# Helium doped hydrogen or deuterium beam as cost effective and simple tool for plasma spectroscopy

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Energetic neutral particles from neutral beam heating systems are widely used for active spectroscopic measurements of key plasma parameters in fusion experiments. Both the plasma discharges and the neutral beam systems are normally operated with hydrogen or deuterium. Helium beams are used in dedicated diagnostic beam lines as they offer deeper penetration and are subject to less background radiation and enable resonant double charge exchange with alpha particles. Neutral beam systems using pure helium either require specialized helium gas pumping with a pumping speed in excess of 1000 $m^3$/h or are restricted to short pulses (normally less than 1 s). A doped hydrogen/helium beam combines the requirements for plasma heating and diagnostics without the need for sophisticated helium pumping. A small flow of helium gas is injected into the plasma source for the time helium particles are required. The helium current is typically 10% of the total extracted current. The reduction in heating power of the doped beam can be kept below 5%. The small amount of helium gas does not cause an excessive pressure rise along the beam line and does not reduce the reliability of the beam heating system. Doped deuterium/helium beams have been successfully tested and routinely used at JET. The HeI beam emission spectra obtained with a doped deuterium/helium beam produce sufficiently strong visible lines for spectroscopic applications. Furthermore, the simultaneous availability of helium and hydrogenic particles in the beam allows us to extend spectroscopic measurements to another atomic system and hence cross-check results from helium beams with those from hydrogenic beams. The only investment required is an additional helium gas inlet system into the ion source. © *2000 American Institute of Physics.* [S0034-6748(00)01610-5]

## I. INTRODUCTION

The development of novel diagnostic tools providing reliable and quantitative values of plasma parameters has been a key factor in the progress of fusion research towards break-even conditions. Of special note in this area has been the use of neutral beams for active charge exchange spectroscopy which has led to a revolution of spectroscopic techniques.[1]

Charge exchange recombination spectroscopy makes use of the emission of radiation following electron capture by fully stripped plasma ions from neutral beam particles. Low Z impurity density and temperature can be deduced from the intensity and width of the emitted line while the impurity flow velocity (plasma rotation) is obtained from the Doppler shift.[2–6] Beam emission spectroscopy is used to measure plasma density fluctuations,[7–10] the local pitch angle of the magnetic field is determined from the polarization of the Stark or Zeemann emission and the total magnetic field strength from the wavelength splitting of multiplets.[11–14] Another application based on the injection of fast neutral particles is the measurement of the plasma density through Rutherford scattering of these fast beam particles.[15–17] Several experiments make use of dedicated diagnostic beam lines, frequently operating with helium.[18–22] Helium beams offer several advantages over hydrogen beams: deeper penetration, the option of diagnosing alpha particles via resonant charge exchange,[23,24] and reduced intensity of background radiation from the scrape-off layer which can mask the measurements.

Optical emission from energetic lithium beams[25] has been successfully used as a diagnostic of plasma density. Thermal helium beams[26] have been used to measure electron temperature and density. Both diagnostics are limited in range by the penetration depth of the neutral particles to the outer regions of the plasma. Energetic helium atoms penetrate much deeper into the plasma than either lithium atoms of similar energy or thermal helium atoms, and therefore offer the prospect of a measurement of plasma parameters inside of the H–mode-or internal transport barriers.

The principal challenge in the production of helium beams is the removal of excess helium gas from the production and neutralization of the helium beam. Without adequate helium gas pumping capacity from cryosorption pumps[27] operation is limited to short pulses by the maximum pressure which the system can tolerate.

Hydrogen beams doped with a minority of helium give access to measurements with helium beam emission and to

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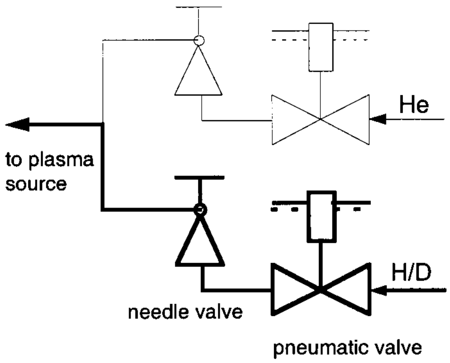


FIG. 1. The standard source gas introduction system is extended by additional on/off and needle valves.

resonant charge exchange with alpha particles without the need for a dedicated helium diagnostic beam. Another advantage of a doped helium beam is the option of simultaneous measurements based on D and HeI beam emission spectra thus providing an ideal test bed for two independent atomic systems to be checked against each other.[28]

Furthermore, if the beam particle flux is adequate the use of a helium doped beam enables us to study the transport of helium following injection. Hydrogen and deuterium beams are likely to have a higher divergence than helium beams resulting from the kinetic energy of dissociated molecular ions. In the case of the JET neutral beam sources, helium beams have roughly half the divergence of deuterium beams. It can be expected that the lower divergence of the helium beam will also be manifest in the doped beam to some degree.

## II. THE CONCEPT OF A DOPED HYDROGEN/HELIUM BEAM

If helium gas is added temporarily to the hydrogen or deuterium gas, which fuels the plasma source of a beam injector, a plasma consisting of hydrogen (deuterium) and helium ions will be produced and extracted from the plasma source. Both ions will then be neutralized in the hydrogen gas target of the neutralizer. The remaining $He^+$ ions are deflected along the same trajectories as $D_2^+$ ions. The amount of helium gas required for this mode of operation is greatly reduced compared to operation with a pure helium beam as:

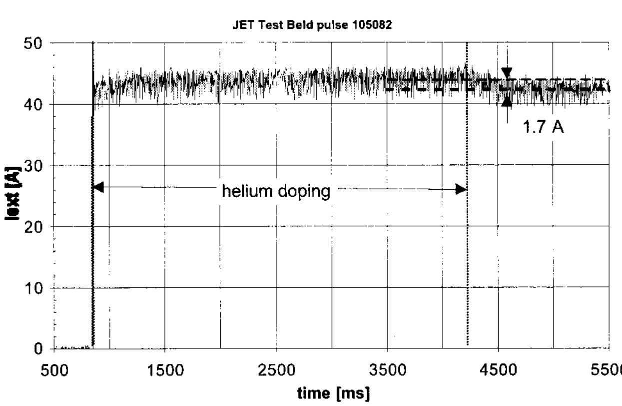


FIG. 2. Current trace of a 60 kV hydrogen beam pulse with helium puff (test bed pulse).

TABLE I. Parameters used for the beam pulse in Fig. 2. The gas flow is estimated from pressure rise, tank volume, and on time of the helium beam. In this experiment the on/off valve discharged a volume of several $cm^3$ after closing, adding to the pressure rise in the tank. The actual helium source gas flow rate is therefore lower and in the range of 0.4–0.5 Pa $m^3/s$.

| | | |
|---|---|---|
| Hydrogen source gas flow | /Pa $m^3/s$ | 1.08 |
| Helium source gas flow | /Pa $m^3/s$ | <0.58 |
| Neutralizer gas flow | /Pa $m^3/s$ | 1.71 |
| Extracted current (without/with helium) | /A | 42.2/43.9 |
| Arc current | /A | 1000 |
| Source pressure with/without helium | /Pa | 0.5/0.36 |

helium gas is only fed into the plasma source but not into the neutralizer, and helium gas is only admitted during the time intervals for which fast helium atoms are required.

The only modification required is the addition of a second gas introduction system to the plasma source (Fig. 1). In such an arrangement it is important to minimize the volume between the on/off and needle valves, as the gas in this volume will be discharged into the plasma source after closure of the on/off valve. For example, the pneumatic valve used[29] here has a trapped volume, which discharges downstream after valve closure. This additional gas load can be avoided with the valve reversed.

## III. EXPERIMENTAL EXPERIENCE WITH DOPED HELIUM BEAMS

The concept was initially tested in the JET Neutral Beam Test Bed[30] and later applied to one of the JET Neutral Beam Injectors.[31] The initial tests were aimed at finding operating parameters that allowed doped beams to be generated without reducing reliability and beam power.

### A. Experiments in the JET Neutral Beam Test Bed

The JET Neutral Beam Test Bed is a large facility consisting of an injector box and a target tank. The volume of the vacuum system is roughly 95 $m^3$ pumped by a liquid helium (LHe) cryogenic pump (250 $m^3/s$ for $H_2$) and two turbo-molecular pumps (5 $m^3/s$ pumping speed). For the beam a standard JET high current beam source [known as Positive Ion Neutral Injector (PINI)] rated for 80 kV, 50–55 A in deuterium, was used. The source gas introduction system was modified as shown in Fig. 1. The on/off valve was controlled by a timer module that allowed time and duration of the valve opening to be set. The LHe cryopump was activated for pumping hydrogen but not helium (no argon cov-

TABLE II. Helium current estimated from the increase in Doppler shifted HeI emission—line $2p\,^1P-3d\,^1D$, 6678 Å.

| The table is based on $\alpha_{He}=1817.1$ as measured in a pure helium pulse | | | |
|---|---|---|---|
| He current/A | Doppler shifted intensity/arb. units | Average He pressure/Pa | On time/s |
| | 1211.7 | $7.60\times10^{-3}$ | 3.492 |
| 4.52 | 2025.4 | $3.60\times10^{-2}$ | 3.492 |
| 4.21 | 2633.7 | $5.90\times10^{-2}$ | 3.458 |
| 4.50 | 3469.9 | $8.80\times10^{-2}$ | 3.528 |
| 5.27 | 4208.2 | $1.10\times10^{-1}$ | 3.502 |
| **4.62** | **Average He current** | | |

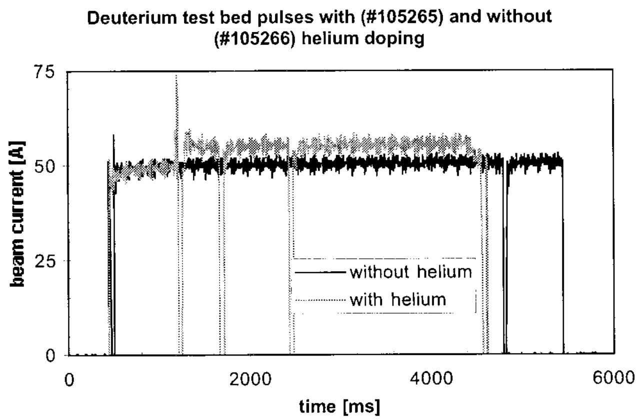


FIG. 3. Comparison of pulses with and without helium puff in an 80 kV deuterium pulse (test bed).

erage of the cryo surface). The Doppler shifted beam emission from collisions between fast helium neutrals and the residual gas in the target tank was measured with an optical spectrometer. The line of sight of this spectrometer was arranged to cross the beam vertically at approximately 8 m downstream of the extraction grid.

### 1. Preliminary tests using hydrogen beams with helium doping

The JET beam sources are normally operated with a gas flow of 1.50 Pa m$^3$/s each into ion source and neutralizer. In the case of a doped beam the hydrogen gas-flow into the ion source was reduced to approximately 1.0 Pa m$^3$/s and 0.5 Pa m$^3$/s of helium gas was added to the ion source for the duration of the doped beam. Figure 2 shows the current trace of a 60 kV hydrogen beam doped with helium. In this case the helium is turned on just before the start of beam extraction. The parameters for the pulse in Fig. 2 are listed in Table I.

After the helium puff the current decreases by 1.7 A. The actual fraction of helium current was estimated from the intensity of the Doppler shifted HeI line emission, $E_{\mathrm{D}}$, in the target tank as

$$I_{\mathrm{He}}=E_{\mathrm{D}}/(\alpha_{\mathrm{He}}p_{\mathrm{He}}+\alpha_{\mathrm{H}_2}p_{\mathrm{H}_2})\tau_{\mathrm{He}},$$

where $p$ is the residual partial pressure in the tank, $I_{\mathrm{He}}$ is the neutral helium particle current, $\tau_{\mathrm{He}}$ the helium beam pulse duration, and $\alpha$'s are constants covering the respective cross sections and the geometry. In a pure helium pulse $\alpha_{\mathrm{He}}$ can be determined from the measured quantities $E_{\mathrm{D}}$, $p_{\mathrm{He}}$, and $I_{\mathrm{He}}$.[32] From a series of pulses with a doped helium beam and an increasing helium partial pressure in the tank from pulse to pulse (turbo pumps valved off) we can estimate the extracted helium current from the increase in shifted line emission and from the increase in average helium partial pressure: $I_{\mathrm{He}}=\Delta E_{\mathrm{D}}/(\Delta p_{\mathrm{He}}\times\alpha_{\mathrm{He}}\times\tau_{\mathrm{He}})$. This is shown in Table II.

TABLE III. Parameters of the pure deuterium beam pulse and the doped pulse in Fig. 3.

| | | |
|---|---|---|
| Deuterium source gas flow | /Pa m$^3$/s | 0.913 |
| Helium source gas flow | /Pa m$^3$ | 0.392 |
| Neutralizer gas flow | /Pa m$^3$/s | 1.383 |
| Extracted current (with/without helium) | /A | 55.4/50.6 |
| Arc current | /A | 1400 |
| Source pressure with/without helium | /Pa | 0.45/0.30 |

TABLE IV. Self-consistent parameter sets of pressures and currents ($p_{n1}$ = pressure at the neutralizer midpoint, $p_g$ = pressure after the acceleration grids, and $p_s$ = pressure in the plasma source).

| Pulse | | 105 082 | 105 082 | 105 265 | 105 266 |
|---|---|---|---|---|---|
| Arc current | /A | 1000 | 1000 | 1400 | 1400 |
| Mass | | 2 | 2 | 4 | 4 |
| Flow source H/D | /Pa m$^3$/s | 1.08 | 1.08 | 0.91 | 0.91 |
| Flow source He | /Pa m$^3$/s | 0.45 | 0.00 | 0.00 | 0.39 |
| $I_{\mathrm{beam}}$ | /A | 43.90 | 42.20 | 50.60 | 55.40 |
| $I_{\mathrm{beam}}$ (H/D) | /A | 35.26 | 42.20 | 50.60 | 45.37 |
| $I_{\mathrm{beam}}$ (He) | /A | 8.65 | 0.00 | 0.00 | 10.03 |
| Flow beam (H/D) | /Pa m$^3$/s | 0.51 | 0.61 | 0.73 | 0.66 |
| Flow beam (He) | /Pa m$^3$/s | 0.20 | 0.00 | 0.00 | 0.23 |
| Flow neutralizer | /Pa m$^3$/s | 1.71 | 1.71 | 1.38 | 1.38 |
| $P_{n1}$ (H/D) | /Pa | 0.20 | 0.20 | 0.20 | 0.21 |
| $P_{n1}$ (He) | /Pa | 0.03 | 0.00 | 0.00 | 0.02 |
| $P_g$ (H/D) | /Pa | 0.25 | 0.23 | 0.22 | 0.24 |
| $P_g$ (He) | /Pa | 0.06 | 0.00 | 0.00 | 0.04 |
| $P_s$ (H/D) | /Pa | 0.41 | 0.36 | 0.30 | 0.34 |
| $P_s$ (He) | /Pa | 0.16 | 0.00 | 0.00 | 0.10 |
| $I_{\mathrm{Helium}}$ | /A | 8.65 | 0.00 | 0.00 | 10.03 |

The helium current in the deuterium pulse is estimated at just under 5 A. This compares with 5 A increase in extracted current and an increase in source pressure by a factor 1.5. So far we have no direct measurement of the partial helium current and have to rely on estimates.

### 2. Preliminary tests with deuterium beams

For historical reasons lower gas flow rates and higher arc currents are frequently used at JET to produce deuterium beams. Figure 3 shows the current traces of a pure 80 kV

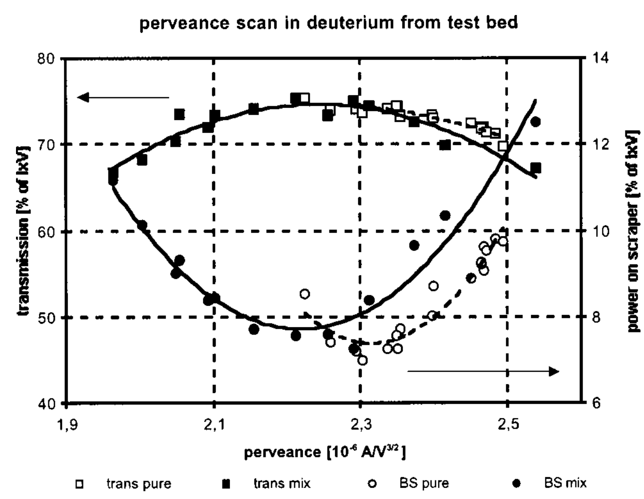


FIG. 4. Power transmission to the test bed beam dump (11 m from the source) and power to a scraper (5 m from the source), plotted against perveance. At optimum perveance the transmitted power passes through a maximum and the intercepted power through a minimum, respectively.

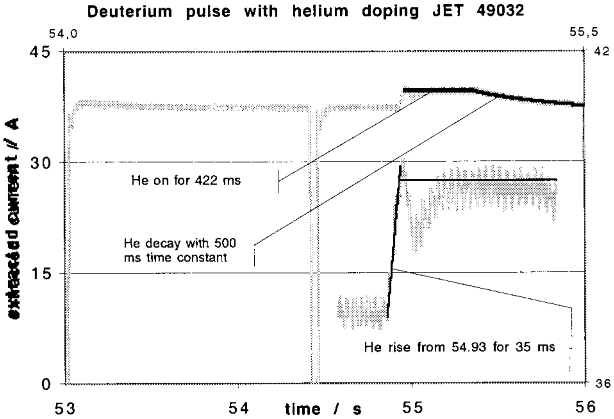


FIG. 5. 75 kV deuterium pulse with helium puff from the JET injector. The extracted current increases by 3 A during the helium puff. The excess current decays with a time constant of 0.5 s after the helium puff.

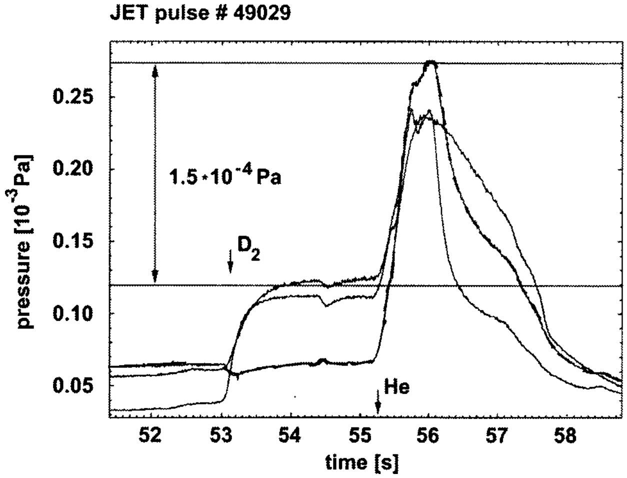


FIG. 6. Typical pressure traces along the beam path during the first JET injection pulse with a doped beam. The deuterium beam is on from 53 to 56 s. He doping is on from 55 to 55.4 s. The pressure rise caused by the helium puff is of the order of $1.5\times10^{-4}$ Pa.

deuterium beam pulse and an otherwise identical pulse with helium puff, both from the test bed. The parameters of the pulses are shown in Table III.

A different approach in estimating the helium current is based on the source filling pressure and the arc efficiency. If we assume that the extracted current $I_\nu$ is proportional to source efficiency $\eta_\nu$ and partial pressure $p_\nu$, that is $I_\nu \sim \eta_\nu \times p_\nu$, we can estimate the helium current as

$$I_{\mathrm{He}}=(I_{\mathrm{He}}+I_{\mathrm{H/D}})\times p_{\mathrm{He}}\eta_{\mathrm{He}}/(p_{\mathrm{He}}\eta_{\mathrm{He}}+p_{\mathrm{H/D}}\eta_{\mathrm{H/D}}). \quad (1)$$

The partial pressure in the source is calculated from the gas flows and the conductance of the accelerator and the neutralizer sections. In the case of the JET source the conductance of both neutralizer sections is in the flow transitional range and has been measured as

$$C=9.1+0.165p_{\mathrm{avg}}. \quad (2)$$

$p_{\mathrm{avg}}$ is the average pressure in the component in Pascal and $C$ is the conductance in $m^3/s$. The pressures in Eq. (1) can now be calculated from Eq. (2) by using the injected flows corrected by the gas transported in the beam. Current and average pressure are iterated until a self-consistent set of parameters is obtained. Table IV shows these parameter sets for hydrogen and deuterium. The helium current equates to 8.7 A for the hydrogen pulse and 10 A for the deuterium pulse, nearly twice above the value derived from the line emission in the case of the deuterium pulse.

The addition of helium in quantities used for the doped beam has very little effect on the beam quality as is demonstrated in Fig. 4. The transmitted power and the power on a scraper located 5 m downstream from the extraction grid are the same for the pure and the doped beam for a given perveance.[33] The figure also shows that the doped beam has essentially the same optimum perveance as the pure beam (the maximum in beam transmission and the minimum in scraper loading occur at almost the same perveance for the pure and the doped beam).

### B. Properties of the beam used for injection at JET

The doped helium beam was operated from PINI 6 of the JET injector at Octant 4. The injector is rated for 80 kV, 50–55 A with deuterium beams. The settings for the deuterium gas flows were close to those used in the test bed pulses (1.0 and 1.5 Pa $m^3/s$ for the deuterium source and neutralizer gas, respectively). The helium gas flow could not be measured accurately but was believed to be of the order of 0.3–0.5 Pa $m^3/s$. The extracted current of the doped beam, operated at 75 kV, is shown in Fig. 5. Helium injection starts at 55 s for approximately 0.42 s and causes a current rise of 3 A. The increased current decays after the end of the helium puff with a time constant of 0.5 s. The associated pressure rise in the duct, recorded by a Penning gauge, is $1.5\times10^{-4}$ Pa (Fig. 6). This compares with a trip limit set at $2\times10^{-3}$ Pa. Taking into account that the time constant for pressure changes is of the order of 1 s, this gives confidence that much longer doped pulses can be performed.

Doped beam operation has been performed at JET on a routine basis and has had no influence on the reliability of the beam system. The actually extracted helium current could not be measured but is estimated as follows. The current of the doped beam pulse injected into the JET plasma (Fig. 5) is approximately 25% lower than the current of the deuterium pulse in the test bed (Fig. 3). It can be assumed that the helium current is also reduced by 25% from 6 A in the case of the test bed pulse to 4.5 A for the pulse to the JET plasma. From the above, typical beam parameters for the JET helium injection were estimated as shown in Table V.

TABLE V. Typical parameters of the doped helium beam used at JET.

| | | |
|---|---|---|
| Distance extraction grid—plasma center | /m | 10.32 |
| Neutral helium current | /A | 3.5 |
| Energy of the helium atoms | /keV | 75 |
| Beam diameter in the plasma center | /m | 0.25 |
| Velocity of the helium atoms | /m/s | $1.9\times10^6$ |
| Average current density of the helium atoms | /A/$m^2$ | 71 |
| Average helium particle density (7.7 m from source) | /$m^3$ | $2.3\times10^{14}$ |
| Average flux density of the helium atoms | /$m^2\,s^{-1}$ | $4.4\times10^{20}$ |

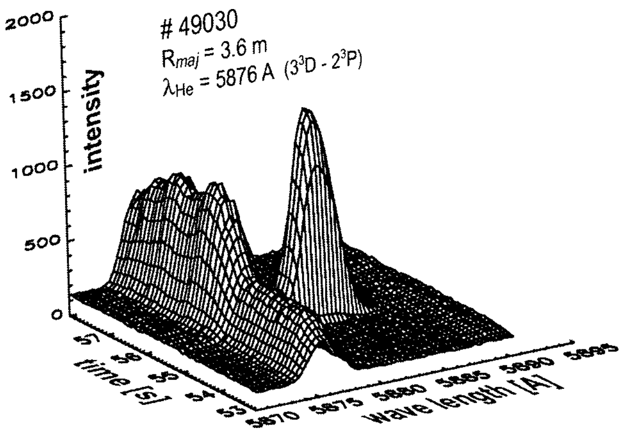


FIG. 7. Intensity of HeI triplet line $2^3P$-$3^3D$ (587.6 nm) emission in a JET pulse for injection of a doped beam. The signal at the left is the unshifted intensity from the outer plasma region; the peak at the right is the Doppler-shifted intensity from the doped helium beam. The signal-to-noise ratio is very satisfactory.

## IV. DISCUSSION

This first application of the active helium beam spectroscopy was a proof-of-principle experiment to investigate whether plasma electron density and temperature profiles can be deduced from suitable emission lines of the fast helium atoms. The evaluation is still ongoing and the results will be reported elsewhere. However, it is of general interest to note that HeI spectra with good intensity can be produced with such doped beams (Fig. 7) without sacrificing the performance of the neutral beam heating system operating with deuterium or hydrogen.

## ACKNOWLEDGMENTS

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[32] The actually measured quantity is the extracted current. The neutral current is the product of extracted current and neutralization efficiency.
[33] Perveance, defined as $I/U^{3/2}$, is the scaling parameter for the space charge blow up of the ion beam ($I$ = extracted current, $U$ = extraction voltage).