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High-throughput charge exchange recombination spectroscopy system on MAST

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A major upgrade to the charge exchange recombination spectroscopy system on MAST has recently been implemented. The new system consists of a high-throughput spectrometer coupled to a total of 224 spatial channels, including toroidal and poloidal views of both neutral heating beams on MAST. Radial resolution is ~1 cm, comparable to the ion Larmor radius. The toroidal views are configured with 64 channels per beam, while the poloidal views have 32 channels per beam. Background channels for both poloidal and toroidal views are also provided. A large transmission grating is at the heart of the new spectrometer, with high quality single lens reflex lenses providing excellent imaging performance and permitting the full exploitation of the available etendue of the camera sensor. The charge-coupled device camera chosen has four-tap readout at a maximum aggregate speed of 8.8 MHz, and it is capable of reading out the full set of 224 channels in less than 4 ms. The system normally operates at 529 nm, viewing the C^{5+} emission line, but can operate at any wavelength in the range of 400–700 nm. Results from operating the system on MAST are shown, including impurity ion temperature and velocity profiles. The system's excellent spatial resolution is ideal for the study of transport barrier phenomena on MAST, an activity which has already been advanced significantly by data from the new diagnostic. [DOI: 10.1063/1.2354309]

INTRODUCTION

The use of charge exchange recombination spectroscopy (CXRS) for measuring ion temperature and rotation profiles is well established in the tokamak field. Indeed, CXRS has already been used effectively on both the START and MAST spherical tokamaks.[1] Advances in MAST performance[2] have produced plasmas with high temperatures and toroidal velocities (in excess of 2.5 keV and 300 km/s), combined with very short profile gradient scale lengths. In order to diagnose these discharges effectively, an upgrade of the CXRS system has been undertaken, to deliver T_i and v_i profiles at high spatial and temporal resolution. The design process included a review of existing diagnostics (e.g., Ref. 3) along with an assessment of recent advances in optical technology. Every component in the CXRS system was considered and a completely new system has been implemented. The new diagnostic is configured to handle T_i values up to 5 keV and v_i values up to 500 km/s, with 5 ms time resolution and 1 cm spatial resolution. Extremely high throughput has been achieved, and a single spectrometer is used to record data from 224 spatial channels simultaneously. This article describes the key elements of the new CXRS system on MAST.

TOKAMAK VIEW SELECTION

To obtain the best possible spatial resolution, new off-midplane holes were cut into the vacuum vessel for the toroidal views, providing optimal views of both the heating beams deployed on MAST. Moving the views out of the plane of the beams also eliminated a problem experienced with the previous diagnostic, whereby bright edge emission from the secondary beam interfered with the weaker core emission from the primary beam.

In addition to these new toroidal views, poloidal views were also added for both beams. The optimum solution for these was found to be in-vessel lenses mounted onto the poloidal-field coil support brackets. The new toroidal and poloidal views are depicted in Fig. 1.

COLLECTION LENSES

Custom collection lenses have been designed for the toroidal views to accommodate up to 80 optical fibers per row, with the ability to stack multiple rows where necessary. The two lenses which view the beams are each currently populated with 64 fibers in a single row. A third toroidal lens is configured to measure the background, with up to 32 fibers (presently 28 fibers are set aside for background, and 2 each

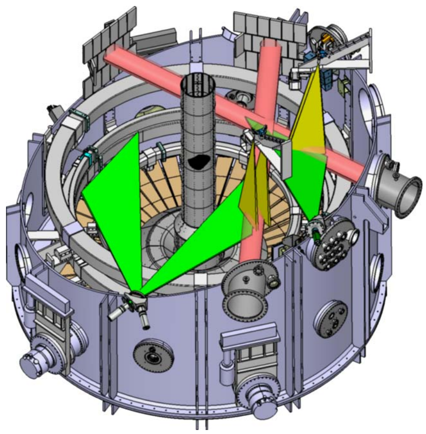

FIG. 1. (Color online) Schematic of MAST, depicting the new CXRS views and the heating beams (green: toroidal, yellow: poloidal, and pink: heating beams).

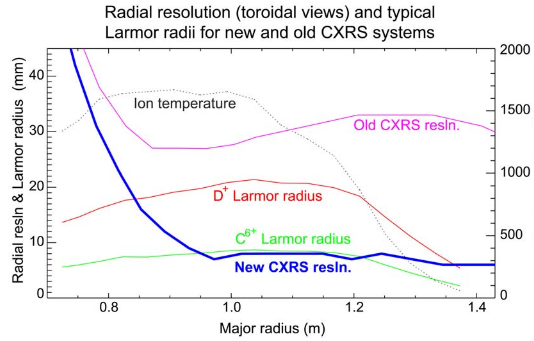

FIG. 2. (Color online) Comparison of the spatial resolution of old and new CXRS systems with typical ion Larmor radii for bulk and carbon ions (the corresponding T_i profile is overlaid for reference).

for a radial view and a calibration input). The focal length of each lens is 80 mm, with the stop positioned at the very front of the lens for optimal coupling through the vacuum window. Light is coupled into the fibers at $f/2$, with the focal plane gently curved to facilitate telecentricity and optimize the fiber coupling.

For the poloidal views, a pair of custom collection lenses views each heating beam in a vertical plane, coupling light into short in-vessel fiber bundles; the light is then coupled through the vacuum boundary with a lens-based optical feedthrough. Each lens is fitted with 32 CXRS fibers, 16 of which sample the beam while the rest sample the background. The lenses are also populated with an extra row of 32 fibers to permit additional impurity spectroscopy. At present, the spectrometer has capacity for the poloidal channels from a single beam at a time (i.e., 64, being 32 each for beam and background).

SPATIAL RESOLUTION

The position of the new toroidal views was optimized such that the lines of sight are almost exactly tangential to the flux surfaces as they intersect the neutral beams, allowing the best possible spatial resolution to be achieved. The collection optics were designed to take full advantage of this: with 400 μm fibers the radial extent of the collection volume is $\leqslant$1 cm for the channels between the magnetic axis and the plasma edge.

This spatial resolution is comparable to or smaller than the ion Larmor radius (see Fig. 2), making it ideal for studying short scale length phenomena, like those observed in internal transport barrier scenarios on MAST. The poloidal views were designed to match this, also achieving $\sim$1 cm resolution.

FIBER BUNDLES

Optical fibers of 32 m length link the collection lenses to the spectrometer, which is situated behind the MAST shield wall. The fiber used is 400/425 μm core/cladding diameter hard-clad fiber, with a nominal numerical aperture of 0.39. To simplify assembly and alignment at the collection lenses and spectrometer, bundles of 8×1 are used, with a total of 28 bundles being coupled into the spectrometer. The bundles are ferruleless to permit tight two-dimensional stacking at the collection lenses.

SPECTROMETER

A schematic of the spectrometer is shown in Fig. 3. The design allows for any operating wavelength in the range of 400–700 nm to be selected simply by moving the output arm of the spectrometer, rotating the grating appropriately, and replacing the bandpass filter. The key components of the spectrometer are briefly described below.

Fiber array and entrance slits. The fibers are arranged in seven columns, each of 32 fibers in height, with the entrance slits placed in direct contact with the fiber array. Straight slits are used, with (at present) a slit width of 200 μm. The slits were laser cut from 25 μm stainless steel shim.

Shutter. A ferroelectric liquid crystal (FLC) shutter has been designed into the system, positioned just after the slits. Its purpose is dual: firstly to prevent smearing during frame-transfer operations on the charge-coupled device (CCD) detector, and secondly to allow us to take best advantage of short notches in the heating beam power in order to quantify the level of background emission from the plasma. The shutter is very fast, with a 10%–90% time of $\sim$35 μs. A disadvantage is that the shutter contains polarizers and thus has a net transmission for unpolarized light of approximately 35%.

Lenses. The spectrometer lenses are both high-end single

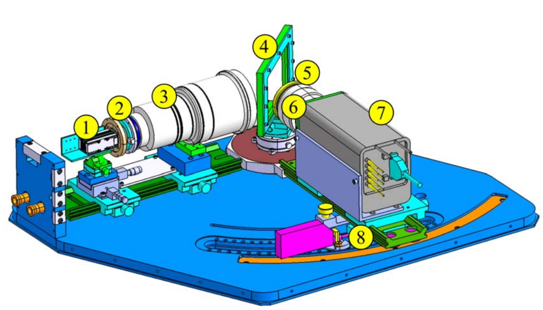

FIG. 3. (Color online) Schematic of the new CXRS spectrometer: (1) fiber mount, (2) FLC shutter, (3) collimating lens, (4) grating, (5) bandpass filter, (6) focusing lens, (7) CCD camera, and (8) movable output arm and actuator.

lens reflex (SLR) models from Canon, EF 200 mm/1.8 L (200 mm focal length, $f/1.8$) and EF 85 mm/1.2 L, for a demagnification ratio of $\sim$2.35. These lenses have superb image quality and very flat image planes; the overall point spread function of the system is $\sim$30 μm full width at half maximum (FWHM). Light is extracted from the fibers at $\sim f/3$, with the apparent excess speed of the $f/1.8$ collimating lens being put to good use by providing enhanced off-axis coupling efficiency and a near-telecentric input from the fibers. This greatly improves the utilization of the precious detector etendue.

Grating. A holographic transmission grating from Kaiser Optical Systems is used. This is quite large (active region $\sim 100 \times 150$ mm^2) and has very high diffraction efficiency of $>$80%. Since the FLC shutter polarizes the light, the grating was optimized for best efficiency for a single polarization.

Bandpass filter. The use of a bandwidth-limiting component permits multiple side-by-side entrance slits to be utilized without spectral overlap. A large (75 mm clear diameter) thin-film interference filter was procured from Barr Associates. The five-cavity design selected offers a near-top-hat band shape. The filter bandwidth is 3 nm FWHM, and the transmission achieved is very high, at $>$75%. Studies showed that the tolerances on the filter center wavelength (CWL) were highly critical to the performance of the system as a whole (poorer tolerances mean the spectral separation of the channels must increase to prevent overlap), so tolerances of 5% of FWHM on both CWL and FWHM were attained. This *doubled* the system throughput achievable with 20% tolerances.

CCD camera. A "BioXight" unit from Pixelvision is used. This camera has a 652×488 pixel sensor, with 12 μm pixels, and four-tap readout with each tap running at 2.2 MHz, with 14 bit analog-to-digital converters (ADCs). The sensor is back illuminated, with QE$>$80%. The entire camera readout sequence (binned into 32 rows) including the frame-transfer operation takes less than 3.5 ms, although the system is generally operated at 5 ms frame period to match the 200 Hz Thomson scattering diagnostic on MAST.

Linear actuator. The excellent optical acuity of the system means that the instrument functions are quite steep sided (10%–90% in $\sim$3 pixels), so the spectrometer design incorporates a linear actuator to microstep the position of the camera arm, permitting subpixel measurements of the instrument functions.

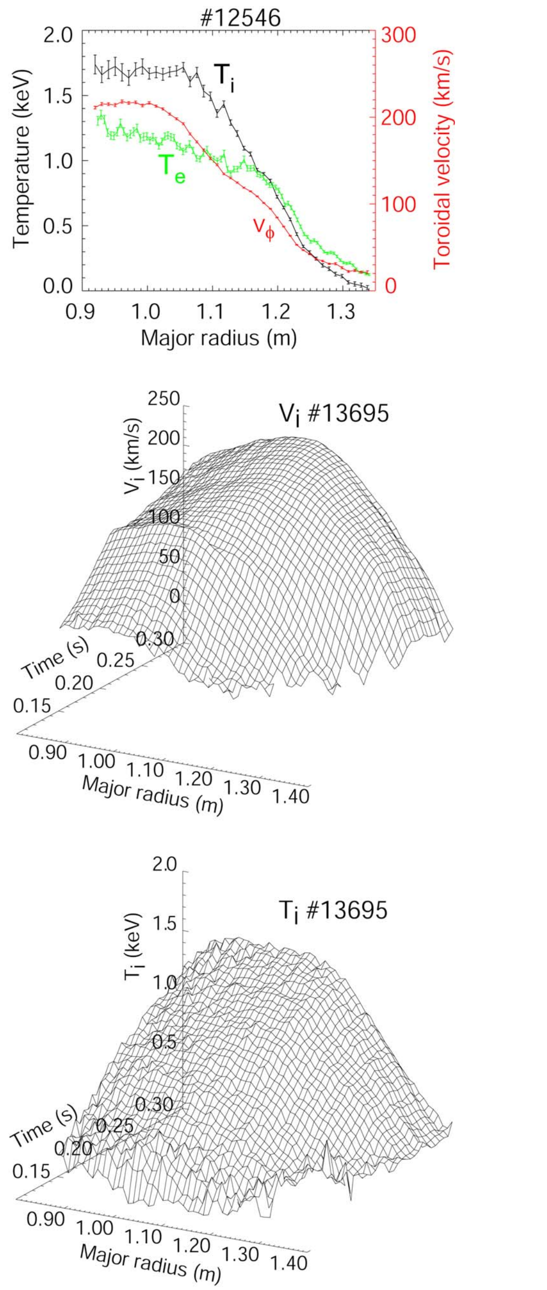

FIG. 4. (Color online) Sample results from the new diagnostic: (a) single time-point v_i and T_i profiles obtained at a beam cutoff, overlaid with T_e profile from the Thomson scattering diagnostic; [(b) and (c)] time-resolved v_i and T_i profiles (at 5 ms, 1 cm resolution) from a recent MAST shot.

RESULTS

Sample results from the new system are shown in Fig. 4. Time-resolved profiles at 200 Hz are now available for many shots. In certain MAST scenarios with very high background emission levels, time-resolved data analysis remains difficult; diagnosis of such scenarios will be enhanced when the capability to notch the heating beams becomes available.

The high-quality profile data available from the new diagnostic validate the design principles used and demonstrate the high throughput available from a single spectrometer system.

ACKNOWLEDGMENTS

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