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PERTURBATION ANALYSIS FOR BEAM TRAJECTORIES. DETERMINING LOCAL SHIELDING CONTAINMENT FOR LCLS-II*

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Abstract

Containment of normal beam losses is a well-established practice for normal operation of particle accelerators, for which well-established tracking codes are applied. However, for exceptional events, such as magnet power failures, severe lattice mis-match, etc., ad-hoc analytical approaches are typically applied. Oftentimes those methods are not automatic; they don't define the full phase-space of mis-steered trajectories and cannot keep up with beam-line upgrades. Moreover, there may exist a disconnect between the teams analyzing consequences of errant beams and those involved in beam-line design. With electron beams exceeding 100 kW, design of LCLS-II at SLAC National Accelerator Laboratory requires exhaustive beam-containment studies to avoid potential destruction of components and excessive dose rates.

Here we present ray-trace studies for LCLS-II performed with FLUKA [1, 2] Monte Carlo code. The implementation of the geometry of the different beam-lines and of the nominal optics was assisted by MadFLUKA [3]. Perturbations to the magnetic were applied to inspect failures compatible with beam operations and hardware settings. Consequences of mis-steered rays and the respective mitigations were also analyzed with FLUKA.

GOALS, PROCEDURE AND ASSUMPTIONS

Scope of the Work

The goals of this work are to compute the envelope of mis-steered rays in critical areas of LCLS-II, and to define an optimized set of beam containment shielding components to trim that envelope so that safety is not compromised.

At SLAC, besides regular shielding provided by the accelerator enclosure, beam containment shielding is composed of protection collimators and masks, which typically are 5 to 20 cm-thick steel components with a pressurized bladder (called BTM) at the back-end that would shut the beam off in case of pressure drop caused by a beam burn-through. Additionally, those components are instrumented with radiation detectors, which are also interlocked to the machine. Figure 1 corresponds to an installed mask at LCLS-I with the according instrumentation.

The following sections cover the methodologies and assumptions followed to perform the ray-trace, as well as the results for two critical areas, such as the Beam Switch-Yard (BSY) and Beam Transport Hall (BTH).

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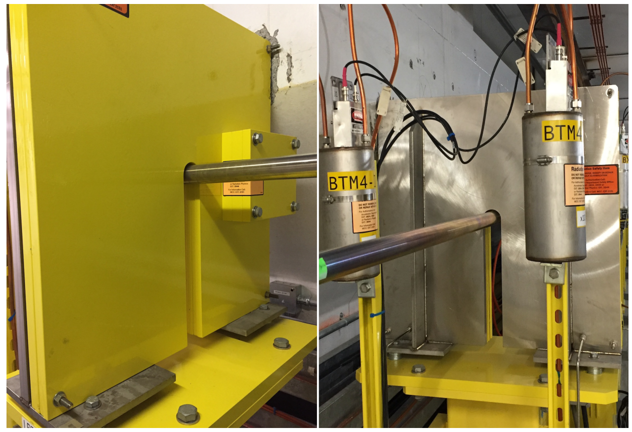


Figure 1: Front (left) and rear view (right) of an installed BTM mask at LCLS-I, instrumented also with ion chambers

Computational Workflow

Ray-trace is performed by simulating a large number of trajectories, each of which is randomly perturbed according to the rules described in next section. This is computed with FLUKA, using a customized version of the magnetic tracking routine "magfld.f". The layout of the beam-lines (up to five in BSY) with hundreds of components, and the reference beam optics are automatically generated with MadFLUKA.

Trajectories are projected on different planes and drawn over the geometry with Flair [4]. Consequences of escaping rays, e.g. derived dose rates, are readily explored in separate simulations using the same geometry in dedicated FLUKA simulations. In case of burn-through calculations, FLUKA results could be directly imported by FEA software, such as Fheat3D. Figure 2 summarizes the file structure and the typical workflow.

Orbit Perturbations and Errors

The following summarizes the failure effects and related assumptions that have been coded in FLUKA user-routine "magfld.f" to generate the ray-trace of LCLS-II:

Off-energy: The magnetic inductance of *bends* or *quadrupoles* is assumed to be mistuned by a factor equal to the ratio of the highest and lowest beam energies for which the magnet might be used, plus a 20 % margin

Polarity: Could be inverted, unless power supplies are monopolar

Quadrupole short-circuits: If power strings to any one of the pole pairs of a quadrupole fail teh result is a skew dipole orientation in any of the four directions ↗, ↙,

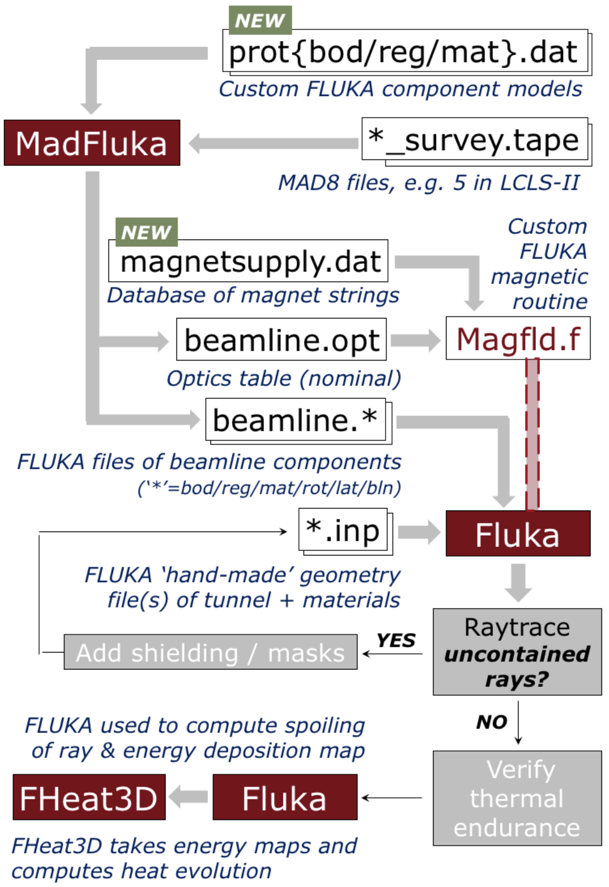


Figure 2: Workflow used to define the ray-trace of LCLS-II

↘ or ↖ of an equivalent strength close to 70 % of its potential dipole strength

Single independent magnet failure: Unrelated errors are not simultaneously considered (e.g. wrong energy settings to magnets in different power supplies)

Quadrupole mis-alignment: Quadrupoles are assumed randomly positioned within 0.5 mm of the beam axis. This number is set higher (1.7 mm) for quadrupoles on undulator girders. Mis-alignment is a pre-existent condition compatible to]other failures

Sextupole and corrector failures: Not considered here due to their weak field, mis-steered rays by those should be absorbed by down-beam components

RESULTS

Containment of Multiple Beam-Lines at BSY

The ray-trace for this area actually begins 420 m upstream of the so-called "muon-shielding", which is a 17 m-long wall in the central line, separating the BSY (C-line) from the BTH. At the end of the BSY, the A-line branches out northwards towards End Station A (ES-A), while the tunnel at the south leads to End Station B (ES-B). Figure 3 shows the layout of BSY as implemented for this study, which includes three LCLS-II beam-lines (SXR, HXR and DML), LCLS-I beam-line and A-line.

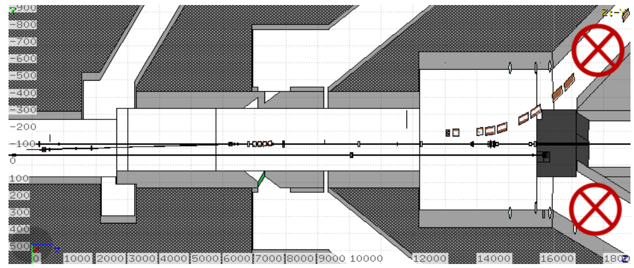


Figure 3: Top view of SLAC Linac sector 28 through BSY and west area of BTH. High power LCLS-II beams mis-steered towards ES-A or ES-B should be intercepted

The "⊗" symbols in Fig. 3 mean that errant LCLS-II beams should not reach ES-A or ES-B, since these are not shielded for high-power beams. Ray-traces in Fig. 4 show that addition of a side mask 330 m upstream of the muon-shielding wall is necessary to block rays towards A-line.

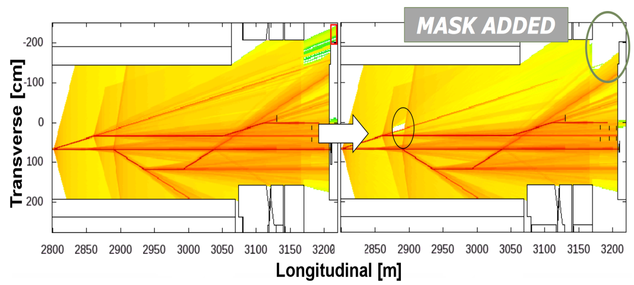


Figure 4: Ray-trace for LCLS-II beam-lines in BSY: (left) without BCS shielding; (right) after adding a small mask

The previous ray-traces did not contain the A-line magnets. Once that beam-line was added to the model, an unexpected effect was discovered. Figure 5 shows how beams steered out from LCLS-II beam-lines towards the north may get to an A-line dipole and be consequently kicked towards ES-A. Mitigation for this will be studied in the future.

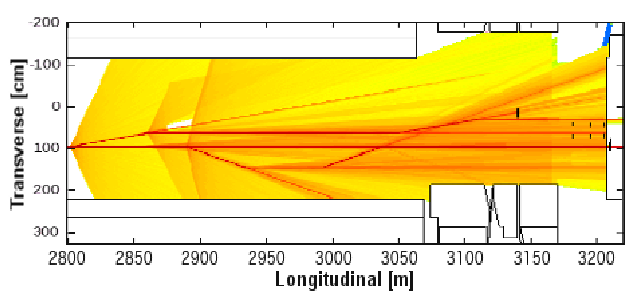


Figure 5: LCLS-II mis-steered beams may reach A-line magnetic fields and be deflected towards ES-A (blue track)

Besides ES-A/B, personnel may access areas down-beam of the muon-shielding. Therefore, mis-steered rays are not allowed to hit that wall from a distance smaller than 100 m, based on (Fheat3D) thermal calculations using energy deposition data from FLUKA simulations, where beam spot size spoiling in the air was intrinsically considered. The clearing effect of four of the seven collimators and masks that were added for that sake is illustrated in ray-traces of Fig. 6.

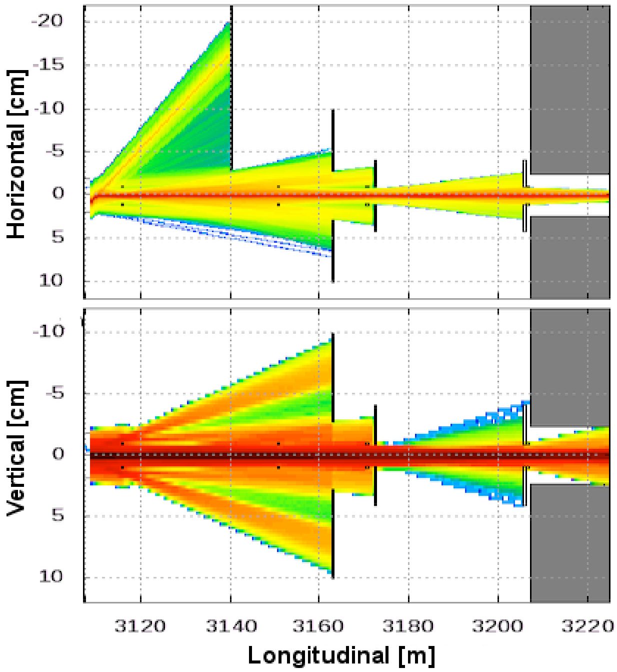


Figure 6: Top view and elevation view of containment of mis-steered beams within 100 m of the muon-shielding wall

Containment for BTH

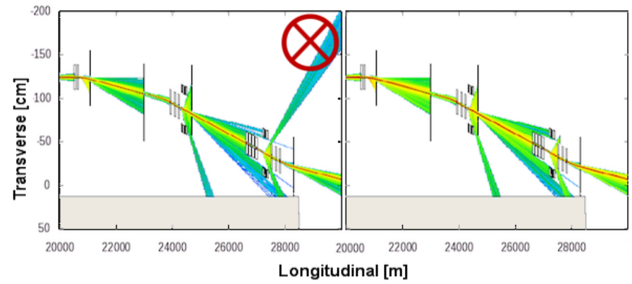
The BTH section includes an over-the-ground building of over 300 m that had been designed to host LCLS-I beams, two orders of magnitude less powerful than LCLS-II.

The ray-trace for the existing LCLS-I beam-line (future LCLS-II HXR), which had been performed analytically, has been revisited, identifying two weaknesses. The first one, shown in Fig. 7(a), happens when the third magnet of the HXR BTH chicane over-straightens the beam, sending it towards the edge of the head-house section of the BTH. A small mask to the north of the beam-line will potentially block those dangerous rays. In the second one, drawn in Fig. 7(b), rays would leak *through* a collimator aperture to then miss next collimator and head towards a sensitive area. This weakness is patched by moving 26.5 m up-beam the second collimator.

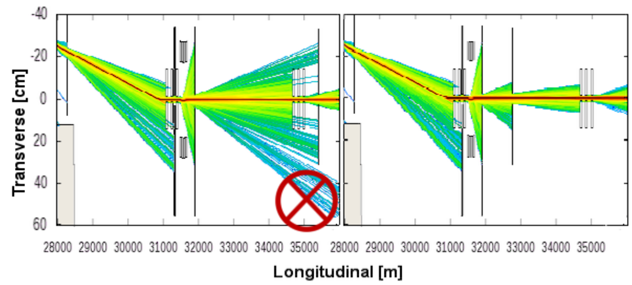
Ray-trace was performed for the other (new) beam-line in BTH (SXR), resulting on eight BTM masks.

Other Areas

Currently, ray-traces are being developed for the undulator and dump-line section, defining shielding to prevent stray beams from hitting the end wall. In doing so, shielding provided by massive components such as the undulators is being accounted for. Such assumption implies implementing a fair geometrical description of those objects in the simulation models.



(a) **Over-bent beams**



(b) **Leaking rays**

Figure 7: Patching two weaknesses in HXR at BTH. "⊗" mark un-allowed trajectories

CONCLUSIONS

Analysis of mis-steering events is crucial in high power accelerators.

FLUKA Monte Carlo + MadFluka have been used to draw the envelope of failures compatible with beam-line hardware.

Needs for masks to catch leaking rays has been evaluated for LCLS-II.

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