Design of a D-alpha beam-ion profile diagnostic

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Injected neutral beams ionize to create a population of beam ions. As they orbit around the tokamak and pass through the heating beams, some beam ions re-neutralize and emit D-alpha light. The intensity of this emission is weak compared to the signals from the injected neutrals, the warm (halo) neutrals, and the edge recombination neutrals but, for a favorable viewing geometry, the emission is Doppler shifted away from these bright interfering signals. Preliminary data from the DIII-D tokamak show that signals from re-neutralized beam ions have already been detected. A three-channel prototype instrument consisting of a spectrometer, mask, camera lenses, and frame-transfer charge coupled device is under development for measurements of the spatial profile of the beam ions. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1784533]

I. INTRODUCTION

One of the most common forms of plasma heating in magnetic fusion devices is the injection of hydrogenic neutral beams. The injected neutrals ionize in the plasma, and execute orbits in the confining magnetic field. As the beam ions gradually thermalize, they form a population of energetic ions in the plasma A number of existing techniques[1] provide information about the beam distribution function. Diagnosis of the beam population is important because the neutral beams often are a major source of energy, momentum, and particles for the plasma. Moreover, the beam-ion pressure and driven current have a significant impact on macroscopic stability properties. Intense populations of beam ions can drive instabilities that redistribute or expel the beam ions from the plasma.[2] This is often the case in experiments in the DIII-D tokamak, where anomalous beam-ion diffusion rates of approximately $0.3 \text{ m}^2/\text{s}$ are often observed.[3] In DIII-D, it is difficult or expensive to detect diffusion at this level using the standard techniques.[4]

There are four populations of hydrogenic neutrals in a typical tokamak plasma: edge neutrals, injected neutrals, halo neutrals, and neutrals from fast ions. Halo neutrals are created when injected neutrals charge exchange with plasma ions, producing a "halo" of thermal neutrals around the injected beam. Some beam ions that orbit through the injected beam neutralize, creating the "re-neutral" population. Excited states from these populations radiate the Balmer series of spectral lines. The Balmer-alpha line, which is a transition from the $n=3$ to $n=2$ energy level, is in the visible range. It can be easily measured with standard lenses, spectrometers, and cameras. The Balmer-alpha transition is also known as H-alpha light or, in the case of deuterium atoms, D-alpha.

The goal of this diagnostic is to measure D-alpha light from re-neutrals to extract information about the beam-ion profile.

In a companion article,[5] the utility of D-alpha light for the diagnosis of beam ions is demonstrated. With a judicious choice of viewing angle, the D-alpha emission from re-neutralized beam ions is Doppler shifted away from the bright emission of recycling and injected neutrals. Simulations indicate that the intrinsic spatial resolution of the technique is determined primarily by the lifetime of the excited neutrals and is ~5 cm. The companion article also presents results from initial data acquired with one of the charge exchange recombination[6] spectrometers. Those results are summarized briefly in Sec. II. The focus of this article is the hardware design goals of an optimized instrument (Sec. III). The actual design of a prototype diagnostic for DIII-D is described in Sec. IV.

II. INITIAL DATA

The primary auxiliary heating source at DIII-D is a set of 80 keV deuterium neutral beams that are injected tangentially at the midplane of the torus (Fig. 1). In the initial experiments, a fiber with a radial sightline viewed the 30° neutral beam. In this geometry, the injected neutrals are traveling away from the fiber. To avoid the bright redshifted emission from the injected neutrals, the spectrometer wavelength was tuned to the blue side of the D-alpha transition. The 30° neutral beam source is modulated with a 50 Hz square wave to distinguish background light from the emission produced by the injected beam. The spectrum (Fig. 2) contains two distinct features: a broad feature between 651 and 654.5 nm produced by re-neutralized beam ions and the strong, approximately thermal line above 655 nm produced by warm halo neutrals. The background produced by visible bremsstrahlung is weak in this low density plasma but is an order of magnitude larger than the re-neutral feature at high density. The observed temporal evolution and electron den-

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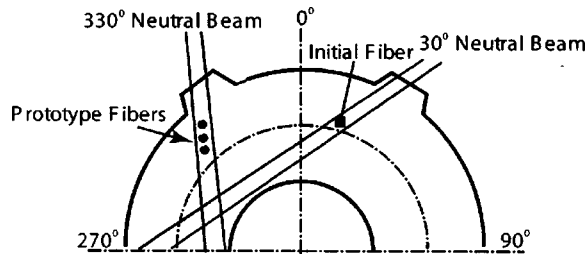[a]Author to whom correspondence should be addressed; electronic mail: yadongl@uci.edu

FIG. 1. Plan view of the DIII-D tokamak showing the paths of the injected neutral beams from the modulated sources, the viewed region for the initial measurements from the radially viewing 15°R0 port (Sec. II), and the viewed region for the prototype diagnostic from the vertically viewing 315°R-2 port (Sec. IV).

TABLE I. Design goals for D-alpha beam-ion diagnostic.

Wavelength range	648–663 nm
Unwanted portion of light	~2 nm
Spectral resolution	~0.5 nm
Minimum integration time	<1 ms
Spatial resolution	5 cm
Throughput	As high as possible

sity dependence of these features confirm their identification. The initial data highlight the importance of a high throughput optical system to facilitate accurate subtraction of the visible bremsstrahlung background. With a high throughput instrument on the Tokamak Fusion Test Reactor, a signal from alpha particles that was <1% of the visible bremsstrahlung emission was successfully measured.[7]

III. DESIGN GOALS

The design goals for an optimized instrument are summarized in Table I. The D-alpha line is at 656.1 nm. The D-alpha emission from re-neutrals is Doppler shifted. The largest shift is about 6 nm corresponding to the largest fast-ion velocity, which is 2.8×10^6 m/s for an 80 keV deuteron. Thus, the beam ion signal spans from 650 to 662 nm. Our system is designed to measure 648–663 nm wavelength range. Since the Stark splitting leads to ~1 nm spread and does not contain any information about the beam-ion distribution function, only relatively coarse spectral resolution (0.5 nm) is required.

The bright signals from recycling, injected, and halo neutrals are several orders of magnitude brighter than the desired signal from re-neutralized beam ions, so the required

dynamic range for the detection system is a challenge. One approach is to oversample very rapidly to avoid detector saturation, then accumulate many time bins to extract the desired signal. Another approach is to filter the unwanted bright features. The cold edge neutrals radiate near the unshifted D-alpha line. The D-alpha signal from warm halo neutrals has a Doppler shift of 1.5 nm, so it is also close to the unshifted D-alpha line. The Doppler shift of the D-alpha signal from injected neutrals can be as large as 6 nm due to their large velocity but, if the sightline is perpendicular to the beam, there is no Doppler shift for the injected neutral signal. Therefore, for this favorable geometry, all of the interfering signals from halo neutrals, edge neutrals, and injected neutrals are around the unshifted D-alpha line with a spread of <3 nm. Either a notch filter or a mask at the focal plane of the spectrometer can be employed to block this portion of the light.

The intrinsic spatial resolution of this diagnostic is ~5 cm so this is the desired resolution of the collection optics.

Background subtraction is essential for this diagnostic because visible bremsstrahlung and impurity radiation can be large compared to the desired signal. Typically, the modulated beam on DIII-D is on and off for 10 ms, so the maximum acceptable integration time is 10 ms. Instabilities such as edge localized modes can modify the background on a 1 ms time scale, so temporal resolution of <1 ms is needed to facilitate accurate background subtraction.

High throughput is important so that photon counting statistics do not degrade the accuracy of background subtraction.

IV. PROTOTYPE INSTRUMENT

The viewing geometry is presented in Fig. 1. Light is collected from multiple sightlines through the plasma. Three vertical views at the 315R-2 port are available for our D-alpha beam ion prototype diagnostic. The fibers looking at the 330° left neutral beam cross the beam centerline at major radii of 179.7, 196.4, and 212.2 cm.

The main elements of the instrument are the collection optics, the spectrometer, and a charge coupled device (CCD) camera. The spectrometer and detector system are designed with maximum light gathering power at the D-alpha wavelength, subject to the constraints of matching the optics on the tokamak. The f/number of the spectrometer should match the f/number of the collection lens; that way we can couple the optical fibers directly to the spectrometer. Otherwise, we need to put in a lens system to convert the f/number, which causes a loss of light due to reflection at the lens surfaces.
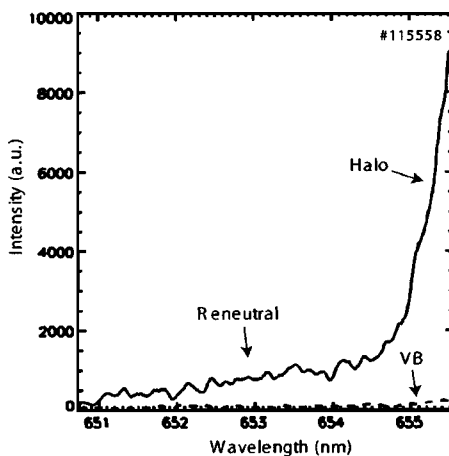

FIG. 2. Spectrum after background subtraction (solid line) from a 10 ms beam pulse into a DIII-D plasma with a line-average electron density of 2.3×10^{19} m^{-3}. The background during a 10 ms beam-off time bin is also shown (dashed line). The feature near the unshifted D-alpha line at 656.1 nm is produced by warm halo neutrals, the broad feature on the left side of the spectrum is produced by re-neutralized beam ions, and the background is primarily from visible bremsstrahlung.
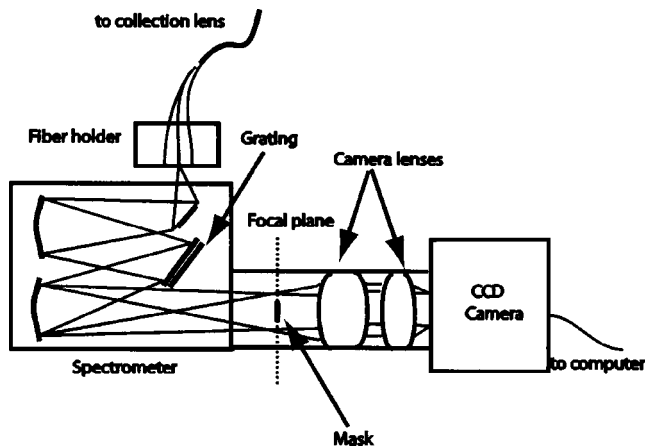
FIG. 3. Schematic diagram of the optical system.

The D-alpha signal detected by the CCD camera is proportional to the slit width. The resolution is proportional to the groove density of the grating in the spectrometer but inversely proportional to the slit width. If we keep the resolution constant, the larger the groove density, the more signal we can detect. The groove density is subject to two constraints. The first one is dispersion. If dispersion is too high, we have trouble demagnifying the image to fit our CCD chip. The second constraint is the optimum range of operation for the gratings. Generally high groove density gratings are optimized for short wavelength.

The experimental arrangement for our prototype diagnostic is presented in Fig. 3. The collection lens has a f/number of about 4.4. The light is imaged onto the 1.5 mm core diameter fibers. The fibers then transmit the light to the 300 mm Czerny–Turner spectrometer SP-2356 from Acton Research Corporation[8] ($f/4$, 1800 g/mm grating). It has a micrometer controlled entrance slit. We can increase the signal by opening up the slit at the expense of spectral resolution. When we use a 100 μm slit width, the resolution is ~0.5 nm. The dispersion is 1.4 nm/mm. The image at the focal plane of the spectrometer is 11 mm wide. We put a mask in this focal plane to block the 2 nm portion of interfering light near 656 nm. An image reducer consisting of a $f/3$ and $f/2$ 35 mm camera lens is put between the spectrometer and the CCD camera to shrink the image to 7.3 mm,

which fits our CCD chip (8 mm × 6 mm). The CCD camera (The VelociCam™ VC105A) from PixelVision™[9] has a high readout rate (2.2 MHz) and digitizes 14 bits. It has four readout nodes capable of accommodating four spectra with one on each quadrant of the chip without cross talk. In this prototype design, we put two spectra on the CCD chip with one on the upper half and one on the lower half in order to simplify the mask design. It can be easily upgraded by modifying the mask and camera lenses. The image area of the CCD chip consists of 652 vertical columns with 488 pixels in each column. Each pixel is square, 12 μm on a side. The detector is back illuminated with a quantum efficiency of 84% at D-alpha wavelength. The camera is cooled by a two-stage thermoelectric cooler to about 230 K. The data are digitized within the camera and are transferred via fiber optics to a PC, where the data are acquired.

Measurements of D-alpha emission are a tehhnique for measurement of beam-ion density profiles. Based on encouraging results from a preliminary test, a prototype diagnostic system has been designed. This prototype instrument spans the entire wavelength range of D-alpha light emitted by re-neutrals. If the instrument works well, a 12-channel spatial array will be based on this design.

ACKNOWLEDGMENTS

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