Magnetic Filter Field for ELISE - Concepts and Design

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Negative ion neutral beam injection heating systems as planned for ITER need efficient precautions in the plasma source to minimize the co-extraction of electrons and destruction of negative ions. One solution is to apply a magnetic filter field of several mT, which reduces the electron temperature and the amount of electrons in the extraction region in front of the plasma grid. For the small IPP prototype sources it has been found, that both, the absolute value of the magnetic flux density in the extraction region as well as its integral along the distance from plasma driver to plasma grid has an important influence on the performance of the source. In the ITER ion sources, a strong current of several kA driven through the plasma grid is used to create the transversal magnetic field. The test bed ELISE (Extraction from a Large Ion Source Experiment) at IPP Garching houses the first negative ion source with the full width of the ITER source, with a similar aperture arrangement of the extraction system and with a magnetic filter field formed by a plasma grid current. One issue of the research at this test facility will be to explore and optimize the magnetic filter field. The paper summarizes experiences and results of previous filter field test campaigns and presents the magnetic filter field design for ELISE.

Keywords: ITER neutral beam injection; negative ion source; magnetic filter field; PG current; ELISE

1. Introduction

The ITER negative ion neutral beam injection (NNBI) heating (HNB) and diagnostic (DNB) systems require an ion source delivering 65 A negative Hydrogen ions and 57 A negative Deuterium ions (HNB only) in front of the accelerator [1-3]. Corresponding to the 1280 apertures with 14 mm diameter in the plasma grid (PG), an extracted current density of 330 A/m² H- ions and 290 A/m² D- ions respectively is needed. The gas pressure of the source is limited to 0.3 Pa and due to technical restrictions of power handling in the extraction grid (2nd grid, EG), the current of co-extracted electrons must be lower than the current of negative ions.

In small test facilities at IPP Garching these current densities at the required parameters have been reached simultaneously [4-7]. An important step to support the development of the full size ion source and injector test beds at RFX Padua, is the IPP experiment ELISE, which is currently in the commissioning phase in Garching [8]. ELISE has half the height but the full width of the ITER ion source. In a three grid system with an ITER like aperture pattern the negative ions shall be accelerated to 60 keV.

In the ELISE negative ion source plasma is produced in four cylindrical drivers via inductively coupling 1 MHz RF power of up to 90 kW each. The plasma expands into the source chamber, passes through the horizontal magnetic filter field (MFF) and reaches the extraction region (ER) in front of the PG. The PG is positively biased with 10 - 20 V against the source body and a "bias plate" covers the PG aside the aperture areas, increasing the surfaces at source potential. Cesium evaporated from two cesium ovens at the side walls of the source shall coat the PG surface in a thin layer, lowering the work function and enhancing the conversion yield of neutral H or D atoms exhausted from the drivers into negative ions [9].

The MFF has a strong influence on the plasma parameters inside the source. It controls extraction probabilities of negative ions as well as electron densities in front of the PG. Together with an adequate biasing and a good conditioning of the converter surfaces an optimized filter is mandatory for the reduction of co-extracted electrons and for sufficient current densities of extracted negative ions in particular.

In small negative ion sources the MFF is produced by permanent magnets attached to both sides of the source. This concept however is not applicable to large sources as a sufficient field strength in the centre of the source is hardly to achieve. In large sources a strong current driven through the PG is used to create the MFF instead. ELISE is one of the first negative ion sources for fusion devices to make use of and explore this technique.

2. Influence of the magnetic filter field

During the last few years at IPP the influence of the MFF on the plasma parameters and on the performance of the negative ion source have been explored extensively. Dedicated experiments have been carried out at the test bed BATMAN at IPP [3,10]. A magnet frame has been built that allowed to vary the position, the strength, the direction and the shape of the MFF without breaking the vacuum, thus keeping the

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conditioning of the source with its sensitive converter surfaces constant.

2.1 Electron temperature and extracted electrons

The original purpose of the MFF in negative ion sources is to reduce the destruction rates of negative ions by collisions with electrons by means of reducing the electron temperature in the ER. It was shown [10], that neither the position nor the shape of the magnetic field but the integral of the magnetic flux density from the driver exit to the ER ($\int|B_x|dz$ or $\int Bdl$) is the constitutive parameter for electron cooling. For an $\int Bdl$ of 0.7 mTm an electron temperature of below 1 eV in front of the PG was measured in all cases (40 kW RF power, 0.6 Pa), which is considered to be sufficient to minimize the destruction rates by electron collisions.

Further it was found in [3] - Fig. 1 shows results - that also the ratio of the co-extracted electron current to the extracted negative ion current j_e/j_{ex} is primarily a function of the $\int Bdl$ of the MFF, not depending on its shape or location. A value of approximately 1.25 mTm was found to suppress the co-extracted electrons in deuterium plasmas sufficiently.

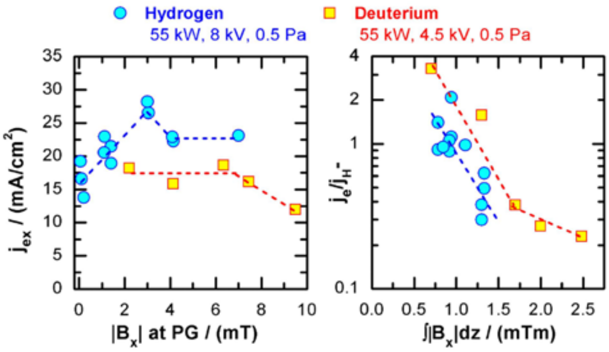

Fig. 1: Extracted negative ion currents and ratio of co-extracted electrons as a function of the magnetic flux density at the PG and the $\int Bdl$ respectively for hydrogen [3] and deuterium plasmas. The results have been obtained at BATMAN with the variable Magnet Frame.

2.2 Plasma Drifts

In RF negative ions sources with a transverse MFF plasma drifts seem to be inherent and are known since many years. It has been found [10], that along the particle movement from driver to PG the maximum of the plasma densities changes from the upper to the lower side (or vice versa depending on the direction of the MFF) implying, that also the directions of the drifts change. These drifts are strongly influenced by strength, position and shape of the MFF. The mechanisms of these drifts however are yet not understood well and a physical description is still pending.

Fortunately the negative ion densities in front of the PG and the beam homogeneity do not or not strongly correlate with the electron densities and the plasma shift, especially for a well conditioned source [11]. The beam asymmetries measured at IPP test bed MANITU are 10 % or less and thus in the ITER range for beam homogeneity (< ±10 %). This indicates, that the negative ions are mainly produced by neutral atoms hitting the PG and that positive ions are needed only in that extend to maintain the quasi neutrality of the ion-ion plasma in the ER [9].

2.3 Extracted negative ion current

It has been found [3], that the extracted negative ion current correlates with the absolute value of the magnetic flux density B_x in the ER. The maximum extracted negative ion current density (>250 A/m², H^-) was observed with a magnetic flux density of about 3 mT at the PG, ct. Fig. 1.

A Test Particle Code was used in [12] to simulate the trajectories of negative ions from their origin (the PG surface) to their place of extraction or destruction. It was found, that the extraction probability is higher for higher magnetic flux densities in the ER as well as for lower starting energies of the negative ions.

Beside other effects, the magnetic field in the ER helps to bend the negative ion trajectories back to the grid. A higher magnetic flux density reduces the gyro radius and therefore the traveling length of the negative ions in the plasma. Thus destructions by collisions - either with electrons, neutrals or ions - are reduced, which finally enhances the overall extraction probability and negative ion yield.

2.4 Plasma confinement and electron dumping

The MFF created by the permanent magnets attached from the sides at the small IPP negative ion sources form a magnetic mirror (B_{max}/B_{min} = 7.9 ... 20.8) which provides a plasma confinement and thus the reduction of losses in the expansion chamber. This may have some influence on the overall RF efficiency of the ion source.

On the other hand it is highly desirable to obtain an ion-ion plasma as pure as possible in the ER. This would not only reduce the amount of co-extracted electrons but also increase the negative ion yield, as the destruction rates by collisions with electrons and predominantly with the surplus positive ions would be reduced.

At the IPP test bed MANITU experiments have been carried out, where an additional electrode was installed in order to scrape off the electron-ion plasma in the ER, which was possible with its interplay with the MFF. Although the plasma density was drastically reduced in the ER, high efficiencies (+ 10 %) at very low currents of co-extracted electrons (j_e/j_{ion} = 0.5) have been observed. In addition a smaller increase of the electron current during long pulses has been noticed.

3. Filter field requirements for large negative ion sources

3.1 Requirements deduced from observations

From observations and considerations mentioned above, the following requirements for an efficient MFF for negative ion sources can be derived:

1. The MFF has to provide a transverse magnetic field with a minimum ∫BdL between plasma driver and PG to cool down the electrons below 1 eV.
2. The MFF has to provide a minimum field strength in the ER parallel to the PG, to bend back the trajectories of the negative ions and enhance their extraction probability.
3. The MFF should allow to control the electron-ion plasma density in the ER in ways which should be further explored in the future.

3.2 Shielding the magnetic field in the accelerator

Regarding solely the current driven through the PG, this is creating the same magnetic field (with inverse direction) in the accelerator downstream of the PG as in the source and ER. This is not acceptable due to intolerable beamlet deflections. Possible countermeasures are:

i. soft iron shielding downstream of the PG, directly attached to the grids (or parts of them) or to the grid frames.

ii. positioning the return current conductors upstream of the PG and thus forming a sort of solenoid that concentrates the magnetic field between its leads and hence inside the source volume. Many different positions and combinations of return conductors are possible, which also helps to shape the field topology and "integral Bdl".

As return current leads are needed in anyway it is self-evident to make use of the latter solution, which is done at ELISE

3.3 Reducing ripples in the field

In the ITER injector the ion beam is divided horizontally in four segments. Accordingly also the grids are divided in regions with apertures and solid blocks. It was shown [13], that the homogeneity of the MFF can be improved significantly if the cross section areas of the aperture region and the solid region approximate. For the ELISE PG this was done by milling pockets into the solid blocks between the aperture areas, leaving wall thicknesses of 1.0 to 1.5 mm.

3.4 Interplay with electron deflection magnets of EG

Embedded into the EG are magnets producing the electron deflection field (EDF), which is primarily responsible to deflect the co-extracted electrons onto the EG surface, thus avoiding further power charging and losses in the accelerator. These magnets are located in between each row of apertures with alternating, in beam direction orientated polarity. As the field lines penetrate the PG and bow over the apertures, electrons are magnetized and guided onto the surface of the PG. This effect is probably the primary electron suppression mechanism in the negative ion sources for NBI. Earlier experiments at IPP with a different EDF that did not penetrate the PG failed due to unacceptable currents of co-extracted electrons.

A parallel orientation of the EDF with the MFF in front of the PG would lead to its alternating enhancement and weakening, resulting in different electron currents of the aperture rows. The heat load onto the EG however is critical and demands an uniform charging. Therefore the orthogonal orientation of EDF to MFF is almost mandatory. In the latter case, the field lines of the EDF are bent in alternating angles, but the absolute EDF strength remains the same for each line of apertures.

The ELISE EG gives the possibility to install the EDF magnets in both directions. They are inserted orthogonal to the MFF (for the start up phase at least).

4. Filter field design of ELISE

4.1 Filter field configurations

Although many experiences have been gained in the past few years, the optimal parameters of the MFF for a ITER size ion source still have to be explored. Therefore the ELISE MFF was designed to be variable and flexible. At present four PG current power supplies, each delivering a current of up to 1320 A can be commanded from the control room and the currents can be changed even within a pulse. They feed the device in two lines, enabling separate control of two return current circuits at the backside and inside the ion source. More power supplies can be added, the system is designed for a total PG current of up to 8 kA.

The ELISE experiment starts operation with a MFF formed by the PG current and three return current leads at the back of the source. The corresponding 2D map of the flux densities, relating to a total PG current of 5.28 kA is shown in Fig. 2a. This field produces an ∫Bdl of 1.02 mTm in between the middle of the driver exit and the grid (along the vertical line in the figure, see also Fig. 2 bottom) where it has a minimum. In a further step the introduction of return current leads inside the source is planned. These leads allow a concentrated field in front of the PG as depicted in Fig. 2b. If both types of return current leads are combined, a field according Fig. 2c results. Controlling both circuits separately, all intermediate patterns are possible.

In addition permanent magnets can be attached from outside of the source. They strengthen the field in front of the PG but primarily produce a plasma confining mirror field like it is shown in Fig. 2d. For this purpose the source walls are designed as thin as possible too.

4.2 Design of the filter field components

The power supplies of the PG current are located in a high voltage cabin outside of the neutron shielding of the experiment. 2 x 2 flexible, water cooled cables (HOMA Type 4011/18) connect the power supplies to a massive copper bus bar, which leads through one of three bushings through the concrete of the neutron shielding. The bus bar consists of 8 copper flats, including the supply for bias current and further potentials.

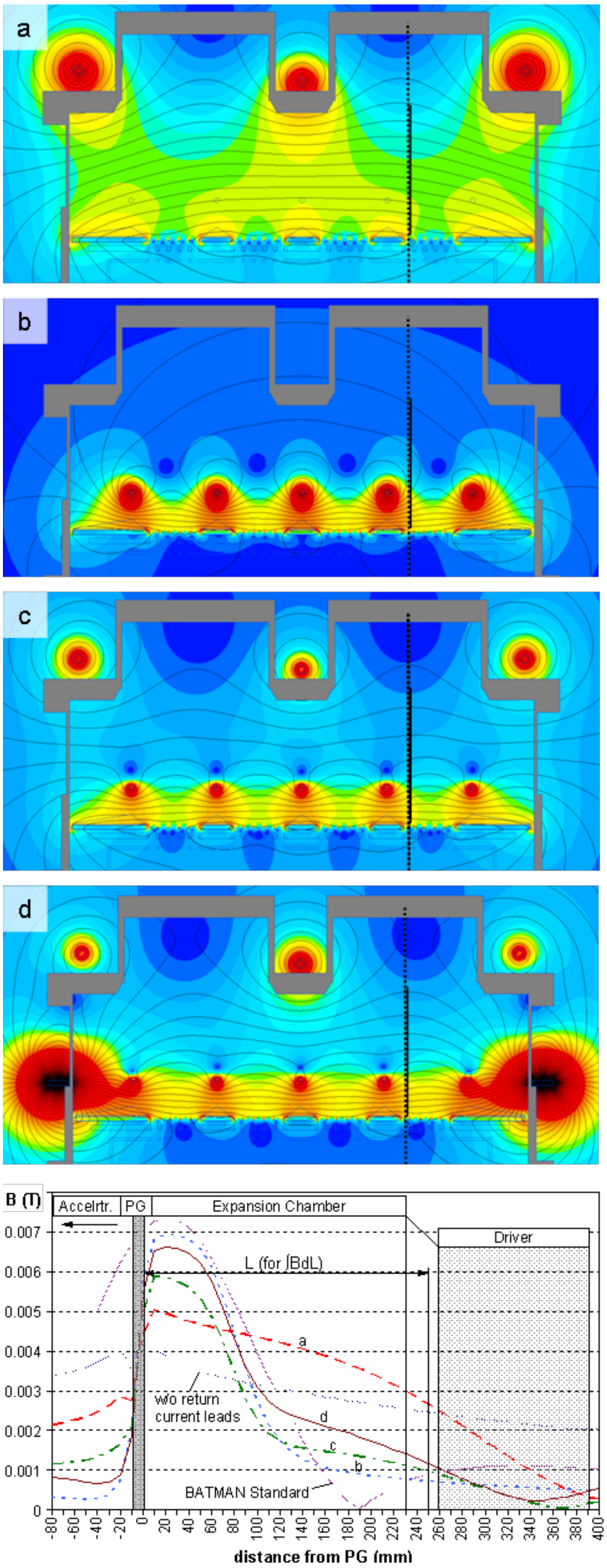

Fig. 2: 2D colour map of possible configurations of the ELISE MFF (horizontal cross section, the drivers on top). Each colour step corresponds to a 0.5 mT step of flux density. The total PG current is 5.28 kA. a: return current through the backside leads, b: return current through inside leads, 70 mm in front of the PG, c: 2.64 kA through backside leads, 2.64 kA through inside leads; d: c with additional permanent magnets at the side of the source. Bottom: Characteristic of the flux densities along the dotted line in the color maps.

Fig. 3 shows the individual parts of the PG current circuit near the source. HOMA cables attach the bus bar to a Ø 56 mm copper feed through (1) from below into the source, downstream of the grids. Inside the source a T-shaped copper bar (2) extends to the width of the PG. 18 lamellas made of 2 x 23 mm², three dimensional bent copper sheets (3) lead to the PG and are directly screwed onto the grid. Due to their flexibility the lamellas allow thermal expansion of the grid in all directions.

The PG itself (4) with its optimized structure as explained in chapter 3.3 consists as all grids of an upper and a lower half. The connection (5) of the both halves has to allow thermal movements in horizontal and vertical direction. Any gliding contact was considered to be risky due to corrosion effects in the caesiated atmosphere and thus undefined contact resistances. Massive plates with carved out, flexible lamellas have been built instead and are extensively screwed onto the halves of the PG. This concept meets the requirements concerning ampacity and remaining forces onto the grids easily too.

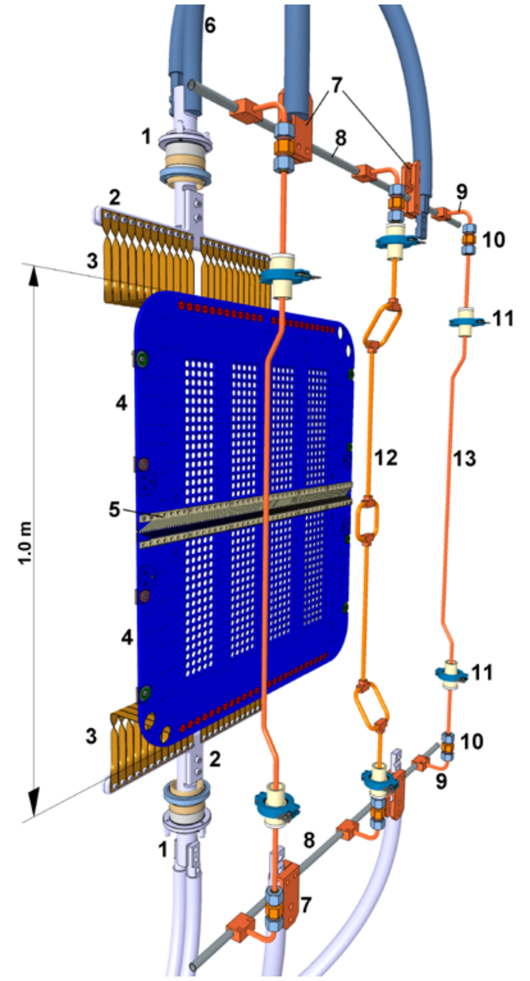

Fig. 3: Current leading parts of the PG filter at the source of ELISE. The description of the numbered parts is given in the text.

On top of the source again HOMA cables (6) connect the feed through with the current distributor (8) for the three backside return current leads. This current distributer is made of a Ø 16 x 2 mm² mild steel tube which grants a small electrical resistance. As the HOMA cables are connected by movable clamps (7), it can act as an voltage divider and the current of the individual back side leads can be controlled in a certain range (ct. Fig. 2b and Fig. 2c where the current distribution was changed). The distributer feeds also the cooling water via brazed T-Fittings and elbows (9) into the backside leads.

The backside return current leads themselves (12, 13) consist of a copper (Cu-DHP) tube Ø 10 x 3 mm² whereat the middle lead (12) needs to surround three diagnostic ports in the source back plate. Due to their small size and electrical resistance the leads have a power consumption of up to 4 kW (assuming a current of 3 kA for the middle lead). The connected cooling system however limits the temperature rise to below 7 K. All three backside current leads are bent close to the source back plate in order to reduce the magnetic field in the drivers. They have to be assembled from inside the driver containment as they extend the KF40 flanges which carry the bushing (11). A special fitting (10) connects the parts of the current leads inside and outside the driver containment.

At the bottom of the source the current flows back through an identical current distributer and HOMA cables to the bus bar at whose end a shunt for current measurement is introduced and from there back to the power supplies. Almost all parts of the PG current circuit are water cooled.

For the inside source return current leads (Fig. 2b-d) a similar installation with cooled copper tubes as it is done for the back side leads is planned. However it was proposed to integrate two more functions to these tubes: First they could house rods of cesium dispensers, which are expected to enable a prompter response and a more uniform Cs layer than the starting up Cs-ovens. Secondly these rods could wear on their outside an insulated layer on additional potential which possibly allows to influence the development of the plasma potential and thus to control crucial particle fluxes.

Summary

The ITER half size ion source experiment ELISE is currently in its commissioning phase and will start operation soon. ELISE is equipped with an ITER like magnetic filter field, formed by a strong current driven through the plasma grid and upstream return current leads. It will start operation with a configuration that produces a widely uniform filter field and an $\int Bdl$ of up to 1.02 mTm. Further extensions allow a concentrated field in front of the PG as well as a vast, overall flexibility of the system that meets the actual scientific findings and support future investigations for the optimization of negative ion production and extraction and electron suppression.

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