The Development of the RF Driven Negative Ion Source for Neutral Beam Injectors[a)]

W. Kraus[b)], U. Fantz, P, Franzen, M. Fröschle, B. Heinemann, R. Riedl, and D. Wünderlich

Max-Planck-Institut für Plasmaphysik, EURATOM Association, 85748 Garching, Germany

(Presented XXXXX; received XXXXX; accepted XXXXX; published online XXXXX)
(Dates appearing here are provided by the Editorial Office)

Large and powerful negative Hydrogen ion sources are required for the neutral beam injection systems (NBI) of future fusion devices. Simplicity and maintenance free operation favors RF sources, which are developed intensively at the Max-Planck-Institut für Plasmaphysik (IPP) since many years. The negative Hydrogen ions are generated by Caesium enhanced surface conversion of atoms and positive ions on the plasma grid surface. With a small scale prototype the required high ion current density and the low fraction of co-extracted electrons at low pressure as well as stable pulses up to one hour could be demonstrated. The modular design allows extension to large source dimensions. This has led to the decision to choose RF sources for the NBI of the international fusion reactor ITER. As an intermediate step towards the full size ITER source at IPP the development will be continued with a half size source on the new ELISE testbed. This will enable the first time to gain experience with negative hydrogen ion beams from RF sources of this dimensions.

I. INTRODUCTION

Compared to filament based ion sources the RF sources have the advantage of simplicity, reliability and longer lifetime. This has led to a variety of applications in industry and science. One of it are ion thrusters for orbital and attitude control of satellites[1] which use rare gas ions as propellant. Based on the experience with these sources in the late 70ties a development program was launched at the University of Giessen to investigate the applicability of RF driven sources for neutral beam injection systems[2]. The goal was to replace the bucket sources or duopigatrons which were used in the NBI systems by then. Several small circular sources were tested with Hydrogen and RF powers up to 20 kW. The results were so encouraging that a large RF source was designed, powerful enough for the NBI of the ASDEX Upgrade Tokamak at IPP Garching[3]. The necessary large step in RF power to more than 100 kW succeeded and so four of these sources are in operation in the 2nd beam line since 1997, delivering positive ion currents of 90 A or 65 A in Hydrogen or Deuterium respectively[4]. By now no malfunction occurred and no maintenance was needed.

However, in future large fusion machines the neutral beam systems will be based on negative hydrogen ions. The reason is the much higher neutralization efficiency at high beam energy, which is required due to the larger plasma dimensions and for current drive. RF sources are even more attractive for NBI in these machines, because the, in principle, maintenance free operation is of particular importance in a radioactive environment, where maintenance and repairs have to be carried out by remote handling. An additional advantage is that the wall material can be chosen freely, which offers more experimental options for optimizing the surface production of negative ions than in filamented sources, where the inner walls are coated with tungsten.

In 1997 the investigation of RF driven negative ion sources for the NBI of ITER was started at IPP. The target values of the accelerated ion current density are 24 mA/cm^2 (H^-) and 20 mA/cm^2 (D^-) respectively[5] and a fraction of co-extracted electrons below 1. Further requirements are operation in long pulses up to 3600s and at low pressure of 0.3 Pa, the latter in order to limit the stripping losses in the extraction system. The ITER source will have giant dimensions (0.9 x 1.9 m^2) and produce a 1MeV- 40A beam in Deuterium. For the experiments at IPP a smaller source prototype of about one eighth of the size of the ITER source was used, the “type 6” source. The development was started with volume production of negative ions from vibrationally excited hydrogen molecules by dissociative attachment of electrons. But it turned out that in this way only a few mA/cm^2 were achievable at elevated pressure[6]. Caesium enhanced surface conversion of atoms and positive ions on the plasma grid increased the negative ion current considerably and reduced the fraction of co-extracted electrons in particular at low pressure. On a short pulse testbed BATMAN the ITER requirements could be satisfied for pulses up to 5 s[7]; on the long pulse testbed MANITU[8] stable H^- beams for up to 3600s could be demonstrated and so the RF source was chosen in 2007 for the reference design for the plasma generation in the ITER neutral beam system. The same RF source will be used in the diagnostic injector for ITER. This paper will review on source related issues of the source development.

[a)] Invited paper published as part of the Proceedings of the 14th International Conference on Ion Source, Giardini-Naxos, Sicily, Italy, September, 2011.

[b)] kraus@ipp.mpg.de

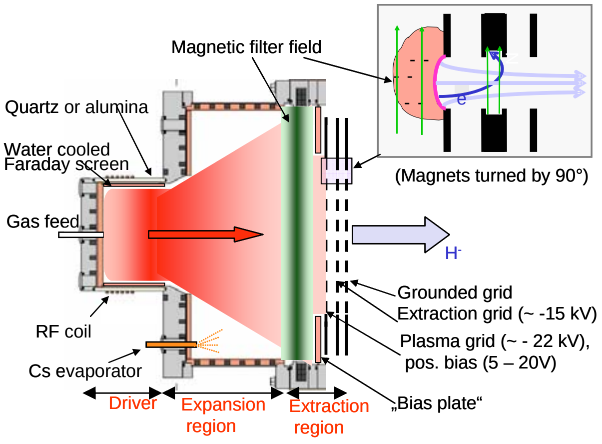

FIG. 1: Working principle of the prototype RF source

II THE PROTOTYPE RF SOURCE

A. Source design

Fig. 1 shows the design principle of the RF sources for negative ion production developed at IPP. The RF power is inductively coupled into a circular volume (“driver”), out of which the plasma is flowing into the main chamber. The main advantage of this concept is the modularity, which enables the extension to large sources. The ITER source will have eight of these “drivers”[18].

Due to the great distance of the plasma production volume to the plasma grid and magnetic filter field the electron temperature close to the plasma grid is reduced to about 1 eV[9], which reduces losses of negative ions by electron detachment.

The insulator cylinder of circular drivers can withstand atmospheric pressure and therefore enables the source operation in air. However, the operational experience showed that a vacuum or SF6 insulation of the RF coil is needed to avoid RF breakdowns at high power[8]. The driver diameter of the “type 6” source is 24.5 cm, the base area of the expansion chamber is 32 x 59 cm^2. Because an RF power of up to 120 kW is applied to the driver, a very high power density of 20 kW/l can be reached. In this range new effects like neutral depletion and saturation of the dissociation of the Hydrogen molecules are determining the plasma properties[9] (see below).

The insulator is made of alumina or quartz and has to be protected by an internal water-cooled copper Faraday shield. Exposed to a high flow of ions severe sputtering took place and copper was deposited onto the plasma grid. This affected the negative ion production in long pulses very much. Coating of the inner surfaces of the driver with Molybdenum solved the problem and increased the long pulse performance of the source considerably [11].

The “bias plate” is in principle an extension of the source walls, which covers the part of the plasma grid without extraction area and leads the source potential close to the extraction area. By applying a positive voltage to the plasma grid with respect to the bias plate the extended boundary layer between magnetic filter and plasma grid can be adjusted in a way that the current of co-extracted electrons is further reduced.

In the prototype source the magnetic filter field is generated by rods of permanent magnets, which are mounted in 30 cm distance from each other in a flange close to the plasma grid. Only a weak field penetrates into the driver, so that the plasma production is not affected. A plasma drift is caused by the filter field in the expansion chamber, which leads to an inhomogenous plasma density, which was measured 2 cm from the plasma grid[10]. The plasma drift changes direction when the polarity of the filter field is changed and depends strongly on the bias voltage. The extracted currents of H$^-$ ions as well as of the electrons, however, depend only weakly on the direction of the drift i. e. on the plasma densities[10]. The results indicate that the source performance is determined to a greater degree by the extended boundary layer close to the plasma grid.

The electrons are deflected out of the beam by small permanent magnets into grooves in the extraction grid. The maximal possible power load on the extraction grid limits the current of co-extracted electrons.

Because the Caesium vapor is released into the source by a nozzle in the back plate at the side of the driver the Caesium handling is determined by the very time-consuming distribution of the Cs onto the plasma grid. A more central position of the Cs-oven or a dispenser close to the plasma grid would facilitate this procedure.

B. Power supply

The RF power is coupled to the plasma by an RF coil of four to six turns which is supplied by a RF generator of 1 MHz via a matching network and a coaxial transmission line. The generators are self-excited oscillators with powers of up to 180 kW. A RF separation transformer enables to keep the transmission line and the generator on ground potential. At ITER such a transformer can not be used and so the power supply has to be on high voltage. Matching can be done either by a variable capacitor in the external matching circuit in series to the RF coil or by

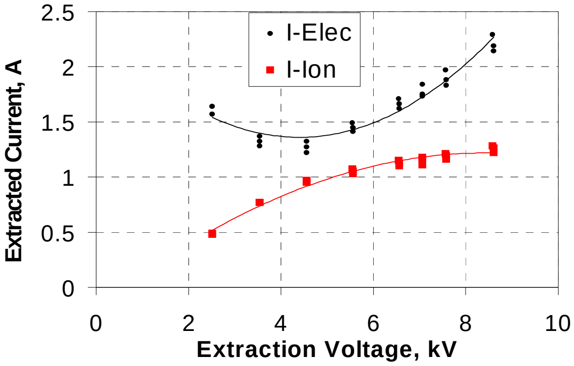

Fig. 2: Example of a voltage scan of the extracted currents at MANITU

changing the generator frequency[11]. The latter avoids remote controlled parts in the radioactive environment of the NBI cell.

C. Extraction system

Due to historical reasons the extraction systems of the IPP testbeds are designed for a perveance optimum at 6 kV. However, to operate at ITER parameters and to achieve higher ion currents an extraction voltage close to 10 kV is necessary. But with this extraction voltage the operation is under perveant, the electron current increases and the slope of the ion current decreases (see Fig. 2). The large testbed ELISE, which is currently under construction, will not be limited in this way.

III PRODUCTION OF NEGATIVE IONS

According to several modeling approaches, which have been developed at IPP, only the H^- ions produced by surface conversion mainly of Hydrogen atoms on the caesiated surface of the plasma grid have a high extraction probability[12]. At high flows of H^0 atoms the H^- current density is space charge limited, if the density of positive ions is not high enough. In order to achieve a more advantageous starting angle of H^- and in this way to increase the extraction probability, the extraction holes of the plasma grid with a diameter of 8 mm are chamfered by 45°.

The main issue, however, is the conversion rate on the plasma grid surface, which is determined by the work function. Under UHV conditions less than 2 eV are possible, but at the background pressure in the ion source of $10^{-5} – 10^{-7}$ mbar, not less than 2.14 eV, which is the work function of the bulk Caesium, has been measured[13]. The work function is not constant and depends on the plasma-on time, the applied RF power, the Cs evaporation and the amount of impurities. Reason is the complex surface chemistry of Cs, about which not very much is known. As a consequence negative ion currents as well as the currents of co-extracted electrons can vary over a wide range at the same plasma parameters. In particular the electron current can change during long pulses and also during experimental periods of days and months. After copper sputtering of the Faraday shield and the source back plate had been prevented by Molybdenum coating an important source of impurities was excluded. The source performance, however, still depends on the leakage rate and the corresponding background pressure.

"Conditioning" of the source means to carefully treat the plasma grid surface by plasma cleaning and renewing the surface layer by Cs which is either evaporated or released from other walls inside the source, which are heated by the plasma. The degradation of the performance in long pulses can be delayed by thick Cs layers on the plasma grid. Cs evaporation during long pulses had no impact on the currents[14], because in the prototype source the Cs oven is too far away from the plasma grid.

Temperature control of the inner surfaces plays an important role; the best results can only be achieved, when the temperature of the plasma grid is more than 140°[14], at higher temperature the performance remains constant. This phenomenon can be explained by the lower sticking coefficient for impurities which leads to a "cleaner" surface[13]. The source walls are kept on 35° – 40° in order to avoid too much trapping of Cs. The bias plate is not actively cooled and therefore a source of Cs which is released in long pulses.

IV RESULTS WITH THE PROTOTYPE SOURCE

A. Source pressure

Below 0.3 Pa the operation of the "type 6" source in pure Hydrogen becomes unreliable. But if enough Cs is released from the bias plate, which takes approx. 20 - 50s, the pressure can be reduced on the long pulse testbed MANITU below 0.3 Pa, an example is shown in Fig. 4. At the larger RADI source (see below) operation down to 0.2 Pa is no problem without Cs.

B. RF power

With the IPP prototype it is not possible to achieve any high ion currents just by applying sufficient high RF power, because the efficiency in terms of H^- current density/RF power decreases steadily at high power (Figs. 3 and 4), the ion currents tend to "saturate" at high power. A reason may be that the dissociation of the hydrogen molecules saturates in the driver at high plasma density or RF power respectively. This has been confirmed by spectroscopic measurements[15]. Although the positive ions contribute less to the negative ion production, they are important for the neutralization of the space charge created by the negative ions[12]. Plasma density also does not increase linearly at high power[15]. As the flow of the hydrogen atoms as well as of the positive ions increases only slowly at high power, it is not surprising, that this is observed also with the negative ions. In pulses of less than 100s an extracted current density of 35 mA/cm² and for several 100s 20-25 mA/cm² has been achieved in Hydrogen at the maximal possible extraction voltage of 8.5

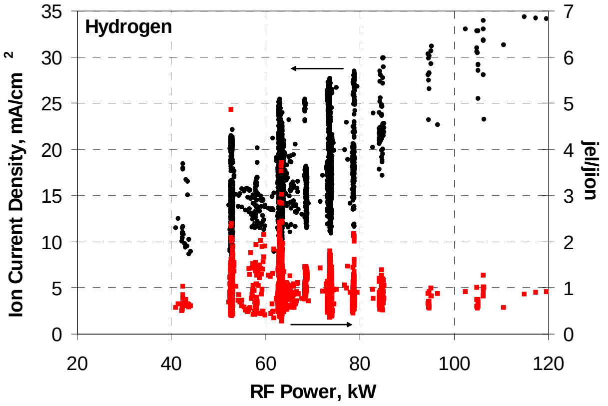

Fig. 3: Power dependence of the ion currents and the electron fraction in Hydrogen at the MANITU testbed

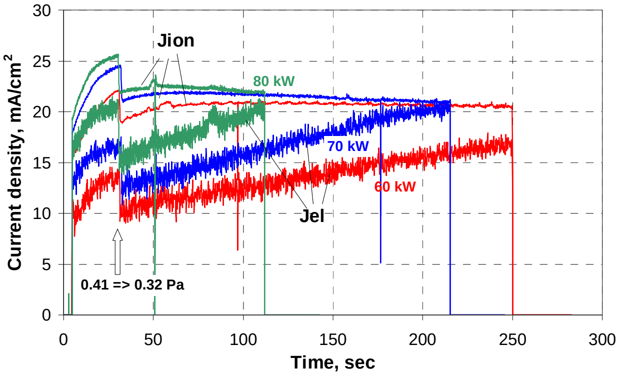

Fig. 4: Long pulse extraction in Hydrogen at the MANITU testbed with different RF power, the pressure was reduced after 25s

kV. With a higher voltage of 10 kV, as it is planned for ITER, higher currents would be possible. The accelerated current density is around 70 % of these values for the used extraction system and has reached up to 25 mA/cm^2.

C. Long pulses

Fig. 5 shows the correlation between the pulse duration and the extracted D$^-$ current density achieved in an experimental period of several weeks on the MANITU testbed. The achieved maximum values are lower in long pulses, because the RF power has to be reduced due to the increasing current of co-extracted electrons (see Fig. 4). If the electron current reaches a limit that is defined by the maximum allowed power load on the extraction grid the beam has to be stopped. This occurs earlier at high power. To a certain extend the rise of the electron current can be controlled by adjusting the plasma grid bias voltage, but it cannot be suppressed for all pulse durations.

D. Deuterium

The results in Deuterium are contradictory; on the short pulse testbed BATMAN no significant differences between H$^-$ and D$^-$ current densities were observed[12], but on the long pulse testbed MANITU the D$^-$ current densities shown in Fig. 5 were considerably lower than the H$^-$ currents. It is assumed that the reason is a difference in the work function on the surface of the plasma grid during the corresponding experimental campaigns.

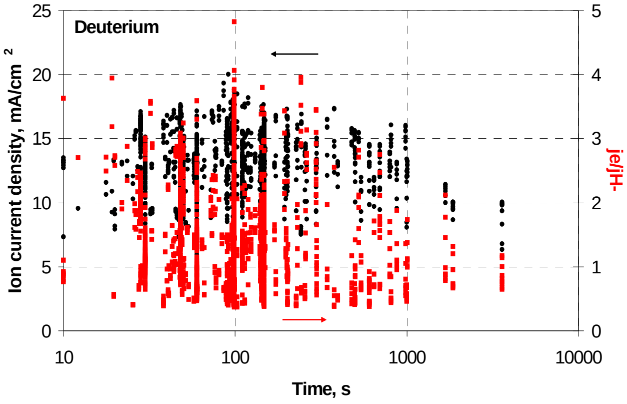

Fig. 5: Extracted ion current and fraction of co-extracted electrons in Deuterium for different pulse durations

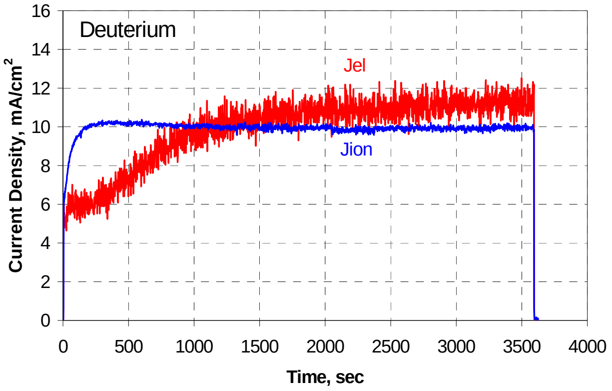

Fig. 6: One hour pulse in Deuterium with 45 kW at 0.3 Pa

The current of co-extracted electrons, is in Deuterium in any case higher than in Hydrogen. This can so far not be explained by theory. In order to suppress the electron current the filter field has be strengthened and the bias voltage has to be enlarged, but in both cases the ion current is also reduced. However, Fig. 6 shows the first one hour pulse in Deuterium, which was achieved at reduced power.

V LARGE RF SOURCES

At IPP two large RF sources with a base area of about half of the size of the ITER source have been designed, the RADI and the ELISE source. Both are equipped with four drivers. In these sources the expanding plasma overlaps in the center of the source and so each driver supplies a part of the expansion volume with lower wall losses compared to the driver of the Type 6 source. Therefore it can be expected that less power is needed for the same plasma density in the expansion chamber.

At the large sources each generator has a maximum power of 180 kW and supplies to two drivers, which are connected in series. Due to the small distance between such a pair, some mutual inductance occurs, which can be observed, when each of the two drivers is supplied by one RF generator separately. Then the matching of one driver is slightly different, if the other driver is operating or not. It is not clear, if this effect has any impact on the source plasma. However, after shielding by a copper plate between the drivers or a cylinder around each driver this effect vanishes.

The width of the large sources exceeds the range of permanent magnets by far. A major goal of the experiments with the these sources is to investigate new filter fields, which are generated by the superposition of fields created by permanent magnets and a current flowing through the plasma grid with different ways of current return.

On the RADI source (inner dimensions: 0.76 x 0.8 m^2) the driver size is same on the type 6 source. The RADI testbed, which has no beam extraction, was

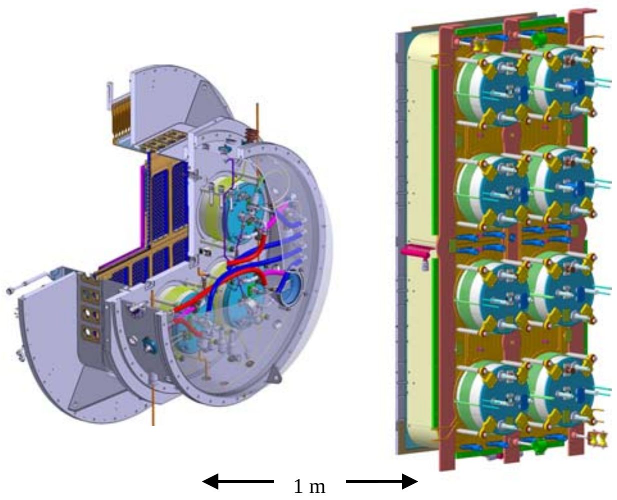

Fig.7: The ELISE and the ITER source

intended to demonstrate the plasma uniformity of a RF source of ITER dimensions, to test different filter field concepts, to gain experience on driving more than one driver with a single generator, and to test an ITER-like RF circuit[16].

The source on the ELISE testbed (extraction from a large ion source experiment) is shown in Fig. 7 together with the ITER source. The base area is slightly larger (0.87 x 1 m^2) in order to improve the plasma homogeneity at the edge of the extraction system. By enlargement of the diameter of the drivers to 28.6 cm the power density in the driver will be lower. A less pronounced neutral depletion effect and a higher dissociation degree are expected from this change. Pulsed beam extraction with a duty cycle of 10/160s and the source running in steady state is planned on this testbed, which is currently under construction and will be commissioned in January 2012[17]. MANITU and RADI have been shutdown in August 2011, because many components like cryo pumps, RF and HV power supply have to be transferred to ELISE.

With an extraction area of 1000 cm^2 and beams of 60kV/20A ELISE is an important intermediate step towards the full size ITER source. The experience gained with in these experiments will support the design and the operation of the prototypes of the ITER source, which will be tested on the PRIMA ion source test facilities at RFX Padua[18].

VI SUMMARY

The R&D work on the RF driven negative ion source has led to a high degree of operational reliability. The required ion currents have been achieved for pulses up to about 100 s, in longer pulses the RF power is limited by the increasing electron currents. The modularity and the ability to extend to larger size, without changing the plasma production concept have been shown on a large source without extraction.

An open issue is the understanding of the surface chemistry on the Caesium covered plasma grid, which determines the long pulse stability of the work function, and of the higher electron currents for Deuterium. The improvement of the long pulse performance after Mo coating of the Copper surfaces in the Faraday shield demonstrated the importance of impurities.

The next step to large sources requires the investigation of novel magnetic filter field concepts, because the solutions of the small scale prototype can not be adopted.

With the small scale prototype the maximal performance has been reached; further improvements are expected with larger sources, because the phenomena, which are caused by the very high plasma density in the driver will be diminished and a higher efficiency of plasma production can be expected due to lower plasma losses.

[1] R. Killinger, H. Basner, G. Kienlein, J. Müller, Electric Propulsion System for ARTEMIS, DaimlerCrysler Aerospace AG, IEPC 99-054

[2] J. Freisinger, H. Löb, Atomkernenergie, Kerntechnik, Vol. 44(1984) no.1, p.81

[3] W. Kraus, M. Kaufmann, Fusion Technology (1989), p. 495

[4] E. Speth, M. Ciric, J. H. Feist, P. Frank, B. Heinemann, W. Kraus, F. Probst, R. Riedl, R. Trainham, O. Vollmer, R. Wilhelm, Fusion Engineering and Design, 46(1999)383-388

[5] R. Hemsworth, Nucl. Fusion 46(2006)211

[6] O. Vollmer, B. Heinemann, W. Kraus, P. McNeely, R. Riedl, E. Speth, R. Trainham, R. Wilhelm, Fusion Engineering and Design 56-57(2001)465-470

[7] P. Franzen, H.D. Falter, U. Fantz, W. Kraus, M. Berger, S. Christ-Koch, M. Fröschle, R. Gutser, B. Heinemann, S. Hilbert, S. Leyer, C. Martens, P. McNeely, R. Riedl, E. Speth and D. Wünderlich, Nucl. Fusion 47(2007)264-270

[8] W. Kraus, H.-D. Falter, U. Fantz, P. Franzen, B. Heinemann, P.McNeely, R. Riedl, E. Speth, Rev. Sci. Instrum. 79, 02C108 (2008)

[9] P. McNeely, S. V. Dudin, S. Christ-Koch, U. Fantz, Plasma Sources Sci. Technol. 18(2009) 014011

[10] W. Kraus, to be published in AIP Conf. Proc. (2011)

[11] E. Gaio, W. Kraus, C. Martens, R. Piovan, E. Speth, V. Toigo, Fusion Engineering and Design 82(2007)912-919

[12] U. Fantz, P. Franzen, D. Wünderlich, Chem. Phys. (2011), doi: 10.1016/j.chemphys.2011.05.006

[13] R. Gutser, C.Wimmer, U. Fantz, Rev. Sci. Instrum. 82, 022506 (2011)

[14] W. Kraus, M. Berger, U. Fantz, P. Franzen, M. Fröschle, B. Heinemann, R. Riedl, E. Speth, A. Stäbler, D. Wünderlich , AIP Conf. Proc.,1097, 275(2009)

[15] P. McNeely, D. Wünderlich, Plasma Sources Sci. Technol. 20(2011) 045005

[16] P. Franzen, Fusion Engineering and Design 82(2007)407-423

[17] B. Heinemann, Fusion Engineering and Design 84(2009)915-922

[18] D. Marcuzzi, A. Palma, M. Pavei, B. Heinemann, W. Kraus, R. Riedl, Fusion Engineering and Design 84(2009)1253-1258