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FOR THE MIRROR ADVANCED REACTOR (MARS)

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ABSTRACT

The engineering design of two high-power steady-state ECRH injection systems is presented for the MARS tandem mirror reactor. With a design power of 57 MW, System I is comprised of 1 MW cavity-mode gyrotrons coupled to a novel quasi-optical launching system for the combination and transmission of the ECRH power to the plasma. System II has a design power of 84 MW and comprises 2.5 MW quasi-optical gyrotron units coupled to a quasi-optical launching system similar in principle to System I but displaying minimal space requirements. Potential operating conditions, parameters and constraints are presented for multi-MW gyrotrons and quasi-optical launching systems, and key ECRH development and technology needs for commercial tandem mirror reactors are defined.

INTRODUCTION

The Mirror Advanced Reactor Study[1] (MARS), currently in progress, is a major conceptual design study of a 1200 MW_e commercial tandem mirror reactor. MARS is a linear mirror fusion machine which uses electrostatic "plugs" at each end of the device to confine a steady state fusion plasma in the long central cell region. A recent major design change in the high field axicell/choke coils at each end of the central cell has resulted in a large increase in ECRH injected power requirements from 57 MW to 84 MW. This has, in turn, resulted in a major change in the engineering design of the ECRH systems. However, in view of the fact that both the original system (designated here as System I) and the new system (designated System II) contain notable and separately distinctive features, both will be presented in this paper.

Electron cyclotron resonance heating (ECRH) is crucial to the formation of the end plugs in MARS. Figure 1 shows a plot of the on-axis magnetic field and potential profile in the end plug region for the latest MARS design (March 1983). The injection of 3 MW of ECRH power at point A in Fig. 1 maintains the 156 keV confining potential there. The beta-depressed ECRH frequency on axis is 71 GHz, however injection at ~ 100 GHz is required for optimum absorption via the phenomenon of plasma "wave trapping" as follows: At this frequency, the resonance surface lies outside the bulk of the plasma. Providing the incident injection angle is between 25° and 55°, ray tracing calculations show that complete internal reflection occurs at the resonance surface resulting in multiple passes through the plasma. Virtually 100% absorption via wave trapping results. Further discussion of this phenomenon is beyond the scope of this paper and will form the basis of a separate report.

Injection of 39 MW of 60 GHz ECRH power at the minimum of the plug mirror (point B in Fig. 1) creates a collisionless mirror-trapped hot electron population which maintains the "thermal barrier" at this point. The thermal barrier effectively decouples the central cell electrons from those in the region of the potential peak.
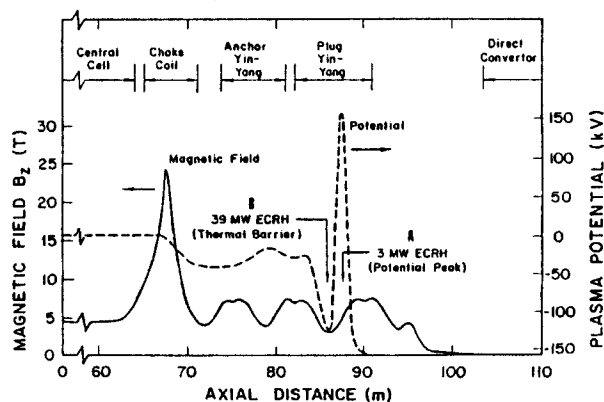

Fig. 1. Magnetic field and potential profile in MARS end cell.

ECRH requirements for the former system (System I) were 1 MW at 95 GHz at point A and 27.5 MW at 64 GHz at point B. Note that the injected powers above are required at each end of the device.

ECRH systems on current and near term experimental devices[2] exhibit powers in the range of only a few tens of kW up to ~ 2 MW. These systems typically comprise charged capacitative power supplies, gyrotron units of up to 200 kW and metallic waveguide transmission systems. However, such systems become inefficient, expensive and impracticable when scaled to the reactor requirements of MARS. Accordingly, a complete steady state 84 MW ECRH system has been configured for the latest design of this reactor. In view of the very high ECRH power requirements, this represents one of the largest ECRH reactor injection systems conceived to date.

GYROTRON SOURCES FOR MARS

The microwave source for fusion ECRH systems is the gyrotron. Current state of the art for developed gyrotrons is the 28 GHz, 200 kW CW, cavity-mode tube.[3] However, employment of 200 kW unit size gyrotrons would be completely untenable for MARS. For example, when launching and transmission losses are considered, System II would require a total of 465 separate tubes! Accordingly, two advanced gyrotron types were specified for the two ECRH systems as follows. System I: 1 MW cavity-mode gyrotron; System II: 2.5 MW quasi-optical gyrotron. It is important to note that one purpose of reactor studies such as MARS is to identify key development and technology needs for the commercial tandem mirror reactor. Therefore, the extrapolation of current gyrotron technology required to specify these tubes for MARS is a reasonable and necessary step in the overall conceptual design of the device.

Current production gyrotrons[3] are of the closed cavity-mode type where the electron beam propagates in the resonance cavity and shares the collector cavity with the wave. The next decade will probably see the construction of cavity-mode gyrotrons up to ~ 1 MW[3]. Therefore, this indicates that, with the exception of direct energy recovery via a depressed collector, the required gyrotron development program for MARS ECRH System I is nearly in place. However, cavity-mode gyrotrons exhibit two undesirable characteristics. First, the output field is in the TE_{on} mode requiring mode convertors with their attendant power losses between the output cavity and the launching system. Second,

as the design power of these tubes is increased, the cavity must be enlarged to dissipate the beam power, making it much harder to couple the desired wave mode efficiently.

Among the alternative multi-MW gyrotron concepts now under consideration, the quasi-optical gyrotron appears to offer a solution to the problems associated with upscaling conventional cavity-mode tubes.[4-6] A schematic of a quasi-optical gyrotron is shown in Fig. 2. This tube achieves perpendicular coupling between the electron beam and the microwave electromagnetic field within an optical resonator cavity based on the Fabry-Perot principle.[4] A quasi-optical proof-of-principle experiment is in progress at NRL in the U.S. for a 150-180 kW, 100 GHz tube.[7]

Relative to the conventional cavity-mode gyrotron, the quasi-optical tube with perpendicular propagation offers a number of distinct advantages. First, since the electron dump is decoupled from the RF cavity, high output powers of > 1 MW should be readily achievable. Second, the output field is in the TEM_{oo} mode so that no mode convertors are required for transmission in a quasi-optical launching system (see below). Thirdly, the operating frequency is variable by adjustment of the optical cavity and magnetic field. Current estimates of the extent of frequency variation are up to ~ ±20%[6] although factors of two or three may eventually be
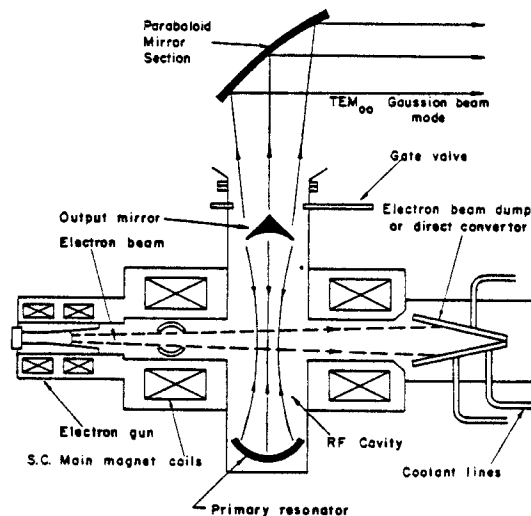

Fig. 2. Schematic of a multi-MW quasi-optical gyrotron.

possible. Tunable gyrotrons offer the facility to adjust the cyclotron resonance condition during startup of MARS as the plasma beta increases. The major disadvantage of the quasi-optical gyrotron is that the overall geometrically-averaged efficiency is lower than in a conventional tube. Maximum efficiencies, given present day analyses, may be only ~ 45%.

Based on these considerations and the large ECRH power requirement for the present MARS baseline, System II is configured with 2.5 MW quasi-optical gyrotron units. This appears to be a reasonable and credible extrapolation of current technology for the operating time frame of MARS (~ 2020). As a backup design, the 1 MW cavity-mode tube, currently specified only for System I, could be adapted to System II. This would, however, require extensive redesign of the end cell region of the reactor due to space constraints.

MARS QUASI-OPTICAL LAUNCHING SYSTEMS

Irrespective of whether cavity-mode or quasi-optical gyrotrons are employed in MARS, reliable power-combining of many high power tubes is required. Accordingly, beam waveguide systems based on quasi-optical principles are specified for the combination and transportation of ECRH power to the plasma. The systems are evolutions of designs previously employed in the WITAMIR[8] and TASKA[9] tandem mirror fusion devices.

Current and near term ECRH transmission systems employ over-moded waveguides. However, such systems cannot be employed in MARS for several reasons. First, the efficiency of these waveguides is very sensitive to the mode purity requirements of the injected wave and can range between 50 and 90%. Moreover, the passive combination of several waveguides would result in unacceptably large losses while active combiners cannot be employed under MARS conditions of high power levels and high magnetic field. Second, metallic waveguides have power density limitations due to breakdown at the conducting walls which limits the power coupled to one guide. Third, multiple arrays of many single guides would be unwieldy and impracticable due to the large number of penetrations in the vacuum vessel. In addition, the requirements on injection angles could not be met. Finally, pressurized insulating gas is required to increase the electric breakdown potential within the guides thus mandating the use of ceramic vacuum windows. Windows capable of handling the CW power levels for MARS, especially given loss tangent degradation under radiation damage, do not exist.

In contrast to the wave mode in a conventional metallic guide, the beam mode in the MARS quasi-optical guide consists of a bundle of waves characterized by a spectrum of propagation constants. The field distribution along the guide can be reset at periodically-spaced conducting mirrors which act as phase transformers. This permits beam transport with minimal diffraction losses. The lowest loss beam mode is the TEM_{oo} and is characterized by a Gaussian radial distribution of the electric field which is also linearly polarized. Since the electromagnetic energy of the beam is concentrated near the axis, wall losses and wall breakdown problems are minimized. Further details on the MARS quasi-optical beam modes can be found in Ref. 1.

Therefore, in contrast to metallic waveguides, the quasi-optical launching system has a number of advantages. First, it affords a low loss combination of many multi-MW gyrotron sources with minimal space requirements. Second, it directs the ECRH onto the plasma at specific angles desired for optimum absorption. Third, propagation proceeds via a TEM_{oo} beam mode with a Gaussian radial distribution of electric field. Therefore, power density constraints are alleviated, the system can operate in a vacuum and no ceramic windows are required.

MARS ECRH SYSTEM I

ECRH System I[1] was configured for an interim reference design of MARS and is based around 1 MW cavity-mode gyrotrons coupled to a quasi-optical launching system. Figure 3 shows schematically one of the four 64 GHz, 13.75 MW, ECRH launchers of System I. Two of these launchers are located at each end of the machine diametrically opposite each other. The microwave beam is launched by a set of dual-mode horns fed by 17 1 MW cavity-mode gyrotrons after suitable mode conversion. Propagation proceeds via the TEM_{oo} beam mode and is transported to the plasma via a phased array of hyperbolic and parabolic mirrors arranged in an offset Cassegrain configuration. Key parameters for System I are given in Table 1.

In addition to the difficulty of scaling cavity-mode gyrotrons to MW power levels, mode convertors are required here to convert the TE_{on} cavity output mode to the TEM_{oo} mode of the launcher. In the system in Fig. 3, a mode convertor at the gyrotron mouth provides an intermediate conversion to TE_{11}. The dual-mode horn is equipped with a second convertor in its
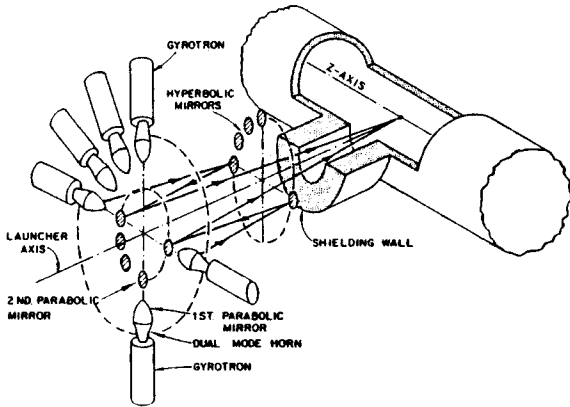
Fig. 3. Schematic of MARS ECRH System I

throat to provide mixed TE_{11}/TM_{11} modes from the TE_{11} imput. These dual modes propagating together in the horn produce, by interference, a near Gaussian radial amplitude distribution at the horn mouth. Upon reflection from the attached parabolic mirror, a uniform phase front beam mode is launched.

The gyrotrons in Fig. 3 are shielded from direct line of sight of the plasma by the offset Cassegrain mirror system. The hyperbolic section mirrors allow the sources of excitation (the dual-mode horns) to be placed concentrically with, but outside of, the second and final parabolic mirror ring. This prevents both aperture blocking and direct neutron streaming to the gyrotrons.

The two big disadvantages of System I are the large number of cavity-mode tubes required for multi-MW power levels (especially those required of System II) and the large power losses (~ 5-10%) in the mode convertors. It does have the advantage, however, of a more credible gyrotron design from a present day viewpoint. Further information on this launching system including system dimensions and details of diffraction losses is given in Ref. 1.

MARS ECRH SYSTEM II

A. System Description

The requirements of ECRH in System II for the final MARS design are rather more stringent than those for System I and include very high

TABLE 1. Key Parameters for ECRH System I

These parameters are for one end of the machine. For total powers etc., multiply by two.

	Point A. Potential Peak	Point B. Thermal Barrier
Injected power[a] (MW)	1.0	27.5
ECRH frequency[b] (GHz)	96	64
No. of launchers	1	2
Design power/ launcher (MW)	1	13.75
Maximum power/ launcher (MW)	2.68	15.18
Gyrotron	1 MW cavity-mode	
No. gyrotrons/launcher	3[c]	17[d]
Total launcher length (m)	20.0	18.27
Dia. of 2nd parabolic mirror (m)	0.46	0.54
Dia. of hyperbolic mirror (m)	0.33	0.38
Diffraction loss/ iteration[e] (db)	0.1	0.1
Reflection loss/ mirror (%)	~ 0.1	~ 0.1
Mode convertor loss (%)	> 5	> 5
Horn loss (%)	> 5	> 5
Total launcher losses (%)	> 10.7	> 10.7

[a]Absorption is ~ 100%
[b]Vacuum field frequency
[c]Includes one redundant gyrotron/launcher
[d]Includes two redundant gyrotrons/launcher
[e]i.e., diffraction losses per mirror spacing(design parameter)

power levels (84 MW), a limited range of injection angles (25°-55°) and restricted access to the injection points due to the plug yin-yang coils and associated neutron shielding. The 2.5 MW quasi-optical gyrotron is the basic component of this system (see Fig. 2). It is coupled to a quasi-optical launching system similar in principle, although different in design, to that described above. Even given the 2.5 MW unit gyrotron size for this system, a considerable number of design iterations were required to locate the ECRH systems in the face of the severe space limitation presented by the current reactor end-cell geometry. The present system is configured for minimal space requirements.

The RF field from the quasi-optical gyrotron is in the TEM_{oo} mode, i.e., directly compatible with a quasi-optical launching structure. However, as shown in Fig. 2, the beam exhibits some divergence ($\sim$ 4-5°) as it exits the RF cavity. This beam divergence is corrected by a paraboloidal mirror section constructed of water-cooled high-purity copper and whose focal point is positioned at the center of the RF cavity (see Fig. 2). A parallel Gaussian beam mode with uniform phase front is therefore produced and propagates parallel to the gyrotron axis. The diameter D of this output beam is 30 cm and exhibits typical intrinsic divergence of $\sim 2\lambda/\pi D$. An additional advantage of this launching system is that only the paraboloidal mirror has direct line of sight to the plasma, so that the gyrotron is subject to only scattered radiation rather than direct streaming.

Figure 4 shows one of the four 60 GHz, 19.5 MW launchers for System II. Two of these launchers are located at each end of the machine. Key parameters for the overall system are given in Table 2. In Fig. 4, each 19.5 MW launcher consists of ten 2.5 MW gyrotrons, two of which are provided for redundancy purposes. The ten paraboloidal phase-correcting mirrors are arranged in two rows containing six and four mirrors, respectively. The two rows are located one behind the other in the same plane. The gyrotrons are placed in parallel rows and are staggered above and below the plane containing the parabolic mirrors. As shown in the figure, the gyrotrons are mounted on the outside of a hollow "fin" extension of the reactor vacuum vessel, with the mirrors mounted inside. This
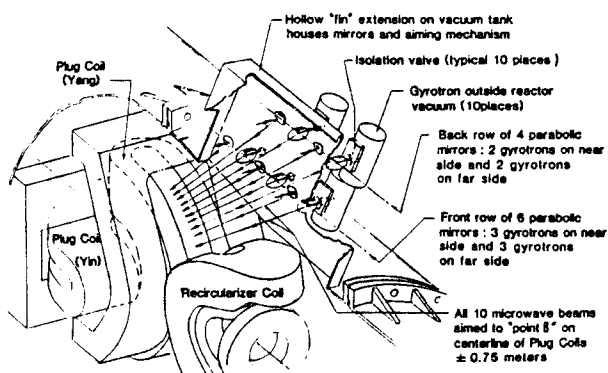

Fig. 4. One of the four 60 GHz, 19.5 MW ECRH launchers of System II.

TABLE 2. Key Parameters for ECRH System II

These parameters are for one end of the machine. For total powers etc., multiply by two.

	Point A. Potential Peak	Point B. Thermal Barrier
Injected power[a] (MW)	3	39
Operational frequency[b] (GHz)	100	60
Startup frequency[c] (nominal) (GHz)	112	84
No. of launchers	1	2
Design power/ launcher (MW)	3	19.5
Maximum power/launcher	7.5	25.0
Gyrotron	2.5 MW Quasi-optical	
No. gyrotrons/launcher	3[d]	10[e]
Max. launcher length (m)	$\sim$ 14.5	14.5
Dia. of paraboloid mirror (m)	0.3	0.3
Mirror reflectivity loss (%)	$\sim$ 0.1	$\sim$ 0.1
Diffraction loss from parallel beam[f] (db)	0.35	2
Beam divergence	0.37°	0.61°
Effective beam diameter at plasma (m)	$\sim$ 0.41	$\sim$ 0.61
Total launcher losses (%)	$\sim$ 0.1	$\sim$ 0.1

[a]Absorption is $\sim$ 100%
[b]Frequency at full plasma beta
[c]Frequency required at zero beta
[d]Includes one redundant gyrotron/launcher
[e]Includes two redundant gyrotrons/launcher
[f]Loss from a parallel beam (retained inside diverging beam)

provides for convenient replacement of gyrotrons without disturbing the machine vacuum.

The resulting fan of ten microwave beams in Fig. 4 is seen to enter the plasma region through the slot defined by the minor arc of the plug yin-yang magnet. Due to the neutron shielding for the magnet, the width of this slot is only 64 cm and, therefore, precludes a circular array of gyrotrons like that employed in System I (see Fig. 3). Transmission path lengths to the plasma from the two mirror rows are $\sim$ 10.5 m and 14.5 m, respectively. At these

distances, the fringing fields from the magnets have fallen to ~ 0.12 T and 0.08 T, respectively. These fields are low enough to permit magnetic shielding of the gyrotron electron guns to below the maximum permissible field levels of ~ 0.01 T.[7] With these transmission path lengths, beam divergence and diffraction effects combine to give effective beam diameters at the plasma of ~ 61 cm. Note, however, that the power density of each beam scales as the square of the electric field which itself has a Gaussian radial dependence. Most of the beam power is, therefore, concentrated within a few centimeters of the beam axis. This beam transport system has minimal launching losses.

B. Power Supplies

With gyrotron efficiencies of ~ 45%, the power supply requirements of ECRH System II is 190 MW. Either one or several supplies are required to provide ~ 2200 A at 90 kV DC to the electron guns. The Graetz bridge power supply was selected for MARS on the basis of its reliability.[1] The bridge supplies the required DC power from the external 230 kV AC line and is comprised of convertor transformers, thyristor valves, DC smoothing reactors and DC harmonic filters. It should be noted that the requirements for the thyristors and other major components of this supply for MARS are well below state-of-the-art today. With depressed collector operation of the gyrotrons, direct conversion of the dissipated beam power may be as high as 80%. This would mean that up to ~ 80 MW of the recirculating power requirements could be discounted, although this does not, of course, result in any reduction in the power supply requirements or, equivalently, in the capital cost of the ECRH system.

C. Radiation Damage to the ECRH System

The ECRH launching system in Fig. 4 has a direct line of sight to the plasma. Neutron source line densities in this region are ~ 10^{17} n $m^{-1} s^{-1}$ and fast neutron fluxes at the gyrotrons were estimated at ~ 2.5×10^{13} $m^{-2} s^{-1}$. There is thus a requirement to assess radiation damage effects to gyrotrons and launching structures. Accordingly, four areas of concern were identified, namely: reflectivity changes in the copper mirrors due to neutron damage and transmutations, swelling and resistivity decreases in the gyrotron insulators, damage to the electron gun filaments and damage to the gyrotron superconducting magnets. Of these, only the latter appeared to be lifetime limiting based on a dose limitation to the superconductor organic insulators of 5×10^{9} rads. A three dimension Monte Carlo neutron transport study is currently being performed to accurately model the effects of neutron streaming in the ECRH launchers and, therefore, assess radiation damage and lifetime limitations.

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