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Status report of the LNS Superconducting Cyclotron

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Abstract The LNS Superconducting Cyclotron has been working in stand alone mode since the beginning of 2000, after 5 years of operation as a booster of the 15 MV Tandem. The new mode has proven to be by far more advantageous than the previous one from the point of view of operation. Working with axial injection, a quite high number of new beam types has been developed. The new mode allows for acceleration of H_2^+ molecules, which break into two protons when crossing a stripper in the beam line out of the cyclotron. 62 MeV protons have been used for radiotherapy since February 2002. The new mode allows to inject a more intense beam as compared to the previous mode. Therefore, an upgrading program of the cyclotron has started, aiming at having an intense extracted beam to be used as a primary beam in a facility for production of radioactive beams. Beam tests have been accomplished to evaluate transmission figures, while the upgrading of the present electrostatic deflectors has started: new deflector systems, able to dissipate high beam power and allowing for easier maintenance, have been designed and will soon be tested in the machine.

Key words cyclotron • axial injection • electrostatic deflectors • proton therapy

Introduction

At the LNS, Catania, the Superconducting Cyclotron was installed in 1990. It was commissioned in 1994 as a post-accelerator of a 15 MV Tandem, already working at the LNS since 1984. In 2000, in order to work in the axial injection mode, with two ECR sources as injectors, the Cyclotron has been equipped with a central region and an inflector [6]. Three phase slits, placed 20 cm far from the center, allow to perform a fine phase selection. The injection system and the re-commissioning of the cyclotron working in the new mode are extensively described in [1]. In Fig. 1 a view of the central region and inflector, including also the three phase slits, is displayed.

The extraction system consists of two electrostatic deflectors, placed in two hills, and seven magnetic channels. Unlike the injection system, the extraction system cannot be conceptually changed due to the geometry of the extraction channel. However, some modifications have already been introduced to the deflectors, and new major changes are planned to be made in the near future. A description of this upgrading phase is given in the next paragraphs.

Beam operations

In January 2000 the re-commissioning of the cyclotron, working in the new mode, was done [1]. Since then, many new beam types have been developed and delivered to the users. In 2001, about 2600 hours of cyclotron beam were delivered to users, and from January to July 2002 the beam hours delivered on target were about 2100. Beam types

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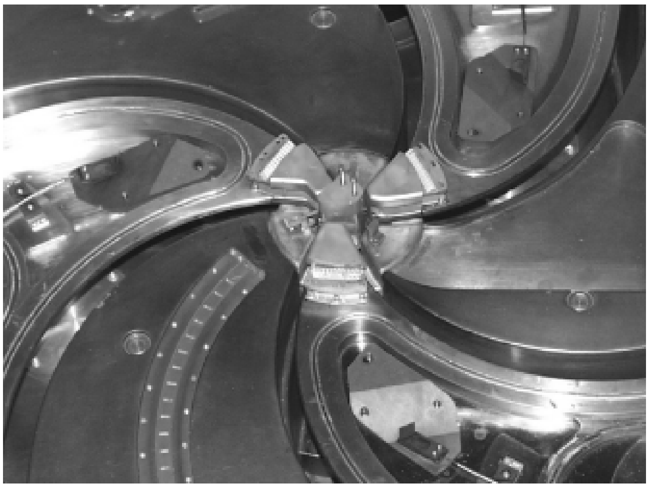

Fig. 1. View of the central region, inflector and phase slits.

developed up to now are reported in [1]. The maximum energy achieved for fully stripped light ions is 62 MeV/amu, concerning heavier ions we report 40 MeV/amu for ^{120}Sn and 23 MeV/amu for ^{197}Au.

As compared to the previous configuration, i.e. with the cyclotron working as a booster of a Tandem, injection is by far easier than in the previous mode, which was based on the use of a stripper foil, since no diagnostic system could be installed in the stripper region. Moreover, the time characteristics of the beam is by far better. The time peak, whose original width is several ns, is made as narrow as 1 ns (FWHM) by adjusting RF phases, amplitudes, slightly tuning the main field and adjusting the positions of the phase slits. The stability of the time structure is now much higher than before: previous instabilities were probably due to the pre-injector high voltage instabilities affecting the pulsing system (bunchers).

A beam test program has begun aiming at operation the cyclotron as a driver in a facility for the production and acceleration of radioactive ion beams. The efficiency factors involved in the three main processes, i.e. injection, acceleration and extraction are being investigated.

Concerning injection, the transmission factor through the injection hole, the spiral inflector and the central region has been measured. As reported in [1], a maximum transmission factor of 9% has been detected, which is a quite good value, considering that the central region reduces the phase acceptance to 30–35°RF. The same amount is measured at the extraction radius, which means that no losses occur in the extraction region due to the resonance crossing.

Typical extraction efficiency is not high, around 30%, due to the machine compactness, therefore, a significant amount of beam is lost somewhere. The most probable place where the beam might be stopped is the first electrostatic deflector, since there is no separation between the last two orbits, but in principle also the extraction path is critical for the beam, since the fringing field is radially defocusing and only local focusing is provided there by the magnetic channels. In order to have an estimation of the beam loss location, a current probe was installed in the extraction channel. There the beam has passed through the two electrostatic deflectors and the first magnetic channel. The new probe showed that most of the beam losses (90%) occur in the electrostatic deflectors and the first channel (M1), while only 10% occur in the extraction channel. Then we started tuning the phase probes to increase the turn-to-turn separation at the extraction radius, and we finally got an extraction efficiency of more than 50%. Further tests are planned to be accomplished, aiming at improving this transmission factor. At present, however, we assume this one as a realistic value, therefore 500 watts of beam power must be dissipated in the deflectors, if 500 watts have to be extracted. In the next paragraph studies and efforts concerning the electrostatic deflectors are described.

Upgrading of the electrostatic deflectors

A new design of the electrostatic deflectors has been accomplished, aiming at improving the electrostatic performance. The new design allows for an easier and quicker way of assembling and replacing parts.

The material of the electrodes is the original one, i.e. a Ti alloy. Several materials have been tested for the electrodes, in particular coatings on the Ti alloy such as Diamond Like Carbon (DLC) and TiN. It has been found that DLC exhibits very good performances at the beginning of the operation, but after several working hours a quick breakdown occurs: therefore, its reliability is poor. This is probably due to its very low surface tension that enhances the probability of emitting micro-tip formation. Moreover, the TiN coated electrodes in the real operational conditions did not show the expected [3, 5] low emission current. The septum is still in Ta, but it is not any longer screwed to the housing, it slides between the liners, this allows for quicker replacement. The liners are in oxygen-free Cu, up to now this seems to be the best material for this application. Compared with Mo (the previous material) the Cu melting temperature is lower (1356 K for Cu, 2890 K for Mo), but its thermal conductivity is higher (401 W/m·K for Cu, 138 W/m·K for Mo), therefore, the evaporation rate is lower. Another important feature of Cu is that, since its surface tension is lower, there is a reduction in the formation of micro-tips and craters once it evaporates on the electrodes. Optical microscopy confirms these hypothesis. Other materials are being studied for the liners, such as coated (by DLC or TiN) and bare Ti, these materials should not form tips once evaporated on the Ti electrodes, since the surface tension is the same.

We are also testing the effects of a glow discharge treatment with O_2. These treatments are of strategic importance since they allow to quickly recover the deflectors. We have also verified that during normal operation a continuous small flow of O_2 is able to reduce the electrodes absorption current. It seems that O_2 is able to sputter the surfaces reducing the number and the shapes of micro-tips on the electrodes and the surface conduction on the insulators. This might also be a reactive sputtering which should be able to oxidize the metal deposition layers converting the metal into non-conductive material such as CuO, Cu_2O or TiO_2, in case of Ti liners. The role of O_2 is not fully understood and further investigation is needed to make it clear.

At the same time we are working on another feature of the deflectors, in view of the use of the Cyclotron with intense beams, i.e. their ability to dissipate a high beam

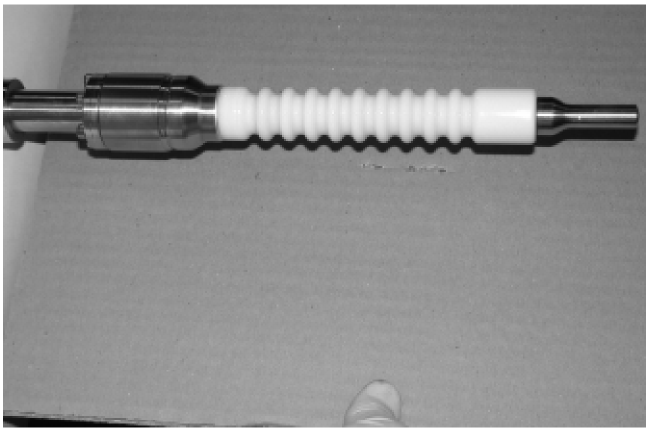

Fig. 2. New high voltage feed-through for the electrostatic deflector.

power. A new electrical feed-through is necessary, since the present one is in polypropylene, directly screwed to the electrode. The new system is able to follow the deflectors movements by means of electronically controlled pneumatic actuators. The first version, assembled in the machine, was not correctly working due to a problem in the electrical contact with the electrode this difficulty has been overcome in a new improved version. Figure 2 shows a picture of the terminal part of the feed-through which makes contact with the electrode. A water cooled housing for the first electrostatic deflector has been manufactured and will be tested in the near future. For both deflectors, the housing will be provided with an automatic disconnection system, therefore in the future activated deflectors will be remotely disassembled.

Use of the Cyclotron beam for radiotherapy

A new proton therapy facility for the treatment of ocular pathologies with a 62 MeV proton beam has been developed (CATANA project) [2]. The first patient was treated in February 2002, and since then 14 more patients have been treated. In Fig. 3 the proton beam line is shown with all its main components, including the chair for the patient positioning.

The proton beam exits in air through a 50 μm Kapton window placed about 3 m far from the isocenter. Before the window, under vacuum, a 15 μm tantalum scattering foil is placed. The first element in air is a second tantalum foil, 25 μm thick, provided with a central brass stopper of 4 mm in diameter. The double foil scattering system is optimized to obtain a good homogeneity in terms of lateral dose distribution, minimizing the energy loss. Figure 4 shows an experimental lateral dose distribution of the 62 MeV proton beam, obtained with a final collimator of 25 mm diameter; data are acquired in water with a silicon diode. A range shifter and a range modulator are placed downstream the scattering system and mounted in two different boxes. Two diode lasers, placed orthogonally, provide a system for the isocenter identification and for patient centering during the treatment. The emission light of a third laser is spread out to obtain the simulation field. Fundamental elements of the treatment line are two transmission monitor chambers and a four sector chamber, implemented to have an on-line control of the dose delivered to the patients and information on beam symmetry, respectively. The last element before the isocenter is a collimator located 8 cm before the isocenter. Finally, two X-ray tubes are mounted for the verification of the treatment fields.

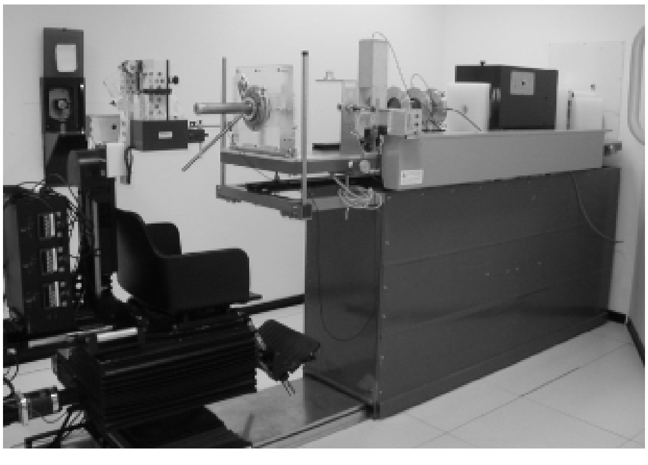

Fig. 3. View of the CATANA beam line.

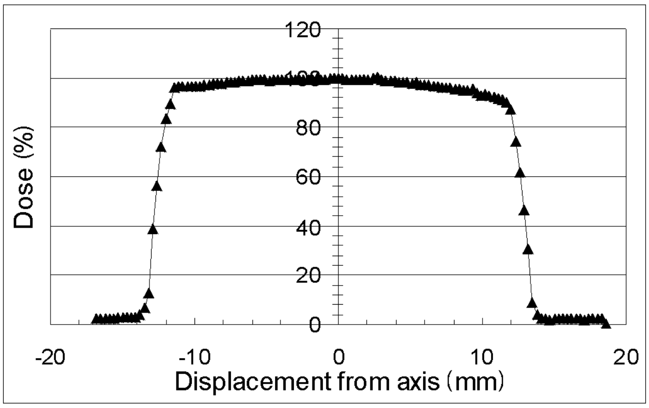

Fig. 4. Lateral dose distribution of the 62 MeV proton beam.

Particular care is devoted to the development of dosimetric techniques for the determination of the absorbed dose with clinical proton beams and 2D and 3D dose distribution reconstruction. A parallel-plate calibrated Markus ionization chamber has been chosen as a reference detector for the absolute dose measurement [4], while gaf chromic and radiographic films, TLD (Thermo-Luminescent Detectors), natural diamond and silicon detectors are the choices for the relative one. Depth dose curves and

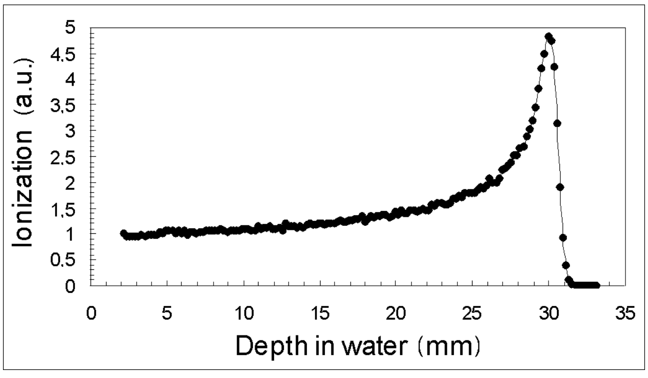

Fig. 5. Bragg peak of the 62 MeV proton beam acquired with a water-tank system and a Markus ionization chamber.

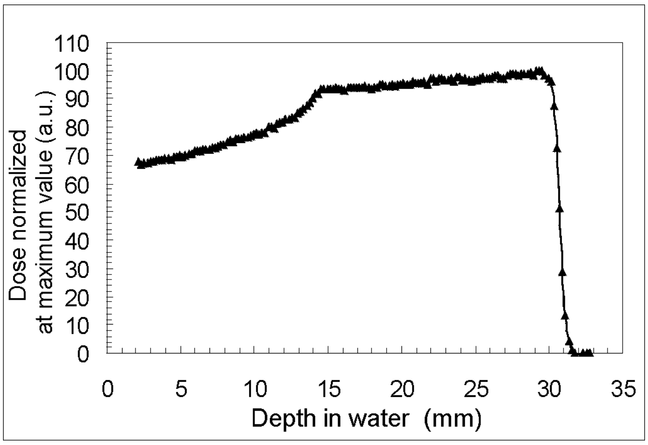

Fig. 6. Spread out Bragg peak obtained with a modulator wheel.

transverse dose distributions, either for the full energy and modulated proton beams, are acquired with a water-tank system provided of three fully computer-controlled step motors. This system is controlled by a soft-ware providing the acquisition and dosimetric analysis of data. Figure 5 shows a depth dose distribution peak in water obtained with the water-tank system and Markus chamber for a non-modulated 25 mm diameter beam at the energy of 62 MeV.

The Full Width at Half Maximum of the Bragg Peak is 2.76 mm, while the 90–10% and 80–20% distal fall-off are 0.8 mm and 0.6 mm, respectively. The entrance to peak ratio is 4.72.

The next step was the realization, in collaboration with the Clatterbridge Center for Oncology (UK), of a wheel modulator to obtain a spread out therapeutic Bragg peak. To do this, several Bragg peaks, for different proton beam energies ranging from 62 MeV to 10 MeV, were acquired with the Markus chamber in a water phantom. Figure 6 shows the spread out Bragg peak obtained with the first prototype of the modulator wheel.

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