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IMPROVEMENTS IN RF MULTICUSP NEGATIVE ION SOURCE*

A. George†, S. Melanson, D. Potkins, T. Stewart, M. Dehnel, D-Pace, Nelson, Canada.
Y. Shimabukuro, Doshisha University, Japan
N.G.R. Broderick, University of Auckland, New Zealand

Abstract

D-Pace's 13.56 MHz Radio Frequency (RF) multi cusp negative ion source uses an Aluminium Nitride (AlN) dielectric window for coupling RF power from an external antenna to the plasma chamber. Ion source operation was limited to low RF power (< 3500 W) due to failures (cracks) occurring on the window during experiments. Such events can cause damages to the vacuum system and plasma chamber. The current work deals with simulations performed on the ion source to study the factors leading to the failure of the window. Based on results from the simulations, a new design was introduced. The improved design yielded positive results in terms of source performance and stability of the AlN window.

INTRODUCTION

D-Pace has established a 13.56 MHz RF ion source [1], which is a hybrid design between TRIUMF licensed filament ion source [2] and RADIS ion source licensed from University of Jyväskylä [3], for generating negative ion beams. The main advantage of the RF ion source over the filament ion source is that the downtime and consumable cost associated with replacement of worn out filaments will not occur.

Section view of the RF ion source and extraction system is presented in Fig. 1. The power for generating and sustaining the plasma is transmitted to the plasma chamber by a 3 turn flat spiral copper coil (RF antenna) placed external to the plasma chamber. A dielectric window made of Aluminium Nitride (AlN) couples the RF power from the antenna into the plasma chamber. The RF coil is placed against this window. The AlN window is held in place by copper flanges and is in contact with the plasma directly. The copper flanges are cooled by water flowing through copper tubes brazed to the flanges. Negative ions are produced inside the low pressure plasma chamber through volume production methods [4]. 10 rows of Sm_2Co_{17} magnets are present along the plasma chamber for plasma confinement. There are three electrodes consisting of the plasma electrode, the extraction electrode and the ground electrode, for ion extraction. The ion source is biased at a negative potential with respect to the ground electrode for the extraction of negative ions.

The D-Pace RF ion source has so far achieved negative ion beam currents of Hydrogen (8.3 mA) and Deuterium (3.6 mA) at a maximum of 3500 W RF power [1]. The RF power was limited to 3500 W during experiments, even though the RF power supply was capable of generating power up to 5000 W. This was due to the AlN dielectric window reaching high temperatures during operation (> 400 °C at 3500 W). The window was also broken during the experiments, creating damages inside the vacuum system. This adversely affected the confidence in stable operation of the ion source and the potential to achieve higher negative ion beam currents.

* Work supported by Callaghan Innovation & Buckley systems, New Zealand.
† a.george@auckland.ac.nz

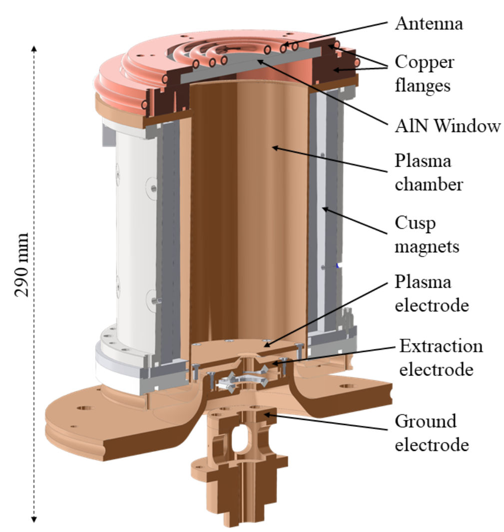

Figure 1: Section view of ion source and extraction.

SIMULATIONS

Thermal Study

A direct measurement of temperature on the AlN window is not possible while running the ion source, due to the presence of the external antenna . Hence, a thermal image of the window and adjacent flanges was captured with a Fluke IR camera immediately after switching off the RF power. The temperature at the centre of the window was reaching around 380 °C in the thermal image, after operating the ion source at 2500 W. The edge of the window was around 180 °C and the copper flanges were around 40 °C.

Based on the results from the thermal image, a thermal model of the ion source was created using Solidworks [5] thermal simulations. The simulations use Finite Element Analysis (FEA) method for solving the geometries. Thermal contact resistance between the parts and convection coefficient values (for heat transfer between ion source and water cooling) were chosen such that the simulated model matched with the temperature distribution in the thermal image. Results are shown in Fig. 2 for an ion source receiving 2500 W

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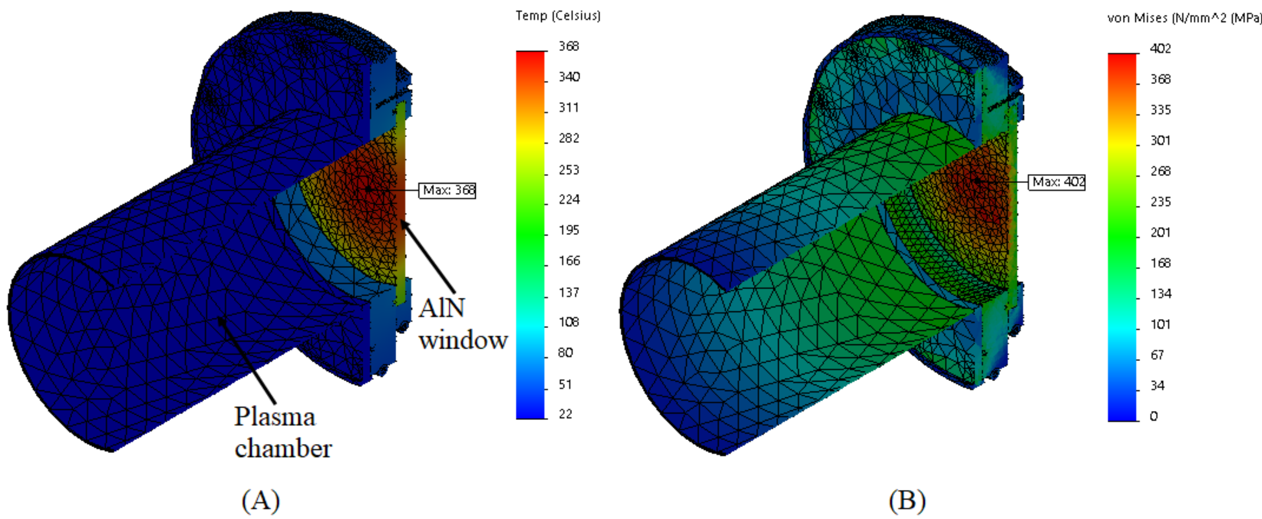

Figure 2: Section view of Solidworks simulation results for the ion source receiving 2500 W RF power. (A) Thermal simulations showing the distribution of temperature on the parts & (B) Stress on the parts using static stress analysis. The static stress analysis uses the results from thermal simulations for stress calculations. The black lines on the surfaces represent size of meshes used for simulations. The model assumes no strain below 30 ^{o}C. The antenna, electrodes and magnets are not included in the simulation.

of RF power. A total heat power of 2500 W was applied on the inner surface of the AlN window to simulate the RF power inside the plasma, assuming no power loss from RF antenna to the plasma. As seen from the results, the maximum temperature of the AlN window reaches up to 359 ^{o}C. Thermal gradients also exist on the window, as the edges are cooler than the centre. The temperature on the adjacent copper flanges is low (< 40 ^{o}C), indicating very low heat transfer between the window and metal flanges.

Static Stress Study

The AlN window is pressed between the copper flanges. Hence the increase in temperature can lead to thermal stress on the window. The stress on the window is studied using the Solidworks static stress analysis. Results from the thermal study is used as thermal load in the static stress analysis in the simulation. The results are shown in Fig. 2. It indicates that the stress on the window can reach up to 400 Mpa at RF power of 2500 W. This is well above the flexural strength of AlN material, which is about 350 MPa [6]. Hence it can be concluded that there is a high probability of failure of AlN window if its operated at high RF powers, due to the thermal stress on the window.

IMPROVED DESIGN

The stress on the AlN window during high power operation can be reduced by decreasing the temperature on the window. In the existing design, the window is cooled indirectly by water circulating through brazed copper tubes around the copper flanges. But simulations indicate that this cooling is inadequate. An improved design was made to increase the heat transfer from the AlN window, as shown in Fig. 3. The outer copper flange was replaced with a jacket made of PEEK material in the improved design. This has channels for water circulation which is expected to cool down the AlN window, so that the thermal stress will not exceed the safe limit even at 5000 W of RF power. The drawback is that the RF antenna is now placed against the PEEK jacket, which can result in low coupling efficiency. But, a higher beam current is expected from the improved design, if 5000 W RF power can be achieved. Simulation studies were performed on the improved design by creating an additional convective heat transfer between the AlN window and water flowing through the channels in the PEEK jacket. Simulation results for temperature and stress distribution on the AlN window for the improved design, for a 2500 W RF power plasma , are shown in Fig. 4. As shown, the resultant temperature (about 55^{o}C) and stress (about 66 MPa) on the window is expected to be very much less than the original design.

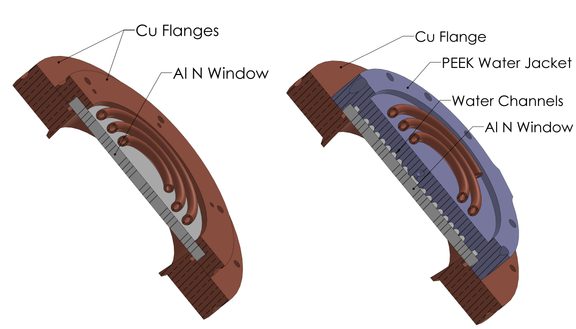

Figure 3: Section view of ion source back plate of the original design (left) and modified design (right).

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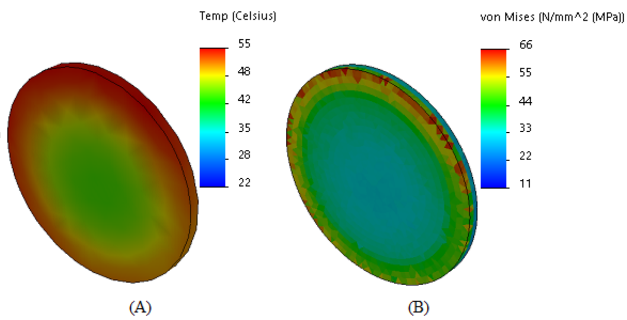

Figure 4: (A) Temperature & (B) Stress distribution on the surface of AlN window that faces the plasma in the improved design for 2500 W plasma power. Other components are not shown.

The improved design was manufactured and experiments were carried out in H_2 plasma. The ion source was operated at the maximum RF power of 5000 W. The temperature of water flowing through the PEEK jacket was continuously monitored. The difference in temperature between the inlet and outlet water in the PEEK water jacket was about 18 °C at 5000 W. The ion source also achieved a higher beam current of 10.7 mA with a 4 RMS normalized emittance of 0.7 mm·mrad. The beam current results are shown in Fig. 5.

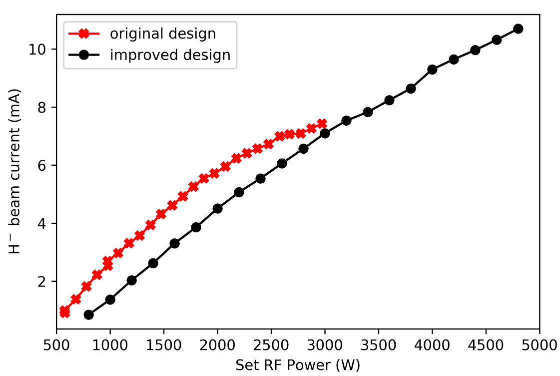

Figure 5: Beam currents achieved for improved design (22 sccm gas flow) and original design [1] (15 sccm gas flow) in H_2 plasma & 30 keV beam energy. Beam current is measured using a Faraday cup placed at a distance of 480 mm from plasma electrode.

COUPLING EFFICIENCY

The percentage of RF power coupled to the plasma from the RF antenna cannot be measured, as there will be loss of energy to the surroundings. The RF antenna should be as close as possible to the plasma for maximum coupling efficiency [7]. As seen in Fig. 3, compared to the original design, the antenna is away from plasma by about 10 mm (thickness of PEEK water jacket) in the improved design. This can lead to loss of energy.

The loss of energy between the two designs can be understood by studying the electrostatic (E mode) mode to electromagnetic (H mode) mode transition [8] characteristics of H_2 plasma inside the ion source. The plasma gets ignited in the E mode and the plasma density in this mode is very low. As power increases, the transition from E mode to H mode happens, accompanied by a sudden increase of electron density inside the plasma. The threshold power required for E-H transition is a good indication of the coupling efficiency. H_2 plasma emission spectrum from both designs are captured using an optical spectrometer, placed 368 mm downstream of the plasma electrode, for different RF powers. The Balmer alpha line intensity in the spectrum is good indication of the plasma density [9] and this is used for identifying the E-H mode transitions.

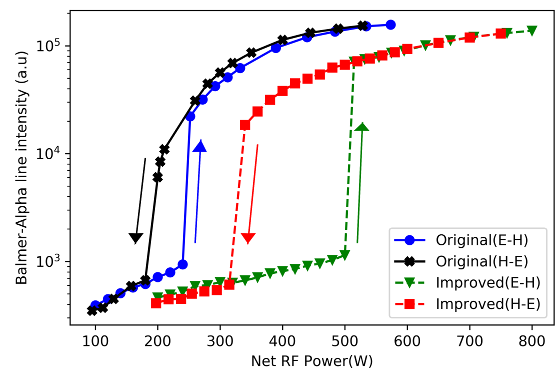

Figure 6: E-H mode transition for original design and improved design(dotted lines) for hydrogen plasma at a gas flow of 10 sccm. The up arrows (E-H) indicate increasing power and down arrows (H-E) indicate decreasing power

The results of the Balmer-alpha line study for the two designs are shown in Fig. 6. The E-H mode transition for the original design occurs at around 220 W and for the improved design it occurs at around 520 W. This clearly indicates more loss of power and lower coupling efficiency for the new design due to increased distance between the antenna and plasma.

CONCLUSION

The study was conducted to solve the failure occurring on AlN dielectric window in the RF ion source. Simulation results indicated that thermal stress on the window was exceeding the failure limit of the material for high RF power operations. The design changes have given positive results in terms of more negative ion beam current and stability in operations. However, there is still scope of achieving more beam current if the coupling efficiency can be improved. Future works aim at making a design in which the RF antenna is immersed in the water jacket and lies as close as possible to the plasma and AlN window, so that the coupling efficiency is high, while maintaining the low thermal stress achieved in the current work.

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