RECENT ION SOURCE DEVELOPMENTS FOR VARIAN'S PROBEAM® CYCLOTRON

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Abstract

The cold cathode Penning ionization gauge (PIG) type proton source of the Varian's ProBeam® 250 MeV superconducting isochronous cyclotron suffers from the usual cathode/chimney erosion during operation. Furthermore, a relatively high hydrogen gas flow is needed to generate a proton beam in the µA range, which induces conditions for RF operation below optimum. In the quest to increase cathode/chimney life time and thereby directly extend service intervals, thus reducing the total cost of ownership, several experimental investigations have been performed at a dedicated test bench at Paul Scherrer Institut (PSI), Switzerland, including material studies, a detailed operation analysis and switching to a hot cathode design.

THE ION SOURCE TEST STAND

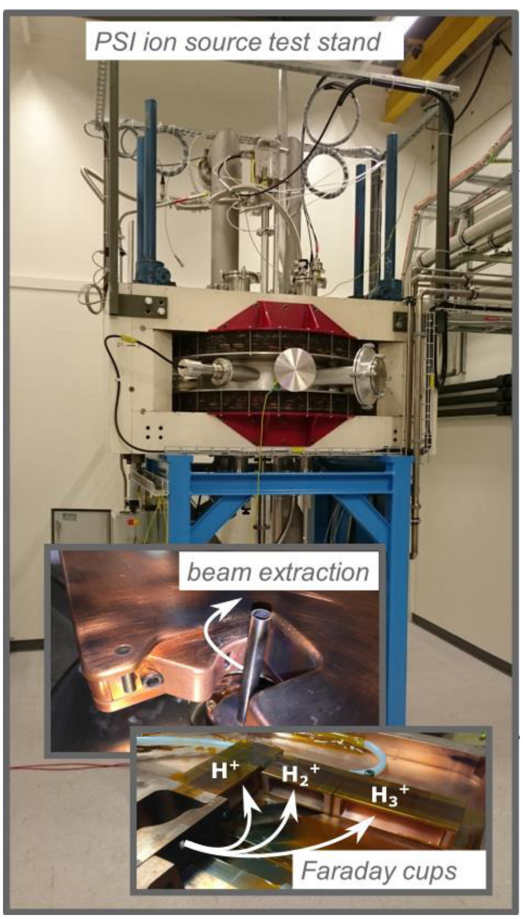

Figure 1: Picture of the test stand. Inserts show beam extraction from source and diagnostic setup.

The dedicated ion source test stand used for this work is located at PSI, Switzerland. A picture of the setup shown in Figure 1. It provides up to 1.4 T central magnetic field, extraction from ion source with typically -30 kV voltage, and ion species separating diagnostics (Faraday cups).

The ProBeam ion source can be operated and its performance experimentally investigated. The main difference to the situation in the ProBeam cyclotron is the lower magnetic field as provided by the test stand's normal conducting magnet. This reduces the confinement of the charged particles in the source plasma and results in higher necessary internal gas pressures, which are achieved by higher hydrogen gas flow rates into the source. While the source in the ProBeam cyclotron is typically run with 1 to 2 sccm hydrogen gas flow, the test stand is operated in the range of 8 to 16 sccm. This difference has to be considered when comparing the results presented here to the situation in the ProBeam cyclotron.

The second difference to the ProBeam cyclotron is the DC extraction at typically -30 kV at the test stand. This does not affect the internal source operation, and has only an influence on the absolute values of the extracted current.

THE COLD CATHODE ION SOURCE

To sustain the internal source plasma, the cold cathode Penning ion source relies on secondary electron emission induced by ions hitting the cathodes. The (only slightly ionized) hydrogen plasma contains mainly H^+ and H_2^+ ions, which have only low secondary electron emission yields (range: 0.2 to 0.5) at the typically used cathode potentials in the range of -1 to -1.8 kV. A stable discharge between few and up to about 300 mA is possible. A schematic of such a source is shown in Figure 2.

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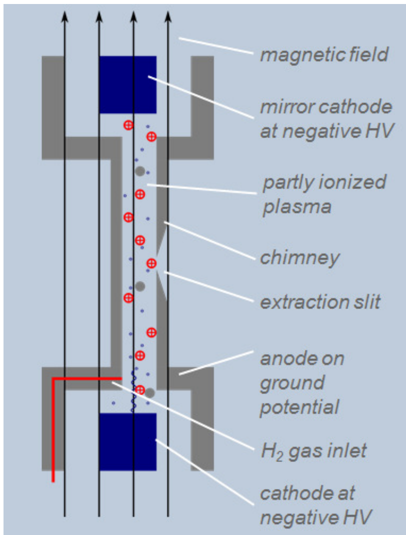

Figure 2: Schematic of the cold cathode Penning ion source. For a typically fixed geometry and constant magnetic field, the discharge characteristics are only depending on internal gas pressure and cathode high voltage.

The cathode material is tantalum (Ta), which is commonly used in such sources due to its low sputter rates and thus potentially high life time. However, it is like other refractory materials prone to hydrogen embrittlement, possibly causing mechanical issues within the material. As the relevant processes are temperature dependent, a thermal analysis of the source design has been performed, resulting in expected cathode surface temperatures in the range of 400 °C due to ion bombardment during operation. This value could also be experimentally verified via IR temperature measurements during source operation. The results of these measurements are shown in Figure 3. The discharge power is for the ProBeam cyclotron typically around 300 W.

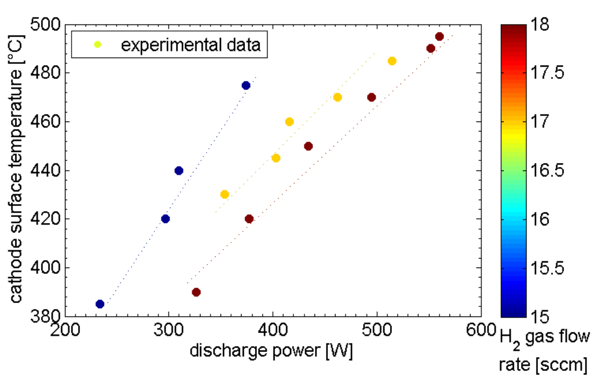

Figure 3: Experimental cathode surface temperature measurements for different flow rates.

First tests of alternative materials have been performed: While titanium suffered from massive sputtering, tungsten showed a similar but still worse behaviour than tantalum, and with niobium massive cracking and material break-up was observed.

Extracted Beam Characterization

Ions are extracted from the source plasma through a small slit in the chimney. Particle trajectories can be determined by extraction potential, geometry, magnetic field strength and charge over mass ratio. With this information three isolated Faraday cups were placed in the setup to independently measure the extracted currents of H^+, H_2^+ and heavier particles (e.g. H_3^+).

Measurements have been performed for different discharge currents and hydrogen gas pressures within the source. Results are shown in Figure 4.

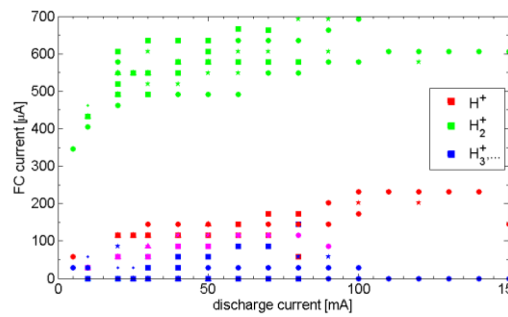

Figure 4: Extracted hydrogen ions from the cold cathode Penning source in dependency of discharge current (x axis) and hydrogen gas pressure (symbol shape).

The dominating ion species is H_2^+. As in general expected from literature, the proton fraction increases with increasing discharge current. In the here performed investigation a slight increase from less than 20% to more than 30% is observed. Furthermore, the ion species ratio is found to be independent from the hydrogen gas pressure within the tested regime of $2x10^{-2}$ to $4x10^{-2}$ mbar. However, scanning a wider pressure range in the ProBeam cyclotron showed a pressure dependency in favour of lower pressures for the proton fraction efficiency.

An estimate on the degree of ionization of the source plasma is possible: Gas flow rates in the range of 12 sccm correspond to equivalent particle currents of 800 mA at full ionization. Measured are instead about 800 µA total electrical current, thus a degree of ionization in the order of 0.1% is assumed, which is in the expected range for such plasmas.

A HOT CATHODE ION SOURCE DESIGN

A hot cathode source design yields several advantages: The necessary electron emission to sustain the source plasma is now a direct process via thermionic electron emission, thus decoupling the electron emission from background gas pressure. This enables the use of lower gas flow rates, which improves the overall vacuum conditions in the cyclotron and is beneficial, e.g., for RF stability; additionally, lower possible cathode potentials might reduce cathode sputtering. Commonly used designs with hot filaments, however, do not seem to be the ideal choice for highest life time of operation. Thus, an approach is

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tested using boride crystals (LaB_6 and CeB_6). These cathodes are commercially available in many types.

Some special thought has to be given to the typically demanding vacuum constrains with these cathodes. However, these general values can be relaxed to some extent when considering the specific partial pressures: While already low partial pressures of O_2 or water vapor lead to significant cathode poisoning and evaporation, the material is basically immune to larger hydrogen partial pressures as the ones to be expected in a proton source design [1].

One cathode of the Penning arrangement was replaced by the hot cathode while the other one was kept in place as mirror cathode at the same potential. Furthermore a power supply for active electrical heating of the hot cathode to working temperatures (around 1500 °C) and a new gas flow controller to access lowest flow rates for hydrogen down to 0.05 sccm was added.

As expected, the hot cathode shows a different operation behavior. Significant current could be extracted already around a drastically reduced hydrogen flow rate of 0.3 sccm (compared to 8 to 16 sccm necessary flow for the cold cathode in the test stand). Furthermore, the expected reduction in necessary cathode potential is observed.

Extracted Beam Characterization

Figure 5 shows first operation results for the hot cathode in the ion source test stand. The worse proton production efficiency is obvious, but still absolute proton numbers seem to be sufficient. The optimum cathode voltage of 300 V is very promising for reduced sputtering effects.

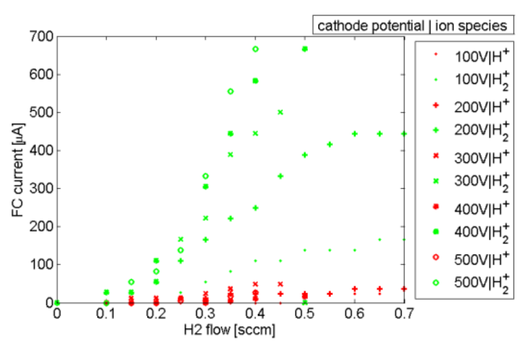

Figure 5: Extracted hydrogen ions from the hot cathode Penning source in dependence of gas flow rate and cathode potential (symbol shape).

CONCLUSION AND OUTLOOK

A test stand for ion source studies is operational at PSI, Switzerland, and first investigations have been carried out to optimize the performance of the ProBeam cold cathode Penning ion source. Additionally, the development of a potentially extended life time hot cathode design is ongoing.

ACKNOWLEDGEMENT

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[1] H.E. Gallagher, J App Phys 40, 44 (1969).

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