COMMISSIONING AND FIRST OPERATING EXPERIENCE WITH THE ECR HEAVY ION SOURCE AT THE PSI PHILIPS CYCLOTRON

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A 10 Ghz CAPRICE 1Tesla ECR Ion Source has been recently installed at the PSI K=120 - Philips Cyclotron. The source performances under the specific local conditions and the transportation of the beam through the axial injection system to the Philips cyclotron is described. First operating experience is discussed. To date beams of ^{12}C, ^{16}O, ^{20}Ne, ^{40}Ar and ^{129}Xe have been succesfully accelerated and delivered to experiments. ^{16}O beams with charge states from 2 to 6 were used to investigate injection and acceleration in the energy range from 2 to 18 MeV/A. Beams intensities of up to 2 eμA on target have been observed. A 2 enA $^{129}Xe^{26+}$ beam (from a natural sample) at 600 MeV demonstates that the present setup is also suitable for the acceleration of heavier species.

1 Introduction

Taken into operation in 1974 the PSI Philips Cyclotron[1] (locally named Injector 1) was used during one decade mainly as injector for the Ring Cyclotron. With the exception of polarized beam injection and a limited backup function it was released from this duty in 1985. Low energy nuclear physics became the dominant field of research, with, however, an increasing part of the beam time being devoted to eye cancer treatment and isotope production. The increasing importance of new research activities in various domains like atomic physics, radiochemistry, biology and nuclear spectroscopy since 1990 strongly called for an improved availability and quality of the heavy ion beams which, in the past, suffered from the limitations set by the use of an internal source. It has been therefore proposed to equip the accelerator with a powerful ECR heavy ion source to be installed at the existing axial injection system [2]

The compact 1T 10 Ghz CAPRICE source developed by Geller's group at Grenoble[3] was considered to best fit the needs of the potential users and the conditions set by the local environment. It is very compact, its modular design makes it possible to implement future upgrades, it has excellent performances for a wide range of gaseous and solid species and the charge states spectrum has a good overlap with the range expected to be usable at the Philips Cyclotron. The source was ordered in 1992 and after successful tests at Grenoble it was delivered at PSI mid 1993.

2 Installation of the Source

The ECR source and the horizontal part of the injection beam line are located underneath the cyclotron, in a magnetically shielded tunnel offering only a very limited space. The beam extracted from the source is analysed by a double focussing 90^0 magnet, passes a set of slits and is transported by a magnetic quadrupole triplet to an electrostatic spherical deflector for bending into the vertical beam line wich is shared with the polarized ion beam. The length of the horizontal section is 3.3 m. The distance between the spherical deflector and the electrostatic mirror is 3 m.

A schematic picture of the axial injection system is shown in Fig. 1.

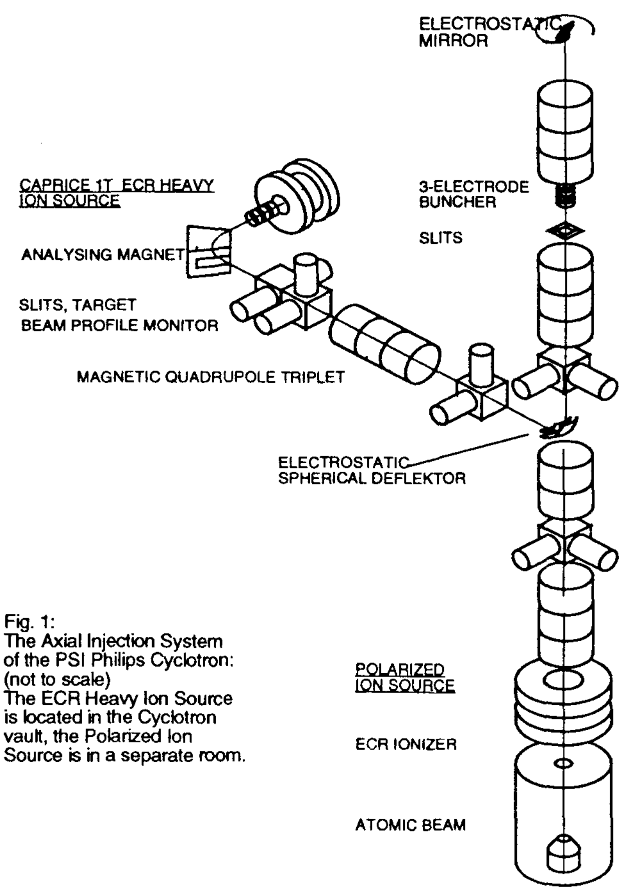

Fig. 1: The Axial Injection System of the PSI Philips Cyclotron: (not to scale) The ECR Heavy Ion Source is located in the Cyclotron vault, the Polarized Ion Source is in a separate room.

The spherical deflector has a movable electrode in order to allow for the passage of the beam from the polarized ion source. In the open position it is also used as electrostatic pulsing system for this beam.

The vacuum system consists in a 60 l/s turbomolecular pump at the entrance of the source, a 500 l/s turbomolecular pump at the extraction, a pump of the same type between analysing magnet and first triplet, and a 600 l/s oil diffusion pump for the beam line section above the deflector. The residual gas pressure is below 4*10-7 mbar.

Beam diagnostic is provided by sets of beam profile monitors and Faraday cups. In addition to the room shielding, compensation of the residual stray field from the cyclotron is achieved by correction magnets and local shieldings of a few critical sections. In order to maintain a relatively easy access for maintenance of the vertical injection line all components are mounted on movable supporting frames.

To minimize the loss in beam time, the main installation work concerning the source, the horizontal beam line and the required infrastructure in the cyclotron vault had to be done during two two-week shutdowns in april and mai 1993. The final completion of this work was performed during service days and stand-by periods in summer and fall.

Besides the installation of the new equipment the vertical part of the axial injection line was modified to accomodate the spherical inflector and equiped with new power supplies. The control system was updated to the present PSI standard.

A check of the performances under local conditions has been done in collaboration with the source supplier in the second week of January 1994 . The equipments added at PSI in order to remotely control the source work properly in the requested ranges and allow for an easy and precise adjustment of all operating parameters. It was therfore possible to start the optimization of the injection beamline and to deliver a Neon beam to the first experiment scheduled in the second half of February 1994. Since then it was extensively used for a series of experiments. Heavy ion production accounts now for about 30 % of the available beam time.

3 Source optimization

The Grenoble ECR CAPRICE source is equipped with a two-electrode extraction system designed for operation at 20 kV. However, since the Philips Cyclotron requires variables injection energies depending on the magnetic field setting and the ions to be accelerated, the source has to be operated with extraction voltages between 5 and 13.5 kV. The extraction voltage dependence of the beam intensity measured for three Argon charge states at the first Faraday cup after the analysing magnet is shown in Fig. 2. The use of the original 20 kV geometry at lower voltages not only results in smaller beam current but it also leads to a significant sputtering of the iron extraction electrode with subsequent insulator metallisation and breakdown.

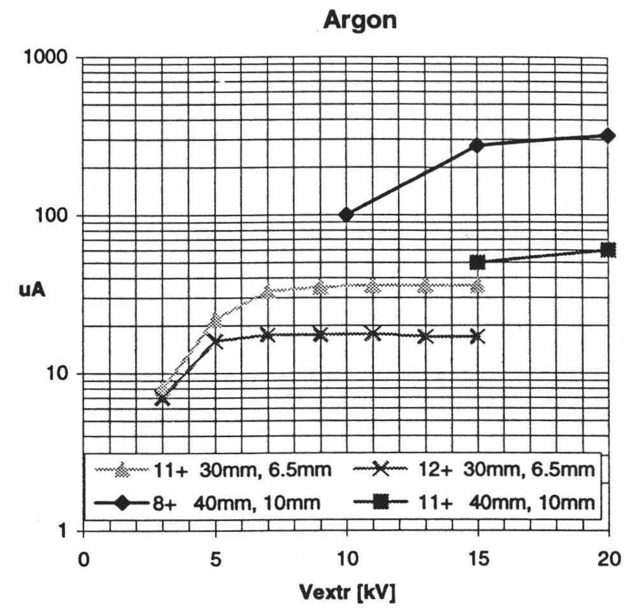

Fig. 2: Beam intensity as a function of the extraction voltage for different charge states and two extractor geometries. The distance between plasma and extraction electrodes and the plasma electrode aperture are indicated. For the measurements with the charge states 11+ and 12+ the source was optimized on state 11+ at 7 kV. The results at 20 kV are from the tests at Grenoble.

A systematic optimization of the extraction geometry for ion type, charge state and energy is under way and has already resulted in a significant improvement of the currents available for injection in the machine. The performances of a few geometries for the extraction of a $^{20}Ne^{6+}$. beam are illustrated in Fig 3. With an optimized extraction a gain by a factor of 1.5 could be observed in comparizon to the original design.

Another phenomena strongly influencing the beam quality is the space charge situation at and past the extraction from the source. An Einzel lens is installed 15 cm from the source. The application of the requested high voltage results in a very noisy beam. On the other hand a potential of +100 V on the lens and on a diaphram in front of it help obtaining a beam of strongly reduced divergence.

The beam transport in the axial beam line and the injection efficiency in the machine depend on parameters like beam quality, bunching factor, recombination, beam behaviour at the inflector and during the first turns in the accelerator which are all becoming critical at the lowest energies. As already demonstrated with the beam from the polarized ion source, better results are obtained in that case if extraction voltages significantly higher than the ones required for injection in the so-called constant orbit mode are used. The lowest practical voltage is therefore 5 kV.

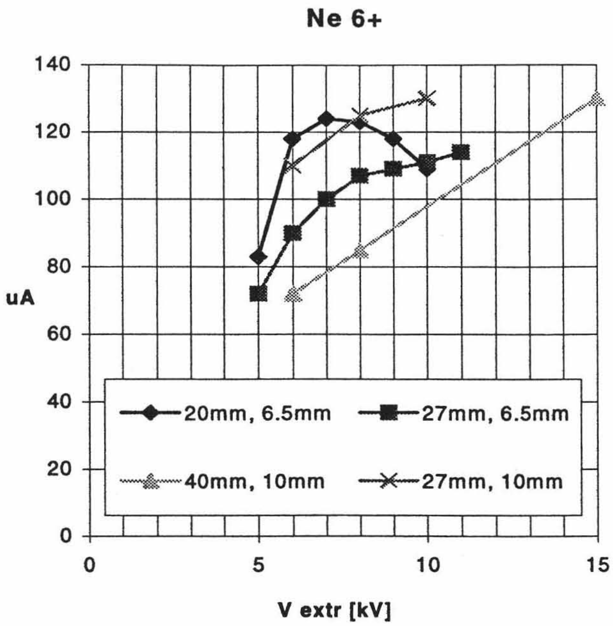

Fig. 3: Influence of the source extraction system on the beam intensity.The intensity of a Neon beam of charge 6+ is plotted for different separations of the electrodes and two diameters of the aperture of the plasma electrode. For the mesurements with the 10 mm aperture the source was optimized at each extraction voltage, in the other cases it was optimized at 7 kV.

While not the whole energy range has been investigated yet it appears that the overall performance is best if a source voltage up to 50% over the nominal value is used, the limit being given by an increasing mismatch of the ion velocity with the fixed three-electrode buncher geometry.

To date, the electrostatic mirror inflecting the beam into the accelerator has only been modified to reach better vacuum conditions. While the beam optics degradation due to sputtering damages at the grid is not dramatical, the reliability may suffer during long operating periods due to the occurrence of electrical shorts between grid and electrode or to a degradation of the stability caused by a too large dark current. An ungridded system is under investigation.

4 Beam acceleration

For the beams produced up to now the machine was operated at magnetic fields between 1.3 and 1.5 T, slightly below the K = 120 value. This range of fields has the advantage that a good radial shaping is achievable with the currently reduced set of operating trim coils. Furthermore, for a given end energy it allows to use a lower Z/A and a higher source extraction voltage which result in larger injected currents.

The following beams have been successfully accelerated and delivered to experiments:

- $^{12}C^{3+}$ at 75 MeV
- ^{16}O with charge states 2+ to 6+ in an energy range from 28 to 280 McV
- $^{20}Ne^{5+,6+}$ from 140 to 180 MeV
- $^{40}Ar^{10+}$ at 280 MeV
- $^{129}Xe^{24+}$ to $^{26+}$ from 500 to 600 MeV

In a first attempt beams of $^{208}Pb^{27+}$ to $^{31+}$ have been internally accelerated to 430 to 600 MeV but could not be extracted yet. These beams are clearly at the limit of the possibilities of the Philips Cyclotron. A 40 MeV $^{20}Ne^{3+}$ has been accelerated, also.

The transport efficiency from the source to the user's target is shown on Fig 4 for a series of beams. Summarizing

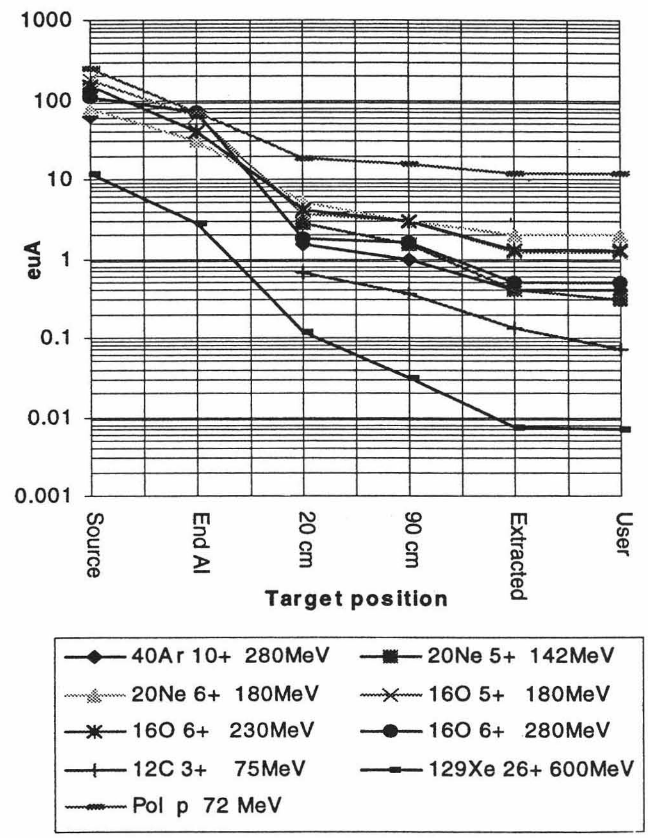

Fig. 4: Beam intensities at different targets and beam radii along acceleration path. When contamination from the Helium or Oxygen buffer gas is present interpolated values are given at the source and extrapolated ones at 20 cm. For Xenon the results are extrapolated to an isotopically pure target. The transmission observed with a proton beam from the polarized ion source is also shown for comparizon.

the behaviour observed with all the beams produced since operation of the ECR ion source started, one might draw the following conclusions:

- The transmission through the axial injection is comparable for all beams
- The injection efficiency defined as the ratio of the bunched beam current at a radius of 20 cm to the one at the last target of the vertical axial injection line (labelled as „end AI" in Figure 4) is less than 12%, significantly lower than the best figure of 25% observed with the polarized proton beam. The bunching factor of 3 to 4 is comparable in both cases. The main reason for the beam loss is, as expected, charge exchange in the residual gas, the pressure of which is estimated to be at least 10^{-6} mbar at the center of the machine ($5*10^{-7}$ mbar at the pumping ports). For Xenon the electron capture dominates as could be observed by a measurement of the charge state spectrum after injection by means of a scan of the machine frequency.
- The transmission from 20 to 90 cm is good for lighter ions with high charge state. For $^{16}O^{2+}$ it is 2 times smaller than for $^{16}O^{6+}$. In the case of Xenon the intensity continues to decrease rapidly by a factor of 3 between 20 and 50 cm and show then a flatter behaviour.
- The extraction rate is generally less than 40 %. The highest rate of 60 % was observed for a 180 MeV $^{20}Ne^{6+}$ beam. The extraction is difficult at the high fields at which the heavy ion beams are produced because the field shape in the extraction region has been optimized at 1 T for the 72 MeV proton beam.
- The machine setup is more delicate in the case of strongly recombining ions where the appearence of „phantoms" may strongly disturb the beam measurements. The handling of intensities in the nA range is at the limit of the available diagnostics elements.

5 Future improvements

While no in-house basic development in the field of ECR heavy ion sources is planned, the effort will continue to concentrate on further optimization of the source operation under the existing conditions. It is, however, intended to test if some of the progress achieved with the following generation of CAPRICE sources[4] is applicable at our source, also.

Additional work is needed to deduce general rules from the present optimization procedure of the extraction geometry of the ECR source. The observed behaviour is compatible with calculations of Spädke et al. for the GSI CAPRICE source[5], however the completion of such an analysis for our specific conditions remains to be done. The possible advantage of a three electrode accel-decel extraction has to be investigated also. A procedure for an automatic beam emittance measurement adapted to our setup is in preparation.

The observed space charge and secondary electron effects on the extracted beams have to be clarified. A refocussing of the beam after extraction is a condition for good transmission through the analysing magnet and a correct matching to the optics of the injection beam line.

The gridded mirror for the beam inflection into the accelerator median plane has to be replaced by a new device fitting in the very limited available space. Experience with damaged grids shows that the requirement on the optical quality is not very critical. It should be therefore possible to use a quite simple system. Calculations and preliminary tests with a perforated plate in front of the repelling electrode are encouraging.

6 Conclusion

The PSI Philips Cyclotron has proven its ability to accelerate lighter and medium heavy ion with an overall efficiency of up to 2 %. Planned improvement should increase this figure by a factor of 2. The energy range covered up to now extends from 2 MeV/A for $^{20}Ne^{3+}$ to 18 MeV/A for $^{16}O^{6+}$.

All experiments performed with the heavy ion beams could benefit from the excellent stability of the source. For the lighter species the intensities correspond generally to the expectation. The heaviest beams have been produced only once and their realisation for routine use is still a challenge.

Acknowledgements

It is a pleasure to acknowledge the very efficient support provided by the PSI technical staff during the installation of the source. Thanks to their efforts the shut down of the accelerator could be kept at a very minimum. The competent work of the Injector 1 crew and of the operation group resulted in a rapid and smooth integration of a variety of new beams in the Philips Cyclotron operation program.

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