

REVIEW AND CURRENT STATUS OF THE 70 MeV HIGH INTENSITY PROTON CYCLOTRON AT LNL

M. Maggiore, P. Antonini, A. Lombardi, L. Pranovi
Laboratori Nazionali di Legnaro, INFN, Legnaro, Italy

Z. Filipovsky, Institute for Positron Emission Tomography, Skopje, Rep. of Macedonia

Abstract

In 2017 the new cyclotron has been successfully commissioned and started the operation at Laboratori Nazionali di Legnaro (LNL) of INFN. The cyclotron is the proton driver foreseen for the Selective Production of Exotic Species (SPES) project, providing the high power beam for radioactive ion beams (RIBs) production by the ISOL technique. The SPES facility is today under construction and first low energy RIBs are expected to be available in 2021. The facility has been designed in order to exploit the versatility of the cyclotron in terms of wide range of energy and beam current extracted: 35 - 70 MeV energy and 20 nA - 500 μ A of average current. Moreover, the possibility to extract at the same time two proton beams allows to share these both for experimental physics session and applications. In particular, at LNL a collaboration between private company and public institution will lead to a profitable synergy in R&D of new radioisotopes and the related production. In the session the results of the commissioning and the operation of cyclotron will be presented as well as the description of the SPES facility together with its potentiality in nuclear physics research and applications.

SPES PROJECT STATUS

The SPES project [1] is developing in the international framework of the new facilities producing radioactive ion beams for experiments exploring the frontiers of nuclear physics. It will mostly provide neutron-rich exotic beams, through the production of fission fragments by the interaction of high power proton beam (8 kW) with UCx targets. The neutron rich exotic ions produced by the above direct reaction, will be selected in mass with a very high resolution on the order of 1/20000 and then, once the charge breeding process increases the charge to mass ratio, the ions are accelerated with ALPI linac booster up the energy of 10 MeV/amu ($A \sim 130$).

SPES project is developing in several branches spreading from fundamental research to applications and interdisciplinary physics. The complexity of the project has required to separate it in four phases with the aim to provide a multipurpose facility:

- α -phase: construction of main building and installation and commissioning of the high intensity accelerator delivering the high power proton beams.
- β -phase: installation and commissioning of Radioactive Ion Beams (RIB) facility. It consists on ISOL targets, low energy beam transport lines, beam cooling device and High Resolution Mass Separator (HRMS), charge breeding system, new RFQ injector and re-acceleration.

- γ -phase: installation and commissioning of equipment and laboratories for production and R&D of radioisotopes for medical applications.
- δ -phase: realization of experimental hall for the production of neutrons beam by interaction of high intensity protons with heavy and light targets.

The SPES project entered in the construction phase in 2010 with the assignment of the tender for the cyclotron supply to Best Cyclotron System Inc. (BCSI) Canadian company.

The α -phase has been accomplished out at the end of 2017: the main building has been constructed and principal plants, services and auxiliary systems were supplied in order to allow the first operation of the accelerator. The cyclotron has been installed in 2015 and finally commissioned in 2017. From mid-2018, in the SPES building several activities have started in order to complete the services (electrics, hydraulics, thermo-mechanics) and the infrastructures (laboratories, finishing of irradiation rooms, additional shielding) necessary to carry out the β - γ - δ phases.

Certainly the β -phase is the most complex and articulated of the project. It includes not only the realization of the items described above but also additional works to provide a significant upgrade of the actual ALPI superconducting linac (cryogenics system, controls, etc..) in order to improve both the performance and reliability. The works related this phase are still ongoing: the ISOL target station is ready to be installed in the dedicated bunker and the low energy beam transport line components are under construction. The beam cooler device is being realized in collaboration with LPC of CNRS at Caen (France). The HRMS design has been completed and the tender for the construction will be launched in few months. The charge breeder has been installed and ready for the commissioning with stable beams. The resistive RFQ to be used as new injector for ALPI booster is under construction. The main schedule foresees the commissioning at low energy of the first beam extracted from ISOL target in 2021. The completion of the SPES commissioning with RIBs at fully energy is expected in 2023.

The γ and δ phases are related to the applications of high intensity proton beam extracted from the cyclotron.

The γ -phase foresees the setting-up of 3 bunkers dedicated to the production of innovative radioisotopes for diagnostics and therapy in medical environment. One low intensity irradiation area is being prepared for nuclear cross-section measurements. Moreover, the laboratories for chemical treatment of the produced radionuclides and for special targets preparation will be equipped. The project funded for this purpose is LARAMED [2].

Finally, the δ -phase concerns the neutron sources. The final goal is to set-up an experimental hall allocating two dedicated beamlines: one for the production of quasi-mono energetic neutron flux by the interaction of few micro-ampere proton beam with thin target made of composite of Beryllium and Lithium and the second for the production of a neutron beam with continuous energy spectrum (in the range of a few keV to 70 MeV) to emulate the atmospheric neutron flux [3].

While the γ -phase progresses in an advanced construction stage and his partial completion (1 irradiation station at high power (35 kW) and 1 irradiation station at low power (35 W)) is scheduled for the end of 2022, the δ -phase is still in the design step.

HIGH INTENSITY FACILITY STATUS

The SPES project involves all the infrastructures of the LNL and the new building above discussed is the main area where the high power proton beam is accelerated, transported and delivered to the targets. This facility [4] was designed in order to exploit the possibility to extract simultaneously two proton beams from the cyclotron and deliver them to the maximum number of irradiation target stations. In such a way to realize a multipurpose facility for providing research and applications in parallel sessions.

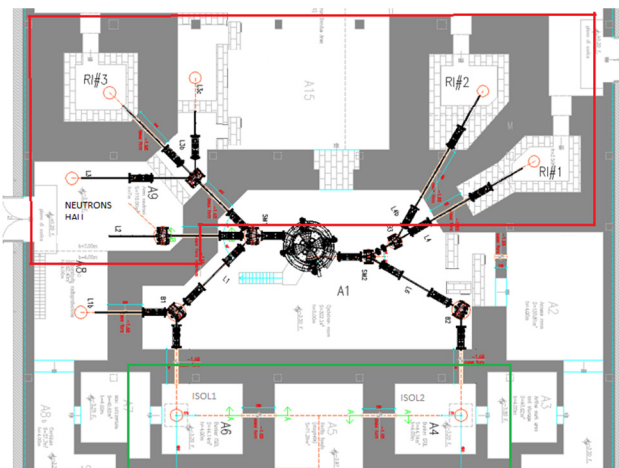


Figure 1: Main layout of high intensity facility at SPES building. The areas dedicated to the applications and R&D on radioisotopes are red underlined. The two bunker for RIBs production by ISOL target are highlighted in green.

General Layout

Mainly the facility is divided into two macro-regions: the EAST area (shown in red in Fig. 1) is dedicated to the applications as radioisotopes production and neutron sources and the WEST (shown in green in Fig. 1) area where the two bunkers for the ISOL target stations have been placed (ISOL1 and ISOL2 shown in Fig. 1).

The core of the facility is the area A1, just in the center of building, which accommodates the cyclotron. Two main beamlines come in opposite direction from the accelerator to the distribution magnets SM1 and SM2. From these, different beamlines guide the beam up to 9 irradiation points.

Three bunkers RI1, RI2, RI3 will be equipped with high power target stations for production and research of radioisotopes for medical use. The pneumatic transport system is expected to deliver the irradiated targets up to hot cells in the radio-chemical laboratories placed on second floor.

Cyclotron C70

The SPES Cyclotron is a four sectors compact cyclotron capable to accelerate H^+ ions up to the maximum energy of 70 MeV. The protons are extracted by the stripping of the H^+ ions passing thru a thin graphite foil where the two electrons were stopped.

The proton beams are available in the energy range within 30-70 MeV and with an average current varying from few tens of nA up to the nominal value of 750 μ A.

In the following Table 1 are summarized the performances.

Table 1: Cyclotron Parameters

Parameter	Value/Description
Cyclotron type	Compact, resistive magnet
Sectors number	4 straight sectors
Accelerated particle	H^+ (protons extracted)
Beam energy range	35÷70 MeV
Beam current range	50 nA÷750 μ A
Magnetic field at centre	1 Tesla
Peak magnetic field	1,6 Tesla
Pole radius	135 cm
Weight	~200 ton
RF system	2 delta-type cavities $\lambda/2$
RF frequency	56 MHz, harmonic=4
Extraction system	Stripping process
Injection system	Axial from external IS
Ion Source (IS)	Volumetric multi-cusp
Nominal intensity IS	6÷10 mA
Voltage IS	40 KV

The vacuum system is equipped with four cryogenic pumps CTI-10 of Brooks Company installed into the two valleys, providing a vacuum level of 3×10^{-6} Pa. A scroll pump allows to get the primary vacuum level of 1.5 Pa. The system is able to achieve high vacuum (5.5×10^{-6} Pa) level, even with only two cryopumps operational, giving very good margins for beam operations.

The RF system consists of 2 delta-type cavities (half-wave) placed in the valleys, providing up to 70 kV of accelerating voltage. The devices operate in 4th harmonic mode at the frequency of 56 MHz. In order to optimize the performance of the whole system, the cavities are fed by two separated amplifiers (dual stage, tetrode based) able to provide up to 55 kW RF power each.

The injection of the beam is axial and a multicusp H^+ ion source (IS) is placed underneath the cyclotron in the pit.

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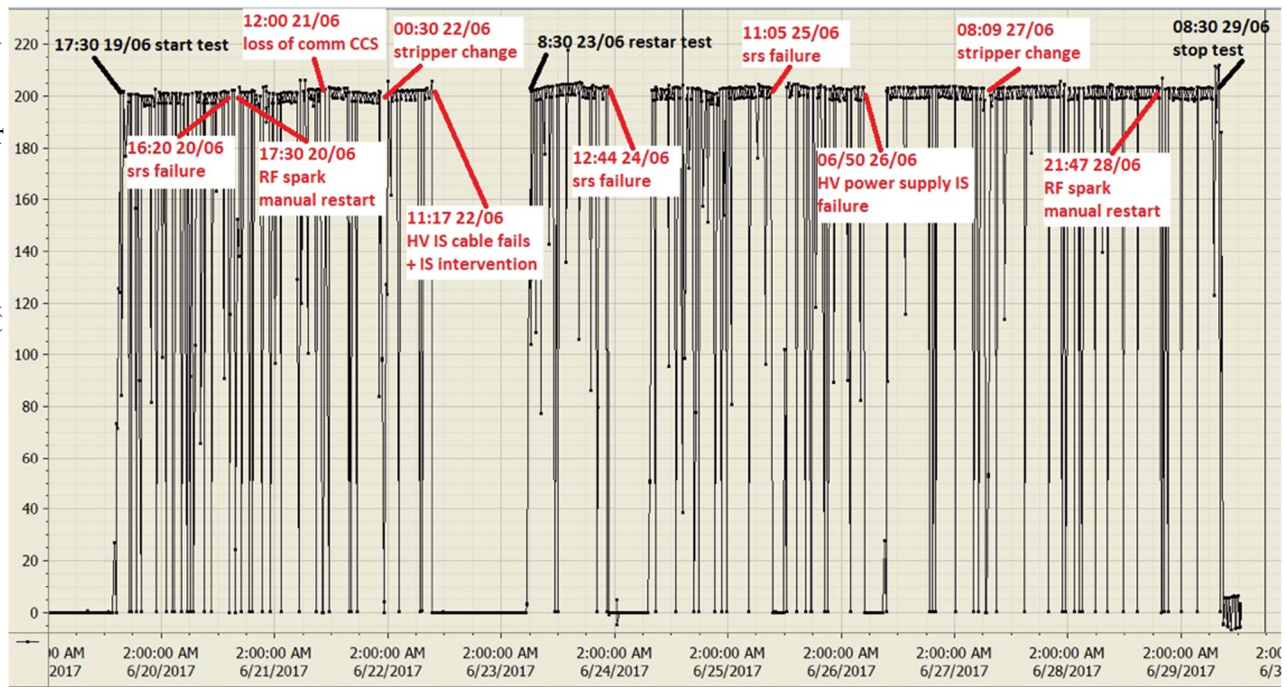


Figure 2: The plot shows the average current trend of beam on target during the endurance test of the cyclotron. In red the most significant events (system failure, stripper changes) were also reported.

A beam stop is placed downstream the IS for current measurement. The injection line is composed by two magnetic solenoids for focusing the beam in series with a couple of quadrupoles needed for beam matching with the inflector entrance. The central region has been designed in order to maximize the phase acceptance up to the value of 50 RF deg. It allows to have margin for optimizing the injected current. A beam stop is placed into the cyclotron intercepting the accelerated particles once they have made few turns (1 MeV energy). It permits to setup the best conditions of the injected beam before the full acceleration and extraction.

The extraction mechanism allows changing the stripper foil without breaking the vacuum in the main chamber. The device has been designed in order to hold up to 20 stripper foils quickly movables and easy to re-charge entirely.

Beamlines and Related Components

Two main extraction lines come from the Cyclotron. Each line ends with a switching magnet (10 tons) bending the beam along three potential lines to be used exclusively.

Each beamline is equipped with a cryogenic pump CTI-8 type and with the necessary beam diagnostics device. A fast gate valve is installed along each beamline line arm, in order to prevent any damage coming from potential vacuum breaks at the target stations.

The four jaw collimators (Aluminium made) placed along the beamlines allows to detect the halo of the beam in order to know the relative alignment. Vertical and horizontal steerers will provide the needed correction to minimize the beam losses. At the end of each beamline, a current monitor (DCCT transformer type) measures the average current of the beam which can be compared to the value

measured with a similar device placed just downstream the cyclotron extraction ports. This comparison is used to calculate the transport efficiency of each beamline.

The commissioning of the cyclotron was carried on along the beamline L1 which connect the accelerator to the ISOL1 bunker. Actually this beamline is the only in operation. Two additional beamlines are currently being installed: the beamline L2 which allows to deliver the beam to ISOL2 bunker and the beamline that connect the cyclotron to the bunker RI3 for LARAMED project. The completion of this work is expected by mid of 2020.

BEAM COMMISSIONING AND OPERATION

BCSI team accomplished out the commissioning of the Cyclotron supply in September 2017. After doing a dedicated training session for LNL operators, the supply was definitively delivered to INFN. The Cyclotron group of LNL has then carried on the beam operation until March 2018, when temporary authorization for beam commissioning expired.

Commissioning Results

The commissioning phases have concerned each system of the accelerator complex installed by BCSI including all the ancillary equipment needed for beam operation.

One of the most important test regarded the long-term run in order to verify the performance in term of beam current stability, reliability and control system efficiency. The test consisted to run the beam on target for 5 days 24 h with a limited number of operator interventions allowed.

The beam specs were chosen to reproduce the operation condition expected for RIBs production: 200 µA of average

current and 40 MeV energy. The beam was then transported along the BL1 and stopped into the beam dump provided by INFN.

The above test has failed two times because of technical failures of the HV insulator transformer providing voltage for ion source platform, whose replacement has required 5 months of machine stop. Once the device was replaced with one more robust than previous, the above test was successfully passed. During the endurance test, a limited number of beam-trips occurred due to the spark of RF system, extraction electrode of ion source and inflector. The frequency of these trips decreases better is the main conditioning of the machine. The plot in Fig. 2 summarize the events which have characterized the above test.

Beam Operations

The beam operations have been carried by out by the personnel of cyclotron team in order to complete the training and to establish the operational limits of the machine as well as its performance in terms of reliability.

Concerning the maximum beam power, the team has achieved the power of 35 kW by delivering 70 MeV protons at 500 μ A. Such a value has been reached different times in several days and kept for tens of minutes without particular problems. Due to a vacuum leakage problem occurred in the Beam Dump device, the endurance test at the nominal maximum power (50 kW) has not been accomplished out. Figure 3 shows the ramp-up current session of the accelerating beam at 70 MeV to get the value of 500 μ A. The procedure takes several tens of minutes in order to stabilize the operation parameters and minimize the beam losses along the transport beamline

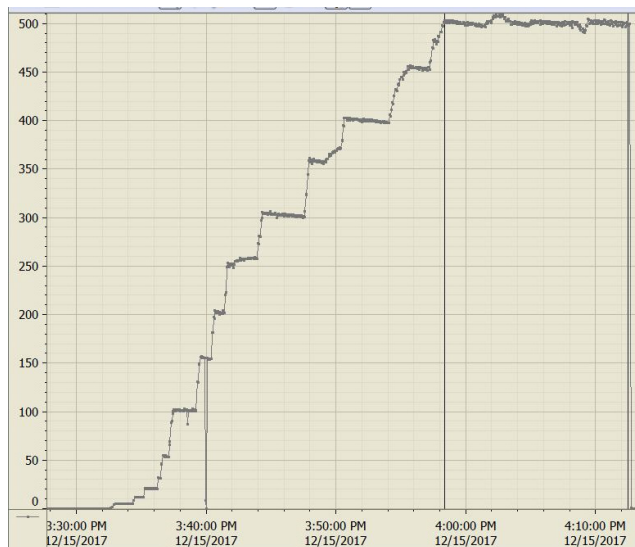


Figure 3: The graph shows the average current (in μ A) of proton beam delivered to the beam dump at 70 MeV versus time.

The optical properties of the beam along the transport line BL1 have been verified and a good matching with the simulations has been observed. The transversal size of the delivered beam was measured in different points along the

beamline by using the three wire scanners (see Fig. 4). It has permitted to check the behavior of beam envelop by modifying the operational parameters of the magnet devices (dipoles and quadrupoles) as well as the extraction conditions from the cyclotron.

The beam operations stopped in March 2018 to allow the preventive maintenance of cyclotron systems and to provide the needed installations expected for SPES project.

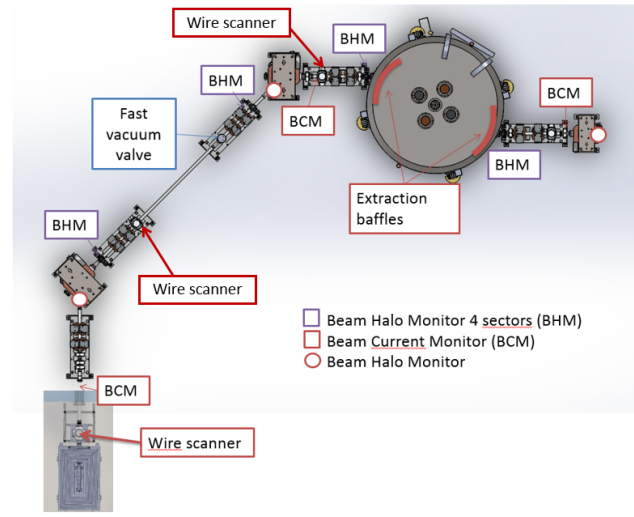


Figure 4: The picture shows the layout of actual installation of the Cyclotron and beamlines in SPES building. The positions of wire scanners used as active beam diagnostic are shown.

Cyclotron Systems Upgrade

As mentioned above, the Cyclotron facility is being expanded with the installation of 3 beamlines by the 2020: two lines will be dedicated to radioisotopes research within the LARAMED project environment. A third beamline is foreseen as complementary ISOL target in the bunker ISOL2.

Actually the cyclotron systems are under preventive maintenance: the hydraulic system was purged and the oil re-filled, the vacuum system and cryogenics equipment were refurbished and the RF power amplifiers were returned.

As future upgrades expected to improve the cyclotron performance, two main devices are under study and design: a collimator system to be installed along the injection line in order to varying the average current of extracted beams avoiding to do it by modifying the voltage of the RF cavities; an axial buncher allowing to optimize the ion source performance and the related injected current to improve the reliability and to get more flexibility [5].

As suitable upgrade of the Cyclotron facility, a new beam dump dedicated for high power beam test has been proposed. The main purpose is to realize a dedicated beam-line for Cyclotron testing which is equipped with a beam dump able to sustain 50 kW beam power.

The high power test beamline will be derived from the second switching magnet placed along the ISOL1 beamline. The high power beam dump will be placed into the wall separating the A1 and A8 room (see Fig. 1). It will allow to have the concrete shield for neutron and gamma radiations generated during the irradiation.

A preliminary study of the new beam dump was accomplished out from the Cyclotron team in order to set the technical parameters of the device: a graphite made structure embedded in an aluminium holder has been studied and the related cooling water circuit has been preliminarily dimensioned (see Fig. 5).

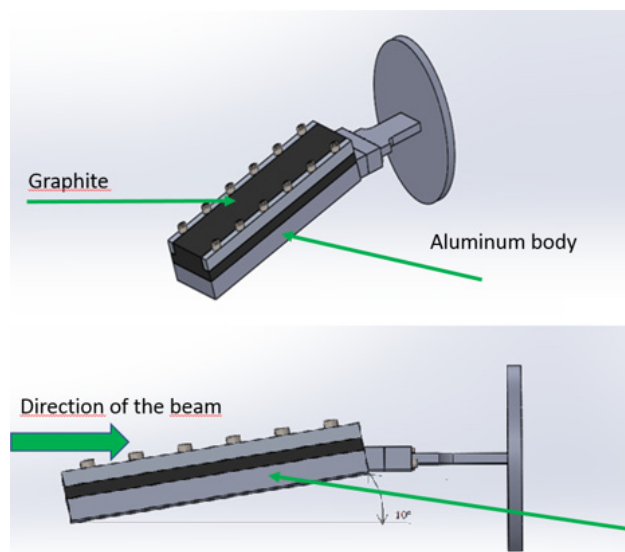


Figure 5: The plots show the preliminary model of the beam dump graphite made to be placed at the end of beamline foreseen for high power beam test.

CONCLUSION

The high power Cyclotron has been delivered at LNL and first beam operations were carried on in 2018. The accelerator has achieved the requested performance and it has demonstrated a satisfactory reliability (even if additional tests will be necessary) and, generally, a very good manufacturing. The LNL cyclotron group is involved in the operation and an intensive program of upgrades is being carried on. In parallel, the high intensity facility is expanding in order to make operational the beamlines and make available the first beams for nuclear research and medical applications. In fact, at LNL the SPES project is entered in the installation phase and most of main components (ISOL targets, low energy beamlines) will be available to work in the next three years.

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