Comparison of ion temperature diagnostics on the Madison symmetric torus reversed-field pinch

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There have been three ion temperature diagnostics operating on the Madison symmetric torus (MST) for the past two years: (i) Charge-exchange recombination spectroscopy (CHERS), which measures the temperature of fully stripped impurity (C^{6+}) ions, and has a spatial resolution of ±1 cm and a time resolution of 3 ms; (ii) Rutherford scattering (RS), which measures the temperature of the bulk majority (D^+) ions, and has a spatial resolution of roughly ±7 cm and a time resolution of 30 μs; and (iii) the ion dynamics spectrometer (IDS), which measures a chordal average of the temperature of partially stripped impurity (C^{4+}) ions, with a time resolution of 10 μs. The first two diagnostics use neutral beams, while the third is passive. The classical ion energy equilibration time $\tau_{ii}<1$ ms between all ion species, so we naively expect that all ion temperature measurements should agree in steady state. Here we present simultaneous measurements of: CHERS and RS profiles in high-current burst-free pulsed poloidal current drive (PPCD) discharges; CHERS and RS profiles in standard high-current discharges; and IDS and RS profiles in standard low-current discharges. Measurements in standard discharges are made a long time before and after magnetic reconnection events, during which there is believed to be a large, nonclassical input of energy to the ions. RS and CHERS measurements consistently agree; IDS measurements are consistently less than RS measurements, due to the effect of the C^{4+} emission profile on the IDS measurements. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1538345]

I. INTRODUCTION

Typical Madison symmetric torus (MST)[1] plasma parameters are magnetic field $0.1\ \mathrm{T}<|B|<0.5\ \mathrm{T}$, electron density $n_e \leqslant 1.5\times10^{19}\ \mathrm{m}^{-3}$, plasma current $I_p \leqslant 500$ kA, and plasma radius $r=0.52$ m. The majority species is deuterium, with carbon, aluminum, nitrogen, oxygen, and boron present as impurities. The plasma is characterized by large magnetic and electrostatic fluctuations, as is typical for reversed-field pinches. The ion temperature has, in the past, been measured by passive charge exchange,[2] and found to be hotter than can be accounted for by electron–ion collisions. Quantifying the extra input power necessary to keep the ions hot requires accurate measurements of the bulk majority ion temperature, which can be made by Rutherford scattering (RS).[3] Since RS has been used only occasionally to diagnose magnetically confined plasmas (on the tokamaks T-3,[4] JT-60,[5] and TEXTOR,[6] and the mirror GDT[7]), we report a comparison between RS and the two other, more well-established ion temperature diagnostics currently on MST. In addition to RS,[8] MST features charge exchange recombination spectroscopy (CHERS),[9] and passive Doppler spectroscopy [the ion dynamics spectrometer (IDS)[10]]. Each of these measurement techniques yields an ion temperature measurement. Are these ion temperature measurements the same? Should they be the same?

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II. APPARATUS

The RS temperature measurement results from the width of the energy spectrum of He beam atoms that have undergone small-angle Coulomb scattering from plasma ions. On MST, this energy spectrum is measured by a neutral particle analyzer. RS has spatial resolution typically ±7 cm, formed by the intersection of the analyzer sightline and the He beam (Fig. 1), and time resolution of 30 μs within the 3 ms beam duration. A temperature profile is acquired by moving the analyzer between shots. CHERS relies on CVI emission at 343.4 nm from C^{6+} plasma ions that have undergone charge exchange with H beam atoms. The CHERS signal-to-background ratio is largest in discharges, such as pulsed poloidal current drive (PPCD) discharges, with high T_e and low neutral densities, which allow a substantial population of fully stripped carbon to build up across the plasma profile. CHERS has excellent spatial resolution, formed by the intersection of the neutral beam and a fiber viewing chord, of ±1 cm (Fig. 2), but a time resolution of only 3 ms, since (with the current spectrometer) the low signal-to-background ratio can be overcome only by averaging many time points. A temperature profile is acquired by moving the viewing fiber between shots. The IDS measures CV line emission at 227.1 nm. It produces two independent temperature measurements, from two viewing chords, throughout a discharge. It has excellent time resolution of 10 μs, but poor spatial resolution, since emission along each viewing chord (Fig. 2) is integrated. We will assume for now that the IDS measurement is radially localized close to the impact parameter of the IDS viewing chord (although this will later be shown to be un-

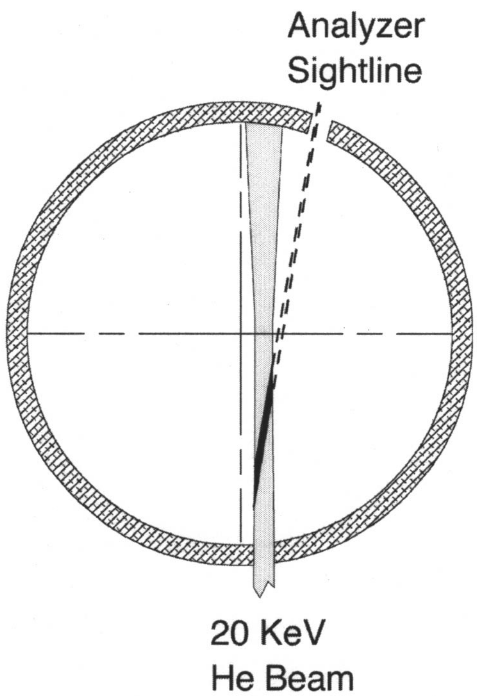

FIG. 1. Poloidal cross section of the MST vacuum vessel, showing the path of the RS beam, and the analyzer sightline for a typical analyzer position. The cross section of the RS measurement volume is shown in black.

likely). The IDS is most useful as a profile diagnostic in low-current discharges, for which $T_e < 200$ eV, and there is significant CV emission amplitude from the plasma core ($r/a < 0.5$).[11] Plasmas hot enough to produce good CHERS measurements are likely to have very hollow CV emission profiles, and therefore produce edge-localized IDS measurements (the two diagnostics cannot actually be used on the same discharge since they share the same spectrometer and fiber bundles).

Signals from all three diagnostics show dramatic changes at the time of magnetic reconnection events (MREs), which occur in standard MST discharges. The CHERS signal cannot be extracted from the plasma background signal, which increases by an order of magnitude at a MRE. CHERS data at this time are lost. The RS signal also must compete with increased signal due to high-energy plasma ions expelled at a MRE, and with increased noise due to plasma electrostatic fluctuations, and may be unreliable during the 100 μs surrounding a MRE. The IDS temperature is apparently trustworthy, typically showing a rapid increase followed by an almost equally rapid decrease, but the emission location may move radially. Since previous work[2] has identified (from passive charge exchange measurements) the existence of a large, nonclassical heat input into the ions in MST at a MRE, the "true" ion temperature during a MRE is unknown, and may undergo large changes. In this article, data taken within ± 100 μs of a MRE from all three diagnostics have been excluded from the analysis.

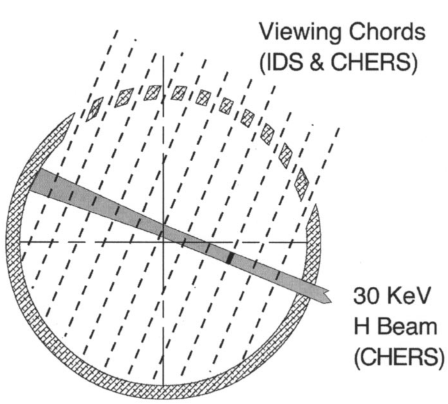

FIG. 2. Poloidal cross section of MST vacuum vessel, showing the eleven viewing chords used by both CHERS and IDS, and the path of the CHERS beam. The cross section of the CHERS measurement volume for chord 9 is shown in black; measurement volumes for other chords are similar.

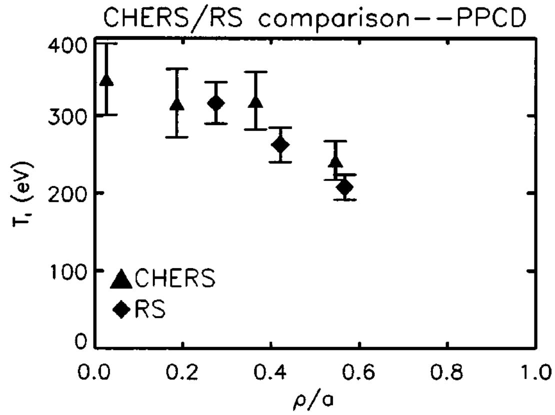

FIG. 3. Data from CHERS and RS taken during high-current PPCD MST discharge. ρ/a values calculated by MSTFIT.

III. DATA

CHERS and RS profiles taken simultaneously during an ensemble of 400 kA PPCD discharges are shown in Fig. 3. Discharges were selected for the ensemble based on the suppression of fluctuations—the "burst-free PPCD" phase—during, and also for at least 1 ms before, the time the beams were firing. Each data point represents an average of 15 discharges. ρ/a values for the data points are based on MST equilibria computed by MSTFIT.[12] The profiles are in excellent agreement. CHERS and RS profiles taken simultaneously during an ensemble of 400 kA standard MST discharges are shown in Fig. 4. Ensemble selection parameters were reversal parameter ($f \sim -0.23$), and plasma density (0.9×10^{13} m$^{-3} < n_e(0) < 1.2 \times 10^{13}$ m^{-3}). Each data point represents 15 discharges. The CHERS and RS beams were fired during current flat top. Standard discharges produce higher background signals for both RS and CHERS than do PPCD discharges, so they present a greater challenge for the diagnostics. Again, the two profiles are similar.

IDS and RS profiles taken during an ensemble of standard, low-current (190 kA) MST discharges are shown in Fig. 5. Ensemble parameters were $f \sim -0.15$ and 0.9×10^{13} m$^{-3} < n_e(0) < 1.2 \times 10^{13}$ m^{-3}. Each data point represents the average over ten or more discharges. The IDS data points were computed by averaging the IDS measurements during the duration of the RS beam, and as before temperature measurements made by both diagnostics within 100 μs of a MRE were ignored. The ρ/a value assigned to each IDS

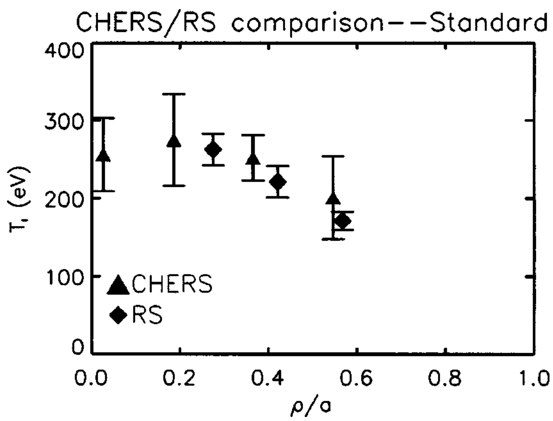

FIG. 4. Data from CHERS and RS taken during standard high-current MST discharge. ρ/a values calculated by MSTFIT.

data point is the impact parameter of the IDS viewing chord. The IDS profile is consistently 20%–30% lower than the RS profile. This apparent discrepancy can be explained by profile effects, as described below.

IV. THEORETICAL EXPECTATIONS

The classical ion–ion equilibration time between species j and k is[13]

$$\tau_{eq}^{j,k}=\frac{\mathbf{3}\sqrt{\mathbf{2}}\pi^{3/2}\varepsilon_0^2\boldsymbol{m}_j\boldsymbol{m}_k}{\boldsymbol{n}_k\boldsymbol{Z}_k^2\boldsymbol{Z}_j^2\boldsymbol{e}^4\ln\Lambda_{jk}}\left(\frac{\boldsymbol{T}_j}{\boldsymbol{m}_j}+\frac{\boldsymbol{T}_k}{\boldsymbol{m}_k}\right)^{3/2}, \quad (1)$$

where $\boldsymbol{T}$ is temperature, $\boldsymbol{m}$ is mass, $\boldsymbol{Z}$ is charge, and $\boldsymbol{n}$ is density (the subscript denotes species), and using

$$\Lambda_{jk}=\frac{\lambda_d}{b_{90}}=\frac{12\pi\varepsilon_0^{3/2}T_e^{1/2}}{Z_jZ_kn_e^{1/2}e^3}\,\frac{(\sqrt{T_jm_k}+\sqrt{T_km_j})^2}{m_j+m_k}$$
$$=9\left(\frac{4\pi}{3}n_e\lambda_d^3\right)\ \text{if either}\ j,k=e \quad (2)$$

for the Coulomb logarithm. This is the time scale for the change of temperature of species j due to collisions with species k. Time scales involving energy transfer between electrons and ions are generally much slower than those involving energy transfer between different species of ions. The most poorly known quantities in the above formulas are the impurity densities. However, these are not needed to calculate $\tau^{\mathrm{imp},D}$. On the basis of the data we may assume C^{4+} and C^{6+} temperatures equal to the D temperature for the purpose of calculating equilibration times. An upper bound on $\tau^{\mathrm{imp},D}$ may then be calculated if a lower bound on n_D can be given. This lower bound may be calculated from Z_{eff}. It is plausible that for standard low-current MST discharges, $Z_{\mathrm{eff}}\sim 2$ for all radii, and that for 400 kA PPCD $Z_{\mathrm{eff}}\sim 5$ in the core, with the dominant impurity being Al^{11+}.[12] In the former case the lowest-Z candidate impurity is C^{4+}, and the lower bound on n_D, which comes by assuming the impurities are entirely C^{4+}, is $n_D/n_e\sim 2/3$; while in the latter case $n_D/n_e\sim 3/5$. For the IDS/RS comparison plasma $n_e\sim 10^{19}/\mathrm{m}^3$, $T_e\sim 200$ eV, and $T_D\sim 100$ eV, which leads to

$$\tau_{eq}^{C^{4+},D}=50\ \mu\mathrm{s}. \quad (3)$$

For the CHERS/RS comparison in PPCD, $n_e\sim 10^{19}/\mathrm{m}^3$, $T_e\sim 850$ eV, $T_D\sim 300$ eV, and

$$\tau_{eq}^{C^{6+},D}=100\ \mu\mathrm{s}, \quad (4)$$

(for the CHERS/RS comparison in standard discharges n_D/n_e cannot be estimated from Z_{eff}, which has not been measured; we will have to assume it is not less than in the other two types of discharge). Then, in the absence of other heat sources and sinks, we should expect that for the discharges studied herein, both the C^{4+} and C^{6+} temperatures should approach the D temperature in much less than 1 ms.

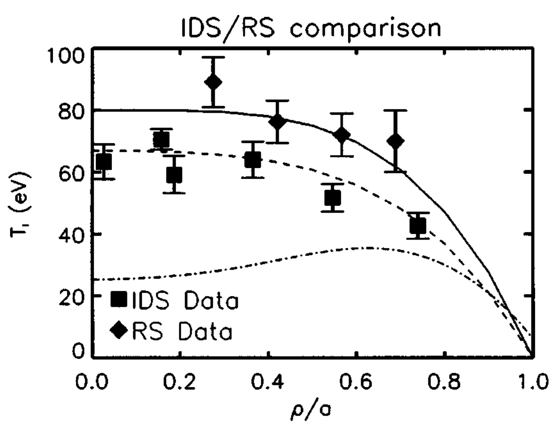

FIG. 5. Data from IDS and RS taken during standard low-current MST discharge, and curves modeling profile effects on IDS measurements. Solid curve: assumed "true" T_1 profile, consistent with RS measurement; dot-dash curve: assumed C–V emission profile (arbitrary units), consistent with measurements shown in Ref. 11; dashed curve: derived IDS profile. ρ/a values calculated by MSTFIT (for IDS data, the ρ/a shown is the viewing chord impact parameter).

V. DISCUSSION

The CHERS and RS temperature profiles shown above are quite similar, as they should be if C^{6+} equilibrates to the D as fast as Eq. (4) predicts. On the other hand, the IDS temperatures appear to be substantially lower than the RS temperatures, even though Eq. (3) predicts that C^{4+} should equilibrate even faster in these colder, low-current discharges than C^{6+} does in the hotter discharges. The passive charge-exchange measurements presented in Ref. 2, which were made in standard 360 kA hydrogen discharges, were also generally higher than simultaneous IDS measurements, even at early times, when $T_e(0)<200$ eV. The simplest explanation is that the IDS is not a core diagnostic, and that all chords are affected by emission from outside $\rho/a=0.5$, even for cold, low-current plasmas. Assuming that the temperatures of D and C^{4+} are equal, and that the RS measurement of the D temperature is correct, we may deduce the apparent temperature measured by the IDS, if the CV emission profile is known. The CV emission profile in low-current MST discharges, away from MREs, has been obtained from Abel inversion of line-integrated CV measurements along five different chords.[11] In Fig. 5, this CV emission profile is shown as a dot–dash line (using arbitrary units). Assuming a "true" temperature profile (solid line) for D and C^{4+} that is consistent with the RS measurements, we deduce that the temperature measurement of the IDS should fall along the dashed line; and indeed the IDS data points do fall close to this line. Therefore, we conclude that even in low-temperature plasmas, the IDS measurement is not core localized. It is of interest to determine whether the ''true'' temperature can be accurately backed out from the IDS measurements, by the inverse of the above procedure, using the CV emission profile.

VI. CONCLUSION AND FUTURE WORK

D, C^{4+}, and C^{6+} temperatures have been measured on MST using the RS, IDS, and CHERS diagnostics, respectively. RS measurements consistently agreed with CHERS measurements: during high-current discharges, D and C^{6+} temperatures were found to be similar. RS measurements were consistently higher than IDS measurements: during low-current discharges, D temperatures were measured to be 20%–30% higher than C^{4+} temperatures across the profile. The equilibration times calculated from classical charged particle collisions lead to the expectation that all species should have the same temperature on time scales long compared to 100 μs. Based on this calculation, we ascribe the difference between IDS and RS temperatures to profile effects. On short time scales, such as within 100 μs of a MRE, the different ion species are not in thermal equilibrium with each other, and measurements of their temperatures should not be expected to agree. The ultimate goal of the current research is to quantify the ion power balance, that is, to find out whether the measured ion temperatures can be sustained by classical, collisional heat transfer from the electrons, and, if not, how much additional input power is needed.

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