Fusion Engineering and Design 131 (2018) 96–104

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Studies on the requirements and design of the High Voltage Radio Frequency Test Facility

A. Maistrello*, P. Jain, M. Recchia, E. Gaio

Consorzio RFX (CNR, ENEA, INFN, Università di Padova, Acciaierie Venete SpA), Corso Stati Uniti 4, 35127, Padova, Italy

ARTICLE INFO

Keywords:
Vacuum voltage hold off
Radiofrequency ion source
HVRFTF
ITER NBTF
PRIMA
MITICA
SPIDER

ABSTRACT

The two projects of the ITER Neutral Beam Test Facility in Padova are MITICA, the full scale prototype of the heating Neutral Beam Injector (NBI) and SPIDER, the full-size negative ion source of the NBI. Both include a Radio Frequency (RF) Ion Source where plasma is produced by the inductive coupling with coils wound around vacuum chambers called driver cases. Each coil is fed at 1 MHz up to a power of 100 kW, which corresponds to a voltage of about 12 kV rms, with nominal plasma parameters.

According to the ITER requirements, the ion source is in vacuum to avoid radiation induced conductivity; concern on the voltage hold off of the source components exists, in particular related to the contact zone between the coil and the driver case characterized by intensification of the E-field.

The development of a test bed called High Voltage Radio Frequency Test Facility (HVRFTF) has been launched to study the issues related to the voltage hold off in this operational environment and to verify the electrical design of the drivers adopted in the ion sources of SPIDER and MITICA.

The paper presents the studies addressed to identify the HVRFTF requirements, to conceive and design suitable driver mock-up to reproduce operative conditions relevant to the RF drivers of SPIDER and MITICA for the characterization of their dielectric strength, to work out a suitable RF circuit for the HVRFTF to generate the required voltage and to design a flexible test arrangement allowing the variation of the quantities which influence the voltage hold off, such as the pressure, geometry and materials of the devices under test, in order to perform parametric analyses.

1. Introduction

The achievement of the performance requested to the ITER Heating Neutral Beam Injectors (NBI – 16.5 MW power delivered to the plasma, −1 MeV energy, 3600 s pulse length), never met before all together in a single device, motivated the development of two experiments SPIDER and MITICA being built in Padova, Italy, in the ITER Neutral Beam test Facility (NBTF), also called PRIMA (Padova Research on ITER Megavolt Accelerator). SPIDER is the full-size negative Ion Source of the NBI with an acceleration of −100 kV, while MITICA is the full scale prototype of the heating NBI with the acceleration of −1 MV [1].

The ion sources for SPIDER and MITICA are composed of a radio-frequency (RF) inductively coupled plasma source and a beam extraction system; the RF magnetic field is generated by a matrix of 8 drivers to heat the plasma with a power up to 800 kW at 1 MHz. The ion source design derives from the R&D carried out at Max-Planck-Institut für Plasmaphysik (IPP) during the past years [2,3], with additional improvements to achieve the desired performance in long duration pulses (up to 1 h) on a full ITER-size device, in a vacuum environment [4,5] and with optimized beamlet optics [6–9].

Among the various issues connected to the fulfillment of the requirements for ITER, there are also those related to the voltage hold off in vacuum of the beam source components; not only for the acceleration grids subjected to very high dc voltage but also for the RF circuits of the ion source. Some concern in this regards has arisen since several years ago and in fact, also in IPP, the last two test facilities RADI and ELISE have been realized with the areas containing the drivers that can be put under vacuum (lower than 10^{-4} mbar [10]) to better simulate the ITER operating condition [11,12]. For ITER heating NBI the concern is greater, since the rear side of the ion source is not directly pumped and the pressure at the moment is only estimated by means of simulation.

In Padova, at the ITER NBTF, a R&D task for the development of a small experimental facility called High Voltage Radio Frequency Test Facility (HVRFTF) has been launched to study the issues related to the voltage hold off at radiofrequency at low pressure and to verify the electrical design of the drivers adopted in the ion sources of SPIDER and

* Corresponding author.
E-mail address: alberto.maistrello@igi.cnr.it (A. Maistrello).

https://doi.org/10.1016/j.fusengdes.2018.04.086
Received 24 October 2017; Received in revised form 6 April 2018; Accepted 21 April 2018
Available online 27 April 2018

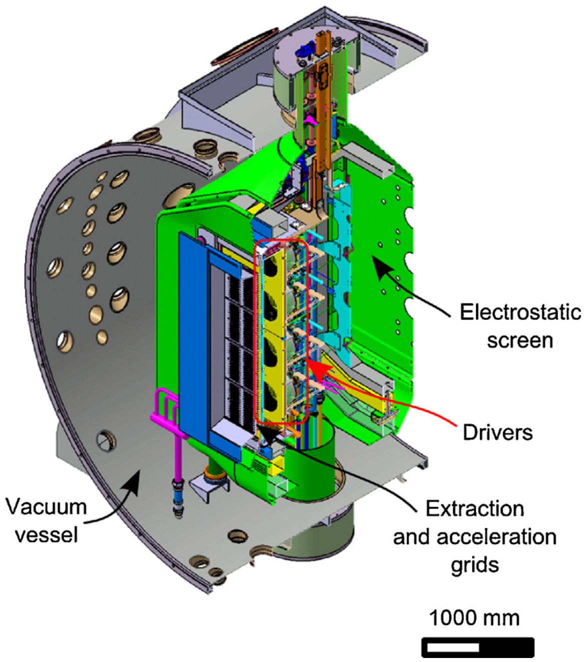

Fig. 1. Cut view of SPIDER vacuum vessel and internal components.

MITICA. The HVRFTF has been thought with the aim to be a test facility capable to reproduce working conditions in terms of voltage, pressure and E-field relevant to the RF circuits of SPIDER and MITICA ion sources.

This paper deals with the studies on the requirements and on the identification of effective design solutions to meet the HVRFTF mission. Two main issues encountered are described in particular: the first one related to the working out of mocks-up suitable for the scope, the second one related to the development of an efficient RF circuit capable to generate the desired high voltage, with low power losses.

2. The SPIDER Beam Source

The SPIDER Beam Source (BS), shown in Fig. 1, is composed of a Plasma Source and an ion extraction system, forming the so-called ion source, and ion acceleration grids. Within the plasma source, eight drivers are filled with hydrogen or deuterium at the pressure of about 0.3 Pa and ions are generated in a region seeded with Caesium-vapour and then extracted and accelerated through three multi-aperture grids (1280 apertures per grid): the Plasma Grid, the Extraction Grid, and the Grounded Grid [7,8]. The BS is placed within a Vacuum Vessel (VV), also containing a beam dump and a diagnostic calorimeter to stop and map the ion beam.

The Ion Source is enclosed within an electrostatic screen at source potential to prevent breakdown between ion source components and the grounded VV. The electrostatic screen is composed of drilled plates to allow the evacuation of the gas from the ion source to the pumping system, mounted on the VV, which is rated to provide a nominal pressure of 10 mPa. The pressure at the Electrostatic Screen outer surface has been estimated by numerical simulation to be around 65 mPa [13]; because of outgassing the region in the rear side of the BS is expected to be characterized by higher pressure.

The drivers are composed of a cylindrical chamber, a RF coil and supporting passive structures; they are arranged in four couples, fed by 4 separated RF circuits (Fig. 2). In each circuit, the series of two RF coils is connected to an impedance matching network [14], composed of series and parallel capacitors installed in the rear side of the BS, too. Each RF circuit is supplied by a 200 kW, 1 MHz RF generator [15].

A 3D CAD view of one driver with the indication of the main components is shown in Fig. 3, while its cross section is shown in Fig. 4. Starting from the external region, the main components found in a driver are: four support rods relatively displaced at 90° to mechanically hold the components; the Electromagnetic shield (EMS) [16], at the ion source potential, surrounding the coil and actively cooled; four so called "combs" made of Vespel SP-1 to support the coil; the actively cooled copper coil; the insulating driver case (DC) made of Aluminum Oxide; the copper Faraday Screen (FS) at ion source potential coated with a Molybdenum layer to reduce the plasma sputtering [7,12]. At the top there are the backplate and the back cover.

The two clearances gap1 and gap2 indicated in Fig. 4 are of particular interest for the analyses presented in the following paragraphs. Gap1 is the distance between the FS lateral wall and the Driver Case and it is nominally equal to 2 mm; gap2 is the distance between the coil and the Driver Case and it nominally equal to 0 mm, since the coil is tightly wound around the DC. However, because of mechanical tolerances of component, it is expected that the Gap2 can be equal to zero in some point. Gap1 is within the Driver Case where plasma is produced at the nominal pressure of 0.3 Pa, while gap2 is outside the driver, where the pressure is estimated to be close to 65 mPa.

3. Voltage hold off issues

Fig. 5 shows a simplified scheme of the circuits supplying the SPIDER BS, in order to synthesize the relative potentials among the different parts. The RF circuits are enclosed within the Electrostatic Screen and connected to the Plasma Source Body; the same states for the drivers FS and EMS. The Plasma Grid and the Electrostatic Screen are polarized with respect to the Plasma Source Body by the Ion Source BIas power supply (ISBI), which imposes a voltage in the order of tens of volts. The Plasma Grid is polarized with respect to the Extraction Grid by the Ion Source Extraction Grid power supply (ISEG), with a voltage of up to 12 kV. Finally the Extraction Grid is polarized with respect to the Grounded Grid by the Acceleration Grid Power Supply (AGPS), with a voltage up to 100 kV. The BS is placed within the Vacuum Vessel, which is grounded.

The RF circuits, supplied by the Ion Source RF oscillators (ISRF), operate at the Plasma Source Body potential and they are surrounded by passive structures almost at the same potential: the FS, the EMS and the Electrostatic Screen.

Operational and plasma parameters influence the RF coil equivalent inductance and resistance, thus the voltage across it. Expected values of equivalent inductance and resistance are 9 μH and 2.3 Ω respectively network [14]. Considering a perfect matching at the resonant frequency of 1.033 MHz, the voltage across the coil at full power (100 kW/driver) is about 12.2 kV rms.

The gas pressure in the RF circuits and driver coils region is far from values typical of Ultra High Vacuum, but since the distances between metallic parts at different potential inside the beam source are shorter than the mean free path of the electrons, the Townsend discharge regime is not expected. Nevertheless, the vacuum space in between the RF coils and the DC, which appears as a triple junction (conductor, dielectric and vacuum) is characterized by intensification of the electric field with possible associated electron field emission leading to possible breakdowns in the ion source backside, as also recently experienced in ELISE [17].

A simplified 2D axisymmetric finite elements model has been developed with FEMM [18], in order to calculate the electrostatic field in the driver coil region. The model includes the geometry of the driver components and related materials properties. The voltage expected with nominal plasma parameters was assumed, with the hypothesis of linear distribution among the coil turns. The present design of the SPIDER driver assumes zero gap between them; a realistic value for gap2 is in the range 0–0.5 mm and the value of 10 μm was assumed in the model.

The analysis has identified intense Electric field (E-field) in the two