Technological aspects of the different schemes for accelerator and ion source of the ITER Neutral Beam Injector

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Abstract

Each Injector of the ITER Neutral Beam system will deliver a power up to 16.5MW and guarantee steady operation for one hour in H or in D. To fulfil these requirements, the Neutral Beam Injector (NBI) must provide a current up to 40A of negative ions accelerated up to 1MV. At present two different schemes for the ion source and the accelerator are under investigation. In the framework of the European tasks in preparation for the ITER construction, the design of the NBI system based on the alternative concepts for these components has been performed including the related Power Supply, 1 MV Transmission Line and Bushing. In this paper the activities performed by Consorzio RFX on this area are presented and the main achievements discussed. In particular the design of the components for the alternative concepts are compared with those of the reference NBI design and the main technological aspects outlined and discussed.

Introduction

The Neutral Beam Injection (NBI) is one of the Heating and Current Drive systems foreseen for ITER. The NBI is based on the acceleration of Hydrogen or Deuterium negative ions up to 1 MV. Two injectors delivering a total power up to 33 MW are foreseen with the possibility of an additional third injector [1,2]. The beam energy of 1 MeV is required in order to penetrate and heat the plasma core. At this level of energy efficient neutralization can be achieved only by negative ions. The NBI must operate initially in Hydrogen and then and for most of its lifetime in Deuterium. To achieve the required power during Deuterium operations, a total current of 40A (corresponding to a current density of 200 A/m^2) has to be delivered by the ion source. According to these requirements a reference design for the NBI based on an arc driven source and an electrostatic multi grid accelerator (MAMuG) has been developed. Producing and accelerating negative ions at the required current and energy and for a pulse length up to one hour is a challenging task and represents a major step forward in NBI technology particularly because the NBI must guarantee reliable operation for a pulse length up to one hour. In Europe an extensive R&D is devoted to develop and test alternative concepts for ion source and accelerator [3]. At IPP Garching (Germany) R&D is in progress on an alternative concept for the ion source based on radiofrequency (RF). Target current densities in H and D have been already achieved and work is in progress to extend the pulse length and the extraction area to values relevant for ITER [4]. At CEA Cadarache (France) the accelerator alternative concept for a single aperture, single gap (SINGAP) system has proved high voltage holding and beam optics as required in ITER [5]. In recent years an extensive activity promoted and co-ordinated by EFDA and carried out by six EU Associations (CEA,CIEMAT,FZK,IPP, ENEA-RFX and UKAEA) has been performed in Europe aimed to revise and update the NBI design for ITER and to bring the design of the RF ion source and SINGAP accelerator to the same level of detail of the arc driven ion source and MAMuG accelerator in the reference design. The technological feasibility has been also assessed considering all the combinations of ion source and accelerator concepts. In particular Consorzio RFX, in the framework of the European activities for ITER, has been working on the revision of the ITER Neutral Beam design since 2004, addressing the design and technological feasibility of the different schemes for power supply system, transmission line, bushing, ion source and accelerator. In particular aspects concerning the mechanical compatibility, cooling requirements under high heat fluxes and electrical insulation have been addressed. In this paper the activities performed by Consorzio RFX will be presented with special emphasis to the most relevant technological issues.

Ion source

Both ion sources have been considered: the arc driven source has been integrated with the SINGAP accelerator, while the RF driven source has been newly designed. Both sources consist of a main chamber facing the plasma grid. The plasma is generated in the RF source by eight RF drivers while in the arc driven source by 72 tungsten filaments. In Fig.1 the designs for the RF and of the arc driven ion source are shown. Overall dimensions are similar, and both sources can be housed in the same quasi-cylindrical support structure. Therefore the ion source choice has no influence on the interface with the rest of the injector, apart from the required specific services. In both sources ions are extracted through a system of two grids at different potentials that also filter electrons from negative ions by means of magnetic fields created by currents flowing in the first grid (plasma grid) and permanent magnets embedded in the second grid (extraction grid). Plasma and extraction grids are similar for RF or arc driven sources. The plasma grid is made of Molybdenum with brazed copper pipes and stainless steel thermal bridges for active cooling. The extraction grid is fabricated by electro-deposition of pure copper with embedded Samarium-Cobalt (Sm_2Co_{17}) permanent magnets and horizontal cooling channels between adjacent aperture rows. An effective cooling of the extraction grid is fundamental to limit the grid temperature well below 300°C during operation, to avoid the demagnetization of magnets and to limit the thermal expansions and bowing of the grid, that could lead to unacceptable misalignments between correspondent apertures of plasma and extraction grids. As the requirements for apertures alignment are quite severe (the maximum allowable misalignment for thermal expansions is 0.2 mm) an effective cooling system is required for the extraction grid, with active control of water inlet temperature and flow rate. An optimized design of the grids has been obtained as a compromise between the conflicting requirements of efficient cooling and good beam optics [6]. Caesium injection in the discharge chamber has been proved very effective in both sources in increasing the negative ion yield as , once deposited, it lowers the work function of the surface. However excessive consumption and accumulation of caesium on the chamber surface can decrease the ion production efficiency, and on the insulators surfaces may produce degradation of their voltage holding capability. Therefore frequent cleaning is needed, requiring the removal of the ion source. Since the major drawback of arc driven source is the need of frequent maintenance operations to replace the tungsten filaments, an alternative design of the filament cassette cooling system [7] was studied in order to simplify the connections and to speed up the RH operations for filaments replacement.

Accelerator

The acceleration process is performed in an electrostatic accelerator. The reference design, based on a multi-aperture multi-grid (MAMuG) accelerator, consists of 5 grids forming 5 acceleration stages of 200 keV. An alternative design, the SINGAP concept, has been proposed where the negative ions are extracted and pre-accelerated to about 30-40keV and acceleration to 1 MeV is accomplished in one step over a distance of 350 mm. This concept is attractive as it offers significant advantages, such as simplification of the high voltage transmission line and bushing and easier horizontal and vertical beam steering. The five acceleration grids in MAMuG are similar to the extraction grid, made of electrodeposited copper with horizontal cooling channels. All the grids in MAMuG are composed by 4 horizontal segments, individually adjusted to obtain a V-shaped geometry of the grid in the vertical direction. This provides the vertical aiming of the beam from each segment. On the contrary plasma, extraction and pre-acceleration grids in SINGAP are plane, but still composed by 4 separate segments to limit thermal expansions, to get easier and more precise manufacturing and the possibility to replace one module of the grid in case of damage. The pre-acceleration grid in SINGAP configuration is similar to the MAMuG acceleration grids, with the addition of wells on the downstream surface and embedded magnets both along horizontal and vertical directions. The SINGAP grounded grid, made of OFHC copper, has 16 large rectangular apertures, a V-shaped geometry in the vertical cross section and thick kerbs where channels for cooling water are drilled. The design of the grids has been carried out with an iterative process aiming to achieve an optimized solution that fulfil the conflicting requirements coming from beam optics (thin grids, large magnets and apertures) and cooling needs (relatively large channels close to the heated surface). The acceleration grids are subjected to relatively large power densities applied on the upstream surface in small areas around the apertures, where stripped electrons hit the copper surface. Then each grid expands, bows and is subjected to thermal stresses mainly around the apertures where large temperature gradients occur. The heat load on each grid in MAMuG configuration ranges from 0.2 MW (for the grounded grid) to 1MW (for the third acceleration grid) while the heat loads on the grids in SINGAP configuration are tens of kW for pre-acceleration grid and about 200 kW for the grounded grid. Present results indicate that an active control of grids temperature by means of adjustment of water inlet temperature and flow rate is mandatory.

Bushing

The 1MVbushing consists of a high voltage (HV) feedthrough for all the electrical bus bars and the water cooling lines of both the ion source and the accelerator. It also acts as a barrier between the SF_6 insulated HV line and the ITER primary vacuum. Therefore it features a double barrier obtained by means of two insulating rings. The candidate material for the outer ring is fibre reinforced plastic (FRP), sealed by elastomer o-ring. The alumina inner ring is brazed together with two small bake-up rings on two metallic plates. The new design based on the SINGAP alternative concept has been worked out by modifying the reference design for MAMuG accelerator and an arc driven source. In fig. 2 the designs developed for both accelerators are shown. The new design for SINGAP has led to a considerable simplification. In fact the structures needed to supply intermediate voltages have been removed and the source and the pre-accelerator assembly are sustained only from the HV bushing. By Detailed Finite Element analyses the electrostatic screens have been redesigned in order to reduce the electric field according to the design criteria. In addition, analyses have been carried out to evaluate the surface electric charging due to the application of dc voltage and the effect of Radiation Induced Conductivity on SF_6 gas and N_2 guard gas on voltage distribution along the Bushing [8]. Mechanical static analyses of the bushing demonstrated a sufficient strength and stiffness of the parts and assembly. On the other hand a significant step forward has been taken with the analyses carried out for the brazed joint, which can be used as the basis for future mechanical assessments assisting the necessary R&D phases. No show stoppers were identified in the adaptation of the reference bushing to the SINGAP configuration and, even better, most of the weaknesses of the MAMuG configuration have been removed. Finally it is worth observing that most of the optimizations and the design solutions carried out for the adaptation of the bushing to the SINGAP alternative can be directly adopted also in the MAMuG configuration.

Transmission line

The reference design is based on a multipolar scheme for MAMuG concept. The major issue concerning the Transmission Line is the design of an effective insulating structure, based on SF_6 and epoxy resin spacers, at 1 MV dc, far beyond any present industrial application (below 500 kV). An alternative scheme has been proposed to replace the multipolar line with five (one per electrode) unipolar lines. The unipolar line design has been developed for the SINGAP concept and the design is shown in fig. 3. It is based on a coaxial scheme and is insulated in SF_6. Inside the inner conductor, water cooled copper busbars are installed to feed the ion source power supply. In particular the issue of the coolant under 1MV voltage has been addressed for SINGAP. The polarisation effects of the dc voltage on the insulating structure have been analysed, leading to special design of post and disk spacers [9].

Power supply system

The Power Supply (PS) system provides the High Voltage (HV) to the accelerator grids (AGPS) and supplies the ion source (ISPS) and the auxiliary components. The studies made in this field were addressed at the assessment of the power supply schemes for the different configuration of the accelerator (MAMuG and SINGAP) and of the ion sources (arc an RF driven) and at the identification of the main technological issues still open. Modifications to the reference design have proposed, as an alternative design for the ion source power supply [11], the analyses of the passive and active protection of the load in case of grid breakdown [12], the PS design for the RF driven ion source [13] and the layout assessment for the NB Injector test facility. The Acceleration Grid Power Supply (AGPS) feeds the acceleration grids in gaps of 200kV each; it is based on five series connected stages of 200kV dc output (fig. 4). The main electric data are summarized in table 1The main technological issue of the AGPS step-up transformers is represented by the -1MV dc isolation transformer due to the very high insulating voltage (1 MV dc) and ac secondary voltage (about 160 kV ac) and the square waveform operation at frequency (150-400 Hz) higher than line frequency. Feasibility assessment was made in collaboration with industry aimed at verifying the possibility to build these transformers. The results of these studies proved the feasibility of the five stages design while, for SINGAP, the conclusion was that a single or two stages solution appears not feasible, because of the combination of large winding voltage and large insulation to ground, and at least three stages are necessary. As for the load protection in case of grid breakdown; the strategy devised consists in switching off as fast as possible all the active power supplies, in optimizing the filter and stray capacitance placed downstream of the power supplies and in introducing additional passive protection devices so as to limit the energy delivered to the fault [12]. Studies were carried out on the passive protection devices and in particular on the core snubber design and on the dc filter design so as to achieve the best compromise between the fulfilment of the requirement on the ripple amplitude and the limitation of the energy delivered in case of grids breakdown. The Ion Source Power Supply (ISPS) is composed of five independent circuits: arc, extraction grid, filaments, bias and plasma grid filters referred at the high potential of -1MV. The approach followed in the ITER reference design was to split these power supplies into a ground-referred section providing for the voltage regulation and fault protection and a section referred at the -1MV voltage. Insulating transformers fed, via a high voltage transmission line, the second section, installed in an SF_6–insulated deck which mainly contained step-down transformers, output diode bridges and passive filters. An alternative design approach for the ISPS has been proposed [1], which is based on the installation of all the power supply system in an air-insulated accessible deck, like a Faraday cage, at -1MV to ground, fed by only one 50Hz transformer insulated for -1MV. This solution allows the reduction of insulating transformers from 8 to 1 and assures the full accessibility to all the ISPS devices, thus guaranteeing easier setting-up, testing, maintenance, and implementation of further modifications and upgrades.

Summary and conclusions

The design of the alternative concepts of ion source and accelerator has been developed to the same level of detail of the reference design for both mechanical and electrical aspects. The main technological issues common or specific of each concept have been identified. The design activity indicates that all combinations of ion source and accelerator are technologically feasible, their complexity depending on the different concepts. The results of this design activity are complementary to those of the European R&D in progress and are expected to contribute to the decision about the ion source and accelerator concepts to be adopted in the Neutral Beam injectors for ITER.

Acknowledgments

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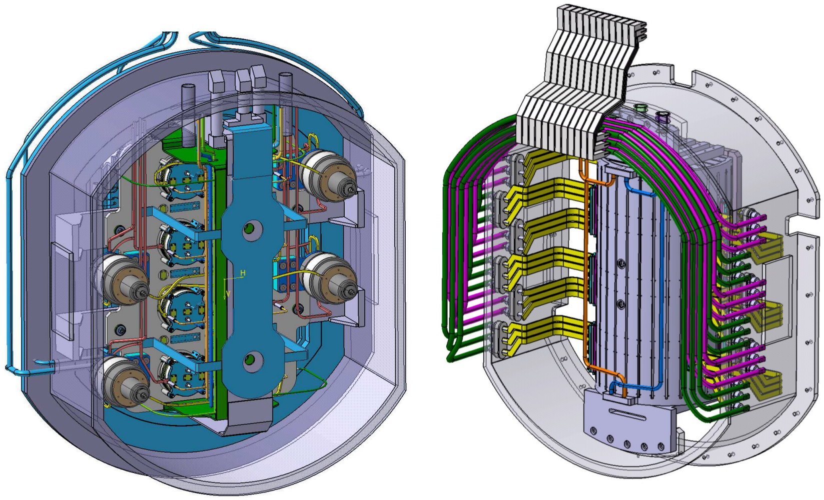
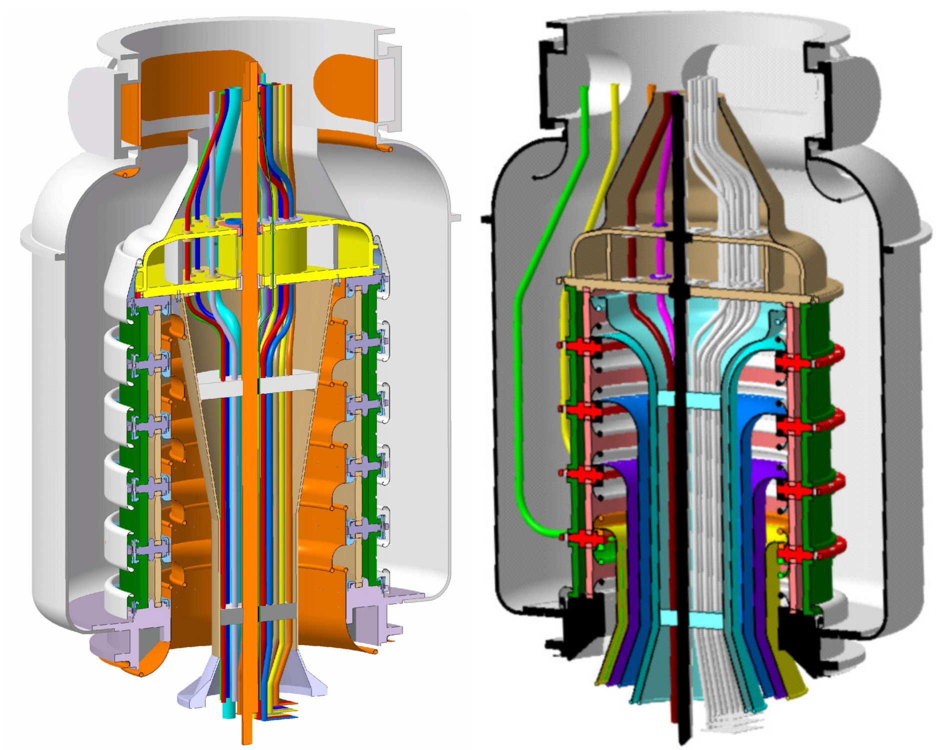
Table 1: Parameters of the Acceleration Power Supply in case of MAMuG configuration

Parameter	**Value**
Main supply voltage/current	-1000 kV / 59 A
Grid 1 voltage/current	-800 kV / 7 A
Grid 2 voltage/current	-600 kV / 6 A
Grid 3 voltage/current	-400 kV / 3 A
Grid 4 voltage/current	-200 kV / 3 A
Current at ground level	40 A
Voltage range of main power supply grid	40 % - 100 %
Voltage control accuracy	± 2 % of the max. value
Max. voltage ripple	± 5 % of the max. value



(a) (b)

Fig. 1 Design of the (a) RF and (b) arc driven ion source (rear view)



(a) (b)

Fig 2 1MV Bushing for (a) SINGAP and (b)MAMuG accelerators

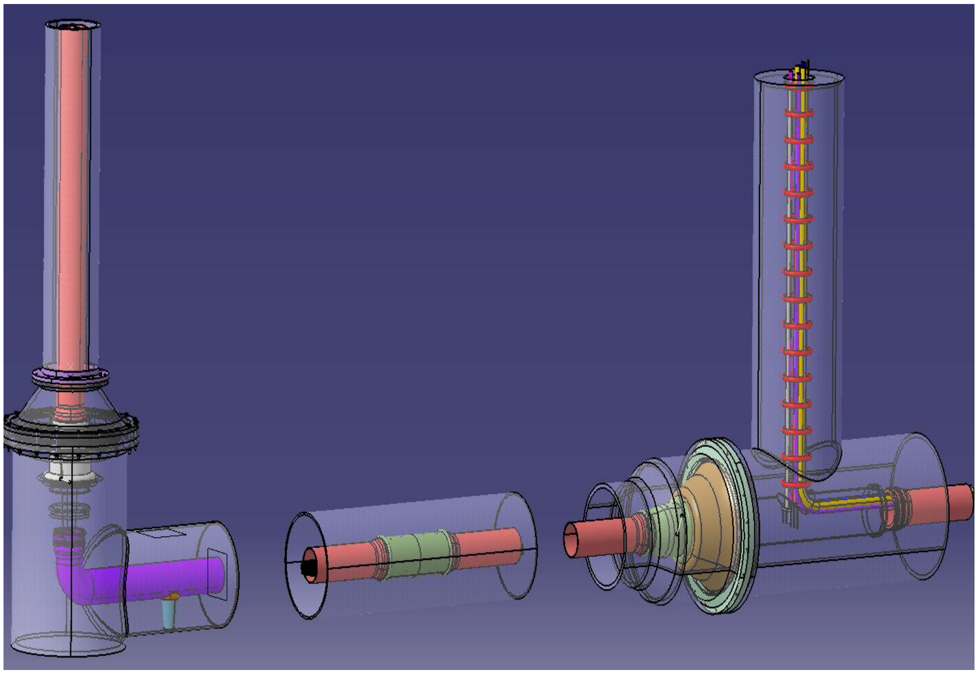


Fig. 3 Transmission line for SINGAP accelerator

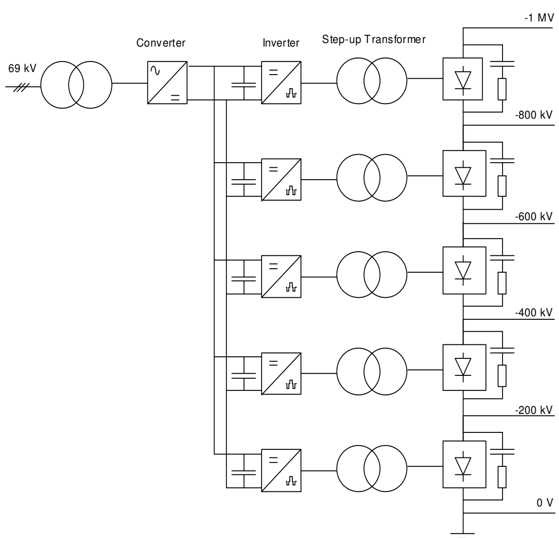


Fig.4 Layout of the AGPS based on five 200kV stages