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ABSTRACT

Several important measurements in the ITER diagnostic mission, including the primary one of core helium ash density, are expected to be addressed using active spectroscopic techniques. These methods rely on the use of a dedicated diagnostic neutral beam (DNB) which has been optimized for the dual requirements of beam penetration and charge exchange cross section. For hydrogenic beams, this results in an optimal beam energy of ~100 keV/AMU. Signal-to noise estimates using realistic geometries and the existing ITER profile and equilibrium data have confirmed the stringent requirements on beam quality and intensity to satisfy the stated ITER measurement precisions. In this paper we consider the use of a neutral helium DNB for making active spectroscopic measurements on ITER, since helium beams offer better penetration in dense plasma for a given energy, and the prospects for given source performance may also be improved. Drawbacks include the more difficult absolute calibration of the beam density profile as well as the fundamental problem of uniquely identifying the source [fusion-based ash, beam core fuelling, or edge DNB neutralizer/source efflux] of the observed He charge-exchange recombination line in order to unambiguously characterize core helium buildup and confinement on ITER.

I. INTRODUCTION

Active plasma spectroscopy, or spectroscopy based upon local signal enhancement via a penetrating neutral atomic beam, is employed as a key diagnostic on almost all present day tokamak devices. The method relies on the characterization (i.e. amplitude, width, and shift) of various intrinsic impurity lines emitted by states which are efficiently populated by charge transfer or charge exchange from beam atoms, a process referred to as charge exchange recombination spectroscopy or CER. This technique is utilized for a wide variety of measurements, including ion temperature (via Doppler broadening of the linewidth), plasma rotation (via Doppler shift of the same lines), and impurity profile information (via quantitative spectroscopy of the line intensities). Studies of core helium ash formation and transport, and the performance of pumped divertors for helium exhaust, have benefited from the precise, local, absolute measurements possible using this technique.[1,2]

Adoption of active spectroscopy for the International Thermonuclear Experimental Reactor (ITER) represents a challenging opportunity. Compared to existing experiments, the relatively large size of ITER will result in severe attenuation of the (hydrogenic) neutral beam as it penetrates to the core region. As pointed out previously[3,4] the energy dependence of the beam attenuation and charge exchange cross sections results in an optimal beam energy of ~100–150 keV/AMU. One cannot simply go to higher energies to improve this situation. By the same token, the substantially longer path lengths through the plasma for the viewing chords imply any spectroscopic measurement, whether active or passive, will have to be made in the presence of a substantial visible bremsstrahlung background (VBB), typically several orders of magnitude larger than the desired charge exchange or emission line intensity. This implies that any usable system must have extremely good dynamic range and low noise. Despite these obstacles, substantial design and development work continues on active spectroscopy systems for ITER because of the unique information they can provide on core plasma conditions. Indeed, in the case of core helium measurements – a crucial indicator of the success of ITER – no credible alternative to CER has emerged.

A detailed performance estimate of a diagnostic system appropriate for such measurements has been carried out using desired measurement resolutions and the relevant ITER geometry, existing ITER plasma profiles and equilibria, and assumed values for the Diagnostic Neutral Beam (DNB) performance.[6] System perfomance was estimated based on calculations of expected beam intensities and signal- to-noise ratios, using a multistep beam attenuation code,[7,8] a self-consistent viewchord set, and the various profile scenarios. The conclusion was that, while measurements well inside the core plasma (i.e., within r=1 m) will be difficult but doable for reasonable optical penetrations and collection efficiencies, it was clear that the stated measurement precisions for these parameters quoted in Table I were not compatible with the expected DNB performance as listed in Table II. This argued either for a relaxation of the desired resolution(s), or further work on a pulsed, high current alternative[9] to the conventional DNB. Such beams would not only substantially improve the signal levels but would permit pulsed detection/background rejection techniques that should considerably simplify the data analysis.[6]

In this paper we consider the relative benefits of using helium as the working gas in the DNB (He-DNB) versus hydrogen for the primary measurement of core helium ash densities on ITER. The use of helium should be considered since for a given beam velocity (energy/AMU) the attenuation may be considerably less than for hydrogen/ deuterium beams.[11] Recent calculations have shown this is true even when the additional attenuation due to the metastable He^0 electron states are accurately accounted for in the beam modelling.[12] In Section II we describe the results of modelling runs for helium beams using the ITER profiles and accurate cross sections which indicate the optimal beam energies for central CER measurements. Section III derives an equivalent signal-to-noise which is compared to the earlier hydrogen results. In Section IV we discuss several drawbacks to the use of a helium DNB that must be addressed before a successful system can be deployed.

Table I
ITER Requirements for Active CER Measurements. These four parameters represent zeroth, first, and order moments of the the emitted He line. From Ref. 5

Parameter	Range Spatial Resolution	Accuracy Temporal Resolution
Helium Density	1%–20% 30 cm	10% 100 ms
Toroidal Rotation	1–200 km/s ~5 cm	30% 10 ms
Poloidal Rotation	1–50 km/s ~5 cm	30% 10 ms
Ion Temperature	0.5–50 keV 30 cm	10% 100 ms

Table II
Specifications for the current hydrogenic DNB design. From Ref. 10

Beam species	H^0
Beam energy	100 (125) keV
Neutral equivalent current	50 A
Beam divergence	0.2 mrad
Beam focus	r/a = 0.3–0.4
Footprint at beam focus	$0.2 \times 0.2\ m^2$
Equivalent H0 density at focus (unattenuated)	$1.8 \times 10 \times 10^{15}\ m^{-3}$ $(\sim 2 \times 10 \times 10^{-4}\ n_e)$
Modulation frequency	5 Hz (100 ms on/off)
Measurement time	1–3 s every 10–20 s

II. HELIUM BEAM PENETRATION MODELING

Modeling and estimation of the observed helium signal depends crucially on accurate cross sections and rates for beam attenuation and helium emission. We have adapted a previously benchmarked multistep collisional-radiative model[7,8] for the specific ITER geometry, profile conditions, and putative DNB parameters listed above. For the calculations presented here, we have used the same reference profiles from the ITER database[9] as used in the previous H-DNB design study (Fig. 1).

The relevant T_e, n_e, Z_{eff}, etc. profiles were first mapped to minor radius using the associated equlibria to provide suitable inputs for the beam attenuation and rate equation codes. Using the appropriate formulations for the He stopping cross sections from Ref. 12 and estimates of the effective emission rate for the $n = 4 \rightarrow 3$, $\lambda = 468.6$ nm transition due to the $He^0 + He^{++}$ CER process, we find the optimal energy for measurements at various radii in ITER (Fig. 2). For measurements within 0.5 m, the beam energy shows a broad optimum with only modest gains above 200 keV/AMU. Higher energies would yield more precision in the measurement (less attenuation implies less uncertainty in the absolute beam intensity) but would be more difficult to implement on an actual DNB (for example, He beam neutralization efficiency drops rapidly with energy).[14]

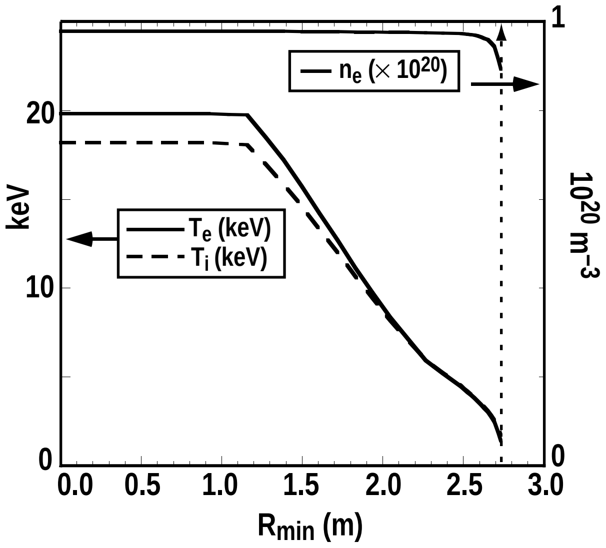

Fig. 1. Reference profiles extracted from the ITER profile database, showing density, ion and electron temperatures for flat and peaked temperature profile scenarios. Z_{eff} profiles for all cases were reasonably flat with Z_{eff} ~1.5. The specified helium ash concentration is 10% From Ref. 13.

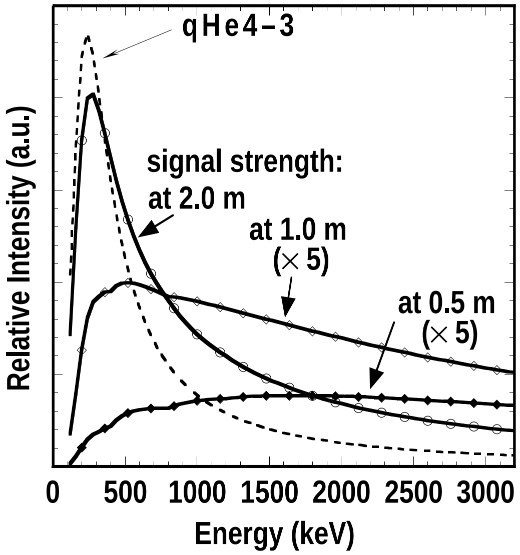

Fig. 2. Results of code runs combining beam attenuation and emission rate for ITER parameters as a function of beam energy. Curves shown represent relative CER signal intensity at several different radii. Also shown is the assumed 4–3 emission rate [from Ref. 12]

III. SIGNAL-TO-NOISE COMPARISON

The signal-to-noise ratio achievable will be determined by the light collection efficiency (absolute He CER signal intensity) as well as the intensity of the continuum visible bremsstrahlung (VBB) background. The signal-to-noise of the He DNB measurements may be estimated under the following assumption: for the case of no competing lines we presume the fluctuations in the background to be the dominant noise source.

Then the SNR will be given by[3,4]

$$\begin{aligned} \mathrm{SNR} &= \frac{N_{He}}{\sqrt{N_B + N_{He}}} = \frac{S_{He}\Delta t DF}{\sqrt{R\ S_{He}\Delta t DF}} \\ &= \frac{S_{He}\Delta t DF}{\sqrt{(S\ \Delta t)(R + DF)}} = \frac{\sqrt{S_{He}\Delta t DF}}{\sqrt{(R + DF)}} \end{aligned} \qquad (1)$$

where S_{He} = Helium CER intensity, R = VBB/He intensity ratio and DF = duty factor for beam. Calculations were performed for the fully ignited case assuming a 50% duty cycle and 100 ms integration time--the cited time requirement. Longer integration times improve the SNR as $\sqrt{\Delta t}$. For the calculation of absolute signal levels shown in Fig. 3 we have assumed the etendue and other optical parameters used in the earlier study: characteristic chord length = 16 m, first mirror collection area = 0.04 m^2, emission collection volume = 2×10^{-3} m^3, collection solid angle $=4.9\times10^{-4}$ sr, etendue through spectrometer = 2×10^{-7} m^2 sr.

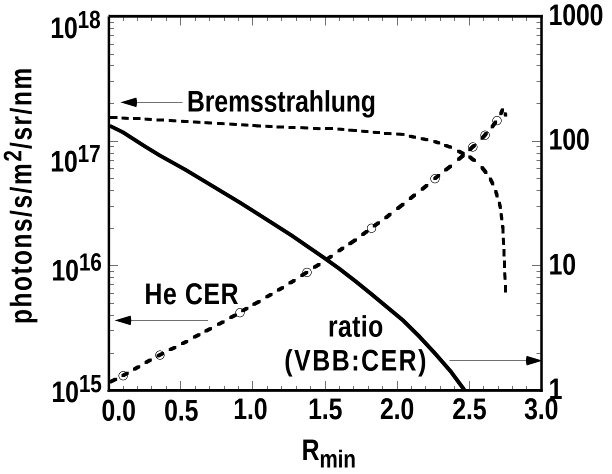

Fig. 3. He CER and bremsstrahlung brightness at 468 nm as a function of radius for the fully ignited ITER scenario, employing a He^0 *DNB and assuming the same optical parameters as in Ref. 6. Also plotted is the emissivity ratio. Beam energy = 200 keV/AMU, assumed neutral current density of* 10^3 A/m^2 *(40 A neutral equivalent current).*

IV. DRAWBACKS TO HE-DNB

The results shown in Fig. 4 must be taken in context. Several disadvantages to the use of helium are briefly discussed below.

A. Ash Fuelling/Contamination

The use of the same species for doping will inevitably result in a He^{++} population in the core which is not due to thermonuclear reactions. These will be indistinguishable from the thermalized alphas which are the object of the measurement. Although the beam density is low compared to n_e, the integrated dose is considerable. For example, 40 A represents a beam fuelling rate of $2.5 \times 10^{20}\ s^{-1}$. This should be compared to the fusion alpha production rate, which at the full rated power of 1.5 GW is equivalent to $5.4 \times 10^{20}\ s^{-1}$. This ratio will be even worse in the startup phase of ITER where n_α will be much lower than in the fully ignited case. This contamination may be exacerbated by the method of neutralization: if helium gas is used in the neutralizer, the neutralizer efflux itself, which is not efficiently cryopumped, may well dominate the amount of helium injected directly by the beam, depending on the edge plasma transport.

B. Plume Enhancement

The standard problem of plume[14] in helium CER measurements occurs when plasma helium neutrals are singly ionized by beam collisions and then drift along magnetic field lines into the spectrometer field of view before they can be ionized to He^{++}. These He^{+} ions are easily excited by electron collisions and will emit at the same wavelength as the CER line, complicating the radial profile measurement. Since the plume signal is generated by the beam, it cannot be rejected through standard modulation techniques. The plume effect for a helium beam will be worse since He^{+} will be continually generated along the beam as it penetrates. Judicious choices of viewchords and angles will minimize the effect, but further modelling efforts are required. Vertical views, which should be relatively insensitive to plume effects, will serve as a check on this. Efflux of thermal He from the neutralizer may dominate as the plume source; depending on the dispersal in the edge it will be much more difficult to reject by choice of viewing geometry.

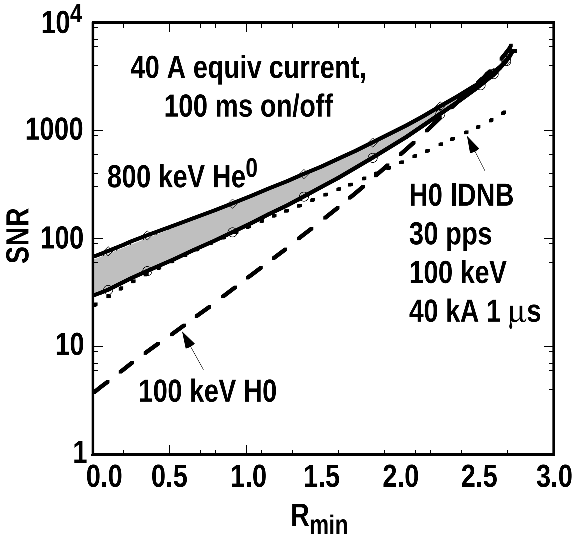

Fig. 4. Signal-to-noise ratio for the ignited ITER case using He-DNB. Also plotted are the equivalent SNR derived in Ref. 6 using the current H-DNB design parameters (beam energy 100 keV/AMU, j_{beam} 10^3 A/m^2,dotted line) as well as using a possible pulsed H-DNB (100 keV/AMU, j_{beam} 10^6 A/m^2, pulse 10^{-6} s, 30 pps, 100 ms total measurement time, dashed line).

C. Beam Emission Spectroscopy Difficulties

Because of the need to know the local beam density for accurate helium (or other impurity) concentration measurements, at high plasma densities standard CER will need to rely on monitoring the Doppler-shifted H_α beam emission to serve as a crucial experimental cross-check of the beam attenuation calculations, which are sensitively dependent on local impurity densities and accurate cross sections. In addition, auxiliary visible bremsstrahlung measurements at the He wavelength, but displaced laterally from the beam, can serve as a further cross-check on the beam calculations. Because of the complexity of the helium beam modelling, the use of a He-DNB will also require *in-situ* BES measurements to be made on the neutral helium emission (including the metastable states if possible) to calibrate the modelling results. As remarked under the previous discussion, substantial He^+ will be produced and excited along the beam; even without plume or other nonlocal effects this beam emission will compromise the $He^{++} \rightarrow He^+$ recombination measurements. It will also make accurate VBB measurements more difficult near the beam, although beam modulation should help here.

V. CONCLUSIONS

Despite the modest improvement in SNR achieved by using the He-DNB with its superior penetration, the additional complications of performing quantitative spectroscopy of an intrinsic impurity while using the same impurity as a charge exchange partner seem to be too formidable on such a large device to yield values of helium core concentrations to the accuracy required. While He CER measurements could certainly be made, the extent to which they would represent the behavior of core helium density due to fusion remains unclear.

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