TEN YEARS OF OPERATION WITH THE LNS SUPERCONDUCTING CYCLOTRON

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Abstract

The LNS Superconducting Cyclotron, commissioned in 1994 as a booster of the Tandem accelerator, has been working independently since 2000, when a central region was installed replacing a stripper device. During the past ten years, a lot of research activity has been carried out in the field of nuclear physics at intermediate energy, mainly using large solid angle array detectors. The Cyclotron was designed to accelerate heavy ions with a maximum charge over mass ratio 0.5. Therefore protons cannot be accelerated. However, the new injection mode allows H_2^+ molecules to be accelerated, which has enabled proton-therapy for tumours of the ocular region: since 2002 patients have regularly been irradiated. Very recently, in the year 2003, a ^{13}C beam with a power of 100 watt has been extracted. In the next months it will be used as a primary beam to produce radioactive fragments of ^{8}Li in the ISOL based facility EXCYT. More generally, the Cyclotron is assuming the role of primary accelerator in EXCYT. A review of the main achievements obtained throughout ten years of operation is given in this article, underlining the most interesting characteristics of the Cyclotron and describing how its performance has been improved.

Figure 1: View of the Cyclotron median plane.

CYCLOTRON ORIGINAL DESIGN

The LNS Superconducting Cyclotron is a three sectors compact machine [1]. A picture of the median plane is shown in Fig. 1.

The three RF cavities work in a range from 15 to 48 MHz, corresponding to an energy ranging from 8 to 100 MeV/amu in harmonic mode h=2. Different harmonic modes, corresponding to smaller energy ranges, are possible.

Superconducting coils inside the cryostat are split into two sections so as to obtain the required isochronous field over a wide operating diagram, reducing the power consumption of 20 room temperature trim coils.

Two electrostatic deflectors and seven magnetic channels allow to extract the ion beam close to the pole radius, 84-87 cm from the center.

The Cyclotron was commissioned in 1994 as a post-accelerator of a 15 MV Tandem. With respect to this working scheme, the following upgrading elements have been implemented in the last six years.

CYCLOTRON UPGRADING

Several major modifications have been introduced with the aim of improving the cyclotron performance.

Radiofrequency dees

The RF dees have been completely redesigned and manufactured of a different material, i.e. copper instead of aluminium [1] to have a better interface with the copper cavities. Taking advantage of the replacement of the old dees, space inside the new dees was provided to install phase slits, which have proven to be of fundamental importance in the high intensity operation (see forth) and in case of particular request for timing quality.

Axial injection

In 1999 axial injection [2] from an ECR source was implemented replacing radial injection from the Tandem. This was a really fundamental change. It was accomplished to have two independent machines, so as to increase the amount of delivered beam time, but especially to increase the Cyclotron capabilities, exploiting the interesting properties of modern ECR sources: higher charge states imply higher energies for heavy ions, and high intensity allows to use the Cyclotron as a primary machine for production of radioactive ion beams. Moreover, axial injection allows to overcome many geometrical constraints given by radial injection. Consequently proton acceleration, forbidden by the operating diagram of the machine, becomes possible, only with axial injection, by accelerating the H_2^+ molecule, to be broken into 2 protons at the exit of the Cyclotron. As a result, proton therapy is being performed as one of the most important applications in the Laboratory (see forth).

Electrostatic deflectors

The electrostatic deflectors have been heavily modified with respect to the original design, being clear since the first commissioning ten years ago that they were the biggest obstacle as far as high intensity and high energy are concerned. Therefore an intense upgrading program has been accomplished to improve the working performance of the deflectors.

Electrostatic deflector materials

Two different (but not independent) phenomena take part in the deflector breakdown. Both of them depend upon the liner (anode) material, melted and evaporated by the electrons emitted by the HV electrode (cathode). One is related to the metal transfer from the liner to the insulator: this increases the surface conduction, i.e. the dark current. The other one is due to the metal deposition on the electrode, which forms a big number of micro-tips enhancing the field electron emission. The old liner materials (molybdenum, tantalum, tungsten) were characterized by high evaporation energy. In the present deflectors they have been replaced by oxygen free copper: even if the copper evaporation energy is lower as compared to the previous materials, interaction with residual gases creates a non-conductive oxide layer, which reduces the surface conduction on the insulators; moreover the tip formation effect is strongly inhibited by the copper low surface tension.

Considerable efforts have been made as far as the electrode material is concerned. Materials with low electron emission and high surface tension were taken into account: 1) a titanium alloy ($TiAl_6V_4$), 2) titanium coated by a Diamond Like Carbon film, 3) titanium coated by a TiN film and 4) anodised aluminium. The last one shows the best behaviour in terms of dark current and stability under the beam action, and has therefore been chosen also for high intensity operations.

With the above described materials, the electrostatic deflectors are able to reach, in operating conditions, i.e. under magnetic field, radio-frequency and beam, an electric field as high as 110 KV/cm with a gap of 6 mm.

Electrostatic deflector mechanics

Several consistent mechanical modifications have been introduced to the original deflector design, in order to use the deflectors with intense beams, considering that the extraction efficiency is relatively low, not exceeding 50%, so that a beam of several tens of watt is dissipated in the septum producing heat.

The first component that needed to be re-designed was the H.V. feed-through: the original one was in polypropylene, directly screwed to the electrode; in the new system the H.V. cable is inserted in a rigid cooled system, able to follow the deflector movements by means of pneumatic actuators.

Another fundamental modification is the implementation of a cooling circuit in the housing of the first electrostatic deflector.

Lastly, the new electrostatic deflectors have been provided with an automatic disconnection system, that allows to remotely disassemble the housing. This is a very important feature from the health physics point of view.

PROTON THERAPY

One outstanding advantage of axial injection is the availability of a proton beam, obtained by stripping, in the extraction beam line, of a H_2^+ molecular beam. In 1999 a project called CATANA [3] started, aiming to the construction of a proton therapy facility for ocular cancer. The first patient was treated in 2002, and up to now a total number of 76 patients have been irradiated. In Fig. 2 a picture of the treatment beam line is displayed, showing the main components that allow to have a therapeutic beam, i.e. endowed with a certain uniformity and a dose profile accepted by the clinical protocol as stated by medical doctors. The main components are collimators, modulators and range shifters, while the dose control is guaranteed by 3 transmission monitor chambers.

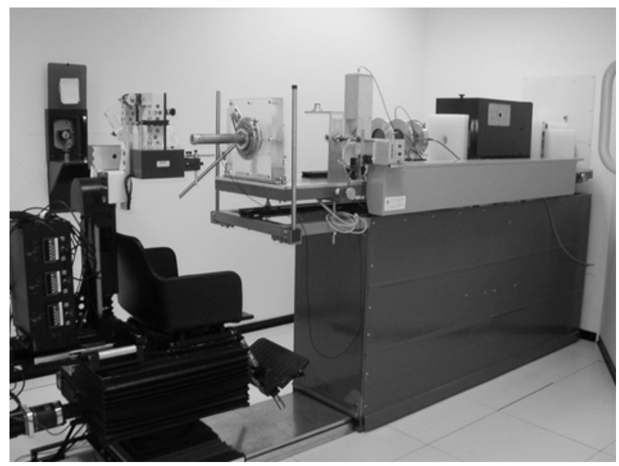

Figure 2: The proton-therapy equipment CATANA.

The first preliminary clinical results can be considered encouraging. All patients had localized deseases, mostly uveal melanoma, with no systemic metastasis. The first data are presently available for 52 patients: they have been collected 6-8 months after the treatment for some patients and after 1 year for part of them. The local control is defined as the tumour shrinkage. A size reduction has been observed for 39 patients while 13 patients maintain a stable size.

INCREASING THE EXTRACTED BEAM INTENSITY

In the last two years, several intervals of the experimental activity have been scheduled to allow for advances of the EXCYT project. During these periods, high intensity beam tests were performed, in order to ascertain the possibility of extracting a light ion beam so intense to be used as a primary beam in the EXCYT facility for production of radioactive beams. The first tests were made with a ^{20}Ne beam accelerated to 45 AMeV. A limitation was found out at a power of 40 watt when trying to increase the extracted beam current. A mechanical damage was caused by the beam in the cooled electrostatic deflector: the septum showed a hole along the median plane (Fig. 3).

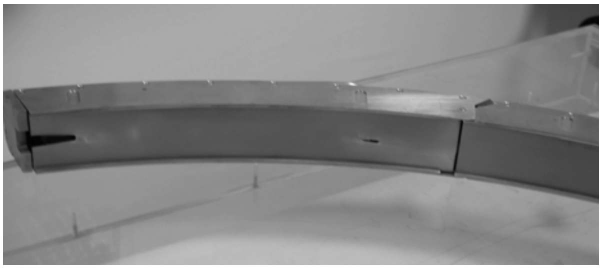

Figure 3: Damaged septum of the electrostatic deflector.

Few months later the test was made again. In this case, a beam of ^{13}C was chosen instead of ^{20}Ne, as the most convenient one to produce a secondary beam of ^{8}Li, selected as the first EXCYT radioactive beam. The test was made using a small chopper installed in the injection beam line, allowing to decrease the beam current in the longitudinal way, i.e. suppressing bursts. In this test, an internal current probe provided with cooling, was available. It proved to be a fundamental tool in the high intensity operation, especially when trying to increase the extraction efficiency, because it allowed to find the best conditions of minimum beam dissipation in the septum. Phase slits were used to increase the extraction efficiency, which reached a maximum value of 60%. As a result of this test, a 100 watt beam power, corresponding to 680 enA, was obtained at the Cyclotron exit (Fig. 4). This current is estimated to be sufficient for an adequate production of ^{8}Li (10^{5}-10^{6} pps on target). Further increase of the beam current was not tried: even though no damage was detected in this second test, the hole produced in the first test demonstrates that the deflector cooling efficiency must be improved.

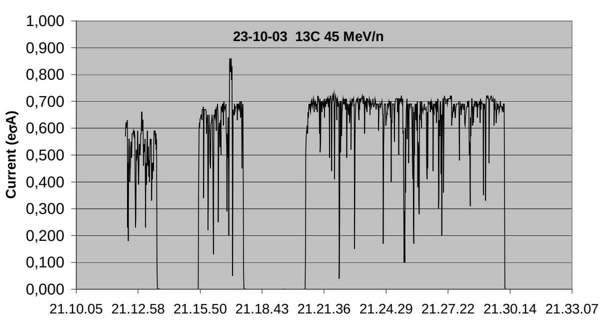

Figure 4: Beam intensity for the 100 watt extraction.

OPERATING DIAGRAM AND BEAM DELIVERY

In the last three years beams accelerated with the Superconducting Cyclotron have been delivered to users mostly in the first seven months. The second part of the year has in fact been devoted to the development of the EXCYT project, as well as to ordinary and extraordinary maintenance. However, in spite of the long break, it has been possible to perform a big number of experiments, thanks to the high reliability and to the capability of quick recover in case of failures. The Cyclotron reliability has significantly improved as compared to the machine performance of some years ago, see Table 1. This has been possible thanks to the above described upgrading and to the replacement of old and obsolete components of the RF system, of the ECR sources and of several power supplies.

Table 1: Cyclotron beam statistics

Year (months)	Delivered hours	Setting hours	Failure hours
2001 (10)	2569	1424	975
2002 (8)	2485	1161	597
2003 (8)	2522	1204	587
2004 (5)	1529	967	187

The Cyclotron operating diagram displayed in Fig. 5 shows the beam types developed to date. As it results from the big number of scattered points, a large variety of ion species has been accelerated over 10 years of operation, during which the edges of the theoretical operating diagram have been approached. Very recently, for instance, an energy of 80 AMeV has been reached for a ^{4}He beam (triangle), the maximum design energy being 100 AMeV, and a 43.5 AMeV ^{112}Sn beam (square) has been delivered. The big amount of beam types is due to the pressing beam demand from users, which has been more and more increasing over 10 years. This feature, together with the new role as a primary accelerator for production of radioactive ion beams and the proton-therapy activity demonstrate that the Cyclotron is a precious instrument for nuclear physics research and applications.

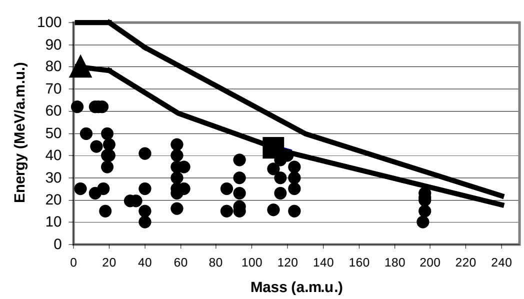

Figure 5: Operating diagram of the Cyclotron.

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