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Spectroscopic Measurement of Impurity Transport Coefficients and Penetration Efficiencies in Alcator C-Mod Plasmas

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Abstract

Impurity transport coefficients and the penetration efficiencies of intrinsic and injected impurities through the separatrix of diverted Alcator C-Mod discharges have been measured using x-ray and VUV spectroscopic diagnostics. The dominant low Z intrinsic impurity in C-Mod is carbon which is found to be present in concentrations of less than 0.5%. Molybdenum, from the plasma facing components, is the dominant high Z impurity and is typically found in concentrations of about 0.02%. Trace amounts of medium and high Z non-recycling impurities can be injected at the midplane using the laser blow-off technique and calibrated amounts of recycling, gaseous impurities can be introduced through fast valves either at the midplane or at various locations in the divertor chamber. A five chord crystal x-ray spectrometer array with high spectral resolution is used to provide spatial profiles of high charge state impurities. An absolutely calibrated, grazing incidence VUV spectrograph with high time resolution and a broad spectral range allows for the simultaneous measurement of many impurity lines. Various filtered soft x-ray diode arrays allow for spatial reconstructions of plasma emissivity. The observed brightnesses and emissivities from a number of impurity lines are used together with the MIST transport code and a collisional-radiative atomic physics model to determine charge state density profiles and impurity transport coefficients. Comparisons of the deduced impurity content with the measured Z_{eff} and total radiated power of the plasma are made.

1 Introduction

The ability to diagnose impurity behaviour in a tokamak with an advanced divertor such as Alcator C-Mod is essential. Absolute impurity density profiles, radiated power losses in the divertor and the main plasma, and impurity source penetration rates from the walls and the divertor plates are all quantities of tremendous interest under a variety of operating conditions. Determination of all of these quantities is dependent on a sufficient understanding of the impurity transport coefficients (ie. particle diffusivities and convective velocities) which govern charge state distribution profiles inside the separatrix. It is generally difficult to measure these coefficients using observations of intrinsic impurities alone, owing to the lack of spatial and temporal control over intrinsic sources. A superior technique for making these measurements involves the controlled injection of trace amounts of non-recycling impurities whose evolution in the plasma can then be monitored in space and time. A system capable of such injections on Alcator C-Mod using the laser ablation technique [1] has been operated successfully during the 1993 run campaign. A 3 J Q-switched ruby laser is used to ablate thin films ($\sim 1\ \mu$m) of selected metallic and non-metallic materials from targets located about 1 m from the plasma. The number of atoms actually incident on the plasma edge during such an injection can be varied by changing either the laser spot size on the target or the energy density of the beam. Including the geometry of the beamline path from target to plasma, a typical spot size of 5 mm results in about 2×10^{17} neutral atoms incident on the plasma edge. Gaseous impurities can be injected through capillary tubes located at several poloidal locations in the divertor and at the midplane. Impurity puff rates of up to 10 torr-l/s, as measured by a differential capacitance manometer, have been used for argon and neon injections. The locations of these injection points are shown schematically in Figure 1.

2 Diagnostic Instruments

A variety of spectroscopic instruments is available for the observation of impurity line emission in a wide range of the spectrum. Among the more versatile instruments used for these observations is a 2.2m grazing incidence VUV spectrograph. Operated with a 600 line/mm grating during the 1993 run campaign, this instrument employs a micro-channel plate image intensifier and a 1024 element Reticon [2] detector and is capable of viewing a band of about 50 Å in width in the spectral range of 50-1000 Å with a resolving power from 400-2000. The ultimate time resolution of the spectrograph is as short as 0.5 ms. The instrument views along a single chord but is scannable in space from an impact parameter of about 10 cm above to about 25 cm below the midplane at the magnetic axis which includes a view through the lower x-point region of a typical diverted discharge. This viewing geometry is also shown in Figure 1. The spatial resolution at the plasma is about 2 cm in the vertical dimension and about 12 cm in the toroidal dimension.

This spectrometer has been absolutely calibrated up to 400 Å at present. A soft x-ray source and a gas-filled proportional counter [3] were used to perform the calibration in first, second and third order up to 114 Å through the use of various discrete K_α lines (Mg, O, N, C, B, Be) with outputs of up to 5×10^{11} photons/s/sr. The calibration was then extended to higher wavelengths using the observed relative intensities of known doublet lines of either intrinsic or injected impurities. A relatively continuous set of such doublets can be found to bridge the calibration over the entire wavelength range [4]. The absolute calibration is accurate to within ± 15 % up to 114 Å, and to about ± 30 % at 400 Å.

Additional spectroscopic diagnostics used for the analysis of impurity emission include a five chord crystal x-ray spectrometer array in the 2.5-4.0 Å range [5] and a set of soft x-ray diode arrays with high spatial resolution [6]. The absolute sensitivity of the x-ray spectrometer has been determined through a consideration of viewing geometry and the physical properties of the crystal and the detector. The soft x-ray diode arrays have been relatively calibrated using a broadband x-ray source. Although they lack the spectral resolution necessary for some analyses, they are nonetheless useful for determining local plasma emissivities in the 0.5 Å to 10 Å spectral region.

3 Transport Coefficients

A detailed series of experiments was carried out using laser ablation injections of 1 μm targets of scandium. Scandium was chosen because it allowed the largest number of available spectroscopic diagnostics to be used. At the plasma densities ($\bar{n}_e = 0.8 - 3.0 \times 10^{20}\, m^{-3}$) and temperatures ($T_{e_0} = 1 - 2$ keV) typical of discharges in C-Mod, significant amounts of hydrogen- and helium-like scandium are present. These charge states of scandium emit strongly in the x-ray, allowing for the use of the soft x-ray diode arrays and the five chord crystal x-ray spectrometer. In particular, the $1s2p - 1s^2$ resonance line in the helium-like spectrum, and the Lyman alpha doublet in the hydrogen-like spectrum are the dominant emitters. The VUV spectrograph is capable of observing the $2p - 2s$ doublet of lithium like scandium at 279.8 Å and 326.0 Å. Observations of these high charge states show a relatively fast influx time (a few milliseconds) during which the scandium is being ionized and transported toward the center of the plasma, followed by a slower exponential decay (tens of milliseconds) when the scandium is diffusing outward without any significant recombination occurring. This exponential decay is indicative of the global impurity particle confinement time. Typical exponential decays are shown in Figure 2, and are found to be measured consistently with each of the diagnostics used. Variation of this confinement time with changing plasma parameters was also observed. An increase in confinement was seen as the plasma current was increased over the range of 0.4-1.1 MA. A weak isotopic effect causing an increase in confinement with increasing mass was seen as the background gas was changed from hydrogen to deuterium to helium. The dependence of confinement time on plasma density was seen to be small. Figure 3 summarizes these observations. Qualitatively, these trends are similar to the energy confinement time scaling on C-Mod [7]. Modelling of these injections has been carried out with the MIST code [8] in order to determine appropriate transport coefficients which are then be applied to the analysis of other impurities. Good agreement with observed time histories of scandium injections was found for spatially constant diffusion coefficients in the range of 3.5-5.0 m^2/s and relatively small values of convection velocities (≤ 2 m/s). Investigation of the dependence of these transport coefficients on the particular impurity species injected detected no measurable differences.

4 Plasma Impurity Content

Having determined a suitable set of transport coefficients over a range of typical operating conditions, measurements of impurity densities in the plasma were possible. By matching observed chordal brightnesses of particular intrinsic impurity lines with emissivity predictions taken from MIST and a collisional-radiative atomic physics model [9] and integrated along the instrumental lines of sight, estimates of the total impurity concentrations in the plasma were made. Information from different lines of several charge states of a given impurity serves as a consistency check on the analysis. The dominant high Z impurity in Alcator C-Mod during normal operation is molybdenum from the plasma facing components. The VUV spectrograph is capable of observing a number of molybdenum lines. Strongest among these are the $3p - 3s$ doublet of sodium-like molybdenum (Mo XXXII) at 127.8 and 176.7 Å and the $3s3p - 3s^2$ line of magnesium-like molybdenum (Mo XXXI) at 116.0 Å. Carbon is the dominant low Z impurity in C-Mod. The Lyman alpha line of hydrogen-like carbon is seen strongly in second order by the VUV spectrograph. Typical brightnesses of these impurity lines during moderate density ohmic operation and the inferred impurity densities are listed in Table I, along with the expected contribution to Z_{eff} and to the expected total power radiated from the core by each impurity. Agreement with visible bremsstrahlung and bolometric measurements is good, adding confidence to the quality of the atomic physics rate coefficients and model. Z_{eff} is generally measured to be less than 1.4 and the total core radiated power for these typical discharges is about 300 kW.

4.1 Impurity Penetration

Experiments to measure the penetration of a given source of impurities through the separatrix into the main plasma were also performed. Using the gas injection and the laser ablation injection systems separately, known amounts of argon and scandium were introduced at the plasma edge. The x-ray crystal spectrometer array was used to monitor the brightness of the helium-like resonance, intercombination and forbidden lines, and the grazing incidence spectrometer was used to observe the lithium-like 2p-2s transitions. From these brightnesses, analyses using the MIST code yielded total impurity concentrations in the plasma. For both types of injections, it was found that the fraction of injected particles observed in the core plasma decreased as the central (and hence the edge) electron density was increased. This is qualitatively consistent with the increase in shielding expected from a decreased mean free path of impurity neutrals outside the separatrix. Particles not penetrating are swept along in the scrape-off layer until they reach a target plate. Less than 0.5% of the total argon (a recycling impurity) injected was observed in the core plasma. This compares with about 10% of the total amount of scandium (a non-recycling impurity) incident on the edge penetrating through to the core. The high directed energy of the laser blow-off injections (~ 1 eV) [1] compared with the isotropic, less energetic gas injections is responsible for these differences in penetration. Figure 4 shows a comparison of these shielding effects for the various injections.

5 Conclusions

Through the use of trace laser ablation injections of non-recycling impurities and a variety of spectroscopic diagnostics, impurity diffusion coefficients and convection velocities have been measured for a range of operating conditions in Alcator C-Mod. Using the MIST code and a collisional-radiative atomic physics model, spatially constant diffusion coefficients and small convective velocities have been found to be consistent with the observed spatial and temporal behaviour of impurity line emission over a range of operating parameters. Intrinsic plasma impurity content has been measured using absolutely calibrated diagnostics in the x-ray and VUV regions of the spectrum and has been found to be consistent with observed Z_{eff} from visible bremsstrahlung and bolometric radiated power measurements.

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	carbon	molybdenum
typical line brightness (photons/s/sr/cm^2)	C VI 3×10^{14}	Mo XXXII 2×10^{14}
central impurity density (cm^{-3})	2×10^{11}	2×10^{10}
contribution to Z_{eff}	0.1	0.2
contribution to core radiated power (kW)	15	140

Figure and Table Captions

Figure 1: Viewing geometry of the VUV spectrograph along with laser ablation and gas puff impurity injection locations.

Figure 2: Exponential decays of laser ablation injection of scandium at t=0.55 s.

Figure 3: Impurity particle confinement time scaling with plasma current and mass of the background gas.

Figure 4: Penetration efficiency of injected scandium and argon.

Table I: Typical ohmic plasma impurity content for $\bar{n_e} \sim 1 \times 10^{20}$ m^{-3} and $T_e \sim 2$ keV.

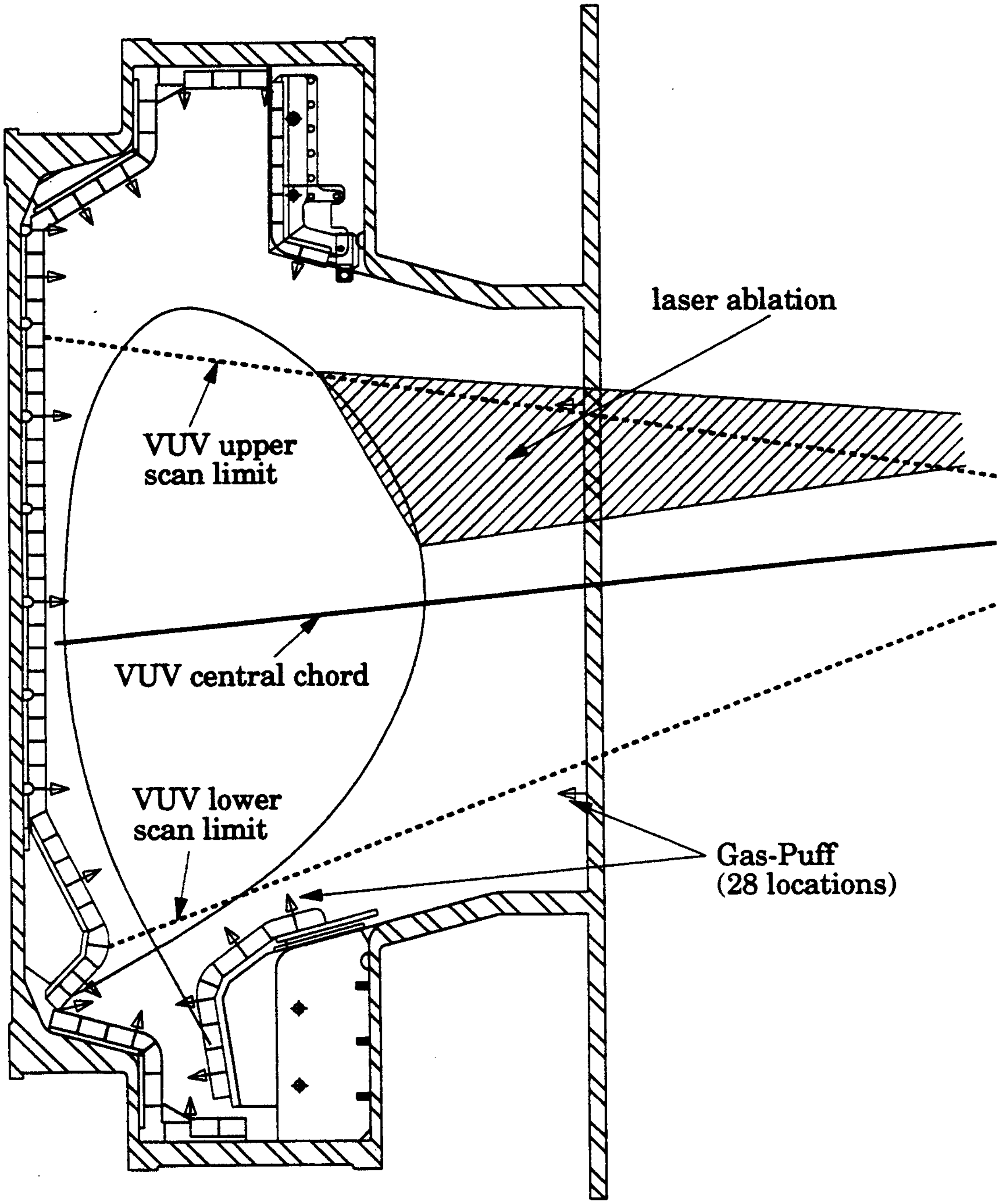
laser ablation
VUV upper scan limit
VUV central chord
VUV lower scan limit
Gas-Puff (28 locations)

Figure 1

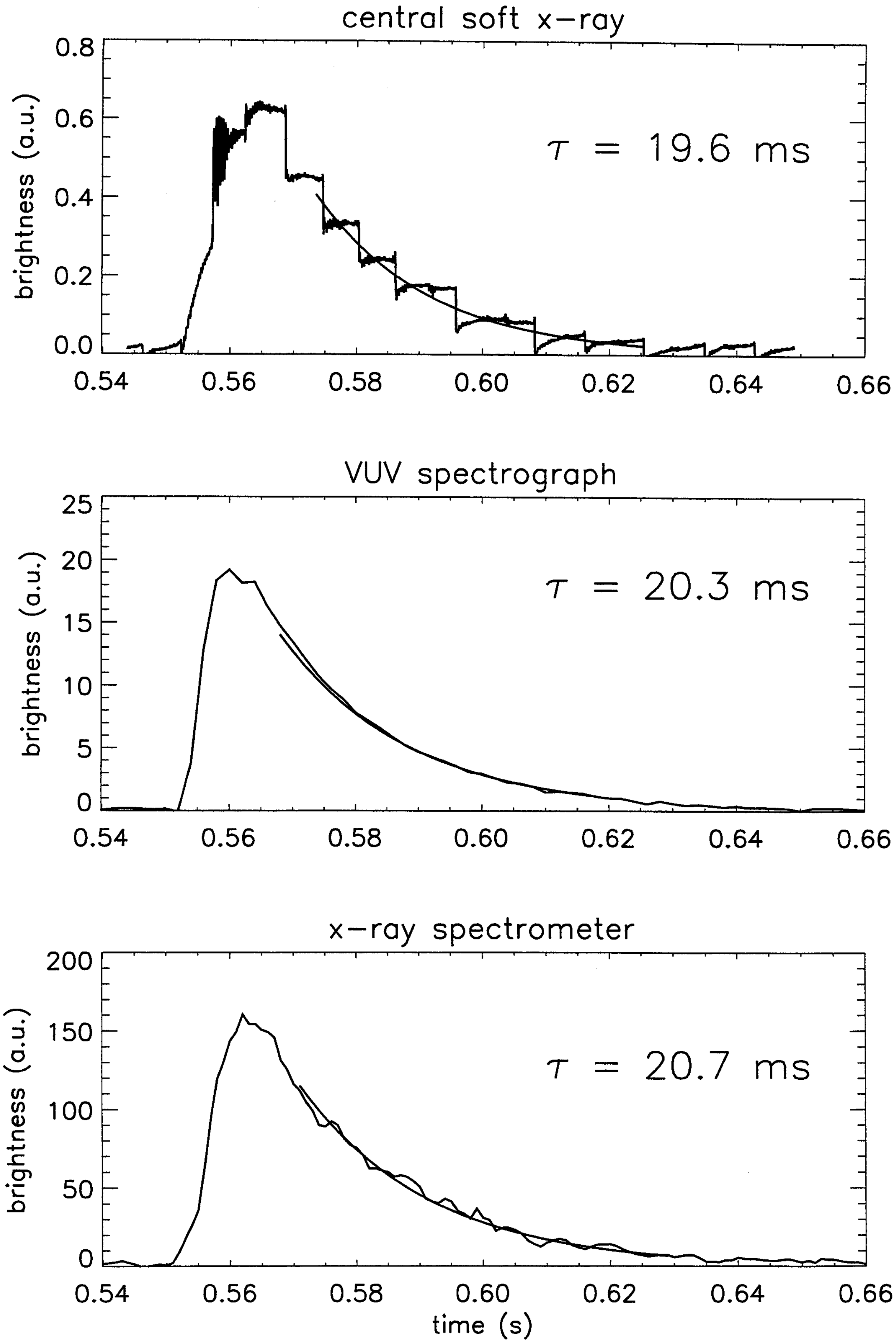
central soft x-ray
brightness (a.u.)
0.0
0.2
0.4
0.6
0.8
τ = 19.6 ms
0.54
0.56
0.58
0.60
0.62
0.64
0.66
VUV spectrograph
brightness (a.u.)
0
5
10
15
20
25
τ = 20.3 ms
0.54
0.56
0.58
0.60
0.62
0.64
0.66
x-ray spectrometer
brightness (a.u.)
0
50
100
150
200
τ = 20.7 ms
0.54
0.56
0.58
0.60
0.62
0.64
0.66
time (s)

Figure 2

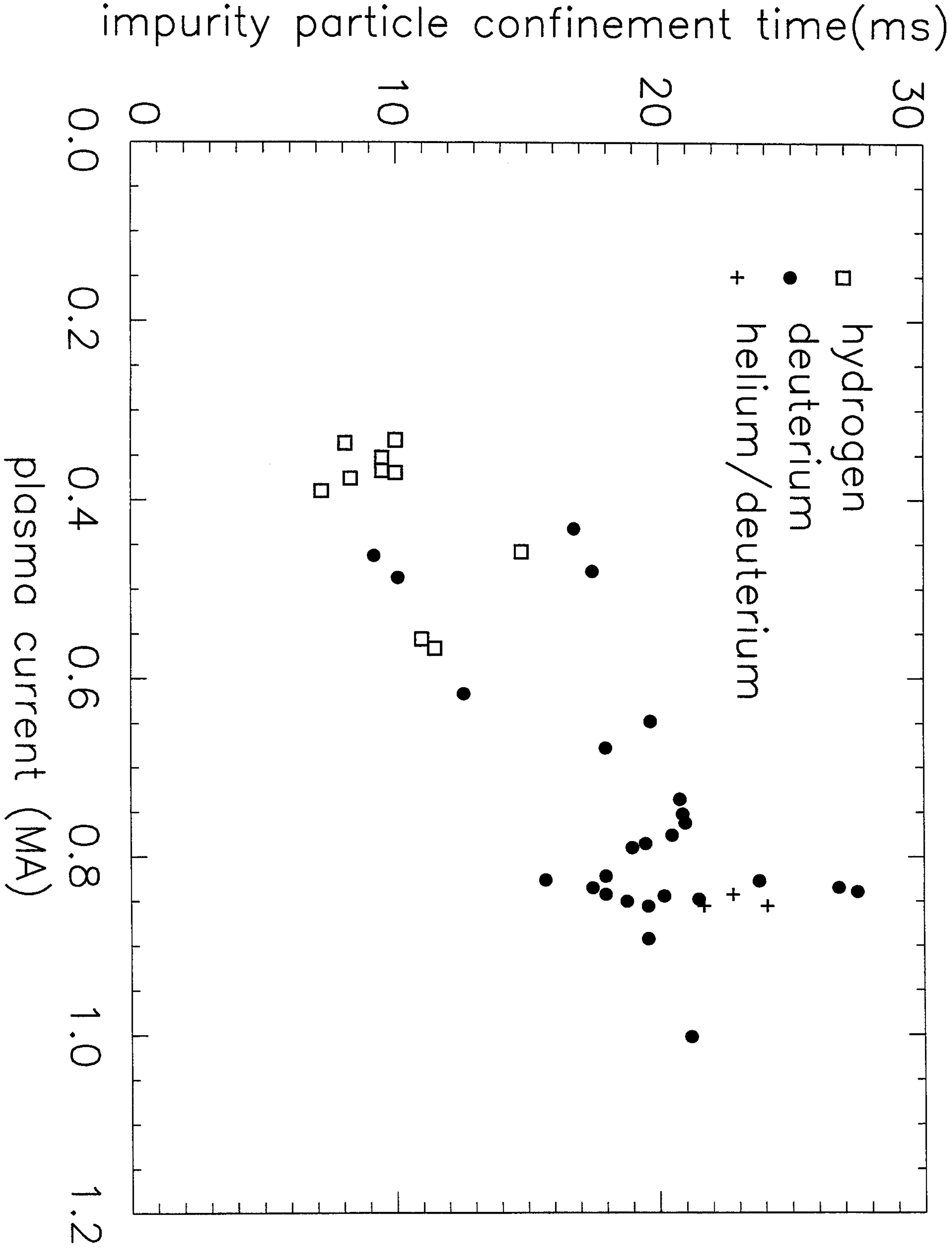
impurity particle confinement time(ms)
0
10
20
30
plasma current (MA)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
□ hydrogen
● deuterium
+ helium/deuterium

Figure 3

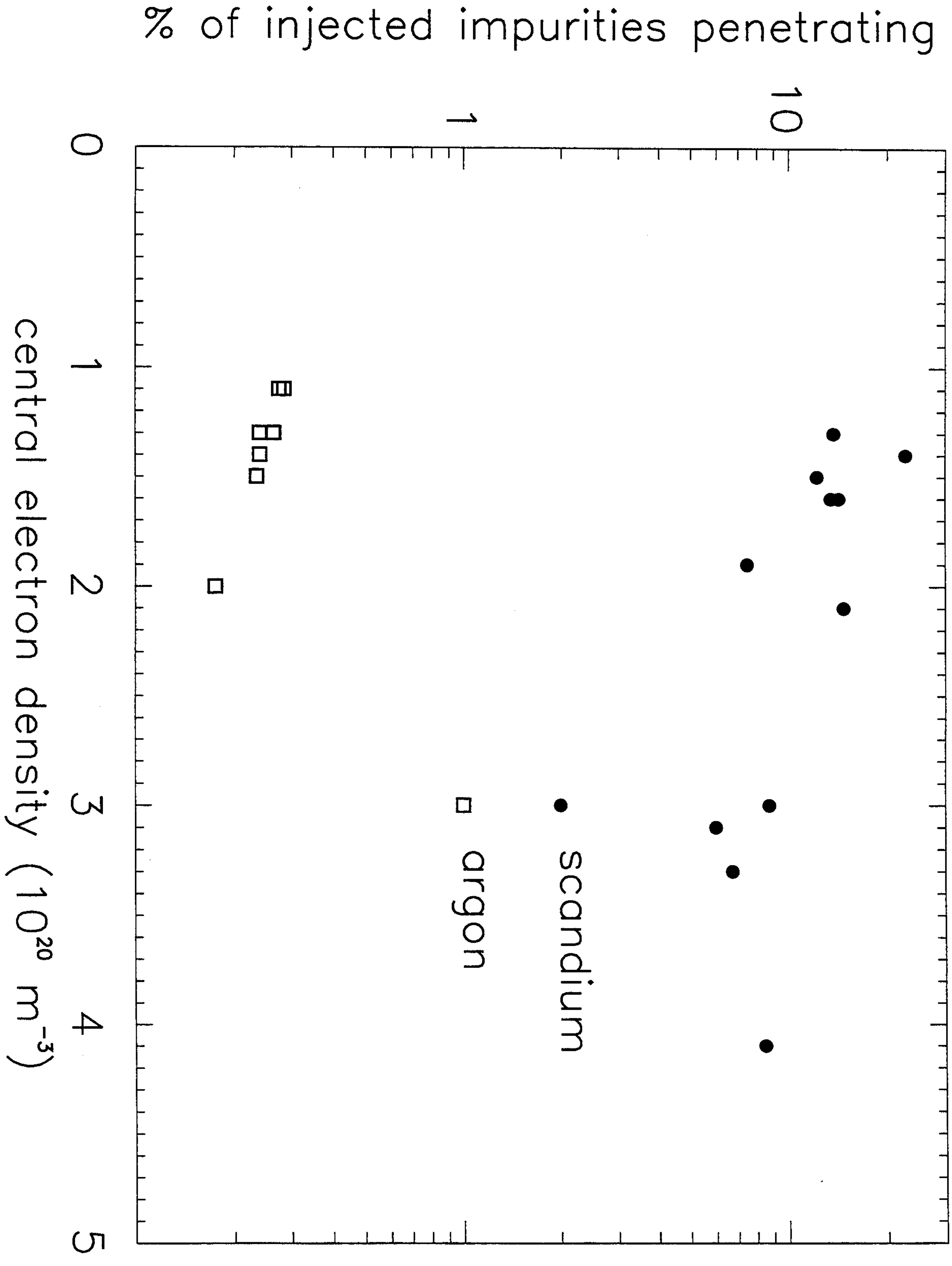
% of injected impurities penetrating
10
1
0
1
2
3
4
5
central electron density (10^{20} m^{-3})
● scandium
□ argon

Figure 4