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USE OF A 2.45 GHz ECR ION SOURCE FOR THE NEUTRON TARGET DEMONSTRATOR PROJECT*

S. Melanson†, M. Dehnel, A. George, S. Suram, D-Pace Inc., Nelson, BC, Canada

Abstract

D-Pace has licensed a 2.45 GHz ECR ion source from Neutron Therapeutics. The ion source will be used for the Neutron Target Demonstrator project at Los Alamos National Laboratory where 10 mA of singly charged krypton ions at 50 keV are required with a normalized 4-RMS emittance of less than 1 mm·mrad. The goal of the project is to show a reverse kinematics neutron capture reaction with krypton 84 ions. Due to the high radiation environment that the ion source will be subjected to, a solid state microwave power supply will be used instead of the traditional magnetron for the experiment. The main advantage of the solid state power supply is that the output is transmitted by a coax cable instead of a waveguide, so the power supply can be located a long distance away from the ion source without the need for complicated and expensive waveguide. The other advantage of the solid state device is that the frequency can be varied from 2.4 GHz to 2.5 GHz. This gives the operator an extra degree of freedom for tuning. We present how the frequency variation affects the beam parameters.

INTRODUCTION

The Neutron Target Demonstrator (NTD) project at the Los Alamos Neutron Science Center (LANSCE) will be the first demonstration of a reverse kinematics neutron capture reaction [1]. Neutrons will be created by spallation of the 800 MeV proton beam onto a target. A beam of Kr-84 ions will serve as the target ions for the neutron capture reaction $Kr^{84}(n,\gamma)Kr^{85}$. D-Pace is providing LANSCE an ECR ion source system capable of producing mA level beam of Kr-84 at an energy of up to 50 keV. Figure 1 shows a schematic of the NTD as well as a CAD model of the ion source system.

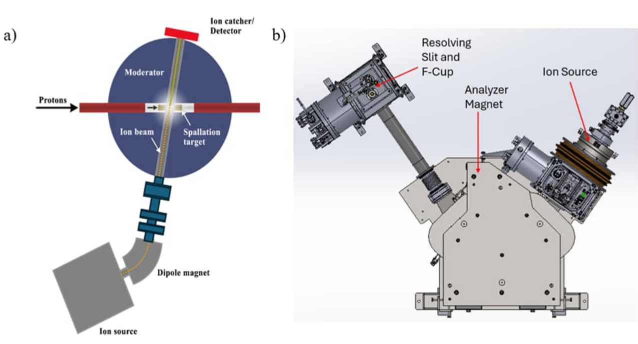

Figure 1:a) Schematic of the NTD project. Figure provided by A. Cooper at LANSCE under LA-UR-24-27491. b) Plan view of the CAD model for the ion source system.

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† stephane@d-pace.com

ION SOURCE

D-Pace has licensed a 2.45 GHz ion source from Neutron Therapeutics [2] which is based on the first 2.45 GHz ion source developed by Wills and Taylor [3]. The ion source is commonly used in their boron neutron capture therapy system producing 30 mA DC of protons at an energy of 50 keV.

The microwave injection system consists of a 3-stub tuner, forward and reverse power monitors. A high voltage waveguide break was designed with alternate layers of G10 and aluminium plates to allow for the microwave generator to be grounded while the ion source is at 50 kV. The microwave power is transmitted through an aluminium nitride window to the plasma chamber.

The magnetic field is produced by three solenoids, labelled back, centre and front, where the front solenoid is closest to the extraction and the back solenoid is closest to the microwave injection. The cylindrical plasma chamber is made of aluminium with a diameter of 76 mm and a length of 95 mm. Boron nitride plates are mounted on both the front and the back edges of the plasma chamber.

The extraction system is formed by four molybdenum electrodes. The plasma electrode aperture has a diameter of 6.5 mm. The first ground electrode, the suppression electrode and the second ground electrode apertures have diameters of 9 mm, 11 mm and 11.5 mm respectively. The suppression electrode is commonly biased at -3 kV relative to ground. The ground and suppression electrodes are installed on a moveable trolley allowing for active tuning of the distance between the plasma aperture and the first grounded electrode by 26 mm.

EXTRACTION OF KRYPTON

The test stand used for testing the extraction of Krypton ions for the NTD project is composed of the ion source, an emittance scanner and a Faraday cup. The Allison-type emittance scanner [4] was mounted at $z = 547$ mm where $z = 0$ mm is the ion source's plasma aperture. The emittance scanner can be mounted in both x and y directions. The Faraday cup was located at $z = 714$ mm. A CAD model of the test stand is presented in Fig. 2.

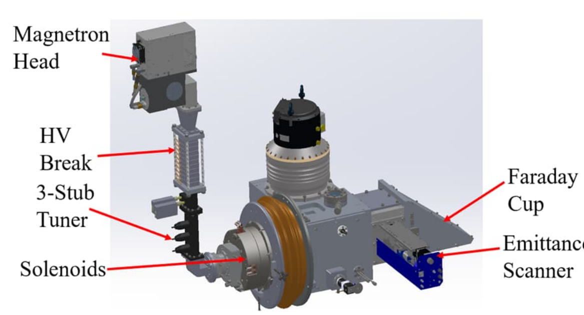

Figure 2: CAD model of the test stand.

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The first tests on the ion source at D-Pace's facility were with hydrogen to confirm the performance of the ion source. The optimum solenoid settings for the extraction of hydrogen beams are presented in Table 1. The optimum gas flow was found to be 1.8-2.2 sccm.

Table 1: Optimum Solenoid Current Range for Hydrogen

Front Solenoid	Center Solenoid	Back Solenoid
50-60 A	5-10 A	75-85 A

The ion source was then optimized for the extraction of krypton. We found that the magnetic field profile needed for krypton was different than hydrogen, with a lower field needed at the extraction. The optimum gas flow is also lower at only 0.1 sccm of Kr gas. A new mass flow controller was ordered to allow for more precise control at the low flows needed. Table 2 presents the optimum solenoid current values for Krypton and Fig. 3 shows the simulated magnetic field on axis for hydrogen and krypton.

Table 2: Optimum Solenoid Current Range for Krypton

Front Solenoid	Center Solenoid	Back Solenoid
0-5 A	50-55 A	75-80 A

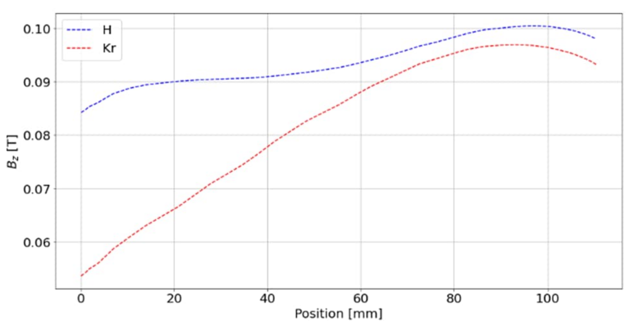

Figure 3: Simulated magnetic field on axis for the extraction of hydrogen and krypton beams. The plasma aperture is located at z=0.

Up to 10 mA of total krypton beam can be extracted out of the ion source at an energy of 50 keV. The charge states have not yet been analysed since the test stand does not yet have a mass spectrometer system installed. Figure 4 plots the beam current as a function of the microwave power and the extraction voltage.

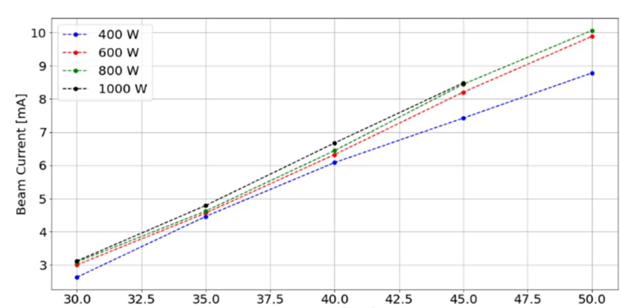

Figure 4: Total extracted krypton beam as a function of the extraction energy for various injected microwave powers.

The beam current is highly dependent on the extraction energy. The extraction gap was actively tuned with every change in energy and microwave power. As expected, the gap increased with the increase in extraction voltage and with the increase in power.

The phase space was analysed in both x and y planes. The normalized 4-RMS emittance was between 0.04 and 0.05 mm·mrad for the x and y emittance as can be seen in Fig. 5.

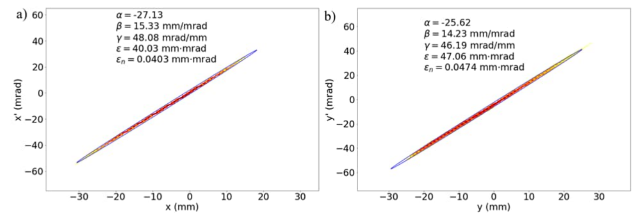

Figure 5: Phase space scans from krypton beams at an extraction energy of 40 keV and a microwave power of 400 W.

SOLID STATE POWER SUPPLY

Due to the high radiation environment of the NTD, there can be no power supplies close to the ion source. This includes the microwave power supply, which will have to be located outside of the bunker, at a minimum of 50 meters away from the ion source. A magnetron could be used, but this would be an expensive and complicated option since a long waveguide would have to be used. Instead, a solid state power supply will be used. A 1.6 kW power supply capable of variable frequency from 2.4 GHz to 2.5 GHz was purchased from RFHIC [5]. The power supply has a coaxial output instead of a waveguide, greatly simplifying the installation of the system for the NTD project. To get the microwave power to the ion source, a 7/16 DIN to WR340 adapter is connected to the ion source's waveguide.

In addition to the coaxial output, another advantage of using solid state power supplies is the ability to vary the microwave frequency. This gives the operator an additional tuning parameter. Figure 6 shows how the krypton beam current varies as a function of the microwave frequency without varying the 3-stub tuners or the magnetic field. From the figure, it is clear that the frequency has a significant influence on the beam current. This is comparable to the influence of the solenoid magnetic field on the beam current for a fixed microwave frequency.

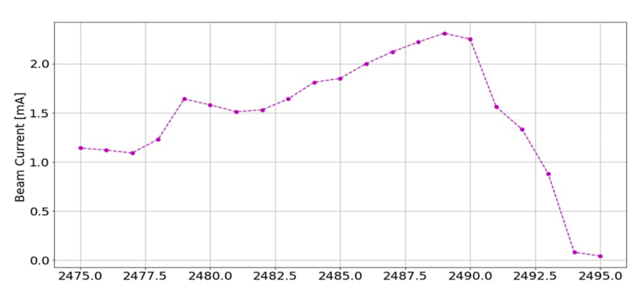

Figure 6: Krypton beam current as a function of the microwave frequency.

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PERMANENT MAGNET SOLENOID

To further simplify the system for the installation in the high radiation environment of the NTD project, D-Pace is investigating the use of permanent magnets to replace the solenoids. This would allow for the operation without any power supplies floating at the ion source voltage, eliminating the need for high voltage and high current cables between the ion source and the power supplies outside of the radiation bunker. A permanent magnet version of the ion source would also reduce the manufacturing and the operating costs as well as simplify the operation of the ion source.

To create the permanent version of the ion source, the solenoid was first simulated using FEMM [6] in a 2D axis-symmetric mode. A good agreement between the simulated model and magnetic field measurements on axis was achieved, confirming the magnetic model. The next step was to create a model with only permanent magnets with the goal of replicating the magnetic field on axis as best as possible. For simplicity of installation, the outer steel shell that houses the solenoid was kept for the permanent magnet version. Standard bar magnets that are available commercially were also used.

The design created uses 2"x1"x1/2" N42 magnets and 1"x1"x1" N52 magnets arranged in a ring configuration. 3D printed plastic parts were manufactured to hold the magnets in place and steel rings were used between the magnet rings to shape the magnetic field as needed. Figure 7 shows the permanent magnet model in FEMM, a CAD model of the assembly and a comparison of the magnetic field on axis between the solenoid and the permanent magnets.

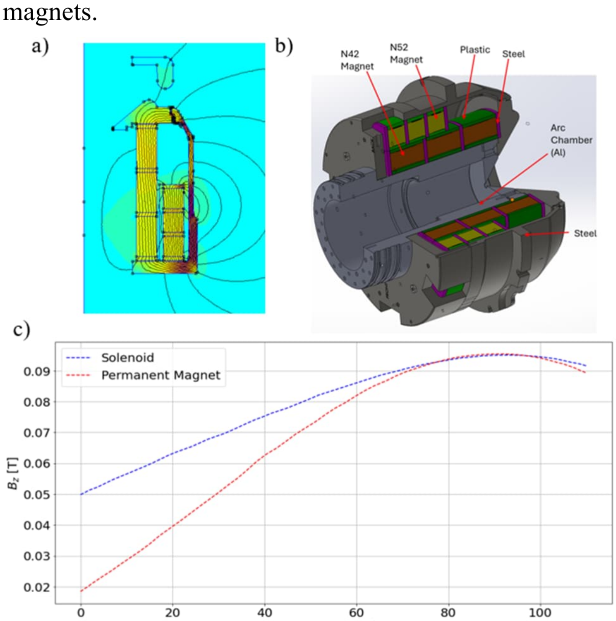

Figure 7: a) FEMM model of permanent magnet solenoid. b) CAD model of the assembly. c) Simulated magnetic field on axis for the solenoid and permanent magnet model.

The permanent magnet assembly was tested on the test stand. A krypton plasma could be ignited in the plasma chamber, however there were frequent high voltage breakdowns when the ion source was set to more than 5 kV. Upon further inspection with a viewing window, a plasma was observed between the ion source and the grounded vacuum box. This plasma discharge is likely caused by the $\vec{E} \times \vec{B}$ trapping of electrons generated in this region. The magnetic field outside the plasma chamber is significantly higher with the permanent magnet than it is for the solenoid, explaining why the discharge is seen only with the permanent magnet version. Figure 8 shows a photograph of the plasma inside the chamber (no voltage applied to the ion source) as well as the discharge seen when a voltage is applied to the ion source.

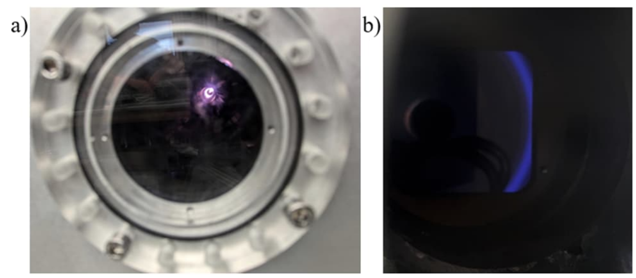

Figure 8: a) Photograph of plasma in the plasma chamber looking through the aperture. b) Glow discharge seen with 5 kV on the ion source.

CONCLUSION AND FUTURE WORK

D-Pace successfully started testing its 2.45 GHz ECR ion source at its facility. This ion source has been shown to extract more than 10 mA of krypton beam and will be used for the Neutron Target Demonstrator project at LANSCE.

A solid state power supply is being used, allowing for variable tuning of the input power frequency.

A permanent magnet version of the ion source is being developed. Initial tests show that a plasma can be generated in the plasma chamber, but frequent breakdowns due to electron trapping in the extraction region prevent the extraction of beam out of the ion source.

The permanent magnet version of the ion source will be redesigned to reduce the magnetic field in the extraction region to prevent the breakdowns seen.

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