VARIETY OF BEAM PRODUCTION AT THE INFN LNS SUPERCONDUCTING CYCLOTRON

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Abstract

The INFN LNS Superconducting Cyclotron has been operating for almost 20 years. Several beams are currently accelerated and delivered, allowing for a wide variety of experimental activity to be carried out. In addition, clinical activity is regularly accomplished: over 11 years of proton-therapy of the eye pathologies, around 300 patients have been treated. This has stimulated a growing number of interdisciplinary experiments in the field of radiobiology and dosimetry. On the side of nuclear physics, a significant achievement is the production of radioactive beams: several rare isotopes are produced mainly exploiting the in-flight fragmentation method. The development activity carried out on several components of the user oriented facility will be described.

THE SUPERCONDUCTING CYCLOTRON

The LNS Superconducting Cyclotron is a three sectors compact machine [1], see the median plane in Fig. 1.

Figure 1: View of the median plane of the LNS Superconducting Cyclotron.

Beam Production

A considerable amount of beam types have been developed in the 19 years of operation. Almost the whole operating diagram has been covered: for fully stripped light ions (Q/A=0.5) the maximum energy achieved is 80 AMeV, 100 AMeV being the nominal one, concerning the heaviest ions the best performance has been reached with a ^{112}Sn 43.5 AMeV beam and a ^{197}Au 23 AMeV beam.

Reliability has been regarded as one of the most important features of the machine through the whole operation period. Particular attention has been paid to the most critical subsystems, from which most of the failures were originated: radiofrequency, electrostatic deflectors, ion sources and cryogenics. In particular, concerning radiofrequency, aluminum dees were replaced with copper dees and coupler insulators were redesigned; at present, we are considering the problem of obsolescence of the first stage valves in the RF power amplifiers: new tetrodes will replace the present ones, no longer produced, therefore some upgrade of the amplifiers will be necessary. The improvements introduced to the electrostatic deflectors and ion sources are described in the next subsections. Cryogenics are also discussed in a separated subsection.

As a consequence, the annual number of hours of failures, that at the beginning of the Cyclotron operation was a percentage as big as 20% of the hours of delivered beam, was significantly reduced by a factor 10 in the best case, so increasing a lot the accelerator efficiency and allowing for a more dense experimental activity. At present, the maximum annual number of beam hours on target ranges from 3000 to 3500 hours.

The annual number of hours necessary for beam preparation is a quite high fraction of the delivered amount, i.e. from a minimum of 25% to a maximum of 50%, depending upon the number of beam types to be developed: the accelerator operation is not an easy procedure due to the compactness of the machine, which implies a poor diagnostic equipment, and to the accelerator versatility, i.e. its wide operating diagram.

Cyclotron beams are used for research in nuclear physics, mainly multi-fragmentation and nuclear structure, for interdisciplinary experiments, mainly in the field of beam interaction with biological matter and of radiation damage of electronic components, and for proton-therapy of the eye pathologies. A section of this paper is dedicated to proton-therapy. The beam distribution among these three activities is variable from year to year, depending upon the beam requests from users, that are evaluated once per year by a Scientific Committee appointed by the INFN President. In Table 1 the beam time distribution is reported for the years 2009 to 2012. The increasing trend of the applicative research is quite evident.

Table 1: Beam Time Distribution from 2009 to 2012

Year	Nuclear physics	Inter disciplinary	Proton-therapy
2009	63%	23%	14%
2010	44%	33%	23%
2011	32%	48%	20%
2012	34%	39%	27%

Status

Development, Commissioning

Electrostatic Deflectors

The Superconducting Cyclotron is the primary accelerator for production of radioactive beams, both exploiting the ISOL technique and using the IFF method. For these applications, a beam intensity as high as possible is required. The main technological problem is then given by the compactness of the cyclotron, the extraction process being based on electrostatic deflection: in fact the extraction efficiency is typically of 50%, which implies that a high beam power is dissipated in the septum of the deflector. Many developments were realized on the deflector [1]. With these modifications, an extraction efficiency of 63% was obtained and a 150 watt beam was extracted in a quite reliable way. In order to further increase the beam power up to 500 watt, it is necessary to search for an increased extraction efficiency. This could be achieved by improving the beam formation at the source exit and realizing a better matching between the source and the cyclotron. The immediate result would be an increased injection efficiency, allowing for the possibility of cutting particles out of the machine acceptance. Beam tests will soon be accomplished to study the problem.

Ion Sources

During the past years of operation, a quite efficient production of ion species has been accomplished by the two ECR sources, a room temperature (Caesar) and a superconducting one (Serse), through a careful scheduling of maintenance. Now both the sources are being upgraded. An autonomous cryogenic system has been designed for Serse, so as to increase its reliability, which in the most recent years has been suffering from the supply priority of the main helium liquefier given to the Cyclotron. The new system is based on two commercial cryo-coolers, which have already been purchased, and on the replacement of the present current leads with high T_c ones. The whole project is planned to be completed by the end of 2014.

Concerning the room temperature source, up to now only gaseous species have been ionized. Now, a new injection system has been realized, where an oven can be installed, so as to allow for the production of metallic beams. A ^{11}B beam has also been produced by means of the MIVOC technique, starting from the m-carborane compound.

Cryogenics

At the LNS a helium refrigeration and liquefaction plant was installed in 1991. The size of the helium liquefier was chosen to allow for the operation of the Superconducting Cyclotron. The company Air Liquide, Sassenage, France, realized the Helial 50-4011 liquefier upon LNS specifications.

The helium liquefier has been working with no long interruption for more than twenty years with an outstanding reliability level. The most serious failure events, concerning the low temperature Turbo-Expander, have been more frequent in the last five years, due to the continuous and unavoidable degradation of many components that need to be replaced and/or revised. In particular, two of these events occurred in January and May 2013. Therefore, in May 2013 a review of the liquefier was done in order to find out the reasons of the last failure events, and to evaluate the general conditions of the system. As a result of this review, it was decided to accomplish an extraordinary maintenance and upgrade of the liquefier, that will take more than 6 months. In particular: a) the PLC Telemecanique TSX17 will be replaced with a new generation Siemens PLC, b) the complex of the warm section will be revamped including seals and piping replacement, c) filters and seals of the main compressor will be replaced.

PROTON-THERAPY: CATANA FACILITY

Since 2002 ocular tumours have been treated with 62 MeV protons accelerated by the Superconducting Cyclotron [2]. In these years around 350 patients have been treated. Uveal melanoma is the most frequent neoplasia, but also different eye diseases, like choroidal metastases and conjunctival and eyelid tumours, have been cured. Proton-therapy allows to irradiate a defined eye target volume with a minimum damage of close critical structures like optic disk, macula, lens and anterior segment.

The Treatment Beam Line

The passive proton beam line, Fig. 2, has been entirely built at LNS. The proton beam exits in air through a 50 μm kapton window placed at about 3 m from the isocenter. Just before the exit window a 15 μm tantalum foil is installed. The first element of the beam in air is a second tantalum foil, 25 μm thick, provided with a central brass stopper of 4 mm in diameter. Range shifter and range modulator are placed inside a box. Two diode lasers, located orthogonally and coaxially to the beam line, provide a system for the isocenter identification and for patient centering. Two transmission monitor ionization chambers provide the on-line control of the dose delivered to the patient. The last element is the brass collimator, whose shape depends upon the tumour shape.
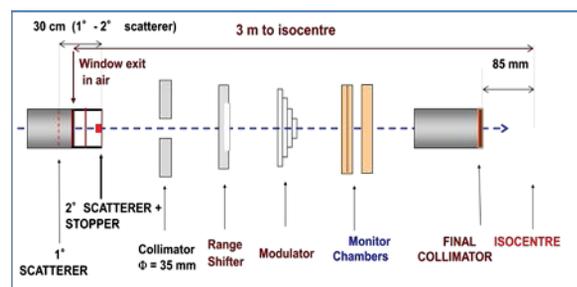
Figure 2: Schematic view of the proton beam line.

Clinical Activity

Treatments are carried out delivering 60 Gy to the melanoma in 4 fractions in 4 consecutive days. Before

each treatment, the eye position is verified and compared to the planned position. The treatment time ranges from 15 to 60 seconds.

Most of the 350 patients (50% women, 50% men), namely 89%, were affected by uveal melanoma. A local tumour control was obtained in 95% of the treated patients, while the cause-specific survival, with a follow-up of 5 years, is 92%.

Improvements are scheduled concerning both the treatment quality from the dosimetric point of view and the beam transport and characterization. In the next future, 5 treatment sessions per year will be accomplished.

FRIBS@LNS IN-FLIGHT FRAGMENTS

Radioactive beams at the Cyclotron energies are currently produced in the extraction beam line of the accelerator, few meters after the exit port, by interposing a thin target (typically Be 0.5-2 mm thick) in the primary beam path [3]. The line optics does not permit a full separation of fragments, therefore a cocktail beam is transported to the experimental apparata. As a consequence, an efficient tagging system must be part of the experimental set-up: it allows to identify the nuclear fragments before impinging in the final target where the nuclear reaction of interest occurs. For instance, the tagging system associated to the CHIMERA detector consists of a large area micro-channel plate (MCP) used as start detector for time of flight measurements (TOF), and a double side silicon strip detector (DSSSD) providing the stop signal. Using a primary beam of ^{13}C 55 AMeV, the scatter plot ΔE-TOF reported in Fig. 3 is obtained. Beams of ^{6}He, ^{9}Li, ^{11}Be, ^{14}B, ^{17}C, ^{18}Ne, ^{68}Ni have been produced using ^{13}C, ^{18}O, ^{20}Ne and ^{70}Zn as primary beams. Quite recently, a primary beam of ^{11}B has been developed in view of the future production of a secondary beam of ^{8}He.
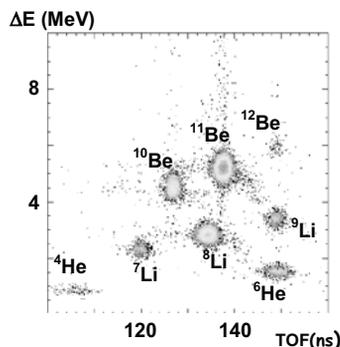

Figure 3: FRIBS@LNS Tagging : identification plot.

LOW INTENSITY BEAM DIAGNOSTICS

Radioactive ion beams produced as described above need to be adequately detected by an efficient diagnostic equipment [3], in order to control the main beam parameters in real time, in particular the beam intensity and the 2-dimensional beam profiles, with sensitivity down to the single particle regime. The aim is to optimize

the whole transport efficiency along the beam line, in order to maximize the intensity until to the final detector.

Several diagnostic stations have been installed from the production target to the experimental halls, each one containing two different devices in order to measure the secondary beam intensity (in particles per second) and to reconstruct the 2D transversal beam profile in real time (beam imaging). Both the devices are installed in pair inside the same cross, each one driven by means of its pneumatic actuator.

Beam Counting

The detector used to measure the beam intensity below 10^6 pps, is based on a plastic scintillator BC408 (τ_{decay} = 2.1 ns, 5 x 5 x 1 cm^3) coupled to a short PhotoMultiplier (Hamamatsu R1924A), that is placed inside the vacuum chamber and powered by an active voltage divider (Thorn EMI – PS 1807/5, Vpower = 6V) installed outside the chamber. It also allows to perform measurements of timing and energy spectra of the secondary ions, thus helping in the isotope identification of the fragments.

Two Dimensional Profiling

In order to visualize the 2-Dimensional beam profile, we use a Position Sensitive Silicon Detector (PSSD), (50x50 mm^2, thickness 500 μm), that intercepts the beam at 0° degrees. It allows to measure the X-Y position of each ion in the beam, thus reconstructing the transversal beam profile in real time, Fig. 4. The strong shape distortion that typically affects the response of such devices has been corrected by means of an algorithm developed by us, that is fast enough to guarantee a real time vision of the beam profile.
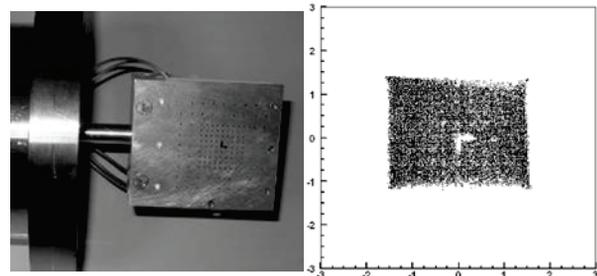

Figure 4: The diagnostic device based on a PSSD. The picture on the right corresponds to a transversal profile of a radioactive beam.

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