SPES CYCLOTRON BEAMLINES

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Abstract

The SPES (Selective Production of Exotic Species) facility purposes are the production of radioactive beams (RIBs) by ISOL technique, the production and the research on innovative radioisotopes and experiments with high intensity neutron beams.

For these reasons, the 70p cyclotron, designed by BEST Cyclotron Systems Inc. (BCSI), has been installed at Laboratori Nazionali di Legnaro (LNL): it is a machine able to produce a beam current up to 700 μA shared into two extraction channels. Beams at the energy values of 35 MeV, 50 MeV and 70 MeV have to be transported to the experimental areas with specific properties and minimizing the beam losses. Here, the main features of the needed beamlines are described.

BEAMLINES OF THE SPES PROJECT

The core of the SPES project is the 70p cyclotron, a 4 sectors machine with room temperature coils, designed to accelerate H^- ions. The extraction by stripping method allows the beam current sharing into two extraction channels: it is possible to carry out simultaneously the production of radioactive ions and other applications [1].

Figure 1 shows the layout of the underground floor of the SPES building. The central vault (A1) houses the 70p cyclotron and it is surrounded by different experimental areas: in particular, there are three bunkers shielded for receiving high power beam (up to 50 kW). Figure 1 reports the beamline for the beam transport to the ISOL target (L1), which was designed by BCSI [2], and the beamlines L3b-L3c and L2, dedicated to the SPES applications. The beamline L1 is actually operational and, with the second extraction channel, it is included in the commissioning of the 70p cyclotron. As concern the other beamlines, the main properties of the achieved solutions are here described: these beamlines have the same initial elements of the beamline L1, from the combo magnet at the cyclotron extraction to the first switching magnet; the new designs have to take into account this fixed part and the preliminary results related to the first machine operations. The main requirement for each configuration is the minimization of the beam losses along the beam path: the allowable limit is 1%.

BEAM TRANSPORT TO ISOL AREA

The beamline to the ISOL area was installed in the vault in May 2015. The beamline design was completed to satisfy all the requirements needed for the ISOL facility, that is, a final RMS spot size around 4 mm. For the cyclotron commissioning by using the beam dumper designed by LNL SPES target team [3], new tunes of the 4 couples of quadrupoles were required, in order to increase the RMS spot size in the range 8 – 12 mm and, then, to optimize the power distribution in the inner surfaces of the device. A summary of the simulation results is reported in Table 1, for the minimum and the maximum values of the RMS spot size: the beam losses are less than the required limit.

Table 1: Simulation Results of the L1 Beamline Tunes

Energy [MeV]	35		50		70	
RMS spot [mm]	8	11	8	11	8	11
Q1 [T/m]	4.99	4.99	6.31	6.31	5.06	4.91
Q2 [T/m]	-5.41	-5.41	-6.69	-6.69	-6.68	-7.66
Q3 [T/m]	-4.35	-4.30	-5.25	-5.15	-5.45	-5.56
Q4 [T/m]	3.05	3.19	3.81	3.81	3.20	3.72
Q5 [T/m]	3.60	3.87	4.51	4.98	5.82	6.84
Q6 [T/m]	-5.06	-5.01	-6.24	-6.52	-7.25	-8.41
Q7 [T/m]	-4.04	-3.81	-4.64	-4.31	-5.90	-4.99
Q8 [T/m]	3.13	2.65	3.34	2.97	4.38	3.35
Losses [%]	0.12	0.22	0	0.19	0.02	0.1

Up to now, the L1 beamline has been fully tested only by using 70 MeV beam and the 4-jaw collimators placed just after the combo magnet have been used to reduce the beam halo. Furthermore, the wobbler system placed just before the A6 bunker entrance has been activated in order to get a uniform beam distribution and to avoid thermal stresses of the beam dumper. These effects have to be included in the complete study of the performance of the L1 beamline and are useful data for the improvement of the design of the new beamlines.

RADIOISOTOPE PRODUCTION

LARAMED (LAboratorio per la Produzione di RAdionuclidi per la MEDicina) is the proposal of LNL for the production of innovative radiopharmaceutical and conventional radionuclides [4]. The beamlines L3b and L3c, which satisfy the requirements described in table 2, share all the elements in A1 hall, then a 45 deg switching magnet is used to bend the beam in the low current experimental area.

Table 2: Main Features of the LARAMED Beamlines

	L3b	**L3c**
Energy range	35 – 70 MeV	35 -70 MeV
Average current	300 μA	< 1 μA
Beam spot size (RMS sigma)	3 mm	3 – 4 mm
Optic layout	3 quad doublets	1 switching magnet, 2 quad doublets

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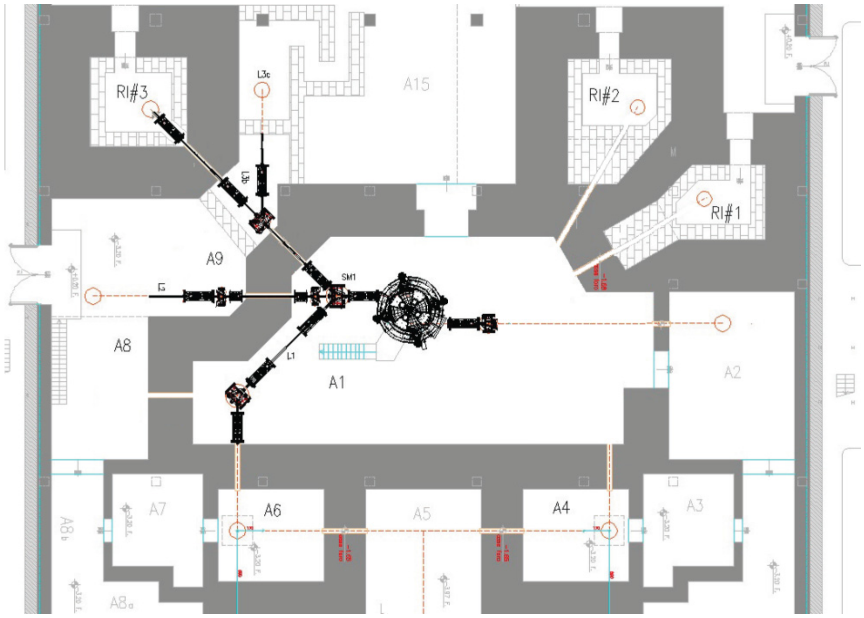

Figure 1: Layout of the SPES facility beamlines. The beamline L1 to transport the beam to the ISOL bunker A6 is under commissioning. The first 45 deg switching magnet along the L1 beamline allows the sharing of the proton beam between the three experimental areas dedicated to experiments with high intensity neutron beams (A9) and the radioisotope production (RI3 bunker and the space aside).

In particular, the L3b beamline follows a straight path from the first 45 deg switching magnet in the A1 vault up to the RI3 bunker: the beam transport is completed by using three couples of quadrupoles; the total line length is 20.8 m. The additional elements needed to complete the L3b beamline have the same properties of the existing L1 beamline elements, which have a maximum gradient value of 10 T/m and an aperture of 102 mm for each quadrupoles. The proposed solutions for the quadrupole tunes and the related envelopes are reported in Table 3 and Fig. 2 respectively: the beam losses for each configuration are less than 0.1%.

Table 3: Quadrupole Tune of the L3b Beamline

Energy [MeV]	35	50	70
Q1 [T/m]	4.682	5.740	8.175
Q2 [T/m]	-5.615	-6.639	-8.680
Q3 [T/m]	-4.422	-4.732	-5.144
Q4 [T/m]	3.831	3.444	3.590
Q5 [T/m]	2.556	2.445	2.562
Q6 [T/m]	-2.113	-2.314	-2.301
Q7 [T/m]	-2.993	-3.112	-3.722
Q8 [T/m]	3.944	4.003	3.968

The L3c beamline has the same elements of L3b beamline in A1 hall, while in A9 hall it needs a 45 deg switching magnet and a quadrupole couple; the total length is about 14.85 m. By using suitable tunes it is possible to produce at the target beam spot with RMS size in the range 3 – 5 mm. In table 4, only the solutions able to obtain a beam spot with a RMS sigma of 3 mm are shown. The beam losses along these configurations are less than 0.1% (see Fig. 3) and occur mainly in the vacuum chamber of the two switching magnets.

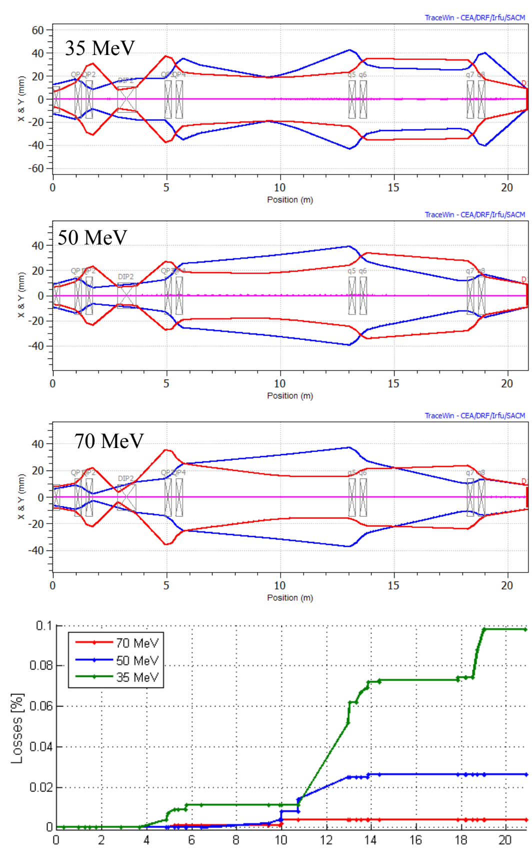

Figure 2: Envelopes (horizontal coordinate in blue, vertical coordinate in red) and beam losses of the beam at the energy values of 35 MeV, 50 MeV and 70 MeV along the L3b beamline.

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Table 4: Quadrupole Tune of the L3c Beamline

Energy [MeV]	35	50	70
Q1 [T/m]	4.987	3.555	7.203
Q2 [T/m]	-5.669	-6.589	-7.798
Q3 [T/m]	-4.738	-5.0394	-6.280
Q4 [T/m]	3.982	4.272	5.374
Q5 [T/m]	-3.705	-2.886	-4.235
Q6 [T/m]	3.717	1.225	3.922

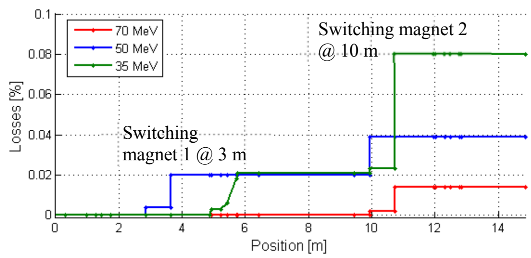

Figure 3: Beam losses along the L3c beamline.

NEUTRON EXPERIMENTAL AREA

The high intensity proton beam is also useful for experiments with intense beams of mono-energetic neutrons and of fast neutrons with the same energy properties of the neutrons observed at sea-level or at flight-altitudes level: these are the purposes of the neutron irradiation facility (NEPIR) of the SPES project [5].

In particular, a complex consisting of two dedicated targets, called the Quasi Mono-energetic Neutrons (QMN) and Atmospheric Neutron Emulator (ANEM), is under study at LNL and it will be placed in A9 hall: the experimental set-up requires a proton beam current of 50 µA in the energy range 20 – 70 MeV. Since the 70p cyclotron is able to produce beams in the energy range 35 – 70 MeV, the use of an energy degrader along the beamline is needed: it means to find out the most suitable position for the device and to evaluate carefully the effects in the A1 vault. The peculiar element of the L2 beamline is a couple of 22 deg vertical dipole magnets: this magnetic chicane minimizes the observation of neutron back-streaming towards the cyclotron hall. In case of the degrader system use, the magnetic chicane allows to achieve the energy selection of the protons and to limit the neutron flux from the degrader to the forward test point.

The design of the L2 beamline requires particular attention because of the limited space available in the A1 hall, between the existing switching magnet and the 3 m wall that separates the cyclotron vault and the A9 hall. In fact, it is necessary to place in few meters, both the first dipole magnet and a couple of quadrupoles in order to achieve a satisfactory focalization of the lower energy-bigger emittance beams (Fig.4). In the actual configuration, L2 beamline consists of the first part of the L1 beamline, from the combo magnet to the first 45 deg switching magnet, plus three quadrupole doublets and the couple of vertical dipole magnets. The beamline length, along the beam path, is about 14.8 m and the vertical jump between the two halls is 2.59 m.

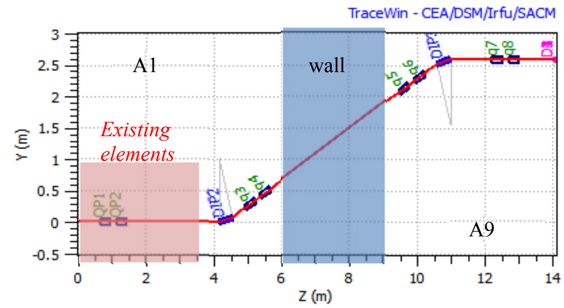

Figure 4: Synoptic (not in scale) of the L2 beamline.

The QMN/ANEM complex requires almost parallel beams with RMS spot size in the range 4 – 7 mm. The simulation results show that this system allows to transport the beam and to achieve several spots in the specified range, with beam losses of 0.2% for the energy value of 35 MeV, while the losses are almost negligible for higher energy values. Also shorter beamline version was completed, to have more space for the targets and the other experimental elements. Moreover, the final configuration will be defined once the degrader position in the A1 hall and the related constrains will be fixed: three different alternatives, in fact, are still under study.

CONCLUSION

All the simulation results here reported were achieved by using TraceWin [6]. While the beamlines for the LARAMED facility are fixed, the beamline for the experiments with intense beams of neutrons needs further study due mainly to reduce the beam energy limits of the 70p cyclotron. Useful data to confirm the effectiveness of these configurations and/or to improve the adopted solutions will be available in the next months, during the 70p cyclotron commissioning. In particular, the transport of beams of different energy along the L1 beamline should outline new critical points and suggest some adjustments in the preliminary configuration.

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