HIE-ISOLDE SC LINAC PROGRESS AND COMMISSIONING IN 2016

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Abstract

After the first successful physics run with radioactive ion beams at HIE ISOLDE, in October 2015 [1], the staged deployment of the linac continued in 2016 by adding a second cryomodule and by refurbishing the first one. During the physics run with one cryomodule, the second cryomodule was being assembled. The refurbishment of the first cryomodule was made necessary to overcome limits imposed by thermal instabilities of the fundamental coupler lines. A modified design for the power couplers was developed and implemented on all the cavities, after extensive validation tests in a vertical cryostat. The paper will describe the lessons learnt from the first commissioning campaign, in particular concerning the fundamental power coupler, the solution adopted, and the results of the 2106 commissioning campaign with two cryomodules, which will allow reaching 5.5 MeV/u for all the species available at ISOLDE.

INTRODUCTION

The HIE ISOLDE project [1] reached an important milestone in October 2015, when the first radioactive ion beam was delivered to the users [2]. A ^{74}Zn beam was accelerated up to ~4 MeV/u by a single cryomodule hosting 5 superconducting quarter wave resonators and a superconducting solenoid for transverse focusing. This cryomodule, a prototype in all respects, had been entirely designed and assembled at CERN, with industrial partners supplying some of the main components. The heart of it, the Nb sputtered superconducting cavities, were manufactured at CERN [3] starting from copper substrates produced in industry. The cryomodule was installed in the new linac, deployed in 2015 with its cryogenics facilities and high energy beam transfer lines.

LESSONS LEARNT IN 2015

The commissioning campaign of 2015 brought to the surface a problem in the RF power coupling system, which was found to be thermally unstable at the chosen operational bandwidths. When running in self-excided loop mode, with constant forward power, the cavity fields were observed to steadily decrease while the loaded bandwidth was increasing and the resonance frequency dropped (see Fig.1). When running in feedback mode, field and frequency could be kept constant only at the price of constantly increasing the forward power.

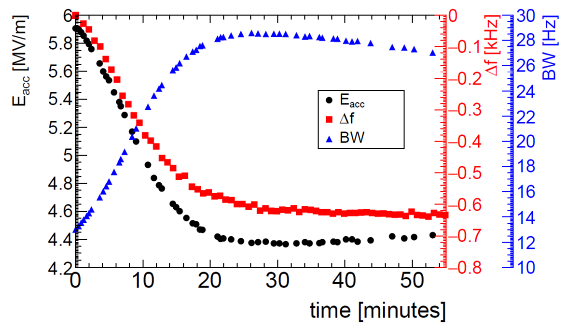

Figure 1: Thermal runaway, as seen in the RF signals.

All these signs were interpreted as the result of the thermal expansion of the coupler antennas.

Detailed thermal and RF models were developed in order to better understand the mechanism at work. The main finding of RF simulations done with CST MS was that a localized RF heating is present on the tip of the capacitive coupling antenna, when the cavity is loaded at the operational bandwidths. The coupler system was modelled with ANSYS, solving the relevant time dependent and non-linear heat equation. The output of the RF simulation was used for the distributed heat source. The calculations showed that the thermal anchoring of the RF cable was not optimal, and that the temperature distribution peaked at the tip of the antenna, reaching 600 K. Dedicated tests in a vertical cryostat confirmed that a thermal runaway could be initiated which would have eventually destroyed the couplers. Figure 2 shows a post mortem dissection of a test coupler after a stress test done for 3 hours at 200 W RF power in the vertical test stand.

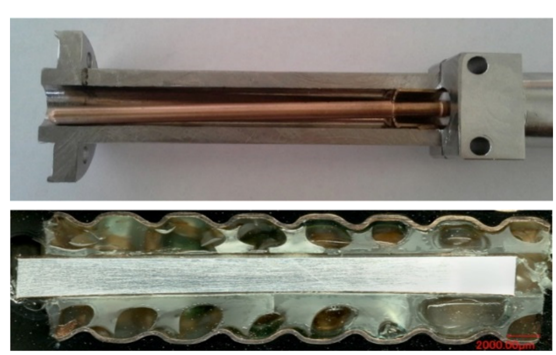

Figure 2: Sections of damaged coupler and RF cable after stress test in vertical cryostat.

ISBN 978-3-95450-169-4

The setup in the vertical cryostat was then used to find safe operational limits for the couplers already installed in the linac. The machine was operated only for 6 hours every day to let the couplers cool down in-between runs, and the accelerating fields were limited to 4 MV/m. Despite these severe restrictions, a selected physics program could be carried out between October and November 2015.

NEW RF COUPLER DESIGN

After benchmarking the numerical model by means of dedicated experiments in the vertical tests stand, design modifications could be evaluated in order to improve the thermal stability of the coupling system. The most effective design parameters were the material of the coupler antenna, the contact between the antenna and the inner conductor of the RF line, and the location of the thermal anchors along the line. The antenna material was changed from a bronze alloy to OFE copper, which was directly soldered on the cable, thus eliminating pressure contacts. A second thermal anchor was added very close to the coupler. The influence of these simple changes on the calculated temperature distribution is shown in Fig.3.

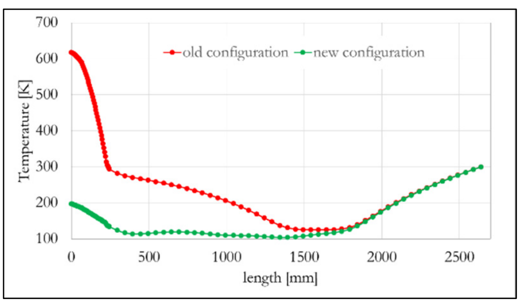

Figure 3: Predictions of the thermal model at 200 W forward RF power, for the old and new configurations.

For each cavity, two additional temperature sensors were implemented to monitor the temperatures of the coupler and of the RF cable. A prototype of the modified coupler was readily produced and extensively tested to validate the design. The result of 4 days running at nominal field (requiring less than 100 W) is shown in Fig. 4.

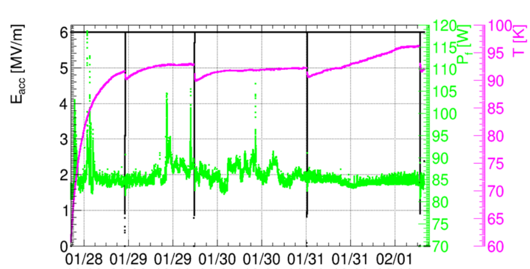

Figure 4: Results of prototype validation, with RF power, accelerating field and coupler temperature during a 100 hours heat run in the vertical test stand.

PREPARATION OF 2016 RUN

The first cryomodule was taken out of the machine at the beginning of the year and brought back to the assembly facility. Venting was carried out with filtered nitrogen in the ISO5 clean room, with a controlled speed to prevent turbulences. One of the cavities, which had shown mild signs of field emission during the physics run, was singled out for a new rinsing. The remaining cavities were left in place. In the meanwhile, 10 new coupler assemblies had been produced and the first 5 units were already integrated in the second cryomodule.

The two cryomodules were finally installed in the linac in early May, ready for cool down (see Fig. 5).

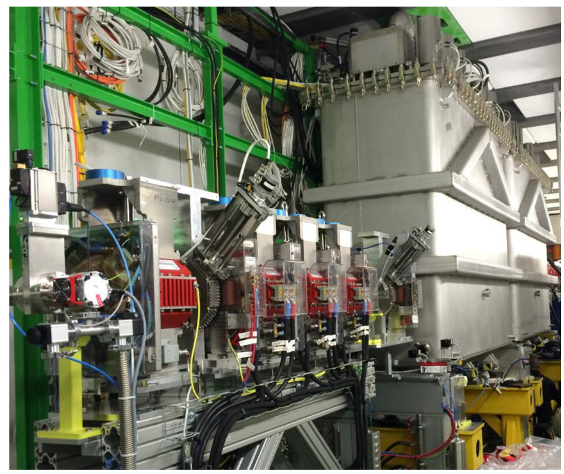

Figure 5: Two cryomodules installed in the linac.

COMMISSIONING OF 2 CRYOMODULES

Due to extended overhauling of the cryogenics facilities, and to the need of recommissioning the automatic processes, the active cool down of the two cryomodules had to be carried out in steps, interleaved with floating periods. Consequently, passive cooling of the cavities by the thermal shields was prolonged for several weeks, and the cavities spent 14 days between 200 K and 100 K (see Fig. 6).

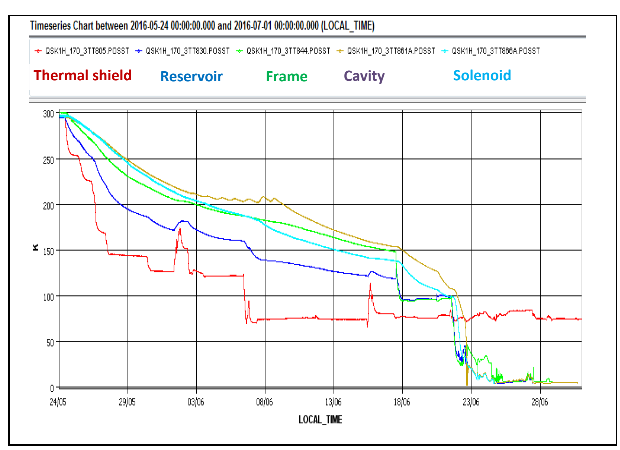

Figure 6: Cool down history of the second cryomodule.

Once the temperature of the cavities reached 200 K, conditioning of the multipacting levels at low field (up to 60 kV/m) was carried out, taking advantage of the variable couplers which are designed to reach sufficient coupling also in the normal conducting state.

Concerning the vacuum system, the residual gas pressure in the second cryomodule was constantly higher than in the first one since the end of the slow pump-down. Moreover, a few days after completion of the cool down at 4.5 K, the pressure started to increase spontaneously (see Fig. 7). Residual gas analysis was carried out and no excess of helium was found in the spectra, however the possibility of a cold leak could not be excluded due to the configuration of the vacuum system. Leak detection on the top plate was not conclusive. The pressure stabilized at 10^{-9} mbar, but the origin of the rise remained unknown.

Figure 7: Vacuum pressure log of the two cryomodules.

After cool down, all the cavities were tuned close to the target frequency. As it was found that one of the cavities had to run at the very bottom edge of the coarse tuning range, in order to create some tuning margin, the master frequency of the linac was slightly decreased (by 1 kHz).

The next step in the commissioning procedure was conditioning of the medium field multipacting levels (around 1.5 MV/m), which was readily achieved in CW.

The couplers were then moved to reach critical coupling in superconducting state, for precise RF measurements of the Q-E curves. All measurements were done my means of the fully digital HIE ISOLDE low level RF systems, which were accurately calibrated beforehand. Fast RF interlocks were set on the forward RF power and on the cavity field to avoid overpowering the cavities.

A portable X-rays monitor was placed inside the shielding between the two cryomodules and its reading was remotely accessible from the control room.

Two cavities, the first and the last one of the first cryomodule, were found to emit X-rays above 3.5 MV/m.

The Q-E curves of all the 10 cavities are shown in Fig. 8. Apart from the two cavities affected by field emission, all the others reach the nominal field of 6 MV/m close or below the specified power dissipation of 10 W. The RF performance is systematically better than in the vertical tests. This is believed to be an effect of the more homogeneous cooling through T_c in the cryomodule [4].

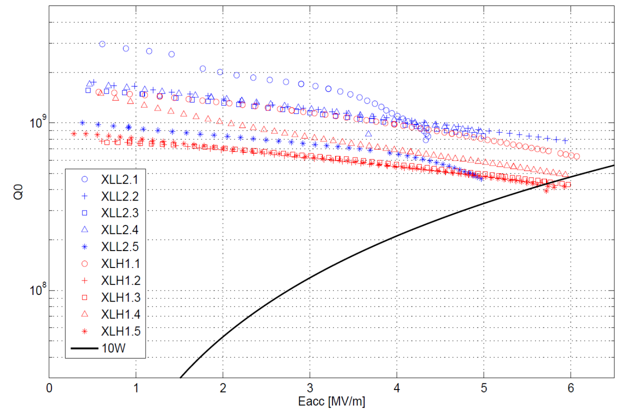

Figure 8: RF performance of all cavities.

Retrospectively, it is quite understandable why the first and the last cavity of the first cryomodule were contaminated, as they are the most exposed to the venting flow. Clearly venting in the clean room with a controlled speed was not enough to protect these two cavities. In light of this experience, in future all cavities will be systematically rinsed after venting. On the other hand, all cavities of the second cryomodule were clean up to 6 MV/m, which confirmed the soundness of the assembly procedures, including the slow pump down protocol.

Attempts to condition one of the two sick cavities with RF power led to a further degradation, so it was decided to back off and operate the two cavities below the onset of field emission. With this constraint, a suitable optics solution was worked out, which would allow to deliver the requested beams for all the experiments scheduled in 2016. The cryomodules are equipped with manifolds foreseen for helium processing. It is planned to try and condition the two cavities at the end of the physics run.

Setting up of the low level RF loops was undertaken after the Q-E measurements: the chosen operational bandwidths were between 5 Hz and 10 Hz depending on the cavity. The loops had to be set up individually, because each cavity works at a different set-point of the tuning plate, resulting in a different Lorentz force detuning coefficient. Moreover, the external perturbations coming from the cryogenics plant affect each cavity to a different extent, according to its position relative to the helium inlet pipes. The main difficulty in achieving stable operation at the nominal field quality (0.1 % RMS in amplitude and 0.2 degrees RMS in phase) was actually a strong perturbation affecting all cavities in a coherent way with a period of about two minutes. After a long search, the source of the perturbation was finally traced to the actions of the control systems in the cryogenics plant, as shown in Fig. 9. Changing the operation point of the plant mitigated the problem. This immediately allowed long runs with all the cavities at the requested field levels with closed loops. On this occasion, it was verified that the coupler temperatures reached equilibria around 100 K, well in line with the predictions of the thermal model.

ISBN 978-3-95450-169-4

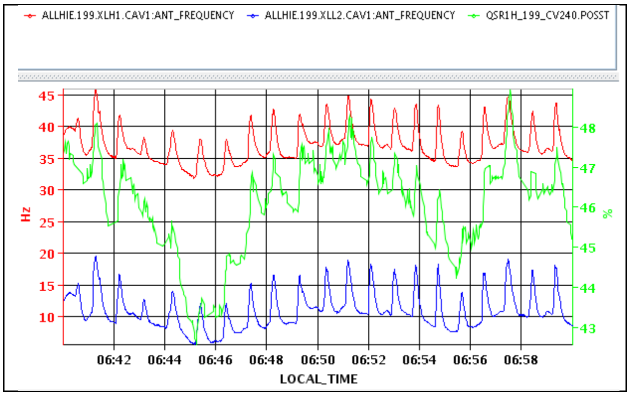

Figure 9: Correlation of cryogenics valve opening and cavity detuning.

Another problem had to be faced during commissioning of the superconducting solenoids, when a short circuit to ground was detected in one of the two circuits (in the first cryomodule). Time Domain Reflectometry was used to locate the fault, which appeared to be on one of the bus bars, outside the superconducting coils. Therefore, the problem could be circumvented by displacing the ground connection from the power converter to the current lead close to the fault. The resulting ground loop was loaded with a 100 Ω series resistor, to suppress parasitic currents through the fault during operation. In order to limit the stored energy, the maximum operating current for this circuit was downgraded to 50 A, which is considered sufficient for good beam transmission through the first cryomodule, for the expected emittances delivered by the normal conducting linac upstream.

The second solenoid reached its nominal current of 110 A with one training quench (at 60 A).

Monitoring of the positions of the active elements with respect to the beam axis is continuously done by means of the MATHILDE system [5]. The measured displacements during the cool down phase are shown in Fig. 10.

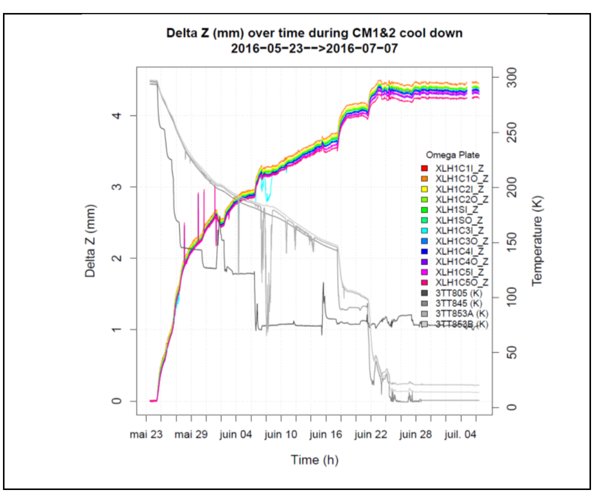

Figure 10: measured vertical displacements of active elements during cool down

The vertical positions moved up by ~4 mm as expected due to the thermal contraction of the supporting structure. Lateral displacements were minor, fractions of mm. After cool down the elements were re-aligned vertically by means of the remotely controlled adjustment systems integrated in the cryomodule design.

BEAM COMMISSIONING

Alignment at cold was the last step in the hardware commissioning programme. However, open issues were still left when hardware commissioning activities were paused to allow starting the beam commissioning work. The most prominent in the short term was that, although the oscillations in the cryogenics plant had been mitigated, they would still cause the two most sensitive cavities to trip on a regular basis, also due to some other not identified sources of detuning. The low level RF settings could still be adapted to cope with that, but the easy solution of increasing the bandwidth indefinitely was not an option, due to the increased risk for the couplers.

The beam commissioning programme had to be severely reduced due to planning constraints. The setup beam was a mixture of C, Ar, O and He ions, with A/u=4. Commissioning of the REX normal conducting injector was done in parallel with the hardware commissioning of the superconducting linac. This was then followed by transport of the beam with the REX energy through the high energy transfer lines, and setting up of all the beam diagnostics boxes.

The next step was phasing of the ten superconducting cavities (see Fig. 11), which also provided a cross check of the calibration of the accelerating gradients. The beam energy was measured with silicon detectors located downstream the cryomodules and independently with one of the dipoles in the high energy transfer lines used as a spectrometer. Other techniques, such as time of flight and phase differences with a scanning slit, were used to assess and improve the accuracy of the energy measurement, which is crucial information for some of the experiments.

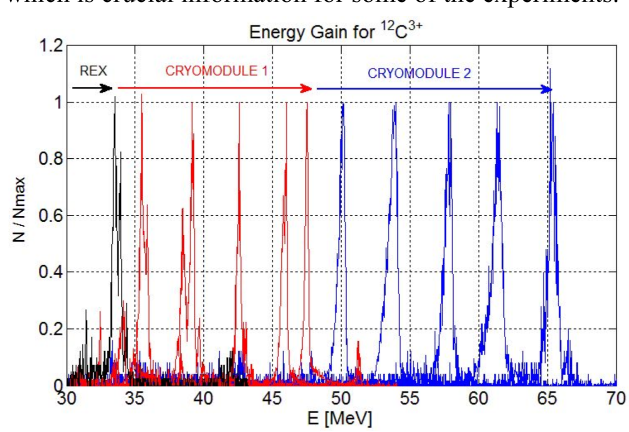

Figure 11: first phasing of the ten superconducting cavities with $^{12}C^{3+}$ beam. The first peak corresponds to the output energy of the REX injector.

Beam acceleration up to 5.4 MeV/u was achieved with the setup beam. The first experiment started taking data on Friday 9 September 2016 with $^{110}Sn^{26+}$ beam at 4.5 MeV/u.

CONCLUSION

With the installation and commissioning of the second high beta cryomodule, which will allow accelerating up to 5.5 MeV/u all the radioactive ion beams available at ISOLDE, the HIE-ISOLDE project completed its phase 1.

The first physics run, in 2015, had been limited in scope due to the uncovered thermal instability of the RF coupling systems. In few months a new design for the coupling lines was developed and validated. A small series of the new couplers was produced just in time to implement them in the second cryomodule, which was being assembled. The first cryomodule was taken out of the machine and retrofitted with the improved couplers. The hardware commissioning campaign in 2016 was marked by new problems, which will demand more work, but none of them seems to represent a showstopper for the incumbent physics run. At the end of the run, two cavities will have to be conditioned at high field, and if that will not be possible, the cryomodule will have to be opened again for a new rinsing of all cavities. The cryogenics process will be further tuned aiming at reducing oscillations which cause detuning of the superconducting cavities.

Work is in full swing to assemble the third cryomodule and to further improve the cavity technology in view of completing phase 2 in the near future.

The HIE ISOLDE superconducting linac is just starting its life of key instrument for the nuclear physics community.

ACKNOWLEDGMENT

We gratefully acknowledge all the technical teams and the CERN management for their continuous support.

We acknowledge funding from the Belgian Big Science program of the FWO (Research Foundation Flanders), the Research Council K.U. Leuven, as well the receipt of fellowships from the CATHI Marie Curie Initial Training Network: EU-FP7-PEOPLE-2010-ITN Project number 264330

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ISBN 978-3-95450-169-4