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LESSONS LEARNED FROM THE HIE-ISOLDE CAVITY PRODUCTION AND CRYOMODULE COMMISSIONING

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Abstract

The HIE-ISOLDE superconducting linac started operations at CERN in 2015 with a first cryomodule hosting five superconducting quarter wave resonators (QWR). These cavities are based on the Nb/Cu technology. In time, two more cryomodules have been assembled, installed and commissioned on line, bringing the energy reach for the heaviest ions (A/q=4.5) up to 7.5 MeV/u. In 2017, while the first three cryomodules were prepared for the physics run, six more cavities were produced of which five will be installed in a fourth cryomodule. With this, the high beta section of the linac will be complete and the energy will reach 10 MeV/u for A/q=4.5. In this paper we review the experience and lessons learned during the construction of HIE-ISOLDE, along with some still open questions.

INTRODUCTION

The High Intensity and Energy ISOLDE (HIE-ISOLDE) project [1] is a major upgrade of the ISOLDE facility at CERN, aiming at increasing the intensity and the energy of the post accelerated radioactive ion beams (RIB) up to 10 MeV/u for the heaviest species available at ISOLDE. The layout of the post accelerator in 2017 is shown in Fig. 1.

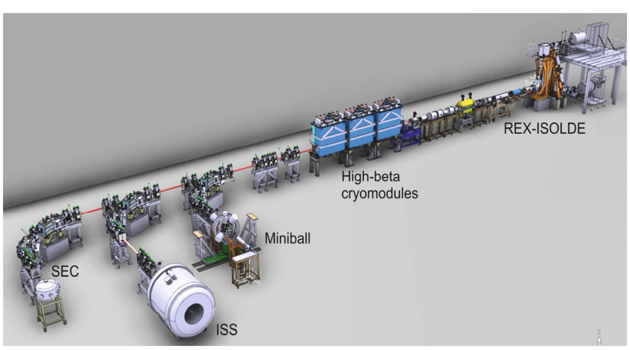

Figure 1: Layout of the HIE ISOLDE linac in 2017.

The principal technology choice, of a superconducting linac based on Nb/Cu quarter wave resonators (QWR), was made in 2007. One year later, R/D on cavity development and design work started. In 2009 the project was formally approved by CERN. Cavity series production started in 2014, and the first beam acceleration with one cryomodule was achieved in October 2015. Since then, one new cryomodule was added every year. A second physics campaign, with two cryomodules, was carried out in 2016, and in 2017 the linac is delivering beam to the users using three cryomodules hosting a total of fifteen high beta QWR and three superconducting solenoids. The cryomodules are of the common vacuum concept following the examples of TRIUMF and INFN Legnaro. A fourth cryomodule is under assembly and will be installed in the winter stop 2017-2018. So far, the performance of the cavities in the linac has been satisfactory, as shown in Fig. 2.

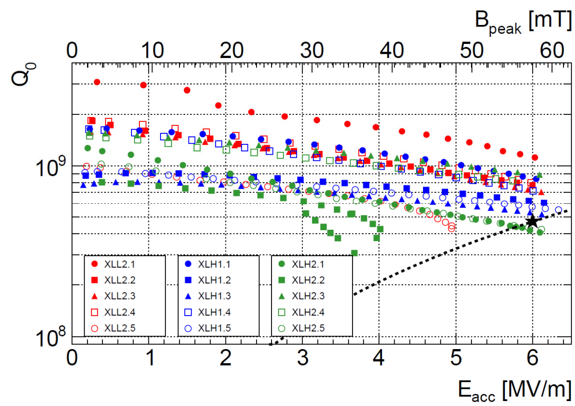

Figure 2: on line performance of the first 15 cavities. The dotted line corresponds to 10 W cavity power dissipation.

ORGANIZATIONAL CHALLENGES

The SRF systems of the HIE ISOLDE linac were entirely designed and for a large part manufactured and assembled at CERN. Only a few key elements were subcontracted to external companies. The complexity and delicacy of the tasks and the diversity of disciplines involved to fulfil them in an environment characterized by multiple projects, sharing infrastructures and resources, posed remarkable organizational challenges.

Project Organisation and Technical Coordination

As it is common in large organizations having to manage multiple activities, CERN has a matrix type organizational model, whereby specialists are pooled in organic units, each delivering their services to different projects. The advantages and disadvantages of such structures for the Organization and for the single projects are well known [2]. In this context the HIE-ISOLDE project was structured in thematic working groups, gathering experts from different organic units to make-as much as possible-consensual decisions and coordinate the work, while maintaining their multiple reporting lines. Since initially little staff was assigned to the project, fellows and students were at the

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forefront. In particular the conceptual design and the initial thrust was achieved thanks to the Marie Curie ITN project CATHI [3], which brought at CERN 20 young researchers.

Workflow and Quality Assurance

The workflow for HIE-ISOLDE cavity production at CERN is shown in Fig. 3. Each activity block in the sequence is to be carried out at a different location on the site, and is placed under the responsibility of the relevant CERN unit, represented by a person in charge of the step. Activity blocks were described in operational procedures, defining the work to do and the parameters to record. Quality Assurance was based on the CERN MTF (Manufacturing and Travelling Folder), supported by printed traveller sheets following the cavity on the ground.

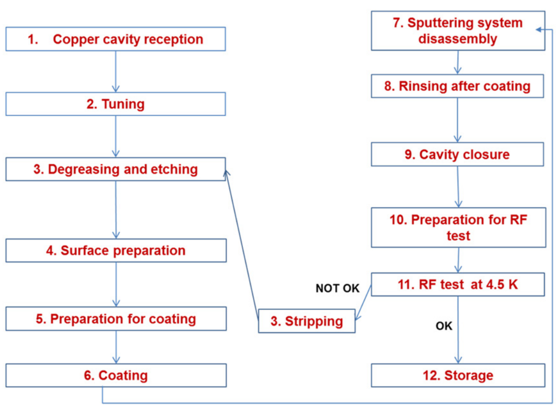

Figure 3: Cavity production workflow at CERN.

Cryomodule assembly in an ISO5 clean room was a more centralized effort, at least geographically, realised by a dedicated team composed of technicians and engineers from different CERN units. Quality assurance was, if possible, even more essential here, as the slightest mishap would endanger the results of months of work: a rigorous system for handling non conformities was put in place, after LHC examples, albeit with a simplified routing.

EVOLUTION OF CAVITY DESIGN

The RF design of the cavity built on the experience of INFN-LNL [4], therefore taking into account the need of very smooth surfaces, and avoiding abrupt changes of curvature, to optimize the coating with sputtered Nb.

The first mechanical design (see Fig. 4) was based on rolled OFE copper sheets with several electron beam (EB) welds and a large helium reservoir on top of the cavity. The beam ports were shaped by plastic deformation. Five cavities of this type were made and used in the initial stages of the R&D. This design was prone to detuning caused by helium pressure through the larger surface in contact with the bath. A second mechanical design [5] was based on two machined pieces, which were shrink fitted and joined by means of a single EB weld on the top part of the QWR. The raw material was OFE forged copper. This design was prototyped at CERN and used in the last phase of the R&D. After successful testing of finished cavities, including thermal and microphonics qualifications, this design was retained for tendering the series production (23 units) of the copper substrates in industry.

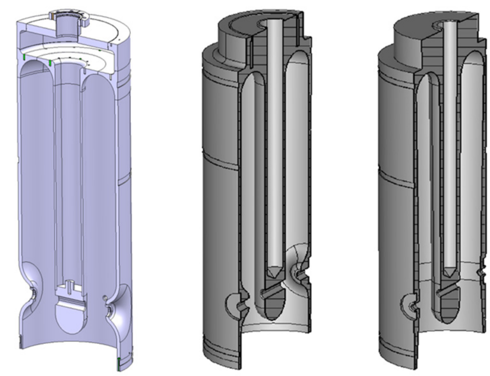

Figure 4: Evolution of cavity design.

Following recurrent issues in the series production with the quality of the finished surfaces, close to the EB welds, a third design was developed, aiming at realising the QWR from a single copper block, thus avoiding all welds. This required a full re-working of the RF design. Two cavities of this type were made so far in industry, and the first was coated and cold tested at the time of writing this report. The details of this recent effort, which was crowned by plain success, are reported elsewhere [6] in these proceedings.

ISSUES WITH CAVITY SUBSTRATES

As it was hinted above, many of the series copper cavities were plagued by defects located close to the EB welds. An example of these features is shown in Fig. 5.

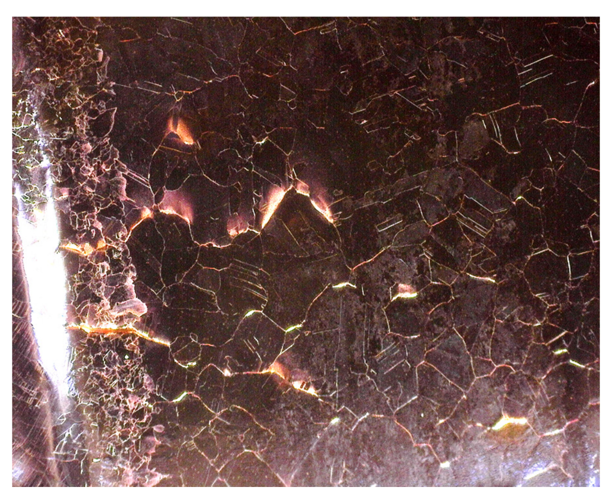

Figure 5: defects on copper substrate.

In depth investigations were undertaken to identify the cause of the phenomenon. Some hypotheses could be ruled out: hydrogen embrittlement was excluded, and the raw

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material was requalified and shown to be able to sustain the manufacturing process without cracking. However no firm conclusion was reached. Substrate defects are thought to have consequences on the final performance of the cavities: trapping of chemicals in the material may occur, with local contamination of Nb layers. Spots of weaker or suppressed superconductivity translate in residual resistance, or become flux nucleation/trapping sites. Some evidence is presented in Fig. 6, showing the surface resistances parameters for cavities with clear substrate defects, and for cavities were defects were not observed.

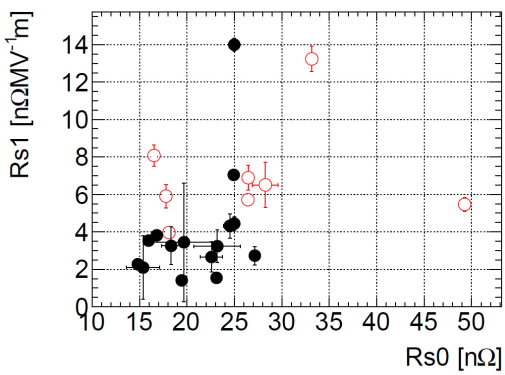

Figure 6: correlation between defects and performance. Empty symbols denote cavities with defects on substrate.

SPUTTERING PROTOCOL

As it was reported in [7] the Nb coating recipe was adapted from the DC bias method developed in INFN-LNL for the QWR geometry. After an initial exploration phase, the sputtering protocol was fixed and implemented for all the 20 cavities, which therefore constitute a homogenous sample of some statistical relevance. Five cavities were stripped and accepted at the second coating and one was coated three times. It seems reasonable to assume that the scatter in performance observed in cold tests doesn't have its origin in the coating process.

The crucial question of the optimization of the Nb film remains partly unanswered. We believe that the quality of the superconducting layer can still be significantly improved, as the BCS mechanism accounts for only a fraction of the observed surface resistance. The relevant dimensions in parameter space include at least the coating temperature, the coating rate, the sputtering pressure, the bias voltage, some critical dimensions like the distance of the cathode to the cavity top, etc. The good region in this multidimensional space remains largely unexplored. R/D on this fundamental topic is still ongoing at CERN [8].

RF MEASUREMENTS

The standard RF characterisation used to qualify the cavities for installation in the linac was the measurement of Q-E curves at 4.5 K. In all cases it was also verified that the target frequency in operational conditions was met with sufficient margin for tuning, and tuners were characterized in terms of resolution and backlash. Whenever the planning allowed it, Q measurements as a function of temperature down to 2 K were done, attempting to separate the BCS contribution from the so-called residual surface resistance. Measurements of the frequency vs temperature were also done on a subset of cavities upon warm up, to get an estimate of the RRR of the Nb layers.

Strategies for Multipacting Conditioning

The HIE-ISOLDE QWR has multipacting bands in the range of 10-60 kV/m, which are localised in the high electric field region of the cavity, and around 1.2-1.7 MV/m, corresponding to trajectories on the cavity top [9].

The low field levels can be reached in the normal conducting state, while the high field levels have to be processed once the cavity is superconducting. Initially, cavities were tested with a fixed coupler, which resulted in long conditioning times. At that time, the low field multipacting was processed at cold. With the introduction of variable couplers, the conditioning process was eased. Furthermore, the strategy of conditioning evolved. It was realised that a full conditioning of the hard levels at low field was necessary before transition. The power levels and waveforms were adapted. Eventually, the procedure was to leave the variable coupler with full insertion during cool down and process with CW up to 100 W starting from 200 K. Finally automatic routines were developed, once the LLRF system became available. This evolution is still ongoing. The low field multipacting levels can usually be processed overnight, while conditioning of the high field levels takes less than one hour at ~ 20 W CW in slightly over coupled conditions.

Strategies against Field Emission

The cavity preparation for cold tests is done according to ISO5 clean room standards, and rinsing with ultrapure water at low pressure (5 bar) is applied. Field emission was observed occasionally. When this happened, RF processing was seldom sufficient to cure it. Helium processing (2 10^{-5} mbar, RF power a few tens of W in CW) was effective most of the times, but not always. In some cases the cavity had to be stripped and coated again. A key improvement was to eliminate the Nb layer from the RF contact with the bottom plate, by masking it during coating. This surface is perpendicular to the sputtering cathode, and the poor adhesion of the film made it a source of metallic flakes.

Decomposing the Surface Resistance

The surface resistance of SRF cavities is traditionally analysed in terms of the BCS and residual components [10]. The latter can in turn be decomposed according to the known non-BCS loss mechanisms, like flux trapping, and true "residual" of unknown origin.

In our case we realised that the experimental procedure to extract the BCS surface resistance failed to give unambiguous results. This was due to two reasons: on one hand, fitting the temperature dependent term to extract BCS parameters is an ill conditioned problem unless it can be constrained by additional information, for example an

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independent measurement of the mean free path. More importantly, the temperature dependent term, usually identified with the BCS contribution, was found to strongly depend on the modality of the cool down, which is difficult to conciliate with the idea of thermodynamic state. Moreover the temperature dependence is increased as a function of field, even at low field. This is shown in Fig. 7 for two cavities which were measured as a function of temperature after a slow and a fast cool down, and at different fields.

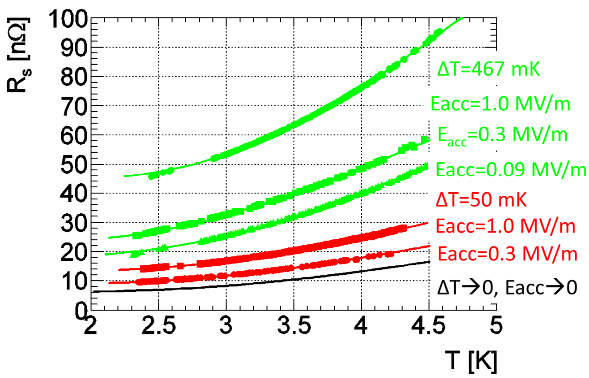

Figure 7: dependence of Rs (T) on field levels and on temperature gradient upon cool down.

It seems clear that a temperature dependent non-BCS loss mechanism is at work in our cavities, which is difficult to disentangle. As the effect seems proportional to the thermal gradient on the cavity when crossing T_c, we still talk of the BCS component as extrapolation for a perfectly homogenous cool down, when an independent estimate of the mean free path is available.

In our analysis of the cavity performance we have introduced three empirical parameters derived by fitting the surface resistance as a function of accelerating field, and which are useful to qualify a cavity. These are the low field surface resistance R_{s0} (intercept to zero field of a linear fit), the linear Q slope R_{s1}: (slope of the linear fit), and the high field Q slope R_{s2} (coefficient of a parabola fitting the surface resistance at high field, in absence of field emission).

Influence of Cool Down Conditions

Already during the R&D phase it was known that the surface resistance would be reduced by a second cool down aimed at minimizing the temperature gradients in the cavity when crossing the critical temperature. All cavities have been qualified with this procedure. Dedicated experiments were done to clarify whether the effect was due to the cool down speed or to the temperature gradient or both, and the result was that the speed does not play any role. These studies are reported in [11]. The current interpretation of this phenomenon calls for flux trapping induced by thermo-electric currents. Given the measured value of the sensitivity of Rs to flux trapping, and the size of the effect the associated field should be easily detectable with flux gate magnetometry. However this measurements are complicated by the topology of the trapped flux, and an independent experimental verification of the theory has so far eluded our efforts. The topic is further developed in another paper of these proceedings [12].

Flux Trapping Sensitivity

The sensitivity of Nb/Cu cavities to flux trapping is known to be low [13], which is why for HIE-ISOLDE no magnetic shielding was foreseen, as for other accelerators using this technology. It was considered important, however, seen that the superconducting characteristics of the Nb layer can depend quite a lot on the deposition process, to measure the actual sensitivity of the HIE-ISOLDE cavities. This was done (see Fig. 8) also in order to specify the stray field of the nearby solenoids. The sensitivity was found to be still very low compared to bulk Nb, but higher than in magnetron sputtered cavities. With very little statistics, there are indications that the sensitivity is higher for better performing cavities, still remaining well below the typical; values of bulk Nb.

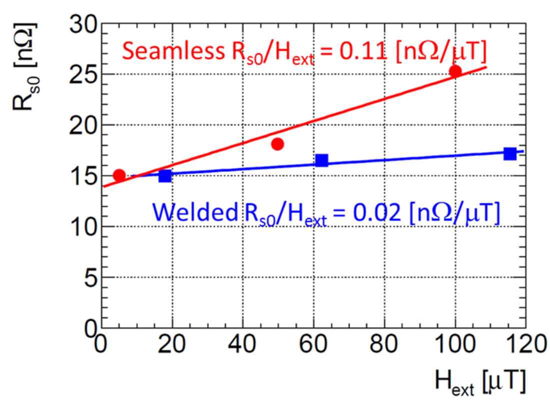

Figure 8: Sensitivity of two HIE-ISOLDE cavities to trapped flux.

Correlations

Correlations among the surface resistance fit parameters have been explored in an attempt to gain some insight in the loss mechanisms. The most intriguing correlation is found between the linear Q slope and the BCS-like term at 4.5 K, obtained by the usual procedure of subtracting the residual term extrapolated at zero temperature. These two quantities are positively correlated, as shown in Fig. 9. The interpretation of this remarkable fact is debatable and will not be attempted here.

Another interesting correlation is reported in Fig. 10 between R_{s0} and R_{s1}, normalized by the thermal gradient at T_c. Here the difficulty for any theory trying to explain the correlation is to justify R_{s1} in terms of flux motion.

No correlation was found between the high field Q slope R_{s2} and the temperature gradient across T_c.

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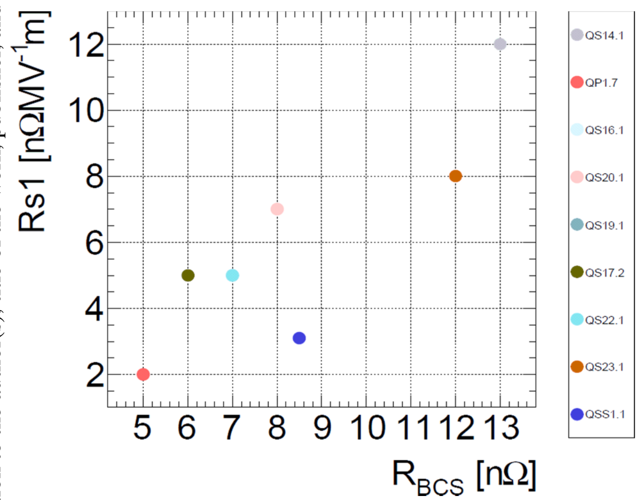

Figure 9: linear Q-slope vs the apparent RBCS.

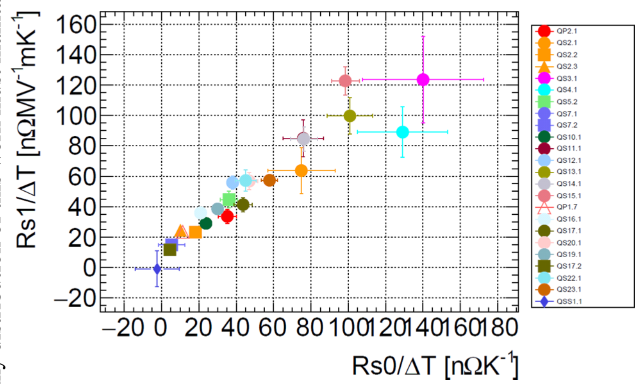

Figure 10: sensitivities to temperature gradients across T_c.

THE PROBLEM OF TUNING

Initial cavity developments were focused on reaching nominal performance in terms of accelerating field and quality factor. Cavities were tested with rigid bottom plates and the problem of tuning was postponed to later.

It was then realised that reaching the target frequency at 4.5 K in vacuum required a careful approach: the design of the tuning system had to fulfil conflicting requirements in terms of resolution, heat transfer, strength, integration in the cryomodule, and stability of the alignments. Therefore the tuning range in operation was limited to less than 40 kHz. The tuning strategy which was adopted is explained in [14]. Understanding the frequency shift between a freshly manufactured cavity and nominal conditions required statistics, which should have been systematically acquired. Frequency data from the initial cavity production was in fact unusable as the environmental conditions at warm (temperature and humidity) were not recorded.

Microphonics, df/dp, and Lorentz Force Detuning

The sensitivity of the series cavity design to the helium pressure was measured, in the vertical cryostat, to be in the order of 0.02 Hz/mbar, which is close to non-existing. Microphonics levels in the vertical test stand were so low to be unmeasurable. The Lorentz Force Detuning (LFD) with 0.3 mm thick tuning plates ranged from 20 to 200 Hz, depending on the position of the tuning plate. Contrary to the vertical test stand however, in the machine environment some issues related to mechanical disturbances were encountered. In the accelerator, the cavities are driven by a digital Low Level RF (LLRF) system which must lock field and phase within very stringent limits [15]. The LLRF system had to be carefully set up to work at reduced bandwidth coping with the LFD and with the external perturbations. The source of vibrations is the cryogenics plant, and vibrations are transmitted to the cavities through the tuning system. This aspect was not sufficiently explored in the design and prototyping of the tuning plates. It remains to be seen whether a thicker plate, allowed to plastically deform at the first tuning and then let to work in elastic regime around the target position, could have offered an alternative, more robust solution.

RF POWER COUPLERS

The fundamental power coupler was specified for 500 W forward power and to be movable such to reach critical coupling both in the normal and superconducting states. The design evolved during the years, but the problem of reliable movement in vacuum and cryogenics conditions was initially central. Improved models were used for the vertical tests until a satisfactory version was achieved and produced in series. However a crucial mistake was done at this stage: all the measurements were done for better accuracy close to critical coupling, which is far from the operating conditions in the linac with enlarged bandwidth and active feedback loops. This was in part due to the fact that the LLRF system was still under development. As a result, we failed to spot that the version of the RF input system installed in the first cryomodule was thermally unstable already at moderate power [16]. The couplers had to be redesigned in a crash program while the first cryomodule was delivering physics with severe limitations in the duty cycle to prevent overheating. The flaw manifested itself after hours of operation, and had gone unnoticed. Dedicated endurance tests at operational bandwidth in the vertical test stand would have revealed it.

CRYOMODULE DESIGN

The design of the HIE-ISOLDE cryomodule is documented in [17]. Its main features are the common vacuum concept and supporting and alignment of the cavities from the top, taking advantage of gravity. The common vacuum imposes strong constraints for the whole life of the machine, even though it allows a more compact design and a simpler mechanical assembly. The actively cooled thermal shield was nickel-plated for better emissivity. However the plating process turned out to be difficult to perform on the large shield slabs with the required quality, and posed some risk of contamination with metallic particles when adhesion of the coating was poor. Retrospectively, a stabilized copper surface could have been sufficient. The measured

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thermal performance of the cryostat was according to design: the heat load at 4.5 K was in the order of 10W.

The accuracy in cavity and solenoid positioning was also well within the specification of 0.1 mm, which fully validated the design of the internal supporting system.

CRYOMODULE ASSEMBLY

The experience with cryomodule assembly is described in [18]. The assembly sequence was detailed in 11 written procedures, elaborated before the start and during the assembly of the first cryomodule. The average duration of the assembly work in clean room was 22 weeks from the second cryomodule on, with two clean room technicians working on the clean assembly proper, two people doing preparation of parts in ISO5 and one for logistics support. Leak checks, electrical checks, RF measurements, survey and alignment work were carried out by other specialized personnel. Blank assemblies were done every time this was possible to anticipate problems with mounting interfaces. Qualification tests, notably for leak tightness of the helium circuits, were strategically disposed all along the assembly sequence. The helium circuits were leak tested as a whole, including the solenoid circuit, prior to assembly of the superconducting cavities. These precautions paid off, and no cold leak was observed in the machine: vacuum levels reached in the 10^{-11} mbar levels, also thanks to the huge pumping speed of the cold surfaces. The superconducting cavities were all rinsed with ultra-pure water after the vertical tests before assembly. Metallic shutters were devised to cover the beam holes and protect the cavities until the moment when the cryomodule was sealed. Also in this case, the results were positive as field emission occurred only in one cavity out of fifteen which had gone through the normal installation procedure.

CRYOMODULE COMMISSIONING

The first cryomodule was technically a prototype, first of its kind. Extensive testing was foreseen to validate design choices concerning vacuum, cool down times, static heat loads, kinematics of cool down and alignment of the active elements, performance of RF couplers and tuners, cavity and solenoid individual performances, and, not least, absence of any interference between solenoid and cavities. Plans had been made to test the cryomodule in a horizontal bunker before installing it in the linac. The test facility was prepared and equipped, among other things, with a flowmeter dimensioned for maximum accuracy at the nominal power dissipation with one cavity on (20 W at 4.5 K). However, when the first cryomodule was ready, it was decided to install it directly in the linac and do the commissioning there. This decision was made considering that transport and installation from the machine back to the clean room represented a small overhead - in case of serious problems - compared to the same situation occurring in the test facility. Indeed, due to the RF coupler issue, the first cryomodule had to be taken back to the clean room to be refurbished, but in the meanwhile we had gained experience with the real cryogenics facility, with the real microphonics environment, we had the possibility to measure the cavities with beam, and to practice beam commissioning. Moreover, a small physics program could still be done by limiting the duty cycle. All these were added values compared with the alternative scenario. Therefore, all in all, we still find the decision was correct. A detailed account of the first commissioning experiences with the HIE-ISOLDE cryomodule can be found in [19].

Cavity Performance Online

Thanks to the variable couplers, the cavity performances could be measured as accurately in the linac as in the vertical test stand. Moreover, time of flight was used to cross check the cavity fields with beam, bringing the measurement uncertainty down to a few percent. Surprisingly, the performance was found to have improved in the linac with respect to the vertical tests, and Q values increased up to 20 % in some cases. Most of the effect was related to the better cooling conditions that could be achieved in the cryomodule, where the temperature gradients across T_c were extremely small.

When the first cryomodule was opened to implement the improved RF coupling systems, venting was carried out by respecting the same gas velocity limitations which had proved effective to protect the cavities upon pump down. In spite of that, two cavities, those that were most exposed to the venting flow, were contaminated and were limited by field emission. Helium processing in situ was successfully applied at the end of the run. The lesson we retained is epitomized by the motto “no venting without rinsing”, but also that a sick cavity can be healed in the machine.

CONCLUSION

The HIE-ISOLDE upgrade at CERN is well under way and already delivering beam to the large ISOLDE physics community since 2015. In spite of all difficulties, it can be called a success. The SRF systems were designed and in large part manufactured at CERN, in a collective effort which resulted in a visible growth of the Organization’s know-how in the field of RF superconductivity. The main lessons learned in the making of it were summarized in this contribution.

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