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A TOKAMAK POWER REACTOR HEATED AT ELECTRON CYCLOTRON RESONANCE BY GYROTRONS †

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Abstract

This paper is a summary of the results of a design study of an electron cyclotron resonance heating (ECRH) system for a tokamak power reactor.[1] Major research topics include: physics constraints imposed on the design of a reactor by the ECR wave absorption conditions; design of the high frequency (200 GHz) gyrotrons needed for plasma heating; the gyrotron power and magnet systems; a microwave transmission system in oversize waveguide for the ECR radiation and evaluation of its losses; absorption of the ECR radiation in the plasma; and techniques for improved reactor modularization. A 100 MW gyrotron system was designed for heating a previously derived tokamak power reactor, the High Field Compact Tokamak Reactor (HFCTR).[2] Our major conclusion is that ECR heating appears to be both feasible and attractive for bulk heating of a moderate size, high density tokamak power reactor. However, if ECR heating is to be a reliable method for bulk heating of plasmas, it will be necessary to have an intensive development program for both high frequency gyrotrons and for transmission systems for high power, high frequency radiation.

Introduction

We have carried out a design study of an electron cyclotron resonance heating (ECRH) system for a tokamak power reactor. Both the physics and engineering characteristics of an ECRH system have been considered. This study addresses important physics questions relating to absorption of ECR radiation in the plasma and its impact on tokamak reactor design. It also identifies the areas of technology in which new research is needed to implement ECR heating on a reactor scale and those areas in which present technology can adequately solve future system requirements.

In most previous reactor designs, the tokamak plasma heating has been accomplished with neutral beam injection. It is known, however, that neutral beam injection may be difficult to achieve with high efficiency and availability and low system cost when heating reactor-size tokamak plasmas. RF or microwave heating has been suggested as an alternative form of tokamak plasma heating. Major RF heating experiments have been carried out on tokamak plasmas primarily at one of the following three (resonant) frequencies: ion cyclotron resonance heating (ICRH), lower hybrid heating (LHH) and electron cyclotron resonance heating (ECRH).

In the present study, we have selected ECR heating for the following reasons. First, ECR heating has come to be more attractive in recent years because of advances in the development of high power gyrotrons operating for long pulses;[3,4] because of the development of weakly relativistic theories of ECR heating of warm tokamak plasmas which predict successful heating of reactor-size tokamaks; and because of the continuing success of ECR heating experiments on tokamaks.[5] Secondly, the physics of the ECR heating process appears to be farily well understood, while the technology is relatively poorly understood. However, there is sufficient information about high frequency gyrotrons and the transmission of high frequency radiation that is possible to make a fairly complete technological evaluation of this problem, as is done in this report. Thirdly, the heating of reactor-size plasmas with neutral beams, ICRH or LHH has been previously considered, while, to our knowledge, this is the first study to consider ECR heating.

Physics Constraints on an ECR Heated Tokamak Power Reactor

We have derived a set of constraints for the operating characteristics of tokamak power reactors which are bulk heated by electron cyclotron resonance heating (ECRH).[6] Four heating modes have been considered: ordinary wave heating at the electron cyclotron frequency, Ω, and at the second harmonic frequency, 2Ω, and extraordinary wave heating at Ω and at 2Ω. For ordinary wave heating at Ω, which appears to be the most promising method, the wave frequency $\omega \simeq \Omega$ must exceed the plasma frequency, ω_p, for wave penetration into the plasma. Our main conclusion is that the need for high density operation ($n_o > 4 \times 10^{20} m^{-3}$) in moderate size tokamak reactors, coupled with the wave accessibility condition $\Omega > \omega_p$, leads to the requirement of frequencies in the 200 GHz range for ECRH of reactor plasmas. A further condition on the heating frequency may be derived by consideration of the ignition condition using empirical scaling laws for the energy confinement time. This latter condition does not increase the heating frequency requirement unless impurities are present or the energy confinement degrades with increasing temperature. We also find that for ordinary wave heating at Ω, the average plasma β is limited to less than 0.039 for a central temperature below 15 keV, assuming parabolic density and temperature profiles. The use of extraordinary heating at Ω might lower the frequency requirement for ECRH of a reactor. However, it appears to be unattractive for reactor operation because, in order for the wave to penetrate to the center of the plasma, the heating ports must be located on the inside (or the top side) of the torus. High beta, lower field reactors can be heated from the outboard side of the torus with second harmonic radiation. However, these devices will have to be heated at frequencies which are generally higher than those needed for devices which are heated with the ordinary wave at the fundamental frequency.

Description of Reactor and Plant

In order to avoid the obvious additional effort related to developing a new reactor design just for this report, we have selected an exisitng tokamak power reactor design and modified the design from neutral beam to ECR heating.

The tokamak power reactor which was selected was the High Field Compact Tokamak Reactor, HFCTR[2]. The major parameters of this device are:

Major radius, R_o (m)	6.0
Plasma Halfwidth, a (m)	1.2
Plasma shape factor, S	1.5
Field at Plasma, B_T (T)	7.4
Average toroidal beta, $\langle\beta\rangle$	0.04

Plasma current, (MA)	6.7
Electron density, n (m^3)	$5 \times 10^{20}(1 - r^3/a^3)$
Electron-ion temp, T(keV)	$12.4\ (1 - r^2/a^2)$
Heating Power, P(MW)	100
Av. thermal power, P_{th}(MW)	2470
Net electric power, P_n(MW)	775

The adaptation of the reactor design to ECR heating requires elimination of the neutral beam lines and ripple field coils and the substitution of a port structure for ECR heating, as dexcribed in detail in the report.[1] The plasma heating sequence to ignition is the same for neutral injection or ECR heating. After a plasma initiation and expansion phase, the plasma is bulk heated to ignition, with the major heating done between 3.9 sec $< t <$ 8.4 sec. After ignition, the plasma burn is sustained by alpha heating. A plant layout of the tokamak power reactor with ECR heating was derived. This layout was needed to define the distance between the gyrotron tubes and the tokamak power reactor (about 30 m), so that a microwave transmission system could be designed.

Design Study of High Power, High Frequency Gyrotrons

The ECR heating of the tokamak plasma to ignition will require over 100 MW of RF radiation at 200 GHz. The most promising source at the present time for providing the required radiation is the gyrotron. Based on present day gyrotron technology, we project a power level of about 100 kW at 200 GHz for a 5 sec. pulse. We have carried out a detailed design analysis of such a gyrotron. More than 1000 gyrotrons would then be needed for heating the tokamak plasma. This approach requires a very large number of sources, but the cost of such an RF heating system can be shown to be less than that of a comparable neutral beam system. The gyrotrons should also prove to be reliable at a power level of 100 kW, with easy replacement of failed tubes. In the future, megawatt power level tubes, based on variations of the gyrotron or on free electron lasers, may be available. Such devices, however, will not necessarily lead to reduced system costs, in part because of the difficulty of transmitting megawatt beams through windows or of operating without windows.

The 100 kW, 200 GHz gyrotron was designed by a parametric analysis using design principles previously applied to a 10 kW, 200 GHz gyrotron.[7,8] The analysis included the electron beam and gun parameters and their correlation to the operating characteristics of the gyrotron cavity. The goal of this analysis was to maximize the overall efficiency of the gyrotron, in order to reduce power supply requirements and enhance cavity and collector lifetime, while maintaining the operating parameters at realistic values. The design included optimization of a wide range of parameters, including the electrom beam voltage, U, and current, I, the working mode of the cavity, TE_{mpq}, the beam radius, R_c, the cavity radius, R_o, the cavity length, L, the ratio of transverse to parallel velocity $\beta_\perp/\beta_{||}$, the system (total) quality factor, Q_t, and the overall efficiency, η. Space charge effects were included in the analysis using an approximate, analytic theory. The results of the analysis are listed below. The overall efficiency, η, is estimated to be 33%.

200 GHz Gyrotron Parameters

ν = 200 GHz	L = 12.5mm		B_o = 7.5T
λ = 1.5mm	$\beta_\perp/\beta_{||}$ = 1.8		Q_t = 2.3×10^3
U = 70kV			η = 0.33
I = 4.4A			P_{rf} = 100 kW
I = 4.4A			
TE_{051} mode			
R_o = 3.94mm			
R_c = 2.82mm			

Figure 1 is a plot of the overall efficiency of the 100 kW, 200 GHz gyrotron as a function of cavity radius and length. For each cavity size, the ohmic heating of the cavity walls in kW/cm^2 is also shown. If the wall loading is limited to 5kW/cm^2 and an efficiency greater than 30% is desired, the cavity mode must be TE_{051} or higher.

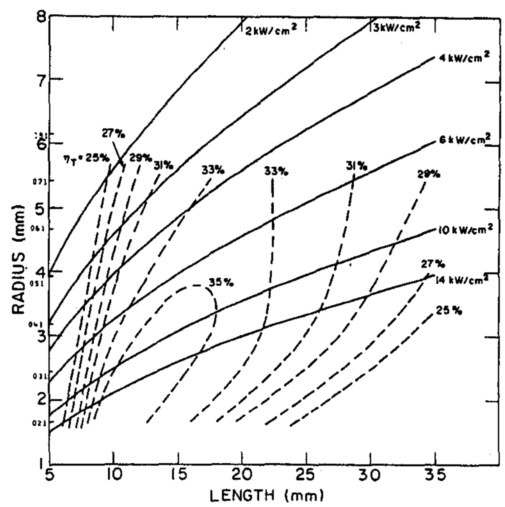

Figure 1. Overall efficiency of 100 kW, 200 GHz gyrotron versus cavity radius and cavity length.

This design represents a significant extension of present day gyrotron technology. A detailed design of the cavity cooling system is presented, indicating that the required power dissipation of 5 kW/cm^2 should be feasible.

Gyrotron Power and Magnet Systems

A basic design of the gyrotron power and magnet systems was carried out. The gyrotron power supply design is similar to that of the state-of-the-art klystron and neutral beam power supplies. The gyrotron cathodes and first anodes require high voltage, moderate current power supplies. A voltage ripple of 0.6% was calculated to be adequate for maintaining full gyrotron efficiency and was incorporated into the design. A standard series regulator configuration was selected, with protection of gyrotron and regulator tubes provided by crowbars. Six cathodes are supplied by a single switch/regulator tube.

The solenoid magnets used to create the ECR magnetic field of 7.5 T, for 200 GHz emission in the gyrotron cavity, are long, superconducting NbTi solenoids with graded current density to enhance field homogeneity. Field uniformity of better than 1% can be achieved in the cavity region.

Microwave Transmission and Wave Launching

A system was designed for transmission of the 200 GHz radiation from the gyrotrons to the plasma of the tokamak power reactor. A system consisting of propagating the TE_{01} mode in oversize copper pipe was selected for the present design for several reasons, the foremost reason being that accurate data are available concerning this technique from field tests of communications systems. A single transmission line for each gyrotron was specified, yielding a total of about 1250 lines, each carrying 100 kW of power. Although such a system has a large number of components, it avoids the problem of attempting to combine radiation from several sources. It also avoids problems associated with transmitting extremely high (megawatt) power levels through windows.

The main transmission system component is a 30 m length of 14 mm diameter circular copper waveguide at atmospheric pressure. This is an oversize guide used to transmit 1.5 mm radiation in the TE_{01} mode. The gyrotron output is transformed from the working mode of the cavity into a TE_{01} mode by a quasi-optical mode transformer. The waveguide run traverses the reactor cell at a height greater than that of the reactor modules, then makes two right angle bends to feed the ECR radiation into the plasma. The radiation is transformed into a linearly polarized mode and launched as a free space wave towards the plasma center. The waveguide system may be easily unbolted from the reactor module for module replacement. The estmated transmission of the microwave system is 80%. However, several components of the system will require further research. In particular, new techniques, possibly quasi-optical methods, must be developed for transformation of the gyrotron output mode to the TE_{01} mode in oversize waveguide. Figure 2 illustrates the waveguide transmission system.

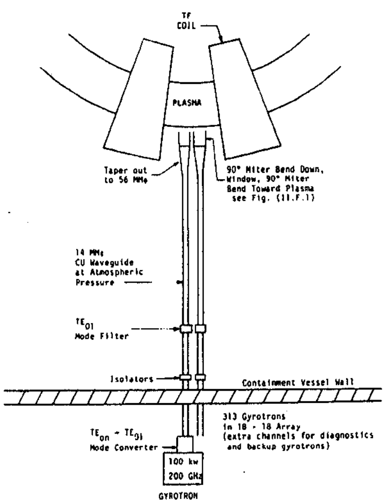

Figure 2. Microwave Transmission System

Wave Absorption in the Plasma

Recently, there have been a number of extensive theoretical analyses of ECR heating of tokamak plasmas, including reactor-size plasmas.[9,10] Some of these studies have included relativistic effects to first order, which are needed for treating plasmas with temperatures of up to 15-20 keV. These studies have concluded that ECR heating should lead to bulk plasma heating. We have obtained some results for ECR heating of the HFCTR reactor in the quasi-transverse limit, neglecting refraction.

For reactor-size plasmas, the absorption of ECR radiation is so strong that the wave cannot penetrate to the resonance point. Hence, in order to heat the plasma center, the heating frequency must match a point located toward the inside of the torus.

The ECR frequency should be increased roughly by an amount $3\Omega_o\ (1-q)^{1/2}\ \beta_T \cos\theta$, where Ω_o is the central ECR frequency, q is ω_p^2/ω^2; β_T is $\sqrt{2T_e/Mc^2}$ and θ is the launch angle with respect to the magnetic field. This effect is rather small, of order 10% or less. The absorption point in the plasma is found to depend on angle of launch (θ), density (n) and temperature (T). Assuming that θ and n are constant, then as T increases to ignition, the location of the absorption point shifts significantly, the shift in major radius being of order $0.3R_o(1-q)^{1/2} \cos\theta$. The heating point, however, stays in the plasma center. The absorption by the tail of the electron distribution can be a problem for reactor size plasmas, but it should not be too signigicant unless θ is very close to 90^o. Calculations which include the poloidal field and plasma pressure would be of interest.

Improved Modularization of the Reactor

HFCTR presented an advanced, fully automated, modularized reactor design which permitted rapid replacement of modules for either scheduled or unscheduled maintenance.[2] However, the HFCTR modularized approach was limited by time delays due to non-mechanical operations such as detritiation of the vacuum vessel prior to disassembly and reestablishment of high vacuum after reassembly. In this report, we suggest that the down-time due to scheduled replacement of reactor modules may be minimized by removing all of the modules at once. It is possible for all old modules and replacement modules to simultaneously move to their desired positions. This technique has the advantage of reducing the total time required in scheduled module replacements for detritiation of the vacuum vessel and for reestablishment of high vacuum after reassembly. It also increases the projected service life of the first generation modules and reduces the activation of the reactor cell, permitting the possibility of human entry (with shielding) into the reactor cell, if needed, during reassembly.

Summary of Advantages and Disadvantages of ECR Heating

The major advantages of ECR heating may be summarized as follows:

- ECR radiation is predicted to penetrate to the center of a reactor-size tokamak plasma, to be nearly 100% absorbed and to result in bulk heating.
- Moderate values of average β, may be achieved in high density, compact tokamak reactors which use ECR heating with ordinary wave radiation (polarization parallel to B).
- ECR heating has several advantages over neutral beam heating. Gyrotrons are sealed and do not share the reactor vacuum system. Failure of a single gyrotron unit will not effect reactor operation. The projected cost of an ECR heating system is less than that of a neutral beam injector system. The microwave transmission system requires no routine maintenance.
- ECR heating is highly localized, allowing control of the temperature profile and improving confinement. The gyrotrons can be applied to gas breakdown and plasma preheating, possibly reducing the size and cost of the ohmic drive system.[11]

The major disadvantages of ECR heating include:

- The efficient, high power, high frequency gyrotrons (or other sources) required for ECR heating of reactor-size plasmas have not yet been demonstrated and will require a lengthy development program. Some components, such as the gyrotron output windows, may be particularly difficult to fabricate. The microwave transmission system will also require a major development program.

- The efficiency, cost and reliability of microwave systems developed for ECR heating will, at least for the next decade or two, be inferior to that of lower frequency microwave systems used for lower hybrid or ion cyclotron resonance heating.
- ECR heating provides direct heating of electrons, with collisional energy transfer required to heat ions. ECR heating does not appear to be usable for RF-driven, steady-state tokamaks.
- For fundamental heating the average beta must be less than $\approx$ 4% for temperatures below 15 keV.

Conclusions and Recommendations

- A detailed design has been carried out of an ECR heating system for a specific tokamak power reactor, the High Field Compact Tokamak Reactor (HFCTR). The present results, when combined with those of the HFCTR report, represents the first detailed study, to our knowledge, of an ECR heated tokamak power reactor.
- Our major conclusion is that ECR heating appears to be feasible and potentially attractive for bulk heating of a moderate size high density tokamak power reactor to ignition.
- Ordinary wave heating at the fundamental cyclotron frequency appears to be the most advantageous option for heating. The plasma wave cutoff condition for this mode limits the average plasma β to $\lesssim$ 4% for T $\leq$ 15 keV.
- For bulk heating of the tokamak plasma to ignition, a power level of about 100 MW, at a frequency of 200 GHz, for 5 seconds is required. Present day gyrotron technology indicates that a power level for a single 200 GHz gyrotron of 100 kW should be practical, with 33% overall efficiency.
- A microwave system has been designed for transmission of the radiation from the gyrotrons to the tokamak plasma. Estimated overall transmission efficiency using the TE_{01} mode in oversize waveguide is about 80%. The number of individual gyrotrons required would be about 1250. Although the quantity of tubes used is large, this design will reduce the importance of individual tube failures and allow the use of windows at the gyrotron output end and at the reactor.
- If ECR heating is to be a viable alternative for bulk heating of tokamak plasmas, it will be necessary to have an intensive development program for high frequency gyrotrons, as well as for transmission systems for high frequency, high power radiation. Key gyrotron problems include electron guns for producing cold beams with large $v_\perp / v_\parallel$; mode competition in the cavity; and output coupling and window construction. The microwave transmission system will require development of mode converters and, possibly, isolators and mode filters.
- The ECR radiation is predicted to be absorbed in the central region of the plasma and to lead to bulk heating. However, a more detailed investigation should be carried out of the effect of the rising plasma temperature on the location of the absorbing point, including the effect of plasma pressure and poloidal field. The possibility of tail heating of the electron distribution also merits further analysis.
- The RF heating system leads to a considerably simpler technique for removal of individual reactor modules relative to a neutral beam injector heating system. The cost of an ECRH system is also projected at less than that of a neutral beam system. The simultaneous replacement of all reactor modules at scheduled intervals is found to minimize the total down-time for module replacement.

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