Experimental Results on Pellet Injection and MHD from the RTP Tokamak

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Abstract. The ablation of hydrogen pellets has been studied in the Rijnhuizen Tokamak Project RTP with a diagnostic with high spatial and temporal resolution. It has been observed that (part of the) ablation cloud drifts away from the pellet in opposite direction. These drifts occur in semi-periodical bursts. A summary of a detailed analysis of this drift of the cloud and its implications for the fueling profile is presented. Stabilization of m/n = 2/1 tearing modes preceding density limit disruptions, has been studied with modulated and continuous ECRH. The results indicate that EC heating of the islands under these conditions is very inefficient. The time dependence of the growth rate of the precursor mode is first algebraic, but becomes exponential in a later phase.

Introduction

The experimental programme on the Rijnhuizen tokamak project RTP ended in September 1998. Since then the base load has been dismantled, and most of the auxiliary equipment (diagnostics, EC heating) has been transferred to the TEXTOR-94 tokamak in Jülich, but analysis of the RTP data base is still going on. In this paper we present some of the results of this analysis concentrating on issues related to pellet injection and related to the m/n = 2/1 precursors of density limit disruptions.

1. Pellet injection

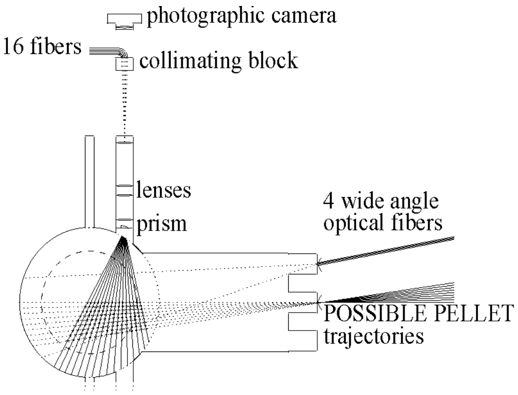

FIG.1. Overview of the experimental setup and the viewing lines of the ablation diagnostics in a poloidal cross-section of the tokamak. The dashed circle indicates the plasma position.

To obtain reliable predictions for the local ablation rate for pellet fueling in a future fusion device, the validity of the currently applied models must be investigated. Important checks of an ablation model are the penetration depth and the fueling profile. The penetration depth of pellets injected into RTP ($R/a = 0.72/0.164$ m, $B_T < 2.5$ T, $I_p < 150$ kA) from the Low Field Side (LFS) with velocities between 0.5 and 1.0 km/s was routinely monitored with two independent diagnostics, shown in Fig. 1. The intensity of the H_α emission from the ablation cloud was measured with high temporal resolution by a detector viewing a large plasma volume, and with good spatial resolution by taking time-integrated photographs of the pellet trajectory. Between those two measurements a discrepancy was found: The H_α signal generally yields a deeper (in average about 0.1 r/a) penetration than the photographs. A dedicated diagnostic, also shown in Fig.1., has been built to clarify this discrepancy. It consists of an array of 16 fibers viewing the pellet trajectory along narrow lines of sight, resulting in a very high spatial and temporal resolution. The initial results with this diagnostic, published in [1], are summarized in Figs. 2 and 3.

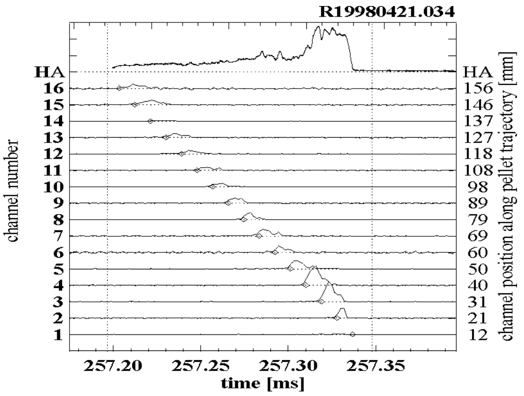

FIG. 2. Example of the ablation process as observed by the fiber-array for a pellet into a rather cold (~500 eV) plasma. The top trace is the H_α monitor. The diamonds indicate the expected passage time of the pellet, when a clear peak is observed at each channel.

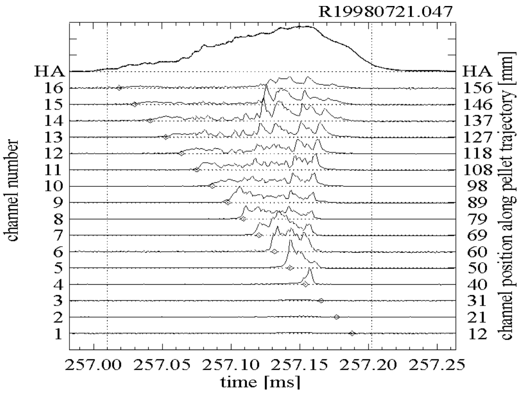

FIG. 3. Example of a pellet into a hot (~ 1500 eV) plasma plotted in the same way as in Fig. 2. The peaks after the passage of the pellet are clearly correlated and indicate light sources moving faster than the pellet and in opposite direction.

We have observed that (part of the) ablation cloud drifts away from the pellet towards the LFS direction with a radial velocity in the range 2.5 to 10 km/s. These drifts occur in semi-periodical bursts. The direction and velocity of this cloud can be explained using the model proposed by Rozhansky [2]. Most of the discrepancy in penetration depth between theory and experiment can be explained by this drift of the cloud which has implications for the fueling profile and the validation of theoretical ablation models. The main results of further detailed analysis [3] are in summary:

- the bursts in ablation cloud drifts occur more often and the clouds live longer with higher T_e.
- in the slide-away regime no separate drifting clouds are observed, but a continuous drifting of ablatant away from the pellet is seen which might be ascribed to the effect of suprathermals see Fig. 4.
- Under certain conditions a density increase is seen in front of the pellet. Fig. 5 displays the n_e-profiles from Thomson scattering for a pellet injected off-axis. One profile is taken just before injection, the other at the moment of closest approach of the pellet to the plasma center. A clear density increase is seen much closer to the center than the pellet position. A possible mechanism is that part of the ablated matter is transferred to the HFS of the plasma center due to the rotational transform. If the drift towards the LFS occurs for this matter, this would appear as a radial inward drift. This is maybe also an explanation for the sometimes observed fast cooling (pre-cooling) of the plasma center in front of the pellet (Fig. 6).

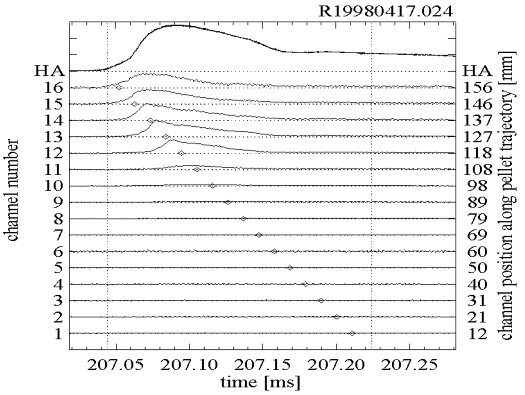

FIG. 4. The ablation process as observed by the fiber-array for a pellet into a low density plasma with a large population of supra-thermal electrons. The ablation cloud seems much larger than in previuos cases, and no secondary peaks can be recognized. This may also be interpreted as a continuos stream of ablatant from the pellet to the plasma boundary.

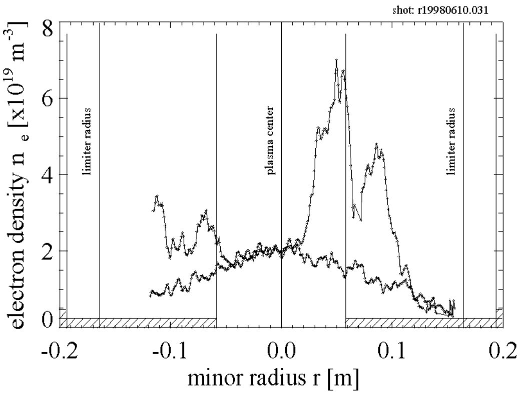

FIG. 5. Two n_e - profiles in case of a pellet injected under an angle, such that its closest approach to the center is 56 mm. The first profile was taken just before injection, the second one when the pellet was at the position indicated by the bar at the bottom. For positive radii the density perturbation clearly extends several cm in front of the pellet.

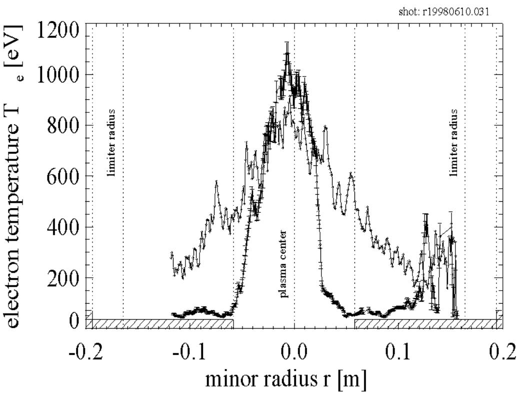

FIG. 6. The Te – profiles for the same discharge as Fig. 5. Also the temperature perturbation clearly extends in front of the pellet, for positive radii.

- the bursts in drift might be an alternative explanation for the striations which are almost always present on the observed H_α signal.

We have also analyzed the radial particle transport during and after pellet injection. The values obtained for the diffusion coefficient D are as expected (1-2 m^2/s) for most conditions, except in the plasma center at the radius of maximum pellet penetration, and in the slide-away regime. Then unusual low values (~ 0.05 m^2/s, close to the neo-classical value) were found, acting as transport barriers induced by the pellet. A possible explanation for both cases of low D is that at the point of deepest penetration of the pellet a region is formed with a high rotational shear. This happens because the toroidal rotation is slowed down with respect to pre-pellet values in the region crossed by the pellet, but the rotation remains at full speed in the center (at least for some time).

2 MHD phenomena

In this section we will present some of the experimental observations of the $m/n = 2/1$ tearing mode that grows prior to density limit disruptions in RTP (briefly presented in [4] and [5], an extensive discussion can be found in [6]). To provoke the disruptions the density was ramped in Ohmic He discharges, using a Ne gas puff. With the Ne puff the radiative density limit could be kept below the cut-off density of the ECE radiometer and of the gyrotron, and the disruptions were reproducible. Plasma currents were typically I_p = 100 kA, with $q_a \approx 4$. Stabilization of the $m/n = 2/1$ modes was studied with both modulated and continuous injection of electron cyclotron (EC) waves (second harmonic from the LFS, 110 GHz, ≤ 320 kW, 0.2 s). A signal proportional to the m=2 component of the perturbed poloidal field ΔB_Θ was used to trigger the gyrotron.

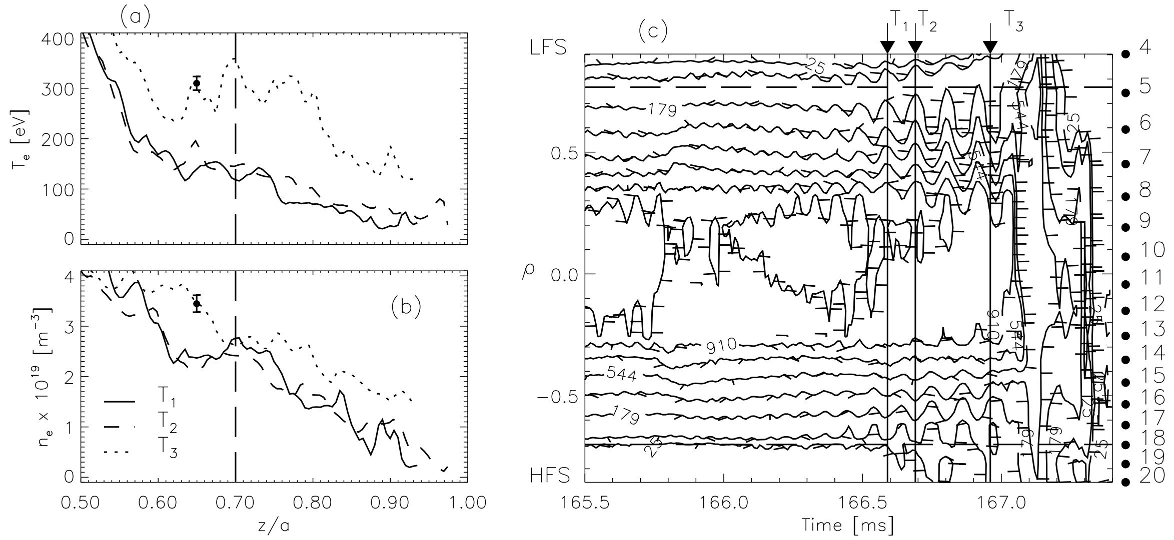

FIG. 7. (a) T_e and (b) n_e high resolution TS profiles measured at the times indicated in (c). Only the profile around $q = 2$ is shown. For clarity just one typical error bar is shown. The vertical dashed line indicates the calculated radial position of the $q = 2$ surface. (c) Time evolution of the radial temperature profile measured from the ECE radiometer. The channel number and its positions are indicated at the right.

2.1 Growth rate

It was found that the mode grows in two distinct phases. In the first phase its growth rate is algebraic with time and in the second phase it grows exponentially. Two independent measurements of the mode growth rate were done. Outside the plasma, with pick-up coils, the growth rate of ΔB_Θ was measured. Assuming that outside the island the temperature, T_e, is a flux function, the displacement of the flux surfaces, $\Delta r = \Delta T_e/(dT_o/dr)$, was measured close to the island by an ECE radiometer. An example of the time evolution of the radial T_e-profile is given in Fig. 7c. Since $\Delta r \propto |w|$ (w denotes the width of the island) and comparing this with ΔB_Θ, it was found that the relation $w \propto (\Delta B_\Theta)^{1/2}$ is observed in both phases for island widths up to 18% of the minor radius, as predicted by tearing mode theory [7]. The values of Δr measured on the LFS come very close to the island width from TS profiles (Figs. 7a and 7b). It is remarkable that the shape of both T_e and n_e inside the mode is neither flat nor monotonous but irregular. Moreover, in the third TS profile, practically at the onset of the disruption, $n_e(r)$ is shifted relatively to $T_e(r)$ inside the mode.

2.2. Mode stabilization

Applying continuous injection in the algebraic phase, it was observed that the $m = 2$ mode could be stabilized, independently of the position of the EC resonance, as long as it was deposited inside or at $q = 2$ and provided that $P_{ECRH} \geq 0.1\ P_{OH}$. Applying cw ECRH in the exponential phase, full stabilization was observed for $0.45 \leq \rho_{dep} \leq 0.7$ if $P_{ECRH} \geq 0.3\ P_{OH}$ Once the mode was stabilized we observed that the disruption was postponed to a new density limit which was proportional to $(P_{Ohm} + P_{ECRH})^{1/2}$. This in accordance with an energy balance between heating power and radiative losses in the edge.

In extension to this we attempted to stabilize the $m=2$ mode during the disruption precursor, with phase controlled modulated deposition of ECRH. No advantage, relatively to cw ECRH, was observed, when modulated ECRH was applied in phase with the O-point. During the exponential growth in most of the cases no stabilization was observed and consequently the

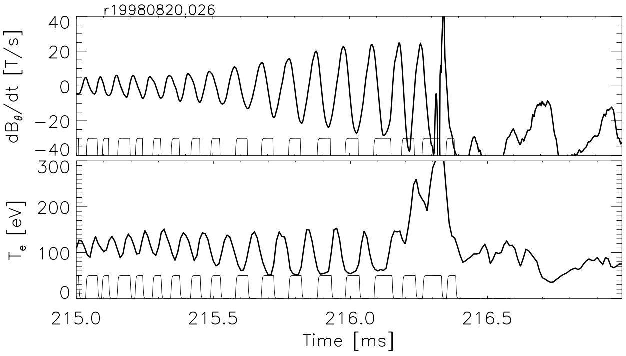

FIG. 8. Modulated ECRH around the O-point of the mode. T_e was measured at $r = 0.6a$. $I_p = 100$ kA, $q_a = 4$, $r_{dep} = 0.7a$, max $P_{ECRH} = 200$ kW and $P_{Ohm} = 360$ kW.

disruption could not be avoided (Fig. 8). These experiments are in contradiction with some numerical simulations that predict a better efficiency of the phase modulated ECRH compared with continuous ECRH. The observations at RTP indicate that when the pre-disruptive contraction of the current profile is due to a radiation induced cooling of the edge of the plasma, modulated EC heating of the islands is very inefficient [4]. The plasma temperature in the island is so low that EC-wave absorption is very poor. Moreover, the toroidal rotation of the island is too slow for the fast energy loss by radiation during the EC off-time and too fast for heating the island during one EC on-time.

Acknowledgement

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