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TriWaSp: A multi-faceted visible spectroscopy diagnostic on the ST40 tokamak

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ABSTRACT: We present a new state-of-the-art Triple Wavelength Spectrometer (TriWaSp), recently deployed on ST40, a high field low aspect ratio spherical tokamak. The TriWaSp has a range of possible applications due to its flexible design; the current configuration focuses on charge exchange recombination spectroscopy from carbon and neon impurities in the ST40 plasma. This paper discusses the detailed setup of the system and presents initial charge exchange ion temperature measurements using a single line of sight, which show good agreement with other ion temperature diagnostics. Building on these commissioning results and forward modelling of the system, a new observation geometry has been implemented for the next experimental campaign which will considerably improve the localisation of ion temperature and velocity profile measurements.

KEYWORDS: Spectrometers; Plasma diagnostics - interferometry, spectroscopy and imaging; Plasma diagnostics - charged-particle spectroscopy

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1 Introduction

A new multifunctional visible-range spectrometer has recently been installed on ST40, a high field, low aspect ratio tokamak built and operated by Tokamak Energy [1]. The Triple Wavelength Spectrometer (TriWaSp) is a high throughput system, capable of measuring spectra from three wavelength ranges simultaneously across multiple lines of sight. As a result, its diagnostic capabilities are wide-ranging, including beam emission spectroscopy (BES); fast ion D_α (FIDA) measurements; and (the focus of initial results) charge exchange recombination spectroscopy (CX).

We present the design of the TriWaSp, its current implementation and initial commissioning results, and discuss the upgrades to the system for the next experimental campaign.

2 Spectrometer design

A sketch of the design of the TriWaSp system is shown in Figure 1. It has a high light collection efficiency, with an f-number of f/1.8. Optical fibres are stacked vertically at the input slit, and a collimating lens transmits the light into the spectrometer. Two dichroic mirrors (with cut-on wavelengths of 502 and 605 nm) split the light into three wavelength ranges, each diverted into a separate 'arm' or channel of the system. Each channel has a 20 nm-bandwidth filter (centred at 494, 527 and 655 nm) to eliminate stray light, before the signal reaches the dispersive component, a custom-designed grism (a grating sandwiched between two prisms). Finally, a lens focuses the light in each arm onto its detector. The detectors are fast cameras, capable of recording two-dimensional data at a rate of up to 1 MHz. The horizontal spectra for each input fibre are stacked vertically over the sensor.

The wavelength ranges of interest for the current TriWaSp configuration encompass four spectral lines, focusing on atomic hydrogen/deuterium and the hydrogen-like charge states of B V at 494.5 nm (CX); Ne X at 524.9 nm (CX); C VI at 529.1 nm (CX); and D_α at 656.1 nm (CX, BES and FIDA). The grisms have between 2800 (D_α) and 3100 (B V) lines/mm, yielding instrument function values below 600 eV for all three channels.

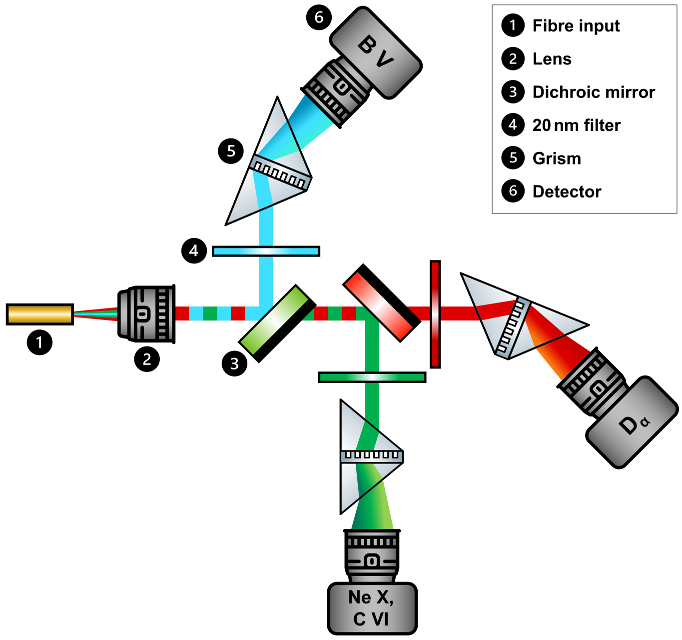

Figure 1: Diagram of the TriWaSp layout.

3 Commissioning results

ST40 has two neutral beam injection systems for plasma heating: a 0.8 MW, 24 keV beam, referred to hereafter as RFX; and a 1 MW, 55 keV beam (HNBI). The existing CX diagnostic on ST40 (a Princeton Instruments Isoplane SCT320 spectrometer and Kuro detector, with up to 18 lines of sight in the midplane, referred to as PI) observes RFX, and the commissioning process for the TriWaSp system has focused on the feasibility of using HNBI for charge exchange measurements.

A single line of sight (illustrated alongside the PI lines of sight in Figure 2a) was used to record initial commissioning data. This view is almost perpendicular to HNBI, and almost radial to the plasma, although it avoids the ST40 centre column. Despite these deficiencies, the experiments yielded promising results, focusing on optimising the signal from the Ne X/C VI channel. A Hamamatsu ORCA-Fusion BT CMOS detector was used to record spectra at 200 Hz, and the ion temperature (T_i) in the ST40 plasma was then extracted using a charge exchange spectrum fitting tool. An example fitted CX spectrum from this channel is shown in Figure 2b.

Results from the TriWaSp were compared to T_i data from CX (Ne X and C VI) measurements with the PI system, and from helium-like argon emission spectra observed by an x-ray crystal spectrometer (XRCS; line of sight illustrated in Figure 2a). Figure 3a shows the T_i time evolution measured during an ST40 pulse by the TriWaSp, PI and XRCS diagnostics. The PI and XRCS results are further discussed elsewhere [2, 3]; here we focus on the TriWaSp performance.

The three systems have high consistency in their temporal evolution behaviour, and the differences in the measured T_i values can be attributed to the differing measurement locations. The XRCS measurements are not localised, as spectra are integrated along a radial line of sight and the location of the emitting Ar XVII ions moves towards the cooler plasma edge as the electron temperature increases. Conversely, the PI data is taken from a more localised line of sight that intersects RFX at a radius of 0.52 m, close to the magnetic axis (located at 0.51 – 0.52 m in the time range 60 – 100 ms). The TriWaSp line of sight observes a slightly off-centre radius of 0.49 m, and is impacted by its suboptimal geometry. The trend of this discrepancy between the PI and TriWaSp is confirmed by FIDASIM forward modelling [4]; Figure 3b shows the predicted T_i measurements for both systems (a radial profile for the PI, and a single data point for the initial TriWaSp geometry), based on an assumed input profile. Although the absolute values of the model output depend on the chosen T_i profile, the simulations indicate that the TriWaSp is expected to underestimate the local temperature to a greater extent than the PI.

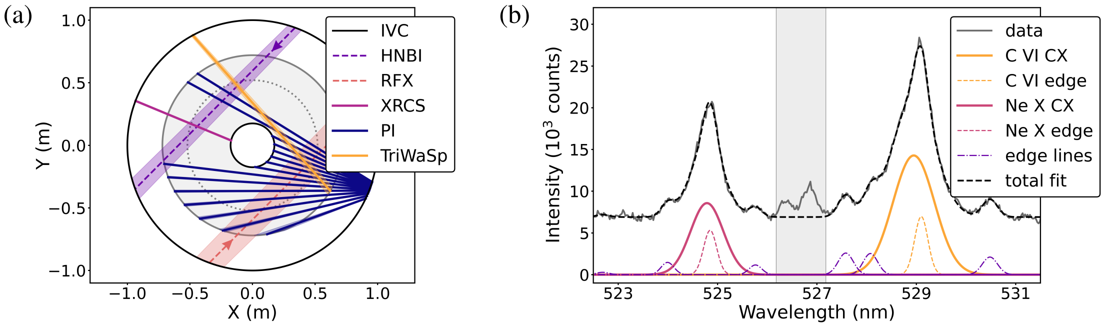

Figure 2: (a) Layout of the ST40 inner vacuum chamber (IVC) and plasma (shaded region), the neutral beams and lines of sight for the x-ray crystal spectrometer (XRCS) and two CX diagnostics (PI and the initial TriWaSp configuration). (b) Example TriWaSp Ne X/C VI spectrum from ST40 pulse #10009. Note that the data background level has been reduced by 25000 counts, and the edge lines in the shaded region have been neglected.

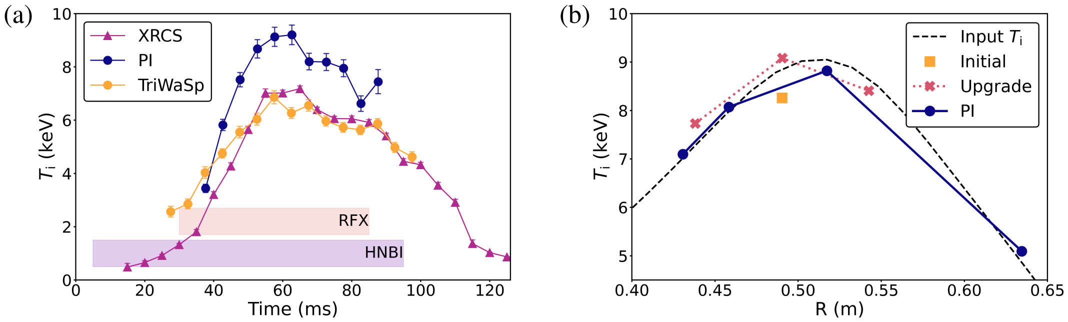

Figure 3: (a) Example time evolution of XRCS, PI and TriWaSp ion temperature data during ST40 pulse #10009. (b) FIDASIM simulations of CX T_i measurements for the PI and initial and upgraded TriWaSp lines of sight, calculated from an assumed T_i input profile.

4 Future work

A redesign of the TriWaSp light collection system has been undertaken in preparation for the next experimental campaign. Three collimators will collect light from three lines of sight steered by in-vessel mirrors (illustrated in Figure 4), a geometry which has three key advantages. Firstly, the view of the plasma is much closer to tangential to the flux surfaces at the intersection with HNBI, which will increase the Doppler shift of the active CX signal compared to the passive line emission, improving the spectrum fitting and enabling measurement of the plasma rotation velocity. Secondly, the lines of sight are no longer perpendicular to HNBI, which will increase the separation of the FIDA spectral components. The intersections with the beam are also further upstream with respect to HNBI, where the beam is less attenuated, which will lead to stronger CX signals. A final improvement is the use of a Princeton Instruments ProEM-HS 512B eXcelon camera on the Ne X/C VI channel. Its on-chip binning capability will allow spectra from the three lines of sight to be recorded at 200 Hz with reasonable sensitivity.

These changes are supported by FIDASIM forward modelling of the upgraded lines of sight (shown in Figure 3b), which predicts a significant improvement in the TriWaSp T_i measurements to within 5% of the input profile. Overall, the new geometry will result in more accurate, higher resolution radial T_i and toroidal velocity profiles from the ST40 CX diagnostics.

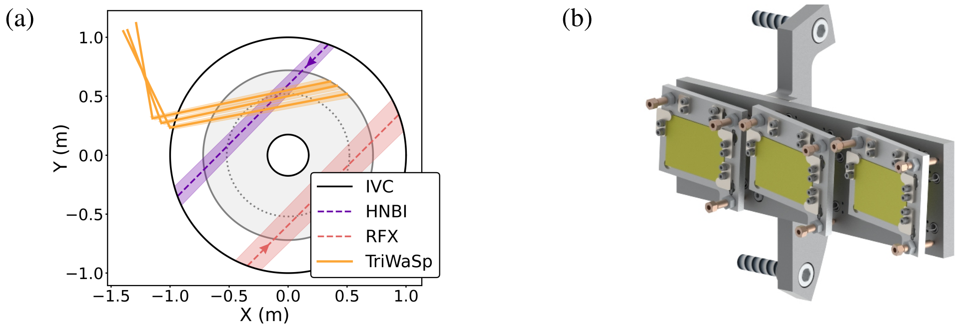

Figure 4: (a) Layout of the ST40 IVC and plasma (shaded), with the two neutral beams and the upgraded TriWaSp lines of sight. (b) CAD model of the mirrors used in the upgraded geometry.

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