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**Oak Ridge TNS Program: Reference
Design and Program Plan for a
TNS ECH Startup System**

R. Rosenfeld

OAK RIDGE NATIONAL LABORATORY
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FUSION ENERGY DIVISION

OAK RIDGE TNS PROGRAM: REFERENCE DESIGN AND PROGRAM PLAN
FOR A TNS ECH STARTUP SYSTEM

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ABSTRACT

The use of microwave radio frequency (rf) heating in The Next Step (TNS) is considered to be a viable approach to accomplishing reliable preionization while significantly lowering the peak power requirements and cost of the ohmic heating power supply system. Electron cyclotron heating (ECH) is a promising type of rf heating in which high power microwave energy is deposited into the plasma region. Preionization by rf heating offers the promise of reducing the need for large loop voltages for plasma breakdown. Power transmission is accomplished by relatively efficient waveguides and flush mounted arrays where rf density gradients and launch angles can be controlled for optimized energy deposition. The proposed system is based on a configuration of five 200-kW gyro-klystrons which will deliver 1 MW at 120 GHz to the plasma area for pulse periods of up to 6.0 sec.

Completion of an operational system could be targeted for December 1989 at an estimated cost (in 1978 dollars) of \$4 million. A discussion and description of a conceptual system are presented. Estimates of costs, schedules, and research and development (R&D) needs are included.

INTRODUCTION

The Next Step (TNS) represents that phase of fusion energy development in which the major emphasis would be directed towards engineering testing and demonstration. The objective of the TNS studies (initiated by the Department of Energy's Office of Fusion Energy) has been to define the characteristics and requirements of a facility dedicated to the engineering testing phase of fusion power development. For this reason, TNS study results are providing a basis for defining an Engineering Test Facility (ETF). Because the scientific basis required for a TNS/ETF will first be available for the tokamak concept, the reactor core of the facility has been based on the tokamak concept. However, the commitment to an ETF with a reactor core based on the tokamak concept does not represent a commitment to tokamaks as the ultimate power reactor concept.

The TNS studies at Oak Ridge National Laboratory (ORNL) were initiated in FY 1977. During FY 1977, the Oak Ridge effort pursued scoping studies in three broad areas: plasma engineering, systems modeling, and program planning. Based upon the findings of the FY 1977 efforts, it was judged that continued activities in the Oak Ridge TNS program should be directed toward preconceptual design with particular emphasis placed on engineering feasibility. As a point of departure for the FY 1978 activities, a Baseline Design was selected, based on the systems modeling effort of FY 1977. The primary objective of our FY 1978 TNS effort has been to evolve the Baseline Design towards a preconceptual design. However, it is emphasized that the FY 1978 effort was not intended to lead to a completed preconceptual design. Therefore, the design resulting from this year's effort is referred to as a Reference Design, rather than a preconceptual design.

This document describes the TNS rf heating system that was conceptually designed to assist in the plasma breakdown and heating and thereby reduce the ohmic heating power supply cost and complexity. Startup scenarios have been examined to determine whether innovative variations in the scenario can reduce or eliminate major technological problems associated with traditional techniques. The traditional startup scenario

for a tokamak involves the application of a large voltage spike to achieve breakdown in the plasma and burn through the radiation barriers of hydrogen and small quantities of low-Z impurities. Extrapolation to TNS leads to estimates of several hundred volts for the pulsed voltage and a few gigawatts for the peak power in the ohmic system.

Experimental evidence and theoretical estimates indicate that launching microwaves from the inside of the torus near the electron cyclotron frequency (120 GHz for TNS) may result in gas ionization and heating of the electrons by extraordinary waves at the upper hybrid resonance. A relatively small portion of the chamber volume is heated, with the dominant energy loss being magnetic field curvature and parallel drifts of the electrons. The ions remain cold because of charge-exchange loss with the neutrals. A stable, currentless plasma may be established even though electron and ion drifts are unequal. Stability is enhanced with the use of a conducting poloidal limiter which reduces the buildup of a vertical electric field. The peak voltage requirements may be reduced by a factor of five, based on estimates for startup with microwave breakdown and preheating. No significant increase in resistive volt-seconds is expected.

1. GENERAL DESCRIPTION OF THE TNS RF HEATING SYSTEM

A rf system that uses high power microwave energy to initiate preionization and plasma heating during the startup cycle could significantly reduce ohmic heating power requirements and cost.

In the reference design developed in the ORNL TNS studies, rf power is generated by a single master gyrotron oscillator driving five gyro-klystron amplifier tubes. The rf power is transmitted through oversize waveguides to penetrations in the torus.

The design requirements for the system have been specified as follows.

- (1) The system delivers 1.0 MW at 120 GHz continuous wave (cw) to the plasma for up to 6.0 sec. The duty cycle is 6%; the lifetime of the system is ten years.
- (2) The system configuration is an oscillator driving amplifier tubes, using gyroklystron devices. Output power transmission and plasma coupling are accomplished with oversize waveguide components.
- (3) The structural requirements call for five shielded canisters, each containing a high power rf source, mounted on top of the vacuum vessel. The high voltage power supplies are installed in a vault area.
- (4) The cost of the system (estimated in 1978 dollars) is \$4 million.

The design description is discussed more fully in Sect. 2. Power generation and transmission problems are reviewed in Sect. 3, and R&D needs are discussed in Sect. 4. Section 5 summarizes system costs and scheduling.

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2. DESIGN DESCRIPTION

The rf power is generated by a single master gyrotron oscillator driving five gyroklystron amplifier tubes. This combination was chosen to minimize frequency shifts (caused by plasma load impedance effects on the oscillator) and possible frequency coherence problems.

The master oscillator operates at the fundamental frequency, produces 1-2 kW, and drives the individual power amplifiers through a 5:1 divider network, as shown in Fig. 2.1.

Each gyroklystron amplifier tube has a 30-dB minimum gain and produces 200 kW. The tubes are 48 in. long and 36 in. in diameter. Several electrical power supplies and provisions for cooling are required for each tube. The electrical operating parameters and cooling requirements are given in Tables 2.1 and 2.2, respectively, for a 200-kW, 120-GHz gyroklystron device. Each tube also uses a superconducting focusing magnet, a solenoid in a dewar which produces 43 kG and requires 6 kW of electrical power and liquid helium cooling. An additional coil is required in the cathode region and must have a 10- to 20-A, 30- to 60-V(dc) adjustable power supply with 10^{-3} regulation. The cathode end of the tube is designed for operation in oil for both voltage holdoff and cooling, and an oil flow of ≥ 2 gpm is required to cool the gun. A small submersible oil pump will be needed for circulation.

Each complete amplifier assembly will weigh ≈ 2000 lbs and occupy an area 6 ft high by 5 ft square. Five assemblies can be located on a platform on top of the center post of the torus, as shown in Figs. 2.2 and 2.3. This arrangement permits accessibility for servicing.

Each output transmission circuit will contain a directional amplifier, transition sections, 15-20 ft of waveguide, and an energy coupler to introduce the microwave energy into the plasma through penetrations in the torus.

The gyrotron amplifiers will each require a negative beam supply [80 kV(dc) at 10 A], a gun anode supply [40 kV(dc) at 0.1 A], cathode supplies (15 V at 10 A), and magnet supplies [≈ 600 A at 10 V(dc)]. Except for the magnet supplies, which should be close to the focusing solenoids, the high voltage power supply systems will be located away

ITEM	DESCRIPTION	POWER	SELLER	COMMENTS
1	120 GHz OSCILLATOR	1KW	VARIAN	LARGE SCALE DEVELOPMENT
2	STANDARD GUIDE	1KW	TRG	NO DEVELOPMENT, CATALOGUE ITEM
3	DIRECTIONAL COUPLER	1KW	TBD	MINOR DEVELOPMENT
4	POWER DIVIDER	1KW	TBD	MINOR DEVELOPMENT
5	GYROKLYSTRON AMPLIFIER	200KW	VARIAN	LARGE SCALE DEVELOPMENT
6	QUASI-OPTICAL CIRCULAR WAVEGUIDE TAPER	200KW	TBD	THESE COMPONENTS WILL REQUIRE LARGE SCALE DEVELOPMENT. SOME CAN BE SCALED FROM THE EBT WAVEGUIDE COMPONENTS. DEGREE OF DEVELOPMENT WILL DEPEND IN PART ON THEIR PERFORMANCE IN THE EBT EXPERIMENT PLUS HOW WELL THEY CAN BE SCALED FROM 28 TO 120GHz. THE TAPERS WILL REQUIRE SIGNIFICANT DEVELOPMENT. THESE COMPONENTS REQUIRE EXPERIMENTAL DEVELOPMENT TO OPTIMIZE VSWR, LOSSES, MODING, COUPLING AND HIGH POWER TESTING FOR BREAKDOWN. THIS ALSO INCLUDES DEVELOPMENT OF A PRESSURE WINDOW DESIGN.
7	QUASI-OPTICAL CIRCULAR WAVEGUIDE	200KW	TBD	
8	QUASI-OPTICAL DIRECTIONAL COUPLER	200KW	TBD	
9	QUASI-OPTICAL MODE FILTER	200KW	TBD	
10	QUASI-OPTICAL CIRCULAR TO LINEAR	200KW	TBD	

Fig. 2.1. Block diagram of TNS rf components.

Table 2.1. Electrical operating parameters

	Minimum	Maximum	Typical
Beam voltage	70 kV	90 kV	80 kV
Beam current	6 A	10 A	8 A
Gun control anode (with respect to cathode)	20 kV	40 kV	30 kV
Heater voltage (ac)	6 V	12 V	9 V
Heater current	4 A	8 A	6 A
Body current		80 mA	40 mA
Gun anode current		80 mA	40 mA
Power output	150 kW	250 kW	200 kW
Efficiency			30%

Table 2.2. Cooling requirements^a

	Flow rate (gpm)	Pressure drop (psi)
Tube collector	200-400	120-140
Tube body	20-30	75-100
Output waveguide	2-4	75-100
Output water load	70-100	30-50

^aAll cooling media (including liquid helium) will be obtained from TNS common supplies.

Fig. 2.2. Plan view (cutaway).

Fig. 2.3. Elevation view (cutaway).

from the reactor in an enclosed vault area. In addition, the operating beam current must be controlled, either by regulation of the heater voltage or by servocontrol with beam current sensing. The heater time constant for beam current control is 40-60 sec.

Union Carbide Power Supply Specification TD-SP-170 can be used as a guide for the requirements of a cw gyrokystron. It describes a supply consisting of variable voltage, regulated, dc power supplies and a regulated heater supply (see Fig. 2.4).

The negative beam supply has a rating of ≤ 100 kV at 10 A. The positive electron gun anode supply is rated at 40 kV at 0.1 A, is electronically regulated, and floats at the negative 100-kV level in a voltage bucking configuration. The regulated heater supply also floats at the negative 100-kV level. These supplies are isolated from ground so that leakage currents to ground within the gyrokystron tube can be monitored.

The electron gun anode supply is equipped with a crowbar which is actuated by excessive gun current or external command and turns the gun off. The beam supply is left on for ease in restoring normal operation. The beam supply crowbar, which is actuated by excessive beam current, excessive body current, or external command, turns off both the beam supply and the electron gun.

Major components of the five individual 80-kV beam supplies (such as transformers, circuit breakers, etc.) could be combined to cut costs. However, this might result in a potential loss of flexibility and maintainability. It is also anticipated that individual operational "tailoring" of tube element voltages will necessitate separate power supply adjustments.

Further investigation and development in the areas of electromagnetic interference (EMI) and x-ray shielding are required for this application. No major problems that would limit feasibility are evident at this time.

Fig. 2.4. Block diagram of 100-kV, 10-A gyrokystron power supply.

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3. POWER GENERATION AND TRANSMISSION

3.1 RF POWER GENERATION

A major problem in the use of ECH heating for tokamaks has been the lack of high power sources in the millimeter wavelength region. Microwave power amplifiers are presently limited in output capacity because of the small resonant cavity sizes which limit their ability to dissipate high heat levels. The gyrotron is a new type of microwave vacuum tube based on the interaction between an electron beam and microwave fields where coupling is achieved by the cyclotron resonance condition. This type of coupling allows the beam and microwave circuit dimensions to be large compared to a wavelength. Power density problems encountered in the conventional traveling wave tubes and klystrons at millimeter wavelengths are avoided in the gyrotron.

Work is in progress at Varian Associates on the development of a 200-kW gyrotron amplifier at 28 GHz. Continuous power levels of 50 kW and pulsed power levels of over 250 kW have been obtained on recent gyroklystron vacuum tubes. These results form a promising basis for the development of the tube which would be needed for the TNS rf startup system (200 kW at 120 GHz). Production-type tubes could be developed and available by 1984 at an estimated cost of \$100,000 each. The TNS startup system would require five gyroklystron amplifiers and an oscillator (gyromonotron) device.

3.2 MICROWAVE POWER TRANSMISSION

The ability to survive the reactor environment is an important characteristic of the components which transmit high power from the gyroklystron tubes to the plasma. The problems of low insertion loss for the components shown in Fig. 2.1 and of power dissipation for the microwave window vacuum seals will require further R&D effort. Design experience and techniques at these frequencies are presently limited to low power waveguide systems. Comments on required technical development are given in Fig. 2.1.

Oversize waveguides will be used to transmit the 200-kW (peak) power at 120 GHz because of their lower attenuation and simpler construction. One problem with oversize waveguides is the generation of unwanted higher order modes,* which can become trapped and result in a loss of energy. To minimize this problem, the diameter of the guides should be the smallest one which will handle the power.

*Modes of a waveguide transmission line designate the distribution of the electric and magnetic fields. TE indicates that the electric field is transverse to the transmission line axis at all points.

4. RESEARCH AND DEVELOPMENT NEEDS

The overall R&D needs are shown in Fig. 4.1. Specific areas of need are discussed below.

4.1 TUBE DEVELOPMENT

The reference design studies indicate that a target power output of 200 kW per tube is a reasonable objective at this time. A tube development program is recommended, and the "technical fallout" from the Varian Associates 28-GHz program should be applied to the development of 120-GHz devices.

4.2 TRANSFER OF RF POWER

The transfer of rf power from the source to the plasma poses several problems in the areas of high power waveguide components and coupling of rf heating to the plasma. A development/test program should be instituted to investigate the power handling of oversize waveguides and the design of mode filters. Optimum materials for waveguides and vacuum seals able to resist radiation must also be developed. Some recommended tasks are described.

4.2.1 Quasi-Optical Oversize Waveguide

The characteristics of various oversize circular and rectangular waveguides should be investigated. Tapers from larger to smaller and from circular to rectangular guides are of special interest. Breadboard models should be built and used to measure attenuation, voltage standing-wave ratio (VSWR), mode characteristics, and the effects of bends, smoothness, material types, and circularity tolerances. Tests would be conducted at low power at a frequency in the 120-GHz range.

Oversize waveguide directional couplers, mode filters, and miter bends should be designed and breadboard models built to measure attenuation, VSWR, and mode purity. Again, tests would be conducted at low power and 120 GHz.

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Fig. 4.1. R&D needs for rf heating system.

Once these investigations are complete, high power testing of waveguide straight sections, bends, mode filters, and directional couplers should take place with 200 kW at 120 GHz with a 4% duty cycle, under both pressurized and unpressurized conditions. The development of the microwave window vacuum seals would tie in with this work (see Sect. 4.2.2).

4.2.2 Pressurization Window

Investigations should include evaluation of materials (such as beryllium oxide) for their loss characteristics, power handling, radiation resistance, and strength and evaluation of possible window locations in the waveguide run. Tests of samples in the waveguide should measure transmission loss and strength by pressurization of the guide at low power. Power handling could be evaluated by subjecting the waveguide and window to 200 kW (peak) with a 4% duty cycle, both with and without pressurization. The radiation resistance characteristics should be confirmed either by analysis or through testing.

4.2.3 Antenna Pattern

A partial full-scale screen mock-up of the torus could be used to investigate antenna designs and determine those capable of coupling the rf radiation into the plasma. Antenna designs could be breadboarded, tested for free space pattern integrity and VSWR, and then mounted on the mock-up for further pattern and VSWR measurements.

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5. COSTS AND SCHEDULING

The system capital cost elements are listed in Table 5.1. Costs are based on tentative performance requirements and moderate technical risks and include preliminary estimates for detailed design, procurement, fabrication, and assembly. Nonrecurring costs for the development of the gyrotron tubes are not included, since it is assumed that basic tube development will be accomplished in the ELMO Bumpy Torus (EBT) program.¹ The TNS program schedule is shown in Fig. 5.1 and indicates the rf system development needs in the context of the total program.

REFERENCE

1. R. A. Dandl et al., *The EBT-II Conceptual Design Study*, ORNL/TM-5955, Oak Ridge, Tennessee (September 1978).

Table 5.1. System cost elements

	Cost (in thousands of dollars)
Gyromonotron oscillator, 2 kW at 120 GHz	100
Six input waveguides (oscillator to amplifiers), rated at 1 kW	30
Six directional couplers, quasi-optical, with 60-dB isolation	60
5:1 rf power divider (five outputs), 200-kW rating	50
Five gyrokystron amplifiers, 200 kW at 120 GHz, 30-dB gain, under development by Varian Associates	500
Five output waveguide sets	50
Five rf couplers	75
Five shielded canisters with guiderails	150
Six high voltage power supply sets (each includes one 80-kV beam supply, one 40-kV gun supply, and one heater supply)	2160
Six superconducting magnet supplies, each 600 A at 10 V(dc)	25
Six cathode supplies, each 60 V(dc) at 20 A with 1-mV regulation, to be supplied by Thorenson	30
Controls, operational and power	100
Flowmeters, piping, valves, etc., for cooling media (oil, water, vacuum helium) from TNS common supplies	80
Systems for monitoring dc and rf performance	70
Ancillary systems (safety interlocks, radiation detection, arc sensing)	100
Self-test system	50
Floor and vault installations	100
A/E site preparation	100
Facilities (power, water, etc.)	100
TOTAL	3930

Fig. 5.1. TNS program schedule.

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