ECRIS DEVELOPMENT AT KVI*

V. Mironov#, J.P.M. Beijers, H.R. Kremers, J. Mulder, S. Saminathan, S. Brandenburg
Kernfysisch Versneller Instituut, University of Groningen, The Netherlands

Abstract

This paper reports on work performed during the last two years to improve the performance of the KVI-AECR ion source, which is used as an injector for the AGOR cyclotron. We have installed stainless-steel screens at the injection and extraction sides and an additional collar around the extraction aperture resulting in better plasma stability and an increase of extracted ion currents. Source tuning is aided by continuously observing the visible light output of the plasma through the extraction aperture with a CCD camera. We now routinely extract 700 μA of O^{6+} ions and 50 μA of Pb^{27+} ions.

Source optimization is supported by extensive computational modelling of the ion transport in the low-energy beam line and measuring the transverse emittance of the extracted ion beam with a pepperpot emittance meter. These efforts have shown that second-order aberrations in the analyzing magnet lead to a significant increase of the effective beam emittance. Work is underway to compensate these aberrations.

INTRODUCTION

The Advanced Electron-Cyclotron-Resonance Ion Source at KVI (KVI-AECRIS) has been used as an injector of multiply-charged ions into the superconducting AGOR cyclotron for several years already. The main demands on the source are defined by the needs of the TRIμP program on fundamental symmetries (Ne^{6+} and Pb^{27+} beams), as well as by radiobiological studies (C^{6+} ions). The intensities of the neon and carbon beams are exceeding the user's requirements and the main concerns are beam stability and reproducibility. The lead intensity is significantly less than requested for the final production stage of the experiment (by a factor of two to three) and efforts are underway to improve both the source performance and the beam transmission through the low-energy beam transport line. The paper is organized as follows: first the KVI-AECRIS is briefly described together with the recent modifications to improve its performance. Then we discuss the visual diagnostics used to observe plasma light emission through the plasma electrode aperture and finally we report on our efforts to improve beam transport through and imaging properties of the analyzing magnet.

SOURCE DESIGN AND MODIFICATIONS

The KVI-AECRIS design is the same as AECRIS-U of LBNL and the 14 GHz source of Jyväskylä. The source is equipped with soft-iron plugs at the injection and extraction sides (B_{inj}=2.1 T, B_{extr}=1.1 T, B_{min}=0.36 T), has radial slits between the hexapole bars for better pumping, and an aluminium plasma chamber with a length of 300 mm and inner diameter of 76 mm. The radial magnetic field in this geometry is lower than for other 14 GHz sources and reaches 0.86 T at the plasma chamber wall.

In addition to the main 14.1 GHz RF heating system, the source is also equipped with a 11-12.5 GHz, 400 W Travelling Wave Tube Amplifier (TWTA), enabling two-frequency plasma heating. In normal operational conditions, however, no benefits of dual frequency heating have been observed.

In the original design the injection plug was shielded from the plasma by an aluminium screen. Also the plasma electrode was made of aluminium and had a cone-like shape. In these conditions the source output was unstable, with frequent changes in the operational modes and moderate extracted currents. We replaced both the injection screen and the plasma electrode with stainless steel ones and changed the shape of the plasma electrode to a flat one. This resulted in large improvements in source performance, with much better stability and reproducibility. We still see jumps in source output, but they are now more controllable. In addition, the extracted currents increased with e.g. typical outputs of Ne^{6+}, O^{6+} and Ar^{8+} ion currents of around 300 μA.

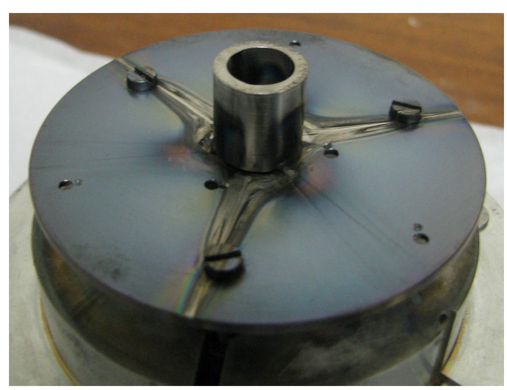

Figure 1: The plasma electrode with its collar.

An additional boost in performance was achieved by installing a collar around the extraction aperture. A picture of the collar is shown in Figure 1. The collar is a stainless steel cylinder with a length of 15 mm, inner diameter of 10 mm and outer diameter of 13 mm. In first instance installation resulted in a significant decrease of the output of the lower-charged ions (O^{4+} and lower). Output of the higher charge states on the contrary increased by a about 20 % The decrease in extracted low charged ions

*This work is part of the research programme of the 'Stichting voor Fundamenteel Onderzoek der Materie (FOM)', which is financially supported by the 'Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO)' It was supported by the European Commission within the Sixth Framework Programme through I3-EURONS (contract no. RII3-CT-2004-506065).
#mironov@kvi.nl

decreased a load on the extraction electrodes; the total extracted current from the source goes down with increasing gas load beyond the level optimal for the high charge states. This is consistent with the point of view that the lower charged ions are less localized at the source axis compared to the higher charged ions.

Second, with the collar we are able to tune the source in such a way as to drastically increase the currents of the highest charge states ($O^{6+,7+}$). This is done by simultaneously applying the gas mixing and two-frequency heating techniques. The tuning is quite sensitive to the inputs (less than 0.1% changes in the magnetic field and input rf power destroy the high output mode). It is very reproducible, however. We are able to extract up to a record 700 µA of O^{6+} in this mode, with a reproducible level of 550 µA, as well as 500 µA of Ar^{8+}. Also the output of Pb^{27+} ions reached a level of 50 µA (estimated value, we measured 25 µA of Pb^{27+} at the end of the transport line). These values are comparable to the outputs of AECRIS-U and the 14 GHz source at Jyväskylä.

The reasons for this high output mode of operation remain unclear, though one can speculate about the formation of internal transport barriers in the plasma at sufficiently high input power analogous to H-mode operation in tokamaks.

VISUAL LIGHT DIAGNOSTICS

For a better understanding of source operation we installed a video camera behind the analyzing magnet, looking into the plasma chamber through the 8 mm diameter extraction aperture. Using a low depth-of-field objective we can distinguish different plasma shapes in the plasma centre (the characteristic six-arm star) and in the injection and extraction regions (three-arm stars). In the visual spectral range we do not observe a strong localization of the plasma inside the ECR zone, but rather a smooth intensity distribution along the source axis. The plasma is radially localized around the axis with FWHM less than 8 mm.

We also observe radial shifts of the plasma close to the extraction aperture that correlate with the jumps in the operational modes of the source, i.e. with abrupt changes in the extracted ion currents. Such shifts occur in the direction of one of the star arms. The extracted currents are clearly at their maximum when the plasma is nicely centred.

Changes in the biased-disk voltage result in changes of the plasma shape. The optimal voltage (which is around 200 V for neon/argon plasmas) corresponds to the smallest plasma size. This is illustrated in Figure 2, which shows the plasma shapes of an Ar plasma in false colours for the optimal biased disk voltage of -200 V (Fig. 2a) and for a floating voltage of -60 V (Fig, 2b). The maximum intensity of the light did not change significantly when varying the disk voltage (changes were around 10% only, with, typically, higher intensity for the lower disk voltage).

These observations are consistent with experiments reported in Ref. [1] that demonstrated a fast reaction of the extracted ion currents to changes in the biased disk voltage. This is not consistent with variations in ion population due to increased ion confinement or to an increase of the plasma density. The function of the biased disk is to reduce the ion radial losses by controlling e.g. the anomalous plasma losses in the radial direction.

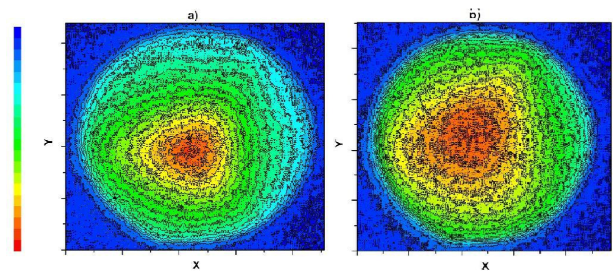

Figure 2: CCD images in false colours of an Ar plasma at the extraction region of the source. In a) the biased disk voltage is -200 V and the extracted Ar^{8+} current is 450 µA, while in b) the disk floats at -60 V and the extracted Ar^{8+} current is only 200 µA.

BEAM TRANSPORT OPTIMIZATION

Reduction of the ion beam losses in the low-energy beam transport line (LEBT) is at least as important as increasing the intensity of the extracted currents. We estimate the ion losses in the LEBT to be around 50%. To cure the problem we performed beam shape diagnostics using beam profile monitors such as harps and BaF_2 beam viewers located at different places along the beam line. We also installed a 4-D pepperpot emittance meter at the focal plane of the 110º analyzing magnet [2]. The measurements are accompanied with extensive computer calculations. For the simulations we use a home-made PIC-MCC Chaos [3] code to calculate the initial distribution of ions at the extraction aperture, and the ion tracking codes LORENTZ-3D [4] and COSY INFINITY [5]. The LORENTZ-3D code was also used to calculate the electric field in the extraction gap and the magnetic fields of the source and analyzing magnet. The simulations were done for He^{1+} ions at an extraction voltage of 24 kV and assuming full compensation of the beam space charge.

The beam profile measurements immediately after the extraction system confirm the initial triangular spatial distribution of the ions. No beam hollowing or filamentation was observed for normal operating conditions, only for some special tunings of the source with highly unstable output.

Further downstream the beam suffers from large second-order aberrations in the analyzing magnet. This magnet is an unclamped double-focusing magnet with straight 37º tilted edges. The magnet gap is 67 mm, bending radius 400 mm and the bending angle is 110º. According to the simulations, the initial beam emittance before entering the magnet is 65 π mm mrad, fully determined by the extraction of the ions in the solenoidal magnetic field of the source. The beam emittance has grown by a factor of up to 5 after the analysing magnet. The estimated losses in the magnet are around 30%. The simulated and measured beam profiles in the focal plane of the analysing magnet are shown in Figure 3. The parabolic shape is a clear sign of the large second-order aberrations of the analyzing magnet. Agreement between the simulated and experimental profiles is satisfactory and shows that the dominant effects determining the beam transport are incorporated in our computational model.

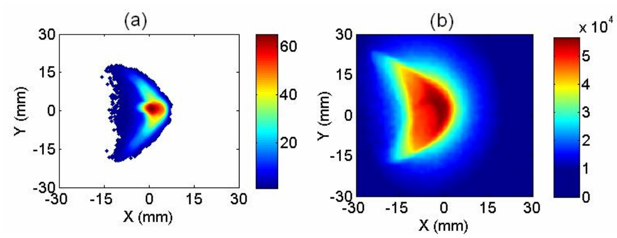

Figure 3: Simulated (a) and measured (b) spatial profiles of a 24 keV He^{1+} beam in the focal plane of the analyzing magnet.

In order to reduce the beam losses in and improve the ion-optical properties of the analyzing magnet we are using our simulation tools to calculate the effects of a modified magnet. The pole gap is increased from 67 to 110 mm and to compensate the second-order aberrations we added sextupole components to the main dipole field following the design of the VENUS analyzing magnet of LBNL [6]. The pole faces at the entrance and exit sections of the analyzing magnet have a positive parabolic curvature, while the pole face in the central region of the magnet has a negative parabolic curvature. In this way both the horizontal and vertical sextupole components of the fringe field are (partly) compensated. The modified pole face of the analyzing magnet is shown in Figure 4. To optimize the curvatures we first used COSY INFINITY to quickly estimate the required sextupole strengths and then LORENTZ-3D for the fine tuning. According to the simulations the full beam is transported without losses through the modified analyzing magnet and the beam emittance is decreased with a factor of two compared to the original magnet.

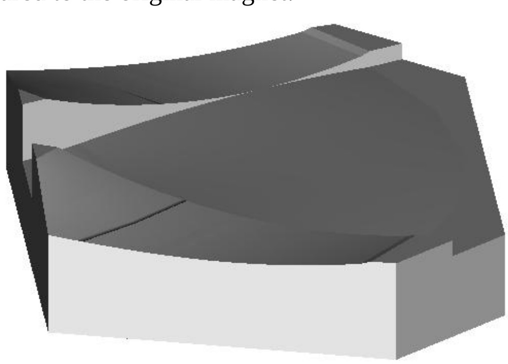

Figure 4: Modified pole face of the analyzing magnet with parabolic shapes to compensate the second-order aberrations.

CONCLUSIONS AND OUTLOOK

We have made good progress to improve the performance and stability of KVI-AECRIS. This was done by replacing the aluminium injection screen with a stainless steel one and the aluminium cone-shaped plasma electrode by a stainless steel flat electrode. We also attached a short cylindrical collar on the plasma-facing side of the plasma electrode. These modifications resulted in very stable source operation and large extracted currents, e.g. 700 μA of O^{6+}, 500 μA of Ar^{8+} and 50 μA of Pb^{27+}. The use of a CCD camera installed on the source axis behind the analyzing magnet to view the visible plasma emission through the plasma electrode aperture has proved to be a valuable tool to tune the source. We have also performed detailed simulations of beam extraction from the source and its transport through the analyzing magnet. The observed beam losses and emittance increase are caused by a too narrow pole gap and large second-order aberrations of the analyzing magnet. Our simulations show that these deleterious effects can be remedied by increasing the pole gap and adding sextupole corrections by modifying the pole face shape, respectively. We will implement these magnet modifications in the near future.

REFERENCES

[1] K. E. Stiebing, O. Hohn, S. Runkel, L. Schmidt, H. Schmidt-Böcking, V. Mironov, and G. Shirkov, Phys. Rev. ST Accel. Beams 2, 123501 (1999).
[2] H.R. Kremers, J.P.M. Beijers, and S. Brandenburg, Rev.Sci.Instrum. 77, 03A311 (2006).
[3] V. Mironov and J. P. M. Beijers, Phys. Rev. ST Accel. Beams 12, 073501 (2009).
[4] See home page of the code at http://www.integratedsoft.com.
[5] K. Makino and M. Berz, Nucl. Instrum. Methods Phys.Res. A 427, 338 (1999).
[6] M. Leitner et al., ECRIS02 workshop, Jyväskylä (FI), June 2002.