D-Alpha Measurements of the Fast-ion Distribution Function in DIII-D*

W.W. Heidbrink (wwheidbr@uci.edu), Y. Luo,
University of California, Irvine
K.H. Burrell and the DIII-D Team
General Atomics

Hydrogenic fast-ion populations are common in toroidal magnetic fusion devices, especially in devices with neutral beam injection. As the fast ions orbit around the device and pass through a neutral beam, some fast ions neutralize and emit Balmer-alpha light. The intensity of this emission is weak compared to the signals from the injected neutrals, the warm (halo) neutrals, and the cold edge neutrals but, for a favorable viewing geometry, the emission is detectable. The intrinsic spatial resolution of the technique is ~5 cm for 40 keV/amu fast ions; the energy resolution is ~10 keV. In DIII-D experiments, we have measured the fast-ion velocity distribution and spatial profile under a wide variety of operating conditions. The technique is best suited for measurements of ~ 40 keV/amu hydrogenic fast ions but useful information on the confinement of 1000 keV deuterium beam ions in ITER may be obtainable.

Diagnosis of the fast-ion population is important because the fast ions are often a major source of energy, momentum, and particles for the plasma. Moreover, the fast-ion pressure and driven current can have a significant impact on macroscopic stability properties. Although dilute populations of fast ions often behave classically, intense populations can drive instabilities that redistribute or expel the fast ions from the plasma. This is often the case in experiments in the DIII-D tokamak, where anomalous fast-ion diffusion rates of approximately $0.5\text{~m}^2/\text{s}$ are commonly inferred during neutral beam injection [1]. In DIII-D, it is difficult or expensive to detect diffusion at this level using standard techniques [2].

Excited states of atomic hydrogen radiate the Lyman and Balmer series of spectral lines. The most familiar of these are the Lyman alpha line, which is a transition from the n=2 to n=1 energy level, and the Balmer alpha line, which is the $3 \rightarrow 2$ transition. Because Lyman alpha is in the ultraviolet, it is relatively difficult to measure but the Balmer-alpha transition emits a visible photon, which is easily measured with standard lenses, spectrometers, and cameras. Light from this transition is commonly called H-alpha or D-alpha.

Conceptually, the use of D-alpha light to diagnose a fast deuterium population is similar to the diagnosis of fast helium populations using charge exchange recombination spectroscopy [3]. Fast helium populations during ^{3}He neutral beam injection were measured on JET [4]. Alpha particles produced in deuterium-tritium reactions were measured on TFTR [5]. For spectroscopic measurements of either fast helium ions or fast hydrogenic ions, avoiding the bright emission from other sources is a major challenge. There are several populations of hydrogenic neutrals in a typical tokamak plasma: cold edge neutrals, injected neutrals, and thermal (halo) neutrals created when the injected neutrals undergo a charge-exchange reaction. Fortunately, for a judicious choice of viewing angle, the light from fast ions is Doppler shifted away from the bright light produced by the other neutral populations.

A paper that explains the diagnostic concept and presents the first observation of signals from fast ions was already published [6]. This paper also discusses several possible applications of the technique. After the first successful measurements using the existing charge-exchange recombination (CER) diagnostic, a dedicated instrument was assembled for this application;

* Supported by U.S. DOE subcontract SC-G903402 and DE-FC02-04ER54698.

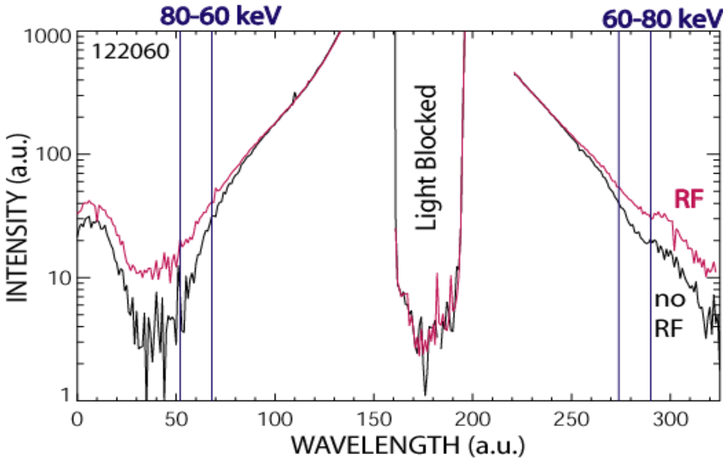

Figure 1. Spectra measured with and without 60 MHz, 4th harmonic ion cyclotron heating. Wavelengths that correspond to a perpendicular energy of 60 & 80 keV are marked.

an instruments paper [7] describes the design of this instrument. Data from this instrument and from spare CER channels were obtained during the 2005 experimental campaign. A wide variety of plasma conditions were diagnosed. Care is required to obtain fast-ion spectra that are free from pollution by halo neutrals, impurity line radiation, bremsstrahlung, and sudden changes in background light associated with ELMs. The data indicate that the achieved resolution was ~10 keV for energy, at least 10~cm spatially, and ~ 5 ms temporally. Figure 1 shows detection of fast ions that are accelerated above the injection energy (80 keV) during ion cyclotron heating experiments. Fast-wave heating at the fourth, fifth, and sixth harmonics accelerate fast ions above the injection energy; the profile data show that the acceleration is greatest near the cyclotron harmonic resonance layer. Pitch-angle scattering and slowing down of beam ions are studied by varying the injection energy, beam angle, plasma density, and electron temperature in MHD-quiescent plasmas. Comparison with neutral particle measurements indicate that neutral-particle diagnostics are much more sensitive to pitch-angle scattering than the D-alpha measurements. In plasmas with instabilities, the spatial profile is often flatter than classically predicted. The spatial profiles in plasmas with internal transport barriers, with helical magnetic perturbations from a nonaxisymmetric coil, and with cascade, toroidicity-induced, and compressional Alfven eigenmode activity are also measured. The 2005 physics results will be published in papers by Luo and Heidbrink.

References

[1] HEIDBRINK, W.W., et al., Nucl. Fusion **42** (2002) 972.
[2] HEIDBRINK, W.W., et al., Rev. Sci. Instrum. **74** (2003) 1743.
[3] POST, D.E., et al., J. Fusion Energy **1** (1981) 129.
[4] VON HELLERMANN, M.G., et al., Plasma Phys. Cont. Fusion **35** (1993) 799; GERSTEL, U., et al., Plasma Phys. Cont. Fusion **39** (1997) 737.
[5] MCKEE, G., et al., Phys. Rev. Lett. **75** (1995) 649.
[6] HEIDBRINK, W.W., et al., Plasma Phys. Cont. Fusion **46** (2004) 1855.
[7] LUO, Y., et al., Rev. Sci. Instrum. **75** (2004) 3468.