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Design of a system of electrostatic probes for the RF negative ion source of the SPIDER experiment

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A test facility (SPIDER) is foreseen to be built in Padova, Italy, in order to test and optimize the RF source of negative ions to be used in the ITER neutral beam injectors. In this contribution the Langmuir probe system designed for monitoring the region, where most of negative ions are expected to be produced, will be presented.

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1. Introduction

The realization of the Heating Neutral Beam (HNB) for ITER represents a technology challenge. ITER will be equipped with at least two HNB systems, each one delivering an effective power to the plasma of about 16 MW of the particles will be accelerated at 1MV [1].

The required initial current of 40A of negatively charged deuterium for each system will be provided by an RF ion source. In order to test, commission and optimize the ion source and all the beam line components of the HNB system for ITER a test bed is foreseen to be built in Padova (Italy). Within this project a specific facility, SPIDER (Source for the Production of Ions of Deuterium Extracted from Rf plasma), will be devoted to test and optimization of the ion source [2]. The negative ions extracted in this case will be accelerated up to 100 kV. In SPIDER, a system of electrostatic probes will measure the plasma parameters and monitor their homogeneity in the region facing the plasma grid, where most of the negative ions are expected to be produced and extracted.

In the next sections after briefly describing the working principle of the SPIDER source, the details of the design of the electrostatic probe system will be provided including the design guidelines, the sensor description as well as integration within the SPIDER facility.

2. The RF negative ion source facility SPIDER

A detailed description of the working principle of a RF source for negative ion production in existing systems can be found in [3], see also [4]. For the present purpose it is worth mentioning that in RF negative ion sources for ITER neutral beams the plasma is produced inside RF drivers (see fig1.a), then it expands in a so called expansion region. Negative ions, for the ITER purpose H⁻ or D⁻, are produced both in the plasma volume and due to surface processes, i.e. on the grids facing the source plasma. Negative ions are extracted through grid holes and then accelerated so as to build the negative ion beam. It is worth mentioning that the surface production processes, which in the existing systems are believed to provide the majority of negative ions, are favored by the presence of a thin layer of Cs, deposited during the source operation on the plasma grid surface through which the negative ions are extracted. For this reason in SPIDER such surfaces have to be maintained at 150°C, by an active heating system.

A further element to be considered is constituted by the magnetic field, which is essentially parallel to the grids and plays the role of filtering out the most energetic electrons in order to fulfill the requirement of ITER HNB concerning the reduction of the co-extracted electrons.

The SPIDER source will be equipped with 2x4 RF drivers. In figure 1a the vertical section of the SPIDER source is shown and some details of the plasma facing components upstream of the

acceleration step are also given in fig. 1b and 1c: the plasma grid is characterized by the presence

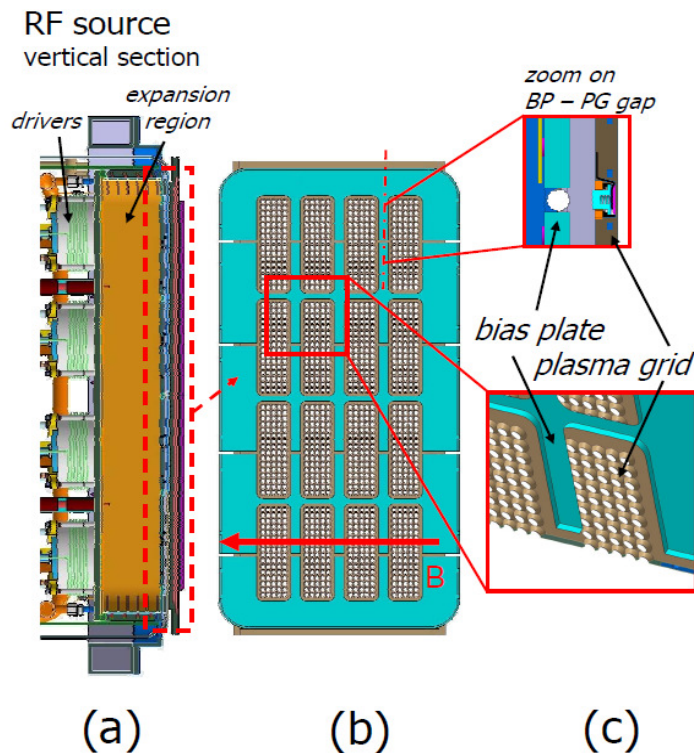


Figure 1 Section of the RF ion source of SPIDER and of the extraction region (a); the bias plate and the plasma grid are evidenced (b, c)

of 4x4 modules of 16x5 apertures through which the ion beam is extracted. The extraction region in the SPIDER experiment is constituted by the plasma grid (PG) and the bias plate (BP), which is a further grid with wide openings corresponding to the modules in the PG [3]. The system is completed by the extraction grid and the acceleration grid, not shown in fig.1.

Given the key role of the extraction region in the negative ion production, the electrostatic probe system exploits PG and BP as supporting structures. It is worth mentioning that also other diagnostics will be installed in this region, in particular spectroscopic ones, so that horizontal cuts of the BP are foreseen. In the SPIDER facility the whole RF source is in vacuum.

3. The design of the electrostatic probe system

3.1. Design guidelines

The main aim of several diagnostics in the SPIDER system is troubleshooting in case the ion beam data is not as expected and providing information for fine tuning and optimization of ion source operation.

Specifically the main aim of the electrostatic probe system is to provide information about uniformity of plasma parameters in the extraction volume where most of negative ions are produced, as well as the investigation of the local plasma parameters in different plasma conditions. The sources of non homogeneity that can be expected [4, 5] are mainly due to differences between the edge and the central part of the extraction region, and to the possible influence of the discrete number of RF drivers located in the ion source. Furthermore it is particularly interesting to investigate the plasma features as close as possible to the grid apertures through which the negative ions are extracted. Finally the electrostatic probe system would provide input data for other diagnostics such as spectroscopy.

The features of the electrostatic probe system, given its exploitation of PB and PG as supports, have to guarantee high vacuum compatibility and operation at 150°C in a hydrogen or deuterium plasma environment, as described in section 2.

In order to meet all these needs, an accurate choice of materials has been performed; considering the long duration of operation, 1 hour pulses with maintenance interventions foreseen about twice a year, the design requires robustness as well as easy assembly and maintenance operations. The

use of caesium vapor during the operations requires accurate short circuit prevention, despite the continuous metallic deposition that characterizes the source operations. This is accomplished by a specific design of the insulating part of the sensors accompanied by a suitable procedure for periodical cleaning and maintenance.

The system design has to account for the presence of a RF plasma produced by the drivers and for a magnetic field of the order of some mT mainly parallel to the grid plane; such magnetic field is originated by a current flowing in the PG itself, aiming at filtering out the most energetic electrons, and by the electron suppression magnets in the extraction grid.

These source features constitute a challenge in the electrostatic probe data interpretation [6,7]. The solution adopted in the design consists in the RF compensation through a reference electrode, with an area relatively larger than that of the electrode itself [8].

The presence of a magnetic field is known to affect the Langmuir probe characteristic and this issue has been accounted for through a design solution with suitable orientation between the sensor collecting surface and the magnetic field. This is the reason of protruding electrodes or sensors placed in the lateral side of BP as described in the next section. In order to make the data interpretation easier a planar probe concept has been adopted for the electrodes and the design accounts for this guideline in the sensor integration on different components of the ion source.

Concerning the operation of Langmuir probes, all sensors will be continuously used to measure the ion saturation current, providing a relative plasma density homogeneity map on three different planes parallel to the PG. It has to be noted that such operating way provides data not affected by RF nor by the presence of magnetic field. The presence of various positive ion species [9] will be accounted for in the ion sound speed [10] and by comparison with spectroscopy measurements.

However also information on local plasma parameters, like electron temperature or Electron Energy Distribution Function, can be deduced upon biasing the sensors and collecting the I-V characteristic. It is worth noting that the collection of the current-voltage characteristic for planar probes, limited to very few electron temperatures above the floating potential allows to obtain reliable plasma parameters [10, 11, 12]; this avoids the need of bringing the electrodes to the electron saturation current branch, which can provide the electron density but is potentially perturbing for the system and where the data interpretation becomes more difficult due to RF and magnetic field. Around the floating potential the contribution of negative ions to the slope of the I-V curve is expected to be negligible, due to the different mass and temperature compared to electrons.

In addition the design has been carried out with the aim of providing the system array with large versatility: an easy design concept simplifies the assembly and maintenance operations. The system will then follow the experimental needs of SPIDER operation: the change of configuration is allowed by the same assembly concept adopted both for the sensing electrodes and for the reference electrodes, which are required for local RF compensation.

3.2. Sensor description

The design concept of the sensors to be installed on the PG and of their constituent parts is

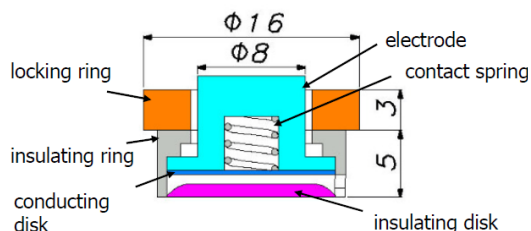


Figure 2 Scheme of sensor on plasma grid; the different components are highlighted

described in the following. The sensors will be installed from the front side of the PG. As shown in fig.2 the main components are the *electrode* and the cable, which is soldered to a *conducting disk*. The electrical continuity is guaranteed by a contact spring, whereas an *insulating disk* and an *insulating ring* provide the electrical insulation from the surrounding metallic component (the PG in this case) respectively on the back side and laterally. The shape of the *insulating ring* involves the

presence of surfaces not directly facing the plasma, due to the need of preventing the risk of short circuits during the operations. All sensor components are held together and fixed to the PG by a *locking ring*, which is screwed to the PG itself, allowing the sensor installation and compressing the spring so as to provide the electrical contact.

Given the dimensions reported in fig.2 the size of the collecting area for ions is 75 mm^2 . According to the basic plasma parameters measured in such kind of RF negative ion sources [3], a density of $0.5 \cdot 10^{18} \text{ m}^{-3}$ and an electron temperature of 1 eV, the expected ion saturation current is 30 mA; with a density of 10^{18} m^{-3} and an electron temperature of 2 eV, the ion saturation current results 85 mA. These values of ion saturation current are not difficult to be measured and allow the estimation of few percent variations to satisfy the main goal of the electrostatic sensor system, namely the measurement of source uniformity.

In order to fulfill an easy change of configuration of the system array, the design of the reference electrode for the PG is based on the same concept as for the sensing electrode, shown in fig.2.

The main difference consists in a conducting plate directly screwed on top of the electrode. The reference plate should provide a relatively larger area exposed to plasma with respect to the collecting area of the sensing electrodes. This is achieved in the PG while considering the constraint due to the area of the grid itself not covered by the BP. On the other hand the reference electrode placed on the BP does not suffer from this constraint, so that a ratio of about 10 can be easily achieved between the plate and the respective sensor.

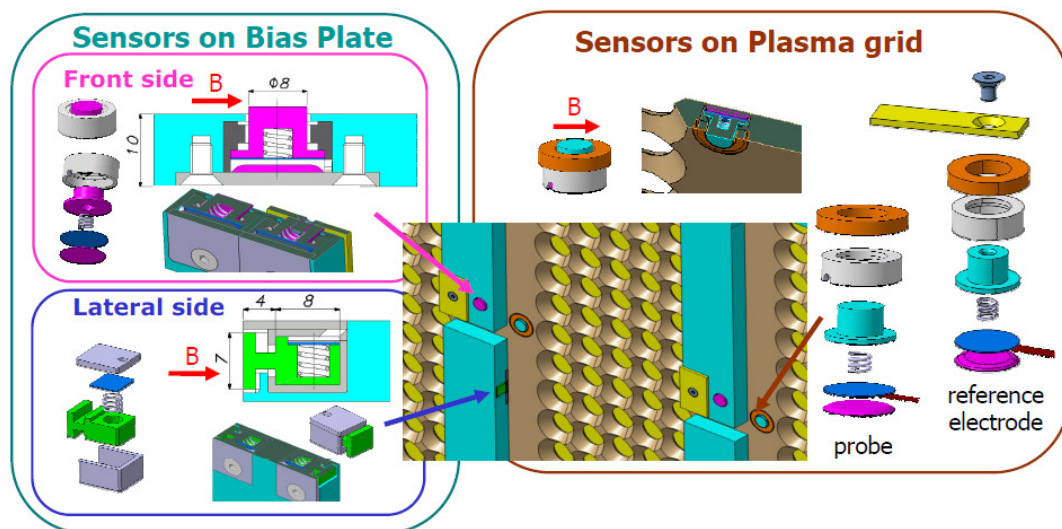


Figure 3 Overview of details of different sensors installed respectively on the plasma grid (right panel), on front side of Bias plate (left panel top) on lateral side of bias plate (right panel bottom). For each case details of the sensor assembly are shown and how it is installed on the respective component of the ion source. The central figure shows the expansion of a region where different sensors are installed on SPIDER ion source.

The integration of the system of electrostatic sensors in the ion source components has been obtained by conceiving the design of essentially three different kinds of sensors.

The first one is the *sensor to be installed on the plasma grid* and has already been described; concerning the BP two different kinds of sensors have been designed: the *sensor on the front side of the bias plate* and the *sensor on the lateral side of the bias plate*.

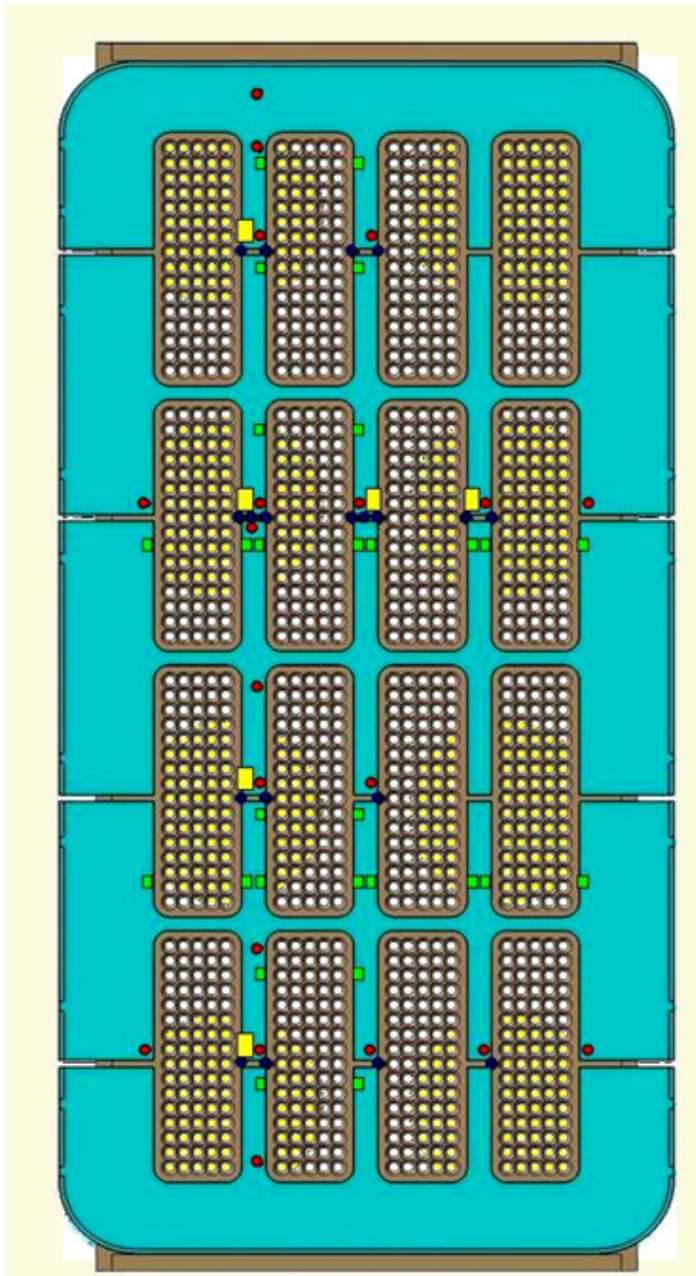


Figure 4 Layout of sensor assembly in the extraction region; the yellow disks on the background indicate the RF driver position. Sensors on PG (blue), sensors on BP front side (red), sensors on BP lateral side (green) and reference electrode on BP (yellow). The reference electrodes on PG are not indicated in this schematic

furthermore for the electrodes to be installed on the PG and on the front side of the BP the respective reference electrodes are also shown.

3.3. Probe system integration in the SPIDER facility

The design of the electrostatic sensor arrays exploits PG and BP as supporting structures. The main technical constraints then concern the cooling channels that allow an active heating of the

Concerning the sensors on the front side of the BP the concept described in fig.1 has been used as a guideline; however in this case the sensor can be installed from the rear side of the BP, so that the role of the locking ring is played in this case by a metallic plate screwed on the back side. The reference electrode for such sensors exploits the same methods as already seen for the sensors on the PG.

Also the sensors to be installed on the lateral sides of the bias plate adopt the concept of the contact spring, however they have the peculiarity of exploiting the BP thickness itself (10 mm). This solution provides a clear advantage from the data interpretation point of view, since the electrode collecting surface is perpendicular to the magnetic field. In this case however the tight available space does not allow the installation of reference electrodes so that they will be used essentially as ion saturation current measurements, with the possibility of using opposite facing electrodes as a double probe, given that they are placed in the same flux tube. In figure 3 the details of the components of the three different types of sensors are shown and how they are installed respectively on PG or BP. The sensor orientation with respect to the magnetic field direction is also shown,

PG and BP up to 150°C during the operations, and the supports of these components. The available thickness of PG and BP (9mm and 11 mm respectively) has to be accounted for. Furthermore all the sensors have to be exposed to the ion source plasma and due to the high voltage differences in the accelerator, the sensors on the PG have to be installed on the ion source side of the grid.

In order to minimize the number of sensors, while pursuing the scientific objectives mentioned in section 3.1, the design involves basically two main complete arrays, to investigate vertical and horizontal non-uniformities of plasma parameters, supplemented by other partial arrays so that the effect of a discrete number of drivers is diagnosed. Specifically the measurements are performed in several vertical positions, corresponding to the center of the RF drivers and in between them. The three different types of sensors are then arranged on 2D arrays placed on planes perpendicular to the beam direction and respectively at 0, 15 mm and 20 mm from the PG surface, to study the axial gradients of plasma parameters. The resulting arrangement of sensors is shown in fig.4. The total number of each kind of sensors is shown in Table I.

The integration of the electrostatic sensor system in the extraction region requires taking care of cable path and their safety during the source operations. For this scope miniaturized coaxial insulated cables, UHV compatible, have been chosen, with diameter of 1.5 mm.

Cables are protected from plasma exposure through their entire length: at first the cable paths exploit the 1 cm gap between PG and BP, so that cables are not exposed to driver plasma; subsequently the cables are installed in trenches and as a further protection a metallic cover will be applied over cable paths. It is worth mentioning that cable path and covers do not reduce the gap space that has to be maintained free for spectroscopic diagnostics purposes.

4. Conclusions

The design of an electrostatic probe system for the SPIDER facility has been presented, including the purpose of the measurements, the design criteria and the adopted solutions. The presence of RF and magnetic fields, deposition of conducting materials during the operations, robustness and easy maintenance are some of the aspects guiding the design work, as well as the constraints related to the integration of the probes in the source design.

Acknowledgments

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Table I. Total number of sensors.

<i>PROBE CLASS</i>	<i>PROBE #</i>
Front side PG	12 (+ 7 ref.)
Front side BP	20 (+ 6 ref.)
Lateral side BP	28