

A TWO-CYCLOTRON CONCEPT FOR THE PRODUCTION OF RADIOACTIVE ION BEAMS

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Summary

A way of coupling the two cyclotrons at Louvain-la-Neuve, to produce and accelerate radioactive ions, is described. Progress of the different subsystems is accounted for. Special attention is given to sixth harmonic mode acceleration in CYCLONE.

Introduction

In the course of 1986, the idea of using the two cyclotrons, operating in adjacent vaults at the Université Catholique de Louvain at Louvain-la-Neuve, to measure directly the cross-section at sub-Coulomb energies of a nuclear reaction involving a nucleus with a half-life shorter than one hour, was proposed. The radiative proton capture on ^{13}N (with a half-life of about 10 minutes) was soon selected as an especially interesting representative of that class of reactions.

The concept consists in using CYCLONE 30^[1], the 500 μA , 30 MeV H^- prototype cyclotron to produce large amounts of ^{13}N and subsequently accelerate the ^{13}N ions with the variable energy, multi-particle cyclotron CYCLONE^[2].

In the fall of 1987, the Belgian Government approved funding for an interuniversity collaboration (involving the Université Libre de Bruxelles, the Katholieke Universiteit Leuven and the Université Catholique de Louvain) for the production of "Radioactive Ion Beams"^[3] and their use for Nuclear Astrophysics experiments.

Facility description

A schematic view of the whole facility is shown in figure 1.

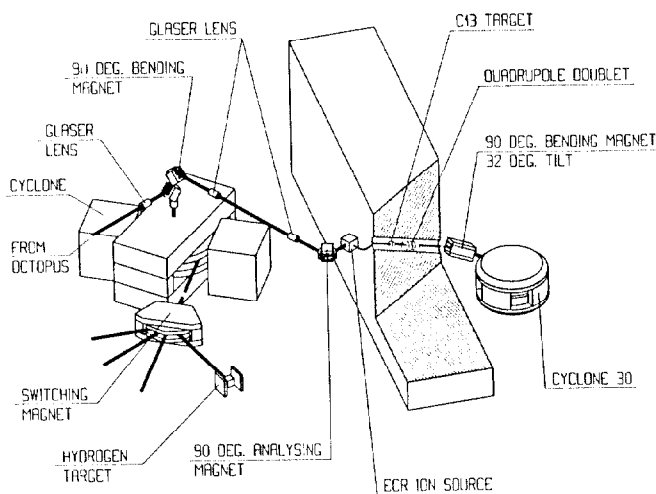


Figure 1.

The high intensity proton beam of CYCLONE 30 is transported to a target located in the shielding wall between the two cyclotrons. This beam line rises under an angle of 32° to allow the installation of the target at approximately the height of the injection line to CYCLONE and to direct the neutron flux behind the target mainly towards the opposite thick shielding wall. This transport line consists of a doubly focusing, 90° bending magnet and a quadrupole doublet.

For the production of ^{13}N the high yield $^{13}\text{C}(p,n)^{13}\text{N}$ reaction was chosen.

A series of experiments have been carried out, using natural carbon (graphite) to determine a suitable target design and to assess the optimum conditions for the extraction of the ^{13}N . Extraction efficiencies (normalized) of 70 to 90 % have been obtained at 200 μA on target, using small amounts of N_2 gas. The extraction yield depends strongly on the temperature distribution in the target which is itself directly related to target and beam geometry.

The ^{13}N extracted from the production target has to be ionized with high efficiency in an ECR^[4] source. Only 1^+ charge state is required. Therefore, a single stage source operating at 6.4 GHz, with an axial field produced by two watercooled solenoids and a radial hexapolar field produced by 12 bars of radiation resistant Sm_2Co_7 permanent magnet material has been built.

The $^{13}\text{N}^+$ ions from the source are analyzed and transported to CYCLONE. Focusing in this line is done with two Glaser lenses. The beam is then bent down and transported through the 90° bending magnet of the OCTOPUS line into the existing axial injection system.

Sixth harmonic mode acceleration

CYCLONE is a sector focused variable energy cyclotron with a K-value = 120 MeV. The maximum proton energy is 90 MeV. It is mainly used for nuclear physics (50 % of the available time) with both light and heavy ions and for routine neutrontherapy and related radiobiology with 65 MeV protons (about 25 % of the time). Some of its features of interest, for the following discussion, are :

- it is equipped with a set of twelve trimcoils allowing to shape the magnetic field to be isochronous at each field level in the range between the maximum proton energy at one end and a quasi perfectly flat field at the other end.
- the acceleration system consists of two 86° independently driven dees, operating in the 10.6 to 23 MHz frequency range.

- light ions are produced with a small internal source ; multicharged heavy ions are produced by an external ECR source, OCTOPUS^[5] and injected axially. The light ion source is inserted radially, the axial injection inflector comes in axially from below while the injected beam comes in from the top.
- to cover the energy range from 90 MeV protons to 2.3 MeV/a.m.u. for heavy ions, three harmonic modes are used :
 - N = 1 for 90 - 20 MeV/a.m.u.,
 - N = 2 for 20 - 5 MeV/a.m.u.,
 - N = 3 for 5 - 2.3 MeV/a.m.u.
- each harmonic and injection mode uses a different central region geometry. Therefore the puller electrode in the W-dee is also removable through an air-lock.

When the idea came up to accelerate also radioactive ions, with CYCLONE, to energies as low as 0.6 MeV/a.m.u., but keeping nevertheless all other modes of operation, a series of specific problems had to be solved. The following paragraphs treat these problems, the solutions that have been adopted and the results obtained so far.

Specific features related to sixth harmonic mode acceleration in CYCLONE

Only low charge states (1^+ , 2^+ eventually) can be considered in order to obtain high enough conversion rates between gas produced in the production target and ions generated in the ECR source. The very low final energy and large mass-to-charge ratio imposes the use of sixth harmonic mode acceleration in CYCLONE. In principle, the two 86° dee system is well suited for this mode: the theoretical gain per turn (over the four gaps) is $3.9 * V_{dee}$, close to the maximum possible value.

The space available in the centre of the cyclotron is very limited so the inflector has to be small radially. Even at the relatively low injection voltage of around 8 kV, the radius of curvature of the incoming ions is in the order of 3 cm. This quite large value implies in case of a spiral inflector, a small height. Calculations show that the parameter K should be less than 0.4 and its shape approaches a quarter of a cylindrical capacitor. In this case ions leave the inflector nearly radially with respect to the cyclotron centre. This aspect is very different compared respect to existing harmonic modes (1, 2, 3) and will require special attention to obtain a centered beam.

Any applied permanent modifications should not deteriorate actual cyclotron performances and removable elements in the centre should be brought in through existing ports.

The width of the accelerating gaps close to the centre is 20 mm and because of weak vertical focusing, a vertical aperture of 40 mm is kept in the dees. Due to the penetration of the electric field, the effective gap width increases to 60 mm, leading to transition times of more than 360° RF. Therefore it is necessary to reduce the first gap width by means of posts in dee and dummy-dee.

The electric field extension can be further reduced by decreasing the vertical aperture. However this reduction results in increasing focusing or defocusing vertical electric forces which depend strongly on RF-phase. Furthermore, smaller vertical apertures require also more precise alignment of the dees with respect to the dummy-dees. Even small such misalignments cause large vertical oscillations. Due to asymmetric RF-heating, the dees move slightly vertically. Therefore these movements have to be cancelled.

The posts however introduce radial defocusing in the median plane and cause larger energy dispersion.

Finally, because of the high harmonic mode, the acceleration is much more sensitive to small deviations of the magnetic field with respect to the isochronous field.

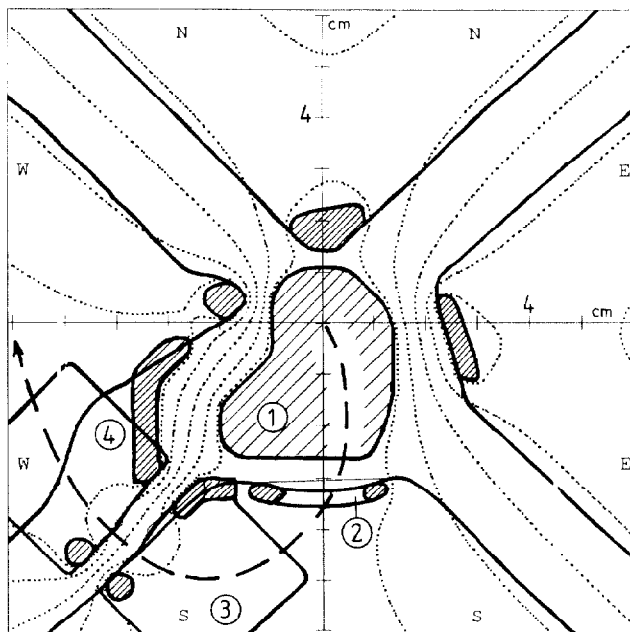


Figure 2. (1) The spiral inflector housing ; (2) the south dummy-dee post ; (3) the removable slit ; (4) the retractable puller.

Central region geometry

The final geometry, obtained after several iterations is shown on figure 2. The equipotential lines shown, were derived from the potential distribution calculated using the RELAX 3D code^[6].

Unlike the lower harmonic modes where the injected beam turns directly from the inflector into the puller and west dee, in sixth harmonic mode, the injected beam passes through a new hole in the south dummy-dee post, to the first accelerating gap confined by a slit in the dummy-dee and a new retractable puller. The effective gap length has been reduced this way to 14 mm. The slit in the dummy-dee is mounted on the mechanism which otherwise carries the internal ion source and can be very accurately remotely positioned. Changing from 6th to other harmonic modes requires changing the puller and source mechanisms. This operation takes about half an hour.

Final calculations of trajectories in the cyclotron centre have been done using a local implementation of the TRIWHEEL code^[7]. At an injection energy of 8.7 keV for $^{13}\text{N}^{1+}$ (final energy = 9 MeV) and 40 kV of dee voltage, phase acceptance taking into account radial motion only was estimated to be 70° (from -50° to 20°). Taking into account the vertical motion this was reduced to about 40° .

Median plane trajectories are shown in figure 3. Starting rf-phases are in the -50° to 20° range.

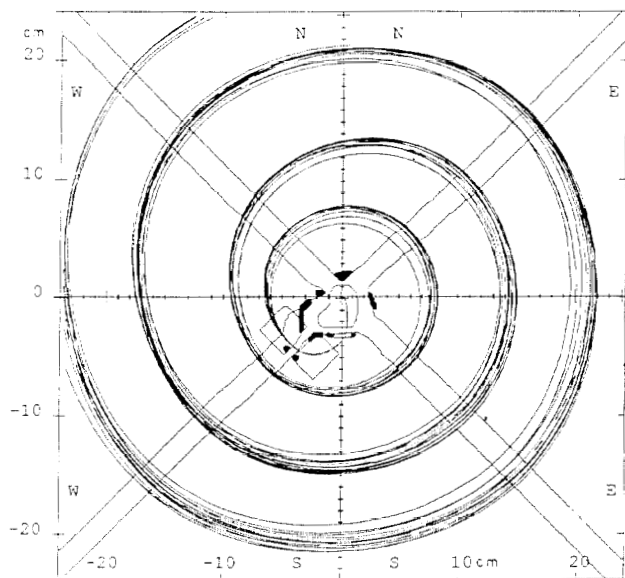


Figure 3.

Spiral inflector^[8,9]

Following the central region design, a spiral inflector was calculated which fitted the initial conditions. Due to geometrical constraints it was not possible to use this ideal inflector. So the final inflector and central region geometry is a compromise between calculated requirements and space limitations.

Inflector parameters are :

- electric height $A = 20.9$ mm
- parameter $K = A/2\rho = 0.3368$
- gap width = 8 mm
- voltage between electrodes = 6.7 kV
- drift angle between the inflector exit and shield exit = 22.9° .

Calculated transmission efficiency, imposing that the transmitted emittance be not larger than the injected and assuming 3 mm beam radius * 100 mrad half divergence, was found to be not larger than 60 %.

Further calculations indicated improved efficiency when using slightly higher dee voltage, higher injection voltage and slight rotation of the inflector. The indications have been verified experimentally during initial beam tests. First beam tests have clearly shown the extremely strong dependence of the transmission efficiency on the respective vertical positions of the spiral inflector and the puller inside the west dee.

Overall transmission efficiencies between injected and extracted beam on target up to 6.5 % have been obtained.

Status of the project (March 15, 1989)

- The 30 MeV-proton beam line is installed.
- Off-line testing of the ECR-source and its analyzing system has just started.
- Installation of the low energy line, wiring, controls, etc. are underway.
- Sixth harmonic mode is operational and routinely used with stable analogous beams for testing and simulation.

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