A 70 KEV NEUTRAL HYDROGEN BEAM INJECTOR WITH ENERGY RECOVERY FOR AN MSE DIAGNOSTIC APPLICATION IN FUSION RESEARCH

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Abstract :

A 70 keV 40 A hydrogen beam injector has been developed at Cadarache for a plasma diagnostic (MSE: Motional Stark Effect) to provide a measurement of the plasma current distribution in the Tore-Supra Tokamak. We present in this paper, the principle and the first experimental results of the injector, where a new type, and advantageous, energy recovery system, based on a magnetic neutraliser plasma confinement, has been developed. The hydrogen ion beam is accelerated to 70 keV with a three-grid multi-aperture system (aperture diameter Φ=11 mm) with an ion current density of $\approx$ 160 mA/cm^2. An ion source with a shape (height 1.2 m, width 80 mm) specifically adapted to the recovery system has been developed to meet the injector requirements: uniformity, high proton fraction (>80%) and high current density, $\approx$160mA/cm^2 over the whole extraction surface (900cm^2). A neutral beam power (H^0) of 500 kW has been achieved with a divergence of $\approx$0.6° at 70 keV.

1 INTRODUCTION

The measure of the current-density profile is important to control, in real time, the equilibrium, the stability and confinement of thermonuclear fusion plasma in Tokamaks[1]. At the operating plasma densities of present-day tokamaks, the neutral beam attenuation is minimal for a hydrogen beam of 60~80keV. As a neutral beam propagates through a plasma, collisions of the beam particles with background ions and electrons will excite beam atoms, leading to emission of radiation. In addition, the Motional Stark Effect[2], which arises from the Lorentz electric field induced in the atom's rest frame due to motion across the magnetic field ($\mathbf{E}=\mathbf{V}_{beam}\mathbf{x}\mathbf{B}$), causes both a wavelength splitting of several angstroms and polarisation of the emitted radiation. The measurement of the polarisation of Stark broadened Hα emission determines the pitch angle of the Lorentz electric field **E**. For a plasma density of 10^{20}m^{-3} on Tore Supra, good resolution measurement of **E** can be achieved with >5 A of 70 keV H^0 injected into the plasma[3,4]; taking into account the low neutralisation rate of hydrogen at 70keV (<35%), the corresponding extracted ion current of the accelerator must be in the range of 35-40A. In the framework of the MSE diagnostic, a developmental work has been undertaken to change one of the neutral beam injectors used in the past for plasma heating into a reliable 70 keV 40A H^0 injector. We present below the new energy recovery system, which allows important simplifications of the entire injector, the new ion source (based on a DRIFT source concept[5]), and the first experimental results on the test-bed.

2 INJECTOR PRINCIPLE

2.1 The recovery system:

A 70 keV 40 A ion beam is formed via a large-area (240 cm^2) multi-aperture three-electrode extraction system. This energetic ion beam is partially converted into fast atoms by charge exchange and dissociation processes with the hydrogen gas injected in a gas cell (neutraliser) adjacent to the accelerator. At this energy, the neutralisation rate is less than 35%, which results in a high, full energy, proton (non-neutralised) beam current (approximately 20 A) at the neutraliser exit. The recovery system consists of an electrostatic deceleration (to $\approx$20 keV) of this intense proton beam, converting the beam kinetic energy into electrical energy. This decelerated ion beam expands strongly under the effect of space-charge forces. This transverse motion is used to allow the decelerated ions to be collected on the recovery electrode (see Figures 1and 2). The potential distribution along the injector is shown on figure 1.

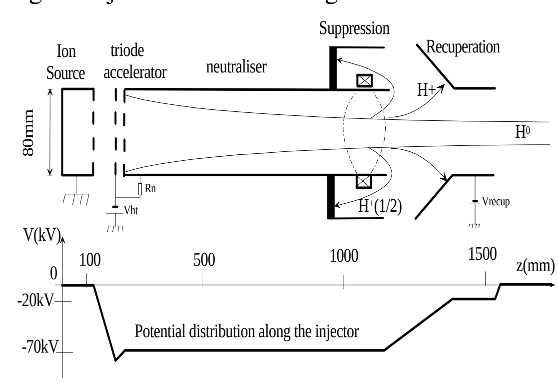

Figure 1: Injector principle

The ion source operates at ground potential, and the neutraliser is biased at the high negative potential (-70 kV) corresponding to the desired neutral beam energy. This polarisation of the injector has the advantage of minimising the energy stored in stray capacitances as there is no power supply on a high voltage platform as is the case in "conventional" systems with the source at high voltage and the neutraliser at ground potential[6].

Confinement is necessary at the exit of the neutraliser to prevent electrons from the plasma created in the neutraliser by the beam from being accelerated to the higher positive potential of the recovery electrode (≈-20kV) or ground. The recovery system previously used[7] operated with a negatively biased electrode (suppression electrode) at the exit of the neutraliser which created a potential barrier, but strong perturbations of the injector potentials occurred when the beam current was increased. In the present injector (see figure 1), the suppression electrodes have been removed, and a magnetic filter located at the exit of the neutraliser acts as an efficient electron trap. The integrated value of this magnetic field on the beam axis is 0.12T.cm, with a maximum magnetic field value of 0.015T; the local electric field is in the range of 0.5kV/cm; the local pressure has been evaluated[8] for a total gas target in the neutraliser of $1.10^{20}m^{-2}$ to be 0.032Pa.

Figure 2 shows a 2D (code SLAC[9]) simulation of the ion beam optics in the recovery stage. The 20A full energy (70keV) ion beam is collected by the recovery electrode, while the low energy (1/3 and ½ of full energy) ion beam (<5A) which results from the collisions of H_3^+ and H_2^+ with neutral gas inside the neutraliser cannot reach the recovery electrode; they are deflected out from the neutral beam, reflected and dumped in an actively cooled target. For these simulations, we have assumed that the neutralisation of the space charge occurs before the magnetic filter, but not after. These simulations also shown that an efficient beam recovery only occurs with a narrow ion beam (hxl: 100x7 cm^2).

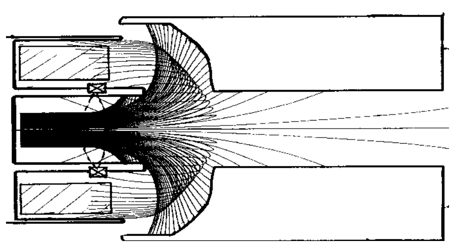

Figure 2:Ion beam simulation in the recovery stage.

2.2 The accelerator:

The beam is composed of only 4 columns of 60 beamlets (240 beamlets of $1cm^2$). The accelerator is a three grid multi-aperture system; the first grid, being the grid at the plasma source surface, is grounded. The beam is focused in the vertical plane at 7.5 m by a combination of aperture offset steering and curvature of the extraction surface (centre of the plasma) It is focussed at 4 m in the horizontal plane by aperture offset steering alone.

2.3 The ion source:

The ion source has been developed to meet the requirement of the injector: a specific shape (height 1.2 m, width 10cm); it must produce a current density of 160 mA/cm^2, with proton rate higher than 80% (5% H_2^+ and 15% H_3^+), with a uniform plasma density within ±10% over the whole extraction surface (~900 cm^2).

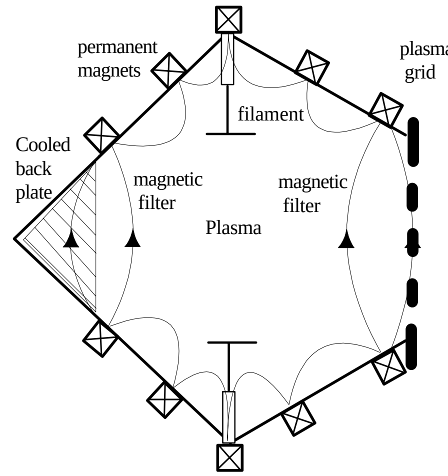

Figure 3 : The ion source

These objective has been achieved with a particular magnetic confinement based on the DRIFT source[5]. The specificity of this magnetic confinement is the compensation of the vertical plasma drift (**B x gradB**) due to the transverse magnetic filter in the front and back face of the source; this results in good plasma uniformity. Moreover, the magnetic filter on the plasma grid level lowers the local electronic temperature.This prevents H_2^+ formation close to the plasma grid, and enhances the destruction, via recombination with the (colder) electrons, of H_2^+ and H_3+. The result is a high proton fraction in the extracted beam. Loss of plasma occurs at the upper and lower source extremities due to both the proximity of the walls and the increased wall area due to the curvature of the extraction surface in the vertical plane (of the plasma

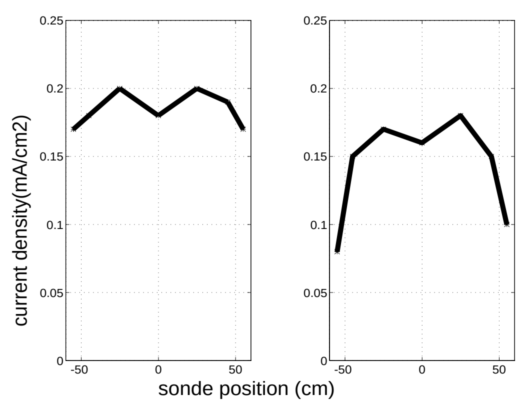

Figure 4: Vertical plasma density along the source: with (left) and without (right) over-polarisation.

grid is 3.5 cm further from the rear of the source at the top and bottom). A correction of the plasma density is made by over polarising the cathodes (filaments) in this area, which increases the ion bombardment energy and thus heats the cathodes (tungsten filaments) more than those elsewhere in the source. A diagnostic of plasma density has been installed to measure the vertical uniformity on the plasma grid level; it consists of the measurements of the ion current that flows in 10 thin ,negatively polarised, rods. Figure 4 shows the ion density measured on the plasma grid level, with (left) and without (right) over polarisation of the cathodes; we clearly see that without polarisation, the plasma density in the source extremity is lower by a factor of 2. With polarisation, the density uniformity is constant within ±10% around

To achieve 170 mA/cm^2; the arc current is 1800 A, the polarisation of the cathodes is –65 V for the central area of the source, and the over-polarisation at the extremity is –20 V (total: -85 V); the normal operating pressure both in hydrogen and deuterium is 0.65 Pa.

3 FIRST EXPERIMENTAL RESULTS

We have run this injector either in hydrogen and deuterium; the measured perveance defined as $P=Id.E^{-3/2}$, where Id is the drain current (ion beam current) and E is the beam energy, corresponding to the best optics is $P_{H2} = 1.8*10^{-6}$ for hydrogen, and $P_{D2} = 1.18*10^{-6}$ for deuterium. The ratio P_{H2}/P_{D2}=1.52 slightly higher than the theoretical value which is √2 (= 1.41) if the species ratio is the same. The neutral beam horizontal profile on the target (located 3 m downstream from the accelerator) results from the merging of the four beamlet columns; it is approximately a Gaussian profile; and at the best optics, the measured divergence is in the range of 0.6-0.7° for hydrogen, and 0.5-0.6° for deuterium.

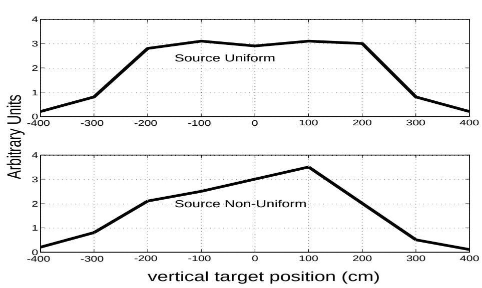

Figure 5: Vertical neutral beam profile on the target.

In figure 5, we can see the neutral beam profiles in the vertical direction, and the influence of the source homogeneity: with a good uniformity of the source, the profile is in good agreement with expected (a quasi rectangular profile). We can also see the effect of a bad polarisation of the source (source non-uniform) on the profile.

On figure 6, we can see the current collected on the recovery electrode either in hydrogen and deuterium at the matched beam perveance. The symbols are the experimental results and full lines are the expected values corresponding to the neutralisation rate with the beam energy. For this calculation, we have supposed that the proton fraction in the source is 80% (5% H_2^+ and 15% H_3^+). The potential of the recovery electrode is adjusted with the recovery current; at E=70keV and Id=36A, the recovery current is 18 A, and the recovery potential is – 30 kV.

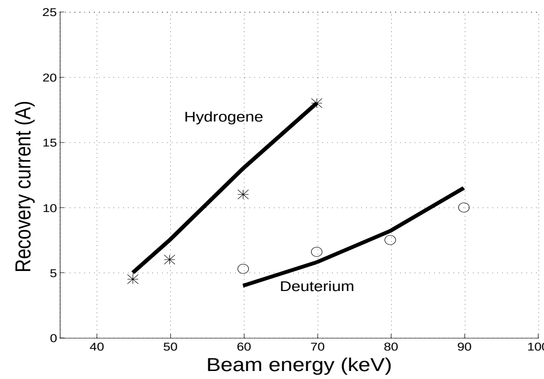

Figure 6: Recovery current (Irecov) vs beam energy (E) ; Marker: experiment; full line: calculation

A summary of the main parameters of the injector is presented in table 1; Pt is the neutral power on the target, the beam duration ranging from 1 to 5s.

Table 1: Summary of experimental results

Gas	E (keV)	Id (A)	Irecov (A)	Pt (kW)
H_2	50	20	5.5	288
H_2	60	27	11.5	373
H_2	70	35	18	450
D_2	70	22	6	520
D_2	80	27	7.5	625
D_2	90	32	10	710

4 ACKNOWLEDGMENTS

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5 REFERENCES

[1] B.W. Rice et al., Rev. Sci. Instrum., vol 70, number 1, January 1999, 815
[2] F.M. Levinton et al., Physical Rev. Letters, 6 November 1989, vol 63, Number 19, 2060
[3] M. Hesse, Association EUR-CEA/DRFC, January 1999, NT Φ / number 136
[4] P. Lotte, DRFC, CEA Cadarache, France, private communication
[5] A. Simonin et al; RSI, vol 70, n°12 (1999), p. 4542-4544
[6] M. Fumelli, Rev. Sci. Instrum. 57 (7), July 1986, 1266
[7] M. Fumelli, Fusion Technology, vol.17, July 1990, 571-576
[8] B. De-Esch, DRFC, CEA Cadarache, France, Private communication
[9]W.B. Hermannsfeldt, Electron Trajectory Program, SLAC report-226 (1979)