STRATEGY OF BEAM TUNING IMPLEMENTATION FOR THE SARAF MEBT AND SC LINAC

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Abstract

Beam dynamics of the MEBT and the Superconducting Linac in the SARAF accelerator are being finalized. A strategy for beam tuning implementation is applied to those sections, leading to specifying the complete set of error tolerances / beam measurements / correctors. A systematic and precise methodology in four steps is applied, leading to fairly distributing the error budget, from which correction schemes are studied, allowing to determine the necessary measurements and correctors.

INTRODUCTION

In the SARAF-phase 2 project managed by SNRC (Israel), aiming at constructing a linear accelerator producing deutons and protons up to the energy of 40 MeV [1], CEA (France) is contributing to the design and the fabrication of the MEBT and the SC Linac (SCL) [2]. As beam dynamics of these two subsystems is being finalized [3], i.e. nominal beam parameters and optics components are being decided, it is time to study the beam tuning schemes allowing to reach these nominal situations when starting from real situations.

In this article, the strategy for beam tuning implementation is described then the three inseparable folds of this procedure, namely error tolerances, beam measurements and correctors are determined.

STRATEGY OF BEAM TUNING IMPLEMENTATION

It is worth saying first that in a perfect world, all the components would be free from errors, then there is no need of beam tuning, simply displaying nominal parameters should be enough. In the real world, none of focusing or accelerating components (quadrupoles, solenoids, bunchers, cavities) is free from errors, it is thus necessary to define the tolerances for those errors, the beam measurements (diagnostic devices) capable of detecting their effects on the beam, and the correctors if any, capable of correcting them. Altogether, those three processes represent the main constituents of beam tuning. They result from the adopted tuning procedure and are intimately linked between them. They cannot be studied separately but should be studied at once. As only small variations around nominal values are considered, they are even linearly dependent to each other. If, for a given type of error, tolerances are doubled, then correctors must be two times stronger and measurements should work in a doubled range with accuracy relaxed by a factor of two.

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The errors can be grouped in two types:

- **Dipolar errors** that affect the beam centroid.
- **Quadrupolar errors** that affect the beam size.

For transverse dynamics, these two errors are well decoupled at first order. For longitudinal dynamics, an error will induce both at the same time.

Let's also distinguish two types of beam measurements:

- **Correction measurements**, when a correction procedure exists, AND when the number of independent measurements is ≤ the number of correctors. Thanks to that, automatic (or fast) correction procedures can be applied, leading to a unique solution of corrector setting. They allow improving quickly the accelerator performances and restoring its primary specifications. In this case, the needed performances for the triplet errors - measurements – correctors can be precisely quantified.
- **Characterization measurements**, when there is no corresponding correction procedure, OR when the number of independent measurements is less than the number of correctors. An infinity of corrector settings can potentially be applied for improving beam properties. Instead of randomly turning the knobs, a careful examination of different configurations is recommended. Those measurements can possibly participate to a long-term beam improvement, and in waiting, will mainly help to survey or control the accelerator status. In this case, tolerance errors would be tighter and the needed measurement performances will be extrapolated from those of "Correction Measurements".

Once those distinctions of error types and measurement types are done, we propose to follow **a precise methodology in four steps** (inspired from [4]) for implementing beam tuning.

Step 1. Fairly distribute the error budget on the optics components, keeping in mind that for small variations considered here, parameter dependencies are linear. For a given error i (e.g. quadrupole misalignment or strength), its individual effect e_i on the beam can be first calculated with whatever an initial small error value. A multiplicative coefficient c_i will then be applied to those initial error values so that dipolar or quadrupolar effects $c_i \times e_i$ on the beam are equal.

Step2. Determine error tolerances and corrector strengths. All the precedent individual errors are combined and a same global coefficient C will be applied to all of them, until residual effects after correction on the beam reach a level that can be judged as tolerable, regarding the available place in beam acceptance. This also allows to calculate the needed corrector strengths.

Step3. Determine needed accuracies for measurements. The precedent step being done without measurement errors, the latter are now progressively introduced up to a level where they deteriorate precedent results by no more than 10-15%. Indeed, the role of measurements being to detect component errors in order to launch a correction, the errors they introduce themselves must be only marginal. (If not, an error leading the beam to a dangerous zone that should be corrected may not be detected, and inversely, a perfect beam may be wrongly corrected sending it to a dangerous zone).

Step 4. Determine tolerances for dynamic errors. Rapid errors, like jitters, vibrations, that cannot be corrected are now progressively introduced, up to a level they deteriorate precedent results by no more than a supplementary 10-15%.

The entire beam tuning implementation is completed by that way.

This can point out a critical component in case of too tight tolerance or too high performance requirements. Either this tolerance/performance can be relaxed to the detriment of beam performances, or a supplementary R&D effort should be made to improve its ability, or its location is not suitable, or the beam optics itself must be revised. At the end, if no solution is found, the Top Level Requirements could be questionable.

In the following, in order to completely determine the triplet error tolerances – beam measurements – correctors, the above proposed strategy will be applied to

- Transverse Dipolar tuning in MEBT, then in SC Linac
- Transverse Quadrupolar tuning in MEBT+SC Linac
- Longitudinal tuning in MEBT+SC Linac.

TRANSVERSE DIPOLAR TUNING

The objective is to cancel beam centroid deviations. The three actors of a dipolar tuning are: dipolar errors, BPMs and dipolar steerers.

The implementation of BPMs and steerers can be determined with the help of Figure 1. When 1 steerer and 1 BPM are located downstream a dipolar error, only the trajectory position at the BPM is corrected but not its angle. In order to correct both, 2 correctors and 2 BPMs are needed, at the condition that the section between the BPMS is free of focusing component. The residual trajectory remains between the error and the first BPM. When there is 1 steerer located right at the dipolar error position, associated with 1 BPM located downward, the trajectory is perfectly corrected everywhere. The residual trajectory is zero. Thus the ideal scheme is to have 1 steerer + 1 BPM at each dipolar error. But this solution is costly in number of steerers and BPMs.

The best compromise is then to have 2 BPMs flanking each group of focusing elements, or in other words, flanking each long straight, associated with 2 steerers located somewhere among the focusing elements. In this scheme, the trajectory is perfectly corrected in long straights. The residual one remains only in the focusing group, where it would not be important because the straights are shorter and the focusing elements generally alternately polarized.

For the MEBT comprising several groups of quadrupoles, the last best compromise solution is applied, while for the SCL comprising solenoids regularly spaced, the almost ideal solution is applied, with 1 pair of correctors within and 1 BPM in front each solenoid.

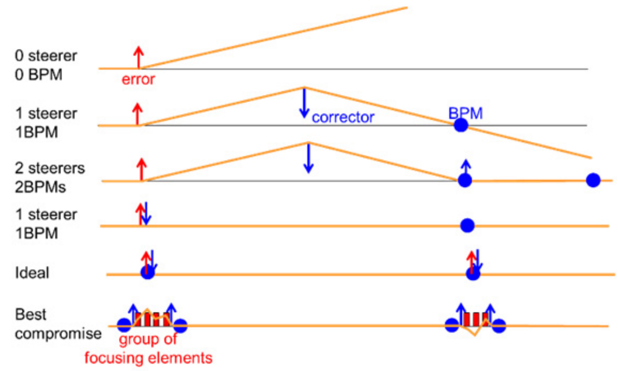

Figure 1: Transverse dipolar correction.

TRANSVERSE QUADRUPOLAR TUNING

The objective of quadrupolar tuning would be to recover beam size the closest to what is theoretically simulated all along the accelerator, that is small enough as regard to the beam pipe wall, so that beam loss probabilities are the lowest. Contrarily to dipolar correction, there is no well-known quadrupolar correction scheme. For SARAF, it is suggested in [5] to use beam size measurements at the MEBT end and at the 4 cryomodule exits.

As there are 5 measurements in 2 planes x and z, i.e. 10 measurements in total, one can potentially use up to 10 quadrupolar correctors. One natural scheme is to use the 4 last quadrupoles of the MEBT, which are designed for transverse beam matching into the SC Linac, and up to 6 solenoids among those in the SC Linac. After trials, it appears that only the exclusive use of 4 quadrupoles is efficient. Adding whatever solenoid combinations, even in case errors come from them, will lead to less good correction and higher corrector strengths. This could mean that as errors are small variations, solenoid used as correctors will introduce too big changes, destroying the lattice regularity, making beam matching to the SCL channel more difficult. On the contrary, if main solenoid fields are let unchanged, any component error can be more efficiently recovered by using the 4 quadrupoles to find out a new beam matching to the SCL channel.

Therefore, the recommended correction scheme consists in 4 quadrupoles at the MEBT end and 5 beam size measurements (horizontal and vertical) at the MEBT end and the four SCL cryomodule exits.

LONGITUDINAL TUNING

As there is no correction procedure for longitudinal dynamics, no static error, no corrector nor measurement are concerned. Only dynamic errors will be addressed,

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those that are not corrected and of which the effects add up, therefore raise up toward the end of the structure.

There is however a calibration procedure, which is a long off-line procedure (duration > 1 day). Based on time-of-flight measurements between two BPMs while turning off cavities in between [6], this is a long procedure that cannot be seen as an automatic correction as those considered here. The application of this procedure will lead to specifications for beam measurements ([7, 8]).

Concretely, in the every-day life of the machine, jitters or thermal shifts of RF phases and amplitudes should not vary more than specifications of dynamic errors, if not a calibration procedure should be launched where specifications of beam measurements should be met.

RESULTS

Figures 2 and 3 show the beam measurements and correctors required for MEBT and SCL.

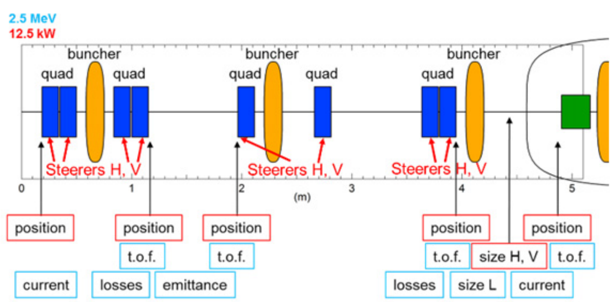

Figure 2: Beam tuning implementation for MEBT. Red, blue frames: correction, characterization measurements.

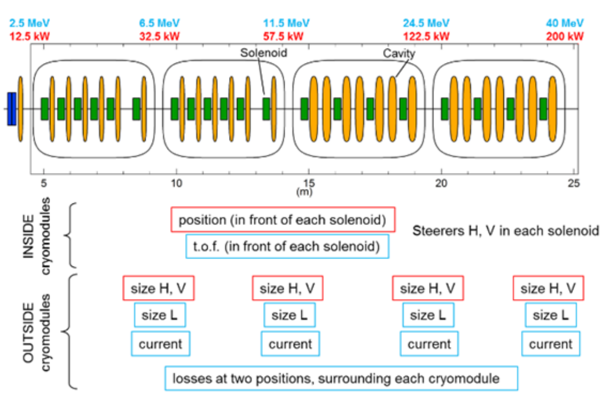

Figure 3: Beam tuning implementation for SCL.

Specifications for error tolerances, measurements and correctors are obtained following the precise methodology in four steps described above. A key parameter of this procedure is the beam acceptance.

In transverse, the available place for the beam is simply determined by the pipe wall. We decided to tolerate error induced combined variations of beam centroid and beam size up to 2/3 (for MEBT) or 1/2 (for SCL) the margin between 3rms beam size and pipe wall.

In longitudinal, there is no such a tangible wall. We decided to tolerate error induced variations on the beam up to 3/2 the longitudinal rms beam size. Notice that the longitudinal acceptance is initially less than that, and important efforts have been dedicated to enlarge it up to this level (see [3]).

With those criteria and the above methodology, all specifications are obtained by means of error simulations in envelope mode. Only at the end, error simulations in multiparticle mode have been launched to check that beam losses are well lower than SARAF Top Level Requirements (Fig. 4). All simulations have been performed with the TraceWin code ([9]).

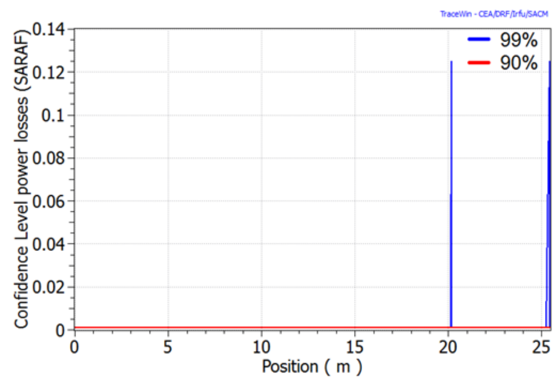

Figure 4: Beam losses along MEBT and SCL normalized to SARAF TLR (<1 is OK). Results of 1000 simulations with 10^6 macroparticles, in the presence of errors and correction.

CONCLUSIONS

A consistent strategy for beam tuning implementation is exposed. It is based on fair distribution of error budget between different error sources then constraining error-induced beam variations after correction to be within beam acceptance. Correction procedures have been examined and optimized. All that allowed to completely specify error tolerances, beam measurements (diagnostics) and correctors at once.

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