and construction of the EBT-IT (Ignition Test) device with planned operation about 1986, as the first serious test of DT physics and ignition in a device designed to cope with the remote handling requirements.

Extrapolation of the program beyond the EBT-IT stage at this point is clearly beyond reasonable credibility.

ORNL-DWG 75-16841R-1

PROGRAM CHART

(Based upon favorable results from EBT-S & EBT-II)



2. EXECUTIVE SUMMARY OF THE EBT PROGRAM

In this section we include a brief description of the EBT confinement system and an overview of critical issues with a related basic program bar chart. This is followed by a more detailed summary of the critical issues relevant to the extrapolation of the EBT confinement system to a fusion reactor and finally the projected costs of the program.

2.1 EBT System Description

The ELMO Bumpy Torus is a toroidal containment concept whose purpose is to provide adequate plasma confinement to make a controlled thermonuclear fusion reactor practicable.

Two features distinguish an EBT system from other CTR approaches:

- An EBT reactor would provide steady state operation, thus eliminating a considerable number of high capital cost engineering problems.
- An EBT reactor would operate at high "beta" (ratio of plasma pressure to vacuum magnetic field pressure). Thus, for a given total plant electrical output, the system would be small and again capital costs would be lower than for intrinsically low beta systems such as tokamaks.

Requirements for operation of an EBT system are a toroidal bumpy (or corrugated) magnetic field structure and an electron-cyclotron resonance heated hot-electron "annulus" contained in each bump of the field. The purpose of the annuli is to provide a modification not otherwise possible of the magnetic fields, so that broad scale instabilities do not form to disrupt the plasma confinement.

The feasibility of this combined system has been demonstrated in the EBT-I experiment at ORNL, and is discussed at greater length in ORNL/TM-4941 (see Section 4.5).

High-power millimeter microwave power supplies furnish the energy to form and maintain the hot-electron annuli. The same sources appear adequately effective in formation and heating of the toroidal plasma

in which the fusion reaction is to occur. Additional heating techniques may later prove advantageous, and radiofrequency or neutral injection heating options will be held open.

Outside the central hot plasma region, EBT systems are expected to be similar to the tokamak systems already studied in much detail in the fusion program, except for the simplifications possible because of the steady state high beta properties.

2.2 EBT Critical Issues Overview

2.2.1 Advantages of an EBT Reactor

A. Steady state operation* after initial startup

B. High energy density, high beta → small size*

*Property leads to reduced capital expense for generating plants.

2.2.2 Key Reactor Engineering Issues to be Resolved

A. Assess reactor engineering factors for Steady State High Beta System

B. Develop fueling and residue removal techniques

C. Refine startup programs

D. Possibility of microwave heating enhanced losses

2.2.3 Key Technological Factors

A. Develop high-power millimeter microwave power sources

B. Design reliable superconducting toroidal magnetic systems

2.2.4 Key Plasma Physics Issues

A. Demonstrate stable operation at high power density ("beta")

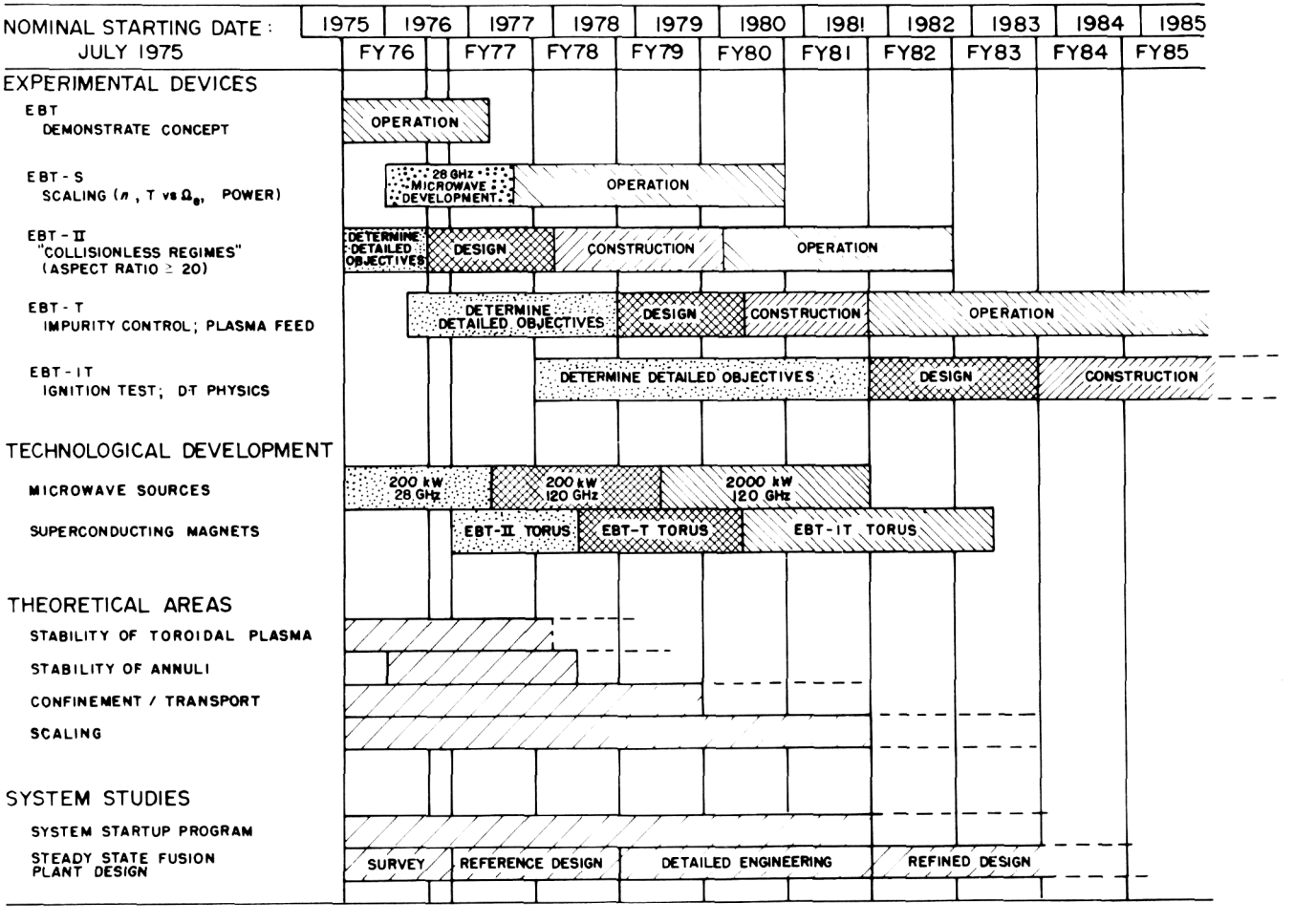
B. Demonstrate collisionless operation and verify scaling laws

C. Assess necessity for supplemental heating

ORNL-DWG 75-16642R-1

BASIC PROGRAM BAR CHART

ELMO BUMPY TORUS PROGRAM PLAN OVERVIEW
Thermonuclear Division, Oak Ridge National Laboratory



2.4 Critical Issues Description

2.4.1 Reactor Advantages of the EBT Concept

2.4.1.1 Operating Mode

Steady state operation at high beta in a large aspect ratio device should alleviate some of the reactor engineering problems associated with low beta or pulsed devices.

2.4.1.2 Operating Cycle

The superconducting magnets will not be operated in a pulsed magnetic field environment. It will therefore be possible to achieve lower costs and designs of higher reliability.

2.4.1.3 Power Grid Considerations

High plasma power density and steady state operation should result in a minimum demand on the generating grid for startup and a smooth delivery of generated power to the grid.

2.4.1.4 Machine Accessibility Considerations

Confinement physics calls for a large aspect ratio device, thereby easing the difficult problems of accessibility and remote maintenance.

2.4.2 Key Reactor Engineering Issues to be Resolved

2.4.2.1 Confinement Machinery Considerations

Although the EBT approach is basically steady state, it has both unique and common constraints and trade-offs to be analyzed. Wall loading, superconductor shielding, annuli maintenance (from an energy input standpoint), and materials choices are all factors which must be assessed within the context of the EBT reactor system.

2.4.2.2 Development, Fueling, and Residue Removal Techniques

For steady state operation of an EBT reactor, methods must be developed for maintaining the fuel ion density in the plasma against losses such as transport and consumption due to DT burning. Fusion reaction products must also be removed during operation to maintain an acceptable fuel ion-to-electron density ratio.

2.4.2.3 Determining Startup (Ignition) Scenarios

When operating in steady state, the level of power required to sustain the system is expected to be relatively small. However, the startup phase requires special consideration in order to minimize power supply capital charges and demands on the electrical grid. Programming of the plasma aperture and density appears to be a possible approach to to this goal, but detailed analyses remain to be carried out.

2.4.3 Key Technological Factors Which Require Research and Development

2.4.3.1 Development of High-Power High-Frequency Microwave Sources

The microwave power technology is sufficiently mature to permit prediction with high confidence that the requisite sources can be developed and that they can be interfaced to the plasma. Contacts are already pending for source development of the 200-kW, 26-GHz Gyrotrons for EBT-S, and of 200-kW, 120-GHz Gyrotrons for EBT-II. Development of the high mode microwave circuitry for EBT-I (55 GHz) has already demonstrated the coupling technology.

2.4.3.2 Development of Reliable Superconducting Magnet Systems

Parameters for EBT-II have been chosen to operate well below critical current density for Nb_3Sn superconducting coils in order to ensure reliable operation. The steady state nature of EBT operation removes difficulties

associated with pulsed operation in other systems. This requirement has been factored into the ORNL Superconducting Magnet Program under H. Long.

2.4.4 Plasma Physics Issues to be Resolved in the Research Program

2.4.4.1 Demonstrate Stable Operation at High Power Density ("Beta")*

The proposed sequence of devices should permit testing operation in the $\beta < 10^{-3}$ range (EBT-I), $\beta < 10^{-2}$ range (EBT-S), $\beta < 10^{-1}$ range (EBT-II), culminating in tests of full high beta operation ($\beta \approx 50\%$) in EBT-T. Eventual operation in the high beta regime is essential for minimizing capital costs in an EBT power plant.

2.4.4.2 Demonstrate Collisionless Operation and Verify Scaling Laws

EBT-S will allow operation at higher B, n, T, and τ, which would then permit more reliable diagnosis and comparison with neoclassical theory, forming a bench mark for scaling tests. EBT-II will provide the first firm check on scaling by taking a large step in the controlling parameter B. In EBT-II, collisionless operation can be ensured by making the torus aspect ratio large enough; values from 20 to 40 are under consideration.

2.4.4.3 Evaluate Other Methods of Heating in the EBT Confinement System

The need for auxiliary heating is intimately connected with the confinement parameters of the device (mainly aspect ratio) and the electron-ion temperature tracking with electron collisional heating. To raise the ion heating rate (if necessary) in order to lower the ambipolar potential, we will investigate beam injection heating using the science and technology already existent at ORNL.

---

*Beta (= β) refers here to the ratio of kinetic to magnetic pressures for the warm toroidal plasma. Elsewhere in the report there is mention of β_A, the same ratio evaluated for the hot-electron annuli.

2.5 EBT Program Plan Costs

ESTIMATED COSTS BY FISCAL YEAR*

(Dollars in $1000)

CATEGORY	1976	1976A	1977	1978	1979	1980	1981
Experimental							
EBT SMY/CMY	9.5/9.0	1.5/3.0	5.0/6.0				
Equipment	$ 600	$ 100	$ 40				
Operating	$1400	$ 325	$ 800				
EBT-S SMY/CMY			5.0/6.0	11.0/10.0	9.0/8.0		
Construction	-	-	-	-	-		
Equipment	-	-	$ 75	$ 150	$ 50		
Operating	-	-	$1200	$2200	$1300		
EBT-II SMY/CMY	2.0/0.0	0.8	6.0		3.0/3.0	14.0/10.0	15.0/12.0
Design	$ 75	$ 55	$ 495				
Procurement	-	-	-	$2700	$5000	$1000	-
Construction	-	-	-	$3000	$5000	$1000	-
Capital	-	-	-	$2000	$ 100	$ 750	$ 500
Operating	-	-	-	-	$ 400	$2000	$2500
EBT-T SMY/CMY	-	-	-	-	12.0/0.0	6.0/0.0	20.0/5.0
Design	-	-	-	-	$1600	$ 800	-
GP (Building)	-	-	-	-	$ 250	$5000	-
Construction	-	-	-	-	-	$1500	$5000
Technology							
Microwaves							
SMY/CMY	5.0/2.0	1.5/0.5	5.0/2.0	5.0/3.0	5.0/3.0	6.0/3.0	6.0/3.0
Equipment	$ 40	-	$ 80	$ 500	$ 100	$ 100	$ 100
Operating	$ 412	$ 120	$ 450	$ 480	$ 500	$ 500	$ 700
Subcontract	$ 300	$ 220	$ 920	$ 920	$ 500	$ 600	$ 700
Superconducting Magnets							
SMY/CMY		0.3/0.3	2.0/2.0	2.0/2.0	4.0/4.0	2.0/2.0	3.0/3.0
Equipment		-	$ 100	$ 200	$ 500	$ 300	$ 500
Operating		$ 150	$ 500	$ 500	$2000	$ 500	$ 700
Supplementary Heating							
SMY/CMY		0.2/0.2	0.2/0.2	0.2/0.2	5.0/4.0	5.0/4.0	5.0/4.0
Equipment		-	-	-	$ 500	$ 500	$ 200
Operating		$ 20	$ 20	$ 20	$ 600	$ 800	$ 500
Theoretical							
Plasma Theory							
SMY/PMY	4.0/2.0	1.0/0.5	9.0/3.0	11.0/5.0	13.0/7.0	14.0/8.0	15.0/9.0
Operating	$ 350	$ 100	$ 995	$1400	$1700	$2000	$2200
System Studies							
SMY/CMY	2.0/0.5	1.0/0.3	4.0/2.0	4.0/3.0	7.0/4.0	7.0/4.0	10.0/4.0
Operating	$ 170	$ 99	$ 569	$ 565	$1000	$1100	$1500

SMY: Scientific & Engineering MY; CMY: Craft MY; PMY: Programmer MY.

*Estimates are from initial conceptual ideas. They are not yet based upon detailed engineering design and are therefore subject to revision.

3. DISCUSSION OF THE SEQUENCE OF EBT DEVICES

In this section we sequentially summarize the major EBT devices, tabulate the parameters of those devices that have been even crudely scoped, and then state the physics issues relevant to these devices.

3.1 Summary of Major EBT Devices

3.1.1 EBT-I

EBT-I has shown that microwave-heated hot-electron annuli can stabilize a plasma confined in a bumpy torus. The limited data now available from the experiment when compared with simplified theory encourage us to believe that EBT operates in neoclassical fashion (at least in the present collisional regime). If neoclassical behavior persists in collisionless operation, an EBT reactor might well be feasible. Status: now operational. Approximate cost: $900,000. B(resonant) = 6.4 kG; 30 kW at 18 GHz; $\beta < 10^{-3}$.

3.1.2 EBT-S

EBT-S represents a scaling experiment to be carried on in the existing torus. The resulting structure should be operational about mid-1977. The intent is to pursue the neoclassically predicted favorable increases in n, T and τ as magnetic field B is raised. At higher n, T and τ, experimental data are more reliable and a more careful test of neoclassical predictions will be possible. At a modest cost for providing the required 26-GHz microwave hardware (no other major machine modification is necessary), EBT-S will provide a subsidiary capability of initial entrance into the collisionless regime in which further verification of neoclassical behavior will be sought. Microwave tubes, controls and coupling circuits will be technological prototypes for EBT-II and later machines. Status: operational in mid-1977. B(resonant) = 10.0 kG; 200 kW at 28 GHz; $\beta < 10^{-2}$.

3.1.3 EBT-II

EBT-II should provide the first test of the scaling laws in which the parameters are given a large increase; it thus represents a key step and decision point for the EBT program. Construction of a new superconducting torus will permit using aspect ratio scaling (to A = major/minor radius $\geq$ 20) to obtain deep penetration into the collisionless regime. The 120-GHz microwave tubes will themselves be prototypes of the very high-power supplies needed for operation of later machines. Auxiliary heating methods will be tested (if necessary) to supplement ion heating from the microwave-heated electrons. Status: optimistically, EBT-II could be operational in early CY 1980. Cost: $\cong$ \$20,000,000. B(resonant) = 43 kG; 2000 kW at 120 GHz; $\beta < 10^{-1}$.

3.1.4 EBT-T

EBT-T is seen as the Technology/Test stage of EBT development in which the important reactor technology programs of system startup, fueling and residue removal are tested. EBT-II is regarded as the first significant scale-up, whereas the EBT-T device would be expected to yield actual ignition plasma conditions in hydrogen. A firm demonstration of ignition would probably be deferred to the succeeding device since the materials handling problems from a DT burn would preclude the flexibility desired at this stage. If EBT-T is of the same scale as EBT-II (no design work has yet been done), it could become operational in the early 1980's.

3.1.5 EBT-IT

EBT-IT should represent the first test of true controlled thermonuclear fusion in an EBT system sized and designed to cope with the radioactive materials and the remote handling necessary at this stage. It would be a true demonstration of the physics/engineering feasibility of an EBT reactor. Obviously a small, embryonic program such as ours, almost completely preoccupied with key physics issues, cannot have generated any details of a device like EBT-IT. We are now at a transition point and will, given the means, develop our program to accommodate design studies such as for EBT-IT.

3.2 Parameter Summary for EBT-S and EBT-II

The EBT-S modification of the existing EBT installation will permit a modest increase in plasma density and temperatures. This will allow some tests of scaling, but the machine will still be in the collisional-collisionless transition regime since the aspect ratio remains at the value 10:1. The plasma diagnostics should be easier and more accurate at higher values of n, T, etc.

The EBT-II device has not yet had final determination of parameters; studies during FY 1976 will provide optimized choices. Prediction of the plasma parameters is uncertain until improved scaling data are obtained from EBT-S; neoclassical scaling suggests the rough values given below. However, the density in EBT devices is a widely varying function of neutral particle feed and heating rates, so that EBT-II could be operated at a lower magnetic field and heated at 28 GHz. This would result in some information on collisionality at lower density and higher aspect ratio, and might usefully justify a speedup of EBT-II in view of extended millimeter wavelength microwave development.

NOMINAL PARAMETERS

EBT-S		EBT-II
7 kG - 14 kG	Magnetic Field (Midplane-Mirror)	30 kG - 60 kG
12 MW	Magnetic Field Power	(Superconducting)
1351 liters	Torus Volume	2700 liters
150 cm	Major Radius	300 cm
10:1	Aspect Ratio	20:1

CW Microwave Power

200 kW (CW) - 28 GHz	Bulk Heating	>2000 kW (CW) - 120 GHz
60 kW (CW) - 18 GHz	Profile Heating	200 kW (CW) - 70-90 GHz

Hot-Electron Annulus - Estimated Parameters

$2 \rightarrow 5 \times 10^{11}$ cm^{-3}	n_e	$1 \rightarrow 6 \times 10^{12}$ cm^{-3}
$100 \rightarrow 500$ keV	T_e	$500 \rightarrow 2000$ keV
$0.1 \rightarrow 0.4$	β_A	$0.1 \rightarrow 0.5$

Toroidal Plasma - Estimated Parameters

$2 \rightarrow 6 \times 10^{12}$ cm^{-3}	n_e	$\sim 5 \times 10^{13}$ cm^{-3}
$150 \rightarrow 400$ eV	T_e	~ 10 keV
$20 \rightarrow 150$ eV	$T_{i,1}$	~ 5 keV
$100 \rightarrow ?$ eV	$T_{i,2}$	?
$\sim 1.0\%$	β_{max}	$\sim 10\%$
400 liters	Volume	800 liters
-	Refrigerator Power	750 watts @ 3.56°K

3.3 Relation of Proposed Devices to Plasma Physics Issues

3.3.1 Scaling Laws

1) In EBT-S it should be possible to test the validity of the neoclassical model in the transition region between collisional and collisionless regimes.

2) In EBT-II it should be possible to test further the neoclassical model in the important collisionless regime; special emphasis will be placed on the effects of the ambipolar potentials on transport.

3) Only at the EBT-II step will it be possible to verify the strong improvement in neoclassical confinement that results from high aspect ratio values; however, some preliminary tests can be carried out by limiters in EBT-S.

3.3.2 High Beta Confinement

Theoretical results to date suggest that macrostable operation will persist for toroidal plasma beta values as large as the beta of the annuli.

1) Tests in EBT-I have been consistent with this for beta up to about 10^{-3}.

2) Neoclassical scaling suggests that EBT-S may attain beta values to about 10^{-2} and EBT-II to about 10^{-1}. Stability will be assessed as the annulus parameters (beta, radial position, size, shape, etc.) are varied.

4. DISCUSSION OF RESEARCH AND DEVELOPMENT PROGRAMS

The discussion of the research and development programs includes the experimental-theoretical plasma physics studies, EBT reactor studies, superconducting magnet development and millimeter microwave power source development.

4.1 Plasma Physics Study Program

4.1.1 Experimental/Diagnostic Program

In order to establish the confinement properties of the EBT experimental devices described in the program outline (i.e., EBT-I, EBT-S, EBT-II, EBT-T, and EBT-IT), it is necessary to augment the diagnostic capability to permit increasingly convenient and reliable measurements of the plasma properties. For programmatic purposes, we subdivide the experimental research program into the following experimental activities:

1) Properties of toroidally-confined ions and electrons.
2) Neutral atom and impurity distributions.
3) Annulus properties and stability.
4) Toroidal stability analysis.

4.1.1.1 Toroidally-Confined Ions and Electrons

The plasma particle parameters, i.e., density and energy, must be measured as a function of space in order to determine the particle and energy confinement times in such a way as to complement the various highly focused experiments. The diagnostic tools for these measurements are as follows:

a) Thomsom scattering of laser lights to determine $n_e(r)$, $T_e(r)$. Development is required for simultaneous measurements in space and for multichannel wavelength determinations.

b) Microwave interferometers for $n_e\ell$ and $n_e\ell(r)$. Continued development of multichannel interferometric techniques is required for the progressively higher densities expected in EBT-S, EBT-II, etc.

c) Energy-resolved energetic neutral particle measurements to determine $n_i(r)$ and $E_i(r)$. Development of a multichannel detector array for simultaneous spatial measurements is required, as are better cross section measurements.

d) Plasma potential determination by an injected energetic charged beam. The influence of the plasma potential on confinement will become increasingly critical as the collisionality of the plasma decreases.

4.1.1.2 Neutral Atom and Impurity Distributions

The feeding of fresh neutral particles into the plasma core in steady-state devices must be controlled to ensure an adequate replacement for outwardly diffusing particles. To understand the mechanisms which determine the wall retention of hydrogen and the companion problem of impurity efflux from the wall represents a major programmatic effort. The divertor-like regions of the surface plasma will be expected to provide a barrier to inwardly diffusing impurities, as they do in present experiments. The control of the plasma in this region through limiter design and, perhaps, applied power and frequency will also be pursued. The principal diagnostic tools are expected to be spatially resolvable visible and ultraviolet spectrometry.

4.1.1.3 Annulus Properties and Stability

For purposes of correlating theoretical stability predictions of the toroidal plasma, particularly as a function of β, the detailed properties of the electron annulus must be determined; i.e., density, energy, and spatial distribution as well as its stability. The diagnostic tools which can presently be predicted are:

a) Spatially resolved diamagnetic measurements (i.e., flux loop arrays).

b) Energetic bremsstrahlung measurements employing collimated NaI(Tℓ) detectors.

c) Potential and fluctuation measurement probes.

4.1.1.4 Toroidal Stability Analysis

To assess the stability boundaries of the toroidal plasma, experiments designed at investigating the unstable regimes are anticipated. In present experiments, two of these regimes have already been identified as C-Mode and M-Mode. The most serious plasma instabilities in these regimes have not yet been identified in detail.

For these studies, the tools required are somewhat difficult to predict, apart from obvious electrostatic and magnetic probes. For purposes of identification of particular modes, the most characteristic signatures are frequency and wavelength, so that spatial correlation measurements as well as frequency determinations will be required.

In all the techniques indicated above, the steady state nature of the experiments permits sampling of data over relatively long intervals, as well as examination of time-dependent properties by spatial correlation measurements. It is apparent that larger-scale data acquisition systems will be required to match the increasing size and complexity of the experiments described. In the immediate future, we anticipate that the four areas of study delimited above will be pursued up to and during the EBT-II experimental period by four groups totaling 8 to 10 physicists with a technical support ratio ranging from 0.5 to 1.

4.1.2 Theoretical Interpretation Program

The EBT theory project supports both the EBT experimental program and its associated reactor system engineering by investigation of the fundamental processes operating in the present experiment and anticipated in future devices.

Currently the theory project is funded at an annual level of 5 SMY. This level must be raised substantially if the EBT program is approved. The complementary program of reactor system engineering is discussed elsewhere. This activity requires a level of support at least as large as the theoretical program.

The key issues, as far as they are known, are summarized here. The focus of theoretical work shifts rapidly as experimental data come in, and no attempt is made here to predict detailed research areas beyond the next three years.

4.1.2.1 Neoclassical Scaling

In EBT-I the density appears to be limited by microwave cutoff which implies $n \propto B^2$. This motivates the sequence of experimental devices having progressively larger B. Using a neoclassical point transport model we find in the collisionless regime T_e, $T_i \sim n^4$ and $\tau \sim n^5$, so that all the important parameters (n, T_i, τ) increase substantially with B.

It appears that collisionless operation, and the consequent reduction of neoclassical losses, can be achieved either by the expediency of increasing the aspect ratio, or by developing some means of modifying the radial electric field. An aspect ratio of at least 16 is necessary for EBT-II, and for adequate safety margin, values in the range of 20-40 are being considered. Economic advantages for reactors accrue from smaller plant size if radial electric field control can be utilized to reduce aspect ratio requirements. According to the neoclassical point model, the T-Mode operation of EBT-I can be interpreted as a result of radial electric fields.

4.1.2.2 Kinetic Transport Model

In the present neoclassical point model the electric field is a parameter (obtained from experiment and primitive theoretical estimates) and is not determined self-consistently. To improve the picture, we have developed a kinetic model which should determine the electron distribution function and provide a self-consistent electric field. Computer codes for this project are under development and will be usable when spatially-resolved data become available from EBT-S.

In FY 1977 we plan to initiate a refined kinetic model to determine the electron distribution function as a function of pitch angle as well as energy and radius. A code will be constructed to analyze EBT-II in the highly collisionless operation, where pitch angle scattering will have increased importance.

4.1.2.3 Transport Coefficients and Fluid Models

We are pursuing improved expressions for the ion neoclassical transport coefficients. One-dimensional fluid codes, which make use of these coefficients, are being developed for use when data are obtained from more complete diagnostics in EBT-S and EBT-II.

As improved transport coefficients become available, they will be incorporated into the existing point model codes. The interaction of the several transport models has already proven useful: the more sophisticated models help calibrate the less sophisticated, while the latter allow rapid scans of parameter space.

A detailed point model has been initiated in conjunction with the plasma engineering group for the joint ORNL-MIT reactor study. This model provides more realism through inclusion of α-particle effects, synchrotron emission, and so on.

4.1.2.4 Microwave Heating

The models presently available for microwave heating have been developed by Grawe, Guest, Eldridge, Sprott and others. McBride of SAI is currently working to improve these models. Highly

refined models of microwave heating will eventually be required for input to the kinetic models. A larger theoretical effort will be necessary so that reliable codes are available at commencement of operation in EBT-II.

4.1.2.5 Equilibrium and Particle Orbits

Two- and three-dimensional computer codes are already in use for solving magnetic equilibria. These codes allow us to study macroscopic stability and guiding-center drift orbits in finite beta fields. An ongoing effort is necessary here because determination of neoclassical loss rates in the kinetic and fluid models requires knowledge of particle orbits. Ultimately it will be necessary to close the loop so that the pressure tensor is self-consistently determined by transport and energy balance.

4.1.2.6 MHD Stability

Present MHD theory predicts that a toroidal beta comparable to the annular beta can be stably confined provided a minimum in B exists and provided the annuli are stable. Experimentally, EBT-I operation is consistent with the MHD results and does not appear to be limited by macroscopic stability. In fact, the transition from the noisy C-Mode to the stable T-Mode of operation occurs at approximately the same value of annular beta that is predicted by theory.

4.1.2.7 Stability of the Annulus

The macroscopic stability of the annulus is understood on the basis of two calculations. Near the peak of the hot-electron temperature, there is an average minimum-B property, which in a Vlasov treatment yields stability for EBT. Outside the minimum-B region the electron temperature is low so that guiding-center theory applies, and it is found that line-tying is necessary for stability. Assessment is required of the amount of cold plasma necessary to provide line-tying, since the microwave power expended to sustain the cold plasma may be significant.

While the beta of the toroidal core in EBT-I is well below that predicted by MHD theory, an EBT reactor must operate near this limit. More detailed theory and experiments will be required to reinforce our present understanding of higher beta operation.

4.2 Plasma Engineering Properties of an EBT Reactor

The principal advantages of an EBT Reactor stem from high beta steady state operation. An optimized reactor plant design and the required research and technology development program will result from an EBT systems study recently undertaken with participation by MIT. Several key features of the EBT Reactor have been identified and will be discussed.

4.2.1 Power Density Scaling

The power density in a burning DT plasma is given by

$$\frac{P_F}{V} = n_i^2 \frac{\langle\sigma v\rangle}{4} Q_F \propto \beta^2 \frac{\langle\sigma v\rangle}{T^2} \quad .$$

In a low-β plasma, β is limited to a few percent and $\langle\sigma v\rangle/T^2$ exhibits a broad maximum between 10 and 20 keV; an optimum operating point which is consistent with the overall plant can be chosen within these criteria. In a high β system additional trade-offs are involved: for example, operation outside the range which maximizes $\langle\sigma v\rangle/T^2$ appears desirable to keep n within limits, because of microwave cutoff or neutral beam penetration requirements. The trade-offs involved in optimizing the high-beta cycle are unique and must be formulated separately.

4.2.2 Startup Procedures

Startup scenarios consistent with microwave cutoff (120 GHz) or neutral beam penetration requirements must be derived to take advantage of high beta operation in EBT. At T = 18 keV, a beta of $\leq$ 0.3 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 dynamics of the EBT system must be analyzed to establish procedures for achieving a high-beta operating point at acceptable density, consistently with constraints imposed by other reactor support systems. The power requirements for startup will dictate power supply criteria and demands from the grid. Two possible techniques have been suggested to minimize the power required for startup (see Section 4.5). The "low density procedure" relies on plasma losses scaling as n^2 and the "restricted cross section technique" depends on $\tau \propto A^2$ during startup. Further analysis is needed.

4.2.3 Maintaining Steady State

A technique for fueling the EBT Reactor must be developed to take advantage of steady state operation; however, this requirement is not unique since it applies to all large systems where the burn time will exceed the particle containment time. In EBT-I, particle density is maintained by introducing neutral gas into the chamber. EBT reactor plasma may be too large to permit adequate neutral penetration for this technique to be effective, so that the particle density will have to be maintained by some other means, such as pellet fueling.

A method for removing residues (fusion products) may be necessary if particle dynamics of transport processes do not lead to this result naturally. Presumably, the operating density, n_e, is fixed, and in an impurity-free system, $n_e = n_i + 4n_\alpha = n_i + 2n_i^2 \langle\sigma v\rangle t$. Thus, a technique for residue removal will be required to prevent fuel ion dilution if alpha-particle containment time is too long. A similar system may be required for the removal of impurities.

Power requirements to sustain the stabilizing annuli must be examined in detail, although this is not expected to be a problem because the ring plasma occupies a relatively small volume.

4.2.4 Overall Plant Design

At this time, no details have been analyzed of the EBT Reactor mechanical, engineering or nuclear design. The main advantages anticipated include relief from access and arrangement problems since the aspect ratio of the device is high. This will facilitate establishment of an acceptable remote maintenance procedure. No plasma current driving system is required. This eliminates the need for operating superconductors in a pulsed magnetic field environment. The shielding thicknesses required to protect the superconducting coils, which will be kept as close to the plasma as possible to minimize the coil size, will be calculated when developing a plant layout. Overall system efficiency, performance and cost will determine the economic viability of the EBT Reactor concept.

4.3 Microwave Development/Technology Program

Multi-megawatt continuous-wave (CW) ECH systems operating at 120 GHz are required by the EBT-T program. This power generation capability is clearly beyond the present state of the art for microwave active devices (tubes). An intensive development program for realization of the required devices will be undertaken through subcontract with private industry. A simultaneous complementary program will be pursued at ORNL for development of complete ECH systems utilizing these devices. Such ECH systems include microwave transmission networks, power supplies, controls, and supporting equipment.

An ongoing study program has identified the "Gyrotron" as the device approach holding greatest promise for generation of 200 kW CW at 120 GHz from a single device. Multiple devices will be used to achieve megawatt systems. Additional encouragement for the Gyrotron approach is provided by recently reported Soviet successes in using such devices for millimeter-wave power generation.

A subcontracted program of device development will be directed initially towards development and delivery of a low-frequency scale demonstration device having 200-kW CW output at 28 GHz. This subcontract, extending over 12 to 18 months, is a critical evolutionary step in the development of 120-GHz devices. The 200-kW, 28-GHz device will be utilized in the primary ECH system for EBT-S. A complementary system development will be undertaken at ORNL over the same period. Development and delivery of the 28-GHz demonstration device is the fundamental pacing element determining completion and operation of EBT-S.

The subcontracted device development program will then proceed immediately to the development of 200-kW, 120-GHz devices. The three-year program will evolve through the successive stages of production of demonstration and prototype devices, device optimization, and construction and delivery of devices appropriate for use in EBT-II systems. Development of the 2-MW, 120-GHz ECH system will proceed at ORNL during the same three-year period. This phase includes the development of 200-kW, 120-GHz bulk heating and 70- to 90-GHz profile heating microwave power modules together with the microwave transmission networks and control subsystems required for operation of an array of at least ten such modules as a complete ECH system for EBT-II. Systems development and testing at ORNL will be facilitated by delivery of operable 120-GHz devices early in the device development program.

Immediately following the development of EBT-II ECH systems utilizing an array of 200-kW, 120-GHz microwave power modules, systems development for EBT-T and EBT-IT will proceed. It is anticipated that these systems will consist of multiple arrays of power modules modeled by the EBT-II systems. Development will be guided by operating experience with EBT-II systems. Device development will continue with the objectives of optimization of reliability, conversion efficiency, and reduction of costs. Systems development will be concentrated heavily upon the areas of reliable organization and control of large numbers of high performance devices, and upon achievement of optimum microwave transmission networks required successively by EBT-T and EBT-IT designs. Since the anticipated requirements of the microwave heating systems in EBT-T and EBT-IT mainly involve increased microwave power input, and since such needs can be met through the use of

multiple power source arrays, it is expected that the required systems will be attainable in a timely manner following successful operation of EBT-S and EBT-II systems.

4.4 Superconducting Magnet Development

Beginning at the EBT-II step in the EBT device sequence, DC power requirements for use of conventional copper coils would be prohibitive. Because the EBT systems will operate in steady state, the use of superconducting coils is natural and cost effective.

Device parameters have been chosen to minimize the level of development required for the magnet system; the requirements therefore should be met by commercial materials. However, it is advisable for the sake of reliability to build and test at least four prototype coils before beginning the main construction phase of the EBT-II. To ensure reliability and adequacy of the coils prior to placing final orders for the full torus, we expect to build a mockup of one complete sector, including fringing effects from the two nearest sectors.

EBT-II is intended to be a 30-kG nominal midplane field device in which we hope to study a high-density, high-power, high beta ring plasma stabilized bumpy torus. The design details of EBT-II are not yet complete, because design engineering time has not been spent on this concept. However, we hope in FY 1976 to start a serious detailed design of EBT-II, given the approval for such activity. From very broad technological and theoretical scaling considerations, and from information learned from the EBT, we know that EBT-II will have a plasma volume similar to EBT-I. It is also expected to have a higher aspect ratio, 20:1 or more, employing, like EBT-I, a mirror ratio of 2:1 in the bumps.

EBT-II will necessarily be a superconducting device, but, as previously indicated, we expect the torus to be an assembly of commercially supplied superconducting coils. Keeping the coil geometry fixed, a conventional copper scale up to the 60 kG and 12-in. bore desired for EBT-II would call for 500 MW of power. Although this

value could be reduced appreciably by a coil design that emphasized power efficiency, the steady state nature of EBT makes it much more reasonable to pursue a superconducting design. Because of the required combination of high current density and high field strength at the conductor, the superconductor itself should probably be Nb_3Sn rather than the more conventional NbTi. The design will be conservative, since experimental time, and consequently data flow, is almost always jeopardized by marginal design.

No toroidal magnet systems have been built using Nb_3Sn, but on the basis of experience with single circular coils and performance of the IMP quadrupole coils (which were subjected to asymmetric magnetic forces), a tentative winding current density of 12,400 A/cm^2 has been chosen as the design value for coils wound from the ribbon conductor.

Detailed planning of the EBT-II magnet system will be carried out when approval and funding of the activity are available.

The full EBT superconducting magnet development project fits naturally into the existing ORNL Superconducting Magnet Development Program under H. Long.

4.5 Concluding Note

More complete details of the topics discussed in this program summary, together with bibliographical references, will be found in the following technical memorandum: R. A. Dandl *et al.*, Research Program for Plasma Confinement and Heating in ELMO Bumpy Torus Devices, ORNL/TM-4941, June 1975.

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