Monte Carlo simulation of beam mis-steering at electron accelerators

Mario Santana Leitner[1], Taiee Liang[1,2]
[1]SLAC National Accelerator Laboratory
[2]Georgia Institute of Technology, Nuclear and Radiological Engineering Department

Abstract

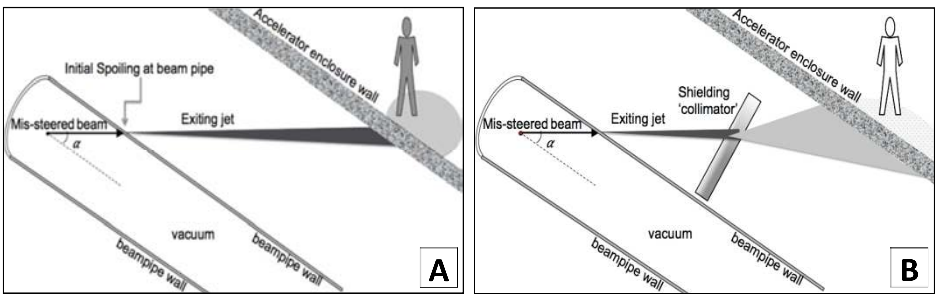
The nominal trajectory and shape of a charged beam in a particle accelerator is determined by the electromagnetic fields that are typically provided by electro-magnets. Those components may eventually be incorrectly tuned or they may experience hardware failures, ultimately leading to a mis-steered beam that could even depart from the beam-pipe and hit components or shielding walls that may not be designed to take direct beam hits. In order to reduce the potentially hazardous radiation levels that would then be generated and the damage to certain components, collimators should be installed around the beam-pipe at strategic locations so that any extraneous trajectory is intercepted and spoiled before reaching sensitive areas. Depending on the beam power and size, those collimators might need to be accessorised with a pressurised vessel to detect if the beam has punctured through the collimator part and has thereby bypassed the shielding.

We present a powerful application of the intra nuclear Monte Carlo particle transport code FLUKA to draw the envelope of mis-steered beams. Additionally, simulations with the same code were carried out to parameterise the heat profile of typical mis-steered beams, so as to help assess where and when collimators require burn-through monitors.

Introduction

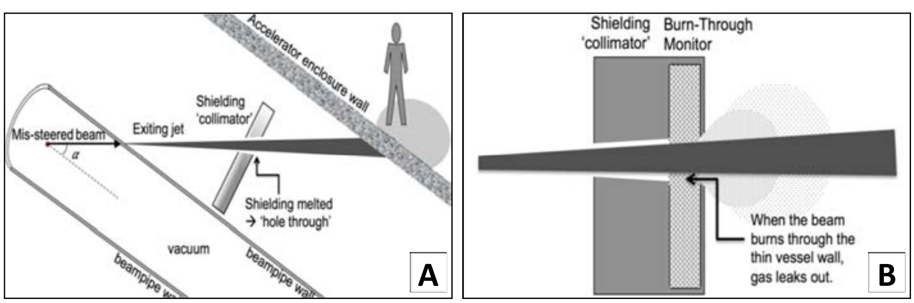
Accelerator enclosures are usually dimensioned for losses occurring along the beam lines, either on insertion devices like stoppers or beam diagnostics, or in beam impedances such as halo-scraping collimators. The radiation shielding design of an accelerator should also include local shielding to cover the low-occurrence, high-risk scenario of beams being lost outside of their regular trajectory, as illustrated in Figure 1. Indeed, the electro-magnets that guide and focus the beam within its nominal parameters may eventually fail steering the beam towards components or shielding walls that may not be designed to take direct beam hits. Such failures may result from inadequate electric powering of magnets due to operational mistakes (e.g. energy mismatch), or hardware failures (short-circuits, radiation-induced electronic bit-flips, etc.), or installation errors (i.e. inversed polarities). Though infrequent, in absence of local shielding the consequences of such accidents could be severe, and therefore, these also entail long shutdowns for extensive investigations and for the implementation of the corresponding corrective measures.

Figure 1: (A) Accelerator enclosure walls are usually dimensioned for normal losses in the beam line and (B) mis-steered beams must be contained with local shielding to prevent high exposure



Ray-trace representations containing all possible errant trajectories compatible with plausible mis-steering assumptions should be generated to define the minimum needs of local shielding. Since this process is intrinsically multi-variant, the approximations used in its creation may impact the size and count of the set of necessary shielding units. The following section addresses this topic.

Figure 2: If mis-steered beams exit the beam pipe, the escaping jets may eventually burn-through local shielding (A) and pressurised gas vessels may detect these instances (B)



Certain local shielding components are equipped with a gas-pressurized vessel that will be ruptured if the escaping jet carries excessive power density. The pressure drop that would follow would be detected by a gauge that would then trigger a beam-shutoff signal through the personal protection system (PPS). This mechanism alerts if the shielding is drilled through by the escaping jets and thus becoming transparent to radiation, as sketched in Figure 2. The system entails supplementary costs and operational burden (e.g. periodic gas refilling required to compensate natural gas leaks) and therefore, it should only be put in place if the local shielding may not sustain the maximum credible heat load. The second part of this paper presents some guidelines on this regard.

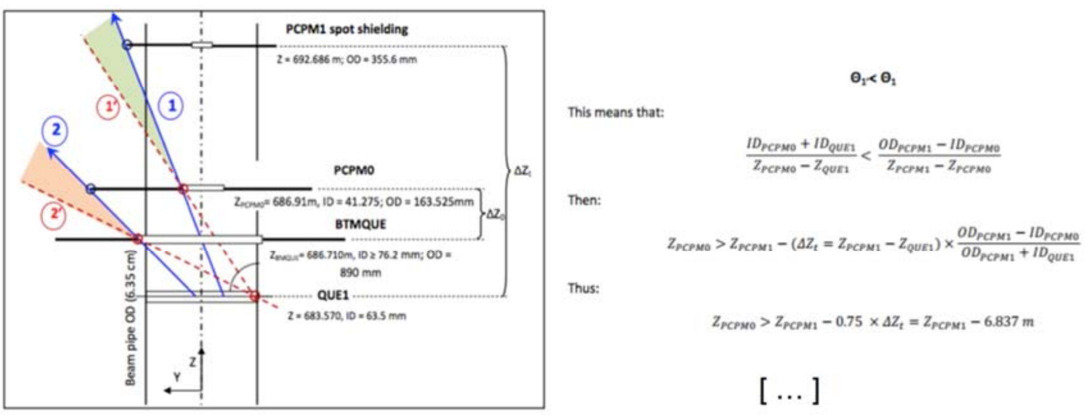
Ray-tracing techniques–new approach with FLUKA Monte Carlo code

Geometric ray-tracing

Ray-tracing for accelerators is usually done analytically, taking into account consecutive (mis)-kicks from two to three magnets. In many simple cases this geometric technique is very efficient as it makes evident the optimal placement and dimensioning of collimators in terms of the magnet locations and mis-steering rules.

However, this method has some serious limitations. For example, if several magnets within a section of a beam line may fail simultaneously, then the analysis tends to become rather cumbersome, as many logic branches open up, and those need to be redefined as a function of the parameters and positions of the components. Figure 3 shows a screen capture for part of an analytical ray-trace for an FEL machine. In that case there were several consecutive magnets that could eject the beam towards a sensitive zone (experimental area at forward angle). The study was extensive, as it had to ensure the collimators would simultaneously lock multiple solid angles. Moreover, for leakage channels originating in downstream magnets, approximations were necessary to account for the effect of previous magnets, and conservativeness in each of the assumptions had to be proved. In such cases, besides tedious, the method is prone to mistakes, and lengthy reviews may be required each time component locations change, as it often happens during the design phase of most beam-lines. Also, this technique usually considers that trajectories are instantaneously bent at a point (the centre) of the magnet. While the latter assumption is usually sufficiently accurate, in some special cases it may end up underestimating the minimum shielding extents.

Figure 3: Screen capture of an analytical ray-trace study



Solid angles of mis-steered rays escaping all collimators are explored as a function of relative locations.

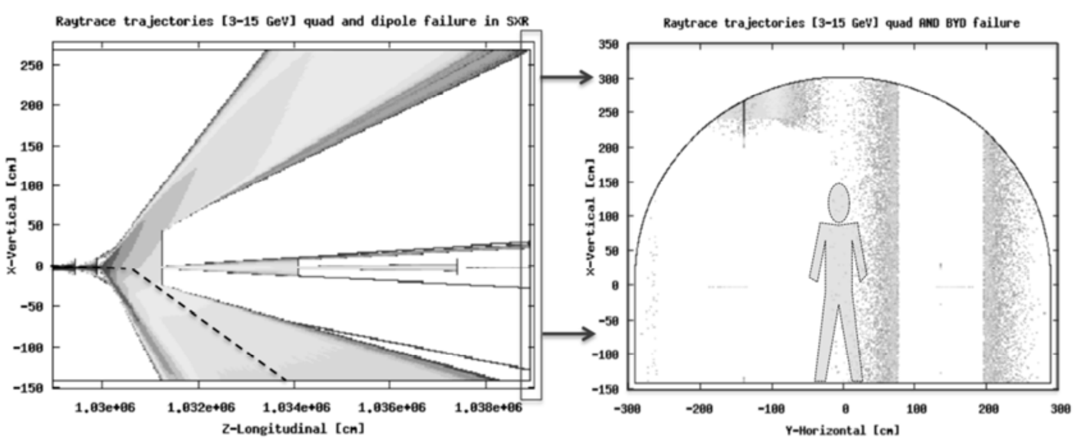
Monte Carlo ray-tracing

State of the art intra-nuclear cascade Monte Carlo (MC) codes like FLUKA [1, 2], MARS [3], or PHITS [4] can track charged particles under magnetic fields. Actually, the beam line optics is often implemented in those codes to determine beam losses and heat loads in components, e.g. amount of beam scraped on a collimator, heat load on it, beam lost on next collimator, etc. On the other hand, the same software is typically used to compute the enclosure thicknesses for those (and other) losses. In such cases it would make sense to utilise the existing geometric and magnetic MC description of the accelerator to draw the ray-trace as well.

The MC ray-tracing concept consists in flooding the system with particles within the credible beam phase-space (energy-position-direction) and having the code track each of those throughout an optics system where magnet strengths may vary anywhere between the limits established in the failure assumptions. Except for local shields and enclosing walls, which are set to a perfectly absorbing material where particles are terminated (e.g. "blackhole" in FLUKA), all components should be assigned vacuum properties so that particles can freely cross them. The resulting envelope of all trajectories is the ray-trace.

This capability has been developed for the FLUKA MC code. Firstly, the geometry of relevant components is defined. This includes regions where magnetic field is present, beam pipe, local shielding and outer walls. Next, the user source routine ("*source.f*") is customised to sample the starting coordinates, the direction and the energy of each particle. Then, the user routine that describes the beam optics ("*magfld.f*") is modified so that the strength of each magnet is randomly adjusted from within its range of variation, as established in the accident scenarios. Since "*magfld.f*" is called at every sub-step along the trajectory of a given particle inside a magnetic region, a condition must be set so that the initialisation of the magnet field strength is performed only upon first entrance to the region. Finally, detectors should be set to score the particle fluence (e.g. "*usrbin*"), and custom scoring should be defined (via "*bxdraw*" routine) to dump the characteristics (energy, starting coordinates, etc.) of particles leaking out of the collimator/local shielding towards the areas of interest.

Figure 4: Left: ray-tracing plot at LCLS-II HXR vertical beam plane for the initial safety collimator design, rays should not reach the end wall behind which there are users, right: hits on the end-wall



In the MC implementation of the aforementioned analytical ray-trace example, particles were originated uniformly within the beam pipe cross-section, with an angular dispersion consistent with possible kicks from magnets located far upstream. The energy was sampled uniformly between the LCLS limits, 2-15 GeV. The strength of magnets was sampled between minus/plus their nominal values. Fine grid fluence maps on both beam planes and on the end wall (at forward angle) were generated to visualise (with Flair [5]) the envelope of ray-traces and the fluence leakage of particles towards the area of interest. Figure 4 shows such plots for the collimator setup defined through the analytical ray-trace. It is observed how the MC ray-trace unveils some weak domains through which some particles could potentially escape and hit the end wall.

The MC ray-tracing method offers many assets. Simulations run very fast, typically filling up the beam mis-steering phase-space to a very significant degree within minutes. Hence, alternative beam-line designs can be swiftly explored by simply adjusting the coordinates of magnets and/or shielding, changing energies, etc. and finally re-launching the simulations. The capability to accurately track particles throughout extended beam optics that is offered by the MC method often spares to adopt conservative assumptions which would otherwise be required by the analytical methods, while revealing some weaknesses that may not be apparent with those techniques. Mis-alignments in the positioning of a magnet can easily be considered by adding tolerance-bound random roto-translations in the local coordinate system used in *magfld.f*. Moreover, inclusion of beam spoiling effects at insertion devices is intrinsically possible when using Monte Carlo transport codes like FLUKA. It should be noted that by replacing magnets with mirrors, and 'magfld.f' by "*usrmed.f*" user routine, photon ray-tracing (e.g. FEL) is also possible in FLUKA.

Power density of mis-steered rays

As explained in the introduction, the design of local shielding that intercepts mis-steered rays involves two steps, namely, ray-tracing to determine optimal location, count and size of local shielding and power density estimations of mis-steered rays to decide whether/which shielding requires burn-through monitors. In this section the shape of the mis-steered jets is characterized as a function of beam energy, mis-steering angle and distance from the exit point. The resulting formulae are meant to be used for ulterior calculations that would reveal whether a particular local shielding could potentially be burnt-through for those given conditions. The results of the study are applicable for high-energy (3-15 GeV) electron beams, but the same methodology could in principle be used for other types of machines.

Jet size response function

FLUKA simulations were carried out for pencil beams ($\sigma_B = 0$) of energies between 3 GeV and 15 GeV, mis-steered at various 'large' angles (30-90 mrad) from within a typical beam pipe of thickness 0.0889 cm. Surface 'detectors' were set at several distances, and particles crossing those were scored. For each of those cases, the profile of the particle stream was seemingly fit to a Gaussian jet. An example is sketched in Figure 5.

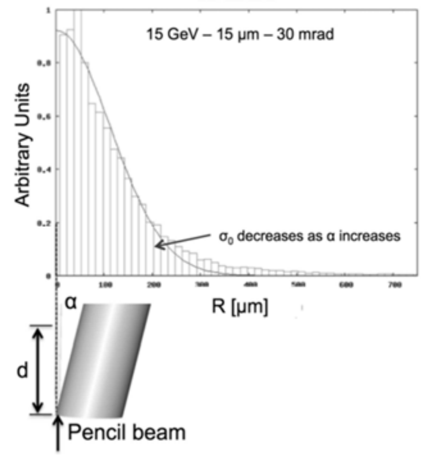
An equation was found (Equation 1) to express the Gaussian size of the exiting jet for a pencil beam (σ_0) as a function of the beam energy (E_0), the mis-steering angle (α) and the distance from the beam escape point (d):

$$\sigma_0 = a_1 \cdot \left(e^{-a_2 \cdot \alpha}\right) \cdot d + b_1 \cdot e^{-b_2 \cdot \alpha} \quad (1)$$

Where:

$$a_1 = 152.14 \cdot e^{-0.11 \cdot E_0}$$
$$a_2 = 2.4 \cdot 10^{-3} \cdot \ln(E_0) + 0.0101$$
$$b_1 = 371.98 \cdot e^{-0.17 \cdot E_0}$$
$$b_2 = 0.0396 \cdot e^{-0.135 \cdot E_0}$$

Figure 5: Sketch of simulation set-up and resulting jet size Gaussian fit



Jet size for finite mis-steered beams

The size of the escaping jet will obviously depend on that of the primary mis-steered beam. In the previous section a response function was derived for a pencil beam, i.e. for a beam of $\sigma_B = 0$. By convolving that expression (Equation 1) with the primary beam profile, the jet size (σ_r) can be obtained for any mis-steered beam shape. The process is straightforward for the typical category of Gaussian cylindrical beams. Indeed, the resulting jet size can then simply be described as in Equation 2:

$$\sigma_r^2 = \sigma_B^2 + \sigma_0^2 \tag{2}$$

This mathematical property is very useful, as it reduces the number of variables in the problem thereby allowing to cleanly express the escaping jet size for any Gaussian beam size with important savings in the number of necessary Monte Carlo simulations, while reducing the complexity of the subsequent fits.

The following sections will expand on this particular, yet key case.

Jet power profile for Gaussian beams

The ultimate goal of this analysis is to obtain parametric formulae to predict the heat load of mis-steered jets in local shielding so that those can be designed accordingly. For that purpose, it is necessary to determine the total energy carried by the exiting jet within a given radius. Since particles in the primary beam suffer inelastic interactions in the beam pipe, the exiting jet will have some energy spread, which needs to be accounted for in the beam shape parameterization.

The earlier fits did not take into consideration the kinetic energy of each event. Now, to obtain the jet power profile (σ_{rE}), that information is used by weighting each particle with its energy. When comparing these with the jet particle profiles, it was found out that the two relate through an angular dependent factor, as shown in Equation 3:

$$\sigma_{rE} = \sigma_r \cdot \{0.1643 \cdot \ln(\alpha) + 0.2137\} \tag{3}$$

Normalisation constant of the energy-weighted Gaussian jet

In order to compute how much power is carried by the mis-steered jet within some given radius, not only is it necessary to know how focused the jet is (σ_{rE}), but also what fraction of the original mis-steered beam does the exiting jet carry in total, i.e. what is the normalisation constant for the energy-weighted Gaussian, C_{rE}

Further mathematical fits to the data stored in the simulations casts the following result (Equation 4):

$$C_{rE} = \frac{f_E(\alpha, d, E_0)}{0.6827 \cdot \alpha_{rE} \cdot \sqrt{2\pi}} \tag{4}$$

With:

$$f_E(\alpha, d, E_0) = \left[f_1 \cdot e^{-f_2 \cdot d} \right] \cdot \left[\left(f_3 \cdot e^{f_4 \cdot \alpha} \right) \cdot E_0 + f_5 \cdot \ln(\alpha) - f_6 \right] \tag{5}$$

Where the fitting coefficients are:

$f_1 = 1.0588$ $\quad f_2 = 0.0110$
$f_3 = 0.0005$ $\quad f_4 = 0.0280$
$f_5 = 0.1490$ $\quad f_6 = 0.4605$

Finally, the power distribution, *P(r)*, of the mis-steered jet is (Equation 6):

$$P(r) = C_{rE} \cdot e^{-\left(\frac{r^2}{2 \cdot \sigma_{rE}^2} \right)} \tag{6}$$

Where σ_{rE} and C_{rE} are respectively defined in equations, and appear tabulated in Table 1 for some typical values of α and d at E_0 = 15 GeV.

Table 1: Example of values σ_{rE} and C for beams of E_0 = 15 GeV and σ_B = 30 μm mis-steered by different angles and measured at distances ranging from 5 to 50 cm

Angle	30 mrad		60 mrad		90 mrad	
d [cm]	σ_{rE} [μm]	C_{rE} * 1E4	σ_{rE} [μm]	C_{rE} * 1E4	σ_{rE} [μm]	C_{rE} * 1E4
5	90.8	4.11	71.8	15.5	90.8	31.5
10	158.1	2.23	117.5	8.95	158.1	19.8
20	294.5	1.07	211.8	4.45	294.5	10.4
30	431.4	0.66	307.0	2.75	431.4	6.52
40	568.4	0.45	402.4	1.88	568.4	4.49
50	705.4	0.32	497.8	1.36	705.4	3.27

Conclusions and future outlook

A beam mis-steering ray-tracing simulation method based on FLUKA code customisation has been presented. The method accurately accounts for magnet failure assumptions as well as other effects such as magnet mis-alignment, or beam interaction with insertion devices. This technique has successfully been used in the design of the safety collimation system of the LCLS-II dump line. Software is being developed to assist in the conversion from MAD [7] beam optics files to FLUKA, so that ray-tracing studies can be expedited.

Spoiling of mis-steered beams at the vacuum pipe has been parameterised as a function of energy, angle, distance to exit point and original beam size. This result will be useful to determine whether local shielding needs to be equipped with burn-through monitors.

Acknowledgements

This work was supported by Department of Energy contract DE-AC02-76-SFO0515.

References

[1] G. Battistoni, S. Muraro, P.R. Sala, F. Cerutti, A. Ferrari, S. Roesler, A. Fassò and J. Ranft, "The FLUKA code: Description and benchmarking" (2007), *Proc. of the Had. Shower Sim. Workshop* 2006, Fermilab 6-8 Sep. 2006, M. Albrow, R. Raja eds., AIP Conference Proceeding 896, 31-49.

[2] A. Ferrari, P.R. Sala, A. Fassò, J. Ranft (2005), "FLUKA: a multi-particle transport code", CERN-2005-10, INFN/TC_05/11, SLAC-R-773.

[3] N. V. Mokhov (1995), "The MARS Code System User Guide, Fermilab-FN-628".

[4] K. Niita, N. Matsuda, Y. Iwamoto, H. Iwase, T. Sato, H. Nakashima, Y. Sakamoto, L. Sihver, (2010),"PHITS: Particle and Heavy Ion Transport code System, Version 2.23", JAEA-Data/Code 2010-022.

[5] V. Vlachoudis (2009), "FLAIR: A Powerful But User Friendly Graphical Interface", *Proc. Int. Conf. on Mathematics, Computational Methods & Reactor Physics* (M&C 2009), Saratoga Springs, NY.

[6] "Linac Coherent Light Source", https://portal.slac.stanford.edu/sites/lcls_public/lcls_ii.

[7] H. Grote, F. Ch. Iselin, "The MAD Program, User's Reference Manual", CERN/SL/90-13(AP).