PROGRESS IN EC HEATING AND CURRENT DRIVE PHYSICS AND TECHNOLOGY AT RTP

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Abstract

Recent achievements in both the technical development program and the experimental physics program related to electron cyclotron waves are described: - first lasing of the Free Electron Maser; - feedback control of the gyrotron output;- second harmonic current drive experiments; - control of the current decay in disruptions; - cross-polarisation scattering experiments.

1. INTRODUCTION

One of the likely candidates for non-inductive current drive, additional heating, start-up assistance, profile control etc. in the next generation of tokamaks is the injection of Electron Cyclotron (EC) power. Moreover, the deposition of EC power is an invaluable tool for investigating the local (electron) transport properties of the plasma and for influencing these locally and globally. Within the EURATOM-FOM association a major part of the effort is devoted to technological developments, such as a new EC source, and to study the interaction of EC-waves with tokamak plasmas. Until September 1998 these studies were done on plasmas in the Rijnhuizen Tokamak Project RTP[1]. In the future the experimental work will be transferred to TEXTOR-94 in the framework of the T(rilateral) E(uregio) C(luster) agreement between the Forschungszentrum Jülich, the Ecole Royale Militaire/Koninklijke Militaire School Brussels and the FOM Institute for Plasma Physics Rijnhuizen.

2. TECHNICAL DEVELOPMENTS

2.1. First microwave generation in the FOM Free Electron Maser

A free electron maser (FEM) has been built as a prototype for a high-power (1 MW), rapid-tunable (130-260GHz) mm-wave source for applications in future fusion research devices. The setup of the FEM is largely determined by the requirement for high overall efficiency (50%). This together with fast tunability and CW operation determines the choice for a dc acceleration and deceleration system rather than a RF system. The choice for a maximum electron energy of 2 MeV and a beam current of 12 A has been made on the basis of simulations of the interaction between the electron beam and the mm waves. The required high system efficiency demands an efficient recovery of the spent electron beam leaving the undulator. For this purpose a decelerator and a depressed collector are incorporated. This results in the basic layout of the fusion-FEM as shown in Fig. 1.

In the first phase of the project the electron beam was successfully accelerated and transported through the undulator and the mm-wave cavity. Loss currents are below 0.05%. In October 1997 first lasing was achieved [2]. The mm-wave output power has been measured at various frequencies and for various electron beam currents and energies. The highest output power reached so far is 730 kW at 205 GHz, for an electron beam of 7.2 A and 1.77 MeV. Both output power and start-up time correspond well with simulation results. The output beam has a Gaussian mode content of more than 99.8 % for all operating frequencies. An electron beam recovery system is being installed to increase the pulse length from its present value of 12 μs to 100 ms.

2.2. Feedback control of EC power and launch.

For ECRH and ECCD studies at the 2nd harmonic frequency at RTP a 110 GHz gyrotron (500 kW, 0.2 s) was used. In the first set-up the 110 GHz beam was launched radially in the midplane from the outboard side using a fixed mirror. In a later stage the launcher has been extended with a set of two in-vessel focussing mirrors. This set of mirrors allows deposition over the poloidal cross-section for poloidal angles in the range of -25^{o} to $+25\ ^{o}$. Toroidally the range of rotation is limited to +/- 30^{o} off-perpendicular. It is possible to sweep the deposition of the RF power, during a plasma pulse, over a preprogrammed trajectory as a first step towards active instability control [3].

Optimum launching in toroidal direction requires elliptical polarization of the beam. Therefore a polarizer, consisting of two grooved, rotatable mirrors, has been installed recently. As a testbed for future applications a system was implemented for feedback control of the EC heating by regulating the gyrotron voltage. An example of its performance is given in Fig. 2. in which the electron temperature – as measured by ECE – is preprogrammed.

3. EXPERIMENTAL RESULTS

3.1. Second harmonic current drive

In the RTP tokamak (R = 0.72 m; a = .164 m, $B_T \leq 2.5$.T; $I_p \leq 150$ kA) second harmonic current drive is obtained with oblique injection of focussed 110 GHz waves from the LFS [4]. The EC driven current is derived from residual loop voltages for co- and counter-drive discharges. Best results are obtained with an off-perpendicular launch angle of 17.5^{o}, $<n_e> \approx 1\mathrm{x}10^{19}\mathrm{m}^{-3}$, $B_T = 1.97$ T, and low plasma current ($q_a \approx 10$). Considerable fractions (typically 25%, maximal 60%) of the plasma current are driven in the plasma center ($r/a \leq 0.2$). The dependence of ECCD on RF power, density, injection angle, and toroidal field has been investigated extensively with linear polarization of the launched power. Then the efficiency – $(n_{e,o})_{19}RI_{CD}/P_{RF}$ - is $\approx 0.1\mathrm{x}10^{19}$ A/Wm^2. In the first experiments with elliptical polarization an improvement of the efficiency of ≈ 30 % is observed. This agrees well with the expected increase in coupling efficiency to the 2X-mode for 17.5^{o} off-perpendicular launching. The RTP discharges with an EC driven current show signs of modified q-profiles [4]. In these discharges the EC power is dominant (10-20 times the Ohmic power, deposited within 10% of the minor radius). Examples of T_e and n_e profile modifications – form Thomson scattering - are shown in Fig. 3. Therefore it is concluded that the analysis method used is questionable and a more sophisticated method is needed.

Only in a very a limited number of shots current drive experiments at preprogrammed power level and/or at preprogrammed temperature were done. As an example we show in Fig. 4. some results from a series of discharges in which the central T_e and the P_{OH} were kept fixed while the plasma current was a free parameter. For perpendicular and counter-injection the same level is reached, whereas for co-injection a considerable higher level is obtained.

3.2. Control of the current decay rate of the current quench

The current decay that follows the energy quench of a major density limit disruption is caused by strongly enhanced Ohmic dissipation, due to the high value of the resistivity reached at that phase. The possibility of decreasing, or even reversing, the current decay rate was investigated by attempting to heat the plasma and thus to decrease the electron resistivity. To do this ECRH was applied at the end of the energy quench (see Fig. 5.). We have shown [5] that ECRH can be used to decrease or reverse the current decay rate of a major density limit disruption. Previously reported dependence of this process on the position of the resonance layer and on the angle of injection [6] was not found anymore when the electron density is ≤ 2/3 of the cut-off density. This indicates that heating gives the stabilizing effect, and it might imply that any other effective method of heating the plasma, besides ECRH, could yield the same effect. Unfortunately it is not possible to be conclusive on the necessary minimum amount of EC power from our experiments due to limitations in the poloidal field circuit of RTP.

3.3. Cross polarization scattering experiments

In a recent series of experiments the phenomenon of mode conversion (or cross polarization scattering (CPS)) was further investigated [7]. It was found that during heating experiments (60 GHz, 160 kW), 40 ms) with the waves injected from the low field side in O-mode a considerable fraction (several percent) was converted to X-mode before reaching the high field side detectors. The main results are that: 1) CPS is only seen with the deposition radius inside the q = 1 surface; 2) The X-mode level strongly diminishes with increasing density; 3) The signals are detected in a narrow band of 10 MHz around the injected frequency; 4) Usually a time delay (up to 20 ms) between the start of the ECR pulse and X-mode signals is observed; 5) There is a strong correlation between the observed X-mode level and the time behavior of the EC emission from the hot core. 6) Frequency spectra have a broadband structure with a maximum around 60 kHz and a typical width of 100 kHz.

It is concluded that the range of plasma parameters for which the cross-polarization scattering is observed correlates strongly with the regime of pronounced filaments (or small-scale structures) [1]. This led to the assumption that the T_e filaments are accompanied by current and magnetic field fluctuations which then could lead to the cross-polarization scattering effect [8].

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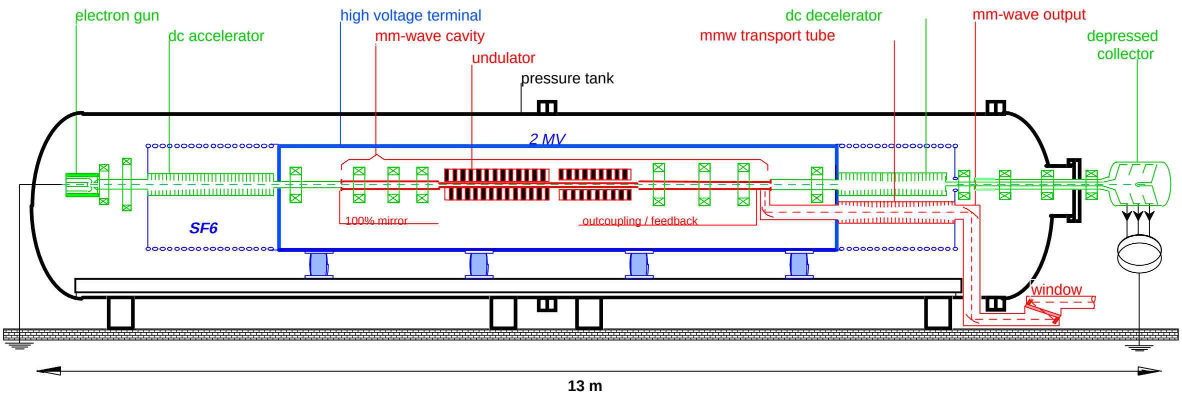

FIG. 1. Schematic layout of the fusion FEM

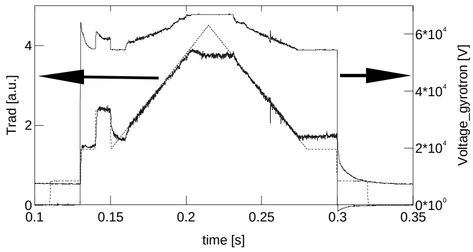

FIG. 2. Time traces of preprogrammed and actual T_e and the gyrotron voltage. The gyrotron is switched on from .13 to .3 s. The measured T_e gets constant when the maximum output of the gyrotron is reached

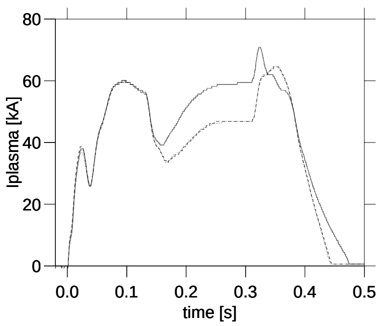

FIG. 4. Time evolution of I_p while central T_e and P_{OH} are kept fixed, for perpendicular and counter-injection (full line) and for co-injection (dashed line).

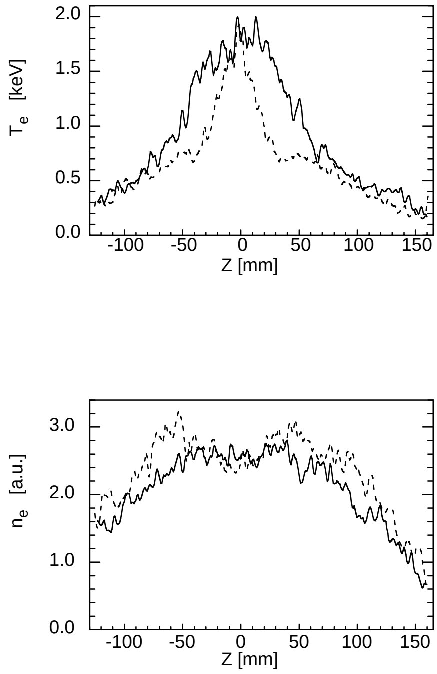

FIG. 3. T_e and n_e profiles during co- (full lines) and counter-drive (dotted lines).

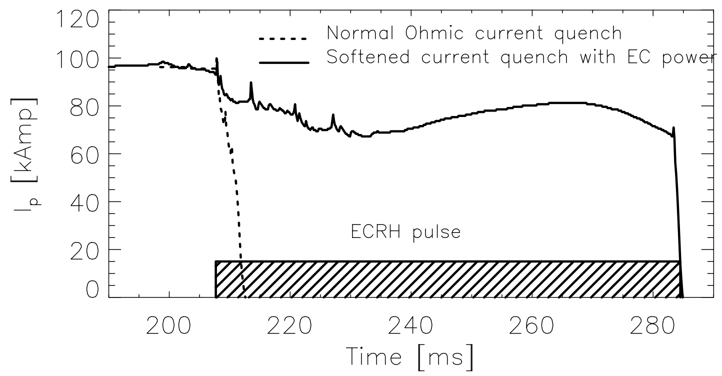

FIG. 5. Plasma current (full line), for a discharge where the current quench was softened and reversed. EC power was 330 kW and the resonance position was at r/a = 0.5. Ohmic heating was 260 kW just before the disruption and reached a maximum of 1 MW after the onset of the disruption at 212 ms. For comparison the plasma current during a discharge when no ECRH was applied is shown.