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Modelling Ion Source Uniformity

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ABSTRACT

Recently it has become clear that the magnetic filter field used in the JET NBI Ion Source, to enhance the monatomic species yield, also produces non-uniformity in the ion density, which causes reduced transmission of the extracted beam. A Monte-Carlo model has been developed to trace the trajectories of electrons and ions through the three dimensional magnetic field of the ion source. This model has reproduced the measured non-uniformity of the filter field ion source. Use of this Monte-Carlo model has assisted the development of a high monatomic yield ion source with improved plasma uniformity.

1. INTRODUCTION

The Neutral Beam Test Bed [1] is a replica of the JET Neutral Beam Injector [2], configured to allow offline development of the Positive Ion Neutral Injector (PINI). The PINI ion source is of the volume arc discharge type with an external pattern of permanent magnets (see Fig 4).The magnet pattern creates long-range filter field that gives an enhanced monatomic species fraction [3]. A high monatomic species fraction is required from the JET NBI Ion Source so that sufficient power is delivered at the full neutral energy. After an extensive development programme [4], a magnet configuration, the SC15S3 super-cusp was chosen as standard for all ion sources used at JET.

2. EVIDENCE FOR NON-UNFORMITY

The non-uniformity of the ion source can be detected using various experimental techniques but the clearest evidence comes from the measurement of the beam transmission and beam divergence.

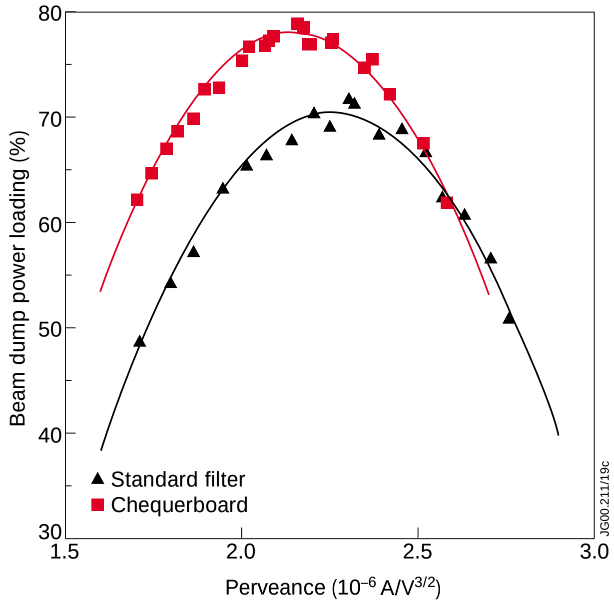


Fig 1 Comparison of beam power transmitted to the Test Bed beam dump for a standard filter source and a chequerboard only source.

2.1 Beam Transmission

The Test Bed operated a PINI where the standard SC15S3 source was replaced with an ion source using only the chequerboard magnet pattern. The chequerboard source showed ~ 10% higher transmission of the beam power to the beam dump (Fig 1). Since the same accelerator grid stack was used in both experiments, the increased transmission can be attributed to a difference in magnetic configuration of the two ion sources.

2.2 Multi-channel Spectroscopy

The Multi-channel Spectrometer uses a CCD array to acquire the spectrally resolved image of the light delivered to a monochromator from 15 fibre optic channels aligned vertically across the ion beam [5].

The analysis of the beam divergence derived from spectroscopic data can be summarised by a plot (Fig 2) which shows the total beam perveance where the local beamlet minimum divergence occurs across the vertical beam axis.

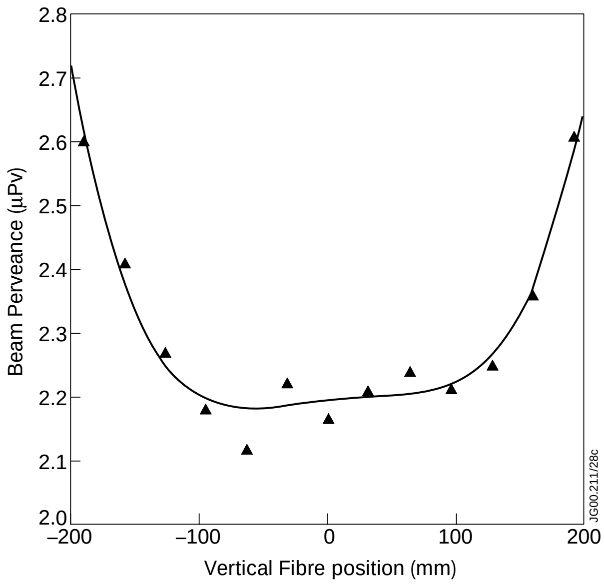


Fig 2 The vertical distribution of the beam perveance where the local minimum beam divergence occurs for the SC15S3 source.

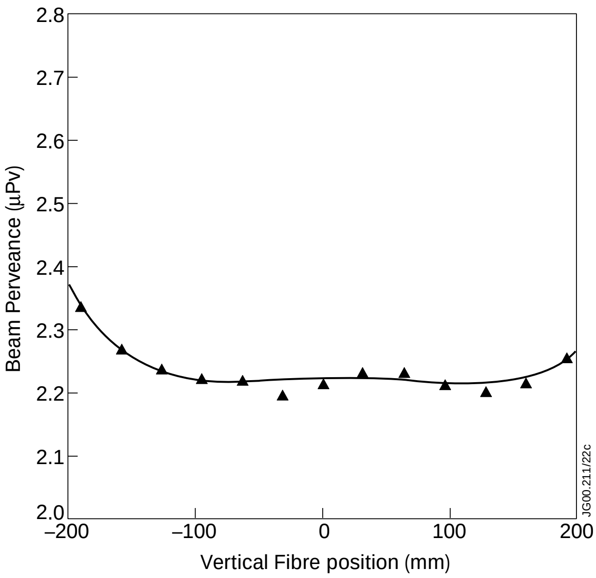


Fig 3 The vertical distribution of the beam perveance where the local minimum beam divergence occurs for the chequerboard source.

This is a strong piece of evidence for non-uniformity in the ion density in the source since, for an array of identical extraction apertures, the local minimum beamlet divergence will only occur when the local source ion density is at the correct value. The plot in Fig 2 is effectively the inverse of the ion density profile in the vicinity of the extraction electrode. Statistical analysis of this profile gives a RMS deviation from a uniform distribution of 4á9%. The same analysis of the beam extracted from the chequerboard source shows evidence of a more uniform ion density (Fig 3). This profile shows a RMS deviation from uniform of only 1á0%.

These beam divergence measurements show clear evidence that the filter field added to enhance the monatomic species yield produces an ion source with a non-uniform ion density.

3. ION SOURCE MODEL

In order to help us to understand the non-uniformity, a Monte Carlo code was developed to simulate the behaviour of the PINI Ion Source, based on the methods outlined by S Ido [6]. Each of the ion source magnets is defined by its position, orientation, size and field strength, and the components of the magnetic field vector are calculated using analytical expressions. The magnetic modelling code superimposes the field of individual magnets to produce a 3-D field map of each component of the magnetic induction. The trajectories of particles in the source magnetic field are solved by a stepwise controlled Runge-Kutta integration. For this simulation, electric fields are not considered so the Lorentz force alone governs the particle motion.

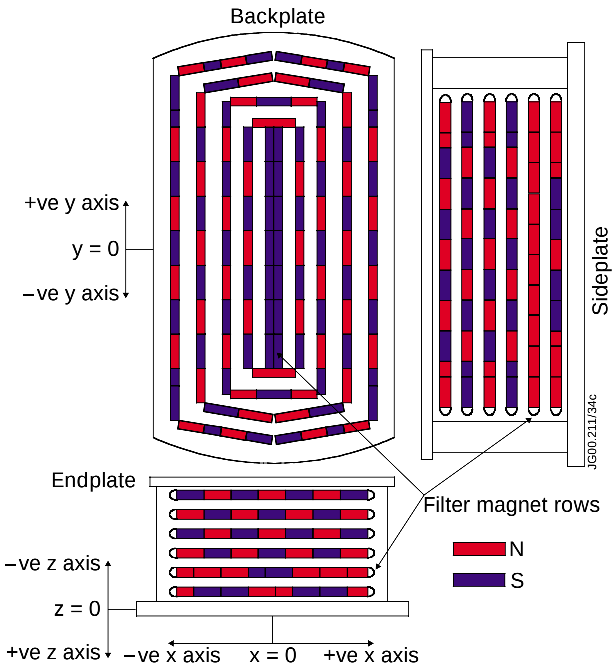


Fig 4 Schematic of the SC15S3 super-cusp magnet configuration.

3.1 Electron Trajectories

The next step of the model is to trace the most significant interactions of the primary electrons, i.e. those with the shortest mean free path. These are the elastic, ionisation and dissociation collisions with the neutral source gas.

Elastic $e + H_2 \rightarrow e + H_2$

Ionisation $e + H_2 \rightarrow H_2^+ + 2e$

Dissociation $e + H_2 \rightarrow 2H + e$

A Chebyshev polynomial fit is used to interpolate continuous data for the energy dependent cross-sections [7]. The cross-sections are used to calculate a mean free path for each value of electron energy and neutral gas density. The reaction that occurs, and the electron trajectory length is chosen at random with a probability given by the relative magnitudes of the corresponding mean free paths. Figure 5 shows a sample calculation of the probability distribution.

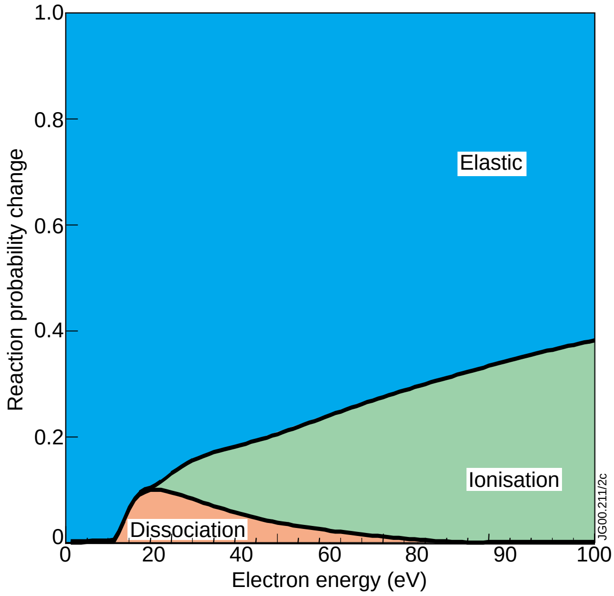


Fig 5 Probability function generated from the mean free path lengths of electrons in a neutral gas density of $3{\cdot}8\times10^{19}m^{-3}$.

3.2 Ion Trajectories

The co-ordinates of the ionisation reactions are used as the starting points for ion trajectory calculations. For this model the H_2^+ ion trajectories are considered since they are the most abundant ions created by the primary electrons. H^+ and H_3^+ ions are generally created in secondary reactions of the H_2^+ ions. Thus following the H_2^+ ions trajectories marks the position of the total ion population. To determine the path of the H_2^+ ions the most significant interactions with the neutral H_2 source gas are used.

$H_2^+ + H_2$ [Elastic]
$H_2^+ + H_2 \rightarrow H_2 + H_2^+$ [Charge exchange]
$H_2^+ + H_2 \rightarrow H^- + H^+ + H_2^+$ [Dissociation]
$H_2^+ + H_2 \rightarrow H_3^+ + H$ [H_3^+ production]

These reactions are modelled in an identical way as the electron interactions. An example of the probability distribution is shown in Fig 6.

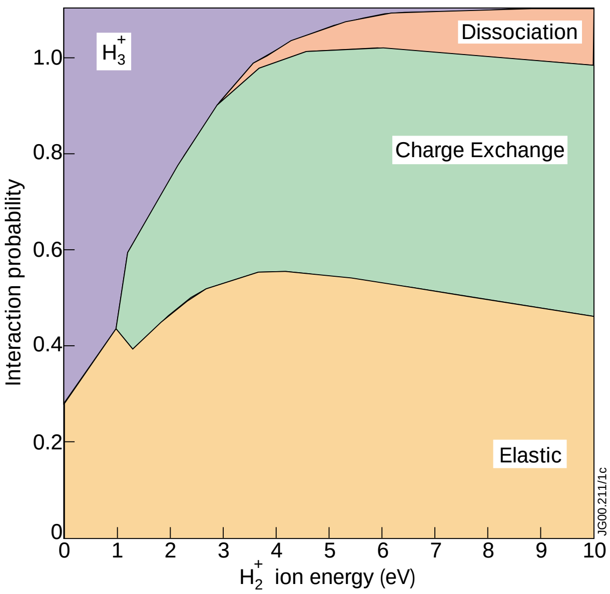


Fig 6 H_2^+ ion interaction probabilities used in the H_2^+ ion trajectory model. A random number is used to select the process that occurs.

3.4 Model of the SC15S3 Source

For the initial conditions of the primary electrons a uniform energy of 100eV is used, which corresponds to the typical arc potential. The electrons are launched from positions along the 24 filaments, with a launch plane

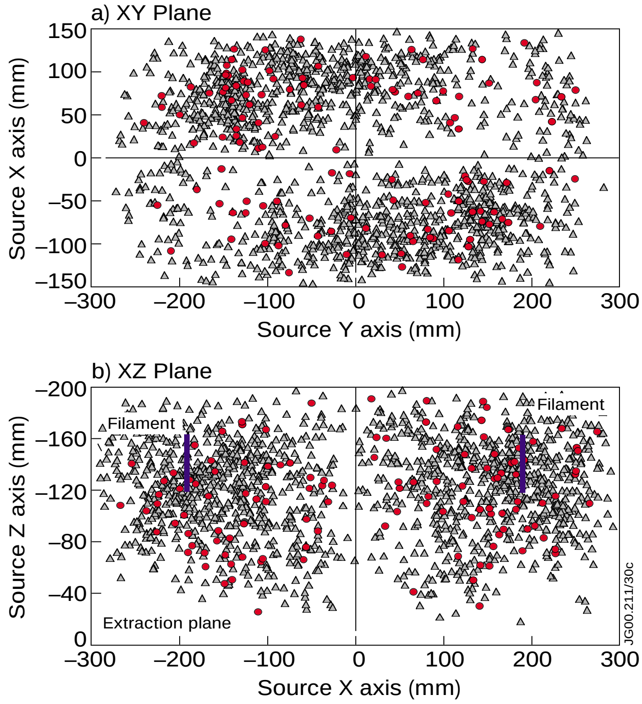


Fig 7   Projections of the inelastic interaction points for 100eV electrons launched from the filaments on a) the XY plane and b) the XZ plane.

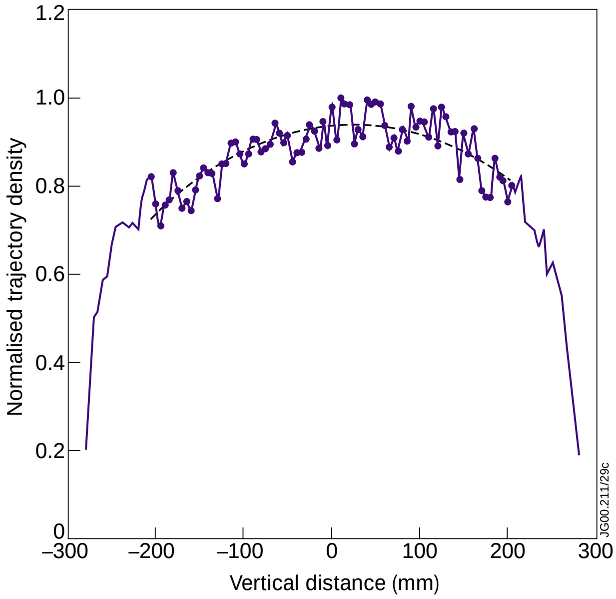
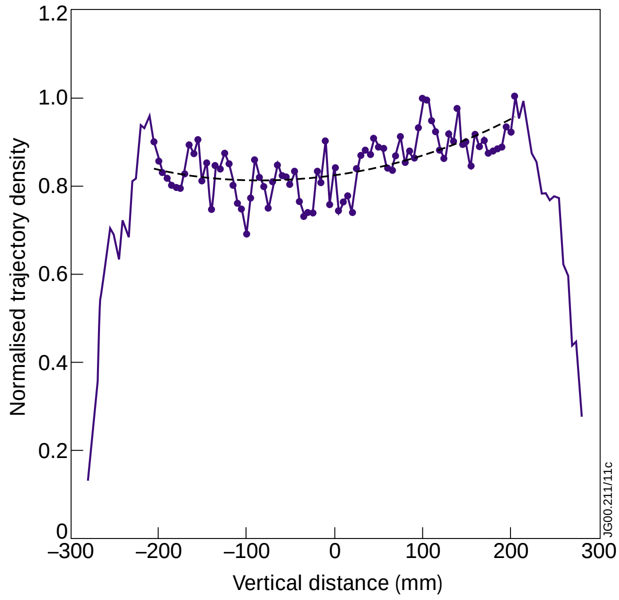


Fig 8   Vertical profile of the trajectory density map, with quadratic polynomial fit to the width of the extraction array.

perpendicular to the filament. In the case shown in Fig 7 a source gas density of 3á81$\times10^{19}$m^{-3} has been used (equivalent to a gas pressure of 4µbar at 750K). Each of the initial 1194 electrons was traced until its energy fell below 10eV or it hit a source wall. The trajectories of the secondary electrons produced in the ionisation reactions were also calculated. Projecting the inelastic interaction points onto planes perpendicular to the source walls gives a qualitative view of the ion production regions. Next, 64000 H_2^+ ions were launched from the ionisation locations calculated by the primary electron model. The ions are each given an initial energy chosen randomly from a normal distribution with a mean value of 0á5eV. The ion trajectories were traced until the energy falls below 0á01eV or a collision with a source wall is detected. An ion density profile can be derived from the number of ion trajectories crossing the extraction plane (Fig 8). The modelled ion profile has a RMS deviation from a uniform distribution of 5á3%. This agrees well with the value of 4á9% derived from spectroscopic measurements.

4.   NEW ION SOURCE DEVELOPMENT

Using the Monte-Carlo code, a variety of magnetic field configurations were modelled prior to experimental tests. The best configuration modelled, NSC_6, appeared to give improved ion uniformity without loss of primary electron confinement. In this case the modelled ion trajectory density profile at the extraction plane has a RMS deviation from uniform distribution of 2á4% (Fig 9).



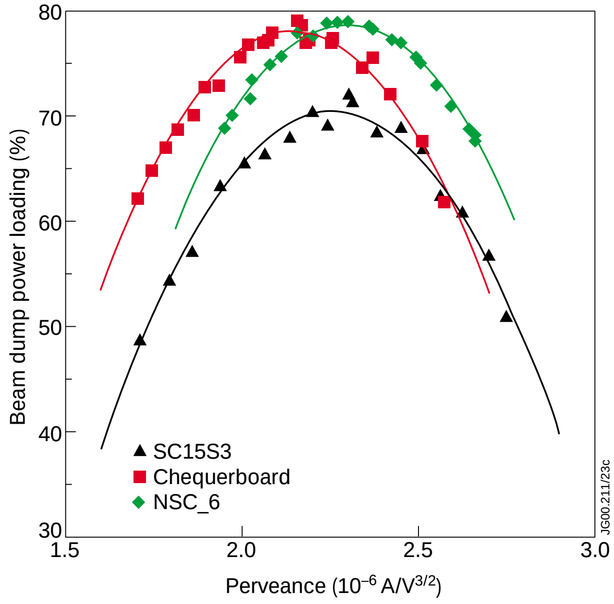


Fig 9 Vertical profile of the trajectory density map, with quadratic polynomial fit to a width of ±200mm about the extraction array centre.

Fig 10 Comparison of the beam transmission to the Test Bed beam dump between the SC15S3, chequerboard and NSC_6 ion sources.

Test of PINIs with the NSC_6 ion source showed that the transmission of the beam to the Test Bed beam dump was comparable to that from the chequerboard only source (Fig 10). Also, the monatomic species fraction of the NSC_6 ion source (87%) is only ~5% lower from the corresponding value of the SC15S3 super-cusp (92%).

The plot of the measured total beam perveance where the local minimum beamlet divergence occurs (Fig 11) shows a RMS deviation from uniform of 2.8%, agreeing well with the predicted value of 2.4%.

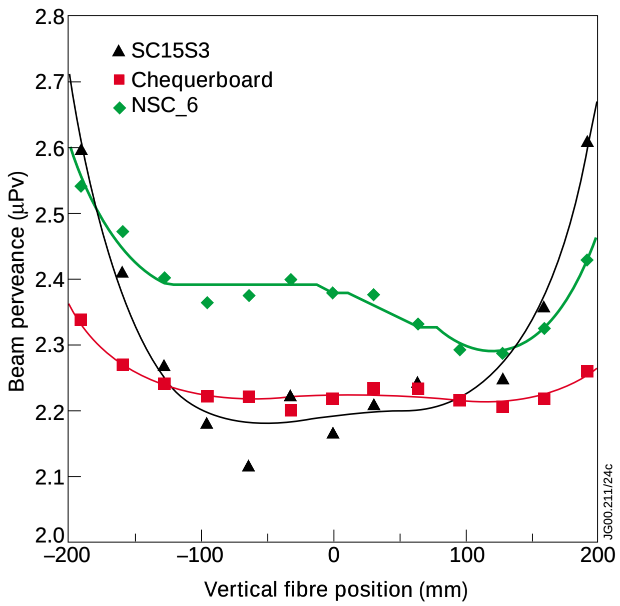


Fig 11 Comparison plots of the total beam perveance at the local minimum beamlet divergence for the NSC_6, SC15S3 and chequerboard ion sources.

5. SUMMARY

Following the evidence that the filter field used in the PINI ion source, to enhance the monatomic species yield, results in ion non-uniformity, a Monte-Carlo model of the ion source used in the JET PINI has been developed. This has successfully reproduced the measured non-uniformity of the ion density from extracted beams. The model has been used to develop a new source configuration, which gives a factor of 2 improvement in ion uniformity.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Falter H-D *et al.*, Proceedings of the 13th Symposium on Fusion Technology, Varese, Italy (1984) 571.

[2] Duesing G, Altmann H, Falter H-D, Goede A, Haange R, Hemsworth R S, Kupschus P, Stork D and Thompson E, Fusion Technology 11 (1987) 163.

[3] Holmes A J T, Green T S and Newman A F, Rev Sci Instrum 58 (1987) 1369.

[4] Green T *et al.*, Proceedings of the 13th Symposium on Fusion Technology, Varese, Italy (1984) 693.

[5] Ciric D, Falter H-D and Godden D J, Proceedings of the 20th Symposium on Fusion Technology, Marseille, France (1998) 469.

[6] Ido S, Hasebe H and Fujita Y, Jpn J Appl Phys 32 (1993) 4761.

[7] Smith K and Glasser A H, Computer Physics Communications 54 (1989) 391.