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MINERVA (MYRRHA PHASE 1) RFQ BEAM COMMISSIONING*

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Abstract

The MYRRHA project [1] aims at coupling a 600 MeV proton accelerator to a subcritical fission core operating at a thermal power of 70 MW. The nominal proton beam for this ADS (Accelerator Driven System) has an intensity of 4 mA and is delivered in a quasi-CW mode. Phase 1 of the project will realise a 100 MeV, 4 mA superconducting linac with the mission of ensuring the ADS requirements in terms of reliability and fault tolerance. As part of the reliability optimisation program the integrated prototyping of the MINERVA injector is ongoing. The front-end of the injector is composed of an ECR proton source, an LEBT (Low Energy Beam Transport line) and a four-rod RFQ accelerating the beam to 1.5 MeV. The present contribution focuses on the current beam tests on the RFQ, including beam matching, RF conditioning, assessment of the cavities' performances and accelerated beam characterisation.

INTRODUCTION

The MYRRHA accelerator is a high power proton accelerator with strongly enhanced reliability requirements compared to similar linac [2].

Its reliability goal is an MTBF (Mean Time Between Failures) of 250 hours, a failure being defined as a beam trip of more than 3 seconds. In order to reach this highly demanding goal, the linac needs to be fault tolerant.

The conceptual design of this linac has been on-going for more than 15 years. As a result of several design and reliability studies, the adopted linac scheme to fulfil the reliability goal is based on 2 distinct sections, as illustrated by Fig. 1 from Reference [3].

- Two equivalent compact injectors with fast switching capabilities [4] for parallel redundancy.
- A fault tolerant superconducting linac. The function of a faulty cavity may typically be taken over by 4 adjacent cavities [5].

In the MINERVA phase of MYRRHA, only one of the two injectors will be built, to which will be connected a super conducting section up to 100 MeV and a HEBT (High energy beam transport line), an extraction line towards the target facilities.

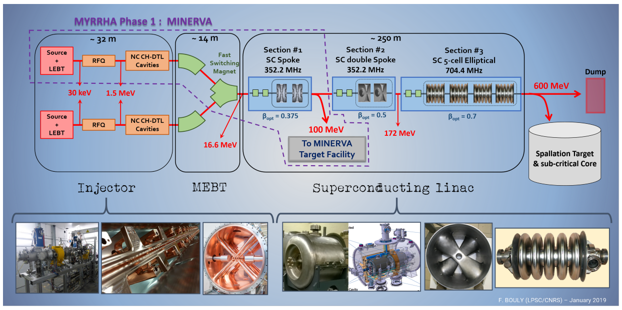

Figure 1: Conceptual scheme of the MYRRHA accelerator for the 100 MeV (MINERVA) and 600 MeV (MYRRHA ADS) phases.

THE INJECTOR TEST STAND

The MINERVA injector is the part that 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 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].

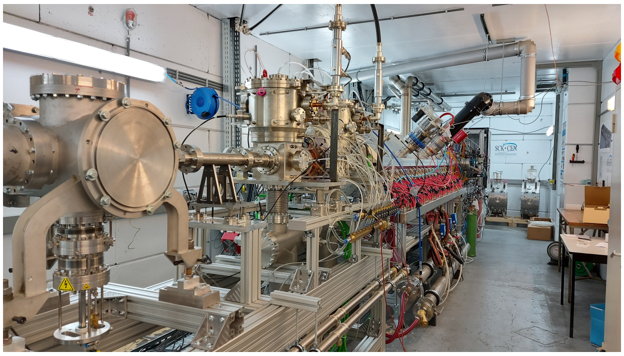

Figure 2: The injector test stand for MINERVA's front-end linac as it is today. The section in the middle with red pipes is the RFQ.

The front-end and the first seven CH cavities are being installed and tested on a dedicated test stand in Louvain-la-Neuve, Belgium. Today we have installed and are currently testing up to the MEBT1 as can be seen from Fig. 2. We started by recommissioning the LEBT that had already been installed and commissioned at LPSC in Grenoble, France [6].

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The two main objectives of the recommissioning were to study: the beam matching from the LEBT to the RFQ and its transmission , as well as space charge compensation transients.

Space Charge Compensation in the LEBT

Space charge compensation (SCC) in a proton beam occurs when the beam potential traps secondary electron generated through multiple ionisation in a gas (residual or added in the beamline) [9]. The reverse polarity of the trapped electrons compensates for the beam's space charge. The SCC is easily broken by an electric field such as the one generated by a chopper, and it takes several micro-seconds to build up again after it is switched off. Using an Allison scanner emittance meter, we measured transverse emittance in the first 200 µs after the chopper is switched off.

The reconstructed time dependent emittances were analysed and fitted using the Plotwin software [10]. First, the experiment was done in nominal conditions: 4 mA DC beam and argon injected into the LEBT to a pressure of 1.6 E-5 mbar around the injection point in the centre of the LEBT. Figure 3 shows reconstructed transverse emittance measured at different time steps after chopper switch off.

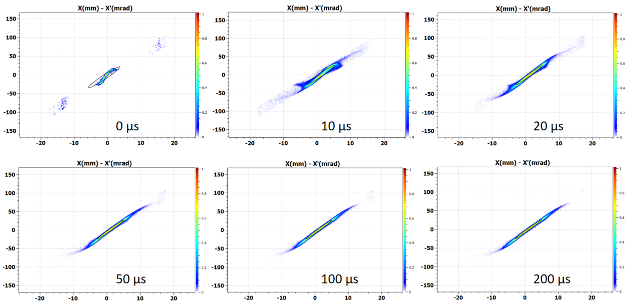

Figure 3: Beam shape at different timing following chopper switch off.

The experiment was repeated without argon injection studying the residual gas based SCC. The remaining pressure in the centre of the LEBT is 5 E-6 mbar in this case. The source current was increased to recover the 4 mA at the RFQ exit. Comparative results for the two cases are shown in Fig. 4. Adding argon in the LEBT improves the steady state emittance and the transient time if we define it as the time elapsed before reaching the steady emittance in a 10 % margin. In fact, extra gas means extra electrons available for ionisation. The resulting higher electron population, explains both the smaller beamsize and the shorter time to reach the equilibrium.

Space Charge Compensation and RFQ Transmission

In a separate setting and after the RFQ was put in operation, a beam current measurement at the RFQ input and output was taken using Bergoz's ACCT [11]. Based on the results from our previous experiment explained in the previous paragraph, one would expect shorter rise-time with a higher SCC level (extra gas injected in the LEBT). This notwithstanding, the measured rise-times in Fig. 5 show the opposite. Both the rise-times at the RFQ entrance and exits seem to be better with residual gas only.

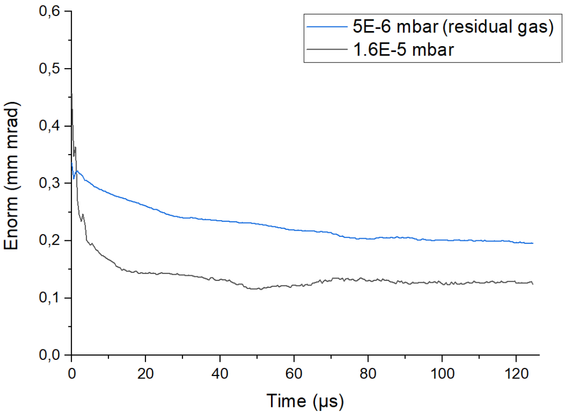

Figure 4: Normalised emittance evolution with respect to time after chopper switch off with and without gas injection.

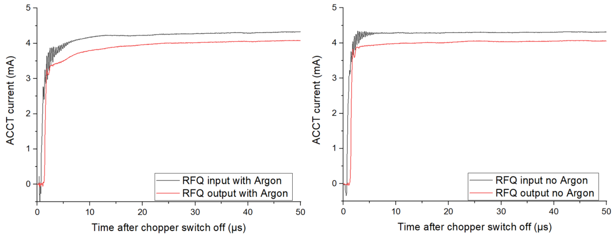

Figure 5: Beam current rise-times before and after the RFQ with (left) and without (right) Argon being injected into the LEBT.

The higher SCC level case appears to suffer more from chopper activation leading to less sharp current rise-time at the RFQ exit compared to when no Argon is injected. This might be an indication that with argon, the difference between the emittance in the first micro-seconds and steady state is so big, that it results into longer periods of mismatched beam.

There is also a small but noticeable difference in rise-time at the RFQ entrance in favour of the low SCC level case. That is most likely thanks to a tail collimation in the injection cone, since the beam has bigger envelops in this case.

From these results, the only added value of injecting argon in the LEBT seems to be the reduced emittance. But, the measured normalised steady-state emittance is 0.11 π.mm.mrad with argon and 0.16 π.mm.mrad without. Since the latter should, in theory, not be a problem because the maximum design value of our RFQ is 0.2 π.mm.mrad, the LEBT could be operated without added gas.

There are still a few open questions on this matter that we hope to find answers to when we can repeat the emittance measurement at the RFQ exit.

RFQ COMMISSIONING

The RFQ was commissioned in two phases, first full RF conditioning and run tests, followed by beam commissioning.

RF Conditioning

Before the RFQ can be operated at high power, the cavity needs a full RF conditioning. This requires a full commissioning of RF amplifiers (solid state in our case) [12], and of the low level RF system [13]. Our RFQ was conditioned up to 140 kW (nominal power being 110 kW) first in pulsed mode and gradually towards CW (continious wave). The power was slowly increased over several hours, allowing the cavity to adjust to higher power which translates in a lesser amount of discharges (see Fig. 6). To improve the conditioning, the RFQ was powered at 120 kW for about 100 cumulative hours in order to demonstrate the long run test capability of the RF system.

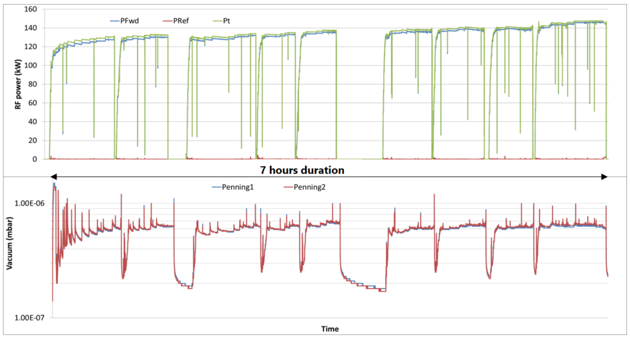

Figure 6: RF conditioning in CW. The power levels are plotted in the top picture while in the bottom picture one can see the measured vacuum inside the RFQ. The vacuum spikes reflect discharges inside the cavity.

RFQ Beam Commissioning

After the long run test, our RFQ was first run with beam in June 2020 at 0.4 mA beam current and 1 % duty cycle. Nominal current (4 mA) was quickly reached a few days later but we kept operating at low duty cycle (5 % maximum) until a full power copper beam dump was installed a few months later.

In December 2020, we achieved for the first time full power after the RFQ in quasi CW mode to respect MYRRHA's pulse structure: 3.8 ms long pulses for ADS, 0.19 ms short pulses for ancillary research activities with 5 µs in between to allow for chopper rise and fall times. Figure 7 shows the scope recording of the ACCT placed at the RFQ exit.

At full power, we measured beam transmission levels in the RFQ after a quick LEBT fine tuning to optimise transmission in nominal conditions. At nominal power, 110 kW equivalent to 44 kV, we measured 95 % beam transmission through the RFQ. Increasing the RF power, the transmission was improved until reaching a plateau at 98 % from 125 kW onward. The results are plotted in Fig. 8. Even though the Toutatis [14] model predicts higher transmission, the obtained results are according to design expectations [7].

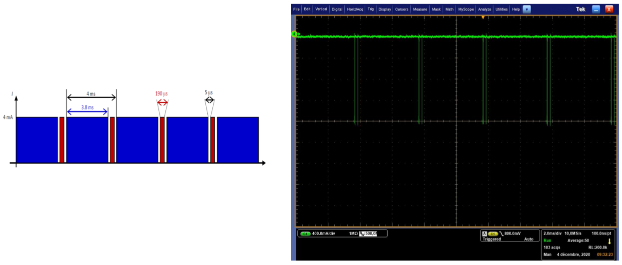

Figure 7: First full power beam respecting MYRRHA pulse structure (see text for details).

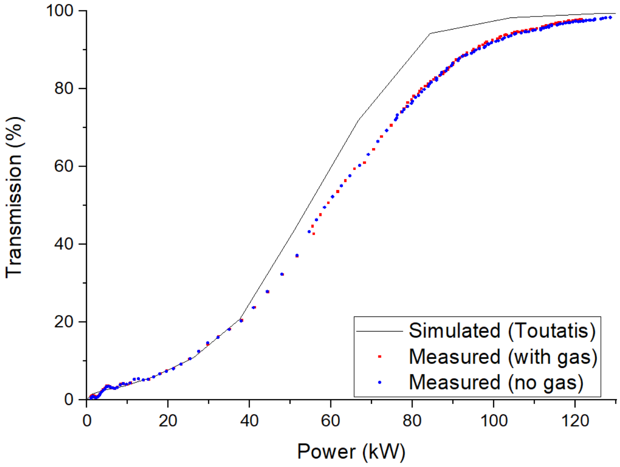

Figure 8: Measured RFQ transmission with and without Argon injection into the LEBT compared to simulations of a perfect model using the Toutatis software [14].

CONCLUSION

MYRRHA's RFQ was commissioned both without and with beam. So far, all the measured performances are according to expectations and no problems were encountered when pushing duty cycle to CW. The RFQ transmission at nominal power (110 kW or 44 kV) is 95 %. This figure can be increased to 98 % from 125 kW (48 kV).

The RFQ transmission is not affected by space charge compensation level in the LEBT and the transmission risetime is even slightly better when working without gas. This opens up the possibility to simplify our LEBT control by removing the gas parameter provided that the transverse emittance is not a limiting issue. This is to be confirmed by transverse emittance measurement after the RFQ.

We are currently ready for RFQ energy measurement by ToF (time of flight), the measurement campaign is scheduled to start in June.

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