Studies of energy deposition in proton absorbers for crystal collimators

Stephen Gibson[1]
with thanks to
BDSIM: Laurie Nevay[1], Jochem Snuverink[1], Stewart Boogert[1],
and input from: Adriana Rossi[2], Alessandro Bertarelli[2], Federico Carra[2], Daniele Mirarchi[2], Roderick Bruce[2], Stefano Radaelli[2]

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2 CERN

3rd EuCARD-2 Annual Meeting, WP11: *Collimator Materials for fast High Density Energy Deposition*, 29th April 2016, University of Malta, Valletta.

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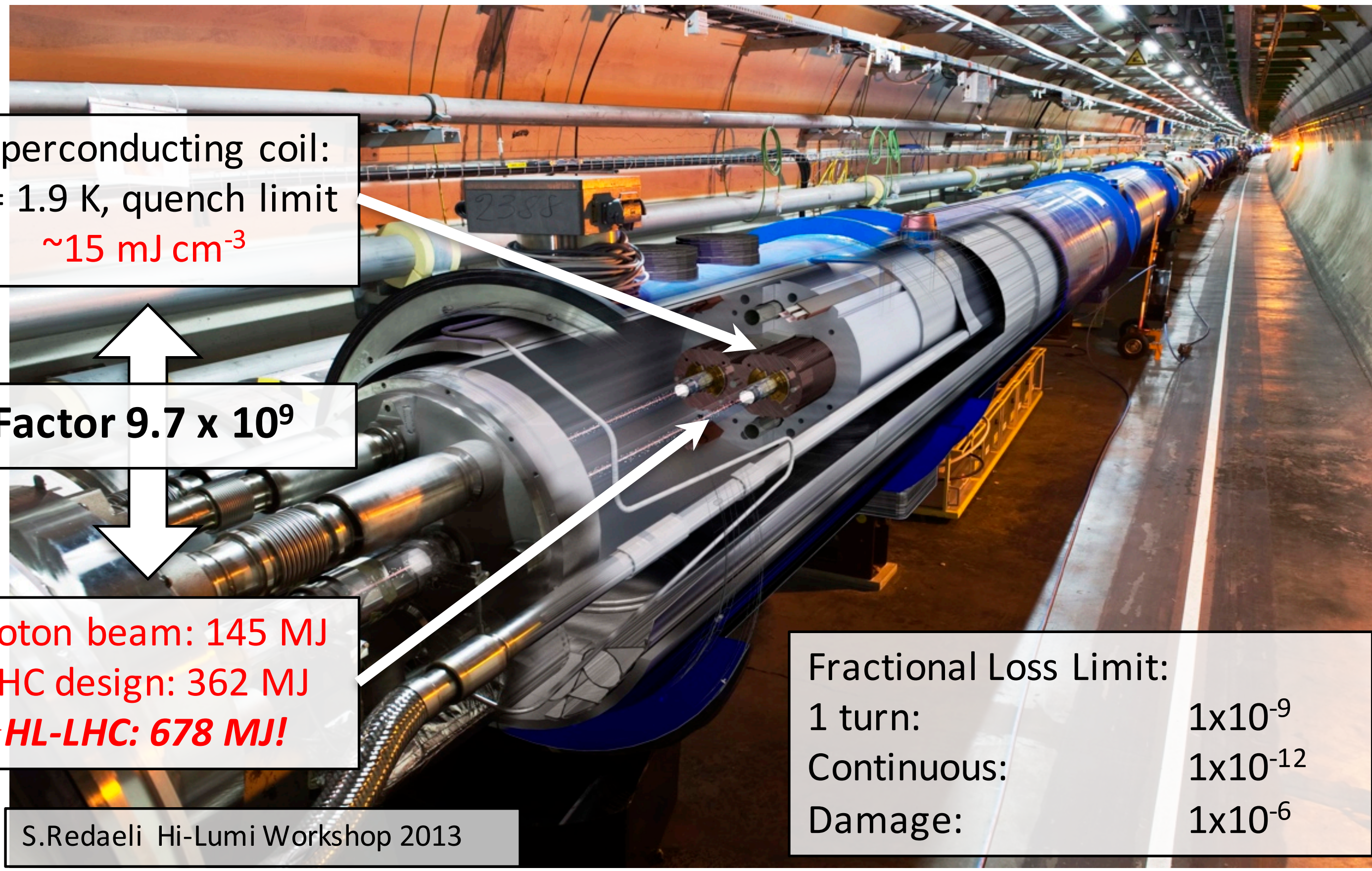
Talk Outline

Outline

- Motivation - crystal collimation
- BDSIM introduction
- Proton absorber models:
  - Jaw geometry
  - Physics assumptions
- Simulation results:
  - Energy deposition profiles
  - Transverse particle maps
  - Particle tracking
- Future work

LHC Collimation Challenges

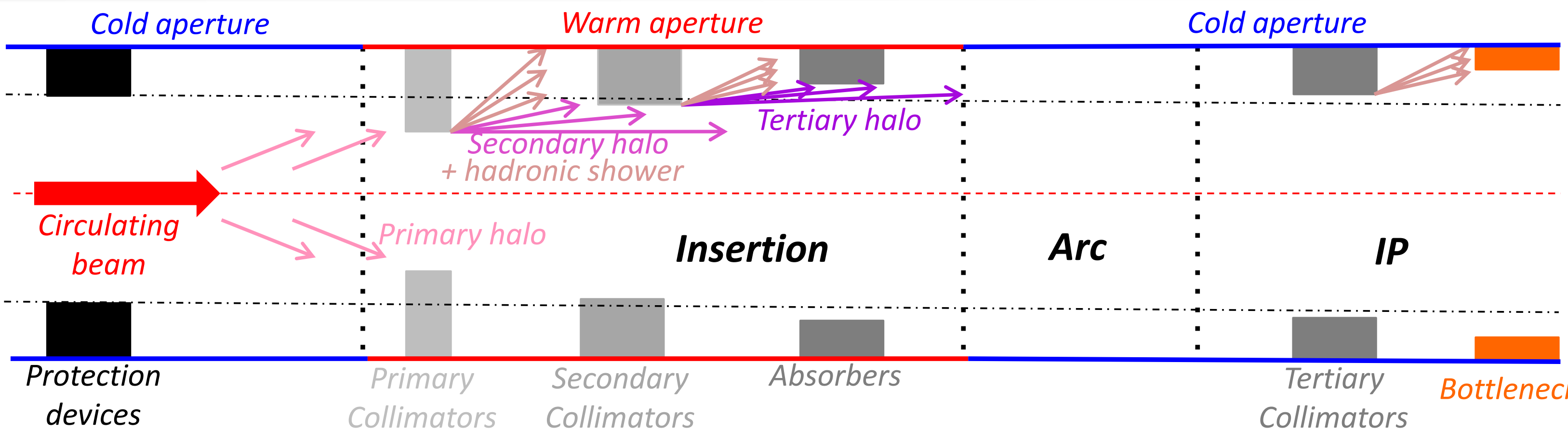
- Collimation system must clean beam halo and protect accelerator by averting a beam loss induced superconducting magnet quench.



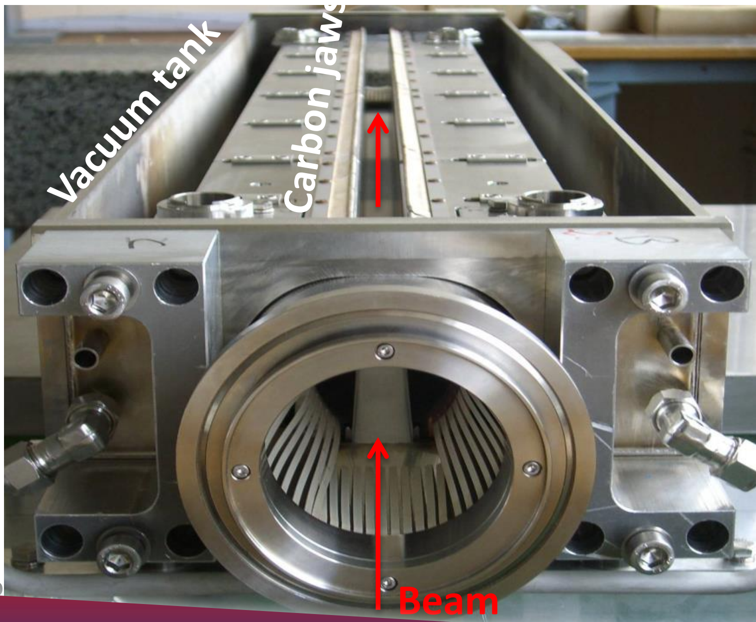
Huge increase in stored beam energy:

Need collimation upgrade for HL-LHC!

Conventional Collimation



~50 two-sided collimators per beam



Intrinsic limitation of amorphous collimation system:

- **inelastic interactions**
  - Diffractive events (p)
  - Fragmentation and dissociation (Pb)
    - ✓ Small deflection
    - ✓ Non-negligible Δp/p

*Escape from the collimation insertion and impact on the magnets (➔ **quench**)*

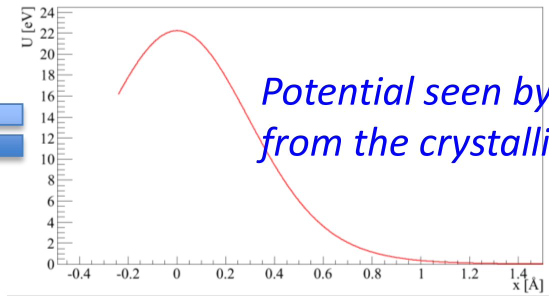
Daniele Mirarchi's talk at [RHUL IOP meeting]

Crystal Channeling Theory

Potential between a particle and an atom described by the Thomas-Fermi model: $V(r) = \frac{Z_i Z e^2}{r}\Phi(\frac{r}{a_{TF}})$

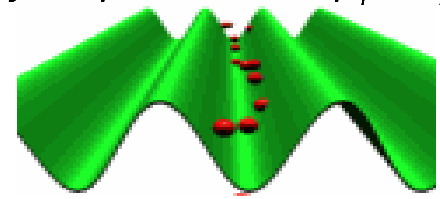
+ Continuous approximation: $U_p(x) = Nd \iint_{-\infty}^{+\infty} V(x,y,z)dydz$

=



Potential seen by protons from the crystalline plane

If the protons have $p_T < U_{max}$

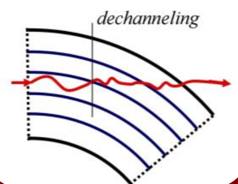


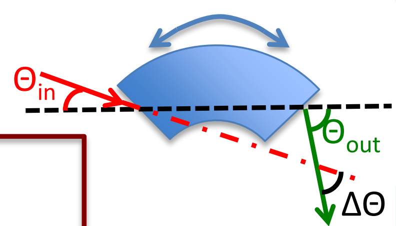
Forced to oscillate in a relatively empty space

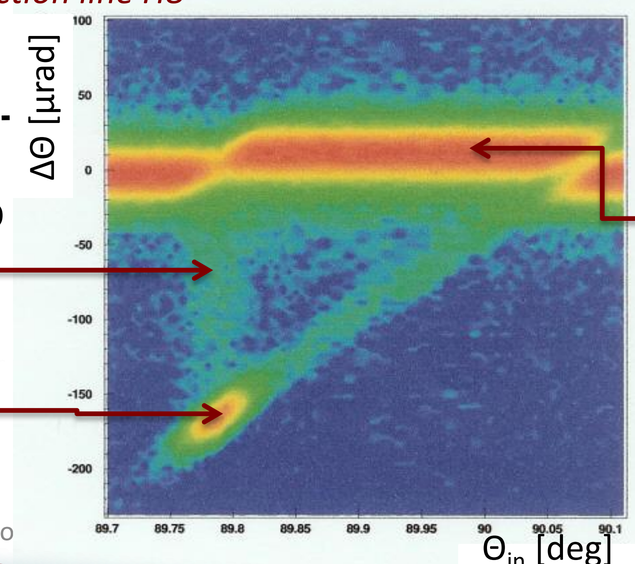
If crystals are bent?

***From test beam** on the CERN-SPS extraction line H8*

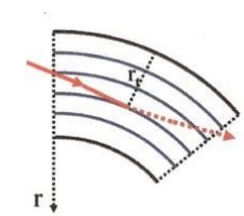
Dechanneling



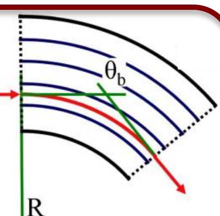




Volume Reflection



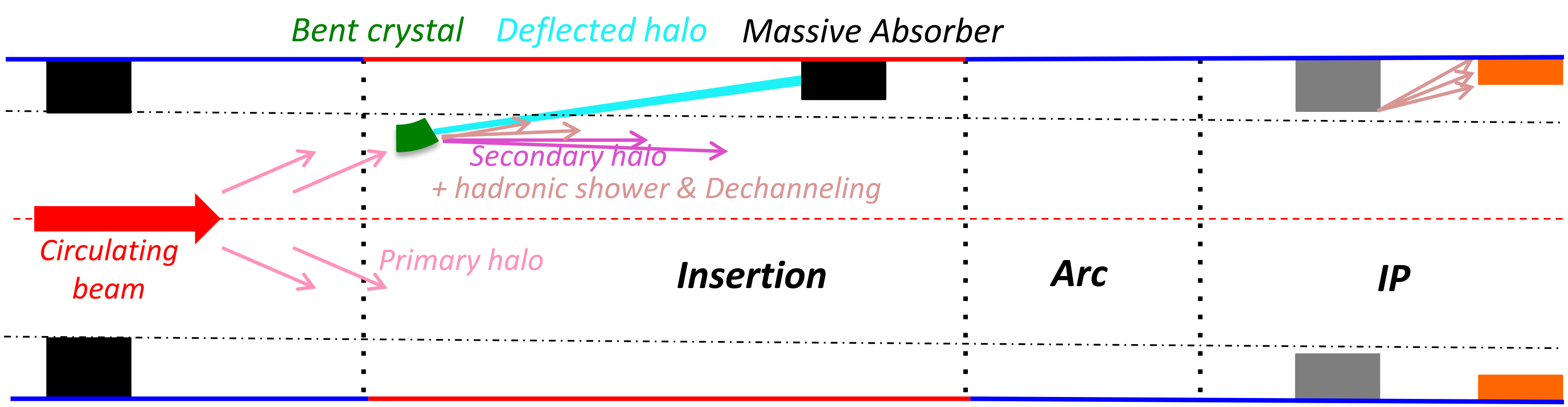
Desired deflection if in **Channeling** for all the path



Daniele Mirarchi's talk at RHUL IOP meeting

Imperial College

Crystal Collimation



Main gains:

- ✓ More compact system (2 stages)
- ✓ Reduction of inelastic interactions
- ✓ Big deflection angle after 1st stage
- ✓ Impedance reduction

Increasing in L

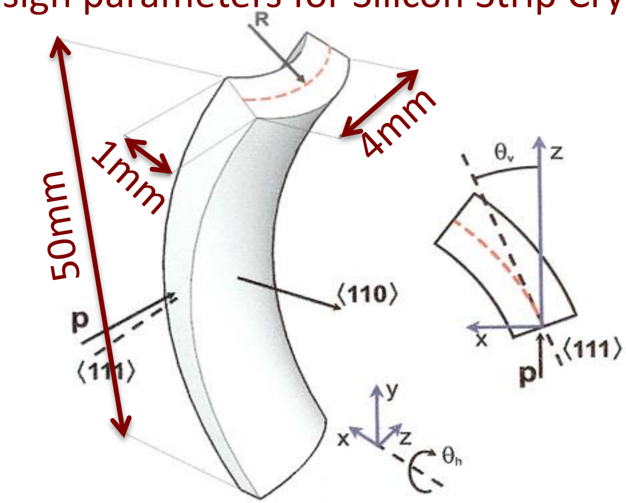
Main challenges:

- $\Theta_c \approx 2.3\mu rad$ @ 7 TeV!
- Extracted halo absorption

This talk!

Daniele Mirarchi's talk at RHUL IOP meeting

LHC design parameters for Silicon Strip Crystals

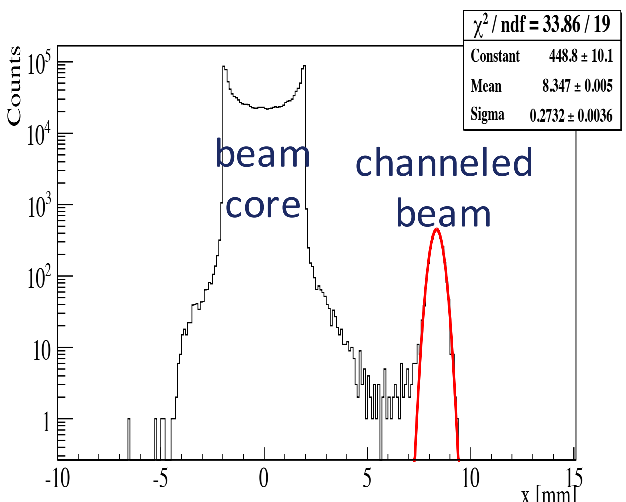


Bending 50μrad ≡ B ≈ 300 T @ 7 TeV!

Experimental tests of crystal collimation

- Exploiting a bent crystal to deflect halo onto a heavy absorber is a promising approach to improve the cleaning efficiency.
- Already tested successfully for over 4 years in the SPS and recently in LHC, see e.g.:
  - CERN-ACC-2015-0143, 'Crystal Collimation for LHC ' **D. Mirarchi Thesis**, Imperial College London.
  - CERN-ACC-NOTE-2016-0035, 'Crystal Collimation with protons at injection energy', R. Rossi, F. Galluccio, A. Masi, D. Mirarchi, S. Montesano, S. Redaelli, G. Valentino, W. Scandale, CERN.

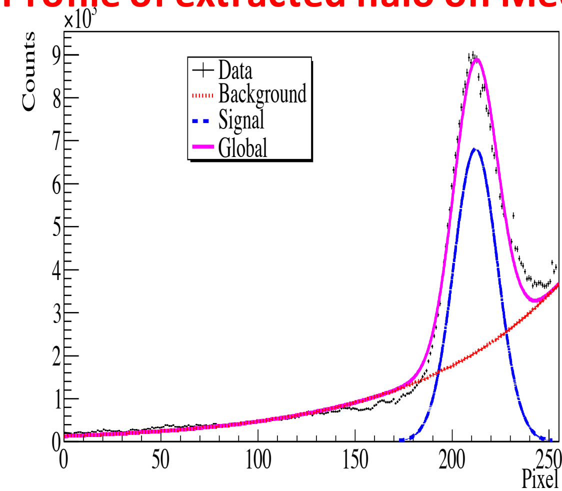
Multiturn SixTrack simulation



Theoretical prediction of the extracted halo position:

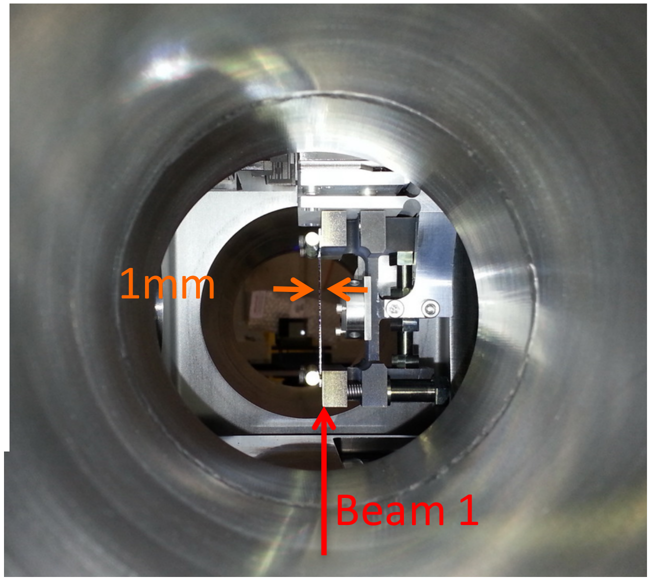
- 8.4 mm and full spot width ~ 700µm

SPS experimental data: Profile of extracted halo on Medipix



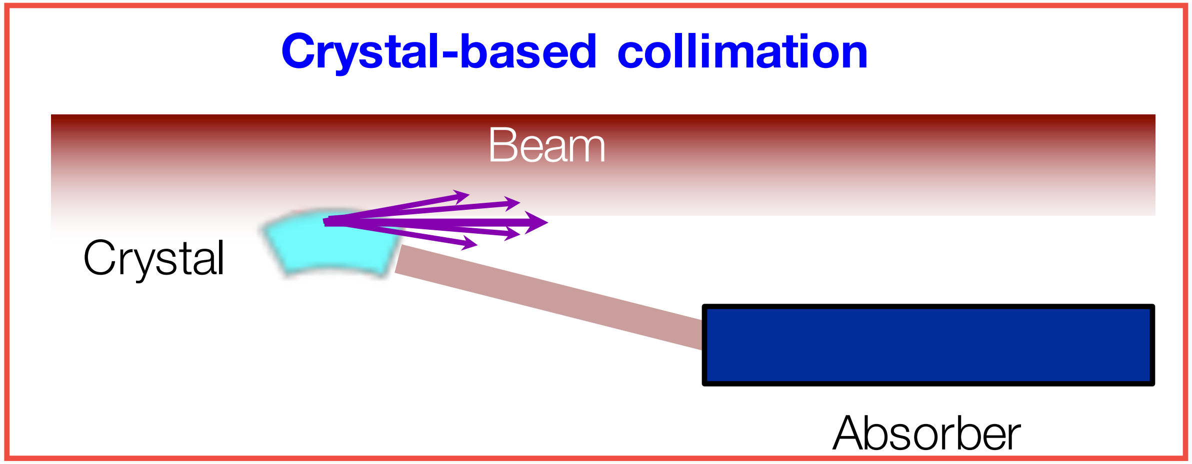
Sigma gauss fit ~ 11.27 pixel * 55µm ➔ ~ 600µm

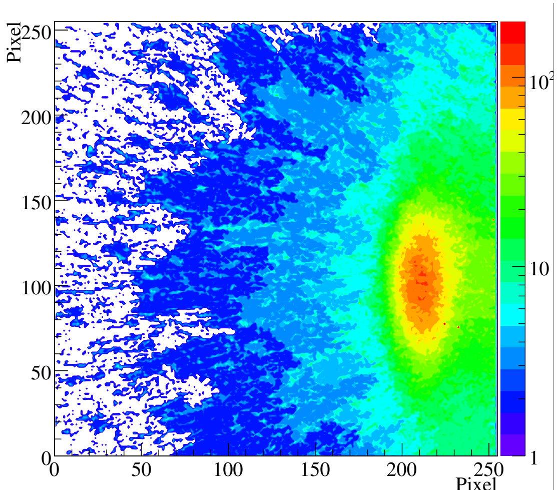
Crystal goniometer installed in LHC IR7



A proton absorber for crystal collimation

- The channeled beam from a crystal typically has small transverse dimensions, which presents a challenging energy density to the proton absorber.
- It was proposed by Adriana Rossi that we simulate the response of an absorber to the beam distribution generated by crystal collimation tracking simulations of Daniele Mirachi.
- The absorber materials and geometry were specified by Adriana to be modelled in BDSIM, a Geant4 based tool, to calculate the energy deposition maps.





Transverse distribution of extracted beam halo (SPS): D. Mirachi thesis.

BDSIM Introduction

People

Stephen Gibson

Stewart Boogert

Laurie Nevay
(JAI)

BDSIM / Collimation

Hector Garcia
(JAI / HL-LHC-UK)

Sixtrack / Fluka
(**CERN based**)

Regina Kwee-Hinzmann
(JAI / HL-LHC-UK)

Sixtrack / Fluka
(**CERN based**)

Jochem Snuverink
(JAI / CLIC-UK)

BDSIM development

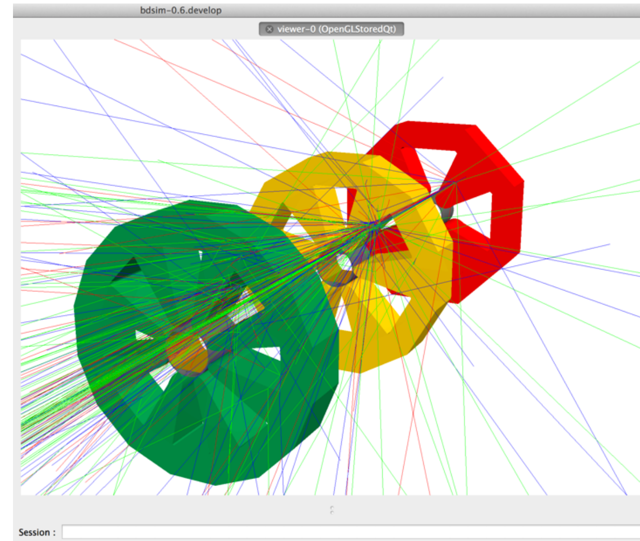
Stuart Walker
STFC

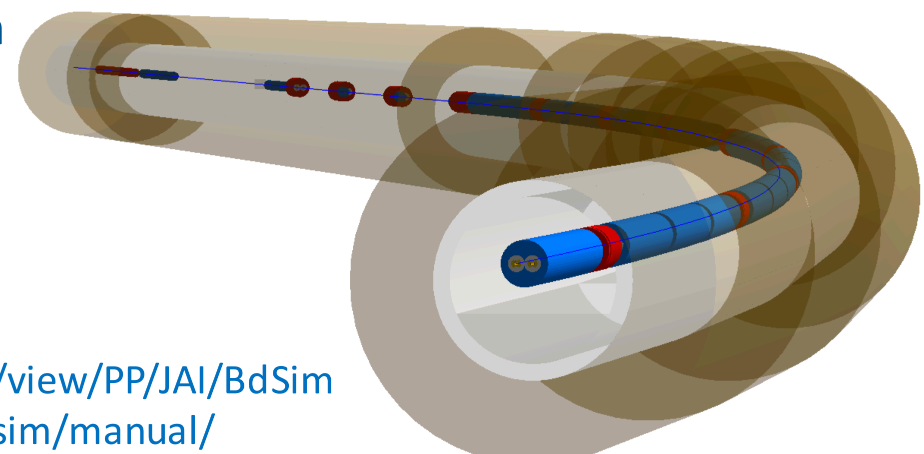
LHC / ATLAS
Backgrounds

+William Shields
JAI
BDSIM Medical
gantries

Beam Delivery Simulation - BDSIM

- Tracking code that uses Geant4
  - Open source C++
- Automatically builds Geant4 model
- Uses MadX-like syntax for text input
- Mixes normal accelerator tracking & Monte Carlo particle physics
- Full showers of secondaries created by Geant4 processes
- Ability to simulate synchrotron radiation
- Simulate energy deposition and detector backgrounds
- Ability to import external geometry and field maps




LHC Segment

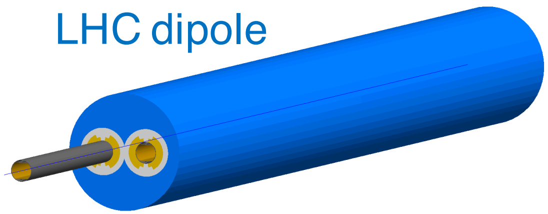
https://twiki.ph.rhul.ac.uk/twiki/bin/view/PP/JAI/BdSim
http://www.pp.rhul.ac.uk/bdsim/manual/

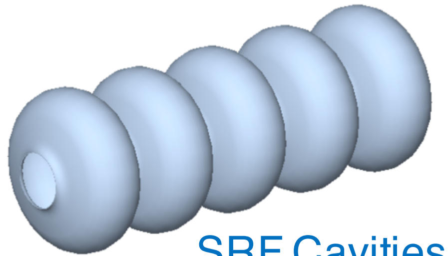
BDSIM Development

L. Nevay
J. Snuverink
S. Boogert

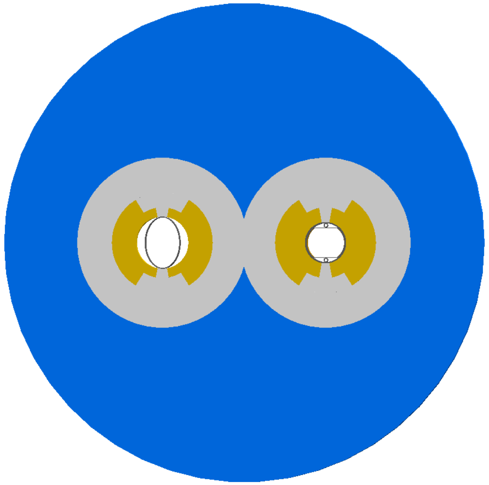
- BDSIM started ~2002 by G. Blair at RHUL
- BDSIM heavily developed since 2013 for LHC
- Complete review, modernisation and validation
- Recent development followed 3 main themes:
  - ***Geometry*** ✓
  - ***Tracking*** ✓
  - ***Physics processes*** ✓

LHC dipole

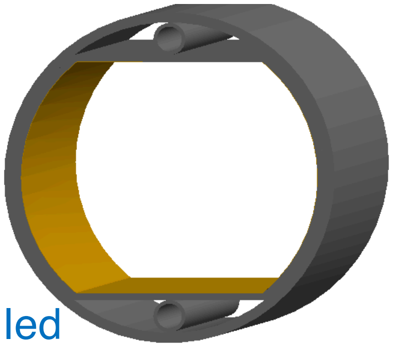




SRF Cavities
(***S. Walker***)

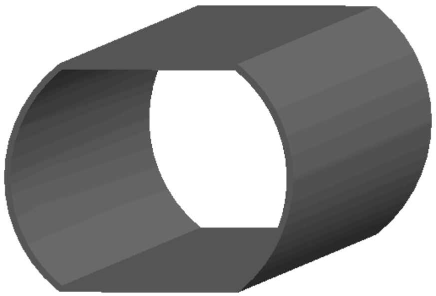


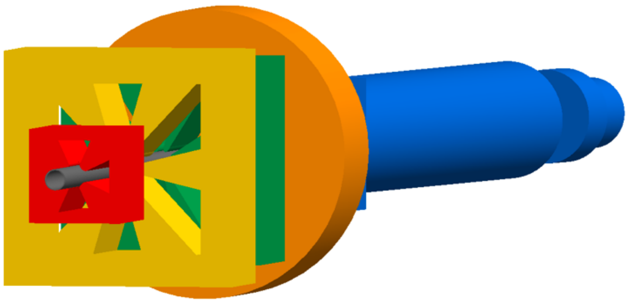
LHC Style



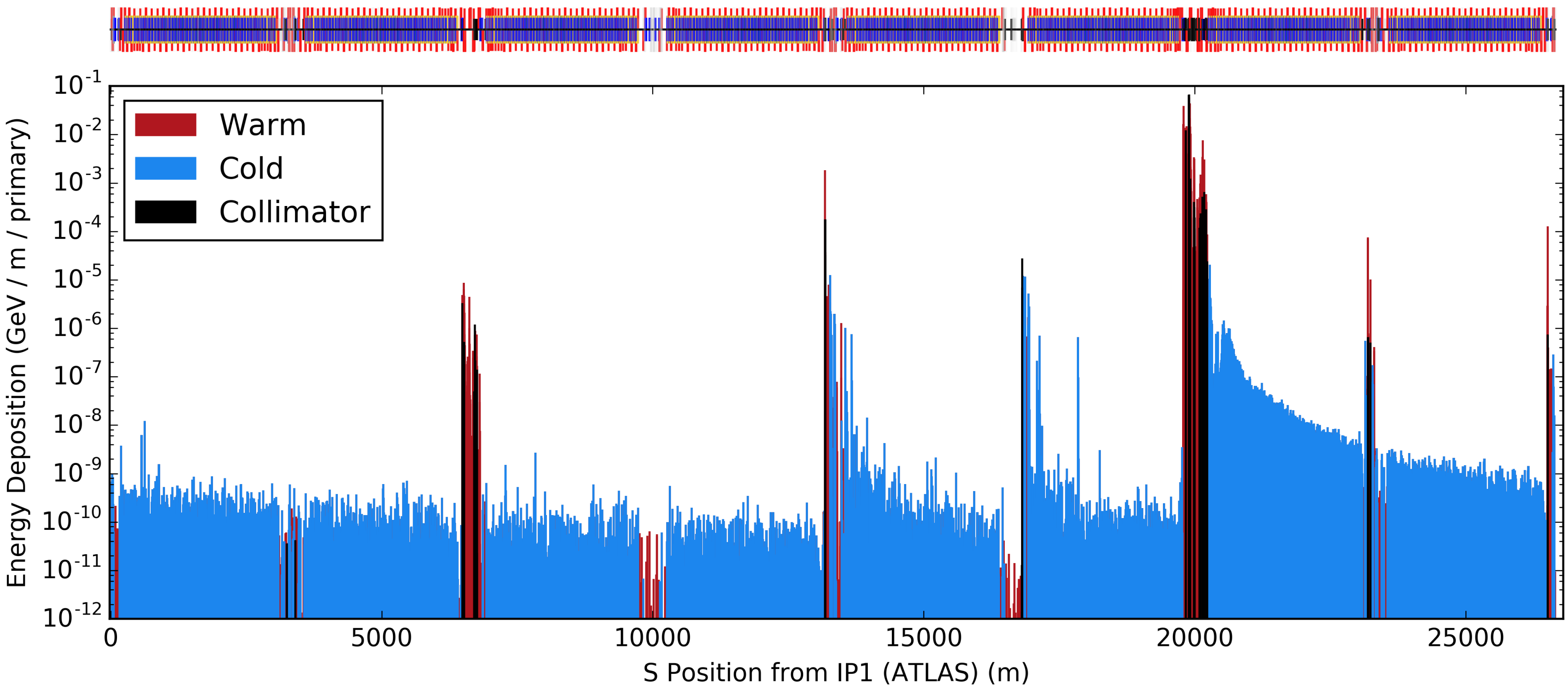
LHC detailed

LHC screen





LHC Energy Deposition Map



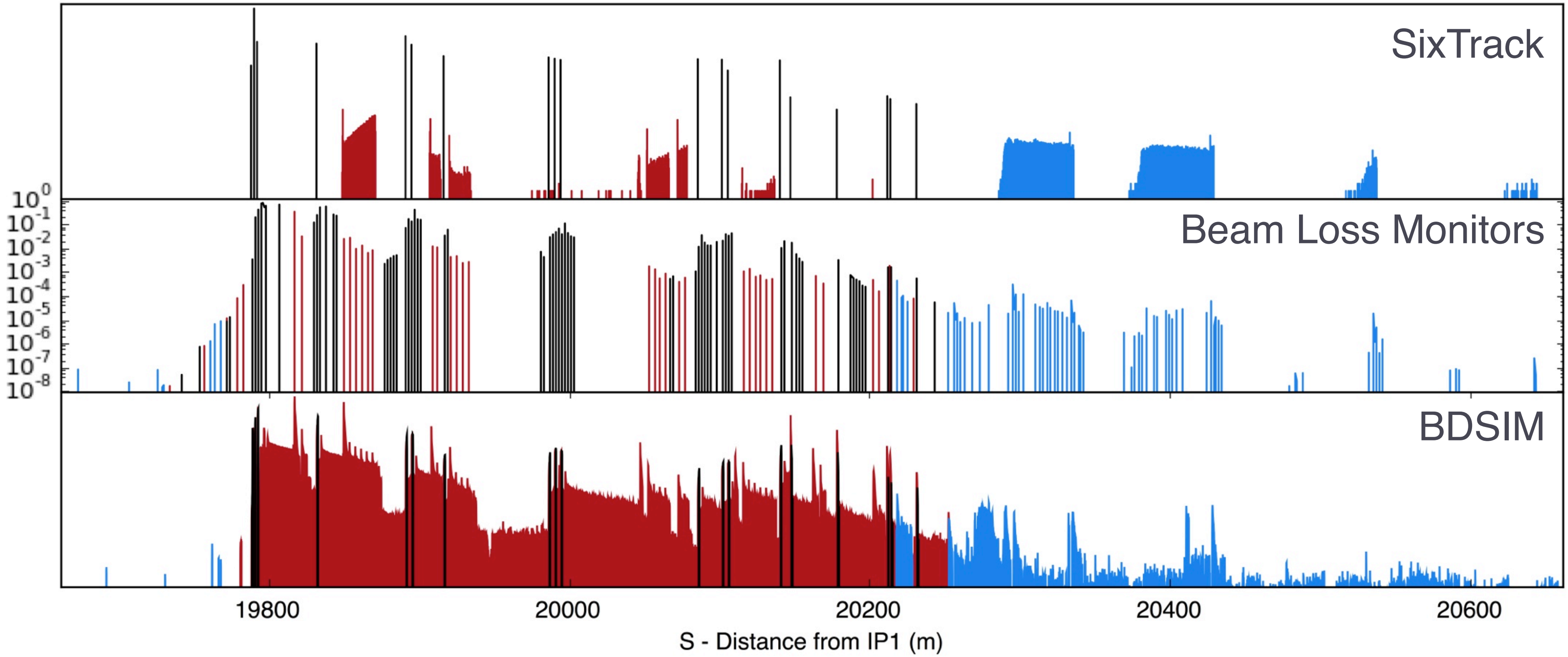
- 1.3 M primaries at 3.5 TeV -> ~ 10^{11} energy deposition hits
- First ever **energy** deposition maps
- Model under validation with existing studies

L. Nevay

Comparison

L. Nevay

- Insertion Region 7 – betatron cleaning followed by (cold) dispersion suppressor
- Validation of existing tool chain: continuous energy losses simulated by BDSIM.



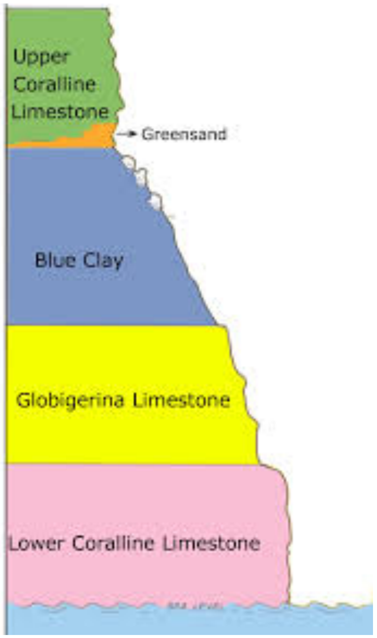
- BLM & SixTrack Data from R. Bruce et al, Phys. Rev. ST Accel. Beams 17, 081004 (2014)

Proton absorber model and simulation results

Absorber geometry and materials

- The absorber is a 5 layer sandwich of the following composition:

5 Maltese rock Layers:



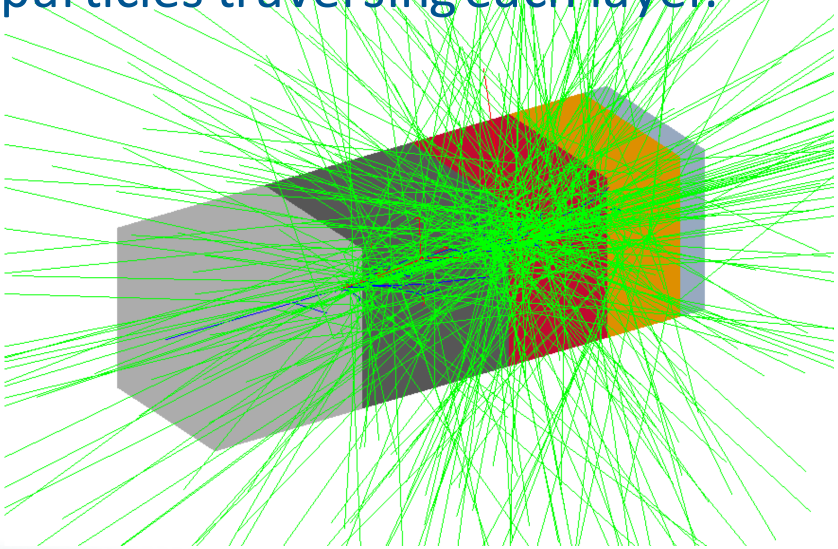
Layer	Length [m]	Material	Density [g/cm³]	Atomic Composition
1	3.0	sponge carbon	0.25	C 100 %
2	3.0	graphite	1.8	C 100 %
3	2.0	molybdenum graphite (MoGr) [CERN MG6530Aa]	2.48	Mo 1.46 % C 98.54 %
4	1.5	copper-diamond composite (CuCD)	5.4	*see below
5	0.5	tungsten	19.2	W 100 %

CuCD:

Element	Molar mass [g/mol]	Density [g/cm³]	%W	Atomic fraction %	(Avg.) atomic number Z
Cu	63.546	8.93	0.62057	23.590	
B	10.811	2.34	0.00417	0.932	11.41645
CD	12.01	3.51	0.375261	75.478	

BDSIM model of absorber geometry

- The materials were implemented in BDSIM, according to the specified absorber lengths.
- The lateral dimensions were unspecified, so the absorber was initially modelled using a default collimator geometry with a 2mm horizontal half-aperture gap, and a very large transverse extent (3m).
- Sampling planes were inserted at the start and end of each absorber layer, to record particles traversing each layer.

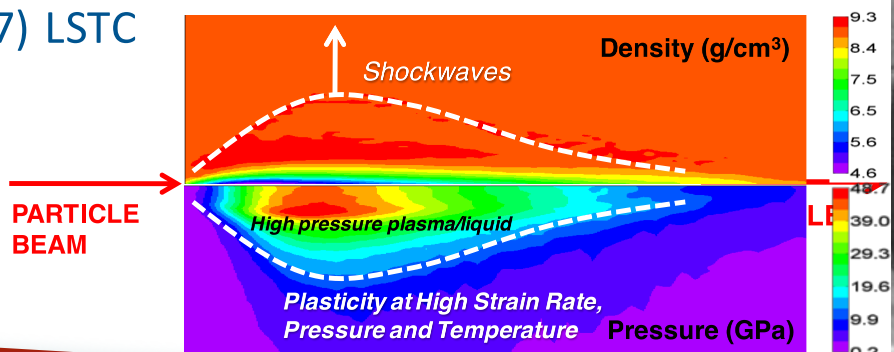


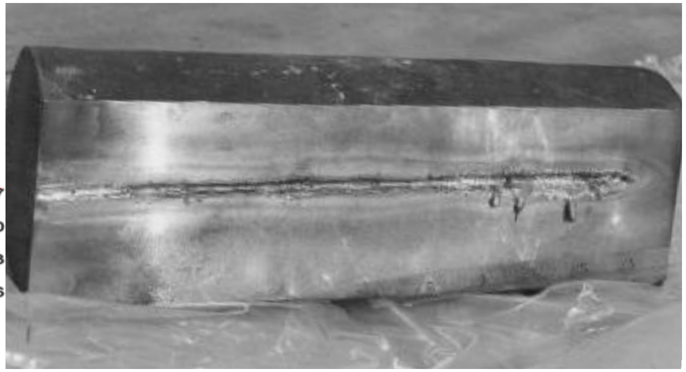
BDSIM model assumptions

- BDSIM model applied the following Geant4 Physics Lists: http://www.pp.rhul.ac.uk/bdsim/manual/model_description.html#physics-lists-in-bdsim
  - **em**: Transportation of primary particles, ionisation, bremsstrahlung, Cerenkov, multiple scattering: *G4EmStandardPhysics*
  - **muon**: muon production and scattering processes. Gamma to muons, annihilation to muon pair, 'ee' to hadrons, pion decay to muons, multiple scattering for muons, muon brehmstrahhlung, pair production and Cherenkov light. *G4MuonPhyiscs*
  - ***hadronic:*** qgsp_bert: Quark-Gluon String Precompound Model with Bertini Cascade model. This is based on *G4HadronPhysicsQGSP_BERT* class and includes hadronic elastic and inelastic processes. Suitable for high energy (>10 GeV).
  - OR:
  - **hadronic_elastic**: Elastic hadronic processes, provided by *G4HadronElasticPhysics*
  - **ftfp_bert**: Fritiof Precompound Model with Bertini Cascade Model. The FTF model is based on the FRITIOF description of string excitation and fragmentation. This is provided by *G4HadronPhysicsFTFP_BERT*. All FTF physics lists require *G4HadronElasticPhysics*

BDSIM model assumptions

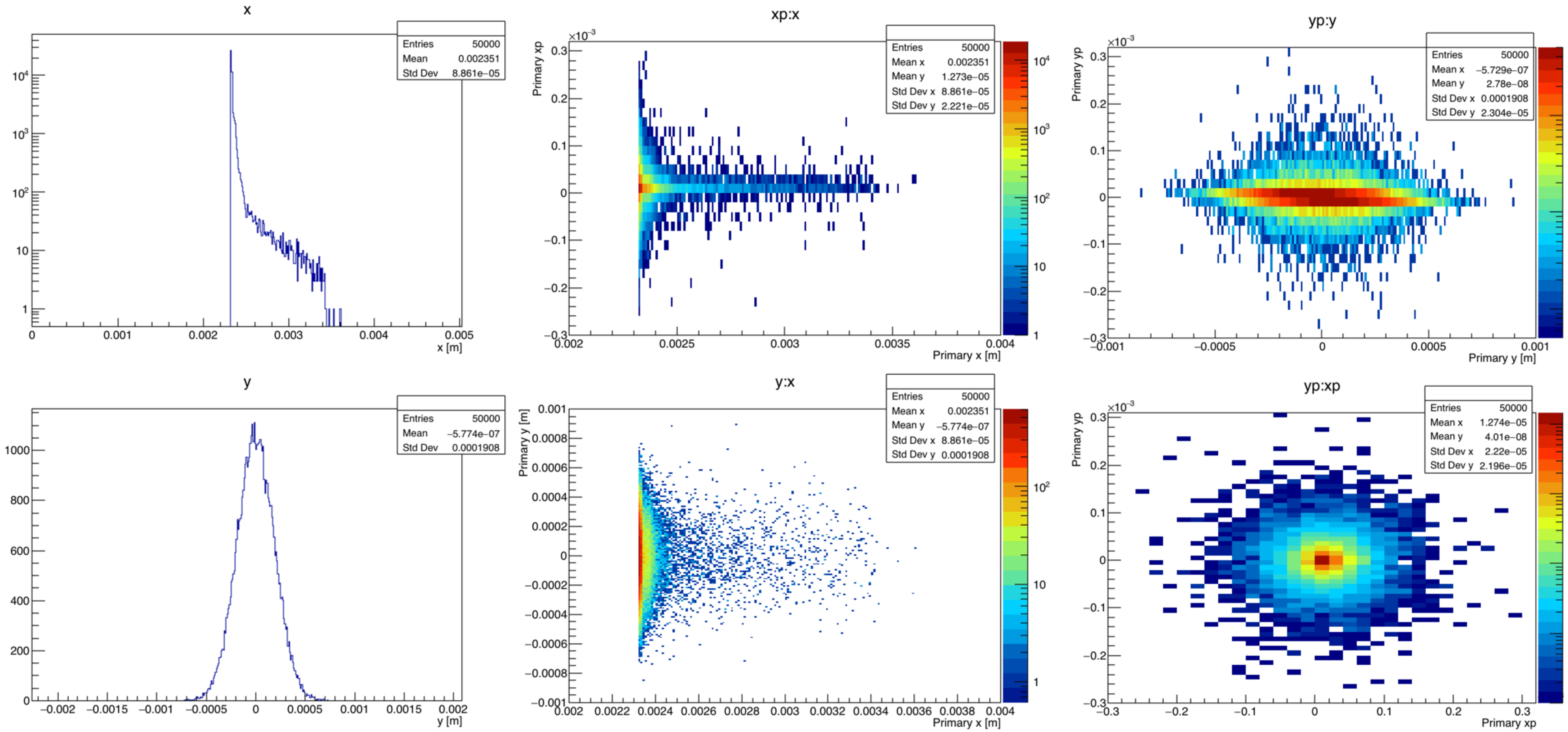
- BDSIM simulates particle transport and interactions in matter and calculates the deposited energy, not the thermo-mechanical response.
- The BDSIM energy map described here could provide input to other dedicated codes such as FEM code LS-DYNA[1], to model the hydrodynamic behaviour using a dedicated three-phase equation of state and the mechanical deviation using a dedicated material model, see e.g.
  - M. Scapin, L. Peroni, A. Bertarelli, A, Dallocchio'Numerical simulation of tungsten targets hit by LHC proton beam', IV International Conference on Computational Methods for Coupled Problems in Science and Engineering
  - [1]Gladman, B. et al., LS-DYNA® Keyword User's Manual – Volume I – Version 971. (2007) LSTC





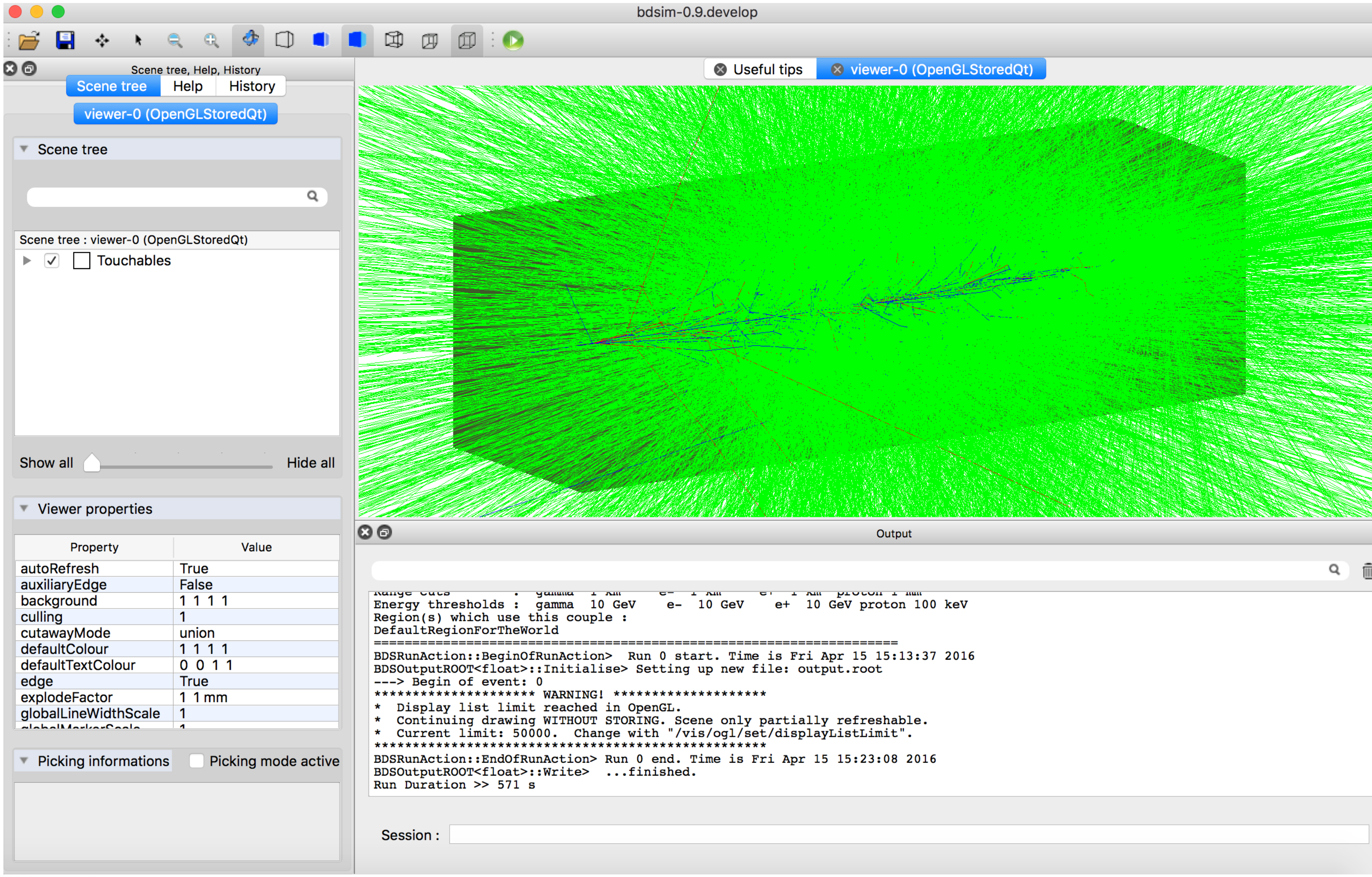
Distribution of primaries

- ~50k primary particles, y=0, x=2.35mm, σ_x =8.85 10^{-5} m, σ_y =1.9 10^{-3} m
- Energy unspecified in file, 7 TeV assumed.



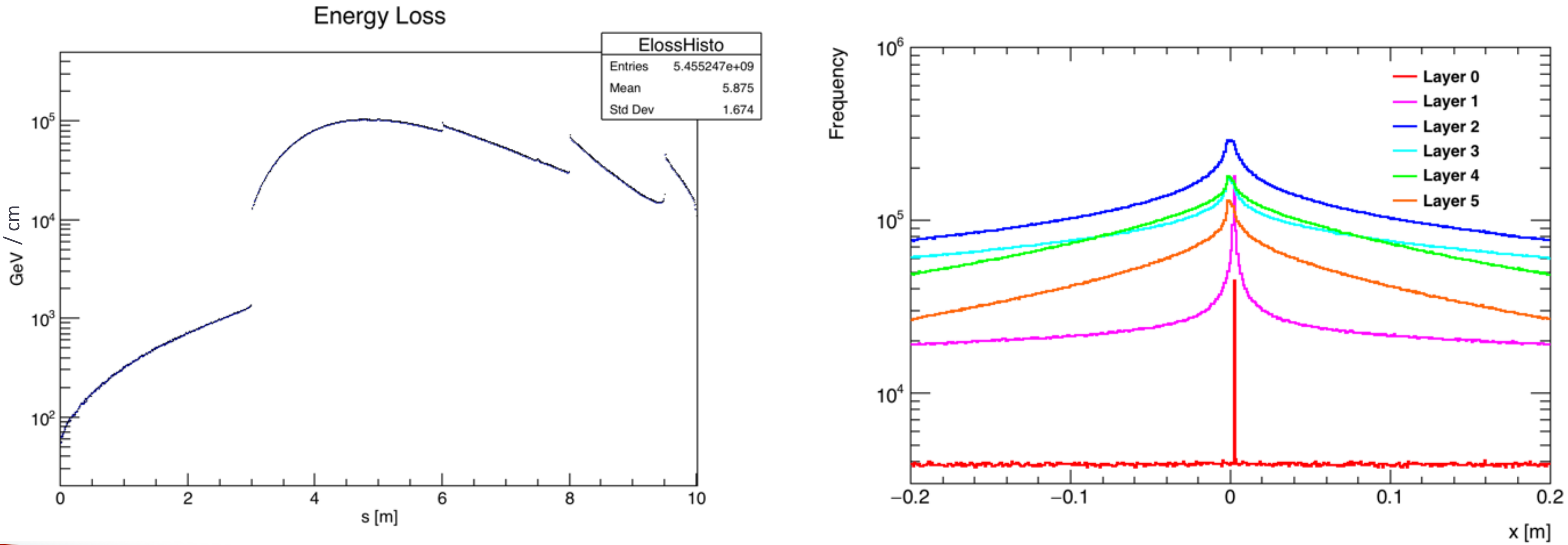
- <xp> =1.27 10^{-5} rad

BDSIM model1 simulation

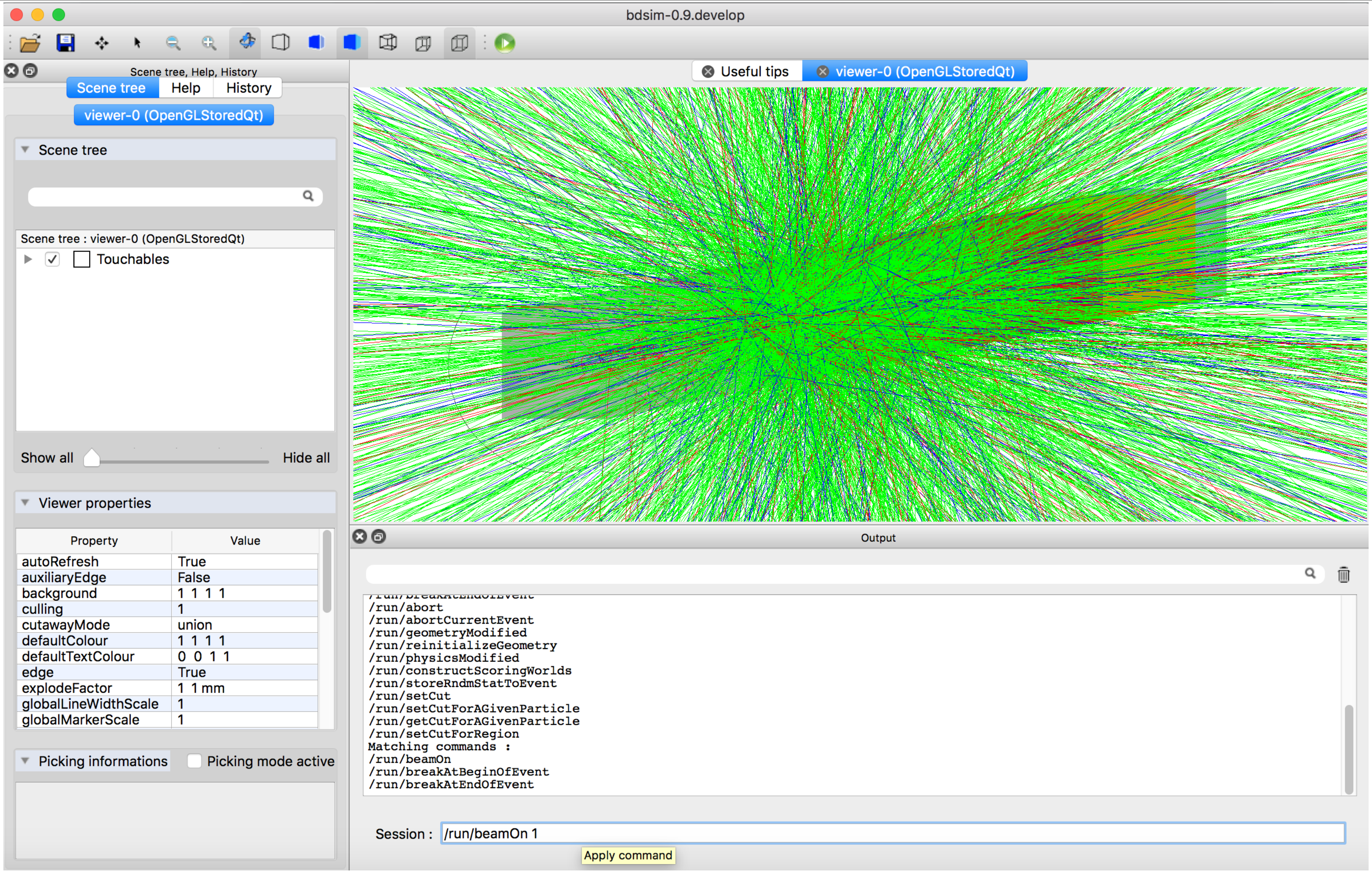


BDSIM model1 results

- Energy deposition along the absorber (for collimator-style geometry):
  - The least energy is absorbed by the first layer of sponge-carbon.
  - Most energy is deposited in layers 2 and 3, of graphite and molybdenum graphite
  - At each boundary a step in energy deposition arises from entering the denser material.
- Particle distribution at each sampling layer shows lateral shower:

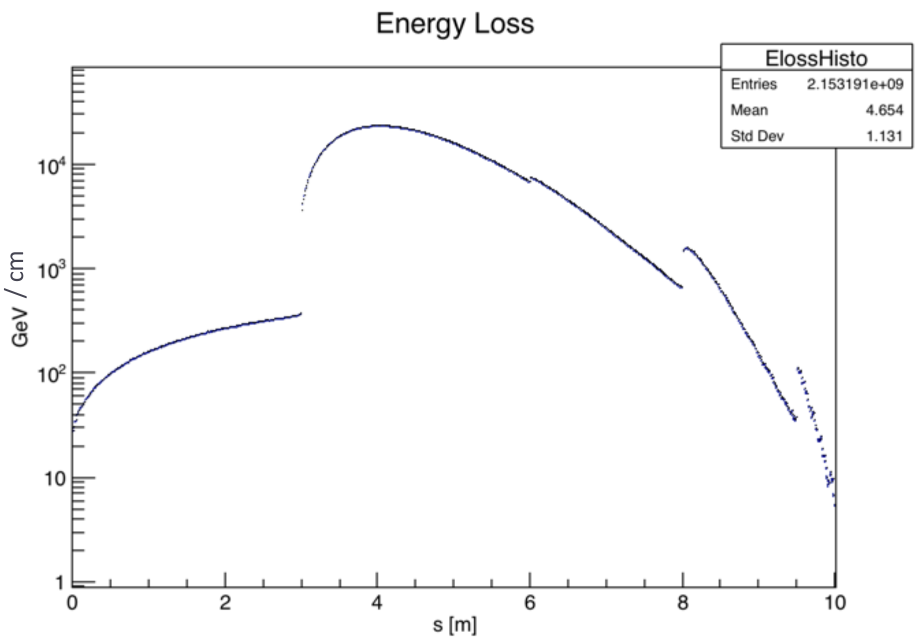


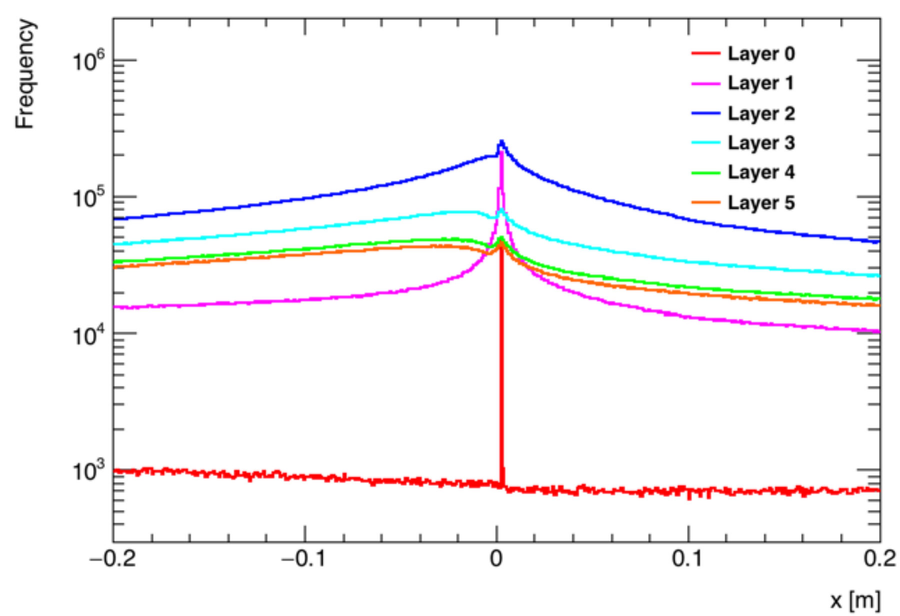
BDSIM model2 simulation



BDSIM model2 results

- Energy deposition along the absorber (for offset jaw geometry):
  - Similar energy deposition profile is shown for the first layers, with a drop off in the latter layers – this may be attributed to the geometry, as on the next slide.
- The particle track distribution at each sampling layer now reflects the X - asymmetry of the setup. Note tracks are also outside the material.

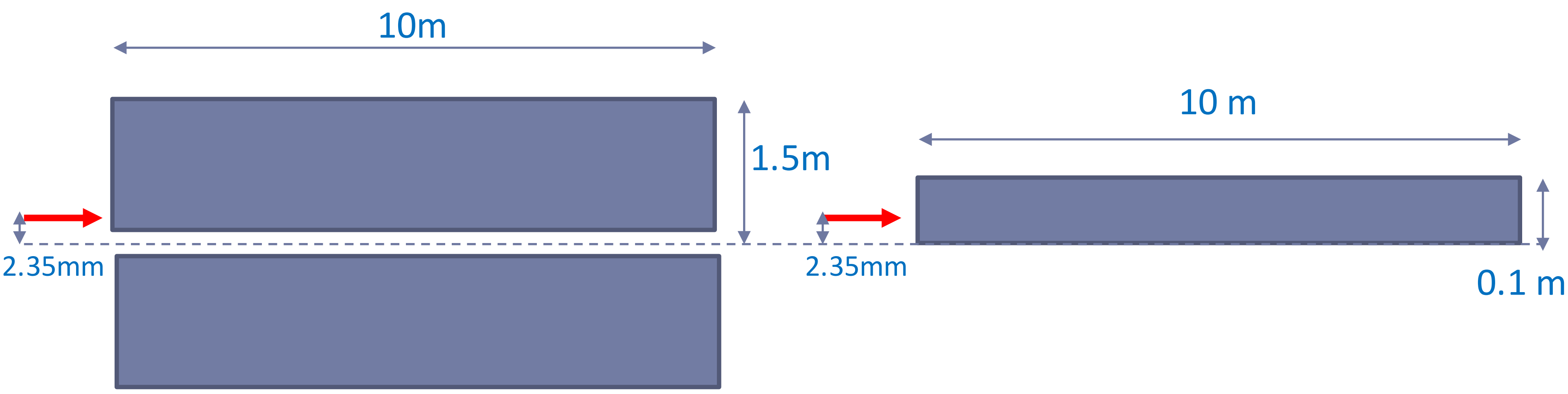




Lateral geometry of absorber models

Model 1

Model 2



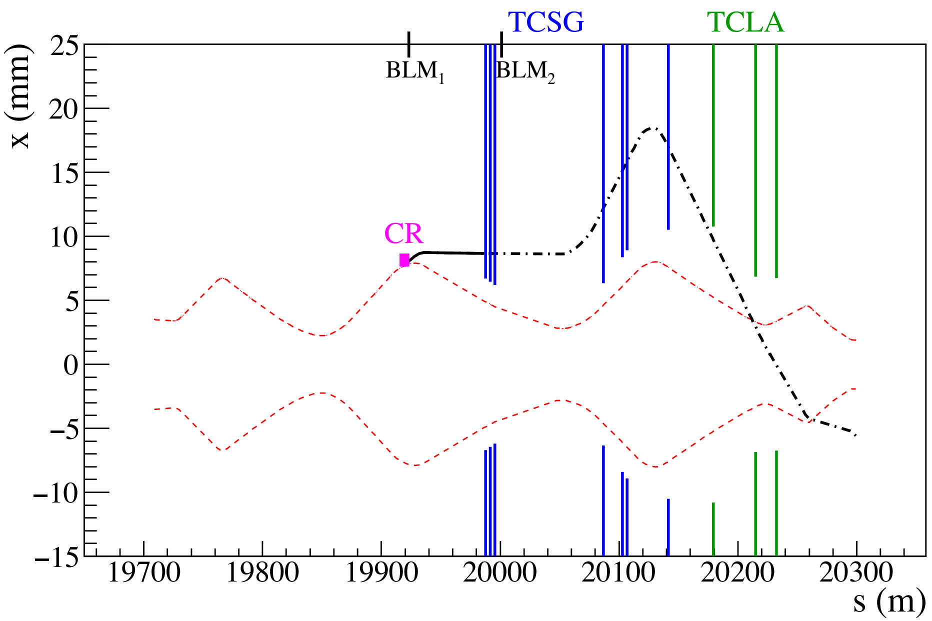
Collimator geometry:
2mm half aperture.
Beam strikes at 0.3mm from corner of absorber.
Large transverse size of material

Single jaw geometry:
2mm half aperture.
Beam strikes at 2.3mm from corner of absorber.
Small transverse size.

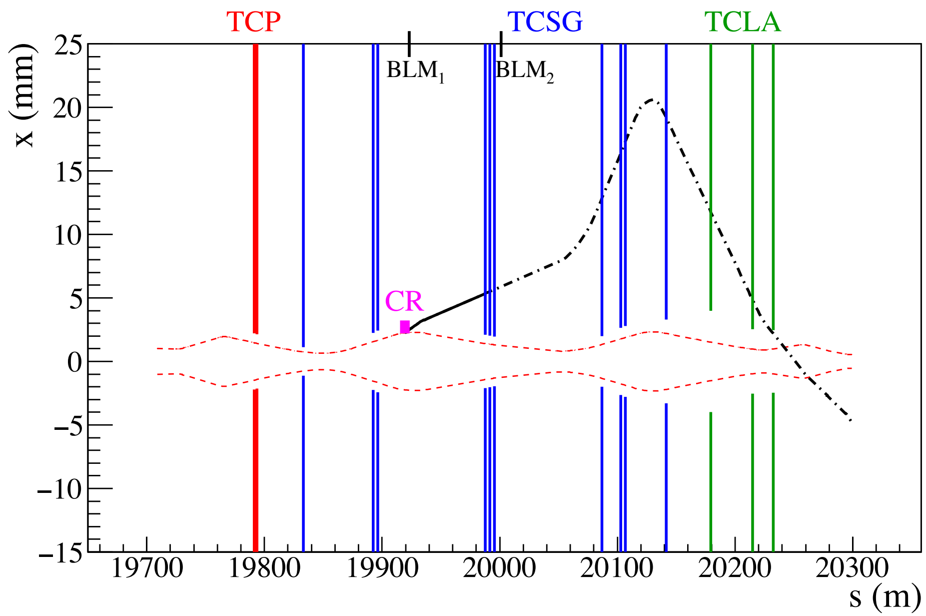
Channeled beam trajectory

IR7 crystal collimation simulations of D. Mirachi:

Injection energy



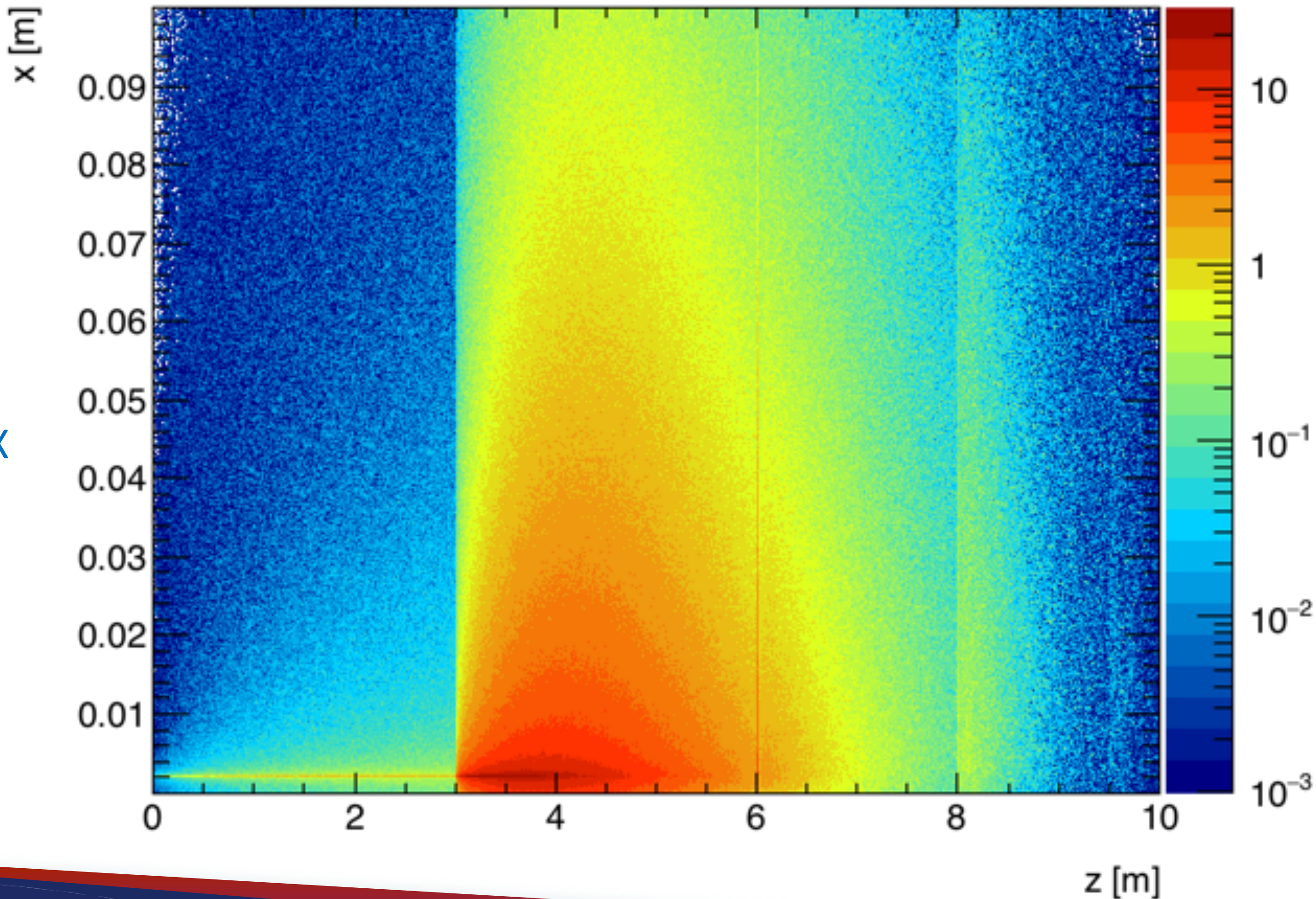
Top energy



BDSIM model2 energy XZ map

- Energy deposition map within absorber for 50000 primaries:

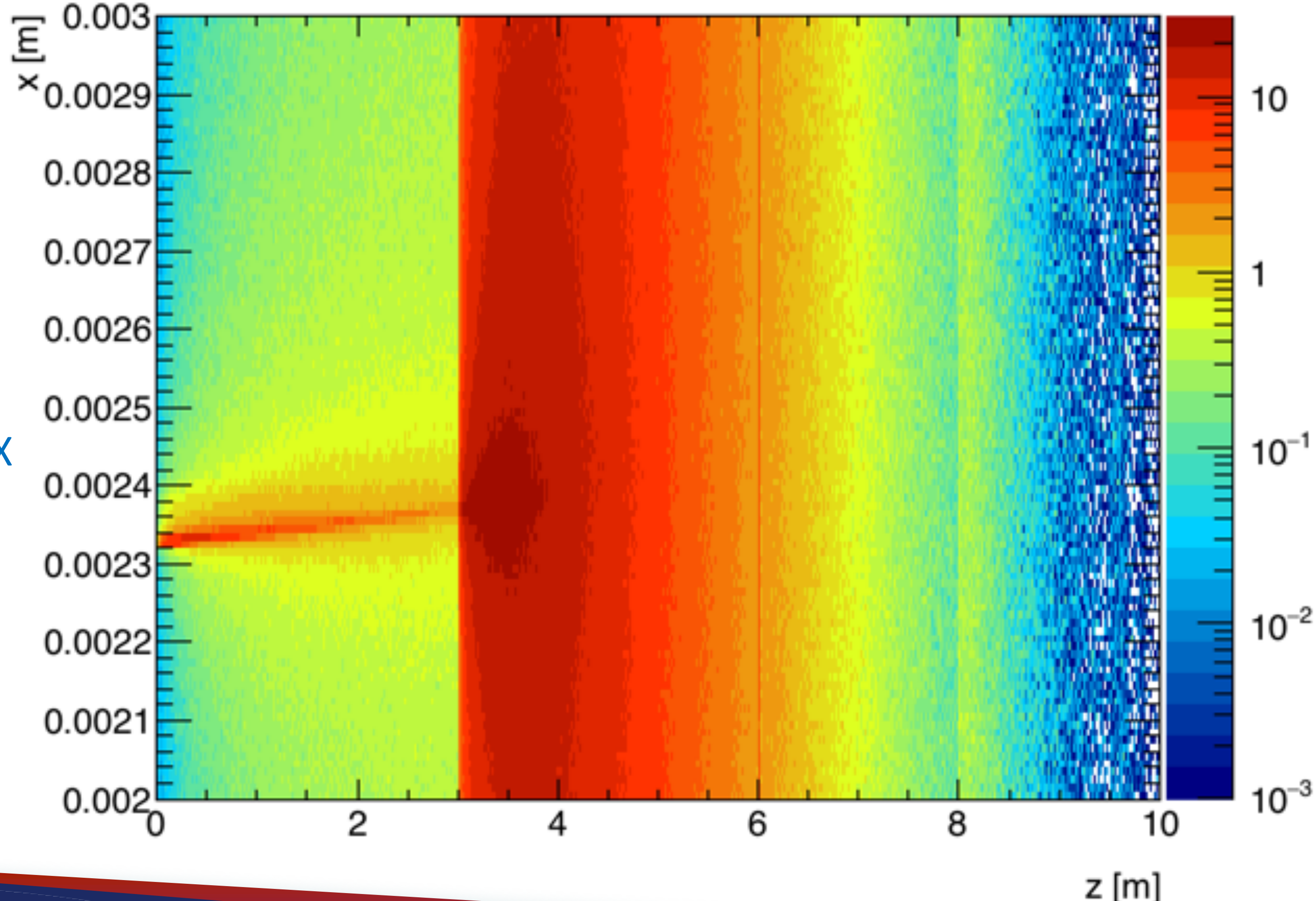
Bin size:
10 micron in X
1 cm in Z



BDSIM model2 energy XZ map

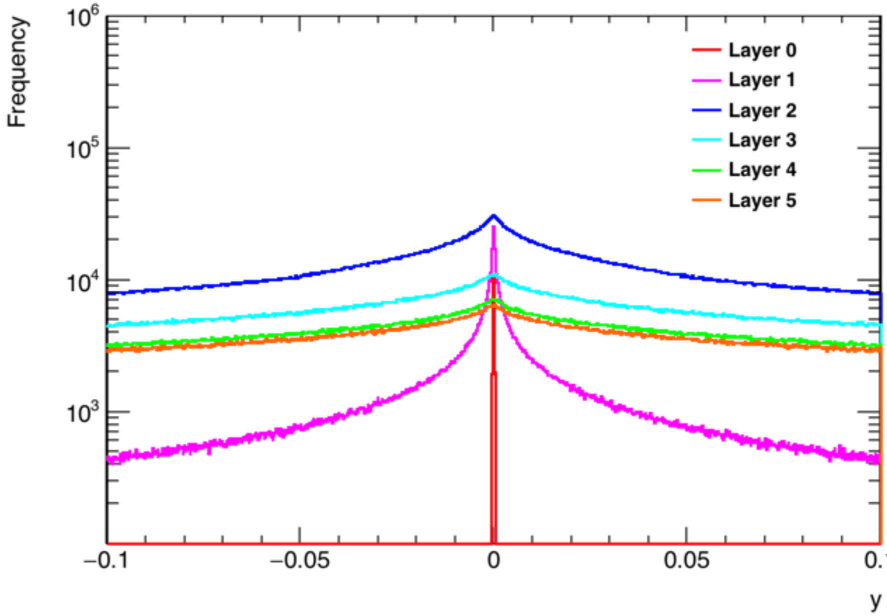
- Energy deposition XZ map within absorber for 50000 primaries:

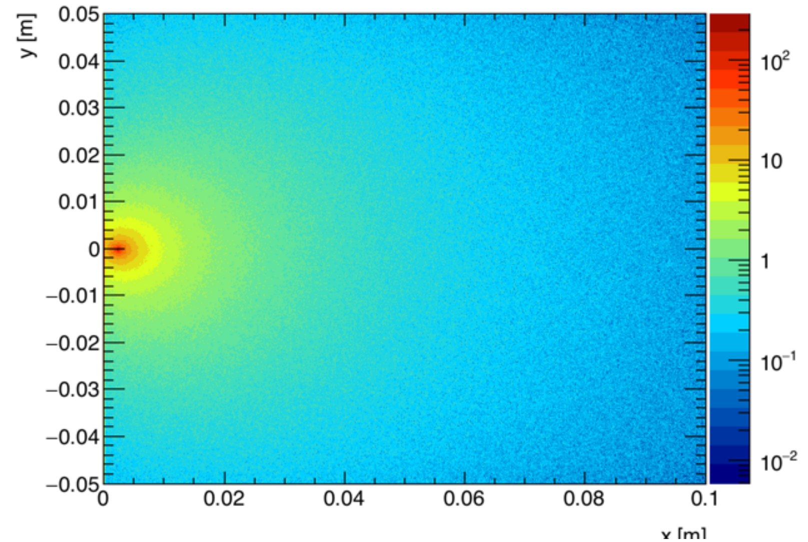
Bin size:
10 micron in X
1 cm in Z

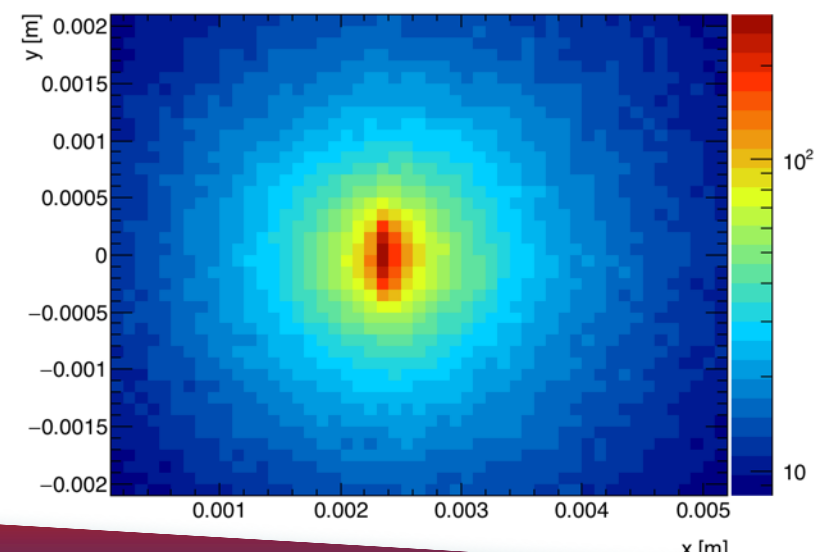


BDSIM model2 energy XY map

- Energy deposition map in XY within absorber for 50000 primaries:
- Y distribution for forward going tracks at each sample layer:

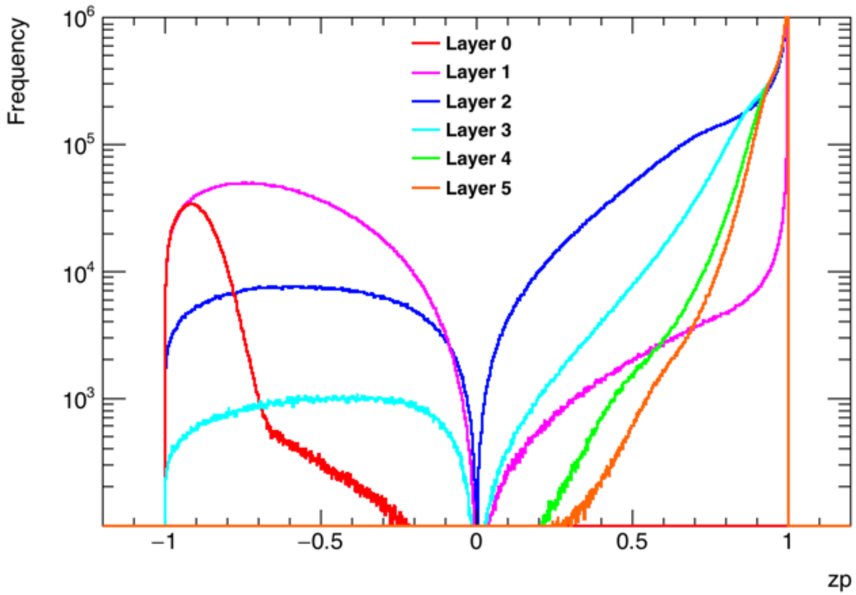


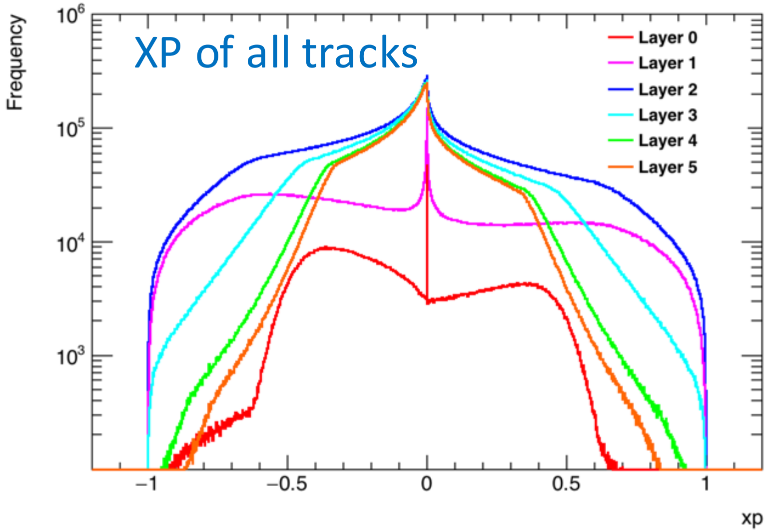


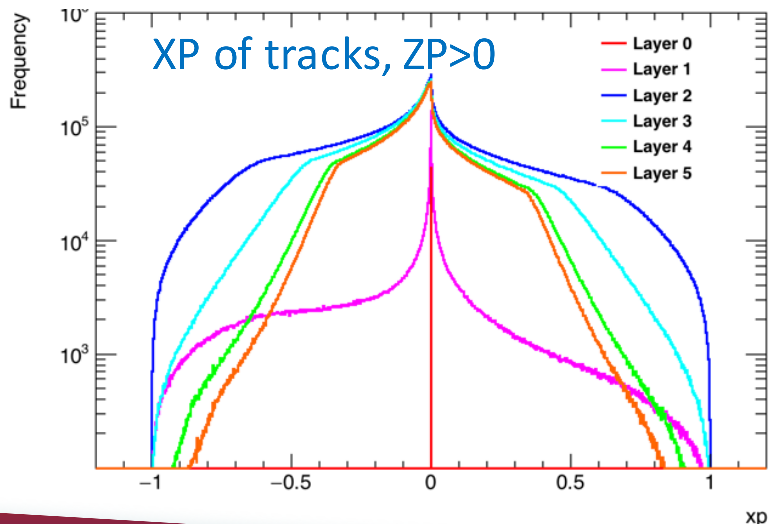


BDSIM model2 tracking

- Particles are tracked back through the sampling layers: zp < 0.







Conclusion and outlook

- Presented first simulations of a proton absorber for crystal collimation in BDSIM:
  - Energy deposition profiles in each layer of absorber, with most energy in layers 2 and 3, of graphite and molybdenum graphite.
  - Detailed Geant4 energy deposition maps produced.
- Outlook:
  - Would be interesting to validate G4 maps against collimator energy deposition studies with other code.
  - Check effect of variation in the G4 Physics List on energy deposition.
  - Output from BDSIM could be used as input to thermo-mechanical model.
  - ***Crystal collimation code could be integrated into BDSIM, allowing a one step simulation of energy deposition, and full tracking of the secondaries produced by the absorber.***

Thank you for your attention