

CYCLONE44: A RADIOACTIVE ION BEAM POSTACCELERATOR-MASS SEPARATOR

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Abstract

CYCLONE44 is a $K = 44$ MeV, compact, variable energy cyclotron, combining efficient acceleration and very high isobaric separation for radioactive ion beams. It has been specially designed and built by the University of Louvain for experiments in the field of Nuclear Astrophysics. Ions with a mass to charge ratio in the range of 4 to 14 can be accelerated to energies from 0.2 to 0.8 MeV/AMU using harmonic modes 8 and 6. Ion beams are axially injected from external ECR-sources, accelerated by a particular two-"DEE" system and extracted by an electrostatic deflector. The design goal with respect to mass resolution for isobaric beams is 1 part in 10.000, with a typical rejection of the unwanted ion of 100.000 to 1. This paper reviews the specific design options, chosen to realize these characteristics. Results of the first accelerated stable $^{14}\text{N}^{+2}$ beam are reported.

1 INTRODUCTION

Postaccelerated Radioactive Ion Beams (RIB) were produced for the first time, at the end of the eighties, using the two cyclotrons of our laboratory [1]. CYCLONE, a multiparticle variable energy cyclotron was (and still is) used for the postacceleration and isobaric separation of the radioactive elements which are produced by bombarding suitable targets with the intense proton beam of CYCLONE30 [2], the prototype of an industrial, high intensity, isotope production, proton cyclotron. These postaccelerated RIB's are used for cross-section measurements of nuclear reactions which are important for nuclear astrophysics and for pilot experiments in nuclear physics.

Although a series of RIB's are being produced successfully [3], this scheme has its limitations:

- CYCLONE has a lower energy limit of 0.6 MeV/A and its overall acceleration efficiency is very poor for this low energy-high resolution mode;
- since CYCLONE30 produces only protons of 15 to 30 MeV, the range of radioactive isotopes which can be produced with a suitable target is restricted.

To overcome these limitations, it was decided to build a dedicated compact cyclotron: CYCLONE44. Its essential characteristic is, besides its energy range, a large acceleration efficiency combined with a high resolving power for isobaric beams. The main characteristics of CYCLONE44 are given in table 1.

Table 1: Main characteristics of CYCLONE44

Energy constant K	MeV	44
Energy range	MeV/AMU	0.2 – 0.8
M/Q range		4 – 14
Max. average field	Tesla	1.54
Extraction radius	m	0.633
Acceleration system		2 variable angle electrodes
Frequency range	MHz	13.3 - 18.5
Max. acceleration voltage	kV	20
Harmonic modes		6 , 8
Injection		axial, spiral inflector
Extraction		electrostatic deflector+passive focusing channel

2 DESCRIPTION OF CYCLONE44

2.1 Magnet

The magnet has a "pill-box" shaped compact yoke, four (almost) straight sectors, twelve concentric circular gradient correction coils situated on top of the sectors and two sets of harmonic coils, located in the valleys near the center and at extraction. The isochronous field profiles which have to be realized are essentially flat because of the low final energies to be reached. Therefore, the power in the trim coils is very low (less than 1 kW), since only differences due to the saturation of the iron have to be compensated for. The maximum power in the main coils is 52 kW.

2.2 High Frequency acceleration system

To reach the high isobaric resolving power (see also 2.3), it consists of two unusually shaped acceleration electrodes connected to two independent resonators. The electrode tips are interchangeable to allow for different central region geometries for the different harmonic modes. Each of these resonators consists of a set of two capacitive panels around the central conductor for coarse frequency tuning and a coaxial cavity with a semi-fixed short circuit plate. The short circuit plate can be repositioned allowing for a shift of the complete frequency range obtainable with the capacitive panels. The system is kept at resonance with a motor-driven plunger extending more or less through the short circuit

plate into the coaxial cavity. The acceleration electrode is mounted on a rigid beam which is fixed at the rear of the coaxial cavity on an adjustable support structure: this system allows very accurate positioning of the electrode tip in the three dimensions. The low level electronics chains comprise cavity tuning, amplitude and phase stabilization loops; 1 kW solid state amplifiers are coupled to the resonators through inductive coupling loops. A microprocessor which receives information about HF-power, electrode voltages and phases, etc controls start-up, cavity tuning, safety interlocks and supervises the running of the HF.

2.3 Isobaric resolving power and centre region

The experience gained with the post acceleration of RIB's has shown that it is crucial to dispose of a system which allows to separate the low intensity RIB from stable isobaric contaminants which can be present with many orders of magnitude larger intensities. To first order, the cyclotron's resolving power R defined as the ratio of the difference of the charge/mass ratio for two ions with respect to the charge/mass ratio of the desired ion, can be expressed by the following relation:

$$R = 2\pi H N$$

where H is the harmonic mode of acceleration (ratio between the frequency of the acceleration voltage and the particle revolution frequency) and N the number of turns of the isochronous particle to reach the final energy. For CYCLONE44 this leads to high harmonic modes (6, 8) and large turn numbers: 265 resp. 200, for $R = 10\ 000$. Given the low final energy, this leads to acceleration voltages of a few kV.

On the other hand, the ion beam is injected axially and to assure reasonable optical characteristics at the ion source extraction and low energy beam transport to the cyclotron, source voltages in the order of 10 kV at least are required. In fact, the higher the source voltage, the better. When looking at the centre region of the cyclotron where the injected beam has to be positioned on a centered acceleration orbit, it appears that this is not possible with such low acceleration voltages.

This problem was solved applying a special central region geometry, shown on figure 1 and by the use of a particular shape of the acceleration electrodes. The axial beam is bent in the median plane by a spiral inflector with tilted electrodes [4] and accelerated twice through the same gap to center the orbit. Notice that this gap has posts and that the azimuthal width of the acceleration electrodes during the first turns is close to 30° for maximum energy gain per turn.

Further out and for the rest of the acceleration process, the azimuthal width of the acceleration electrodes is reduced considerably to reduce the energy gain per turn far below maximum in order to still reach the required number of turns. The voltage gain per turn (ΔW) for an isochronous particle crossing the electrode's symmetry axes at the HF's zero crossing, in harmonic mode H with

V volts on electrodes of θ_{DEE} width, is given by the following relation:

$$\Delta W = n_{gaps} * V * \sin(H * \theta_{DEE} / 2).$$

For CYCLONE44, the energy gain per turn needs to be reduced by an average factor of 3 which leads to an average "DEE"-angle of only 6.5 degrees. This way of accelerating will, to some extent which is tolerable in our case, deteriorate the final beam quality.

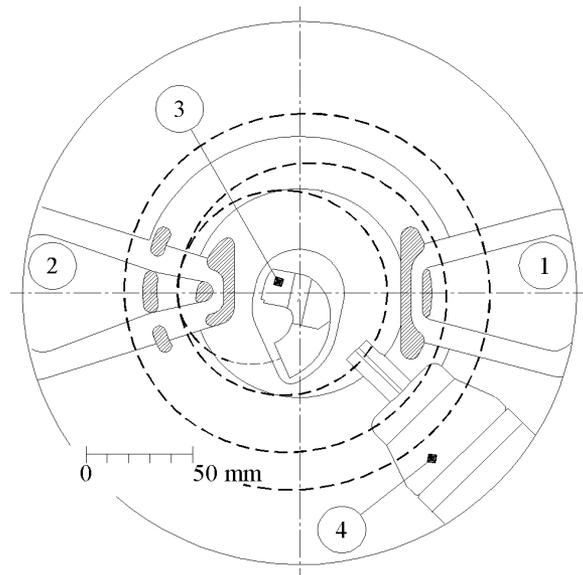


Figure 1 : Central region geometry for 6th harmonic mode acceleration: 1: "DEE"1; 2: "DEE"2; 3: spiral inflector; 4: main probe.

2.4 General layout of CYCLONE44

Figure 2 shows a median plane view of the cyclotron. Besides the elements which have already been discussed, it consists of an axial injection system including a double-gap sinusoidal buncher and an extraction system consisting of an electrostatic deflector followed by a passive focusing channel.

3 FIRST RESULTS

An off-line ECR-source has been used to produce a $^{14}\text{N}^{2+}$ beam at 23.6 keV energy with an intensity of $8\ \mu\text{A}$ after the analyzing slits. The beam was transported to the axial entrance of the cyclotron yoke where $5.3\ \mu\text{A}$ or 65% were measured, after optimization of some of the beam transport and cyclotron parameters around their calculated values. The beam was followed to extraction radius with the integral beam probe and $2\ \mu\text{A}$ (25%) were measured after the first turn before the beam passes for the second time in "DEE2", $1\ \mu\text{A}$ (12.5%) at radius 15cm and $0.48\ \mu\text{A}$ (6%) at extraction radius where 7.8 MeV are reached.

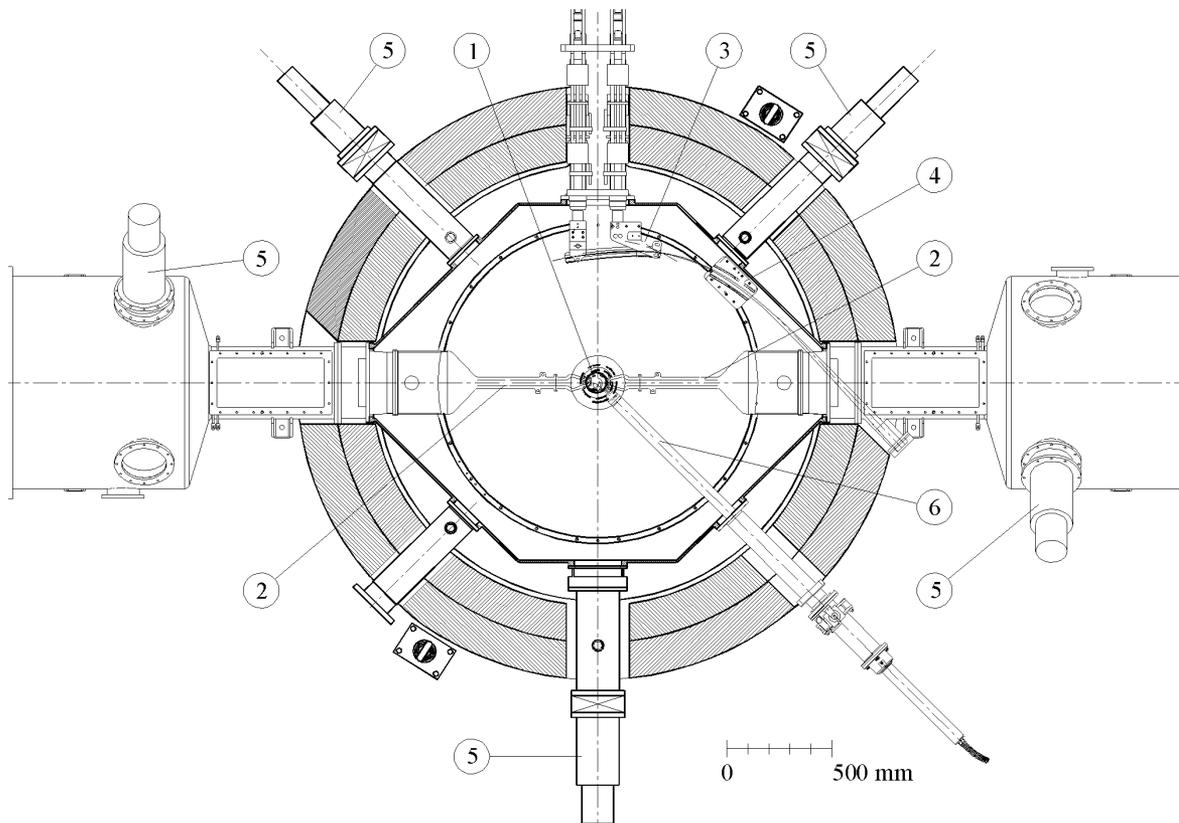


Figure 2 : Median plane view of CYCLONE44: 1: inflector; 2: accelerating electrode; 3: electrostatic deflector; 4: passive focusing channel; 5: cryopump; 6: beam probe.

4 CONCLUSIONS

The first result obtained with a stable beam shows that, as far as it could be verified up to now, most of the parameters come very close to their calculated settings and hence the numerical simulations prove to be quite accurate. Losses in the beam line are due to slight misalignments and to some obstacles which intercept some beam: it is straightforward to cure these. The ratio of 40%, between the intensity at the entrance in the yoke and the intensity on the first turn can be attributed to the fact that a sinusoidal bunching voltage is used: this could be improved by using a sawtooth voltage. The losses between the first turn and 15cm radius are mainly in the axial plane and are due to some mismatch, as was shown by the numerical simulations. This can be improved by adding orientable quadrupoles in the injection line. Still 50% of the beam was lost between 15cm radius and extraction due to the poor vacuum ($3 \cdot 10^{-7}$ Pa) because of the very short time since the cyclotron had been pumped down.

The extraction system has to be installed and the extraction process and the final resolution have to be tested shortly. If the numerical predictions verify further well and when the improvements mentioned before, will be implemented, we hope to reach, if not to exceed, the goals set for this project.

5 ACKNOWLEDGEMENTS

This paper presents results of research funded by the Belgian Programme on Interuniversity Poles of Attraction (PAI) initiated by the Belgian State, Federal Services of Scientific, Technical and Cultural Affairs, and by the Interuniversity Institute for Nuclear Sciences (IISN).

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