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First operations of the LNS heavy ions facility

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Abstract

A heavy ion facility is now available at Laboratorio Nazionale del Sud (LNS) of Catania. It can deliver beams with an energy up to 100 MeV/amu. The facility is based on a 15 MV HVEC tandem and a $K = 800$ superconducting cyclotron as booster. During the last year, the facility came into operation. A ^{58}Ni beam delivered by the tandem has been radially injected in the SC and then has been accelerated and extracted at 30 MeV/amu. In this paper the status of the facility together with the experience gained during the commissioning will be extensively reported.

1. Introduction

A heavy ion facility designed at an energy up to 100 MeV/amu, is now operating at Laboratorio Nazionale del Sud (LNS) of Catania. The facility is based on two accelerators: a 15 MV HVEC tandem [1] and a $K = 800$ Superconducting Cyclotron (SC) which, in a first stage, will operate as booster. The SC project was conceived by the late Francesco Resmini and it has been developed in collaboration with the INFN-LASA group of Milan. Its features have been extensively reported in previous papers [2,3] so we now will recall the main milestones of the project. The SC was moved from Milan to LNS in 1990 after the first cool-down and the preliminary magnetic measurements done at LASA. In May 92, the cryostat was completed with all the radial penetrations, vacuum tested and reassembled inside the magnet yoke. Since November 1992, the coils have regularly been at the liquid helium temperature in order to allow excitation of the magnet and the final magnetic measurements. After these steps and the installation of the SC in its final configuration in May 94 the beam injection, acceleration and extraction test started and were successfully concluded on December 22nd of the same year with the extraction of a 30 MeV/amu ^{58}Ni beam. In June 95 this beam was available in the experimental rooms and in July 95 the first nuclear physics experiment was successfully carried out. The layout of the accelerators facility is shown in Fig. 1 together with the experimental areas now available at LNS. In this paper we will report the status of the main accelerators components and the experience gained during the final commissioning of the facility.

2. Tandem status

The HVEC SMP tandem has been in operation since 1983. In 1986, after replacing the HVEC resistors with the new Vivrad resistors both for column and for the tubes, we obtained reliable running of the machine at 13 MV. In June 1988 a maximum operating voltage of 14 MV was reached after introducing a ^{137}Cs radioactive source of 2 Ci. At this high gradient the belt lifetime decreased to about 1500 h, an unacceptably low value for normal operations. Considering this problem and looking at the maximum voltage requested for the tandem to work as an injector for the SC we decided to realize in 1990 a full upgrading. We changed the charge system introducing the down-charge system and modifying the so-called "structure" around the belt from the old half-open shape with the spacers placed under the belt, to the new "triangular" shape with the spacers placed alternatively up and down around the belt. Moreover the forth and the fifth tubes were lengthened from 78 to 84 in. equal to all the others. The first tube was fully redesigned with a geometric length of 92 in. and an equivalent length of 84 in. and with a shortened straight circular section (all half value resistors) at the entrance followed by a 7° inclined electrode section to guarantee good electron suppression. We fully recalculated the beam optics in order to increase the transmission. Operational experience sup-

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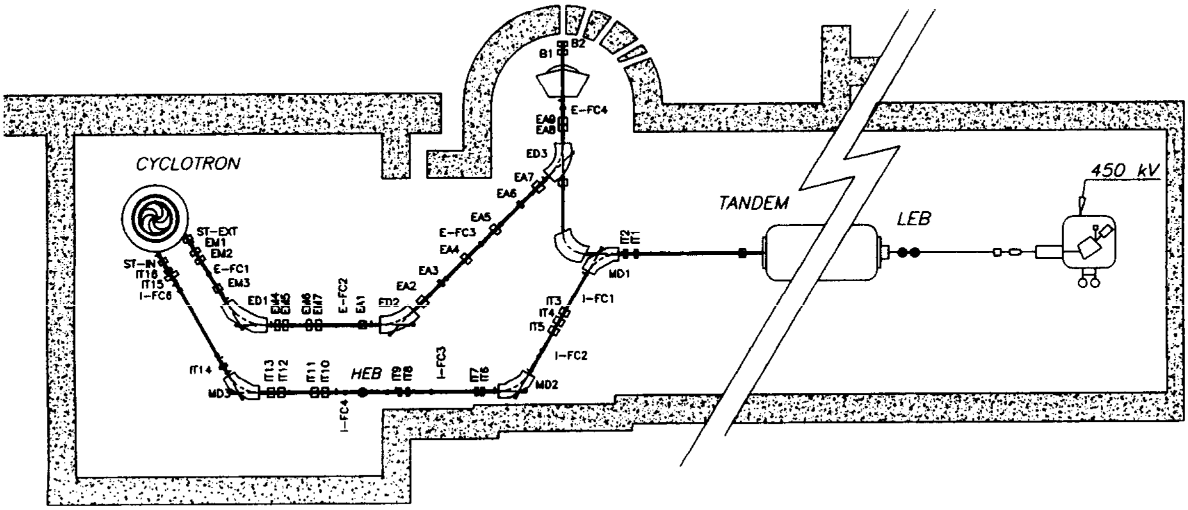

Fig. 1. LNS heavy ion facility floor plan.

ports the fundamental role of the two electrostatic triplets placed before tandem entrance.

In this new condition the requested operating voltage of 15 MV and a longer belt meanlife (5000–6000 h) have been obtained. Moreover the beam transmission at 13 MV, using the new 450 kV pre-injector with a Kingstone 200 sputtering source, has been 86% for light-medium ions (O or Si) and 65–70% for medium-heavy ions (Ni or I). These transmission values are the maximum possible considering that a grid with a transparency of 86%, is placed at the first accelerating tube entrance.

3. Magnet excitation and field measurements

The magnet excitation of the SC started in Catania in November 92 and, after the solution of minor problems in getting the power supplies to drive the pure inductive load of the coils, we could reach the extreme corner of the magnetic operating diagram of 4.8 T with positive currents feeding the two sections of the coils. In these conditions a decentering force of less than 1 ton was measured. The next step was to reach the other extreme point of the operating diagram corresponding to a magnetic field of 3 T with negative current in the beta coils. During this test, we had an accident caused by a large decentering force acting on the wall of the cryostat chamber. Consequently the cryostat suddenly moved 1.6 mm away. Its recentering was done by means of a dedicated mechanical structure developed and built for this purpose without disassembling the cyclotron. In August 93, the operation was completed and the cryostat vacuum chamber was secured to the yoke.

The magnetic field measurements were completed in April 94. A moving search coil measurements device was employed [4] consisting of a search coil mounted on a motorized cart with an optical incremental encoder giving the radial position. The signal furnished by it was monitored using a voltage to frequency converter. The field was measured up to $R = 88.7$ cm with a step of 1 cm and we spanned the full azimuthal extension at steps of 1° or 2°. An absolute measuring accuracy of 1 G on the average field and a reproducibility of 0.1 G were obtained. Our attention was mainly devoted to the behaviour of the trim coils form factor and to the investigation of the field imperfection sources (like the misalignment of the measuring system, coils and vacuum chamber off centering, holes in the yoke and poles, sectors imperfection) mainly looking at the 1st harmonic. We centered the coils to minimize the forces at the extreme corner of the operating diagram. In this position the coils are misaligned by 0.6 mm with respect to the sectors symmetry axis and, as a consequence, there is an induced 1st harmonic which changes with the main coils current. With the coils centred with respect to the magnetic field of the sectors the 1st harmonic is minimized and it is invariant with the excitation. However this position limits the operating diagram of the machine due to the large decentering forces on the coils. This problem could be solved in future reinforcing the horizontal tie rod terminals. Nevertheless, good compensation of the 1st harmonic was found by placing six iron shims on the liner in order to obtain a mean residual contribution lower than 3 G and with a maximum value of 7–9 G reached at the extraction radius (see Fig. 2). This is compatible with acceleration and 1st harmonic control of the precessional extraction obtained through the use of the harmonic coils.

4. RF system

The RF system has been presented and discussed elsewhere [5,6]. The six identical half $\lambda/4$ cavities,

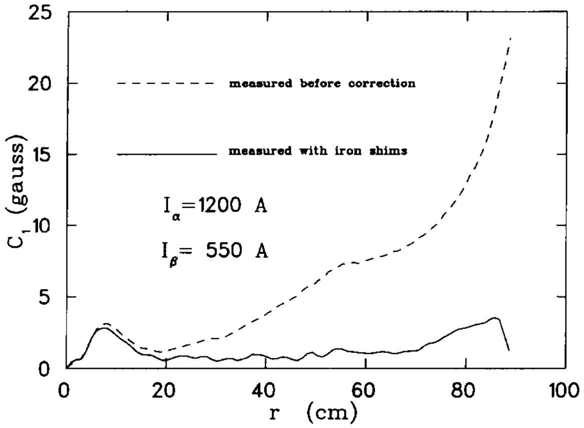

Fig. 2. A typical first harmonic amplitude with and without iron shims correction.

assembled at Milan, were tested inside the cyclotron magnet in July–September '93. Since the SC can be operated in three different harmonic modes (1, 2 and 3), the three cavities must support dee voltages either in phase (harmonic mode 3) or out of phase by 120° (harmonic modes 1 and 2). In the last two cases, the crucial point is the mutual parasitic coupling [7]. A mutual capacitance between dees 1 and 3 of the order of few pF has been measured [7] using a Network Analyzer (NA). This is 50 times smaller than the level where problems arise. The operational frequency range fits the one of the power amplifiers, which are a little wider than strictly required (15 to 48 MHz). All the other cavity parameters (*Q*-factor, shunt impedance, etc.) are very close to the expected values.

The three cavities are conditioned with the magnetic field on and a vacuum of $\sim 10^{-6}$ mbar. The cavity performance is not very sensitive to the conditioning procedure. The lowest levels of multipactoring, which are situated in the region of the dee gaps, are the most critical to be passed and occur for dee voltages ranging between 60 and 200 V. After a shut-down and a machine opening, these low voltage multipactoring levels need conditioning for 1–3 h. This time is independent of the power used to pulse the cavity, the pulse shape and duty cycle. Low power conditioning (10–50 W) is preferred. A second group of multipactoring levels is situated, for all the three cavities, between 2 and 4 kV. To pass these levels, a pulsed input power of few kW is preferred to reduce the conditioning time to less than one hour. No conditioning time is required up to 60–70 kV, while to get a stable operation at 100 kV, at least 5 h are required. Taking into account the cavity shunt impedance, the amplitude of the dee voltage, as defined in Ref. [5], is measured by one of the six loops installed into the sliding short plate (three each), calibrated with the NA [8]. An absolute dee voltage calibration, measuring the X-ray spectrum has also been done [9].

During the first test, with the magnetic field on, we had a total of seven coupler failures, which look similar. The damaged coupler showed a metalized region on the ceramic insulator, while the failure was detected as a sudden pressure increase into the vacuum chamber, caused by a water leak in the ceramic cooling circuit. The failures were caused by the effect of the magnetic field which focussed and stabilized the resonant beam of electrons which can carry significant power (in one case we have estimated a power of about 70 W) across the inner and outer walls of the coupler. Our solution is to modify the coupler design in a way similar to that proposed and successfully tested by other laboratories (TAMU and MSU). With few modifications the insulator position and orientation have been changed, to annul the effect of the magnetic field. The new couplers were installed and successfully tested inside the machine in December 1994. From their installation to date, they have been in operation for more than 2000 h and no problems have been detected.

The electronic control system of the cyclotron RF system is a natural evolution of that discussed in Ref. [10]. Settings and procedures via computer were not fully satisfactory, especially setting and locking the amplitude and phase loops. It was necessary to redesign some components of the electronic control system improving it both in reliability and maintenance time. The three amplitude loops, one for each cavity, are automatic locked, just when the dee voltage attains the reference setting value. They ensure an amplitude modulation noise, of the voltage on the dee, below 5×10^{-5}. Three phase loops maintain the phase difference between the dees, with a stability of ±0.2°. In order to avoid undesiderable detuning due to Joule heating, three phase loops, locked to the same stable frequency source, are adjusted to maintain the tuning of each cavity. A trimming capacitor, able to compensate for tuning drift of up to 40 kHz, is placed on the dee. These capacitors are very useful in adjusting the RF frequency to optimize the accelerated beam. All these loops are automatically relocked when the RF power is turned on after any shut down.

5. Internal diagnostic and extraction system

The main beam diagnostic device for the beam development is a current probe which can be moved along the median spiral line of the hill, so covering the whole acceleration range (Fig. 3). The movement of the probe is accomplished by means of a train, whose rails are screwed to the copper liner and whose carriages are equipped with graphite slides in order to assure both low friction and small mechanical play. Its absolute position is measured with a step of 0.1 mm by an absolute encoder. The probe permits two different kinds of measurements. A scintillating screen allows observation and measurement through dedicated analysis software, the radial and axial beam dimensions, using a small CCD camera inserted in the probe head. Alternatively, an aluminum plate is used to

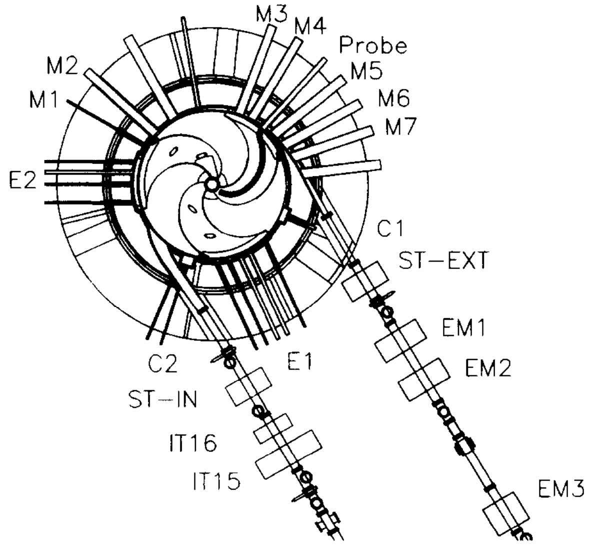

Fig. 3. SC median plane.

measure the total beam current. We can choose between the two different measuring methods by translating the scintillator in front of the aluminum plate. This movement is accomplished by means of a coil inserted in the probe head. The coil can be supplied with a current of about 100–200 mA and, in the presence of the main magnetic field of the SC, it turns itself around so moving the scintillator plate of about 10 mm. In this way the beam can hit the plate or the aluminum block, permitting beam dimensions or current measurements respectively. Considering the limited space available inside the cyclotron, a CCD camera with a diameter of 17 mm and a length of 80 mm and a sensitivity of 2 lx has been chosen. The CCD camera works very well at radii larger than 45 cm, while for smaller radii, noise generated by the RF cavities does not permit clear observation of the beam spot. The image system allows measurement of radial and axial beam dimensions with a precision of 0.1 mm while the total current measuring system has a resolution of 10 pA. The experience gained during the commissioning demonstrated good mechanical and electronic reliability of the current probe.

Beam diagnostics along the extraction channel after the two electrostatic deflectors, has been carried out using five differential and two integral probes designed to monitor the radial width and position. Moreover, at the entrance of each magnetic channel, an integral current probe is installed in a configuration giving the vertical position of the beam centroid. In all cases the current is measured by means of a current to voltage converter connected to the main control system and a resolution of 10 pA has been obtained.

The beam extraction is carried out over 270° and requires two electrostatic deflectors, E1 and E2, seven magnetic channels, M1 through M7, and two compensating bars, C1 and C2, (Fig. 3) whose positions have to be adjusted when varying the ion species and their energies. All these systems are moved by means of stepping motors connected to linear screw actuators and their position monitoring employ absolute encoders.

The electrostatic deflectors, realized with titanium electrodes, have been tested with and without the beam. The maximum field needed for the more energetic ions is 140 kV/cm. During the commissioning, the deflectors have worked with an electrostatic field of 75 kV/cm in a configuration having a gap of 6 mm for the first and 8 mm for the second deflector. At these values they demonstrated for at least 8 weeks, good reliability and no maintenance were requested. During a short time test, a maximum field of 100 kV/cm has been achieved with 6 mm gap. Based on experience in other laboratories [11] using gas for deflector conditioning and also for normal operation, we have recently carried out some tests on the first deflector flowing O_2 gas. The test has been done with a deflector that had already worked in normal operation for at lest 8 weeks. The test showed that using O_2 gas flow, it is possible to recover the electrostatic performance in case of damage during normal operation. During this test an electric field of 110 kV/cm has been obtained. This value is well suited for the extraction of high energy beams. Considering this experience, we are going to design and install a plant to flow O_2 gas in both deflectors.

6. Control system

The SC and the related beam transport lines are fully computer controlled [12]. The control system has been distributed according to functional criteria with functional accelerator subsystems controlled by a single control unit. The field level of the control system has been implemented using a high speed serial bus (Bitbus) even if GPIB and RS232 connections have been used for particular devices. The control level has been realized with MS-DOS PCs 386/486 controlling functional accelerator subsystems. The PCs are then connected to the operator console by means of an ETHERNET network. The console has been implemented as a Local Area VaxCluster of DEC 4000/60 Vaxstations and with a 4000/90 Vaxstation as boot member. Object oriented graphics software has been developed allowing the full control of the facility. The system has been fully operational since 1992 and it has been used satisfactorily during all the stages of the SC commissioning.

7. Tandem–SC beam transfer line and bunching system

The tandem–SC beam transfer line has been designed in a modular way to decouple the two accelerators in transversal and longitudinal phase space [13] and to simplify set-up and tuning. It consists of three sections: analysis, achromatic transport and matching. The setting and the tuning of the beam line is typically made following the modular structure of the line and using Faraday Cups (FC) and scanning wires Beam Profile Monitors (BPM) as diagnostic elements. In all cases, 100% beam transmission has been accomplished along the line. Emittance measurements have been along the transport line with different methods: direct measurements by means of slit or multislit and indirect ones by means of the three gradients method. [14,15]. The emittance value measured for the Ni beam used during the commissioning is 0.8 π mm mrad in both transverse planes.

The coupling between the two accelerators requires a bunching system. It is necessary to bunch the tandem beam at the same frequency of the SC RF system, i.e. 15–48 MHz, or at subharmonic frequency. Our goal is to have a temporal bunch length at the SC stripper position shorter than the ±3° RF. This value is required for a good injection into the cyclotron. The bunching efficiency has to be better than 60%. These tasks are accomplished by the Low Energy Buncher (LEB), located just in front of the tandem and by the rebuncher, placed between the tandem and the SC [16].

The LEB is a double drift buncher, consisting of two cavities in $\lambda/4$ mode separated by a drift space. The temporal length of the bunches after the LEB is 1–3 ns for all ions tested. The two cavities of the LEB were originally designed to work in the ranges 15–48 MHz and 30–96 MHz, respectively. In order to increase the interburst time, as requested by experimental physicists, we have decreased the frequencies of both cavities and now the LEB is working at 13 MHz.

The rebuncher, placed in the coupling line between the dipoles D2 and D3 (see Fig. 1), is a two gap single copper cavity, resonating in $\lambda/4$ mode in the frequency range 54–200 MHz. If the pulses delivered by the LEB are shorter than ±10°, it is possible to drive the rebuncher in the 4th harmonic and to have a satisfactorily large range of linearity, ±40° RF of the applied sinewave voltage, to rebunch the pulses. The maximum of voltage needed to obtain a time focus at the center of the cyclotron is 30 kV. High power tests have been satisfactory though beam test have never been carried out because we have had a power amplifier failure just during the SC commissioning.

To measure the length of the bunches delivered by the LEB a μ-channel plate and a Time Amplitude Converter (TAC) have been used. Temporal lengths as short as 2.3 ns were measured for ^{58}Ni at a frequency of 13.75 MHz and efficiencies of the order of 50% have been recorded. The timing of the extracted 30 MeV/amu ^{58}Ni beam was also measured by a BaF$_2$ scintillator crystal placed in the accelerator room near a Faraday cup 10 m from the cyclotron [17]. The signals from the γ-rays in the scintillator were used as a start signal, and the RF of the buncher was the stop. In Fig. 4 we show the measured temporal beam distribution. The FWHM of 2.5 ns is almost equal to 2.3 ns measured before the injection (the resolution of the detector was 0.6–0.8 ns). This value will be better using also the rebuncher. In this case we expect a FWHM of 1 ns. The interbursts time is 72.8 ns (see Fig. 4). The peak was very sharp and the small satellite between the two peaks corresponds to the cyclotron frequency.

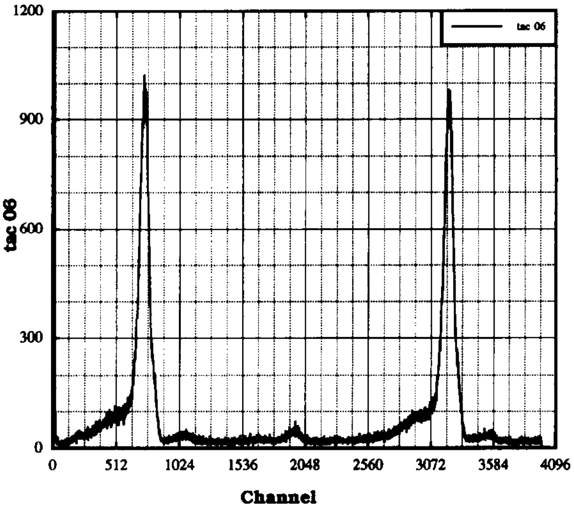

Fig. 4. Measured timing of the extracted beam with only the LEB operating.

8. Superconducting cyclotron commissioning

As mentioned before in May 94 we started the injection and acceleration tests in the SC selecting a 30 MeV/amu ^{58}Ni^{16+} beam as the first beam. The SC was set at a magnetic field of 3.2 T and a ^{58}Ni^{4+} tandem beam was radially injected at an energy of 47.5 MeV corresponding to a terminal voltage of 9.5 MV. The beam to be accelerated in the SC has to be stripped by a 30 μg/cm^2 carbon foil placed close to the center of the SC at a radius of 145 mm. The expected stripper efficiency for charge state 16$^+$ is about 20% and a stripper meanlife of about 150 h can be reported. The horizontal and vertical beam size is controlled by means of the last two quadrupole singlets of the coupling line, IT5 and IT16 in Fig. 1. The control of the azimuthal and radial position of the injection trajectory is obtained using the steering magnet ST-IN, positioned just at the end of the coupling line (Fig. 3). In this way it is possible for the beam to intercept, or not, the stripper foil. In this second case, the injected beam can be intercepted by the main current probe at a radius of 450 mm. Then the operator can measure the total current and check the radial and axial beam position and size. During the commissioning an injection efficiency of 70% has typically been measured. We believe that the main losses are inside the injection channel due to the beam vertical dimensions. The large vertical size can be due to a wrong positioning of the last vertical focusing quadrupole singlet IT15 which cannot be supplied at the nominal value of the current. This problem will be solved during the next machine maintenance period.

With the trajectory set so that the injected beam is stripped and the RF off, it is possible to see the different charge states in the range $13^+–16^+$ in the radial range between 150 and 200 mm, by moving the current probe. With the RF on, only charge state 16+ is accelerated and we have found that the beam current is practically constant up to a radius of 800 mm as shown in Fig. 5. The RF system has been set at a frequency of 27.5 MHz and the accelerating voltage was 70 kV. Pulsing the tandem beam with the LEB only, there is a gain in the accelerated beam current of a factor of 2 or 3 compared to operation without it. More stable and reproducible buncher operations may increase this value. The pressure in the accelerating chamber is 7×10^{-6} mbar after 24 h pumpdown and reaches the operating pressure of 2×10^{-6} mbar after 48 h [18].

In the radial region between 800 and 870 mm, there is a beam loss mainly due to the crossing of the coupling resonance $\nu_r = 2\nu_z$. An axial beam blow-up is generated with current losses on the upper and lower part of the accelerating chamber. Activation has in fact been measured just in this region. This effect is minimized by centering the orbits precisely by the trim coils 3 and 4 to produce a first harmonic of the right amplitude and phase. An efficiency of 80% in resonance crossing has typically been obtained. Another contribution to the beam loss is due to cyclotron phase curve that, in this region has its minimum, causing the loss of those particles which are at the limit of the phase acceptance range. Presently, injecting inside the SC a current of 180 nA, we will have about 32–35 nA at a radius of 870 mm, just before the first electrostatic deflector. We believe that this value represents the maximum obtainable transmission efficiency considering the bunching efficiency and the cyclotron phase acceptance. The beam current distribution measured by means the moving probe is shown in Fig. 5.

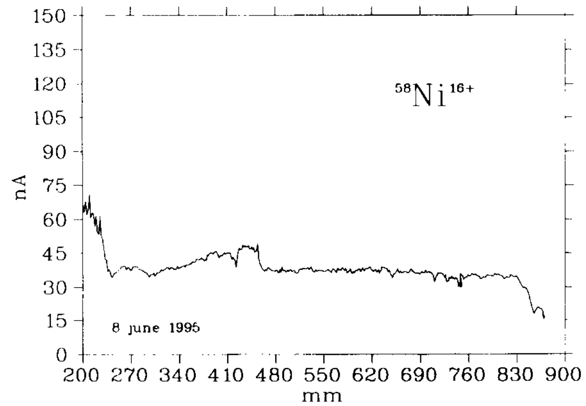

Fig. 5. Measured beam current distribution during acceleration inside the SC.

The beam extraction is accomplished by means of two electrostatic deflectors and seven magnetic channels. The calculation showed that, for the extraction of the 30 MeV/amu ^{58}Ni beam, an electrostatic field of 65 kV/cm is necessary and only five magnetic channels (M1, M4, M5, M6, M7) are required. We positioned the deflectors and these channels in the calculated positions and, with a small adjustment in the deflecting voltage, the beam was observed on the main current probe inside the extraction channel at a radius of 970 mm. With a small adjustment of the channel positions and removing the main current probe, the beam is transported outside the cyclotron to the first Faraday cup position. During the commissioning, we have typically measured an extraction efficiency of about 20% with a peak value of 30%. We consider these values to be quite satisfactory as a starting point. Other laboratories report for this kind of accelerator a maximum extraction efficiency of about 55%. Our extraction efficiency has been obtained applying an extraction bump using the last two harmonic coils aiming to achieve a good inter-turn separation, through the controlled excitation of the $\nu_r = 1$ resonance. At this moment we are not able to estimate the total transport efficiency along the extraction beam line, but a value of 80% can be considered realistic up to the experimental areas. During the first nuclear experiment accomplished in July 95, a mean value of 4 nA has been measured at the target position.

9. Future plans

Until the end of 1995, we are planning to deliver a 30 MeV/amu Ni beam for nuclear experiments. As well, we will try to increase the energy up to 50 MeV/amu. In response to the nuclear experimenters requests, new beams will be available next year and we will try to make the machine able to span the whole operating diagram. In parallel the main work will be done for the installation of a superconducting ECR source employing axial injection to increase significantly the performance in terms of maximum energy and intensity. Different new activities are planned and funded for our heavy ion facility. The most significant one is the development of a radioactive ion beams (RIB) facility based on the use of SC to produce high energy and high intensity primary heavy ion beams striking a thin/thick target producing exotic beams. This project is intended to furnish RIBs, either at intermediate energy or at an energy around the Coulomb barrier. In this latter case, the tandem will be used to accelerate the exotic nuclei produced by interaction on the thick target. Moreover, the use of a 70 MeV proton beam is being planned for medical application with particular attention to the treatment of shallow cancer like that of the ocular region.

In memoriam

The superconducting cyclotron project was conceived, promoted and guided by Francesco Resmini. His decease, in 1984, undoubtedly made the cyclotron completion more difficult. We always remember his skillfulness and the enthusiasm he had for his "job" and the way he was able to transmit this enthusiasm to his collaborators. All of us are happy to dedicate the successful accelerator commissioning to his memory.

Acknowledgements

We would like to thank all the people of the LNS SC and tandem groups and of the LASA SC group for their dedicated work on the development of the LNS heavy ion facility.

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