COMMISSIONING OF THE MYRRHA LOW ENERGY BEAM TRANSPORT LINE AND SPACE CHARGE COMPENSATION EXPERIMENTS *

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Abstract

The MYRRHA project [1] aims at the construction of a new research reactor in Mol (Belgium) to demonstrate the nuclear waste transmutation feasibility with an Accelerator Driven System (ADS). In its subcritical configuration, the MYRRHA facility requires a driving proton beam with a maximum power of 2.4 MW. Such a continuous wave beam will be delivered by a superconducting linear accelerator. The linac injector will be composed of: a proton source, a low energy beam transport line (LEBT), a 176 MHz RFQ and CH-DTL cavities. The LEBT prototype has been built and is presently installed and operated at LPSC Grenoble (France). An experimental program has been carried out to optimise the tuning of the line, the beam transport, and to study the space charge compensation mechanism.

INTRODUCTION

To fulfil the performance (4 mA – 600 MeV) and reliability requirements for an ADS operation [2], the present design of the MYRRHA accelerator is based on a superconducting linac solution [3][4]. In the linac injector a 30 keV beam is produced by an electron cyclotron resonance (ECR) ion source, then this beam is transported through the Low Energy Beam Transport line (LEBT) and matched to the RFQ input. The 1.5 MeV bunched beam at the RFQ output will then be accelerated up to 17 MeV by CH-cavities [5].

The LEBT represents the first three meters of the MYRRHA accelerator. The purpose of this line is to ensure a reliable transport of the DC (Direct Current) 30 keV proton beam from the source to the RFQ and to condition the beam to ensure its proper acceleration and minimise beam losses in the following accelerating devices. A centred matched converging beam must be provided at the RFQ input, with reasonable transverse emittances (ideally $\varepsilon_{RMS.norm.proton} \leq 0.2$ π.mm.mrad) and the following Twiss parameters: $\alpha = 0.88$; $\beta = 0.04$ mm/(π.mrad).

In addition the LEBT should enable to clean the proton from other species (such as H_2^+ and H_3^+), also extracted from the source. The last function of the LEBT will be to create the beam time structure. In nominal operation the MYRRHA accelerator must produce a CW beam with periodical interruptions to: monitor the sub-criticality level of the reactor core (25 Hz repetition rate with 2 ms holes) and/or to adjust the mean beam power.

As a consequence the LEBT design is based on a compact magnetic solution. The beam dynamics studies, the engineering design and the construction have been supported by european** projects and SCK-CEN. The construction has been a collaborative work between LPSC (CNRS/IN2P3) and SCK-CEN teams. The commissioning and space charge compensation (SCC) [6] experiments are carried out in the MYRTE* framework. It mainly involves, LPSC, SCK-CEN and CEA, as well as COSYLAB [7] and ADEX companies for dedicated control system developments.

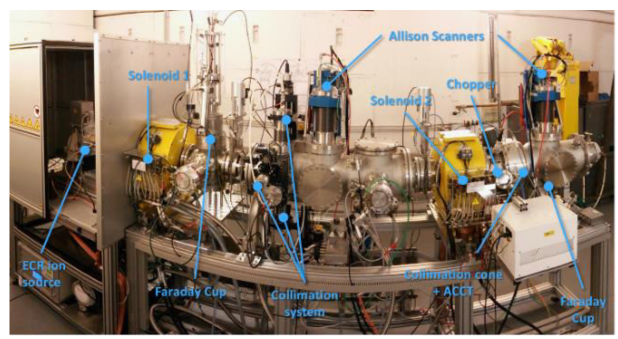

Figure 1: MYRRHA LEBT at LPSC Grenoble.

The LEBT presently installed and operated at LPSC, in Grenoble, is presented on Figure 1. The 2.45 GHz ECR M1000 source was provided by Pantechnik (France). The beam is extracted at an energy of 30 keV. The beam transport and focusing is ensured by two solenoid magnets - with integrated dipole steerers - provided by SigmaPhi (France). Motorised collimators, located in the middle of the LEBT, are used to intercept beam halo and to adjust the beam current. Several beam diagnostics enable to measure the beam current (Faraday cups, ACCT), the profile and transverse emittances (Allison scanners). At the end, a short RFQ interface section hosts an electrostatic beam chopper, adopted to give the time structure to the beam delivery towards the future MYRRHA reactor.

Associated to its ion source, the LEBT was commissioned: the beam transmission has been studied and the tuning explored to provide the right beam parameters at the RFQ input. The line was also used to perform low-energy beam physics experiments on the SCC phenomenon.

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LEBT TUNING

The first step in the commissioning was to tune the beam extraction settings from the ECR source, to minimise non-linearities in the transverse phase space beam distribution. The ECR source performances have been assessed: a stable DC beam of a 25 mA (total current) can be safely produced (no voltage breakdowns). The fraction of protons as regards to other species (H_2^+,H_3^+) hase been estimated to ~80 %, by emittance measurement analysis. It was assessed that the source could only remain stable if it operates at minimum current of ~8.5 mA (total current), below this value the plasma regime can become unstable.

To study the LEBT beam transmission, the source was set to produce a 9 mA beam. The beam current was controlled (with a standard deviation of ± 0.42 %) with an adaptive and predictive feedback system - developed by ADEX company- which permanently adjust the RF power injected in the ECR source. Only steerers inside solenoid 2 were adjusted to correct misalignments. Solenoids current were set to the design values - calculated with a TraceWin [8] model - that should enable to obtain the expected Twiss parameters for RFQ injection: $I_{solenoid1}$ = 70 A and $I_{solenoid2}$ = 77 A.

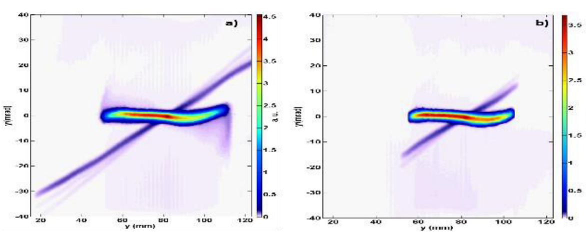

Figure 2: Beam distribution in the vertical phase space mesured at the middle of the LEBT: a) without collimation, b) with collimation

The collimators aperture was then adjusted to obtain a 4.5 mA beam current at the LEBT output. Figure 2 shows the effect of the collimators (aperture set to 48 mm) on the beam distribution in the vertical phase space measured with the Allisson scanner placed right behind the collimation system (cf. Figure 1). In this configuration the proton beam is almost propagating as a parallel beam. One can also notice that three straight lines indicating other species (H_2^+, H_3^+, heavier ions?) are separated thanks to the focusing effect of solenoid 1 and can be partially cleaned by the collimators.

Then in this first configuration the beam transmission as function of the solenoids focusing (current intensity in their coils) has been evaluated by scanning the settings of both solenoids as shown on Figure 3. Due to H_2 gas injected in the source, the pressure in the line was 1.1 10^{-5} mbar.

The effect of the residual pressure was studied by injecting different types of gas in the LEBT. As an example, Figure 4 shows the measured transmission when Kr is injected in the line to increase the pressure up to 2.4 10^{-5} mbar. Between Figure 3 and Figure 4 one can observe that the transmission map is modified. Nevertheless it must be noticed that the collimator aperture had to be reduced to a value of 37 mm in second case to adjust the beam current value to 4.5 mA. Indeed it appears that the transmission around the target settings ($I_{solenoid1}$ = 70 A and $I_{solenoid2}$ = 77 A) have been improved with Kr injection and have a direct effect on the beam distribution.

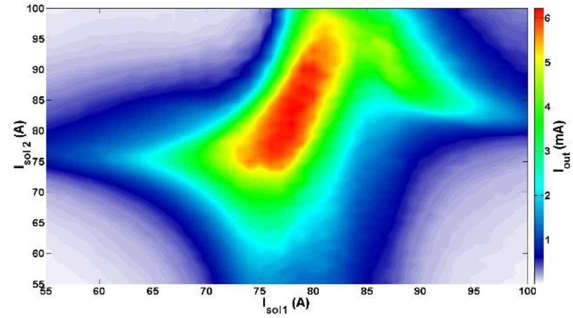

Figure 3: Transmission map (P = 1.1 10^{-5} mbar, collimators aperture = 48 mm).

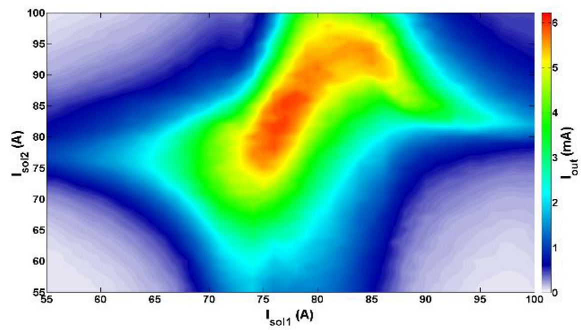

Figure 4: Transmission map with Kr injection (P = 2.4 10^{-5} mbar, collimators aperture = 37 mm).

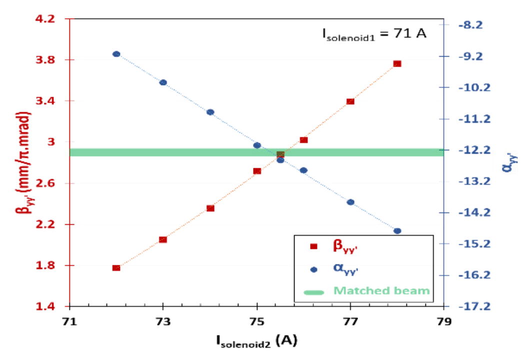

Figure 5: Twiss parameters measured at the LEBT output as a function of Solenoid 2 focusing (I_{sol1} = 71 A, P = 2.4 10^{-5} mbar, collimators aperture = 37 mm)

In configuration of Figure 4 the solenoids settings were fine tuned to adjust the transverse Twiss parameters at the LEBT output. To match the beam into the RFQ these parameters should be: $\alpha = 0.88$; $\beta = 0.04$ mm/(π.mrad). However, the emittance measurements could only be achieved 262 mm after the final collimation cone output (location of the Allisson scanner). The Twiss parameters that should be targeted at this location to obtain a proper matched beam in the RFQ were evaluated by simulation: with a simple beam transport on a drift by assuming a space charge compensation rate of 85 %. The estimated value are $\alpha = -12.3$; $\beta = 2.9$ mm/(π.mrad). The Figure 5 shows the measured

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evolution of the Twiss parameters in the vertical phase space as a function of the current in the coil of solenoid 2. In that case $I_{solenoid1}$ = 71 A and for $I_{solenoid2}$ = 75.5 A the beam is matched to the Twiss target values.

SPACE CHARGE COMPENSATION

Steady State

The beam parameters and the emittances were measured in different configurations: injection of different gas types (Ar, Kr, He), variation of the pressure level and of the solenoids focusing strength. We present here, on Figure 6, one result example showing the evolution of the proton vertical emittance, measured after Solenoid 1 as a function of the pressure level within the line. Here the pressure was modified by Kr injection. In this case, the solenoid focusing strength was kept constant ($I_{solenoid1}$ = 69 A). The beam current was also kept at a constant value at the emittance measurement location (I_{proton} = 8.5 mA) and no collimation was applied.

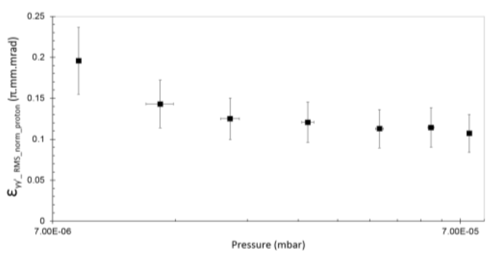

Figure 6: Measurement of the proton vertical emittance as function of the residual gas pressure after solenoid 1.

Measurements shows that the emittance decreases with the gas pressure increase. In addition, the beam divergence also decreases with the pressure increase and it seems that the beam emittance distribution is less affected by nonlinear effects [9][10]. To confirm these results SCC degree measurement were carried out with a 4-grids energy analyser developed at CEA Saclay. Preliminary measurement analysis shows that SCC compensation increases from ~85 % to ~95 % with the gas pressure (assuming a Gaussian beam distribution). The possible perturbation of the Allison scanner itself on the measurement is also being explored with a WARP model of the LEBT [9]: when the diagnostics intercept the beam, secondary electrons are emitted from the Allison scanner copper screen which may locally increase the electrons population and modify the SCC. Though the analysis of our experimental results is still in progress these preliminary results tends to confirm that an increase of the residual gas pressure improves the SCC degree, as already observed and modelled [11][12][13]. This would help in minimising non-linear effects on the beam dynamics. An increased gas pressure would also be an advantage to minimise the compensation time when the beam is chopped.

Chopper and Transients

The chopper system has been successfully commissioned by measuring the beam current transients (cf. Figure 7) with the ACCT placed at the end of the LEBT. A 4 kV voltage enables to completely deviate the beam (in agreement with the 3.7 kV foreseen by simulations [10]). It has been evaluated that the chopper voltage rise time is ~400 ns, which is mostly limited due to impedance matching between the chopper and the high voltage switch. An upgrade of the hardware system is in progress to decrease this switch time. No voltage breakdowns occurred up to 10 kV deviation voltage, even with an increased residual gas pressure up to ~1.10^{-4} mbar.

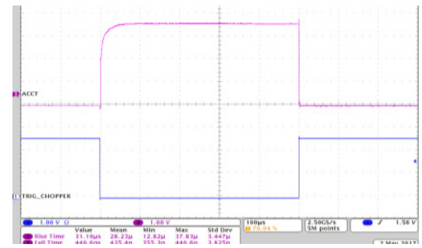

Figure 7: Macro-pulse of 500 µs by chopping the beam at the end of the LEBT (P = $1.9.10^{-5}$ mbar, $V_{Chopper}$ = 4kV).

A measurement of the beam current rise time (i.e. when the chopper is switched down) as function of the residual gas pressure is presented on Figure 8. The presented rise time is the time necessary to reach 95 % ($\tau_{95\%}$) of the maximum value ("plateau"). The measurements were achieved by keeping a constant DC beam current (6 mA) value at the end of the line while the pressure was increased by Krypton injection; the focusing of the beam also required some slight adjustments as a function of the gas configuration.

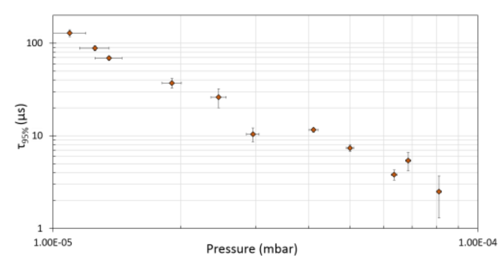

Figure 8: Evolution of the beam rise time when the chopper is switched-off as function of the residual gas pressure (Kr injection).

The measurements showed that the rise time decreases by a factor ~100 while the gas pressure increases by a factor 10. Even if the SCC pattern is perturbed on a relatively short distance (~30 cm long, around the chopper), these results show that the neutralisation time depends on the pressure - and therefore the optimisation of the beam transmission during transients-, which is in agreement with models [6].

CONCLUSION

The MYRRHA LEBT is fully commissioned, a method to tune the beam parameter at RFQ injection has been proposed. The influence of the residual gas in steady state and transients on the beam SCC was explored. It showed that using Ar or Kr gas may help to minimise the neutralisation time and to improve the beam dynamics. Nevertheless "classic" models of beam dynamics have shown their limits in modelling the exact behaviour of the beam. The analysis of the experimental data and modelling studies are in progress to give a better understanding of the SCC process occurring in the line. The next step in the project will be to move the LEBT to Louvain-La-Neuve (Belgium), where it will be coupled to the 4-rod 176 MHz RFQ [14] to continue the MYRRHA injector commissioning.

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