Development of a thermal helium beam emission diagnostic for WEST

<u>O.M. Jones</u>[1], O. Meyer[2], H. Xu[3], S. Sorrentino[4], R. Baude[1], A. Escarguel[1], J.H. Harris[5],
J-C. Hatchressian[2], C.C. Klepper[5], S. Larroque[2], Ph. Lotte[2], J-Y. Pascal[2] and B. Pégourié[2]

1. *Aix-Marseille University, CNRS, PIIM, 13397 Marseille cedex 20, France*
2. *IRFM, CEA Cadarache, 13108 St-Paul-lez-Durance cedex, France*
3. *ASIPP, 350 Shushanhu Rd, Hefei, Anhui 230031, China*
4. *Università Degli Studi Di Napoli Federico II, Piazzale Vincenzo Tecchio 80, 80125 Napoli, Italy*
5. *Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6169, USA*

1. Introduction

Electron density n_e and temperature T_e in the outermost few millimetres of fusion plasmas may be inferred from the intensity ratios of visible emission lines of atomic helium. Accurate kinetic profiles in this region are important as constraints in the modelling of plasma-surface interactions. Two thermal helium beam injection and diagnostic systems are planned for the WEST (*W Environment in Steady-state Tokamak*) device:

- An injector capable of producing a narrow, collimated beam for radial injection near the machine midplane, to infer n_e and T_e profiles near the last closed flux surface.
- A capillary injector near the ICRH antenna limiter which will give an insight into localised changes in plasma conditions relevant to RF power coupling.

Here, we describe conceptual studies and ongoing design work pertaining to both injectors.

2. Diagnostic principle and key parameters

Thermal helium beam emission spectroscopy for electron density and temperature diagnostics relies on measurement of the ratios of two pairs of He I lines: the ratio of the singlet lines at 6678 Å and 7281 Å is primarily density-dependent, while the ratio of either of these lines to the triplet line at 7065 Å is primarily temperature-dependent. By combining measurements of the line intensities with an atomic physics model which accounts for the populating and de-populating mechanisms of the relevant states, the electron density and temperature in the volume of emission may be inferred.

In order to provide useful profiles, the interaction between the helium gas and the plasma should remain localised. There are two principal ways to achieve this: either the helium injector can be placed close to the edge of the plasma, or the injector can be designed to produce a highly collimated beam. The midplane injector on WEST will adopt the latter approach, while the injector embedded in the ICRH antenna protection will adopt the former.

To produce a collimated beam, a high Mach number is required in order to minimise the thermal spread of the beam. This is achieved by allowing gas from a high-pressure reservoir to expand into a low-pressure chamber with continuous vacuum pumping. As the gas expands, it cools. The low temperature results in a low sound speed, which protects the core of the beam in the so-called *zone of silence* from external perturbations. Using a collimating apparatus, the unperturbed central part of the expansion may be 'skimmed' to obtain a collimated beam of the desired width. Figure 1 is a schematic diagram of this system.
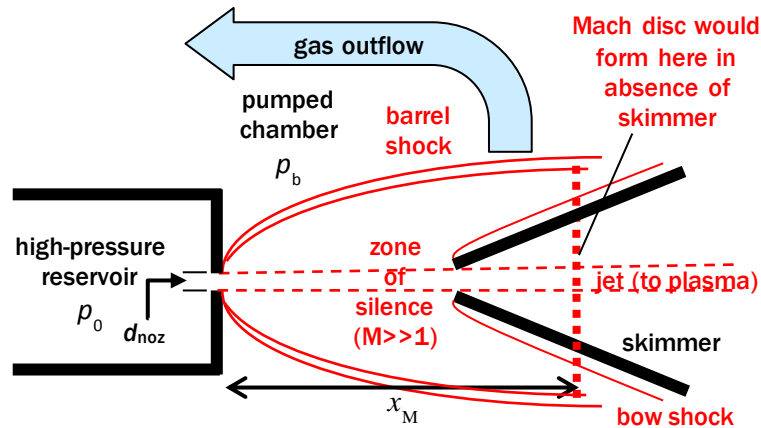

Figure 1. Schematic diagram of the apparatus used to obtain a collimated beam by adiabatic expansion of gas from a high-pressure reservoir.

The flux from the reservoir and the subsequent degree of cooling upon expansion are determined by the parameters p_0, d_{noz} and p_b. Following Campargue[1], we find that with a 70 bar reservoir pressure, a 40 μm-diameter nozzle and a 300 μm-aperture skimmer placed 18 mm downstream, the particle flux through the nozzle and skimmer are 1.2×10^{21} s^{-1} and 1.6×10^{17} s^{-1} respectively. Interaction with the skimmer is weak if the Knudsen number Kn = λ/D, where λ is the mean free path and D is the skimmer diameter, is large. In that case, the beam divergence may be limited to ~0.5°. The nozzle flux equates to 5 Pa m^3 s^{-1} to be evacuated by the pumping system. A piezo valve will control the gas flow in ~100 ms pulses at 2 Hz, so that the pump fore pressure remains low (<1 Pa) and the background pressure p_b is ~10 Pa.

The injector situated behind the ICRH antenna, by contrast, will use a capillary to conduct gas to the face of the antenna limiter. This limiter may be placed within 20 mm of the last closed flux surface. A narrow capillary shortens the response time of the injection to the opening and closing of the piezo valve. Figure 2 is a schematic diagram of this system. A reservoir pressure of 0.4 bar and a capillary tube of 300 μm diameter and 250 mm length provide a suitable particle flux to the plasma of 3×10^{18} s^{-1}, and a response time of <10 ms.

To obtain the best possible spatial resolution, lines of sight should be perpendicular to the beam and tangential to the flux surfaces. Based on a simulated equilibrium and the kinetic
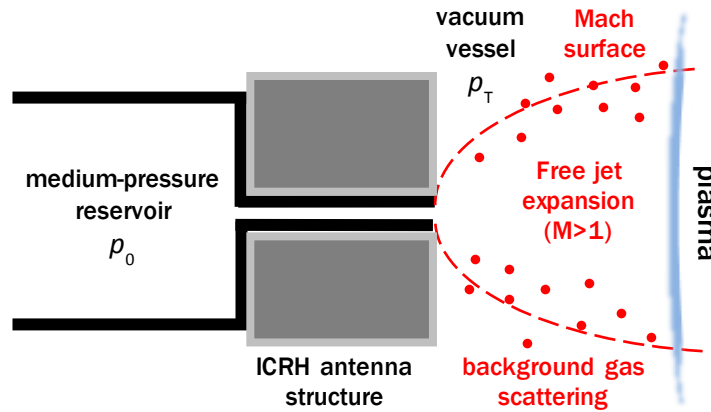
Figure 2. Schematic diagram of the apparatus used to obtain a free jet by expansion of gas from a pressurized reservoir through a capillary tube.

profiles expected in WEST, an estimate of the signal from the midplane helium beam was calculated based on the optimum line-of-sight geometry. It was found that with a 2.5 mm spot size on the beam, measurements with a reasonable signal/noise ratio could be obtained over a 6 mm spatial range. The measurable ranges of plasma parameters are given in table 1.

Parameter	Range
T_e (eV)	10 – 150
n_e (10^{19} m^{-3})	0.05 – 2.5
R (m)	2.94 – 3.00

Table 1. Estimated ranges of electron temperature, electron density, and radial coverage of the midplane helium beam emission diagnostic on WEST.

Since the beam width in the region of observation is expected to be between 10 and 12 mm, and the minor radius of the plasma in WEST is ~500 mm, the resolution is not significantly affected by the curvature of the flux surfaces over the finite extent of the beam.

3. Mechanical design of the midplane injector

The principal challenges in the mechanical design are the requirement for active cooling of the injector assembly, and the high accuracy required of the alignment between the nozzle and the skimmer. Figure 3 shows these components in detail. The piezo valve is limited to a temperature of 120°C; hence the reservoir requires a secondary cooling circuit.

The piezo actuator is a *PX 500*, produced by *Piezosystem Jena*. It has a total travel range of 500 μm, and is controlled with a -20/+130 V amplifier. This device has been used for helium gas puff valves on TEXTOR[2] and on Wendelstein 7-X and ASDEX-Upgrade[3].

The skimmer is produced by *Beam Dynamics, Inc.*, and is made of copper. The form of the skimmer is designed to minimise interference caused by scattering of particles from inner and outer surfaces. It will be clamped in place with a Viton O-ring on a mount designed
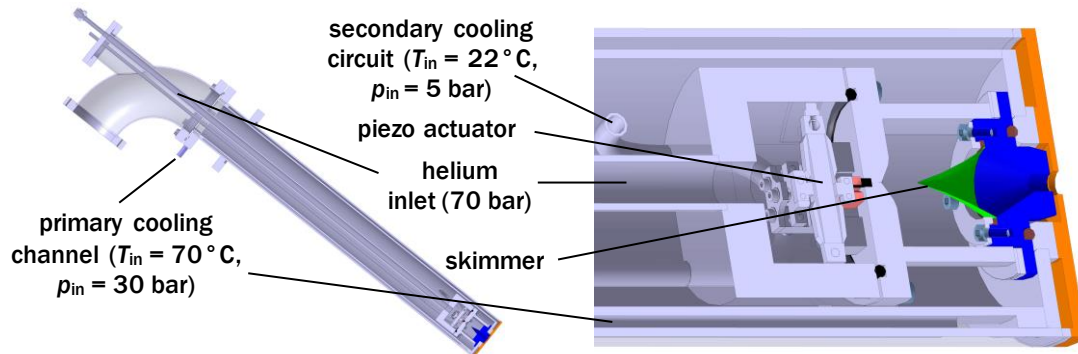
Figure 3. 3D model of the injector assembly to be inserted into the WEST vacuum vessel (left), and a detailed view of the head of this insertion including the reservoir, piezo valve and skimmer (right).

to allow the nozzle – skimmer spacing to be adjusted. The mount must be produced with a tolerance of less than 50 μm to ensure concentricity of the skimmer orifice with the nozzle. A *Beam Dynamics* skimmer was used in a similar system previously installed on TEXTOR[2].

As a final validation of the mechanical design, thermomechanical studies have been performed to evaluate the efficacy of the cooling system and the structural integrity of the design. The results of this analysis are shown in figure 4.
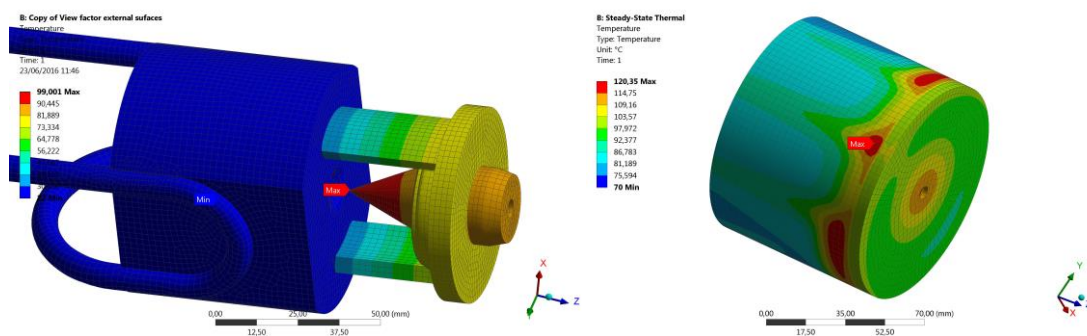

Figure 4. Temperature profiles based on steady-state thermal analysis of the internal part of the injector (left), and the head of the external part of the injector when exposed to the radiated heat flux from the plasma (right).

4. **Conclusions and References**

A thermal helium injector to produce a collimated beam for He I emission spectroscopy has been designed for the midplane of WEST. This should allow localised electron density and temperature profile measurements up to 10 mm inside the last closed flux surface. A capillary injector to be placed behind the ICRH antenna limiter is also planned.

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