第 31 卷 增刊 I　高 能 物 理 与 核 物 理　Vol. 31, Supp. I
2007 年 7 月　HIGH ENERGY PHYSICS AND NUCLEAR PHYSICS　Jul., 2007

A 2.45GHz High Current Ion Source for Neutron Production*

J. W. Kwan1) R. Gough R. Keller2) B. A. Ludewigt
M. Regis R. P. Wells J. H. Vainionpaa

(Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA)

Abstract A 2.45GHz microwave-driven ion source is being used to provide 40mA of deuterium ion beam (peak current) for an RFQ accelerator as part of a neutron source system. We have also designed a 60kV electrostatic LEBT using computer simulations. In our experiment, we measured the hydrogen and deuterium ion beam currents as functions of discharge power, gas flow, and magnetic field strength. The required beam current was obtained using less than 700W of net microwave power with a gas flow of less than 1.5sccm. From the rise time data, it was determined that in order to obtain a high percentage of atomic ions in the beam, the beam extraction should start after 1ms of switching on the microwave power. At steady state, the proton fraction was above 90%.

Key words microwave-driven, ECR ion source, proton, deuterium, beam

1 Introduction

At LBNL we are designing an accelerator-driven neutron source (ADNS) for scanning cargo containers to detect shielded nuclear material. The key components of this system 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. A schematic diagram of the device is shown in Fig. 1. With the gas target at 2 atmosphere pressure, the system can produce neutrons with energy up to 8.5MeV in a forward directed flux of up to $2\times10^7 n/cm^2/s$ at 2.5m distance from the target[1]. The 200MHz, 5 m long, RFQ is designed to accelerate D^+ ions to 6MeV[2].

Our design goal is to have a time-averaged beam current of nominally 1.5mA. At ~5% duty factor and taking beam loss into consideration, the required peak current from the ion source is ~40mA D^+ ions with a pulse length of ~0.3ms and 180Hz repetition rate.

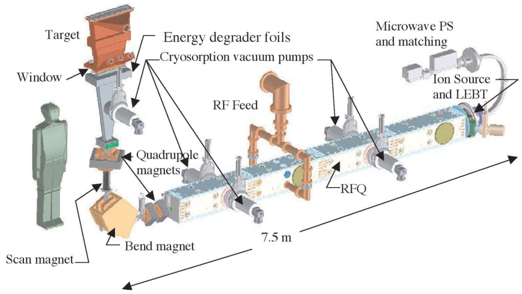

Fig. 1. Schematic diagram of the ADNS system.

For this application, we have chosen to use the 2.45GHz microwave ion source because of its capability in producing high ion current density, at high duty factor, and low maintenance requirement. As part of the engineering R&D, we have tested a prototype ion source to determine the design parameters, measuring both proton and deuteron beam characteristics. Based on these parameters, we have also designed an electrostatic LEBT. The results of ion source testing and the designed beam optics are reported here.

Received 20 April 2007

* Supported by US Dept. of Homeland Security

1) E-mail: jwkwan@lbl.gov

2) Current affiliation: Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

232 — 235

2　The injector design

The ion source being tested is similar to the one developed by Taylor[3]. This type of ion source has been shown to efficiently produce very high current density beams[4] and to provide reliable, long life, low maintenance usage[5]. A cut away view of the ion source with the extraction diode is shown in Fig. 2. The plasma chamber is 9.2cm in diameter and 12.7cm long. Microwave power is transmitted via a rectangular waveguide through an aluminum nitride window into the plasma chamber. The beam outlet aperture is 6mm in diameter. A boron nitride liner is placed in front of the source electrode (facing the plasma) for improving the yield of atomic ions. An axial magnetic field, that is required to set up the electron cyclotron resonant condition, is produced by passing approximately 106A of dc current through the field coils. We recently learned that these field coils can be replaced by permanent magnets while preserving good performance[6]. We will consider this approach in our future design.

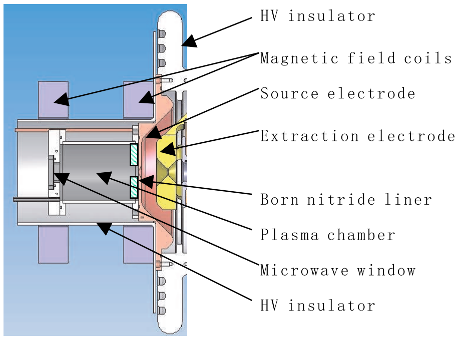

Fig. 2.　Schematic diagram of the ion source.

A 60kV electrostatic low energy beam transport section is used to inject the extracted beam into the RFQ accelerator. After extraction (at 60kV), the beam envelope adjustment is done by two Einzel lenses. Furthermore, two pairs of deflection electrodes are embedded in the middle ground electrode to allow steering of the ion beam (in x and y directions) in order to position the beam spot at the center of the RFQ entrance.

In the simulation, an average ion mass of 2.3 is used to include the effect of mixed molecular ion species. An axial magnetic field of ~0.1Tesla is assumed in the region just in front of the aperture but is turned off at the center of the extraction electrode. This is to approximate the effect of a field clamp to keep the ion source's solenoid field from extending downstream. In general, the maximum voltage gradient in the LEBT is kept to less than 100kV/cm in order to prevent high voltage breakdowns.

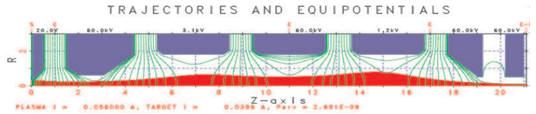

Fig. 3.　Simulation using PBGUNS for the LEBT design.

Figure 3 shows a layout of the LEBT electrodes and the beam envelope predicted by computer simulations using the PBGUNS[7] code. The source aperture radius (1st electrode on the left) is 0.3cm and the 1st gap is 1cm. The entire LEBT length is 20cm. Electrode potentials are at 60kV, ground, 56.9kV, ground, 58.8kV, ground, and the last one is RFQ entrance plate which is at ground potential. As shown in the figure, the ion beam is transported through the LEBT with plenty of clearance. According to the simulation, the normalized single rms r-r' emittance is 0.04π·mm·mrad at the exit of the LEBT. The corresponding x-x' emittance is 0.02π·mm·mrad.

3　Experimental results

Our main goal was to determine the optimum operating parameters for the ion source. We have constructed the first 3 electrodes in the LEBT and used them to extract beams from the ion source. An electronic gas flow controller is used to adjust the ion source pressure. At a typical gas flow of 1.5sccm, the corresponding hydrogen gas pressure inside the plasma chamber is estimated to be 0.16 Pascal.

Figure 4 shows the beam current measured by a Faraday cup as a function of microwave power. It was difficult to measure the net power (forward minus reflected power) accurately. The beam currents increased almost linearly with the net microwave power until they reached the space charge limits, at about 62mA for hydrogen and 44mA for deuterium. As expected, these limits are inversely proportional to the square root of mass. For comparison, 44mA of H^+ at 60kV was 10% above the designed perveance.

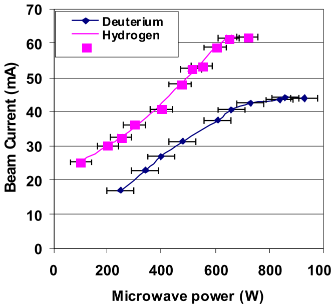

Fig. 4. Beam current from the microwave ion source.

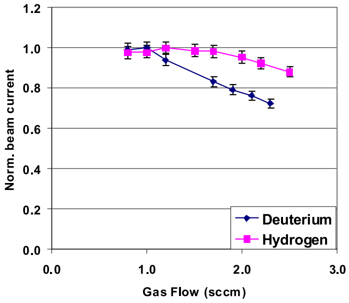

Fig. 5. Optimum gas flow was between 1.2—1.5sccm.

The data in Fig. 4 were obtained with a gas flow of 1.5sccm and with 106A of dc current applied to the magnetic field coils. Both of these parameters were near their optimum values as shown in Fig. 5 and Fig. 6. At gas flow of 1.0sccm or below, the beam current became very noisy. According to the calibration, 106A of field coil produces a B field of 875Gauss (which corresponds to the ECR frequency of 2.45GHz) at 2.5cm in front of the rear window. The magnetic field distribution is shown in Fig. 7.

At 180Hz and 5% duty factor, the required beam pulse length for ADNS is 278μs. Depending on the beam current rise time, turning on the beam pulse can be done by switching either the microwave power or the extraction voltage. Fig. 8 contains a typical oscilloscope trace of the Faraday cup current. Although it only took 20μs for the hydrogen ion current to reach 80% of equilibrium value, the slower rise for the remaining 20% was about 1ms. The deuterium rise time was faster, at around 0.6ms. The situation was actually more complicated because we must also consider the distribution of ion species in the beam current. After all, it is the rise time of the atomic ions that matters most in this application.

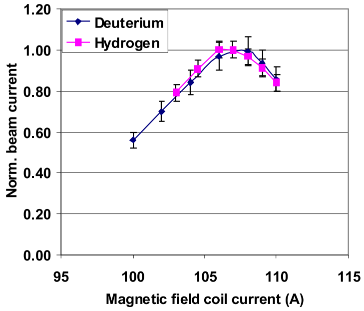

Fig. 6. Optimum magnetic field was at 879 Gauss when the field coil current was at 106.5A.

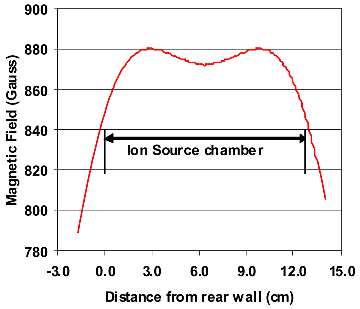

Fig. 7. Magnetic field distribution produced by 106.5A of field coil current.

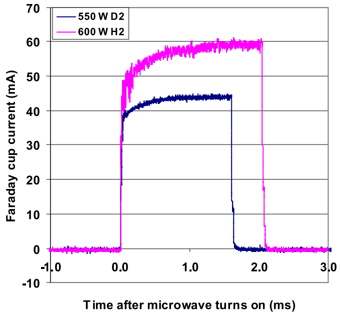

Fig. 8. The total beam current verses time (oscilloscope).

A Wien (ExB) filter was used to measure the fractions of ion species contained in the beam. As expected, the atomic ions H^+, and the molecular ions H_2^+ and H_3^+ were seen (likewise for deuterium). The ratios changed during the rise time and approached equilibrium after about 1.5ms. In fact, the gradual build up of the H^+ fraction was responsible for the long rise time seen in the total beam current monitored by the Faraday cup. Fig. 9 depicts the time dependence of the various hydrogen species when the ion source was operating at the level of about 600W net microwave power, and with 1.5sccm gas flow and 109A coil current. At steady state, the fractions of H^+, H_2^+, H_3^+ and impurity (mass = 18.7) were 92.2%, 5.3%, 0.8% and 1.7% respectively. These results were in agreement with that reported by Tanaka[8]. (Tanaka's data showed a factor of 2 faster in rise time but less current density for the same microwave power).

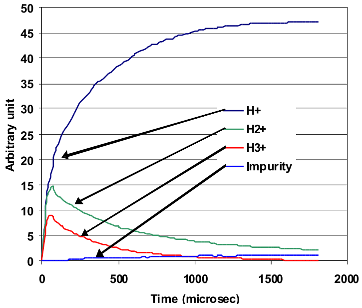

Fig. 9. Ion species varying as a function of time.

In comparison, the atomic ion fraction was poor when operating the ion source without a boron nitride liner. In most cases, the equilibrium fractions of H^+, H_2^+, H_3^+ were 47.6%, 38.1% and 14.3%. The rise time structure was similar but faster than that with the presence of boron nitride liner. Typically the initial jump took ~5μs and was followed by a slower rise of 200μs to reach equilibrium.

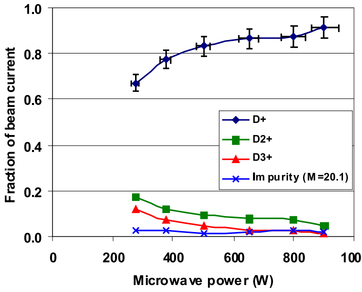

Fig. 10. Ion species varying as a function of discharge power.

The deuterium species rise times were nearly the same as the hydrogen ones (as in Fig. 8 with boron nitride liner). We have also measured the equilibrium deuterium ion species fractions as a function of discharge power at the optimum gas flow of 1.2sccm and 107A magnetic field coil current. The result is shown in Fig. 9. In general, both the rise time and the fraction of the atomic ions improve with discharge power.

4 Conclusion

We have tested a 2.45GHz microwave-driven ion source to produce high current proton and deuteron beams for injection into an RFQ accelerator. The required current of 40mA deuterium beam was obtained using less than 700W of net microwave power with a gas flow of less than 1.5sccm. By measuring the rise time of each ion species, it was determined that in order to obtain a high percentage of atomic ions in the beam, the beam extraction should start after 1ms of switching on the microwave power. At steady state, the atomic ion (proton) fraction was above 90%. We are in the process of setting up a scanner to measure beam emittance; results from that measurement will be reported in a future paper.

5 Acknowledgments

The author would like to thank John Staples, Derun Li, Alex Ratti, Joe Wallig, and Don Syversrud for their valuable discussion and technical support. We would also like to thank Argonne National Lab for lending us the ion source. This work is supported by the US Dept. of Homeland Security and the Dept. of Energy under contract number DE-AC03-76SF00098.

References

1 Ludewigt B A, Bleuel D L, Hoff M D et al. Accelerator-Driven Neutron Source for Cargo Screening, 19th International Conference on the Application of Accelerators in Research and Industry, Fort. Worth, Texas, Aug 20—25, 2006
2 Staples J W, Hoff M D, Kwan J W et al. Design of an RFQ-Based Neutron Source for Cargo Container Interrogation, Linear Accelerator Conf., Knoxville, TN, Aug 21—25, 2006
3 Taylor T, Mouris J F. Nucl. Instr. Meth. Phys. Research, 1993, **A336**: 1—5
4 Sherman J D et al. Rev. Sci. Instrum., 2002, **73**: 917
5 Derenchuka V P. Rev. Sci. Instrum., 2004, **75**: 1851
6 SONG Z, PENG S, YU J et al. Rev. Sci. Instrum, 2006, **77**: 03A305
7 PBGUNS Version 5.04, copyright Aug. 2001 by Jack E. Boers Ph.D. and Thunderbird Simulations
8 Tanaka M, Hara S, Hae T et al. Rev. Sci. Instrum., 2004, **75**: 1894