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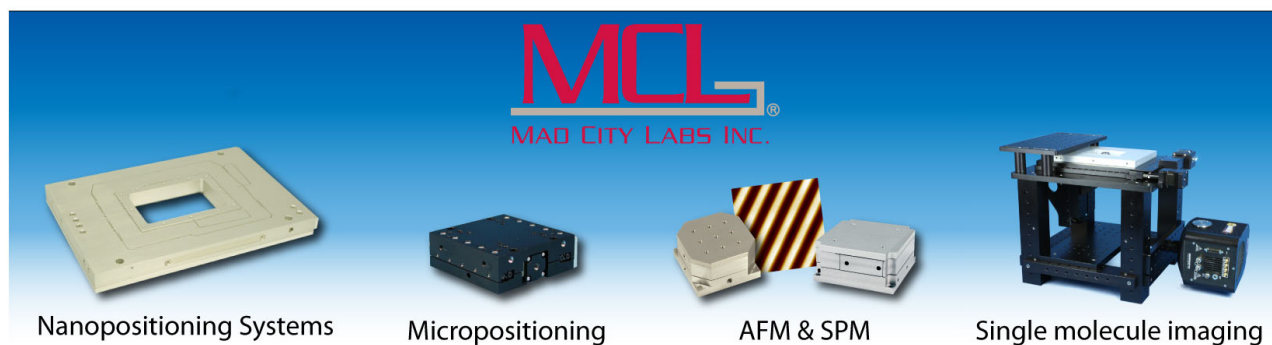
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Power efficiency improvements with the radio frequency H^- ion source

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CW 13.56 MHz radio frequency-driven H^- ion source is under development at the University of Jyväskylä for replacing an existing filament-driven ion source at the MCC30/15 cyclotron. Previously, production of 1 mA H^- beam, which is the target intensity of the ion source, has been reported at 3 kW of RF power. The original ion source front plate with an adjustable electromagnet based filter field has been replaced with a new front plate with permanent magnet filter field. The new structure is more open and enables a higher flux of ro-vibrationally excited molecules towards the plasma electrode and provides a better control of the potential near the extraction due to a stronger separation of the main plasma from the plasma electrode. While the original system provided better control over the e^-/H^- ratio, the new configuration has led to a higher production efficiency of 1 mA H^- at 1.75 kW RF power. The latest results and upgrade plans are presented. © 2015 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4932008>]

I. INTRODUCTION

A new MCC30/15 cyclotron developed at D. V. Efremov Institute, St. Petersburg, Russia, has been commissioned at the University of Jyväskylä accelerator laboratory (JYFL). The device produces up to 200 μA of 18–30 MeV H^+ and up to 60 μA of 9–15 MeV D^+ from negative ions with high-efficiency stripping extraction. The beams will be used for medical isotope production and nuclear physics experiments at the IGISOL facility. The filament-driven ion source currently used for the production of the injected H^- and D^- beams is limited to about 130 h continuous operation between filament changes when high beam intensity is needed. The ion source is located in the cyclotron vault and therefore a significant waiting time for the vault cooldown is required before filament change is possible. This kind of operation is not acceptable as 350 h and longer experiments are expected once the facility is fully operational. A CW 13.56 MHz radio frequency-driven ion source, RADIS,^{1,2} for production of H^- and D^- beams is under development for replacing the filament-driven source. The goal of the RADIS project is to develop a new ion source to produce at least 1 mA of CW H^- beam or 500 μA of CW D^- beam at the cyclotron injection energy of 19 keV, with a maintenance interval of at least one month.

II. UPGRADE OF THE ION SOURCE

The ion source design chosen for the RADIS is a multicusp chamber with an external planar spiral RF antenna

behind a flat AlN RF window on the back of the ion source. Previously, the ion source had a front plate with embedded adjustable electromagnet (EM) electron filter. The electron filter had a maximum peak field of 65 mT and full-width at half-maximum (FWHM) of 20 mm. Most typically, the filter was operated at a peak field of 23 mT on axis² (the on-axis field is presented in Fig. 1). The front plate was also electrically isolated from the plasma chamber to enable plasma electrode biasing for tuning the cold plasma region near the extraction aperture, where the H^- ions are formed. While the EM filter provided continuous adjustability, the construction also had its disadvantages. The old front plate structure exposed a large area of metal surface to the plasma with poor or non-existent magnetic confinement. This caused high currents in the plasma electrode bias and plasma losses resulting in poor efficiency.

The ion source has been upgraded with a new front plate structure using a permanent magnet (PM) for the electron filter (see Fig. 2). The new front plate has better magnetic confinement and it is more open near the extraction aperture, which allows more ro-vibrationally excited molecules to enter the region near the extraction to improve the volume production of H^- . Also because the biased plasma electrode is well separated from the main plasma by the filter field in the new front plate geometry, it will be possible to adjust the local plasma potential near the extraction as in the TRIUMF-type H^- sources.³ The electron filter field can be tuned by adjusting the magnet spacing (characterized by the distance from center of the magnet on one side to the center of the magnet on the other side) and by using either large ($10 \times 10 \times 80$ mm³) or small ($5 \times 10 \times 80$ mm³) PM. This provides an adjustment range with peak fields ranging from 8.5 mT to 40 mT. By using 5 mm thick spacers in positioning the magnets, it is possible to achieve seven different PM configurations. Instead of using the peak on-axis magnetic field to characterize the filter field intensity, we prefer to use the filter field integrated along the

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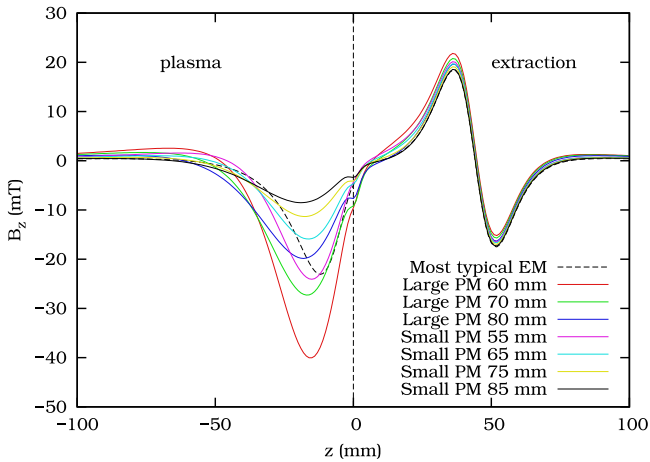


FIG. 1. Magnetic field on the axis of the ion source for seven different permanent filter field magnet configurations and the most typically used electromagnet setting. The magnetic field at the extraction is used to dump the co-extracted electron beam and to correct the deflection of the H^- beam. The plasma facing surface of the plasma electrode is located at $z = 0$.

axis. The peak and the integrated fields are shown in Table I for all seven PM configurations and the most typically used EM filter configuration. The on-axis magnetic fields of these configurations are plotted in Fig. 1. The rest of the ion source and the test stand is described in detail in Ref. 2.

III. RESULTS

With the original front plate, production of 1 mA H^- beam, which is the target intensity of the ion source, has been reported at 3 kW RF power.² Using the new PM front plate structure, higher power efficiencies have been achieved. The effect of different PM filters on the ion source performance has been studied with $\phi 6$ mm and $\phi 7$ mm plasma electrode apertures, the latter being used with the EM filter as well. The measured H^- beam current is presented as a function of integrated filter

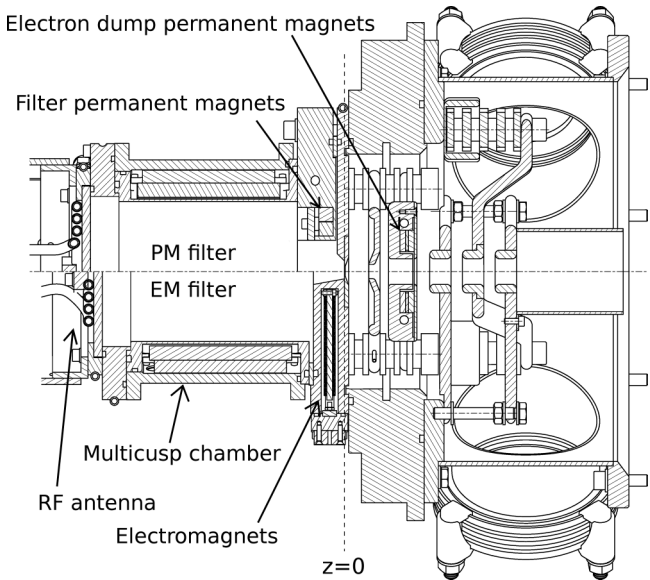


FIG. 2. Cross section view of the ion source. The new PM filter configuration is shown above the center line and the old EM filter configuration below.

TABLE I. Properties of the seven PM configurations (number shown is distance from the center of magnet to center of magnet) and the most typical EM filter setting.

| Configuration | Peak field (mT) | Integrated field (T mm) |
|-----------------|-----------------|-------------------------|
| Most typical EM | 23 | 0.52 |
| Large PM, 60 mm | 40 | 1.01 |
| Large PM, 70 mm | 27 | 0.78 |
| Large PM, 80 mm | 20 | 0.63 |
| Small PM, 55 mm | 24 | 0.57 |
| Small PM, 65 mm | 16 | 0.43 |
| Small PM, 75 mm | 11 | 0.35 |
| Small PM, 85 mm | 8.5 | 0.28 |

field at 1000 W RF power in Fig. 3. The best results with the $\phi 7$ mm aperture were achieved with large magnets having 80 mm separation. The performance as a function of RF power is presented for this case in Fig. 4 labelled with run 7. The target intensity of 1 mA H^- was achieved at 1.75 kW RF power. The run 7 was a systematic study with the electron dump current kept constant at either 1 mA, 10 mA, or 20 mA by adjusting the plasma electrode bias voltage. The highest currents were achieved by allowing higher current at the dump with lower bias voltage. With $\phi 6$ mm aperture, the optimum was achieved using the small magnets with 75 mm separation. With weaker filter fields in each case, the source optimization was limited by high leakage currents on the extraction high voltage supplies and therefore operation with RF power larger than 1 kW was not sensible.

IV. DISCUSSION

The development efforts are bringing the RF power efficiency of the ion source closer to the desired level of 1 mA/kW but difficulties still remain. One of the biggest problems is the high current drain on the high voltage power supplies. For example, when the source is tuned for maximum (696 μA) H^- beam production using small PM with 75 mm

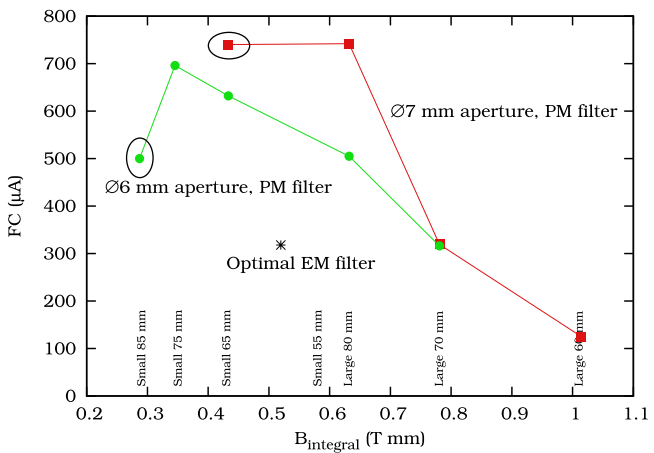


FIG. 3. Measured H^- beam current as a function of integrated filter field at 1000 W RF power. Other parameters have been optimized at each data point. The circled data points were limited by high current on einzel lens power supply.

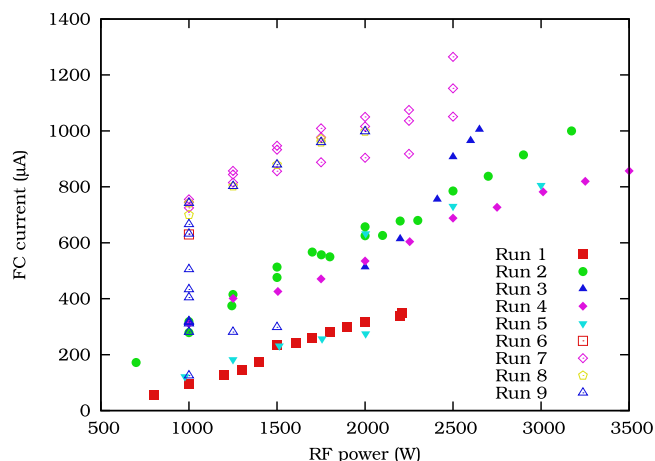


FIG. 4. Measured H^- beam current as a function of RF power. Runs 1–5 (filled symbols) were produced with EM filter, while runs 6–9 (open symbols) were produced using different PM filters.

separation, the source power supply has to provide 15 mA at 19 kV, the e-dump power supply provides 28 mA at 6 kV, and einzel power supply provides 10 mA (maximum current of the power supply used) at 20 kV. The puller electrode power supply does not supply measurable current. The puller and e-dump power supplies float at source potential (see Fig. 5). Therefore, the electron beam going to the e-dump does not contribute to the source power supply current. A possible explanation to the observations is that about 15 mA of negatively charged particles (mostly electrons) is escaping the source/puller/e-dump system and of these particles 10 mA hits the einzel electrode, about 1 mA (H^-) goes to the Faraday cup FC1 at 410 mm from plasma electrode, and 4 mA to grounded electrodes or other grounded surfaces. By comparing current readings from FC1 to the next Faraday cup FC2, which

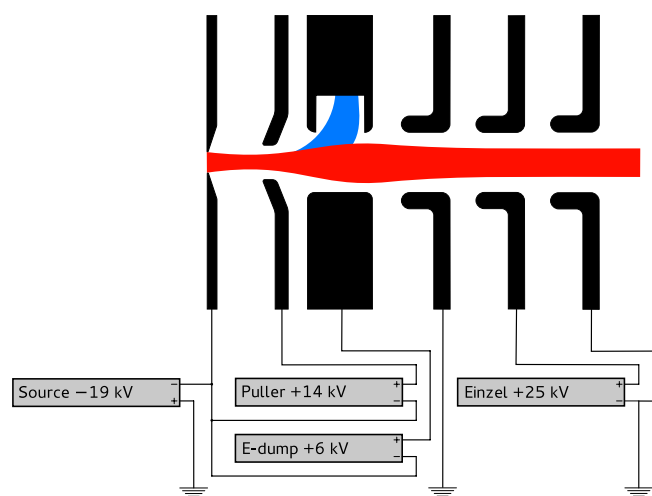


FIG. 5. High voltage power supply connections. The puller and e-dump power supplies float at source potential. Nominal voltages are shown on power supplies.

is located 970 mm from the plasma electrode and has an additional PM deflector, it has been verified that at least 90% of FC1 reading is H^- .

The origin of the escaping particles is unclear. They can be either co-extracted electrons from the ion source, which have propagated through the e-dump or secondary electrons emitted at the e-dump. The burn marks at the bottom of the e-dump are a clear evidence of the primary electrons hitting there with a pattern also observed in simulations. Therefore, it seems more probable that the observed current is mainly secondary electrons. Secondary electrons emitted from the e-dump electrode have also been observed to cause problems in the similar magnetized ion einzel-lens dump of Linac4 at CERN.⁴ The main problem of the electron dumping method used in these cases is that the secondary electrons experience accelerating electric field towards the neighboring electrodes, increasing the probability of particle escape. In systems, where electrons are dumped on the puller electrode, for example, the Texas A&M and RADIS H^- ion sources, the fields are opposite and mitigate electron escape.^{1,5} No problems with electron dumping have been experienced with these sources.

Regardless of the origin of the charged particles, the high current deposits a significant power on the uncooled einzel lens, which has been observed to glow red-hot in some conditions. The high operating temperatures have caused alignment errors due to movement caused by thermal expansion. To meet the durability requirements set on the source, the leakage current has to be reduced. Assuming that the problem is caused by secondary electrons escaping from the electron dump, the dump will have to be re-engineered to better trap the secondaries or the dumping topology will have to be changed to contain the electrons. Also while upgrading the extraction system, the current construction, where MACOR insulators are used to support the high voltage electrodes inside a large vacuum tank, may be changed to a so-called extraction stack, where an insulator plate is placed between each electrode. The extraction stack allows water cooling on the electrodes and the insulators can be shielded from line-of-sight from beam to prevent charge accumulation causing sparking on insulator surfaces.

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