MARS Heating Systems

S.A. Freije, D.M. Goebel, L.J. Perkins, G.W. Hamilton, and J.D. Fink

May 1983

UWFDM-523

Presented at the Fifth ANS Topical Meeting on the Technology of Fusion Energy, 26-28 April 1983, Knoxville, TN.

FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

MADISON WISCONSIN

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.

MARS Heating Systems

S.A. Freije, D.M. Goebel, L.J. Perkins, G.W.
Hamilton, and J.D. Fink

Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

May 1983

UWFDM-523

Presented at the Fifth ANS Topical Meeting on the Technology of Fusion Energy, 26-28 April 1983, Knoxville, TN.

MARS HEATING SYSTEMS*

S.A. Freije, TRW, Inc.
Oak Ridge National Lab.
P.O. Box Y - FEDC Bldg.
Oak Ridge, TN 37830
(615)576-5450

D.M. Goebel
TRW, Inc.
One Space Park R1/1170
Redondo Beach, CA 90278
(213)536-1547

L.J. Perkins
Nuclear Engineering Dept.
University of Wisconsin
Madison, WI 53706
(608)263-3893

G.W. Hamilton
Lawrence Livermore National Lab.
P.O. Box 5511 - Mailstop L-644
Livermore, CA 94550
(415)422-9800

J.D. Fink
Negion, Inc.
4023 East Ave.
Hayward, CA 94542
(415)422-6715

ABSTRACT

The conceptual designs of supplemental heating systems for a tenth of a tenth of a kind, commercial tandem mirror reactor have been developed. A high power ECRH system at 60GHz maintains the thermal barrier in each endcell and a second low power system at ∿100GHz increases the magnitude of the potential peak. The sloshing ion distribution in the plug is produced by a 475KeV negative ion neutral beam. An ICRH system and a low power 5KeV neutral beam provide a hot plasma in the anchor region for pressure weighting of the geodesic curvature, thus ensuring stability.

INTRODUCTION

The Mirror Advanced Reactor Study (MARS) addresses a commercial tandem mirror reactor. A tandem mirror is a linear magnetic fusion device which utilizes a positive electrostatic potential in the plug region to confine a steady state fusion plasma in a solenoidal central cell.[1] The device operates in a full thermal barrier mode,[2] enabling it to achieve high performance with reasonable magnetic and neutral beam requirements in the plug. Two main objectives of MARS are to design an attractive fusion reactor producing electricity and synfuels in a tenth of a kind commercial device, and to identify key development and technology needs for the commercial tandem mirror and its forerunners. The study is the most detailed design to date, satisfying many plasma physics and engineering requirements simultaneously.

The paper is divided into four major sections. Section I provides a brief description of the basic device and explains the necessity of each of the heating systems. The latter three sections describe three endcell heating systems; the sloshing ion neutral beams, the high power electron cyclotron resonance heating (ECRH) system for the thermal barrier, and the ion cyclotron resonance heating (ICRH) system in the anchor region.

MARS DESCRIPTION

MARS is a major two year study of a commercial tandem mirror reactor. An accompanying paper describes the overall MARS configuration;[3] so, only a few brief remarks are made here to put the heating systems purposes and requirements into perspective.

The device has two main regions: the central cell and the endcell (one at each end of the central cell). A schematic of the device, including many of the endcell systems, is shown in Figure 1. The central cell is where >95% of the fusion power is produced, and is relatively simple technologically. In this region, the fusion plasma is sustained by alpha heating (ignition) and by steady-state fueling via pellet injection near the ends of the central cell. The central cell has a length of 131m (distance between the magnetic peaks in the choke coils) and produces 2575MW of fusion power. With 305MW of recirculating power, a direct convertor at each end of the device which collects ∿330MW, and a thermal conversion efficiency of 32% the net electrical power of the plant is 1200MWe. A start-up heating system is envisioned to be ICRH, but is not presented here since its design is slated for the latter portion of the study.

The endcells contain the interesting physics and most of the complexity. One of the advantages of tandem mirrors is that the supplemental

*TRW work supported by Lawrence Livermore National Lab. contract No. 5299101; University of Wisconsin and Livermore work funded by U.S. Department of Energy

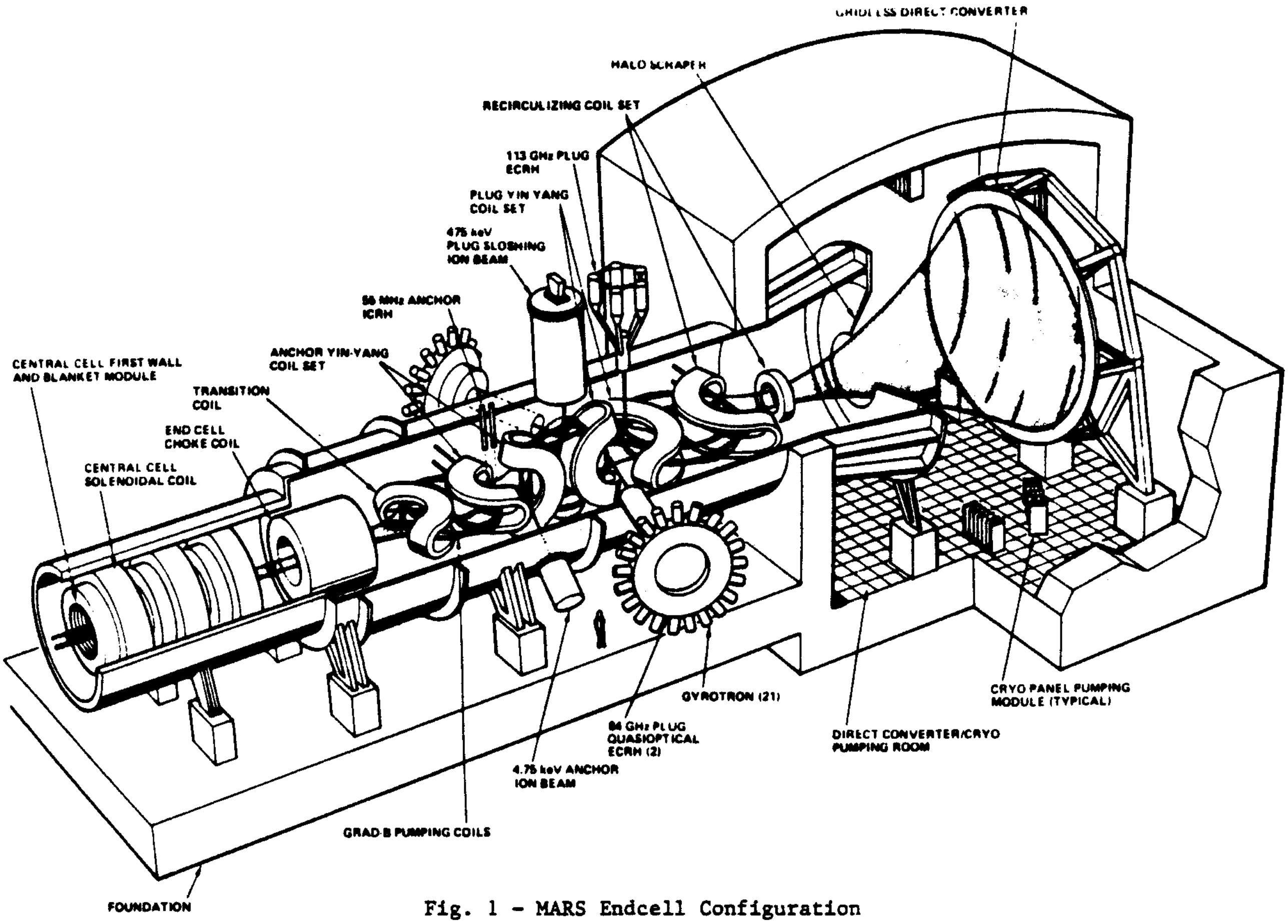

Fig. 1 - MARS Endcell Configuration

heating systems are removed from the high fluence central cell. The current MARS endcell configuration satisfies many physics constraints imposed by plasma equilibrium and MHD stability, particle confinement, and plasma microstability. The required heating systems are essential to the creation and maintenance of a number of species of particles and their distributions which satisfy the constraints. The endcell has four regions which fulfill specific functions; these are shown with respect to the axis-magnetic field and potential profiles in Figure 2. A high field, 24T hybrid coil makes up the choke region. This choke coil limits the number of central cell ions and electrons that leak into the endcells. Those leaky particles which are reflected by the potential peaks and return to the central cell are called "passing" particles, while some collisionally scatter and become "trapped" in the endcell. Trapped particles are removed in the transition region by a mechanism called drift pumping. This process prevents the trapped particles from filling the thermal barrier which would reduce reactor performance. A radial diffusion is induced by an oscillating field perturbation.

The plug contains the remainder of the heating systems which produce the thermal barrier, enhance the magnitude of the potential peak, and create the sloshing ion distribution. In the thermal barriers, "hot" electrons are heated at point b to high energy by ECRH so that they are mirror trapped and collisionless. A resulting potential depression isolates the central cell electrons from those at the positive potential peak. Without the isolation, neutral beam, ECRH, and magnet requirements would increase dramatically. The hot electrons also provide a high pressure component in the plug region of good curvature contributing to MHD stability.

A second ECRH system heats another group of electrons, the "warm" electrons, located near the potential peak at point a. Since the potential at the positive peak is driven by

$$\phi_c = \left(\frac{T_{ep}}{T_{ec}} - 1\right)\phi_b + T_{ep} \ln\left[\frac{n_p}{n_c}\left(\frac{T_{ec}}{T_{ep}}\right)^{1/2}\right],$$

the electron temperature at the peak, T_{ep}, has a large impact on the magnitude of the peak. ϕ_c and ϕ_b are shown in Figure 2; the c and p subscripts on densities and temperature correspond to those values in the central cell and plug.

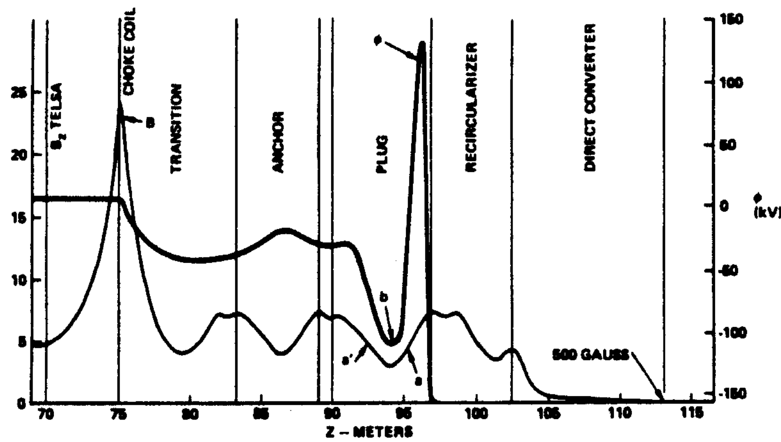

Fig. 2 - MARS Axis-Magnetic Field and Potential Profiles

The plug neutral beam is injected perpendicular to the field, near the inboard yin-yang mirror peak, to provide the two-peaked ion density distribution function, the sloshing ions. The sloshing ions play a critical role in the microstability of the endcell.

Table 1 gives the power and frequency or energy requirements for each of the heating systems. The last three sections will focus primarily on the sloshing ion neutral beam, the thermal barrier ECRH system, and the anchor ICRH system. The remaining ECRH system is discussed only with respect to similarities to the thermal barrier ECRH system; the anchor neutral beam is considered to be current technology and is not discussed here.

Table 1 - Supplemental Heating Systems' Requirements

	$P_{absorbed}$ (MW)	$P_{delivered}$ (MW)	Frequency or Energy
ECRH at A	6.6	6.6	f_v = 113GHz, f = 100GHz
ECRH at B	78.	78.	f_v = 84GHz, f = 60GHz
ICRH in Anchor	7.4	8.7	55 or 100MHz
Sloshing Beam	6.0	10.5	475keV
Anchor Beam	0.1	0.1	5keV

Sloshing Ion Neutral Beam System

The neutral beam heating systems for MARS initially included an axicell beam, charge exchange pump beams, and sloshing ion beams similar to the configuration to be used on MFTF-B. The 200keV axicell beam was discarded due to the very poor access in between the 20-24 Tesla axicell magnets; for this and other reasons, the axicell was eliminated from the configuration. The charge exchange pump beam, intended to remove trapped ions in the barrier and transition regions, was to provide 143MW of single species 97kV neutrals on target. A positive ion source based system with gas neutralizer was designed for this task, but required over 350MW of recirculating power and well over 90% atomic ions from the sources. Negative ion sources, coupled to a high stripping fraction laser photodetachment cell, decreased this recirculating power to about 200MW. However, the low negative ion currents possible per source necessitated that very large beam lines be constructed, complicating the access and location problems in the endcell region. The charge exchange pump beam was discarded in favor of low frequency drift pumping to remove ions in the transition region, resulting in more compact endcells and a higher machine Q.

The MARS sloshing ion beam system, shown in Figure 3, injects 5.2MW of 475kV neutrals into the 5.56T point of each plug at an angle of 70°-80°. A trapping fraction of 0.57 results in a total trapped power 6.0MW. The ion source is an LBL self extraction negative deuterium ion source which utilizes a cesiated surface to convert positive ions formed by an rf plasma generator in a magnetic multipole bucket containment geometry into negative ions. The 1 meter long, 1.5 cm wide ribbon beams are pre-accelerated to 80kV by a standard electrostatic accelerators and injected into a transverse field focusing (TFF) transport and pumping region to remove the neutral gas from the source. The beam then enters a four stage high voltage TFF accelerator which produces the 475kV ions. A high energy beam transport (HEBT) system provides neutron shielding and bends the beams into the laser neutralizer system. A Chemical Oxygen-Iodine Laser (COIL) with a folded resonator to increase the interaction length between the ions and laser flux achieves 95% stripping of the negative ions. The laser operates continuously and requires about 1MW of electrical power. The un-neutralized ions are deflected out of the neutral beam in the duct region, and the high energy neutrals pass through

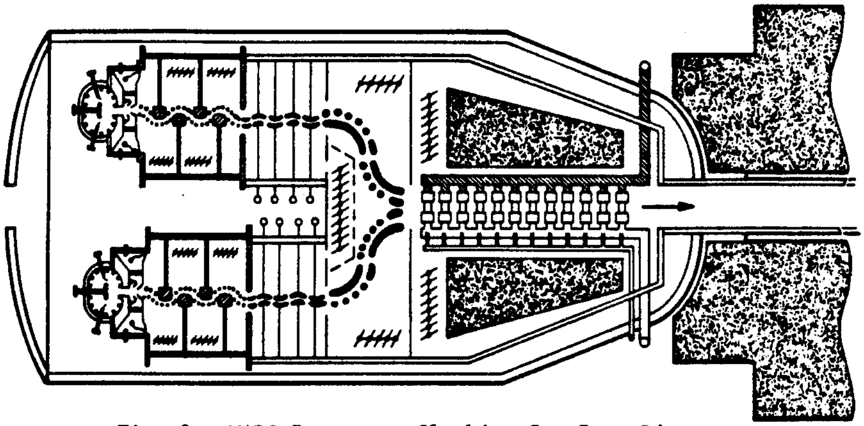

Fig. 3 - MARS Prototype Sloshing Ion Beam Line

the plug coils to the target plasma.

The sloshing ion beam line parameters are summarized in Table 2. The advantage of the TFF accelerator concept is that high current ribbon beams can be accelerated and transported over large distances with no angular spreading, and that most of the beam losses occur at low energy. The long path length at the ions in the transport regions allows the neutron shielding to be increased and permits possible hands on maintenance of the sources and accelerator components. Magnetic shielding of the entire beam line to less than 5 gauss is required, and a superconducting shield is presently being designed to achieve this task.

A small neutral beam line is also required for the anchor region to produce 4.75kV ions for heating by an ICRF system. The total neutral current of 30A is produced by an H_2^+ positive ion source operating at 9.5kV. Present neutral beam technology with electrostatic accelerators and gas neutralizers can easily provide this beam, and this system will not be detailed here.

Table 2 - MARS Sloshing Ion Beam Line Parameters

Source current	7.3A
Beam Size	0.5cm x 100cm
Number per beam line	2
Pre-accel. voltage	80kV
Loss in pre-accel.	15%
Loss in LEBT	9%
Loss in HV accelerator	1%
Loss in HEBT	1%
Neutralizer stripping fraction	95%
Duct loss and scrapeoff	5%
Current density at source	50 mA/cm^2
Current density at laser	35.5 mA/cm^2
Total target current	10A
Energy	475kV
Laser power (wall power)	1MW
Laser efficiency	10%
Mirror reflectivity	0.999
Scattering losses in laser	0.2%
Mirror size	3 cm x 4 cm
Source efficiency	20kW/A
Magnetic shield size	3m I.D. x 6m
Total electrical efficiency	71%

THERMAL BARRIER ECRH SYSTEM

The thermal barrier ECRH system delivers 39MW to a region about point b at each end of the device. In Table 1, the heating frequency is 60GHz compared to a vacuum frequency of 84GHz because of the high beta and relativistic shifts. Ray tracing calculations indicate that a range of launching angles exists at this frequency such that the waves become internally trapped. Hence, although the single pass absorption is quite small at the hot electron temperature of 840keV, multiple passes result in total absorption in a region ±75cm about point b.

Current ECRH systems with 200kW gyrotrons, overmoded waveguide transmission, and small power supply units, are expensive, inefficient, and would be cumbersome at reactor power levels. Since MARS is to identify development needs, the ECRH system design has not been limited to existing technology. Instead, based on recent progress and what should be achievable in the MARS timeframe, 2020, a compact, efficient, and low cost system has evolved.

The system consists of two launchers per end; a launcher has ten 2.5MW, 60GHz quasi-optical gyrotrons, each of which emits toward a parabolic reflector. Two gyrotron arrangements have been considered: the one shown in Figure 4 and another in which all gyrotrons and reflectors are equidistant from the plasma axis. The power supply is a single unit similar in concept to those used in AC/DC convertor stations.

Issues with respect to very high power transmission in waveguides that are not too overmoded and vacuum windows have led to the selection of a quasi-optical transmission system which is an evolution of designs previously employed in the Witamir[5] and Taska[6] tandem mirror studies. Quasi-optical transmission also allows for low loss transport and combination with more relaxed constraints on power density. Since the system is in a vacuum, no vacuum windows are required; fast gate or isolation valves are sufficient.

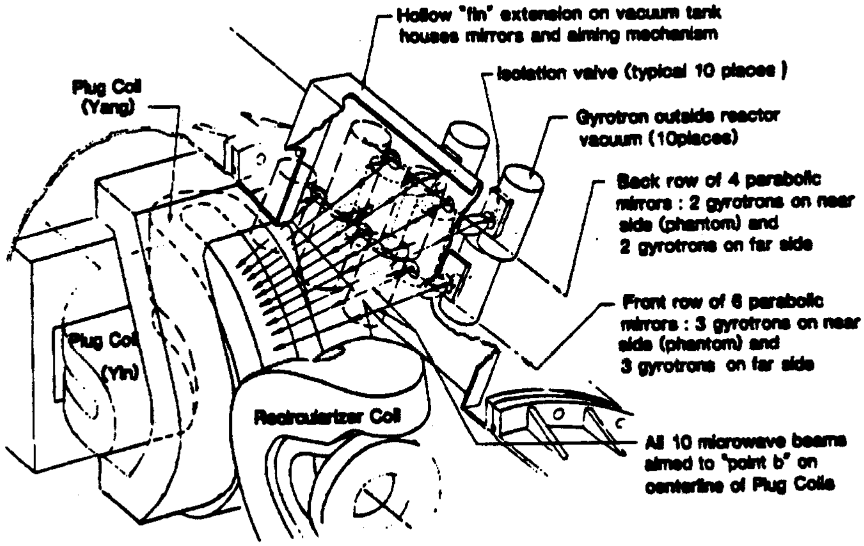

Fig. 4 - MARS ECRH Beam Access to End-Plug

The basic concept of a quasi-optical system is the beam waveguide, where a beam is guided without expansion and without use of metallic waveguides or resonators. This is accomplished by passing the beam through or reflecting it from a series of phase transformers. Beam modes are characterized by the product of a Gaussian (radially) and the generalized Laguerre polynomials, however the lowest order mode is simply the TEM_{oo}.[7]

Since the quasi-optical gyrotron emits a Gaussian beam with an angular divergence dependent on frequency and cavity dimensions, no mode convertors are needed as would be with the conventional gyrotron emitting TE_{on} modes. The antenna is a paraboloidal reflector illuminated by a nearly spherically diverging Gaussian beam from the gyrotron. The apex of the horn coincides with the focus of the paraboloid, and the axis of the gyrotron rf cavity is perpendicular to the axis of the paraboloid. The section acts as a combined right-angle reflector and phase corrector so that the wave appearing at the circular aperture has a plane wavefront.[8] The gyrotron/antenna is shown in Figure 5; note that the reflector enables shielding of the gyrotrons from streaming neutrons. At ECRH frequencies, neutron damage to the mirrors should not degrade their performance.

Gyrotrons typically are closed cavity devices, with the electron beam co-linear with the rf cavity. In order to control ohmic losses at higher powers large cavities are required. However, for large cavities, desired modes become increasingly more difficult to obtain and isolate. Although the quasi-optical gyrotron is only at an early development stage, it has many attractive features: variable frequency and high power capability, lowest and dominant mode is TEM_{oo}, and the electron beam and rf cavity are perpendicular, making beam recovery easier. The disadvantages

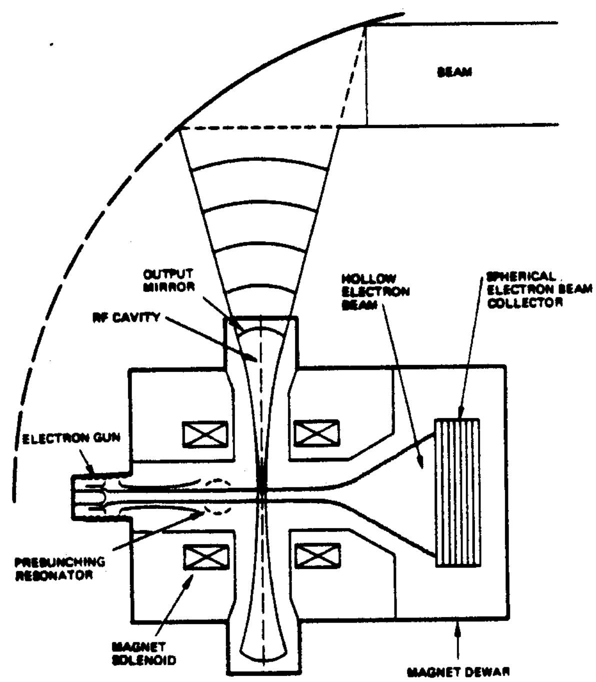

Fig. 5 - Quasi-Optical Gyrotron, Antenna Concept

are its lower efficiency and need of development.

Efficiencies between 35 and 50% are predicted by theory for a quasi-optical gyrotron with a prebunching cavity;[9] for the MARS 45% has been assumed. A multistage direct convertor collects the power of the electron beam at ~80%.

Before discussing the power supply, a comment on the second ECRH system is appropriate. The basic components of the potential barrier ECRH system are similar to those described above. The major differences are: the delivered power is 6.6MW and the heating frequency is 100GHz. The system consists of one launcher per end with each launcher containing three 2MW gyrotrons (two operate at 1.7MW and one redundant).

The power supply must deliver ∿218MW to the 34 operating gyrotrons (4 for point a and 32 for point b) at a voltage of -90kV. One or several supplies could be used to accomplish cost savings, with little loss of reliability. The technology required has been well developed since it is similar to that used for AC/DC conversion for DC transmission; typical levels for a 12-pulse convertor are 500MW at ± 400kV and 1250A, and they have proved quite reliable. MARS requirements are much less demanding and could be accomplished with a reasonable engineering effort.

A one pole, 12-pulse convertor consists of three quadrupole groups, each of which is formed by four thyristor valves. The "station" contains all necessary transformers, breakers, filters, reactors, and arresters to control total DC output and protect the convertor. In addition, each gyrotron has its own switch tube, and modulator/regulator to control input voltages and for individual protection.

ANCHOR ICRH SYSTEM

The anchor ICRH system delivers 8.7MW at 55MHz and/or 110MHz. In the latter portion of MARS, confinement and heating rate computations will be performed to determine whether heating is done at the fundamental or second harmonic of H.

The fundamental system would utilize two pair of antennas per anchor. The antennas are modeled as short circuited sections of stripline, electrostatically shielded by an array of metal strips.

Second harmonic heating of H at 110MHz offers several advantages: 1) the heating of H would be more selective than the fundamental since the second harmonic of H coincides with the fourth harmonic of D and 2) the higher frequency opens the waveguide launching option. Even at 110MHz, a rectangular vacuum guide is quite large, ~ > 1.4m; a ridged waveguide on the other hand would be a factor or two-three smaller but would have less power handling capability. Although the coupling physics of waveguides in the ICRH range have not been proven, waveguides would be simpler for maintenance purposes.

The remainder of the system consists of similar conceptual designs i.e., conventional coaxial transmission systems with multi-stub tuning and a multi-stage amplifier chain with associated power supplies and equipment. The two different frequencies would require a different set of amplifiers; at 55MHz, the FPA is the 8974 tetrode while for 110MHz the FPA is the 8973.

SUMMARY

The MARS endcell has been described along with the necessity of the various heating systems. Three of the five endcell heating systems have been presented. The study is two thirds complete; issues for these systems will be resolved and designs of the remaining systems will be completed in the last portion of the study.

ACKNOWLEDGEMENTS: The writers would like to express their appreciation for discussions of physics with B.G. Logan and R. Campbell, of endcell geometry considerations with W. Neff.

REFERENCES

1. T.K. FOWLER and B.G. LOGAN, "The Tandem Mirror Reactor," Comments on Plasma Physics, 2, 167(1977, and G.I. DIMOU, ET AL., "Open Tray with Ambipolar Mirrors," Fiz. Plasmy, 2, 597(1976).

2. D.E. BALDWIN and B.G. LOGAN, Phys. Rev. Letts., 43, 1318(1979) or D.E. BALDWIN, ET AL., "An Improved Tandem Mirror Fusion Reactor," UCID-18156, Lawrence Livermore National Laboratory Report(1979).

3. B.G. LOGAN, "The Mirror Advanced Reactor Study (MARS)," in the Proc. of the 5th Topical Mtg. of the American Nuclear Society on the Technology of Fusion Energy,(1983).

4. L.J. PERKINS and S.A. FREIJE, "Engineering Design of the Quasi-Optical ECRH Injection Systems for the Mirror Advanced Reactor," in the Proc. of the 5th Topical Mtg. of the American Nuclear Society on the Technology of Fusion Energy(1983).

5. B. BADGER, ET AL., "WITAMIR-I, A University of Wisconsin Tandem Mirror Reactor Design," UWFDM-400, University of Wisconsin Fusion Engineering Program (1980).

6. B. BADGER, ET AL., "TASKA, A Tandem Mirror Fusion Engineering Facility" UWFDM-500, University of Wisconsin Fusion Engineering Program (1982).

7. G. GOUBAU and F. SCHWERING, "On the Guided Propagation of Electromagnetics Wave Beams," IRE Trans. on Ant. and Propag., AP-9, 248 (1961).

8. J.N. HINES, ET AL., "The Electrical Characteristics of a Conical Horn-Reflector Antenna," IEEE Tran. on Microwave Th. and Tech., MTT-12, 555(1964)

9. K.R. CHU, ET AL., "Methods of Efficiency Enhancement and Scaling for the Gyrotron Oscillator," IEEE Trans. on Microwave Th. and Tech., MTT-28, 318(1980).