HIE-ISOLDE: THE SUPERCONDUCTING RIB LINAC AT CERN

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Abstract

In the frame of the upgrade of the ISOLDE facility at CERN, a R&D program on superconducting linac for Radioactive Ion Beams (RIBs) has started in 2008. The linac will be based on superconducting Quarter Wave Resonators (QWRs) and will make use of high field SC solenoids for the beam focusing. The sputtering technology has been chosen as the baseline technique for the cavity manufacturing and prototype and sputtering tests are in advanced state. A status report on the SC activities will be presented.

INTRODUCTION

In the present REX-ISOLDE facility the RIBs are accelerated to high energies with a compact Normal Conducting (NC) linac, making use of a special low energy preparatory scheme where the ion charge state is boosted so that the maximum mass to charge ratio is always $2.5 < A/q < 4.5$. This scheme consists of a Penning trap (REXTRAP), a charge breeder (REXEBIS) and an achromatic A/q separator of the Nier spectrometer type. The NC accelerator is designed with an accelerating voltage for a corresponding maximum A/q of 4.5 and it delivers a final energy of 3 MeV/u for $A/q < 3.5$ and 2.8 for $A/q < 4.5$. After charge breeding, the first acceleration stage is provided by a 101.28 MHz 4-rod Radio Frequency Quadrupole (RFQ) which takes the beam from an energy of 5 keV/u up to 300 keV/u. The beam is then re-bunched into the first 101.28MHz interdigital drift tube (IH) structure which increases the energy to 1.2 MeV/u. Three split ring cavities are used to give further acceleration to 2.2 MeV/u and finally a 202.58 MHz 9-gap IH cavity is used to boost and to vary the energy between $2 < E < 3$ MeV/u. Fig. 1 illustrates the scheme of the present linac.

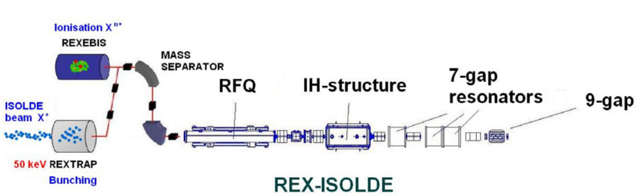

Figure 1: REX-ISOLDE present scheme.

The operation of the REX complex has started in 2002 and it sports now the largest variety of accelerated radioactive ion beams available worldwide [1].

In order to respond to the ever increasing demand for beams of higher energy, higher intensity and better quality (purity and emittance-wise) [2], a new upgrade program has been launched under the name of HIE-ISOLDE.

The higher energy requirement is achieved by means of a modular superconducting linac based on QWRs which will be installed downstream the normal conducting linac. In the short term the new accelerator modules will boost the energy up to 5.5, 8 and 10 MeV/u, while in the longer term, part of present normal conducting linac will be replaced by new superconducting cavities in order to allow the full energy variability between 1.2 and 10 MeV/u [3]. The staging of the installation allows to minimize the down time of the physics program and to profit of the periodic winter shutdown period to commission the machine. Fig 2 shows a possible scheme for the machine installation.

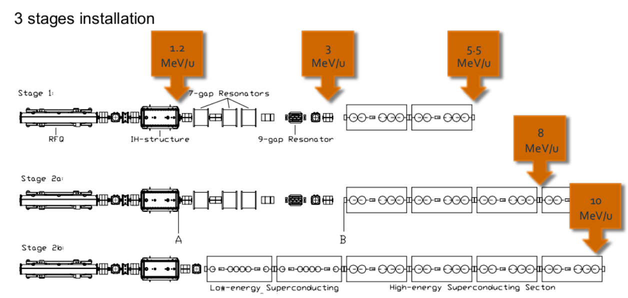

Figure 2: HIE-ISOLDE installation staging.

Concerning the higher beam intensity, ISOLDE will profit from the ongoing upgrade of the proton injectors chain at CERN [4] which will allow the beam power on target to be doubled and for which new target stations, targets and their associate handling system will need new development. Moreover, an upgrade of the REX trap and charge breeder is planned to cope with the increased intensity.

Finally in order to improve the quality of the beam a new mass separator with higher resolution is under study and new targets and ion sources are under development.

Because of the limited resources available the priority of the HIE-ISOLDE project has been given to the design and construction of the SC linac. In particular the R&D effort has focused on the development of the high β cavity ($\beta = 10.3\%$), for which it has been decided to adopt the Nb sputtered on Cu substrate technology. Other R&D activities are related to the beam dynamics studies which seek to define a very compact accelerating lattice and consequently the shortest possible machine, a design of compact SC solenoids with limited fringe fields, and the study of the cryomodule concept.

CAVITIES DESIGN

The superconducting linac is designed to deliver an effective accelerating voltage of at least 39.6 MV with an average synchronous phase ϕ_s of -20 deg. This is the minimum voltage required in order to achieve a final energy of at least 10 MeV/u with $A/q = 4.5$. Because of the steep variation of the ions velocity, at least two cavity geometries are required in order to have an efficient acceleration throughout the whole energy range. A total number of 32 cavities are needed to provide the full acceleration voltage. The geometries chosen corresponding to *low* ($\beta_0 = 6.3\%$) and *high* ($\beta_0 = 10.3\%$) "β" cavities maintain the fundamental beam frequency of 101.28 MHz and their design parameters are given in Table 1. The design accelerating gradient aims at reaching 6 MV/m with a power consumption of 7 W per low β cavity and 10 W per high β cavity.

Table 1: Cavity design parameters

Cavity	**Low β**	**highβ**
No. of Cells	2	2
f (MHz)	101.28	101.28
β_0 (%)	6.3	10.3
Design gradient E_{acc}(MV/m)	6	6
Active length (mm)	195	300
Inner conductor diameter (mm)	50	90
Mechanical length (mm)	215	320
Gap length (mm)	50	85
Beam aperture diameter (mm)	20	20
$U/{E_{\text{acc}}}^2$ (mJ/(MV/m)^2	73	207
$E_{\text{pk}}/E_{\text{acc}}$	5.4	5.6
$H_{\text{pk}}/E_{\text{acc}}$ (Oe/MV/m)	80	96
R_{sh}/Q (Ω)	564	554
$\Gamma = R_{\text{S}} \cdot Q_0$ (Ω)	23	30.34
Q_0 for 6MV/m at 7W	$3.2 \cdot 10^8$	$7 \cdot 10^8$
TTF max	0.85	0.9
No. of cavities	12	20

Coupler

An adjustable power coupler has been designed with a large dynamic range. In fact the Q_{ext} can be adjusted between 10^4 up to 10^9 so that it is possible to reach critical coupling at room temperature and a moderate undercoupling when the cavity is superconducting. This feature allows to perform some preliminary room temperature conditioning that should help in cleaning the multipacting barrier at low field level and allow to fine tune the coupling needed for the field and phase stabilisation loops. From the mechanical point of view the sliding mechanism concept is dust free as the contact points are reduced to the minimum (see Fig. 3). This should avoid any seizure of the moving parts and guarantees the functionality of the system. A full electromagnetic design of the coupler line has been performed and reported in [5]. The mechanical design is now frozen and construction is expected to be completed by end of November.

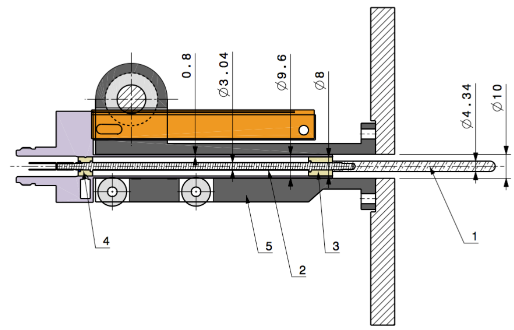

Figure 3: Coupler schematics.

Tuner

The tuning system chosen for the HIE-ISOLDE cavities takes advantage from the experience developed at TRIUMF [6]. An *oil-can* shaped diaphragm of CuBe has been hydroformed with a pressure up to 120 bar. All radial slot necessary for the elongation and contraction of the diaphragm are performed with a laser beam. The same plate can be mounted directly on the low β cavity or welded to a flange in the case of the high β cavity. The actuator is designed to have no backlash. A coarse frequency tuning range of 220 kHz is expected. Such large tuning range (for this type of cavity) allows to maintain the tolerance on the geometry to a value in the order of tenth of mm. The first prototype of the tuner is available and the internal surface should be sputtered by the end of 2009.

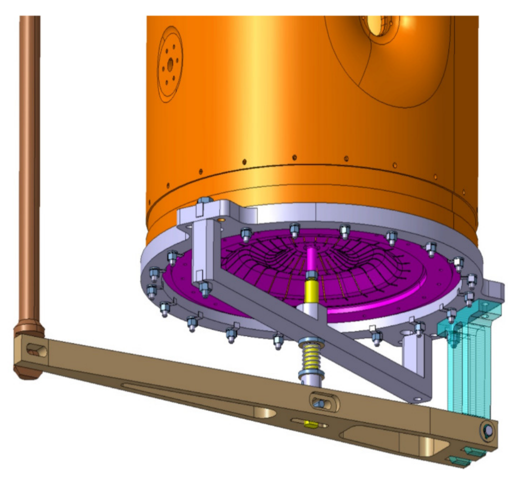

Figure 4: 3D view of the tuner with the lever actuator.

BEAM DYNAMICS

The main goal of the beam dynamics study is to define an optics and acceleration scheme that minimises the machine length and at the same time maintains the emittance of the beam. The resulting lattice has been discussed in [7] and latest results are reported in [8]. In the high β section the lattice consists in a short drift length outside the cryomodule where all the beam instrumentation and small corrector magnets will be installed, followed by two superconducting cavities, a single SC solenoid and finally three more SC cavities (see Fig. 5).

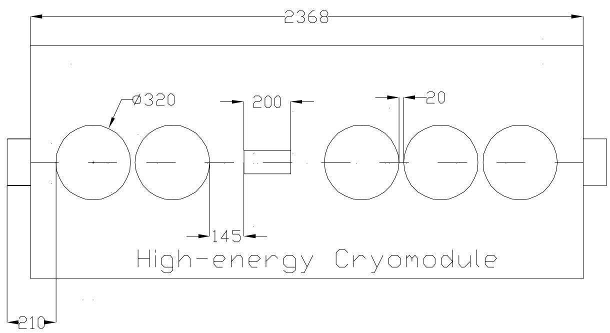

Figure 5: Schematics of the high energy cryomodule.

A full three dimensional integration of the motion equation routine has been written in order to study the motion of the single particle inside the high β cavity. The electromagnetic cavity fields used in the tracking code were calculated using the MWS code [9]. The multi-particle beam dynamics simulations are performed by implementing the fields map in the TRACK code [10].

An intrinsic characteristic of the QWR is the asymmetry of the electromagnetic field in the beam region. There is in fact a net magnetic component which steers the beam depending on the accelerating phase. The radial electric field is also not symmetric and the compensation scheme proposed by Ostroumov [11] would lead to a loss of aperture of roughly 30% in case of a circular aperture. It was then decided to modify the shape on the beam port from circular to a race-track one, and the loss of aperture due to the compensation scheme is now only 1%. Fig. 6 shows the effect of the compensation scheme. The net diverging kick given to the beam is reduced to less than 0.1mrad only for the first cavity and as soon as the beam picks more velocity the kick becomes rapidly negligible.

Fig. 7 shows the result of the beam dynamics study of the high energy section in case of a beam with A/q=4.5 and with a transversed matched beam coming from the present NC machine.

The beam dynamics study in now focused on the error study, considering longitudinal fast error (RF jitter) and static error as well as static transverse misalignment. It is found that the longitudinal emittance in the high energy section of the machine increases by 20% if the RF jitter is limited at 0.5% in amplitude and at 0.5 deg in phase for a beam with A/q=4.5. In the latest study a high order analysis of the defocusing term has been performed and results shows that even in the case of solenoid focusing with asymmetric beams the transverse emittance is still kept under control [12].

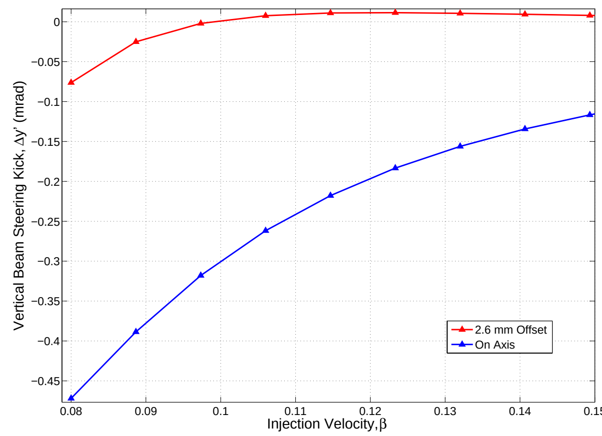

Figure 6: Divergence of the beam in case of a compensated (red) and not compensated (blue) case for a synchronous phase of -20 deg as a function of the incoming beam velocity.

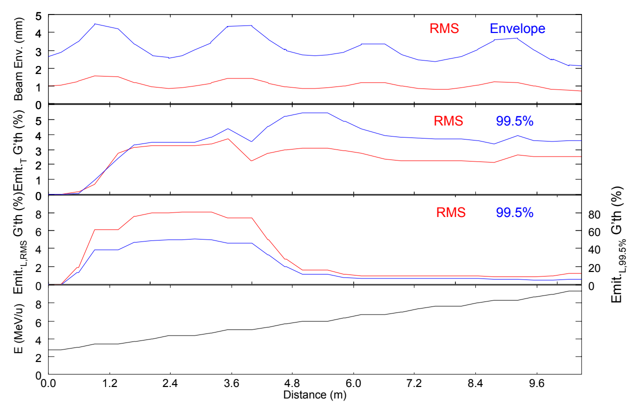

Figure 7: Beam dynamic of A/q=4.5 in the case of the high energy section only.

SC Solenoid

The employment of the SC solenoids as unique focusing elements allows to increase the transverse acceptance of the beam with respect to the un-matched beam condition and allows a great reduction of the tuning knobs, hence making the tuning and operation of the machine easier. The magnetic and mechanical specifications of the solenoid are summarized in Table 2.

Table 2: Solenoid specifications

Magnetic Integral $\int B^2 dz$	$16.2\,\mathrm{T^2\,m}$
Mechanical Length	0.4 m
Fringe field at 23 cm from center	$< 0.2\,\mathrm{G}$
Inner Diameter	30 mm

A 2D electromagnetic study of the solenoid has been performed: the specifications are met with 360A Nb_3Sn coils which produces a peak field in the center of the solenoid of 120kG. The return yoke is made by high quality iron. The fringe fields level are at the level of 50G when the solenoid is powered at the maximum field. This value is largely safe when the QWRs next to the solenoid are superconducting. Fig. 2 show a schematic of the mechanical assembly of the solenoid.

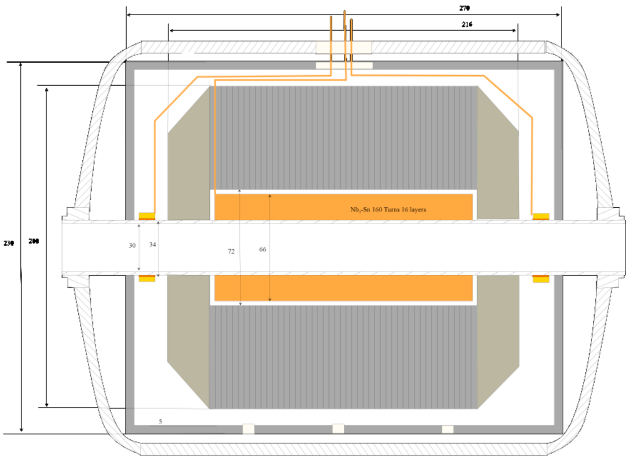

Figure 8: Solenoid schematics.

A comparison of the parameters between Nb-Ti and Nb_3-Sn solenoid giving the same field has been performed and results are listed in Table 3. A model for checking the tools and assembly procedures of the coils is in preparation.

Table 3: Parameters comparison between Nb-Ti and Nb_3-Sn solenoid

Parameters	Nb-Ti	Nb_3-Sn
Number of turns #	16500	4500
Wire length (m)	5200	740
Working point (%)	93	55
Operating current (A)	100	360
Inductance (mH)	3500	142
Stored energy (kJ)	17.5	9.5
Radial force (kN/rad)	250	145
Coil weight (kg)	36	5.2
Inner diameter (mm)	34	34
Outer diameter (mm)	166	70
Solenoid length (mm)	250	250

HIGH β CAVITY MANUFACTURING

The construction of a high β cavity prototype started in the middle of 2008 and the copper body which makes the substrate for the Nb sputtering was completed in April 2009. During the same period a new sputtering chamber was constructed and is now under commissioning. The cavity manufacturing process is reported in [13] and now the critical fabrication steps have been identified. In details the long longitudinal full penetration electron beam weldings have shown the creation of some porousness that could harm the Nb deposit. This defect could be removed by passing the electron beam in smoothing mode from the inside of the cavity - this operation would require the use of a special electron beam welding machine with a miniaturized head - but it was not felt as a immediate action to take. Moreover after the chemical etching all the microdifects seems to be disappeared and hence not harmful for the subsequent Nb sputtering. The most critical and also time-consuming step was the direct extrusion of the beam port. This step requires high precision in mounting and remounting the different tools and particular care in handling the cavity since for the production of the beam ports, the cavity needs to undergo to eight heat treatments which locally soften the copper. Finally the construction of the prototype suffered a couple of accidents which are related to human errors. For this reason a strong QA procedure needs to be in place for the series production. The cavity has been checked also with a series of RF measurement, especially the variation of the resonance frequency during the several manufacturing steps and all the measurements are in line with the prediction. The mechanical fabrication of the copper cavity has been completed and the chemical polishing has been performed. Details about the different procedures for the surface treatment are reported in [14] Fig. 9 shows the cavity after the final low water pressure rinsing subsequent to the chemical polishing.

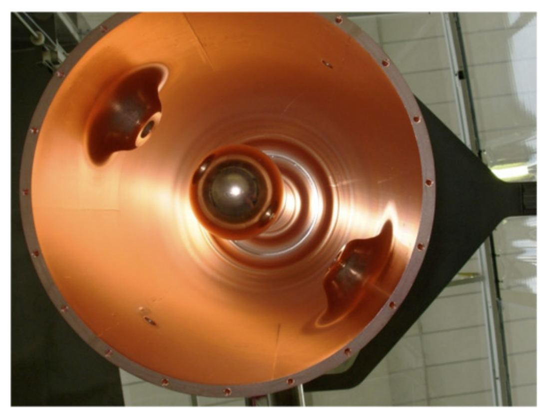

Figure 9: Cavity copper substrate towards final machining steps.

In parallel to the copper cavity a dummy cavity made in stainless steel was built. The purpose of this dummy cavity is to use it as samples holder for the characterization of the plasma inside the chamber, to test the assembly procedure of the sputtering chamber itself and to serve also as a training tool for the handling operation during the chemical treatment.

The sputtering chamber is now operational and the first plasma has been produced. The vacuum level of the chamber after baking reached the 10^{-9} mbar level and a procedure is now in place to routinely obtain this value. This is of course of great importance as the vacuum level is directly linked to the quality of the Nb films produced. All subsystems have been checked and a characterization of the plasma and hence of the Nb deposit quality is ongoing as a function of the different gas pressure level, cathode voltage and bias voltage. First Nb deposit on the copper cavity is expected towards the end of October. Fig. 10 shows on the left a moment during the installation of the dummy cavity inside the sputtering chamber and on the right the sputtering chamber closed.

Figure 10: On the left the dummy cavity during mounting for the first sputtering. On the right the sputtering chamber closed

CRYOMODULES

An initial study of the cryomodule concept was reported in [15]. Specifically, in that report the choice for a single vacuum system with an active thermal shield was shown to best fit the requirements of the new machine. In the last months, work has continued at a level of a concept study and a series of major choices have been taken concerning the dimensions, accessibility, assembly procedure and maintenance of the cryomodule, the holding system for the cavities and for the solenoid, and the alignment system.

One of the general consideration that set the pathway to the concept of the HIE-ISOLDE cryomodule was the maintenance service. In order to minimize cost and downtime of repairs it is clear that the maintenance should take place at CERN and that at this point one needs to consider the available infrastructure such as clean rooms. All the clean rooms at CERN are quite limited in height but they are quite large and long. As a consequence the dismounting of the cryomodule can occur only if the access is from the lateral side (see Fig. 11). Starting from this consideration a study concerning the stability of a mechanical structure with two openings on the side has been performed and found that this structure is feasible. The mounting and pre-alignemt of the cavities will be externally in the support girder which, with the help of a special forklift can be positioned inside the cryomodule and hooked to the support stems. Given the recent result in the error study it has been decided to have a separate frame for the support of the solenoid which can be adjusted from outside even when the system is cold.

Concerning the alignment system, it is under study the possibility to use a BCAM system [16]. Such a system consists of a calibrated laser source that can track changes in the position with an accuracy in the order of few tens of μm with a rather large span in distances. The advantage of such system is that the active part of the alignement system is kept outside the vacuum envelope and that it is possible to perform a continuous survey so that in case of accident one can retrace the position of the different elements just before the accident. A small test set-up to test the window perturbation of the measurement is being prepared.

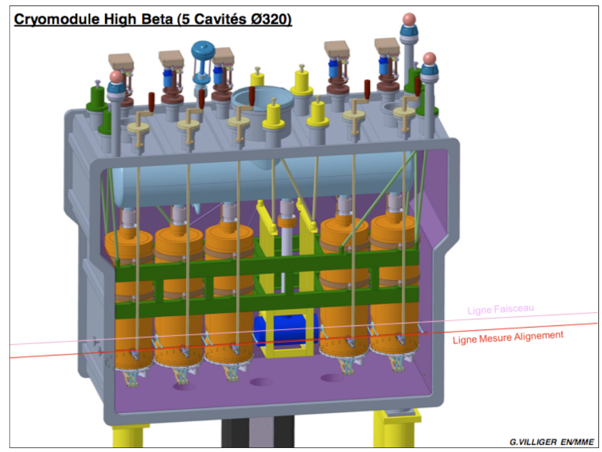

Figure 11: Cryomodule schematics.

INFRASTRUCTURES

A study covering all the issues of the infrastructure and the integration of the machine inside the experimental hall is ongoing. This has permitted to identify the suitable area for the construction of the building for the compressor for the liquid He system, the location of the He liquefier with the associated control room and also the other subsystem like the new ventilation unit, the new electricity distribution panels and the position of the different racks. This aspect of the project cannot be left behind as the location of such infrastructures determines the free space left for the accelerator, for the high energy beam transfer line and for the physics instrumentation. Fig. 12 shows the result of the study. Around the linac a semi-permanent tunnel-like shielding made of concrete blocks will be installed all along the machine length. This is strictly required from the radioprotection point of view as the whole area will remain accessible during the physics runs. The LHe liquefier will be installed at the end of the machine in a separate light construction building. In this way it is possible to minimize the length of the LHe distribution system and to maintain the geometry of the line as simple as possible which is a condition for a easier and stable operation of the cryogenic system.

SUMMARY

The HIE-ISOLDE proposal has been submitted to the CERN management which has recognized the scientific

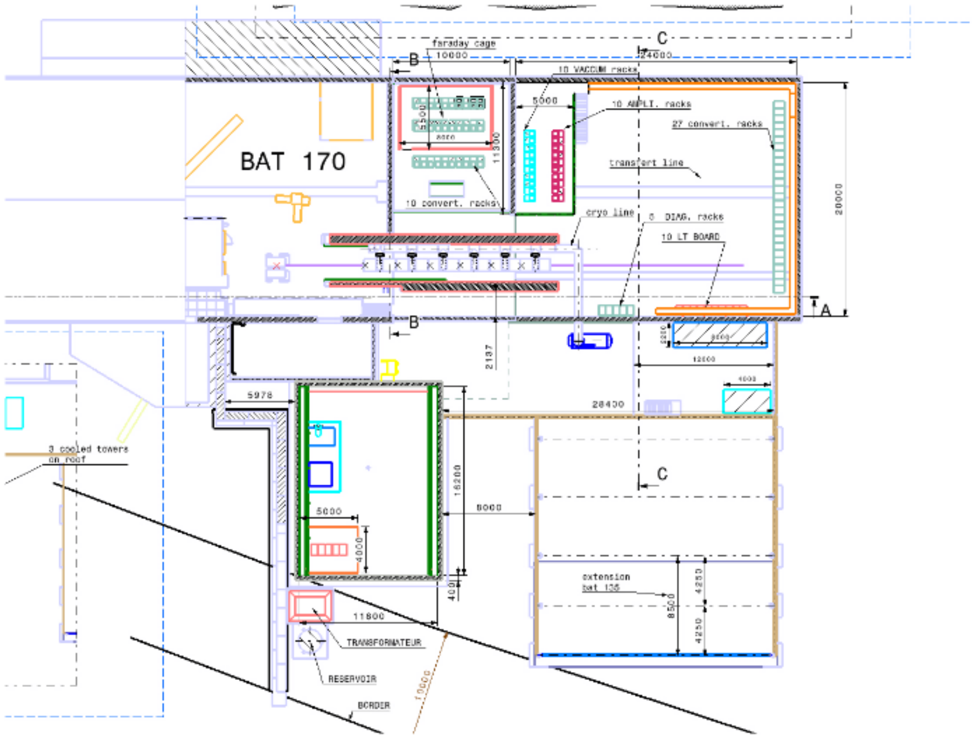

Figure 12: ISOLDE facility planimetric view. In the bottom left part one can identify the compressor building, while on the centre right there is the He liquefier. This configuration minimizes the length of the LHe distribution line, and set the condition for the optimum operation of the cryogenic system.

value of the project. The R&D cavity will continue with the production of 5 more cavities and with the construction of a single cavity test cryostat. RF tests will be initially performed at TRIUMF and the validation of the cavity construction procedure will follow soon after.

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