BEAM DYNAMICS STUDIES FOR THE SARAF MEBT AND SC LINAC

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Abstract

The SARAF MEBT and Super Conducting Linac (SCL) transport and accelerate deuterons or protons from the RFQ to the final energy. In this report, beam dynamics studies for this section are described. A rational distribution of the different roles of the MEBT leads to defining its necessary quadrupole/rebuncher composition. This allows easy beam re-tuning following changes from the RFQ or the SC Linac. After observing evidences of beam losses mainly due to phase unhooking, efforts have been dedicated to enlarge the SCL longitudinal acceptance. A combination of cavity field phases is found so that the required final beam energy is also fulfilled.

INTRODUCTION

The upgrade of the Soreq Applied Research Accelerator Facility (SARAF), managed by the Soreq Nuclear Research Center, aims to deliver 5 mA deuteron and proton beams at 40 and 35 MeV respectively [1]. The Commissariat à l'Energie Atomique et aux énergies alternatives (CEA) is in charge of the design and the building of a Medium Energy Beam Transport (MEBT) line and a Superconducting Linac (SCL) [2] to complete an existing structure consisting of an ECR ion source, a Low Energy Beam Transport and a Radio Frequency Quadrupole (RFQ).

This article describes the beam dynamics optimizations and performances of the MEBT and the SCL. All simulations are performed with the TraceWin code. [3]

MEBT

The role of the MEBT is to match the beam coming from the RFQ to the SC Linac, while additionally ensuring out-of-energy particle cleaning, beam measurements, along with preserving room for technical tasks such as pumping or beam stopping. A fast chopper system is also kept as an option.

If only considering the main role of the MEBT, beam matching to the SC Linac, i.e. achieving at the entrance of the SC Linac a given beam size and divergence in x, y, z (6 parameters), then using 2 rebunchers and 4 quadrupoles are sufficient. Due to the additional required functions, a longer MEBT is certainly needed, involving more focusing elements in order to avoid high beam size peaks.

This is why a 3rd rebuncher is added. In the same way, 2 more quadrupoles are needed for restraining the transverse beam size on a longer distance, which would mean 6 quadrupoles in total. Considerations for chopping the beam in one given plane (x for example) implies a parallel beam envelope in this plane, which can be done with 1 more quadrupole. To be safe, one final quadrupole is included, it can also be used, for example, to make a parallel beam envelope in the non-chopping plane. In total, 8 quadrupoles are expected. All have a precise role. The first quadruplet is for setting given beam sizes and divergences in x and y in the middle of the MEBT, thus facilitating beam measurements there (and beam chopping in the future). The last quadruplet role serves the same purpose at the SCL entrance in order to perfectly match the beam to its focusing lattice. That way, the MEBT has 2 independent modules that do not interfere with each other, in case of a RFQ output change, only the first quadruplet is adjusted, and in case of SCL change, only the last quadruplet can be adjusted.

The resulting MEBT configuration and beam envelope are shown in Figure 1. Envelope peaks are balanced in order to minimize the biggest peak, inducing by this way the balancing of quadrupole and rebuncher forces, therefore minimizing also the biggest forces.

The drift between the 4th and 5th quadrupoles is expected to host diagnostic devices and the optional chopper where the x beam envelope is parallel. Dumping of the chopped beam can be implemented in the drift between the 6th and the 7th quadrupoles. It is worth pointing out that space charge effects, like halo growing, are the most visible in those two long drifts.

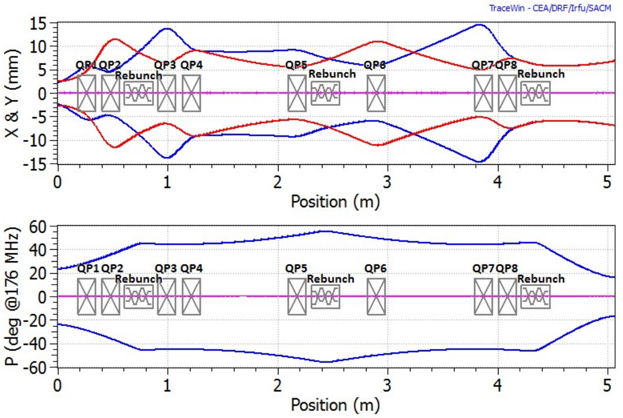

Figure 1: 3-σ envelopes of deuteron beam along the MEBT. Top: transverse envelope, x in blue and y in red. Bottom: longitudinal envelope.

Three sets of x-y scrapers are distributed along the MEBT to limit transmission of beam halo and non-accelerated ions from RFQ to SCL.

The MEBT delivers a clean and round beam to the SCL.

SC LINAC

The SCL is composed of four ~5 m long cryomodules. The first two consist of 6 identical low beta (0.091) half-wave resonator (HWR) cavities each with extra room for an optional cavity. The last two cryomodules include 7 high beta (0.181) HWR cavities each. Their maximal accelerating fields are respectively 6.5 MV/m and 7.5 MV/m [4].

The transverse beam size is contained by 20 superconducting solenoids with higher fields as the energy increases, see fig.5. Transverse tuning for getting a steady beam size does not present any difficulties. On the contrary, longitudinal tuning in order to reach the required energy and stay within the beam loss limits is not straightforward because of the poorly periodic structure inherent to configurations with short cryomodules.

Indeed, a first tuning of cavity phases leads to important beam losses, all coming from particles unhooked in the longitudinal dimension. Furthermore, error simulations (introducing fluctuations of 1% for the field amplitude and 1° for the phase) in envelope mode show that the longitudinal acceptance must be at least 1.5 times greater than the longitudinal rms size in order to keep the beam within the SCL acceptance. Major efforts are then dedicated to enlarge the SCL longitudinal acceptance.

For that, let's first point out that it is useless to enlarge the global longitudinal acceptance as it is currently defined, because the beam phase space is not homothetic to the acceptance but occupies a rather off-centered part of it. It is then decided to tackle the problem in another way: consider the actual input beam with longitudinal emittance homothetically multiplied by $(1.5)^2 = 2.25$ and search to adjust synchronous phases in order to minimize or even to get rid of all losses with this enlarged input beam. In addition, efforts are made to obtain a compact output beam, not strongly distorted by nonlinearities.

Three main issues remain to enlarge the SCL acceptance a) The RF field sinusoidal behavior makes the problem nonlinear b) The field amplitude and phase determine the accelerating and the focusing forces at once, and those ones are interfering c) The transmission of the beam depends on the whole phase setting and not on any individual phase, meaning that a big number of phase combinations should be explored.

After trying different methods, it was found that the following procedure in 2 steps gives satisfying results:

- With the TraceWin code, adjust cavity phases to get at the SCL exit a maximized beam energy together with a maximized number of particles in a well delimited range of phase and energy.

With the above result, starting from the first cavity, search the field phase allowing to obtain the maximum of particles for the before-mentioned phase-energy range, fix it, then repeat the same investigation for the next cavity, until the last one.

These two steps could be reiterated, always with the enlarged emittance. The numerous multi-particle simulations that should be launched make this procedure tedious. But the main issue is that a better solution may be missed. Another procedure for mitigating these inconveniences is being studied.

The best result so far is presented in Figure 2. The longitudinal beam input, compared to the dynamic acceptance, shows a satisfying margin. The beam energy at the SCL exit is 40.7 MeV for deuterons and 36.9 MeV for protons, which is slightly beyond the required values. The obtained margin in energy is roughly the accelerating capacity of one low-β cavity.

The SCL configuration and the beam envelope are shown in Figure 3.

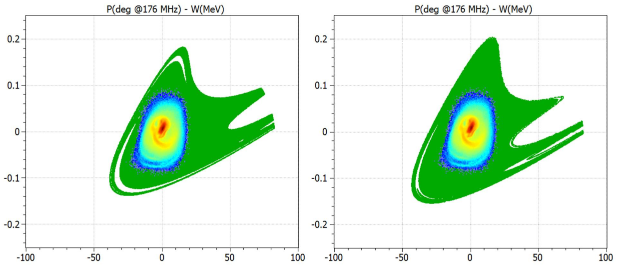

Figure 2: Beam distribution in the phase-energy space at SCL entrance for deuterons, compared to the dynamic acceptance in green. Left and Right: before and after optimization.

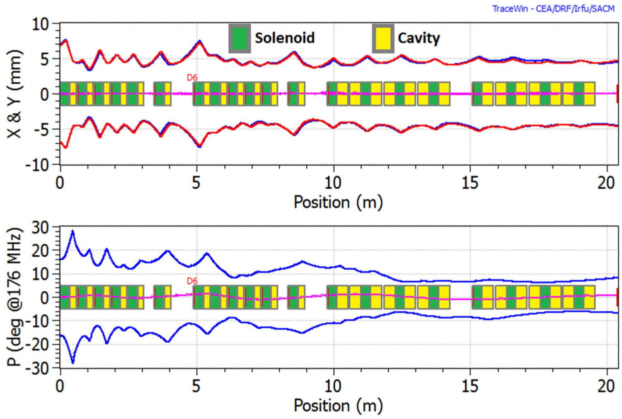

Figure 3: 3-σ envelopes of deuteron beam along SCL. Top: transverse envelope, x in blue and y in red. Bottom: longitudinal envelope.

RESULTS FOR MEBT AND SCL

The beam density is presented along the MEBT+SCL structure in Figure 4. In the transverse dimension, there is a comfortable margin between the beam external border (for 10^6 macro-particles) and the pipe wall, especially in the cryogenic part where beam losses are much more harmful. In the longitudinal dimension, the margin with the theoretical dynamic acceptance ($-\Phi_s$, $+2\Phi_s$) is more irregular.

Once this satisfying nominal setting is obtained, the next step is to check its robustness regarding effects of errors. A thorough study of beam tuning implementation has been developed, consisting in fairly distributing the error budget, then in determining the entire set of error tolerances, correctors and diagnostics by following a systematic procedure in 4 steps (see [5]). The obtained results are applied in the following. The used input beam is the one coming from the RFQ where out-of-energy particles are artificially removed. That is because most of those particles can be stopped by an appropriate setting of MEBT scrapers, a procedure that is not implemented in the error simulations, and those which pass through cannot be mitigated by any of the optimizations studied here.

Figure 5 shows the cumulated beam density over 1000 simulations with 10^6 macro-particles in the presence of errors and corrections. The radial density shows that there is no losses. Only a few particles (over 10^9) get close to the pipe wall, essentially near the transition sections between cryomodules. The longitudinal density shows unhooked particles, essentially at the end of the SCL, which do not lead to major losses. Figure 6 shows indeed that there are only losses for 1 error set (over 100) in the MEBT, at a level much lower than the SARAF requirements.

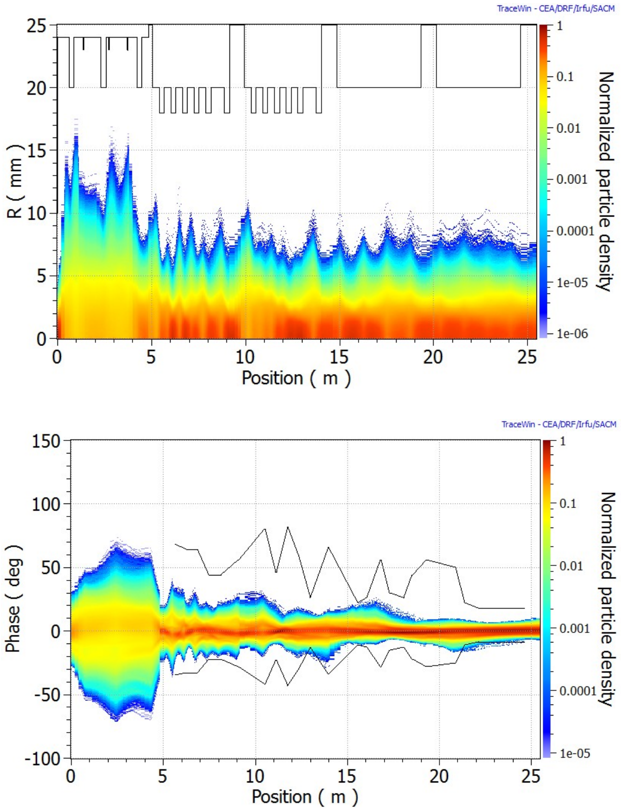

Figure 4: Beam density in transverse (top) and longitudinal (bottom) along MEBT (about 5m long) and SCL. The continuous lines represent respectively the pipe wall or the theoretical linear acceptance.

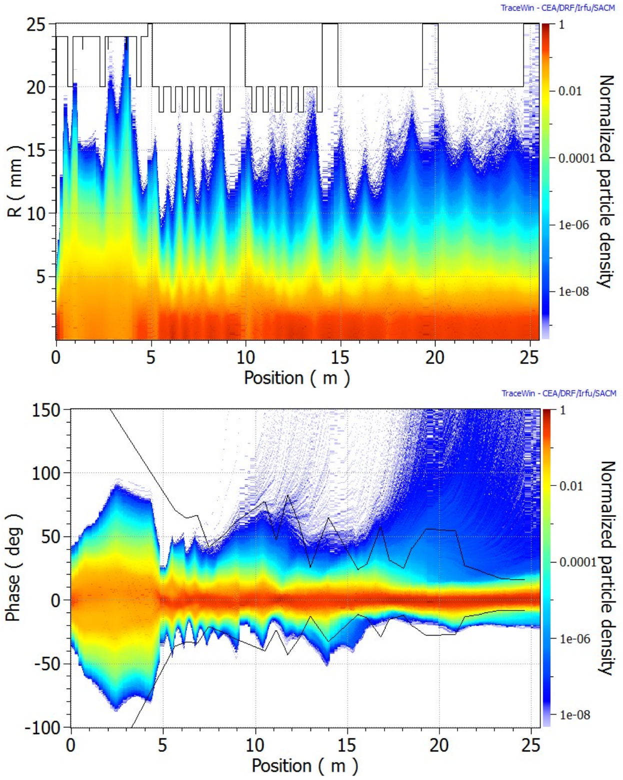

Figure 5: Beam density as in Figure 4, but cumulated on 1000 simulations with 10^6 macro-particles in the presence of errors and corrections.

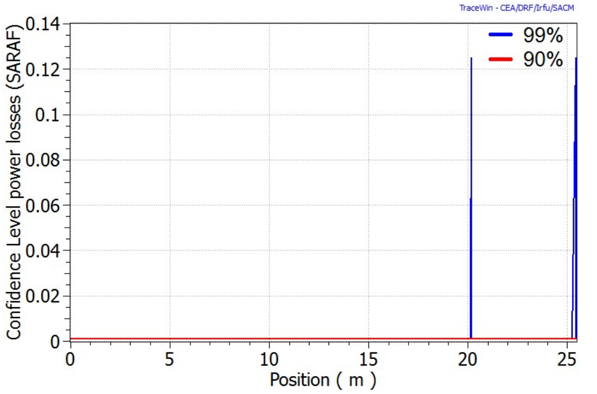

Figure 6: Beam losses along MEBT + SCL normalized to SARAF requirements, i.e. < 1 is OK. Notice that loss constraints are very tight in order to allow hands-on maintenance, for example less than 1 nA/m for energy over 10 MeV.

CONCLUSION

The arrangement of the MEBT structure is discussed and the optimized number of quadrupoles and rebunchers is decided. Efforts for enlarging the longitudinal acceptance in the SCL are detailed, consisting in finding a combination of cavity phases allowing to obtain in the same time the highest final beam energy. As a result, all SARAF required performances in terms of losses and final energy, are obtained with a good margin in an optimized way.

REFERENCES

[1] A. Kreisel *et al.*, in *Proc. LINAC'14*, Geneva, Switzerland, paper WEIOB02.

[2] N. Pichoff *et al.*, presented at IPAC'17, Copenhagen, Denmark, paper TUPVA052, this conference.

[3] D. Uriot *et al.*, in *Proc. LINAC'14*, Richmond, VA, USA, paper MOPWA008.

[4] G. Ferrand *et al.*, in *Proc.* IPAC'16, Busan, Korea, paper WEPMB003.

[5] P.A.P. Nghiem *et al.*, Copenhagen, Denmark, paper MOPIK057, this conference.