COMMISSIONING OF THE MAX 700 MHz TEST STAND*

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Abstract

The MYRRHA project aims at the construction of an Accelerator Driven System demonstrator. The criticality will be sustained by an external spallation neutron flux produced thanks to a 600 MeV high intensity proton beam. This beam will be delivered by a superconducting linac which must fulfil very stringent reliability requirements. Under the MAX (MYRRHA Accelerator eXperiment) program, which aims at pursuing the R&D activities on the ADS-type accelerator, a 700 MHz Cryomodule was developed. The main goal of this test stand is to dispose of a facility to carry out "real scale" reliability oriented studies on a RF Superconducting cavity of the high-energy linac section. This module holds a 5-cell elliptical cavity equipped with its blade cold tuning system and its coaxial power coupler. The experimental work undertaken at IPN Orsay, has allowed to fully qualify the module in machine configuration (high RF power, at 2K), including assessment of the tuning system and measurement of microphonics spectrums. During this study the dynamic behavior of the fast tuning system of the cavity was also measured. We review here the obtained results and lessons learnt by operating this module.

INTRODUCTION

MYRRHA (Multi-purpose Hybrid Research reactor for High-tech Applications) is a new fast spectrum nuclear facility which is planned to be built at SCK-CEN in Mol (Belgium) [1]. This 100 MW_{th} nuclear reactor is especially designed to demonstrate the ADS (Accelerator Driven System) concept for the transmutation of high level radioactive wastes. To operate, the sub-critical reactor requires a continuous wave (CW) proton beam, with a maximum power of 2.4 MW (600 MeV - 4 mA). In addition to the high beam power, one has to consider that frequently repeated beam interruptions can induce high thermal stresses and fatigue on the reactor structures, the target or the fuel elements, with possible significant damages especially on the fuel claddings. Therefore the accelerator will have to be extremely reliable. The present tentative limit for the number of allowable beam trips is 10 unexpected interruptions longer than 3 seconds per 3-months operation cycle.

In this purpose, the accelerator design is based on a redundant and fault-tolerant scheme to enable the rapid mitigation of RF failures [2]. The conceptual design of this ADS-type accelerator had been recently consolidated in the frame of the MAX project (EURATOM FP7) [3]. It is composed by a 17-600 MeV superconducting main linac [4] with independently-powered spoke and elliptical cavities, fed by a redundant 17 MeV injector [5].

In the continuation of the work initiated within the FP6 EUROTRANS programme [6], a prototypical cryomodule of the medium-energy section of the MYRRHA proton linac has been developed, built and fully tested in "accelerator-like" configuration, and a few reliability-oriented experiments have been performed in view of the foreseen MYRRHA fault-recovery procedures [2].

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THE MAX CRYOMODULE 700 MHz TEST STAND

Jointly developed by INFN Milano and IPN Orsay, the MAX prototypical cryomodule is composed of the following elements: a MYRRHA-type/TRASCO β=0.5 elliptical superconducting cavity [7], as illustrated in Figure 1, a slow mechanical Cold Tuning System (CTS), a fast piezo-based CTS, a high-power coupler, a 80 kW IOT operating at 700 MHz, a digital Low Level RF (LLRF) feedback system coupled to the CTS control loop, a cold valve box and all cryogenic circuits (2K, 4K, coupler supercritical cooling loop).

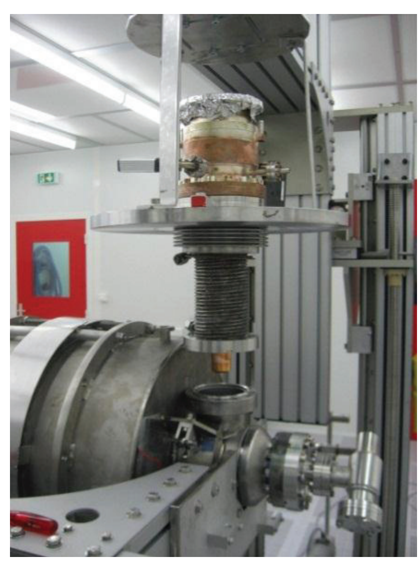

Figure 1: 5-cell SRF elliptical β=0.5 cavity being connected to its high-power RF power coupler in clean room.

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The cryomodule has initially been installed and operated at low RF power, without high-power coupler. These tests have been made to tune and improve the whole cryogenic performances of the module and to perform first RF measurements of the cavity in critical coupling configuration using a PLL RF loop, together with first assessment of the cold tuning system operation. In parallel, two 700 MHz high-power couplers have been also conditioned up to 62 kW in CW mode for the needs of the experiment. These main initial results are summarized in [8].

CRYOMODULE COMMISSIONING

The first successful complete commissioning of the MAX cryomodule test stand at 2K and high RF power, using the 80 kW IOT, has been performed in March 2014.

During this test, before filling the cryomodule with liquid helium, a coupler reconditioning has first been performed at room temperature. After cooldown, the cryogenic operation of the module has been fully validated, with a special focus on the qualification of the cooling loop of the coupler external conductor, using supercritical helium at 5K. The static heat loads have been measured for each component; they are in agreement with the design expectations and with previous measurements of [8].

RF power tests have been performed on the cavity in PLL configuration. The cavity quality factor Q_0 has been estimated by crosschecking the RF measurements with the measured helium flow at the cryomodule output, with and without RF power. The obtained results are summarized in Figure 2.

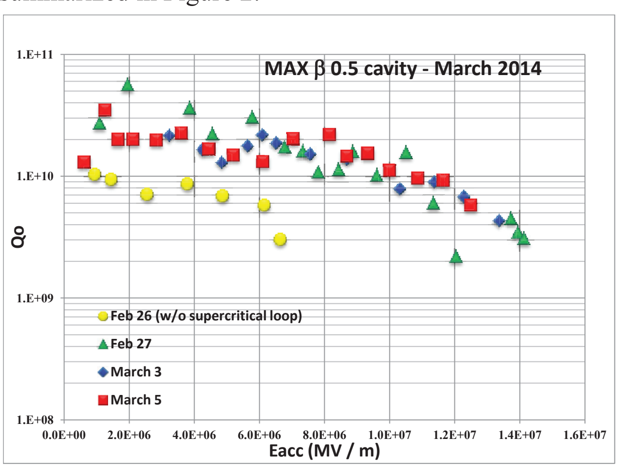

Figure 2: Measurements of the cavity performance at 2K.

Accelerating gradients up to 14 MV/m have been reached (quench), which is coherent with the measured values during the previous low-power tests [8] and with the older tests in vertical cryostat [9]. This value is fully acceptable and is higher than required for a nominal operating value of the cavity in MYRRHA (8.5 MV/m in normal conditions, up to 11 MV/m in fault recovery conditions). Two multipacting barriers were identified at 5.5 MV/m and 7 MV/m but easily processed. High field emission electron activity was recorded beyond typically 8 MV/m. It is also to be underlined that operation without using the power coupler supercritical cooling loop drastically decreases the cavity performances (early quench), as illustrate in Figure 2.

Several other cavity characteristics have been assessed. The static Lorentz coefficient has been estimated between 9 and 16 $(Hz/MV/m)^2$, that is also coherent with [9], and the cavity sensitivity to helium pressure variations has been measured around 350 Hz/mbar. These are very high values for a superconducting cavity which will operate with a quite narrow RF bandwidth (about 100 Hz in the MYRRHA case) and this confirms that SC very low-beta elliptical cavities are very soft mechanically, that might represent a serious drawback in terms of operation stability and reliability. The incident coupling Q_i has been estimated to about $3.5.10^7$, which is about 3 higher than expected (experiment goal was 10^7), further reducing the cavity operational cavity bandwidth to about 20 Hz. This is explained by the last cavity field profile measurements: it unfortunately showed a cavity field flatness notable degradation leading to a lower field level at the coupler location. This degradation probably happened during the repair of a leaking titanium weld on the cavity tank.

Finally, several measurements have been performed with the slow and fast piezo-based cold tuning systems during the cryomodule commissioning, including basic frequency control tests and measurements of microphonics spectrums, with and without piezo excitation, using a CRM monitor. The main background microphonics vibration was measured around 2 Hz. It is identified as a possible excitation from the compressor of the supercritical loop. Two additional peaks at frequencies 20 Hz and 115 Hz were also recorded with rather high amplitude, as shown in Figure 3.

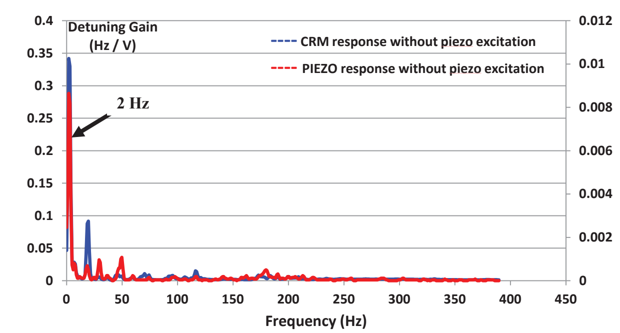

Figure 3: Measurement of microphonics background noise.

RELIABILITY-ORIENTED EXPERIMENTS

The main objective of the last MAX test which took place in June 2014 was to demonstrate the feasibility of the main steps of the RF cavity fault-recovery scenario [2] in real-scale, using the Cold Tuning System (CTS) with the adaptive control of ADEX [10] coupled to the digital LLRF control loop. In such a scenario, the phase and field

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set-points of the compensating cavities need to be quickly (but smoothly) changed without inducing instabilities in the different control loops. Simulations show that such a procedure should be feasible [11].

Coupled to the piezo-based CTS control loop, the digital LLRF controller has achieved successful control of the cavity field up to 3 MV/m, with very encouraging measured phase and amplitude RMS errors (about 0.5% and 0.5°). These tests have also allowed examining the response of the whole system to RF field set point changes, which is satisfactory when using ramps to ensure optimal stability (see Figure 4). Moreover, fast detuning of the cavity has been demonstrated using the piezo-capability of the tuner that provides a total detuning range of nearly 10 kHz on this cavity, that is coherent with the required 100 bandwidths.

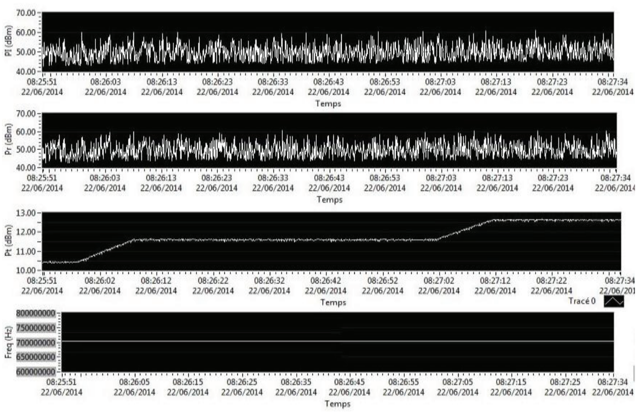

Figure 4: Measured powers during a field set-point increase.

Nevertheless, at high gradients (> 3 MV/m), the control process became unstable, especially due to the very narrow cavity bandwidth and to its very high sensitivity to mechanical perturbations. In particular, Lorentz force detuning effects seem to induce high frequency microphonics (70 Hz) that is too fast to be properly compensated by the piezo tuner loop, and that drives the whole system into instable conditions.

OUTLOOK

The 700MHz prototypical cryomodule of the MAX test stand has been fully characterized and successfully operated at 2K and high RF power. The performance of the LLRF and of the cold tuning system regulation loops have also been assessed, and a few experimental tests have been successfully performed to demonstrate the main sequences of the fault-recovery scenario that is foreseen for MYRRHA. Nevertheless, several problems have been encountered (linked to cryogenic operation, instrumentation, power coupler conditioning process, coupler supercritical cooling loop, RF control stability at high field levels…). Even if most of them have been solved, this underlines that particular care needs to be taken during the design and implementation phases of such a complex system.

It is recommended in the future to:

- Design and develop the different MYRRHA cryomodules taking into account the different lessons learned during this MAX experiment; reliability still needs to be improved on several key points (e.g. power coupler cooling).
- Improve the design of the elliptical low-beta cavity to make it much less sensitive to mechanical perturbations, or even consider to use an alternative cavity type with better mechanical performance (e.g. Spoke) for this 100-200 MeV energy range.
- Pursue the development of the LLRF+CTS coupled control systems and the on-going assessment of the fault-recovery procedures; the results obtained up to now are very promising but there is still room for improvement, in particular for the compensation of high frequency microphonics. It is also recommended to try to pursue these control activities using a more "reasonable" cavity on the mechanical point of view.

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