

Smart Phantom Simulation: Preliminary Design Document

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1 Accelerator Beamline – MAD-X

Need to characterize the beam with certainty at some point, this would serve as the start of the MAD-X simulation.

1.1 Requirements

Position Distribution

The position distribution can be retrieved from any one of the detectors in the beamline from when a measurement is made. Hence, it makes sense to use one of the SFX monitors as the start of the simulation. Important to note that the last SFX monitor in the IR1 beamline is dead (T1-01-001-SFX). **Take beam profile from a measurement in one of the SFX monitors in the line.**

Angular Divergence Spread + Orientation

Cannot be measured, needs to be inferred. **Match simulation to trajectory measurements** in order to infer the divergence spread of bar and the orientation in horizontal phase space.

Vertical Twiss Parameters + Vertical Beam Emittance

Both are unknown but can be inferred by **fitting particle tracking to trajectory measurements** or **perform a quad scan in order to obtain the Twiss parameters and emittance.**

1.2 Beam Distribution Generation (Copied from task writeup)

To generate the vertical Gaussian phase space distribution for simulations, the particles were generated according to:

$$Y = \sqrt{\varepsilon_y \beta_y + \left(D_x \frac{\Delta p}{p}\right)^2} a \quad (1)$$

$$PY = (c - \alpha_y b) \sqrt{\frac{\varepsilon_y}{\beta_y}} + D_{py} \frac{\Delta p}{p} \quad (2)$$

where Y is the position and PY are the angular divergence in vertical phase space and p is the momentum. α_y , β_y , D_y , D_{py} are the vertical Twiss parameters and ε_y is the vertical emittance. a , b , c are Gaussian random numbers generated with a mean value of 0 and a standard deviation of 1. As can be seen, the vertical beam distribution is heavily dependent upon the Twiss parameters, but once the beam distributed is generated the simulation is quite close to measurements.

For the horizontal phase space things are a bit more complicated as the beam distribution is decoupled from the horizontal Twiss parameters. Several methods to attempt to characterize the ‘bar of charge’ were made, each with varying degrees of success. There are essentially three major degrees of freedom which need to be specified in order to characterize the full ‘bar of charge’:

1. Horizontal beam position distribution
2. Horizontal beam angular distribution
3. ‘Bar of charge’ orientation in phase space

First to characterize the horizontal beam position distribution, one can use the results from one of the SFX monitors in the beamline. From these measurements one can obtain the position distribution and create a Monte Carlo distribution from that. The trouble is that it needs to be at an SFX position, but for the T2 beamline, the EX-02-001-SFX detectors corresponds to the start of the T2 beamline. The main complication lies with the other two degrees of freedom which cannot be easily measured. The theory behind the ‘bar of charge’ is that the angular spread must be significantly smaller than the position distribution, and previous simulation when MedAustron was commissioned puts the angular spread at an order of 10^{-4} rad. As for the orientation of the ‘bar of charge’ by optics design, the bar of charge should be flat at the start of the simulation, i.e. at the EX-02-001-SFX monitor. However, this was not the case, and in the extraction line there isn’t a position where the orientation is known for certain. Hence for the angular distribution and the orientation, these values had to be inferred by particle tracking and comparing the results to the SFX monitors in the beamline.

1.3 Verification

Verification of the simulation comes from comparison of the FWHM predicted by simulation to SFX monitor measurements.

1.4 Output

A ‘master file’ of tracking to end of the beamline (entrance of vacuum window). One such file for each particle type, particle energy (may not be necessary if orbit correction is done well). **Need to define the number of particles to track in such a file.** Such a file would serve as an input to simulations for scattering in the medical nozzle.

1.5 Summary

Input Parameters Needed

| Parameter | β_y | α_y | D_y | D_{py} | $\varepsilon_{geom,y}$ | $x_{distribution}$ | $x'_{distribution}$ | θ_{bar} | # of Particles | Magnet Settings |
|-----------|-----------|------------|-------|----------|------------------------|--------------------|---------------------|----------------|----------------|-----------------|
| Value | ? | ? | 0 | 0 | ? | ? | ? | ? | ? | Machine Model |

Output Parameters

| Parameter | x | x' | y | y' | z | Energy | Particle Type |
|-----------|-----|------|-----|------|-----------------|--------|---------------|
| Value | ? | ? | ? | ? | Assumed to be 0 | ? | Proton/Carbon |

2 Medical Nozzle – BDSIM

MAD-X cannot simulate scattering, need another simulation tool to do so, i.e. BDSIM which uses some of the physics processes from Geant4.

2.1 Requirements

Physics lists

Need to determine **which physics lists** will be used for the simulations to give sufficient accuracy required. It has been noticed that there is some discrepancy in the simulated transverse beam profile compared to measurements. Preliminary investigation suggests it is likely to be an issue with the physics processes.

Also it seems to have been previously noticed that Geant4 appears to underpredict the lateral scattering when compared to both measurements and other simulation tools (i.e. Fluka and MCNPX). This appears to have been present for both protons and carbons from what I have observed. **How does this impact the simulations for energy deposition in the detector/phantom?**

Geometries

Approximations of geometries of the nozzle have already been modelled in GDML format. Important parts of the geometries are: Dose Monitoring Components (ITS, DDS1, DDS2), Ripple Filter (2 used for carbon), Range shifter (was not used for carbon in IR2H), so instead it was just air in my simulations.

From start to end of nozzle.

Nozzle Basic Parameters

| Nozzle Element | Thickness [mm] | Material |
|----------------------|----------------|----------------------|
| Vacuum Window 1 | 0.195 | Aluminum + Hostaphan |
| Vacuum Gap | 14 | Vacuum |
| Vacuum Window 2 | 0.195 | Aluminum + Hostaphan |
| Air Gap 1 | 23 | Air |
| ITS | 90 | Mixture of Materials |
| Air Gap 2 | 48 | Air |
| DDS 2 | 120 | Similar to ITS |
| Air Gap 3 | 2 | Air |
| DDS 1 | 120 | Similar to ITS |
| Air Gap 4 | 40 | Air |
| Ripple Filter 2 | 2 | PMMA |
| Air Gap 5 | 16 | Air |
| Ripple Filter 1 | 2 | PMMA |
| Air Gap 6 | 37 | Air |
| Range Shifter | 30 | PMMA |
| Air Gap 7 | 66 | Air |
| Nozzle Exit Window | 0.18 | Kapton |
| Air Gap to Isocentre | 650 | Air |

2.2 Verification

Verification of simulations transverse beam profile can be obtained from beam profile monitors: DDM, MiniQ and/or Lynx.

2.3 Output

ROOT file from which analysis can be done to filter particles, energies, etc. The required output depends on what simulation tool is used to model the phantom/detector and the required input for that tool.

2.4 Summary

Input Parameters Needed

| Parameter | x | x' | y | y' | Energy | Nozzle Geometries | G4 Physicslist | Phantom position | # Particles |
|-----------|-----|------|-----|------|--------|-------------------|----------------|------------------|-------------|
| Value | ? | ? | ? | ? | ? | Done (GDML) | ? | ? | ? |

Output Parameters

| Parameter | x | x' | y | y' | Energy | Particle Type | Others? |
|-----------|-----|------|-----|------|--------|---|---------|
| Value | ? | ? | ? | ? | ? | Carbon, Proton, e^- , γ , etc. | ? |

3 Phantom – BDSIM?

If using BDSIM then the same requirements as for the nozzle.

3.1 Requirements

Physics lists

- Which physicslists combination used for simulations?
- Lateral scattering is underpredicted in Geant4, which is quite noticeable at the lower energies (about -10% for 120 MeV/u carbons from what I have seen at isocenter position, differs based upon selected physics options)

Geometries

Modelling just the phantom can probably just use the inbuilt BDSIM geometries for simplicity. The outer dimensions of the phantom are 300 mm x 300 mm x 300 mm and the tank itself is made of PMMA along with the structure to hold the cells at the top.

From entrance to exit.

Phantom Basic Geometry

| Element | Thickness [mm] | Material |
|--|---|----------|
| Entrance Window | 3.05 (Lateral dimensions are 170 mm x 170 mm) | Air |
| Water Gap | ? | Water |
| Scintillating fibre layer 1 – horizontal | 0.25 (?) | ? |
| Scintillating fibre layer 1 – vertical | 0.25(?) | ? |
| Water Gap | ? | Water |
| Additional SciFi + Water (?) | ? | ? |
| Flask | ? | ? |
| Additional SciFi + Water (?) | ? | ? |

3.2 Verification

Measurements with detector?

3.3 Output

ROOT file from which analysis can be done to filter particles, energies, etc.

3.4 Summary

Input Parameters Needed

| Parameter | x | x' | y | y' | Energy | Phantom Geometries | G4 Physicslist | # Particles |
|-----------|-----|------|-----|------|--------|--------------------|----------------|-------------|
| Value | ? | ? | ? | ? | ? | To be confirmed. | ? | ? |

Output Parameters

| Parameter | x | x' | y | y' | Energy | Particle Type | Others? |
|-----------|-----|------|-----|------|--------|---|---------|
| Value | ? | ? | ? | ? | ? | Carbon, Proton, e^- , γ , etc. | ? |