

Design integration of SINGAP accelerator and RF source in the ITER NB injector

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Abstract— The paper deals with the design integration of two alternative solutions for the negative ion source and accelerator of the ITER Neutral Beam (NB) injectors. The first alternative concerns the new 1 MV accelerator, named SINGAP, which has a single acceleration step instead of the five steps of the reference design. The second modification introduces a radio frequency (RF) negative ion source replacing the traditional filament solution. Design criteria, solutions and critical issues are presented in the paper.

Keywords: injector; negative ions; ion source; accelerator

I. INTRODUCTION

The reference design of the ITER Neutral Beam injector foresees a filament ion source and a Multi Aperture Multi Grid (MAMuG) accelerator with five acceleration stages of 200 kV [1]. The main reason for this choice is the previous experience on the existing injectors with acceleration voltages up to 500 kV, but the specific requirements for ITER NB injectors in terms of availability, maintenance, beam aiming and steering, would advise for different solutions having significant advantages from an engineering point of view. After a thorough revision of the present reference design the alternatives of a radio frequency (RF) ion source [2] and a SINGLE Aperture - SINGLE GAP (SINGAP) accelerator [3] have been considered for the ITER NB injector. Aim of these activities is to eventually compare the different solutions and to make a clearly justified choice for the final design. The two design solutions presented in the following sections consider both the arc driven and the RF sources integrated in the injector with a SINGAP accelerator. The complete assembly of the system with indication of the main components is shown in figure 1 for the arc driven source case.

II. HIGH VOLTAGE BUSHING

The 1 MV High Voltage (HV) bushing, which consists in a HV feedthrough for all the electrical bus bars and the water cooling tubes of both ion source and accelerator, acts as a barrier between the gas insulated HV line and the ITER primary vacuum [1].

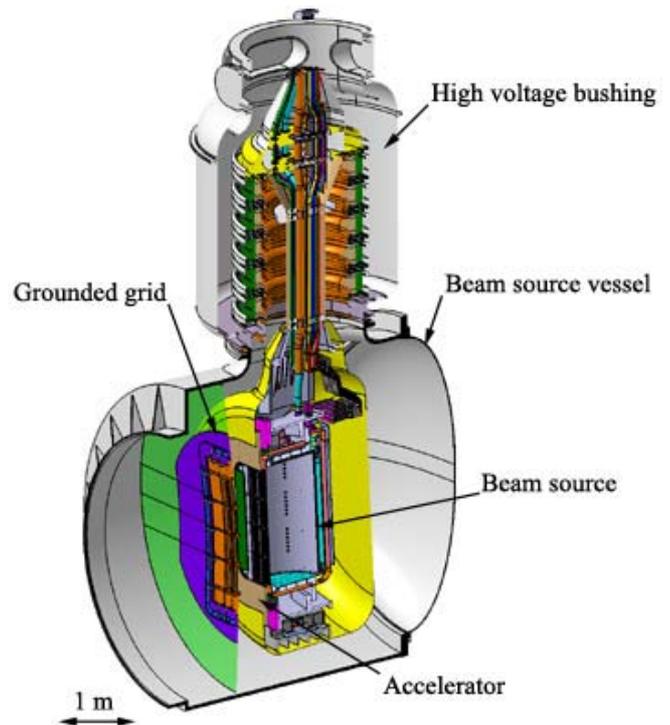


Figure 1. Section view of the HV bushing, beam source and accelerator in SINGAP configuration.

The new design of the HV bushing consists in the adaptation of the reference design to the SINGAP alternative concept. The inner 1 MV screen (High Voltage Screen, HVS) is deputed to sustain the beam source, whose dead weight is then supported by the bushing. Also the coolant lines of the pre-acceleration grids have been added inside the HVS [4].

The 1 MV insulation is still achieved by means of five stages, each composed of a mid flange and an inner and outer insulating ring, whose candidate materials are alumina (Al_2O_3) or C221 steatite (Magnesium silicates), and fiber reinforced plastic, respectively. The inter-space between the two rings is filled with nitrogen at 1.0 MPa, while the volume outside the outer ring and inside the bushing vessel is filled with SF_6 at 0.6 MPa.

FE electrostatic analyses have been carried out to optimize the new design with particular attention to the shape of the electrostatic screens and conductive structures. FE mechanical analyses have been also carried out considering operational and testing load cases. Details on the analyses and design solutions can be found in [4].

III. ARC DRIVEN SOURCE

The integration of the SINGAP 1 MV accelerator [3] with the arc driven ion source, that is the source in ITER reference design [1], has led up with a deep revision of the extractor which is composed by the plasma grid, the extraction grid, and their support structures. Furthermore a complete new design of the pre-acceleration grid has been carried out. The fixing systems of the grids have been developed to allow free isostatic thermal expansions.

The plasma, extraction and pre-acceleration grids have been designed on the basis of the results of beam optic calculations [5]. The reliability of the grids subjected to steady state and cyclic heat loads, has been verified with detailed thermo-mechanical analyses.

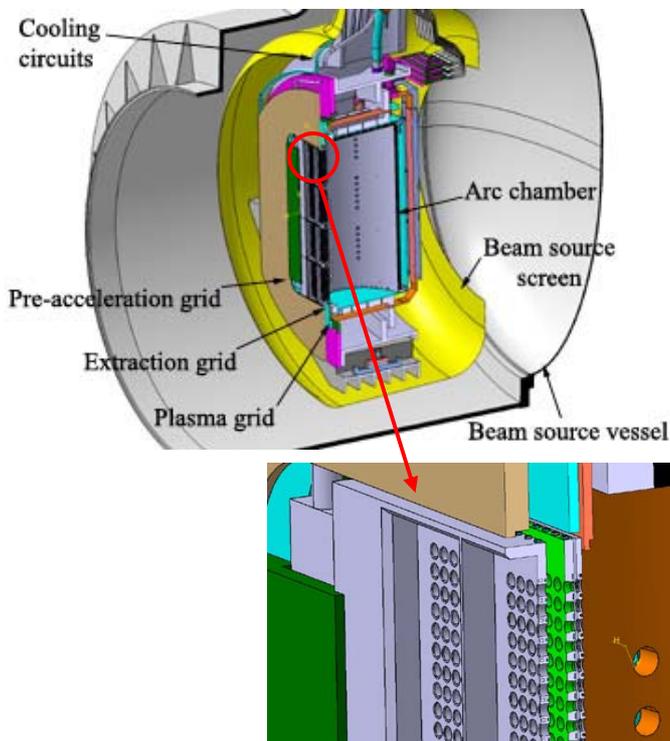


Figure 2. Plasma, extraction, and pre-acceleration grids in SINGAP accelerator.

As shown in figure 2 and table I, the SINGAP concept foresees, starting from the arc chamber, a plasma grid (at 1 MV reference potential) followed by the extraction grid (at relative potential of 6 kV) and the pre-acceleration grid (at 40 kV). The distances between arc chamber and plasma grid, and between the grids are, in order, 30, 3, and 20 mm.

The arc chamber and each grid are actively cooled by demineralized water flowing in independent hydraulic circuits.

For the extraction and pre-acceleration grids the cooling pipes have also the function to close the electrical circuits, while for the plasma grid and the arc chamber specific electrical bus bars are foreseen. The main hydraulic parameters of the circuits are presented in table I. The coolant inlet pressure of 2 MPa is fixed on the basis of the pressure drops in the cooling circuits.

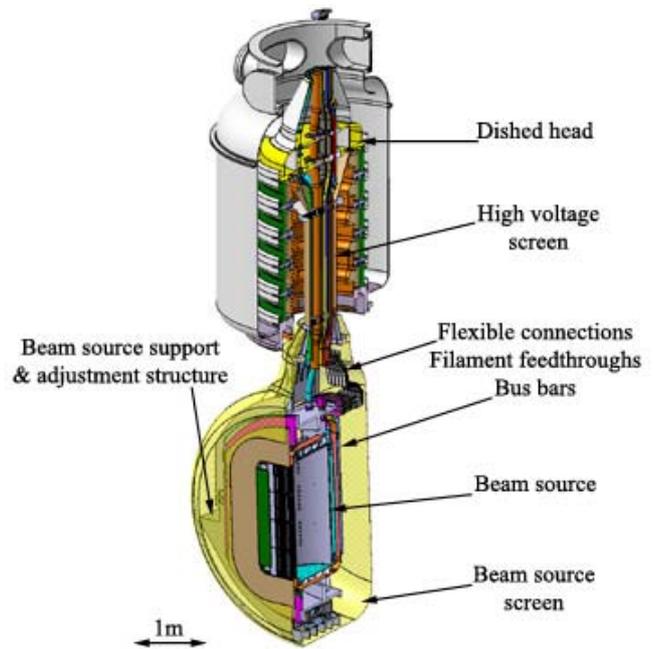


Figure 3. Beam source sustained by the high voltage screen of the bushing.

The beam source support and adjustment structure is directly connected to the bushing central tube, which is linked to the dished head, as shown in figure 3. The bushing central tube has the functions of beam source support and electrostatic high voltage screen. The positions of filaments feedthroughs, bus bars, flexible connections and the geometry of the arc chamber support structure have been modified to allow the integration of the beam source support structure. A new beam source screen has been designed to satisfy the electrostatic requirements.

TABLE I. MAIN PARAMETERS OF THE ARC DRIVEN SOURCE COMPONENTS

| Parameters | Components | | | |
|---------------------------------|-------------|-------------|-----------------|-----------------------|
| | Arc chamber | Plasma grid | Extraction grid | Pre-acceleration grid |
| Material | OFHC copper | Mo | OFHC copper | OFHC copper |
| Voltage [kV] | -1000 | -1000 | -994 | -960 |
| Coolant inlet temperature [°C] | 20 | 55 | 55 | 55 |
| Coolant outlet temperature [°C] | 40 | 88 | 140 | 62 |
| Coolant velocity [m/s] | 2.0 | 4.0 | 2.0 | 2.0 |

IV. RF DRIVEN SOURCE

The RF source designed for the ITER NB injector consists of a main case (1.82 m by 0.86 m, internal chamber dimensions), eight RF drivers and all the relevant auxiliary systems (see figure 4).

Four identical electric circuits include a series of two RF coils wound on two RF drivers, a variable capacitor and a fixed capacitor in parallel (see figure 5). An alumina plasma-spray layer is foreseen on the outside of the copper conductor of the RF coils for insulation purposes, considering vacuum and radiation material compatibility.

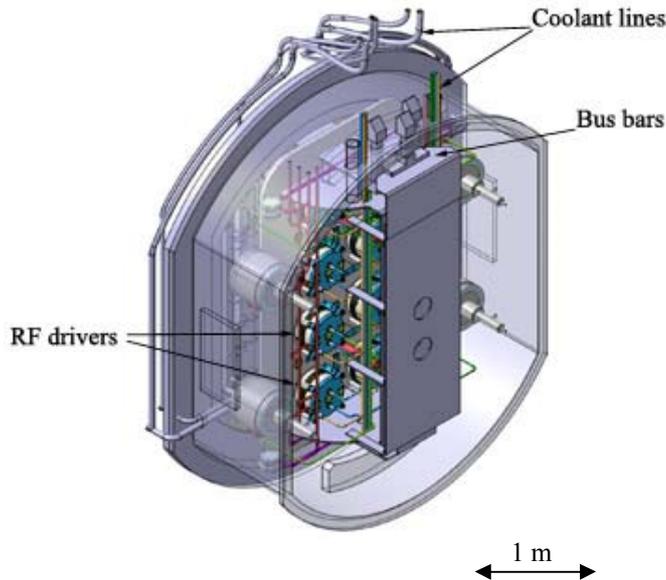


Figure 4. RF source assembly.

Three separate hydraulic circuits exhaust the heat from the components under operational conditions. The main case, welded and internally copper plated, needs an accurate cooling system to allow for an effective temperature control, to get an optimal distribution of the Caesium layer inside the expansion chamber.

The drivers have actively cooled circuits for the RF coils and for the Faraday Shield (FS), particularly critical for the large power density deposited and the small space available for the cooling channels.

Fully electrodeposited copper FSs are foreseen, each of them with 18 coolant loops in parallel, $3 \times 1 \text{ mm}^2$ cross-section flow area and 4 m/s water velocity.

The support structure designed for the arc driven source has been slightly modified in order to support the main case and the capacitors. Changes of the HV bushing feedthroughs are foreseen for the RF power supply conductors.

The main advantage of the RF source with respect to the arc driven one is the absence of filaments maintenance, but a critical issue that has to be faced up is the need of tuning for matching of the RF variable capacitors.

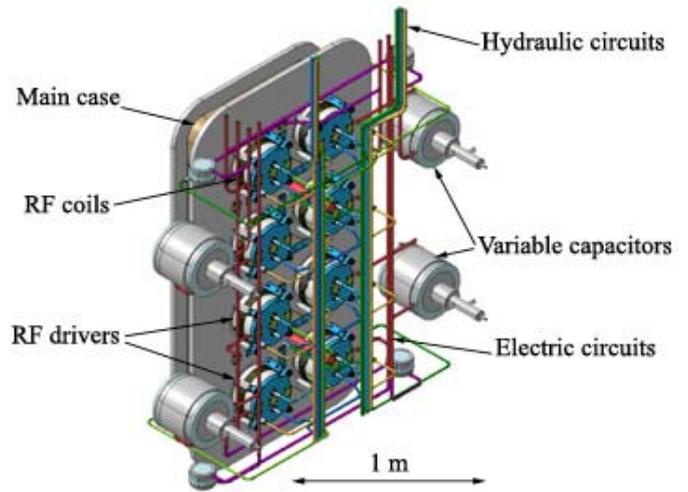


Figure 5. RF source services.

V. GROUNDED GRID

The SINGLE Aperture - SINGLE GAP concept (SINGAP) accelerates the ions to high voltage in one single step of 1 MV [3]. Instead of having a classic multi-aperture exit grid, a grounded grid with only 16 large apertures is used. These 16 apertures (hyperapertures) correspond to the 4 channels per 4 segments in the pre-accelerator (see figure 6).

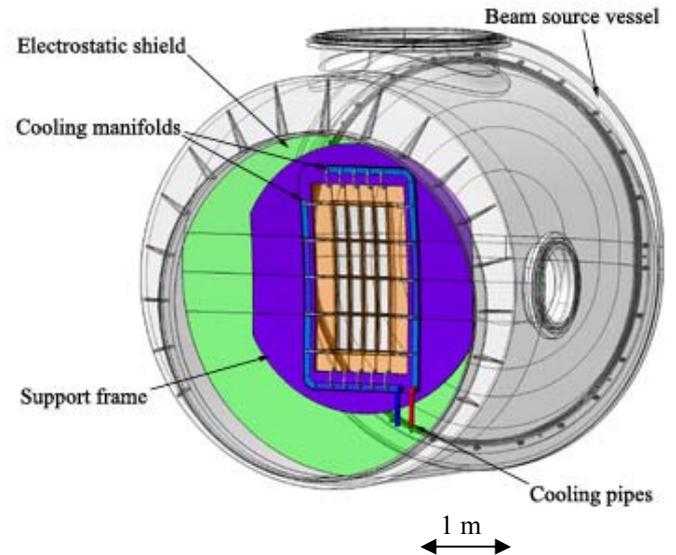


Figure 6. Grounded grid assembly.

A. Beam optics and design requirements

Thick edges (“kerbs”) are foreseen around the apertures on the upstream side of the grid to provide an additional focusing force to counteract the beamlet-beamlet interaction. In this way, the $4 \times 4 \times 80$ pre-accelerated beamlets from the pre-acceleration grid are merged into 4×4 “hyperbeamlets”.

The grounded grid is “V” shaped along a vertical cross section, as shown in figure 7. This design provides vertical beam groups steering.

The grounded grid has to be shifted vertically of ± 15.4 mm around its nominal position to achieve the required transmission and beam on/off axis steering [1].

B. Grounded grid assembly

The grounded grid, made of OFHC Cu, is fixed to a stainless steel support frame by means of two pins and an anchor plate.

The grounded grid assembly is positioned 350 mm downstream of the pre-acceleration grid and is supported by the beam source vessel. A remotely operated system is foreseen for beam steering via vertical adjustment of the grid position.

A stainless steel electrostatic shield is foreseen around the support frame in order to guarantee the voltage hold off in the vacuum insulation.

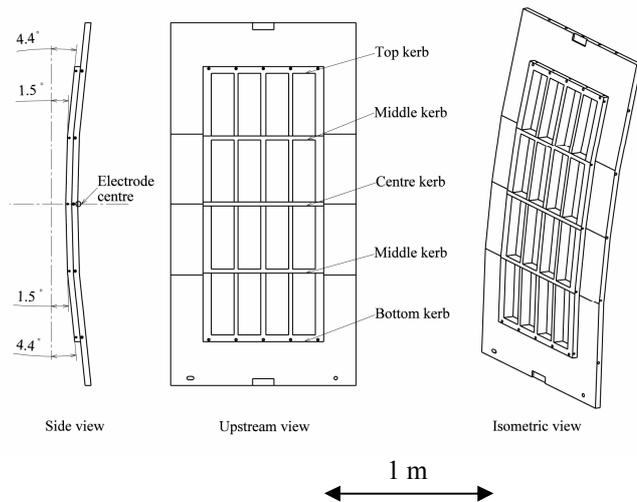


Figure 7. Views of the grounded grid.

C. Hydraulic design and thermo-mechanical behaviour

An active cooling circuit has been developed for the grounded grid and its support frame. The coolant (demineralized water) flows in the grounded grid through couples of cooling channels in each kerb, both vertically and horizontally. The inlet-outlet (I/O) water feeding connections are located on the lower region of the beam source vessel on the same side foreseen for the water I/O headers of the beam line components [1].

TABLE II. HYDRAULIC PARAMETERS OF GROUNDED GRID COOLING CIRCUITS.

| Flow rate [kg/s] | Coolant velocity [m/s] | Cooling channels diameter [mm] | Convection coeff. [W/(m ² K)] |
|------------------|------------------------|--------------------------------|--|
| 3.0 | 2.0 | 10 | 15000 |

The hydraulic parameters shown in table II assure the grid temperatures presented in table III.

The thermo-hydraulic assessment has been carried out by means of analytical models. Numerical nonlinear analyses are

ongoing to verify the actual thermo-mechanical response of the grounded grid in operating conditions, considering both steady state and transient cyclic heat loads [6].

TABLE III. COOLANT AND GROUNDED GRID TEMPERATURES.

| Temperatures [°C] | | Average power density 60 W/cm ² | Bottom horizontal kerb 120 W/cm ² |
|--------------------|--------------------|--|--|
| Coolant (Water) | Inlet | 55 | 55 |
| | Outlet | 63 | 71 |
| | Average | 59 | 63 |
| Grounded grid (Cu) | Inner wall channel | 79 | 101 |
| | Exposed surface | 103 | 147 |
| | Cu bulk | 91 | 124 |

VI. CONCLUSIONS

An alternative design of the ITER NB injector has been developed, considering both SINGAP accelerator and RF ion source. Electrical, hydraulic and thermo-mechanical analyses demonstrated the feasibility and reliability of the proposed design. A thorough comparison with the ITER reference design can be now carried out to eventually identify the preferred design configuration.

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