Large–Area, High–Transparency Extraction System for Negative Ions

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1. INTRODUCTION

In the frame of a collaboration between CEA Cadarache and IPP Garching investigations have been carried out to extract negative hydrogen ions from a large–area rf source (32 x 61 x 19 cm^3) by using a medium–size extraction system of 69 cm^2 with 45 holes [1]. To demonstrate the plasma uniformity of the rf–source a large–area extraction system has been designed and is under manufacturing now.
For reasons of economy it was decided to modify an existing PINI extraction system for positive ions (triode, extraction area 390 cm^2, 774 apertures, transparency 37%), which means:
- to add a magnetic filter in front of the plasma grid,
- to keep the plasma grid and earth grid, and
- to replace only the decel grid by a new extraction grid.

The design was made compatible with the AUG rf-source for positive ions and similar types.

2. DESIGN OF THE EXTRACTION SYSTEM

2.1 Magnetic Filter

The necessary filter field in front of the plasma grid for the production of negative ions will be generated by permanent magnets outside the extraction area. Their arrangement is limited by the available space inside a PINI main insulator. A magnet flange underneeth the source body embeddes 2 layers, each containing 3 rows of Co–Sm magnets (see fig.1).
They create at the center of the plasma grid a maximum horizontal field B_x = 84 gauss and a line integrated field along the beam axis z of $\int Bdz$ = 1800 gauss·cm (-25 < z < 25cm) The transverse component of the filter field along the x–axis (horizontally) and along the y-axis (vertically) of the extraction area is shown in fig. 2.

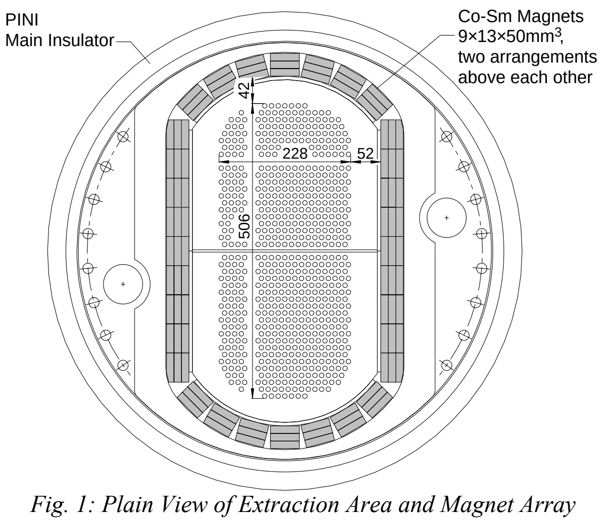

Fig. 1: Plain View of Extraction Area and Magnet Array

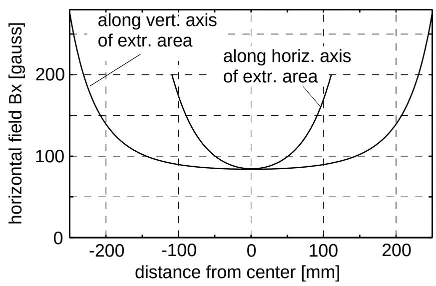

Fig. 2: Transverse Filter Field

2.2 Extraction Geometry

The design values for this extraction system are a deuterium current density $J_{D^-} = 20$ mA/cm^2 , extraction voltage $V_{ext} = 5.4$ kV, acceleration voltage $V_{acc} = 27$ kV (calculated ratio $V_{ext}/V_{acc}= 5$). The optimum perveance for one beamlet is 2.3 * 10^{-9} A/V$^{3/2}$, for the full extraction area 1.8 * 10^{-6} A/V$^{3/2}$. The geometry of the system is shown in fig. 3.

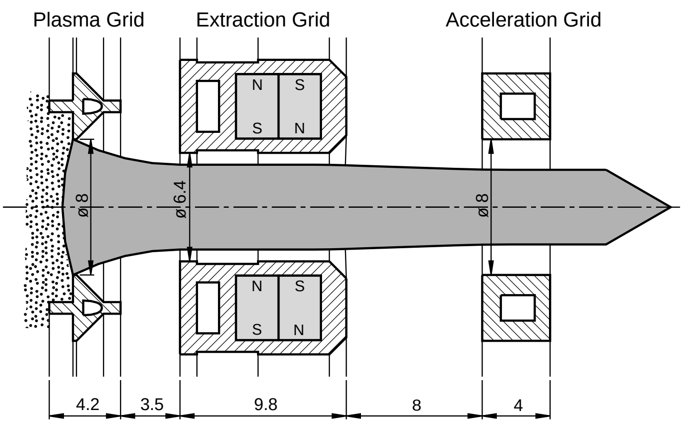

Fig 3: Extraction Geometry

Trajectory calculations (chap. 3) delivered an optimum beamlet divergence of 7.5 mrad with the aspect ratio $r_{aperture}$/gap = 1.14.

The beamlet steering is defined by:

- the existing aperture displace–ment between the plasma grid and acceleration grid (0.036 mm hor., 0.028 mm vert. per row). Using the same hole position for the extraction grid as for the plasma grid and having the displacement only within the acceleration gap leads to a convergent beam with a horizontal focal length of 11.7 m and a vertical one of 15.2 m.

- the existing magnetic fields: The horizontal filter field across the grid deflects the beam vertically by 6.3 mrad for the central beamlet and 9.6 mrad for the outer ones. The electron suppression field deflects the beam furthermore horizontally by 2.4 mrad. Both effects can be compensated with the beam steering mechanism.

- mechanical inclination of the two half-grids by 15 mrad (vertical focal point = 7.9 m).

2.3 Mechanical Design of Extraction Grid

This new grid had to be designed in a way that the existing aperture pattern is compatible with cooling channels, grooves for the electron deflection magnets, and electron traps inside the holes. It is 9.8 mm thick with ø 6.4 mm extraction hole, details are shown in fig. 4.

The magnets are arranged in a different way compared to other extraction systems: Two rows of magnets „on top of each other“ (w.r.t. beam dir.) with opposite polarity are placed between the extraction holes. All the magnet rows have the magnets oriented in the same way and form by that a dipol magnetic field with $B_{ymax}= \pm594$ gauss, which deflects all the electrons in the same direction (see fig.5). Also all beamlets are deflected in the same direction and not alternating as usual. This effect could be used to compensate for the steering of the beam due to the external filter field. It is not used for that grid, because then the magnet rows would have to be positioned vertically, which is difficult to combine with the existing aperture pattern.

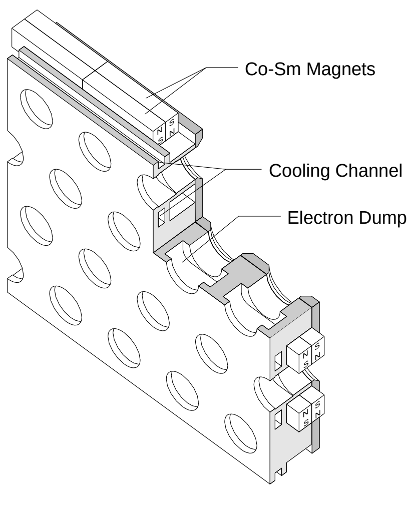

Fig. 4: Design of Extraction Grid

The electron trap is a pocket inside the grid which prevents backscattered and secondary electrons from escaping the grid and being accelerated. Its shape is defined by the surrounding geometry and reduces the estimated electron leakage from about 8% to 2%.

The cooling channels are placed „on top of" the magnet rows with internal manifolds along the sides of the extraction area. The cooling is designed to take out the power deposited by the electrons for a current $J_e/J_{D^-} \approx 4.5$ (see chap. 4).

The grid is manufactured by electrodeposition of copper onto a base plate (oxygen free copper). This method ensures vacuum tightness of the cooling channel relative to the extraction holes and magnet grooves with a remaining wall thickness of 1 mm. For higher experimental flexibility the magnets are inserted in the grooves after manufacturing and hold in place by a separate lid. The connection to the water system is done like in all PINIs via friction welded stainless steel stub pipes.

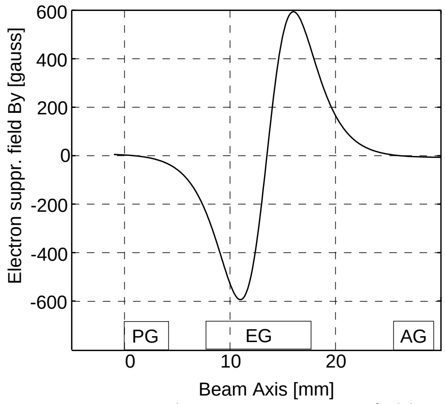

Fig. 5: Electron Suppression field

3. ION AND ELECTRON TRAJECTORIES

The trajectories of electrons and ions have been calculated in the full threedimensional magnetic field with the code OPERA-3d/SCALA (improved version, simulates plasma behavior). The deflection of the electrons is strongly influenced by the inhomogenous filter field. Fig. 6 shows the transverse component of the field along the axis of a central beamlet, an outer and an intermediate beamlet (x = 80 mm). The ion and electron trajectories in a horizontal and in a vertical cross section are given in fig. 7, with V_{ext} = 5.4 kV, V_{acc} = 27 kV. Due to the inhomogeneous filter field the trajectories vary over the surface of the extraction area. In the outer region the electrons are mainly influenced by the filter field and hit partly the front surface of the grid.

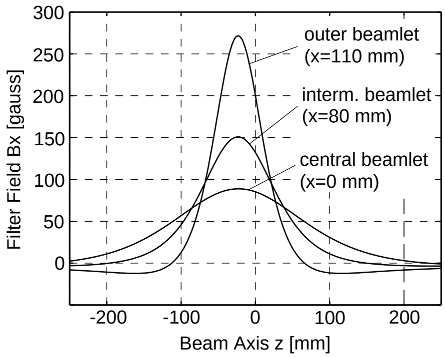

Fig. 6: Tranverse Field along Beamline Axes

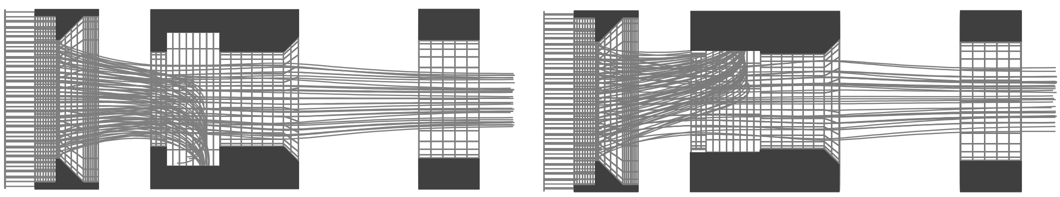

Fig. 7: Ion and Electron Trajectories for a Central Beamlet,
horiz. cross section (left) and vertical cross section (right)

4. THERMAL CALCULATIONS

Counting the impact of electrons onto the grid surface results in a locally detailed heat load distribution over the grid surface (total 230 W, $J_e/J_{D^-} \approx 4.5$). With this input finite element calculations were carried out (with the code ANSYS) to avoid local overheating of the surface and boiling of the cooling water. The model was generated for one hole with half a magnet groove and half a cooling channel, both above and below the hole. Embedding this model into an entire grid was made by setting thermal boundary conditions on all intersection surfaces, e.g. temperature of left side = temperature of right side.

The cooling channel is 3 x 1.3 mm^2, the flow velocity is 10 m/s, water temperature 20°C, the pressure 8 bar and the pressure drop over one channel 1.9 bar. The heat transfer coefficient to the water was calculated to be 66 x 10^3 W/m^{2}K and is constant over the range of operation.

The finite element model, the meshing and power loaded areas as well as the temperature results are shown in fig. 8 for a central beamlet. The highest temperature (160°C) occurs inside the electron trap. Similar calculations have been carried out for outer and intermediate beamlets with different power loaded areas and consequently different temperature distributions. The surface temperature exceeded nowhere 175°C, the copper surface inside the cooling channel stays below 105°C. Further mechanical stress and deformation calculations will be done.

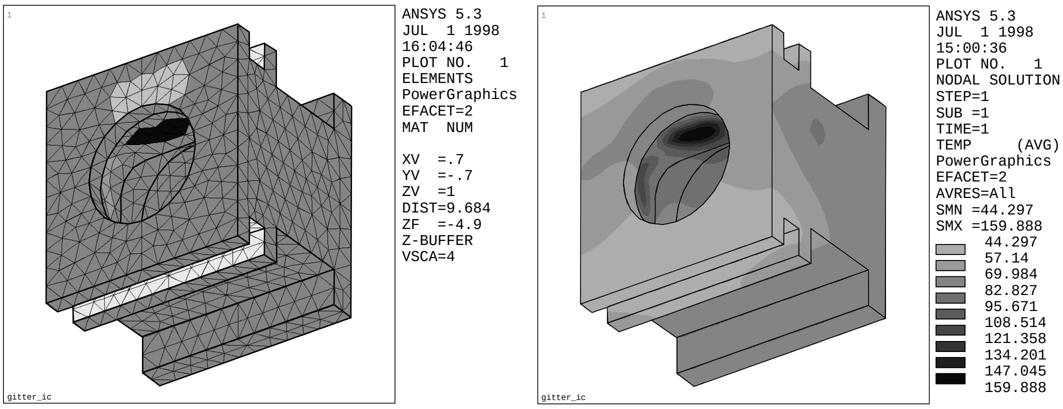

Fig. 8: Finite Element Model with Power Loaded Areas (left side) and Temperature Distributions (right side)

5. SUMMARY

The design of a negative extraction system by using as many parts as possible from a positive extraction system has successfully been completed. The high transparency of 37% could be maintained even with additional electron suppression magnets and electron traps. The magnet arrangement promises some advantages for further systems.

Manufacturing of the filter field flange and the extraction grid has started in July 98 and will be finished by the end of the year.

Acknowledgement

The support on FEM calculations by Dr. O. Jandl was greatly appreciated.

References

[1] Frank, P., „*Progress of the BATMAN RF-Source for Negative Hydrogen Ions*“, this conference, no. 387

[2] Kraus, W., „*Large -area RF plasma sources for fusion applications*“, presented at the ICIS conference, Sept. 1997