STATUS OF THE HIE-ISOLDE LINAC

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Abstract

The HIE-ISOLDE project aims at increasing the energy of the radioactive beams (RIB) of REX-ISOLDE from the present 3 MeV/u up to 10 MeV/u for A/q up to 4.5. This will be accomplished by means of a new superconducting linac, based on independently phased quarter wave resonators using the Nb sputtering on copper technology, and working at 101.28 MHz. The focusing elements are superconducting solenoids providing 13.5 T^2m field integral. These active elements are contained in a common vacuum cryostat. The presentation will cover the status of advancement of the HIE-ISOLDE linac technical systems. The performance of the superconducting elements will be presented, together with the assembly work of the cryomodule in clean room and the planned qualification tests in the horizontal test facility at CERN.

INTRODUCTION

The superconducting post accelerator for the HIE-ISOLDE project [1] entered gradually the construction phase in 2013 after an R/D stage which had taken off in 2009 with the formal approval by CERN. The staging and the schedule of the project were reviewed at the beginning of 2014: the present plan foresees to deliver beams up to 4.2 MeV/u for the heaviest species in autumn 2015 with a single high-beta cryomodule. A second cryomodule will then be installed during the winter shutdown 2015/2016 bringing the energy to 5.5 MeV/u for all the radionuclides available at ISOLDE. This will complete phase 1, making Coulomb excitation studies possible up to A/q=4.5. A second phase will consist in adding two more high-beta cryomodules, thus doubling the available accelerating voltage. Finally, in phase 3, two low-beta cryomodules would be installed, replacing some normal conducting structures of the present REX-ISOLDE. This will allow varying continuously the energy between 0.45 and 10 MeV/u together with an improved beam quality. A detailed description of the optics and beam dynamics design choices for the linac can be found in [2]. The design minimized the longitudinal space for the 40 MV linac, optimizing transmission and emittance growth.

The high-beta cryomodules house five superconducting Quarter Wave Resonators (QWR) based on Nb/Cu technology [3], [4], and a superconducting solenoid for beam focusing, while their low-beta counterparts will contain six QWR and two SC solenoids.

Following the examples of ISAC-2 in TRIUMF [5] and of ALPI in INFN-LNL [6], the active elements are installed in common vacuum cryostats, i.e. the beam vacuum and the insulation vacuum are in common.

Normal-conducting steerers, alignment equipment and beam instrumentation are located in-between the cryomodules, together with the vacuum systems and valves which create a vacuum sector of each cryomodule.

As we write, all the main contracts for the procurement of the linac hardware are running, and intense work is ongoing at CERN to produce the superconducting cavities, carry out acceptance tests and prepare the infrastructure and the assembly of the cryomodules in clean room conditions. This paper offers a snapshot of the main activities one year before the scheduled commissioning of the HIE-ISOLDE linac with beam.

GENERAL INFRASTRUCTURE

The long shutdown of the CERN accelerators in 2013-2014 was used to upgrade the general infrastructure of the existing ISOLDE facility to the needs of HIE-ISOLDE with minor disruptions to the physics programs. The entire ISOLDE water-station has been replaced first and became operational in time for the 2014 low energy run of ISOLDE. Two new buildings were added to the complex to house the HIE-ISOLDE services.

The Compressor building contains the now fully installed and tested water cooling systems supplying REX-ISOLDE, the warm elements of the HIE-ISOLDE High Energy Beam Transfer lines (HEBT) as well as the different power convertors and RF amplifiers with demineralized water. Regarding the cryogenics system, the two He tanks are in place outside the building, and the installation of the overhauled ALEPH compressor units is ongoing. The ALEPH Cold Box is being renovated and

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will be installed at the end of the summer. It will provide 800 W of equivalent cryogenic power at 4.5 K, which covers the needs of the first two phases. The cryogenic distribution lines and the jumper boxes feeding the cryomodules in the tunnel with liquid He at 4.5 K will be installed towards the end of this year.

In the Cold Box building, the systems for controlled air cooling of the ISOLDE experimental hall and of the service buildings have been installed and tested.

In the ISOLDE experimental hall, the shielding tunnel, which consists of more than 550 tons of concrete blocks to assure operational radiation values well below the limitations for a CERN surveyed area, is in place. For safety with regard to oxygen deficiency in case of a major release of helium in the cryomodules, a solution was found in guiding the He flow outside the tunnel roof.

For the three HEBT lines the elements' supports are all in place. The installation of cooling water and pre-vacuum exhaust tubing is about to start, after which the first quadrupoles, correctors and dipoles as well as diagnostic boxes will arrive to the hall. Controls, DC and RF cables for a total length of more than 65 kilometres are being installed and racks for RF systems, power supplies, beam instrumentation, and vacuum systems are in place.

To ensure the ISOLDE Low Energy Physics programs and to continue in parallel the HIE-ISOLDE installation work the ISOLDE experimental hall is being divided into a working zone and an experimental zone. Access conditions will be adjusted accordingly.

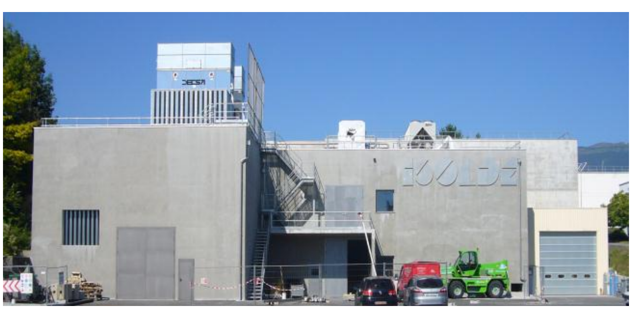

Figure 1: New HIE-ISOLDE service buildings housing cryogenics, cooling & ventilation and RF systems.

SC CAVITIES

In 2013, the R/D program on the superconducting cavities converged to a detailed protocol which yielded the specified accelerating field of 6 MV/m, at 7 W, with a 30% margin on the specified cryogenic dissipation. A detailed report on the final phases of the R/D is in [7]. The series production started in early 2014, using the two copper substrates which had been produced at CERN to bridge the gap with the start of the industry production. The cavity procedures for substrate preparation and Nb coating at CERN are documented in [8] and [9].

Before producing cavities ready to be installed in the accelerator another problem had to be solved: mastering the cavity tuning. The tuning strategy was described in [10]. Trimming of the cavity length by machining the outer conductor implies an accurate knowledge of the resonance frequency shift between the warm cavity before Nb sputtering and the coated cavity in operation (4.5 K and vacuum). Statistics on the warm to cold shift had been gathered in the prototype phase, but the first two cavities of the series production displayed shifts higher than anticipated. A special tuning plate was then developed to correct the frequency of these cavities. One of them, which had a lower Q, was stripped of the Nb layer and the frequency was corrected by mechanically trimming the length of the inner conductor. Meanwhile, the origin of the excess shift was identified in the variable time the cavities were spending in the chemical polishing bath. A correlation was uncovered between the time of polishing and the shift in the resonance frequency (Figure 2). Once this understood, trimming of new cavities was successfully achieved with the required accuracy.

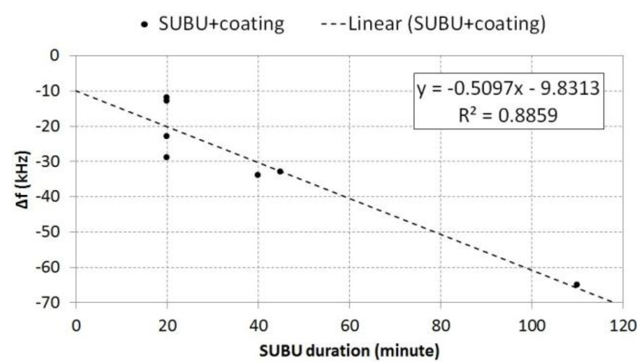

Figure 2: Correlation between resonance frequency shift and chemical polishing time.

The first industry produced copper cavity (QS1) was received in June 2014, and was processed at CERN. Some imperfections of the electron beam weld, which is located close to the peak magnetic field line, are believed to be the cause of the lower RF performance. The performance of the first 3 series cavities is shown in Figure 3.

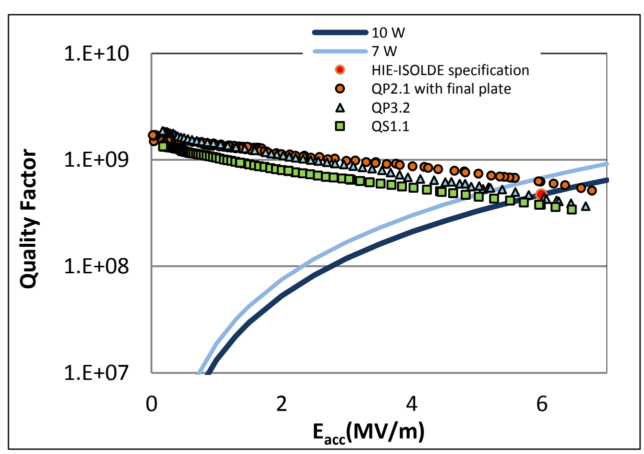

Figure 3: Performance of the first 3 series cavities. The red dot indicates the HIE-ISOLDE specification.

RF SYSTEMS

As mentioned, the HIE-ISOLDE accelerating system will be based on independently phased Quarter Wave Resonators, working at 101.28 MHz. A sketch of the RF system is depicted in Figure 4.

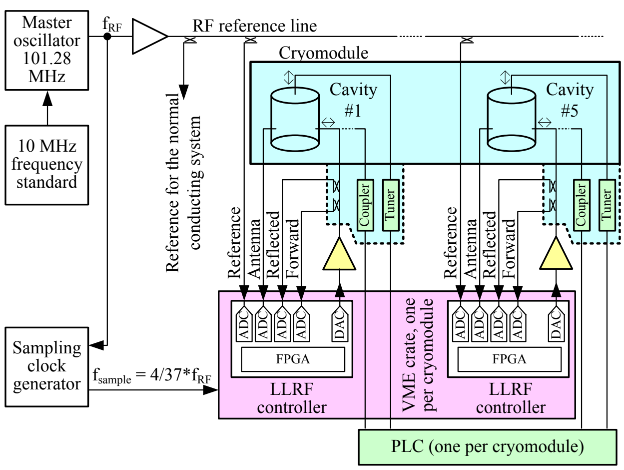

Figure 4: Sketch of the HIE-ISOLDE RF system.

A negligible beam loading and the insensitivity of the rigid copper cavity substrates to vibrations allow running the resonators at a relatively high Q_{LOADED}, typically $1x10^7$ to $5x10^7$ (bandwidths of 10 down to 2 Hz). Therefore the cavities shall be powered by standard FM transmitter amplifiers, commercially available, providing 700 W at 1 dB compression point, water cooled.

The low-level RF (LLRF) system excites and keeps the cavity field stable at the requested operating point. The system is of the generator-driven type, and has a self-excited loop mode to find and track the resonance frequency of the cavity at start-up. The values of the accelerating voltage and phase can be easily changed to adapt the linac for a new ion species in a matter of seconds. Another function of the LLRF system is to provide an automatic cavity conditioning tool during the cavity cool down process and after extended idle periods.

The LLRF system is based on VME form factor modules. Advances in the ADC and DAC technology allowed using a direct RF sampling approach, together with a direct digital quadrature demodulation. After digital processing, the cavity excitation signal is directly generated in the RF domain by a fast DAC. More information on the system can be found in [11]

Due to space and cost constraints, the LLRF system will be housed in 14 shielded racks nearby the linac, instead of a traditional “Faraday” cage. The LLRF and RF power racks have been installed in spring 2014 and the cabling campaign will start in September 2014. A full RF system for the first cryomodule will be installed in spring 2015.

SC SOLENOIDS

Transverse beam focusing at the HIE-ISOLDE linac will be provided by superconducting solenoids [12], integrated in the common vacuum cryostats. The magnets are based on Nb/Ti superconducting graded coils surrounded by an iron yoke, and enclosed in a stainless steel vessel filled with liquid helium at 4.5 K. The operational point is at 81% of the load line, the coils are passively protected with bypass diodes and parallel resistors, and the powering Nb-Ti leads are cryostable. The presence of the neighbouring superconducting cavities imposes tight specifications on the remanent magnetization (to avoid flux trapping) and on the stray field at nominal current (to avoid overcoming the lower critical field of the Nb layers on the RF surfaces). Table 1 lists the main design parameters of the solenoid.

Table 1 –HIE-ISOLDE SC Solenoid Main Parameters.

Bore diameter [mm]	31
Magnet length [mm]	312
Nominal operating Current I_{nom} [A]	115.5
Peak field at solenoid magnetic center [T]	7.86
Integrated square field at I_{nom} [T^2.m]	13.5
Stray field at 230 mm from solenoid magnetic centre [G]	12
Remanent magnetization at 230 mm from solenoid magnetic centre [G]	0.26

The series production started in industry in 2014. Four coils have been produced. Figure 5 shows the training performance of the first magnet achieving the nominal field. A small detraining was observed after the second thermal cycle, but the magnet reached again nominal field after 2 quenches.

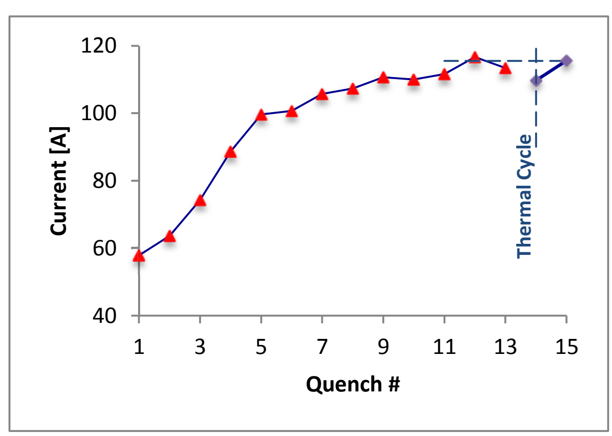

Figure 5: Training performance of the first solenoid.

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The magnetic field was measured by means of axial scans with a Hall Probe. The measured field profile is shown in Figure 6. The maximum stray field at the cavity position is well within the specifications.

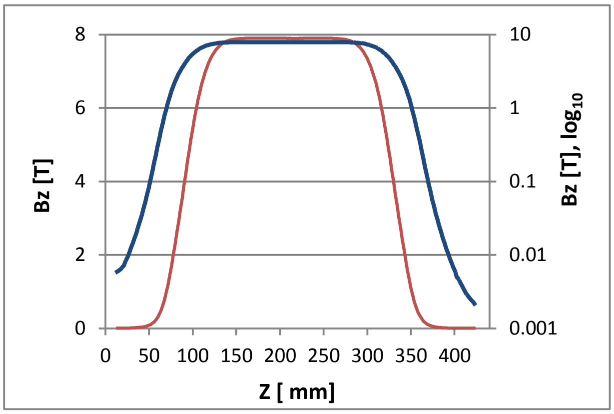

Figure 6: Magnetic field along the beam axis at Inom (dotted line: logarithmic scale).

The solenoids will be delivered already integrated in their helium vessel ready to be installed in the cryomodule.

CRYOMODULE ASSEMBLY

The design of the cryomodule is detailed in [13]. A stainless steel vacuum vessel contains the cavities and the solenoid, surrounded by a thermal screen which is actively cooled with helium gas at 55 K and 13 bar at the inlet. The active elements are supported close to the beam axis on precise reference surfaces which in turn are mechanically connected to the top plate. Liquid helium at 4.5 K is supplied to a common reservoir and distributed to cavities, solenoid and support frame. A 3 D model of the HIE-ISOLDE cryomodule is shown in Figure 7.

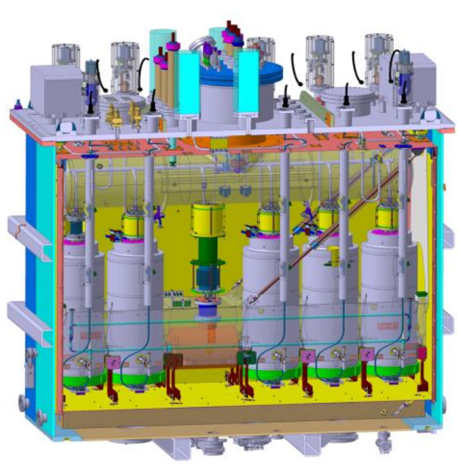

Figure 7: HIE-ISOLDE high-beta cryomodule.

The elements of the cryomodule, together with specially developed assembly tooling, are being procured through several contracts with industry which are coming to the delivery phase in a staggered fashion as from August 2014. Several key elements are produced in the CERN main workshop. The assembly of the cryomodule components will take place in an ISO5 clean room, which was set up and commissioned at CERN for this purpose. Detailed procedures are being elaborated for the assembly work, which will be interleaved with a thorough set of quality checks covering cleanliness, leak tightness, alignment, and electrical quality assurance. This work is starting in August 2014 with the requalification of the clean room after the installation therein of an ISO5 compatible precision assembly tower.

CRYOMODULE TESTING

After assembly and the final qualification tests at warm, the finished cryomodule will be transported with a dedicated tool to a nearby Horizontal Test Facility for a complete set of qualification tests in operational conditions, prior to installation in the linac tunnel.
The test campaign will cover the vacuum and cryogenics performance, monitoring and alignment adjustment of the active elements, conditioning and RF measurement of the superconducting cavities, power tests of the superconducting solenoid, and commissioning of the LLRF and of the tuning systems. Cold testing of the first cryomodule is scheduled in February 2015.

ALIGNMENT AND MONITORING

In addition to classical machine survey, to run the linac in optimum conditions, the active components, cavities and solenoid, must be aligned and monitored on the REX-ISOLDE Nominal Beam Line (NBL) within a precision of 0.3 and 0.15 mm respectively at one sigma level along directions perpendicular to the beam [14].

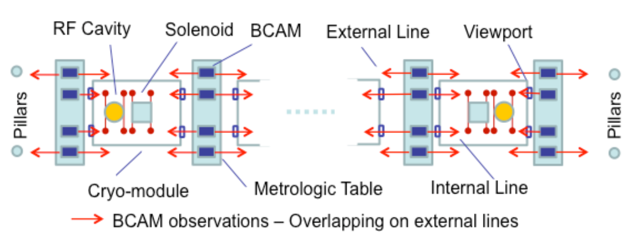

Figure 8: Sketch of the alignment system - Top view.

As sketched in Figure 8, the Monitoring and Alignment Tracking for Hie-IsoLDE (MATHILDE) system [15] uses a set of newly developed double-sided HIE-ISOLDE Brandeis CCD Angle Monitor (HBCAM) [16]. These sensors are similar to calibrated cameras equipped with laser diodes that enable reciprocal sensor observations as well as light spots or targets measurement. HBCAMs are fixed to metrological tables in order to create a close geometrical network link to the Nominal Beam Line by reference pillars. Two external lines of sight, one on each side of the cryomodule, are created and act like a frame. The HBCAMs belonging to the internal lines are placed in front of viewports and allow the observation of targets attached to the active elements and of the HBCAMs situated on the previous and next table.

Targets must be compatible with vacuum and cryogenic conditions, be measurable from several directions and have a narrow shape (6 mm max). The design is based on the properties of prototype 4 mm diameter glass ball lens with high refraction index (~2). Targets equipped with these balls were tested at CERN. The precision of the reconstructed target displacement measured by a HBCAM is about 10 microns in object space at one sigma level. HBCAM measurements were successfully done on targets placed in vacuum and cryogenic conditions (down to 5K). The effects of viewport crossing have been modeled, verified by tests, and corrections were implemented in the software routines [17]. Tests with an early computation shell of the Monitoring and Alignment Tracking for Hie-Isolde Software (MATHIS), still under development, have shown that the one sigma precision for the reconstruction of a full set of 7 metrological tables is within 20 microns.

As of august 2014, the full set of HBCAM sensors and associated electronic equipment is already procured. The target support is designed and a price inquiry is ongoing. The metrological tables are in the final design phase.

BEAM INSTRUMENTATION

New beam diagnostics devices have been developed for the HIE-ISOLDE project, in particular for the measurements of the intensity, energy, transverse and longitudinal profiles, and transverse emittance of the stable pilot beams. The instruments will be integrated in octagonal-shaped vacuum chambers with 5 radially distributed ports available for the installation of instruments or collimating devices plus a port for vacuum pumping. The beam intensities, in the range between 1 pA and 1 nA, will be measured by means of Faraday cups (FC). Due to constraints on the longitudinal space available in-between the Linac cryomodules, a particularly compact FC was designed with an aperture of 30 mm and overall length of only 16 mm. Beam energy and longitudinal profiles will be determined by using commercial PIPS silicon detectors [18]. The transverse beam profiles and positions will be obtained by scanning a V-shaped collimator slit upstream a FC. A resolution of the order of 0.1 mm in the transverse beam position has been estimated. Two options for measuring the transverse emittance are available: one using the existing REX-ISOLDE slit and grid system, the other by the combined use of two scanning slits and a FC. Experimental tests with beam of all the mentioned devices have been carried out successfully between 2011 and 2013; more details can be found in [19]. A new VME card was designed for controlling the actuators and the FC, and also a new front-end preamplifier for the beam intensity measurements. As the tight longitudinal constraint is not present in the HEBT section, longer boxes will be installed there, allowing for the use of a standard FC. Contracts have been signed with industry for the production of the fully assembled diagnostic boxes (6 short and 9 long), electronic modules are also under final production. The installation of the equipment is scheduled to start at the beginning of 2015.

SOFTWARE AND CONTROLS

Software and controls at the HIE-ISOLDE linac will be based on a three tier architecture widely used in CERN accelerators [20]. The machine will rely on the controls infrastructure already deployed in the injector complex. Cryogenics and vacuum controls will be as well based on CERN standard solutions used in other machines. For beam operations, high level applications have been developed including a settings generator, beam diagnostics tools, and tools for automatic cavity phasing as A/q is varied [21], [22]. Dry runs of hardware groups, starting with the transfer lines, will begin in autumn 2014 using the operational software.

CONCLUSION

Work is in full swing at CERN and in industry towards the construction and commissioning of the HIE-ISOLDE linac, foreseen in summer 2015. The main technical issues regarding the performance of the superconducting elements have been solved. The first cavity had a lower performance than the best achieved on the prototypes, but still acceptable. All the main components of the machine are being produced, either at CERN or in industry, and the work on the general infrastructure is progressing well. The next challenges will be the clean room assembly of the cryomodules, and their subsequent qualification tests in operational conditions.

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