HIGH INTENSITY OPERATION OF THE AGOR-CYCLOTRON FOR RIB-PRODUCTION

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Abstract

A facility for experiments with radioactive ion beams, produced in inverse kinematics with heavy ion beams, has been built at the KVI. The experiments require primary beam intensities $\geq 5 \times 10^{12}$ pps, corresponding to ~1 kW beam power, for beams up to Pb. The upgrade of the superconducting AGOR cyclotron to meet this requirement is described and the present status given. The on-going work to validate critical aspects is discussed.

INTRODUCTION

Over the last few years the KVI has developed a research programme on fundamental symmetries and interactions [1]. The aim of this programme is to find clues to new physics underlying the Standard Model of particle physics. This is done by searching for violation of the T-symmetry, which may manifest itself in the β-ν correlation in nuclear β-decay and by non-zero permanent electric dipole moments (EDM) of elementary particles, nuclei and atoms. In the experiments searching for these phenomena measurements are made on radioactive atoms trapped in magneto-optical traps (MOT). For the β-decay experiments in first instance short-lived Na-isotopes have been selected, while for the EDM- experiments theory indicates that short-lived Ra-isotopes are the best candidates.

The short lifetime (~1 second to a few minutes) of the isotopes implies that the radionuclides have to be produced, separated and prepared for trapping on-line. Heavy ion induced reactions in inverse kinematics reactions [2] are used to produce the radionuclides. For the Na-isotopes ^{20}Ne-beams in the energy range 20 - 40 MeV per nucleon are used, while the Ra-isotopes will probably be produced using a ^{208}Pb-beam of about 10 MeV per nucleon. Taking into consideration the production rates (10^{-5} - 10^{-6} per incident particle) and the overall efficiency of the whole chain between the production target and the final detectors (10^{-4} - 10^{-5}) [3] the intensity of the primary beam should be in the range 10^{12} - 10^{13} particles per second for all beams up to Pb, corresponding to a beam power of around 1 kW, to reach sufficient statistical accuracy within a reasonable time.

An extensive R&D-programme has been undertaken to perform these experiments at the AGOR-facility. It consists of the development of a large fragment separator [4] and all the equipment needed for the measurements in the MOT [5], which will be described briefly, and a major upgrade of the AGOR-cyclotron, which is the main subject of this paper. The cyclotron upgrade consists of

- reconstruction of the existing ECR ion source; the construction of a new source in a second phase and improvement of the low energy beam transport (LEBT) to maximize the transmission from the source into the cyclotron.
- reconstruction of part of the extraction system to cope with the high power density.
- development of a beam loss monitoring and control system to prevent damage to components in the cyclotron and high energy beam transport by excessive beam loss.

Furthermore, the limits on beam intensity imposed by the interaction of the beam with the residual gas and space charge effects are being investigated.

RIB FACILITY

The low energy radioactive ion beam facility at the KVI is schematically shown in fig. 1.

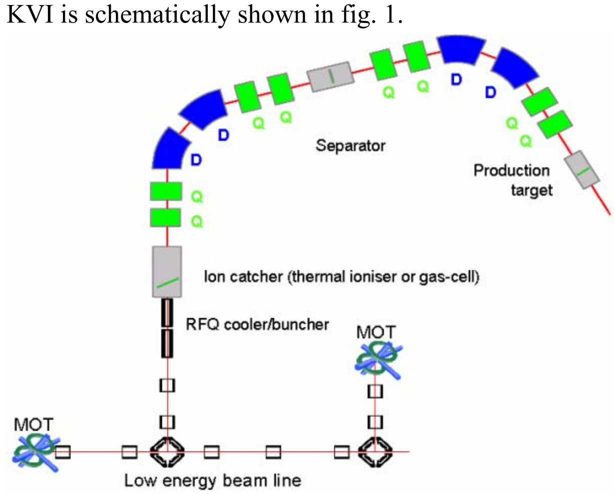

Figure 1: Schematic layout of the KVI RIB facility

Depending on the type of reaction the production target is located either at the entrance of the separator (direct and fragmentation reactions) or in the chamber halfway the separator (fusion reactions) [4]. In the latter case the second half of the separator is gas-filled in order to collapse the charge state distribution in the final focal plane. In the former case a wedge is installed in the intermediate focal plane to allow a complete separation of the different species in the final focal plane. With a suitable ion catcher the collected radioactive ions are converted into a low-energy 1^+-ion beam, which is then cooled, purified and bunched in a gas-filled RFQ [5]. The ions are then neutralized and collected in a first MOT, which also acts as a final purification step, before transferring them to the second MOT where the measurement is performed. The overall efficiency is essentially determined by these last two stages [3], which are presently being commissioned on-line, after successful completion of the off-line commissioning with stable ions.

ECR ION SOURCE DEVELOPMENT

The required beam intensity of 10^{12} - 10^{13} pps on target is for most beams beyond the capability of the existing CAPRICE 14GHz ECR ion source [6]. Analysis of the performance of other 14 GHZ sources led to the conclusion that the required intensity could be achieved for beams up to at least Ar by converting the source to an AECR-type source [7]. This is sufficient to perform the β-decay experiments, investigate the intensity limitations of the AGOR-cyclotron and validate the modifications of the cyclotron. For the very heavy ions like Pb a source operating at ≥18 GHz is needed to reach the required intensity.

The commissioning of the converted source was completed at the end of 2005 [8]. The present performance of the source [9] already significantly exceeds the requirements for the requested beams up to Ar. The installation of additional 12 GHz RF heating and optimisation of the extraction geometry based on detailed simulations are expected to lead to still higher intensities, in particular of the higher charge states.

Important factors in achieving the required intensities are the transmission of the beam from the source to the inflector in the cyclotron centre and the injection efficiency. With the first harmonic sinusoidal buncher a typical injection efficiency of 30 % is obtained, which is the product of a 35 % bunching efficiency and an 85 % geometrical transmission [10]. The installation of an additional buncher to increase the bunching efficiency is under consideration.

Despite the 140π mm mrad acceptance of the LEBT the transmission of the beam to the injection point of the cyclotron was in the past limited to 25 %. Recent simulations of the beam formation in the extraction zone of the ECR ion source have led to a better understanding of the emittance, which has translated in an increase of the transmission up to 50 %. For further improvement measurements of the full 4-dimensional phase space distribution are essential. An emittance meter combining the pepperpot and scanning techniques has been developed and is presently under commissioning [11].

EXTRACTION SYSTEM

The extraction system of the AGOR cyclotron consists of an electrostatic deflector (ESD), two electromagnetic deflectors (EMC1 and EMC2) and a quadrupole channel (QP). The electromagnetic deflector EMC2 and the quadrupole channel QP are superconducting. Beam losses may lead to immediate damage and operational constraints for the electrostatic deflector and the super-conducting channels. Neutron and γ-rays may in the long run result in damage of the insulation of the coils in the electromagnetic channels. However, the operation with 150 - 190 MeV proton and deuteron beams, which reach the insulation of the conductor in the room-temperature deflector EMC1 and produce high neutron fluxes compared to the heavy ion beams, has not resulted in a measurable deterioration of the insulating properties over a period of ten years.

Electrostatic deflector

The electrostatic deflector is a three-hinged device (see figure 2). The gap between the septum and the cathode is 5 mm; the maximum operating voltage is 50 kV. The 0.125 mm tungsten septum is loosely clamped in an aluminium support on both sides of the median plane to avoid deformation under thermal load. The present deflector has only passive cooling through the aluminium nitride insulators of the cathode and the aluminium support structure.

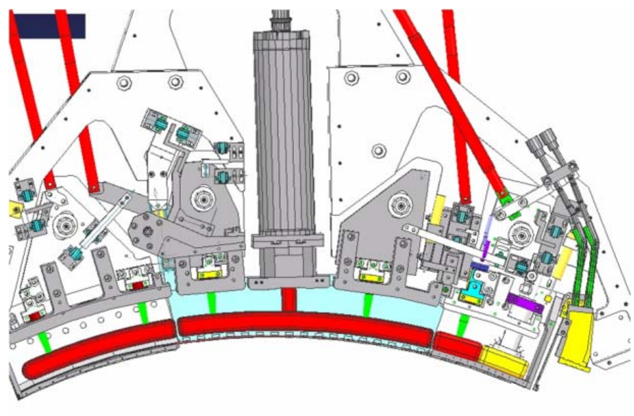

Figure 2: Top view of the new ESD design. The beam enters from the right. The red curved parts represent the cathode.

The typical transmission of heavy beams through the deflector, measured with a radial probe at the deflector exit, is 90 % as is illustrated in figure 3. The beam profile at the exit of the ESD has been deduced from the slope of the radial profile.

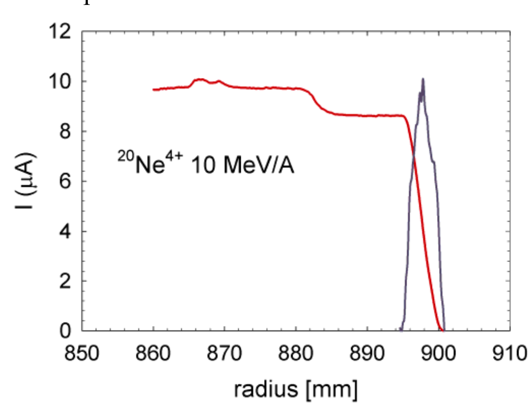

Figure 3: Beam intensity as a function of radius and radial profile of the extracted beam measured with the radial probe at the exit of the ESD.

Using a septum with a straight entrance edge heavy ion beams of E/A ~ 25 MeV with a power up to 100 W have been extracted on a routine basis. After tests at 200 W small cracks at the septum edge were observed, but these did not influence the operation of the deflector. After installing a septum with a V-shaped notch to spread out the beam losses a ^{20}Ne-beam at E/A = 23 MeV with a power of 300 W has been extracted for an extended period. On the basis of thermal calculations we estimate that under these operating conditions the maximum temperature of the septum is about 1500 K. The planned increase of the beam power to 1 kW requires active cooling of the deflector. To avoid evaporation of tungsten from the septum and its subsequent deposit on e.g. the cathode insulators the septum temperature should not exceed 2000 K (vapour pressure 10^{-10} mbar). The necessary redesign and prototype testing is underway.

Water-cooling will be installed on the support of the septum and on the insulators. The effective length of the deflector will be slightly shortened to prevent radiative heating of the cathode by the first part of the septum. The consequent increase in deflector voltage has been achieved without problems. A water-cooled block (yellow part just to the right of the cathode in fig. 2) will be installed opposite the first part of the septum to directly evacuate a maximum of power.

Furthermore the possibilities to improve the conduction cooling of the septum by increasing its thickness outside the median plane, as done at NSCL [12], are being investigated.

Superconducting channels EMC2 and QP

The electromagnetic deflector EMC2 and the quadrupole channel QP are superconducting magnets. The coils are located outside the cyclotron median plane, so that they can not be directly hit by the beam. Operating experience with proton and deuteron beams has shown, however, that localised power dissipation at the 1 W-level in the aluminium cold mass leads to quenching the coils.

In the beam hole of the channels a screen cooled by the 4.5 K boil-off gas of the coils is mounted. In contrast to the protons and deuterons the range of the heavy ion beams is not sufficient to pass through this screen, so that the coils can not be quenched by the beam hitting the cold mass. However, if mistuning causes a significant fraction of the heavy ion beam to be dumped on the screen, the thermal radiation load on the cold mass will lead to a quench.

During an experiment with an E/A = 23 MeV ^{20}Ne-beam with a beam power of 300 W the temperature of the return gas from the screen increased proportionally with the beam intensity from 6 K at zero beam intensity to 12 K at 300 W, corresponding to a beam loss in the screen of 5 W. No influence on the temperature of the cold mass or on the liquid He consumption was observed. From these measurements we conclude that beam losses up to 100 W in the channel, resulting in a temperature increase of the screen to slightly above 100 K, will not pose any problem. Under these conditions the heat load on the cold mass is about 0.3 W. Because of the T^4-behaviour of the radiation load from the screen on the cold mass losses above 100 W will rapidly lead to insufficient cooling capacity at 4 K.

BEAM LOSS CONTROL

Low energy heavy ions have a short range in matter (~20 mg/cm^2 for 208Pb at E/A = 6 MeV). The resulting local power density in components hit by the beam is up to 4 kW/mm^3 (Pb in W), which may lead to damage on a millisecond time scale. An autonomous system to monitor and control the beam losses in the cyclotron and the high energy beam transport (HEBT) is therefore essential for safe operation at high intensity. Furthermore, the system should ensure that intercepting diagnostics such as grid profilers can only be inserted at low beam intensities. Such a system, using concepts similar to those used for beam loss control at GANIL [13] and at the GSI UNILAC [14] is currently under development.

In the control mode an intensity “balance sheet” for the cyclotron and the different sections of the HEBT is established using non-intercepting inductive probes at the entrance and exit of each section and direct current measurements on slits and diaphragms. For each section intervention and interlock levels for the loss are defined. When the loss exceeds the intervention level the beam intensity is reduced until the beam loss is again below the intervention level; loss larger than the interlock level will lead to switching off the beam and return to tuning mode.

In the tuning mode a pepperpot in the LEBT limits the beam power to about 10 W. At this intensity intercepting diagnostics are not damaged and loss of the complete beam will not lead to damage. Diagnostics can only be inserted when the system operates in tuning mode. Transmission can then be measured using either the probes of the system or radial probes in the cyclotron and the faraday cups along the HEBT.

The inductive probes require the beam to be chopped. A duty cycle of 90 % at maximum current has been adopted. To minimize thermal cycling of the septum of the electrostatic deflector the chopper frequency should be as high as possible. However, the 20 °RF bunch results in a spread in transit time through the cyclotron of up to 10 µs, which led to the choice of a 2 kHz chopper frequency. Thermal calculations of the septum show that this results in temperature variations of less then 5 K

BEAM – RESIDUAL GAS INTERACTION

Beam induced deterioration of the vacuum is a well-known phenomenon [15], which has mainly two origins:

- desorption induced by ions and electrons created in collisions between beam particles and the residual gas.
- desorption induced by beam particles that are lost after a charge exchange reaction with the residual gas.

Both processes exhibit a positive feedback, which results in a hard limit on the beam intensity. The former leads to a vacuum instability, while the latter causes a maximum in the beam intensity that can be extracted.

Ion induced desorption

The production of ions and electrons in the collisions between the beam particles and the residual gas can be estimated from the stopping power of the beam particles in the residual gas and the average ionisation energy of the residual gas.

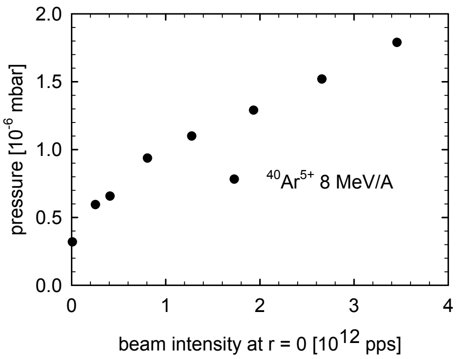

Figure 4: Pressure as a function of the injected beam intensity for $^{40}Ar^{5+}$ accelerated to 8 MeV per nucleon.

In the AGOR cyclotron about 100 ionisations are produced for $^{40}Ar^{5+}$ ions accelerated to E/A = 8 MeV at a pressure of 10^{-6} mbar. From the observed intensity dependence of the pressure (figure 4) and the total pumping speed of 4 m^3/s it is concluded that the desorption yield should be around 500 to explain the measurement. On the basis of the typical ion/electron energy of O(10 eV) and the 1 eV desorption enthalpy for H_2O, which dominates the residual gas, it is concluded that the desorption yield is at least an order of magnitude less and thus can not explain the observed pressure increase. This conclusion is supported by the observation that the dependence of the pressure increase on ion species is not consistent with the predicted behaviour. For $^{20}Ne^{6+}$ at E/A = 23 MeV one would expect the intensity dependence of the pressure to be half that for the ^{40}Ar-case; the actually observed dependence is a factor ten smaller.

Beam loss induced desorption

The cross section for charge exchange reactions between heavy ions and the residual gas is strongly dependent on the charge state and energy of the ion. Reported values [15 - 17] lie in the range 10^{-18} - 10^{-16} cm^2. Measurements of the transmission for an 8 MeV per nucleon $^{40}Ar^{5+}$ beam (figure 5) give an energy averaged charge exchange cross section of 10^{-16} cm^2, while for a 10 MeV per nucleon $^{20}Ne^{4+}$ beam the energy averaged cross section was found to be 3×10^{-17} cm^2. The systematic error in these values is at least a factor 2 because of uncertainties in the calibration of the pressure measurement. The low intensity transmission for these beams at a pressure of 3×10^{-7} mbar is 90% and 95%, respectively.

After a charge exchange collision the ions will eventually hit the vacuum chamber resulting in desorption from the wall. The desorption yield is strongly dependent on the energy of the ion and the angle of incidence on the wall [18]. From the measurements on the $^{40}Ar^{5+}$ beam an average desorption yield of 4×10^5 has been derived. This value is an order of magnitude higher than the values reported in refs [15] and [18]. The discrepancy is even larger when considering that those values correspond to (nearly) grazing incidence, while the present case is an average over all incidence angles. The measurements indicate that a maximum intensity of 1.4×10^{12} pps can be extracted for this beam with a transmission of 50 %.

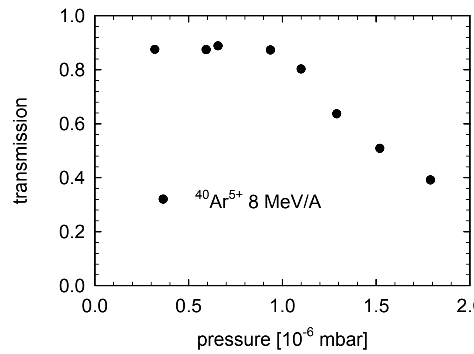

Figure 5: Transmission as a function of pressure for $^{40}Ar^{5+}$ accelerated to 8 MeV per nucleon.

For the $^{20}Ne^{6+}$ beam at E/A = 23 MeV the desorption yield has been found to be about one order of magnitude less. Together with the three times smaller charge exchange cross section this results in an intensity limit well beyond the required 10^{13} pps.

The large differences in charge exchange cross section and desorption yield make extrapolation to other, heavier beams very uncertain. Measurements for a range of ions and energies will have to be made to establish the systematics.

Remedies

A simple model using an energy independent charge exchange cross section and desorption yield shows that the key factor to raise the intensity limit is to reduce the ratio of the desorption yield over the pumping speed. The possibilities to increase the pumping speed are very limited because of space constraints and the fact that the pumping speed in the cyclotron is already conductance limited. Reduction of the desorption can be achieved by baking the vacuum chamber and RF-resonators. Due to low-temperature soldering material used in several locations the maximum temperature should not exceed 320 K, making the removal of the adsorbed compounds a time-consuming process. In view of the results reported in ref [18] cleaning with an Ar or He glow discharge is not a solution either.

SPACE CHARGE EFFECTS

Central region

The maximum current that can be transported through the central region of the cyclotron is determined by the vanishing of the axial focussing. It is approximately given by [19]

$$I_{\max} = A\omega_0 \varepsilon_0 \nu_z^2 \frac{\Delta\varphi}{2\pi}\frac{\Delta E}{q} \quad (1),$$

where A is the full height of the beam; ω_0 the angular frequency of the particles; ν_z the axial betatron frequency at zero current; $\Delta\varphi$ the phase width of the bunch; ΔE the energy gain per turn and q the charge of the particle.

In the central region of the AGOR-cyclotron the magnetic contribution to ν_z is about 0.1. Neglecting the additional focussing generated by the RF fields the intensity at which axial focussing vanishes for the lowest energy beams (E/A = 5.5 MeV; Q/A = 0.12) is found to be $I_{max} \approx 100$ μA. The current corresponding to 1 kW beam power amounts to 20 μA, which will give rise to a tune shift $\Delta\nu_z = 0.01$ in the central region. It is thus not expected that space charge effects will have a significant influence on the transmission of the central region. Experiments with a 10 % duty cycle $^{20}Ne^{4+}$ beam of E/A = 10 MeV with a peak intensity up to 10 μA have not shown any deterioration of the injection efficiency.

Extraction

The AGOR-cyclotron employs multi-turn extraction with a precession motion excited by the $\nu_r = 1$ resonance to increase the turn separation at the entrance of the electrostatic deflector. As the resonance passage and the beam extraction are separated by around ten turns only, it is not expected that the turn separation at extraction is significantly influenced by longitudinal space charge effects. This has been confirmed in experiments with a 10 % duty cycle $^{20}Ne^{4+}$ beam of E/A = 10 MeV: no decrease of the extraction efficiency has been observed up to the highest peak current of 10μA.

CONCLUSIONS

The upgrade of the existing 14GHz ECR ion source has for gaseous elements up to Ar resulted in beam intensities exceeding what is needed to deliver a 1 kW beam on target. These high intensity beams have allowed us to make progress in studying the feasibility of delivering a 1 kW beam.

We have demonstrated that the present electrostatic deflector equipped with a septum with V-shaped notch allows delivery of heavy ion beams with a power up to 300 W for regular experiments. A new, cooled deflector, which is currently under development, should allow delivery of beams up to 1 kW.

Measurements on the superconducting extraction channels indicate that under normal operating conditions the thermal load on the cold mass does not significantly influence the operation of the channels up to a beam power of 1 kW.

The fundamental limits on the beam intensity due to space charge effects and the interaction between the beam and the residual gas have been investigated. The injection and extraction efficiency do not exhibit intensity dependences at beam intensities corresponding to half the dimensioning case (20 μA $^{208}Pb^{27+}$ at E/A = 5.5 MeV). We therefore conclude that space charge effects will not preclude reaching the intensity objectives.

The transmission through the acceleration region is determined by the beam loss induced desorption yield and the charge exchange cross section of the ions. Experiments have shown that these vary strongly as a function of ion species and may for certain beams limit the intensity that can be achieved. A systematic study needs to be undertaken to determine to which extent this process will limit the attainable intensities to values below the objectives.

ACKNOWLEDGEMENT

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REFERENCES

[1] H.W. Wilschut, Hyperfine Interactions **146** (2003) 77;
H.W. Wilschut, AIP Conf. Proc. **802** (2005) 223;
K.P. Jungmann *et al*., Phys. Scr. **T104** (2003) 178

[2] E. Traykov *et al.*, NIM **A572**(2007)580

[3] E. Traykov, PhD-thesis, University of Groningen (2006)

[4] G.P.A. Berg *et al*., NIM **A560**(2006)169

[5] A. Rogachevsky, PhD-thesis, University of Groningen (2006)
M. Sohani, PhD-thesis, University of Groningen, to be published

[6] A.G. Drentje, H.R. Kremers, J. Mulder, J. Sijbring, Rev. Sci. Instrum. **69**, 728 (1998)

[7] Z.Q Lie and C.M. Lyneis, Rev. Sci. Instr. **65**(1994)2947
H. Koivisto *et al*., Nucl. Instr. Meth. Phys. Res. **B174**(2001)379

[8] H.R. Kremers *et al*., Rev. Sci. Instr. **77**(2006)03A311

[9] H.R. Kremers, J.P.M. Beijers, S. Brandenburg , J. Mulder, High En. Phys. Nucl. Phys. **31**(2007) 90
J.P.M. Beijers *et al*., Proc. ICIS07, to be published
S. Brandenburg *et al*., these proceedings

[10] S. Brandenburg and J.W. Nijboer, KVI Annual Report 2003, http://www.kvi.nl/~annrep/homepage.html

[11] H.R. Kremers *et al*., Proc. DIPAC2007, to be published

[12] S. Alfredson *et al.*, AIP Conf. Proc. **600**(2001)133
[13] C. Jamet *et al*., Proc. DIPAC2005(2005)169
[14] H. Reeg, J. Glatz, N. Schnieder H. Walter, Proc. EPAC2006(2006)1025
[15] E. Mustafin *et al*., NIM **A510**(2003)1999 and references therein
[16] A.S. Schlachter, Proc. ICCA1984 (1984)563
[17] V. P. Shevelko, I. Yu. Tolstikhina, Th. Stöhlker, NIM **B184**(2001)295
[18] E. Mahner, J. Hansen, J.-M. Laurent, N. Madsen, PRST-AB **6**(2003)013201
[19] H.G. Blosser, M.M. Gordon, NIM **13**(1961)101