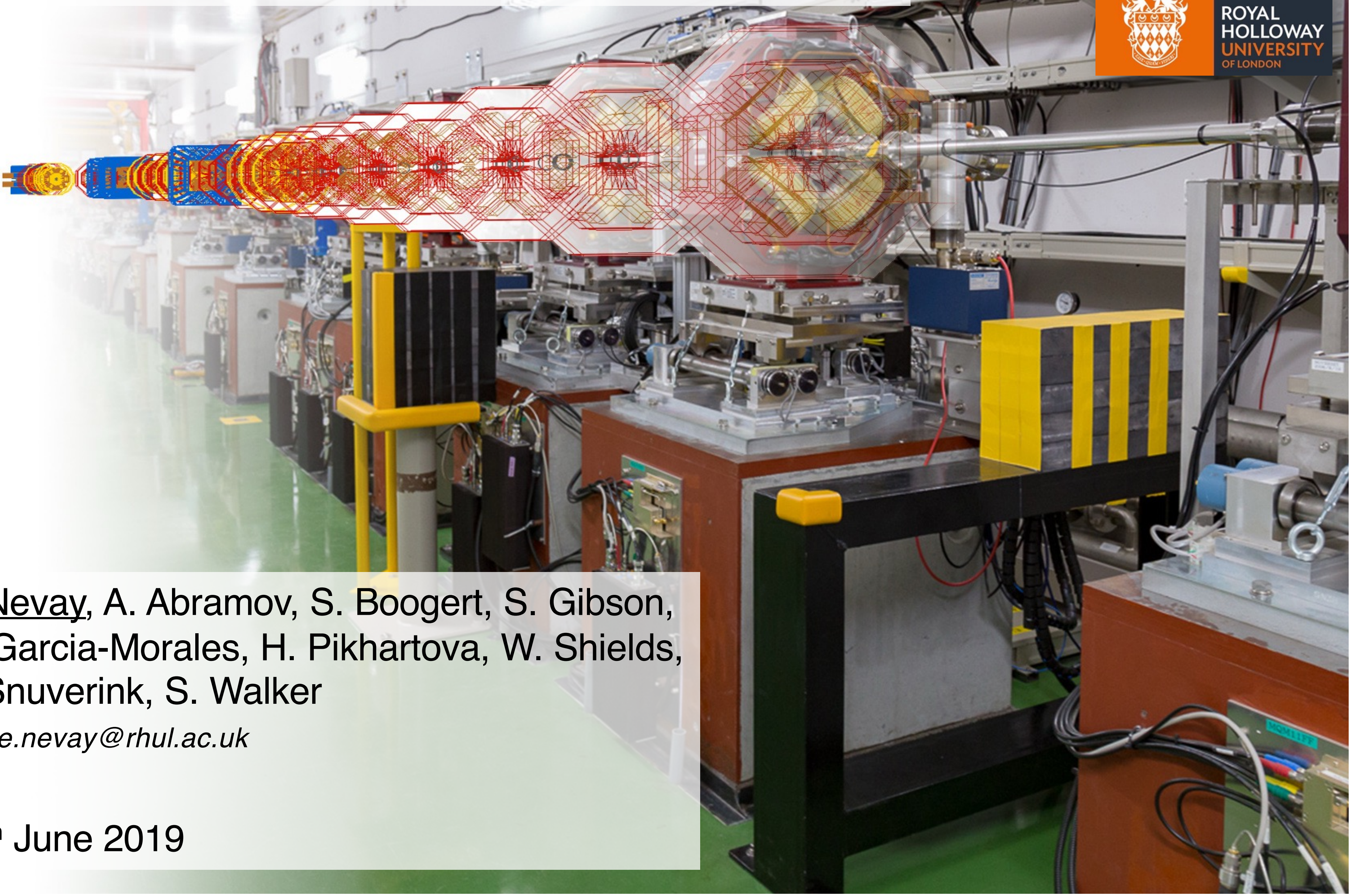
Mixed Accelerator and Particle Physics Simulations



L. Nevay, A. Abramov, S. Boogert, S. Gibson, H. Garcia-Morales, H. Pikhartova, W. Shields, J. Snuverink, S. Walker

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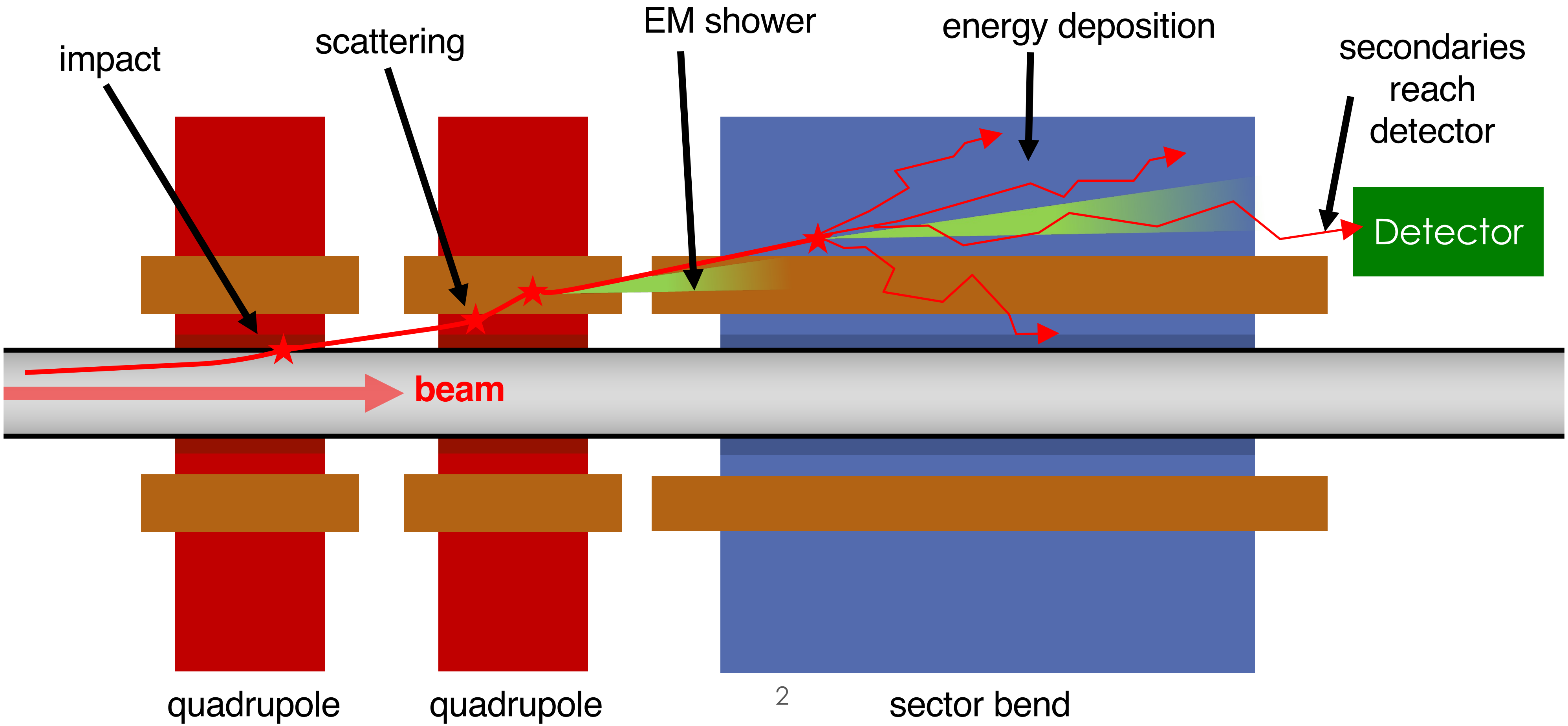
John Adams Institute for Accelerator Science

ROYAL HOLLOWAY UNIVERSITY OF LONDON

14th June 2019

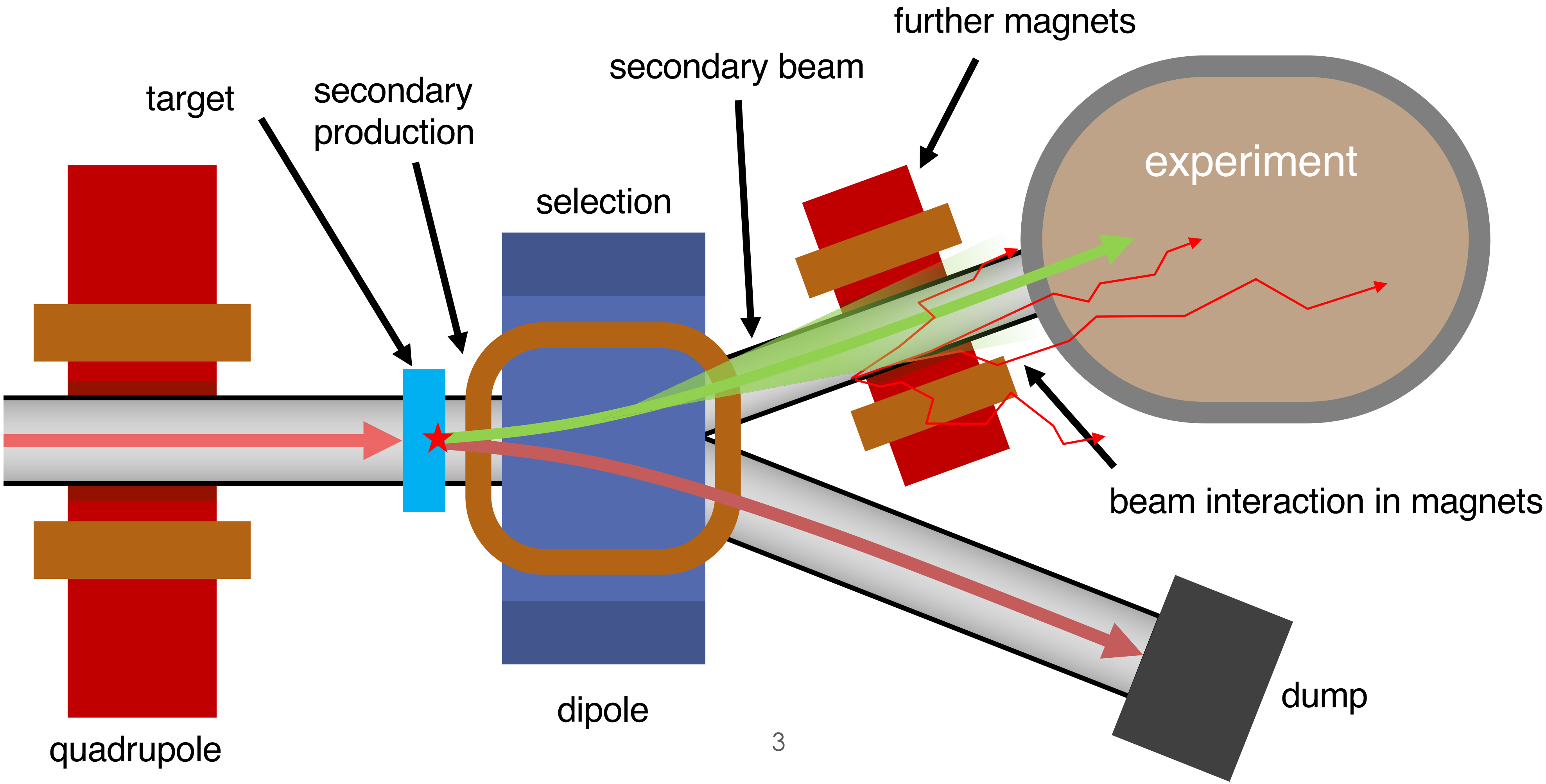
Beam Loss

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



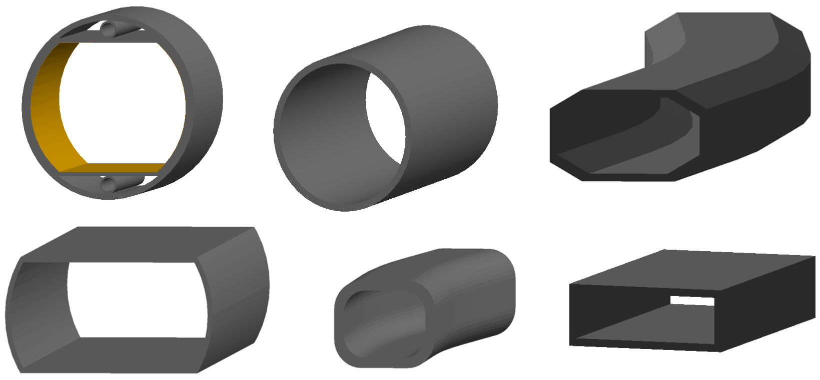
Secondary Beam

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

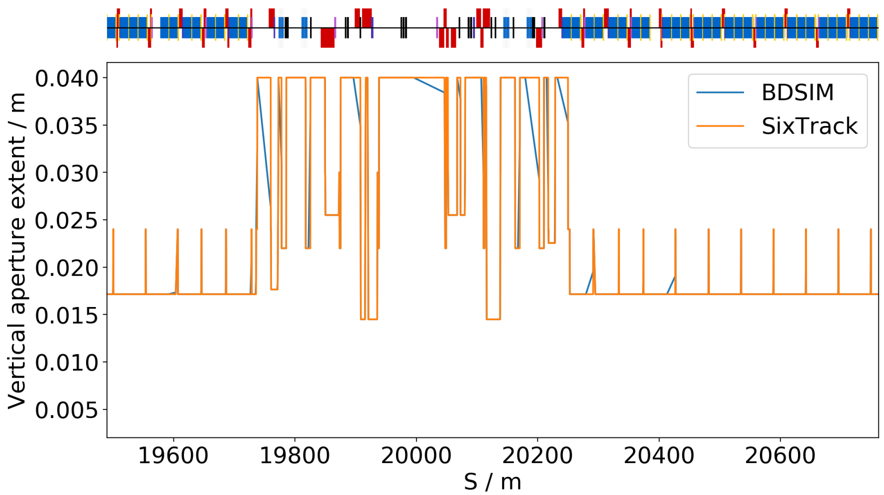


Tracking Losses

- 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



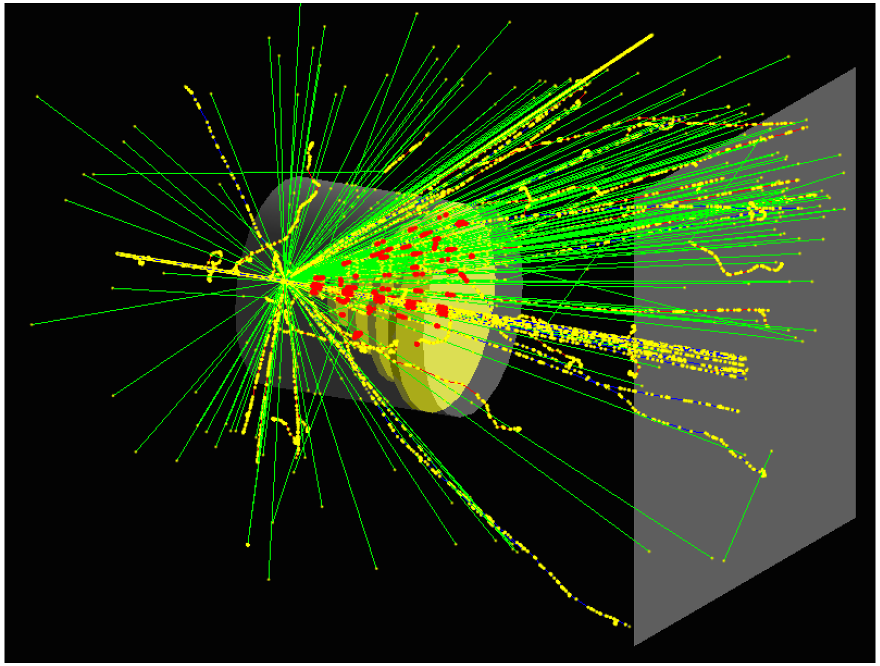
Different aperture shapes

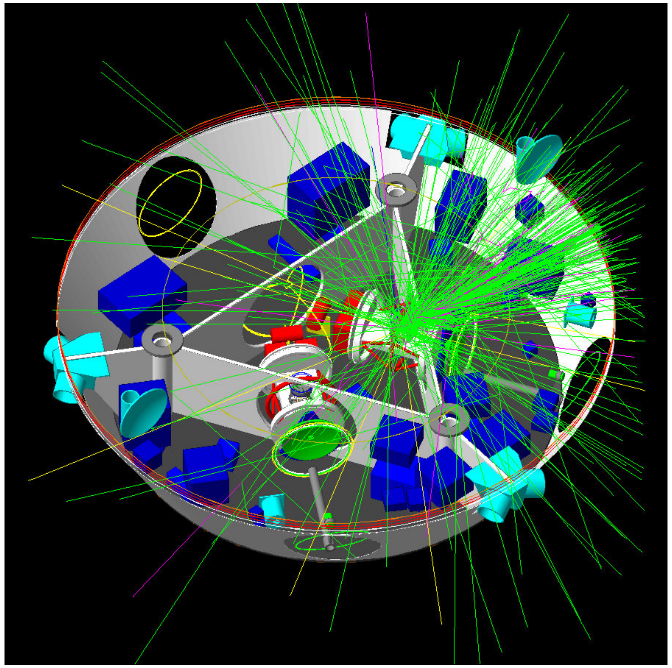


Vertical Aperture models compared.

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'



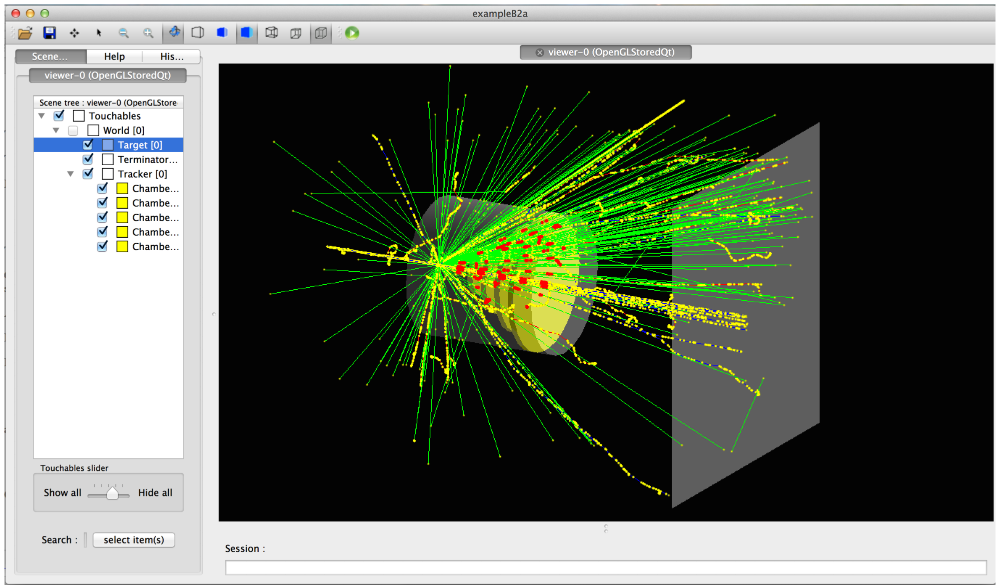


Which Physics Package?

- 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

http://geant4.web.cern.ch

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

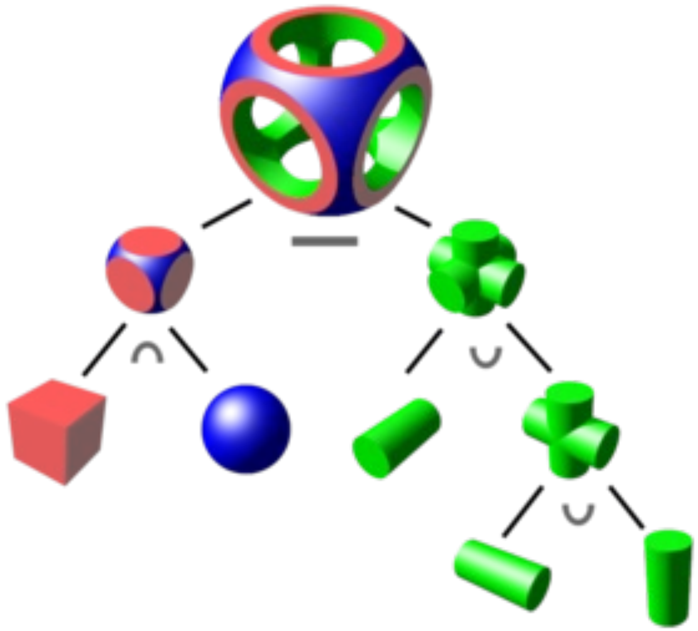


Geant4 example of proton hitting calorimeter

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

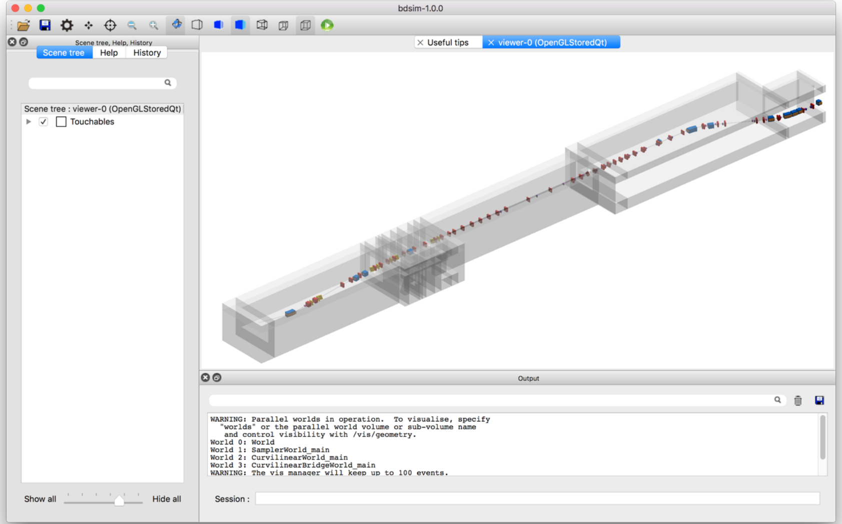


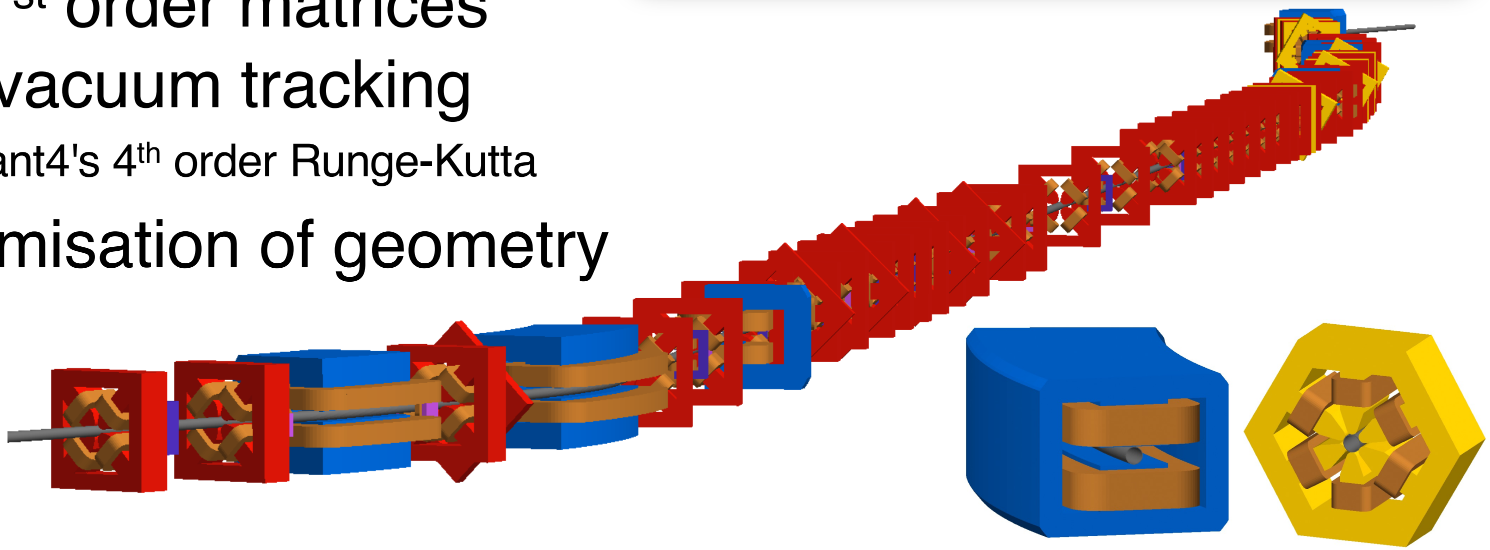
constructive solid geometry

- rarely do people therefore make such a model…

A Solution - BDSIM

- 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





Example Syntax

- "GMAD" - Geant4 + MAD

sm.gmad

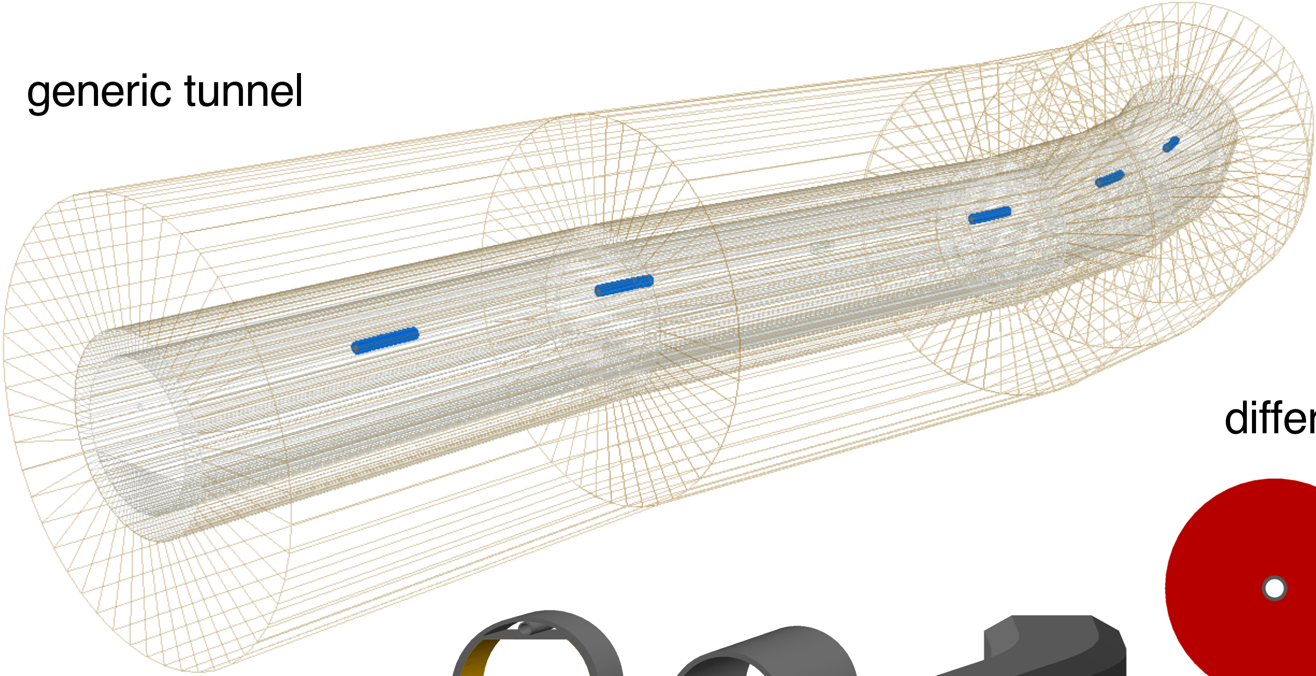
```
d1: drift, l=1*m;
q1: quadrupole, l=1*m, k1=1.3, magnetGeometryType="polesfacet";
c1: rcol, l=0.6*m, ysize=5*mm, xsize=5*mm, material="Copper", outerDiameter=10*cm;
s1: sbend, l=1*m, angle=0.10;

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;
```

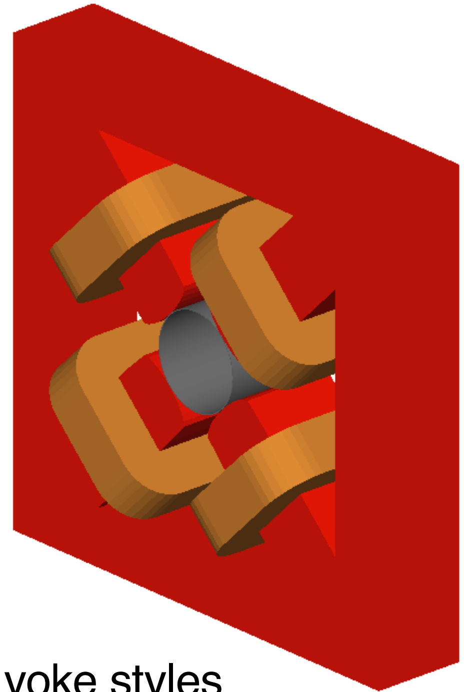
```
-:---  sm.gmad        All L3     Git:develop  (Fundamental)
Wrote /Users/nevay/physics/reps/bdsim/examples/simpleMachine/sm.gmad
```

Generic Geometry

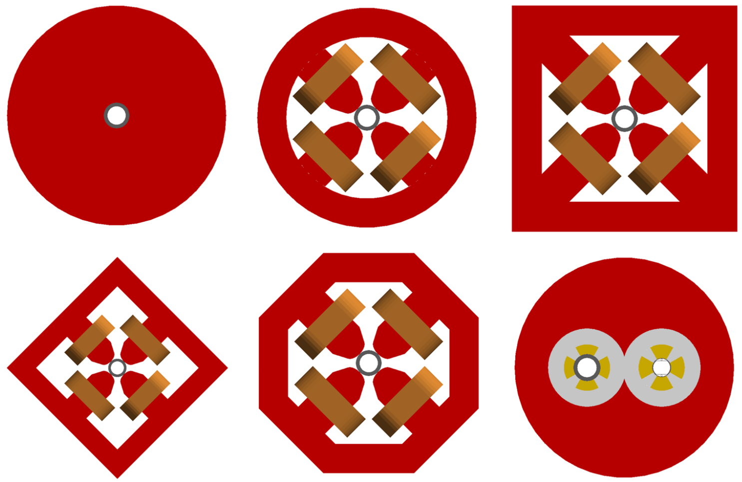
- Variety of styles for each component
  - coils included correctly even if magnet split
- Selection of generic tunnels included

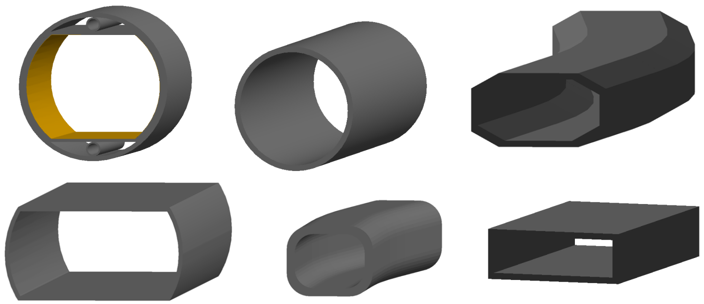
generic tunnel





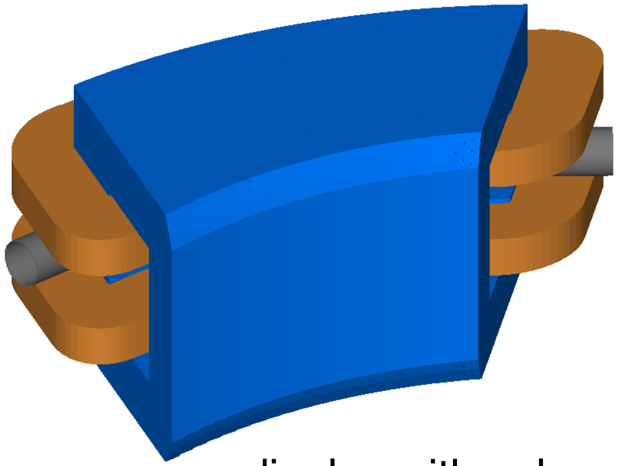
different yoke styles

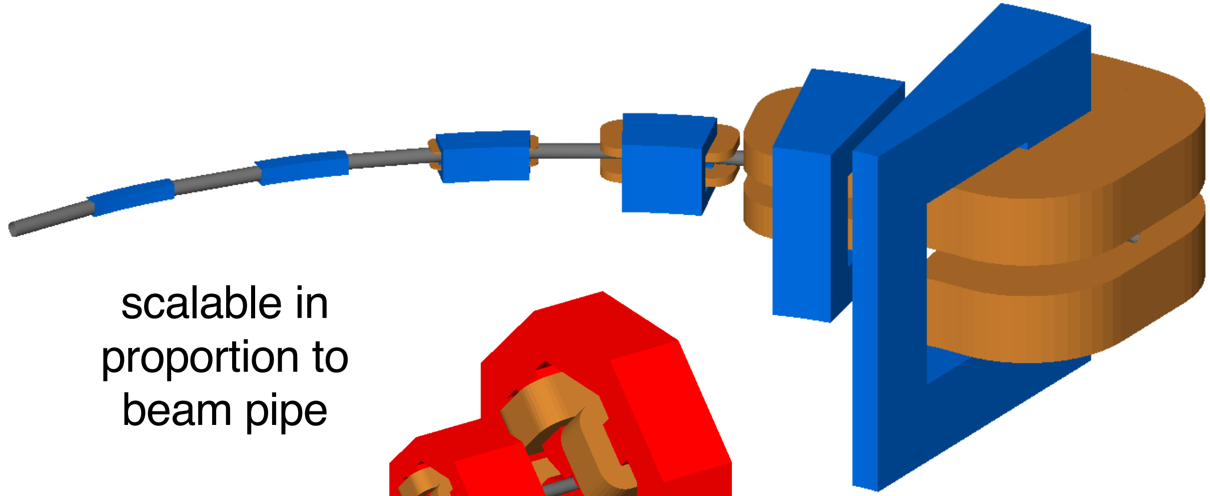




all common aperture
types available

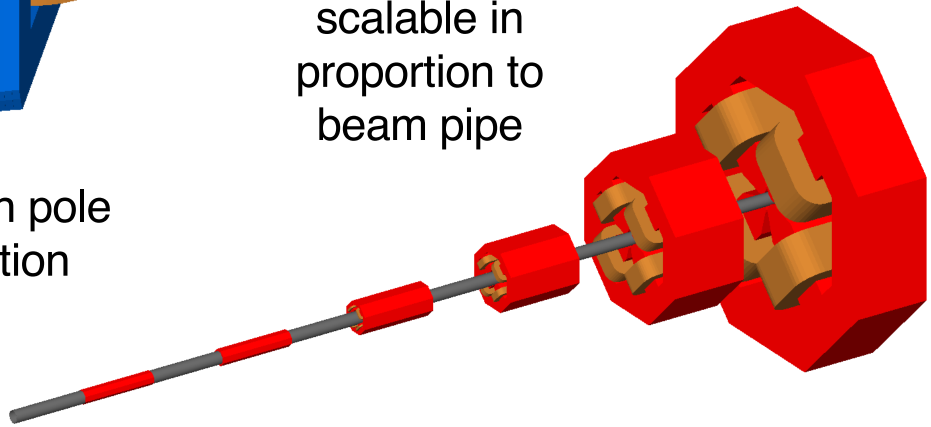
Scalable Geometry



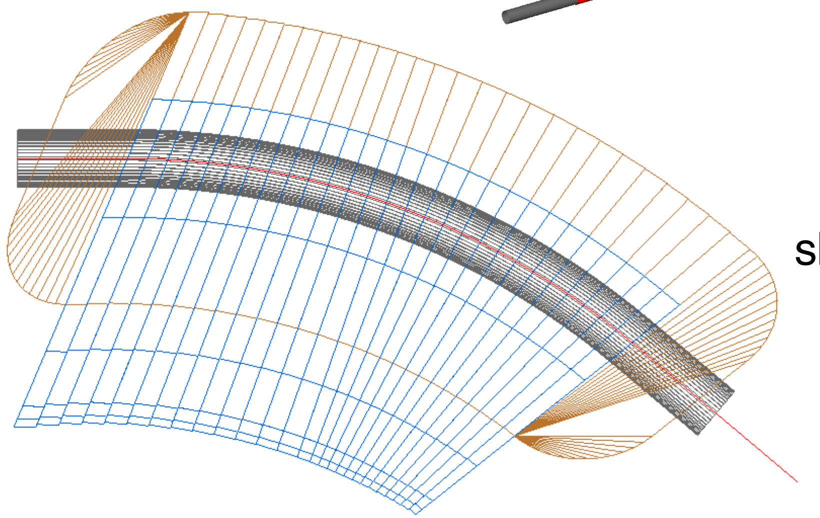


scalable in
proportion to
beam pipe

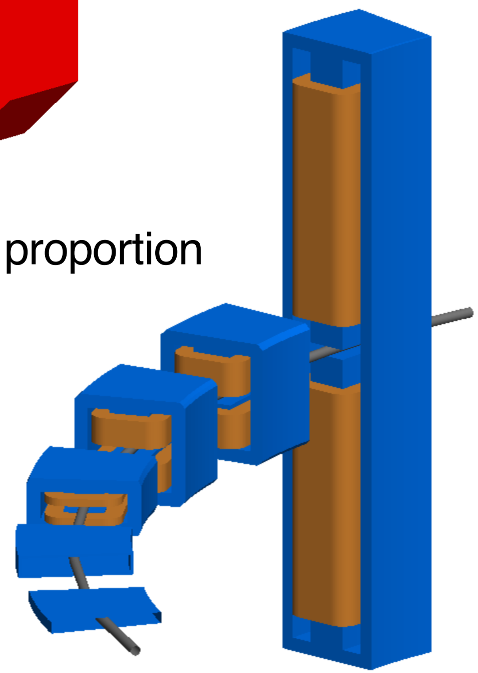
dipoles with pole
face rotation



scalable in proportion

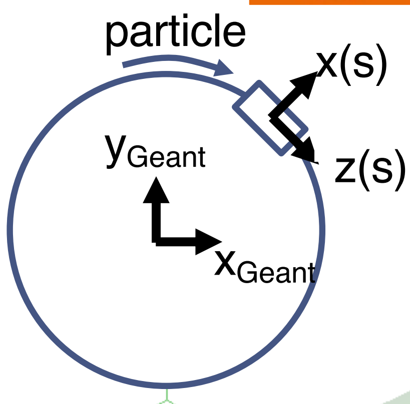


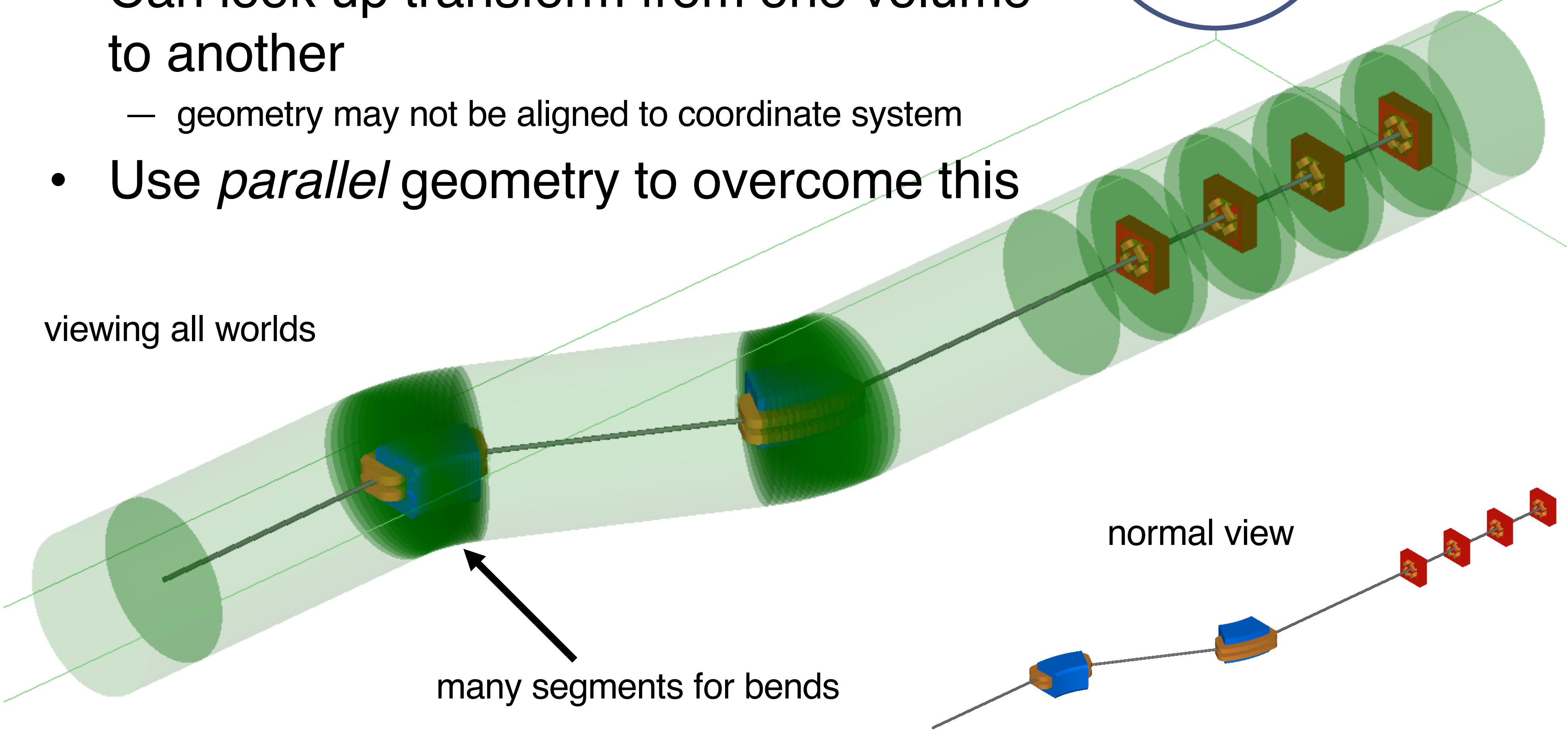
dipoles built in
slices to allow any
shape required



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



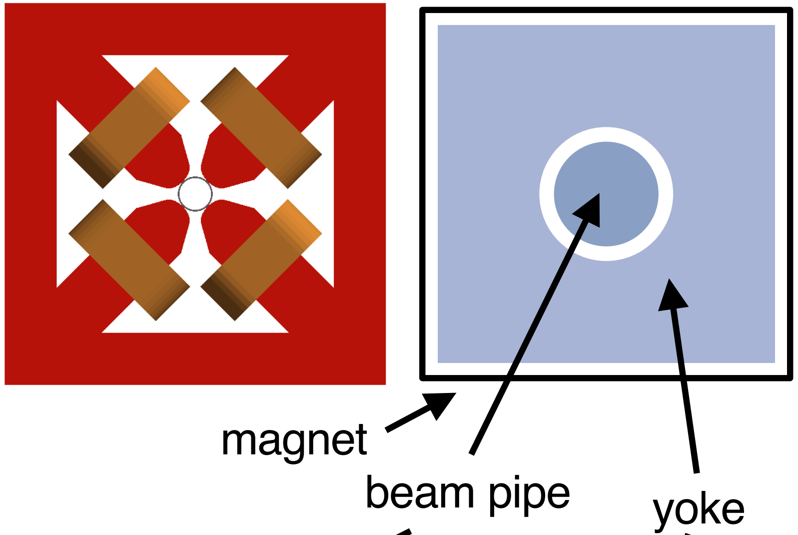


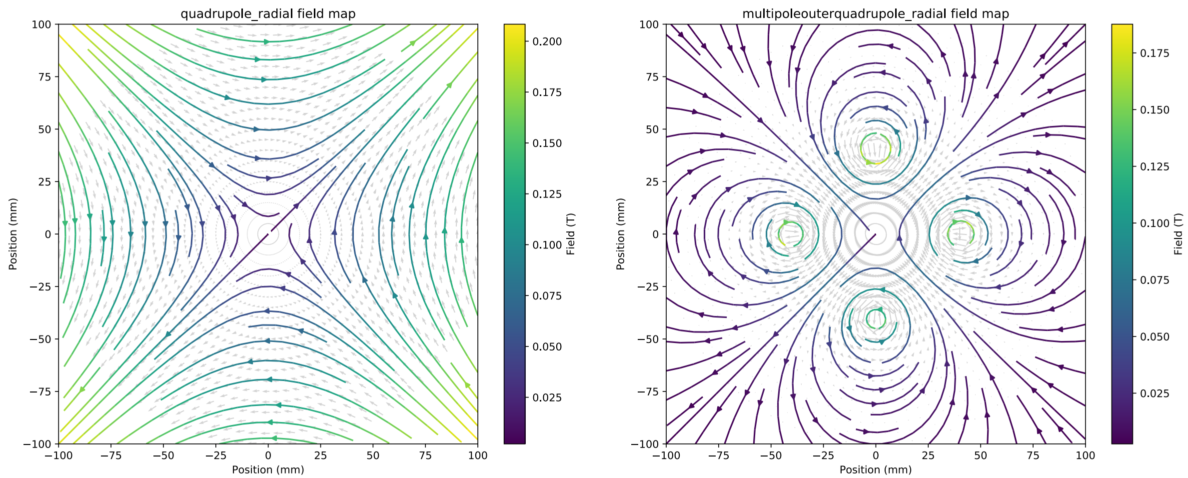
Tracking Implementation

- 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

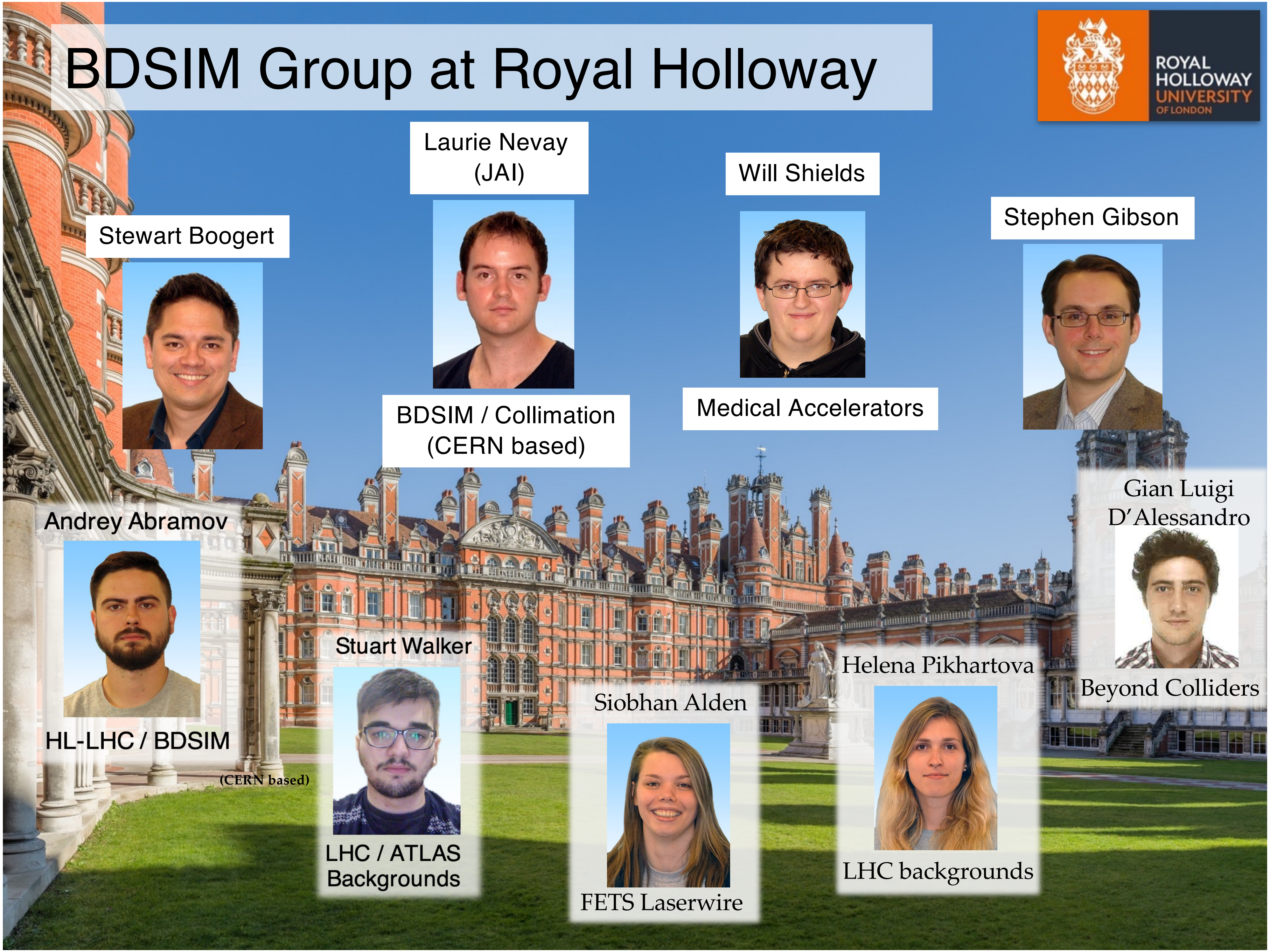
$$
\begin{aligned}
B_x &= \frac{\partial B_y}{\partial x} y \\
B_y &= \frac{\partial B_y}{\partial x} x \\
B_z &= 0
\end{aligned}
$$

quadrupole field example





Examples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ROYAL HOLLOWAY UNIVERSITY OF LONDON
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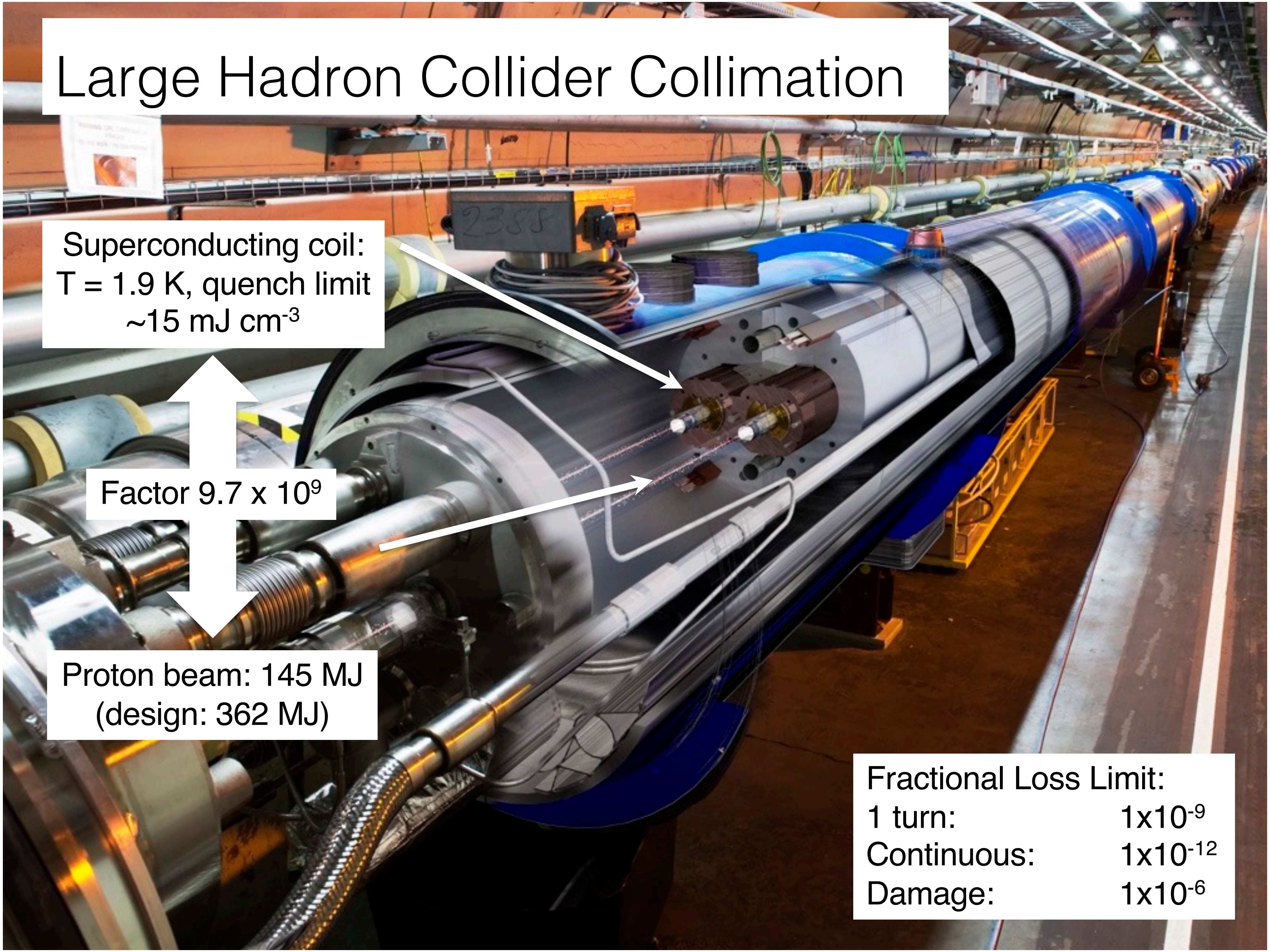
BDSIM / Collimation (CERN based)
Will Shields
Medical Accelerators
Stephen Gibson
Stewart Boogert
Andrey Abramov
HL-LHC / BDSIM
(CERN based)
Stuart Walker
LHC / ATLAS Backgrounds
Siobhan Alden
FETS Laserwire
Helena Pikhartova
LHC backgrounds
Gian Luigi D'Alessandro
Beyond Colliders

Currents Studies

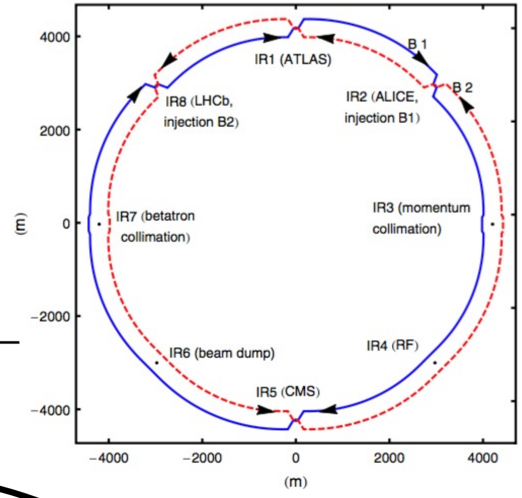
- LHC / HL-LHC Collimation, non-collision backgrounds, high power beam failure scenarios
- IBA & ULB proton therapy gantries
- PSI Isotope Production Line
- CCAP (medical) at Imperial College London
- Clatterbridge Occular Proton Therapy Line (UCL / Liverpool)
- AWAKE Plasma Accelerator Spectrometer (CERN / UCL)
- Gamma Factory at CERN
- FASER experiment at CERN
- DESY XFEL undulator dose
- KLEVER Beyond Collider experiment at CERN

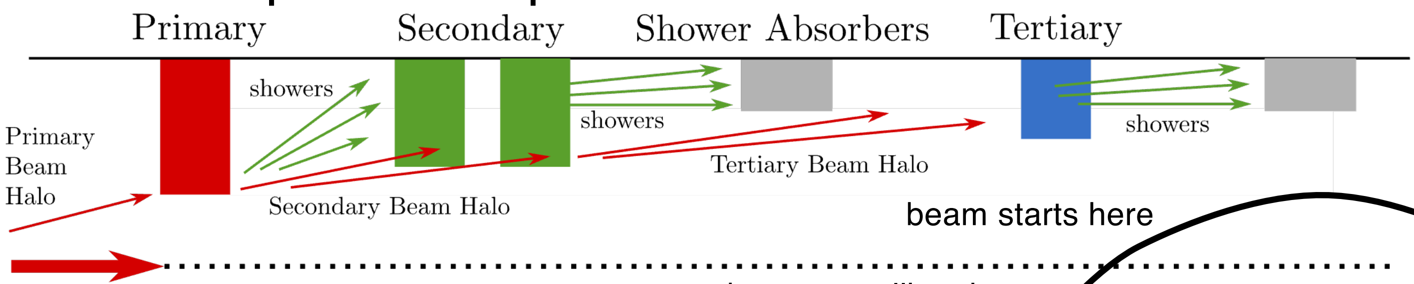
Large Hadron Collider Collimation

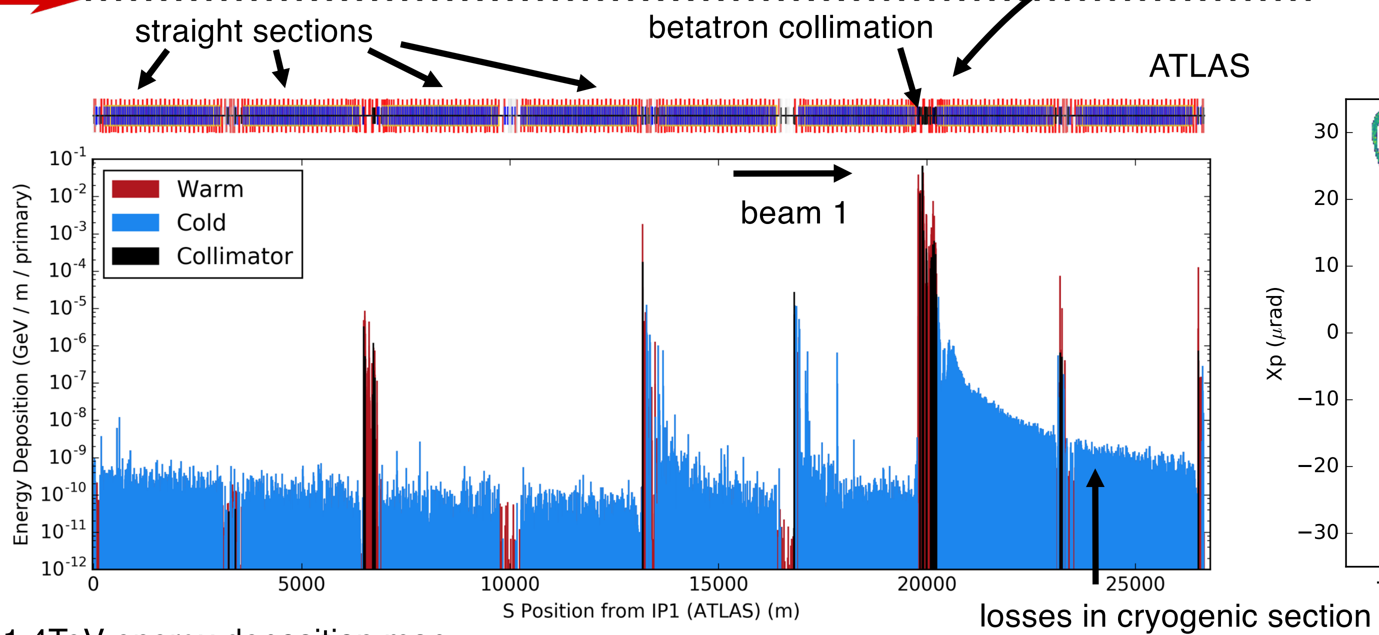


LHC Collimation

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

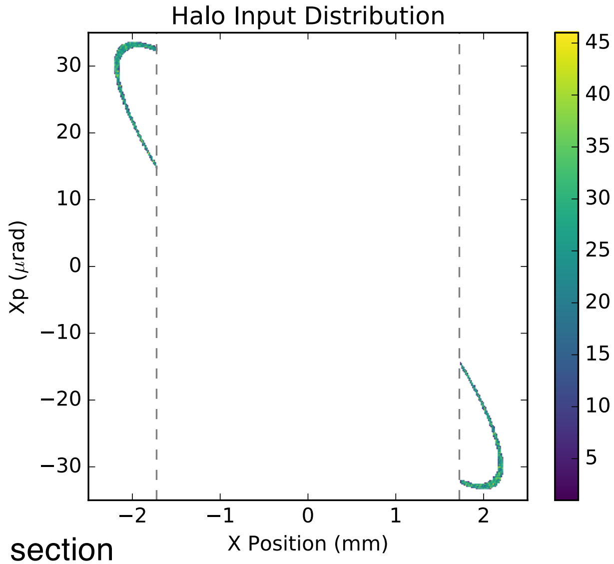






B1 4TeV energy deposition map

Example halo distribution



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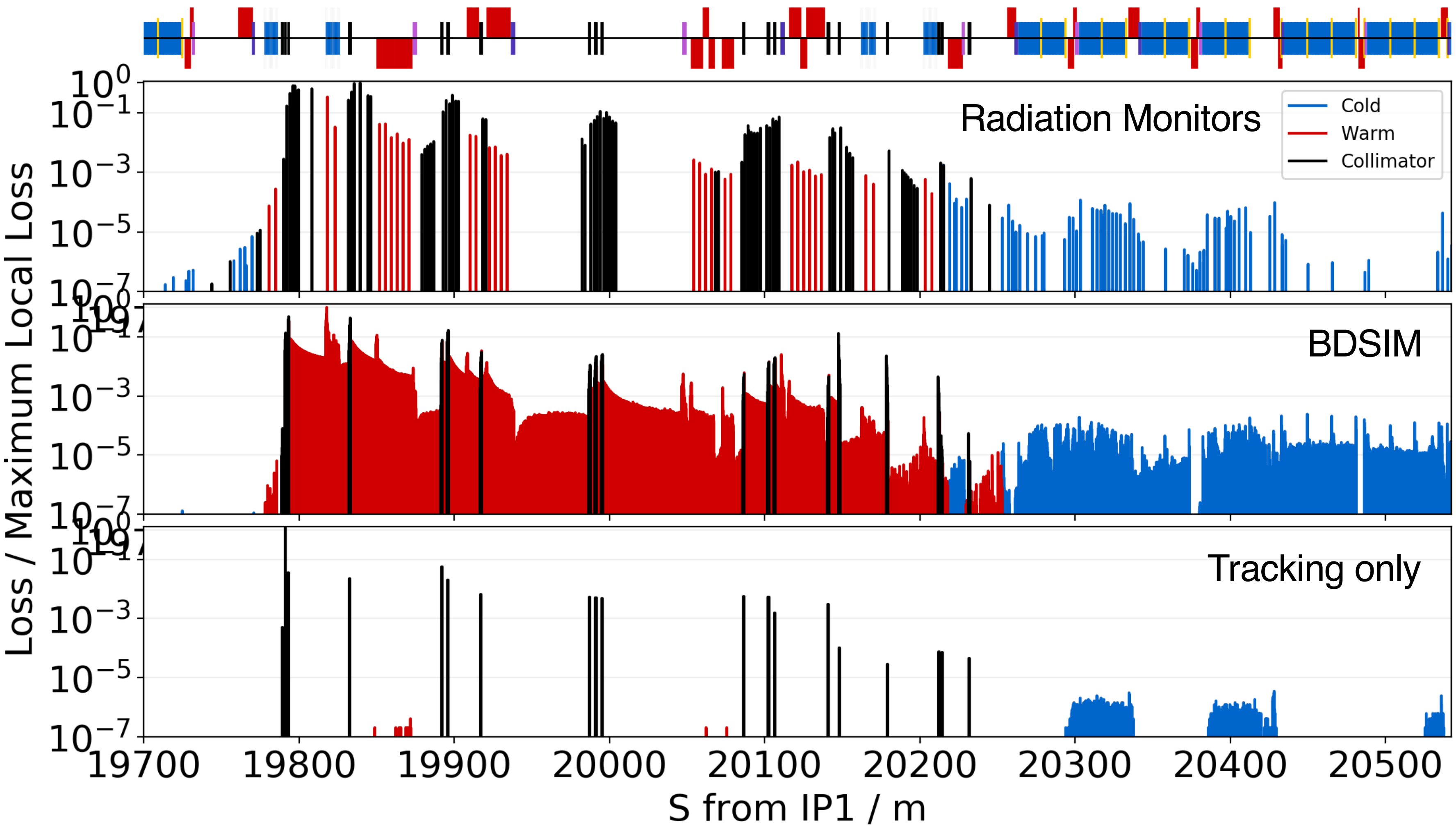
LHC Comparison



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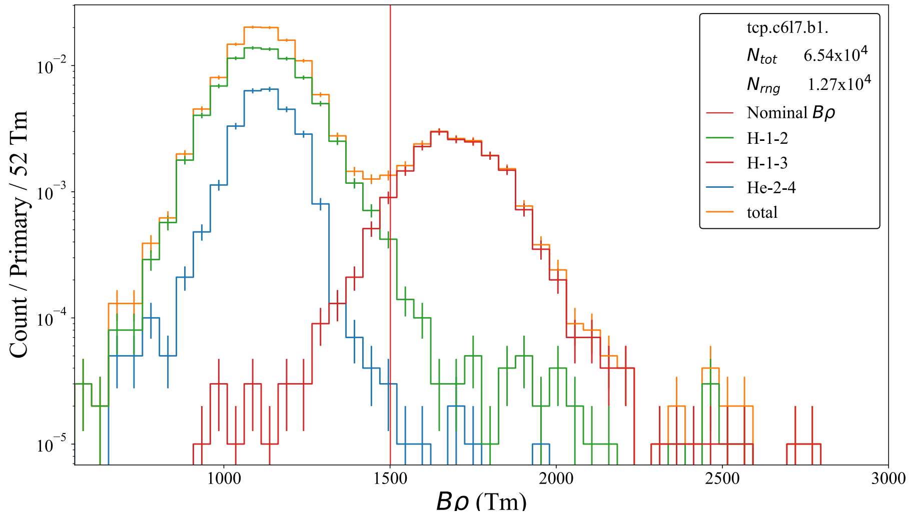
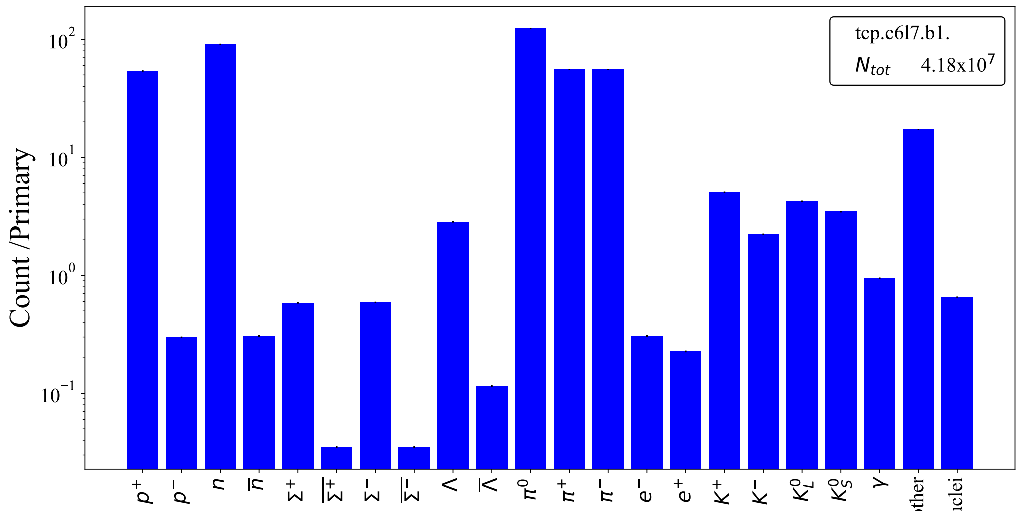
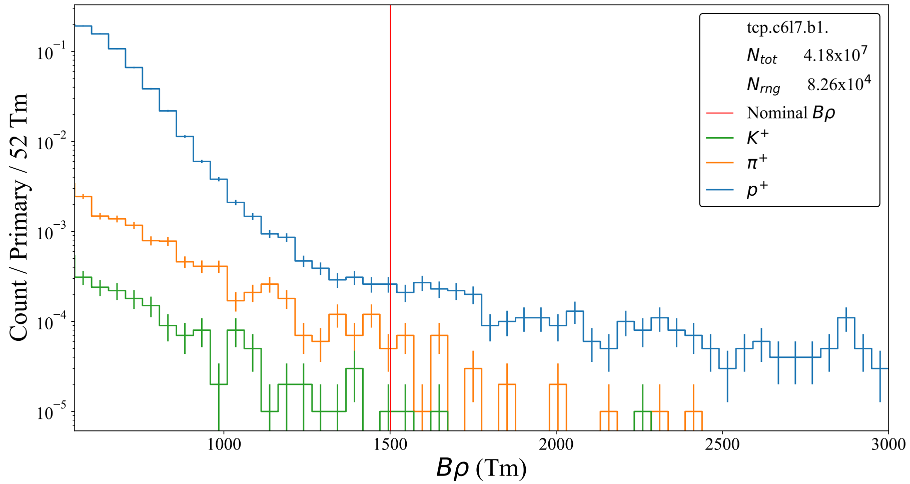
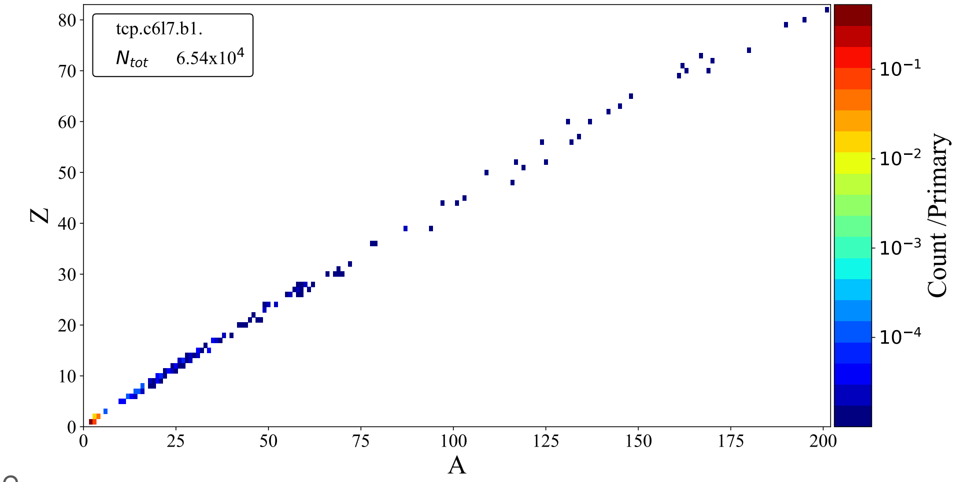
LHC Ion Collimation

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





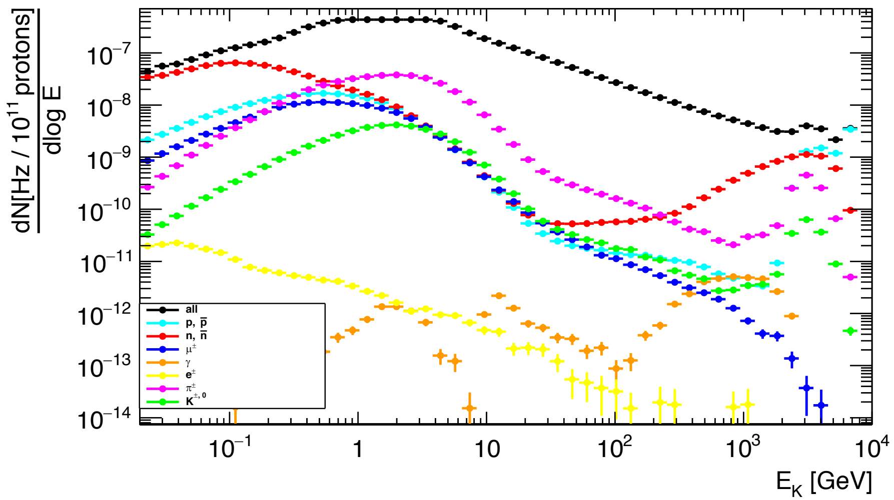


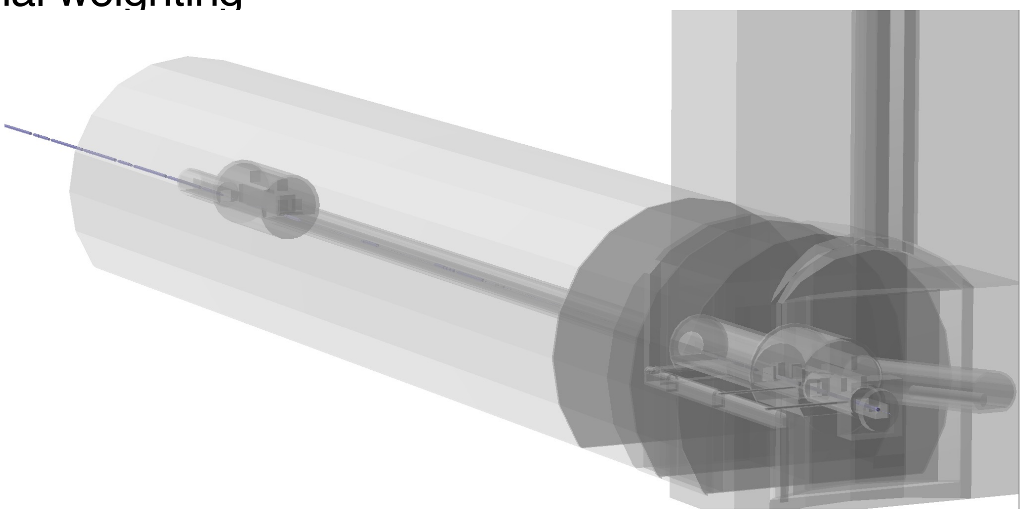


A. Abramov

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





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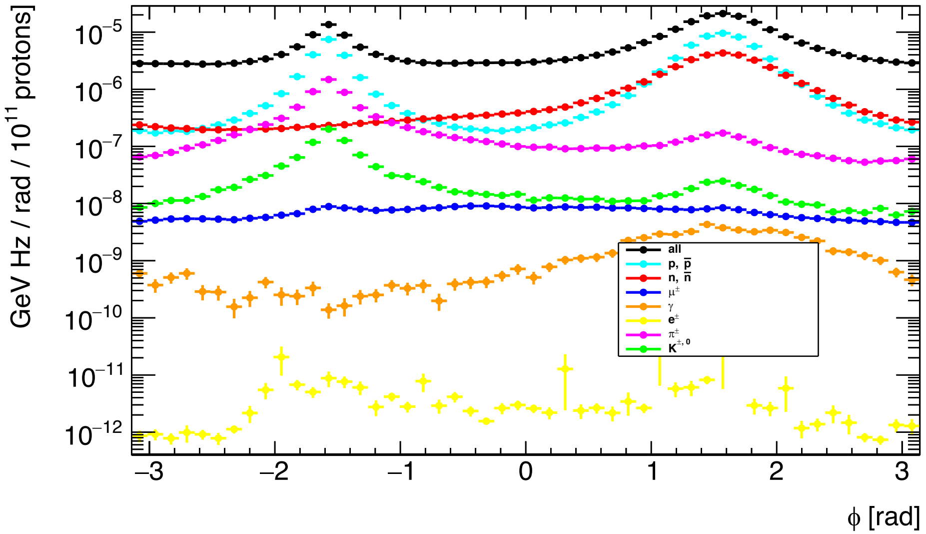
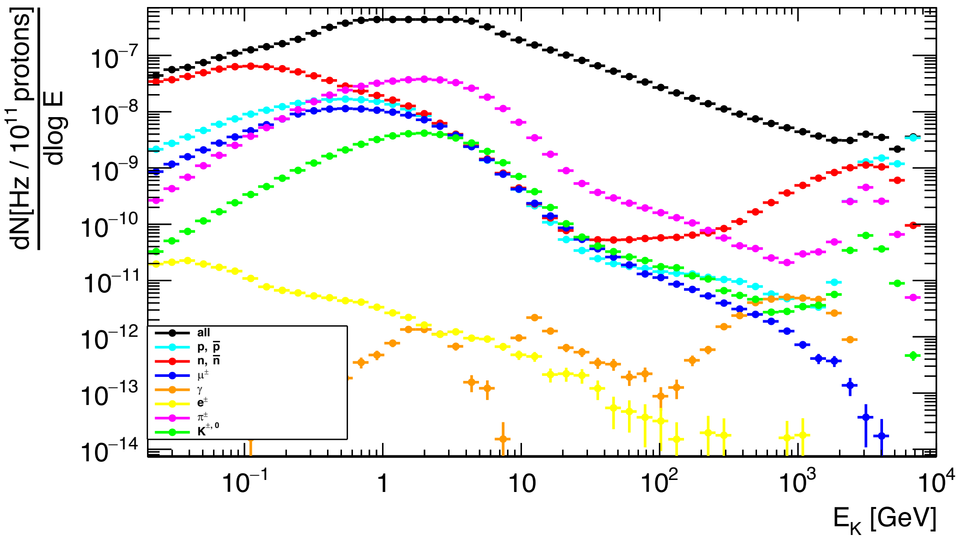
LHC Non-Collision Backgrounds II

Azimuthal rate for different species

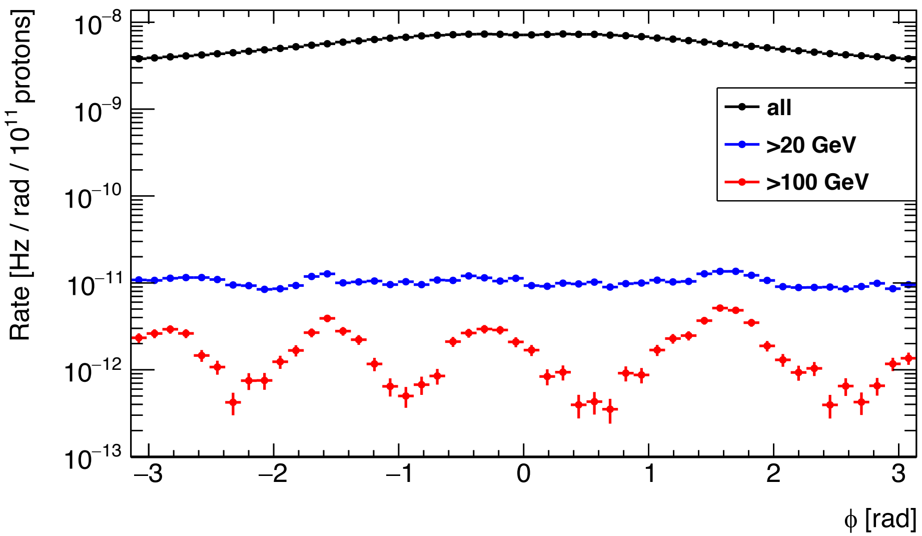


- Particles recorded at 'interface plane'
  - start of detector cavern
- Transferred to dedicated ATLAS simulation



Overall particle spectra at interface plane

Azimuthal rate for different muon energies



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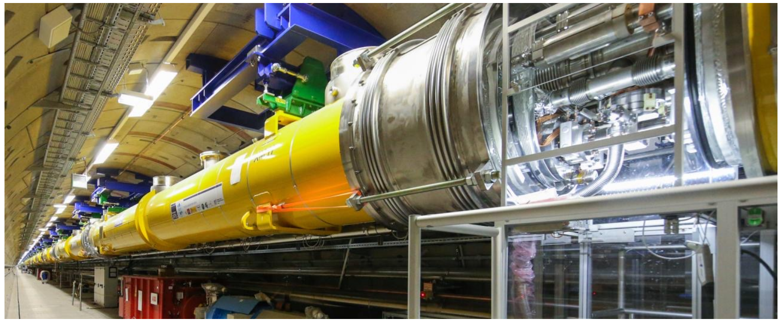
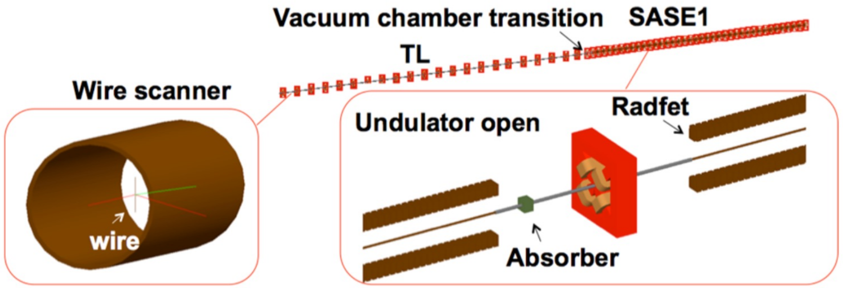
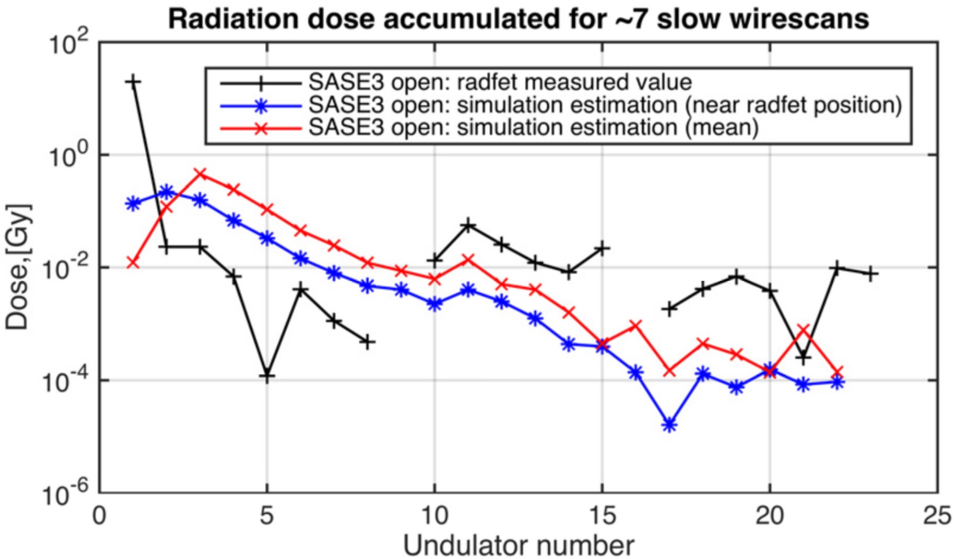
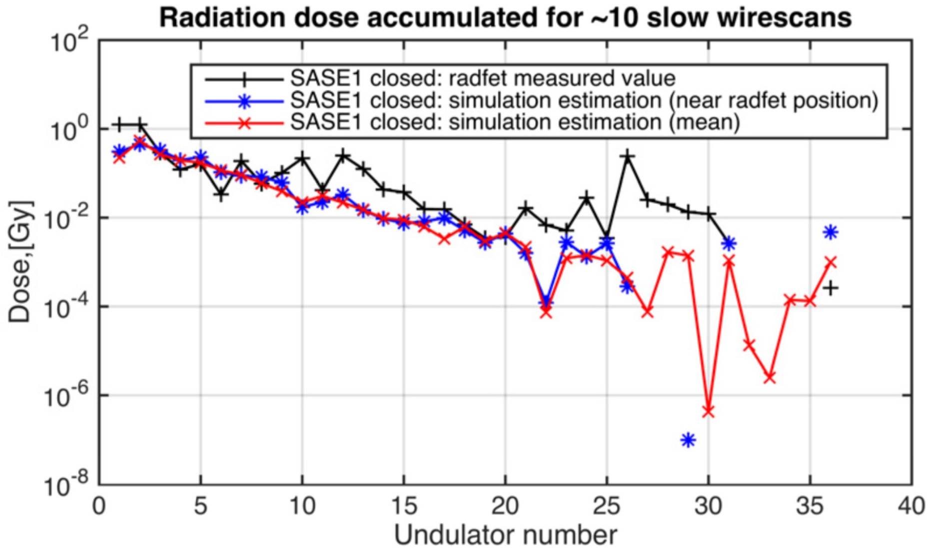
DESY XFEL Undulator Dose

- 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







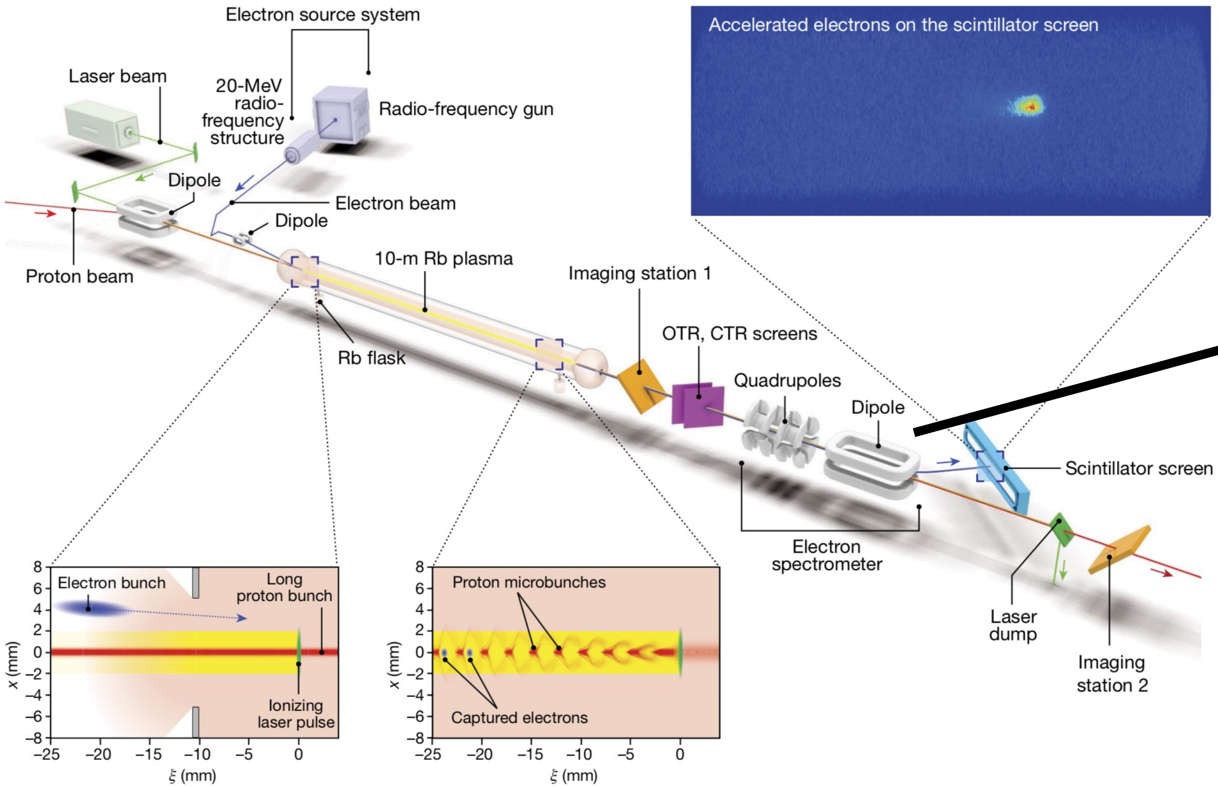


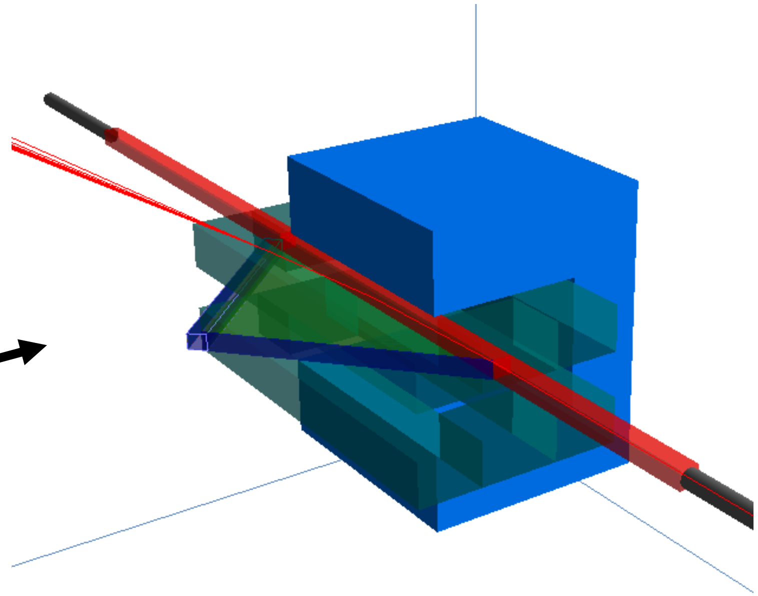
https://doi.org/10.18429/JACoW-IPAC2018-THPMF022

S. Liu, I. Agapov at DESY

AWAKE Dipole Spectrometer

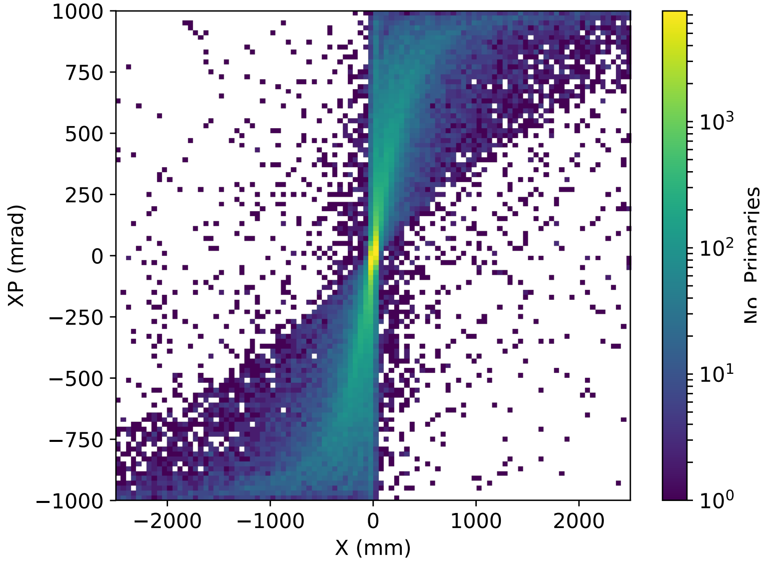
- Proton driven plasma wakefield accelerator at CERN
- Simulate electrons through dipole spectrometer
  - field map for detailed motion
  - physics required for synchrotron radiation, scattering and screen interaction
- Recently used for the calibration of the dipole
- https://www.nature.com/articles/s41586-018-0485-4



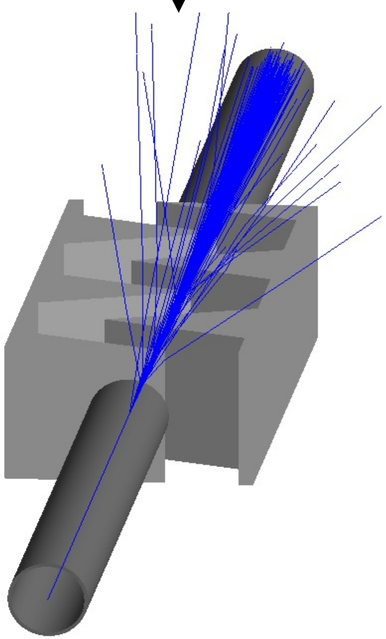


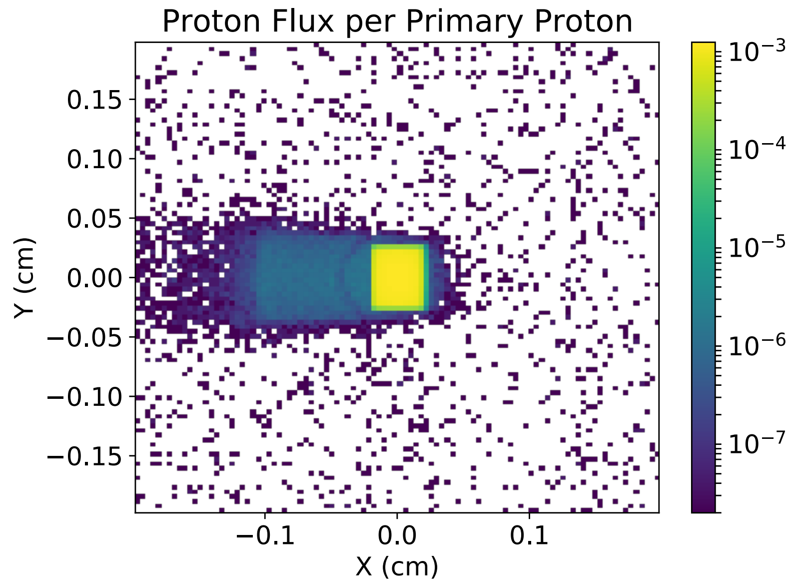
Hadron Therapy

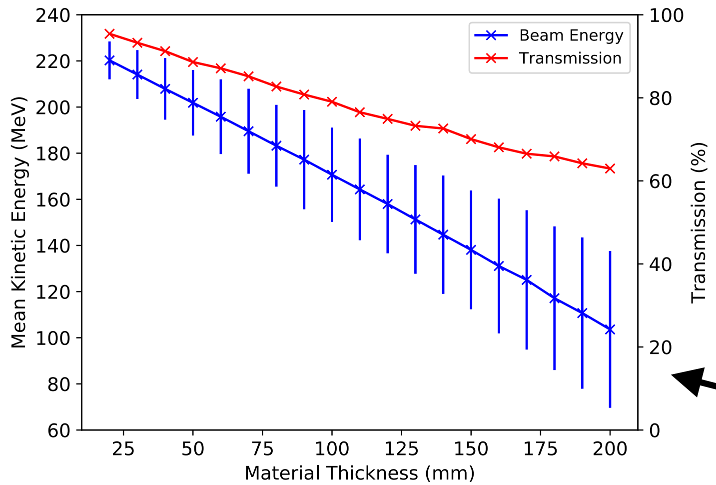
- Recent application to low energy medical facilities



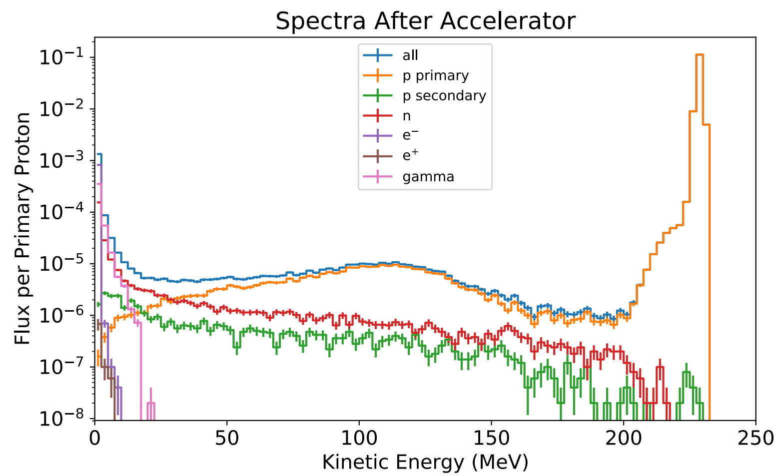
energy degrader







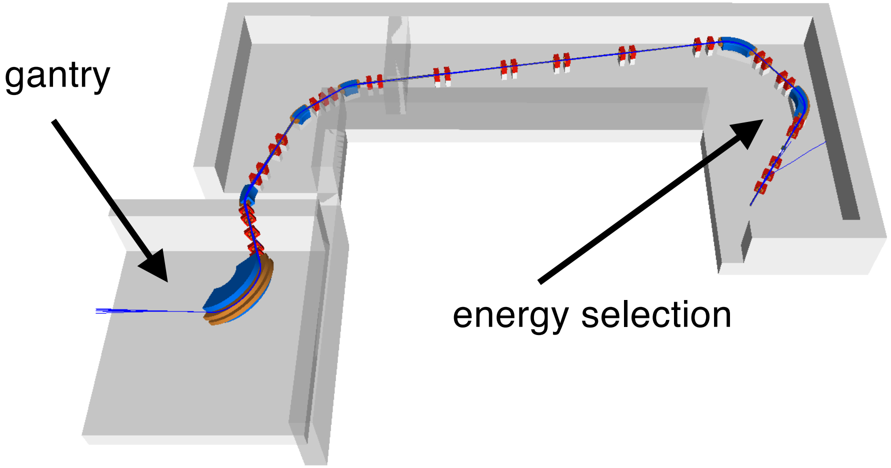
transmission and energy spread

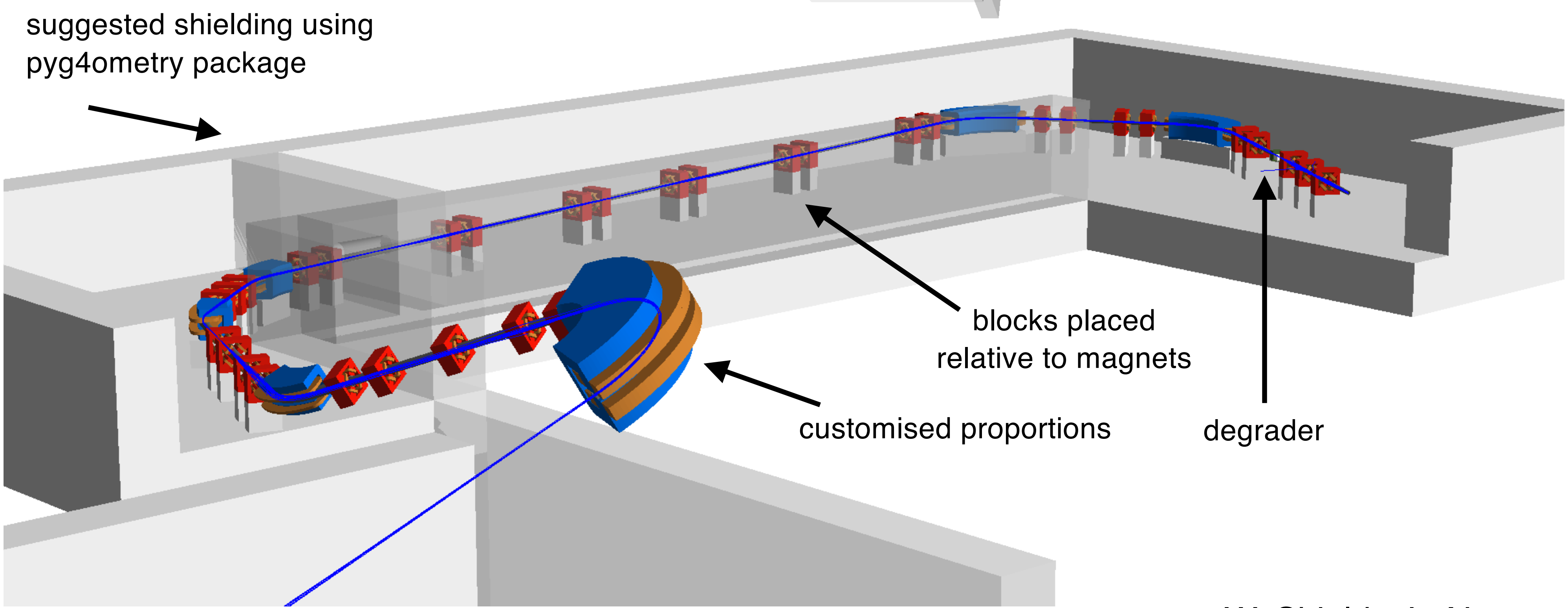


L. Nevay, W. Shields

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

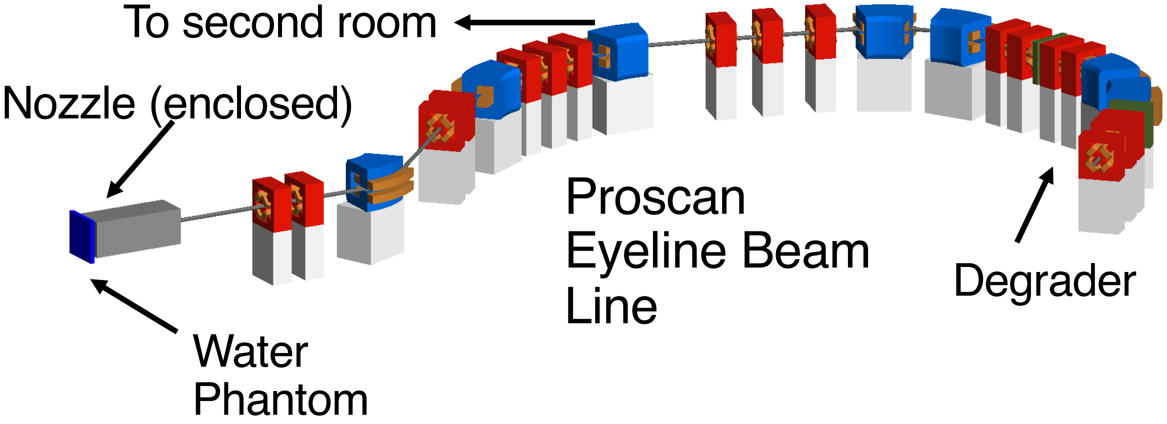


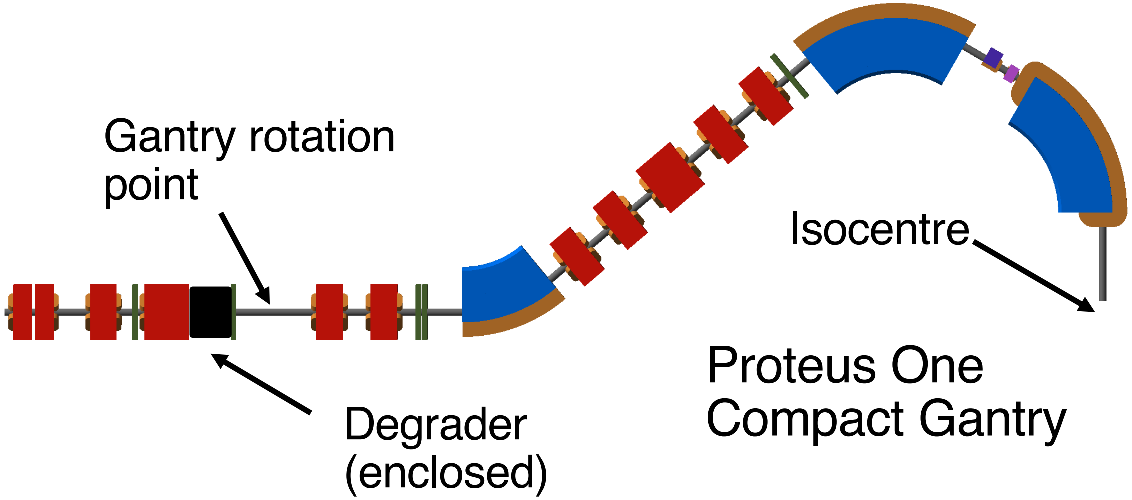


W. Shields, L. Nevay

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.

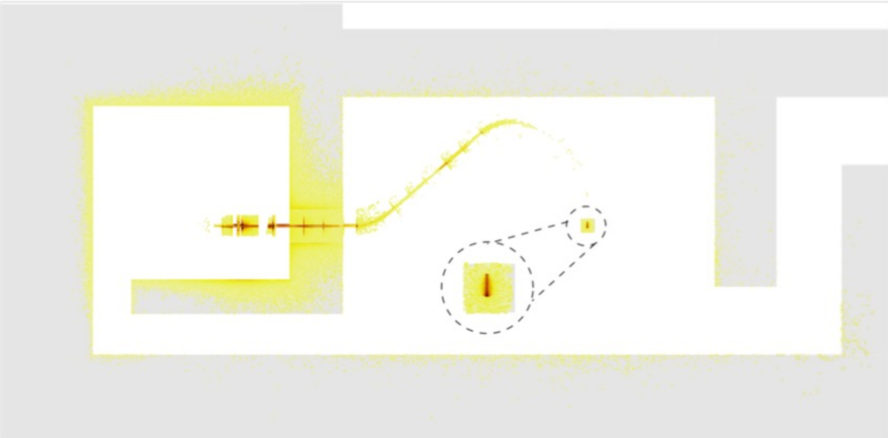




W. Shields. E. Gnacadja, R. Tesse, C. Hernalsteens

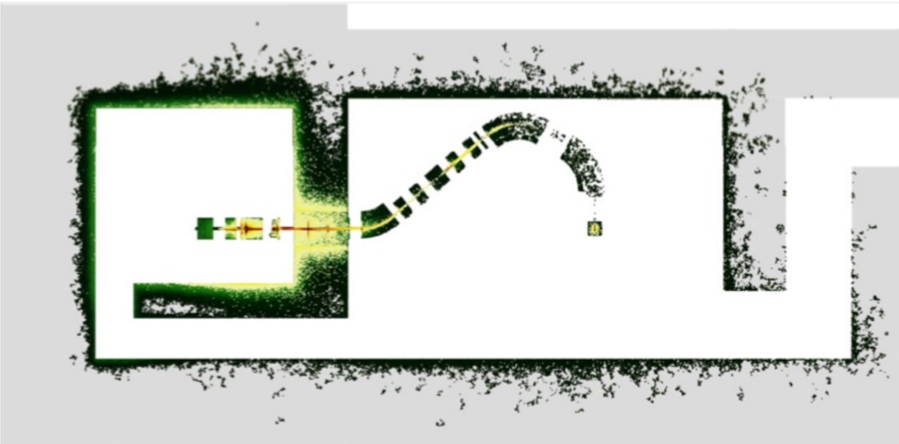
Shielding Activation Studies

Proton interactions

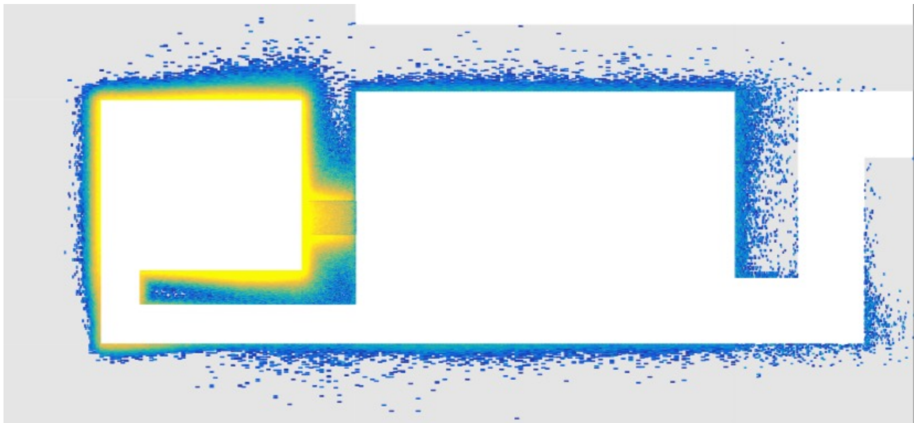


- Calculate shielding activation rate from spallation and neutron capture.

Protons & Neutron interactions

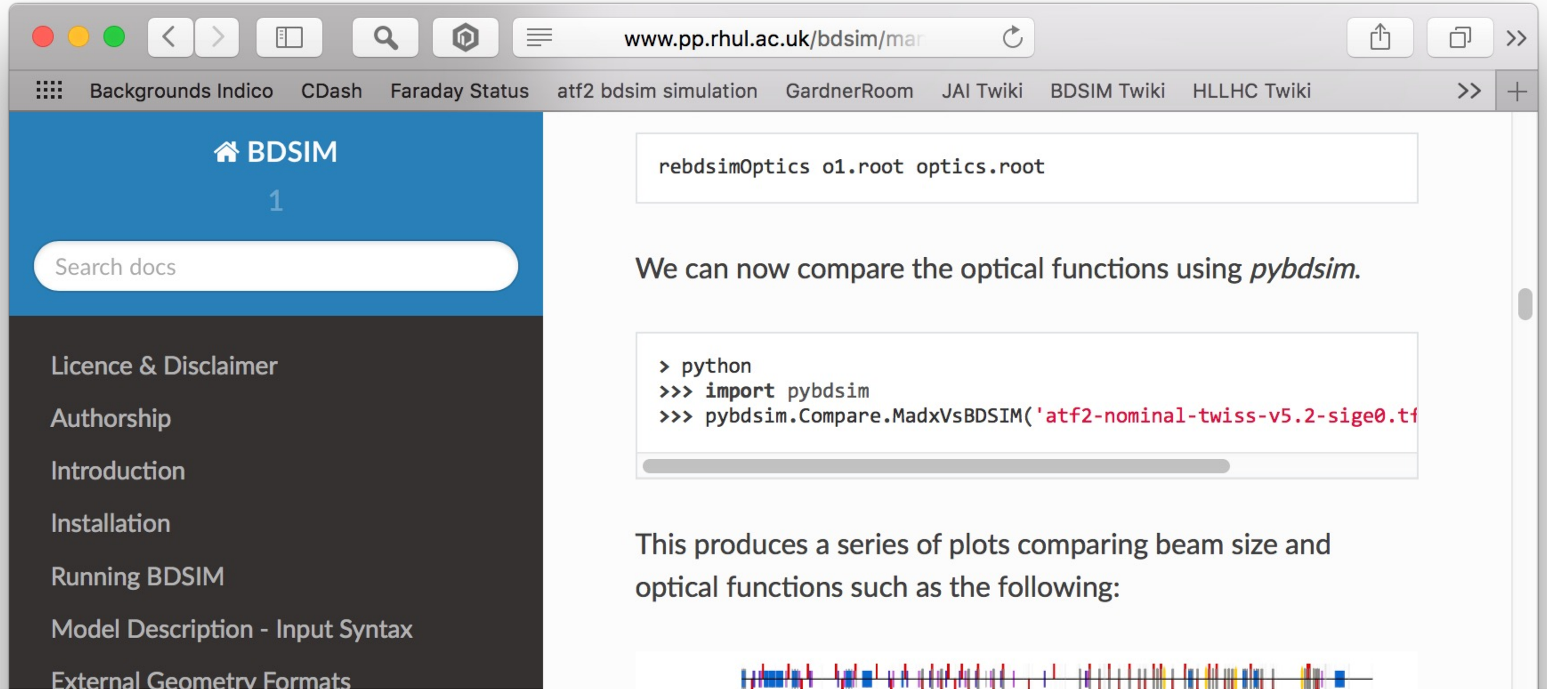


Shielding only



Links

- paper: [*https://arxiv.org/abs/1808.10745*](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

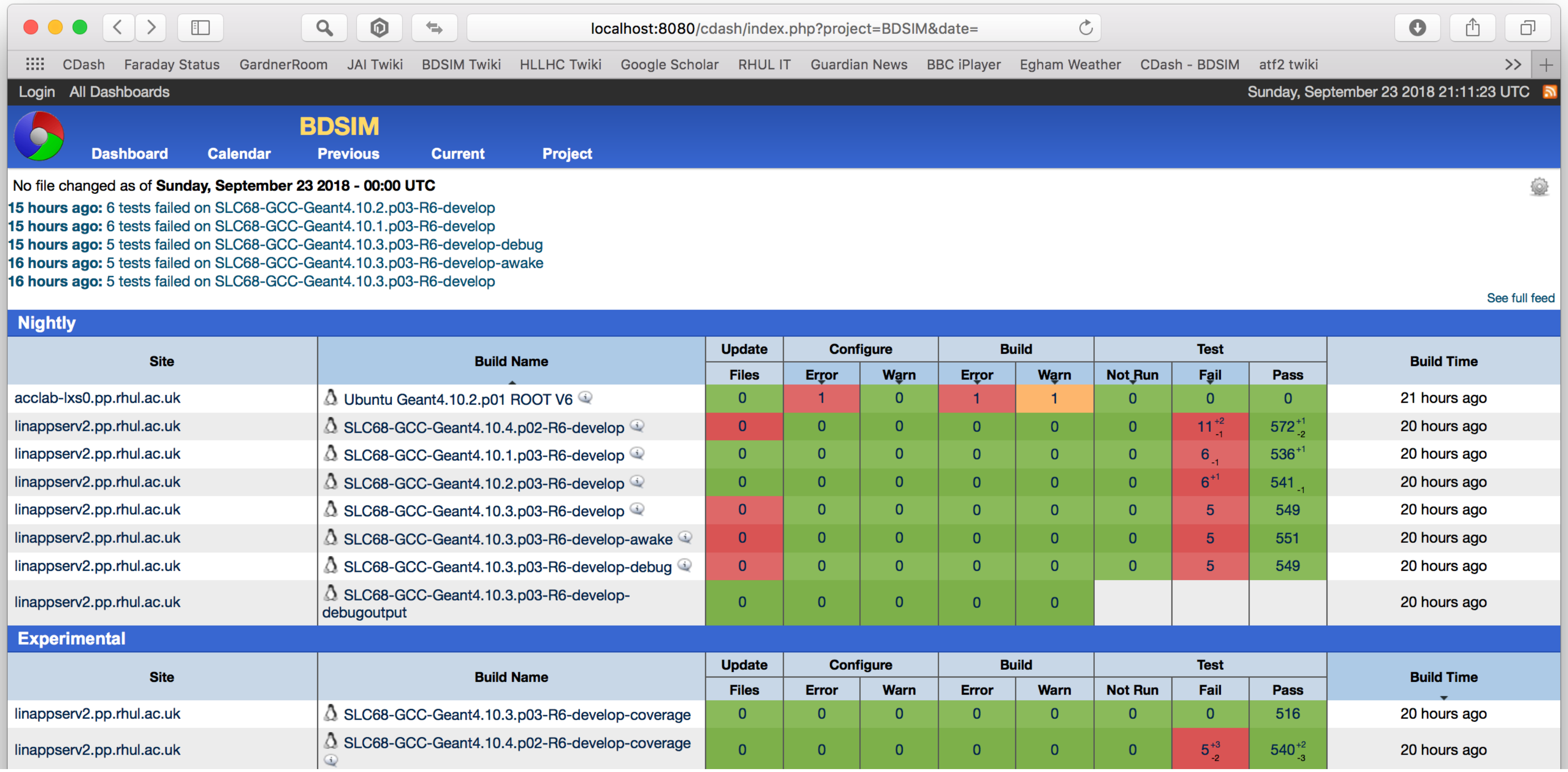


Collaborative Development

- Public git repository
- ~ 70k lines of open source C++ under GPL3
- Public issue tracker
  - https://bitbucket.org/jairhul/bdsim/issues
  - also for feature requests
- Complete Doxygen documentation for C++
  - http://www.pp.rhul.ac.uk/bdsim/doxygen/
- Detailed manual regularly updated
  - http://www.pp.rhul.ac.uk/bdsim/manual/
  - html & pdf

Quality & Testing

- Open source C++ software in git repository
  - https://bitbucket.org/jairhul/bdsim/wiki/Home
- Nightly testing of ~ 680 tests
  - 6 builds, SLC6 & CC7
  - > 90% code coverage
  - regression testing



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acclab-lxs0.pp.rhul.ac.uk	Ubuntu Geant4.10.2.p01 ROOT V6	0	1	0	1	1	0	0	0	21 hours ago
linappserv2.pp.rhul.ac.uk	SLC68-GCC-Geant4.10.4.p02-R6-develop	0	0	0	0	0	0	11^{+2}_{-1}	572^{+1}_{-2}	20 hours ago
linappserv2.pp.rhul.ac.uk	SLC68-GCC-Geant4.10.1.p03-R6-develop	0	0	0	0	0	0	6_{-1}	536^{+1}	20 hours ago
linappserv2.pp.rhul.ac.uk	SLC68-GCC-Geant4.10.2.p03-R6-develop	0	0	0	0	0	0	6^{+1}	541_{-1}	20 hours ago
linappserv2.pp.rhul.ac.uk	SLC68-GCC-Geant4.10.3.p03-R6-develop	0	0	0	0	0	0	5	549	20 hours ago
linappserv2.pp.rhul.ac.uk	SLC68-GCC-Geant4.10.3.p03-R6-develop-awake	0	0	0	0	0	0	5	551	20 hours ago
linappserv2.pp.rhul.ac.uk	SLC68-GCC-Geant4.10.3.p03-R6-develop-debug	0	0	0	0	0	0	5	549	20 hours ago
linappserv2.pp.rhul.ac.uk	SLC68-GCC-Geant4.10.3.p03-R6-develop-debugoutput	0	0	0	0	0				20 hours ago

Experimental

Site	Build Name	Update Files	Configure Error	Configure Warn	Build Error	Build Warn	Test Not Run	Test Fail	Test Pass	Build Time
linappserv2.pp.rhul.ac.uk	SLC68-GCC-Geant4.10.3.p03-R6-develop-coverage	0	0	0	0	0	0	0	516	20 hours ago
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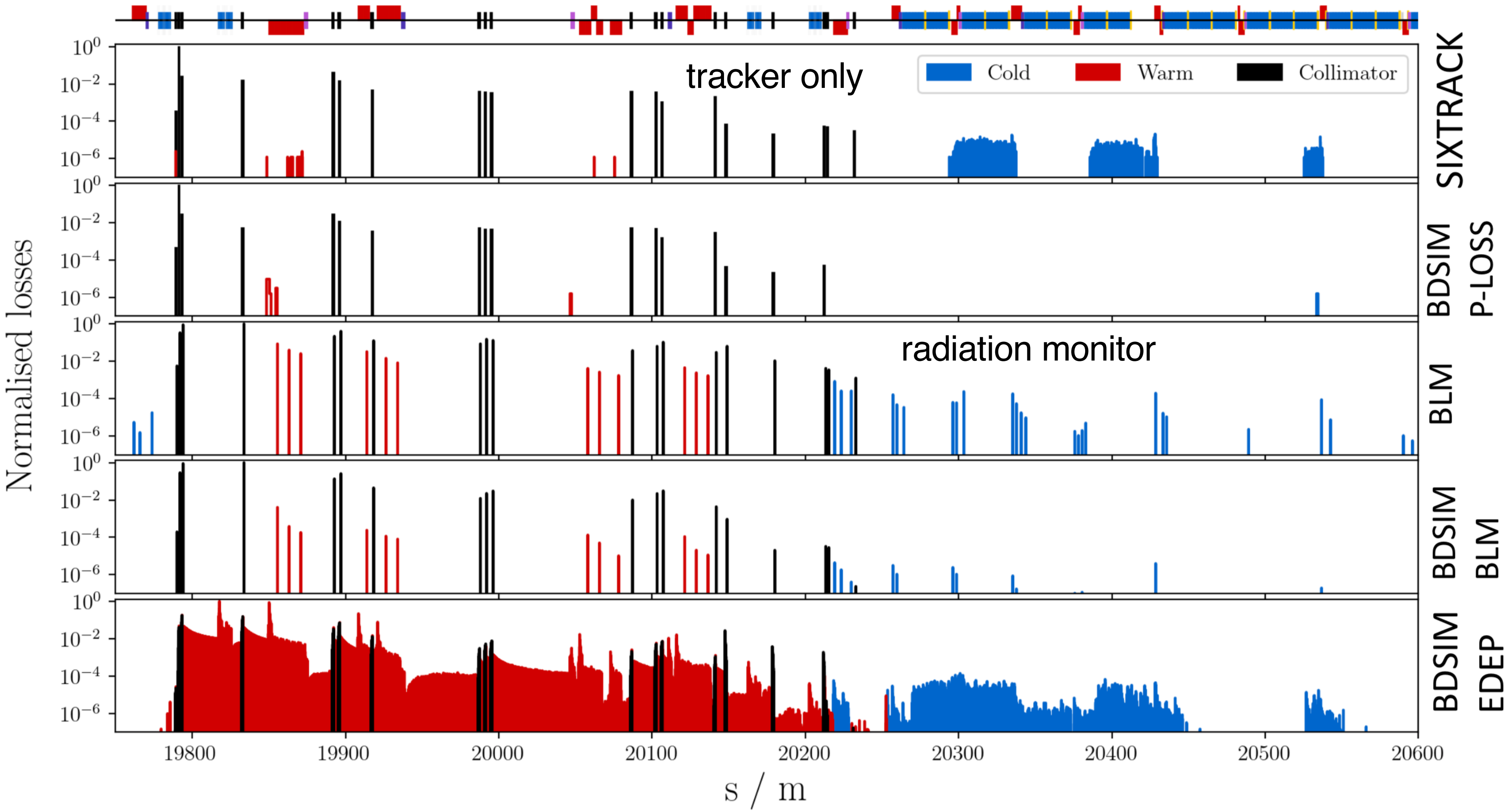
ROYAL
HOLLOWAY
UNIVERSITY
OF LONDON
Thank you

Backup

LHC Comparison

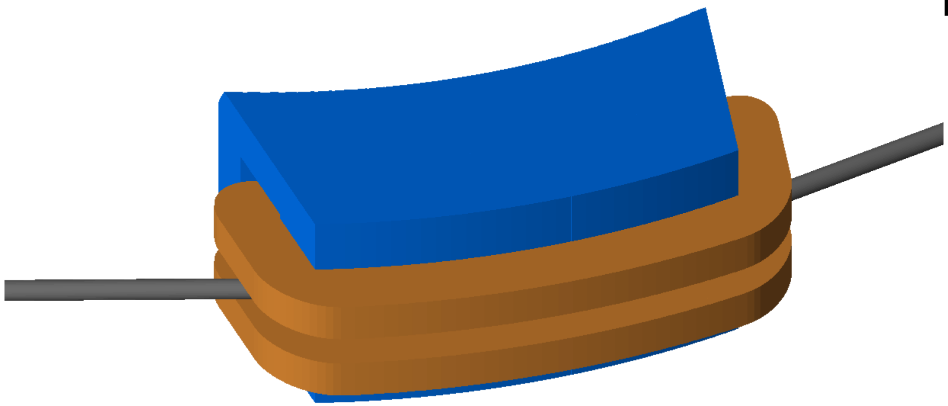


Stuart Walker, IPAC 2019

Pole Faces & Thin Elements

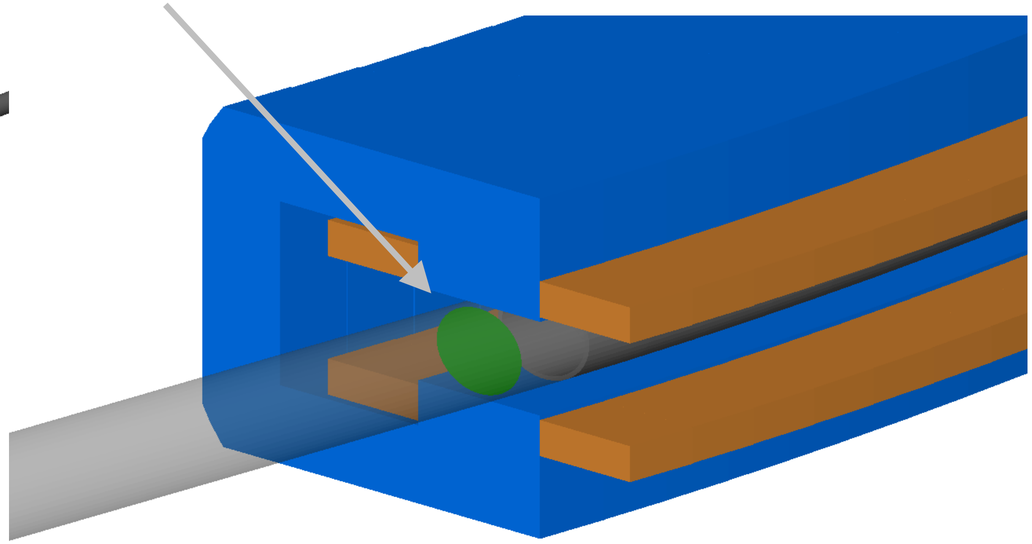
- Imperfections usually implemented via 'thin' elements in tracking
  - entrance / exit or in the middle of magnet
- Pole face rotations contribute significantly to optics
  - crucial for low energy applications
  - Implementation using 1st order matrix formalism

Revert to Geant4 based integrator in non–paraxial limit.



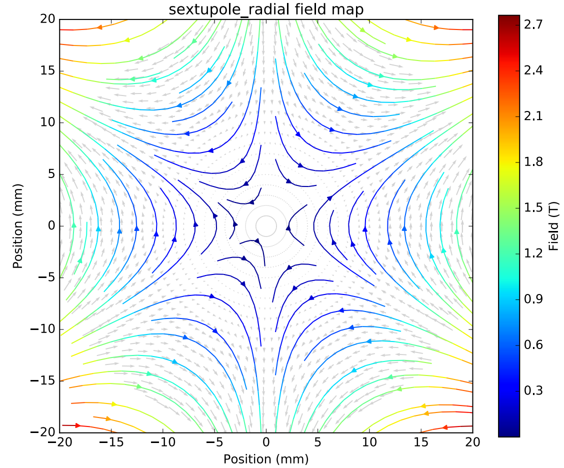
Angled beam pipe and yoke geometry as well as coils

Thin element for fringe field



Field Maps

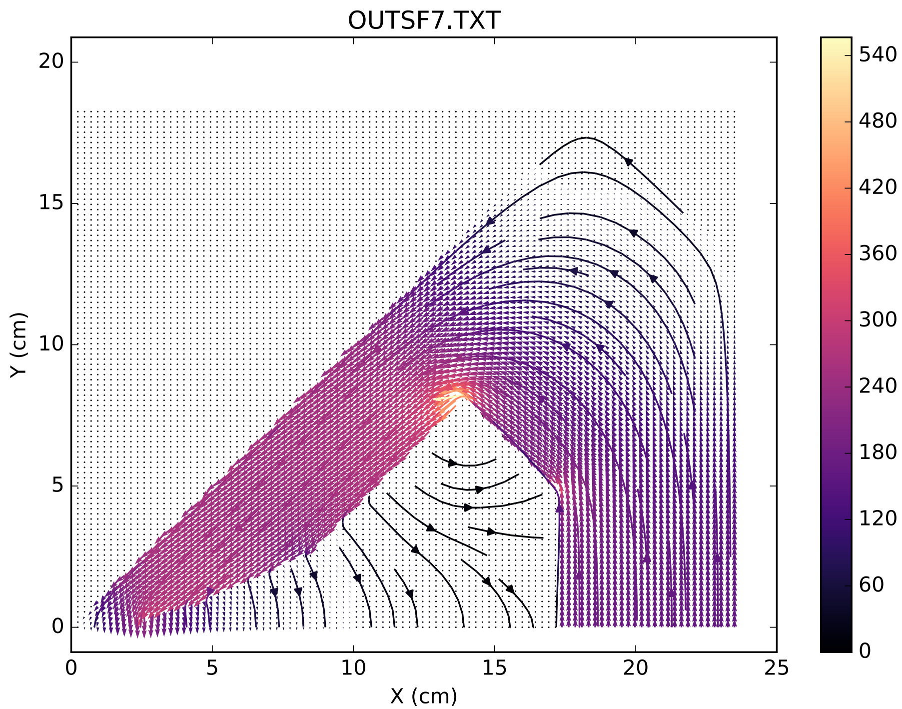
- Equations describe pure fields
- Can overlay field map on BDSIM generic element
  - yoke or vacuum separately or both together
- 1- 4D loading and interpolation
  - nearest neighbour, linear and cubic interpolation



ideal sextupole field

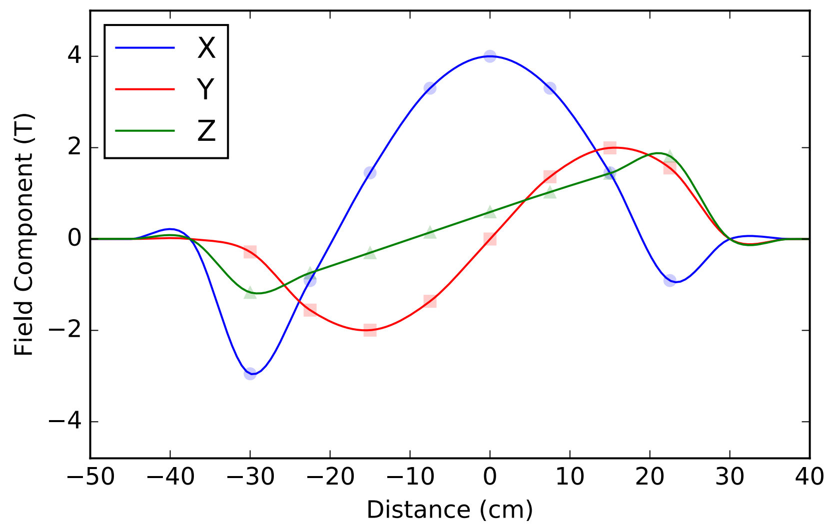
$$B_x = \frac{1}{2!}\frac{\partial^2 B_y}{\partial x^2} 2xy$$

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



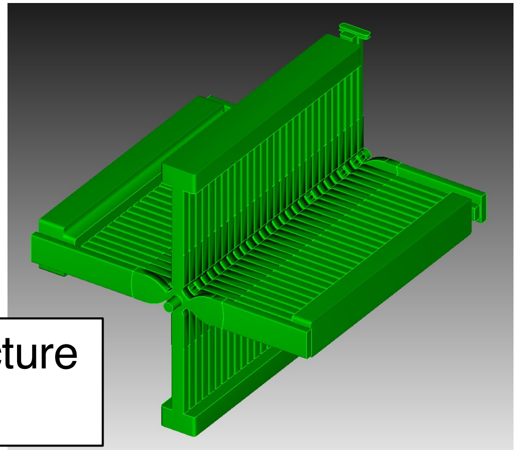
example field map from Poisson 2D

example interpolation



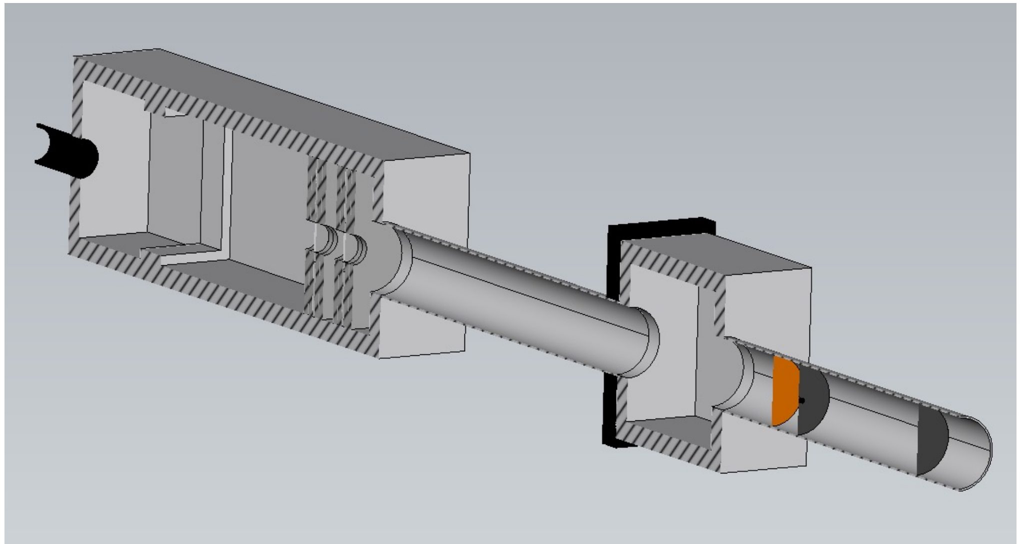
Complex Models

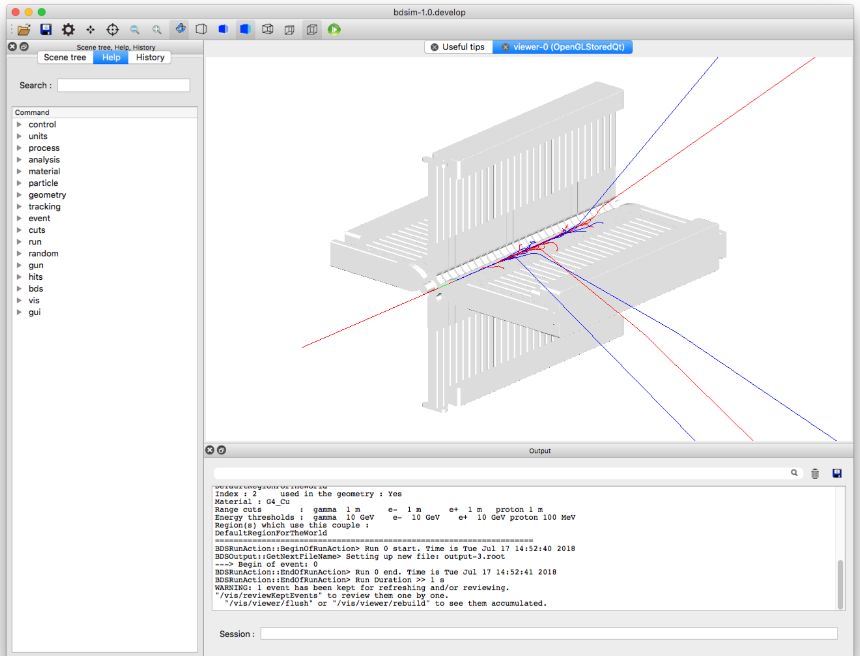
- Developed Python package to process CAD models
  - "pyg4ometry"
- Create mesh from STEP file
  - using Open Cascade and FreeCAD (free) tools
- Smaller models more suited



CLIC vacuum structure from STL file

Clatterbridge occular treatment nozzle





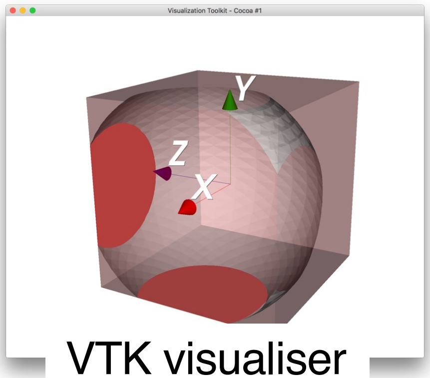
pyg4ometry

https://bitbucket.org/jairhul/pyg4ometry

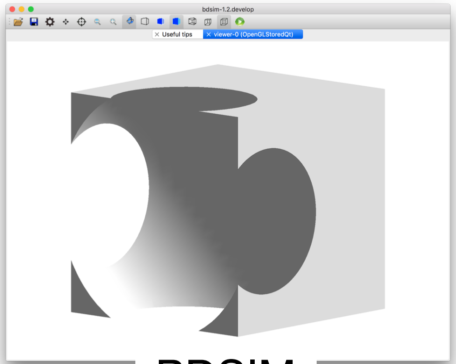
- Python package to create Geant4 geometry in GDML
- Python class for each Geant4 primitive solid
- Combine with meshes from STL / STEP
- Generate meshes and uses VTK visualiser

```
boxSolid1    = _g4.solid.Box('box1',100,56,78)
boxLogical1  = _g4.LogicalVolume(boxSolid1,'G4_Cu','boxLogical1')
boxPhysical1 = _g4.PhysicalVolume([0,0,0],[0,0,0],boxLogical1,'boxPhysical1',worldLogical)
```

- Creates its own mesh
- Use mesh to identify overlaps
- Easy to create simplified pieces



VTK visualiser



BDSIM