Status of Simulation of Laser-Target Interaction

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Introduction

- A beam needs to be tracked to evaluate the design for LhARA.
- TNSA (target normal sheath acceleration) simulation to produce a beam.
- Track through Stage 1 of LhARA and compare capture and transport.

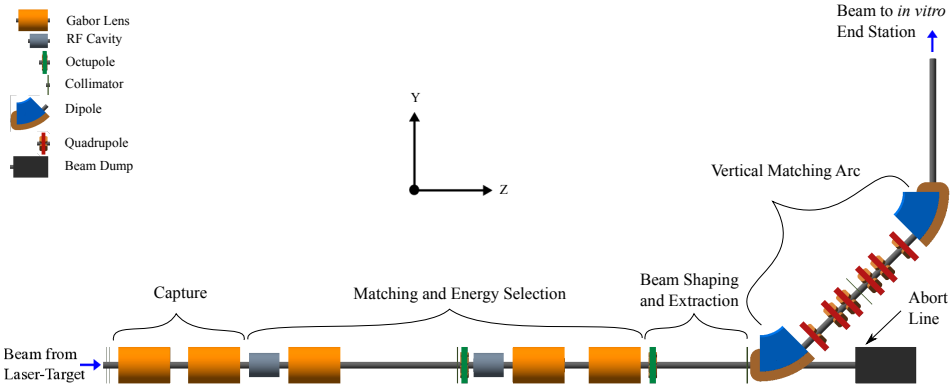


Figure: Schematic diagram of Stage 1 of LhARA.

Target Normal Sheath Acceleration (TNSA) Mechanism

- The TNSA mechanism occurs for an intense laser pulse interacting with a thin foil to produces a flux of ions.

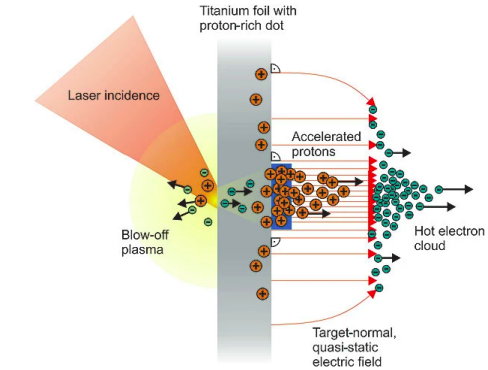


Figure: Schematic diagram of the TNSA process from Schwoerer [1].

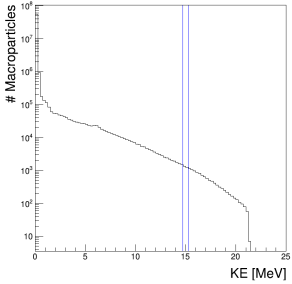


Figure: Example of kinetic energy spectrum of protons from a TNSA simulation. Blue bars indicate the selected energy range between 14.7 and 15.3 MeV.

- Broad range of energies is obtained, only a small fraction is of interest to reach the end station.

Simulation Codes

Smilei

- Particle-In-Cell (PIC) code for plasma simulation [2].
- Simulate the TNSA interaction to produce a distribution of particles.

BDSIM
Beam Delivery Simulation

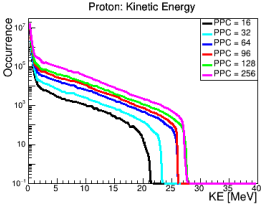
- Uses Geant4 toolkit to simulate transport and particle-matter interactions [3].
- Propagates beam from Smilei through beam line.

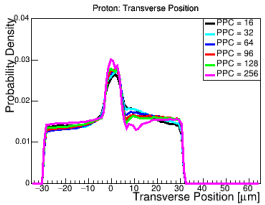
GPT
General Particle Tracer

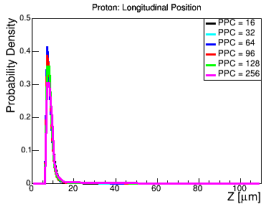
- 3D particle tracking with various 2D and 3D space charge models [4].
- Include space charge effects in distribution.

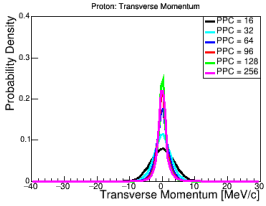
Smilei Simulations

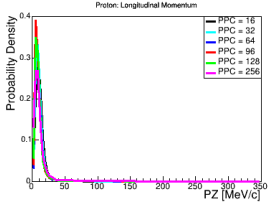
- First step was to avoid numerical effects affecting the simulation results, this involved convergence testing for several parameters.
- 2D simulations were run for this.











Smilei 2D Simulation for Proton Macroparticles

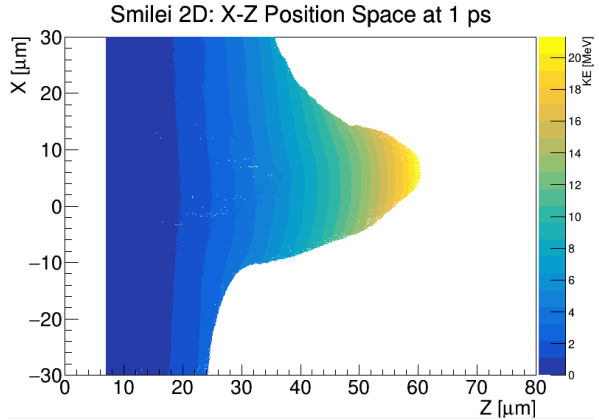


Figure: 2D positional spread of proton macroparticles.

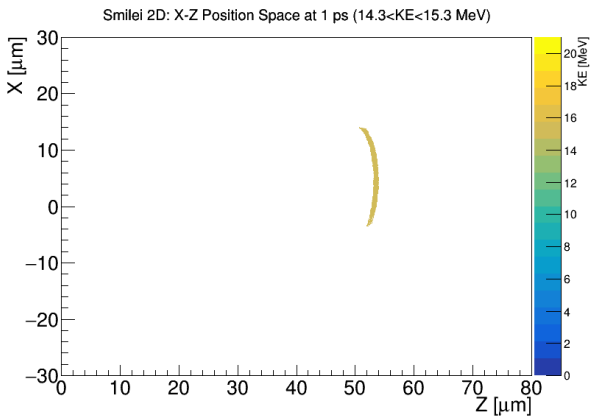


Figure: 2D positional spread of proton macroparticles for energies of interest.

- From simulation, proton macroparticles from beam are off-centred and only a small proportion are energies we are interested in.

Dimensionality

- Ideally we would run a 3D simulation and track the protons through the beamline...
  - Computationally expensive to run: Time, Resources, and Memory.
- However, a 2D simulated macroparticle **energy spectrum is enhanced** compared to 3D simulations to experiments [5, 6, 7, 8].
- The additional degree of freedom in 3D weakens overall electron heating.

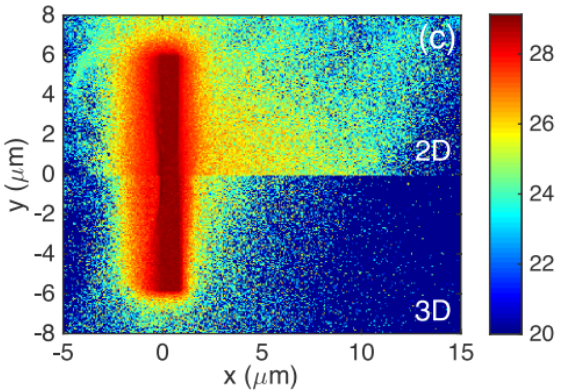


Figure: Comparison of electron plasma obtained between a 2D and 3D simulation, colours represent intensity. Taken from Xiao *et al.* [5]

Dimensionality

- Different ways to get around this issue for 2D simulations, which tend to scale parameters to better match to experimental results [9, 10].
- But without a laser system to compare against, had to accept that we can only generate and track a **qualitative** beam.
- We decided to sample the 2D simulation assuming that the **same correlations** would be present for the added transverse dimension.

Sampling Method

Summary of method:

1. **Assume the same correlations** for both transverse axes as in simulation.
2. Sample the kinetic energy.
3. Sample the momentum components from momentum correlations in simulations.
4. Sample the position coordinates based on correlations between momentum and position.
5. Center the distribution for momentum and position for energies in the range of interest.

A limitation of the current implementation of this sampling method is that it takes some time to run, particularly if done for all energies.

- So in order to get sufficient statistics for tracking and to gauge the performance of the optics, a beam with energies only between 14.7 and 15.3 MeV was generated.

Vacuum Nozzle

The beam coming from the rear of the foil was tracked for 5 cm to the vacuum nozzle without space charge in BDSIM.

- The vacuum nozzle has an opening aperture with a radius of 2 mm.
- The collimated beam is tracked for another 5 cm through the nozzle in GPT to include space charge.
- The beam is collimated on exit with a radius of 2.87 mm.

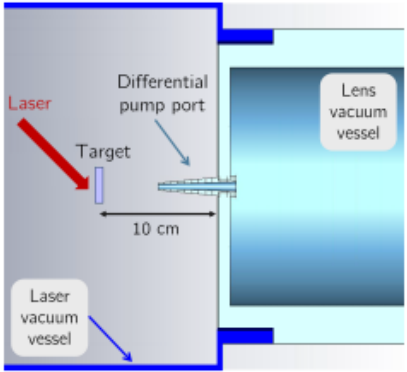
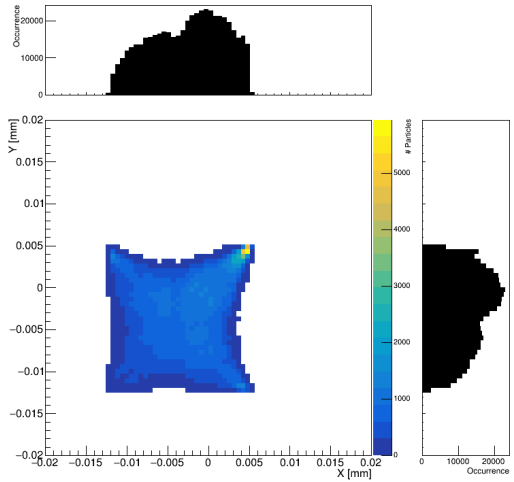


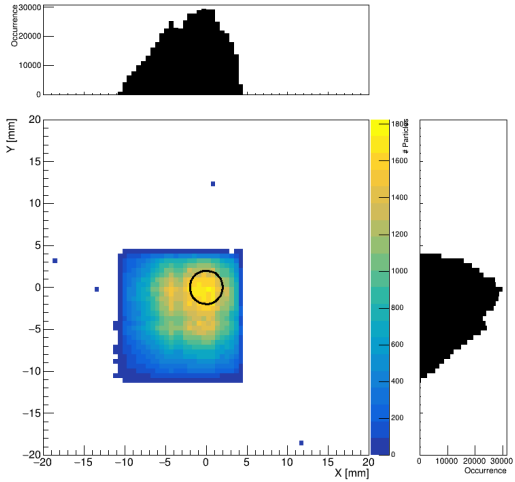
Figure: Interface between laser target and first Gabor lens.

Tracking Beam to Vacuum Nozzle

Sampled Beam from Foil

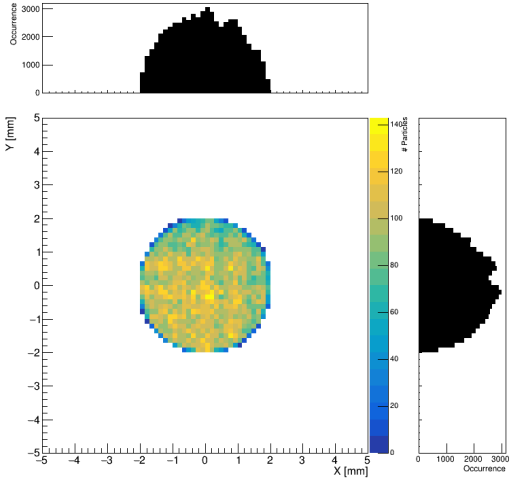


Sampled Beam before Nozzle

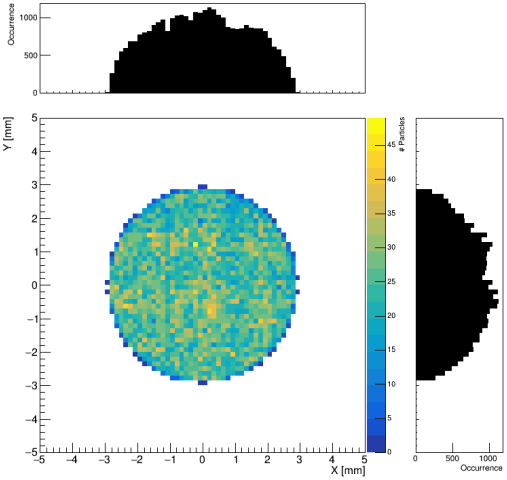


Tracking Beam through Nozzle

Sampled Beam at Start of Nozzle

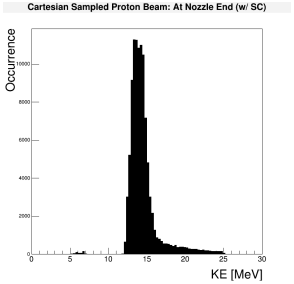


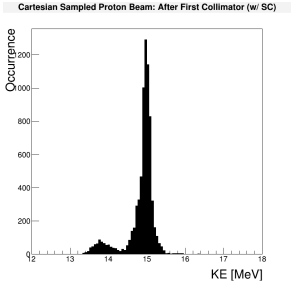
Sampled Beam at Exit of Nozzle

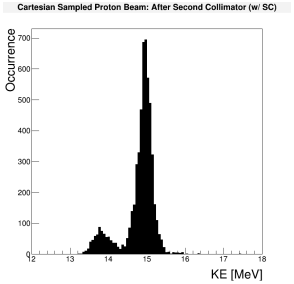


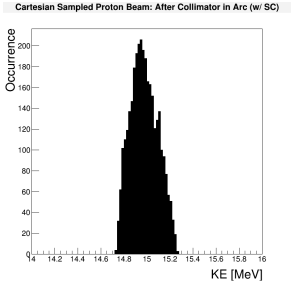
Collimators and Energy Distribution

- As mentioned the sampled beam only contained the energies of interest ($14.7 < \text{KE} < 15.3\,\text{MeV}$)
- A preliminary sampled beam with larger energy spread ($> 5\,\text{MeV}$) was tracked.
- Placement of collimators appears effective.
- Still need to verify for the lower energies ($< 5\,\text{MeV}$).



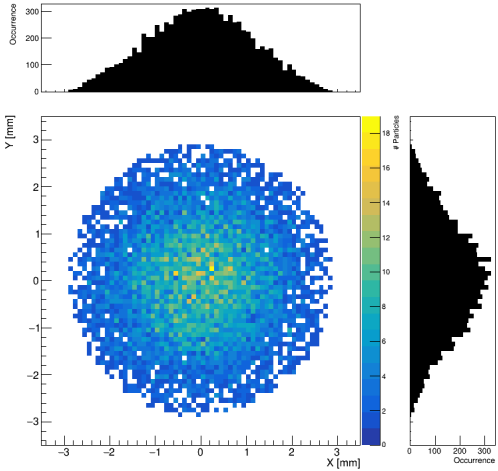




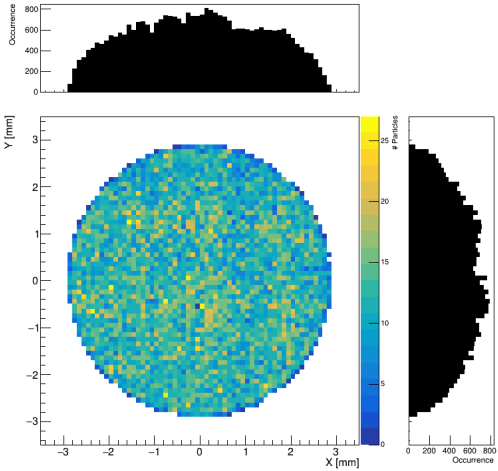


Beam Comparison at End of Nozzle

Ideal Beam: End of Nozzle

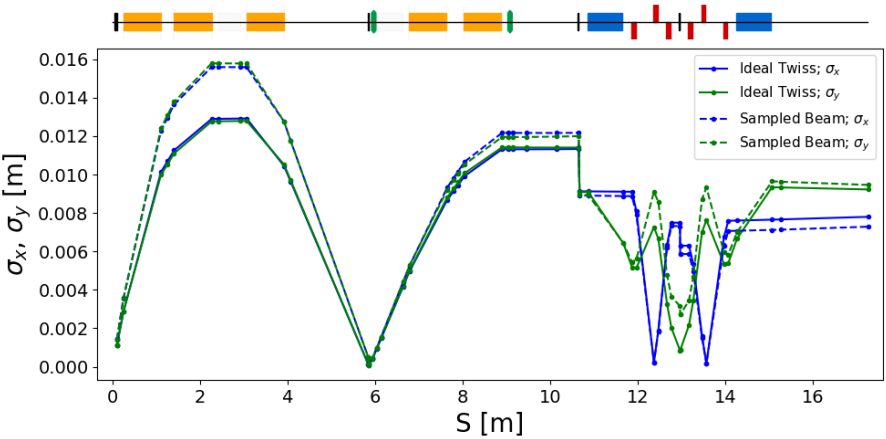


Sampled Beam: End of Nozzle



- Ideal beam and sampled beam are distributed differently (both beams between $14.7 < \text{KE} < 15.3$ MeV).

Beam Size Evolution Comparison (GL modelled by solenoids)

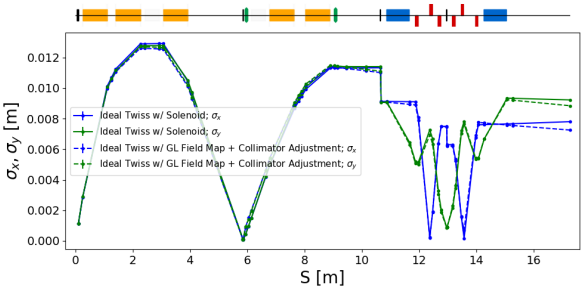


- Ideal beam simulation compared against sampled beam.
- Space charge effects in vacuum nozzle included for both beams.
- Comparable beam size after first collimator.

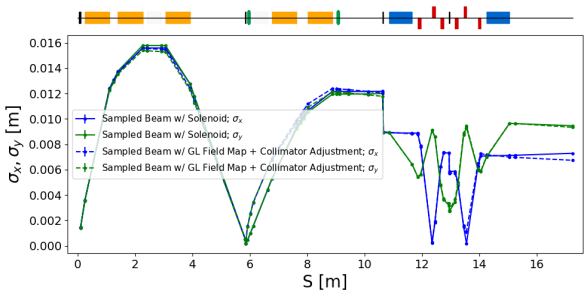
Beam Size Evolution Comparison (solenoids compared against field maps)

- Modelling Gabor lenses with field maps resulted in similar performance to solenoids, but requires some repositioning of first collimator.

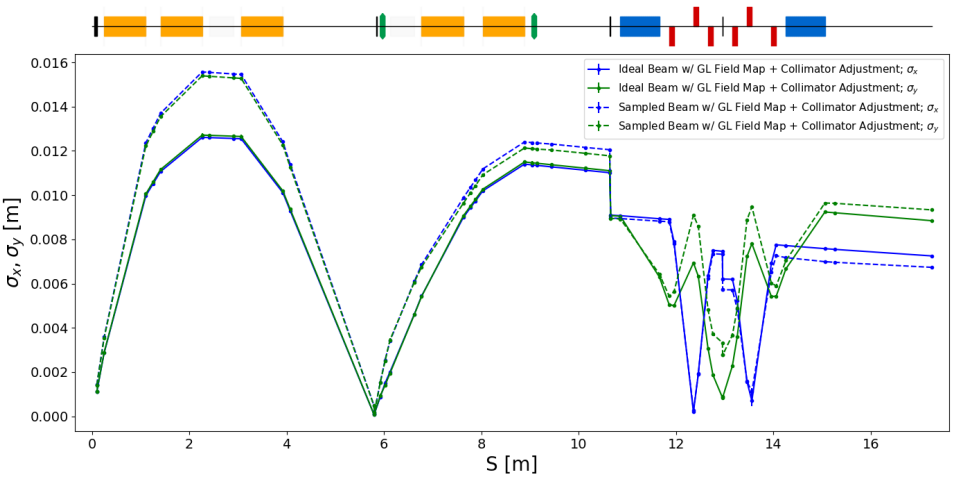
Ideal Beam



Sampled Beam



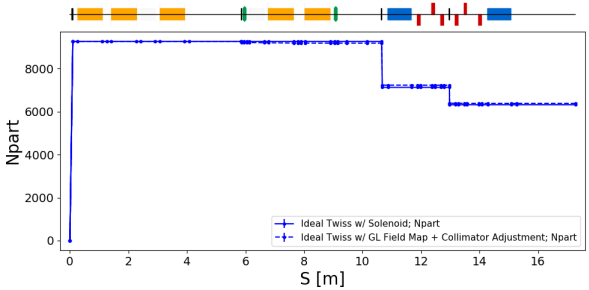
Beam Size Evolution Comparison (GL modelled by field maps)



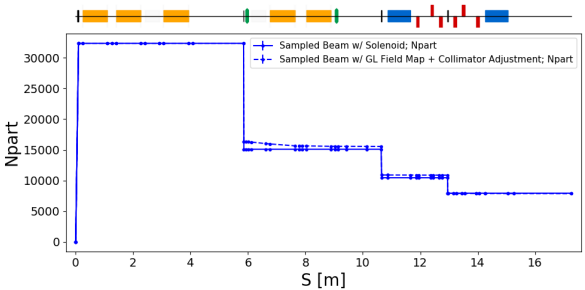
- Slightly more discrepant results between the two beams for field maps compared to solenoids.

Some Optimisations Needed

Ideal Beam

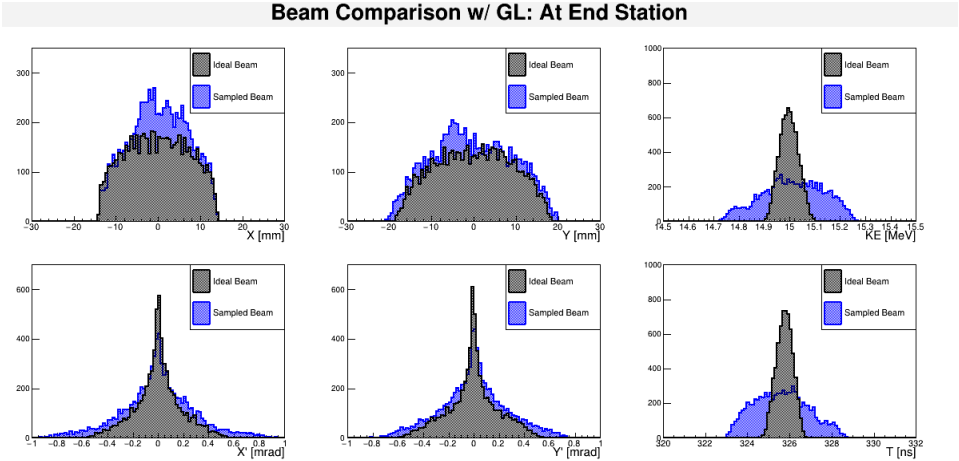


Sampled Beam



- Sampled beam size is larger, leading to a bigger proportion of the beam being lost.

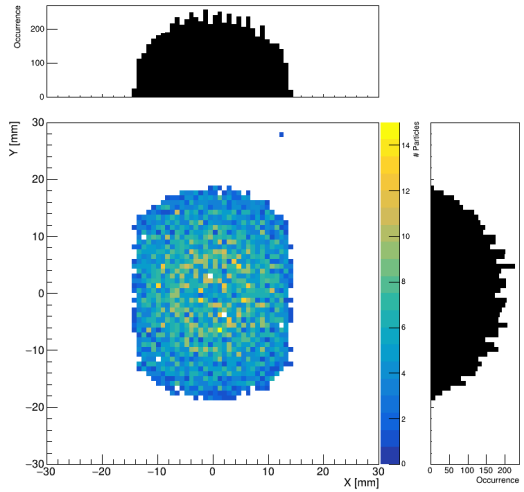
Some Optimisations Needed



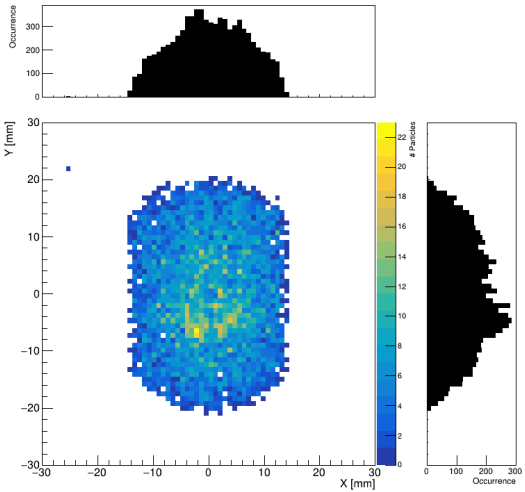
- There is a discrepancy in final energy range, but it can be shown that adjusting the collimator in the arc can restrict to a narrower energy range to recover more comparable distributions if needed.

Beam Comparison at End Station

Ideal Beam w/ GL: Stage 1 End

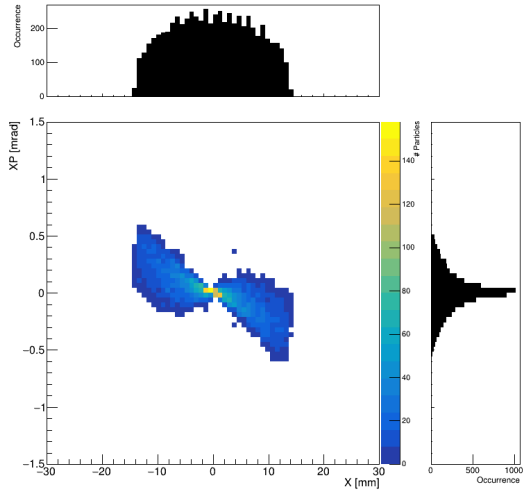


Sampled Beam w/ GL: Stage 1 End

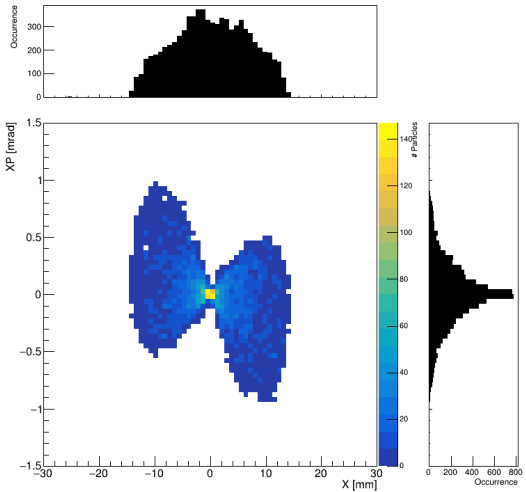


Beam Comparison at End Station

Ideal Beam w/ GL: Stage 1 End



Sampled Beam w/ GL: Stage 1 End



Conclusion

- 2D simulation of TNSA interaction to produce a beam of protons.
- Sampling method to approximate a 3D beam for tracking.
  - Ongoing efforts for a 3D TNSA simulation.
- Ideal and sampled beam were tracked through Stage 1 beam line (modelling Gabor lenses as solenoids) with generally comparable results.
- Slightly more discrepant results were found when modelling Gabor lenses with field maps.
- Optimisations needed to better improve the comparison results.

References

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