Testing of a pulsed He supersonic beam for plasma edge diagnostic in the TJ-I U torsatron.

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Abstract: A new, compact atomic beam source based on the supersonic expansion of He has been developed for application as a plasma edge diagnostic. The beam is produced from a pulsed valve with a duration between 0.2 to 2 msec and a nominal repetition rate of < 500 Hz. A terminal speed ratio > 10 and a divergence of ±1 degree have been achieved at stagnation pressures below 2 bar . The diagnostic has been tested in ECRH plasmas on the TJ-I U torsatron, representing the first application of a supersonic beam to plasma characterization, to our knowledge. Operational conditions which minimised the total amount of He injected into the plasma were chosen. Non perturbative injection conditions in the low density plasmas could be obtained at local He densities of $\approx 1 \times 10^{11}$ cm^{-3} and beam diameter < 1 cm. Due to the relatively low electron density of the ECRH plasmas, and to the good penetration characteristics of the supersonic He beam, the diagnostic could be used up to fairly low values of the normalised plasma minor radius, r/a (a=12 cm). Details of the optimisation of the atomic beam diagnostics and typical results for steady state conditions in the TJ-I U plasmas are presented.

I.INTRODUCTION.

The characterisation of the plasma edge in fusion devices is a crucial issue in order to understand the plasma transport properties and to model the interaction between a plasma and its material surroundings (1) and much effort has been devoted to the development of specific diagnostics (2) for this task. Of particular success have been the diagnostics based on the interaction of atomic beams with the plasma, wich offer good spatial and temporal resolution, and different approaches have been developed in the last decade (3). Several types of beam sources, such as thermal ($E<0.1$ eV), blow-off(few eV) and accelerated (tens of keV) have been already applied to edge diagnostics (4) . One of the simplest systems, based on the application of atomic beams, consists of the injection of a thermal He beam (5) into the plasma. The monitoring of the proper set of emission lines produced by electron impact excitation of the injected atom in the plasma edge allows, with the help of a collisional-radiative model, the evaluation of the electron density and temperature profiles and their evolution during the plasma discharge. One of the main drawbacks of the method is the intrinsic complexity of the model. This is due not only to the large number of electronic levels involved in the production of the monitored emission lines, but also to the spatial and velocity spread of the effusive beam, thus resulting in a smearing effect on the reconstructed profiles. Besides, perturbation of the plasma edge parameters can be produced due to the injection of a relatively large flux of atomic species. Such a high flux is required in the case of He due to its low excitation efficiency by plasma electrons. For these reasons, the use of supersonic beams, which have wide application in other fields of physics and with better properties (6), has been proposed for plasma edge diagnostics (7).Typically, the production of such beams requires a complex set-up, which is often not suitable for coupling to a fusion device with restricted access. In the present work, a compact source for the generation of a supersonic beam is described, as well as its testing as an edge diagnostic in a fusion device, the TJ-I U torsatron.

II. EXPERIMENTAL

a) He beam diagnostic.

A compact pulsed, supersonic beam source, suitable as a plasma edge diagnostic, has been developed. It is based on the standard nozzle/ skimmer combination (8). A commercial fast piezoelectric valve (Laser Technics LPV) is fitted with a circular nozzle and mounted in a removable disk (fig.1). A nominal diameter of 0.3 mm was used for the present application. The valve can be operated in either a continuous or pulsed mode,the latter at a maximum repetition rate of 500 Hz and pulse width from 0.2 to 2 ms. In the present work, a pulse duration of 1 ms was used, once per plasma shot at a constant time. In order to produce the beam, the central part of the free jet formed in the expansion of the gas is extracted by a commercial skimmer located in front of the valve. It has a parabolic profile and a very thin wall near the diaphragm (100 µm), minimising the perturbations on the beam. For the present experiments, a circular diaphragm of 0.5 mm diameter was chosen. Since the beam characteristics are strongly dependent on the nozzle-skimmer geometry, the piezoelectric valve was mounted on a homemade x-y-z translation system. Two micrometric screws are used for the alignment of the beam (± 5 mm displacement), while a linear manipulator (25 mm range) is used to control the nozzle-skimmer distance, which critically affect the beam properties. Gas is supplied to the valve through flexible tubing. The whole system is mounted into a small vacuum chamber (V < 5 l), and a thin walled bellow is inserted for vacuum displacements. The chamber is pumped by a S=240 l/s turbomolecular pump to a base pressure of < 1×10^{-7} mbar, so that a pumping time of V/S =20 ms is achieved. The beam source is coupled to the plasma device through a 35 mm CF shut-off valve, as displayed in fig. 1.

Opposite to the thermal sources, the properties of the supersonic beams cannot be simply predicted from elemental geometry considerations (9). Therefore, a systematic characterisation of the beam was performed by coupling the source to a diagnostic system specially designed for that purpose. A full description of the testing and comparison of the results with the ideal performance is given in a separate paper (10), so only a brief description is given here. Some of the most relevant beam parameters are summarized in Table I. The beam temporal shape, divergence, velocity distribution and absolute intensity were measured directly for the optimised plasma diagnostic configuration. All these parameters were basically determined from the source pressure (0.4-2 bar in this case) and the optimum nozzle/ skimmer separation. A compromise for such distance has to be found due to the attenuation of the beam by the background gas during the pulse at long distances, and the poor beam quality, mostly due to skimmer interference, at short ones. For stagnation pressures up to 2 bar, the best value found was 1.5 cm. The temporal shape of the pulse is also strongly affected by the same effects. In fig.2a, the temporal behaviour of the beam intensity, as recorded by the special fast ionisation gauge (4μs rise time) arrangement developed for *in-situ* analysis is shown for two different gas species. As seen, a significant decay in beam intensity is observed during the pulse for the Ar beam. Conversely, an almost constant intensity level is seen in the case of He for the same conditions due to its lower attenuation efficiency (σ_{Ar}/σ_{He}= 2.8). The onset of attenuation (<10%) for He pulse durations Δt>2ms is considered here as the maximum allowed pulse duration under the geometrical constraints of the source. A longer tail can also be observed after the pulse in the figure. It corresponds to the effusion of gas through the skimmer due to the pressure build-up during the beam formation,and is therefore characterized by the vacuum system time constant previously reported. The beam divergence, that in principle can be defined by simple geometry, was also recorded experimentally. A value of ±1 degrees was measured, in agreement with expectations. Thus, for a typical distance of 30 cm between the source and the plasma observation region, a 1 cm spatial resolution (FWHM) in the poloidal and toroidal directions can be obtained. This divergence could be improved by the simple insertion of a collimator between the source (skimmer) and the plasma, provided that enough pumping is allowed into the enclosed region. Such pumping can be done through the fusion device itself. The velocity distribution of the beams extracted by the skimmer were determined by the time of flight (TOF) technique in a separate experimental set-up. This set-up is described in detail in reference 11. The He beams produced in the chamber just described enter the diagnostic system through the skimmer. The flight path, L, for these measurements was 60 cm and the geometric gate function of the chopper had a FWHM of 23 μs. From the time of arrival distribution, the flow velocity (u) and the velocity spread of the He beams characterized by the speed ratio (S) are obtained. An example of such measurements is given in fig.2b. Values near theoretical predictions were obtained for both parameters, although the velocity spreading was systematically higher than expected. In all cases, however, speed ratios higher than 10 were found. This represents a large improvement respect to the thermal beam case. Finally, the absolute beam intensity was determined by comparison with an effusive source. Values systematically lower than the theoretical estimates were inferred. The values obtained correspond to local densities of $\approx 10^{11}$ cm^{-3} at 30 cm from the source. Saturation of the intensity at higher stagnation pressures was observed. Combined with the background pressure rise effect previously mentioned, an optimum value for stagnation pressure of 0.5-1.5 bar was chosen for the source.

An important issue for atomic beam injection in diagnostic applications is attenuation by the plasma background gas. In the case of supersonic beams, this effect can lead to the degradation of the beam properties in ways which are not easy to model. Experiments oriented to assess the relevance of such an effect were performed in a separated chamber. Values for the attenuation cross section of the He beam of 1 (He) and 0.75 (H_2), in units of 10^{-14} cm^2, were obtained. Interestingly, only a moderate variation in the speed ratio was observed even at the highest attenuations studied (90% of initial beam)

Finally, it should be mentioned that, depending on the fusion device characteristics, simple upgrading of the diagnostic should be possible by scaling-up the present design. As an example, the same set-up used in the generation of the beam can produce intensities up to 7 times higher if a 25 l chamber and a 2000 l/s pump were used (10).

b) Installation and testing in the TJ-I U torsatron

The beam source was installed in the TJ-I Upgrade for testing as an edge diagnostic. The device (12) is a l=1, m=6 torsatron with major radius of R=0.6 m and minor radius a=0.10 m. The magnetic field at the axis is 0.5-0.7 T. ECRH plasmas are generated and heated using a 37.5 GHz gyrotron (X-mode, 2nd harmonic, P=90-250 kW, pulse length 20 ms). Line average electron densities of about 0.2-0.5x10^{13} cm^{-3} and central electron temperatures in the range of 100-200 eV, are typically obtained. Langmuir probe measurements of plasma edge parameters near the LCMS typically yield values of Te(a) ≈ 10-15 eV and $n_e(a)$ ≈ 0.5-1x10^{12} cm^{-3}. Access to the plasma is provided through 18, 250 ISO K flanges (equatorial, top and bottom positions) and 6 inner, ISO K 63 flanges. The beam source is coupled to an equatorial flange through a 35 CF flange (see fig. 1). Several optical windows are available for observation of the beam fluorescence. However, due to geometrical constraints of the device, no observation directly perpendicular to the beam injection direction could be made in the same toroidal position. In the experiments here reported, a bottom window which is displaced 20^0 in the toroidal direction with respect to the He beam input was used. This allowed an almost tangential observation of the plasma periphery. A set of two mirrors was used to collect the plasma light which was then imaged through a lens (f= 25 cm, ϕ= 50mm) onto two detectors. The latter consisted of an interference filter coupled to a photomultiplier (PMT, Hamamatsu R3896). A 50% beam splitter was used for the simultaneous recording of the two He emission lines monitored for temperature measurements,i.e., at 706.5 and 728.1 nm (5). A spatial resolution of about 4 mm parallel to the He beam is reached by placing a collimator in the entrance of PMT. The full beam width determines the poloidal and toroidal resolution. The sensitivity of the whole system was calibrated with the ratio of He lines in the He glow discharge used as routinary wall conditioning procedure in the TJ-I U torsatron. By simultaneously scanning the two photomultipliers profiles of the He emission along the beam are obtained on a shot to shot basis. An improvement in the collection system is in progress presently for single shot profile recording. In order to perform *in situ* alignment of the diagnostic, a home-made fast ionisation gauge, similar to that used for the He beam characterization, was mounted in a linear/rotary manipulator and installed in the same equatorial flange as the beam (10). It enables detection of the beam pulse with both toroidal and poloidal resolution, at a location equivalent to that of the LCMS,and with a time resolution of 5 μs. For that purpose, the filament/ grid arrangement is shielded with a perforated screen. Rotation of the detector by 90 degrees enables us to locate the incandescent filament in the same position as the diagnostic region, thus allowing the focusing and geometrical calibration of the detection optics.

Injection of the He beam into the TJ-IU plasma was made for several experimental conditions. A stagnation pressure of 1-1.4 bar and a pulse length of 1 ms were chosen for the beam testing experiments. The observation region was scanned on a shot to shot basis, while the photomultiplier signals were recorded directly onto the standard data acquisition system of the TJ-IU, together with other relevant traces. The power supply electronics of the pulsed valve were triggered externally from the main control system in order to provide a good synchronisation with the plasma operation. A systematic delay of 400 μs between the electrical pulse and the actual beam injection was observed. This was due to the time of flight of the He atoms and the electronics delay. Figure 3 shows some of the typical results. The time evolution of the two relevant He emission lines is shown in figure 3a at two different radial locations, together with the C V emission intensity. This latter is used as a reference of an intrinsic plasma impurity. A fast rise in the emission intensity is observed upon injection of the beam pulse in all cases. This is followed by a longer tail whose intensity relative to that of the pulse depends on the radial position, the lower relative level corresponding to the inner region. No effect on the beam injection is seen on the intrinsic impurity line. As mentioned before, this tail is produced by the pressure rise in the beam source during the pulse and thus it has a broader spatial distribution than the beam. Therefore, for example, the (uncorrected) intensity ratio between the recorded lines at the He pulse is $R=I_{728}/I_{706}\approx 0.58$ (inner) and 0.25 (outer), respectively, while same ratios for the line intensities at the tails are 0.4 and 0.21 respectively. The lower electron temperatures (lower ratios) associated with the tails would be consistent with a larger spatial integration of the region where the background gas diffuses for the line-of-sight used in the present configuration. The possible effect of the He pulse on some relevant plasma parameters can be determined from fig. 3b, This shows the pulse shape,the ECE signal at the plasma edge (r/a= 0.8), C V line and the line average electron density. As seen, no disturbance in any of these parameters is observed, as would be expected for the low He fluxes injected and the low intrinsic radiation efficiency of this species. Langmuir data on saturation current and floating voltage near the LCMS show also no change during the beam injection (13).

Two radial scans, made on a shot to shot basis at constant magnetic configuration ($\iota(0)=0.21$) and plasma density of $n_e \approx 4\times10^{12}$ cm^{-3}, are shown in fig.4. As seen, a monotonous increase in the ratio of He line intensities is obtained as the observation region is moved inwards, i.e., to higher Te values. This is in qualitative agreement with the collisional-radiative model (14). Also, it should be noted that the range of observations is located well inside the plasma, the innermost ρ value corresponding to a $\approx$ 8 cm travel of the beam into the plasma, thus implying a low attenuation of the beam. Conversion of the data displayed in the figure into temperature radial profiles requires the application of the collisional-radiative model for the particular conditions of the system. The data reported in the bibliography (5) would yield temperature values near 40 eV even in the innermost radial positions of the scan, and values similar to the Langmuir probe data for the outer ones. However care must be taken in the conversion for the TJ-IU conditions. This is due to the possible presence of non-thermalised electrons (15), that would distort the computed ratios, and to the long relaxation distances expected, at least for the outermost points (5). Thus, for example, relaxation times up to 10 μs are expected for the electron densities characteristics of the LCMS, corresponding to beam travelling distances three times larger than the observation region. For the innermost values, a lower smearing effect is expected, its particular value depending on the electron density profile. Preliminary data of a Li beam diagnostic indicate values of ne $\approx 2\times10^{12}$ cm^{-3} at $\rho=0.5$, and therefore the local Te values at this position should be well represented by the intensity ratio, provided full thermalization of the electrons. Comparative experiments with other diagnostics (ECE and Langmuir probes) are presently in progress to dilucidate these effects.

III. SUMMARY.

A supersonic He atomic beam has been developed for plasma edge diagnostics of fusion devices. The source of the beam has been made compact enough to be easily coupled to the small torsatron TJ-IU, while still providing good beam characteristics, such as low divergence, high speed ratio and low He influx. The beam has been tested in ECRH low density plasmas and non-perturbative edge conditions have been achieved. From our beam test results, it is seen that a simple upgrading of the source can be performed for application to other fusion devices, such as the TJ-II stellarator.

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FIGURE CAPTIONS:

Figure 1. Schematic lay-out of the diagnostic and its coupling to the TJ-I U. 1. pulsed valve, 2. skimmer, 3. isolation valve, 4. alignment and detection gauge, 5. magnetic coil.

Figure 2. a) Traces of beam intensity for two gas species, uncorrected for relative calibration factors.b) Time of Flight (TOF) signal of the He beam for a speed ratio of S=20. See text for details.

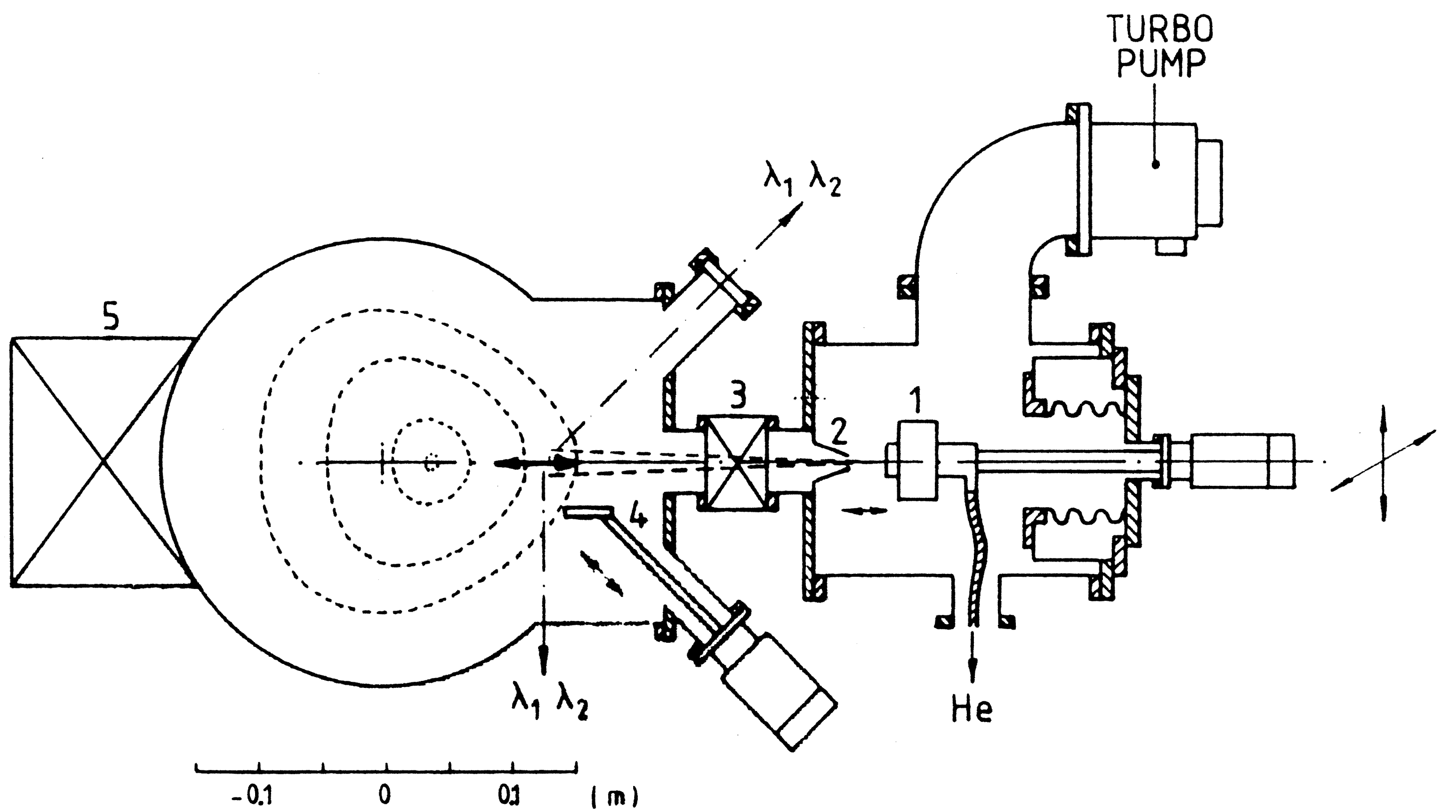
Figure 3. a) Evolution of some emission line intensities during the plasma shot, starting at 9 ms. From top to bottom : CV, He lines at 728 and 706 nm, $\rho=r/\langle a\rangle= 0.47$ and same lines at $\rho=0.62$. Data uncorrected for calibration factors. The He beam (1 ms width) is injected at 18 ms. b) Evolution of some typical plasma traces during the injection of the He pulse.

Figure 4. Radial profile of the He line intensity ratio for $\iota=0.21$ taken in a shot to shot basis. The normalised radius ρ is displayed in the abscissa.Two scans are shown.

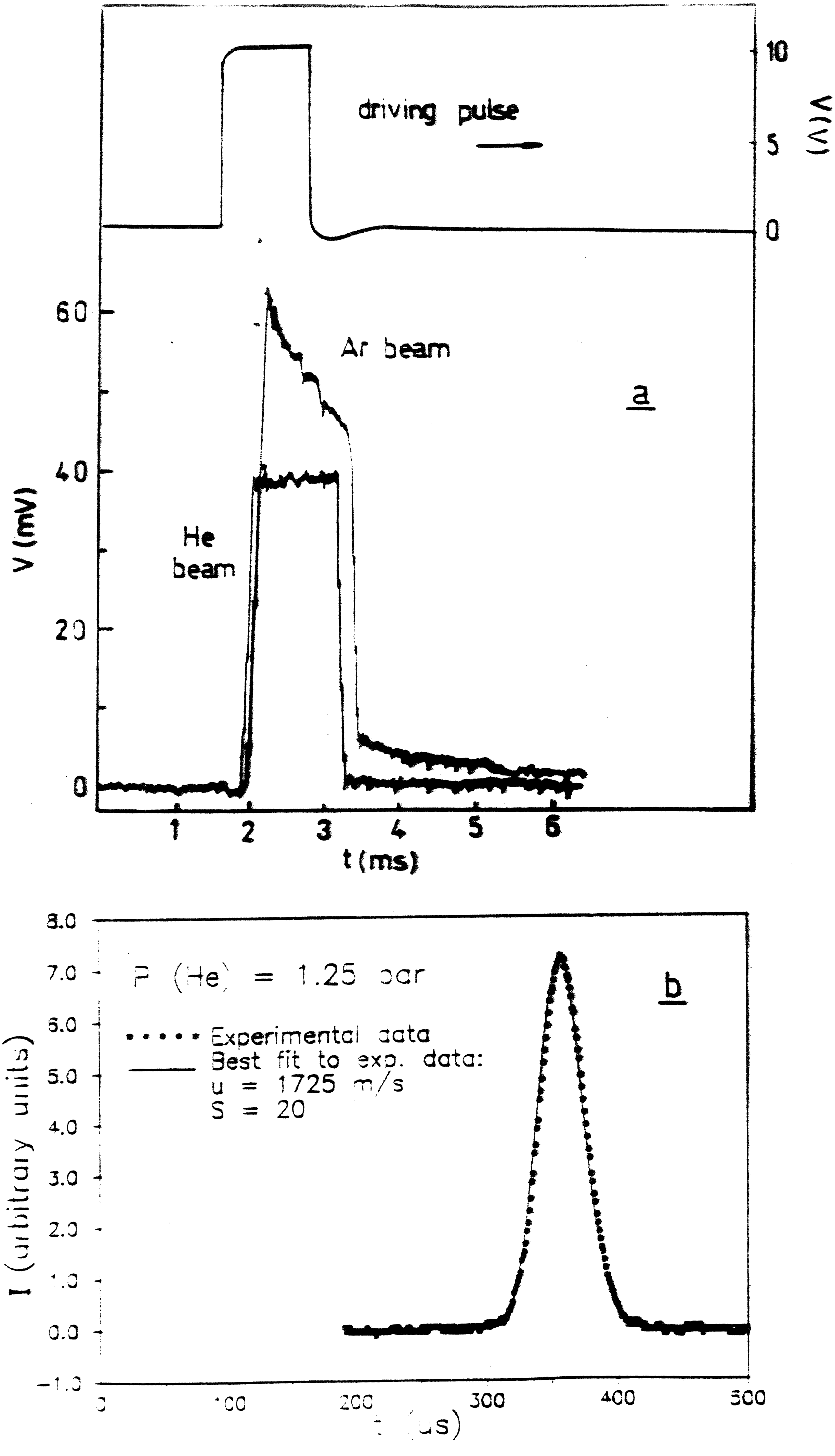
Table I

Summary of the supersonic beam parameters

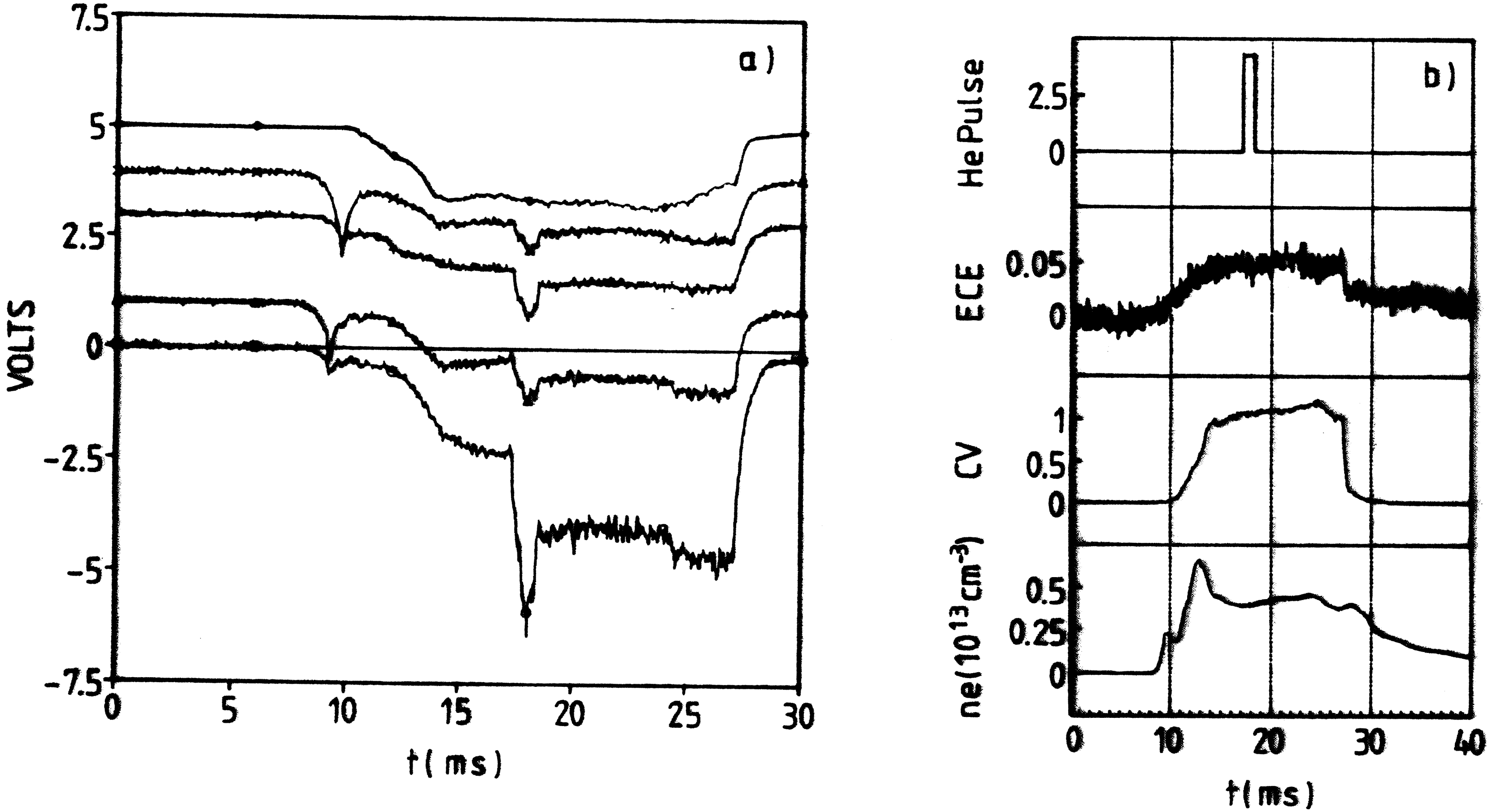
Nozzle diameter	0.3 mm
Skimmer diameter	0.5 mm
Stagnation pressure	400 - 2000 mbar
Pulse width	0.5 - 2 ms
FWHM at 30 cm from the source	< 1 cm
Speed ratio	12 - 24
Density at 30 cm from the source	0.9 - 2.5 ($\times 10^{11}$ cm^{-3})
Terminal parallel velocity	1.5 - 1.75 ($\times 10^{5}$ cm/s)
Speed ratio for 90% attenuation	10

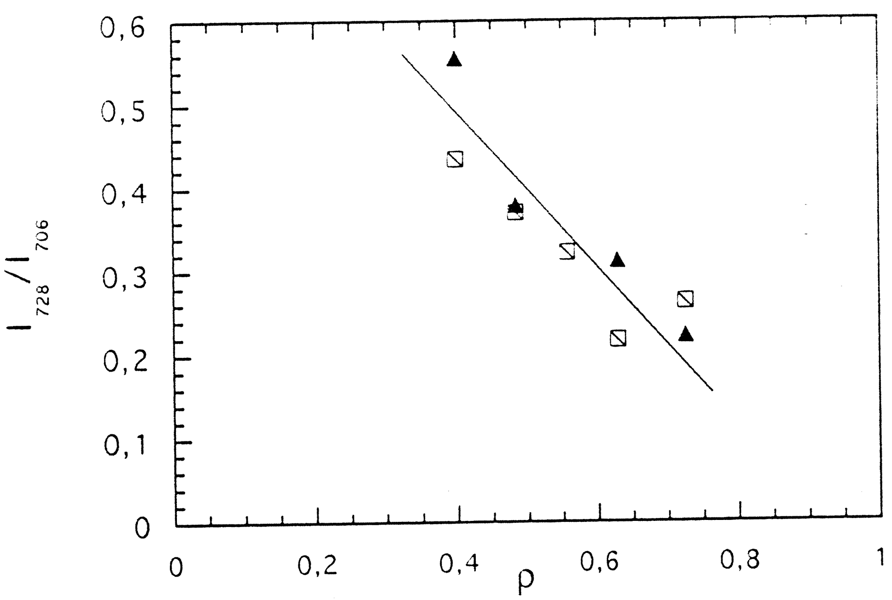


TURBO
PUMP
λ_1 λ_2
5
3
2
1
4
λ_1 λ_2
He
-0.1
0
0.1
(m)



driving pulse
V(V)
10
5
0
Ar beam
a
He beam
V (mV)
60
40
20
0
1
2
3
4
5
6
t (ms)
P (He) = 1.25 bar
b
Experimental data
Best fit to exp. data:
u = 1725 m/s
S = 20
I (arbitrary units)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
−1.0
0
100
200
300
400
500
t (μs)


a)
VOLTS
7.5
5
2.5
0
-2.5
-5
-7.5
0
5
10
15
20
25
30
t(ms)
b)
He Pulse
2.5
0
ECE
0.05
0
CV
1
0.5
0
ne(10^{13}cm^{-3})
0.5
0.25
0
0
10
20
30
40
t(ms)


0,6
0,5
0,4
0,3
0,2
0,1
0
I_{728}/I_{706}
0
0,2
0,4
0,6
0,8
1
ρ