LONG-PULSE OPERATION OF THE NEW 800 KW, 140 GHZ GYROTRON ON TEXTOR

E. Westerhof[1], J.A. Hoekzema[2], M.R. de Baar[1], M.F.M. de Bock[1],
W.A. Bongers[1], A.J.H. Donné[1], E. Farshi[1], K.H. Finken[2],
A.F. van der Grift[1], G.M.D. Hogeweij[1], R.J.E. Jaspers[1], H.R. Koslowski[2],
A. Krämer-Flecken[2], O.G. Kruijt[1], A. Lazaros[1], X. Loozen[2],
N.J. Lopes Cardozo[1], A. Merkulov[1], J.W. Oosterbeek[2], P.R. Prins[1],
J. Scholten[1], F.C. Schüller[1], C.J. Tito[1], and TEC Team

Partners in the Trilateral Euregio Cluster:
1) FOM-Institute for Plasma Physics Rijnhuizen, Association EURATOM-FOM,
PO Box 1207, 3430 BE Nieuwegein, The Netherlands, www.rijnh.nl.
2) Institut für Plasmaphysik, Forschungszentrum Jülich GmbH,
EURATOM Association, D-52425 Jülich, Germany.

e-mail: E.Westerhof@rijnh.nl

Introduction

The Electron Cyclotron Resonance Heating (ECRH) system in operation on the TEXTOR tokamak is dedicated to the study and manipulation of localised transport and MHD instabilities. Results obtained in experiments with a preliminary 110 GHz, 500 kW, 0.2 s ECRH system have been described in [1]. The recent shutdown for installation of the Dynamic Ergodic Divertor [2] has been used towards a major upgrade of the ECRH system. This paper describes these improvements, which have led to the achievement of a 3 s, 800 kW ECRH pulse in the TEXTOR plasma. In particular, the improvements to critical components in the high power microwave transmission and launching system are described, which were necessary for successful operation of the new high-power (800 kW) long-pulse-length (> 3 s), 140 GHz gyrotron. In addition, a brief overview is given of first physics results obtained with the new ECRH system. These results cover the scope of the TEXTOR ECRH programme including manipulation and measurement of local electron transport, and control of MHD instabilities.

Upgrade of the TEXTOR ECRH system to 140 GHz, 800 kW, > 3 s

New gyrotron The heart of the upgraded ECRH installation is formed by a new 140 GHz Gycom gyrotron. It is a diode type gyrotron with a demonstrated efficiency of up to 38%. The output window is edge cooled CVD diamond. After special matching optics, the Gaussian content of the beam is > 99%. In acceptance tests, the gyrotron achieved its specifications of 800 kW power and 3 s pulse length and a 10 s pulse at the slightly reduced power of 670 kW.

Launcher Measurements of the stainless steel launcher-mirror used for the preliminary ECRH experiments showed surface losses at a rate of 3% mainly caused by deposits on the mirror surface [1]. On the basis of these measurements an unacceptable surface temperature rise of 2000 K would be expected during a full power 3 s pulse of the new gyrotron. As a temporary solution before installation of a new full copper mirror, a central copper insert was mounted in the existing mirror. After the expected pollution of the mirror surface by tokamak deposits, a surface temperature rise of an acceptable 600 K was expected for the copper insert during a 3 s full power pulse. However, after more than six months of operation and a dozen of boronizations, measurements revealed a bulk temperature rise of only 7 K for a full power 1.5 s pulse indicating surface losses of about 0.2 %, consistent with a clean Copper surface. Contrary to expectations, the mirror is found not to pose any limit to operations.

Tokamak vacuum window The next critical point in the quasi-optical transmission line is the tokamak vacuum barrier, which is currently formed by a water free quartz window of 180 mm diameter, resonant at 110 and 140 GHz. Measurements of the window surface temperature have been performed to assess the microwave absorption and to set safe limits for the maximum pulse length of the current system. A temperature rise in the centre of the window of 200 K is measured after a 1.5 s, 800 kW pulse. This is consistent with an expected window absorption of 1.8 %. A cooling time of about 6 min is observed with forced air cooling. Based on these observations the maximum pulse length for safe, full power operation was set to 3 s with a duty cycle of 1:500.

A new CVD diamond window with edge cooling, similar to the gyrotron window, is under preparation and will be installed later this year together with a new fast-steering launcher [1]. After this upgrade the system is expected to be fully compatible with the 10 s, 800 kW capability of the gyrotron.

Transmission line shielding The final obstacle on the way to achieving a pulse length of 3 s proved to be the build up of stray radiation in the final section of the quasi-optical transmission line in front of the tokamak window. The stray radiation is due to reflection from the tokamak window, which is placed under a 1^{o} angle with respect to normal incidence of the wave beam in order to prevent reflections back into the gyrotron. Measurements with thermal paper placed in the reflected beam show an unexpected high level of reflected radiation of about 2%. This is most likely due to a small deviation of the window thickness for resonant transmission of the 140 GHz radiation. Arcing occurred mostly in the section of the transmission line between the mirrors of the “zoom” and the mirror immediately before, on which the beam is coming from above (see Fig. 1a). This part of the transmission line was already (partly) shielded to prevent stray radiation from damaging sensitive equipment in the vicinity. In order to absorb some of the stray radiation, stones were placed at critical surfaces in this part of the transmission line: a measure that, however, proved to be insufficient in order to prevent arcing for pulses longer than about 2 s.

During a recent improvement of the transmission line shielding, the zoom was removed and the mirror just in front of it lowered to direct the beam directly onto the tokamak window. The reflected beam from the tokamak window now reaches the top edge of the mirror at the bottom of the vertical section in the transmission line. The reflected power is now absorbed by water circulating through teflon tubes in parts of this vertical section of the line (see Fig. 1b). In the top part of the vertical section, the reflected power that just hits the bottom mirror is absorbed. The remaining reflected power that passes over the mirror is diffused by a curved plate mounted above the bottom mirror and is absorbed in the lower part of the vertical section. These measures proved to be sufficient to prevent arcing caused by the reflected power, and allowed us to increase the pulse length to its current maximum of 3 s. The experiments reported below, however, have mostly been done with the old transmission line set up.

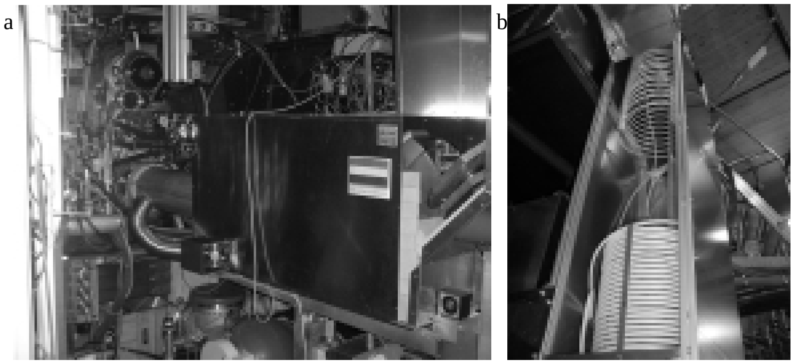

Figure 1 (a) Picture of the final section of the quasi-optical transmission line in front of the tokamak window. The microwave beam enters from the top right. Stray radiation from window reflection causes arcing predominantly just below the right most mirror. In the new set up this mirror is moved down while the mirrors of the "zoom" (just to the left) are removed. (b) Picture of the new vertical section of the transmission line shielding with one side of the aluminium cover removed to show the teflon water tubes mounted for absorption of the stray radiation.

Machine integrity The presence of the DED coils on the high field side of the tokamak poses a particular problem for the safe operation of the TEXTOR ECRH system: although the DED coils are protected from the plasma and from direct irradiation from the high power microwaves by Carbon tiles on ZrO isolation, some non-absorbed ECRH power has been found to penetrate the spaces between tiles. This causes arcing and has been seen to damage both the Carbon tiles and the underlying ZrO isolation. Several measures are taken to prevent the ECRH operation in plasmas with incomplete absorption. First, ECRH operation is only allowed at sufficiently high plasma current and density ("plasma present module"). Second, two sniffer probes mounted at different positions along the torus measure the level of non-absorbed 140 GHz radiation. Gyrotron operation is terminated when a preset level of radiation is measured on any of these probes.

Physics results

Creation of an internal transport barrier It was observed previously on T-10 that after off-axis ECRH the decay of the central electron temperature $T_e(0)$ could be delayed by up to 25 ms [3,4]. The delay depends sensitively on the ECRH deposition radius relative to the sawtooth inversion radius: the longest delay is seen for heating just outside the inversion radius. The delay is attributed to the creation of a transport barrier as a consequence of a transient reduction of the shear at q = 1 [4]. Experiments have been carried out on TEXTOR to confirm these observations. In particular, the dependence of the delay time on the foregoing ECRH pulse has been investigated by applying four pulses (400, 200, 100, and 50 ms) in a single discharge. The 500 ms between pulses is sufficient for complete relaxation of the central plasma current. The longest delay times were observed after the shortest (50 ms) ECRH pulses. An example is shown in Fig. 2.

Transport measurements The effect on transport of the magnetic field perturbations induced by the Dynamic Ergodic Divertor (DED) has been measured by means of modulated ECRH (MECH). For these studies the DED has been operated to create a dominant m=3, n=1 perturbation, which is accompanied by a large m=2, n=1 side band. Above a threshold in the DED current, the 2/1 side band triggers a m=2, n=1 tearing mode [5]. MECH has been applied during DED operation both below threshold and in the presence of the m=2, n=1 tearing mode. Figure 3 shows the phase and amplitude profiles for these two cases. The strong flattening of both the phase and amplitude profiles in the presence of the 2/1 mode indicates an increase of transport over the entire cross-section of the plasma. Below threshold for the 2/1 mode triggering, the DED perturbations appear not to affect the transport significantly.

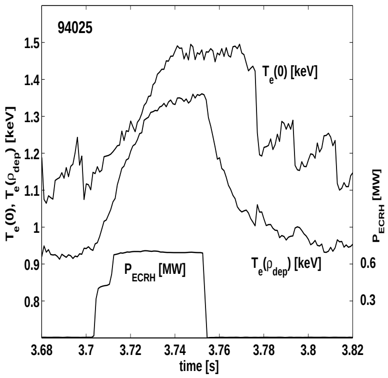

Figure 2 The evolution of $T_e(0)$ and $T_e(\rho_{dep})$ in response to a 50 ms ECRH pulse is shown. The decay in $T_e(0)$ is delayed by ~25 ms (corresponding to ~1 τ_E).

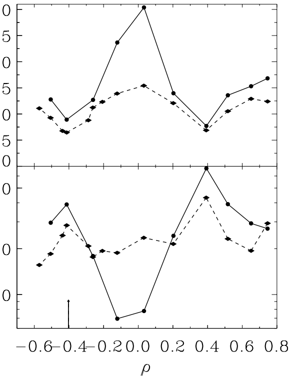

Figure 3 Phase (ϕ) and amplitude (A) of temperature fluctuations in response to MECH. Full: below threshold for 2/1 mode. Dashed: in presence of 2/1 mode.

MHD control The long pulse capability of the new gyrotron has been exploited to study the effect of ECRH and ECCD on sawteeth: by a slow ramp down of the toroidal magnetic field during the gyrotron pulse the ECRH/ECCD location is scanned through the q=1 surface on the high field side. Figure 4 shows the results in terms of the sawtooth period normalized to the ohmic one as a function of the deposition radius for ECRH as well as for co- and counter-ECCD. The range in deposition radius covered by the data is incomplete, as arcing in the transmission line prevented the completion of the planned 3 s pulses.

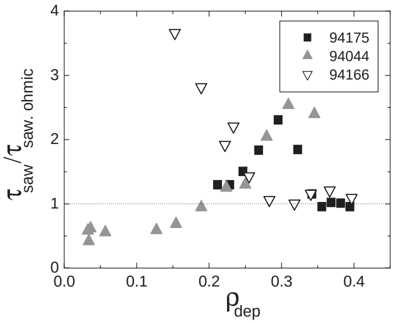

Figure 4 The sawtooth period normalised to the ohmic sawtooth period is shown for three discharges as a function of the normalized deposition radius ρ_{dep}, which is changed during ECRH/ECCD by a slow B_T ramp down. The toroidal injection angle in the three discharges is perpendicular (#94175) for ECRH, and -20^o (#94044) or $+10^o$ (#94166) off-perpendicular for co- and counter-ECCD, respectively.

The effects of localized ECRH on the m=2, n=1 tearing modes, that are triggered by the DED, have been studied. A reproducible target discharge was set up, with a toroidal field of B_T = 2.25 T, plasma current I_p = 300 kA, and 300 kW of NBI for diagnostic purposes (CXRS, MSE). The DED is then operated in its AC mode at 1 kHz with a maximum current of 2 kA in each coil, well above threshold for triggering of the m=2, n=1 tearing mode at the q=2 surface at approximately mid radius, $\rho_{q=2} \approx 0.5$. For these parameters the cold EC resonance is located at a major radius just inside the q=2 surface on the high field side, and the ECRH deposition has been varied by changing the vertical injection angle. ECRH is then applied in the flat top phase of the DED to study its effect on the 2/1 mode. A relative estimate of the amplitude of the 2/1 mode is obtained from the fluctuations of the 141 GHz ECE originating from close to the q=2 surface. The effect of ECRH will be quantified in terms of the ratio of the ECE fluctuations during ECRH over those without ECRH. Apart from changes in the 2/1 mode amplitude, the ECE fluctuations may be affected by changes in the T_e gradient or a shift in the position of the q=2 surface. However, the ECE data are consistent with the relative changes in the m=2 magnetic perturbations from the plasma as obtained from an analysis of the data from the Mirnov coils, whenever the latter were available. The results of a shot to shot deposition scan of 800 kW ECRH are shown in Fig. 5a. A power scan (200 – 800 kW) at the optimum deposition radius seems to indicate that the 800 kW is slightly below the limit for complete suppression of the mode.

At the optimum deposition radius, the effectiveness of ECRH modulated in phase with the 2/1 mode rotation has been studied. As the 2/1 mode is locked to the DED perturbation, this can be achieved by control of the gyrotron power on the basis of the phase of the AC current in any of the DED coils. The fast, 1 kHz modulation of the gyrotron power is achieved by modulation of the gyrotron beam voltage between 57 and 71 kV, corresponding to output powers of 150 and 800 kW respectively [1]. A duty cycle of 50% for the high power phase has been used. Figure 5b shows the effectiveness of mode suppression as a function of the phase shift of the gyrotron power relative to the current in a particular DED coil. The arrows indicate the phase shifts at which the ECRH is centred at the O-point or X-point of the 2/1 magnetic island. Although the mode is suppressed in all cases, the suppression is clearly most effective when the power is located at the O-point rather than at the X-point.

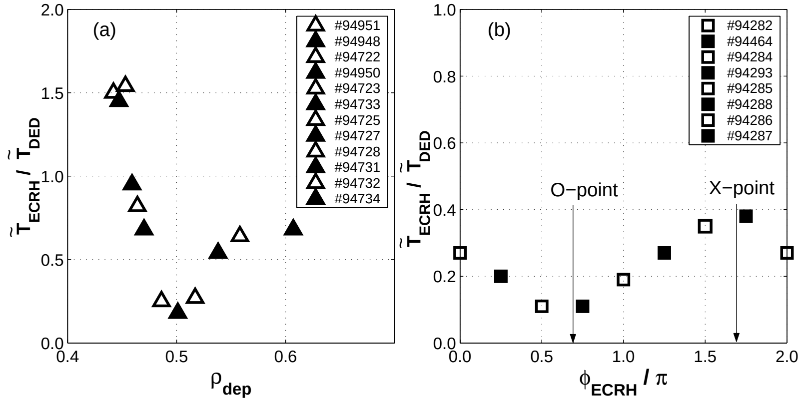

Figure 5 (a) The suppression of the 2/1 mode by localized ECRH is shown as a function of the deposition radius. (b) The suppression of the 2/1 mode by modulated ECRH (at optimum $\rho_{dep} = 0.5$) is shown as a function of the phase relative to the magnetic island. Discharge numbers are listed in the order in which they appear from left to right in the figures

Acknowledgements

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