HIE-ISOLDE: FIRST COMMISSIONING EXPERIENCE

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Abstract

The HIE ISOLDE project [1] reached a major milestone in October 2015, with the start of the first physics run with radioactive ion beams. This achievement was the culminating point of intense months during which the first cryomodule of the HIE ISOLDE superconducting linac and its high-energy beam transfer lines were first installed and subsequently brought into operation. Hardware commissioning campaigns were conducted in order to define the envelope of parameters within which the machine could be operated, to test and validate software and controls, and to investigate the limitations preventing the systems to reach their design performance. Methods and main results of the first commissioning of HIE ISOLDE post accelerator, including the performance of the superconducting cavities with beam, will be reviewed in this contribution.

INTRODUCTION

The cryomodules developed at CERN for the HIE ISOLDE project [1] host five superconducting quarter wave resonators and a superconducting solenoid. The cavities are based on the Nb/Cu technology already in use at CERN and for the ALPI machine of INFN in Legnaro. The cryomodule design is of the common vacuum type, which makes the assembly process very critical to avoid contamination of the RF surfaces. More information on the superconducting elements and on the cryostat is in [2], [3]. After a few years of development the first cryomodule- technically a prototype- was assembled and installed in the ISOLDE linac tunnel in view of inaugurating the rich physics program as scheduled at the end of 2015. The commissioning work started in May and extended over the whole summer, with the goals of qualifying the hardware systems for operation with beam within safe boundaries in the parameters space, validating software and controls, and to identify eventual limitations and non-conformities.

COMMISSIONING PROCEDURES

The commissioning activity involved several teams of experts and had to fit into a tight planning. The cryomodule subsystems to be qualified are very often interdependent, and the sequence of tests to be performed needs to be carefully thought out, in order to avoid inefficiencies, performance reductions, or even damage to the equipment. To this end, a detailed procedure was elaborated and adopted throughout the commissioning period. Besides the sequence of tests, the entry and exit conditions for each step, acceptance criteria and safety aspects were detailed. The main steps of the procedure for the cryomodule commissioning are listed in Table 1 below.

Table 1: Commissioning Steps of HIE ISOLDE Cryomodules

1	Slow pump down
2	Interlock checks
3	Instrumentation checks
4	LLRF setup
5	Cool down
6	Alignment and monitoring
7	RF conditioning above Tc
8	RF tests at cold
9	Solenoid tests
10	Heat load measurements

VACUUM PERFORMANCE

The common vacuum design implies a need to control the pumping speed during all transients until the molecular regime is reached, to prevent movements of particulate which may contaminate the RF cavities. To this end the gas velocity close to the cavities was kept below 0.3 m/s.

The vessel was evacuated after assembly and transported to the linac under static vacuum with valves pinched off.

The vacuum performance was extremely good: after cool down, pressures in the low 10^{-11} mbar range were reached.

CRYOGENICS ASPECTS

The first cool down of the cryomodule was achieved in about 3 weeks. The process was subject to constraints on the allowed temperature gradients across the cryomodules subsystems, motivated by thermo-structural limits and by the need to concentrate cryo-pumped gases outside the RF surfaces. Considering that the cryogenics plant was being commissioned at the same time, the availability of the cryogenics system was very good. In one occasion, the cryomodule was over-pressurized due to an instability of the plant, and the rupture disk burst open with release of helium in the ISOLDE hall. The situation could be handled promptly: the rupture disk was replaced before the system had the time to fully de-pressurize, avoiding a full warm up. The incident was thoroughly analysed and corrections in the cryogenics process logic were implemented to mitigate the risk of similar events in the future.

The static heat load on the cryomodule was measured using a boil off technique, and found to be in line with the design value of 10 W at 4.5 K.

SURVEY AND ALIGMENT

The position of the active elements on the beam line were monitored by means of a newly developed system based on optical targets which can be observed from outside the cryomodule [4]. During assembly, cavities and solenoid were deliberately positioned about 4 mm below the nominal beam line (NBL) to anticipate the vertical retraction of the suspended supporting system. After a small adjustment at cold, the centres of all these elements could be aligned within 0.1 mm, which is well below the specifications (0.3 mm for the cavities and 0.15 mm for the solenoid).

RF PERFORMANCE TESTS

A newly developed, fully digital Low Level RF system was deployed to control the superconducting cavities. Its functions include locking of the resonators on their resonance for measurement and conditioning, and on amplitude and phase set-points for beam operation. The LLRF system also controls the variable couplers and the tuning system. One of the first operations was to set all cavities close to the target frequency of the HIE ISOLDE linac (101.28 MHz). Conditioning of the multipacting levels started during the cool down phase, using ~50 W CW power fed to the warm cavities. The variable couplers and the self excided loop function of the LLRF system were instrumental for an efficient conditioning of all the multipacting bands around 20 kV/m, which can be reached still in the normal conducting state. The HIE ISOLDE cavities display as well a multipacting band around 1.5 MV/m, which must be conditioned in the superconducting state. Once the cavities were free of multipacting, their Q vs E curves were measured, making use of the variable couplers to achieve critical coupling conditions. The measurement results are shown in Fig. 1.

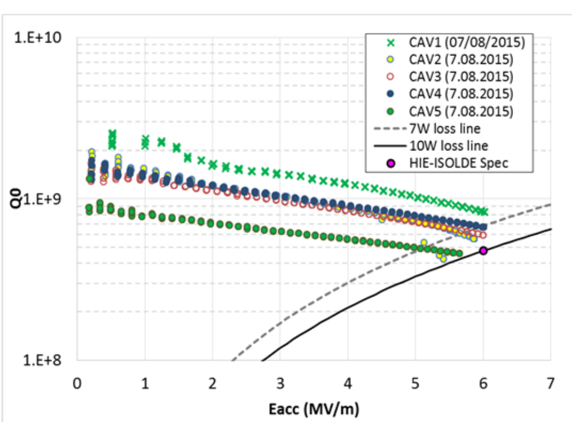

Figure 1: RF performance of the superconducting cavities in the cryomodule.

Two features deserve attention: the first is that, with one exception, all cavities reached nominal field without field emission, which convincingly demonstrates the soundness of the assembly procedures. One cavity, which had been subject to a small delamination of the Nb film, had a mild field emission onset above 5 MV/m. The second, even more remarkable fact is that the RF performance in the cryomodule was better than in the vertical tests of the individual cavities, insofar as Q values were concerned. After a careful search aimed at eventual systematic errors, it was concluded that the effect is real and it is due to the optimal cooling conditions in the cryomodule. The surface resistance of the Nb sputtered films on HIE ISOLDE cavities is only in minor part (less than 30%) explained by the BCS mechanism. Indeed, already during the development phase, it was established that an important component to the residual resistance was linked to the temperature gradient across the cavity during the superconducting transition. The likely loss mechanism is trapped magnetic flux generated by thermoelectric currents [5]. All cavities are tested in a vertical cryostat taking care of minimizing the temperature inhomogeneity during the superconducting transition. There remains however a residual gradient. The performance of the cavities in the cryomodule is very close to an extrapolation to zero temperature gradient during cool down. Indeed, in one of the cavities this had been already achieved in the vertical test and the two measurements are matching.

A crucial test was the combined powering of the cavities and solenoid together, which verified the absence of any perturbation from the stray magnetic field of the solenoid on the cavities. The stray field had been specified to well below the lower critical field of niobium, but a large uncertainty remained on the actual values of the latter in our sputtered Nb films.

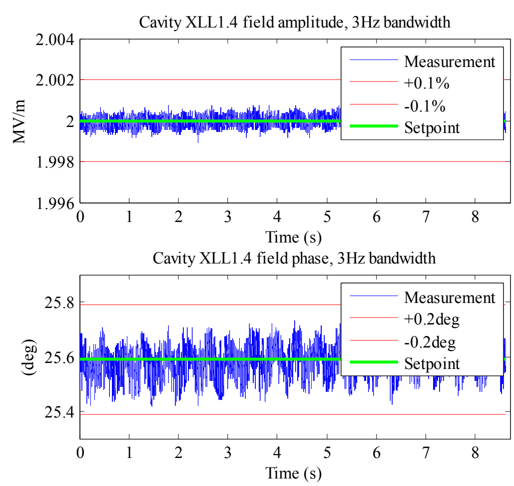

Figure 2: Performance of the LLRF system.

Once the cavities were measured, the variable couplers were moved again to the chosen bandwidth for beam operation (10 Hz), and setting up of the LLRF feedback loops started. The specifications called for 0.1 % RMS

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stability in amplitude, and 0.2 deg. in phase. As shown in Fig. 2, the requirements were met with a large margin.

SOLENOID PERFORMANCE

The superconducting solenoid had been trained to nominal current at the factory and was operated with ~20 % margin. No natural quench were observed. One quench was provoked to check the reaction of the cryogenics systems to the deposited energy in the helium bath. The pressure rise was found to be negligible, as expected. The solenoid is self-protected by means of a bypass network of resistors and diodes. A small issue encountered was the change of differential impedance upon polarity reversals, which was detected by the sensitive controls of the power converters and caused trips when operating in current mode. The problem was circumvented by running in voltage mode when the polarity needed to be swapped, in particular to carry out degaussing cycles prior to warm up.

RF COUPLER LINES INSTABILITY

When enlarging the bandwidth, with the consequent increase of the RF power needed to maintain and control high fields in the cavities, we faced the main issue of the commissioning campaign, which would determine all the subsequent events in the project.

The RF signals were found to be drifting in a way which could only be interpreted as the effect of a slow expansion of the coupler antenna. Indeed this was confirmed with off line tests in a vertical cryostat, highlighting a design flaw in the RF feed system, which would lead to thermal breakdown in a few hours operation at nominal parameters. Following these findings, a crash program was launched to understand and solve the problem. A new design for the coupler lines was developed, to be installed in the second cryomodule, and retrofitted to the first. In the meanwhile, it was decided to concentrate the efforts on pushing the performance of the LLRF system and operate at reduced bandwidth in order to limit the forward power. This was possible because the level of microphonics of the stiff copper cavities is very low, as is their sensitivity to helium pressure fluctuations (0.01 Hz/mbar). Eventually, operation at 3-4 Hz bandwidth was achieved, which allowed to stabilize the cavities at 4 MV/m accelerating field with about 35 W forward power. The main difficulty in reducing the bandwidth was the huge Lorentz force detuning coefficient caused by the thin tuning plate at the bottom of the quarter wave resonators. In order to contain the risk of thermal breakdown in the coupler lines, it was also decided to limit the daily duration of cavity powering to 6 hours, to allow cooling of the RF couplers and lines in between runs. From the list of approved experiments a selection was made keeping into account these constraints: the scene was thus set for the beam commissioning campaign, as reported in another paper [6].

CAVITY PERFORMANCE WITH BEAM

The first phasing and acceleration of a stable beam was at the same time the final confirmation of the accuracy of the RF measurements. The beam energy was measured with a silicon detector located downstream the cryomodule and independently with one of the bending magnets in the high energy transfer lines used as a spectrometer. The cavity phases were scanned to observe the sinusoidal modulation of the output energy. The accelerating voltages resulting from the three methods agree within 3%.

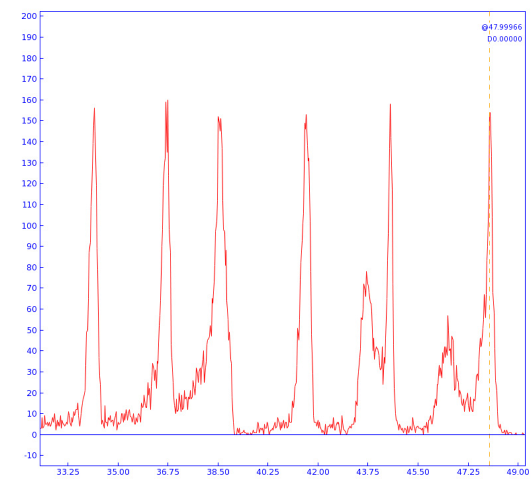

Figure 3: phasing of the five superconducting cavities with a $^{12}C^{4+}$ beam. The first peak corresponds to the output energy of the REX injector.

CONCLUSION

The first commissioning of the HIE-ISOLDE linac was carried out in 2015. The overall performance of the main technical systems was satisfactory. A weakness was identified in the main RF coupler lines, which limited the scope of the first physics run. Despite this setback, the machine could be prepared for a first significant physics run starting in October 2015, thus inaugurating a new era of measurements for the ISOLDE community.

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