ESS LINAC
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Subject :

Error study with both H^- short pulse and proton long pulse in ESS linac with TraceWIN

Author(s) : N. Pichoff, D. Uriot

Affiliation(s) : CEA-Saclay DSM/DAPNIA/SACM

Introduction

In an accelerator, errors are of two kinds:

- Static errors: The effect of these errors can be detected and corrected with appropriate diagnostic and correctors. For example, beam position measurement coupled with steerers can compensate the quadrupole or cavities misalignments. Correction strategy should be known to be able to estimate their impact on beam dynamics.
- Dynamic errors: The effect of these errors cannot be measured. Fortunately, they have usually lower amplitude than static errors. They are, for example, the vibrations of the elements or the RF field control errors (in phase or amplitude). The knowledge of the correction scheme is not needed to study their statistical impact. They are responsible for beam orbit oscillations around the corrected orbit (this notion of orbit is also extended in the longitudinal motion).

In ESS both short and long pulses are needed to fulfil the user requirements.

- The short pulse is injected into a compressor ring. For a maximum efficiency and to avoid a too large activation, H^- are accelerated and stripped into protons at the injection point. Thus, the short pulse is made of H^-.
- The long pulse is directly conducted into the spallation target. There is no specific need of H^-. Both proton or H^- beams can be used. The advantage of H^- is obvious as it proposes to accelerate only one type of particle in the linac. However, the long pulse requirements are not achieved by H^- sources at the present day. Moreover, beam losses rate is higher with H^- than with protons because of the stripping on residual gas. A fallback solution is to use protons for the long pulse. The main advantage is that proton sources have already the required performances. Nevertheless it has to be shown it is possible to guide two beams of opposite charge in the same linac.

In [1], the authors have already shown it was possible to transport two beams with opposite charge in the superconducting sections with an appropriate correction scheme. In this paper, the calculations have been extended to the full linac (common part between both beams).

Simulation model

In [1], the authors have developed a code dedicated to superconducting linac. This model has been extended and applied in the TraceWIN code.

The TraceWIN code is now able to simulate the transport of two beams simultaneously in the same linac. Random errors are applied to each linac element and the correction scheme can be calculated according to the measured positions of both beams.

The correction scheme is based on the following assumptions:

- Each BPM is able to measure the position of both beams in horizontal (X) and vertical (Y) directions. Each BPM gives then four data: X_{H-}, Y_{H-}, X_{H+} and Y_{H+}.
- Each steerer is deviating beams in both directions. In this model, they take place in quadrupoles (by adding some spires to the quadrupoles coils). Each steerer is commanded by 2 entries (S_X: kick in horizontal direction to H^+ and S_Y: kick in vertical direction to H^+). The kicks are opposite for H^- and H^+.

It is obvious than 2 steerers should be coupled to 1 BPM in order to solve a system of four equations (one for each BPM positions) with four unknown (the horizontal and vertical deviations in each steerer). The proposed scheme is plotted on figure 1.

From the SDTL to the SCL, the focusing scheme is the same: doublet.
The two steerers placed in the same doublet are coupled with the following BPM placed just before entering the following doublet. The advantages of this scheme are the following:
- Each Steerers-BPM unit is independent from the others allowing an easy correction,
- The cavities are placed in between the steerers and the associated BPM allowing a good correction of their displacements,
- The steerers placed in the quadrupoles are directly correcting the effects of the quadrupoles misalignment (which is the main source of beam displacement).

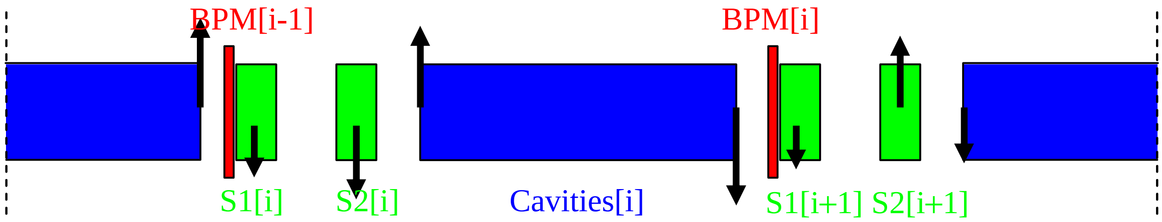

Figure 1 : Correction scheme in the ESS doublet lattice at high energy (>20 MeV). In blue are cavities, in green are quadrupoles including steerers, in red are BPM. The dark black arrows represent the element random misalignments. Steerers S1[i], S2[i] are coupled with BPM[i].

The system that should be solved is:

$$\begin{cases} X^-[i](S1_X[i], S1_Y[i], S2_X[i], S2_y[i]) = 0 \\ Y^-[i](S1_X[i], S1_Y[i], S2_X[i], S2_y[i]) = 0 \\ X^+[i](S1_X[i], S1_Y[i], S2_X[i], S2_y[i]) = 0 \\ Y^+[i](S1_X[i], S1_Y[i], S2_X[i], S2_y[i]) = 0 \end{cases}$$

In TraceWIN, this system is linear and is solved by inverting matrices.
If the positions given by the BPM without corrections are:

$$\begin{pmatrix} X0^-[i] \\ Y0^-[i] \\ X0^+[i] \\ Y0^+[i] \end{pmatrix}.$$

If -M1$^-$[i] is the transfer matrix of H$^-$ from S1[i] to BPM[i], -M2$^-$[i] is the transfer matrix of H$^-$ from S2[i] to BPM[i], M1$^+$[i] is the transfer matrix of H$^+$ from S1[i] to BPM[i] and M2$^+$[i] is the transfer matrix of H$^+$ from S2[i] to BPM[i], TraceWIN has to solve:

$$\begin{pmatrix} M1^-_{1,2} & M1^-_{1,4} & M2^-_{1,2} & M2^-_{1,4} \\ M1^-_{3,2} & M1^-_{3,4} & M2^-_{3,2} & M2^-_{3,4} \\ M1^+_{1,2} & M1^+_{1,4} & M2^+_{1,2} & M2^+_{1,4} \\ M1^+_{3,2} & M1^+_{3,4} & M2^+_{3,2} & M2^+_{3,4} \end{pmatrix} \cdot \begin{pmatrix} S1_X \\ S1_Y \\ S2_X \\ S2_Y \end{pmatrix} = -\begin{pmatrix} X0^- \\ Y0^- \\ X0^+ \\ Y0^+ \end{pmatrix}.$$

An error can be added to the beam position measurement. A random number between –X and +X is then added to the BPM data without corrections:

$$\begin{pmatrix} X0^-[i]+dX^-[i] \\ Y0^-[i]+dY^-[i] \\ X0^+[i]+dX^+[i] \\ Y0^+[i]+dY^+[i] \end{pmatrix}.$$

The effect of this measurement error is that the correction scheme tries to steer the beam around a trajectory that is not the perfect central trajectory.

The measurement of the correction scheme efficiency is made by calculating the rms residual orbit over a large number of error sets having included the correction. It is calculated the following way:
For each error set (label i from 1 to n), at each position s:

$$\tilde{r}(s)=\sqrt{\frac{1}{n}\sum_{i=1}^{n}x_i^2(s)-\left(\frac{1}{n}\cdot\sum_{i=1}^{n}x_i(s)\right)^2+\frac{1}{n}\sum_{i=1}^{n}y_i^2(s)-\left(\frac{1}{n}\cdot\sum_{i=1}^{n}y_i(s)\right)^2}\ .$$

The distribution of the beam transverse positions in horizontal or transverse directions at a given position in the linac has a Gaussian shape. The rms residual orbit is $\sqrt{2}$ times the standard deviation of the distribution. The probability to be beyond 2 times the rms residual orbit is 1.8%. The probability to be beyond 3 times the rms residual orbit is 1.2 10^{-4}. The probability to be beyond 4 times the rms residual orbit is 1.1 10^{-7}.

Simulation results

Only the static errors are taken into account in this study. Errors with different amplitudes have been used depending on the linac section. The amplitude of the static errors are summarised in the table below. For an error amplitude of *A*, the element error has an equivalent probability to be between –*A* and +*A*. The rms error is then *A*/2.

section	Quads	dx (µm)	dy (µm)	θ_x (°)	θ_y (°)	θ_z (°)	dG/G (%)
	Cavities	dx (µm)	dy (µm)	θ_x (°)	θ_y (°)	dφ (°)	dE (%)
Funnel	Quads	125	125	0.1	0.1	0.1	0.5
	Cavities	125	125	0.1	0.1	1	1
Deflection	Quads	125	125	0.05	0.05	0.05	0.5
	Cavities	125	125	0.05	0.05	1	1
SDTL	Quads	125	125	0.2	0.2	0.2	0.5
	Cavities	125	125	0.1	0.1	1	1
CCL	Quads	125	125	0.1	0.1	0.1	0.5
	Cavities	300	300	0.2	0.2	1	1
SCL	Quads	125	125	0.03	0.03	0.03	0.5
	Cavities	2000	2000	0. 2	0. 2	1	1

Long pulse with H^-

When the long pulse is made of H^-, only one charge state is transported through the linac. The correction scheme is then much easier as only one steerer per lattice is needed. In these conditions, the steerer is kept in the first quadrupole of the doublet. The associated residual orbit over a set of 100 linacs is plotted on figure 2. Except in the funnel line (where the

diagnostics positions are not perfectly optimised for the moment), the residual orbit is between 40 µm and 220 µm.
By adding a ± 200 µm BPM measurement error (equivalent to 141 µm RMS in r), the residual orbit becomes this plotted on figure 3. The residual orbit is then between 160 µm and 270. By adding a ± 500 µm BPM measurement error (equivalent to 354 µm RMS in r), the residual orbit becomes this plotted on figure 4. The residual orbit is then between 440 µm and 610.

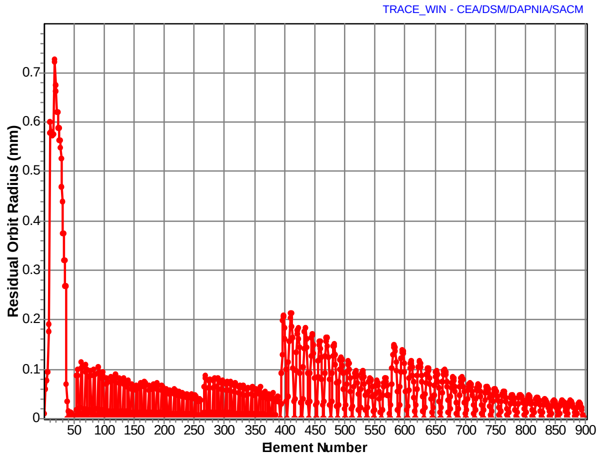

Figure 2 : Residual orbits of only H^- in the linac without BPM measurement errors.

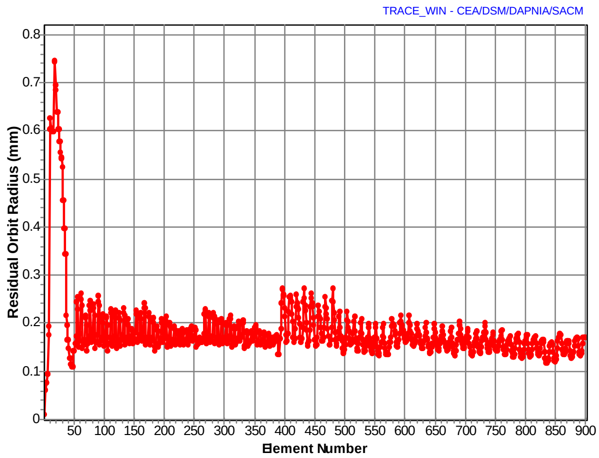

Figure 3 : Residual orbits of only H^- in the linac with ±200µm BPM measurement errors.

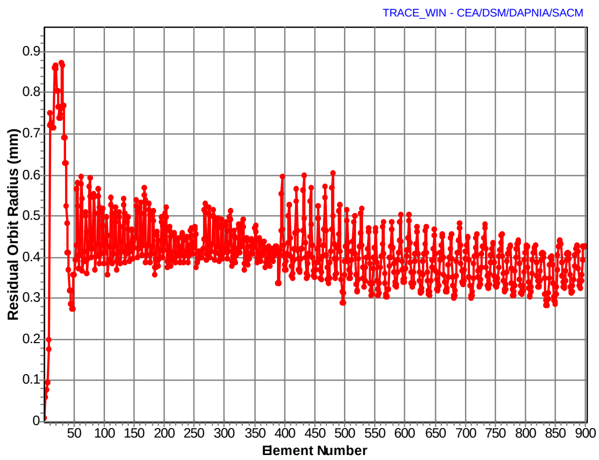

Figure 4 : Residual orbits of only H$^-$ in the linac with ±500µm BPM measurement errors.

Long pulse with H$^+$

When the long pulse is made of H$^+$, the scheme presented before with two steerers associated to 1 BPM is needed. The associated residual orbit over a set of 100 linacs is plotted on figure 5. Except in the funnel line (where the diagnostics positions are not perfectly optimised for the moment), the residual orbit is about 200 µm.

By adding a ± 200 µm BPM measurement error (equivalent to 141 µm RMS), the residual orbit becomes this plotted on figure 6. The residual orbit is then about 300 µm. By adding a ± 500 µm BPM measurement error (equivalent to 354 µm RMS), the residual orbit becomes this plotted on figure 7. The residual orbit is then about 600 µm.

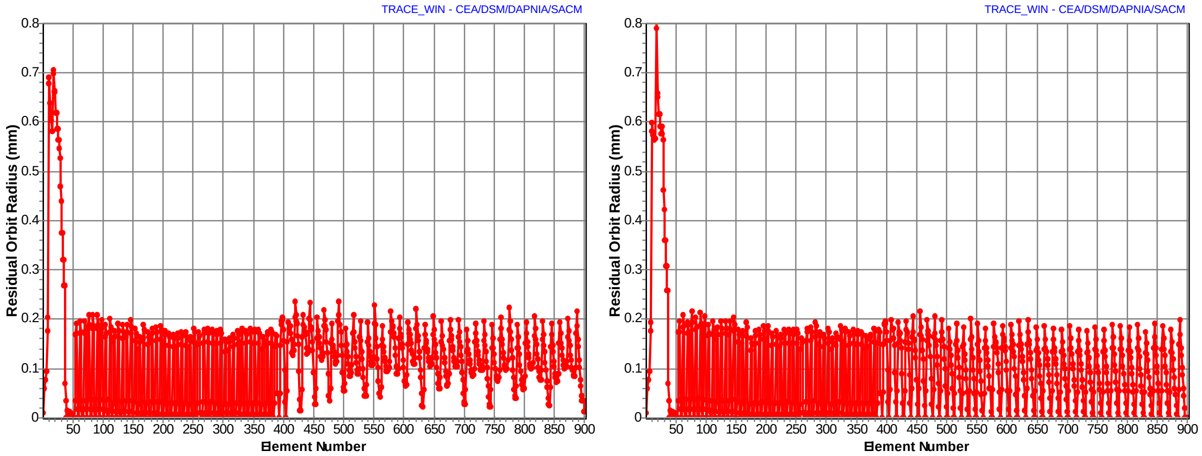

Figure 5 : Residual orbits of both H$^-$ (left) and H$^+$ (right) in the same linac without BPM measurement errors.

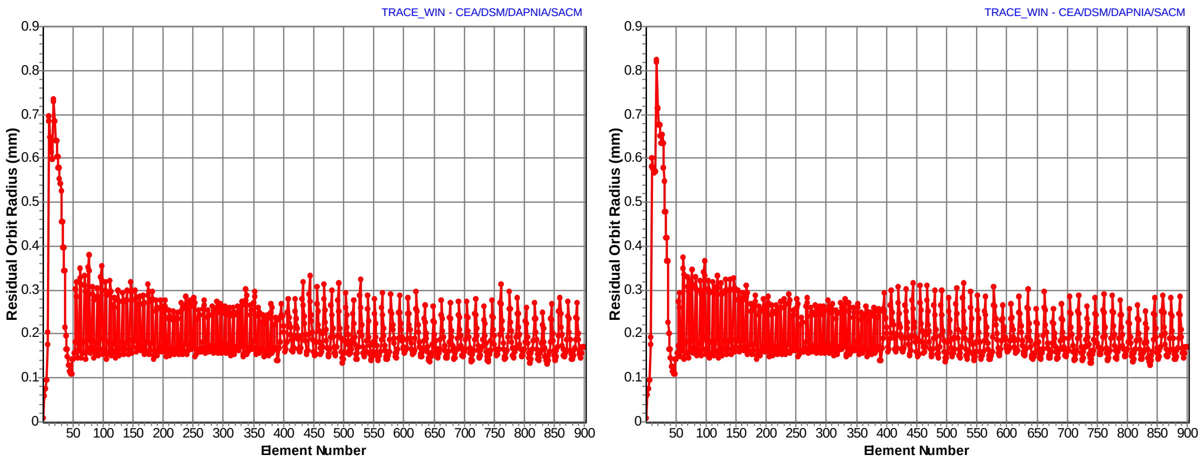

Figure 6 : Residual orbits of both H$^-$ (left) and H$^+$ (right) in the same linac with ±200µm BPM measurement errors.

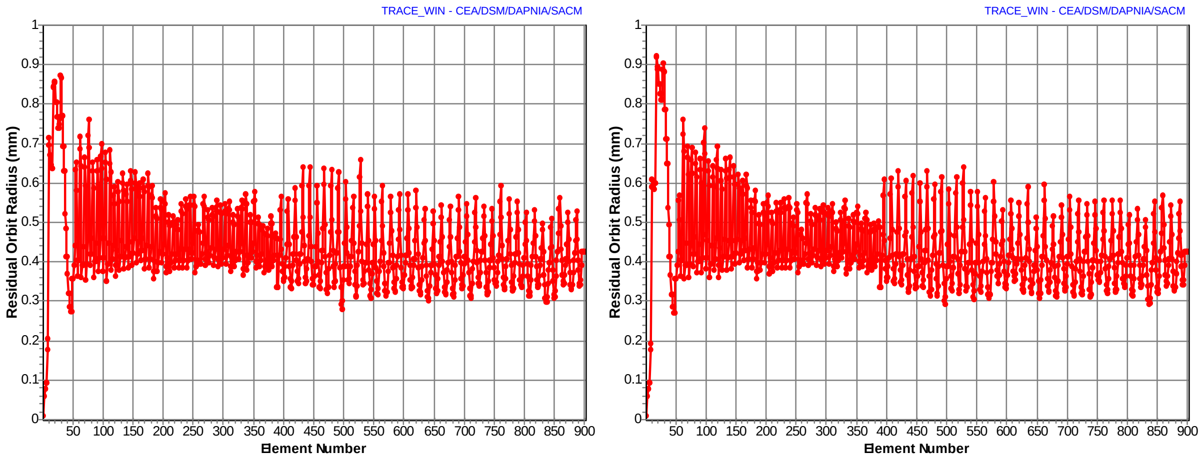

Figure 7 : Residual orbits of both H^- (left) and H^+ (right) in the same linac with ±500µm BPM measurement errors.

Conclusion

The transport of both H^- and protons in the same linac is possible within a residual orbit small compared to the beam rms radius (around 3 mm) and the linac aperture radius (15 mm in the SDTL (until element #260), 17.5 mm in the CCL (until element #400) and 45-50 mm in the SCL). Even a 500 µm error on BPM measurements should be handled without problems.

[1] N. Pichoff, D. Uriot, *Beam monitoring scheme in a SCL*, Internal note DSM/DAPNIA/SEA 2000/25, or ESS Technical note ESSLIN-TN-1001-03.