CHARACTERIZATION OF THE VERSATILE ION SOURCE (VIS) FOR THE PRODUCTION OF MONOCHARGED LIGHT ION BEAMS

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Abstract

The Versatile Ion Source (VIS) is an off-resonance Microwave Discharge Ion Source (MDIS) which produces a slightly overdense plasma at 2.45 GHz of pumping frequency. In the measurements carried out at INFN-LNS in the last two years, VIS was able to produce more than 50 mA of proton beams and He^+ beams at 65 kV, while for H_2^+ a current of 15 mA was obtained. The know-how obtained with the VIS source has been useful for the design of the proton source of the European Spallation Source, to be built in Lund, Sweden, and it will be useful also for other facilities. In particular, the paper deals about the design modifications of VIS, in order to use it as injector of H_2^+ of the ISODAR facility, will be also presented.

INTRODUCTION

The VIS source [1] is a MDIS installed at INFN-LNS as test-bench for the production of high intensity, low emittance proton and light ion beams and for studies of plasma physics [2]. In VIS a slightly overdense plasma is generated by means of a 2.45 GHz off-resonance discharge in the 0.1 T magnetic field produced by a movable permanent magnets system. A four electrodes extraction system allows extracting the ion content and injecting it in the LEBT. The entire source has been designed in order to present many advantages in terms of compactness, high reliability, capability to operate in cw mode or in pulsed mode, reproducibility, and low maintenance.
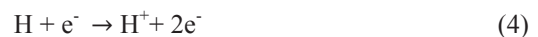
VIS is able to produce up to 50 mA of low emittance (< 0.2 π.mm.mrad) proton beams, but opportune modifications in the experimental set-up are needed depending on the ion to be optimized. In particular, in the following paper we focus our attention to the production of H_2^+. The use of this molecule instead of H^+ may represent a solution of the space charge effects affecting the acceleration of high intensity proton beams. H_2^+, indeed, allows the decrease of the generalized perveance, the parameter which measures the space charge effect, because of the larger m/q ratio with respect to protons. Generation of a high intensity (25-50 mA) H_2^+ beam is key point of the IsoDAR [3] and DAEδALUS [4] experiments. Both these experiments will make use of a MDIS as injector of a new high power cyclotron. Since the intensity of H_2^+ beams generated by VIS is not enough to satisfy the IsoDAR requirements, a series of

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studies and design modifications on the VIS source to increase H_2^+ intensity has been carried out.

He^+ AND H_2^+ PRODUCTION WITH VIS

The production efficiency of different ions is strictly related to the characteristics of the plasma which generate them. Modification of the VIS experimental set-up can affect directly the plasma parameters; it has been shown that the shift of the permanent magnets affects the plasma electron temperature [5], while the insertion of insulators, like BN at the endplates of the source, or an alumina tube embedded along the walls of the plasma chamber, can affect the ion lifetime and density [6,7]. He^+ ions are generated by means of ionization of the neutral helium due to electron impact. The cross section of the ionization reaction gets the maximum above 100 eV electron temperature, a value much larger than the usual electron temperature in MDIS (20-25 eV). The plasma temperature has been modified by shifting the permanent magnets with respect to the plasma chamber. The magnets system has been moved with steps of 2 mm from the home position towards the microwave line, over a maximum shift of 6 mm. The best results have been obtained when magnets were placed at the reference position (Z=0) and with a $6^.10^{-5}$ mbar pressure [8]. Furthermore both the BN disks and the alumina tube were inserted in the source to increase the electron density and the extracted current ($I_{extr} \propto n_e$). The comparison of He^+ obtained at different values of the permanent magnets positions are shown in Fig. 1.

In a hydrogen plasma, four reactions have the largest possibility to occur:

$$H_2 + e^- \rightarrow H+H + e^- \tag{1}$$

$$H_2 + e^- \rightarrow H_2^+ + 2e^- \tag{2}$$

$$H_2^+ + e^- \rightarrow H^+ + H + e^- \tag{3}$$

$$H + e^- \rightarrow H^+ + 2e^- \tag{4}$$

The plasma parameter which mainly affects the H_2^+ production is the ion lifetime. H_2^+ molecules, indeed, are metastable in a plasma because the possible collisions with electrons (reaction n.3) can lead to the molecule break-up. Ion lifetime can be decreased in a MDIS by removing the alumina tube and the BN in the extraction region. Such a modification of the experimental set-up allows an improvement of the H_2^+ fraction from 5-10% up to 50%. Unfortunately, the increase of the H_2^+ fraction is

accompanied by a strong decrease of the total current (H^+ + H_2^+) due to the electron density decrease. Figure 2 shows the best results, obtained with both BN placed at the source endplates, at a pressure of $2 \cdot 10^{-5}$ mbar and when permanents magnets were shifted by 4 mm from the reference position; about 15 mA of H_2^+ have been obtained in the range 700-1000 W of microwave power with a H_2^+ fraction close to around 45%.
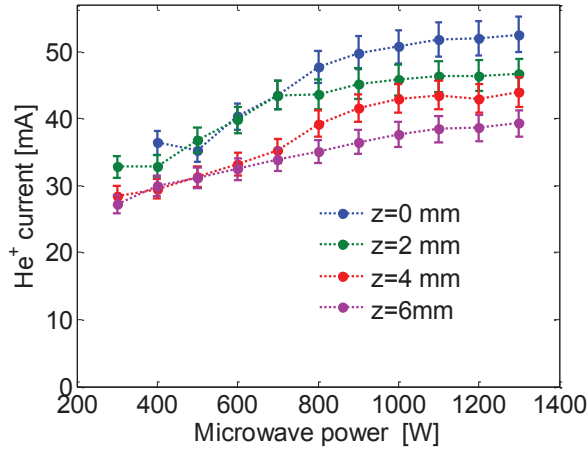

Figure 1: Comparison of He^+ current at the pressure of $6 \cdot 10^{-5}$ mbar for different positions of the permanent magnets.
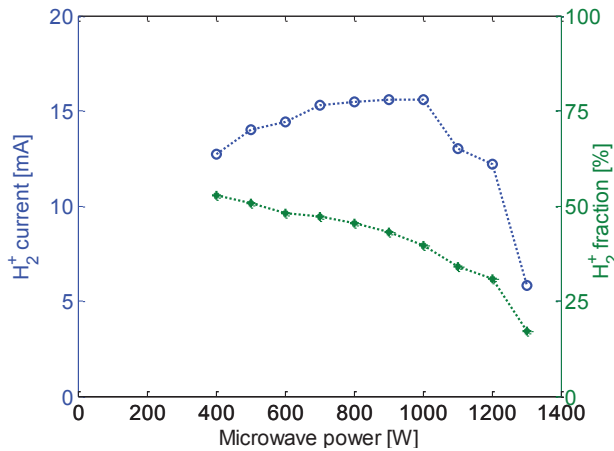

Figure 2: H_2^+ current and proton fraction at the pressure of $2 \cdot 10^{-5}$ mbar. Permanent magnets were shifted by 4 mm from the reference position and BN disks were placed at the source endplates.

GUIDELINES FOR THE NEW H_2^+ SOURCE

The overall H_2^+ current produced by the VIS source does not fulfil the requests of the ISODAR experiment (25-50 mA). In order to fulfill the ISODAR requests a new plasma chamber and microwave line is being designed at INFN-LNS. The new H_2^+ source will work at 2.45 GHz with the same magnetic and extraction systems actually used on VIS. Some remarkable modifications in the source dimensions and consequently in the microwave coupling will allow to increase the H_2^+ fraction without any loss in the total extracted current. The dimensions of the plasma chamber play a fundamental role in determining the mean ion lifetime in plasma. In particular, if the conditions for Simon diffusion arise [7, 9], a rough estimation of ion lifetime as a function of the chamber dimensions leads to:

$$\tau_i \approx \frac{L^2 r^2}{8D_i} \frac{L+r}{L^3+2r^3} \qquad (5)$$

L and r being respectively the length and radius of the chamber, while D_i is the ion diffusion coefficient. Equation 5 shows that the confinement time is dominated by the smallest dimension. Since in ion sources typically r<L, chamber radius determines mean ion lifetime in plasma. Consequently, the best way to reduce the ion lifetime is the reduction of the plasma chamber radius, according to [1011]. The overall output current depends on the plasma volume which can be extracted from the source; in a MDIS, such a volume is proportional to a flux tube of the dimensions of the source extraction hole. If the chamber radius is much larger than this characteristic dimension, no influence of the output current is expected.

The generation of the H_2^+ molecules and their fraction in a hydrogen plasma can be modeled by means of the balance equations, the set of equations representing the plasma in the stationary state [12]. By including the ion lifetime calculated from equation (5), the H_2^+ fraction can be estimated (Fig. 3). The simulation, performed with Matlab, shows that a chamber radius of 20 or 25 mm would double the H_2^+ fraction with respect to VIS. However, the reduction of the radial size of the ion source cavity, at the frequency of 2.45 GHz, needs an efficient design to ensure the match between the non-uniform taper waveguide transition from WR284 to the smaller plasma chamber. A study on the transition between the WR284 and a smaller size waveguide, preserving 2.45 GHz as operating frequency, is shown in the next section.
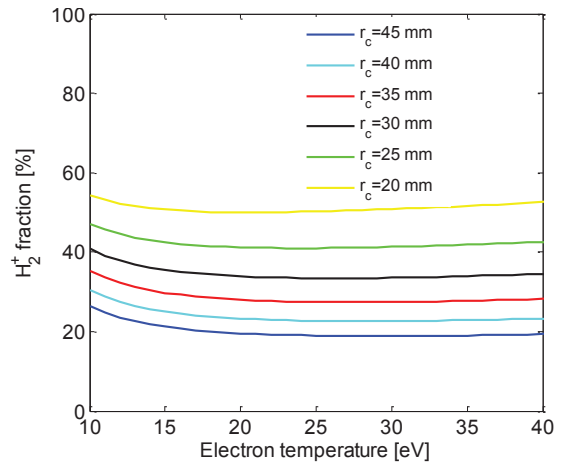

Figure 3: H_2^+ fraction as a function of electron temperature for different chamber radius r_c.

FEM SIMUATIONS OF THE NEW INJECTION SYSTEM

In rectangular waveguides, physical size is the primary lower-frequency limitation or cut-off frequency that is $f_c=c/2a$, where c is the speed of light in vacuum and a is the waveguide width. In order to operate in the dominant mode TE_{10}, the width of waveguide must be approximately a half wavelength at the frequency of the wave to be transported.

According WR284 standard with $a= 72.136$ mm, we can obtain an f_c of 2.079 GHz and so we can operate in the dominant mode TE_{10} at the operating frequency of 2.45 GHz. However, a smaller cross section, chosen with a width of 3 cm, because of the reduced radius of plasma chamber, increase dramatically the cutoff frequency to 5 GHz, resulting impossible to operate at 2.45 GHz with conventional rectangular waveguide. Therefore, to extend the maximum practical bandwidth, we will employ a double ridge waveguide that, compared to rectangular waveguides, shows the advantages of very wide fundamental mode operation bandwidths and lower cutoff frequency. The low cutoff frequency allows a small cross section and hence a compact size of ridge waveguide. Furthermore, great design flexibility exists in ridge configuration, according to different electrical and mechanical requirements. Accordingly, a linear tapered double ridge waveguide transition structure for the dominant mode (TE_{10}), with low reflection coefficient has been designed. The transition is shown in Fig. 4. The structure has been simulated with the commercial electromagnetic simulation software CST microwave studio, based on the finite integral technique, and with COMSOL Multiphysics, based on the finite element method with very good agreement between the two different solver techniques, validating the simulations. Figure 5 shows the magnitude of the scattering parameter S_{11} and S_{21} simulated in CST over the 2.1 to 3.4 GHz band: for the designed transition, the S_{11} is always less than -10 dB for the frequency range considered, while from the S_{21}, it can be seen that the wave propagation at 2.45 GHz has been restored in the waveguide with very low losses.
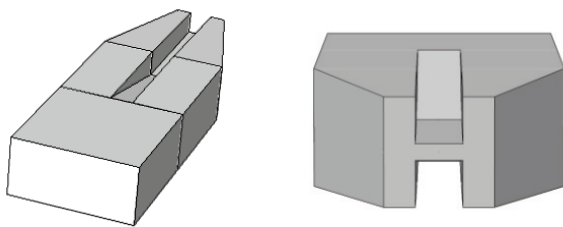

Figure 4: a) Tapered double ridge waveguide transition structure; b) Cross section of double ridge waveguide.
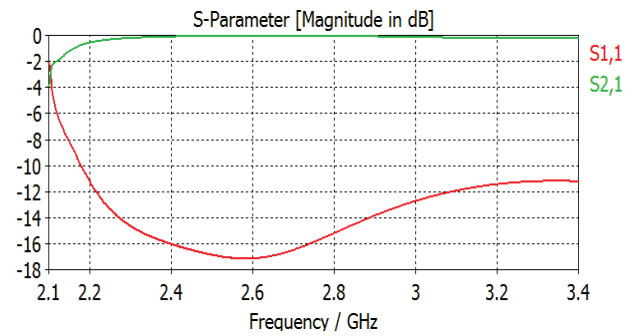

Figure 5: CST simulated S_{11} and S_{21} versus frequency for the linear double taper.

CONCLUSIONS

The VIS source is able to produce more up than 50 mA of low emittance proton beams. Moreover, by modifying the experimental set-up, it can produce more than 50 mA of He^+ and up to 15 mA of H_2^+. However, the performances in terms of H_2^+ production are not sufficient to fulfil the requirements of the IsoDAR project. In order to increase the H_2^+ current, a new structure is going to be defined. The simulations show that the reduction of the chamber radius is a key point for the increase of the H_2^+ current, therefore a novel plasma chamber and microwave injection are under design at INFN-LNS.

ACKNOWLEDGMENTS

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