DEVELOPMENT OF A PERMANENT-MAGNET MICROWAVE ION SOURCE FOR A SEALED-TUBE NEUTRON GENERATOR

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Abstract

A microwave ion source has been designed and constructed for use with a sealed-tube, high-yield neutron generator. When operated with a tritium-deuterium gas mixture the generator will be capable of producing $5 \cdot 10^{11}\,\mathrm{n/s}$ in non-proliferation applications. Microwave ion sources are well suited for such a device because they can produce high extracted beam currents with a high atomic fraction at low gas pressures of $0.2 - 0.3\,\mathrm{Pa}$ required for sealed tube operation. The magnetic field strength for achieving electron cyclotron resonance (ECR) condition, $87.5\,\mathrm{mT}$ at $2.45\,\mathrm{GHz}$ microwave frequency, was generated and shaped with permanent magnets surrounding the plasma chamber and a ferromagnetic plasma electrode. This approach resulted in a compact ion source that matches the neutron generator requirements. The needed proton-equivalent extracted beam current density of $40\,\mathrm{mA/cm^2}$ was obtained at moderate microwave power levels of $\sim 400\,\mathrm{W}$. Results on magnetic field design, pressure dependency and atomic fraction measured for different wall materials are presented.

INTRODUCTION

A permanent-magnet microwave ion source has been developed for a high-yield, sealed-tube neutron generator (Fig. 1). The generator is designed to operate with a high ion beam current of $100\,\mathrm{mA}$ at $100\,\mathrm{kV}$ acceleration voltage and to produce a high neutron yield of an estimated $5 \cdot 10^{11}\,\mathrm{n/s}$ in deuterium tritium (D-T) operation for homeland security, non-proliferation, and nuclear safeguards applications. The beam is extracted through a $60 \cdot 6\,\mathrm{mm^2}$ slit to decrease the beam current density on the water-cooled, V-shaped target.

The permanent-magnet microwave ion source replaces the original RF ion source [1], which exhibited a tendency of internal sputtering at the low operating pressures (approx. $0.2 - 0.3\,\mathrm{Pa}$) in a sealed tube neutron generator. Microwave ion sources, however, are known to run best at these low pressures and, in addition, provide the advantage of high atomic fractions in hydrogen or deuterium/tritium plasmas.

In this work we report on the influence of the source pressure and the magnetic field on extracted beam current and show the dependency of the atomic fraction on different wall materials.

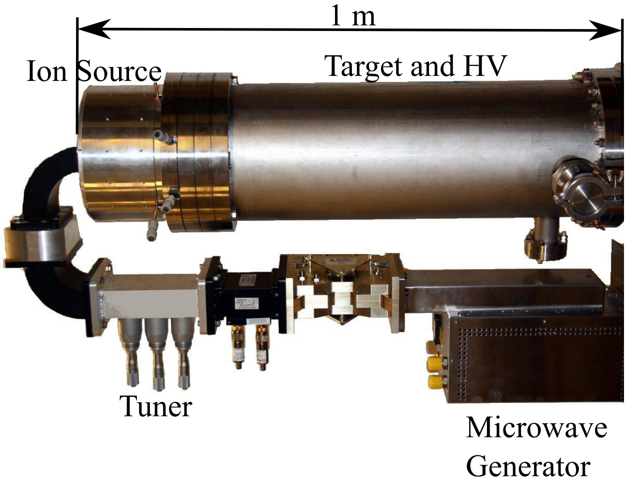

Figure 1: Neutron generator setup.

MICROWAVE ION SOURCE AND NEUTRON GENERATOR DESIGN

The plasma source consists of a cylindrical aluminum chamber (100 mm long and 90 mm in diameter) with a ferromagnetic steel extraction plate in the front, cf. Fig. 2. The back is made out of stainless steel and includes the microwave/vacuum window. The chamber and both end plates are water cooled. In order to efficiently couple the microwave energy into the plasma, the electron-cyclotron resonance ($\omega_{\mathrm{ECR}} = \frac{e}{m} B$) is utilized. We use a microwave frequency of $\omega = 2.45\,\mathrm{GHz}$ which meets the ECR condition for a magnetic field of $B = 87.5\,\mathrm{mT}$. Earlier microwave ion sources used magnetic field coils for generating the magnetic field [2]. To make the generator more transportable, one needs to reduce the size, weight, and power consumption. Therefore, we replaced the field coils with seven bars of permanent NdFe-magnets to generate the magnetic field. The ferromagnetic extraction electrode provides several advantages: it returns the field lines, extends the full field strength close to the extraction slit, and greatly reduces the magnetic field in the beam extraction region. With this design the microwave ion source can be directly fitted onto the neutron generator tube without any further adaptation of the ion beam optics.

The microwave ion source is part of the neutron generator assembly, cf. Fig. 1, which consists of the high voltage and target section (the larger upper tube in Fig. 1), where the extracted beam is accelerated and neutrons are produced in a nuclear fusion process in a deuterium/tritium

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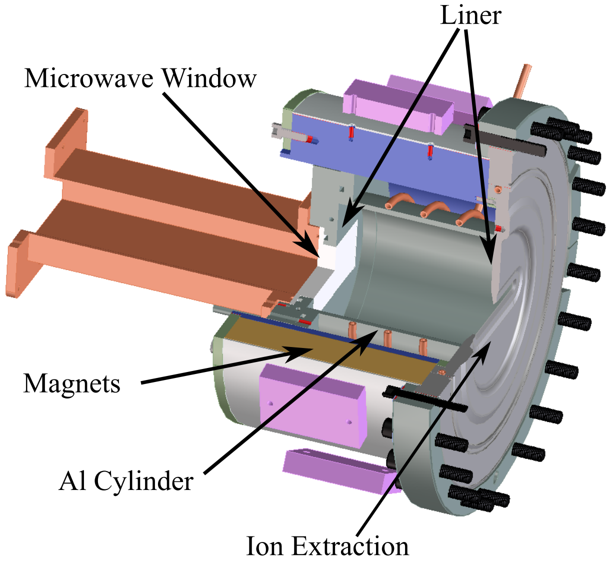

Figure 2: Microwave ion source. 100 mm long and 90 mm in diameter.

containing target, and attached to it is the ion source with waveguide, tuner, and the microwave generator. For operation with tritium, the generator has to be of a sealed-tube design. This implies no differential pumping, and that the pressure in the source is close to the one in the beam acceleration section. To ensure stable high-voltage holding and little beam loss in the gas, one needs to operate the generator at a low pressure of about $0.2 - 0.3\,\mathrm{Pa}$.

ION SOURCE EXPERIMENTS AND RESULTS

Magnetic Field

We performed an extensive study of the magnetic field conditions for an optimal extracted ion beam current [3]. Just for this study we installed an additional magnetic field coil behind the microwave window and seven radially movable ferromagnetic steel plates outside of the magnets. The combination of different coil currents and radial positions of the steel plates allowed us to manipulate the shape and strength of the magnetic field. Magnetic field simulations with the code RADIA [4] agreed very well with the measured values in the vicinity of the window.

We will briefly sum up the results and expand it with simulations of magnetic fields close to the microwave window for different ion beam currents. We showed previously [3] that different magnetic fields related to maximum beam currents do not need to agree throughout most of the ion source but they have to match the ECR condition right at the microwave window. Here, we extend the data to non-optimal beam currents for different magnetic fields shaped by two different setting of the steel plates, red and blue lines in Fig. 3, and by different field coil currents.

The extracted ion beam current reaches a maximum when the ECR condition is matched at the window (solid lines). We consider two cases (red and blue) which differ inside the ion source by roughly 10%. If the magnetic field at the window is smaller than $B = 87.5\,\mathrm{mT}$ the extracted beam current decreases in both cases (dotted lines). Overshooting the magnetic field also leads to a decrease of ion beam current (dashed line). If one now compares the difference of the magnetic field inside the source for both ideal cases (solid lines) with the difference between an ideal and the non-ideal cases (e.g. all blue lines), one can clearly see that the latter differs less. For a good energy transfer into the plasma it is required that the ECR condition is matched at the plasma-window surface whereas the magnetic field inside the bulk plasma is less important. To maximize the source efficiency, we redesigned the permanent magnet configuration to match the ECR condition right at the microwave window.

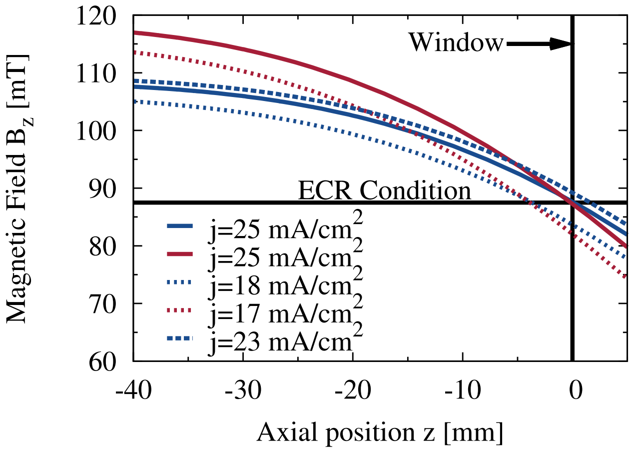

Figure 3: Magnetic field close to the microwave window for different extracted beam currents. The optimal cases (solid lines) matches the ECR condition at the window.

Pressure

A crucial parameter for the use of an ion source for a sealed-tube generator is its operating gas pressure. Without active pumping the ion source must operate at the low pressure, typically $0.2 - 0.3\,\mathrm{Pa}$, required in the ion beam acceleration section.

We have investigated the pressure dependency of the source performance by measuring the extracted beam current with a Faraday cup as a function of source pressure. The results of our experiments show that the microwave ion source works best at a pressure of $0.2\,\mathrm{Pa}$. With increasing source pressure the ion beam current decreases slightly linearly, cf. Fig. 4.

For pressures below $0.1\,\mathrm{Pa}$ it is hard to ignite a plasma and if it ignites, it tends to be unstable. This behavior with pressure can be explained by collisionality. If the pressure is too low, the chance of an ionizing collision is too small and the plasma cannot be ignited or sustained. On the other hand, if the pressure is too high, the electrons collide more

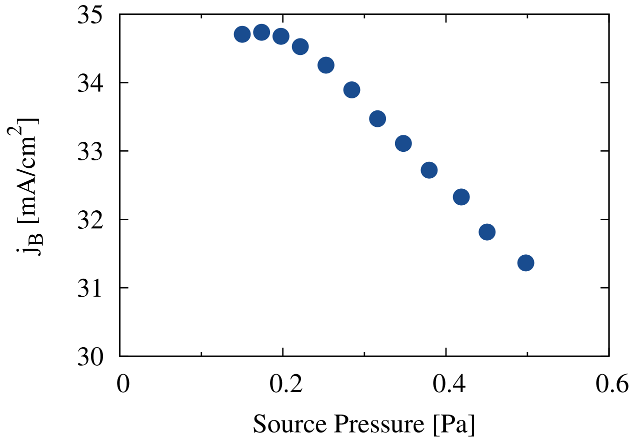

Figure 4: Dependency of beam current on pressure at 400 W microwave power.

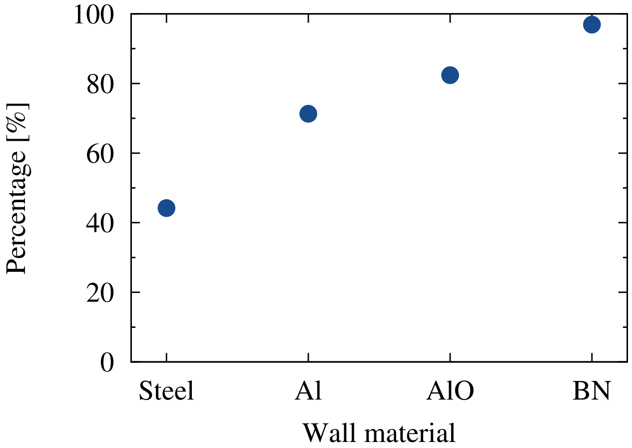

Figure 5: Percentage of proton fraction in an ion beam for different liner materials at 500 W and 0.13 Pa.

often with ions and neutral species, which leads to a lower level of ionization and thus to a smaller extracted beam current.

Wall Liner Materials

Ion source wall materials have a significant impact on plasma parameters and ion source performance. Earlier works reported on high atomic fractions with dielectric materials but did not compare them with each other or with non-dielectric materials [5]. It is desirable to have a high atomic fraction to achieve a high neutron yield at the lowest possible acceleration voltage. The kinetic energy an atomic ion gains in the acceleration section is twice the kinetic energy per nucleus of a molecular ion. For an accelerator voltage of 100 keV the D-T total cross-section is five times higher than for 50 keV and the neutron yield is proportional to the product of the cross-section and the beam velocity [6].

We have investigated the plasma-wall interaction with liners made of aluminum, alumina (AlO), and boron-nitride (BN) which covered front and back plates of the ion source, cf. Fig. 2. The reason for just covering these surfaces is found in the different interaction areas for the neutral and charged species. The ions are bound to the magnetic field and hit mainly the front and the end plate. The neutral gas atoms on the other hand move freely inside the source and, since the area of the cylinder wall is much larger, gas-wall-interactions take mainly place on the cylinder wall.

The ion beam was analyzed with a magnetic spectrometer, i.e. a Faraday cup behind a bending magnet. For the uncovered stainless steel back plate and ferromagnetic steel front plate the atomic fraction is comparatively low, about 45%. Alumina liners increased the atomic fraction to over 80%, but the highest fraction was obtained with the boron-nitride liners at about 95% protons, cf. Fig. 5. This underlines the importance of the plasma-wall interaction for the atomic fraction.

The results of this section will be published in greater detail in a future publication.

CONCLUSION

New results for our development of a permanent-magnet microwave ion source for a high-yield, sealed-tube neutron generator were presented. Matching the ECR condition at the microwave window is necessary to achieve the high extracted beam current. Although the magnetic field inside the ion source has no significant influence on the extracted beam current. Also investigated was the dependency of the extracted beam current on the source pressure. The current is highest at a low pressure of 0.2 Pa and decreases linearly with increasing pressure up to 0.5 Pa. We characterized the influence of the wall material on the atomic fraction by using different liner materials in the areas most affected by plasma-wall interaction. Using boron-nitride as a wall material increased the proton fraction to over 95%. The ion source development is expected to lead to increased neutron generator efficiency and thus higher neutron yields.

ACKNOWLEDGMENT

This work was supported by the Office of Proliferation Detection of the US Department of Energy at the Lawrence Berkeley National Laboratory under contract number DE-AC02-05CHI1231.

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