

Progress of the RF H⁻ Ion Source Project at RAL

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Abstract. An radio-frequency (RF) driven long-lifetime H⁻ ion source operating at 50 Hz with 1.5% duty factor and 35 keV beam energy is currently under development for the ISIS Neutron and Muon Source at Rutherford Appleton Laboratory (RAL). The new ion source is designed operate in conjunction with an upgraded medium energy beam transport (MEBT) that will provide improved transport efficiency and reduced beam losses. This paper will give an update on the progress made on the project and an overview of the development of the support equipment required for the operation of the ion source with an emphasis on the details of the RF and high-voltage power supply systems.

1 Introduction

The combined ion source and MEBT upgrade project at RAL are intended to make improvements to the beam transfer efficiency into the first accelerating tank of the Linac, allow the installation of an electrostatic beam chopper to reduce head-tail instabilities and beam losses in the synchrotron and develop a more reliable external RF coil inductively coupled plasma (ICP) RF driven un-caesiated ion source that can provide the required beam current. The project and early progress have been described in Refs. [1-3]. The ion source low energy beam transport (LEBT) are shown in Figure 1.

2 Uncaesiated RF ion source

Following the early stages of commissioning the ion source RF, microwave and high voltage extraction systems and ignition of the first plasma, an initial attempt was made to satisfy the specified beam requirements (35 mA, 300 μ s, 50 Hz) for the new MEBT with an uncaesiated ion source operating in a purely volume mode of H⁻ ion production. The challenges in trying to achieve this in volume mode at 1.5% duty factor are dealing with the co-extracted electron current (on the order of Amperes) and the plasma chamber power dissipation.

The RF ion source is a volume mode hydrogen ICP operating in the region of 2 - 4 MHz with an external RF coil and aluminium nitride plasma chamber, no cusp magnetic field, with the filter field provided by permanent magnets external to the plasma chamber and a biased plasma electrode. The extraction system is a 2-stage design with co-extracted electrons dumped into the puller electrode. The H⁻ beam is then post-accelerated to 36 keV into the 2 solenoid LEBT and then on to the ISIS 665 keV radio frequency quadrupole (RFQ) or to the RFQ acceptance mask during the initial experiments. Reliable plasma ignition is achieved using a 2.45 GHz electron cyclotron resonance (ECR) ignition gun

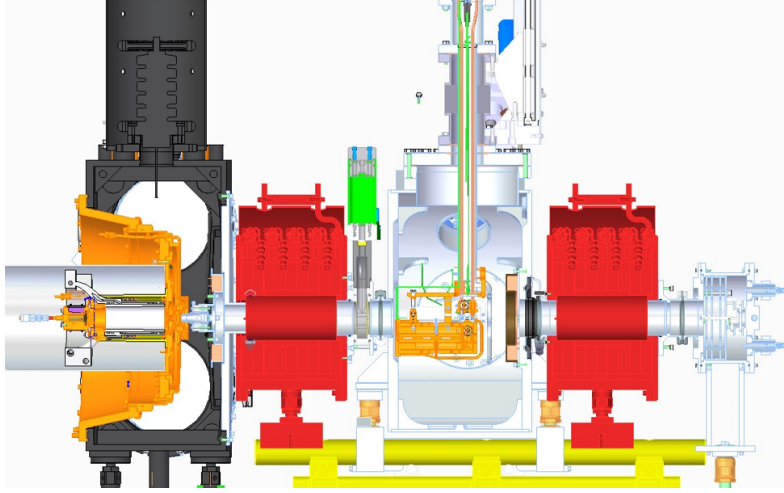


Figure 1: Schematic view of the ion source, LEBT and RFQ mask

that provides an initial supply of electrons to seed the plasma. Plasma facing windows coupled to optical fibres with views of the main plasma and extraction region are available for performing time-resolved plasma diagnostics and optical emission spectroscopy. A schematic view of the ion source, LEBT and RFQ mask is shown in Figure 1.

During the initial beam commissioning of the uncaesiated ion source with all RF and high voltage systems at nominal values the extracted beam current was measured using a Faraday cup located within the diagnostics vessel of the LEBT. The examples of beam and co-extracted electron current pulses (measured in the Faraday cup and extract power supply) in Fig. 2. show the large number of co-extracted electrons (on the order of Amps) which was severely limiting both for the extraction electrode power dissipation and the power supply voltage droop; this limited running of the ion source to 6.25 Hz repetition rate. Co-extracted electrons were also found to be impacting on and melting the protection electrode, a component of the extraction system that is biased to -900 V as a consequence of implementing a current limiting resistance in the acceleration biasing system to protect the high voltage power supplies in the event of breakdowns. The current and voltage associated with this electrode were also measured to aid diagnostics.

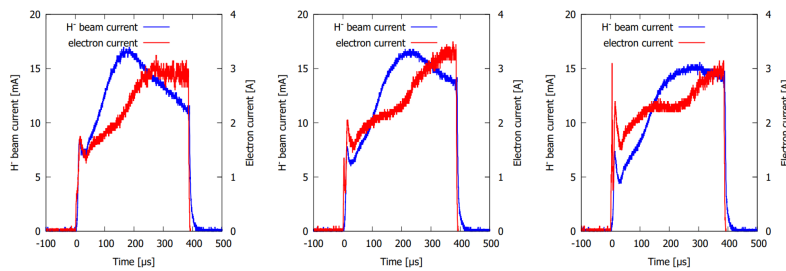


Figure 2: Beam current measurements into the Faraday cup

Table 1: Ion source parameters during uncaesiated commissioning

Parameter	Value
Forward RF Power	58 kW
Reverse RF Power	8 kW
RF Frequency	3.39 MHz
Hydrogen Flow	34 sccm
Plasma Electrode Bias	14 V
Extraction Voltage	11.2 kV
Solenoid 1 Current	460 A
Solenoid 2 Current	475 A

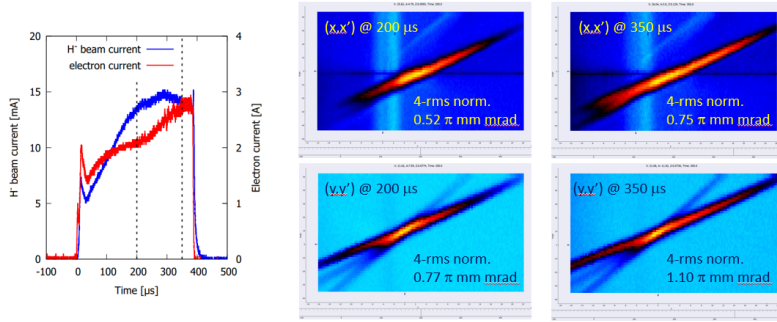


Figure 3: Beam emittance measurements and example beam pulse during scan

At this stage during uncaesiated running a series of emittance measurements were taken using an Allison[4] type scanner located within the diagnostic vessel of the LEBT. The emittance measurements of 0.52 to 0.75 π mm mrad in x and 0.77 to 1.10 π mm mrad in y, as shown in Fig. 3, are promising and within specification for the RFQ acceptance. With the RFQ mask installed in place of the real RFQ the efficiency of beam transmission through the LEBT was confirmed to be approximately 85% as shown in Fig 4. Examples of ion source parameters during this run are shown in Table 1.

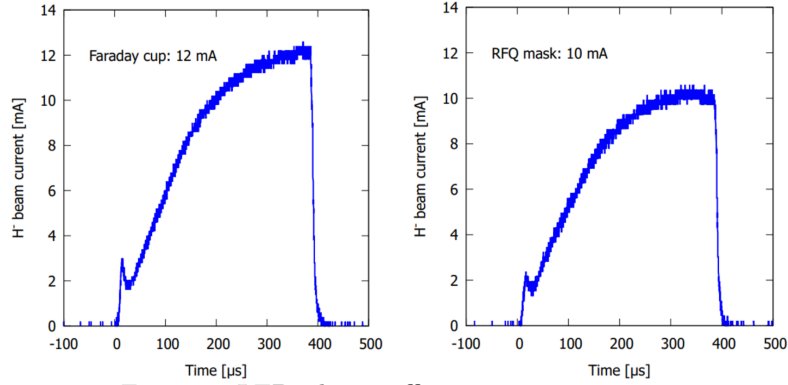


Figure 4: LEBT beam efficiency measurements

An attempt to optimise the filter field strength was then made in the range from 11 mT to 17 mT with measurements taken for both beam and co-extracted electron current. As expected the beam current increased with reduced field strength, however electron current was also increased. To support an increased electron current, a modification to the extraction power supply was made to double the size of the capacitor bank to 2 μ F. An optimum was then reached at 14 mT which allowed longer pulse operation but at reduced repetition rate (to prevent damage to electron dump) as shown in Fig 5.

The beam pulse shape shown in Fig 5. has a distinct peak at the end of the pulse at the point where the RF power is gated off, this can be interpreted as a problem with the formation of the plasma meniscus and suggests that the extraction system requires optimisation. Simulations using IBSimu[5] of the extraction system were then re-run with realistic values for electron and H⁻ beam current. These pointed toward there being an issue with secondary electrons leaking out from the electron dump and causing damage to the protection electrode.

The results of re-run simulations with the realistic parameters from Table 2 are shown in Fig 6. with H⁻ high-lighted in red, primary electrons in yellow and secondary electrons in magenta. The simulation and damage revealed by physical examination of the protection electrode shown in Fig 7. confirmed that there was an issue with secondary electrons. The conclusion from these results is that caesium must be added in order to increase beam current and reduce the number of co-extracted electrons.

3 Caesiated RF ion source

A caesium delivery system was designed based on the approach at Spallation Neutron Source (SNS) [6,7] which uses caesium-chromate cartridges contained within a compressed air-cooled converter collar located

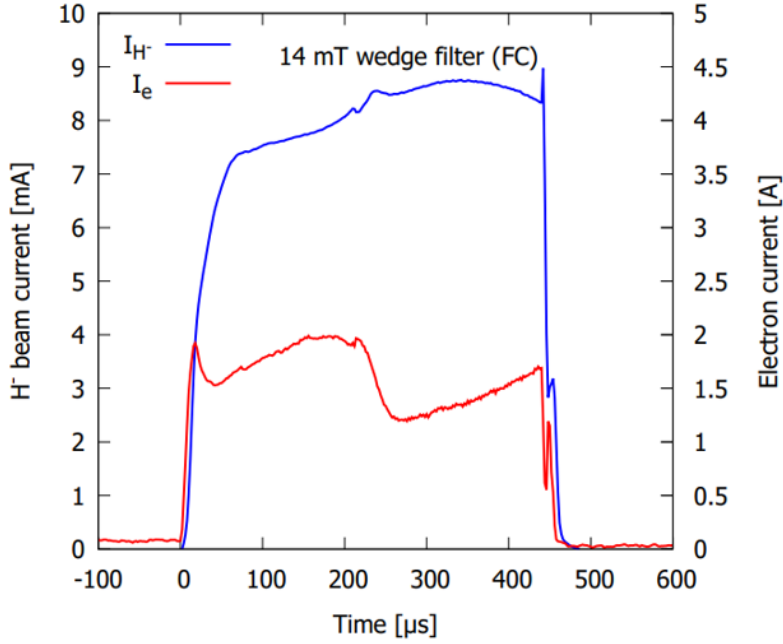


Figure 5: Beam and electron current with wedge filter at 14 mT

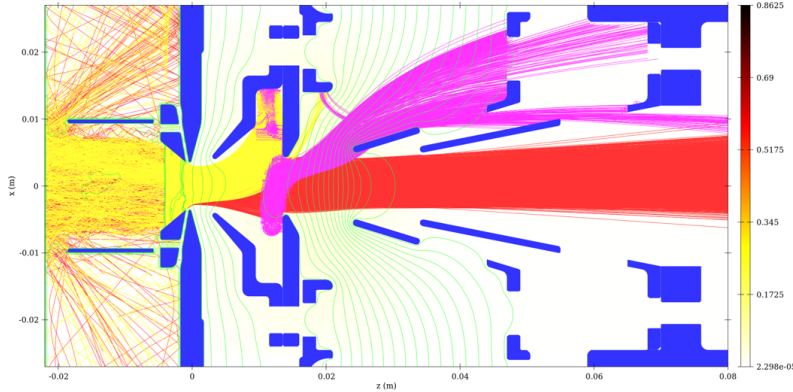


Figure 6: Extraction simulation with realistic parameters (H^- high-lighted in red, primary electrons in yellow and secondary electrons in magenta)

Table 2: Realistic ion source simulation parameters

Parameter	Value
Extraction voltage	8 kV
Acceleration voltage	28 kV
H^- current	10 mA
Electron current	3 A

at the ion source aperture. The inclusion of the new collar necessitated a redesign of the main ion source flange to provide the air cooling supply and 4 thermocouples to monitor the collar temperature. The collar and flange are shown in Fig 8.

The thermal connection between the collar and converter needed to be changed from the SNS design due to the lower duty factor for ISIS (400 us, 50 Hz) compared to SNS (1 ms, 60 Hz) operation. The modification allows the collar to reach the nominal temperature for caesium release.

With the new caesium delivery system installed and a closed-loop air-cooling system in operation an initial attempt at caesiation was attempted. The presence of caesium within the plasma was confirmed after observing an increase in beam current from 10 to 20 mA and measuring the plasma optical emission spectrum using a Thorlabs CCT10 CCD spectrometer at 1 ms integration time and in-line optical



Figure 7: Damage to protection electrode from secondary electrons

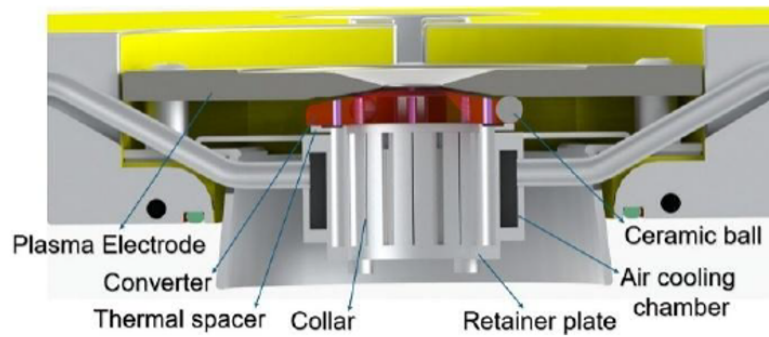


Figure 8: Caesium collar and new flange

attenuation. The beam current and persistence of the caesium line in the optical spectrum shown in Fig 9. seemed to be limited by a significant amount of water within the plasma, an oxygen 777 nm peak was observed in the spectrum that was as high as the hydrogen Balmer-gamma peak at 434 nm, the lack of nitrogen peak also suggests water rather than air. The proposed solution to the was to bake the aluminium nitride plasma chamber without its integrated water cooling jacket.

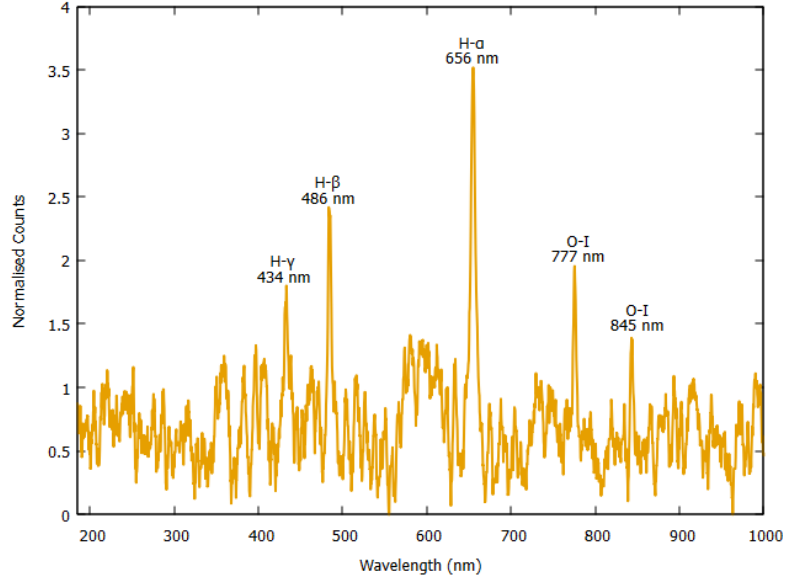


Figure 9: Optical spectrum showing hydrogen, caesium and oxygen lines

4 Future Plans

With the plasma chamber water cooling jacket removed to allow bake-out an air-cooling solution was implemented using 3D printed compressed air nozzles directed onto the plasma chamber. Removal of the cooling jacket also allowed for the installation of a tightly fitting RF coil; this resulted in improved RF power coupling to the plasma and more reliable ignition. A reduction in water contamination was seen in the optical spectrum but no further attempts were made to caesiate.

A simulation was run with parameters (30 mA H^- , 100 mA electrons) matching those that would be expected from caesiation[8] and with a 1 mm increase of the plasma-electrode to puller gap, the result is shown in Fig 9.

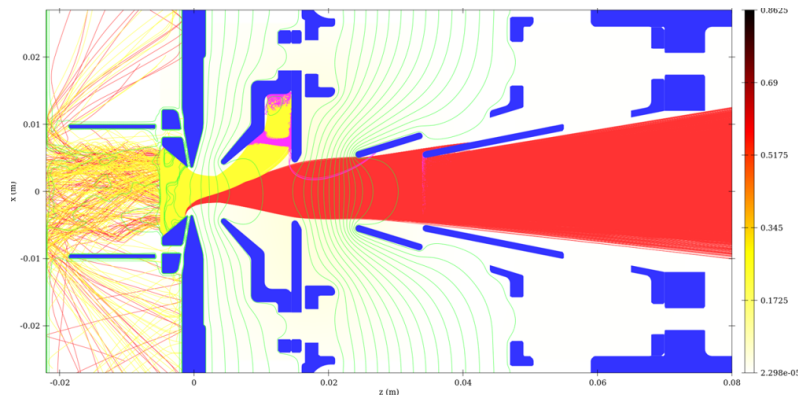


Figure 10: Simulation of the modified extraction system

Another outcome from the decision to switch to caesiation is that this relaxes the requirements for the extraction power supply, allowing it to potentially fit into a smaller volume within an RF screened enclosure around the ion source. This RF enclosure or booth would isolate the major ion source RF

components from the LEBT, MEBT and their sensitive diagnostic systems and prevent RF interference once the ion source goes into full operation. The booth will also house all other power and instrumentation equipment required for ion source operation.

5 Outlook

Development of the RF ion source has taken longer than expected due to the challenge of reaching stable operation at high duty factor and a decision was made to re-configure the test stand to use the ISIS Penning type ion source for MEBT beam commissioning. The RF ion source was able to provide a low repetition rate beam measured at 5 mA at the end of the MEBT before moving to the Penning ion source. It is planned to continue with the Penning ion source for the initial installation of the MEBT on ISIS in the 2027 long shutdown whilst development work on the caesiated RF ion source continues.

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