New Beam lines for the NUMEN experiment at INFN-LNS

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Abstract. The NUMEN experiment at INFN-LNS demands an upgrade of the Superconducting Cyclotron (CS) to deliver beam with power up to 10 kW for ions with mass $A < 40$ amu. To transport these high power beams, it is mandatory to build a new extraction beam line from the CS and to upgrade the existing beam transport lines to maintain the beam losses below 100 W, both in the accelerator room and along the beam transport areas. Moreover, a new fragment in-flight separator will be built to produce radioactive ion beams, but also to perform energy selection of the beam extracted from the cyclotron, to be delivered to the MAGNEX spectrometer with an energy spread below 0.1% FWHM. The use of a 10 kW ion beam implies also to redesign of the beam transport line inside the MAGNEX experimental room to allow the installation of a new large and well shielded beam dump beyond the apparatus.

1. Introduction

The NUMEN experiment [1,2,3] needs to use mainly beams of Carbon, Oxygen and Neon with intensity up to $10^{14}$ pps delivered to the MAGNEX spectrometer [4,5]. The required energies for these beams are in the range 15-70 AMeV, which corresponds to a beam power in the range 1-10 kW. Due to the compactness and the relatively small extraction radius of the INFN-LNS Superconducting Cyclotron (CS) the inter-turn separation at the extraction radius stays around 1 mm. This low inter-turn separation and the features of the Electrostatic Deflectors (ED) limit the extraction efficiency to 60%. Moreover, it is convenient to maintain the beam losses inside the CS below 100 W to mitigate the activation of the machine. For these reasons the maximum beam power delivered by the CS is 140 W [6]. To overcome this limit, the extraction by stripping, just for a set of ions with $A < 40$, was proposed [7]. Indeed, for these light ions with energies higher than 15 AMeV the stripping extraction allows to achieve extraction efficiencies higher than 99% [8], and we could accelerate and extract beams with power up to 10 kW.

Therefore, the CS will be upgraded with the installation of a new cryostat containing a new set of superconducting coils and a new extraction channel designed to allow extraction of the beam by stripping [7]. The existing extraction beam line will be also maintained to allow electrostatic extraction of all ion beams with low power.

In figure 1 the layout of the CS with the two extraction lines is shown. To connect the new extraction channel to the existing beam transport line, it is mandatory to design a new extraction line that is described in section 2.
2. A new extraction line for the high power beams

The difficulties to design an Extraction Line (EL) both for the electrostatic extraction and for the stripping extraction and the request of the user community to maintain the availability of all the ions, imposed to design the upgraded CS with two EL (see figure 1). The main differences between the two EL are the direction of the beam and the trajectories across the fringing field of the cyclotron. The new extraction channel crosses the fringing field in a faster way than the present one. This allows to achieve smaller transversal beam sizes along the new extraction path and moreover the values of position and angular dispersion vs. energy (element of transport matrix $R_{16}$ and $R_{26}$) are lower than through the existing extraction channel [9].

Although, the tail of energy spread of the beams extracted by stripping arrives up to ±0.3%, the choice to have a new EL allows to maintain the radial beam size at values lower than 30 mm, and to mitigate the beam losses along the extraction trajectory. Moreover, the extraction channels of the new EL will be equipped with thermal shield to mitigate the effect of the beam losses due to the beam halo.

The new EL starts at the exit point shown in figure 1, and transports the beam up to the so called achromatic waist where the two extraction lines join each other. According to the layout of figure 1, the first active element of the new EL is a steering magnet, which has to adjust the beam direction in a...
range of ±0.5°. This steering magnet has an effective length of about 300 mm and the requested magnetic field is lower than 8 kGauss. The other magnetic elements are two quadrupoles and two symmetric bending magnets with a horizontally focusing quadrupole in between. This first part of the beam line has the role to cancel the energy-position and energy angle correlation of the beam. After this section, two additional quadrupoles reduce the vertical beam envelope to clear the vacuum chamber of the bending magnet ED1 of the existing line, see figure 1. In particular, the vertical beam size has to be smaller than 26 mm, that is the free gap of the vacuum chamber of the bending magnet ED1. Finally, the last three quadrupoles are the same as in the existing line and produce a small beam spot at the achromatic waist position, as shown in figure 1.

The new EL is designed to transport beams with a maximum magnetic rigidity of 2.7 Tm and with a normalized emittance of 1 π mm-mrad. In figure 2 the radial and axial beam envelope, and the dispersion along the transport line are shown for the case of 20Ne at 71 AMeV. Similar beam envelopes were achieved also for other eight simulated cases [9].

3. A new beam line as energy selector and fragment in-flight separator
To transport the 10 kW beam to the Magnex room, the transport efficiency should be increased up to 99%. This would imply to replace the existing quadrupoles and probably also some dipoles with new ones with larger diameters. This upgrading should produce a serious interference with the operations of almost all the experimental rooms of the laboratory. For these reason we choose to build a by-pass line to the existing transport line with an acceptable impact on the two experimental rooms called "20° and 40°". The new line is designed as an achromatic FRAGMENT In-flight SEparator (FRAISE) [10], and will be well shielded to allow to stop in this area a beam power up to 2 kW. These features allow to use this beam line also as an energy selector. Although the energy spread of the beam extracted from the cyclotron could have tails up to ±0.4%, it could be possible to reduce the energy spread of the beam delivered to the NUMEN experiment down to 0.1% FWHM.

4. Beam Lines inside the MAGNEX experimental room
In order to run experiments with 10 kW beams, a suitable well shielded beam dump is needed. In the NUMEN experiment different primary beams come out of the spectrometer on the left side of the Focal Plane Detector (FPD) or on the right side. A possible solution is shown in figure 4, where the transport beam line, the MAGNEX spectrometer and the beam dump inside the experimental room are displayed. In particular, the 0° position of the spectrometer has been rotated of 70° in respect to the present position, to allow the exit of the primary beam on the left and right side of the FPD and

Figure 3: The new beam line will be used either as a fragment in-flight separator or as an energy selector.
maintain the beam lines from MAGNEX to the beam dump inside the north wall of the LNS. The west wall of MAGNEX room has to be shifted of about 3 m, to allow the installation of the beam dump. To mitigate the background to the FPD, the beam dump is installed underground, about 5 m below the median plane of MAGNEX and about 3.30 m below the ground. A rotating 90° bending magnet, placed over the beam dump, bends the beam in the vertical direction. The beam coming out from the right side of the FPD is transported to the beam dump by a steering magnet, a quadrupoles doublet, a 80° horizontal bending magnet and a second quadrupole doublet focuses the beam to the beam dump through the vertical 90° bending magnet. The transport of the beam coming out from the left side of the FPD is accomplished by a steering magnet and one quadrupole doublet to focus the beam on the beam dump through the vertical 90° bending magnet. To switch from the left side to the right side of the transport beam line it is mandatory to rotate the 90° vertical bending magnet of about 50°. The rotation of the MAGNEX spectrometer some time implies to dismount partially the left side or the right side beam line. The new position of MAGNEX implies to build an additional achromatic beam transport line consisting of a triplet of quadrupoles, of two symmetric 50° bending magnets with a radially focusing quadrupole in between and of a quadrupole doublet to focus the beam on the target.

Figure 4: MAGNEX experimental hall. On the right side the new beam line is shown. On the left side, the two lines outgoing from MAGNEX and the beam dump are also shown.

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