FIRST YEARS OF OPERATION OF THE LNS SUPERCONDUCTING CYCLOTRON

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The K800 Superconducting Cyclotron was commissioned in 1994 and has been in continuous operation since then. In 1996 many efforts were made to reach a condition of reliable operation. Several ion types have been accelerated and delivered to experimental halls. The demand for different beams has given the opportunity to explore several regions of the operating diagram of the machine: different magnetic field values have been set, as well as several RF frequencies have been used. The results demonstrate that the Cyclotron allows to accomplish a large variety of nuclear physics experiments, even if the maximum performance has not yet been achieved. A few sub-systems are being upgraded in view of the "high intensity" operation (which is required for radioactive beam production) and in order to reach the maximum performance: upgrading is planned on the RF system and on the electrostatic deflectors. A new axial injection system has been designed to operate the machine in stand-alone mode.

1 Introduction

The LNS K800 Superconducting Cyclotron was commissioned from June 1994 to June 1995 [1]. Several experiments and instrumentation tests have been accomplished since the date of beam availability, i.e. July 1995.

The first year was mainly spent looking for reliability and understanding beam dynamics features by means of the available diagnostic tools [2].

In this year many improvements were introduced to the RF system and to the stripper system, which has to guarantee the possibility of changing foils when damaged.

In 1996 the Cyclotron beam assignment was done according to the suggestions of an international Program Advisory Committee. The scheduled running time was about 5000 hours per year, including both Tandem and Tandem-Cyclotron operations. In the same year, two new beam types, namely ^{58}Ni at 16.5 and 45 MeV/a.m.u., were developed adding to the 30 MeV/a.m.u. ^{58}Ni beam with which the Cyclotron was commissioned in 1994. In 1997 and 1998 several new beam types were developed fulfilling the request of experimental groups.

Due to frequent power failures, causing the liquid helium liquefier and all power supplies and RF amplifiers to turn off, two Uninterruptable Power Supplies of 1 MW each were installed to guarantee continuous operation despite of electricity failures.

The Cyclotron is successfully working, proving a reliable accelerator. This has encouraged us to put efforts in the upgrading of the machine, aiming to accelerate and extract intense primary beams for production of radioactive isotopes.

2 Status of the Cyclotron

The Cyclotron is presently operated as a booster of a 15 MV Tandem. The Tandem beam is injected in the median plane of the Cyclotron and reaches a stripper placed 10-20 cm far from the center, where the charge state to be accelerated, 3-4 times the initial one, is produced.

This mode requires a careful setting of the injection parameters (Tandem voltage, injected charge state, stripper position), which has to fulfil a number of conditions, the most important being the beam injectability in the geometry assigned [2], but on the other hand allows for a relatively free operation of the RF system (harmonic mode and amplitude).

The beam types developed to date are listed in table 1, together with the main acceleration parameters. Their distribution in the operating diagram of the Cyclotron is shown in figure 1. The RF frequencies and harmonic modes used for these beams are listed in table 1. The maximum voltage applied on the electrodes of the electrostatic deflectors is 65 kV, which corresponds to an electric field of 110 kV/cm, the gap being of 6 mm.

In all cases, the operating setting of the main coils and trim coils was always very close to the one derived from the magnetic measurements data [3], except for the amplitude and phase of the centering and extraction first harmonic, which are tuned during operation. The operating main coils current differs from the calculated one by 0.1-0.3 A, i.e. 0.006-0.02%.

Table 1 : Beam types developed to date

^{A}X	E MeV/n	Q_f	Q_f/A	B_o kgauss	F_{RF} MHz	h
^{7}Li	50.0	7	0.43	27.0	35.458	2
^{32}S	19.5	10	0.31	23.8	34.293	3
^{40}Ca	24.8	13	0.32	25.6	38.365	3
^{40}Ca	40.0	13	0.32	31.9	31.871	2
^{58}Ni	16.6	12	0.21	33.0	20.992	2
^{58}Ni	29.5	16	0.27	32.4	27.500	2
^{58}Ni	45.3	19	0.33	33.5	33.742	2
^{93}Nb	15.5	19	0.20	32.3	30.431	3
^{93}Nb	29.5	22	0.24	37.8	27.500	2
^{197}Au	10.0	28	0.14	37.2	24.385	3

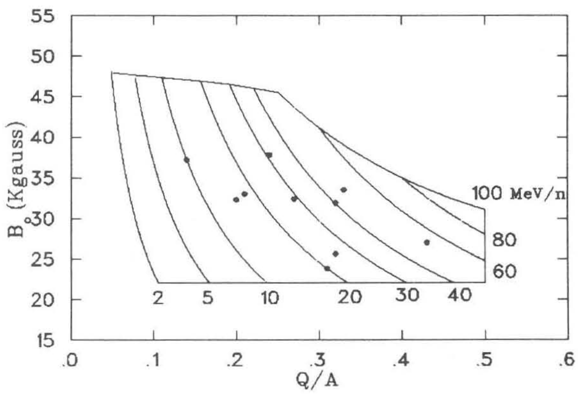

Figure 1: Operating diagram of the Superconducting Cyclotron: distribution of the beam types developed to date

In October 1997, the main coils were radially displaced by 0.5 mm. This was necessary to reach high field levels (above 4.1 Tesla, maximum 4.8 Tesla) so as to develop heavy beams at high energy. Magnetic field data had been taken with the coils placed in this position, which minimizes the radial forces on the coils, but increases the first harmonic component of the main field at extraction [3]. For the commissioning of the machine, the choice had been made to have the main coils in the so-called central position, more advantageous from the point of view of the beam dynamics, minimizing the first harmonic amplitude, but limiting the performances of the Cyclotron. After having displaced the coils in the present (and final) position, we immediately checked that the 30 MeV/amu ^{58}Ni beam was correctly accelerated and extracted. As expected, a different first harmonic component was necessary to compensate the intrinsic first harmonic generated by the coils displacement.

2.1 Method of operation

For all the above beams, injection, acceleration and extraction operations are accomplished by means of the main probe of the Cyclotron, covering almost the whole radial range, as described in [2]. The Tandem beam, injected inside the Cyclotron, is detected by the scintillator of the probe before being stripped. The beam current is also measured on the probe to make sure there are no losses. The accelerated beam is monitored in its whole radial range by measuring the beam current on the main probe; when crossing the $\nu_r=2\nu_z$ resonance, the beam behavior is observed on the scintillator of the main probe. This allows to set correctly the first harmonic provided by the innermost trim coils to center the beam. An example of off-centered and centered beam is shown in figure 2. After having gone through the two deflectors and some magnetic channels, the extracted beam, still inside the yoke, is again observed on the scintillator of the main probe.
The injection efficiency of all the beams developed is 100%. The acceleration efficiency, intended as the ratio between the beam current after and before the resonances, is almost 100%. The extraction efficiency ranges from 30% to 90%, depending upon the beam trajectory inside the deflectors.

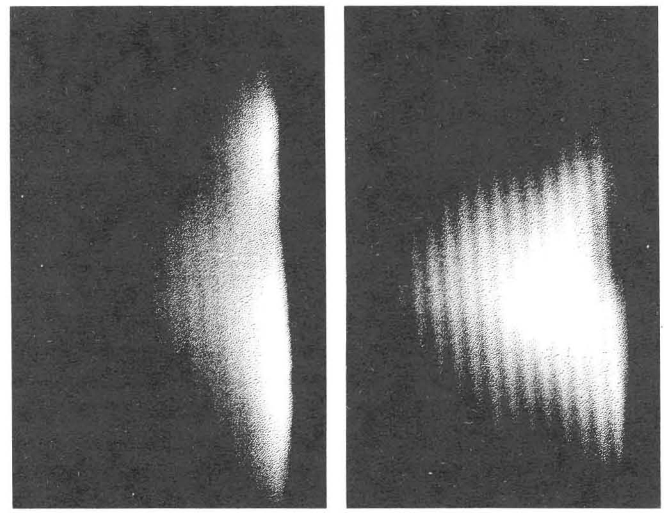

Figure 2: Off-centered (left side) and centered (right side) beam at the extraction radius (R_{probe}=870 mm)

3 Upgrading of the Cyclotron

In 1995 the EXCYT project [5] was approved by our Institute: radioactive ion beams will be produced on a thick target by light ion beams accelerated at the energy allowed by the Cyclotron. Considering all possible efficiency factors, it turns out that a primary beam current of 1 pμA is necessary to get reasonable intensities of the secondary beams. Since the present beam intensity we are used to handle is 50 enA, the problem is to be carefully evaluated.
Moreover, during these years of operation, the need of improving some sub-systems has emerged as a condition to reach the maximum design capabilities.
In the following sub-sections, the most significant changes and improvements that are being introduced are described.

3.1 Axial injection

The Superconducting Cyclotron is presently operated as a booster of the 15 MV Tandem. Switching to the axial injection mode gives first of all the possibility of having a simpler and more reliable accelerator system, and secondly of improving the performance of the Cyclotron, in terms of intensity of all ion beams and energy of ions with mass higher than 50 a.m.u. [6]. This is possible by means of a highly performing superconducting ECR source, constructed in collaboration between our laboratory and the CEA of Grenoble, which just a few weeks ago has been installed at LNS after having been successfully tested at Grenoble. The source produces high charge states with intensities much higher than room temperature sources. For some light ion beams, the expected intensity to be injected into the Cyclotron is close to 300 times the intensity of the beam delivered by the Tandem.

The new injection mode implies the replacement of the stripper system with an axial injection system, i.e. an inflector and central region complex.
The design study of a central region and inflector system [7] has been completed. The high intensity operation mode has been considered, but the possibility has been maintained of accelerating each ion type in a wide energy range. A 3D view of the central region and inflector designed is shown in figure 3.
In the new injection mode, the Cyclotron will be operated in constant orbit mode. The harmonic mode of acceleration is h=2, which allows for an energy range of 8-100 MeV/amu. The maximum source voltage is 30 kV. The inflector will be a spiral type one, with a gap of 6 mm, an electric radius of 2.7 cm, a K value of 1.2. The maximum electric field that will be applied is 22 kV/cm.

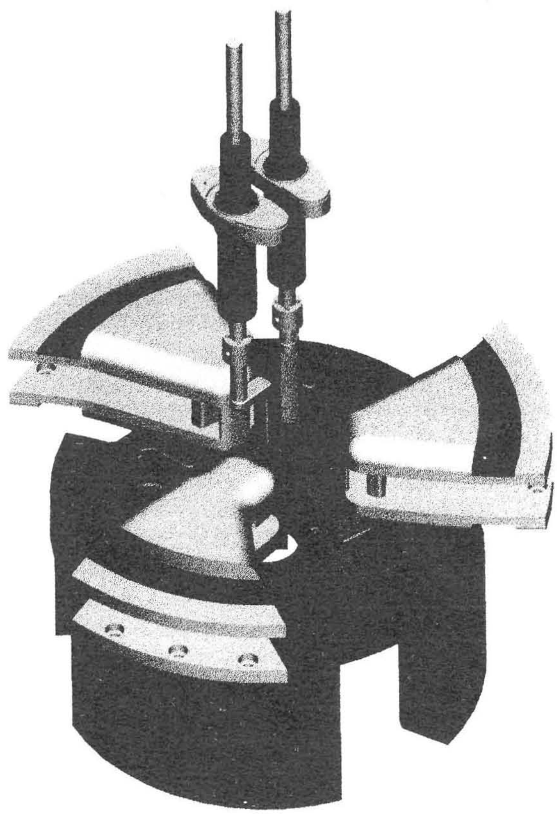

Figure 3 : 3D view of the axial injection system

3.2 Phase selection

A slit system has been designed to perform fine phase selection in a place far from the central region. It consists of three small wedges, with a maximum thickness of 2 mm, that will cut phases according to the simulations made in [8]. We hope to reduce the phase range from 35 °RF (the phase band allowed by the central region) to 6 °RF. This is quite important for the following fundamental reason. Due to the large acceptance of the Cyclotron and to its compactness, there is usually no separation between orbits at extraction. Consequently, multi-turn extraction frequently occurs, and an extraction efficiency quite different from 100% is observed. By reducing the phase range of the beam to be extracted, and making use of a first harmonic bump to excite the ν_r=1 resonance, single-turn extraction should be feasible. Single-turn extraction guarantees a good timing definition of the beam, which is very often a strong condition required by many nuclear physics experiments. When operating the Cyclotron with intense beams, single-turn extraction is mandatory to protect the deflectors from activation.
The position of the phase slits has been chosen to be 20 cm from the center. Here, by setting properly the first two trim coils, so as to opportunely shape the phase curve, it is possible to have a certain radius-phase correlation [9] which guarantees to reduce the phase range.

3.3 Upgrading of the RF system

The RF system has extensively been described elsewhere [1,4]. The three couples of accelerating electrodes of the current radiofrequency system have been redesigned for the following reason. The present aluminium dees have reached limited performances over the last few year's operation: limited heat dissipation which prevents from achieving the maximum design voltage, causing melting of some parts, craterisation of part of the dee's surface facing the copper coupler. The latter is due to the high secondary emission coefficient of aluminium oxyde [10]. Therefore the new dees are copper made. As mentioned in the previous sub-section, a phase selection system is planned to be inserted in the dees. The design of the new dees has been accomplished aiming also to facilitate maintenance operations.
At the beginning of this year the aluminium dees of cavity 2 were dismantled and the new copper dees were installed and successfully tested. Measurements at low power level were carried out on cavity 2 with aluminium and new copper dees: no appreciable change in capacitance, Q value and shunt impedance was found. A dee voltage of 100 kV at 27.5 MHz was easily reached, with a magnetic field of 4 Tesla, by gradually conditioning the cavity. At the moment, we are running the RF system with two cavities with the old aluminium dees and one with the copper dees. After a couple of months of operation with different kinds of beam, the new electrodes were perfect without any sign of burns or sparks as we usually found in the aluminium ones. After the first period of tests we started working the other two couples of dees, which will be ready next September.
A few improvements have recently been introduced to the RF control equipment. A multi-driving RF source has been developed and installed; it ensures the phase-locking between the RF system of the Cyclotron and the different RF pulsing systems placed along the beam line only using one radio frequency synthesiser source.
The main parameters of the RF system, except the voltage of the dees, can be read and set from the Cyclotron console room through a PC. In the near future the setting of the voltages will also be included in the console, at least allowing tuning them in a safety range.

3.4 Electrostatic deflectors

The electrostatic deflectors consist of a high voltage electrode made of a titanium alloy (Ti-6Al-4V), a septum of tantalum and liners of molybdenum. The present gap is 6 mm and the electric field required to extract the most energetic ion is 140 kV/cm.
Since the beginning of the Cyclotron operations, an intense R&D program has been accomplished in order to reach the above electric field. Attention was paid to the study of the mechanism generating the electrostatic breakdown, which is due to the electrons emitted by the cathode surface for field effect [11]. It is strongly dependent on the chemical and physical state of the electrode surfaces. Then we started characterizing the surfaces in terms of roughness and morphology. Mechanically polished electrodes of Ti-6Al-4V with a roughness better than 1 μm were manufactured [11]: they gave a first significant improvement in the operational performance of the electrostatic deflectors, allowing to increase the maximum electric field reachable from 80 to 95 kV/cm. In parallel we have studied the effect of some coatings like TiN (titanium nitride), obtained as film coating or by thermal treatment [12], and DCL (diamond carbon like) in order to strongly reduce the field electron emission and improve the surface hardness. This work has been done having in mind not only the possibility of increasing the electrostatic performance but also the possibility of extracting high power beams (up to 1 kW) as required for the EXCYT project [5]. The study has initially been carried out in a test stand working with a deflector simulator of reduced size (1/5 of the real size). The results are summarized in figure 4. It is clear that the DCL coating, realized by plasma deposition, permitted to reach the best electrostatic performance. The realization of this coating on the real electrodes is not a trivial problem due to the significant increase of the surface area to be treated.

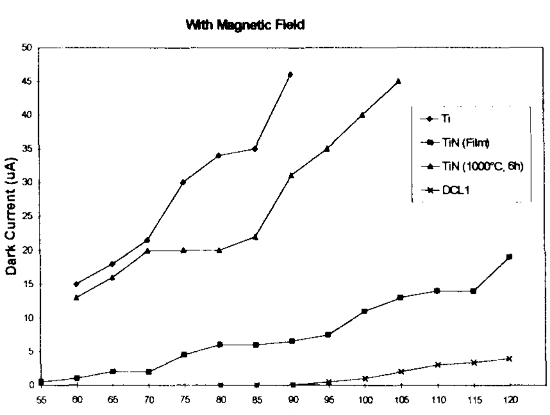

Figure 4: Electrostatic properties of different electrodes of the deflectors

A first test on the real deflector permitted to improve the operational performance of the deflectors up to 110 kV/cm.

After 8 months of operations the coating was not damaged by the beam, although its adhesion was not perfect. A second batch of electrodes was realized paying more attention to the roughness of the electrode surfaces before deposition. In fact a higher roughness implies a higher plasma deposition time to get the same thickness and adhesion of the coating. We are investigating on possible techniques for the realization of this coating on large area electrodes.

4 Conclusion

The LNS Superconducting Cyclotron is presently delivering ion beams in a wide mass and energy range for nuclear physics experiments, most of the operating diagram having been explored. An upgrading program has begun, aiming to improve several sub-systems and to get extracted light ion beams ($7 \leq A \leq 48$) with intensities of 1 pμA: more or less consistent modifications are planned to be introduced in the injection, acceleration and extraction systems.
The axial injection mode will also allow to accelerate H_2^+ beams, which will be delivered for proton therapy [13].

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