CHAPTER IV

The SPES Proton Driver

Introduction

The production of neutron rich exotic beams at the SPES project is based on the direct reaction of a proton beam on an UCx target. The exotic species, produced by Uranium fission, will be extracted from inside the target using the ISOL technique.

To be competitive in the international scenario of the research with exotic beams, a fission rate of 10^{13} number of fission/s is recommended.

In order to fulfil the summarized SPES mission it is required a primary accelerator system (from now on defined as Driver) in order to have an accelerated proton beam with adequate energy, intensity, reliability and availability.

The Driver needed for the SPES complex consists in:

- The source
- The accelerator
- The transfer line
- The field level control system (operation, status, safety, security, logging)

The ancillaries (cooling system, electrical power distribution, dry nitrogen distribution system, high pressure air distribution system) are not, strictly speaking, included in the Driver but at we will define some guidelines to be passed to the building and the services designers.

The cyclotron technology is mature and the market has already “off the shelf” integrated solution for the medical isotope production with the beam energy and beam intensity figure very close to the SPES requirements (e.g. ≈ 1 mA, ≈ 30 MeV protons). Consequently, also to minimize the human resources to be dedicated to this part of the whole project, it has been decided to acquire a “Commercial Cyclotron” with technical characteristics a little bit above the “off the shelf” products specifications but that have been already demonstrated to be feasible and prototyped by commercial companies and installed in other Laboratories.

After an international competition and bid we ordered a cyclotron at the Best Cyclotron System Inc that, associated with the Best Theratronics presented the most convenient technical economical offer for a “turn key” system.

The proton beam necessary to reach this fission rate using the direct target technique, described in this chapter, has to have the following characteristics:

• Energy of the order of	40-50 MeV
• Minimum current	200 μA (~ $3.3*10^{14}$ p/s)
• Beam spot size on the target	Φ 40 mm (circle area 1260 mm^2)
• Primary proton flux	~ $2.6*10^{11}$ p/(mm^2*s)
• Beam uniformity on the target	± 1%
• Beam time structure	CW

- Beam intensity stability on target
    - Fast (time scale μs) ± 10%
    - Medium (time scale s) ± 1%
    - Slow (time scale min) ± 1%
- Machine reliability 90% of the scheduled working time
- Machine availability ≥ 5000 h/Y

Using these specs as guideline has been request proposals with the following technical characteristics:

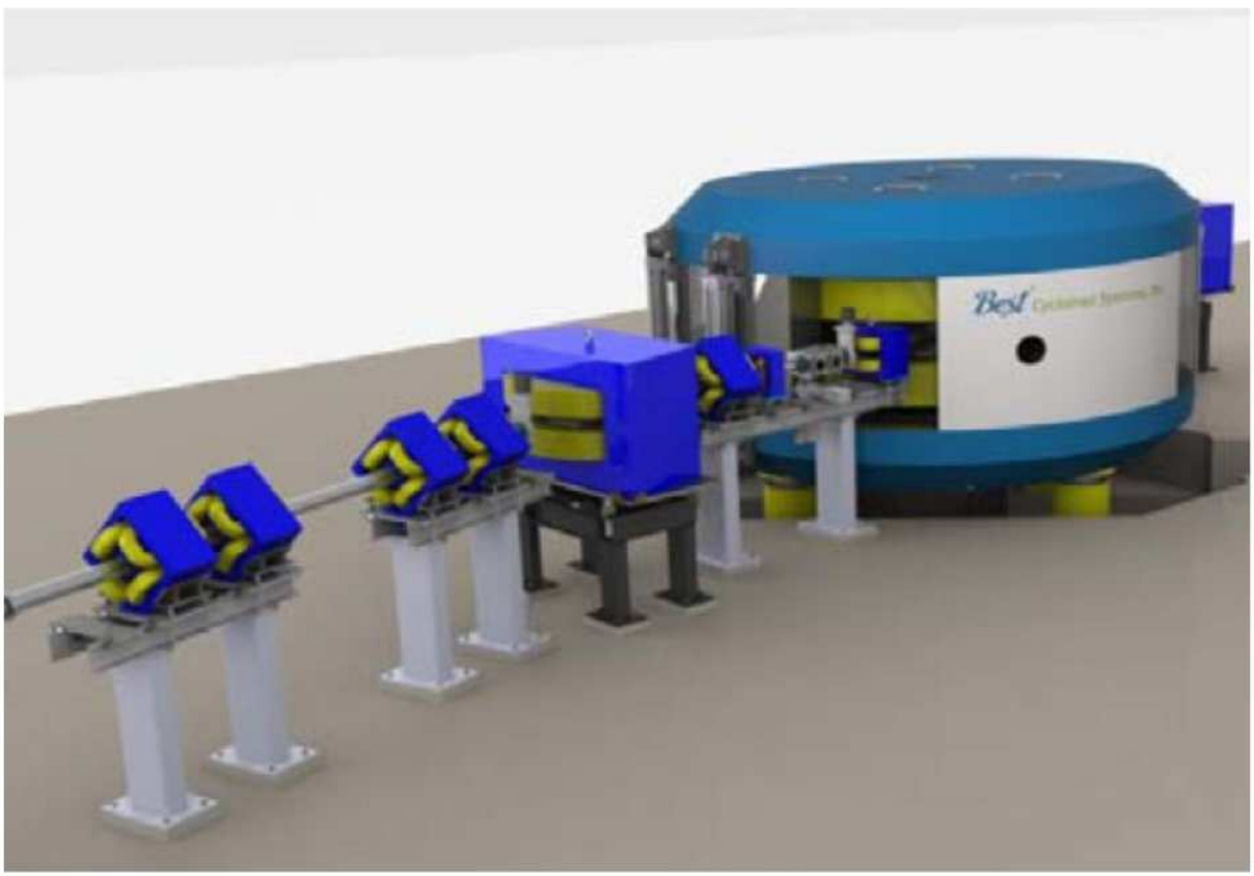
- Proton energy variable in the range 35-70 MeV
- Total current outside the cyclotron two extraction lines ≥700 μA (~ 4.2*1015 p/s)
- Operation vacuum (beam on) ≤ 2·10-5 Pa
- Momentum spread Δp/p of the extracted beam < ± 0.2%
- Beam spot size on the target Φ=40 mm (area 1260 mm2)
- Beam spot size on the target variation along beam
- direction at 300 μA of current at different energies ±1% in spot size over L=180 mm
    - Beam current density uniformity for proton better than 5%
    - Beam time structure CW
- Beam intensity stability on target for proton beam
    - Fast (time scale μs) ± 10%
    - Medium (time scale s) ± 1%
    - Slow (time scale hour) ± 1%
- Emergency switch-off time < 50 μsec
- Machine reliability >95% of planned operation time
    - Planned operation time (sum of all the users) ≥ 7500 h/Year
- Beam current losses:
    - Injection line ≤ 1%
    - Central Region ≤ 90 %
    - Acceleration ≤ 5%
    - Extraction ≤ 1%
    - Transport line ≤1%

On top of the previous specification the cyclotron must be able to serve contemporary users (two or more).

In the present chapter are described the major technical specifications of the Best Cyclotron offer.

The Cyclotron Technical Specifications

The BEST cyclotron is a compact four straight sector machine, energized by a pair of room temperature conducting coils. The cyclotron is able to accelerate H^- beam, provided by an external multi-cusp ion source, up to the energy of 70 MeV. Since the proton extraction is done by the stripping process, the final energy varies within 35-70 MeV. Two independent extraction channels placed at 180° one respect to the other, provide the simultaneous extraction of two beams. The maximum beam current deliverable is estimated to be 800 µA. The table # shows the main parameters of the machine.



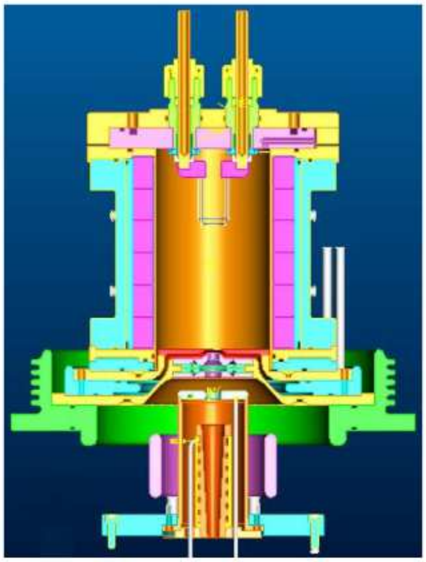
layout of the cyclotron with the extraction beam line.

Main technical characteristics of the Best Cyclotron

Main magnet	B_{max} field: 1.6T coil current: ≈ 127kAT 4 sectors, deep valley hill sector angle: 50° varying hill gap: 6 – 4.69 cm
RF resonators (two resonators connected)	frequency: 58MHz, harmonic: 4th dissipated power: 28kW dee voltage: 60 - 81kV dee angle 36°
External ion source and injection line	multi-cusp H^-, 15-20mA DC beam current: 800µA axial injection, 40kV spiral inflector
Vacuum	ion source: < 1 x 10^{-5} Torr main tank: < 1.5 x 10^{-7} Torr
Extraction	simultaneous dual beam 2 stripping multi-foil carousels variable energy 35-70MeV
Beam lines	2 way switching magnet Up to 4 beam lines

4.2.1 The source

The BEST Cyclotron adopts an ion source with a multi-cusp configuration to provide the H-beam with a current of about 15-20 mA in order to deliver at the exit of the cyclotron a final current of 750 µA or more.



The Layout of the multi-cusp ion source

The source assembly consists of a tabular plasma chamber with ten columns of permanent magnets to provide a stronger multi-cusp effect field and serves as a virtual filter, a three electrode extraction system, a top cover with a confinement magnet inside. In the extraction system, there two pairs of small permanent magnet embedded in the extractor for electron filtration and a compact electric magnet ring enclosed on the ground electrode for the axial steering of the beam. The ion source adopts double filament, which proves to better than single filament through the experiment.

Based on the requirement for the system which is 40keV for injection line of the cyclotron, the ion source extraction configuration has been designed in order to provide a H- beam with 0.605 pi mm-mrad of normalized emittance.

4.2.2 The accelerator

Injection

The BEST proposes the injection of the beam into the cyclotron by mean of a axial transport line upwards to the spiral inflector which bends beam 90° into the central region at the median plane. The DC beam with energy of 40 keV is injected from the ion source located at the bottom of the magnet to the cyclotron. The injection line utilizes two solenoids and three quadrupole magnet for transverse focusing and a buncher for longitudinal bunching. For the H- beam, the space charge effects is taken into account and 95% neutralization is used which can be achieved with a vacuum of more than 10-4 Pa.

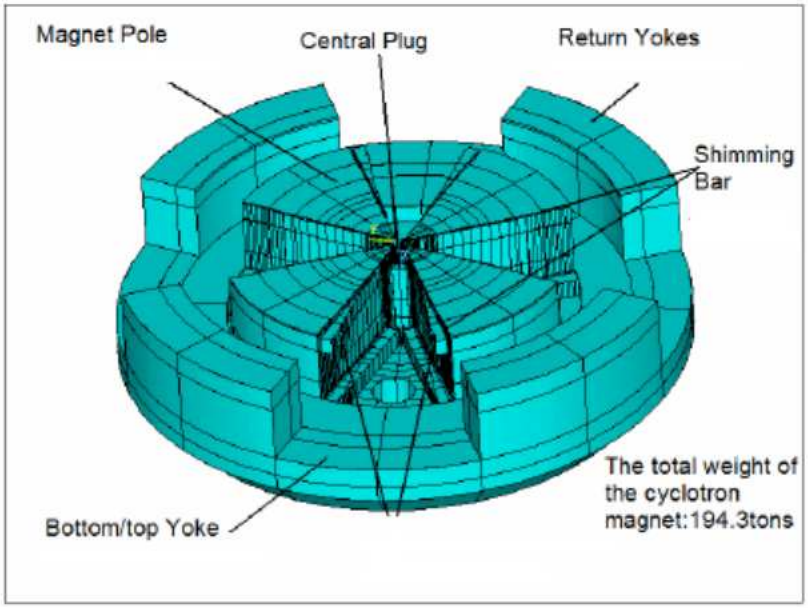
The central region design provides the matching point closely to the exit of the spiral inflector and the reference parameter at the inlet of the central region, which should be used as the confinement conditions for the inflector. The principle of the design is that the spiral inflector should be capable of bending the H- beam onto the median plane with the transmission efficiency higher than 80%. The preliminary design of the spiral inflector sets the voltage at 13.8 kV (±6.9 KV) and the gap of 8 mm.

The Magnet structure and power supply

The 70 MeV cyclotron consists of 2 top/bottom yoke, 4 return yoke, 8 magnet poles, 16 shimming bars and two central plugs. The top/bottom and the return yokes are cast and other parts will be forged. The eight of the magnet is 2.46 m and the diameter of the top/bottom yoke is 4.54 m. The radius of the magnet pole is 1.4 m. The hill gap is variable: it is 6.03 cm in the central region and gradually reduced to 4.69 cm at the outer radius. The total weight of the iron is 195 ton.

Iterative mapping and shimming procedure will proceed to obtain isochronous field. To provide large flutter which consequently yields strong vertical focusing, a deep valley structure has been used.

The mapping system consists of measurement arm, supporting ring, and the driving mechanism. Such mapping system is fully automatic. The accuracy of radial position within 0.1 mm, and the accuracy of azimuthal position is within 10''. The relative error of measured magnetic field is less than 0.15 ‰.



Layout of the lower part of the magnet

In order to get the proper magnetic field, the main coil system consists of a pair of normal conducting coils water cooled. Since to energize the magnet needs 126'855amp turns (total current), each coil contains 546 turns, being the nominal current 116.43 A. The size of the conductor is chosen to keep the current density to 1.085 A/mm^2. Based on the magnetic system, the basic requirements of DC power supply for main coil are:

Power: 30 kW (120A/250V)

Stability: $\pm 10^{-5}$

RF System

The 70 MeV radiofrequency system consists of two independent cavities separated and shielded at the center design providing a symmetrical Dee voltage distribution for optimum beam centering.

The two separate resonators will be driven by individual amplifiers and low level radiofrequency control (LLRF). The advantages of this design are:

- Symmetrical Dee voltage distribution thus eliminating beam centering problems due to RF
- Reduced coupling power per cavity, coupler design less critic
- Minimizes cavity mismatch with beam loading, lower VSWR
- Allows fast beam modulation through phase modulation in the LLRF control

The cavity design adopts the "triangular" stem structure for increased Dee voltage distribution toward the outer radii (reduce Lorentz stripping).

Each cavity design is half wavelength of the fourth harmonic of the fundamental frequency and present the following design parameters:

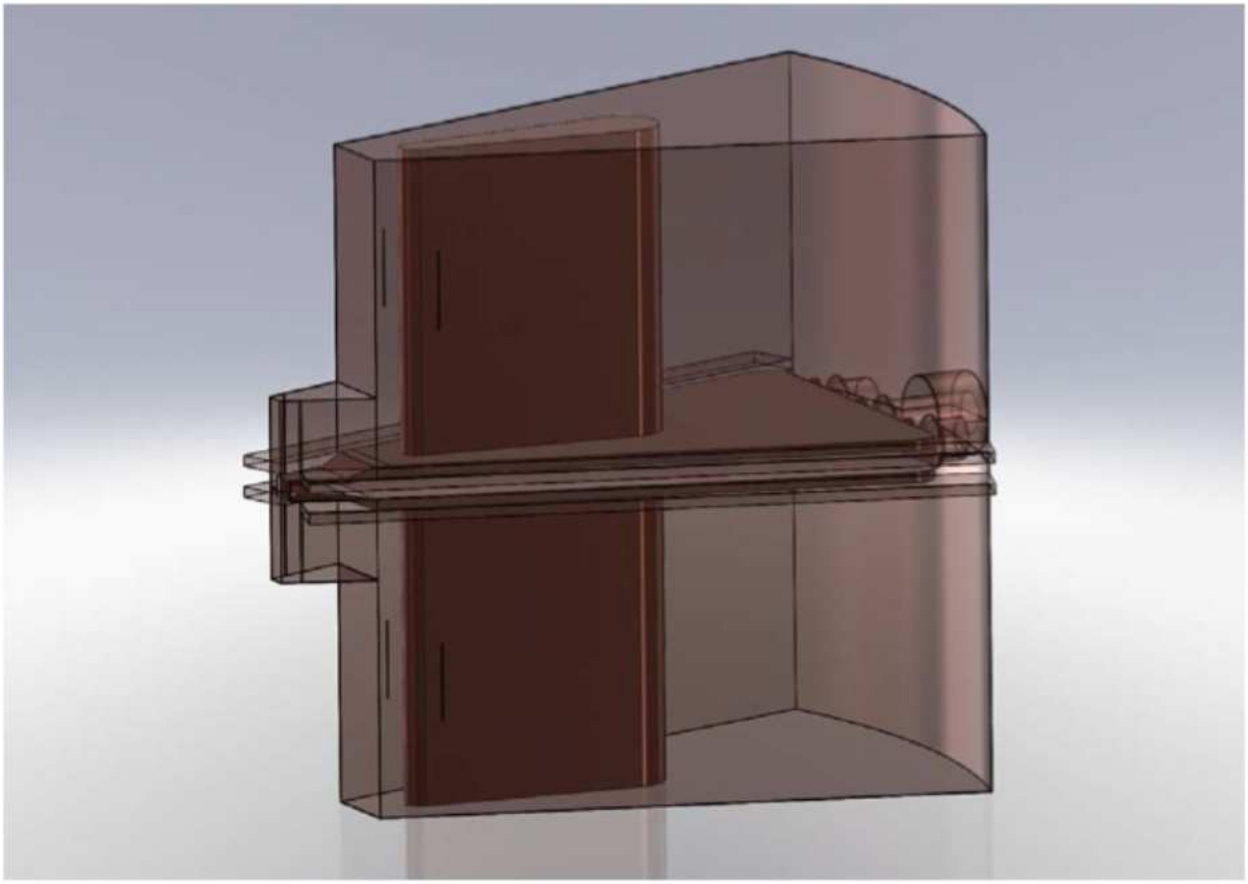
- Single stem of triangular structure and double acceleration gap
- Capacitive coupling and tuning.
- Angle between gaps: 33°
- Cavity height 1262mm.
- Resonant frequency: 56- 58MHz (fixed after mapping)
- Quality factor: 11467
- Voltage distribution: 60-80 kV
- Average shunt impedance along the acceleration gap: 167 kOhm.
- Estimated power dissipation: 13.6kW

The coupling of the cavity adopts a fix capacitive method, which allows the simplicity and economy. Cylinder type ceramic is selected as insulator to separate the vacuum and air. The shape of the inner/outer conductor of the coupling window is designed in a way to have good VSWR and also to prevent excessive multipacting at certain power level. Air and possible water cooling is considered in the detail design.

BCSI has the experience of designing air and water cooled coupling mechanisms up to 100kW single coupler design. Such a design has been installed in commercial 30MeV cyclotrons and it has been successfully tested in operation at power levels of 66kW (continuous operation for radioisotopes production). It is estimated at this time that the coupler will be movable for optimum beam matching with beam load.

The RF system will be equipped with two 50kW independent amplifiers each driving a cavity. Each amplifier will be fully contained in three cabinets that will be attached in the present design. There is also the option of separate positioning the main high voltage supply for the amplifier tube. The amplifier layout configuration is shown in Figure 2.

The capacitive coupling mode for the resonant cavity and two independent high power amplifiers for driving two resonant cavities respectively are preliminarily determined. A single "triangular" stem, double acceleration gap, room temperature structure will be used in the Dee resonant cavity design to meet the requirements. Though "triangular" stem is more difficult to fabricate, in return, it can provide better mechanical support for the Dee plate. The cavity layout drawing is presented in Figure 4.4.

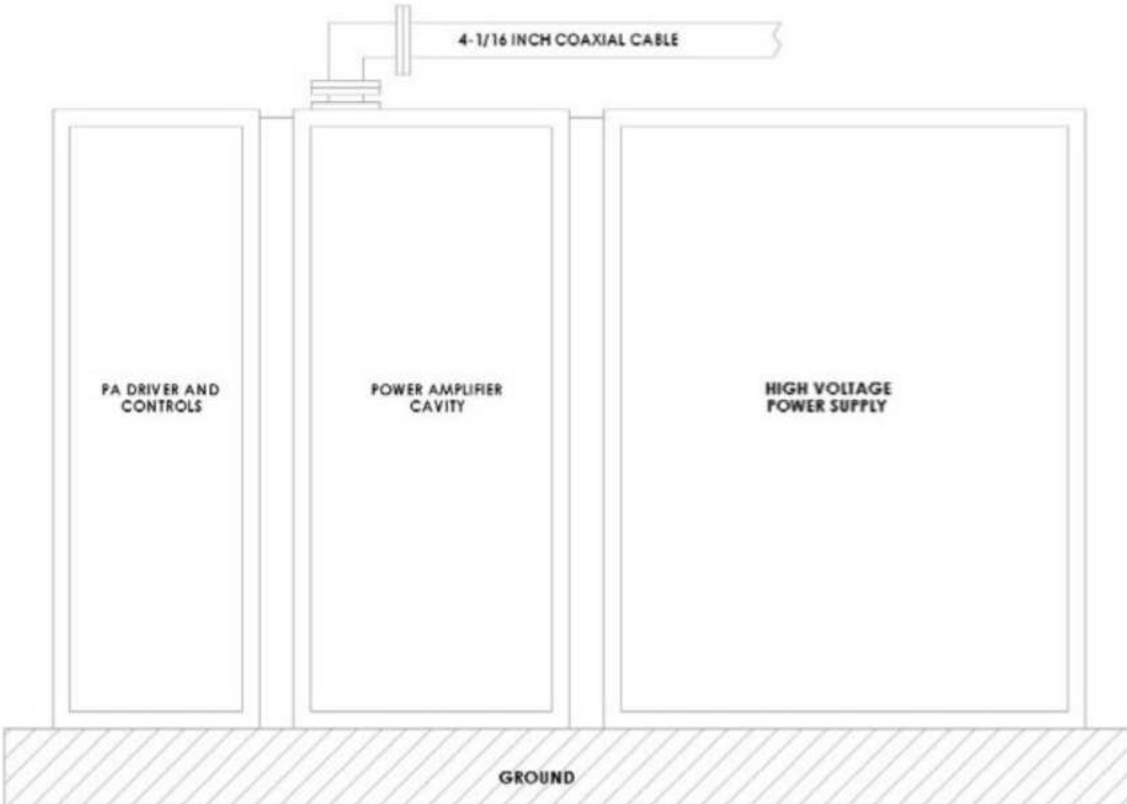


□□□□□□□□: *RF Cavity Model*

The resonant cavity comprises of the following components: dee assembly including dee plates and stem, ground return electrode further referred as liner, coupler, coarse trimmer (fixed with the frequency), fine trimmer (motor driven) for dynamic frequency adjustment and pick-up probes.

RF Amplifier layout

The RF system will be equipped with two 50kW independent amplifiers each driving a cavity. Each amplifier will be fully contained in three cabinets that will be attached in the present design. There is also the option of separate positioning the main high voltage supply for the amplifier tube. In this way power supplies can be located in an adjacent electrical room.



RF Amplifier Configuration

The directional coupler near coupling window provides the monitoring signals of forward power and reverse power supervision. In the mean time, it also can be used for the low level RF control circuit. The directional coupler near amplifier provides VSWR measurement and necessary protection for the final stage. The high power phase shifter (trombone) is necessary to move the side resonance away from the cavity resonance frequency.

The power budget for the RF amplifier is:

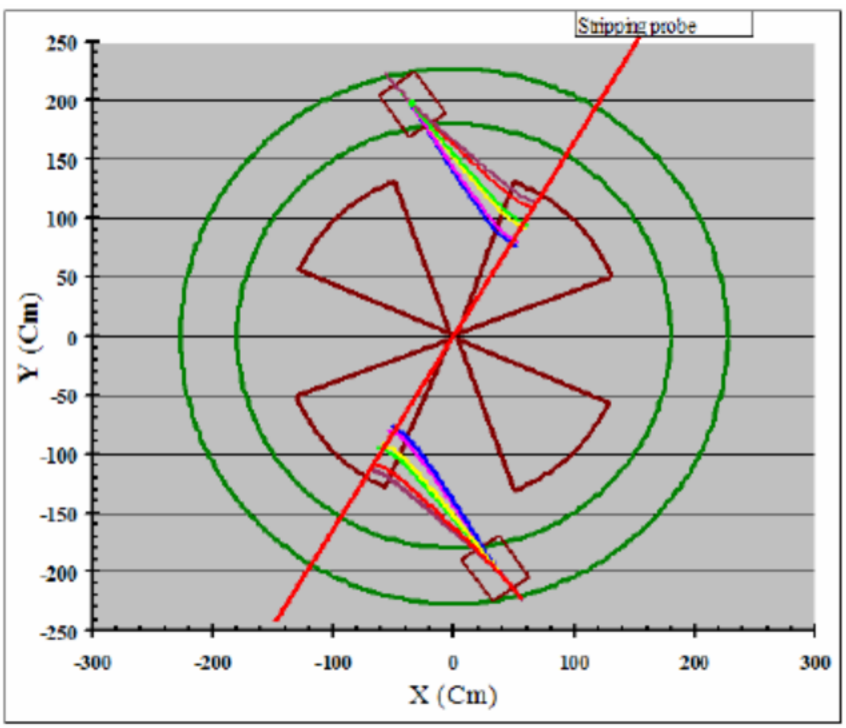
Extraction Energy	70	MeV
Bean Intensity	700	μA
Beam Power	49	kW
Cavities dissipation (Ideal Condition)× 2	27.2	kW
Cavity dissipation(RF Engineering) × 2	38	kW
Low level control power reservation × 2	10	kW
Total Power for two Amplifier	97	kW

Extraction

The 70 MeV high intensity cyclotron is designed to deliver proton with energy in the range 35-70 MeV. The cyclotron will be equipped with two extraction combination magnets, placed at 180° one respect to the other. Any proton beam extracted by the H- stripping process in the energy range 35-70 MeV, will be transported at a crossover point inside one of the extraction magnets. The crossover point is the starting point of the extraction line.

The total beam current measured outside the two extraction combination magnets should be not lower of the 99% of the full beam current at the extraction radius.

The positions of the stripping points and the combination magnets are fixed by calculating the extraction trajectories of extracted proton beams after stripping foil for different energy. In order to reduce the envelope of extracted beam, the combination magnet is fixed at the adjacent yokes of main magnet in the direction of valley region. The stripping probe is inserted in the radial direction from the main magnet pole and proton beam will be extracted from the direction of the valley. The stripping probe is inserted in the radial direction from the main magnet pole to the cyclotron center along the line of 60° (see fig. 2). The minimal inserted position of the stripping probes to extract proton beam at lower energy (35 MeV) is 92 cm. In order to extract different energy beams, the stripping probe can be moved along the radial direction and rotated along the angle.



Extraction scheme for proton at different energies

For the stripping extraction system, the carbon foil will be used. For the extracted energy of 70 MeV, the stripping efficiency is about 99.96%, when the carbon foil thickness is 120μg/cm2. In order to reduce the time of changing foils, the stripping foil changing devices are put in the independent vacuum chamber.

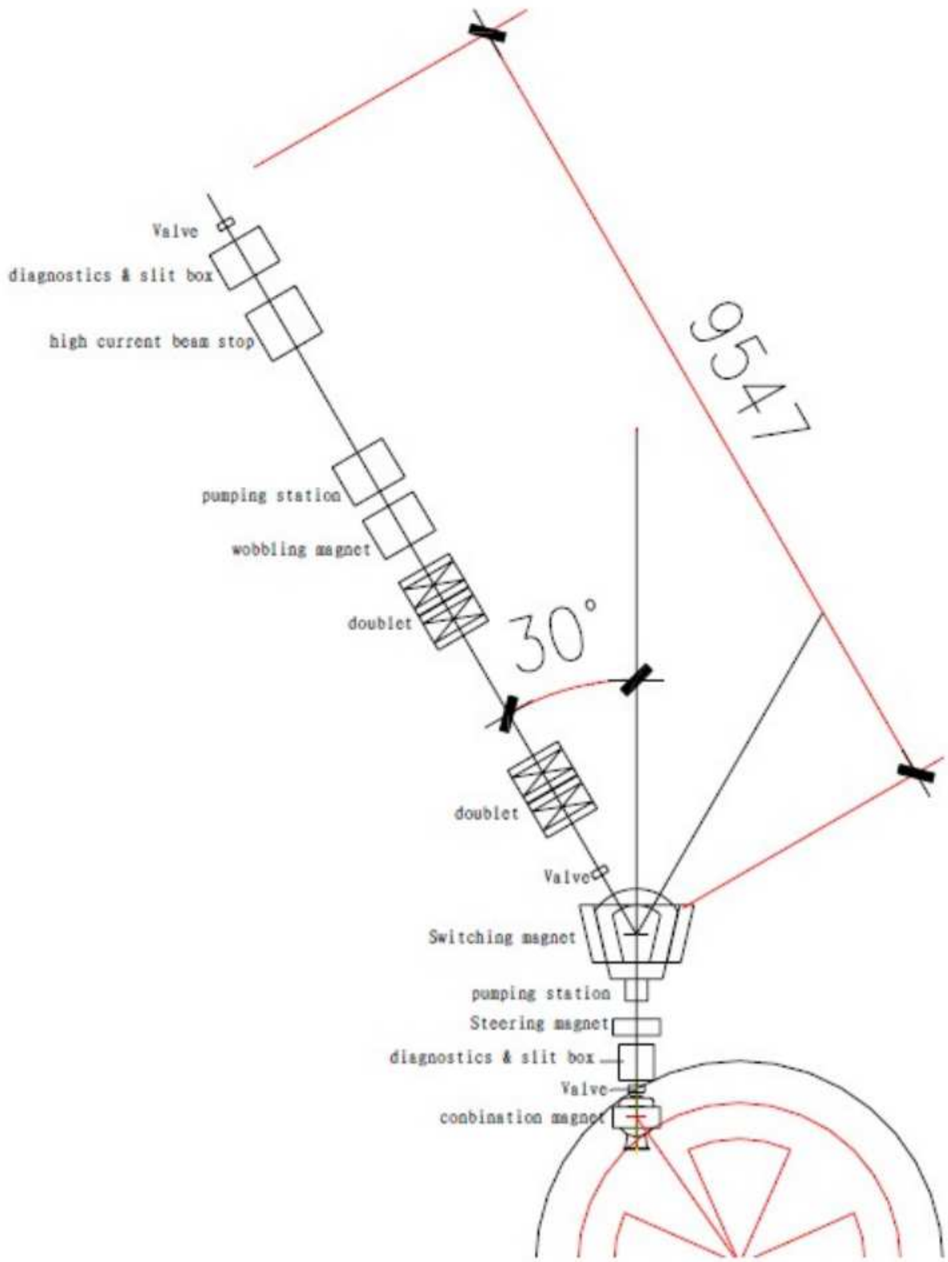
4.2.3 The transfer beam line

The Cyclotron has to be equipped with two transfer beam line in order to deliver the protons to the experimental halls, including the area for the RIB production. Such transfer line has to be supplied by the BEST firm.

The beam transfer line has been designed in order to deliver the proton beams extracted from the cyclotron at different energies varying within 35-70 MeV end at the maximum current of 700 μA. High extraction efficiency and low beam loss are designed for the beam line. Optics matching of the beam lines with the matrix of the fringe field and the dispersion effects are taken into account during the extraction.

A combination magnet is placed in the cyclotron yoke to bend the extracted beams with different energies into one common line. A gate valve following the combination magnet is used for the high vacuum. After the gate valve is a diagnostics and slit box, which is not only used to measure the beam current (faraday cup) and the beam profile (scan wires), but also used to cut the beam halo. On this common line, there is also a steering magnet to adjust the beam position in vertical direction (the horizontal direction can be adjusted by using the switching magnet. Then is a ±30° switching magnet to allot beam to different targets, a pumping station box connects to the vacuum chamber of the switching magnet to obtain the high vacuum (1×10-5 Pa).

After the switching magnet, a gate valve is used for the vacuum, then located two doublets to focus the beam (see fig.3). A wobbling magnet is selected to let beam scan on the target to get the beam current density uniformity better than 5%. Then is the pumping station for the high vacuum and the diagnostic box with the faraday cut and beam scanner, there is also a collimator before the target to get Φ=40 mm spot on the target.



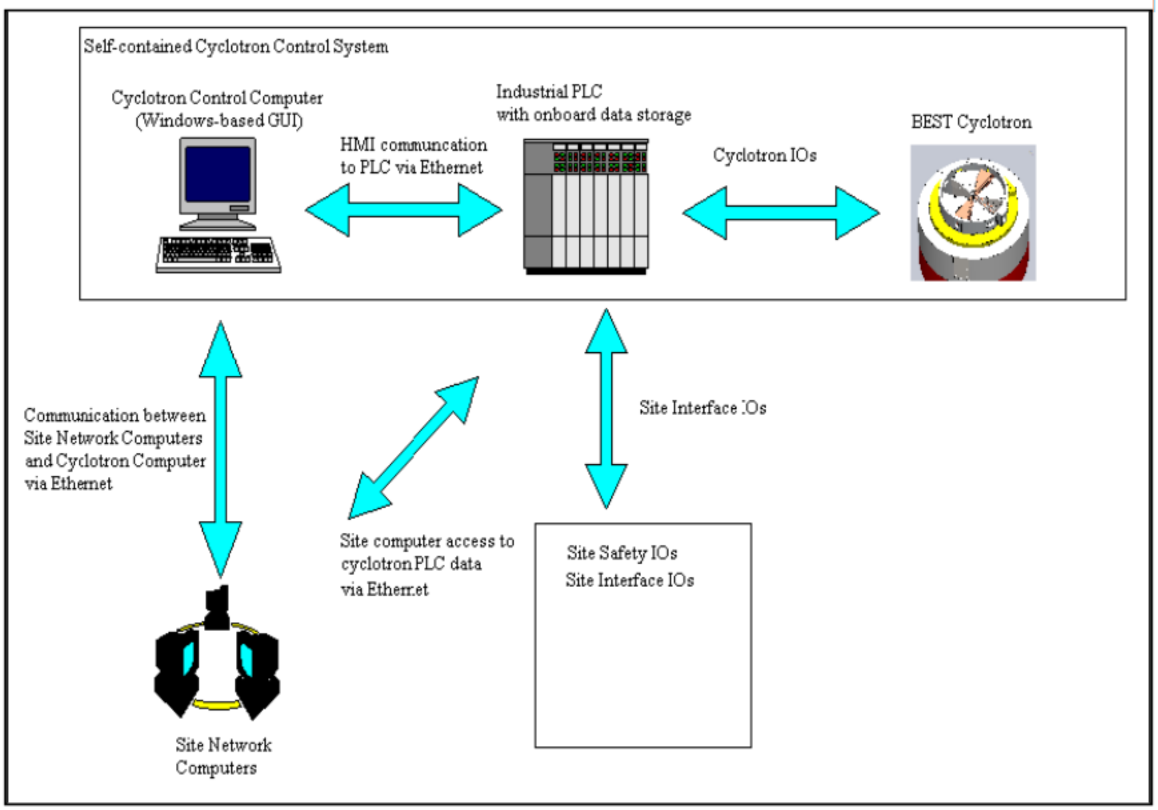
□□□□□□□□□□*Layout of the beam transfer line*

4.2.4 The control system

Cyclotron Control System, General Aspects

The control system for the Best Cyclotron is a self-contained operation control system designed around OMRON PLCs in conjunction with software from OMRON. It includes a graphical user interface written in CX-Supervisor which is operated from a standard PC. The source code is written in Ladder Logics using CX-Programmer software from OMRON.

The general operation of the Best cyclotron will be controlled by OMRON CJ2 series PLC. The PLC acts as the CPU of the cyclotron. The PLC allows for rapid monitoring of the cyclotron as well as general controls of the different subsystems. It handles all safeties and the interlocking of all the cyclotron components. The other hardware of the control system consists of the digital and analogue inputs and outputs of the CJ2 PLC system as well as data storage and processing unit SPU. The SPU hardware is used for consistent data collection of the cyclotron subsystems. There will be communication between the existing LNL accelerator complex control system via Ethernet or hardwired I/Os to the PLC. This allows for the exchange of data with the existing control system and the control system of the Best cyclotron and the safeties of the facilities.



Schematic of the Cyclotron Control System

Best Cyclotron Systems will provide the source code for both the PLC and HMI interface. The source code and HMI interface remain the property of Best Cyclotron Systems and are to be solely used for the operation and servicing of the BEST cyclotron they are purchased with. The CX-Programmer and CX-Supervisor developer license will be provided with the control computer.

The Best Cyclotron Systems' ladder logics program for the operation of the cyclotron is written in OMRON's CX-Programmer. The source code for the PLC will be provided with the license for CX-Programmer. User manuals for CX-Programmer will be provided. Any changes to the PLC source code can only be made with the written consent of Best Cyclotron Systems. The Best Cyclotron System HMI interface is written in CX-Supervisor. A runtime license of the CX-Supervisor is provided with the source code. A development version of the CX-Supervisor can be provided to the customer upon request. CX-Supervisor is a Windows-based program with the entire graphical user interface designed and written by Best Cyclotron engineers. Best

Cyclotron control engineer will work to interface all the necessary graphical controls screens with the LNL personnel.

LNL personnel will receive extensive hands-on on-site training of the maintenance and use of the cyclotron and control system with Best cyclotron operators and BEST Cyclotron control engineer. LNL personnel also have the option of having training classes with Best cyclotron instructors on cyclotron simulators at Best facilities.

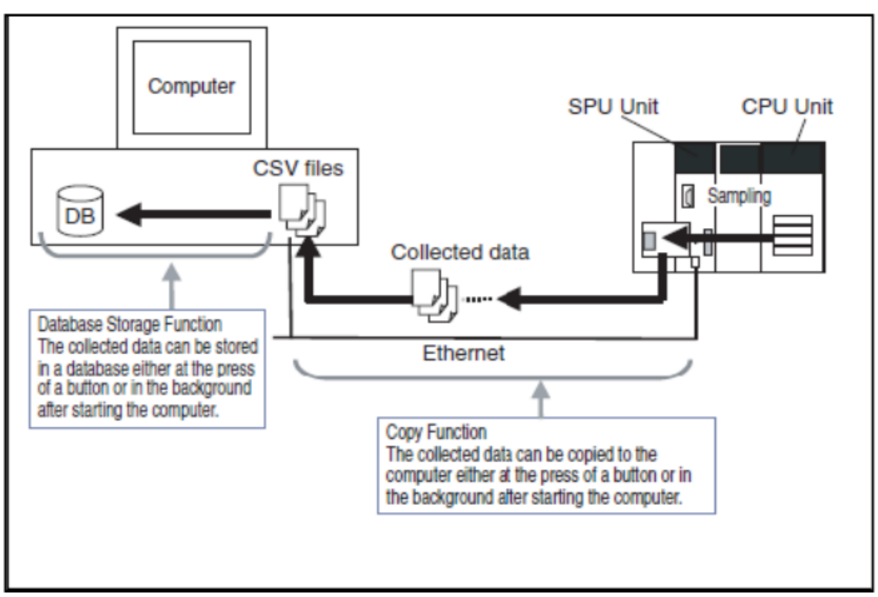
Logging and recording of the status and historical

The logging and recording of the data necessary for restoring the cyclotron after an emergency or accidental stop is done by an on-board high-speed data storage and processing unit (SPU). This unit is part of the PLC and is independent on the HMI computer. This allows for high speed data collection and ensures that no data is loss in the communication process. This data can be stored every second in a CSV (Comma Separated Value) format and can be periodically transferred onto the control computer via the Ethernet.

This data collection is independent of the control computer HMI so data is collected even when the communication between the HMI computer and the PLC has been lost. The data can be periodically downloaded to the computer for data analysis outside of the control system.

In conjunction with the SPU, the HMI software package CX-Supervisor is also taking data from the PLC and making its own database. This allows for long period logging and recording for the status and all the machine parameters every hour. This storage database can be stored in a CSV format or any other database format for archiving. The CXSupervisor software allows for data to be logged directly to an existing database. This provides direct storage of data in third party format, allowing for easy analysis using familiar tools. If the operators desire, the CX-Supervisor database allows for the data to be stored in a database that can be assessable via an existing EPICS system.

The proposed data handling and recording is done by a SYSMAC SPU from OMRON. This unit reads the PLC I/O memory directly according to the collection methods and stores the data in CSV files. It can record all the data from the equipment controlled by the PLC. The SPU data files can be transferred to a computer via the Ethernet and exported to Excel.



Schematic of the Logging system

4.2.5 Ancillaries

Technical requirements

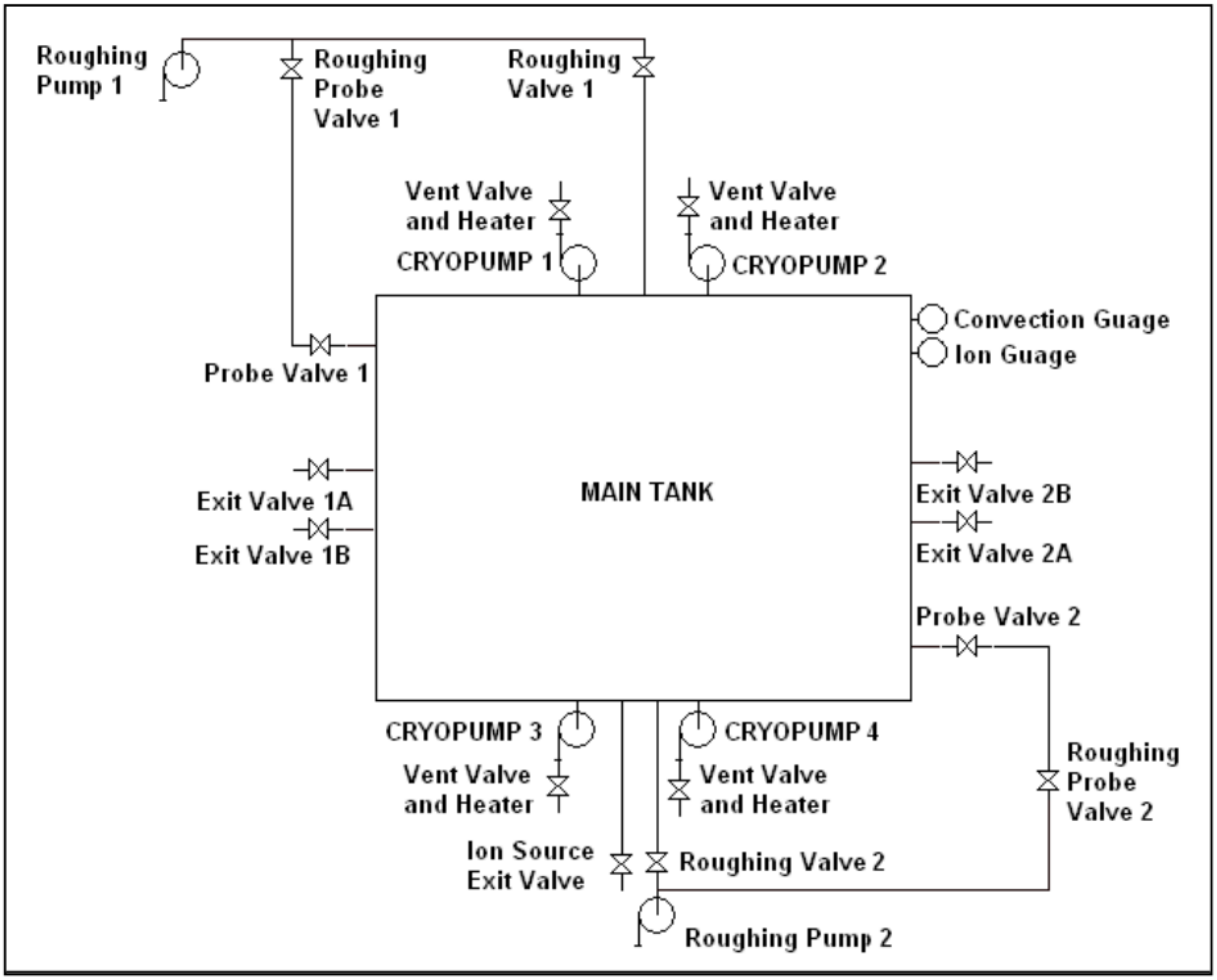
BCSI has specified the technical requirements to drive correctly the cyclotron equipments, as follows:

- Temperature and Humidity Specification (Temperature must be maintained around 20° and Relative Humidity around 45-75% in the main rooms)
- Air Cooling system (28.6 kW to be removed from the main rooms)
- Air change or Ventilation requirements
- Water cooling requirements (Chiller with 250kW cooling capacity)
- Compressed air system
- Industrial gas plant (High purity hydrogen and Dry Nitrogen bottles are required)
- Electrical specifications (Power required 325kVA)

Vacuum system

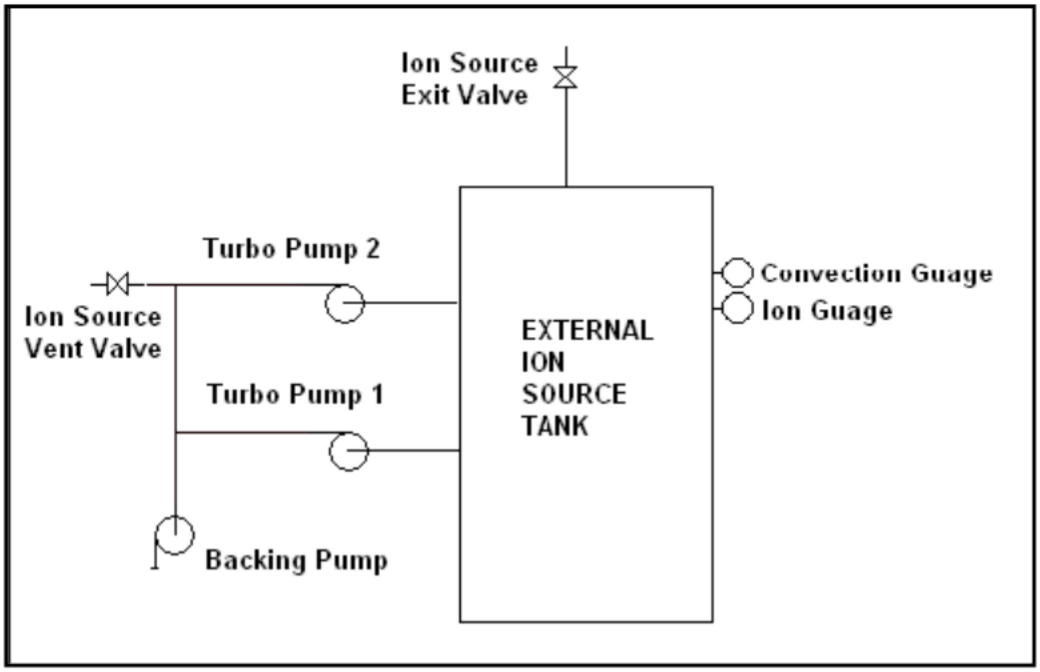
Vacuum system description

The cyclotron (CYC) vacuum system is shown in the block diagram of Figure 1. The operational vacuum is supplied by 4 cryopumps. The roughing vacuum is supplied by two mechanical pumps. The valves and vacuum monitoring points are indicated in the Figure 4.10.



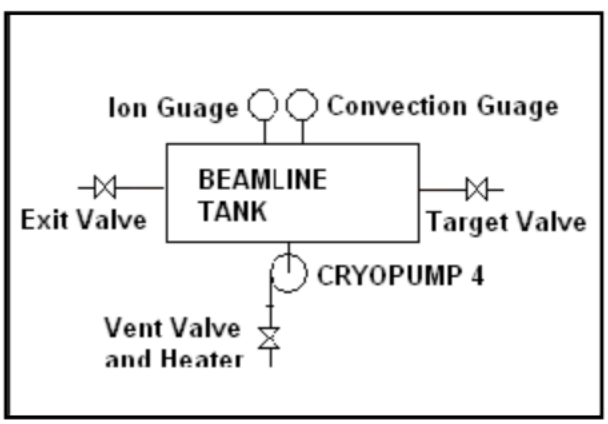
Vacuum system block diagram

The ion source and injection line (ISIS) vacuum system requires a very high hydrogen pumping speed. Consequently two turbomolecular pumps deliver the vacuum required for ISIS. The mechanical pumps mentioned earlier provide the roughing vacuum, while a dedicated mechanical pump backs the turbos. The ISIS vacuum system including the pumps, valves and monitoring points is presented in Figure 4.11.



Ion source and injection line (ISIS) vacuum system diagram.

The beam line (BL1) likewise possesses its own vacuum system comprised of two cryo pumping station located one in each beam line section. A typical section is shown in Figure 3. The operating vacuum is delivered by a cryopump. The mechanical pumps mentioned earlier provide the roughing vacuum. The BL1 vacuum system one section including the pumps, valves and monitoring points is shown in Figure 4.12. The system is adequate for BL1 equipment. It is recommended that LNL targetry have its own vacuum pumping system. A similar vacuum system is equipping the (BL2) beam line section up to and including the switching magnet (one pump station only).

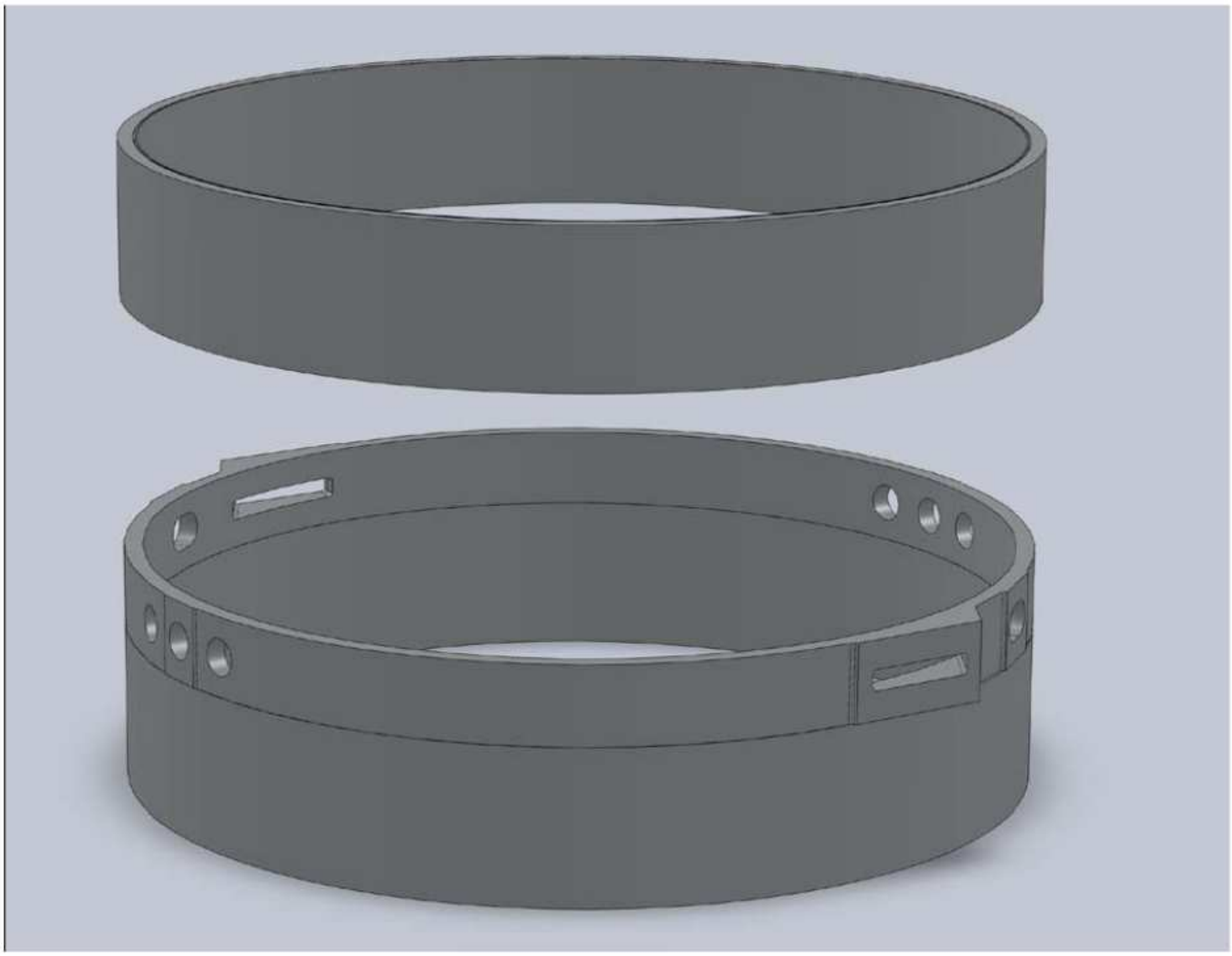


Typical vacuum system block diagram for one beam line section

Vacuum chamber layout

The vacuum chamber is designed with three separate rings which is a very common principle design used in many commercial and research cyclotrons (Figure 1). This design allows for easy access inside the vacuum chamber when the cyclotron is opened for maintenance or servicing including resonators removal if necessary. The material used for all three sections is Aluminium for low radiation activation.

At opening, both lower and middle vacuum rings are fixed and vacuum sealed on the lower base plate of the magnet. The upper ring is fixed and vacuum sealed on the upper magnet plate and will be lifted at the same time with the upper plate of the magnet. Figure 4.13: Vacuum walls layout



Vacuum walls layout

Both upper and lower vacuum wall rings are of an identical design and without penetrations. Double O-ring seal with intermediate vacuum channel or/and high level radiation hardness O-ring will be used.

The detail design will allow for easy replacement of all vacuum O-rings. The procedure of replacing the upper O-ring between the upper vacuum wall section and magnet plate is a standard procedure used in many cyclotrons and consist of disconnecting the vacuum wall section from the upper plate from within the vacuum and lift the magnet plate only with the hydraulic system. In this way the upper section of the vacuum wall will stay with the middle section and access is gain to replace the O-ring seal.

All sections of the vacuum chamber are in close mechanical contact therefore providing perfect electric ground contact between the rings and with both magnet plates. The specification for O-rings and corresponding channel design will be adequate to provide perfect seal at the same time as mechanical contact is achieved.

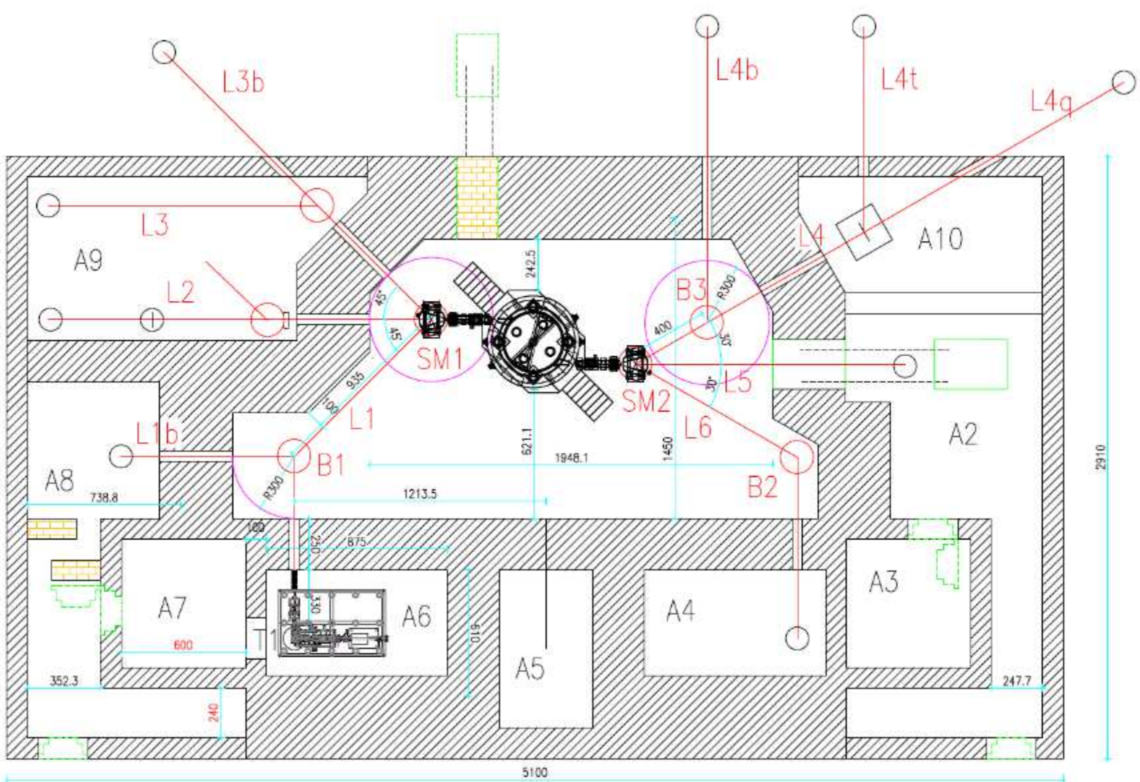
The nickel plating of iron surfaces will be use electroless plating techniques just adequate to fill the steel pores. The plating will be done after assembly of the cyclotron steel. Plating will be about 10 μm thick.

The Cyclotron Building Interface

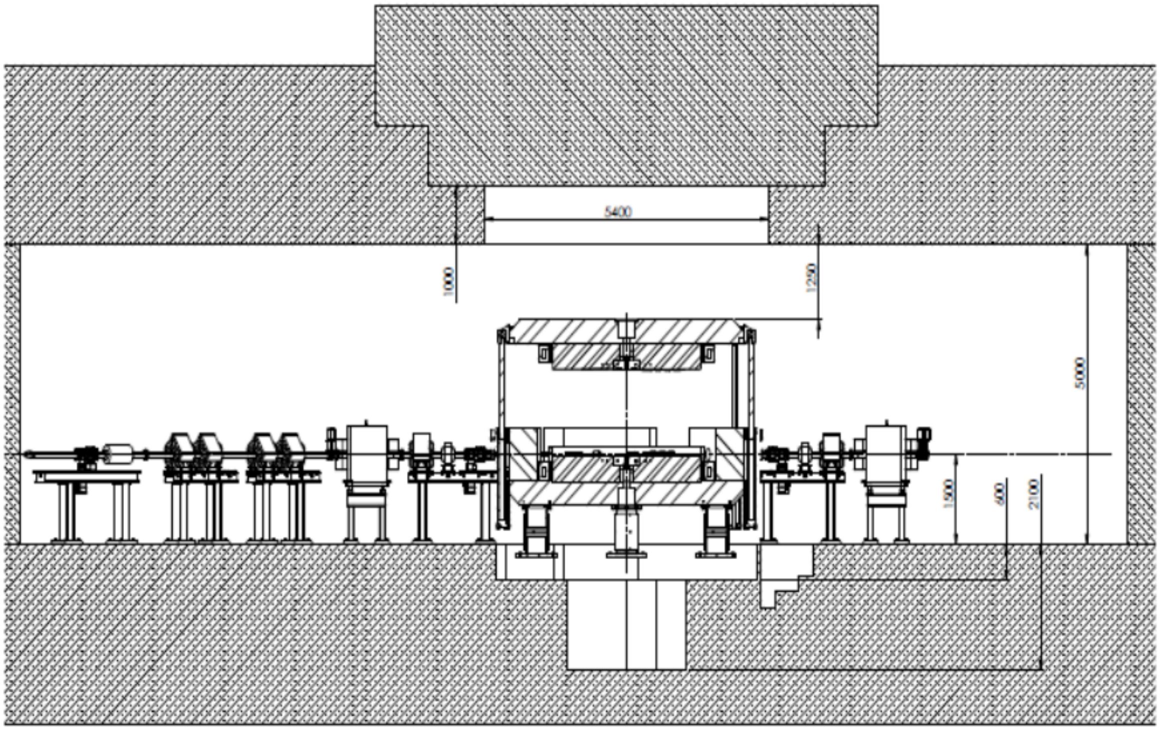
A list of rooms required to house the cyclotron and the related equipment (including main cyclotron, beam lines, power supply cabinets, de-ionized water package, water and air distribution manifolds) have been identified by INFN and BEST. As follows:

- Cyclotron Room
- Cyclotron Control Room
- Power Supply Room & Service Room
- Active Work Area and Storage
- Maintenance, Spare Parts Inventory Room
- Cyclotron Laboratory
- Decontamination Room

The cyclotron will be housed in the cyclotron room, layout suggested by BEST shown as follows.



Planar view of the Cyclotron Room



Section view of the Cyclotron Room

Conclusions

A proton driver based on a cyclotron with energy 40-50 MeV and current 0.2 mA fulfils the requirements for the SPES project as the direct target is actually designed for 8kW power. A driver with a capability of 50KW (70 MeV, 0.75 mA) with the possibility of a current upgrade reaching 1.5mA and a beam power of 100kW is indeed very interesting for the development of the SPES project, as further developments of SPES will be in the direction to increase the maximum sustained power in the target, with the aim to increase the RIB intensity and to follow the EURISOL trend for a 100kW direct target.