COMMISSIONING OF CYCLONE44, A CYCLOTRON FOR LOW ENERGY RADIOACTIVE BEAMS

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CYCLONE44 is a compact cyclotron dedicated to the acceleration and isobaric separation of unstable ions. It will cover an energy domain between 0.2 and 0.8 MeV per nucleon, and will be used for experiments in nuclear astrophysics. The design features of the machine, which has to combine a high acceleration efficiency and a high mass resolving power in order to provide pure radioactive beams in the presence of intense isobaric contaminants, is presented. The status of CYCLONE44, which has accelerated its first stable beam a few days before the conference, is reported.

1 Introduction

Since 1989, the Louvain-la-Neuve radioactive ion beams facility uses two cyclotrons coupled by an on-line ion source to produce and accelerate radioactive ions. The intense 30MeV proton beam of the first machine, CYCLONE30, is sent on a dedicated target to produce unstable elements which are ionized in an ECR source before being accelerated in the second cyclotron, CYCLONE (fig.1).

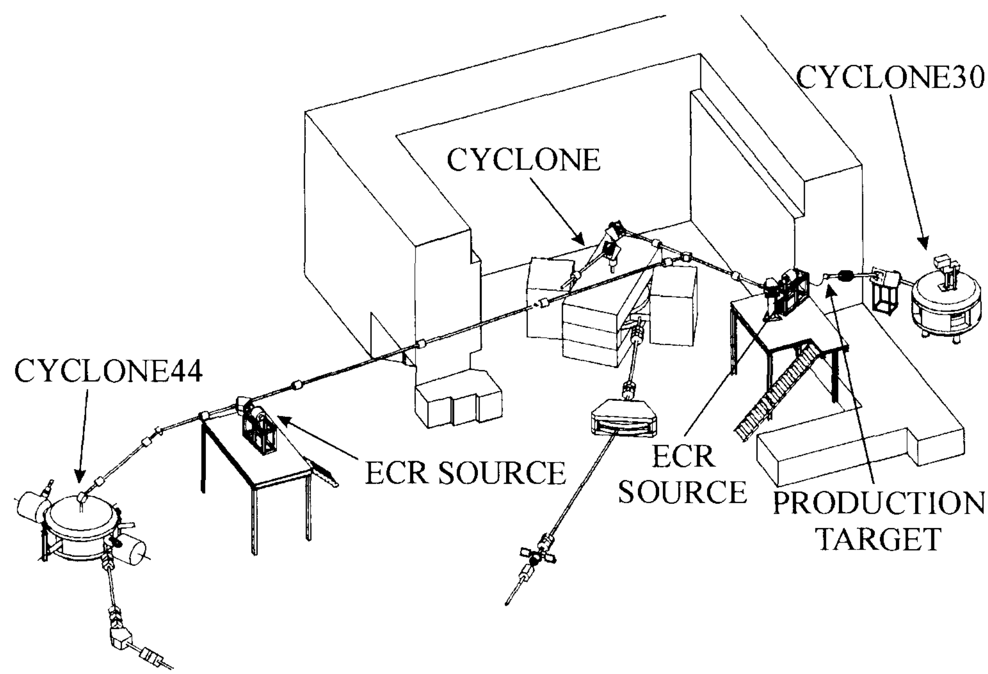

Figure 1 : The Louvain-la-Neuve radioactive ion beam facility, with CYCLONE30 and CYCLONE as it is presently used and with CYCLONE44.

Because these exotic elements are close to the stability line, they are injected in CYCLONE together with intense (several orders of magnitude larger) beams of elements having almost the same mass over charge ratio (m/q), and coming either from the production target or from the residual gas in the source. To achieve a high purity in the final beam, the post-accelerator is tuned as a high resolution mass separator, and the intensity of the contaminant is considerably reduced after the acceleration process. Details about the production, acceleration and uses of these beams have been given elsewhere [1,2].

Although the present facility is quite flexible, it has some major limitations, in particular for experiments in nuclear astrophysics which require beams in the low energy range (between 0.1 and 1.0 MeV/A). One of these limitations is that the lowest energy of CYCLONE is 0.56 MeV/nucleon, another being that, at this low energy, the acceleration efficiency is limited to a maximum of a few percent, depending on the mass resolution to be achieved. In the case of the acceleration of ^{18}F ($T_{1/2}$ = 110 min), where the relative mass difference with the stable contaminant ^{18}O is 9.9 10^{-5}, this efficiency is of the order of 0.5 % only. For other beams, like ^{19}Ne ($T_{1/2}$ = 17 s), where this difference is larger (2 10^{-4}), it reaches 3% [1].

For these reasons, a new cyclotron, CYCLONE44, has been constructed. It will cover the energy range between 0.2 and 0.8 MeV/nucleon, and is designed to combine a high acceleration efficiency (one order of magnitude larger than it is in CYCLONE) and a high mass resolving power. As it will be explained below, the main challenge in the design of this machine lies in the combination of these two requirements. The main characteristics of CYCLONE44 are given in table 1.

Table 1 : Main characteristics of CYCLONE44

Energy constant	K = 44 MeV
Energy range	0.2 – 0.8 MeV/A
M/Q range	4-14
Max average field	1.54 T
Extraction radius	0.633 m
Acceleration system	2 variable angle electrodes
Frequency range	13.3 – 18.5 MHz
Harmonic modes	6 – 8
Max. acceleration voltage	20 kV

2 Description of CYCLONE44

2.1 Magnet

After a careful study of the reactions of interest for nuclear astrophysics that could be studied with the Louvain-la-Neuve facility, it appeared that a cyclotron with a K value of 44 MeV would cover the required energy domain if, like it is with CYCLONE, multiple charged ions are used. This option, which relies on the use of ECR sources, considerably reduces the size and the cost of the project.

The main characteristics of the magnet are given in table 2. It has four sectors, a compact (pill-box shaped) yoke, and was designed with the help of the Tosca computer code. It is equipped with 12 circular correction coils, installed above the sectors, and with two sets of harmonic coils located in the valleys near the central and the extraction region. As the energies to be reached are low, the field profiles are almost flat, and the main role of the trim coils is to compensate for the saturation of iron at each field level (average field between 0.8 and 1.54 T).

Table 2 : Parameters of the CYCLONE44 magnet

Pole diameter	1.56 m
External diameter	2.86 m
Height	1.5 m
Extraction radius	0.633 m
Weight of iron	56 tons
Hill gap	12 cm
Valley gap	24 cm
Number of sectors	4
Angle of the sector	33 – 65 degrees
Max hill field	1.95 T
Max valley field	1.0 T
Main coil	
Number of turns	420
Max current	500 A
Max voltage	105V
Correction coils	12 pairs
Injection harmonic coils	4 pairs
Extraction harmonic coils	4 pairs

The field measurements, which have been done with a mapping system built by our colleagues from Dubna, have shown a good agreement with the Tosca calculations [3].

2.2 Acceleration system

2.2.1 Shape of the electrodes

The specific feature of CYCLONE44 is that it has been designed as a radiofrequency mass spectrometer. In an isochronous field, the mass resolving power of a cyclotron R = (m/q) / Δ(m/q) is, in first approximation, given by [4]:

$$R=2\pi H N$$

where H is the harmonic number of acceleration, and N the number of turns required for the acceleration of the isochronous particle to the final energy.

In CYCLONE44, the harmonic modes 6 and 8 have been chosen to cover the energy range between 0.2 and 0.8 MeV/A. However, even with these rather high harmonic modes, the number of turns required to obtain a mass resolution of 10.000 is 265 and 200, respectively for H=6 and 8. In a conventional two "Dee" system, this implies that the maximum peak acceleration voltage would be less than 6kV. It would then be less than the ECR source voltage, which has to be of the order of 10 kV at least in order to assure reasonable optical characteristics for the injected beam. A preliminary study of the central region has shown that, with this low acceleration voltage, it was impossible to get around the inflector.

To solve this problem, the dees have been shaped with a dee angle which varies from the central region to the extraction (fig 2). In the 6[th] harmonic mode, the dee angle is close to 30 degrees during the first turns, in order to have the maximum energy gain per turn in the central region, while it is smaller further out to reduce the energy gain per turn. With this geometry, it is possible to reach the required number of turns to have a high resolving power, while keeping a reasonable voltage (comparable to the injection voltage) on the acceleration electrodes. The electrode tips can be changed to allow for different central geometries in harmonic modes 6 and 8. The harmonic 8 mode will be developed later.

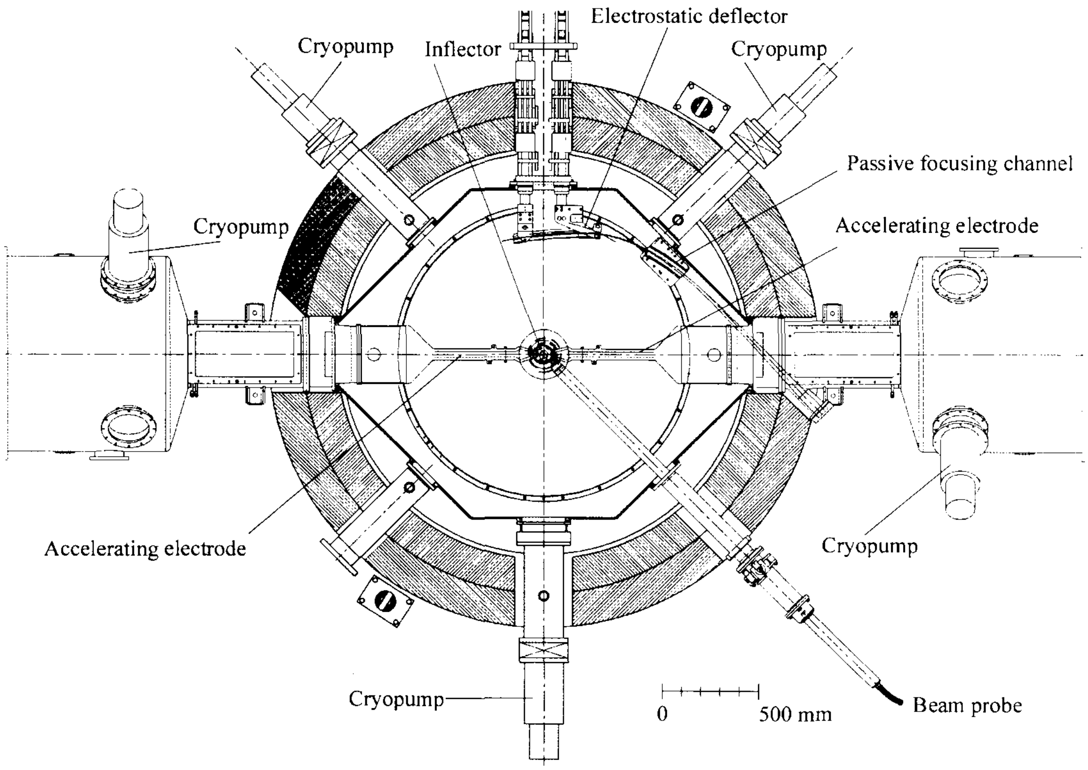

Figure 2 : Median plane view of CYCLONE44

2.2.2 Resonators

The electrodes are connected to two independent resonators (fig 3). Each of them consists of a set of two capacitive panels, which move around the central conductor for coarse frequency tuning, and a coaxial cavity with a semi-fixed short circuit plate. (The latter 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.

Each acceleration electrode is mounted on a rigid beam which is fixed at the rear of the coaxial cavity on an adjustable support structure. This allows an accurate positioning of the electrode in the 3 dimensions.

Each resonator is powered by an independent solid state amplifier able to deliver 1.2 kW of RF-power. It is coupled to the cavity through an inductive loop. Both resonators are controlled by a microprocessor. The measured characteristics of the RF system are given in Table 3. The quality factors that have been measured are slightly lower than expected. This is due to the fact that, at this stage of the project, part of the elements are not welded together to allow for modifications if necessary. As a consequence, the RF contacts are weak in some areas. This will be improved by welding together pieces that have not to be dismounted anymore.

Table 3 : Some characteristics of the RF-system

Frequency range	13.3 – 18.5 MHz
Q factor	5085 at 18.5 MHz 4507 at 16.9 MHz
Phase stability	0.1°
Amplitude stability	$\pm 1.\ 10^{-4}$

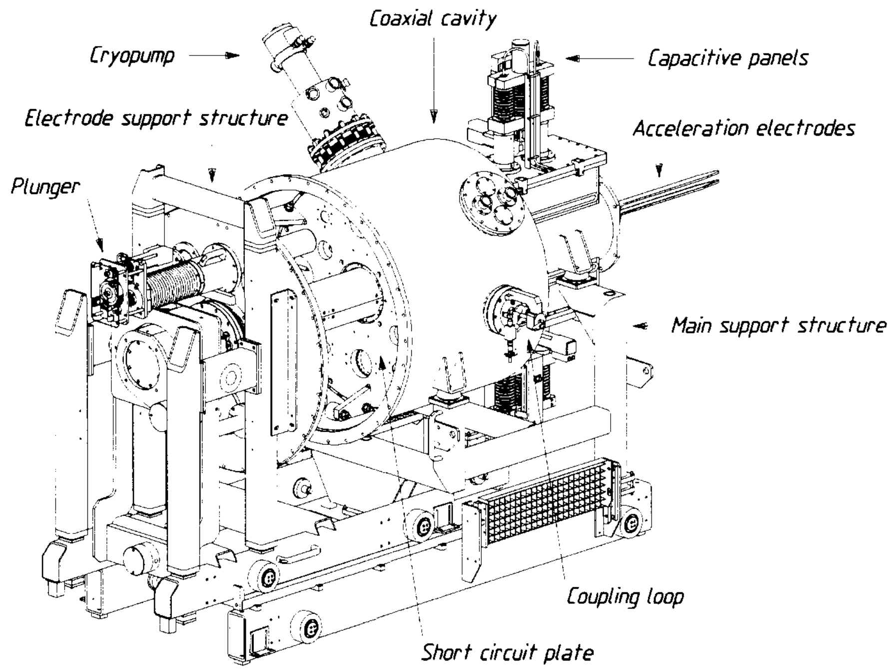

Figure 3 : The resonator

2.3 Central region

The axial beam is bent in the median plane by a spiral inflector with tilted electrodes to modify the centering [5]. As the electrode voltage is comparable to the injection voltage, the beam is centered by passing twice through the first electrode (microtron-mode), before starting classical cyclotron acceleration as shown in figure 4.

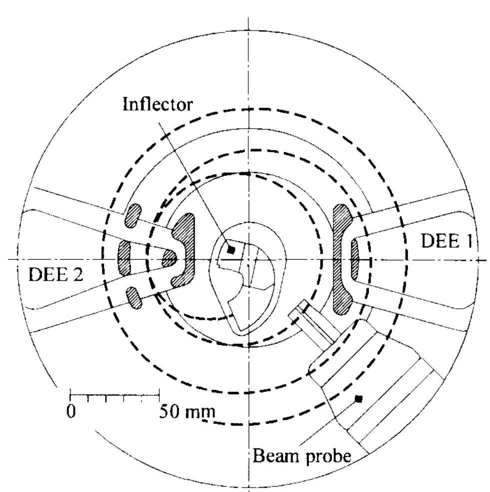

Figure 4 : The central region for the 6^{th} harmonic mode

2.4 Extraction

The beam will be extracted with a rather short electrostatic deflector with a voltage of the order of 35 kV. Its entrance and exit positions and gaps are remotely controlled. It is followed by a passive focusing channel made of 3 iron bars (fig. 2).

2.5 Vacuum system

CYCLONE44 is pumped by 3 cryogenic pumps directly connected to the acceleration chamber, with a pumping speed (for nitrogen) of 800 l/s for two of them, and 1500 l/s for the third one. Two other cryogenic pumps (1500 l/s) are installed on the resonators. The correction coils are separated from the main chamber, and continuously maintained under vacuum by a 12 m^3/h primary pump.

During pumpdown and venting, these volumes are connected together through a by-pass to prevent excessive stress on the lids. A residual pressure of a few 10^{-7} mbar is expected in the acceleration region.

2.6 Beam injection line

For the commissioning of the machine, an ECR source identical to the one which is used to ionize the radioactive ions has been installed close to CYCLONE44. It is connected to it by a small injection line which uses Glaser lenses for focusing and is equipped with a sinusoidal buncher located at the entrance of the yoke (fig. 5).

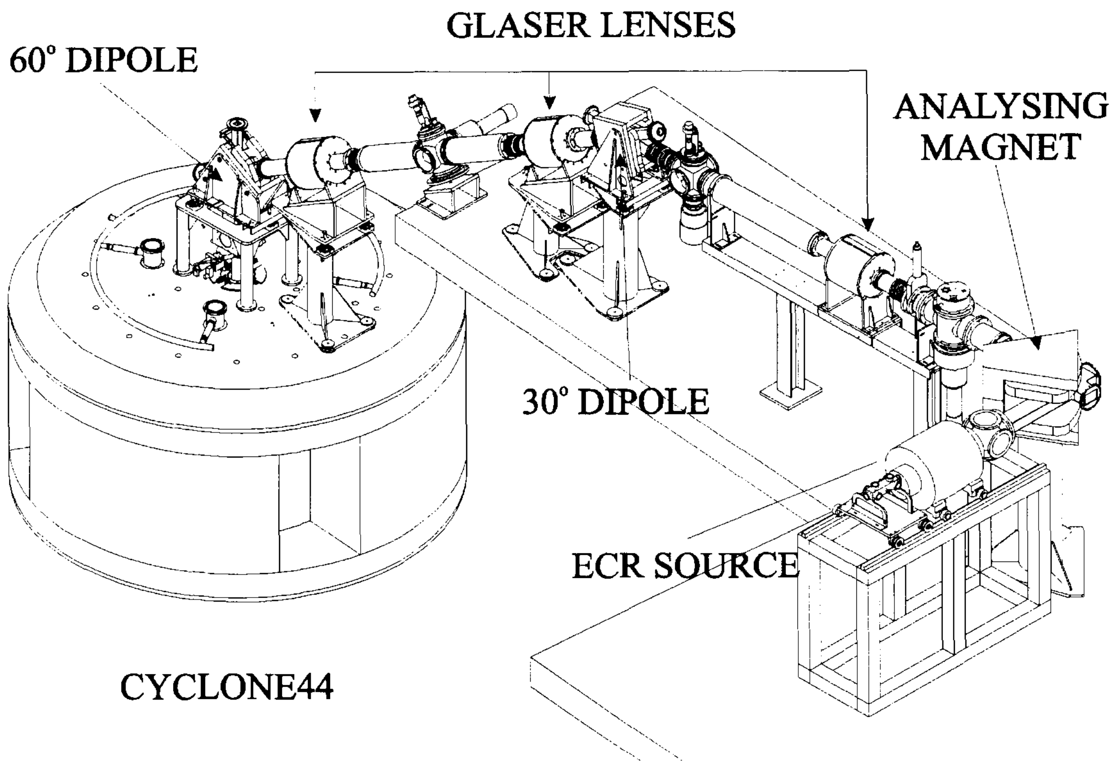

Figure 5 : The beam injection line used for the commissioning of the cyclotron

3 First beam

The installation of all these subsystems, except the deflector, began a few weeks before this conference, and the machine has been put under vacuum recently. Altough the pressure inside the machine is still rather high (of the order of 2.10^{-6} mbar), a first beam of $^{14}N^{2+}$ has been accelerated to 0.56 MeV/A. The main parameters for this beam are given in table 4.

Table 4 : Parameters of the first beam in CYCLONE44

Ion	$^{14}N^{2+}$
Final energy	7.8 MeV (0.56 MeV/A)
Source voltage	11.8 kV
Inflector voltage	2.5 kV
Frequency	15.6 MHz
Harmonic mode	6
Acceleration voltage	12.4 kV
Magnetic field	1.19 T
Extraction voltage	28 kV

Starting with a beam of 8 μA, measured after the analysing magnet of the source, 5.3 μA (66%) has been transported to the entrance of the yoke. After the first turn, this intensity was 2 μA, at 15cm it was 1 μA, and it was 0.48 μA at the extraction radius. This corresponds to 6% of the initial intensity. It has to be noted that the parameters of the various elements of the cyclotron were very close to the calculated ones, showing the excellent quality of the numerical simulations.

4 Conclusions

Several equipments have to be installed to still improve the global transmission like a skew quadrupole and a sawtooth buncher in the low energy line. But after only a few days of pumping, the pressure inside the machine is certainly the major factor of limitations. By measuring this transmission at various pressure levels, we estimate it will improve by a factor of 2, when a pressure level of a few 10^{-7} mbar will be reached.

Due to voltage breakdown at the deflector, the beam has not been extracted yet, but this problem should be solved soon. When the beam will be extracted, we shall test the mass resolving power of the machine with a $^{18}F^{2+}$ beam, to check that it is clearly separated from an $^{18}O^{2+}$ beam. Finally, in January 1999, the low energy beam line, which will connect CYCLONE44 to the RIB ECR source, will be installed and new experiments in nuclear astrophysics, with short-lived elements like ^{19}Ne, will start around CYCLONE44.

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