Detail Design of the Beam Source for the SPIDER Experiment


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Abstract

The ITER Neutral Beam Test Facility (PRIMA - Padova Research on Injector Megavolt Accelerated) is planned to be built at Consorzio RFX (Padova, Italy). PRIMA includes two experimental devices: a full size plasma source with low voltage extraction called SPIDER (Source for Production of Ion of Deuterium Extracted from RF plasma) and a full size neutral beam injector at full beam power called MITICA (Megavolt ITER Injector Concept Advancement). SPIDER is the first experimental device to be built and operated, aiming at testing the extraction of a negative ion beam (made of $\text{H}^-$ and in a later stage $\text{D}^-$ ions) from an ITER size ion source. The main requirements of this experiment are a $\text{H}^-$ / $\text{D}^-$ current of approximately 70 A / 50 A and an energy of 100 keV. This paper presents an overview of the SPIDER Beam Source design, with a particular focus on the main design choices, aiming at reaching the best compromise between physics, optics, thermo-mechanical, cooling, assembly and electrical requirements.

Key words: source, design, ITER, NBI

1. Introduction

The main purpose of the SPIDER experiment is to optimize the performance of an ITER-like ion source by maximizing the extracted negative ion current density and its spatial uniformity and by minimizing the ratio of co-extracted electrons, in order to match the ITER requirements [1, 2].

The Beam Source has the function of creating and accelerating the negative ions starting from hydrogen or deuterium gas, and can be considered as one of the main devices inside the NBIs. In SPIDER, the Beam Source assembly, kept at -100 kV by electrical power supplies and ceramic insulators, is made of a Radio Frequency (RF) ion source and a three grids extraction/acceleration system. For the ion source, a detailed design has been developed in collaboration with IPP in order to reach the ITER size and requirements [3, 4, 5, 6, 7]. For the extraction/acceleration system, a high performance cooling system, a proper layout of the components and a suitable fixing system for the grids have been designed in collaboration with IPR and CEA [8, 9].

The main performances requested for the beam source of SPIDER are: approximately 70 A / 50 A accelerated beam current of $\text{H}^-/\text{D}^-$ at 100 keV, 0.3 Pa source pressure, 3600 s pulse length, 1.5 x 0.6 m$^2$ cross section with a total aperture area on the plasma grid of 0.2 m$^2$. The beam source for SPIDER foresees the same plasma source as for ITER and the same first two grids (plasma and extraction grids), that extract the negative ions from the plasma source. The main differences lay in the following acceleration stages. In SPIDER there is just another acceleration stage of 100 kV to the grounded grid.

Figure 1: Overall section view of the SPIDER Beam Source

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The beam source for SPIDER consists of a complex chamber (plasma source) where the gas is injected and ionized in order to produce negative ions and a system of grids at different potential (accelerator) that extracts and accelerates the ions out of the source. The two subsystems are fixed to the common support structure that features the mechanical interface towards the vacuum vessel where the source will be operated. This structure includes a positioning system that allows to align the diagnostic optical lateral and bottom accesses on the source with the corresponding windows on the vessel.

2. Radio Frequency ion source

The Radio Frequency (RF) ion source is the component where the negative ions, that in ITER will be extracted and accelerated towards the tokamak chamber, are generated. The RF ion source will be housed in the rear part of the beam source structure, mechanically fixed to the source supporting frame in four points located on the sides of the rear drivers plate. The RF ion source had been designed for MITICA [3]; adaptation to SPIDER device and further detailing for the preparation of the Call for Tender caused some modifications, described in the following sections.

The RF ion source is a complex chamber, featuring a main space, enclosed in a structure called source case and facing the plasma grid, on whose surface most of negative ions are generated, and eight rear smaller chambers called drivers, where the gas is injected (hydrogen or deuterium). RF coils wound around the lateral wall of the drivers, and connected to a 1 MHz oscillator, transfer the RF power and ionize the gas: the resulting plasma flows then into the main chamber, where the additional presence of caesium enhances the number of negative ions generated on the surface of the plasma grid.

The RF ion source also includes a series of auxiliary systems: the electric circuit for power input, the cooling circuits for heated components, the gas supply system, three ovens to dispense the caesium inside the source, starter filaments to initiate the plasma and several diagnostic sensors to monitor and control the source behavior. Ports are foreseen on the surface of several elements, in order to allow the connection of the auxiliary systems and the diagnostic accesses.

2.1. Description of main components

The drivers’ plate, shown in Fig. 3 is the vertical rear wall of the case and is made of 2 different plates: a first stainless steel plate, called “rear drivers plate” acts as support for the drivers and all other components (Cs ovens, etc.), whereas a second CuCrZr plate, called “plasma drivers plate” faces the plasma in the chamber and is bolted to the rear one by means of pinscrews that allow the relative differential thermal expansion.

The plasma drivers plate has been divided in four sub-plates, individually constrained to the rear drivers plate, in order to facilitate manufacturing, as complex steps are foreseen, like electro-deposition of copper and deposition of a thin layer of molybdenum. Back-streaming positive ions (BSI+), created by stripping reactions in the accelerator, are expected to be accelerated back towards the source and to impinge on this component.
with considerable peak power density [8]. The consequent heat loads are carried away by dedicated cooling circuits (see Fig. 3).

The source case lateral wall thickness is rather low (4 mm) in order to minimize the distance between confining magnets and plasma. The cooling ducts are machined on the internal surface, then an electro-deposited 1 mm thick layer of copper contributes to the uniformity of temperature distribution on the case and closes the cooling channels.

The drivers (see Fig. 4) are the components where the power is transferred in the RF ion source and the plasma is generated. They are cylindrical structures directly connected with the source case.

The Faraday shield (FS) is a cylindrical cup that protects the driver case from the plasma. High heat load is deposited on the inner surface from plasma interaction and on the inner rear surface from the BSI⁺ coming from the accelerator, therefore two complex cooling circuits are foreseen to remove the power. Cuts are foreseen on the lateral wall (LW) to prevent circulation of eddy currents, without direct sight of the driver case from the plasma, in order to protect the alumina. In order to facilitate manufacturing and to measure separately heat load deposited on LW and back plate, the FS is made up of two parts: the back plate and the FS cooling circuits are independent and have been obtained on separate components. A disc faces the plasma as rear vertical surface and houses the back plate cooling ducts, whereas the LW is a cup with two layers of manifolds in the rear plate that are the inlets/outlets of the LW cooling ducts. Starting from a CuCrZr disc for the back plate and an OFHC disc for the LW, the FS components are obtained by machining of the cooling channels, alternated with electro-depositing of copper. In between the back plate and the LW, a stainless steel structure has been inserted for plasma confinement, in order to house permanent magnets and minimize their distance from plasma.

3. Extraction/acceleration system

A dedicated extraction/acceleration system has been designed for the SPIDER experiment (see Fig. 5), made of three grids - the Plasma Grid (PG), the Extraction Grid (EG) and the Grounded Grid (GG) - plus a Bias Plate (BP). Each grid features 1280 apertures, where the ion beamlets are extracted from the ion source and accelerated up to 100 kV.

All the grids are made by electro-deposition of pure copper onto a copper base plate. This technique permits to obtain a very complex geometric shape (with very small cooling channels that run inside the grid and embedded magnets) and to have good mechanical properties, due to the high purity and to the very small grain size.

All the grids are actively cooled. The extraction and grounded grid supports are composed of a mounting flange, that is fixed and connected through ceramic insulators to the main support structure, and a frame whose purpose is to support the four segments of the grid. The frame position can be registered with accuracy during the assembly of the beam source in order to fulfil the requirements on the grid apertures alignment.

![Figure 4: Driver assembly: (a) Overall view; (b) Cooling system for the lateral walls of the Faraday shield; (c) Cooling system for the back plate of the Faraday shield.](image-url)
3.1. Design analysis and optimization

New calculations on beam optics, magnetic fields and thermo-mechanical aspects have defined the geometry of the grids. Physics and engineering aspects have been treated at the same time with an integrated approach, and the contemporary optimization of the different aspects have been reached using an iterative process. As exemplified in Fig. 6 for the extraction grid, evaluations on the pressure drop and water distribution in the cooling circuits have been carried out using Computational Fluid Dynamics (CFD) techniques. The temperature, stress and deformations of the grids have then been calculated with elasto-plastic finite element models and using as input the heat loads estimated with Monte-Carlo codes (simulating the physics of the negative ion beam and electrons).

3.2. Optimized magnetic configuration

A magnetic filter field at the edge of the plasma source can provide a more efficient extraction of negative ions with respect to electrons. On the other hand, the magnetic field in the accelerator should be kept as low and uniform as possible in order not to spoil the beam optics and aiming.

To reach these goals, an optimization of the magnetic configuration has been carried out for the SPIDER accelerator [10]. The path of the plasma grid current has been divided between several conductors in proper positions: two forward bars have been added at the sides of the PG, while the return bars have been moved close to the ion source back plate, as visible in Fig. 5b. Moreover, ferromagnetic material has been inserted in the GG (see Fig. 5c). These modifications have been found to help obtaining a uniform filter field near the PG on the upstream side and a low and uniform field in the accelerator. At the same time this solution have brought a much lower stray field in the area surrounding the ion source.

3.3. Bias plate

The bias plate is a copper plate, divided in 5 elements, that is located inside the plasma source, in front of the plasma grid and close to extraction region. Its main purpose is to contribute to reduce the electron content co-extracted with negative ions, and then maximize the extracted ion current density: this is obtained by biasing the voltage of the plate with respect to the plasma grid and the RF source.

The bias plate is mechanically integrated with the plasma grid. As its surface interacts with the plasma inside the plasma source, cooling circuits are foreseen inside the 5 elements to remove the heat load deposited and a molybdenum coating is necessary to prevent copper sputtering.

3.4. Plasma Grid

The Plasma Grid is the first grid facing the plasma in the ion source and it is composed of four segments. It is heated by the plasma inside the RF ion source, with a surface power density that is estimated to range between 3 and 20 kW m$^{-2}$. This grid is required to operate at a temperature of about 150$^\circ$C in order to enhance the negative ions surface generation from the interaction with the cesiated surface. A molybdenum coating on the...
plasma side is foreseen to prevent copper sputtering inside the source. A current (up to 5 kA), flows in the vertical direction, to provide a horizontal magnetic field that reduces electron temperature and the number of co-extracted electrons.

The apertures are designed with conical chamfers on the upstream and downstream sides of the grid. A larger surface for negative ion production and an easier extraction are obtained with this solution.

The PG and its piping have to be electrically insulated (for voltage up to 30 V) from the bias plate and from all other components in order to avoid the flow of a portion of the PG current on the support structures.

In order to guarantee the best planarity of the whole plasma grid during operation, each PG segment has a 6 points fixing system (onto the PG frame) made of a fix dowel at the center of the right side (following the beam direction), one dowel sliding horizontally on the other side (allowing thermal expansion) and four screws at the four corners that keep the segment in contact with the frame. At the six points the segments have cylindrical ceramic bushings, that are about 0.5 mm thicker than the thickness of the grid in order to avoid the segments to be widely in contact with the frame aiming at reducing the thermal conductivity towards the supporting frame itself.

3.5. Extraction grid

The extraction grid has an electric potential that is 10 kV higher than the PG, so that the negative charged ions (H\(^-\) or \(^3\)He\(^+\)) can be properly extracted from the RF chamber. Suppression magnets, embedded in the grid, have the function to deviate the trajectories of the co-extracted electrons, making them collide with the grid surface. The consequent power loads are quite high and concentrated, hence this grid is the most critical from the structural point of view, and is designed with a high performance cooling system.

As the Plasma Grid, also the EG is composed of four segments having 320 holes each one. The fixing system follows the same concept as the one previously described for the PG.

3.6. Grounded grid

The grounded grid has the function to accelerate the ion beamlets up to a potential of 100 kV, and is also loaded by co-extracted and stripped electrons. As the PG and the EG, the GG is composed of four segments having 320 holes each one. The fixing system is identical to the EG one.

This grid has compensation magnets to compensate for the ion beamlet deflection due to the magnets in the EG. To be effective, these magnets must work only on the upstream side, with no magnetic field on the downstream side. For this reason and to minimize the filter magnetic field (given by the PG current) inside the accelerator, a soft iron plate is placed on the downstream side, attached by means of screws (allowing differential expansion) to the copper part (hosting the cooling channels and the permanent magnets).

4. Interfaces and electrostatic shield

An electrostatic shield surrounding the whole SPIDER beam source have been designed in order to decrease the risk of an electrostatic breakdown among components at different voltages (see Fig. 1). Three high voltage bushings are foreseen: one at the top for the electrical supplies and diagnostic signals and two at the bottom for the cooling water and gas supplies. Several diagnostic viewports have been introduced in the vacuum vessel, in order to match the lines of sight foreseen on the source.

5. Diagnostic measurements

The SPIDER beam source is the first beam source to be built with full ITER-like dimensions. With such large dimensions, one of the main issues is to obtain uniform operating conditions overall the whole extraction area. In order to be effective in developing the performances of the beam source for ITER, it should be monitored by means of a proper set of diagnostics, uniformly spread over the extraction region. In particular, the plasma inside the ion source should be kept under observation as much as possible, in order to know in a precise and detailed way the operating conditions of the experiment. This could help understanding the physics of the machine and to find possible ways to improve the performances.

Moreover, in order to control the temperature during operations and also for safety reasons, thermal measurements are highly required for the Ion Source Back Plate, RF drivers and grids, as well as at the inlet and outlet of the cooling circuits.
5.1. Internal and external diagnostics

Several diagnostic sensors (thermocouples and electrostatic probes) are foreseen to be mounted inside the SPIDER beam source [11]. The sensors, with the related cables, are integrated with the components design, aiming at obtaining as much information as possible on the operating conditions of the machine without interfering with its performances.

In addition to these sensors, complex diagnostic systems are hosted externally to the vacuum vessel, like source emission spectroscopy and tomography, cavity ringdown, optical cameras (both in the visible and infrared range) etc. The design of the SPIDER beam source have been developed taking into account that the lines of sight of these diagnostics must not be covered with any mechanical component.

5.2. Thermal measurements

A comprehensive set of thermal measurements is foreseen for the SPIDER experiment. The cooling systems for the RF ion source and the extraction/acceleration system (see the scheme in Fig. 7) are designed in such a way that independent calorimetry measurement, by means of calorimetric thermocouples (measuring the water temperature at inlet and outlet) and flow meters, can be carried out for the different RF drivers and grid segments. This could bring useful information about the uniformity of the operating conditions across different parts of the machine.

Other thermocouples are attached directly to the main components (grids, plasma drivers plate etc.) to measure their temperature during the operations.

Suitable design solutions, manufacturing technologies and diagnostic systems have been chosen to cope with the requirement set for the first full-size ITER ion source.

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