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Simulation of the gas density distribution in the large vacuum system of a fusion-relevant particle accelerator at different scales

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ABSTRACT

The accurate determination of the gas density distribution in negative ion accelerators plays a substantial role for the protection of the components and the efficiency of the system. The presence of background gas in between the electrodes has the highest impact on the beam properties and on the heat loads on the electrodes. The full-scale ITER beam source and extractor test facility SPIDER is studied considering the large vacuum vessel (4 m diameter), the pumping system, the plasma source (hydrogen gas filling pressure of ~0.3 Pa) and the geometry of the in-vacuum components. On a smaller scale, the beam source and the multi-aperture electrodes (provided with apertures having an inner diameter of ~12 mm) is accurately modeled. In these applications, the gas-surface interaction plays an important role and is therefore studied with dedicated models (on the nano-scale) to improve the predictive capability of molecular gas flow simulations.

1. Introduction

The ITER Neutral Beam Test Facility (PRIMA) is being constructed at Consorzio RFX (Padova, Italy). It includes two experimental devices: the full size neutral beam injector prototype, called MITICA, and a full size ion source that will optimize the hydrogen/deuterium negative ion production and extraction, named SPIDER (Source for Production of Ion of Deuterium Extracted from RF plasma) [1]. SPIDER is presently under construction, and the experimental activities are expected to start in 2016. The SPIDER accelerator was designed to satisfy the physics and engineering requirements of the ITER Heating Neutral Beam Injector [2]: an extracted current density greater than 355/285 A m^{-2} for H^-/D^- ions respectively, an ion beam energy of 100 keV, and a pulse duration up to 3600 s. As shown in Fig. 1, the SPIDER Beam Source (BS) is contained in a Vacuum Vessel (VV), which contains also a beam dump and a diagnostic calorimeter to stop the ion beam. The negative ions are extracted from plasma generated by radio-frequency drivers and seeded with Cesium-vapor, and accelerated through three multi-aperture grids (1280 apertures per grid): Plasma Grid (PG), Extraction Grid (EG), and Grounded Grid (GG). The discharge is sustained by a continuous gas injection, with a throughput adjusted to give a source filling pressure $p_f = 0.3$ Pa in the absence of plasma. By flowing through the grid apertures, the gas is evacuated frontally through the vertical pipes composing the Electron Dump (ED), or laterally through the gaps between grids and the support flanges. The accesses for gas pumping are visible in Fig. 2(a), through the electrostatic screens; the cross-section of the ion source and accelerator is highlighted in Fig. 2(b), with the ED in the foreground.

In this phase of preparation to the experimental campaigns, there are multiple reasons to perform a complete detailed study of the vacuum system, analyzing the gas flow from the injection points to the pumping system.

First of all, the background gas density profile along the path of ion beamlets affects the ion beam in many ways. It causes a net loss of beam particles and a generation of stray particles, by collision processes occurring during acceleration; it helps in compensating the beam space charge by ionization processes, with consequences on the beam ion transport and trajectories; it affects the measurements of diagnostics, which shall include corrections to consider the local gas density and gradients. Precise numerical evaluations of the gas distribution are important to tackle these issues [3,4]. Secondly, the presence of gas on the back side of the beam source may cause electric discharges and the generation of sustained plasma in the region behind the Radio Frequency (RF) drivers, as it is noticed in ELISE [5]; calculations of gas flow and pressure in that region can help in evaluating the problem, and be

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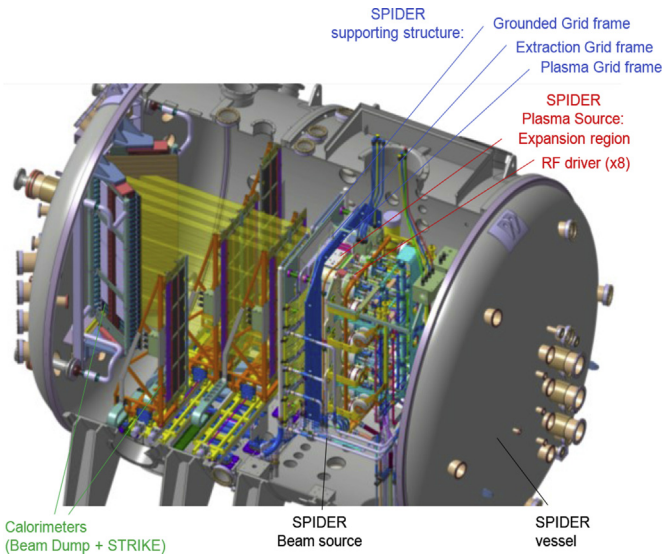

Fig. 1. Cut view of the vacuum vessel and internal components in SPIDER.

used to study a possible solution. Finally, a confirmation of the nominal requirements for gas injection and pumping system is desirable: in nominal operating conditions, the pressure in the vessel, and the required gas throughput to maintain the nominal filling pressure, is known only approximately.

The gas flow regime shall be identified for the proper choice of the analysis method. The Knudsen number $Kn = \lambda/L$, defined as the ratio of the elastic mean free path λ and the characteristic geometrical dimension L, is commonly used as an indication of the relevance of mutual gas particle collisions in a gas flow; a situation referred to as *molecular flow* occurs when the macroscopic flow behavior is mostly determined by the collisions with solid walls, and this regime is typically assumed for $Kn > 0.5$ [6] or $Kn > 1$ [7]. All the regions where gas flow and appreciable gradients exist in SPIDER, which are subject of the study, exhibit a Knudsen number greater than unity: this is verified in those flow regions at maximum pressure, which is through the apertures of the first grid PG ($Kn \sim 3$), in the flow regions of large characteristic size at the pumping ports of the VV ($Kn \sim 1.5$), and halfway through the ED ($Kn \sim 6$) and the support flanges of the BS ($Kn \sim 2.5$). It is expected that the use of *free molecular flow* methods, which assume that the effect of mutual particle collisions is totally negligible, may yield in these *Kn* ranges of early molecular regime accuracies on the conductances within approximately 10%: the calculation *a posteriori* of the *Kn* in the flow regions, and a discussion of the expected error introduced with this approximation, are given in Section 4.2. On the other hand, to neglect intermolecular collisions allows for the use of numerical methods of reduced computational cost, therefore allowing the engineering study of large gas flow domains of great complexity; in this case, dedicated to the proper design and use of fusion equipment. Free molecular flow approximation is generally considered a reasonably good approximation for the calculations related to gas flow in negative ion sources (e.g. Ref. [8]). It has been used in the past for the study of the full size ITER beam source and accelerator [3,4], and in geometries and parameters similar to negative ion multi-grid accelerators it was experimentally verified to produce predictive estimations of the gas conductance within small errors [21].

The regions of gas flow, and the processes occurring at various length scales playing a role in the macroscopic flow behavior, shall be studied by different methods. This paper describes the numerical modeling activities carried out to study these topics, grouped according to the scale of the simulation.

Section 2 presents the study of the gas flow through the three accelerator electrodes by using a model of one row of beamlet apertures with periodical boundaries. The gas exits from the Plasma Source (PS) to the vacuum vessel through the grid apertures of diameter ~12 mm: in this region, it interacts with the beam ions causing large effects on the overall beam parameters. The flow regime for H_2 at room temperature in this domain is molecular with *Kn* between 3 and 6. The use of Test Particle Monte Carlo (TPMC) techniques [9] permits to study different initial velocity distribution and scattering operators for gas-wall interactions, thus evaluating their effects on the gas flow.

In Section 3, the complete model of the Beam Source (BS) is described: it was used to study the overall molecular conductance out of the BS (~2 m high). The gas flow model of the large Vacuum Vessel (VV) is presented in Section 4; given the number of geometrical details that had to be considered, the BS was modeled separately from the large VV (diameter ~4 m). The operating conditions are obtained by an iterative scheme, which considers the solution of the two models; for this iterative application, a model based on View Factors (VF) technique – known also as angular coefficients method – is best suited, and the AVOCADO code is used to the purpose [10]. The VF method implemented in AVOCADO uses surface meshes to discretize the flow domain, and needs no

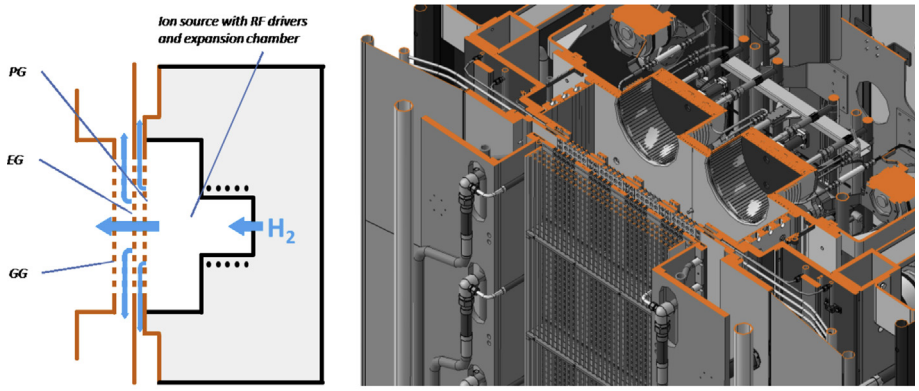

Fig. 2. (a) Sketch of gas injection in the ion source and pumping through front grids and lateral frames; (b) horizontal cross-section, showing from top-right to bottom left the ion source with the circular RF drivers, the three electrodes, and the electron dump in the foreground.