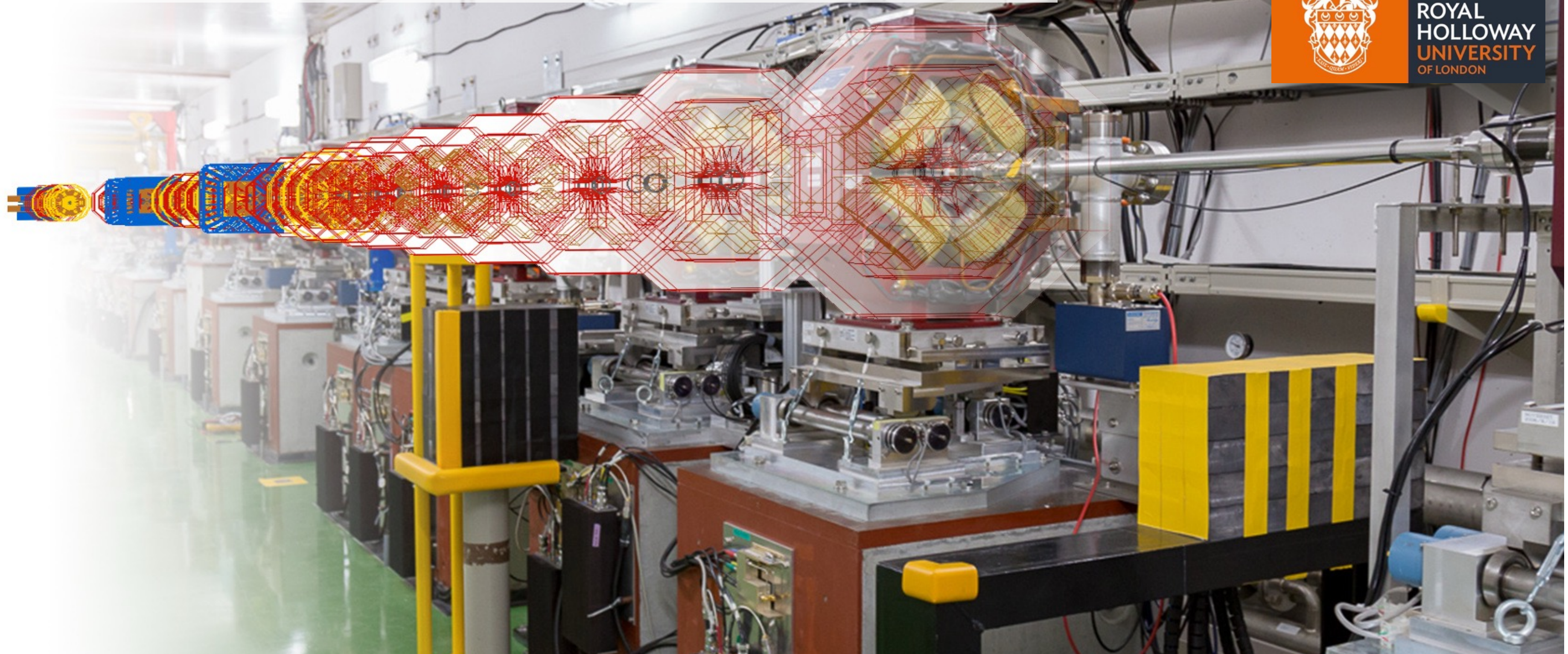
Mixed Accelerator and Particle Physics Simulations



John Adams Institute for Accelerator Science

ROYAL HOLLOWAY UNIVERSITY OF LONDON

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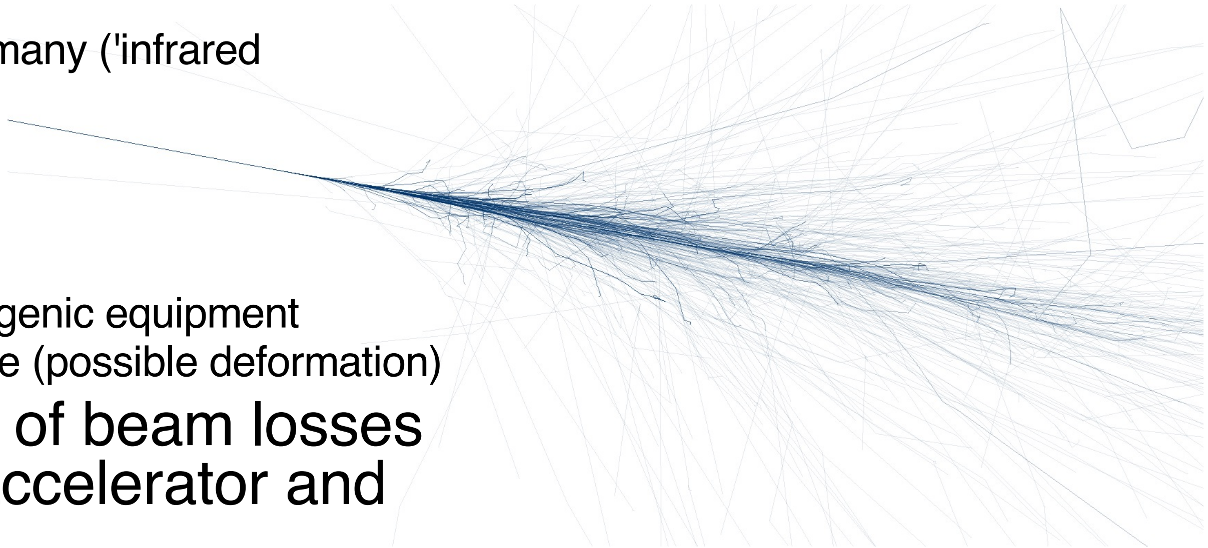
Outline

- Brief introduction to the problem
- Description of a solution
- Examples & Applications
- Future directions

Introduction

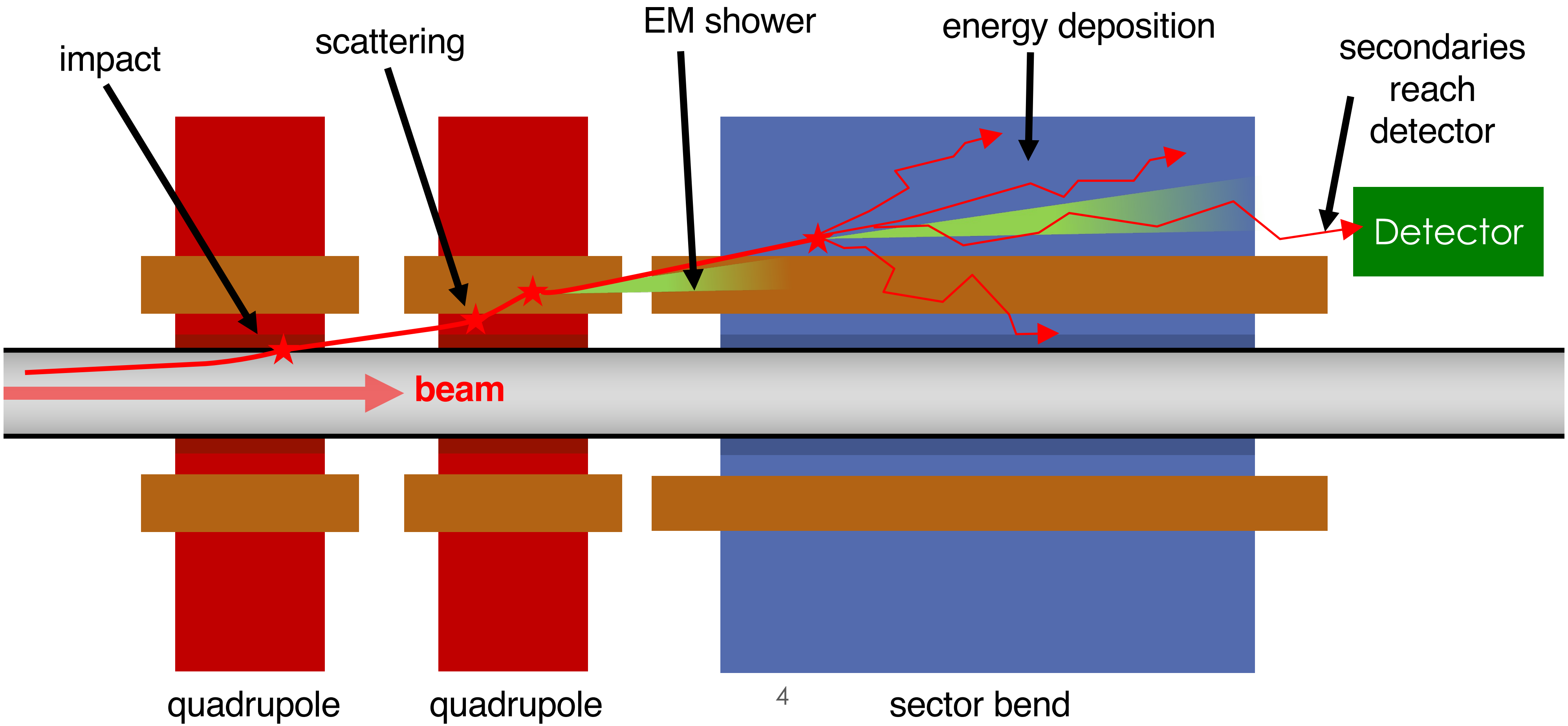
- No particle accelerator perfectly contains all particles
  - either by design tolerance (certain capture %)
  - via stochastic processes (intra-beam scattering, beam-beam, collective effects)
- High energy particles lead to many secondary particles
  - photons, e^-, e^+, nuclear fragments, exotic unstable particles, etc.
  - one initial particle leads to many ('infrared divergence')
- Beam loss leads to:
  - detector background
  - energy deposition
  - heat loads, possibly in cryogenic equipment
  - radio-activation and damage (possible deformation)
- Prediction and control of beam losses is crucial to both the accelerator and experiment operation

1x 10 GeV e^- in copper



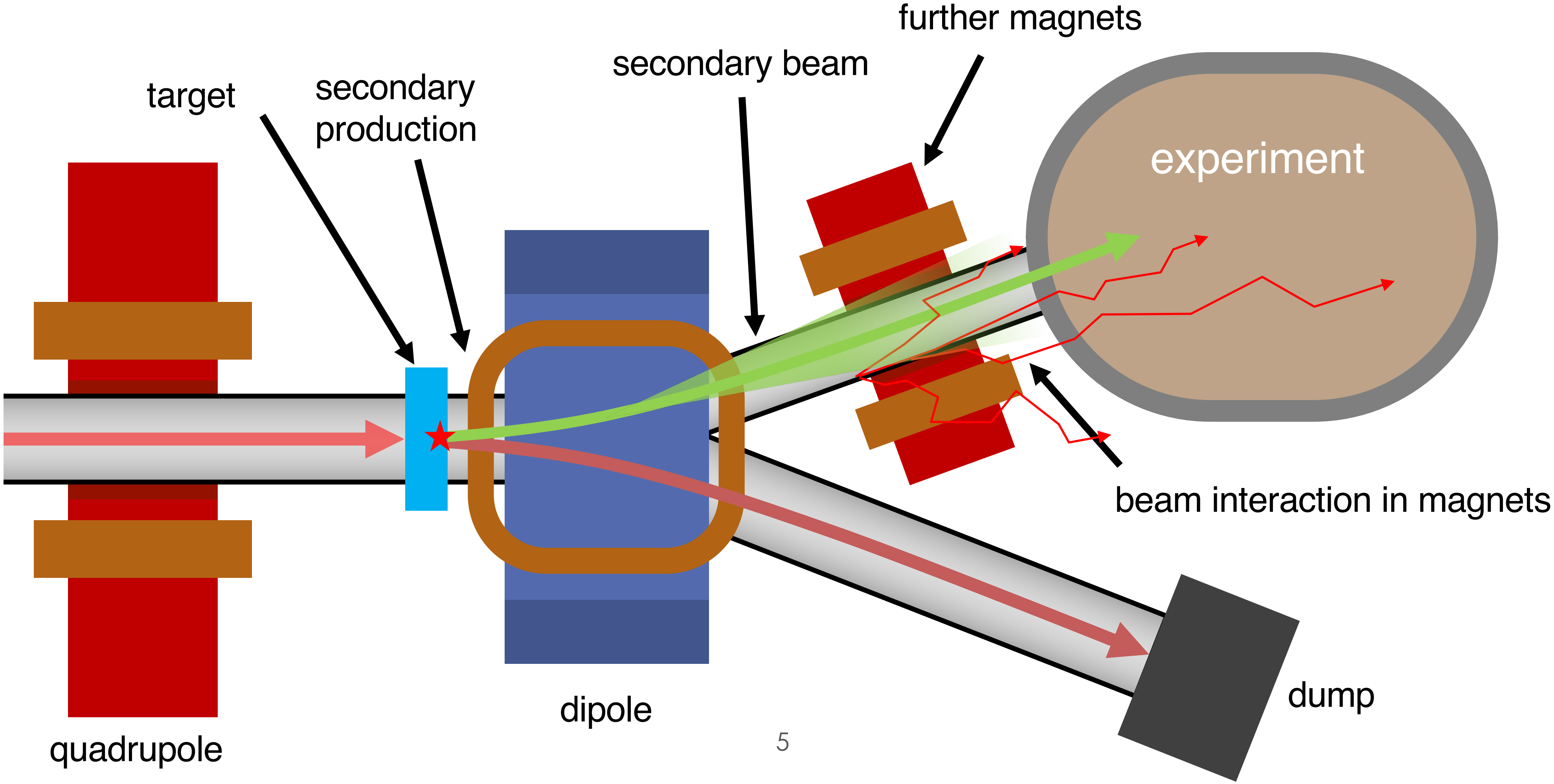
Beam Loss

- Cut-through of an accelerator
- Particle impacts aperture at some point
- Secondary particles and radiation propagate some distance
- Energy deposited in many components

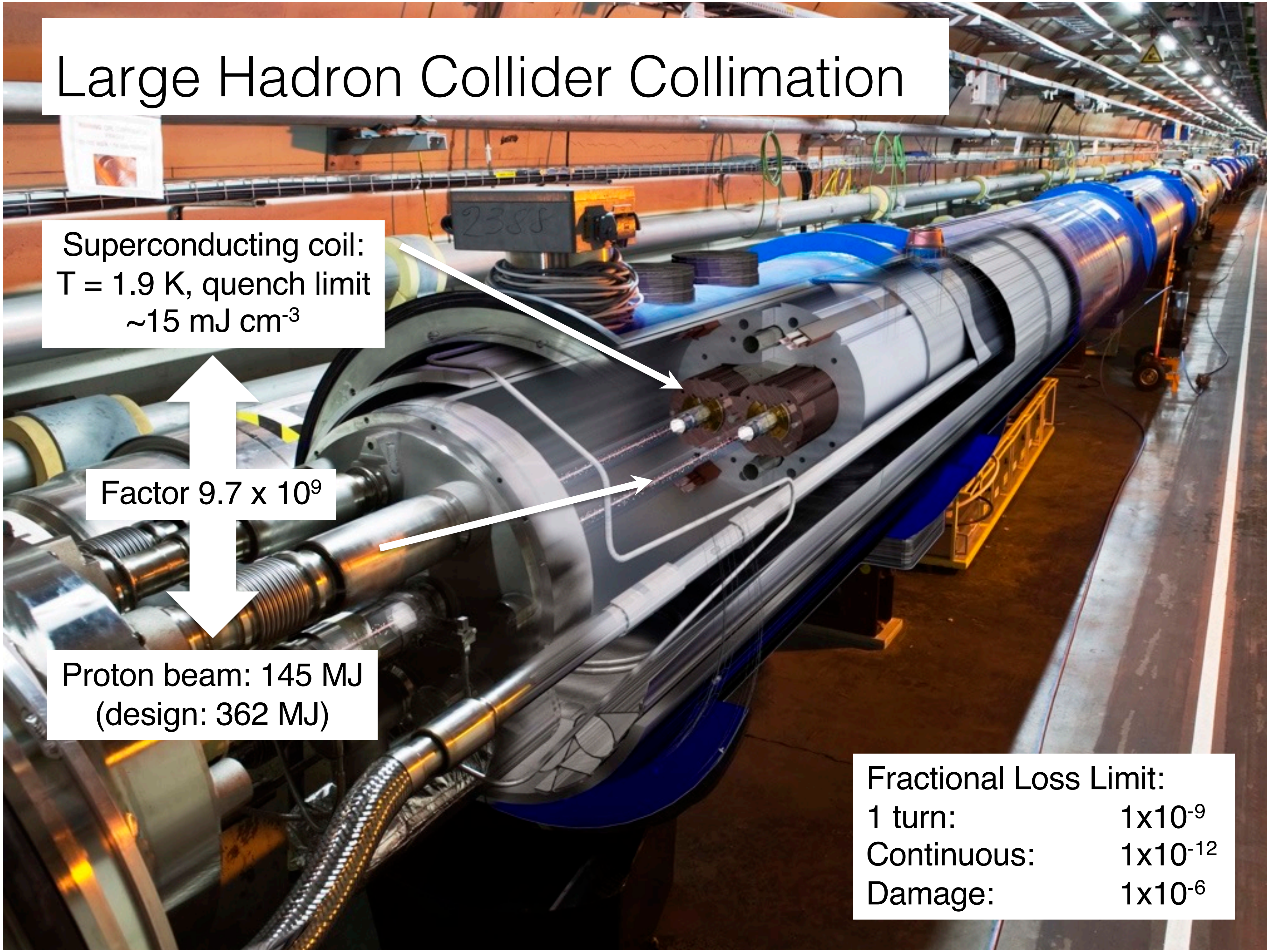


Secondary Beam

- Secondary particle production from impact with target
- All of beam impacts target
- Both beams transported in magnets afterwards

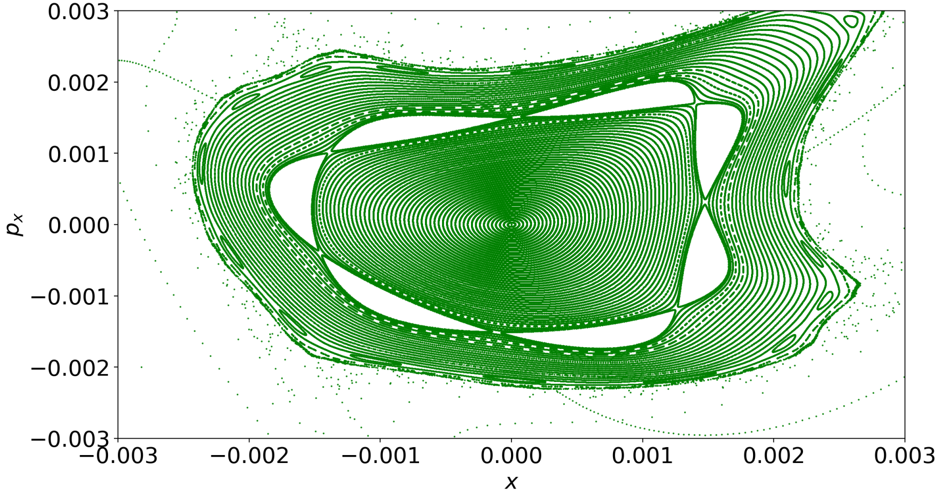


Large Hadron Collider Collimation

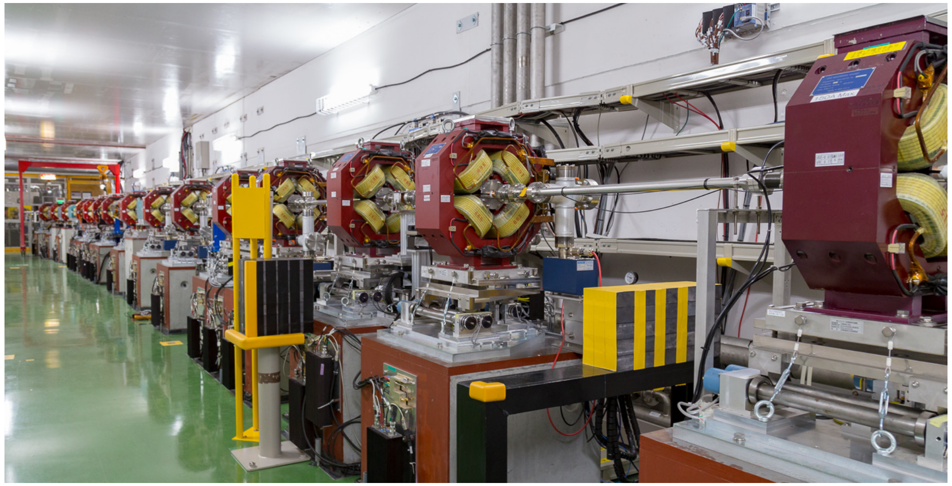


Accelerator Tracking

- Electromagnets used to guide particles
  - variety of types, each with different strengths
- Need to predict motion of particle through magnets
- Specific fields can have specific mathematical solutions
- Require physical accuracy and strict energy conservation
- For any arbitrary B / E field use numerical integration
  - however, slower and limited accuracy
  - not useful for many thousands of operations - error increases

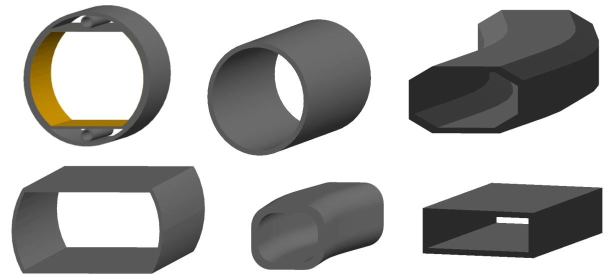


Example Poincaré map through nonlinear fields

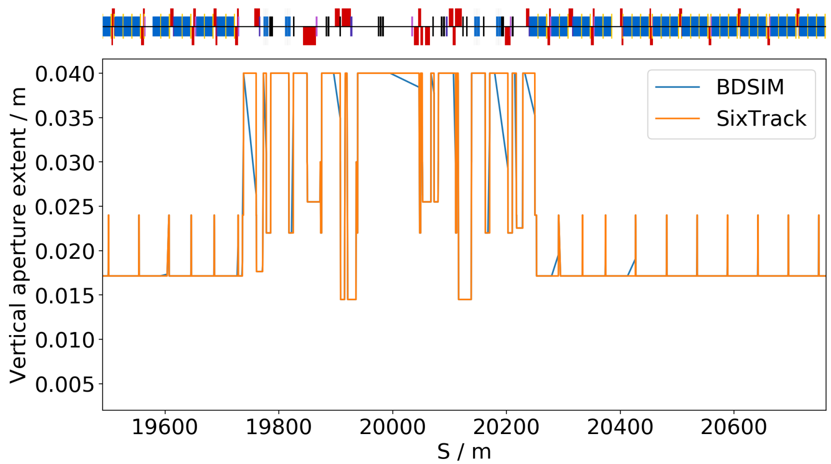


Tracking Losses

- Specialised codes exist for accelerator tracking
  - MADX, PTC, Sixtrack, Zogoubi, OPAL etc
- Most have specialty area
- Typically 'losses' are when coordinates exceed aperture
- High energy particles don't just stop!
- People commonly correlate impact with measured radiation
  - sometimes acceptable for low energy applications
  - not valid for high energy
- Need the interaction with material



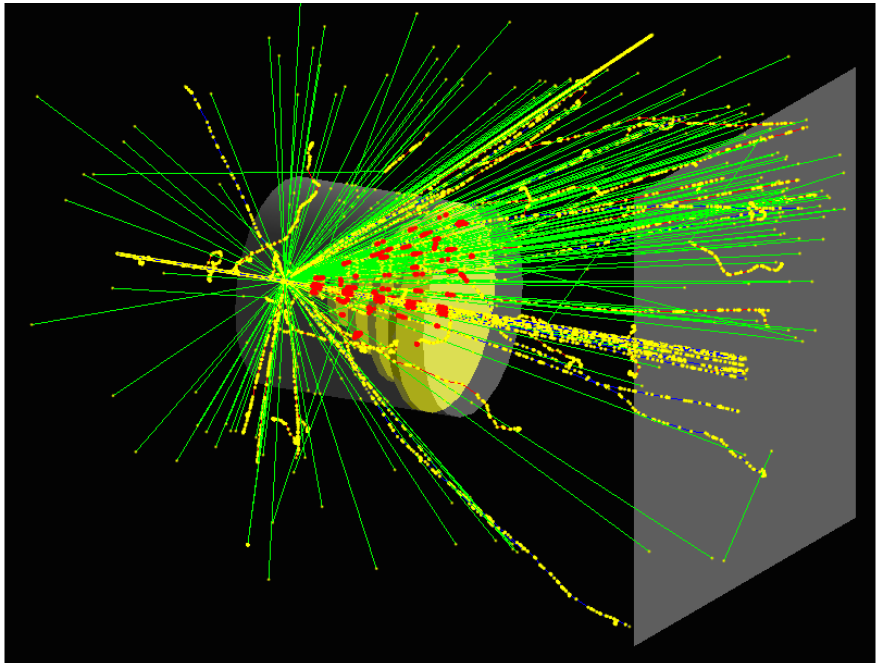
Different aperture shapes

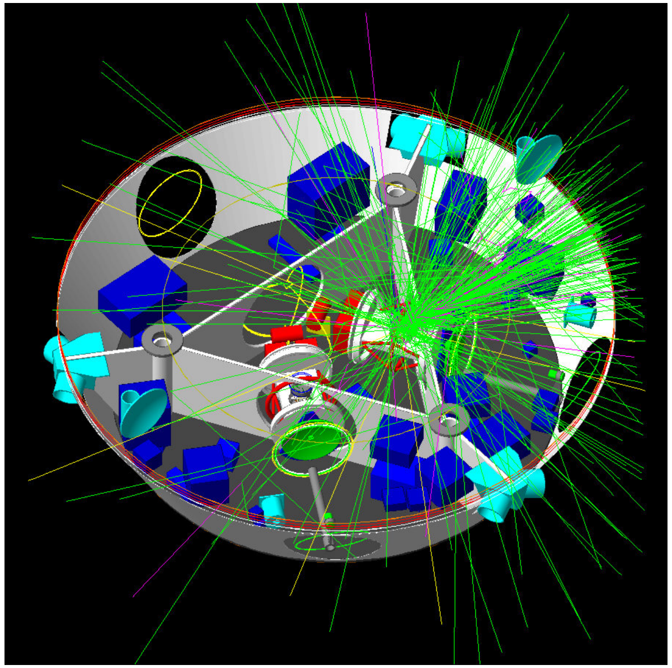


Vertical Aperture models compared.

Radiation Transport Simulation

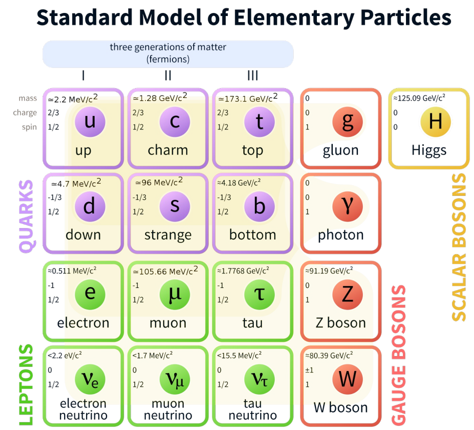
- 3D particle physics models are common simulation
  - simulate interaction with material
  - simulate motion of charged particles in fields
- Used to create 'fake' data ('truth') for detector experiments
- Compare real data statistically with Monte Carlo
- Identify how well analysis identifies the 'truth'

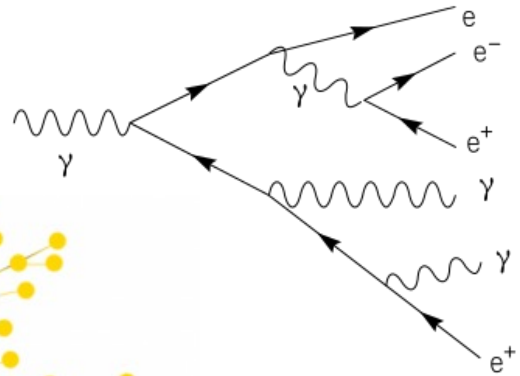


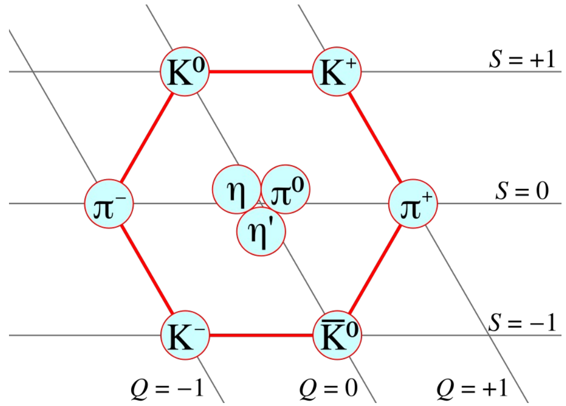


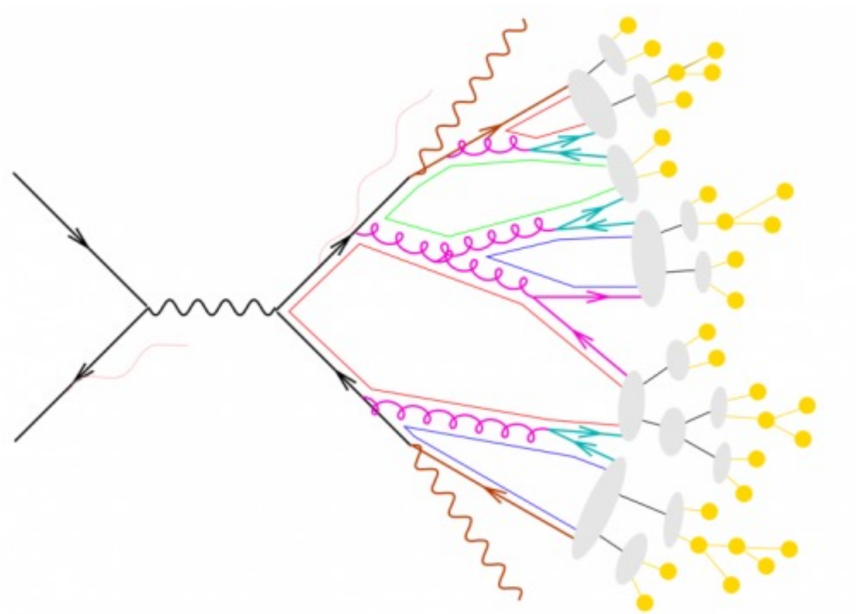
Particle Physics Processes

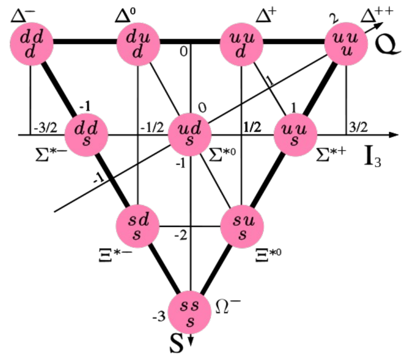
- Large variety of particles
- Large variety of processes & models
  - some data based, some pure model based, some mixed
  - different models for different energy ranges
- Available libraries - FLUKA, Geant4, MARS











Existing Combined Simulations

- Specialised codes for accelerator tracking or radiation transport models
- Current solutions use a variety of approaches:
  - track up to impact on aperture
  - simulate most relevant parts separately - pass between codes
- Make use of existing physics package!

Accelerator Tracking

- SixTrack
- PTC / MADX
- Transport
- Lucretia

Radiation Transport

- FLUKA
- Geant4
- MARS
- MCNPX

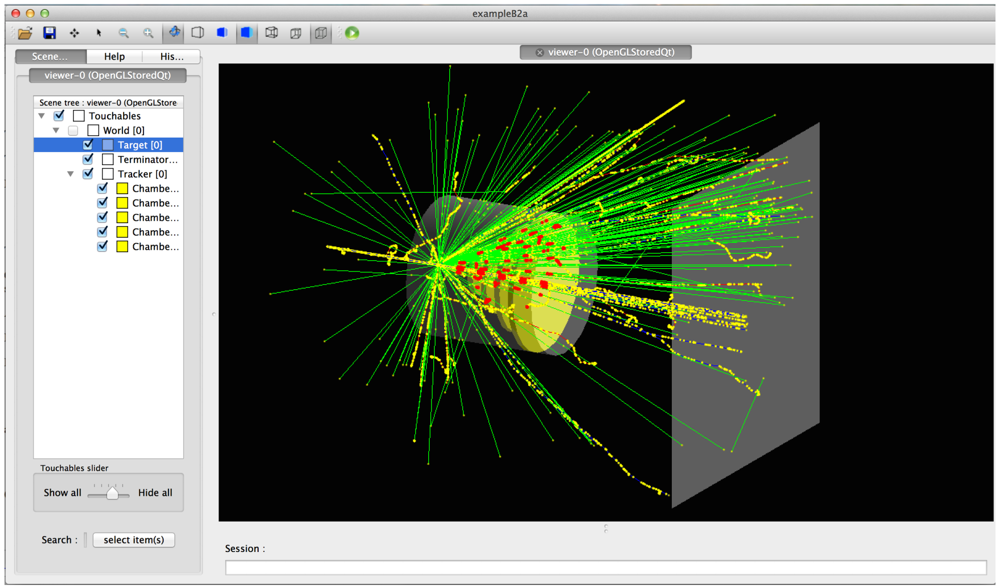
Which Physics Package?

- Geant4
  - open source C++ class library
  - no executable program
  - conceived to simulate particle detectors
  - extensive particle physics models
  - regularly updated ~ every 6 months
  - used by detector community
  - > 10^{10} events simulated at CERN in last year alone

- FLUKA
  - ASCII input
  - also extensive particle physics models
  - used by radiation shielding community
  - closed source Fortran
  - highly restrictive licence

GEANT4 A SIMULATION TOOLKIT ✓

http://geant4.web.cern.ch



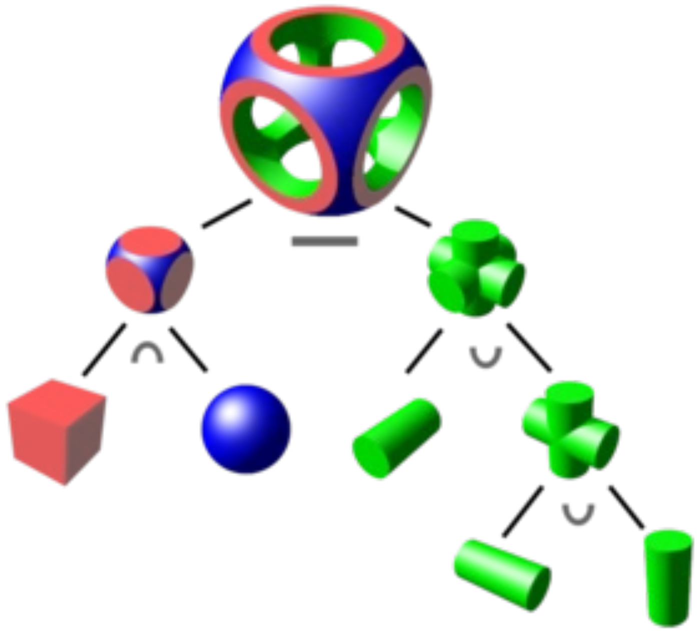
Geant4 example of proton hitting calorimeter

Complexity…

- Creating 3D model of an accelerator is laborious
- Many people, many years work
- Hard coded to that application
- Complex to create and validate

- Tracking codes complex in implementation
- Speciality can vary depending on application

- rarely do people therefore make such a model…



constructive solid geometry

A Solution

BDSIM
Beam Delivery Simulation

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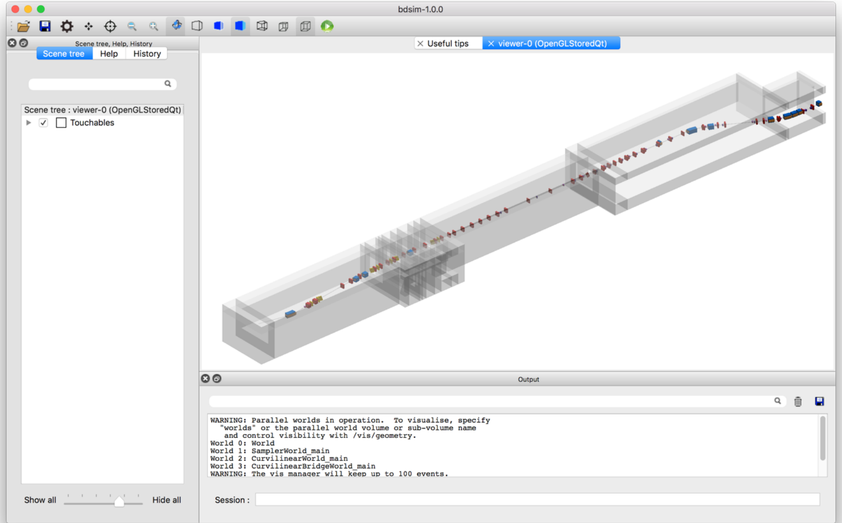
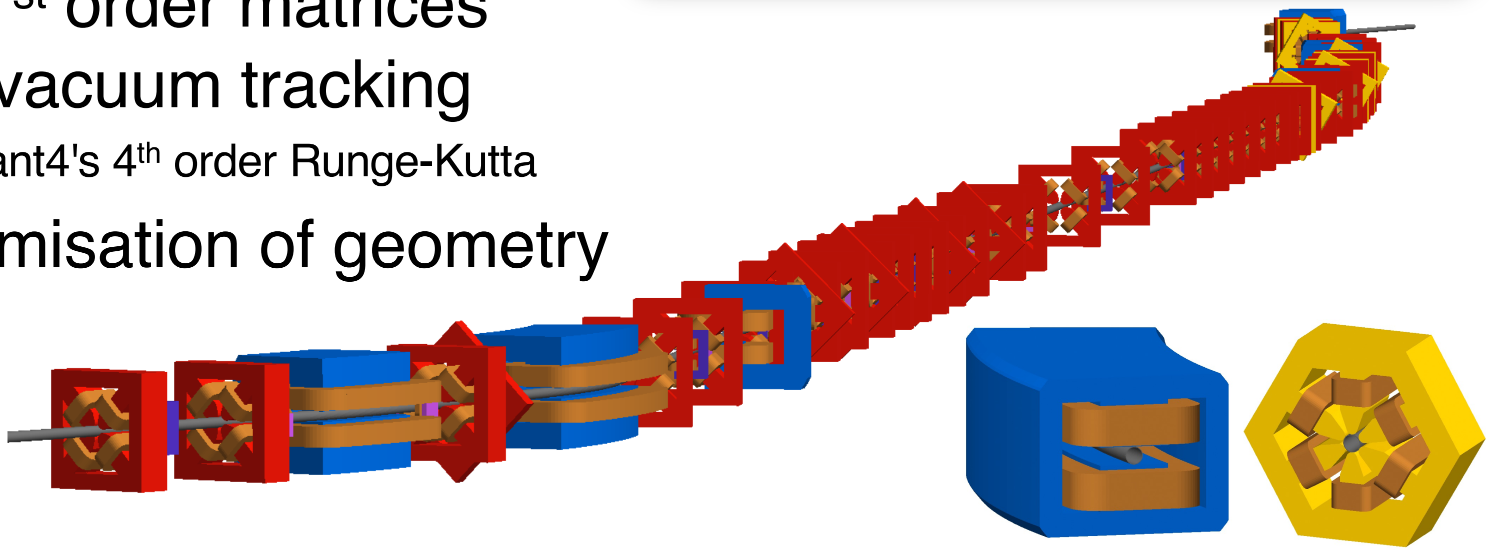
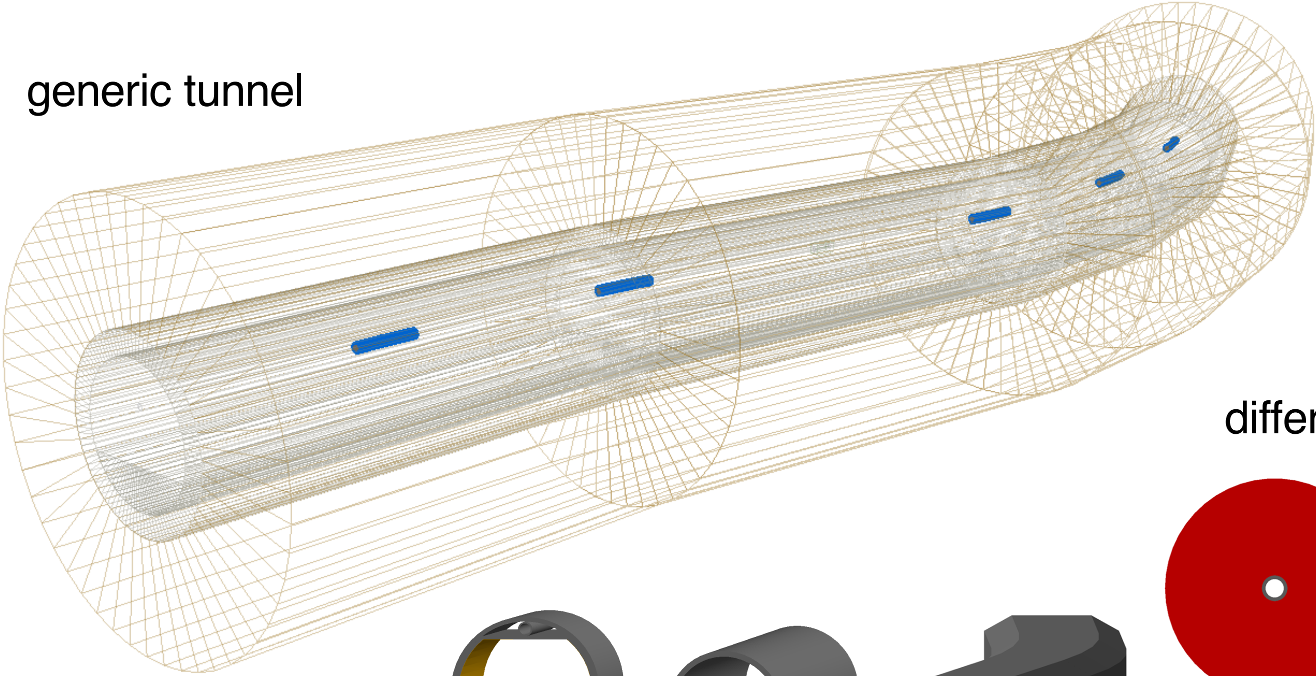
- Add accelerator tracking to 3D radiation transport code
- Use a library of scalable generic accelerator geometry in Geant4
  - you can learn a lot with generic geometry
- Convert from common accelerator description formats
- Thick lens 1st order matrices used for in-vacuum tracking
  - replaces Geant4's 4th order Runge-Kutta
- Allow customisation of geometry and fields



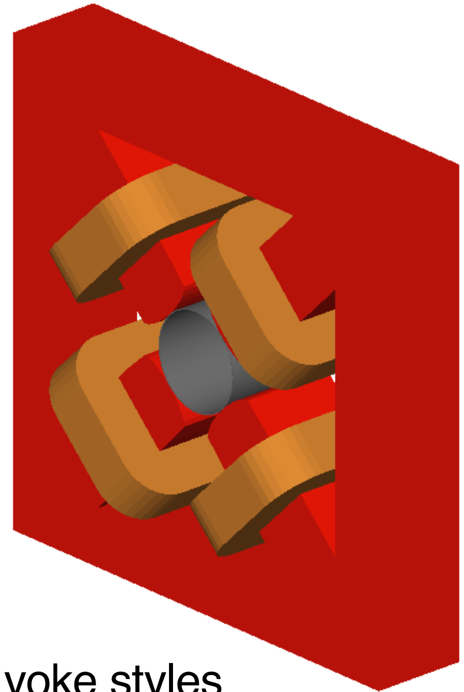


Generic Geometry

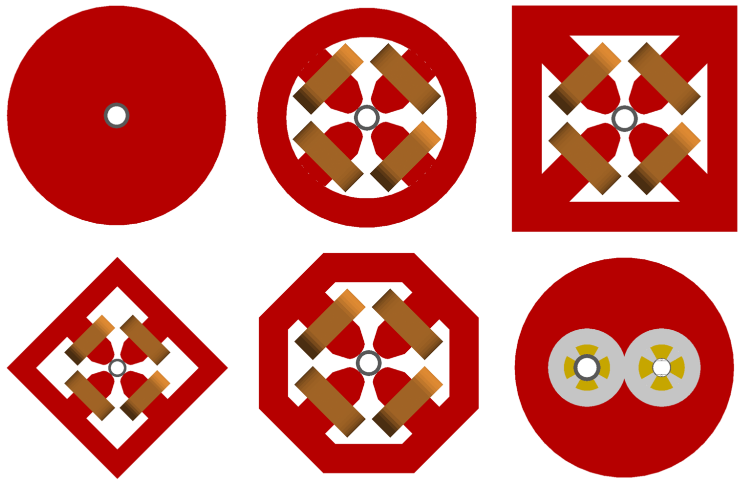
- Variety of styles for each component
  - coils included correctly even if magnet split
- Selection of generic tunnels included

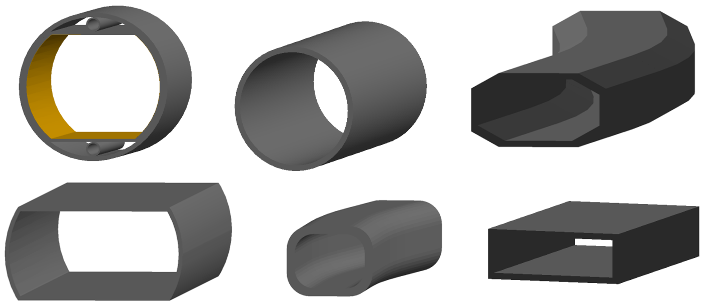


generic tunnel



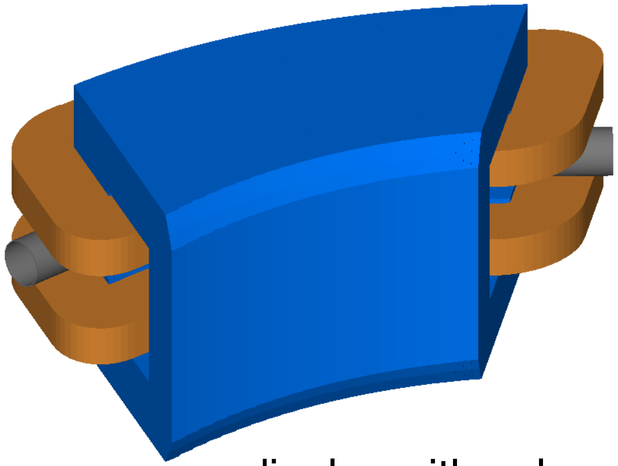
different yoke styles



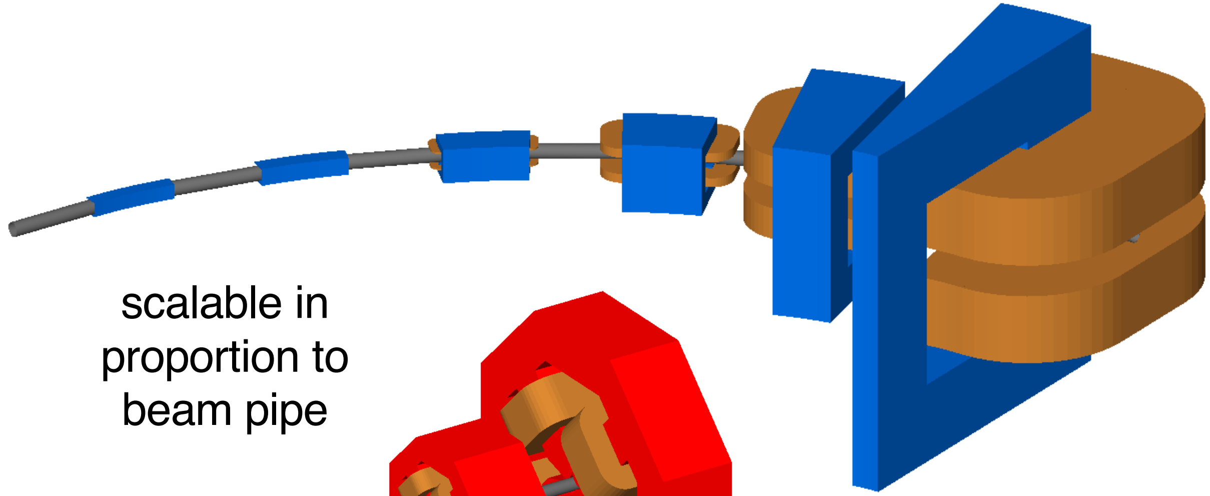


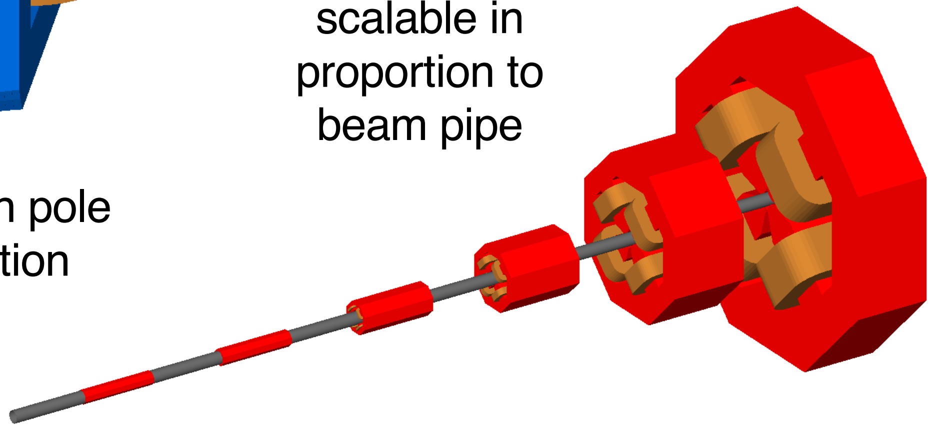
all common aperture types available

Scalable Geometry

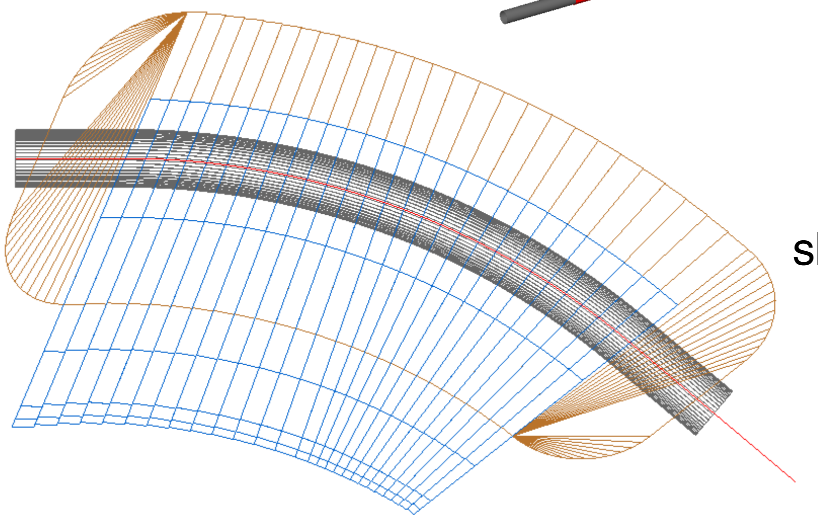


dipoles with pole face rotation

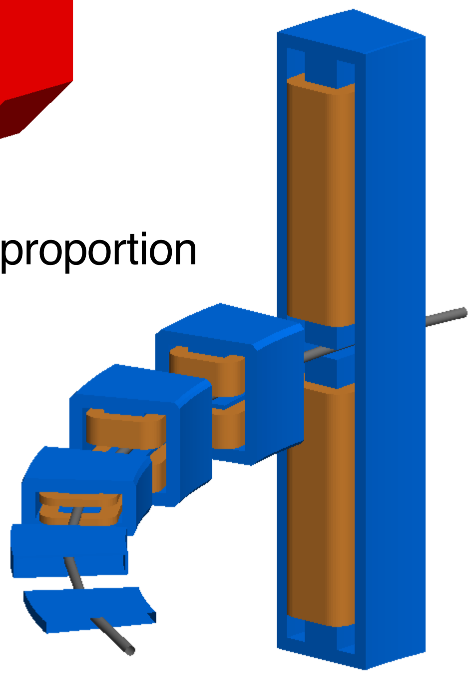




scalable in proportion to beam pipe



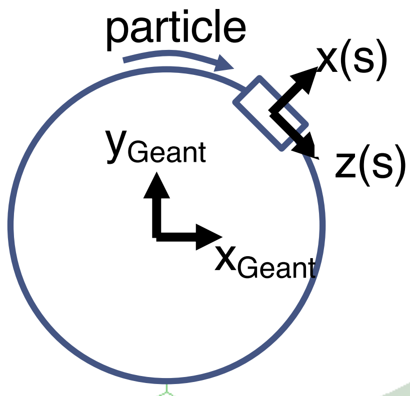
dipoles built in slices to allow any shape required

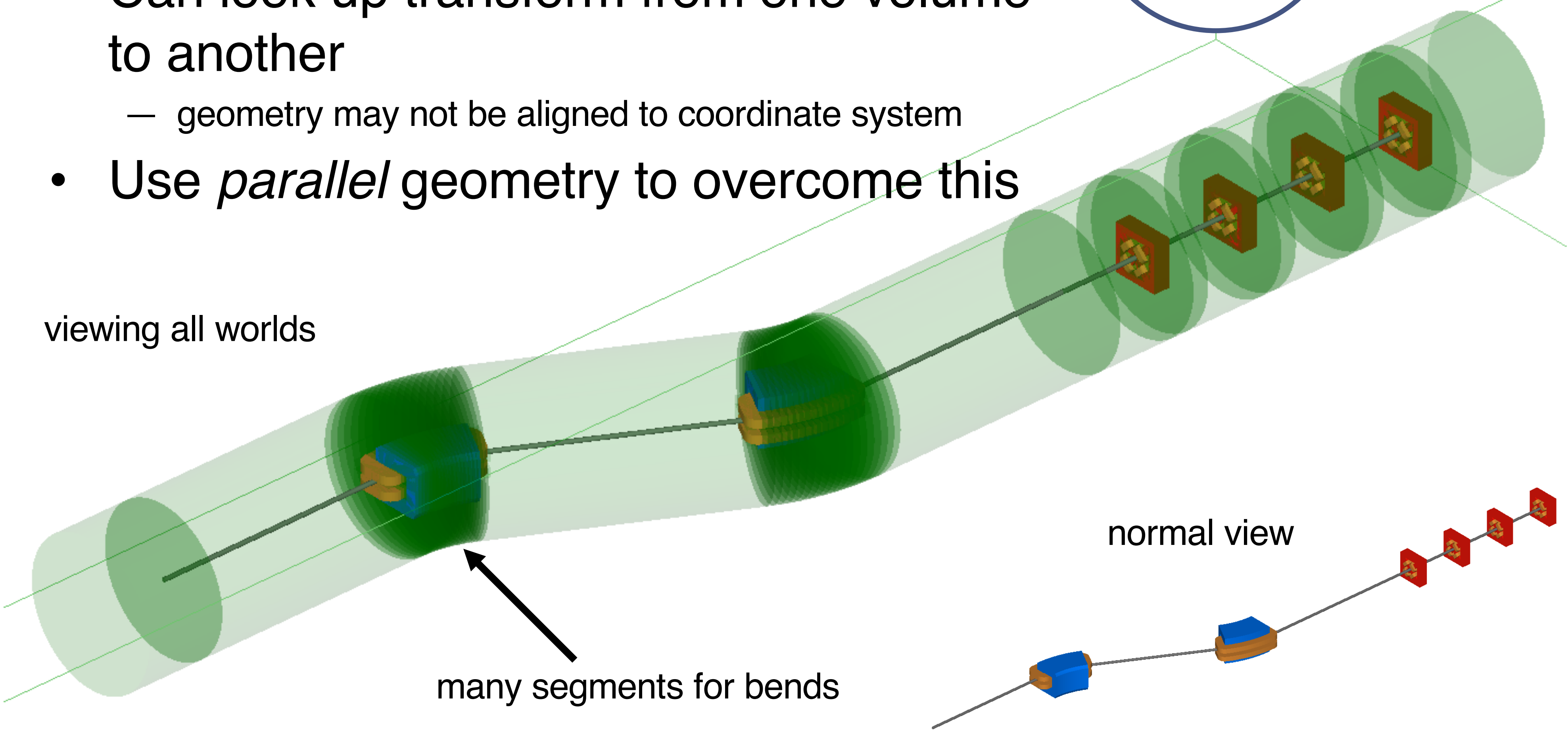


scalable in proportion

Coordinate Transforms

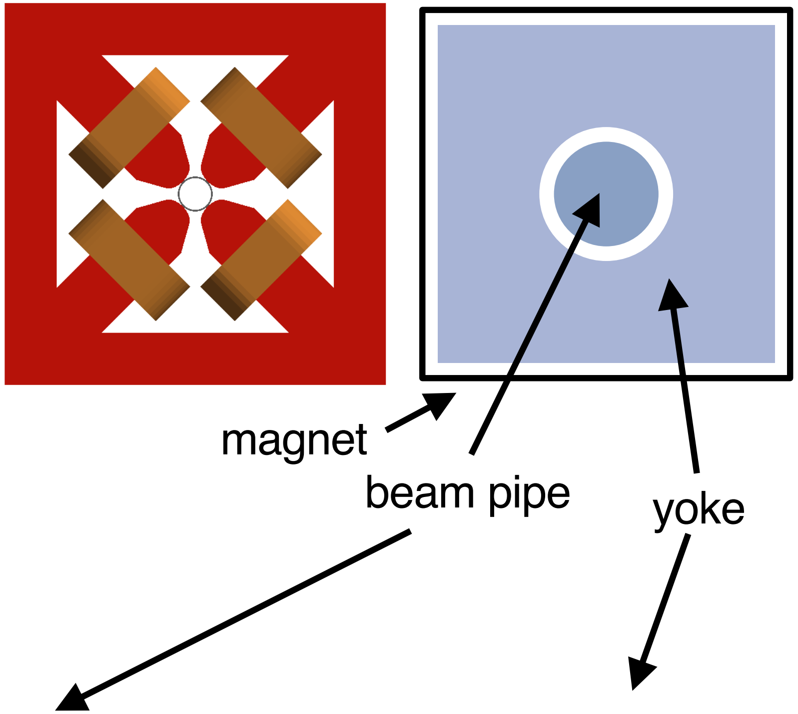
- Accelerator tracking uses a curvilinear coordinate system following the beam
- Geant4 uses 3D Cartesian coordinates
- Can look up transform from one volume to another
  - geometry may not be aligned to coordinate system
- Use *parallel* geometry to overcome this





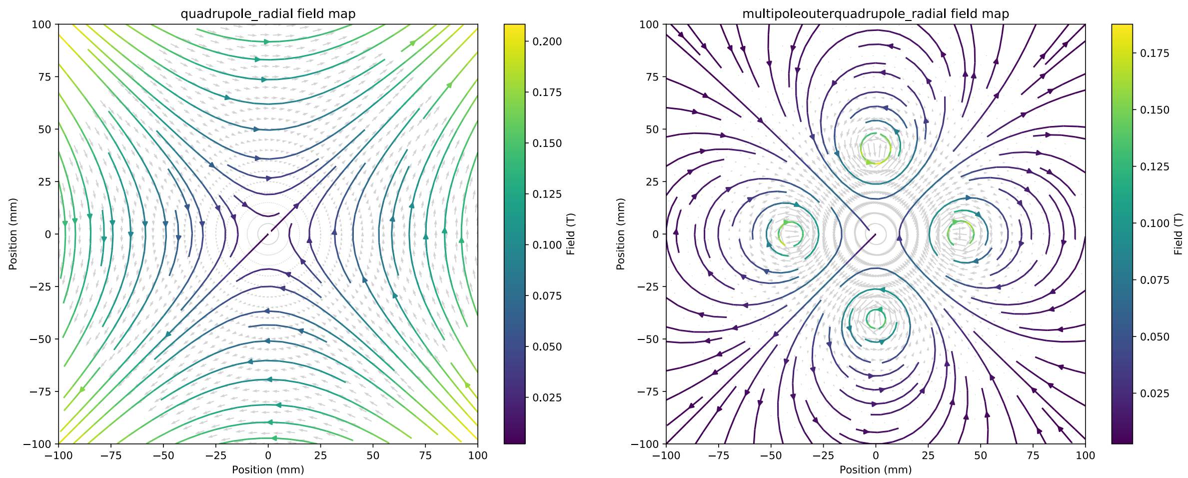
Tracking Implementation

- Custom numerical integrators
  - for 1st order matrix transport maps
- Fall back to RK4 if…
  - non-paraxial (backwards / sideways)
  - low radius of curvature (spiralling)
- Provide suitable fields
  - 'paste' these onto volumes in 3D geometry
  - pure field in vacuum
  - current source yoke field
- Requires curvilinear coordinate system



$$
\begin{aligned}
B_x &= \frac{\partial B_y}{\partial x} y \\
B_y &= \frac{\partial B_y}{\partial x} x \\
B_z &= 0
\end{aligned}
$$

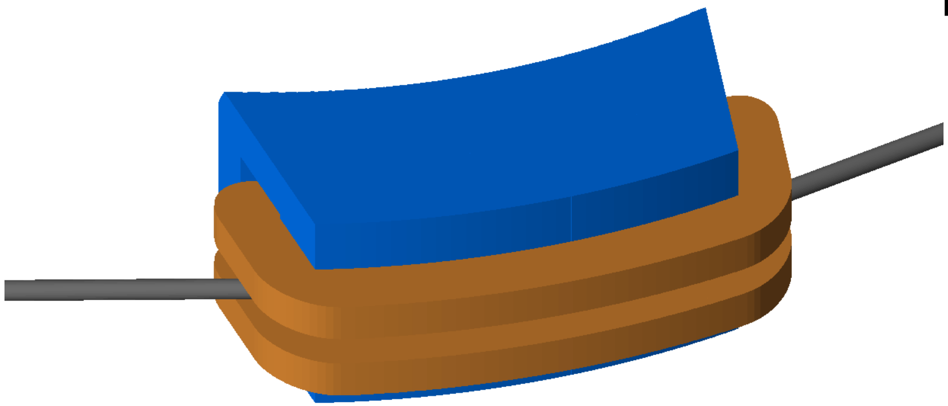
quadrupole field example



Pole Faces & Thin Elements

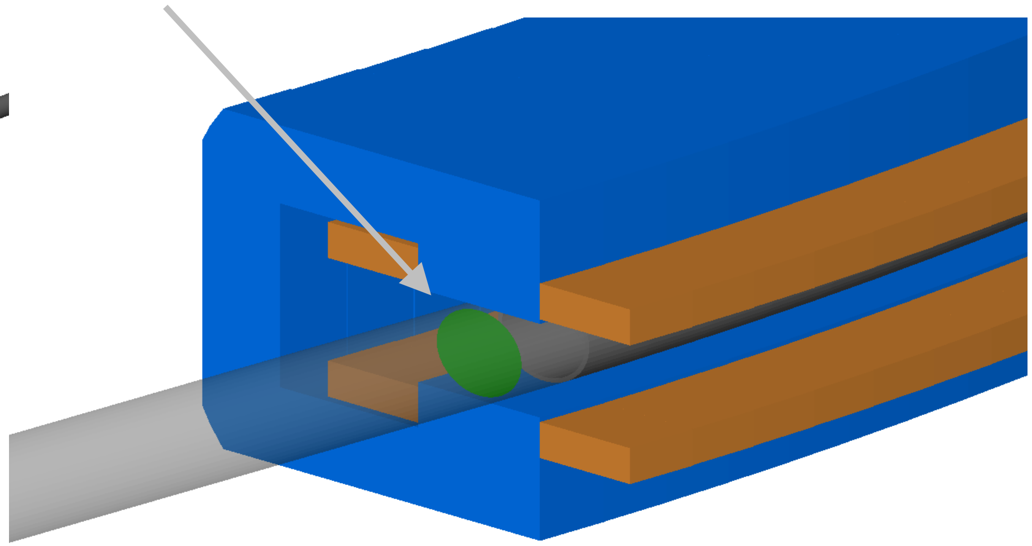
- Imperfections usually implemented via 'thin' elements in tracking
  - entrance / exit or in the middle of magnet
- Pole face rotations contribute significantly to optics
  - crucial for low energy applications
  - Implementation using 1st order matrix formalism

Revert to Geant4 based integrator in non–paraxial limit.



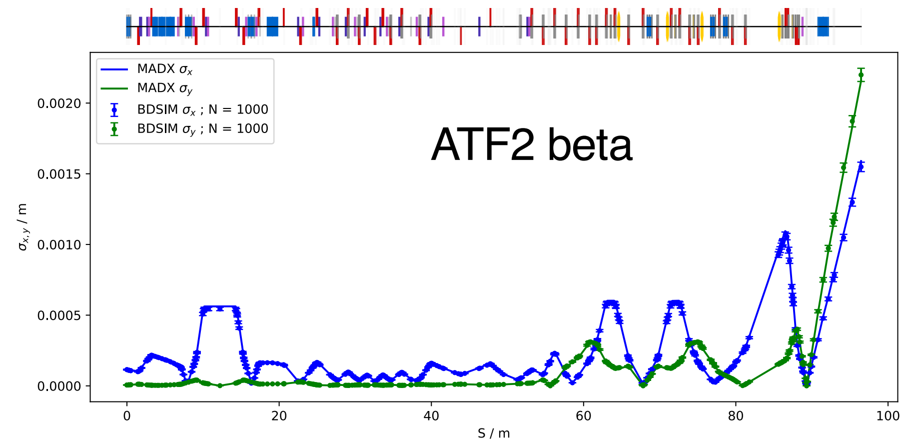
Angled beam pipe and yoke geometry as well as coils

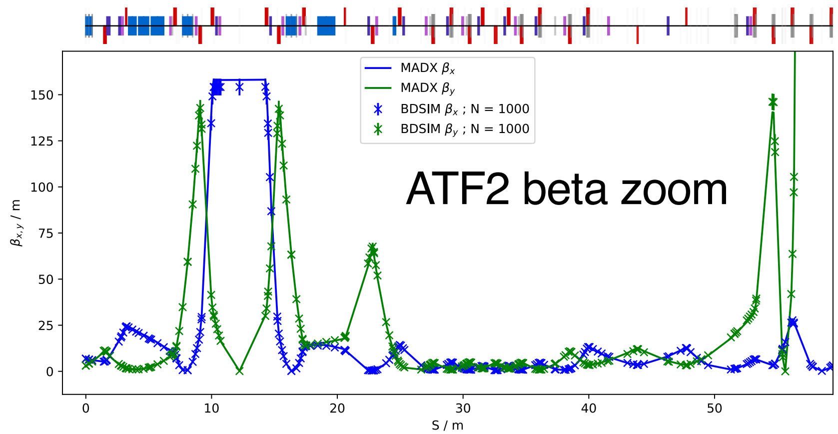
Thin element for fringe field

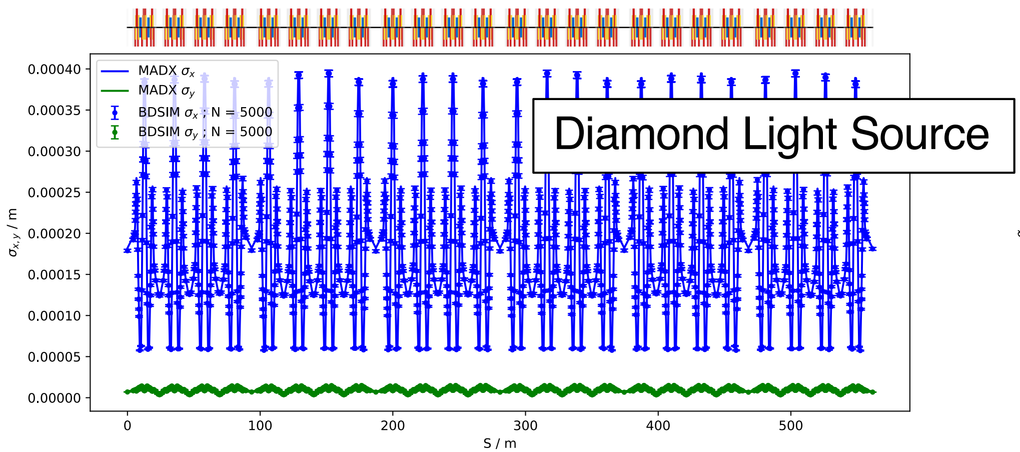


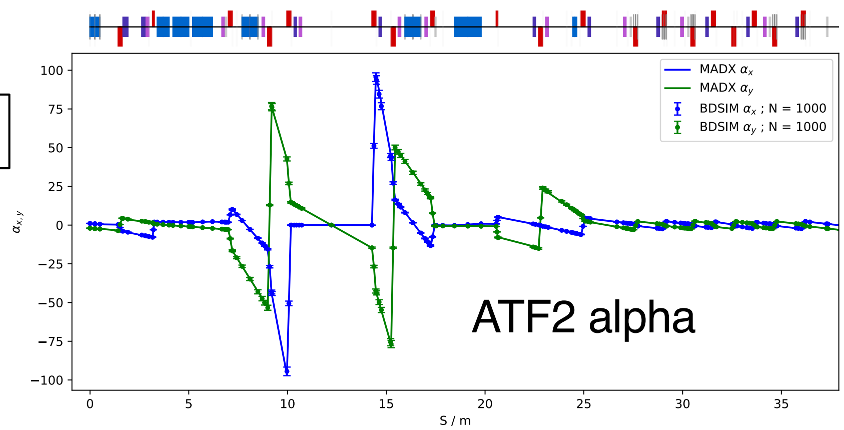
Optical Function Comparison

- Compare particle distribution after each element
- Calculate optical functions from particle distribution
  - using (up to) 4th order moments



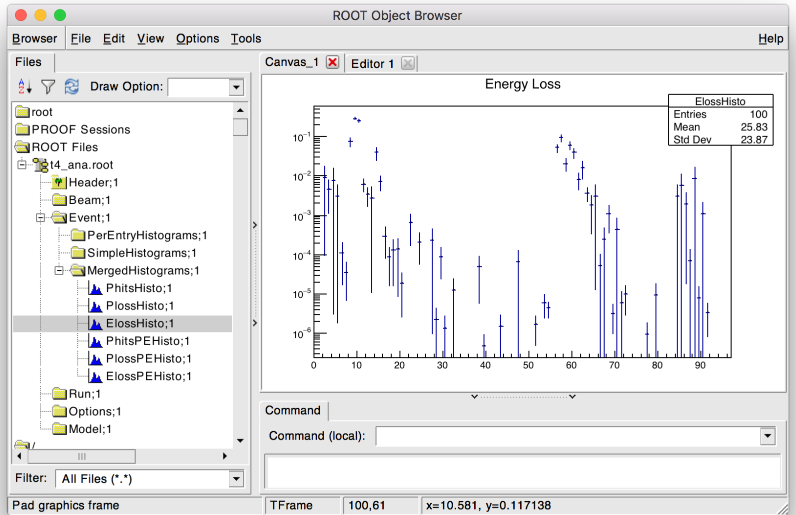




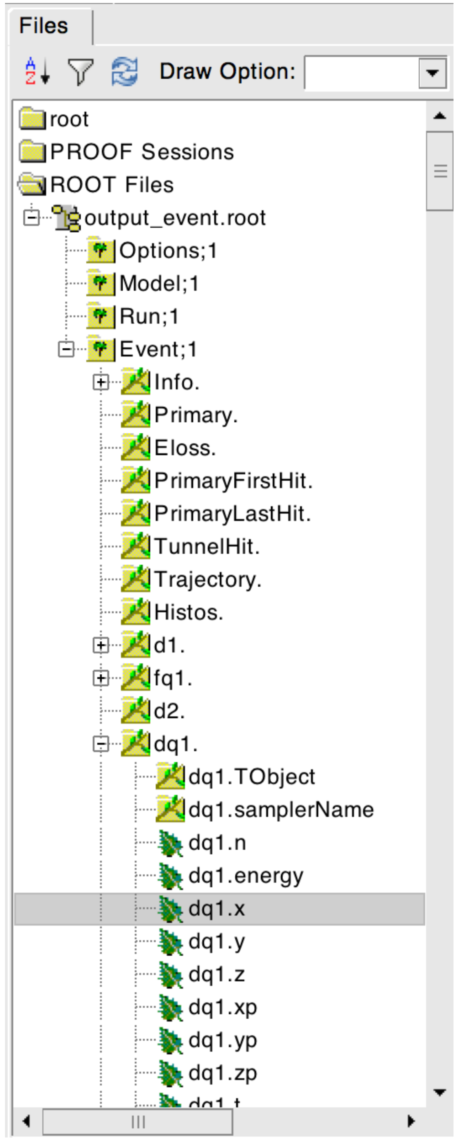


Output & Information Reduction

- A particle physics simulation produces a potentially huge amount of information
  - coordinates of every step of every particle…
- Event by event storage
  - 'Event' is the minimal unit of simulation - typically one particle fired into the model
  - unlike tracking code, not 1 particle to 1 event
  - crucial for correct statistical uncertainties
- Use ROOT format for data
  - highly suited to ***large*** particle physics data and analysis



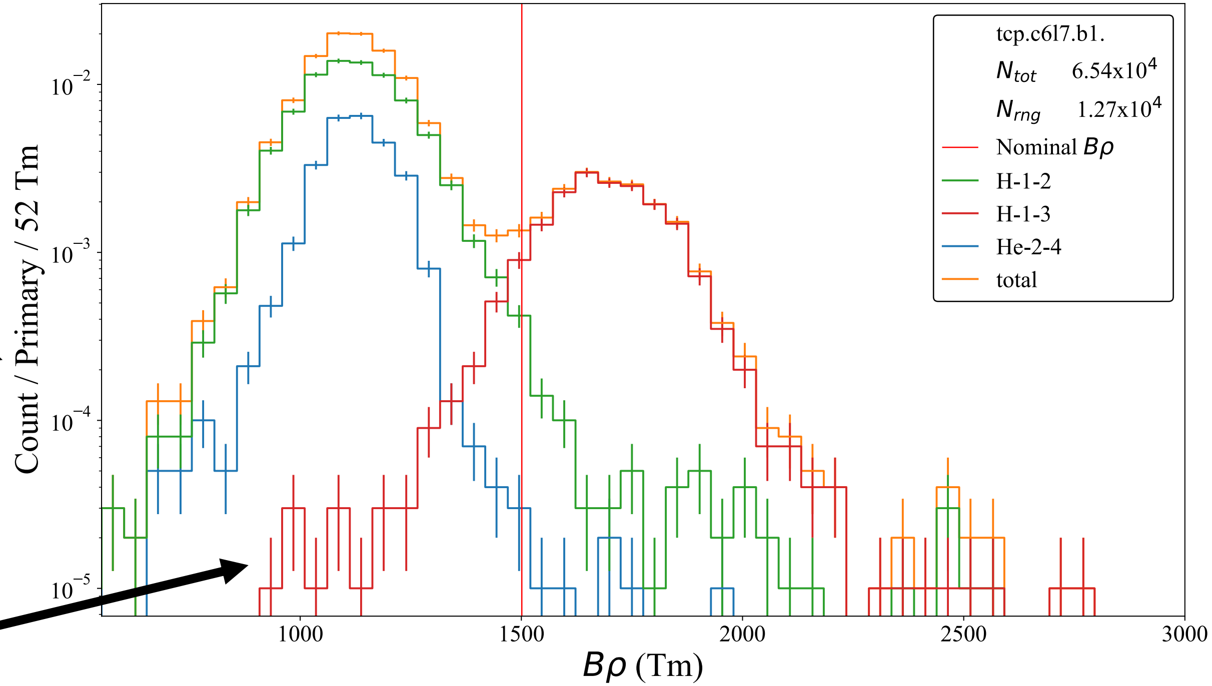
typical data browser



A Statistical Picture

- We never simulate the same as reality
  - Typical number of particles is 10^{10} per bunch
- Simulate a smaller sample and scale
  - must simulate many events as outcome different in physics models
  - time consuming
- Require statistical uncertainties!
- What precision is required?

Per particle simulated



errors!

Analysis

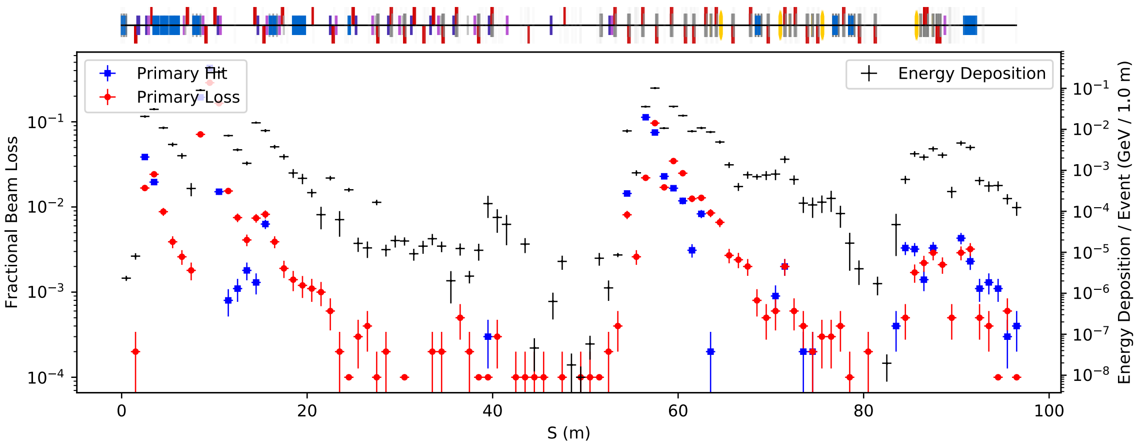
- Event by event analysis -> everything's a histogram here
- e.g. all neutrons over 20GeV that interact between 10-20m?
  - no problem!
- Use High Energy Physics style analysis
  - uncommon in accelerator tracking specialities

variable to be histogrammed

analysisConfig.txt

```
InputFilePath      ../../data/sample1.root
OutputFileName     ./ana1.root
# Object          treeName    Histogram Name        # Bins       Binning                         Variable                     Selection
Histogram1D        Event.      EnergyLoss            {22}         {0:22}                          Eloss.S                      Eloss.energy*Eloss.weight
Histogram2D        Event.      Flux                  {30,30}      {-2.5:2.5,-2.5:2.5}             fq1.y:fq1.x                  fq1.energy*fq1.weight
Histogram3D        Event.      Flux3D                {30,30,100}  {-2.5:2.5,-2.5:2.5,0:1}         fq1.x:fq1.y:fq1.energy       1
Histogram2D        Event.      Neutrons              {50,50}      {-2:2,-2:2}                     fq1.y:fq2.x                  fq1.weight*(fq1.partID==2212)
```

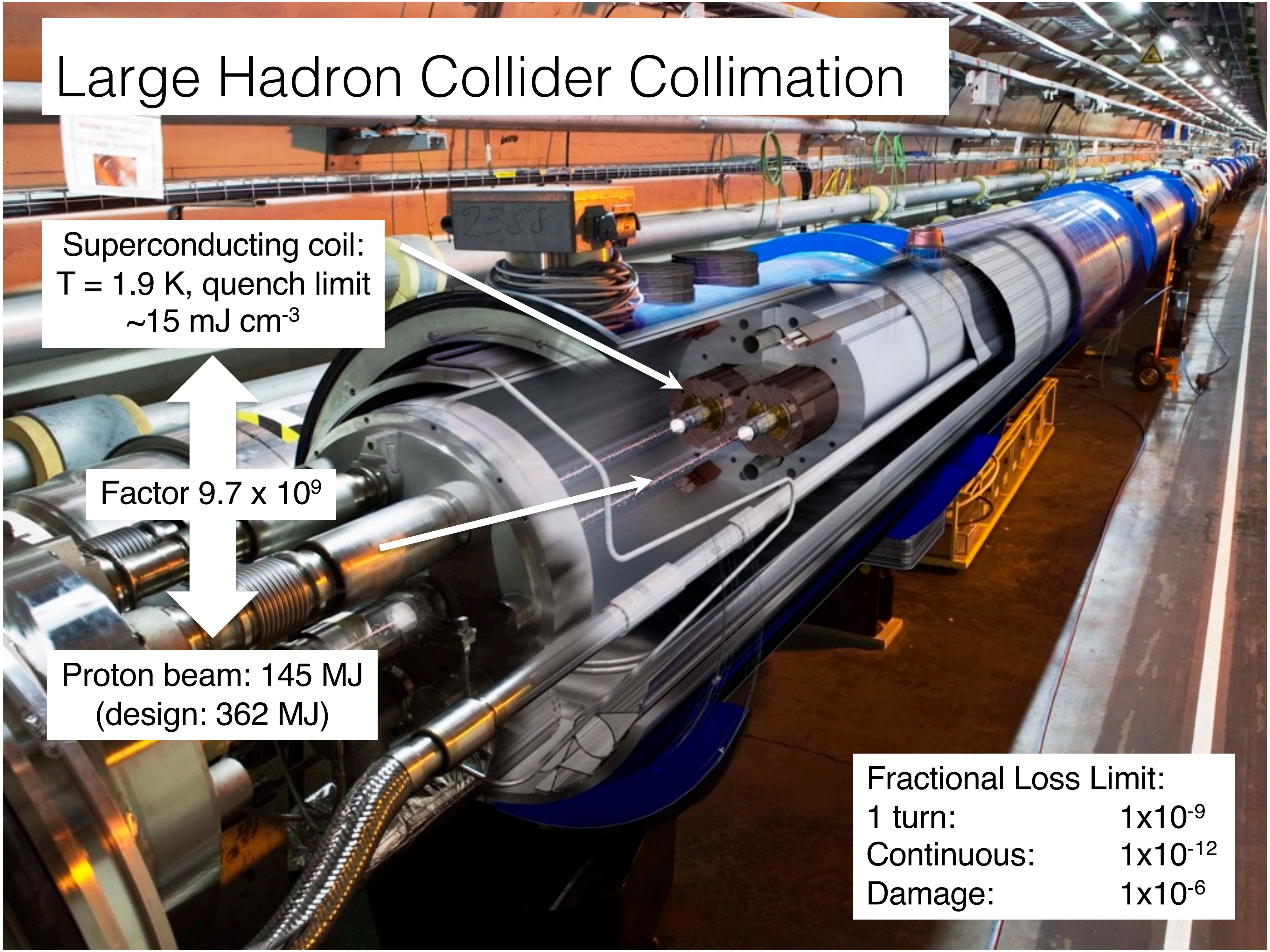
'selection' is weighting
can be Boolean and or numerical



basic impact, loss and
energy deposition analysis

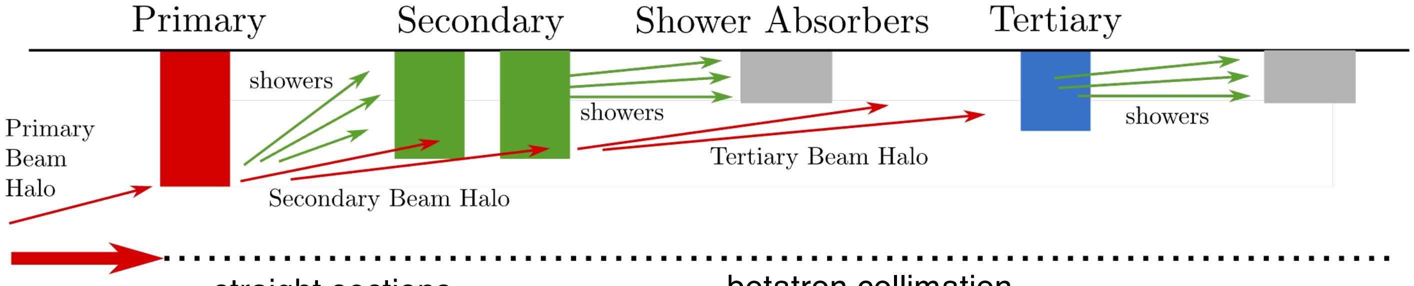
Examples

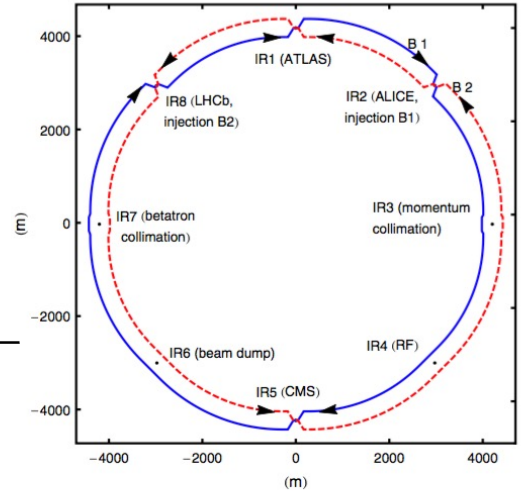
Large Hadron Collider Collimation

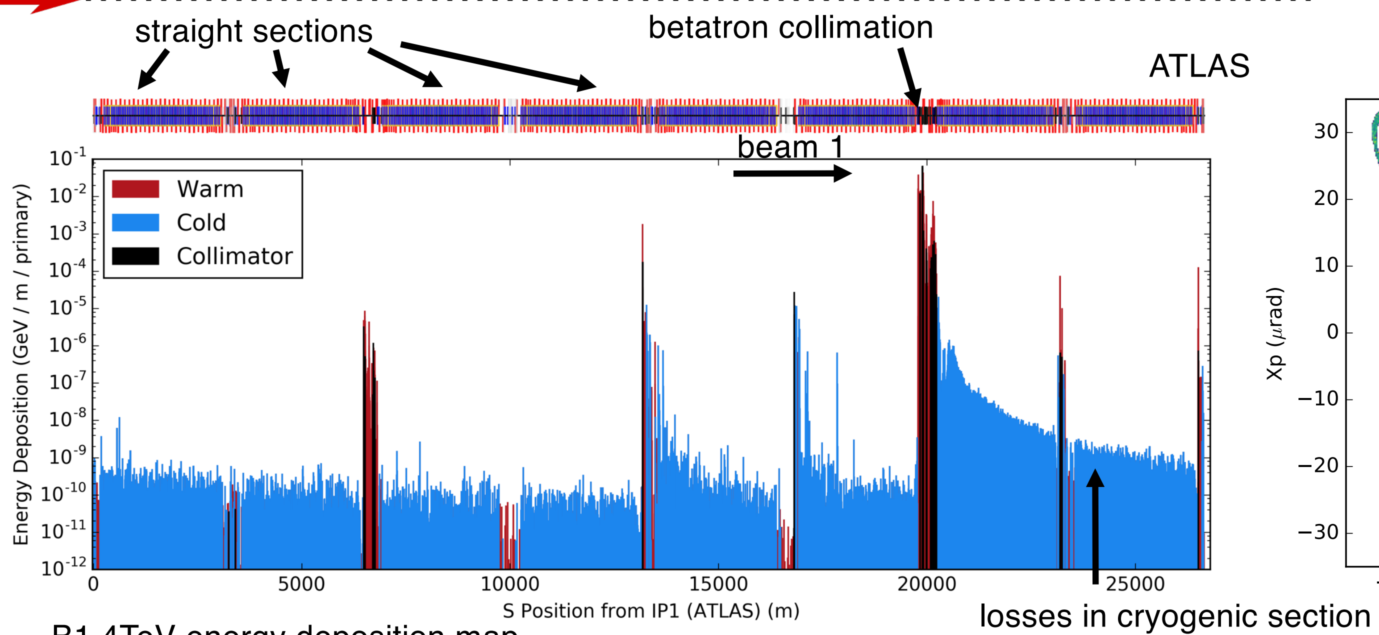


LHC Collimation

- Halo populated during beam storage
  - must be continually removed
- Simulate halo as it touches collimators
- Require 1:10^6 precision

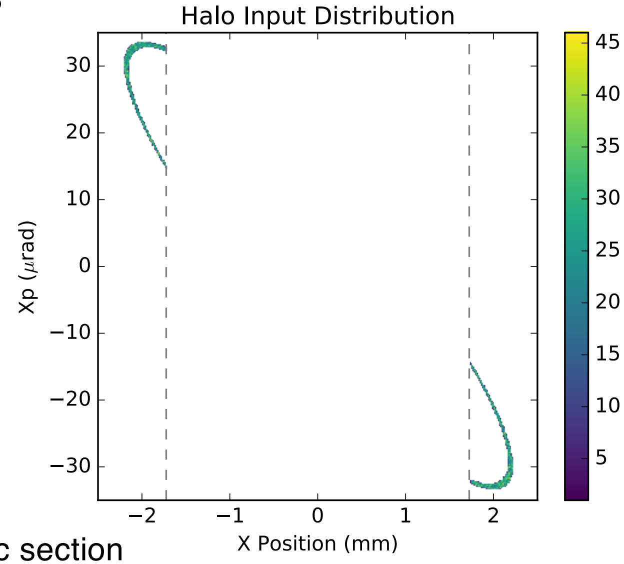






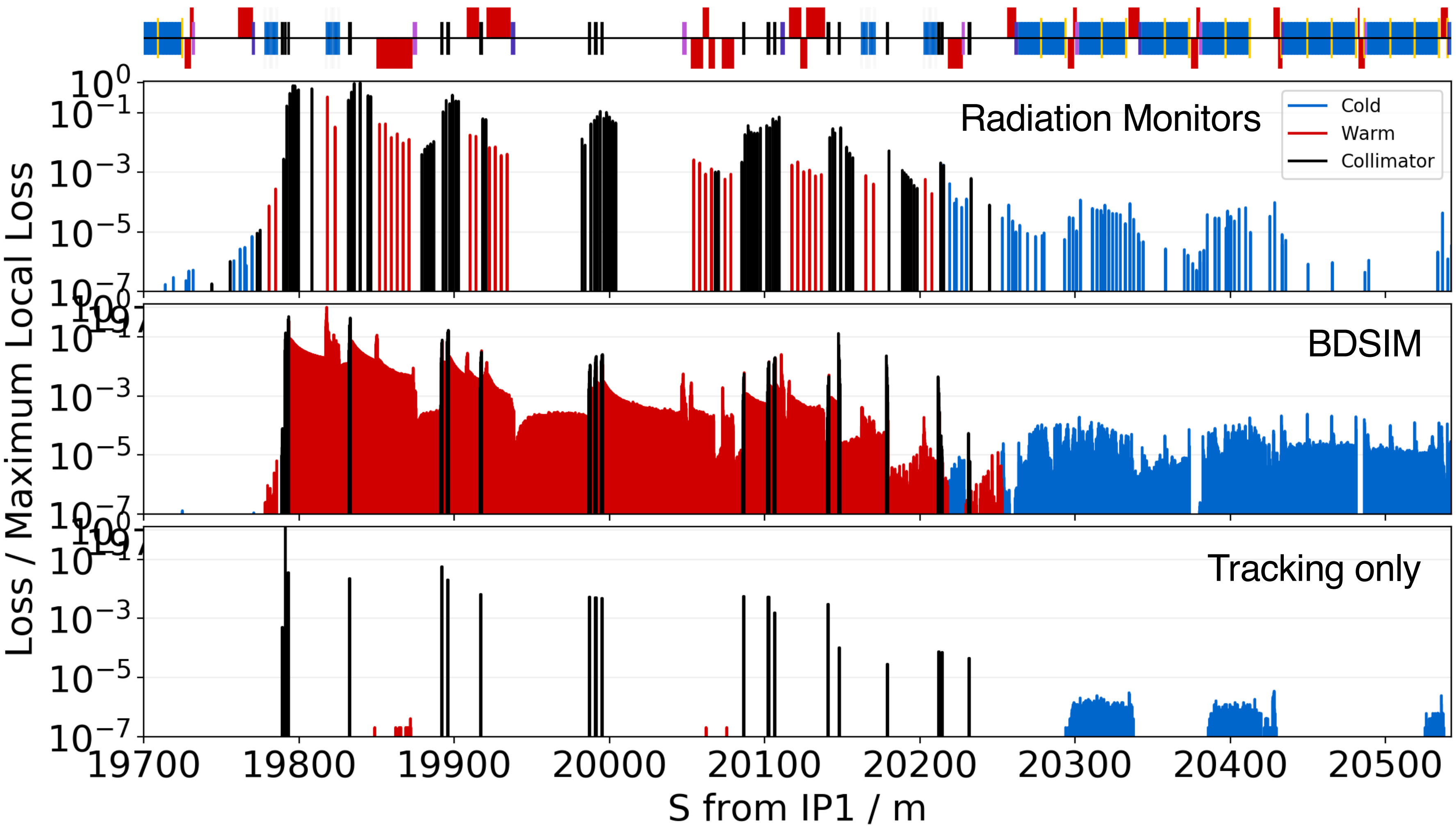
B1 4TeV energy deposition map

Example halo distribution



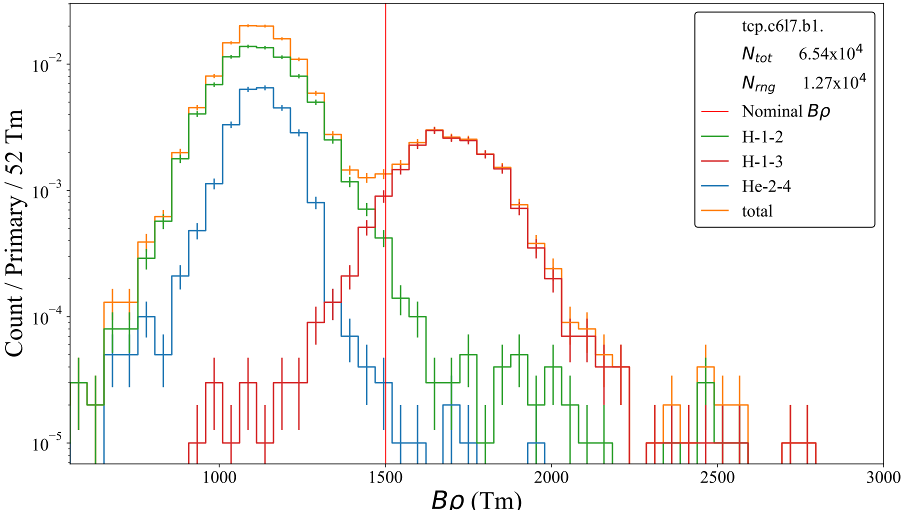
L. Nevay, S. Walker

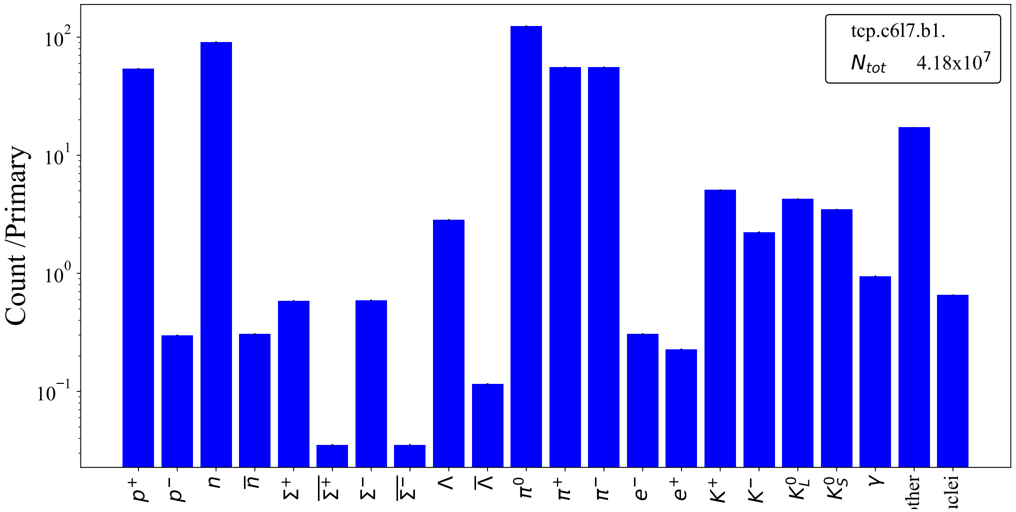
LHC Comparison

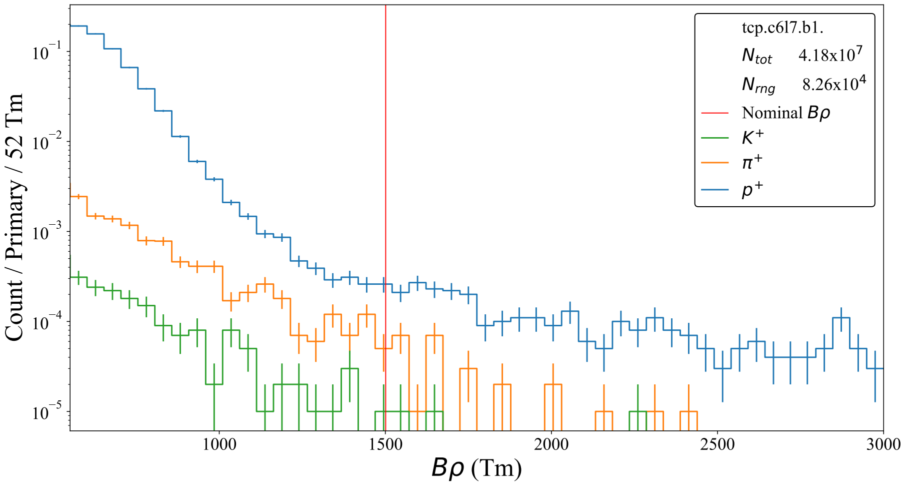


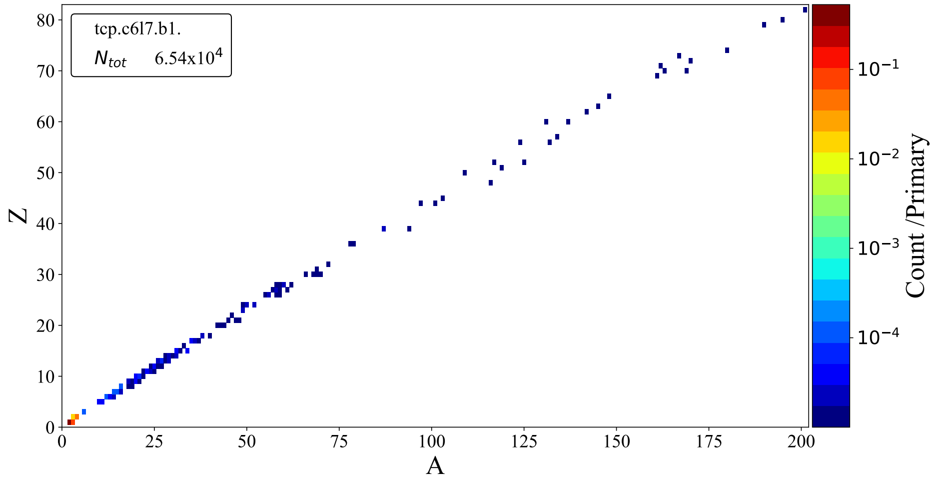
LHC Ion Collimation

- Similarly, same model can be used with ions
- Fragmentation - many fragments around nominal Bρ





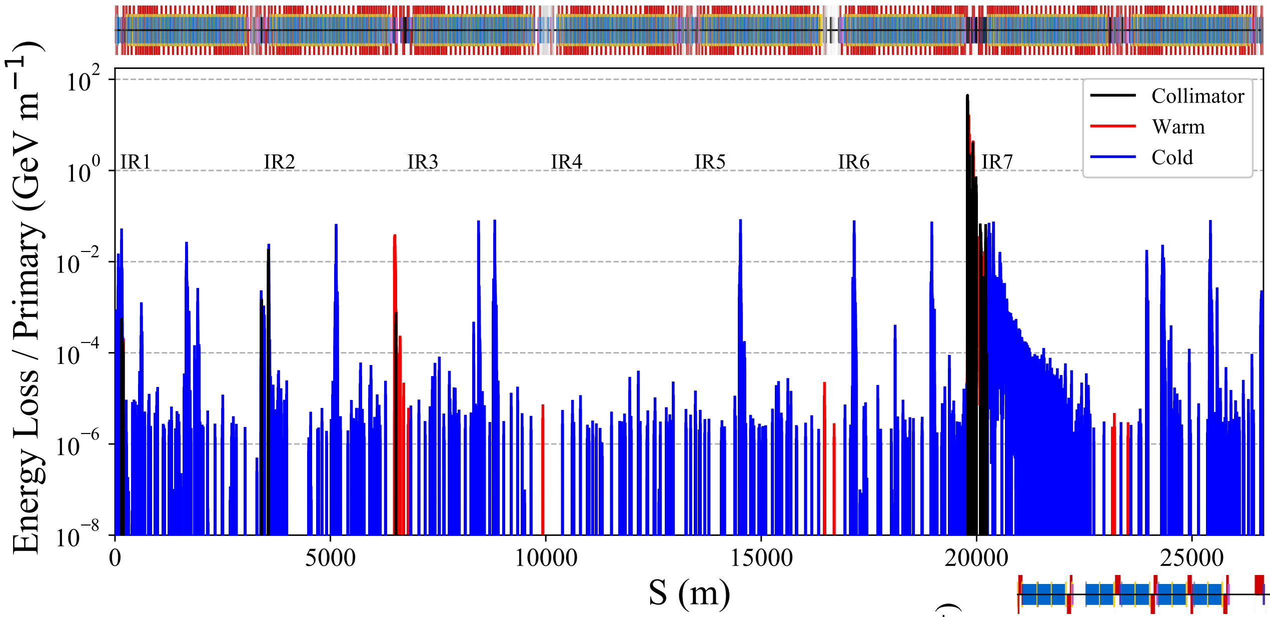




A. Abramov

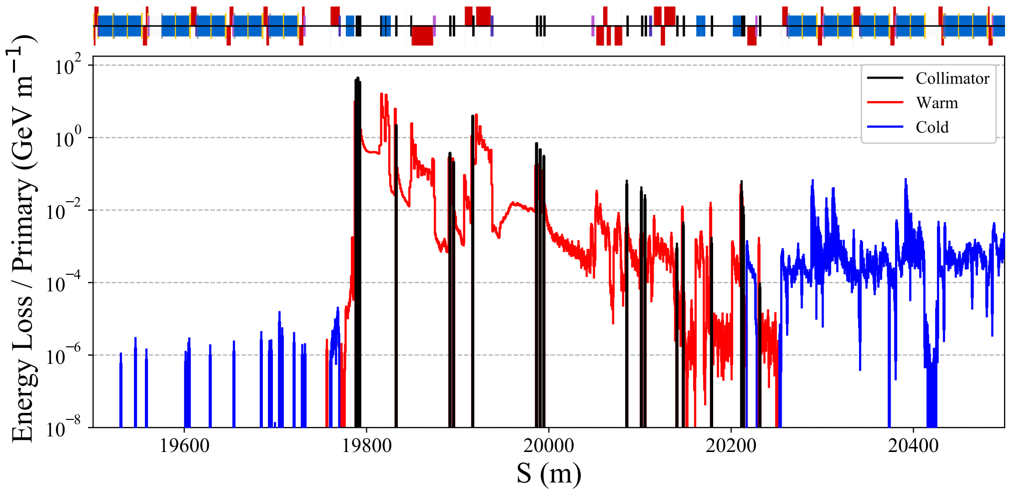
LHC Ion Collimation II

- Energy deposition around ring



- Significantly more loss spikes around ring
- Beam intensity limit much lower
- Collimator impacts only at S = 20000m here

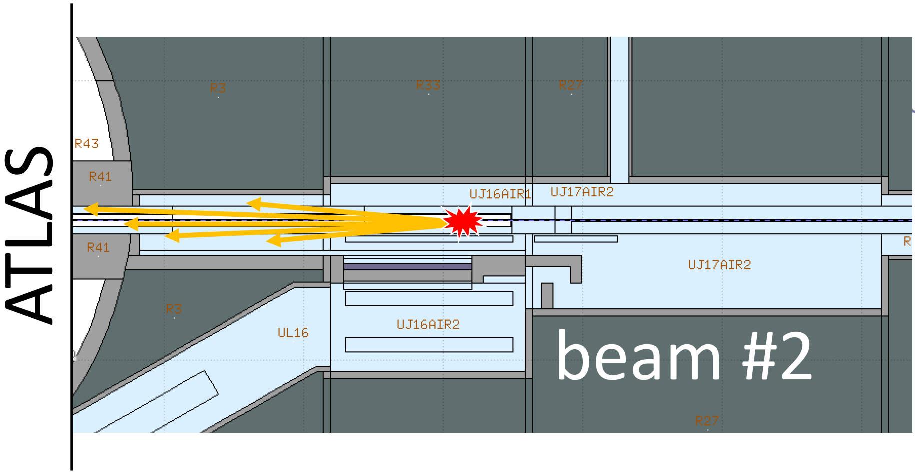
- Zoom of collimation section ('IR7')
- Coded losses on collimators, warm and cold sections

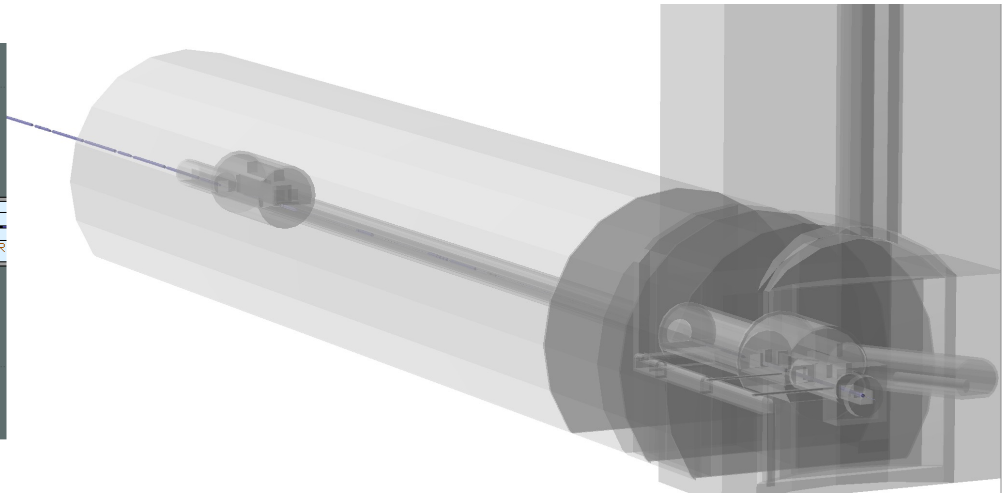


A. Abramov

LHC Non-Collision Backgrounds

- Interaction with residual vacuum creates measurable background in ATLAS and CMS detectors
- Modelling ATLAS background using BDSIM
  - last 500m of machine before ATLAS
  - single pass simulation
  - predict observed rates in pixel detector
  - IR1 tunnel model converted from FLUKA
- Bias proton inelastic scattering with residual vacuum
  - subsequent interactions with normal weighting

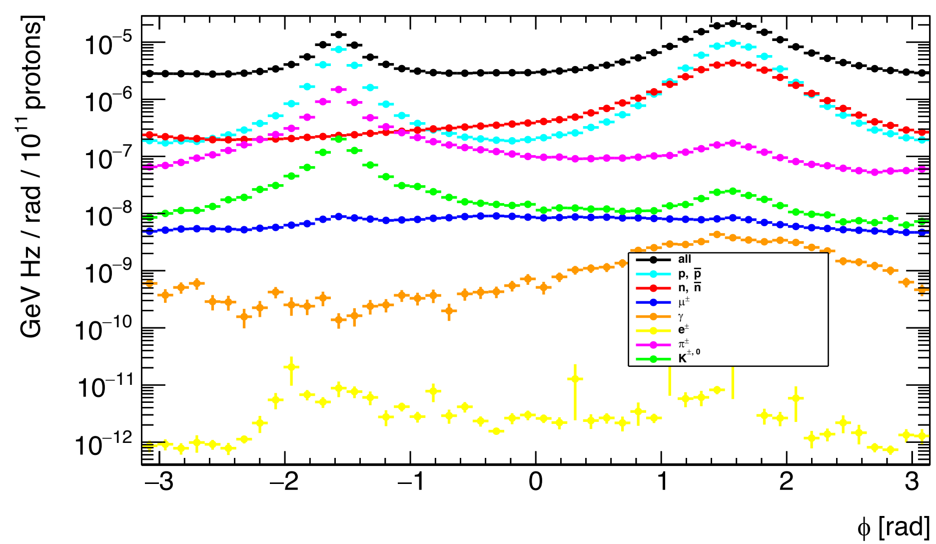




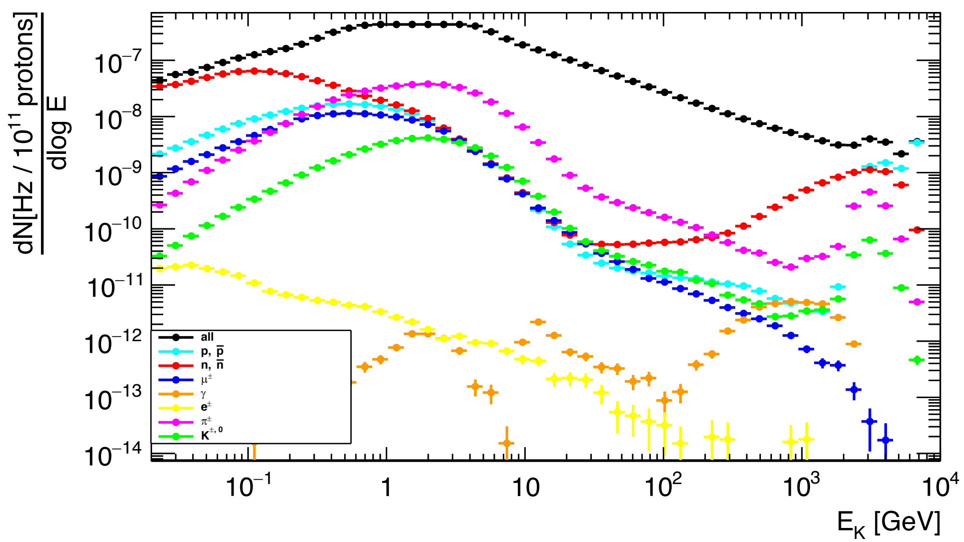
S. Walker, S. Gibson

LHC Non-Collision Backgrounds II

Azimuthal rate for different species

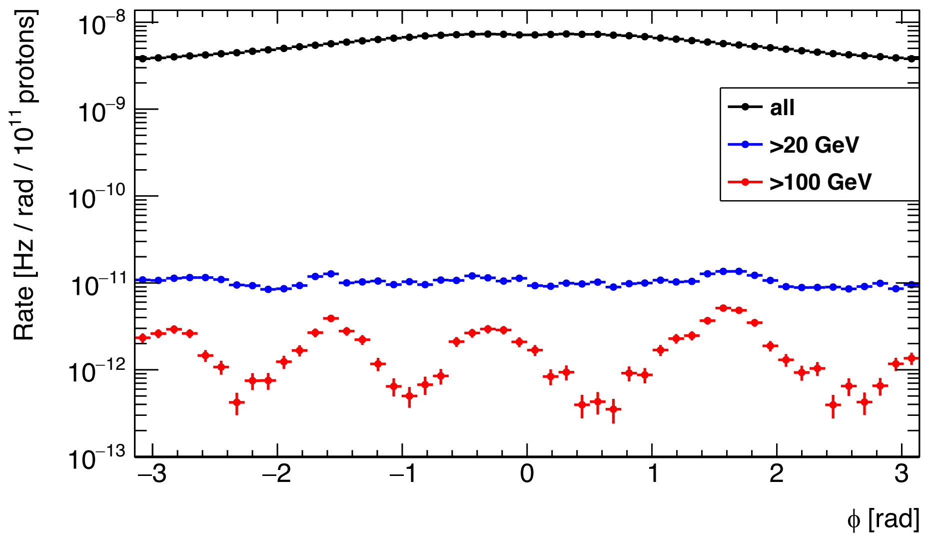


- Particles recorded at 'interface plane'
  - start of detector cavern
- Transferred to dedicated ATLAS simulation



Overall particle spectra at interface plane

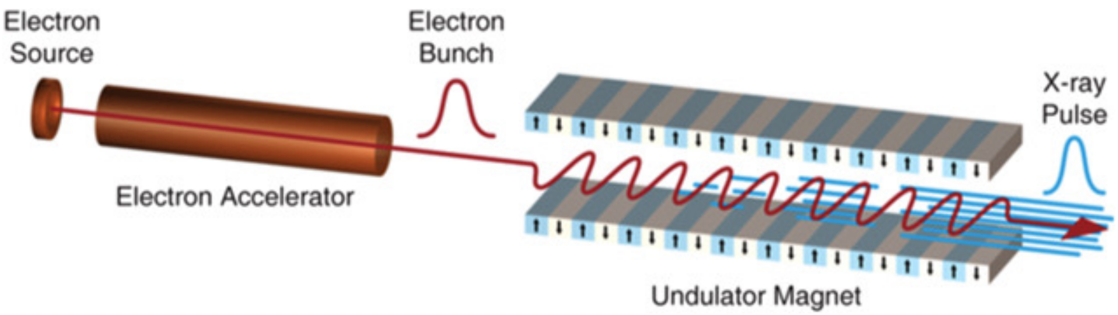
Azimuthal rate for different muon energies

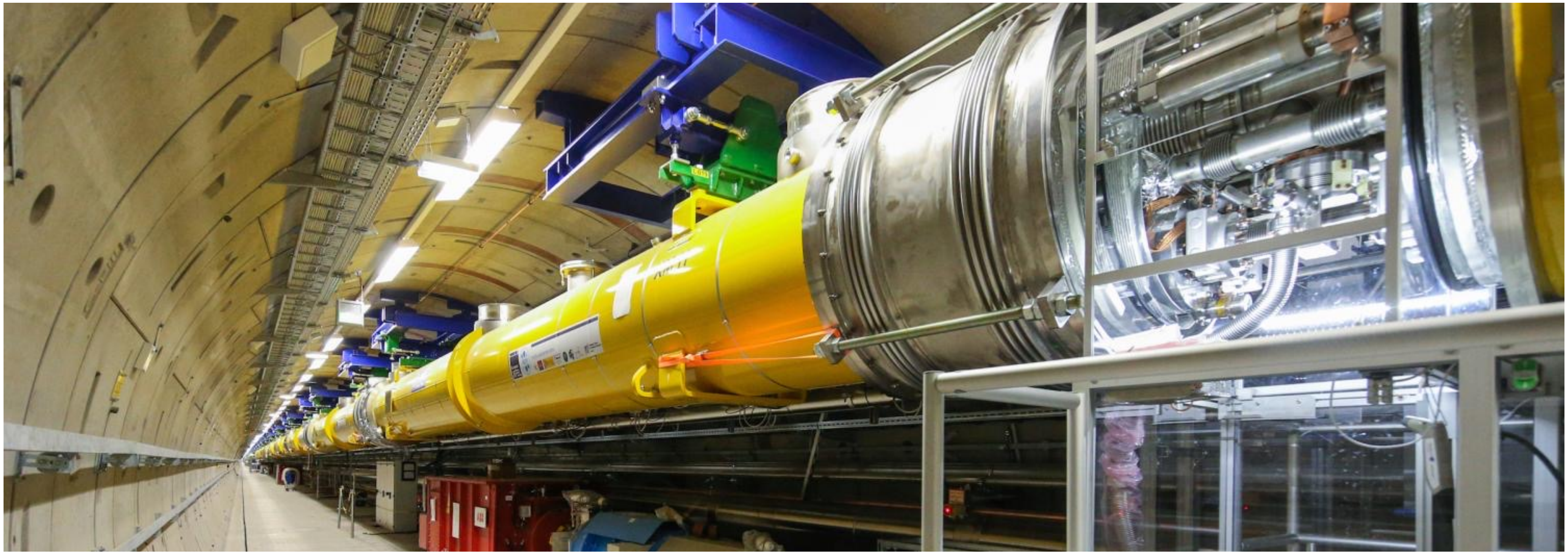


S. Walker, S. Gibson

DESY XFEL in Hamburg

- XFEL = X-ray Free Electron Laser
- Use e⁻ beam for X-rays
- Radiation can damage permanent magnets

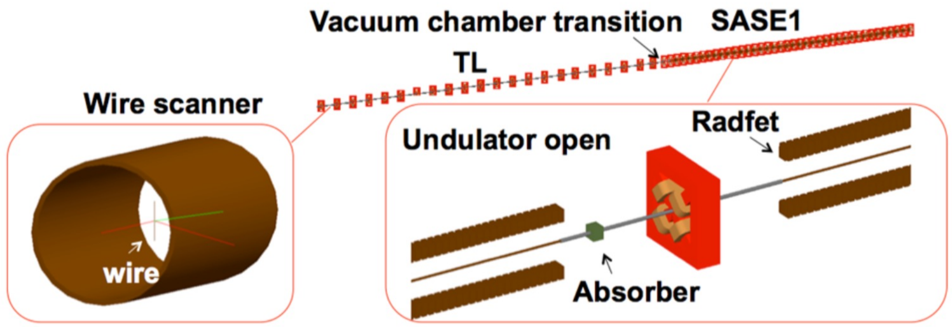


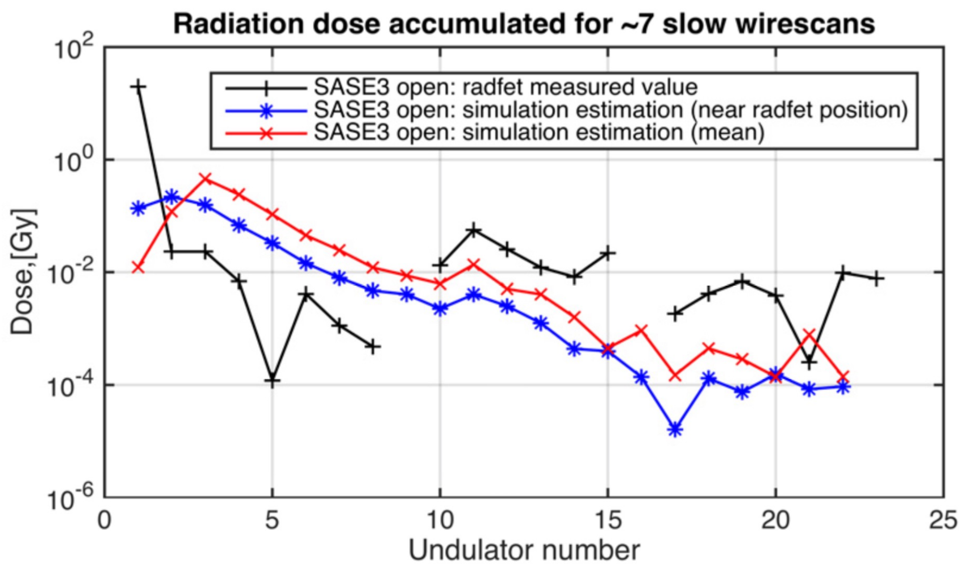


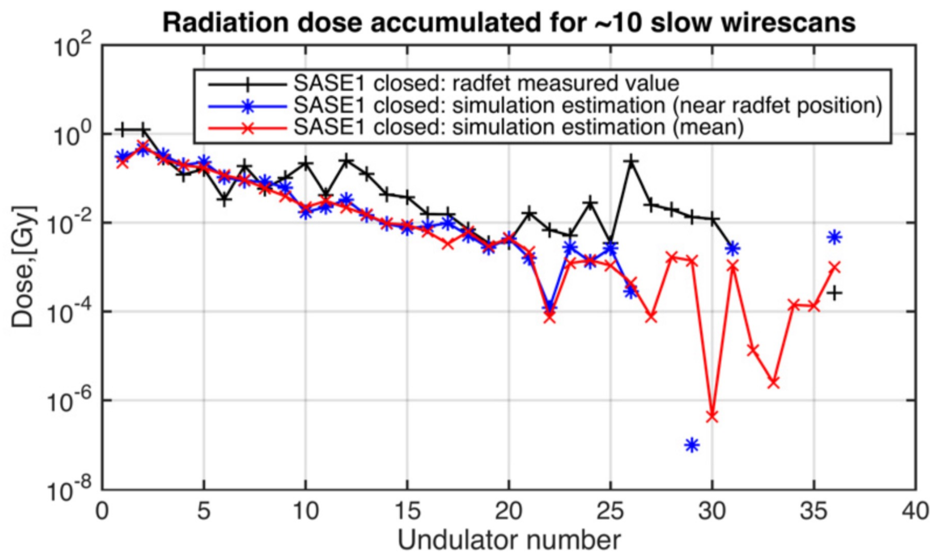
https://iopscience.iop.org/article/10.1088/1402-4896/aa5281

DESY XFEL Undulator Dose

- Undulator dose higher than original design
- Caused by secondary neutrons and synchrotron radiation
- Simulations compare to RADFET detectors on each undulator
- Improving shielding
- Diagnostics create radiation





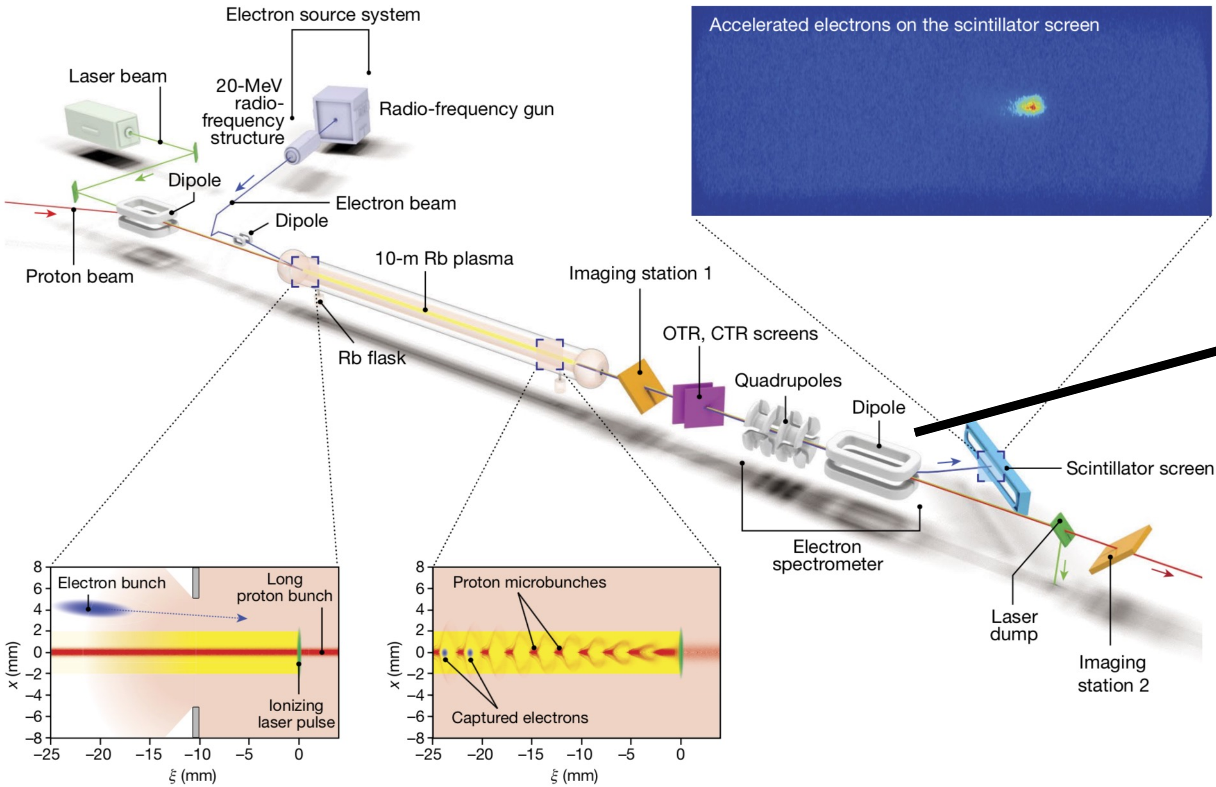


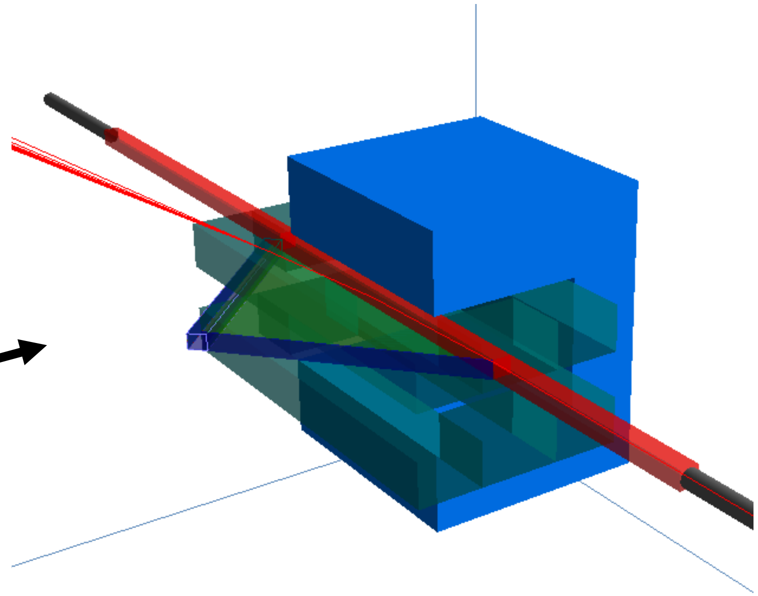
https://doi.org/10.18429/JACoW-IPAC2018-THPMF022

S. Liu, I. Agapov at DESY

AWAKE Dipole Spectrometer

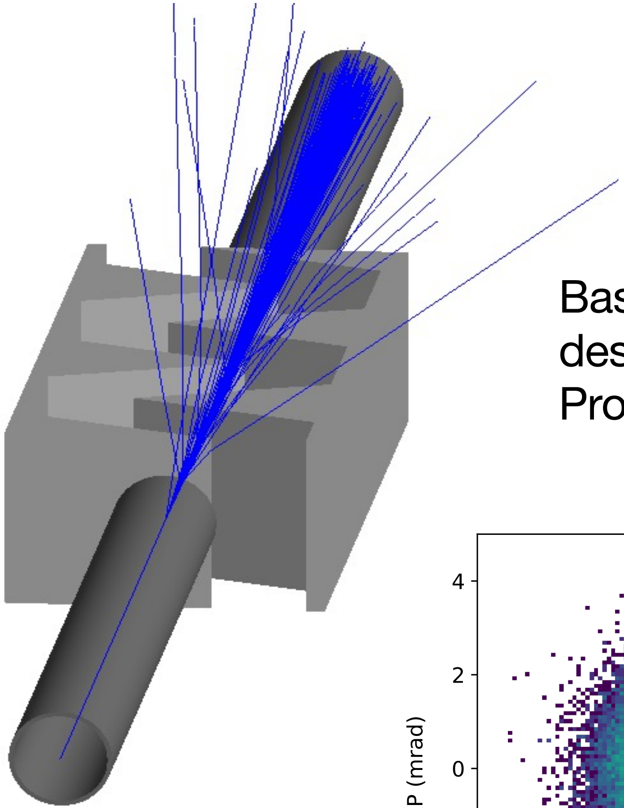
- Proton driven plasma wakefield accelerator at CERN
- Simulate electrons through dipole spectrometer
  - field map for detailed motion
  - physics required for synchrotron radiation, scattering and screen interaction
- Recently used for the calibration of the dipole
- https://www.nature.com/articles/s41586-018-0485-4



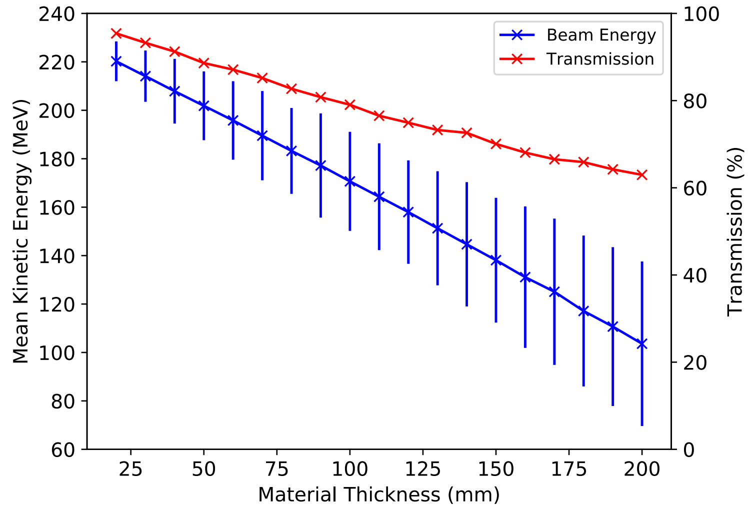


Hadron Therapy Degrader

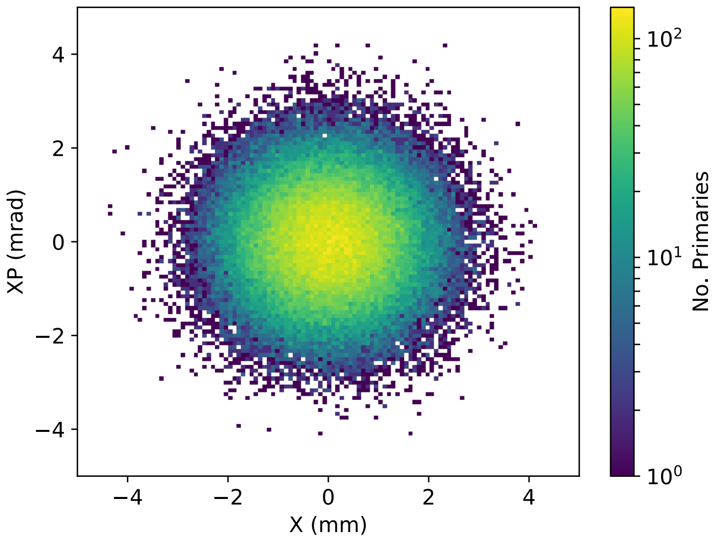
- Use variable material depth to degrade beam energy

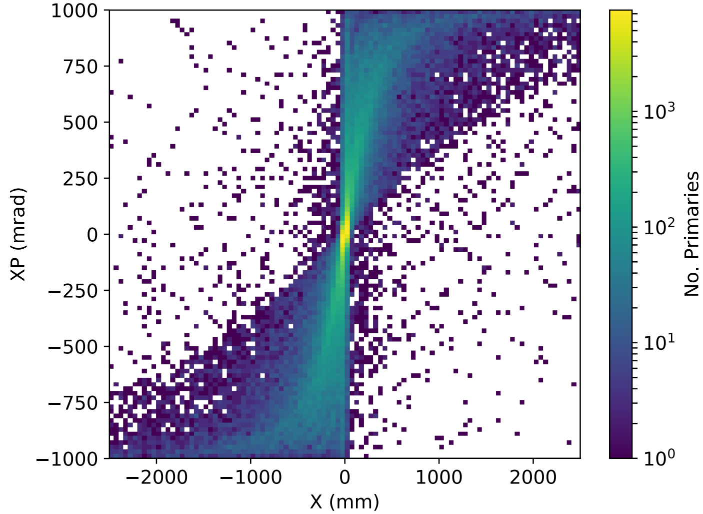


Based on the degrader design at the Center for Proton Therapy at PSI.



Horizontal phase space before (left) and after (right) a degrader.

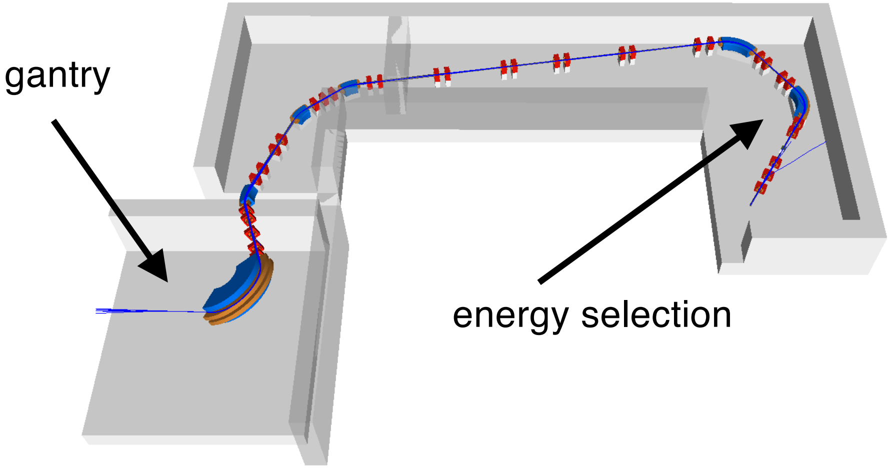


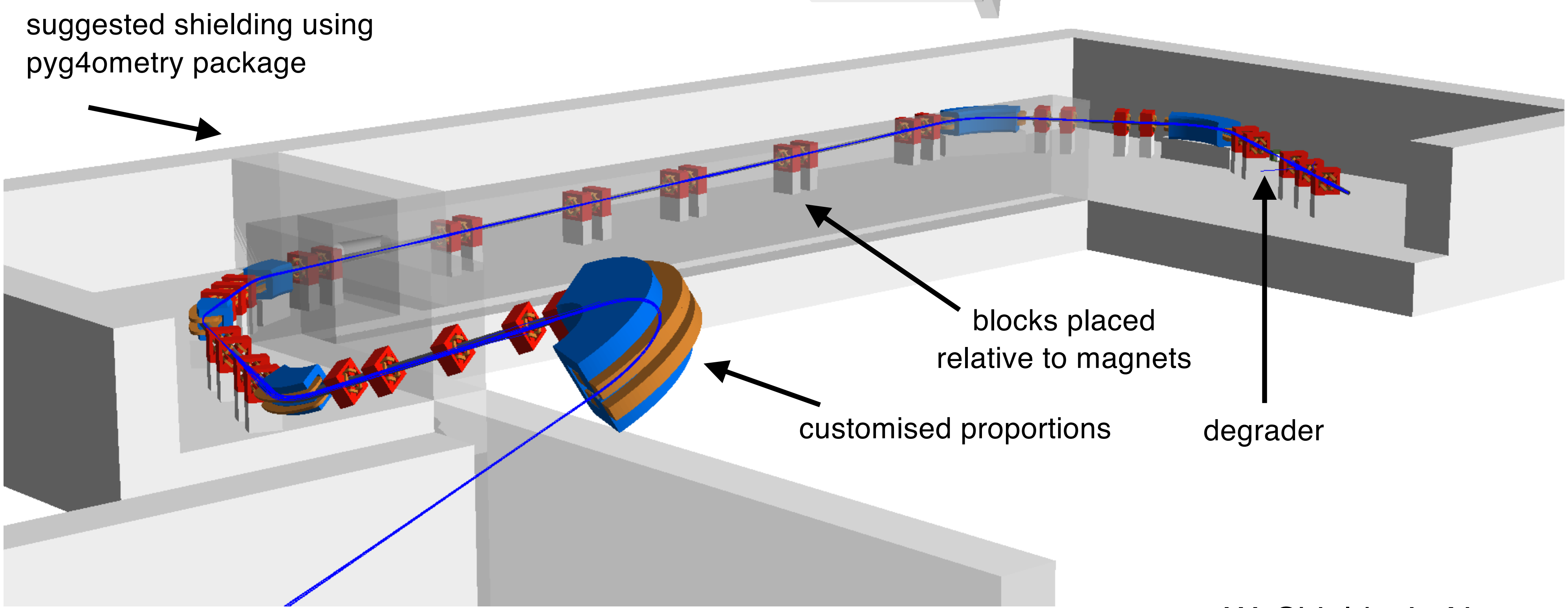


W. Shields

Example Model - PSI Gantry 2

- Paul Scherrer Institute in Switzerland Gantry 2
  - lattice at publicly available http://aea.web.psi.ch/Urs_Rohrer/MyFtp
- Conceptual design - different machine build

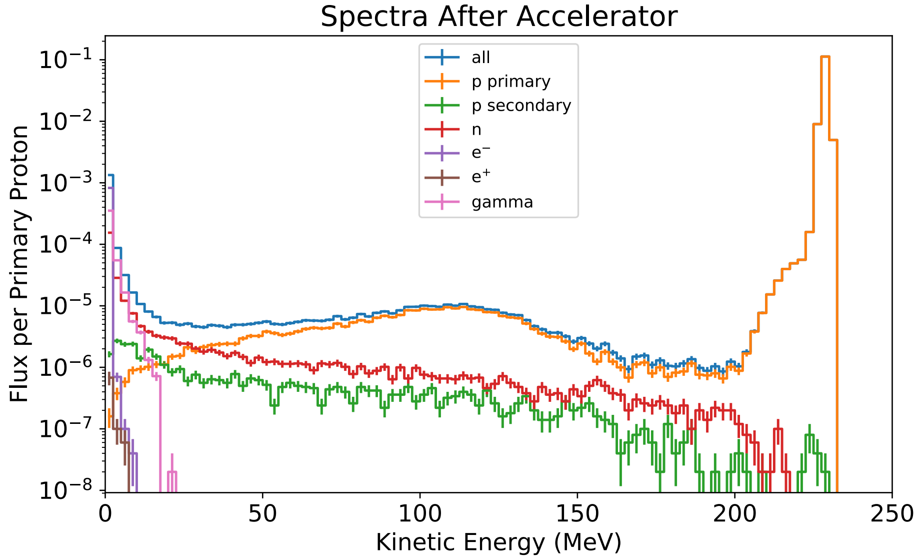


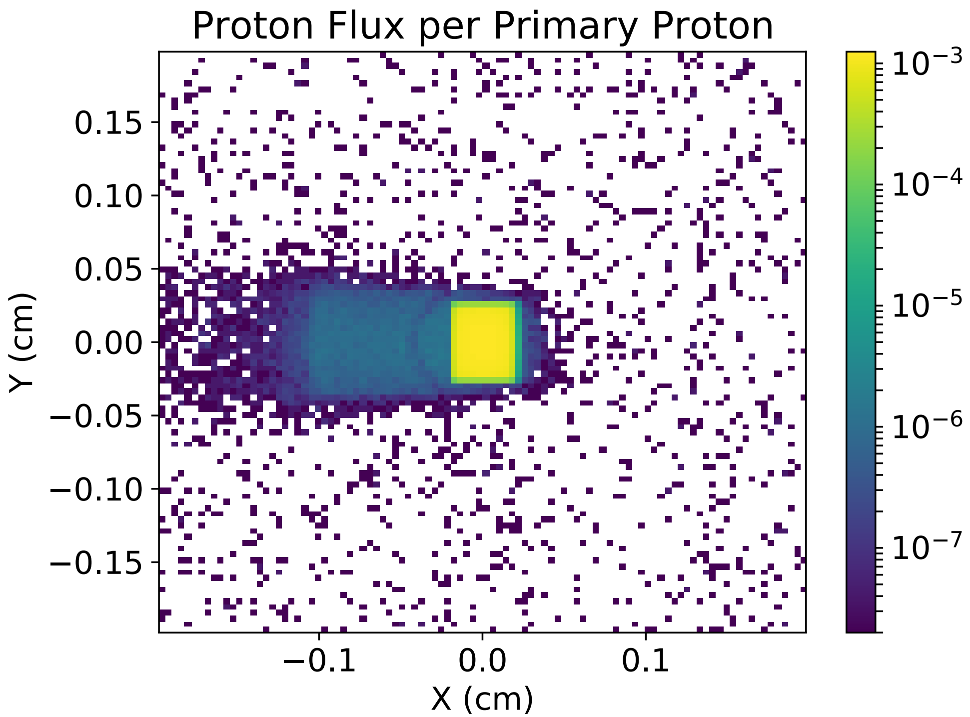


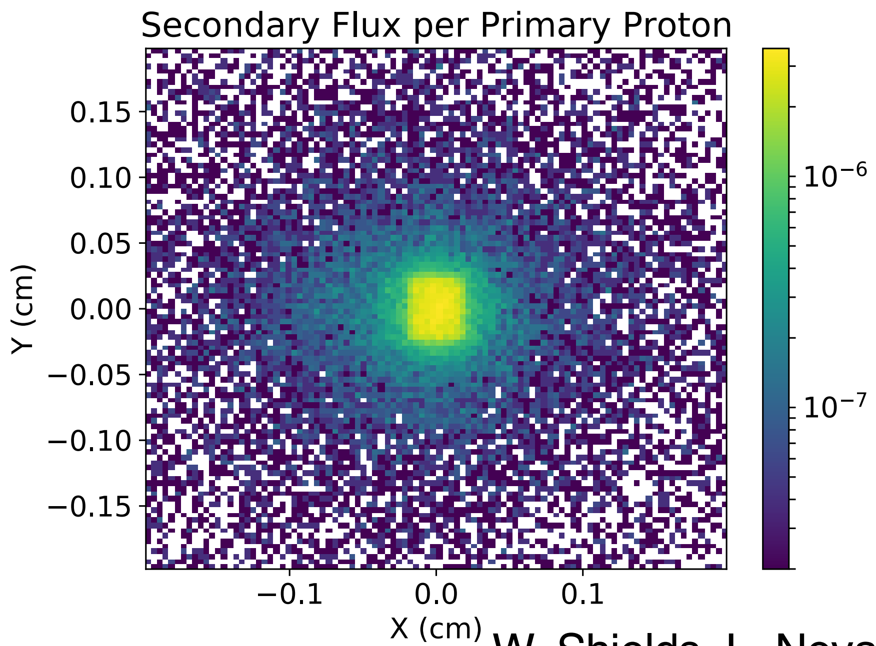
W. Shields, L. Nevay

Beam Profiles

- Beam profiles after last magnet
  - before nozzle
- Flux of secondaries predicted
- Spectra of all particles
- Can include nozzle as external geometry



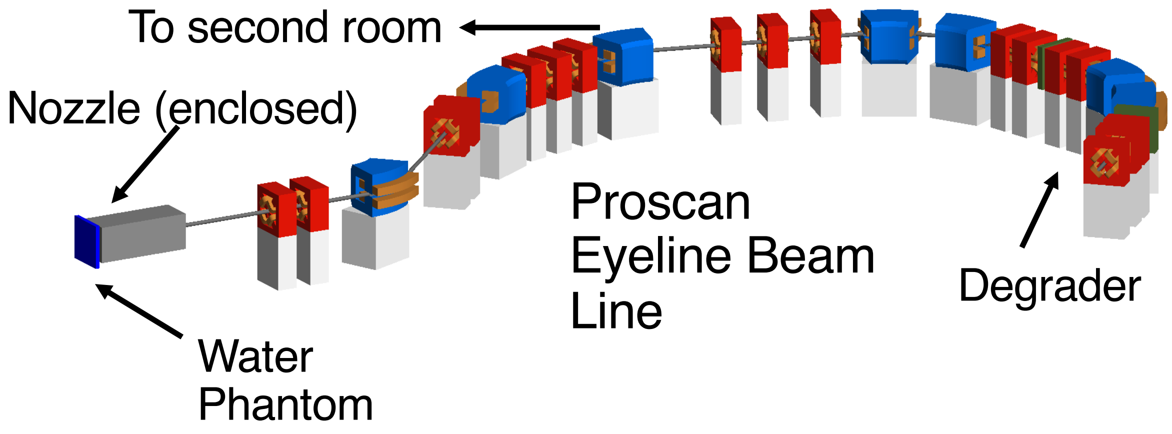


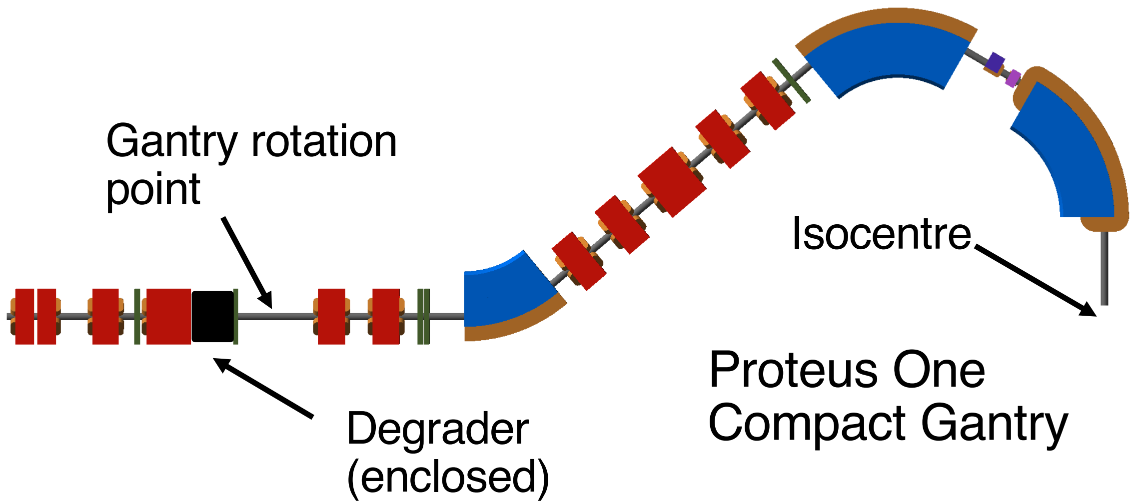


W. Shields, L. Nevay

Collaboration with IBA

- Simulation of two beam lines:
  - Proteus ONE – 250 MeV Gantry
  - Proteus PLUS – 70 MeV static beamline
- Improve beam profile with optimised nozzle and optics.
- Enhanced dose rate from degrader efficiency studies.
- Loss maps for shielding activation.

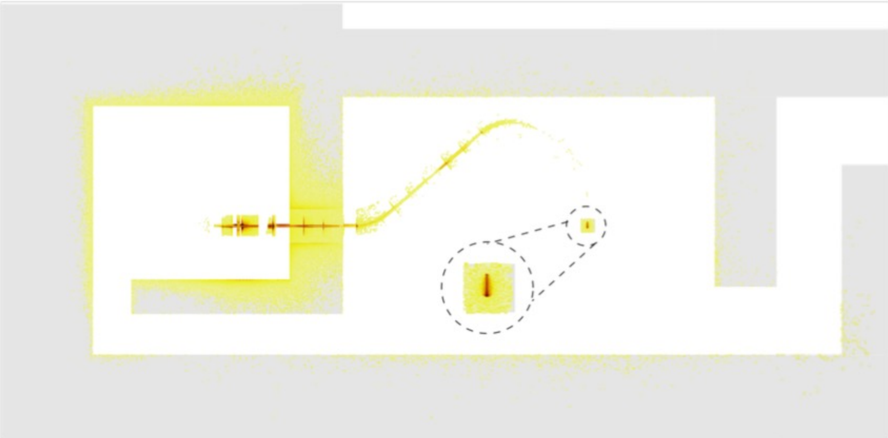




W. Shields. E. Gnacadja, R. Tesse, C. Hernalsteens

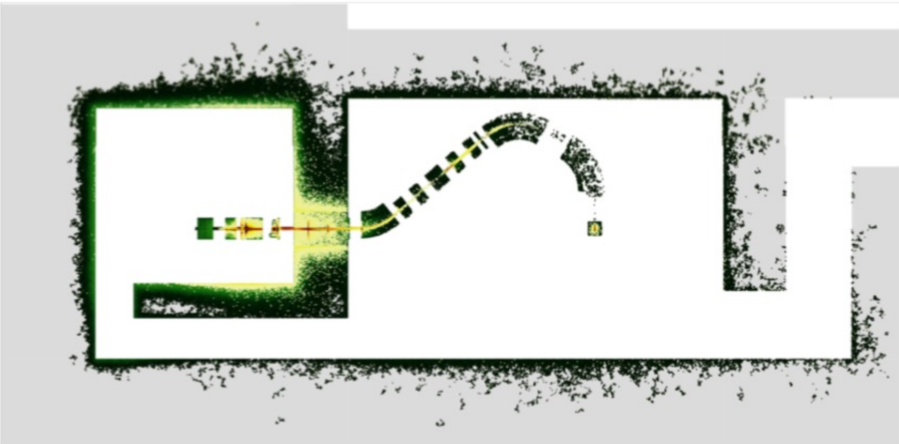
Shielding Activation Studies

Proton interactions

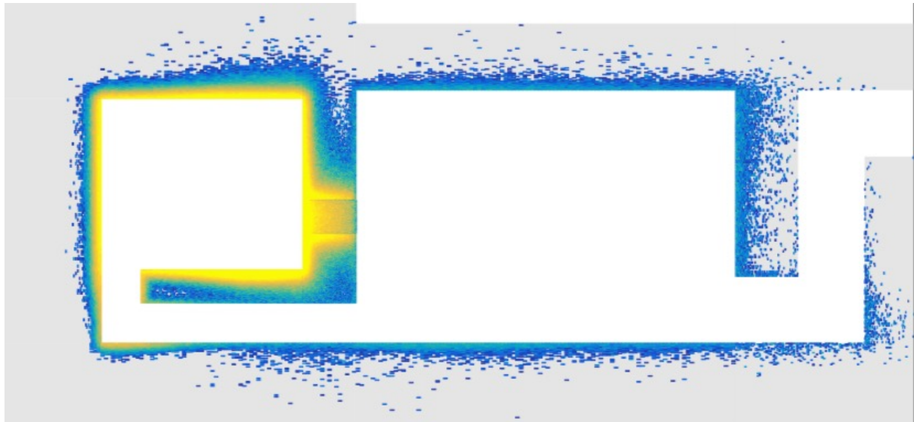


- Calculate shielding activation rate from spallation and neutron capture.

Protons & Neutron interactions

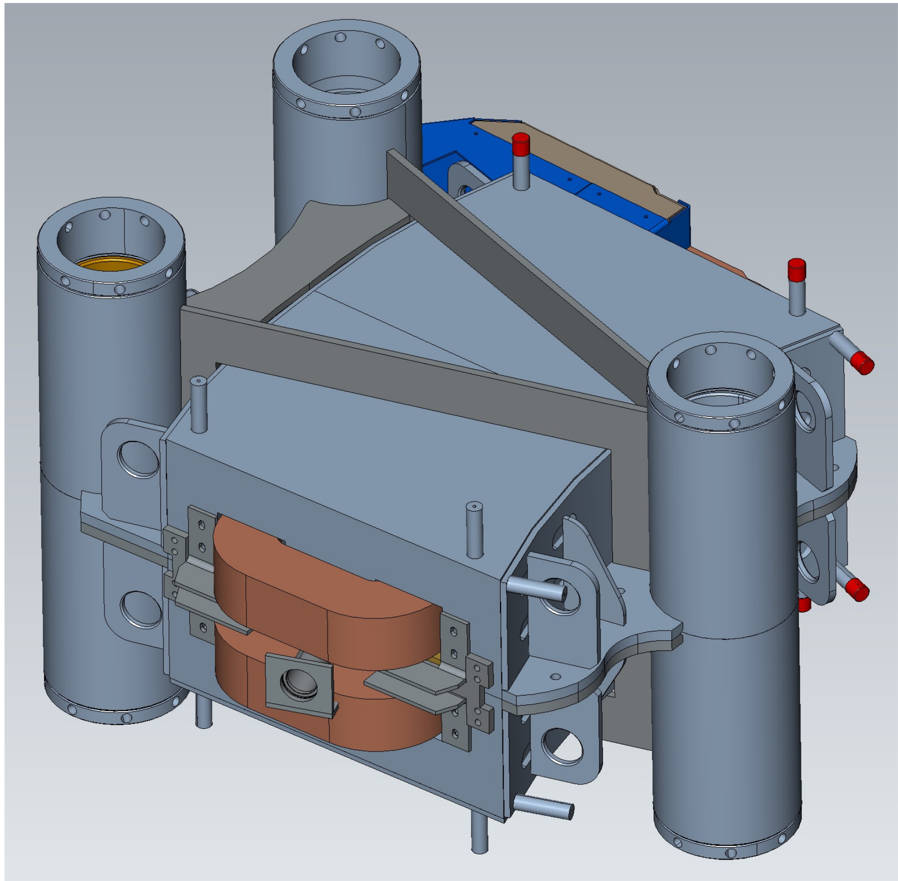


Shielding only

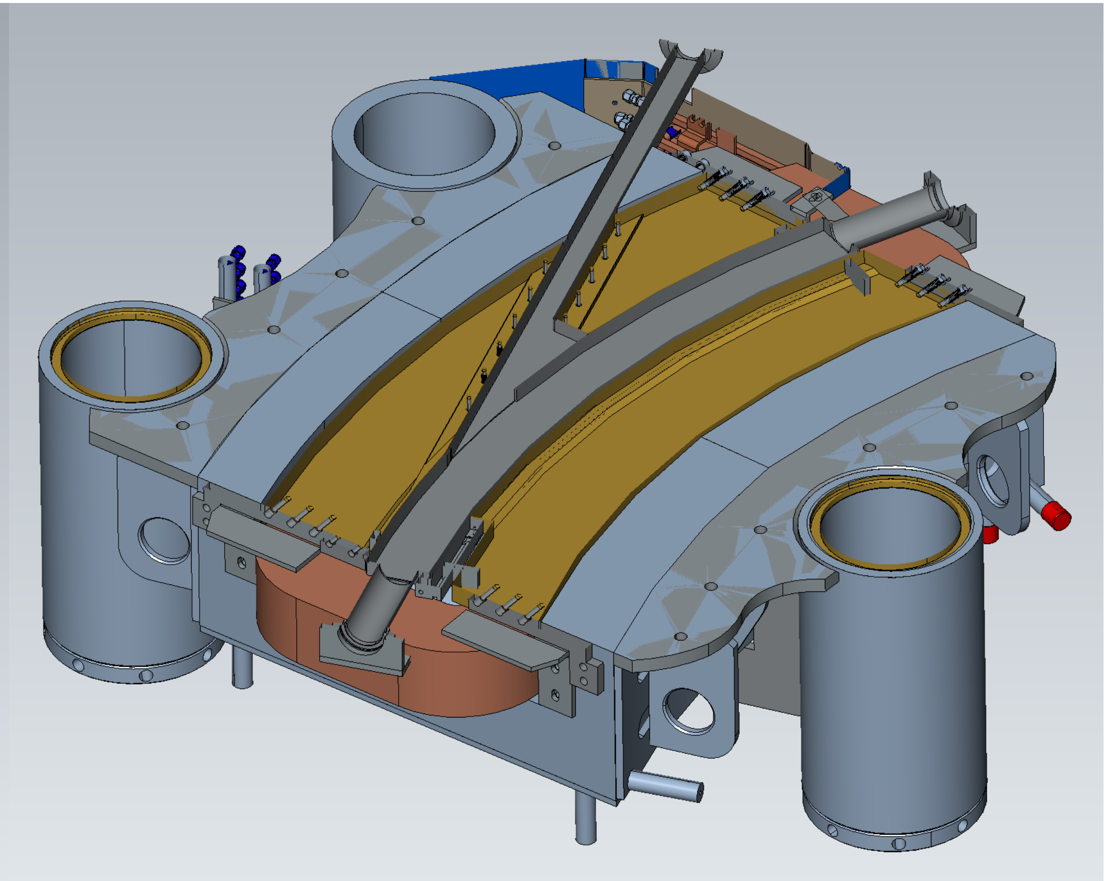


Future Directions - Geometry

- CAD used extensively to build components
- Radiation model often made by hand separately
- Ideally 1:1 model - why repeat construction?



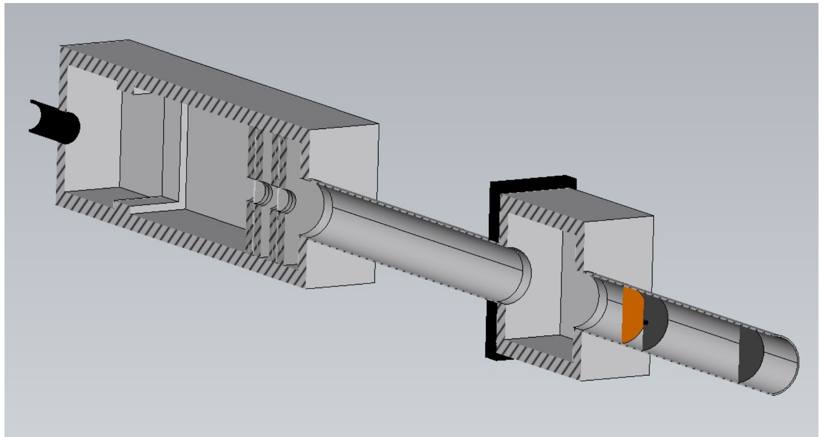
IBA dipole magnet



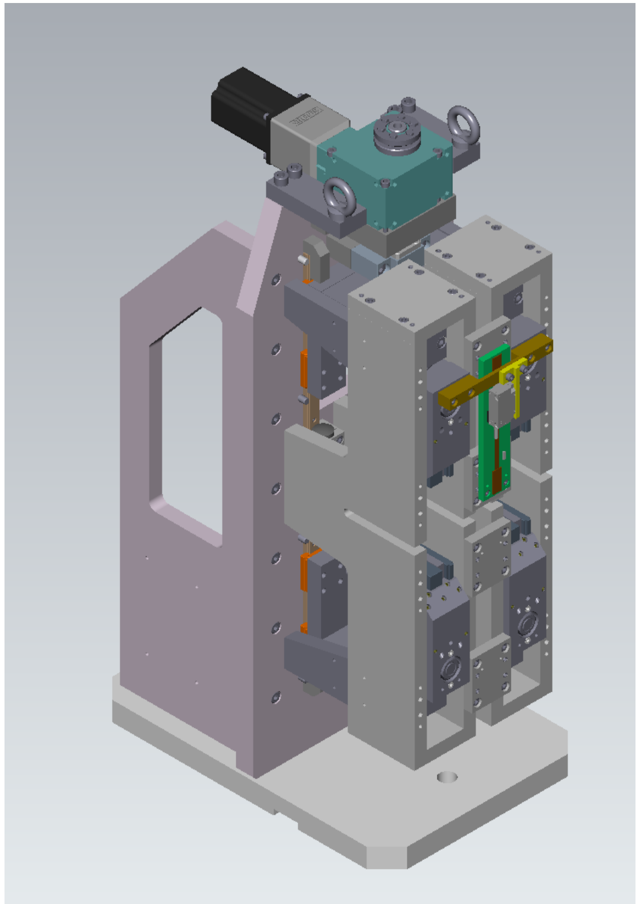
complex aperture

Automatic Geometry for Radiation

- Many features are unnecessary (labels, screws)
- Accurate level of detail not required
  - for radiation what matters most is the amount of mass
- Different description - cannot translate directly
- Use tessellated mesh -> inefficient
  - depends on level of detail



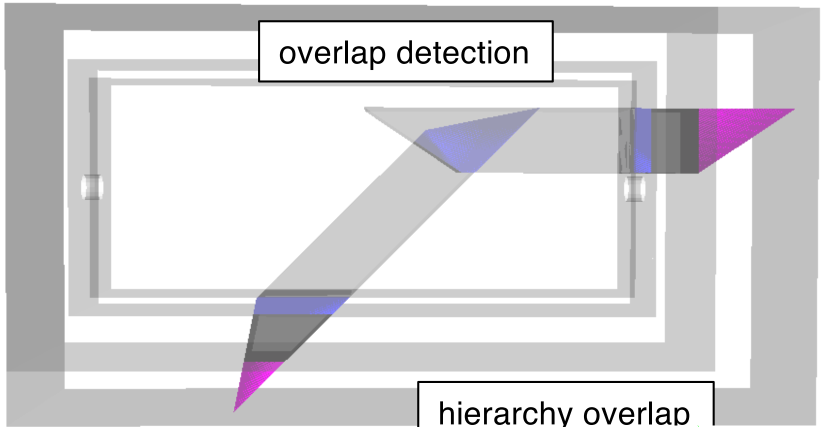
Clatterbridge occular treatment nozzle



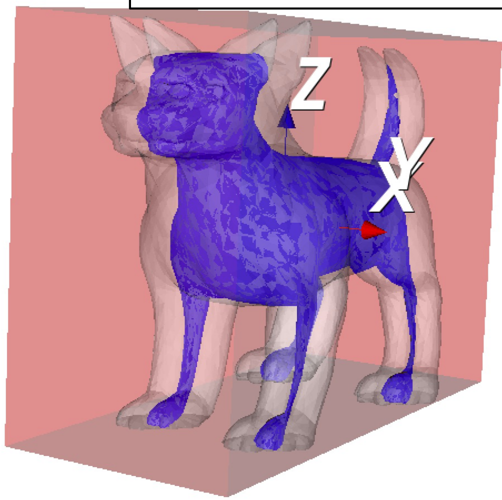
Example DESY phase shifter with actuators

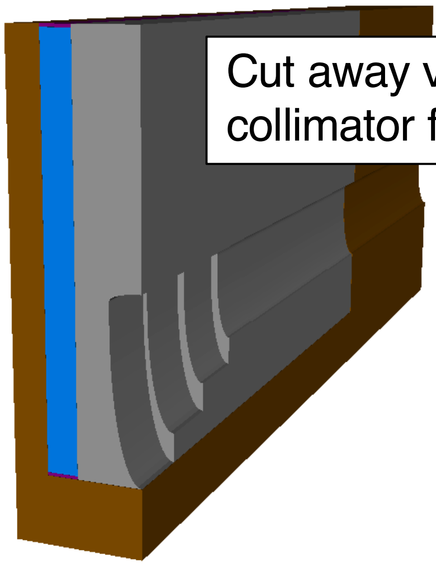
pyg4ometry

- Work ongoing on conversion library
- Computational approach to mesh

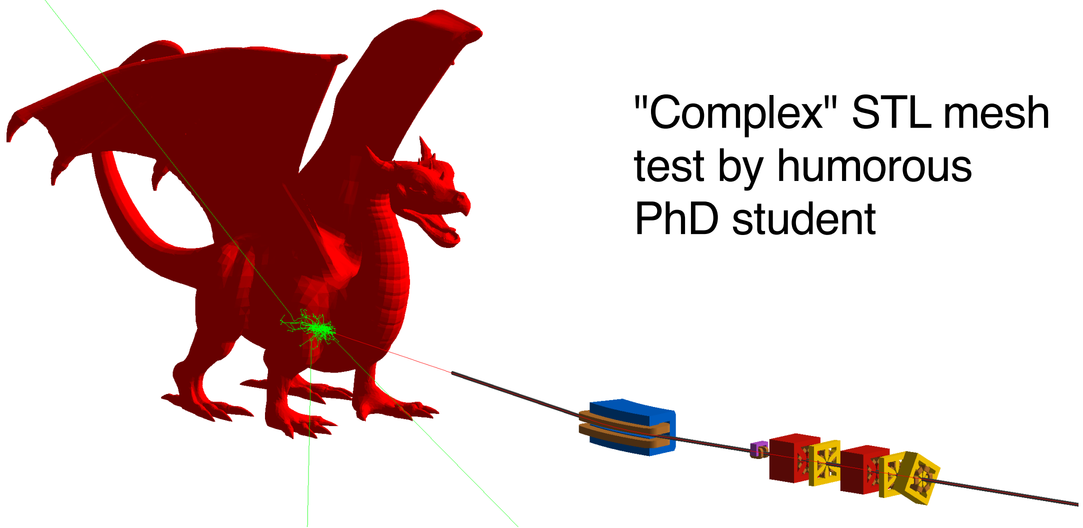


Overlap identification with complex STL mesh





Cut away view of custom collimator for CLIC



"Complex" STL mesh test by humorous PhD student

Summary

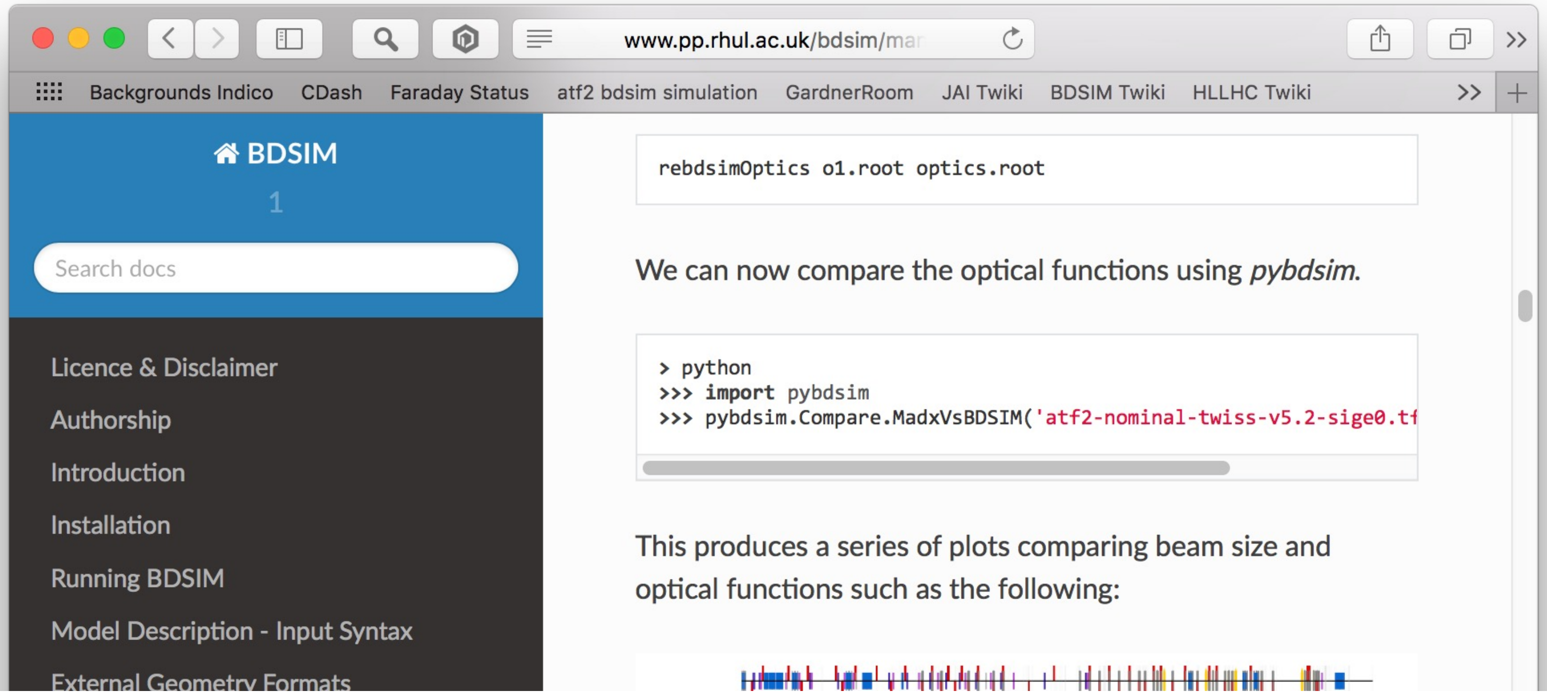
- Strategy of combined simulation demonstrated
- Spectrum from accelerator tracking to particle physics
- Radiation simulation geometry often different from realistic geometry
- Summary of high to low energy application from LHC to medical treatment facilities


ROYAL HOLLOWAY UNIVERSITY OF LONDON
Thank you

Backup

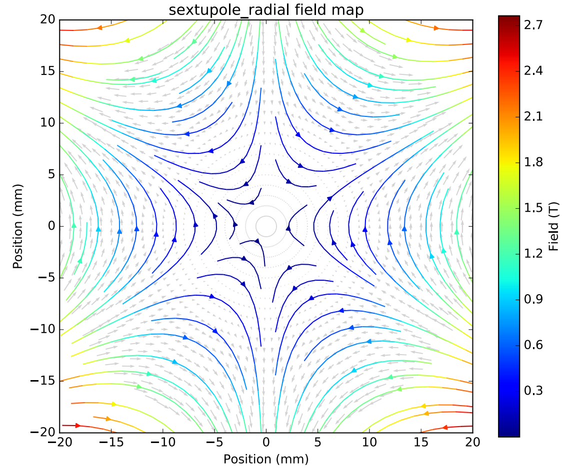
Links

- paper: *https://arxiv.org/abs/1808.10745*
- main website: http://www.pp.rhul.ac.uk/bdsim
- manual: http://www.pp.rhul.ac.uk/bdsim/manual
- git repository: https://bitbucket.org/jairhul/bdsim/wiki/Home
- Issue tracking & feature request
  - https://bitbucket.org/jairhul/bdsim/issues



Field Maps

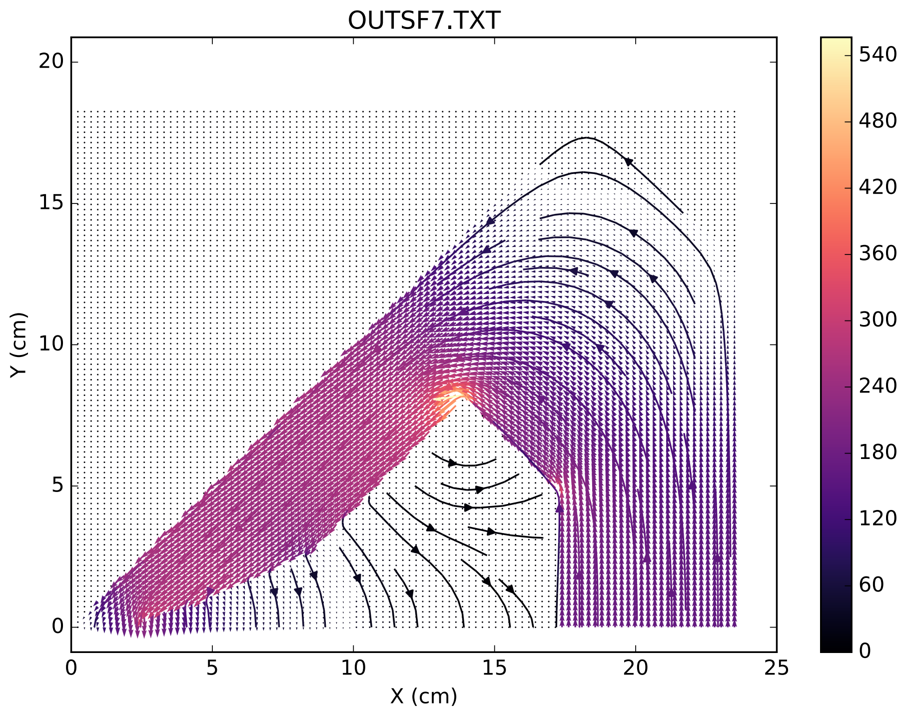
- Equations describe pure fields
- Can overlay field map on BDSIM generic element
  - yoke or vacuum separately or both together
- 1- 4D loading and interpolation
  - nearest neighbour, linear and cubic interpolation



ideal sextupole field

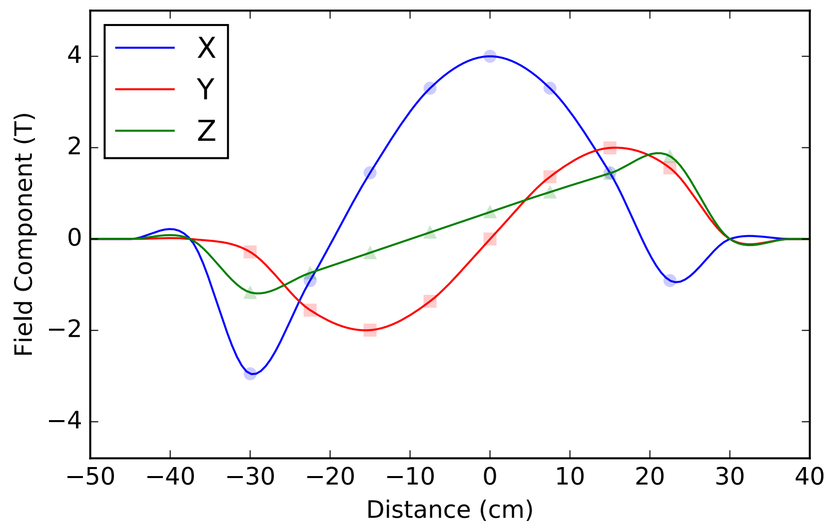
$$B_x = \frac{1}{2!}\frac{\partial^2 B_y}{\partial x^2}\,2xy$$

$$B_y = \frac{1}{2!}\frac{\partial^2 B_y}{\partial x^2}\,(x^2 - y^2)$$



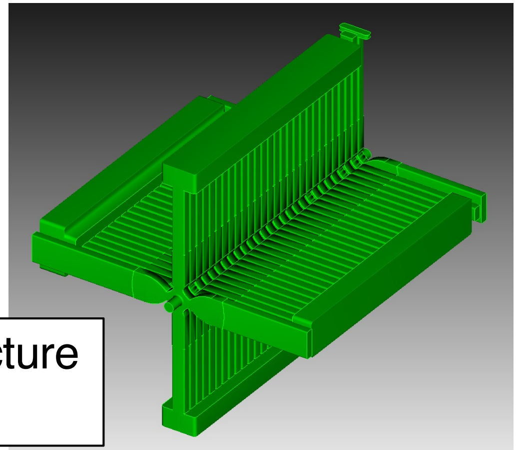
example field map from Poisson 2D

example interpolation



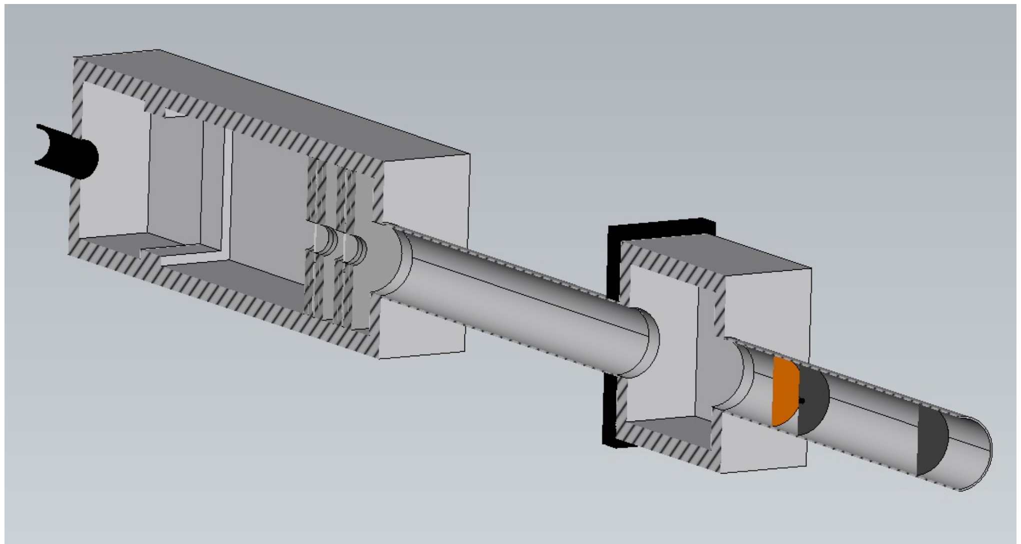
Complex Models

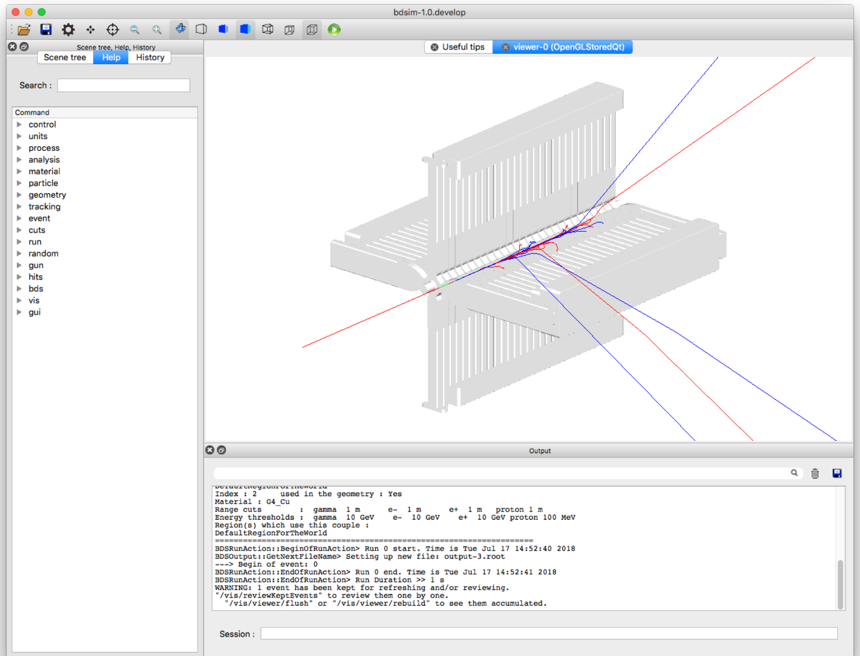
- Developed Python package to process CAD models
  - "pyg4ometry"
- Create mesh from STEP file
  - using Open Cascade and FreeCAD (free) tools
- Smaller models more suited



CLIC vacuum structure from STL file

Clatterbridge occular treatment nozzle





Example Syntax

- "GMAD" - Geant4 + MAD

sm.gmad

```
d1: drift, l=1*m;
q1: quadrupole, l=1*m, k1=1.3, magnetGeometryType="polesfacet";
c1: rcol, l=0.6*m, ysize=5*mm, xsize=5*mm, material="Copper", outerDiameter=10*cm;
s1: sbend, l=1*m, angle=0.10;

l1: line = (d1, q1, d1, c1, d1, s1);
use,period=l1;

sample, all;

option, ngenerate=1,
        physicsList="em";

beam, particle="proton",
      energy=10.0*GeV,
      X0=0.001,
      Y0=0.001;
```

```
-:---  sm.gmad        All L3     Git:develop  (Fundamental)
Wrote /Users/nevay/physics/reps/bdsim/examples/simpleMachine/sm.gmad
```