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MYRRHA-MINERVA INJECTOR STATUS AND COMMISSIONING*

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Abstract

The MYRRHA project [1] at SCK CEN, Belgium, aims at coupling a 600 MeV proton accelerator to a subcritical fission core operating at a thermal power of 60 MW. The nominal proton beam for this ADS has an intensity of 4 mA and is delivered in a quasi-CW mode. MYRRHA's linac is designed to be fault tolerant thanks to redundancy implemented in parallel at low energy and serially in the superconducting linac. Phase 1 of the project, named MINERVA, will realise a 100 MeV, 4 mA superconducting linac with the mission of demonstrating the ADS requirements in terms of reliability and of fault tolerance. As part of the reliability optimisation program the integrated prototyping of the MINERVA injector is ongoing at SCK CEN in Louvain-la-Neuve, Belgium. The injector test stand aims at testing sequentially all the elements composing the front-end of the injector. This contribution will highlight the beam dynamics choices in MINERVA's injector and their impact on ongoing commissioning activities.

INTRODUCTION

The MYRRHA Accelerator is a 600 MeV proton linear accelerator part of a flexible irradiation facility being created by SCK CEN in Belgium as a test-bed for transmutation and as a fast-spectrum facility for material and fuel developments.

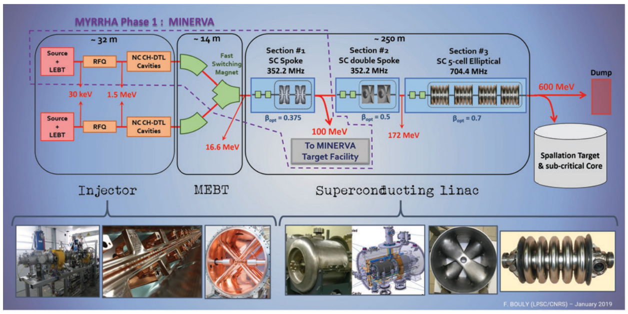

Figure 1: Aceelerator scheme for the 100 MeV (MINERVA) and 600 MeV (MYRRHA ADS) phases [2].

This ADS consists of a low energy section (injector or Linac front-end) characterized by low beam velocity and a highly modular medium-and-high energy section (a so-called main linac) connecting a series of independently controlled accelerating superconducting cavities. Figure 1 depicts the accelerator and its two sections.

When compared with other accelerators of the same class [3], a major distinctive character of this system is given by its considerably harder reliability requirements: in MYRRHA, beam trips of a duration exceeding 3 seconds are considered as a system failure leading to a plant shutdown. In terms of MTBF, this corresponds to requiring a mean time between consecutive failures of at least 250 hours during the system's operative cycle (90 days). A common strategy to meet reliability requirements is given by fault-tolerance, namely the systematic adoption of provisions to compensate for unexpected deviations of the system state originating inside or outside of the system's boundaries. Given the complexity of our linac system, two fault-tolerance design patterns have been selected in function of the characteristics of the section they shall be applied to:

- In the low-energy section, hot spares shall be used as a form of parallel redundancy: two equivalent 16.6 MeV injectors with fast switching capabilities [4] shall be put in place.
- In the main linac section, the availability of similarly structured cavities shall be capitalized so as to realize a serial redundancy strategy, with the functions of failing cavities to be compensated by their four nearest neighbors [5].

The MYRRHA project is scheduled to proceed in stages, with a first accelerator only based on a single injector connected to a superconducting section and an extraction line to a set of target facilities. In the first MYRRHA stage, MINERVA, the main linac shall be based on single-spoke cavities and reach 100 MeV. In a second stage, the accelerator shall be extended with double-spoke and elliptical cavities up to a full-fledged 600 MeV configuration. A final stage will see the accelerator connected to a subcritical nuclear reactor.

THE INJECTOR TEST STAND

The MINERVA injector accelerates the beam up to 16.6 MeV. Its front-end is composed of an ECR proton source, a 2.6 m long LEBT (low energy beam transport line) [6] and a four-rod RFQ accelerating the beam to

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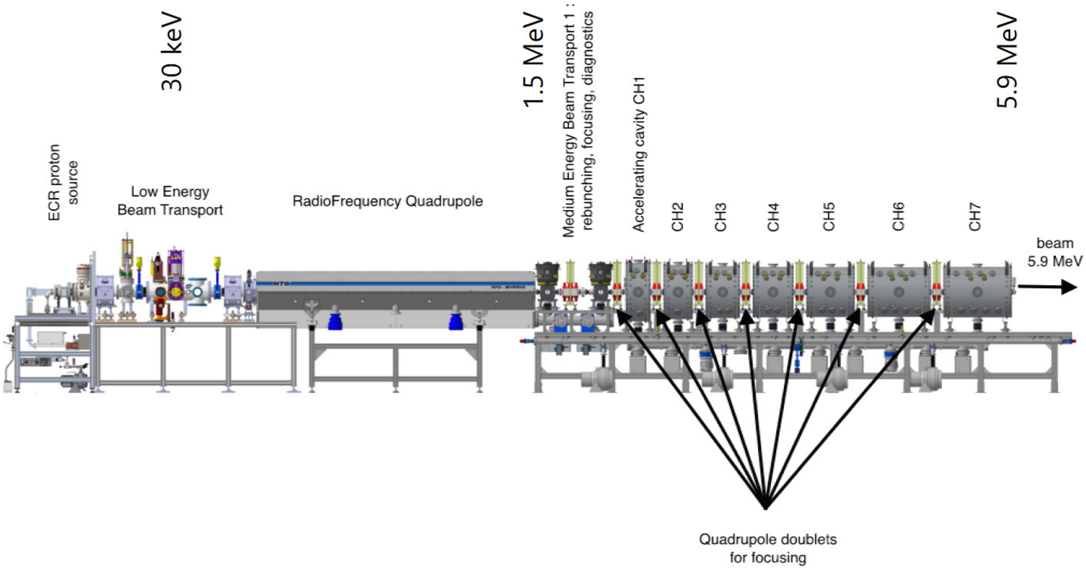

Figure 2: The injector test stand for MINERVA's front-end linac from the ECR source to the 7th accelerating cavity (up to 5.9 MeV).

1.5 MeV [7]. After the RFQ comes a small matching section with quarter wave resonators, called MEBT1, followed by a series of normal conducting CH cavities [8].

The front-end and the first seven CH cavities are being installed and tested on a dedicated test stand in Louvain-la-Neuve, Belgium, on the Cyclotron Resources Center (CRC) site. Today we have installed and are currently testing up to MEBT1 (see Fig. 2). We started by recommissioning the LEBT that had already been installed and commissioned at LPSC in Grenoble, France [6]. The two main objectives of the recommissioning have been (1) the study of the beam matching from the LEBT to the RFQ and its transmission, and (2) the study of space charge compensation transients, achieved by observing in detail the effects of enhanced space charge compensation when injecting gas into the LEBT.

For a defined current at the source exit, one can demonstrate by scanning through combinations of the two solenoids, that RFQ beam transmission is better optimised when argon is injected into the LEBT. Transmission maps without and with argon are shown in Fig. 3 where it is clear that transmission at high current is improved. Previously [9], we also measured that adding argon allowed smaller steady-state emittance to be achieved. But that said, gas addition improves neither the transmission at nominal current nor the current rise-time at the RFQ exit. Therefore, unless there is a need for high beam current (>5 mA), the added value of injecting argon is limited.

RFQ BEAM COMMISSIONING

The first stage of RFQ beam commissioning, including full power commissioning, was carried out in 2020. As presented in Ref. [9], all the measured performances were according to expectations and no problems were encountered when pushing duty cycle to CW. The RFQ transmission at theoretical optimal power (110 kW or 44 kV) was 95 %, which could be increased to 98 % at 125 kW (48 kV). In

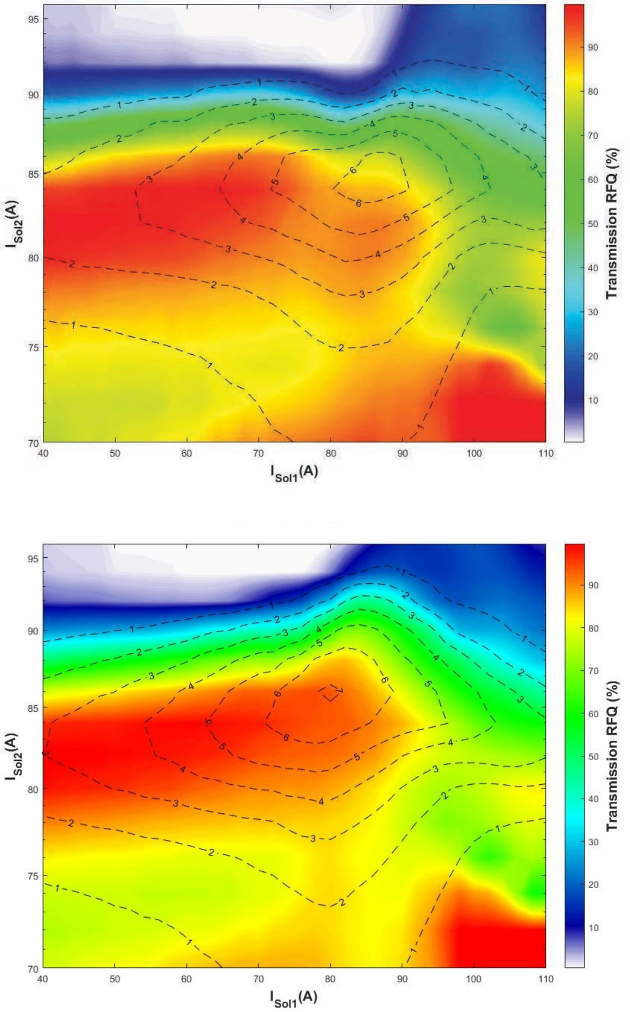

Figure 3: RFQ transmission maps with RFQ output isocurrent curves when scanning the solenoids in the LEBT for residual gas (top picture) / injected argon (bottom picture) in the LEBT.

the last months, we found out that running the RFQ also improved the transmission performances. We can now reach 98.9 % transmission at 4 mA around our new nominal RF power: 120 kW (46.5 kV).

The second stage of commissioning, carried out from Mid-2021, had as main objective the measurement of beam energy at the RFQ exit by time of flight (ToF).

The Time of Flight Method

The bunch's time of flight between two beam phase pick-up systems (BPM or phase probe) can be estimated based on the phase shift measured at both detectors assuming that the number of RF buckets between the two is well known and that the phase offset due to cables and electronics is well calibrated [10]. If the bucket number is not known, a third pick-up is needed to determine it.

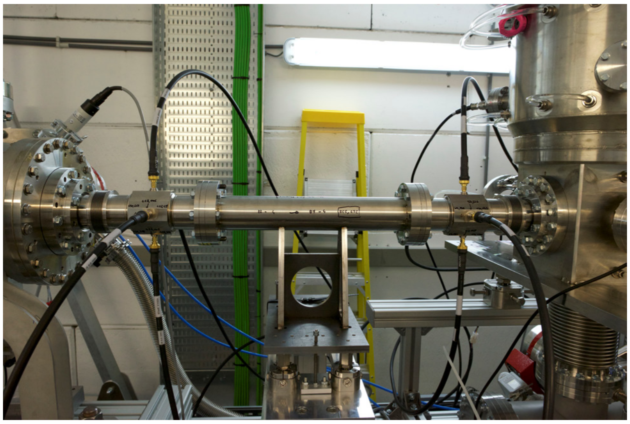

Figure 4: Setup for ToF measurement between two BPM.

The setup in Fig. 4 is composed of two BPM (at black cables location) developed for MYRRHA during the MYRTE project [11]. It is installed at the end of MEBT1, after the second quarter wave rebuncher (see Fig. 2). A third BPM placed between the two rebuncher cavities has been used for bucket count verification.

RFQ Energy Measurement

The ToF setup described in the previous section was used for RFQ energy measurement with both bunching cavities switched off and detuned.

The measured output energy shows small fluctuations with respect to the RF power level inside the RFQ as can be seen from Fig. 5. These fluctuations are believed to come from synchrotron oscillations due to input energy mismatch. Below 90 kW, the beam bunching is not complete and the phase measurement shows more and more statistical variations until the system becomes unable of locking the phase.

The measured reference energy at nominal power (120 kW) is 1.494 ± 0.003 MeV. The uncertainty margin covers statistical uncertainties and phase and distance errors from both BPMS. The obtained result is fairly close to the expected 1.5 MeV and is fully in the acceptance range of the downstream cavities.

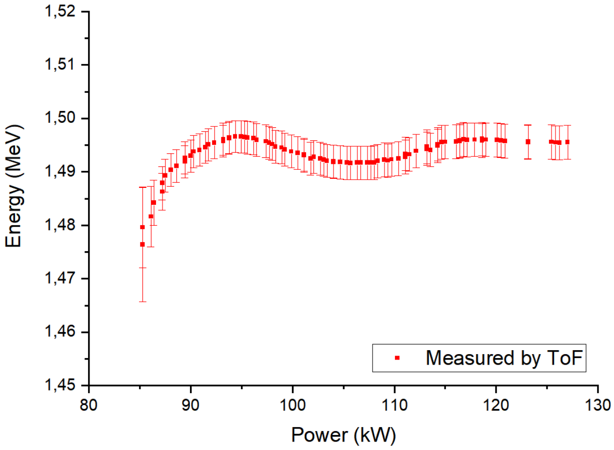

Figure 5: RFQ output energy with respect to RF power inside the RFQ.

It was previously demonstrated in equivalent installations that the oscillation in function of RF power is sensitive to the RFQ input energy [12]. In an effort to minimise the oscillation, we attempted an input energy scan by changing the source platform voltage.

As can be seen from the results in Fig. 6, increasing the platform voltage from 30.0 kV to 30.4 kV improves slightly energy stability. No improvement was observed passed 30.4 kV. Being the energy stability at 30.0 kV already good (only ±4 keV variation), improving it to ±3 keV variation does not seem as an improvement worth pursuing. The final decision on source platform voltage optimisation will have to wait for emittance measurements.

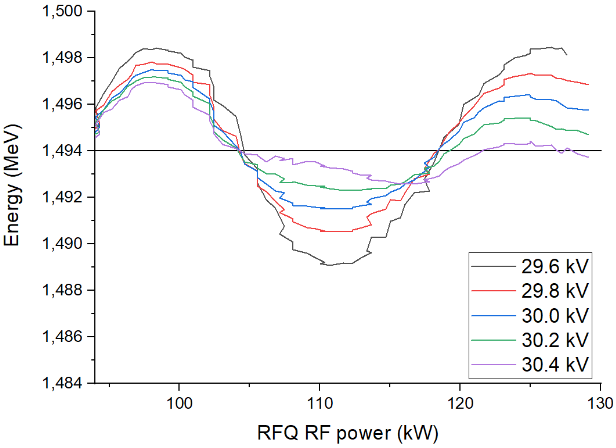

Figure 6: Fluctuations due to synchrotron oscillation for different RFQ input energy defined by the source platform voltage.

We have in the same measurement campaign tried to test RFQ energy stability both in time and for different input beam currents. The energy variation in time was better than 1 keV over an hour of measurement and across different measurements (for the same LEBT and RFQ setpoints). Our next step is to install diagnostics to measure the longitudinal

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emittance. This should also help to conclude on the source platform voltage choice.

MEBT1 TUNING

MEBT1, for first medium energy transport line, is the first matching section right after the RFQ. Its main goal is to match the beam into the longitudinal acceptance of the CH section linac. It is composed of two quarter wave rebunchers (QWR1 and QWR2) and one quadrupole triplet as shown in Fig. 7.

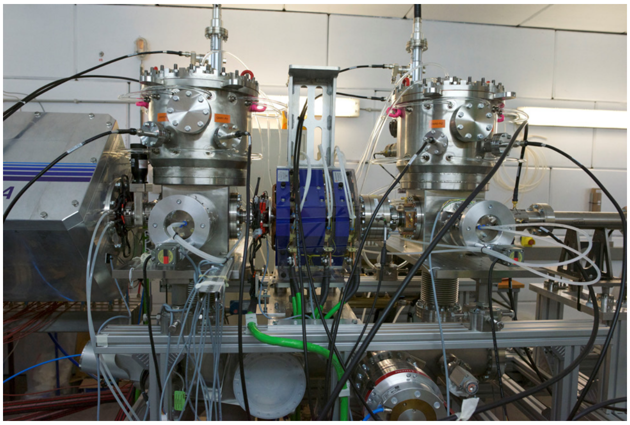

Figure 7: MEBT1 composed of two quarter wave rebunchers and one quadrupole triplet as currently installed at the injector test stand.

The full RF conditioning of QWR1 and QWR2 was done in less than a day each. For these cavities, we use the same type of solid state amplifiers as for the RFQ [13] and dedicated in-house cavity tuners and LLRF systems on RFSoC FPGA [14].

The tuning of MEBT1 was done in two steps. First, the triplet was fine tuned around its beam dynamics determined setpoints in order to optimize beam transmission through MEBT1.

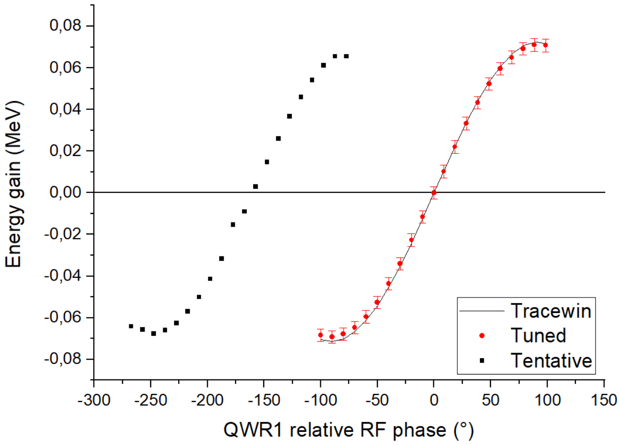

Figure 8: Measured relative phase versus energy gain before (tentative) and after tuning a quarter wave rebuncher to match Tracewin simulation.

Then, the rebunchers were tuned in phase and amplitude using the same ToF setup as for energy measurement. They were tuned so as to match an energy variation pattern simulated by the Tracewin code [15] with very good agreement as shown in Fig. 8.

Based on the good agreement between measurements and simulations, we are confident that the beam has the right characteristics for entering the first accelerating CH cavity. We should soon receive diagnostics that will allow us to confirm this with transverse emittance and bunch shape measurements.

CONCLUSION

In the last months, we have achieved the measurement of RFQ beam energy and tuning of our first RF cavities using a ToF setup composed of two BPM. A third independent BPM was used for bunch count or energy range confirmation.

The measured RFQ energy is 1.494 MeV which is in the acceptance range. Added to alomst 99 % transmission at nominal current and good behavior in CW mode, the RFQ has so far performed very well through all the milestones.

We are currently preparing the transverse emittance and bunch shape test bench. The diagnostics to be used are expected on site by the end of the year and the measurements are planned for the first quarter of 2022.

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