

# A REALISTIC CORRECTIVE STEERING ALGORITHM: FORMALISM AND APPLICATIONS\*

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## Abstract

The corrective steering algorithm in TRACK has been recently updated to be more realistic. A simplified formalism will be presented along with the method of implementation. As an important application, the algorithm was used to determine the number of correctors and monitors required for the front-end of the High Intensity Neutrino Source (HINS) linac at Fermilab. The algorithm allowed us also to find the optimum locations for the correctors and monitors as well as the required corrector field strength and the required monitor precision for an effective correction. This correction procedure could be easily implemented in an accelerator control-room for real-time machine operations.

## ALGORITHM AND IMPLEMENTATION

Previous versions of the corrective steering algorithm as implemented in TRACK were described elsewhere [1, 2]. We have recently updated the correction procedure and a simplified algorithm is presented in Fig. 1.

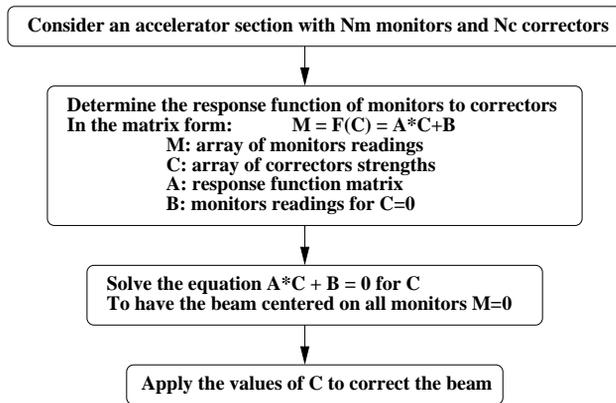


Figure 1: Algorithm for the corrective steering procedure.

In TRACK, instead of solving the matrix equation  $A*C+B=0$  for the array of corrector field strengths  $C$ , with  $A$  being the response function of monitors to correctors and  $B$  the monitors readings for  $C=0$ , we perform a least square minimization of the equivalent function given below:

$$f(C_{i_c}, i_c = 1, N_c) = \sum_{i_m=1}^{N_m} \frac{(\sum_{i_c=1}^{N_c} A_{i_c i_m} * C_{i_c} + B_{i_m})^2}{\sigma_{i_m}^2}; \text{for } |C_{i_c}| \leq C_{\max}$$

In this way, we can include the monitor precision  $\sigma_{im}$

\* This work was supported by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357.

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and the maximum corrector field strength  $C_{\max}$  in the solution. Monitors with different precisions will have different weights in the minimization procedure. The minimization should lead to an approximate solution in the case of an over-determined problem (more equations than variables) and to the best solution in the case of multiple solutions (under-determined problem).

## APPLICATION TO THE HINS FRONT-END LINAC

This realistic corrective steering procedure could very well be applied in the design phase of an accelerator project to determine the monitors and correctors requirements for an effective beam center correction as well as in the control room of an operating accelerator. We present here the results of its application to the front-end linac of the HINS project [3] being built at Fermilab.

### Optimized Locations of Monitors and Correctors

After multiple iterations, the optimum numbers and locations of correctors and monitors for an effective correction were determined. Figure 2 shows the locations of the required correctors and monitors on the three sections of the linac, namely the room-temperature section (RT), the SC single-spoke type I section (SSR-I) and the SC single-spoke type II section (SSR-II).

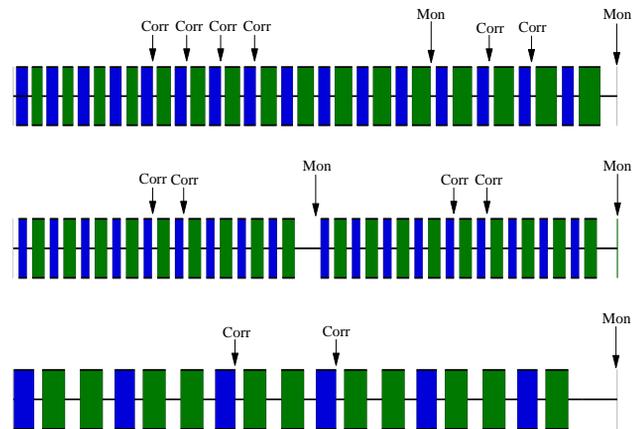


Figure 2: Optimized locations of correctors and monitors in the HINS front-end linac: RT-section (top), SSR-I section (middle) and SSR-II section (bottom). In green are the RF cavities and in blue are the solenoids.

In the case of the HINS linac the correctors are dipole coils attached to the selected solenoids as shown in Fig. 3. More details can be found in references [4] and [5].

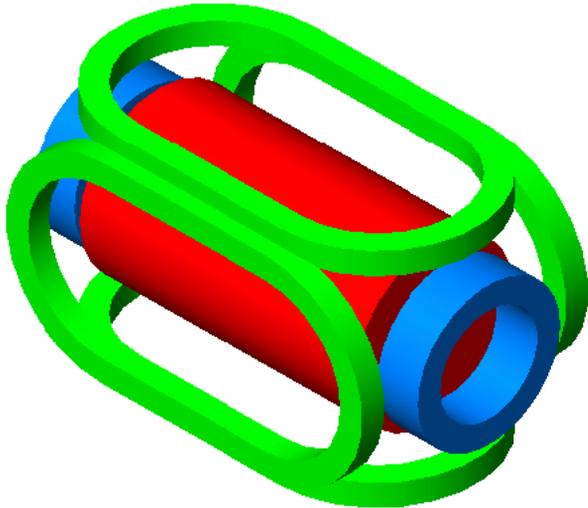


Figure 3: A compact SC solenoid with bucking coils and two sets of dipole coils for corrective steering.

*Correction Results: Beam Centers and Envelopes*

Figure 4 shows the beam position and angle centers as well as the beam emittances and envelopes before and after correction for 100 random sets of misalignments errors applied to the linac. We can clearly see the difference before (red curves) and after (blue curves) applying the correction procedure. In this case we used virtual monitors that can measure both the position and angle to be able to correct both of them. In reality, special measurements will be required to determine the response function for the angles.

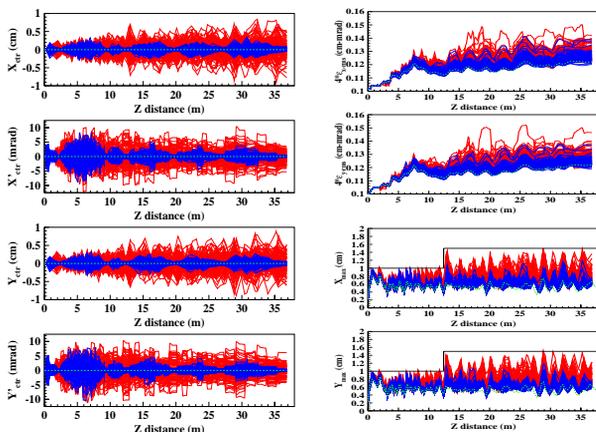


Figure 4: Beam position and angle centers (left) and beam emittances and envelopes (right) before (red curves) and after (blue curves) applying the correction procedure for 100 randomly misaligned linacs. In green is the ideal case without misalignment and in black is the aperture.

The effect of the correction procedure on the beam envelopes can be seen on the two lower right plots of Fig. 4. As the envelope-to-aperture ratio is reduced we expect a significant reduction in beam loss.

Table 1 gives the fraction of beam lost before and after correction for the three sections of the linac. The misalignment errors in this case are 300 μ for solenoids, 500 μ for RT cavities and 1 mm for SC cavities. We notice a reduction in beam loss of about two orders of magnitude which reflects the efficiency of the correction procedure.

Table 1: Fraction of Beam Lost Before and After Correction

Section	RT	SSR-I	SSR-II	Total
Before correction	$2.4 \cdot 10^{-3}$	$8.2 \cdot 10^{-6}$	$7.0 \cdot 10^{-5}$	$2.5 \cdot 10^{-3}$
After correction	$5.5 \cdot 10^{-5}$	$8.8 \cdot 10^{-6}$	$7.1 \cdot 10^{-7}$	$6.5 \cdot 10^{-5}$

*Correctors Field Strength Requirements*

Figure 5 shows the distribution of correctors field strength used in the correction procedure given as the product B\*L of the magnetic field B and the effective length L in Gauss\*cm.

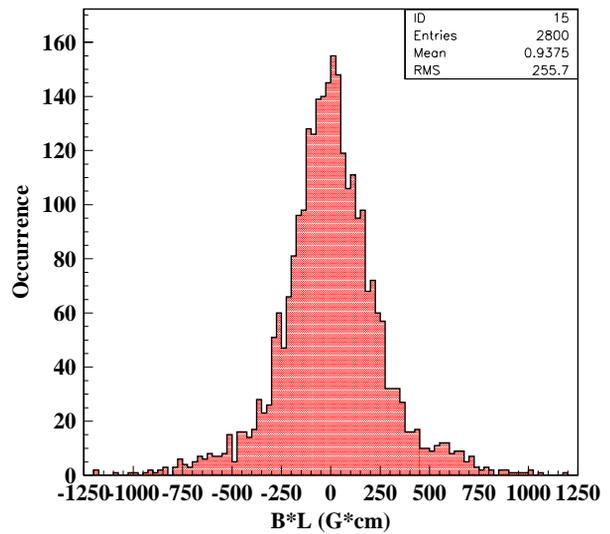


Figure 5: The distribution of correctors field strength B\*L used in the correction procedure.

The B\*L distribution is peaked at 0 with an rms width of 250 G\*cm and a tail extending to 1250 G\*cm. As an extra precaution, the actual coils were designed to go as high as 5000 G\*cm.

### Monitors Precision Requirements

To study the effect of the monitors precision on the efficiency of the correction procedure, we applied the correction procedure assuming three different monitor precision values:  $10\ \mu$ ,  $30\ \mu$  and  $100\ \mu$ . In all these simulations we assume a  $100\ \mu$  error on the center of the monitors in addition to other elements misalignments. Figure 6 shows the results in the form of beam position and angle centers for the different values of monitors precision.

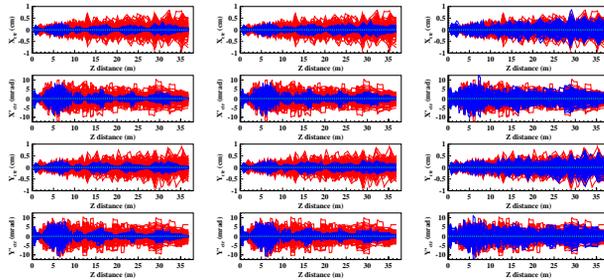


Figure 6: Beam centers before (red) and after correction (blue) for different values of monitors precision:  $10\ \mu$  on the left,  $30\ \mu$  in the middle and  $100\ \mu$  on the right.

We clearly notice that when the monitor precision is in the same order of its misalignment error, the correction procedure becomes inefficient. For monitors misalignment of  $100\ \mu$ , the precision should be better than  $30\ \mu$  for an effective correction.

### APPLICATION TO A REAL ACCELERATOR

To apply the correction procedure to a section of a real accelerator we suggest the following steps:

- With the actual misalignment and before applying correctors ( $C=0$ ), the beam will not be centered on all the monitors:  $M(C=0) = B \neq 0$ . In this way we determine the array of monitors offsets  $B$ .
- Perform measurements by turning on the correctors one at a time to determine the response of the

monitors downstream. In this way we determine the response function  $A$ .

- Solve the matrix equation  $A \cdot C + B = 0$  for  $C$ , or use a least square minimization method to include the monitors precision and the maximum corrector strength. In this way we determine the array of correctors values  $C$ .
- Apply the values of  $C$  as correctors strengths on the real accelerator.

### SUMMARY

We have updated the corrective steering algorithm in TRACK to be more realistic. It uses a least square minimization method instead of solving a matrix equation. It has been successfully applied to the HINS Front-End linac being built at FermiLab. The numbers and locations of correctors and monitors have been optimized for an effective correction. The algorithm solves for the required corrector field strength including the monitors precision. This correction procedure could be easily implemented in an accelerator control-room for real-time machine operations.

### REFERENCES

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