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Initial results from the lost alpha diagnostics on Joint European Torus

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Two devices have been installed in the Joint European Torus (JET) vacuum vessel near the plasma boundary to investigate the loss of energetic ions and fusion products in general and alpha particles in particular during the upcoming JET experiments. These devices are (i) a set of multichannel thin foil Faraday collectors and (ii) a well collimated scintillator, which is optically connected to a charge-coupled device. Initial results including the radial energy and poloidal dependence of lost ions from hydrogen and deuterium plasmas during the 2005-06 JET restart campaign will be presented. © *2006 American Institute of Physics.* [DOI: 10.1063/1.2217928]

I. INTRODUCTION

Magnetically confined fusion plasmas of the present and future rely on good confinement of energetic ions, e.g., injected neutral beams (NBI), ion cyclotron resonant frequency (ICRF) heating tail ions or fusion-produced alpha particles, to maintain efficient heating. The Joint European Torus (JET) has substantial NBI and ICRF capability, and may also conduct future experiments with deuterium-tritium (DT) plasmas that would generate 3.5 MeV alpha particles. Consequently, it is an ideal facility for the study of fast ion losses. In addition, the design and construction of a fast ion loss diagnostic for JET may have application to the International Thermonuclear Experimental Reactor (ITER). Accordingly, we have recently installed two fast ion loss diagnostic devices on JET. These consist of a set of thin Faraday foil collectors and a scintillator probe. Thin Faraday foil detectors, in which ions that are lost from a fusion plasma are detected as current to ground in a metallic foil near the plasma boundary, have been used to investigate ion losses on NSTX,[1] DIII-D,[2] and JET.[3] Similarly, scintillation detectors have been widely employed to study ion losses on TFTR,[4] NSTX,[5] and other machines.[6] The present devices are intended to study lost ions in general and *d-t* fusion product alpha particles in particular during the upcoming JET campaigns. The design and expected signal levels in these devices have been discussed in previous contributed papers to this conference series.[7,8]

II. FARADAY FOIL DETECTOR KA-2

The Faraday cup array will detect the current of fast ions at multiple poloidal locations, with a dynamic range from 1 nA/cm^2 to 10 mA^2 at a temporal resolution of 1 ms. The detectable range of α-particle energies is about 1–5 MeV. The energy resolution for 3.5 MeV α particles is estimated to

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FIG. 1. (Color online) Photograph of the JET Faraday foil lost ion diagnostic KA2 showing the five pylons.

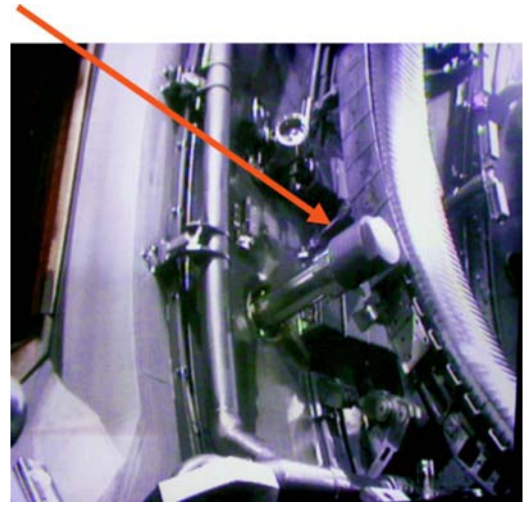

FIG. 2. (Color online) Photograph of the JET scintillator lost ion diagnostic KA3.

be about 15%–50%. The array has been installed in Octant 7 and consists of nine detectors spread over five poloidal locations between $z=22$ and 80 cm below the midplane. A recent photograph of KA2 indicating the five poloidally distributed foil sets is shown in Fig. 1. Radially, the detectors are equally spaced on three locations between 25 and 85 mm behind the adjacent poloidal limiter. Each detector consists of at least four 75×25 mm^2 Ni foils (2.5 μm in eight of the detectors and 1.0 μm in the ninth), which are separated by insulating mica foils. Depending on its energy, a particle can pass through a certain number of foils before it is stopped in one foil, thus causing a current signal. The detection of the temporal evolution of the current signals in all foils in the radially and poloidally distributed detectors will allow a map of particle energies at different locations.

III. SCINTILLATION DETECTOR KA-3

The scintillator probe has been installed in Octant 4, in a lower limiter guide tube (input slit: $z=-280$ mm, $\varphi=123.75°$, $R=3.799$ m). A photograph of the probe is shown in Fig. 2. The scintillator probe will allow the detection of particles with a pitch angle between 30° and 86° (5% resolution) and a gyroradius between 20 and 140 mm (15% resolution). It is located in the lower limited guide tube of Octant 4, about 28 cm below the midplane. The underlying principle of scintillator measurements is the emission of light by a scintillating material after a particle strikes this material. Selection criteria for the particles that hit the scintillator are introduced by using a set of collimators within the magnetic field of JET. An optical arrangement within the scintillator probe is used to transfer the light emitted by the scintillator towards a charge-coupled device (CCD) camera and a photomultiplier array through a coherent fiber bundle.

IV. INITIAL RESULTS

A. Faraday foil detectors

KA2 has observed lost ions during ICRH and NBI heating. Examples of results obtained during ICRH are shown in Figs. 3–6. In Figs. 3–5 we look, respectively, at the energy, and radial and poloidal dependences of lost ions during a 1.4 MW ICRF pulse (64556) with $B_T=2.5$ T and $I_p=2.0$ MA. The energy dependence, Fig. 3, in which the ions are largely stopped in the first three foils, is consistent with a flux of protons with a maximum energy of about 1.5 MeV.[9]

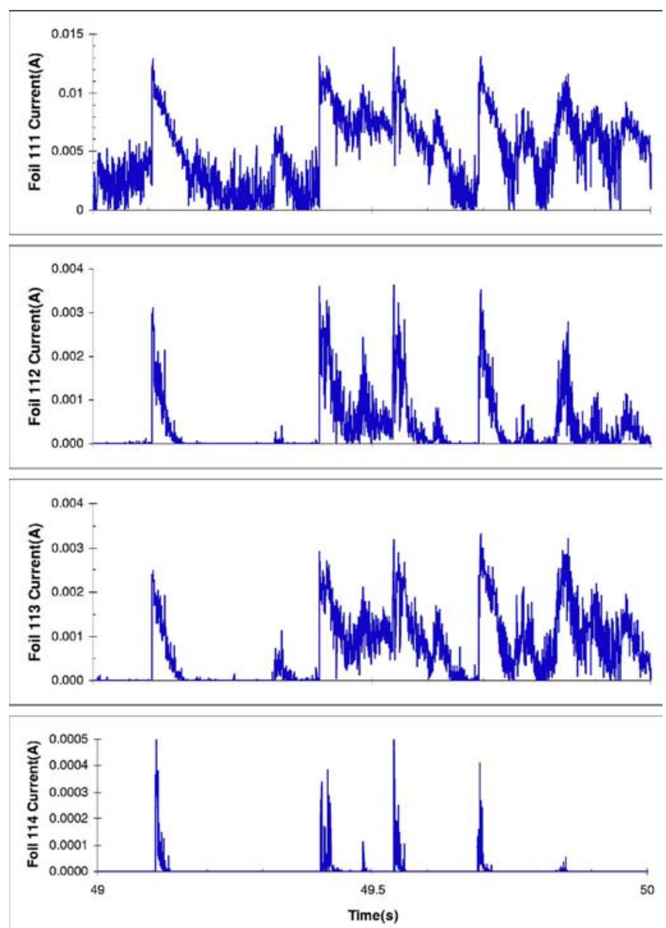

FIG. 3. (Color online) Comparison of currents in four successive foils 111, 112, 113, and 114 for JET pulse 64556 indicating energy discrimination capability of KA2. The energy of the proton flux is roughly 1.5 MeV.

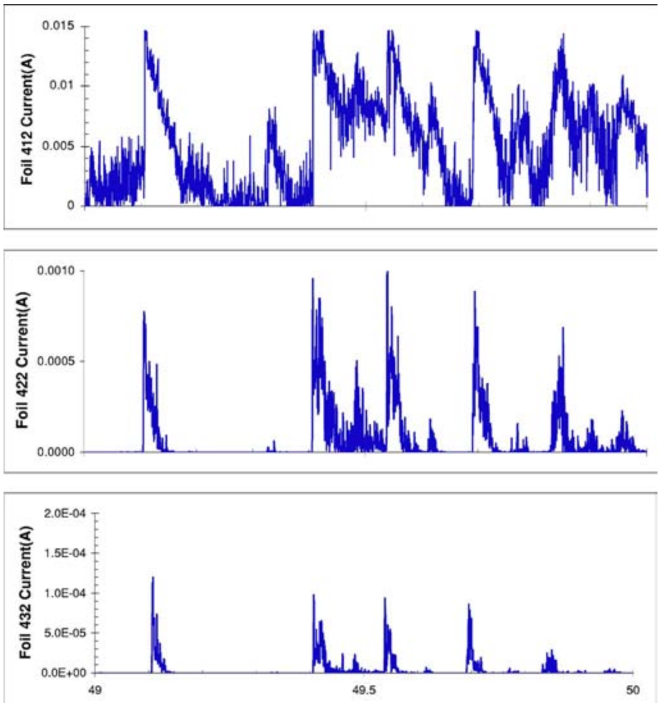

FIG. 4. (Color online) Comparison of currents in foils 412, 422, and 432 for JET pulse 64556 indicating radial dependence of lost ion flux.

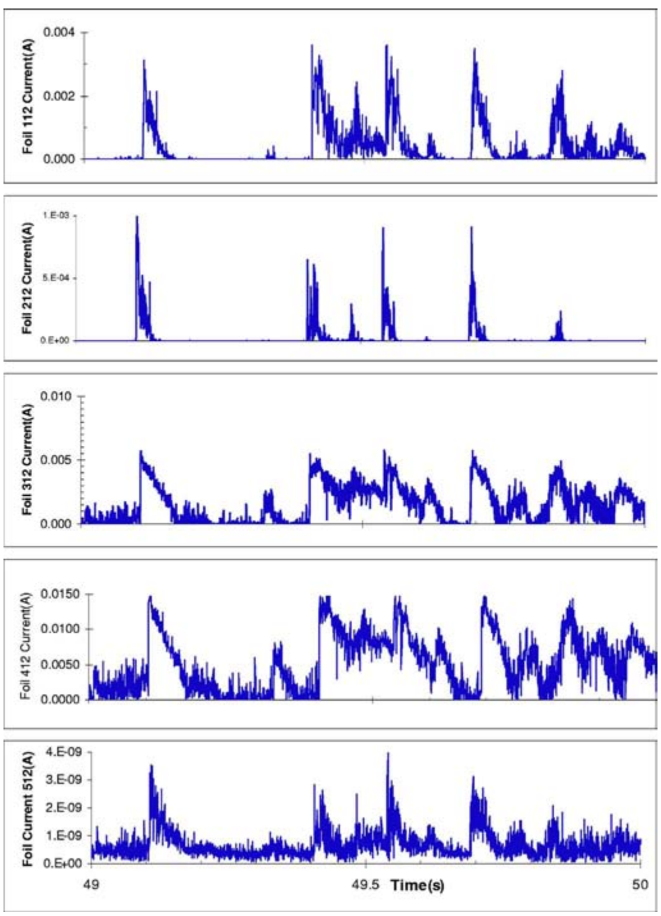

FIG. 5. (Color online) Comparison of currents in foils in pylons at poloidal angles 9° (top trace), 15°, 21°, 27°, and 33° (bottom trace) for JET pulse 64556 indicating poloidal dependence of lost ion flux.

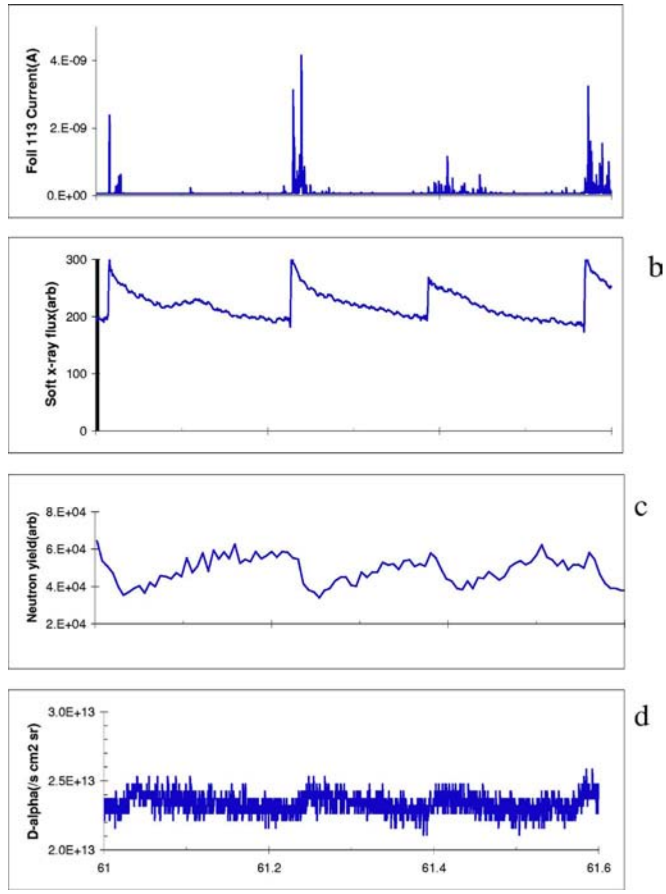

FIG. 6. (Color online) Comparison of current signal in KA2 (a) with soft x-ray flux at outer divertor (b) and neutron yield as measured in fission chamber (c) and edge D_α light (d) for JET pulse 65558.

The radial dependence, Fig. 4, indicates a drop-off of about a factor of 100 in flux proceeding from the foil set closest to the plasma to that farthest (a distance of 60 mm). The poloidal dependence, Fig. 5, shows a predominance of ion losses at pylons 3 and 4, which are at angles of 21° and 27° below the machine midplane. While we have yet to carry out detailed orbit calculations for energetic protons, we have completed detailed calculations of alpha particle orbits from *d-t* fusion plasmas as part of the KA2 design process.[7] It is interesting to note that these lost alpha calculations likewise predict a poloidal angle between 15° and 27°. In addition, it is interesting to compare the currents measured with KA2 to other diagnostic indicators consistent with ion losses. In Fig. 6, we compare the currents in foil 113 with the intensity of the edge D_α light, the soft x-ray signal, and the intensity of neutron production for JET pulse 65558 (B_T=2.2 T, I_P =2.0 MA, and P_{ICRF}=2.7 MW). Not surprisingly, current bursts as picked up in KA2 correspond to spikes in the x-ray and D_α signals and to a drop in the neutron production. Finally, we have observed an interesting correlation between neutron production rate versus plasma current and lost ion current versus plasma current during a series of very recent NBI "blip" experiments (JET pulses 65971–65977 with blips of 1.2 MW NBI power of 100 ms duration every ~500 ms, with the plasma current linearly decreasing with time between 50 and 60 s into the pulse). A comparison of NBI power, neutron yield, and ion current in foil 111 during one

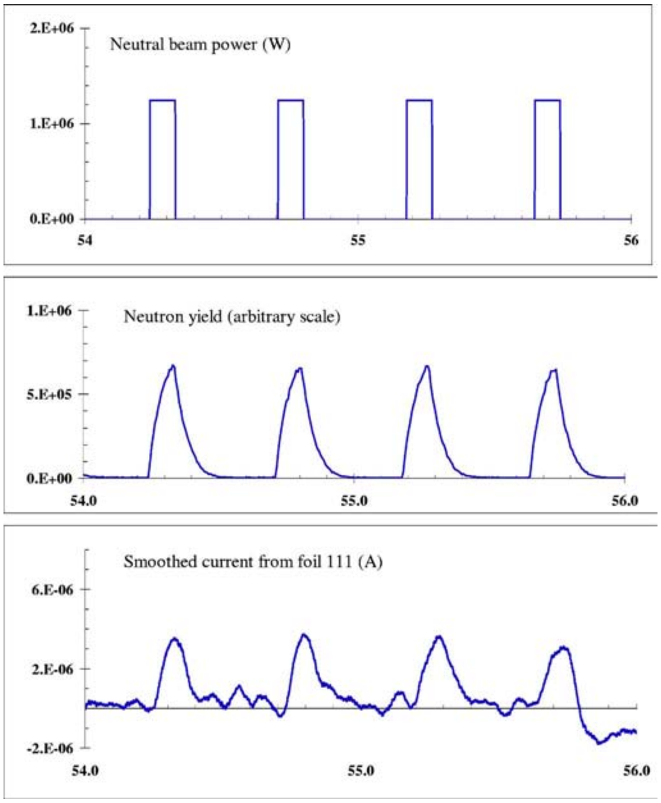

FIG. 7. (Color online) Comparison of NBI power, neutron flux measured in fission chamber, and smoothed current signal from KA2 foil 111 for JET pulse 65971.

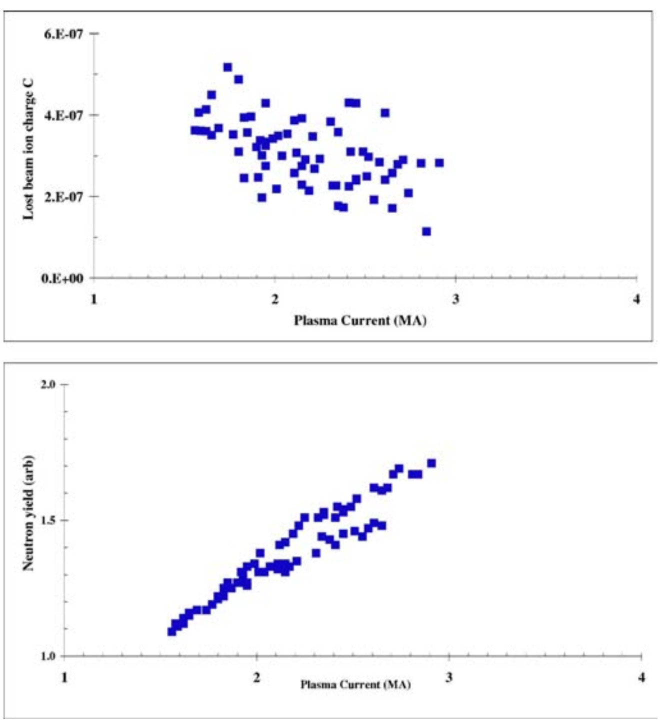

FIG. 8. (Color online) Comparison of neutron yield and integrated current in foil 111 vs plasma current during JET NBI blip pulses (for JET pulses 65971, 65972, 65975, 65976, and 65977). The foil currents and the neutron signals are integrated over a 200 ms time interval starting with the onset of each beam blip of the beam blips. The maximum neutron yield following each blip is about 3×10^{14} neutrons/s.

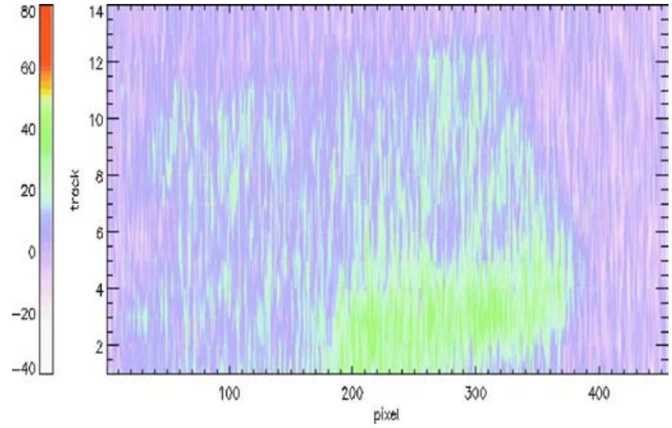

FIG. 9. (Color online) KA3 scintillator probe CCD image of JET pulse 65857 at 57.0 s.

of these pulses is shown in Fig. 7. The maximum energy of a proton stopping in the 2.5 μm foil 111 is about 400 keV. This is consistent with the neutral beam energy of 80 keV. The pitch angle of the entering protons relative to the local vertical is $20° \pm 15°$. These parameters are compared in Fig. 8, where there is an increasing correlation between reaction yield and I_p and a roughly decreasing correlation between foil current (lost beam ions) and I_p.

B. Scintillator detector

The scintillator detector has recently begun to generate images during JET pulses. One of the first images is shown in Fig. 9. In addition to CCD images of the scintillator, KA3 is able to measure the ion current onto the scintillator, using basically the same electronics as used by the foils in KA2. In Fig. 10 the current from foil 111 (the front foil of the radially innermost of the three foil sets in the top pylon) in KA2 is compared to the current incident upon the scintillator foil in the companion lost ion diagnostic KA3, which is roughly

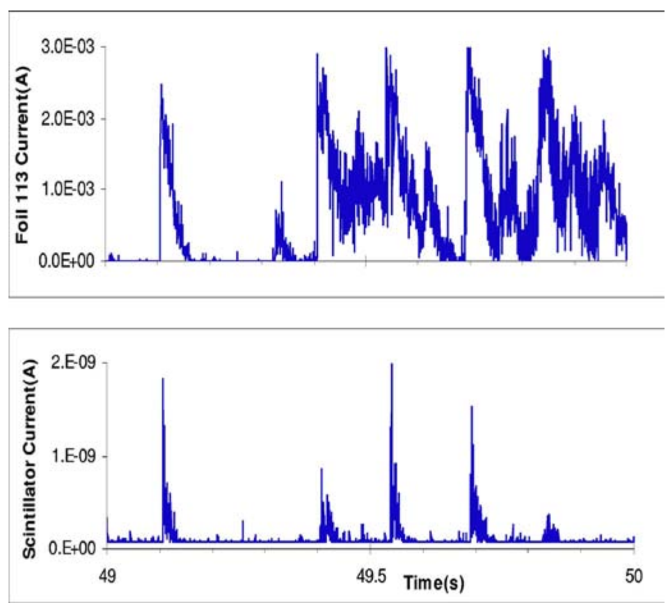

FIG. 10. (Color online) Comparison of current measured in Faraday foil detector KA2 (top) and scintillator probe KA3 (bottom) for JET pulse 64556.

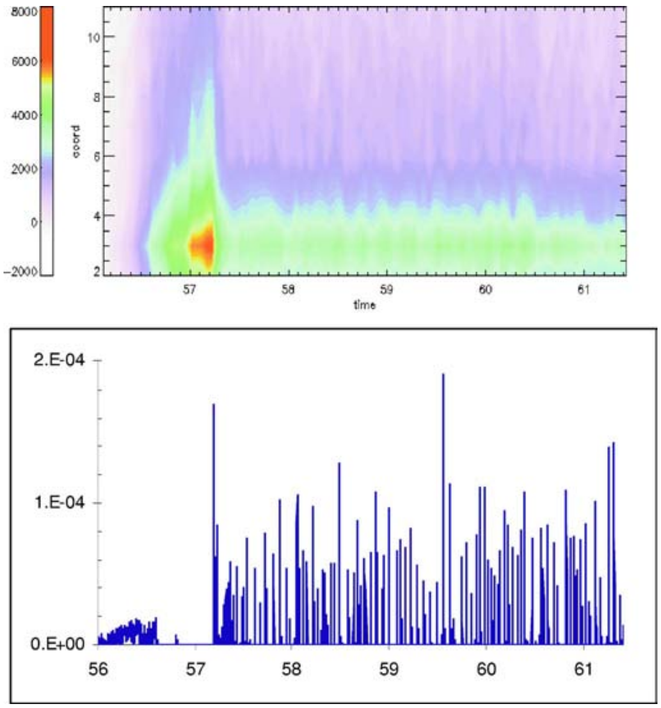

FIG. 11. (Color online) Comparison of energy distribution vs time from scintillator (top) and current in front Faraday foils in top pylon (bottom) in the region of sawtooth crash at 57.2 s for JET pulse 65857.

one-third the way around the torus from KA2. The KA3 current signal is correlated both with particle losses showing also on the CCD and with some of the signals picked up by the foils of KA2. These are very promising indications that both diagnostics, while different in design, will aid in explaining the same processes originating in the plasma. They will be complementing each other with good synergy. Finally, in Fig. 11, there is a comparison of the energy signal as a function of time obtained from the scintillator by integrating over the isoenergetic pixels at successive times with the currents from the front, second, and back Faraday foils in the top pylon. Although the contrast in the scintillator image is fairly low in Fig. 9, this integration yields a strong, clearly recognizable signal in Fig. 11. This is for JET pulse 65857, in which there is a sawtooth crash at about 55.2 s. In addition to the strong signals associated with this crash, there is a good correspondence at times of weaker signals as at 58.5 and 59.6 s.

V. DISCUSSION

Both the Faraday foil and scintillation lost alpha diagnostic detectors have been successfully installed in JET, and observations during initial commissioning plasmas indicate that both systems are properly working. The assessment of their performance limits is under way and will be extended using synergies that have been demonstrated.

ACKNOWLEDGMENTS

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