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Diagnosing fast ions in ITER by collective Thomson scattering

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Introduction. Here, we outline the main findings of a comprehensive study of the feasibility of measuring fusion alphas and other fast ions in ITER by collective Thomson scattering[1]. The measurement requirements for the confined fusion alphas in ITER[2, 3] demand a time resolution of 100 ms, a spatial resolution of one tenth the minor radius ($a/10$), and resolution of the full fusion alpha distribution from 100 keV to 3.5 MeV. The requirements on velocity space resolution are still to be defined.

Collective Thomson scattering (CTS) can provide spatially and temporally resolved measurements of the 1-D fast ion velocity distribution along a direction which depends on the scattering geometry[4]. In particular, the distribution parallel or near perpendicular to the magnetic field can be measured. The parallel distribution would bring out the dynamics of alphas on passing orbits, one sign of the velocity corresponding to motion in the co-direction (the direction of the plasma current) and the other sign to the counter-direction. CTS cannot distinguish an alpha particle from four deuterons moving with the same velocity. Measured distributions are thus a sum of the alpha and other fast ion distributions, each weighted by the square of the specie charge. Fast deuterons from NBI move in the co-direction and spread out in the perpendicular velocity space. Their energies reach 1 MeV and thus superimpose with the alpha distribution up to energies of 2 MeV in the co-direction and to a slightly lesser extent in the perpendicular direction. Recent studies[5] indicate that the beam ion contribution will generally not dominate the alpha contribution to the CTS spectra for the reference ELMy H-mode type discharge, while for the reference reversed shear discharge the co-traveling beam contribution can be comparable to the co-traveling alpha contribution in the plasma centre. Measurements in the counter direction would almost be free of beam contributions, and thus give essentially clear access to measuring that part of the alpha distribution in all plasmas. If the alpha distribution were, isotropic this measurement would suffice to define the velocity distribution. The fusion alpha distribution and its dynamics are in fact expected to be anisotropic, making measurements in the perpendicular and in the co-directions valuable despite the overlaid beam distribution. Here it is fortuitous that the interaction between a fast ion population, with a given velocity distribution, and the rest of the plasma, in particular wave particle interactions, is largely the same irrespective of whether the fast ions are alpha particles or deuterons. Thus, the dynamics observed in the perpendicular and co-directions will be common to beam deuterons and alphas.

With this background, we augment the measurement requirements with the need to resolve the parallel direction, co- and counter-, as well as the perpendicular direction. Further, we require that the velocity space resolution permits at least 8 velocity bins to be resolved either side of zero, i.e. for the parallel measurements we require at least 8 velocity bins be resolved in the counter-direction and 8 bins in the co-direction, and that with an uncertainty of less than 20 % of the average fast ion velocity space density.

From considerations of spatial resolution, plasma access, scattering cross section and current or potential availability of sources, the investigations can be limited to systems with probe frequencies in the ranges of 60 GHz, 170 GHz, 3 THz and 28 THz, which were all studied in Ref. 1. Here we summarize the findings for the 60 GHz and 28 THz systems.

60 GHz range. With a probe frequency near 60 GHz the fast ion distribution can be resolved in 16 velocity bins with and accuracy of 20 % for an alpha density down to $2\times10^{17}m^{-3}$. This is achieved with a temporal resolution of 100 ms, a spatial resolution of typically $a/10$, and near full radial coverage. Thus, this system satisfies the ITER measurement requirements. The system design is based on existing[6] or near term technologies, including the probe source assumed to be a long pulse gyrotron delivering 1 MW.

The upper electron densities at which the 60 GHz systems can meet the full set of diagnostic requirements are $1.3\times10^{20}m^{-3}$ for the parallel measurements and $1.2\times10^{20}m^{-3}$ for the perpendicular measurements, both at an electron temperature of 25 keV. These densities are at the Greenwald limit. At 35 keV, the density limits reduce to $1.0\times10^{20}m^{-3}$.

The 60 GHz system is the only system which can meet all the measurement requirements with existing or near term technology. The system requires one probe for measuring the full profile of parallel distributions and one probe for the profile of perpendicular measurements. A diagnostic for measuring the profile of the fuel ion ratio, n_D/n_T, can be integrated into the system, which resolves the perpendicular fast ion distributions. This would require no additional openings in the plasma facing components and no additional front end mirrors.

28 THz range (CO_2 laser). A CTS at 28 THz would use a CO_2 laser as the source for the probe[7, 8]. At this frequency, the geometry is limited to scattering angles around 0.5°. This implies that to measure the parallel velocity distribution and hence the counter-direction, where the beam ion population is negligible, the beam lines must pass vertically through the plasma. The small scattering angle gives rise to long scattering (measuring) volumes. To reduce the extent of the scattering volume and hence improve the spatial resolution, and to increase the signal strength, one seeks to reduce the widths of the probe and receiver beams. To achieve a scattering volume length of 50 cm corresponding to a relative resolution of $a/6$ (the ITER measuring requirement is $a/10$) a Gaussian beam radius of 1.3 mm is required. With such narrow beams, the velocity space resolution only permits a single velocity bin to be resolved either side of zero velocity, i.e. far short of the 8 bins we set as target and achieved with other systems. With only one bin resolved, the measurement would not constitute a measurement of the distribution but merely a weighted average over the counter-traveling part of the fusion alpha distribution. This limitation is due purely to the beam width and geometry and cannot be helped by increasing the probe power or pulse length. With a Gaussian beam radius of 2 mm, the spatial resolution is $a/4$ and the velocity space resolution permits two independent velocity bins to be resolved in the counter-direction. Achieving the target of resolving 8 velocity bins in the counter-direction requires a Gaussian beam radius of 1 cm (scattering angle reduced to 0.4° to compensate the reduced signal with wider beams) leading to a scattering volume length of 5 meters, i.e. resulting in no spatial resolution for the vertical beam line. The conclusion is that a CO_2 laser based CTS cannot resolve the fusion alpha velocity distribution in the counter-direction, where NBI ions are negligible, with a spatial resolution which meets the ITER measurement requirements.

To combine reasonable velocity space resolution with reasonable spatial resolution it is necessary to use a geometry where the probe and receiver beams are tangential to the toroidal direction. In this geometry, a spatial resolution of $a/4$ can be achieved together with a velocity space resolution providing 8 velocity bins either side of zero. The parallel velocity distribution cannot be measured, only the perpendicular distribution. While still short of the measurement requirements, it does represent an interesting diagnostic capability.

A 20 % relative uncertainty for an alpha density of $8\times10^{17}\text{m}^{-3}$ can be achieved with a probe pulse energy of 100 Joules and a pulse length of 1 μs. Achieving the measurement capability of the 60 GHz system, as required for the lower alpha density of $2\times10^{17}\text{m}^{-3}$, demands a pulse energy of 400 Joules. This at a pulse rate of 10 Hz to meet the ITER requirements. The CO_2 system benefits from not having any practical operational limits in density or temperature.

Discussion. The only CTS system which can meet the ITER measurement requirements for confined fusion alphas is the 60 GHz system. This includes measuring the fusion alphas in the counter-direction where there are essentially no beam ions. This is achievable with existing or near term technologies, the most demanding of which is the development of a 1 MW, long pulse gyrotron at 60 GHz. Such gyrotrons already exist for the more challenging higher frequency of 140 GHz. The technologies have been tested successfully on current machines. The system can meet the full set of measurement requirements for electron densities up to the Greenwald limit for the reference electron temperature of 25 keV. At higher temperatures, the CTS operational density limit is reduced such that the limit effectively is a beta limit, close to the plasma operational limits. Thus, it is not expected that this limit will be of practical consequence. The 60 GHz fast ion diagnostic can be combined with a fuel ratio diagnostic at 60 GHz which uses the same front ends as the 60 GHz fast ion diagnostic. A conceptual design of a fast ion 60 GHz CTS for ITER has been developed[1, 9]. The CO_2 laser system cannot meet the measurement requirements. In particular, the system cannot measure the velocity distribution of the fusion alphas in the counter direction with the required spatial resolution. Resolving 8 velocity bins leads to no spatial resolution, while resolving 3 velocity bins leads to a resolution of $a/2.5$. The CO_2 laser based system can measure the perpendicular distribution with a spatial resolution of $a/4$. A CO_2 laser based CTS does require significant source developments.

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