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A new fast-ion D_α diagnostic for DIII-D[a)]

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The fast-ion D_α (FIDA) technique is a charge-exchange recombination spectroscopy measurement that exploits the large Doppler shift of Balmer-alpha light from energetic hydrogenic atoms to infer the fast-ion density. Operational experience with the first dedicated FIDA diagnostic on DIII-D is guiding the design of the second-generation instrument. In the first instrument, dynamic changes in background light associated with plasma instabilities usually dominate measurement uncertainties. Accordingly, the design of the new instrument minimizes scattering of cold D_α light while monitoring its level. The first instrument uses a vertical view to avoid bright interference from the injected-neutral beams. The sightline of the new instrument includes a toroidal component but only measures blueshifted fast-ion light that is Doppler shifted away from the redshifted light of the injected neutrals. The new views are more sensitive to fast ions that circulate in the direction of the plasma current and less sensitive to the trapped-ion and countercirculating populations. Details of the design criteria and solutions are presented. *© 2008 American Institute of Physics.*
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I. INTRODUCTION

After initial tests showed that it was possible to measure a Doppler-shifted fast-ion feature in the wings of the bright Balmer-alpha line,[1] a dedicated instrument was designed and installed on the DIII-D tokamak to provide routine measurements of the fast-ion density.[2] In addition to this dedicated instrument, existing spectrometers were tuned to the blueshifted side of the D_α line for many experiments. A comprehensive instrument paper on the results from these instruments was recently published.[3] Spatial profiles from these instruments appear in several recent physics papers. Comparisons of the data from quiet plasmas with classical predictions validate the fast-ion D_α (FIDA) technique.[4] FIDA measurements are useful for diagnosing the acceleration of fast ions during wave heating.[5] Flattening of the fast-ion profile by Alfvénic instabilities has also been reported.[6,7] A pair of FIDA instruments[8] have been installed on the National Spherical Torus Experiment and began collecting data in 2008.[9]

From the point of view of instrumentation, the FIDA measurement resembles a laser-scattering measurement. The spectral intensity of the cold D_α line is many orders of magnitude brighter than the desired Doppler-shifted signal. The desired signal is produced by fast ions that undergo charge-exchange reactions with an injected-neutral beam. The spectral intensity from the injected neutrals is two orders of magnitude brighter than the desired signal. Thus, it is imperative to avoid interference from the bright light produced by cold and injected neutrals. The first-generation FIDA instrument[2,3] views the injected-neutral beam vertically from below the plasma. After a Czerny–Turner spectrometer that is centered on the cold D_α line disperses the light, an opaque bar in the focal plane blocks the light from the cold and injected neutrals. The remaining light is measured by a charge coupled device (CCD) camera.

In this paper, we summarize the operational lessons learned from the first-generation FIDA instrument (Sec. II); for further details, consult Ref. 3. A new instrument that is presently under construction will complement the existing instruments (Sec. III).

II. OPERATIONAL LESSONS FROM THE FIRST INSTRUMENT

Our first dedicated instrument uses a low-noise camera and views an intense ~30 A heating beam.[3] With this installation, read-out noise and photon counting statistics usually make negligible contributions to the measurement uncertainty. Uncertainties in background subtraction are the dominant source of error. The measured spectrum M has eight distinct contributions:

$$M = D_f + b + I_{cx} + i_{ncx} + d_{cold} + d_f + D_{inj} + D_{halo}, \qquad (1)$$

where D_f is the fast-ion signal (the desired spectrum), b is the visible bremsstrahlung, I_{cx} are the impurity lines that are excited by charge exchange with the injected beam, i_{ncx} are the intrinsic impurity lines, d_{cold} is the scattered D_α light from edge neutrals, d_f is the passive light from fast ions that interact with edge neutrals, D_{inj} is light from injected neutrals, and D_{halo} is light from the cloud of "halo" neutrals that surround the beam. Here, the upper-case symbols represent contributions that are *only* present when the injected beam is on, while the lower-case symbols represent contributions that are always present. In principle, the entire spectrum can be modeled and fitted but this requires accurate knowledge of every term in Eq. (1) and may introduce large systematic

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errors in the inferred D_f. For empirical background subtraction, there are two basic ways to remove the lower-case contributions. The first is to modulate the injected beam and the second is to measure light from an equivalent, toroidally displaced view that misses the beam. Either method introduces potential errors. Beam modulation assumes that the lower-case contributions are *temporally* constant. Equivalent views assume that the lower-case contributions are *toroidally* constant. Ideally, one uses both as a check on the consistency of the results. In the first-generation DIII-D instrument, beam modulation alone was employed.

The upper-case contributions I_{cx}, D_{inj}, and D_{halo} are not removed by either background subtraction technique. Charge-exchange impurity lines are fitted and subtracted from the spectrum. In DIII-D, where the dominant impurities are carbon and oxygen, the blueshifted side of the spectrum has fewer impurity lines than the redshifted side of the spectrum. For both sides of the cold D_α line, removal of the I_{cx} contribution seems to work well but the blueshifted spectra are considered more reliable.[3] The injected-neutral signal D_{inj} comes directly from the beam itself. In the first-generation instrument, the geometry of the sightline eliminated the Doppler shift of the injected neutrals so that the light from the injected neutrals could be blocked by an opaque blocking bar. The halo feature D_{halo} is produced by charge exchange of the injected beam with thermal ions, so its spectral width is modest compared to the fast-ion feature. Nevertheless, light from any of the upper-case sources that scatters in the instrument can contribute to the signal at fast-ion wavelengths; this scattered light is not eliminated by either background subtraction technique.

A major goal of the FIDA diagnostic is to measure the effect of instabilities on the fast-ion population. Transient instabilities alter the density profile, which alters the bremsstrahlung b, and often dump particles and energy into the plasma edge, which alters the cold D_α light d_{cold}, the passive fast-ion feature d_f, and the intensity of impurity radiation i_{ncx}. Instability bursts can violate the assumptions of either background subtraction technique. Beam modulation assumes temporal stationarity, which is obviously violated by a burst of magnetohydrodynamics activity. An equivalent view assumes toroidal symmetry, but most instabilities have toroidal variations; for example, imaging of D_α light during edge localized modes (ELMs) shows strong spatial nonuniformities.

In practice, with the present system, the most reliable measurements of the fast-ion spectrum D_f are obtained in stationary plasmas with a quiet edge. Reliable measurements during an ELM or other strong perturbation of the edge are virtually impossible; these time slices are usually discarded. Analysis of the data suggests that scattered cold D_α light d_{cold} causes most difficulties. In principle, once the optics are assembled, the scattered contribution at fast-ion wavelengths should be a fixed fraction of the edge-line intensities so, if their intensity is accurately measured, a correction for temporal changes in d_{cold} and i_{ncx} should be possible. Initially, we used an independent measurement of the cold D_α light with a fairly similar sightline to analyze this effect. The results[3] confirm the importance of scattering in the measured signal but, in practice, spatial nonuniformities in the D_α emission are too great for a reliable correction. It is essential to measure the cold D_α light along the same sightline as the primary measurement. Recently, we replaced the opaque blocking bar in the spectrometer focal plane with a narrow strip of OD3 neutral density filter. This is a convenient and economical expedient: we now obtain a direct measurement of the cold D_α intensity without saturating the CCD camera.

The implications of our operational experience for the design of future instruments is summarized below.

Spatial resolution. The intrinsic resolution of the technique is limited by the mean free path of the $n=3$ atomic energy level, which is a few centimeters for typical DIII-D densities and energies. Important physical scales (e.g., the fast-ion gyroradius, radial extent of fast-ion instabilities, or the radial extent of the fast-wave absorption layer) are not significantly smaller than this, so radial resolution of a few centimeters is adequate. Spatial scales in the vertical (poloidal) direction tend to be longer, so poorer vertical resolution is acceptable. In practice, radial channel-to-channel spacing of $\sim$4 cm appears adequate.

Spectral resolution. By spectroscopic standards, the spectral resolution can be poor. The intrinsic resolution of the technique is limited by Stark splitting, which is $\sim$1 nm in DIII-D. Also, because the Doppler shift is determined by only one component of the velocity, excellent resolution of the velocity-space dependence of the distribution function is impossible. Physically, the distribution function is not expected to have sharp features in velocity (except above the injection energy). Moreover, the FIDA measurement performs substantial averaging in velocity space[3,5] so, under ordinary circumstances, the spectral shape of the FIDA line D_f is nearly isomorphic.[4] On the other hand, a narrow instrumental response function does facilitate removal of impurity lines from the spectrum. In practice, the width of our instrumental response function is comparable to the Stark splitting; the observed spectra appear well resolved even with this relatively poor resolution. For most analysis, we integrate the D_f spectra over the wavelengths that comprise the fast-ion feature.

Temporal resolution. Physically, the distribution function can change at the frequency of an instability ($\sim$100 kHz for an Alfvén instability). Another consideration is the timescale for changes in background light, which is $\sim$0.1 ms. The present instrument has 1 ms resolution and, as expected, large changes in the spectra are observed in successive time bins. An ideal system would be faster. Light levels are adequate for 1 ms temporal resolution but, for faster resolution with good photon statistics, more light is needed.

Bright interference. The present instrument uses a vertical view and a blocking bar (or neutral density filter) to eliminate the bright cold D_α line and the light from the injected neutrals. Future installations are not restricted to vertical views, however. As long as the orientation of the sightline shifts the injected-neutral light into an uninteresting portion of the spectrum and this portion is filtered or blocked, other views are feasible. (An example appears in Sec. III.)

Scattered light. Scattered light from the cold D_α line

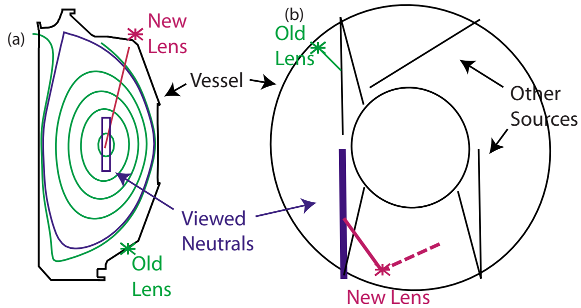

FIG. 1. (Color online) (a) Elevation of the DIII-D vessel, together with typical flux surfaces (curves), the vertical extent of the neutral-beam footprint (elongated box), and the positions of the new and old lenses (*). (b) Plan view of the vessel. The thick line represents the neutral beam source used by the measurement; the thin lines represent other sources that create fast ions. A sightline that intersects the injected beam in the midplane and its toroidally offset equivalent view (dashed) are shown, as is one of the sightlines for the original installation.

appears in the measured spectra of the present instrument. Future instruments must (a) minimize scattering and (b) monitor the cold D_α line along the measured view.

III. CONCEPTUAL DESIGN OF THE NEW INSTRUMENT

Figure 1 shows the geometry of the new views. The fibers collect light with both a vertical and a toroidal component. The radial positions of the views span from the outside of the plasma to the magnetic axis ($R=175-225$ cm). (The FIDA signal is proportional to the product of the injected-neutral density and the fast-ion density; because the injected beam attenuates, for the same fast-ion density, larger signals are anticipated at large major radius than at small major radius.) For an f-number of 1.8, the radial spot size at the midplane is $\sim$5 cm. The vertical resolution is determined by the vertical extent of the injected beam (and its surrounding halo), i.e., about 50 cm. In the radial and vertical directions [Fig. 1(a)], the new views resemble the existing vertical views; however, in the toroidal direction, the geometry is quite different [Fig. 1(b)]. DIII-D is equipped with four neutral beam boxes: three boxes inject in the direction of the plasma current, while one injects countergoing particles. The existing fibers view a cosource at a small toroidal angle to minimize the Doppler shift. The new fibers view a countersource from behind the source so that the injected-neutral light is redshifted. Only the blueshifted portion of the spectrum is utilized for the D_f measurement. For synchronous measurement of the background light, some fibers view in the opposite direction toroidally.

Figure 2 shows the geometry of the measurement from a different perspective. The two countersources create fast ions that have negative values of pitch $p=v_\parallel/v$. In contrast, under typical operating conditions, most of the fast ions are created by the cosources and have positive values of p. The new views measure photons that are emitted at a pitch that is very similar to the majority of fast ions created by the near-tangential cocirculating neutral beams (the most commonly used sources at DIII-D). Thus, these fast ions produce large blueshifts and will dominate the measured signal.

The portion of velocity space measured by the existing and new views is quantified in Fig. 3. As discussed in Ref. 5,

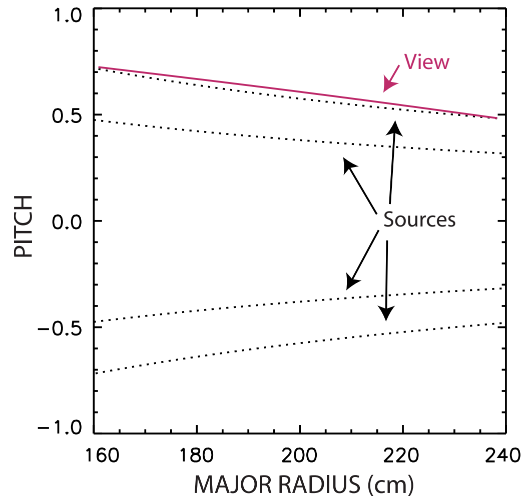

FIG. 2. (Color online) Pitch v_ϕ/v vs major radius R for the four beam geometries available on DIII-D (dotted lines) and for neutrals heading toward the collection lens shown in Fig. 1 (solid line).

it is convenient to quantify the velocity-space sensitivity of a fast-ion diagnostic by a weight function $W(E,p)$. (Here E is the energy of the fast ions and p is the pitch.) The measured signal is proportional to the convolution of this weight function with the fast-ion distribution function $\int(W\times F)dEdp$, where $F(E,p)$ is the distribution function. Figures 3(b) and 3(d) show the typical weight functions for an existing and a new view, respectively, at a particular wavelength. The chosen wavelength corresponds to the Doppler shift of a deuteron with 50 keV of energy that is entirely in the direction of the emitted photon. (We call this wavelength $E_\lambda=50$ keV.) Because the toroidal orientation of the new view is aligned with the pitch of the cogoing ions, the new view is sensitive to fast ions with $p\simeq 0.5$ and $E\simeq 50$ keV. In contrast, because the old view only measures the vertical component, its weight function is quite different. Figures 3(c) and 3(e) show the resulting integrand $W\times F$ for a case of exclusively coinjection with near-tangential sources. For the new view, the signal at this wavelength is dominated by 50 keV fast ions with the pitch of the injected neutrals. In contrast, for the old view, the signal is dominated by full-energy ($\sim$75 keV) fast ions. For this cocirculating fast-ion population, the spectral intensity of the new view should be twice as bright. In general, the new view is sensitive to the cocirculating population, while the old view detects all three classes of orbits: cocirculating, trapped, and countercirculating. Comparison of the views should prove useful in determining which portion of the fast-particle population interacts with various instabilities.

The instrumentation for the new diagnostic is illustrated in Fig. 4. The first major element is a bandpass filter with properties similar to those employed in a beam-emission spectroscopy (BES) diagnostic.[10] The long-wavelength edge of the filter is located to attenuate the unshifted D_α line by approximately three orders of magnitude in order to attenuate interference from d_{cold} while monitoring its level. To minimize scattering and maximize the signal, a transmission-grating spectrometer[11] is employed. The low-noise CCD camera[12] has 0.5 ms temporal resolution and accommodates

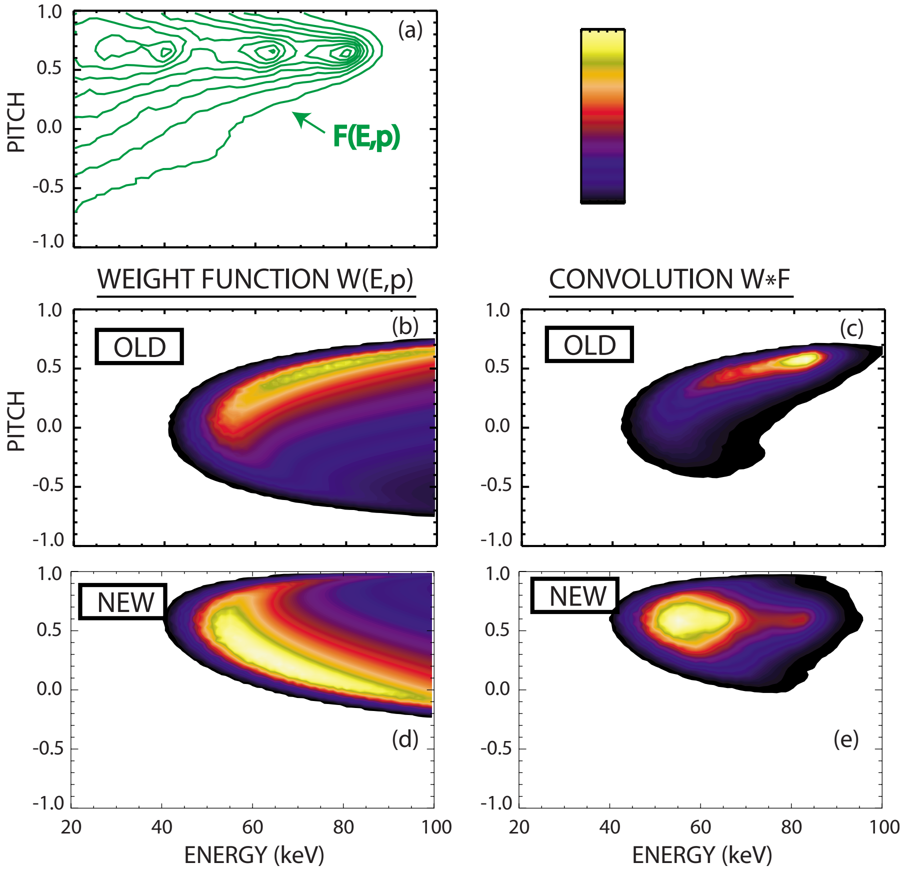

FIG. 3. (Color online) (a) Linear contours of a fast-ion distribution function $F(E,p)$ produced by injection of a co-going near-tangential source at $R = 180$ cm as calculated by TRANSP. (Ref. 13) Linear color contours of the weight functions $W(E,p)$ for a Doppler shift of 4.8 nm for (b) a vertical view and (d) the new view. Product of the illustrated distribution function with (c) the vertical weight function and (e) the new weight function. The calculation of W uses the assumptions and parameters described in the Appendix of Ref. 5.

eight spectra. The measured views are selected at a fiber patch panel. For detailed study of the fast-ion profile, radial positions that complement the existing nine radial positions are selected. For detailed study of the velocity-space dependence of the distribution function, fibers that view the same radii as the existing fibers are selected. For careful checking of background subtraction, some channels are devoted to toroidally displaced background views.

In addition to this primary instrument, a second instrument similar to the "fast" NSTX FIDA diagnostic[8,9] employs a bandpass filter and photomultipliers to measure changes in fast-ion density with ~0.1 ms temporal resolution.

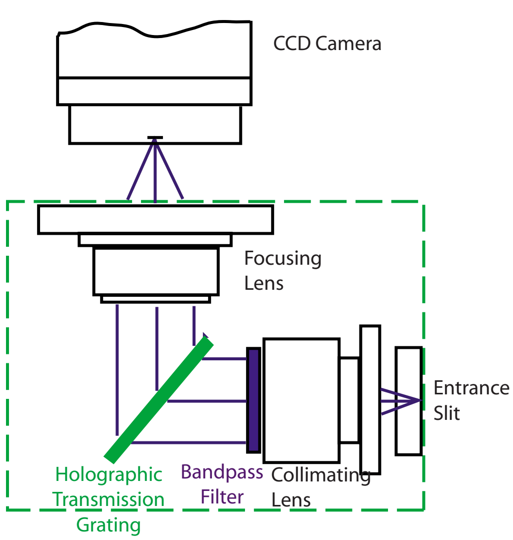

FIG. 4. (Color online) Schematic diagram of the new instrument.

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