MICROWAVE ION SOURCE AND BEAM INJECTION FOR AN ACCELERATOR-DRIVEN NEUTRON SOURCE *

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Abstract

An over-dense microwave driven ion source capable of producing deuterium (or hydrogen) beams at 100-200 mA/cm^2 with an atomic fraction > 90% was designed as a part of an Accelerator Driven Neutron Source (ADNS). The ion source was tested with an electrostatic low energy beam transport section (LEBT) and measured emittance data was compared to PBGUNS simulations. In our design a 40 mA D^+ beam is produced from a 6 mm diameter aperture using a 60 kV extraction voltage. The LEBT section consists of 5 electrodes arranged to form 2 Einzel lenses that focus the beam into the RFQ entrance. To create the ECR condition, 2 induction coils are used to generate a ~875 Gauss magnetic field on axis inside the source chamber. To prevent HV breakdown in the LEBT, a magnetic field clamp is necessary to minimize the field in this region. The microwave power is matched to the plasma by an autotuner. A significant improvement in the atomic fracion of the beam was achieved by installing a boron nitride liner inside the ion source

INTRODUCTION

An accelerator-driven neutron source for screening cargo containers to detect shielded nuclear material [1-4] was designed at Lawrence Berkeley National Laboratory (LBNL). The key components of the ADNS include a high current D^+ ion source, a low energy beam transport (LEBT) section, a RFQ accelerator, beam bending and scanning magnets, and a deuterium gas target (see Fig. 1). [2] This paper discusses is the ion source and LEBT section shown in Fig.2. Taking beam losses into consideration, the required peak current from the ion source is ~40 mA D^+ ions with a pulse length of ~0.3 ms and a 180 Hz repetition rate.

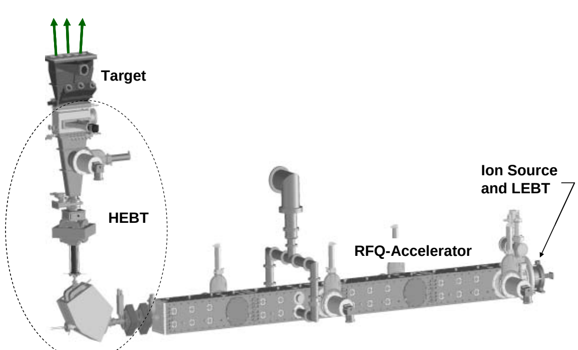

Figure 1: ADNS system CAD model.

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For this application, we have chosen to use a 2.45 GHz microwave ion source due to its high power efficiency, and reliability. [5,6] In order to minimize neutron generation at the test stand, most of the ion source and LEBT tests were performed using hydrogen gas instead of deuterium. Thus the required peak current scales to ~57 mA of H^+ for a matched perveance.

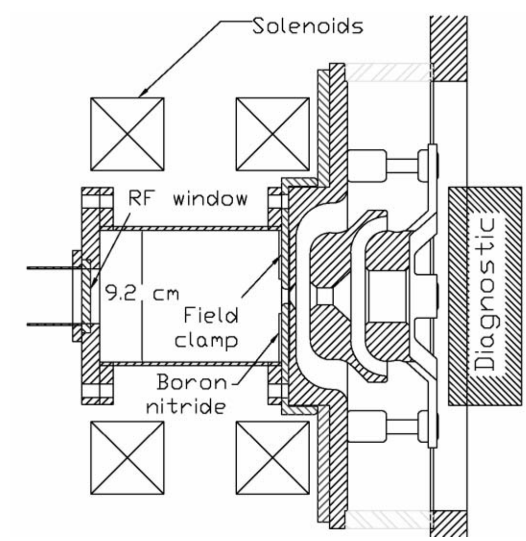

Figure 2: Schematic of the ion source and the test extraction system. The diagnostic element can be a Faraday cup to measure the current, a Wien filter to measure the ion species or a pepper pot to measure the emittance.

ION SOURCE

The design of the ion source is presented in Fig. 2. The 2.45 GHz microwaves are generated by a magnetron and transmitted to the ion source using a wave-guide. The RF is impedance matched to ion source by an auto-tuner. A pair of solenoids is used to generate the axial magnetic field required for creating an ECR condition.

It is necessary to shield the LEBT from the stray magnetic field because the field affects the beam optics and causes high voltage break down problems. This was accomplished by installing a magnetic steel plate at the source exit. However the magnetic field clamp at the present location has an adverse effect on the beam current and species. A boron nitride (BN) liner was used inside the plasma chamber to increase the atomic fraction and extracted current density. [1,7,8] Optimum operation of the source is achieved with gas flow of ~1.5 sccm (equivalent to ~0.15 Pa operating pressure).

Ion Source Performance

Figure 3 shows the effect of the clamp on the magnetic fields in the source and the LEBT. Figures 4 and 5 shows the effect of the clamp on the ion current and species fractions. With the clamp about a factor of two more power is required to achieve the same extracted beam current than without the clamp. In absence of the clamp the desired H^+ fraction of >90% was achieved at Rf-power of ~700W. We estimate that RF-power >2000 W is required to achieve the desired ~90% H^+ fraction when the clamp is installed.

There are a few possible reasons for the reduced source performance. The stronger field caused by the clamp near the BN lining was shielding the BN from the plasma and thus reduced the effect of BN in producing H^+ ions. The deformation of the magnetic fields by the clamp (Fig. 3) affects the coupling of RF power to the plasma and hinders the plasma flow to the extraction, thus reducing the source performance. It has been shown [6] that the highest D^+ or H^+ species fraction and currents are achieved if the magnetic fields are uniform through out the source.

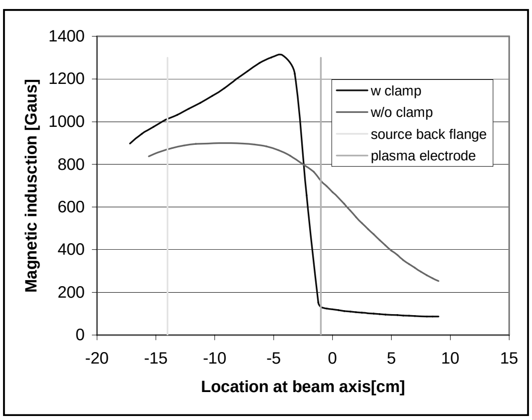

Figure 3: Magnetic fields along the central axis of the source. Measurements were performed with a 106 A induction current.

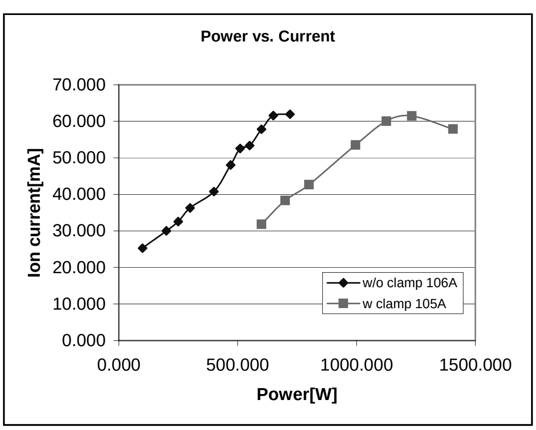

Figure 4: Ion current as function of RF power for setup with and without field clamp. In both cases, the extraction voltage was 60kV, the gas flow 1.5 sccm and magnetic induction currents 105-106 A.

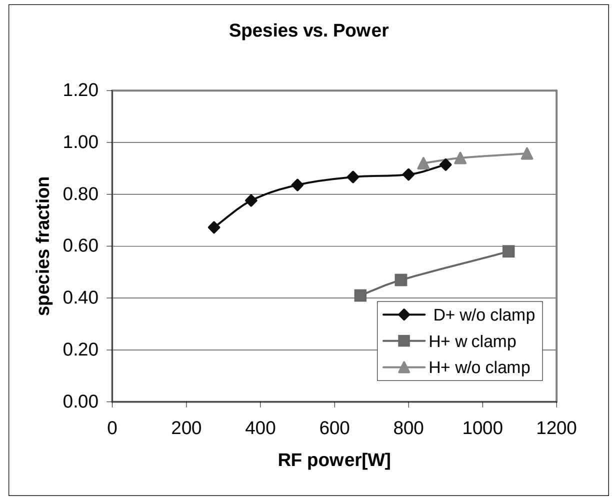

Figure 5: Measured H+ and D+ fraction as a function of power. Gas flow was 1.5 sccm and magnetic induction currents 105-109A.

LEBT

The PBGUNS simulation code [9] was used for the LEBT design. The LEBT consists of an extraction gap and two Einzel lenses, a total of 6 electrodes, as shown in Fig. 6. The two Einzel lenses provide good control over the Twiss parameters at the entrance of the RFQ. In the designed LEBT the required 40 mA of D^+ current is delivered to the entrance of the RFQ with an emittance of $\varepsilon_{n,1RMS}$ = 0.0195 pi-mrad-mm and Twiss parameter values of α = 0.535 , β = 0.0518 mm/mrad and γ = 24.84 mrad/mm. The beam is well inside the RFQ acceptance of $\varepsilon_{n,1RMS}$ =0.055 pi-mrad-mm, α = 1, β = 0.07 mm/mrad and γ = 28.57 mrad/mm.

In order to confirm the accuracy of the simulations, we built a test extraction system and compared the measured emittance with the corresponding simulation results. The test extraction system consists of a triode setup and beam diagnostics as shown in Fig.2.

The emittance measurement system consisted of a multi-slit screen positioned 1.2 cm downstream of the last electrode followed by a kapton foil 9.8 cm downstream of the slit screen. Each slit was 0.2 mm wide and the separation between slits was 1.27 mm. The ion source operating parameters during the emittance measurement (Fig. 7) was as follows: a gas flow of 1.5 sccm, RF power of 1070 W and a magnet coil current of 106 A. The measured ion current was 22 mA and the species distribution was: 58% H^+, 21% H_2^+, 10% H_3^+ and 10% impurities (mass ~ 17 and ~25). Using Eg. 1 the effective mass is $m_{eff} \approx 2.4$ amu.

$$m_{eff} = \left(f_1\sqrt{m_1} + f_2\sqrt{m_2} + f_3\sqrt{m_3} + \ldots \right)^2 \quad (1)$$

Here f_n and m_n are species fractions and the masses of the species n.

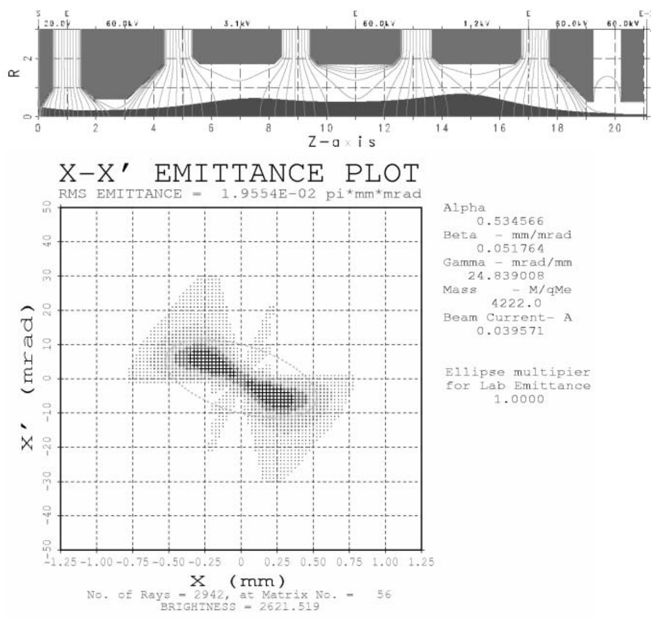

Figure 6: PBGUNS trajectory plot and emittance at the entrance of the RFQ for the designed LEBT.

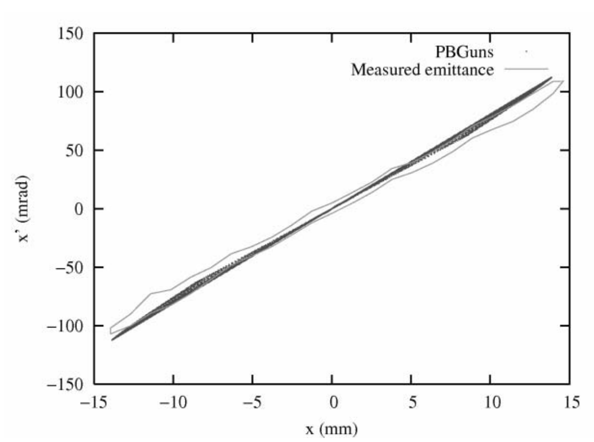

Figure 7: Measured and simulated emittances. The ion current was 22 mA, the effective mass 2.4 amu, and the B-field 100 Gauss.

Figure 7 shows the measured emittance and x-x' phase plot from the PBGUNS output for the measured current and effective mass.

In addition to the beam current and ion species, the beam spot size and divergence are affected by the LEBT geometry, electrode voltages and magnetic field in the LEBT. Errors in the definition of any of these variables in the simulation might cause the minor discrepancies in beam spot size and divergence seen in Fig. 7. Space charge in the drift region and charging of the kapton foil behind the slit screen were not taken into account when determining the measured emittance. Within the measurement tolerances it seems that the measured and simulated emittances are in good agreement.

CONCLUSION

The current and species required for the ADNS application were achieved in absence of a magnetic field clamp [1]. A considerable reduction in the extracted ion currents and H^+ fraction occurred when the field clamp was placed on the plasma electrode. This problem can be overcome by either optimizing the position of the field clamp (e.g. at the back of the extraction electrode) or by using permanent magnets (PM) to generate the required magnetic fields. PM sources have been shown to work well [10] and stray fields from permanent magnets are not as far reaching as the fields caused by the induction coils.

The measured emittance agrees with the simulated emittance thus confirming the validity of the PBGUNS calculations.

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