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The ITER full size plasma source device design

P. Sonato[a,*], P. Agostinetti[a], G. Anaclerio[a], V. Antoni[a], O. Barana[a], M. Bigi[a], M. Boldrin[a], M. Cavenago[b], S. Dal Bello[a], M. Dalla Palma[a], A. Daniele[c], M. D'Arienzo[a], A. De Lorenzi[a], A. Ferro[a], A. Fiorentin[a], E. Gaio[a], E. Gazza[a], L. Grando[a], F. Fantini[a], F. Fellin[a], A. Luchetta[a], G. Manduchi[a], F. Milani[a], D. Marcuzzi[a], L. Novello[a], R. Pasqualotto[a], M. Pavei[a], R. Pengo[b], S. Peruzzo[a], A. Pesce[a], N. Pilan[a], R. Piovan[a], N. Pomaro[a], M. Recchia[a], W. Rigato[a], A. Rizzolo[a], G. Serianni[a], M. Spolaore[a], P. Spolaore[b], S. Sandri[c], C. Taliercio[a], V. Toigo[a], M. Valisa[a], P. Veltri[a], P. Zaccaria[a], A. Zamengo[a], L. Zanotto[a]

[a] *Consorzio RFX, EURATOM-ENEA Association, Corso Stati Uniti 4, I-35127 Padova, Italy*
[b] *INFN, Legnaro, Padova, Italy*
[c] *ENEA, Frascati, Roma, Italy*

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ABSTRACT

In the framework of the strategy for the development and the procurement of the NB systems for ITER, it has been decided to build in Padova a test facility, including two experimental devices: a full size plasma source with low voltage extraction and a full size NB injector at full beam power (1 MV). These two different devices will separately address the main scientific and technological issues of the 17 MW NB injector for ITER. In particular the full size plasma source of negative ions will address the ITER performance requirements in terms of current density and uniformity, limitation of the electron/ion ratio and stationary operation at full current with high reliability and constant performances for the whole operating time up to 1 h. The required negative ion current density to be extracted from the plasma source ranges from 290 A/m^2 in D_2 (D^-) and 350 A/m^2 in H_2 (H^-) and these values should be obtained at the lowest admissible neutral pressure in the plasma source volume, nominally at 0.3 Pa. The electron to ion ratio should be limited to less than 1 and the admissible ion inhomogeneity extracted from the grids should be better than 10% on the whole plasma cross-section having a surface exposed to the extraction grid of the order of 1 m^2.

The main design choices will be presented in the paper as well as an overview of the design of the main components and systems.

1. Introduction

In the framework of the strategy for the development and the procurement of the NB systems for ITER, it has been decided to build in Padova a test facility, including two experimental devices: a full size plasma source with low voltage extraction and a full size NB injector at full beam power (1 MV). These two different devices will separately address the main scientific and technological issues of the 17 MW NB injector for ITER. In particular the full size plasma source of negative ions will address the ITER performance requirements in terms of: current density, current density uniformity, limitation of the electron/ion ratio, low source pressure and stationary operation at full current with high reliability and constant performances for the whole operating time up to 1 h.

Most of these main requirements are well beyond the experimental capabilities of the present devices and the full size ion source device presented in this paper will realize a necessary step to develop the knowledge and the technologies to be adopted in the full power 1 MV injector for ITER.

The plasma source concept originally foreseen in the ITER DDD was based on a high number of tungsten filaments; this design option has been recently revised and discarded in favour of the RF plasma source developed at IPP and well experienced in the last years [1–4]. The main drawbacks of the filament option were the necessity of a frequent filament substitution and the co-deposition of tungsten films on the plasma source limiting the efficiency of the surface negative ion production and causing therefore a high Caesium consumption resulting in frequent remote handling maintenance for the substitution of the Cs reservoir.

The RF plasma source featuring dimensions large enough to produce a negative ion current of tens of Amperes is the challenge required to the device presently under detailed design in Padova

* Corresponding author. Tel.: +39 049 8295037; fax: +39 049 8700718.
E-mail address: piergiorgio.sonato@igi.cnr.it (P. Sonato).

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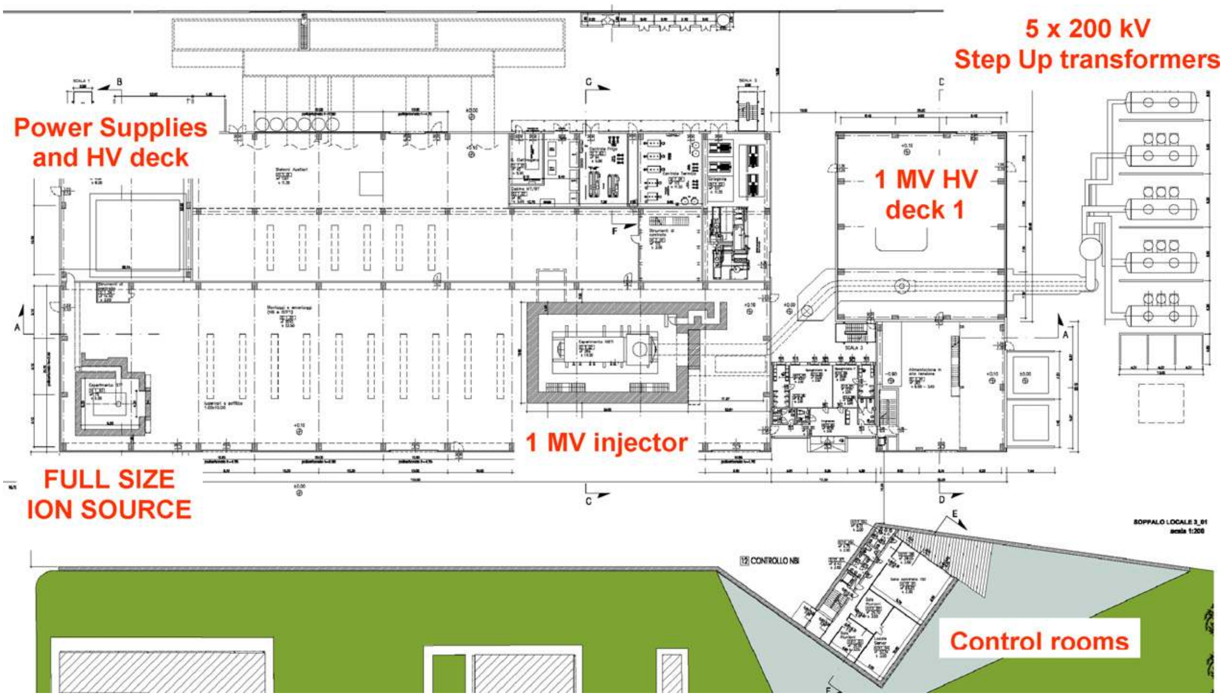

Fig. 1. The neutral beam test facility site in Padova.

with the contribution of other European laboratories (namely: CEA, IPP, UKAEA) and of Institute for Plasma Research (India) involved to develop the ion source also for the Diagnostic Beam Injector to be installed in ITER.

2. The site

The Padova research area where presently the activities of the Consorzio RFX are hosted will also host the two above-mentioned devices. In Fig. 1 the new building for the two experiments is shown, the control rooms are for both devices in a separate building. The full size source experiment is located on the left hand side of the building. The main building is divided in two parts, the main and the highest one host the two experimental devices, whereas the adjacent building hosts the experimental service plants, like cooling system, cryogenic systems, power supplies of the full size ion source, etc. The whole length of the main building is 110 m. A total surface of 7000 m^2 of new buildings has been designed to host the two experimental devices.

The presently existing power station at 400 kV will be adapted to supply the necessary energy as well as the other conventional services to operate the facility.

3. The plasma source

The main requirement for the full size ion source is to demonstrate the capability to produce high negative ion current density as specified in Table 1 at a source pressure of 0.3 Pa or at a desirable lower pressure.

A second important requirement is to demonstrate the capability to limit the extraction of electron to ion ratio to a value lower than 1 for the full power injector and less than 0.5 for the diagnostic beam injector.

A third requirement is to be able to produce and extract a beam having a uniformity better than the 10% over the whole plasma surface amounting to approximately 1.5 m^2.

A fourth requirement to be met by the experiments is the capability to produce and to extract the negative ion plasma for one hour assuring also the beam modulation required by the operation of the full power ITER beam and the diagnostic beam.

The last main requirement for the plasma source and the beam extraction is the capability to optimize the Caesium consumption and the tolerance to the presence of light impurities.

The plasma source based on the RF concept includes eight RF drivers with external water cooled five turns coils operated at 1 MHz [5,6]. Each couple of coils at the same height in the plasma source are series connected and the matching system for each couple of coils is made by two capacitances connected in series with the coils, and one capacitance connected in parallel. Each couple of coils is fed by a single 1 MHz power supply to minimize the costs. The rear view of the plasma source is shown in Fig. 2 where only the right side RF sources are visible, the others being shadowed by the filter current feeding system. The electrostatic shield of the source rear side is not shown in this figure.

In Fig. 3 a single RF driver with the screwing system to the source case backplate is shown in detail. In the section of Fig. 3 the water-cold Faraday screen, the driver cooled backplate and the confinement magnets housing are also visible.

Table 1
Ion current density requirements for the full size ion source.

	Ion	Energy (keV)	Stripping loss (%)	Extracted ion current density (A/m^2)	Extracted ion current (A)
HNB D	D^-	100	14	290	48
HNB H	H^-	100	14	330	56
DNB	H^-	100	14	350	60

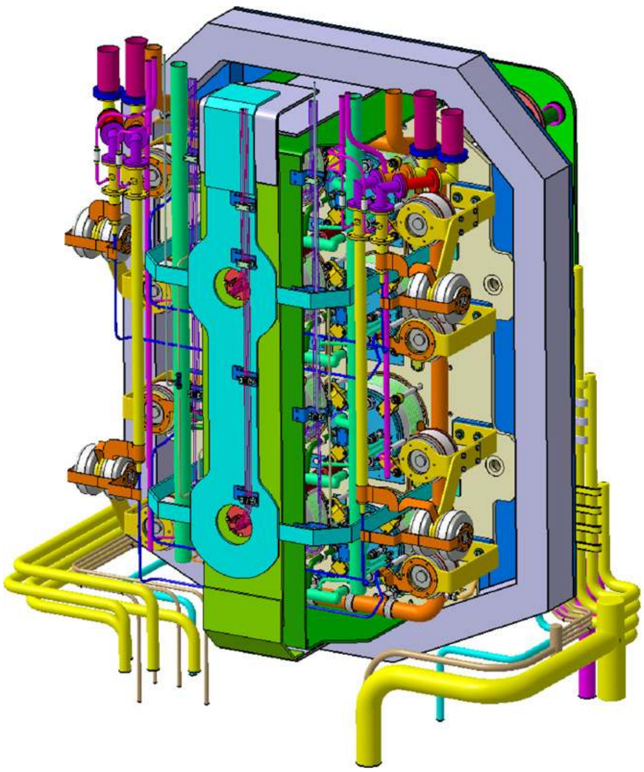

Fig. 2. The rear side view of the whole plasma source including the support frame.

4. The extraction and acceleration stages

The plasma in the source interacting with the Caesium coated surface of the plasma grid (PG) will create negative protium and deuterium ions that will be extracted through 1280 beamlets separated in 16 groups that are in couples faced to a single driver. Each group of beamlets is composed by a matrix of 16(vertical) × 5(horizontal) holes. The temperature of the PG will be controlled at 150 °C. The PG can be biased with respect to the source to prevent positive ions from being extracted; a vertical current flows in the PG to create a horizontal magnetic field that, in combination with the magnetic field produced by an appropriate system of permanent magnets, is able to confine and remove from the extraction zone close to the PG the most energetic electrons that reduce the amount of the negative ions [7]. The filter magnetic field is optimized to be as uniform as possible and has amplitude in the order of 5 mT. On the plasma source side close to the PG it is also foreseen a Bias Plate made of copper acting as a reference potential all around each group of beamlets. The Bias Plate is working at the same temperature of the plasma grid and the potential with respect to the plasma grid can be adjusted by a dedicated power supply.

A three grid system is foreseen to extract and accelerate at 100 kV the beam to allow its characterization. The three grids are shown in Fig. 4 together with their independent cooling circuits operated at different temperatures.

The reference holes geometry is presently under design optimization by means of the existing numerical tools to maximize the expected performances.

The three grid system will include also the design of all the magnetic tools to filter and divert the co-extracted electrons.

5. The vessel, the vacuum and gas injection gas system

The source will be housed in a cylindrical Stainless Steel vessel maintained in high vacuum by means of a combined system of turbomolecular and cryogenic pumps that will be able to maintain a pressure lower than 0.05 Pa in the RF coils regions to prevent the formation of a RF discharge. This pressure level must be guaranteed in presence of the maximum throughput of H_2 gas of approximately 7 Pa m^3/s (5 Pa m^3/s is foreseen for D_2).

The vessel design (Fig. 5) foresees the presence of four segments: the two lids, one on the plasma source side including a number of accesses for maintenance, diagnostics and pumping, the other being the lid on the beam side where the beam stopper will be housed, and two dedicated cylindrical sectors: the first one housing the plasma and beam source where all the bushings (electrical and hydraulic) and the source diagnostic ports are foreseen, a second cylindrical sector that houses the vacuum viewing ports for the beam diagnostics, the pumping system and other services.

The whole vessel has a length of 5.45 m and a diameter of 3.5 m and the mean vessel thickness is 10 mm except some localized reinforced parts.

The sector dedicated to support the plasma and beam source is the most critical one (Fig. 6). The insulated adjustable source frame supports required a detailed mechanical and electrical design as well as all the bushing where all the electrical and cooling vacuum interfaces are located. Unlike the design of the 1 MV injector, it has been decided to separate the electrical bushing from the hydraulic ones to simplify the bushings themselves and to allow to supply the cooling water through independently fed cooling circuits for an

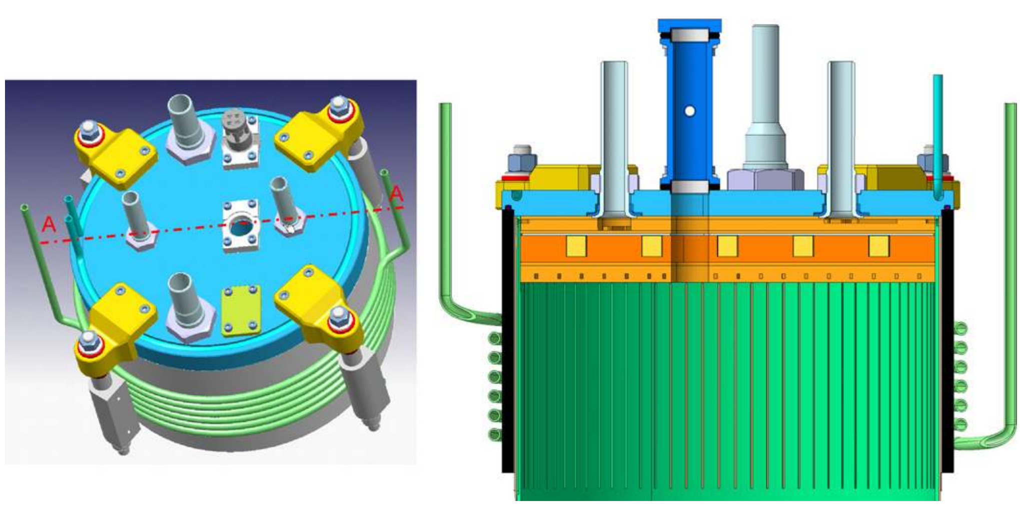

Fig. 3. A single RF driver (on the left) and its section showing the faraday shield, back plate heat removal system and the magnets housing.

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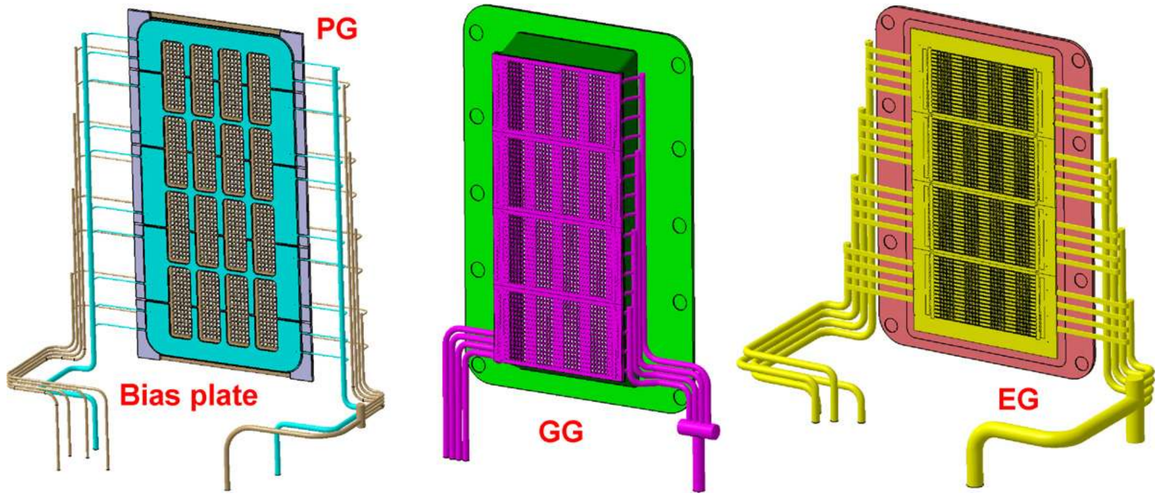

Fig. 4. The three grid system with their cooling circuits: plasma grid (PG), extraction grid (EG), and grounded grid (GG).

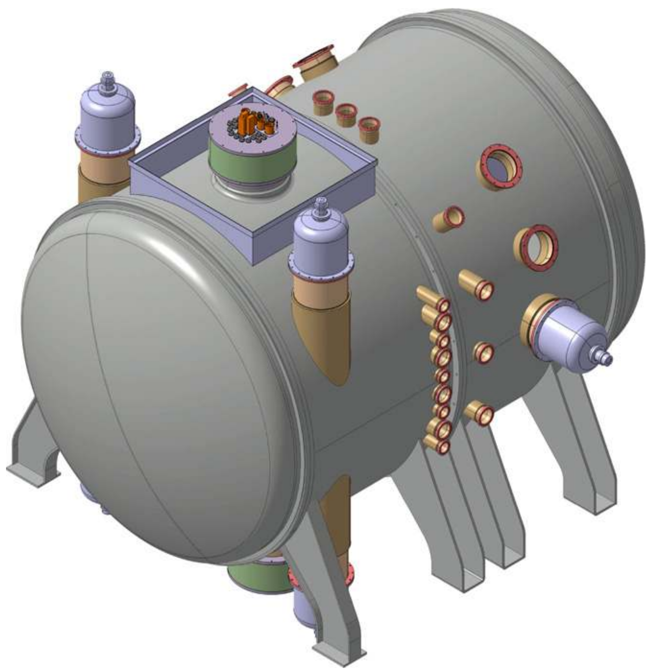

Fig. 5. The vessel with all the sectors: source sector, diagnostic sector and pumping sectors, the source lid (on the front) and the beam lid (on the rear).

independent calorimetric measurements on all the source components.

From the electrical point of view, the vessel is maintained at ground potential, whereas the source is at a voltage of −100 kV, therefore accurate electrostatic analysis has been performed to maintain the field at a reasonable low level.

6. The power supply system

The source requires a number of power supply systems all maintained at −100 kV in a high voltage deck in a dedicated high voltage power supply hall.

Since the source is a prototype for the 1 MV injector, the source power supplies are the same and, in particular, the high voltage deck will host: the four 250 kW tunable 1 MHz RF power supplies for the corresponding plasma drivers [8], the starting filaments PS, the Cs oven PS, the magnetic filter current PS and the bias PS for the extraction grid and the plasma grid. All these power supplies are fed through a 100 kV insulating transformer. In Fig. 7 the electrical scheme of the power supply system is shown. In Fig. 7 on the left side is shown the 100 kV power supplies for the low voltage acceleration grid, this power supply polarizes the plasma source and carries the whole beam current collected on the whole grounded components, whereas the extraction grid power supply has to carry the ion current and the electron current magnetically deflected on it. The acceleration grid power supply (AGPS) has to be designed to meet the required modulation of the beam for both the 1 MV injector and the Diagnostic Beam injector.

One critical aspect correlated with the power supply system is the protection concept against the unavoidable breakdowns that can occur between high voltage and grounded components (vessel and grounded grid) and in particular between the extraction and the grounded grids [9].

In Fig. 8 the protection system to limit the energy in the breakdown and to limit the EMI effects on the neighbouring components and lines is shown. The system has been conceived to allow as much as possible flexibility to mitigate the breakdown effects, in this way a resistive dumper has been series connected to the grounded grid, a distributed core dissipative snubber has been designed inside the transmission line, finally a concentrated core snubber and a magnetic core have been inserted in the connection line between the AGPS and the High Voltage Deck (HVD).

A detailed electromagnetic circuit model has been implemented to study the fast transients to allow the parameter optimizations of the protecting items.

All the power supplies are fed at 22 kV from the existing on site 400 kV power station.

7. The transmission line

The transmission line connects all the high voltage components in the plasma and beam source with the specific PS at the HVD. As shown in Fig. 1 approximately 30 m of transmission line has been designed. In Fig. 9 the typical section of the transmission line is shown.

A 1 × 1 m square shaped grounded screen made of conventional conductive panels electrically joined has been foreseen, a dedicated ground conductor is inserted to collect all the ground currents coming from the grounded grid, the beam dumper and the vessel.

The 100 kV multi-conductor line is enveloped in a circular 0.5 m conductive screen to limit the electric field to be lower than 0.6 kV/mm. Inside the envelope the conductors are arranged on

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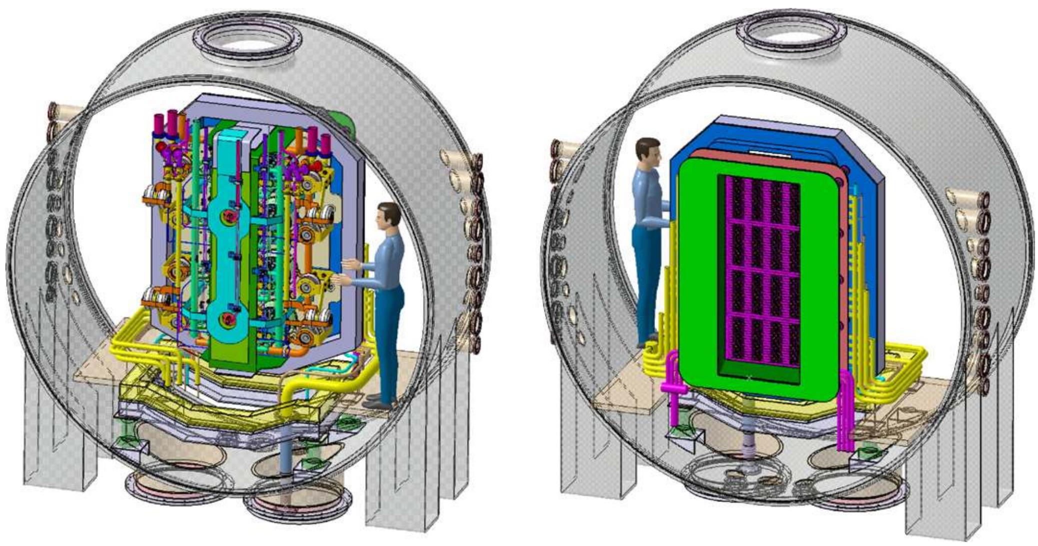

Fig. 6. The ion source inside the vessel source sector.

conventional cable carriers and separated in agreement with the different type and electrical characteristic of the cables to limit the electromagnetic negative effects in particular between low level diagnostic signals and RF currents.

8. The main diagnostic systems

The diagnostic system will be focused to characterize the plasma in the source and to investigate the performances of the extracted beam with respect to the main requirements.

First of all the electrical measurements will allow to discriminate all the currents flowing in the different components in the stationary conditions and will allow to measure the relevant break-down characteristics on the most critical components and PS systems.

The individual cooling circuits will be monitored with both flowmeters and thermocouples to allow a detailed stationary calorimetry.

A reasonable number of local thermocouples will be embedded on the most relevant component to integrate the calorimetry information in particular to try to discriminate relevant non-uniform temperature distribution.

A number of pressure, flow measurements and mass spectrometers will integrate the vacuum and gas injection system.

Then the most relevant optical (emission and active) diagnostics will be devoted to characterize the plasma properties as close as

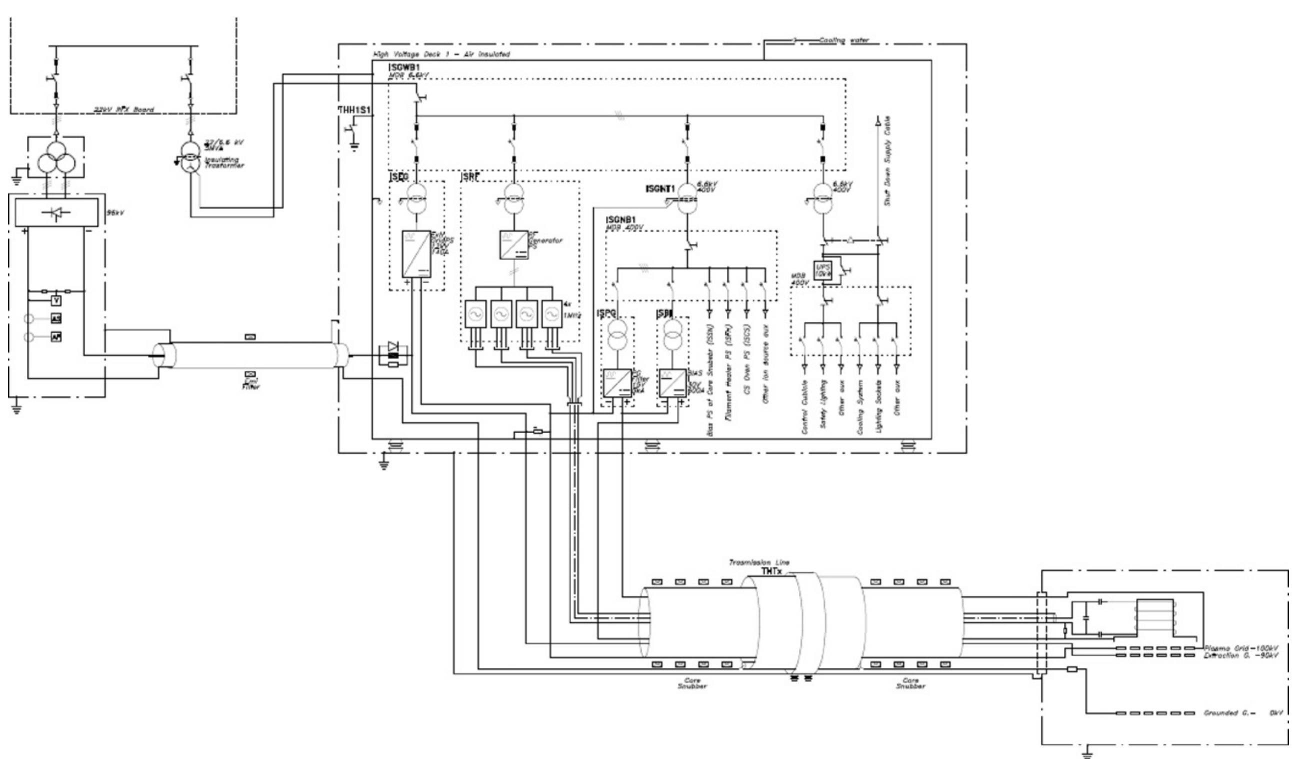

Fig. 7. The electrical scheme of the power supplies.

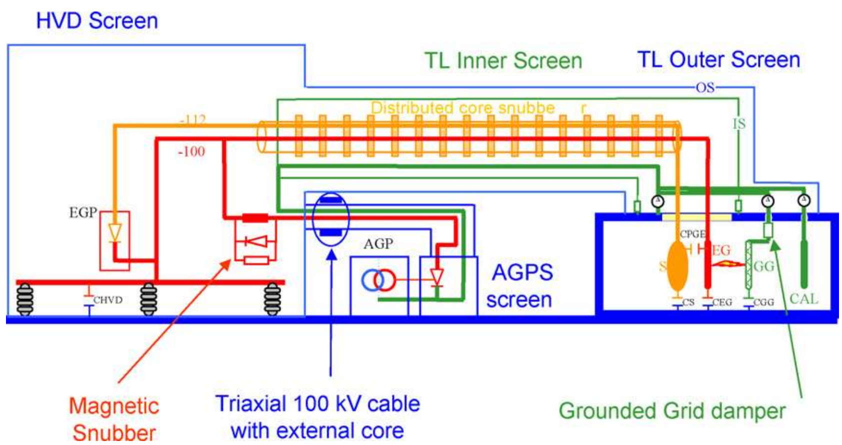

Fig. 8. The protection concept to reduce the breakdown effects (HVD is the high voltage deck, AGPS is the acceleration grid power supply, TL is the transmission line).

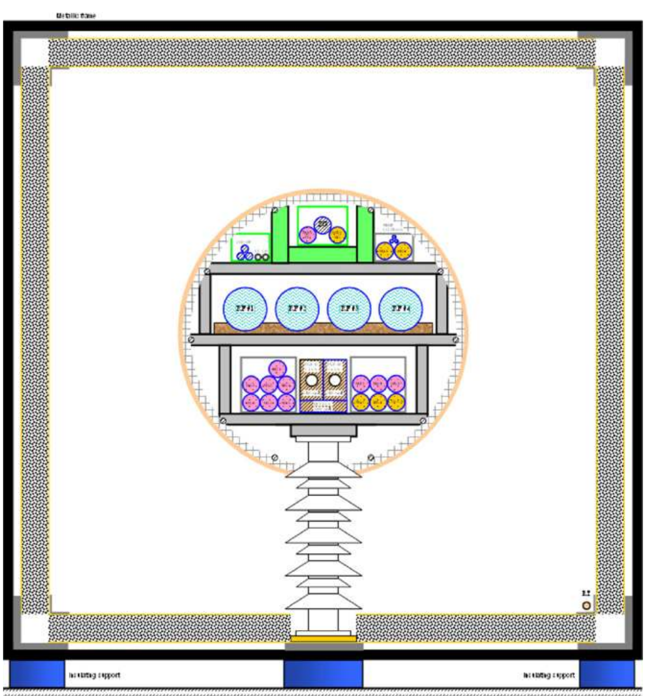

Fig. 9. The transmission line typical section.

possible to the plasma grid where the negative ions are produced and then extracted.

The low voltage accelerator will allow the characterization of the beam properties and in particular the beam uniformity.

Two beam dumpers are presently foreseen, one passively cooled made by graphite able to operate only for short pulses (maximum pulse length less than 10 s) that could supply detailed information on the beam footprint.

A stationary beam dumper actively cooled will be thermally monitored to have stationary global information on the whole beam.

Finally visual inspection of the source and of the grids is envisaged to monitor the electrical and thermo-mechanical behaviour of the source components.

9. Conclusions

The design of the ITER full size negative ion source prototype for the neutral beam injectors is under finalization and it is foreseen to start the call for tender action by the autumn 2008, in parallel with the establishment of the new buildings to host the source prototype and later on the ITER 1 MV prototype injector in Padova.

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References

[1] W. Kraus, P. McNeely, E. Speth, B. Heinemann, O. Vollmer, R. Wilhelm, Development of large radio frequency negative-ion sources for nuclear fusion, Review of Scientific Instruments 73 (2002) 1096–1098.
[2] E. Speth, H.D. Falter, P. Franzen, B. Heinemann, M. Bandyopadhyay, U. Fantz, W. Kraus, P. McNeely, R. Riedl, A. Tanga, R. Wilhelm, Development of a RF source for ITER NBI: first results with D-operation, Fusion Engineering and Design 74 (2005) 279–282.
[3] P. Franzen, H.D. Falter, E. Speth, W. Kraus, M. Bandyopadhyay, A. Encheva, U. Fantz, T. Franke, B. Heinemann, D. Holtum, C. Martens, P. McNeely, R. Riedl, A. Tanga, R. Wilhelm, Status and plans for the development of a RF negative ion source for ITER NBI, Fusion Engineering and Design 74 (2005) 351–357.
[4] P. Franzen, H. Falter, B. Heinemann, Ch. Martens, U. Fantz, M. Berger, S. Christ-Koch, M. Fröschle, D. Holtum, W. Kraus, P. McNeely, R. Riedl, R. Süss, S. Obermayer, E. Speth, D. Wünderlich, RADI—a RF source size-scaling experiment towards the ITER neutral beam negative ion source, Fusion Engineering and Design 82 (2007) 407–423.
[5] D. Marcuzzi, P. Agostinetti, M. Dalla Palma, H.D. Falter, B. Heinemann, R. Riedl, Design of the RF ion source for the ITER NBI, Fusion Engineering and Design 82 (2007) 799–805.
[6] D. Marcuzzi, M. Dalla Palma, M. Pavei, B. Heinemann, W. Kraus, R. Riedl, Detail design of the RF Source for the 1 MV Neutral Beam Test Facility, this conference.
[7] R. Nocentini, R. Gutser, B. Heinemann, M. Froschle, R. Riedl, Plasma grid design for optimized magnetic filter field configuration for the NBI test facility ELISE, this issue.
[8] M. Recchia, A. Zamengo, W. Krauss, M. Bigi, C. Martens, V. Toigo, Electrical and thermal analyses for the radio-frequency circuit of ITER NBI ion source, this issue.
[9] M. Bigi, A. De Lorenzi, L. Grando, K. Watanabe, M. Yamamoto, A model for electrical fast transient analyses of the ITER NBI MAMuG accelerator, this issue.

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