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A pellet ablation diagnostic system for the RFX reversed field pinch

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In view of the installation of a multiple pellet injector on the RFX experiment, an integrated diagnostic system has been designed to monitor the pellet behavior in the plasma. The evidence in the reversed field pinches (RFPs) of large poloidal and toroidal pellet deflections along magnetic field lines due to asymmetric ablation, calls for a 3D system with good space and time resolution. Two arrays of H_α detectors will view the trajectories of the pellets from below and from behind and a digital charged coupled device (CCD) camera will view the injection poloidal section from a tangential viewpoint. The two systems will allow the complete determination of the time-resolved trajectory of each pellet. The space integrated H_α emission rate will be measured by a large angle detector and by a space integration of the CCD camera measurement. © *1995 American Institute of Physics.*

INTRODUCTION

The RFX reversed field pinch ($R=2$ m, $a=0.5$ m, $I_{max}=2$ MA) will be equipped with a pellet injector built by the Risø National Laboratory[1] designed to fire up to eight pellets with speed from 1000 to 1400 m/s and masses in the interval $1.5–5\times10^{20}$ atoms. An interesting feature of the pellet injection in RFPs is the evidence of large trajectory deflections of the pellets both in the poloidal and in the toroidal plane.[2] The deflections are due to a rocket effect generated by asymmetric ablation processes.[3] It is thought that the asymmetry is caused by suprathermal electrons fluxes hitting the pellets from the electron drift side.[2] Modeling with a code the asymmetric ablation of a pellet in a RFP plasma[4] we expect for RFX that the maximum deflections will be of $\approx$30 cm at the plasma axis both in poloidal and toroidal direction. To counter these deflections, which could otherwise prevent the pellets from effectively fueling the plasma core, the injector has been designed with an adjustable poloidal angle of injection relative to the plasma center in the range 0°–20°. In Fig. 1 are shown three examples of trajectories: in case **a** the injection is on-axis and the ablation is symmetric; in case **b** the same pellet is deflected due to an asymmetric ablation; whereas in case **c** the injection angle is optimized (15° in this case) to reach the plasma center. It is clear that accurate data on the pellet ablation and trajectory will be necessary. In this paper we describe an integrated pellet diagnostic system designed to this end.

The main tool to determine the trajectory of the pellet is made of two arrays of H_α detectors. The first one, viewing the pellet from below, reconstructs the projection of its trajectory on the equatorial plane, whereas the second one, viewing the pellet from behind, determines the vertical motion due to the poloidal component of the deflection. Hence the two H_α arrays provide a complete 3D determination of the pellet trajectory.

In addition, an H_α monitor, measuring the space-integrated time-resolved H_α emission from the pellet cloud, and a CCD camera, viewing the pellet trajectory in the poloidal plane from a tangential port, are employed. The information provided by the two H_α arrays, the H_α monitor, and the CCD camera should permit an accurate reconstruction of the pellet trajectory and of the deposition profile and the comparison of the experimental data with the results of the ablation codes.

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DOUBLE H_α DETECTOR ARRAY

The first H_α detector array covers the area reachable by the pellet as seen from below and is made of a fanned array of nine small telescopes viewing the plasma at different poloidal angles from a vertical access window (see Fig. 1). Each telescope consists of an 8-mm-diam 18-mm focal length lens, and a 400-μm slot toroidally oriented and at 18.35 mm from the lens. Aligned along the slot are four optical fibers of 1-mm-diam core, imaging different portions of plasma toroidally. The first one is centered on the axis of injection whereas the other three are progressively shifted towards the expected toroidal deflection. The four sets of nine fibers from different telescopes looking at the same section are collected by collimators coupled to H_α interferential filters on four photomultiplier detectors. The focal plane of the 36 fibers is at 900 mm from the lenses, which corresponds to the mean position of the pellet.

As a pellet travels along the major radius towards the center of the machine, it will cross the lines-of-sight of the subsequent fibers coupled to the same detector (e.g., row 1 and trajectory **a** in Fig. 1). Therefore, as long as the lines-of-sight are well separated and the pellet light emitting cloud is not too large, a series of well identified maxima should be seen on the detector signal, making it possible to determine both the speed and the penetration depth of the pellet. In case the pellet is deflected toroidally, its motion will be followed by the adjacent rows of fibers (e.g., trajectories **b** and **c** in Fig. 1).

Each fiber views a cone whose section in the equatorial plane is a rectangle $\approx$50 mm long toroidally and 20 mm wide along the major radius. The spacing along R is $\approx$100 mm, which is large enough to avoid the pellet being viewed simultaneously by two fibers, assuming the pellet emitting cloud is $\leqslant$15 mm wide.[5,6]

A second array of H_α detectors detects the vertical mo-

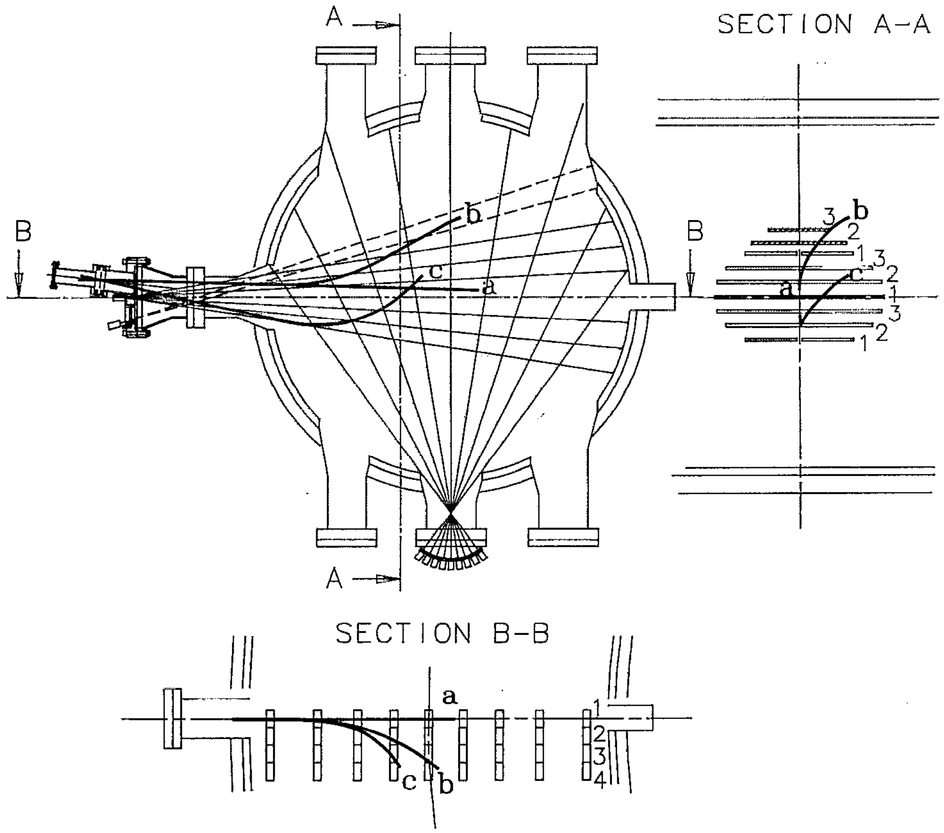

FIG. 1. Poloidal section of the RFX machine with the two array of H_α detectors and three simulated pellet trajectories. The projections of the view zones of the first array on the equatorial plane and of the second one on its focal plane are also shown.

tion of the pellet due to the poloidal deflection. It consists of three telescopes looking at the plasma from three windows mounted on the injection port itself as shown in Figs. 1 and 2: the injection line is displaced upward to allow the maximum downward tilt compatible with the diameter of observation pipe, two 38-mm circular windows lie horizontally symmetrical on the plasma equatorial plane and the third window is centered and displaced below the equatorial plane. The position of the telescopes relative to the windows is shown in Fig. 2.

Each telescope has a 12.7-mm-diam 25.4-mm focal length lens, a series of 300 μm wide parallel slots positioned at 26.23 mm from the lens and a row of 6–9 adjacent 1-mm-diam core optical fibers just behind each slot. The fibers are focused by the lenses at 700 mm from the telescopes which again represents the mean pellet-lens distance. All the fibers from the couples of homolog slots at the two telescopes horizontally displaced are collected together forming a fan of seven view zones on the focal plane (see Fig. 1). The third telescope is used for the two upper chords for a total of nine. The fibers are connected through H_α interferential filters on three different detectors interlacing the view zones as shown in Fig. 1. In fact, since the pellet does not necessarily have a monotonic upward or downward motion, it is necessary to use at least three detectors in sequence to determine the direction unambiguously. The height of each zone in the focal plane is $\approx$8 mm, whereas the width depends on the vignetting of the cylindrical access pipe. The spacing between the zones is $\approx$40 mm to prevent the pellet from being viewed simultaneously by two detectors.

The total number of H_α-like photons per second emitted from the pellet neutral cloud $N(H_\alpha)$ is given by[7]

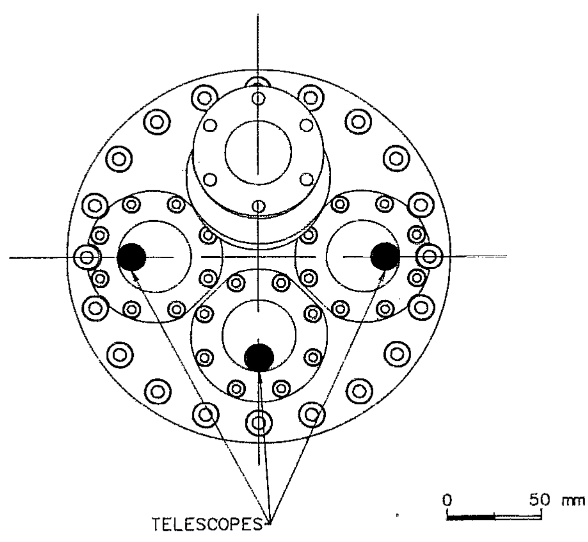

FIG. 2. Back view of the vacuum flange on the injection port with injection line pipe (centered upward) and the three observation windows. The position of the H_α detector telescopes relative to the windows is shown.

$$N(H_\alpha)=g(n_e,T_e)\cdot N(H), \quad (1)$$

where $N(H)$ is the number of atoms ablated per second and $g(n_e,T_e)$ for RFX ($T_e\approx 1$ keV, $n_e\approx 0.5\times 10^{19}$ m^{-3}) is $\approx 1/30$. With an average pellet-detector distance of about 700 mm, the power incident on each telescope when it sees the pellet is of the order of 0.2 W. This is about three orders of magnitude more than the H_α power coming from the background plasma and should guarantee a good signal-to-noise ratio.

The minimum pellet transit time across the detectors line-of-sight ($\geqslant$10 mm) is 7–8 μs for the highest pellet injection speed, which is $\approx$1400 m/s. Thus the minimum sampling frequency for the AD converters, to take at least ten samples of each pellet crossing, is $\geqslant$1 MHZ. The AD converters will be triggered at each pellet fire time and will sample for intervals of 3–4 ms, in order to reduce the amount of data to be analyzed.

TOTAL H_α POWER DETECTOR

An absolutely calibrated detector will be installed on the same window of the first H_α detector array. It views the plasma with a large poloidal and toroidal aperture and reveals the total (space integrated and time-resolved) H_α emission from the pellet cloud. The signal from the above detector will be used to estimate the ablation rate,[6] but also to cross-check the signals from the two H_α arrays and to improve the resolution of the trajectory reconstruction. In fact, on the one hand, the envelope of the maxima of the sum signal of each array should track the total H_α emission, on the other hand, the latter will detect possible large fluctuations which could cause error in the trajectory reconstruction algorithm and it will also allow one to interpolate and/or extrapolate the reconstruction beyond the discretization due to the arrays.

CCD CAMERA

A CCD camera located on the equatorial plane, 60° apart from the injector section, will monitor the pellet trajectories with a tangential view. A stainless-steel mirror placed inside the diagnostic port provides a sufficient viewing angle to observe the pellet path inside the plasma almost completely. The camera will integrate the observation of the pellet poloidal deflection as determined by means of the telescope arrays offering the advantage of a higher degree of spatial resolution at the expense of a time integrated information. For instance, besides the pellet trajectory, important characteristics such as the shape of the ablation cloud may be obtained.[5]

Two different cameras will be alternatively used: a 128 $\times$128 pixels CCD (DALSA CA-D1-0128) with a maximum of 900 frame/s or a 756$\times$498 pixels CCD with the standard CCIR video rate (50-Hz frame rate interlaced) that can be shuttered down to 0.1 ms. The faster camera will resolve the time averaged trajectory of each of the eight pellets (which will be fired at intervals $\geqslant$4 ms) with a spatial resolution of $\approx$5 mm, whereas the standard one might not resolve the single pellet, but will provide a spatial resolution of $\approx$1 mm.

For both the cameras an automatic control and acquisition system has been developed as a PC-based stand-alone system, linked to the main acquisition system of RFX. The software has been written in the Labview (a trademark of National Instrument Corporation) graphical programming system, which has a high degree of modularity and flexibility. The full-time sequence required by the cameras is provided, so that a precise synchronization with the pellet injection will be possible. The output signal is digitized with 8-bit resolution by a frame grabber with 8-MByte onboard memory that also accepts nonstandard video rates with a maximum scan rate of 20 MHz (Data Translation DT3851). The images will be automatically displayed after the shot and saved on disk.

CONCLUSIONS

In view of the installation of a multiple pellet injector on RFX, an integrated diagnostic system has been designed to monitor the pellet trajectory and ablation rate. Two arrays of H_α detectors permit a complete 3D reconstruction of the pellet trajectory, and H_α detector measures the total emission from the pellet cloud, and a CCD camera views the pellet trajectory in the poloidal plane from a tangential port. The diagnostic will be used to characterize the pellet ablation processes in RFPs and to study the scaling of the penetration depth both with the plasma and the pellet parameters.

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