SPOKE CRYOMODULE PROTOTYPING FOR THE MINERVA PROJECT*

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Abstract

In the framework of the MINERVA (MYRRHA 100 MeV) project a first prototyping period started at the end of 2017. During this period a prototype cryomodule fully equipped (Spoke Cavities, Cryomodule Vessel, Cold Tuning System, Magnetic shielding, Power Couplers…) as well as its operating and controlling components (LLRF, RF amplifiers…) will be studied and manufactured. The aim of this prototyping period is first to complete the study of all the components and to validate the manufacturing and the assembling procedure in order to freeze the specifications for the serial construction. On the other hand the prototypes will serve as a test stand allowing to study and adjust the 'Fault Tolerance' strategy parameters, which is a challenging operating concept specific to the MYRRHA LINAC. This paper presents the various tasks related to this Spoke Cryomodule prototyping and their status.

INTRODUCTION

The MYRRHA [1] (Multi-Purpose Hybrid Reactor for High Tech Applications) project aims to build a hybrid reactor, driven by a superconducting LINAC (600 MeV, 4 mA max. CW) in order to demonstrate radiotoxic waste transmutation.

Since the first quarter of 2016, SCK•CEN has endorsed the construction of the first part of the MYRRHA accelerator up to an energy of 100 MeV called MINERVA. MINERVA, planned to be in operation in 2027, will feature a proton target facility with an ISOL target station.

A period of R&D has started in July 2017 and aims to manufacture and test the main and critical components of the MINERVA accelerator. In this framework SCK.CEN in collaboration with CNRS/IN2P3 laboratories (LPSC, LAL, IPNO) and the ACS company are in charge of the prototyping of a full equipped low energy (Beta=0.37, 352 MHz) SRF cryomodule. Each components (SRF 'Spoke' Cavities, Cryostat, Low Level RF control, Power Couplers, RF Amplifiers, Cavity Tuning System…) will be manufactured and assembled to be tested in a dedicated test bench. Tests will be performed at full RF power and will be focused on the reliability and the 'Fault Tolerance' strategy aspects which are the challenging goals for the MYRRHA accelerator. In this paper we describe the main characteristics, the conceptual design, the assembly and test facilities as well as the status of each components and tasks.

RELIABILITY AND 'FAULT TOLERANCE' STRATEGY

The coupling of the accelerator with the nuclear reactor requires a very small number of beam trips, in order to reduce the thermal stresses on the reactor mechanical structure. The requirement for the accelerator MTBF (mean time between failures) is above 250 hours and the allowed number of beam trips longer than 3 seconds must not exceed 10 per 3-months operating period. These two strong requirements have been taking into account for the overall accelerator design by using a reliability study done on the SNS LINAC operating feedback, during the former MAX European project. Several engineering typical concepts were used like conservative design, margins, maintaining operations improvements, manufacturing reproducibility, components redundancy, availability requirements.

The injector line components, was identified to have the greatest beam trips probability. The LINAC is then designed with a double complete injector line, where a fast switching magnet placed at the beginning of the SRF section will be able, in case of failure, to switch from one injector line to the other.

The main and most challenging concept to overcome the beam trips on the SRF section is the so called 'Fault Tolerance' strategy [2] which aims to a fast (less than 3 seconds) compensation of a failed cryomodule by adjusting the parameters of the adjacent ones. The general layout and the beam dynamics of the LINAC was designed to fulfil the fast compensation requirement. This fixed various design choices, as the number of focusing components and beam diagnostics, components specifications with 2 operating modes (normal operation and operation with compensation), the number of cavity per cryomodule, on the basis that if one full cryomodule is off it can be compensated by the others.

CRYOMODULE

The cryomodule houses 2 Spoke (beta 0.37, 352 MHz) cavities, cooled at 2K from an external valves box and powered with a 10 kW CW RF power coupler (see Figure 1).

Spoke Cavities

The single Spoke cavity have been designed with conservative parameters (E_{pk}/E_{acc}=4.29, B_{pk}/E_{acc}=7.32 mT/MV/m) and taking into account former spoke cavities manufacturing feedbacks. The cavities will have a beta optimal of 0.37 at 352 MHz with E_{acc}=7 MV/m for nominal operation and E_{acc}= 9.1 MV/m for fault recovery operation (E_{acc} is given at β_{opt} normalized to $L_{acc} = N_{gap}.\beta.\lambda/2$).

Two prototypes with identical RF design have been manufactured and tested in the framework of the MYRTE European project. The purpose was to optimize the cavity RF surface preparation process (chemical etching, High pressure rinsing and mainly high temperature baking parameter and process optimizations). Tests results (E_{acc}=9.1 MV/m with $P_{RF} < 10$ W) are inside the specified values. The maximum measured gradient with the optimized surface preparation processes was E_{acc}=15 MV/m before quench, which gives a very good margin and fulfils the reliability requirement.

Two additional prototypes for the MINERVA cryomodule are currently under manufacturing and are planned to be delivered in September 2019. These two prototypes were optimized for their mechanical characteristics. The aim is to lower the sensitivity of the RF fundamental mode frequency to the slow helium bath pressure fluctuations and to the fast micro-phonics perturbations, in order to reduce the tuning system overall operating time, for reliability purposes.

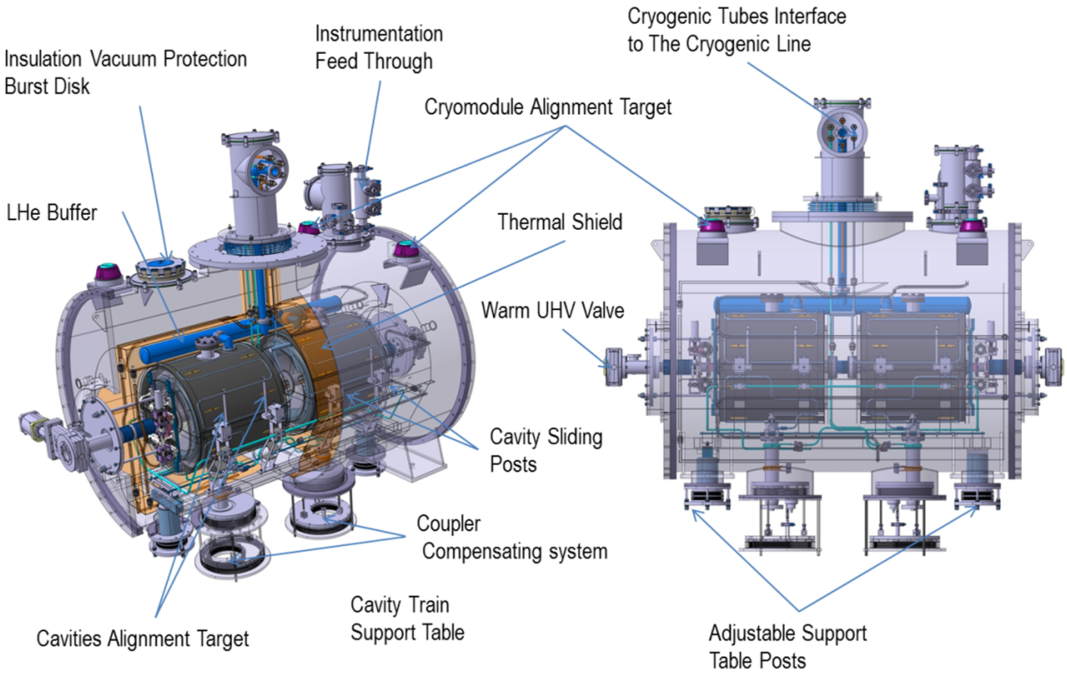

Figure 1: MINERVA spoke (beta=0.37, 352 MHz) cryomodule conceptual design.

Tuning System

The tuning system for MINERVA (see Figure 2) is derived from the ESS Spoke cavities tuning System. It stretches the cavity on its axis, by means of double lever arms actuated by a screw-nut system and motorized by a stepping motor. Two piezoelectric actuators are inserted in the lever arm parts to stretch the cavity along its axis with a range of around 10 micrometres at around 2 K and for a maximum oscillation frequency of 800 Hz.

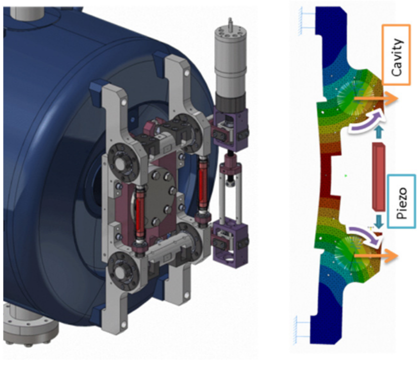

Figure 2: MINERVA spoke tuning system.

The design requirements are mainly subjected by the reliability and the fault tolerance strategy requirements. A dedicated cryostat has been manufactured to qualify the piezo electrical actuators, and different mechanical components (screw-nut system, ball bearings, planetary gearhead, stepping motor…) and will be used for long term operation at 80K under vacuum during 1 year.

To handle the fault compensation a very fast detuning (cavity completely detuned in less than 3 seconds) is required. A solution using an over-dimensioned stepping motor with a high acceleration capability has been tested and has shown its feasibility. The mechanical design is under progress and 4 tuning systems (two for long term operation tests and two to be installed inside the cryomodule) are planned to be manufactured for the beginning of 2020.
In parallel, a specific control board, designed to be inserted in the LLRF MTCA chassis, is under development.

RF Power Couplers

The Power Coupler for MINERVA (see Figure 3) features a ceramic warm window maintained above 15°C with an air circulation and a hollow internal conductor (antenna) cooled with water and maintained at a maximal temperature of 300K. Several diagnostics and control probes are placed on the ceramic block; one electron pick up, an optic fibre, a glass window, and two Penning vacuum gauges (redundancy for reliability purposes). The outer conductor features two heat interceptions, one at around 60 K and the other at around 10 K. The estimated [3] heat loads by solid conduction are 8.8 W at 60K, 2.3 W at 10 K, 0.4 W at 2K. The estimated radiative heat load is 0.4 W at 2K. The RF design [3] was made for 80kW CW in travelling wave mode operation and a conservative value of the maximal electric field was obtained (0.5 MV/m@80kW).

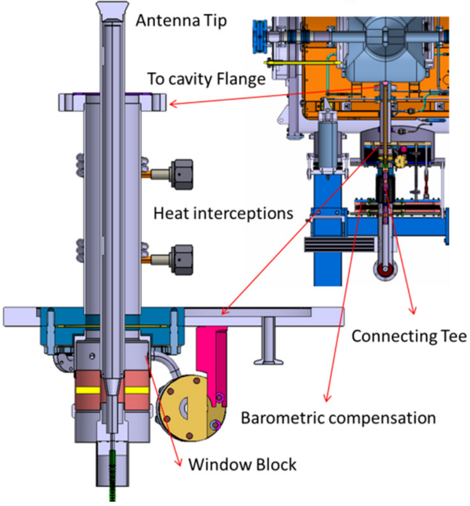

Figure 3: MINERVA spoke power coupler.

The antenna tip is designed with a 'mushroom type' shape to reduce the RF perturbations on the cavity. Simulations done on the MUSICC3D [4] software shows that the first multipacting barrier (not situated at the ceramic window) occurs at 67 kW @ 0.37 MV/m, which is above the maximum operating RF power [3].

Other components design, as the transition tee allowing the connection of the RF coaxial line and the antenna cooling tubes has been done as well as the design of a barometric compensating system aiming to reduce the pressure loads on the cavities when evacuating the cryomodule vacuum vessel. The manufacturing of 4 power couplers is about to start and the delivery is planned for the summer 2020.

The power couplers will be conditioned in the LLA facility, formerly used for the X-FEL power coupler production. The design of the specific tooling for the MINERVA couplers and the manufacturing of a conditioning cavity are under progress.

Cryomodule Vessel

The Cryomodule Vessel houses the different mechanical and cryogenic systems required to support and maintain at 2 K the SRF cavities (see Figure 1). It features one thermal shield cooled at around 60 K, a phase separator feeding the cavity helium vessel at around 2 K, and various loops at 60K and 10K to feed several heat interceptions used to optimize the overall cryogenic power on the cavity supporting frame, the power couplers and the warm-cold transitions. The evaluated static thermal loads are below 90W @60K, 8W@10K and below 3W@2K.

The cavities are supported on a dedicated frame with position adjustment and thermal contraction compensation functionalities. A part of this frame is assembled with the cavities, the power couplers, the warm-cold transition and the cryomodule extremities valves, in a class 4 clean room, before being inserted inside the cryomodule vessel (cryostating). A special attention was taken to simplify the cryomodule assembly (cryomodule and assembly tools design) in order to obtain a good reproducibility during the serial manufacturing and during the maintaining operations. The cryomodule vessel is currently under manufacturing and is planned to be delivered in spring 2020.

Cryogenic Valves Box

The cryomodule will be feed with cryogenics fluids from an external cryogenic valves box, connected by mean of a cryogenic 'jumper' (see Figure 4). The valve box houses all the cryogenic valves, including the JT valve and the sub cooling heat exchanger. Such a choice was made to separate the functionality of the cryomodule vessel and the valve box, with the aim to simplify the manufacturing and to increase the LINAC components modularity. A special attention was required for the design of the cryogenic 'jumper', as too important thermal loads on the 2K returning tube would unbalance the sub cooling heat exchanger and impact the mass flow production of the JT valve.

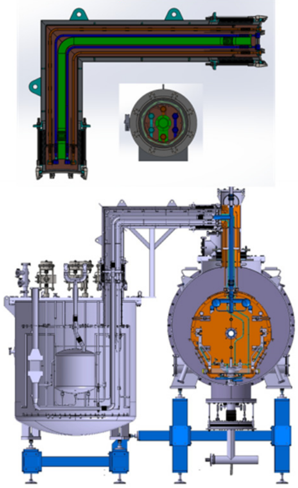

Figure 4: Valves box and 'jumper'.

The valve box designed for the MINERVA prototyping is for tests purposes only. It is designed to be consistent with the IPNO cryogenic test installation and will operate in liquefier mode with external LHe dewars. The 60K fluid will be provided by mean of liquid nitrogen at 77K, the 10K from liquid helium vaporisation and the 2K pumped bath by mean of roots pumps at 300K. The characteristics of the heat exchanger, the cryogenic valves, including the JT valve, and the phase separator have been over-dimensioned to a maximal power of 90W@2K, in order to test the SRF cavities at their upper limits.

The valve box detailed design is achieved and the call for tender is planned to be published in summer 2019.

Test and Assembly Facilities

The cryomodule tests will be done at the IPNO Supratech existing facility. This facility is equipped with a liquid helium liquefier, providing around 50L/h, a helium bath pumping group providing around 120W @2K and the different required cryogenic auxiliaries (heaters, tubing, transfert lines, pressure regulation, gas recovery…) as well as its C&C system.

For the MINERVA cryomodule a dedicated C&C system based on Siemens PLC was studied. It is orientated for tests purposes and consequently features a large amount of diagnostics, especially for the cryomodule thermal behaviour (thermal loads on cavities' frame, on power coupler external conductor, on warm cold transitions…) and the cavities RF dissipated power measurements (calorimetric and bath pressure variation measurements). For the Cryomodule/Valve Box system the number of I/O is designed for 64 Cernox type temperature sensors, 78 Pt100 type temperature sensors, 20 heaters, 3 pressure sensors, 4 flow meters and the typical I/O for vacuum and liquid level measurements and control. The cryomodule C&C will have to communicate with the existing cryogenic facility as well as with the cryomodule RF control system and will have, for this purpose, EPICS capabilities. The overall PID (see Figure 5) as well as the complete instrumentation list and the cryogenic sequences have been done and a call for tender concerning the hardware manufacturing and the programming is planned for the summer 2019.

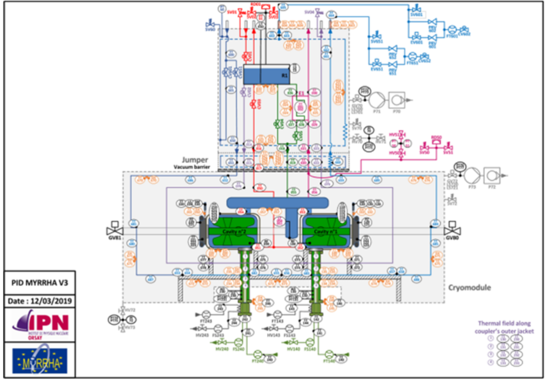

Figure 5: Valves box and cryomodule PID.

The RF power system implementation in the test area has started (electrical power supply and cooling system modifications) and the installation of the two 20 kW CW RF amplifiers and their auxiliary components (RF circulators and RF loads, measurements couplers, coaxial lines...) is planned from the summer 2019.

The cryomodule assembly and the cavity surface preparations will be done in the IPNO Supratech facility. The facility features an 85 m^2 clean room with 45 m^2 in Iso 4 equipped with a HPR system, a chemical polishing facility, a 600 litres capacity oven able to operate up to 1400°C at 10^{-6} mbar and assembly dust free areas for the cryostating operation. The cavity surface preparation (H_2 removal) has been studied in the framework of the MYRTE European project. It has led to the definition of the process parameters and to the optimization of the sequence to apply to the chemical polishing, the high pressure rinsing and the cavity baking.

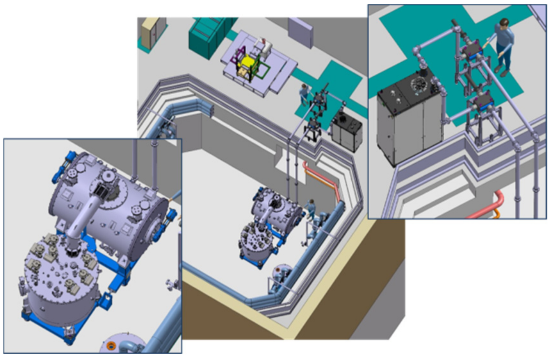

Figure 6: Test bench.

The test bench for the MINERVA (see Figure 6) Spoke cryomodule is equipped according to the different components tests schedules and availabilities; RF amplifier and equipped RF power lines commissioning, cryomodule and valves box cryogenic characterisation, cryomodule RF characterisation at low RF power and at least characterisation of the fully equipped cryomodule (tuning system, magnetic shielding, power couplers, LLRF and tuning control…) at nominal RF power for components validation and fault recovery tests.

RF SYSTEMS

A MTCA based digital low Level RF (see Figure 7) is under development to control the accelerating field induced into the Spoke cavities with a stability of +/- 0.1 degrees and +/- 0.1 % for the phase and the amplitude respectively. The system will have to manage the frequency tuning by fast communication with the cavity tuning system control board (piezo-electrics actuators and stepping motor C&C). The LLRF system will also fill the role of a like Machine Protection for the multipacting current, RF arcs and reflected powers pending the future global MPS development for MINVERVA by SCK. Concerning the global supervision, the development is based on EPICS, CSS and IPMI tools for "Health" MTCA rack monitoring.

An AMC board, IFC-1420 from the IOxOS company has been chosen for the digital part of the LLRF. The board features slots for FMC extension boards:

- First slot is used for a signal acquisition board with 10 ADC 16 bit channels and 4 DAC 16 bit channels dedicated to MicroRTM interface.
- Second slot will house a multipacting and arc detections board dedicated to the RF couplers with several inputs and outputs for externals interlocks from the cryogenic and auxiliaries PLC in particular and LLRF status.
- An extension module will also be used for a future specific data interface with a MPS.

The other boards needed for the complete system as the cavity tuning system control board has been tested with piezoelectric actuators with success. A New version is in progress for implementing the stepping motor control. The MRTM-based RF front-end board design in collaboration

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with IOXOS is in progress including the down-converter channels and RF output channel. About the timing, the EVent time Receiver and the EVent timing Master (AMC boards from the MRF company) tests are in progress.

In parallel with the hardware prototyping, EPICS and VHDL software developments are in progress. The complete system is planned to be available at the beginning of 2020.

Three RF amplifiers using the solid-state technology for reliability purposes have been designed and manufactured by the IBA company. Two 20 kW (CW at 352 MHz) will be used to power the spoke cavities. With the specified coupling QL= 1.5 10^6, it leads to a RF power of 4 kW at E_{acc}=7 MV/m (nominal operation) and a power of 17.6 kW for E_{acc}=15 MeV, which fulfils with a sufficient margin the fault recovery requirements. One 80 kW (4 times the maximal operating RF power) will be used for the power coupler conditioning in standing waves mode The RF amplifiers are planned to be deliver for characterisation tests before the end of 2019.

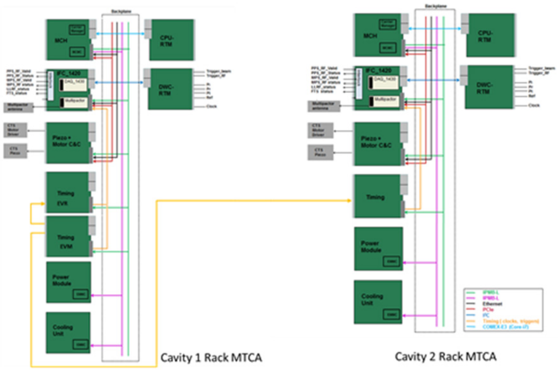

Figure 7: LLRF system layout.

CONCLUSION

The MINERVA Spoke (0.37, 352 MHz) prototyping is under progress. The main components are fully designed or currently under manufacturing. A special attention, requiring important manpower, is done on the manufacturing follow-up in order to control the manufacturing methods and have a sufficient feedback to set, with a quality approach, the specifications and the procedures for the industrialization of the serial production. We assume that a good reproducibility in the manufacturing is strongly correlated to the reliability and the availability requirements of the MINERVA LINAC

The second important aspect of the prototyping period is to investigate the effects, preferably with long term tests, of the fault recovery requirements on the various cryomodule components. These tests will give inputs for the components specification but also can give important inputs for the LINAC operations.

The first cryogenic tests with cavities and at low RF power are planned to start before the end of 2020 and will be continued with full RF power and fault tolerance operating tests.

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