# PRODUCTION AND USES OF HEAVY IONS BEAMS AT THE PSI PHILIPS CYCLOTRON

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Since the installation of an ECR Heavy Ion Source in 1993 the acceleration of lighter heavy ions has become an important part of the operation of the PSI Philips Cyclotron. The production of these beams under the specific conditions set by the experimental program is discussed. Their use in various fields of research is presented.

## 1 Introduction

The PSI Philips Cyclotron is operated to the benefit of a large variety of applications and research fields. The current distribution of the available machine time is as follows:

- 30% for medical research and applications.
- 25% for low energy nuclear physics.
- 25% for atomic physics and radiochemistry.
- 10% for injection of polarized protons into the Ring Accelerator.
- 10% for various irradiations for technical purposes.

The beam is delivered on target during about 5300 hours/year. The production of heavy ion beams accounts for more than half the beam time allocated to research at low energy. Mostly requested are beams of $^{12}C$, $^{16}O$, $^{18}O$, $^{19}F$, $^{20}Ne$ and $^{22}Ne$ at energies ranging from 2 to 20 MeV/A. They are essentially used for atomic physics and radiochemical investigations of heavy elements.

First experiences with the production and acceleration of heavy ions at the PSI Philips Cyclotron have already been reported at a previous conference [1]. The present paper deals primarely with some revisited aspects of the axially injected beam, improvements in beam diagnostics, and particular requirements set by the research program on the beam production.

## 2 Beam production

### 2.1 The ECR Heavy Ion Source

The heavy ion are produced with an ECR source of the Caprice 1T, 10 Ghz type purchased in 1993 from CEN Grenoble. A source of very compact size was a must due to the very limited space available underneath the Philips Cyclotron. The Caprice source is ideal in this respect, and its performances meet best the need of the PC users community. Since the performances of the ECR source for alpha and single charged helium ions are excellent, too, this source is also used for the production of these light species.

The Grenoble ECR Caprice source was originally designed for an extraction voltage of 20 kV. Since the Philips Cyclotron requires lower, variables injection energies the source extraction geometry had to be optimized accordingly. The performances of the source as a function of the extraction geometry and for extraction voltages down to 5 kV have been discussed in a previous contribution [1]. Most of the beams currently used request extraction voltages below 6.5 kV. Since a very flexible operation with frequent changes of beam type is expected by the users modifications of the geometry are not practicable during the runs and a compromise between the different requirements had to be found. We presently use a configuration with an extraction hole of 10 mm diameter and a ground electrode with an aperture of 20 mm at a distance of 27 mm from the plasma electrode. The divergence of the beam is strongly reduced if a downstream suppressor is biased to -50 to -80 Volt and if the source is tuned in such a way that the total extraction current is between 2 and 4 mA.

The previously observed poor transmission and injection efficiency pointed to an additional difficulty in handling the lowest energy beams. A severe problem here is the complicated emittance pattern, due to the influence of the hexapole field, which might even lead to the existence of three partial beams with very different optical properties. An example of emittances measured at low extraction voltages is shown in Figure 1. Only a part of the beam can match the 500 mm mrad acceptance of the axial injection system. Thus, the optimization of the beam intensity in a Faraday cup is by far not a sufficient criteria to settle the operating parameters of the ECR source under such extreme conditions. In practice one of the beamlets has to be selected by a slit system and the source must be reoptimized accordingly.

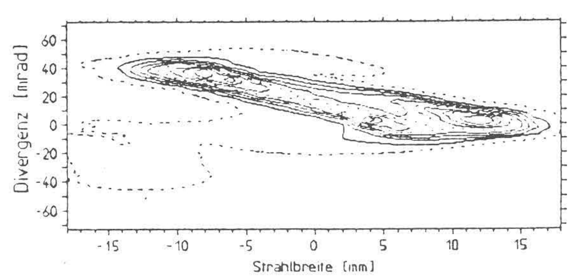



Figure 1: Emittance of a $^{18}O^{5+}$ beam extracted at 6 kV

The quality of the beams extracted at the lowest voltages is thus far from ideal and call for a thoroughly reinvestigation of the beam formation in ECR sources operated under such conditions. Even if the modes of operation of both sources are not comparable, the investigation of Xie on the magnetic field configuration at the extractor of the Berkeley source may be a useful hint to a cure of this problem [2].

## 2.2 Axial Injection

The ions extracted from the ECR source are analysed by a 90 degree double focusing magnet, selected by a slit system and focused by a quadrupole triplet in a 15 cm radius electrostatic spherical deflector bending the beam in the vertical direction. The computer control of the slit system and the online processing of the signal from the first beam profile monitor allow for an automatized emittance measurement generating the diagrams shown in Figure 1. The system is also very useful to analyse beam profiles and current distribution on the beam stops of the axial injection. The vertical transport line is equipped with two magnetic quadrupole triplets, and two three-electrode bunchers are installed in the beginning and in the middle of this section. The pressure is of the order of $4\ 10^{-7}$ mbar. The loss by recombination is nevertheless acceptable for the lighter ions, since a transmission of up to 90% through the 6.3 m long injection line has been observed with selected beamlets of low emittance.

The bending of the beam into the median plane of the cyclotron is achieved by means of a gridded electrosatic mirror with an eletrode separation of 3 mm. The original Tungsten mesh has been replaced by a stainless steel grid produced by photoetching techniques. It withstands sputtering damages for periods as long as 2000 hours of operation.

The beam intensities transported to the inflector reach up to 40 μA. The observation that an increase of the beam intensity in the axial injection beamline may result in a decrease of the current observed in the machine suggests that space charge effects in the inflector are important. Therefore, a careful selection of the usable beam with analysing slits is mandatory to minimize the contamination of the beam with components reaching the mirror but outside the acceptance of the accelerator.

The injection efficiency is 15 to 20%, depending on the ion species and the vacuum conditions in the accelerator.

## 2.2 Beam Acceleration

The main features of the acceleration of heavy ions in the Philips Cyclotron have been presented at the 1995 Conference. From the experience gained to date it become possible to predict the performance of new beams and thus evaluate the suitability of the accelerator for a certain experiment.

Figure 2 shows the expected intensity versus energy range for a $^{20}$Ne beam. The parameters considered in this example are the source performances and the injection and extraction efficiencies. Experimental values are available for 3+, 5+ and 6+ ions. For each charge state the intensity drop at higher energies is due to the decreasing extraction efficiency at higher magnetic fields. The low energy limit results from the loss of the beam in the accelerator. This effect is due to the inability to correctly shape the field of the PSI Philips Cyclotron with the available trimcoils in the range of .8 to 1.25 T. The overlap between the different charge state is however generally sufficient to overcome this problem. Experiments with modest intensities can be performed in a very wide energy range. Higher beam currents are restricted in the 5 to 8 MeV/A range.

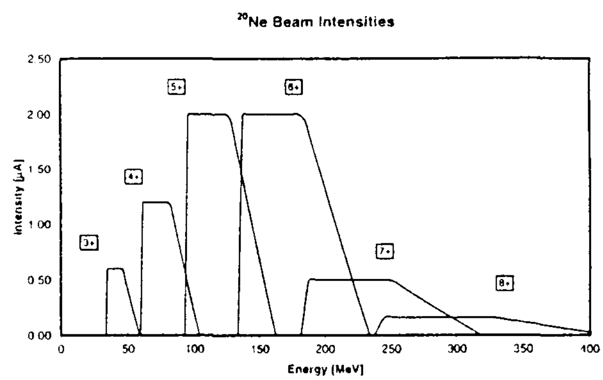



Figure 2: Predicted $^{20}$Ne beam intensities in the energy range of the PSI Philips Cyclotron.

The analysis of the behaviour of the phase of 40 beams produced at main fields in the 12 to 16 T range made it possible to remove uncertainties in the original field measurements. The resulting increased reliability in the calculation of the trimcoil setting has greatly reduced the need of machine time for beam development.

## 2.3 Stabilization of the accelerated beam

Experiments in high resolution spectroscopy set severe requirements on the beams delivered on target. A high stability of the beam position over days and the need to keep the current constant at a level of a few percents during hours can only be achieved with a dynamical control of the accelerator parameters. The currently available procedures are illustrated in figure 3.

Since, with the exception of the phase detector, parameters like limits, gains or time constants can be set by software the system is very flexible and can be adjusted according to the actual conditions of the accelerator and to the specific needs of the experiment.

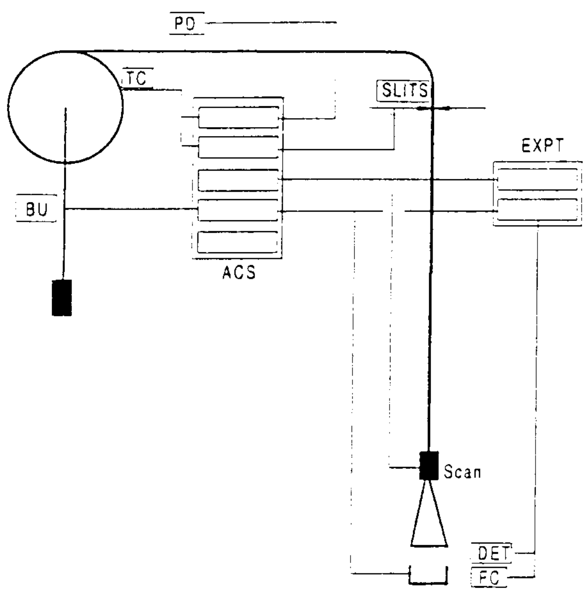



Figure 3: Feedback system for the control of the beam stability. Signals from the phase detector (PD) or from slits are used to apply field corrections with the outermost trimcoil (TC). The variation of the buncher voltage (BU) eliminates current instabilities. The signals from a Faraday cup (FC) or from monitor detectors (DET) are processed by the experiment and/or the Accelerator Control System. The last steering magnet can also be used for beam scanning.

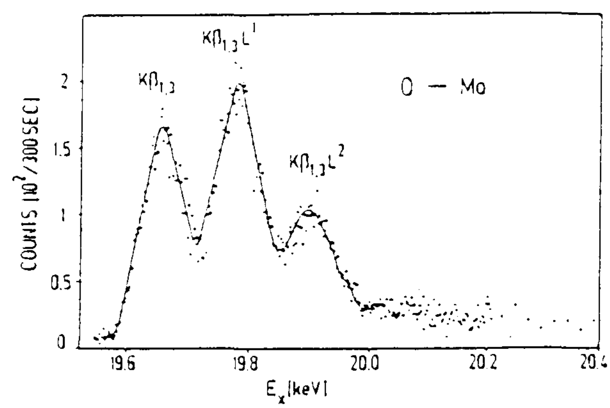
## 3. Uses of the heavy ion beams

The main fields of application of the heavy ion beams at PSI are atomic physics and heavy element research. While in the first case the quality of the beam like precise focusing or long time stability are important, the second kind of experiments rely essentially on the intensity of the beams.

### 3.1 Atomic physics experiments

The detailed understanding of atomic inner-shell ionization processes is of interest for many disciplines. Results of such investigations are used for example in trace element analysis, ion implantation, fusion diagnostic, astrophysics, X-ray lasers or nuclear physics. The high resolution spectroscopy of the X-ray emitted after multiple ionization induced in ion/atom collisions is a very sensitive tool to check the validity of the current theoretical approximations. However, the analysis of the very complicated structure of the spectra critically depends on the quality of the experiments.

Bent crystal spectrometers of the transmission (DuMond) and reflection (von Hamos) types are operated at PSI by the Fribourg group. Their research concentrates on ionization processes induced by medium velocity ions (He, $^{12}$C, $^{16}$O, $^{20}$Ne) induced in low and mid-Z atoms. The fundamentals of the method based on the measurement the L-shell (and M-shell) vacancy production probability in collisions associated with the removal of one K-shell electron is discussed in ref. [3]. The limits of this technique is indeed given by the precision level at which satellite lines of higher order can be observed. The figure 4 illustrates the progress achieved with the use of beams produced by the ECR source. The upper spectrum has been obtained with the transmission spectrometer and a 110 MeV Oxygen beam from the internal PIG source. For each point the data were collected during 300 s. The lower spectra shows the same measurement with the beam from the ECR source and a data acquisition time of 70 s per point. The improvement is dramatic not only in statistics, but also in respect of the systematic errors. The much better beam stability over the time requested for the complete scan practically eliminates the need of a recalibration of single points or part of the spectrum. The satellite lines at 20 keV were not detectable in the first experiment.



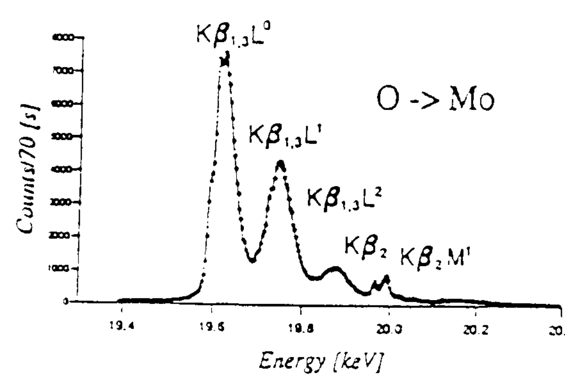




Figure 4: X-ray spectra observed after inner-shell ionization of Mo by 110 MeV 16O ions. The upper spectrum has been measured with a beam from the internal PIG source, the lower one with the ECR source.

With the improved beam quality and the advanced characteristics of the newly installed von Almos spectrometer it become even possible to investigate line shift and broadening arising from chemical or physical bounds of target atoms on surfaces.

### 3.2 Heavy element research

The investigation of the properties of the heaviest elements is very fascinating for several reasons: the nuclear physicist is much interested in the evolution of the life time of the neutron rich elements as the predicted neutron magic number of 162 is approached, the chemist is aiming at the correct location of the new elements in the Mendeleew table. A challenge is indeed the development of efficient methods for single atom chemistry, too. So far elements up to z = 112 have been synthesized.

A most spectacular result in the chemistry of the heavy elements is the allocation of element 106 (Seaborgium) to group 6 based on the observation of the decay chain of 7 atoms at UNILAC [4]. The involved research group has intensively used the PSI Philips Cyclotron for the development of the chemical methods. Several techniques were optimized in model experiments by means of the investigation of the chemical analogues like W under identical conditions. The investigation of element 104 (Rutherfordium) is an important part of this program, too.

So far the following beams and target have been used at PSI for heavy element research:

- $^{18}$O and $^{20}$Ne on Gadolynium for the production of $^{165\text{-}169}$W isotopes by the Gd($^{18}$O,xn) and Gd($^{20}$Ne,xn) reactions.
- $^{18}$O and $^{19}$F on Dysprosium for the production of neutron-deficient W and Re isotopes
- $^{18}$O on a Curium target for the production of element 104 (Rutherfordium) by the $^{248}$Cm($^{18}$O,5n)$^{261}$Rf reaction.
- $^{22}$Ne on $^{244}$Pu to synthesize $^{261}$Rf
- $^{19}$F on a Curium target to investigate the production of element 105 (Dubnium) by the reactions $^{248}$Cm($^{19}$F,5,4n)$^{262,263}$Db.

The requested energies around 7 MeV/A are well in the range where the attainable intensities make such experiments feasible at PSI. The necessary know how in the handling of the radioactive targets and the radiochemical infrastructure are available at PSI.

The production rates for some transactinides are listed in table 1. Currently, the intensities available at PSI reach 1 (electrical) μA for $^{19}$F and 2 μA for the oxygen and neon beams.

Table 1: Production rates of transactinides for chemical studies (Assumptions: 750 μg/cm2 target: .5 particle-μA beam)

| | | | | |
|---|---|---|---|---|
| $^{261}$ **Rf** | (78 s) | $^{18}$O + $^{248}$Cm | 5 nb | **1.5 atoms/min** |
| $^{262}$**Db** | (34 s) | $^{18}$O + $^{249}$Bk | 6 nb | **2 atom/smin** |
| $^{265}$**Sg** | (7 s) | $^{22}$Ne + $^{248}$Cm | .4 nb | **8 atoms/h** |
| $^{266}$**Bh** | (10 s) | $^{22}$Ne + $^{249}$Bk | 50 pb | **1 atom/h** |
| $^{279}$**Hs** | (9 s) | $^{26}$Mg + $^{248}$Cm | 5 pb | **2.5 atoms/day** |

A schematic of the target set up is shown in figure 5. The recoiling isotopes are collected on aerosol particles and transported by mean of a capillary gas jet in less than 10 s to the radiochemistry laboratory. A sophisticated interlock system warranties the proper function of the target assembly. In addition an automatic fast closing valve, a special vacuum system interlock and radioactivity monitors protect the beam line and the environment against failure of the target window or of the transfer line.

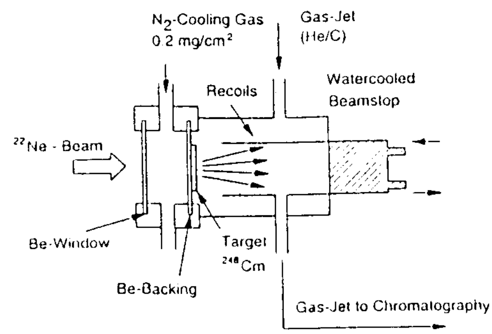



Figure 5: Schematic of the gas jet target for the production of heavy elements.

## 4 Conclusion

Since the start of the operation of the ECR Heavy Ion Source in 1994 a new generation of experiments has become feasible at PSI Philips Cyclotron. As shown by the reported rates of production of heavy elements in reactions induced by lighter heavy ions the race for higher beam intensities is still open. The present performances of the ECR source in respect of the beam optical properties in a very marginal mode of operation are certainly not at the ultimate state of the development.

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