BDSIM for Muon Simulations

L. Nevay, S.T. Boogert, S.M. Gibson
on behalf of BDSIM group & developers

UK Muon Collider and nuSTORM 2nd Collaboration Meeting
27th September 2021

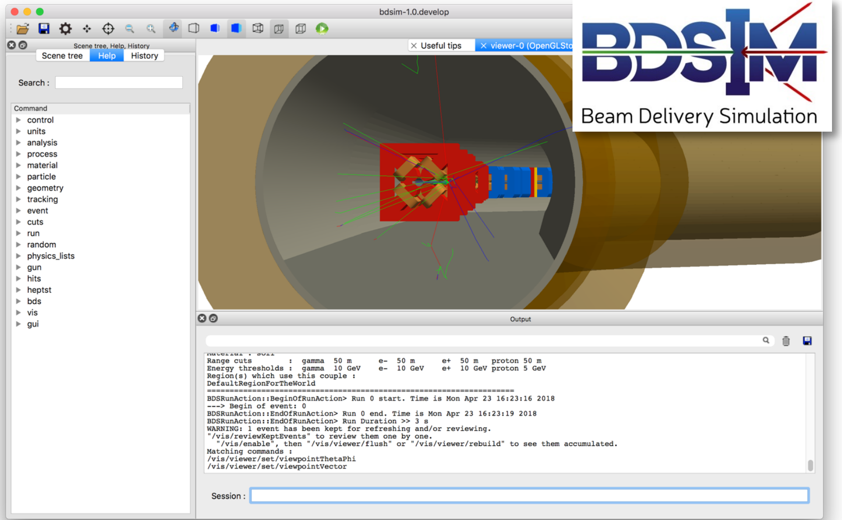
Introduction

- BDSIM overview
- Example applications
- Relevant features
- Collaboration and extension
- Potential for muon simulations

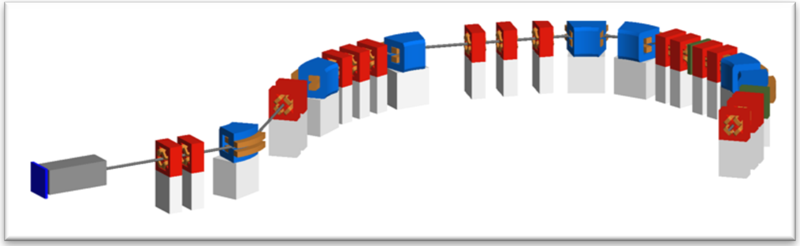
Beam Delivery Simulation (BDSIM)

- BDSIM is a tool to study beam losses and backgrounds in accelerators
  - for when we expect ***particle-matter*** interaction
- Based on Geant4 which is commonly used to make 3D detector models
- Automatically build 3D Geant4 models of accelerators using generic geometry
- A combination of accelerator tracking and 3D radiation transport
  - tracks all secondary particles produced by Geant4
  - includes in-flight processes such as ***decay***
- Optical tracking including fringe fields that matches MADX

[Computer Physics Communications (252), July 2020, 107200](#)



Beam Delivery Simulation

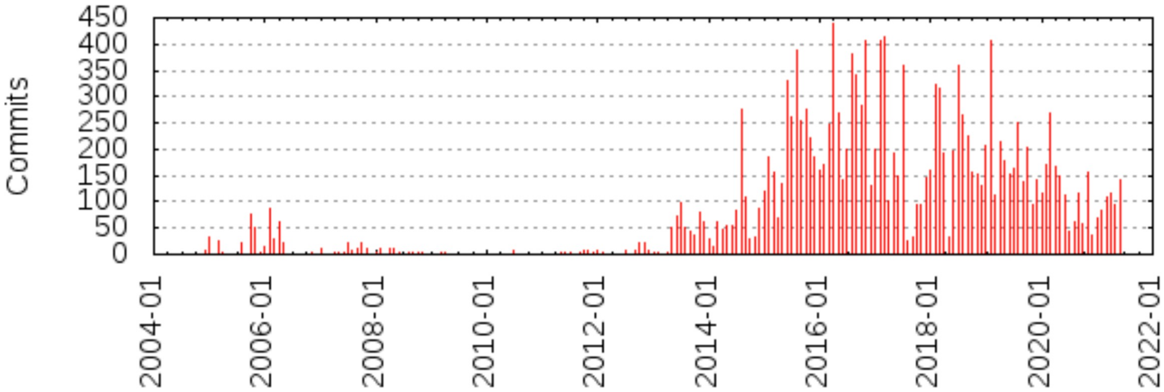


BDSIM - website - manual - paper

A Bit of History

- BDSIM was started by G. Blair in 2004
- Original purpose was muon backgrounds for linear colliders
  - require accelerator tracking + interaction with material + decay
- Since 2013 it has been modernised and vastly extended
  - new geometry library, circular machine support, new output and analysis, biasing

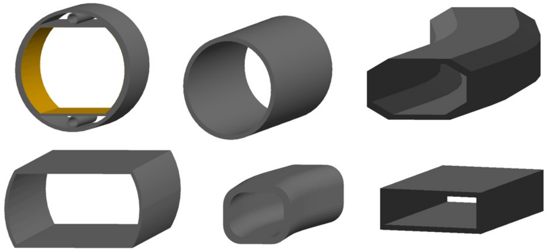
- Publication in 2020
- New applications to low energy medical systems



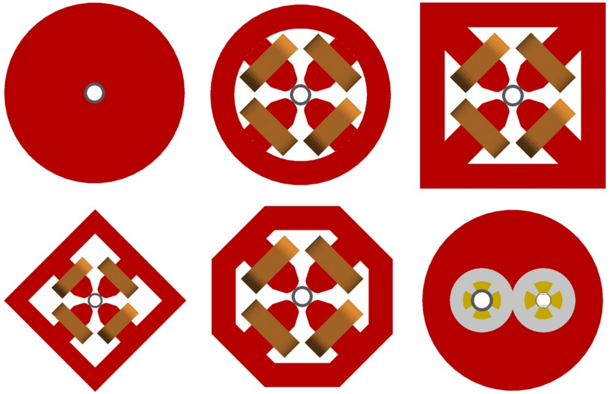
The 3D Model - Complexity & Time

- Accelerators are typically repetitive and similar in design
- Described by list of elements in order:

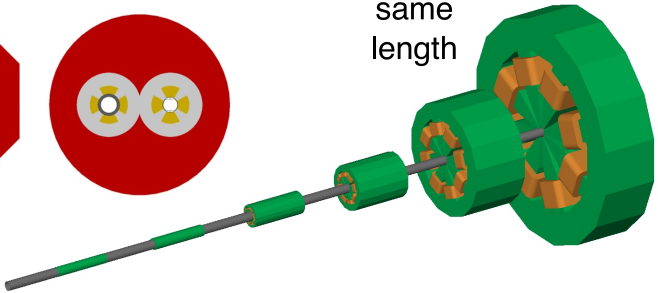
```
drift, dipole, drift, quadrupole, drift, quadruple, drift
```



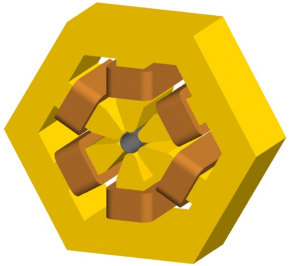
- Provide library of typical accelerator components with adjustable proportions



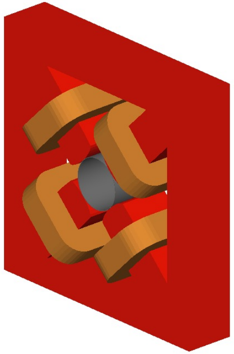
different yoke styles



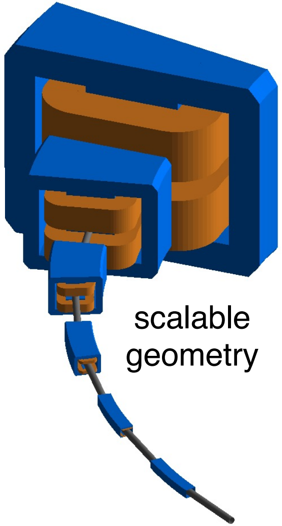
all the same length



sextupole



quadrupole



all the same length

scalable geometry

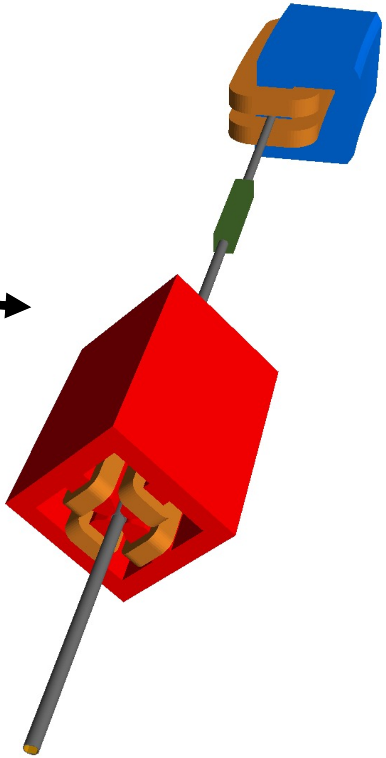
Example BDSIM Syntax

- Human-readable input with parser: "GMAD" syntax - Geant4 + MAD(X)

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;
```

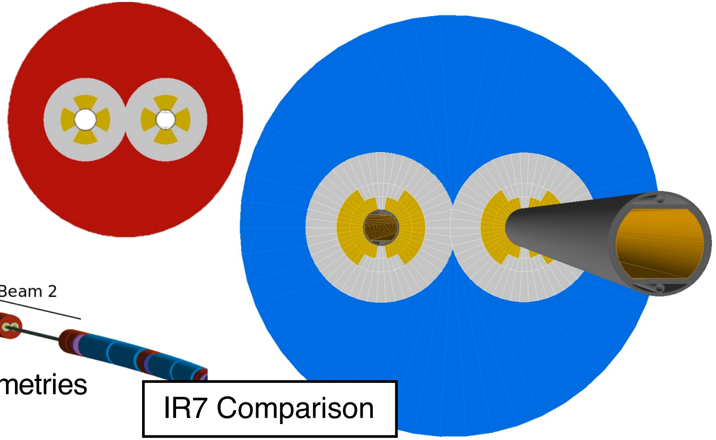
```
-:---  sm.gmad        All L3    Git:develop  (Fundamental)
Wrote /Users/nevay/physics/reps/bdsim/examples/simpleMachine/sm.gmad
```



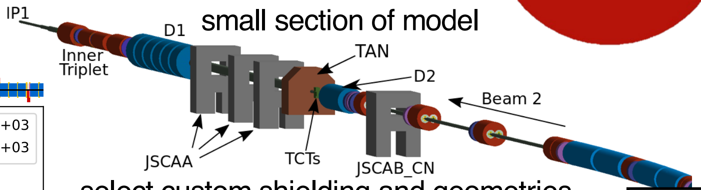
LHC Ion & Proton Collimation

- Full LHC ring model created in BDSIM / Geant4
  - for studying collimation and detector backgrounds
  - ~15k beam line elements with ~300k volumes
  - supports multi-turn tracking
  - mostly based on simplified geometry

generic arc geometry

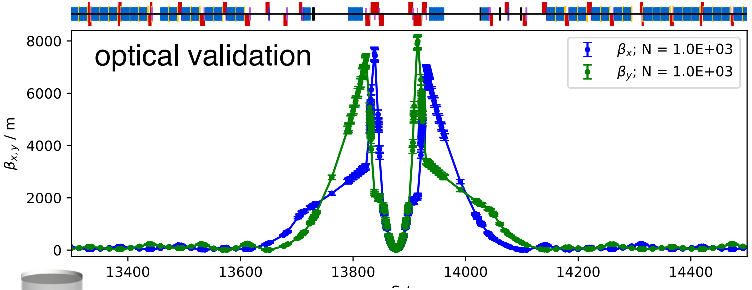


small section of model

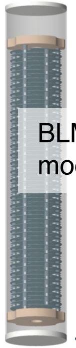


select custom shielding and geometries

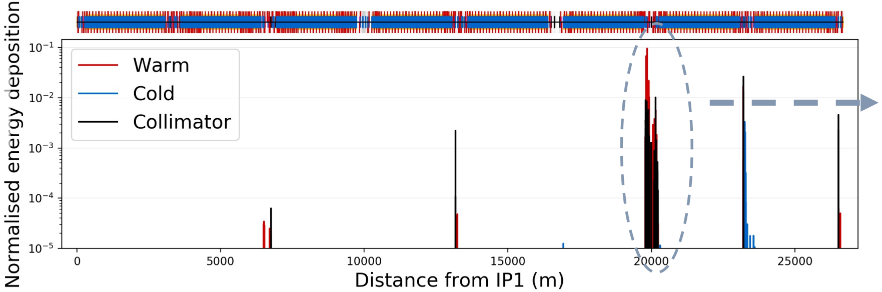
optical validation



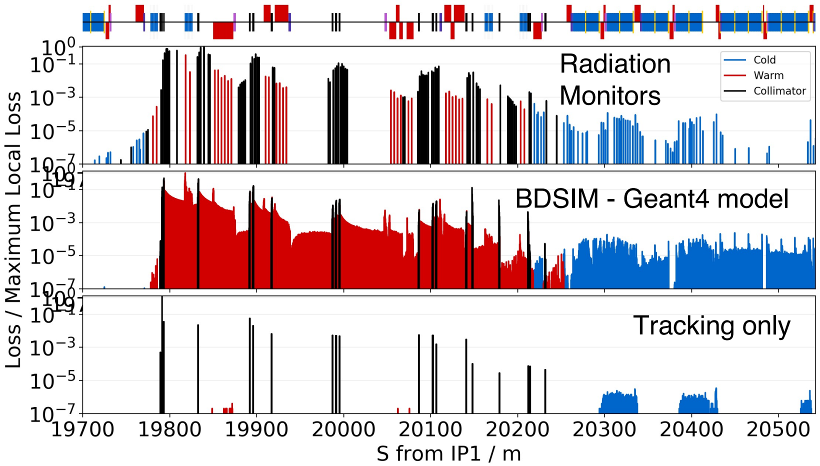
BLM modelling



proton loss map for collimation



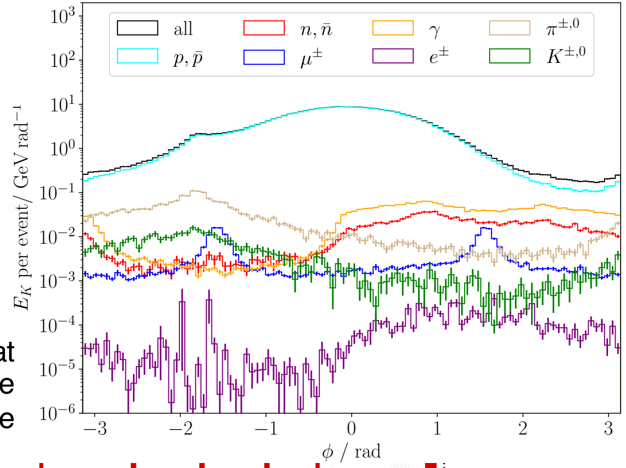
IR7 Comparison

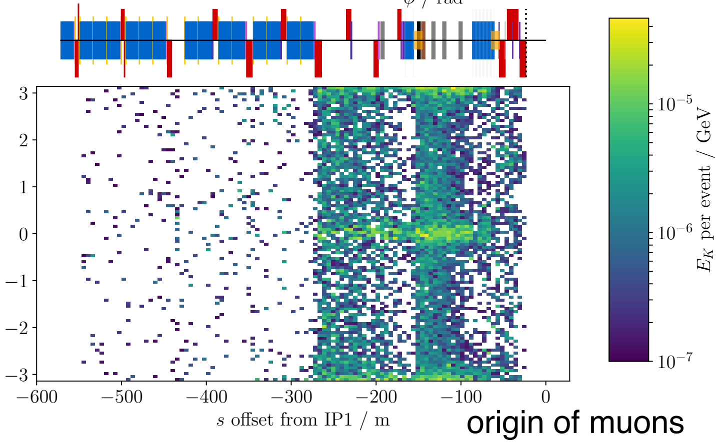


ATLAS Non-Collision Backgrounds

- Detailed model of IR1 leading up to ATLAS created
- Beam simulated up to "interface plane" 22.6m before
  - hand off to dedicated ATLAS simulation
- Simulate experimental pressure bumps using cross-section biasing in select regions
- Simulations allow understanding of origin and transport of penetrating background
- Good agreement with experimental data found

spectra at interface plane

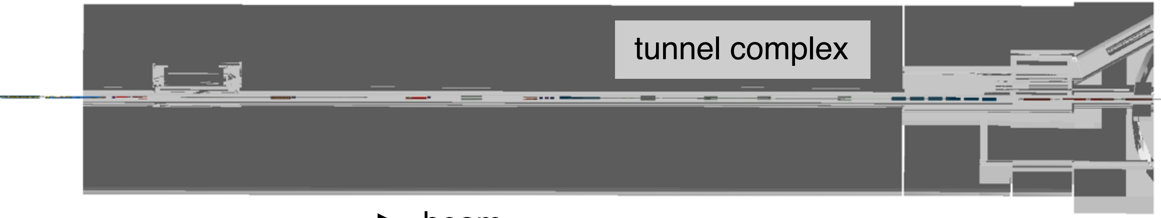




origin of muons

S.D. Walker thesis 2020

~300m before ATLAS

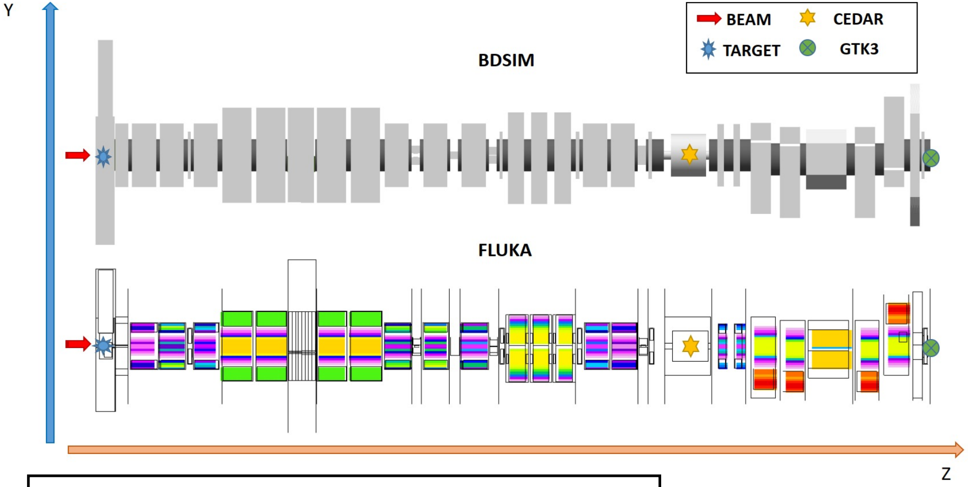


beam

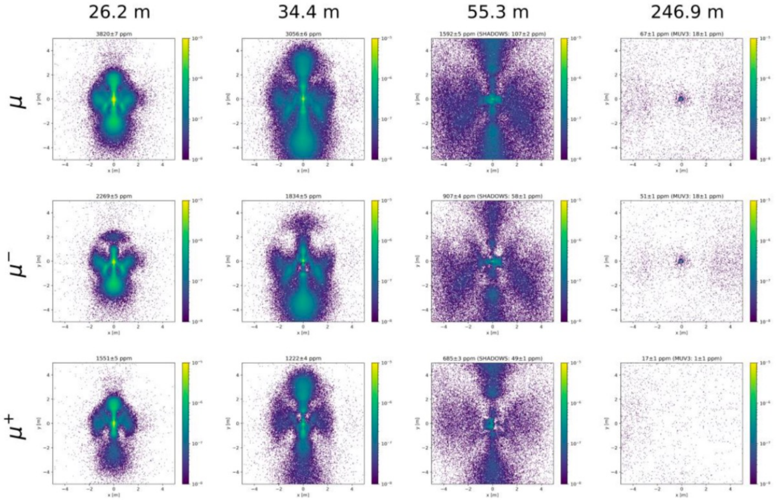
ATLAS IP

NA62 / KLEVER

- NA62 at CERN to study rare charged Kaon decay
- Highly detailed model built by PhD student Gian Luigi D'Alessandro https://arxiv.org/abs/1703.08501
  - joint CERN BE-EA-LE & RHUL PhD



G.L. D'Alessandro, F. Stummer

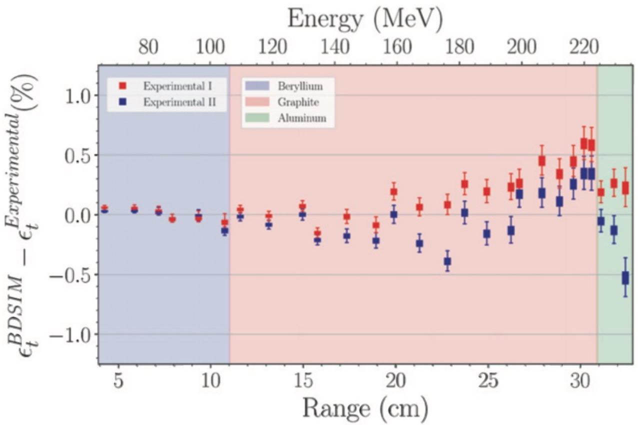


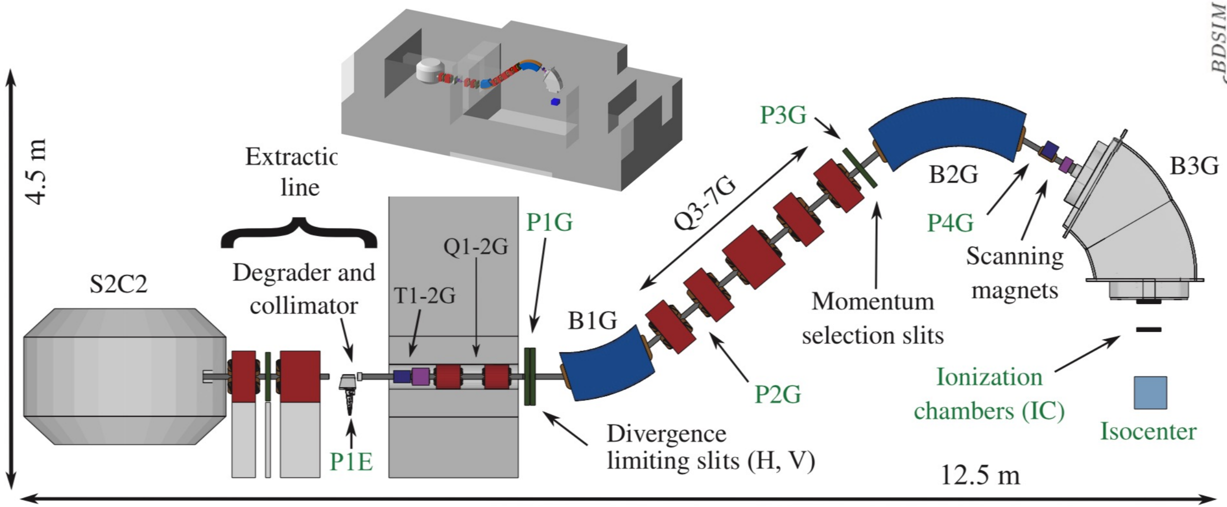
muon distribution at various planes

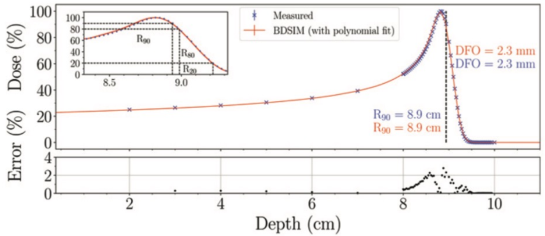
W. Shields, C. Hernalsteens, L. Nevay, R. Tesse

IBA Proton Therapy

- In collaboration with ULB & IBA we simulated their Proteus One system
- Beam launched from exit of cyclotron
  - interaction in material throughout including degrader
- Excellent agreement in Bragg peaks in water phantom
  - full start-to-end simulation
- Further developments underway for space-charge





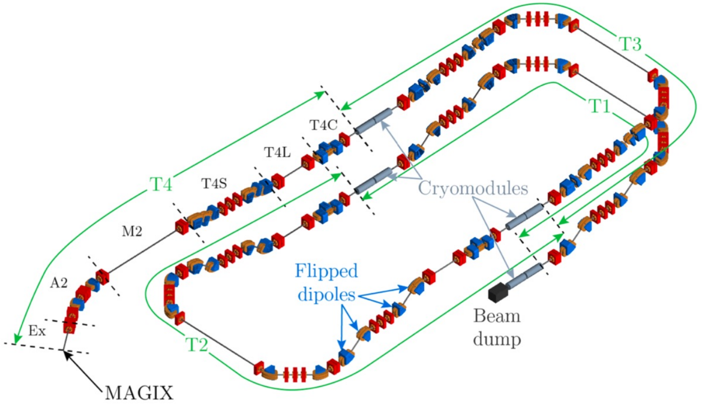


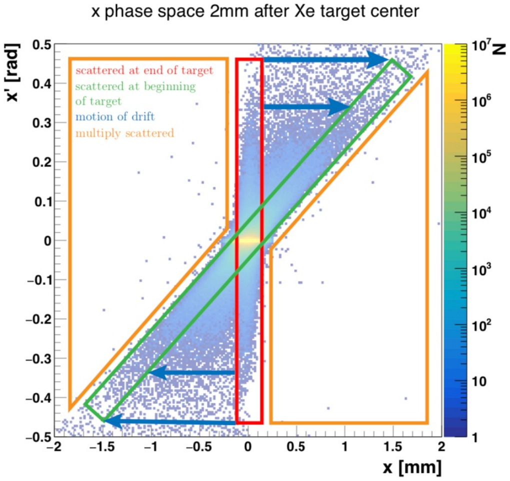
(a) Depth-dose profile for a range of 8.82 cm.

C. Hernalsteens, L. Nevay et al., European Physics Letters, 132 (2020) 50004

MAGIX @ MESA Collimation

- MAGIX @ MESA - energy recovery linac
- Study of halo created by interaction with gas target
- Design of collimation system





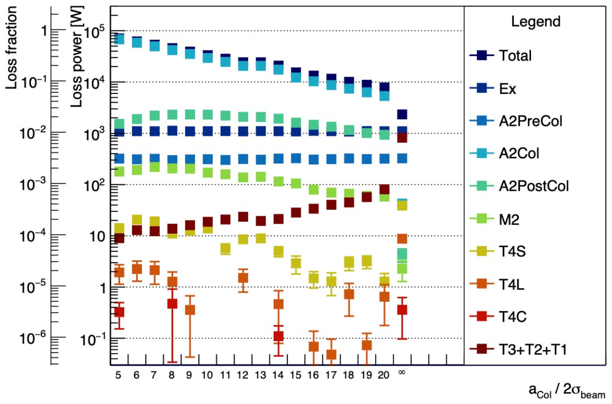


Figure 7.3: Collimator aperture sweep for a Xe target induced halo.

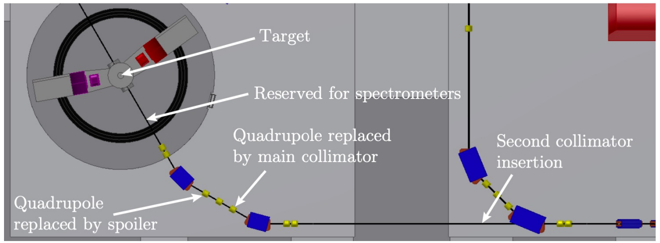


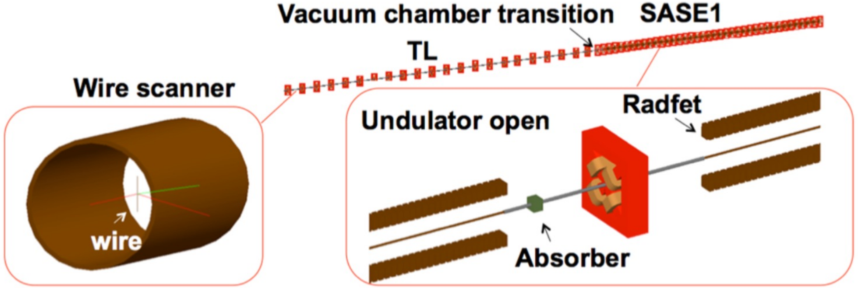
Figure 4.2: Collimator insertions for halo collimation in the MAGIX arc. Dipoles are shown in blue, quadrupoles in yellow. The area in the circular platform around the MAGIX target is reserved for spectrometer movement.

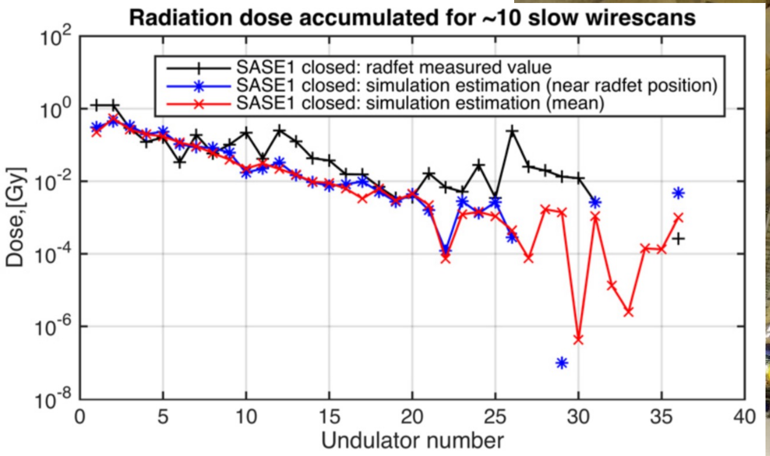
Thesis (2021): http://doi.org/10.25358/openscience-5808

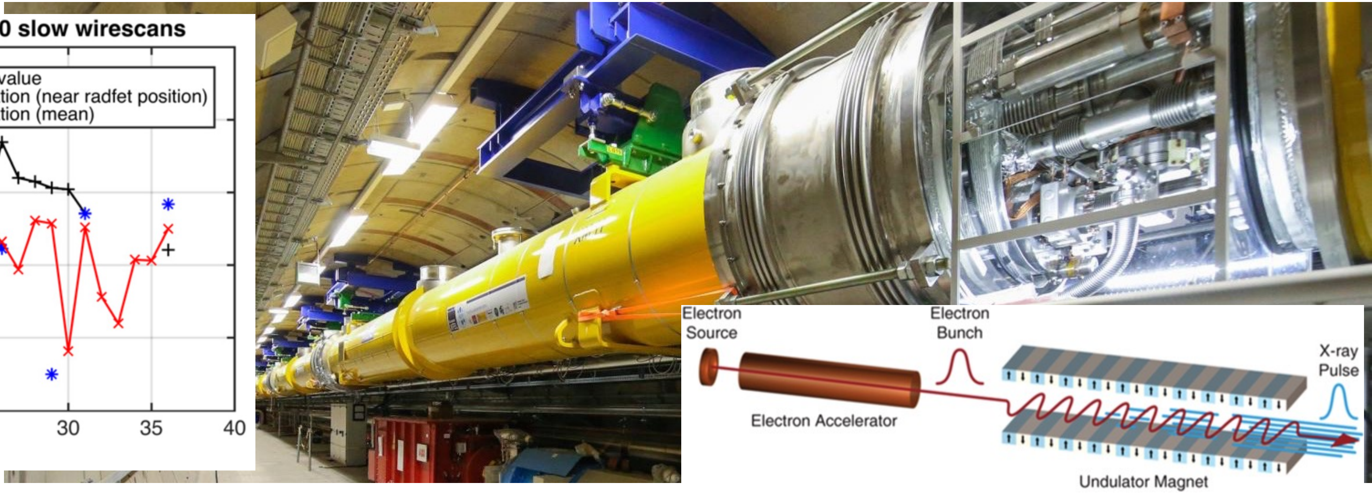
B. Ledroit and K. Aulenbacher 2019 *J. Phys.: Conf. Ser.* **1350** 012138

DESY XFEL in Hamburg

- X-ray Free Electron Laser I(XFEL)
- Use e$^-$ beam for X-rays
- Radiation can damage permanent magnets
  - from both synchrotron radiation and beam losses
- Simulate maximum use of wire-scanners







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

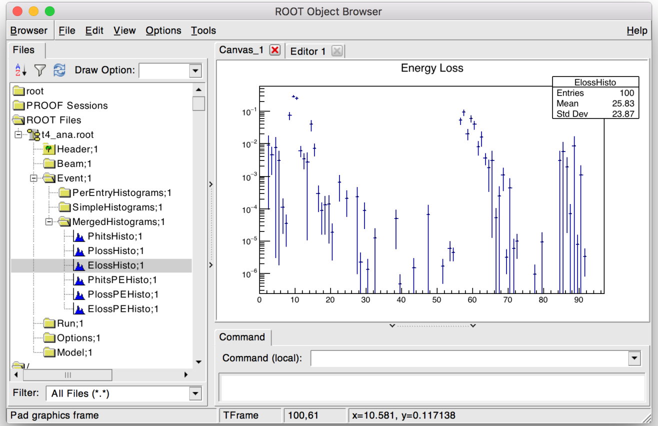
Analysis & Understanding of Beam Losses

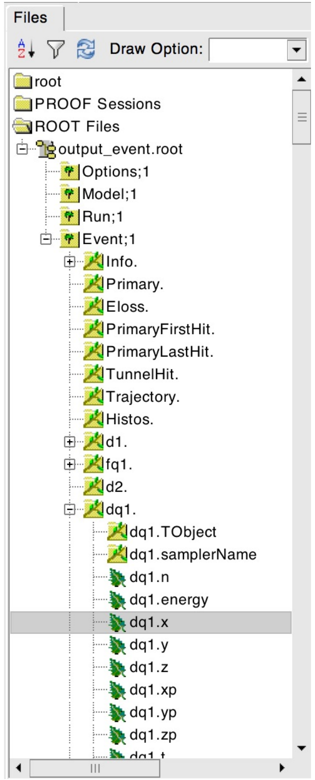
- BDSIM uses ROOT for data and analysis
  - "per event" analysis allows the history or each particle to be understood
  - complete statistical uncertainties for simulation convergence
  - scalable to billions of events and multi-TB data sets
- Understand origin and mechanisms of particular radiation at a particular point
- Filtering based on any parameters in the data
- Included easy-to-use tools for making histograms and combination of results

History of $\overline{\nu}_{\mu}$

π^{-} -> $\overline{\nu}_{\mu}$	59.99 +- 2.66 %
K^{-} -> $\overline{\nu}_{\mu}$	12.72 +- 1.20 %
K_{L}^{0} -> $\overline{\nu}_{\mu}$	5.83 +- 0.92 %
3122 -> π^{-} -> $\overline{\nu}_{\mu}$	4.02 +- 0.11 %
K_{S}^{0} -> π^{-} -> $\overline{\nu}_{\mu}$	3.15 +- 0.10 %
p -> π^{-} -> $\overline{\nu}_{\mu}$	1.66 +- 0.08 %
primary : $\overline{\nu}_{\mu}$	1.31 +- 0.44 %

Example history analysis of neutrinos reaching FASER experiment at the LHC





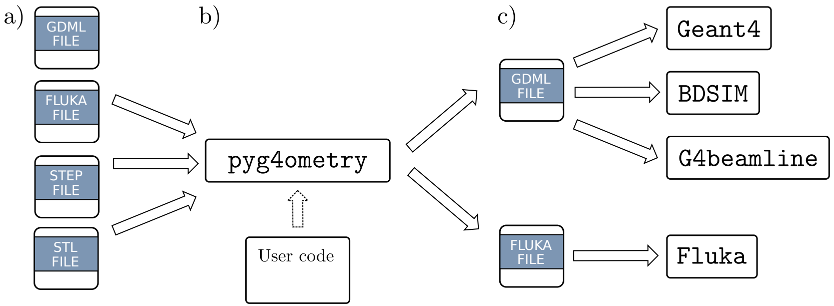
Relevant Features for Muon Simulations

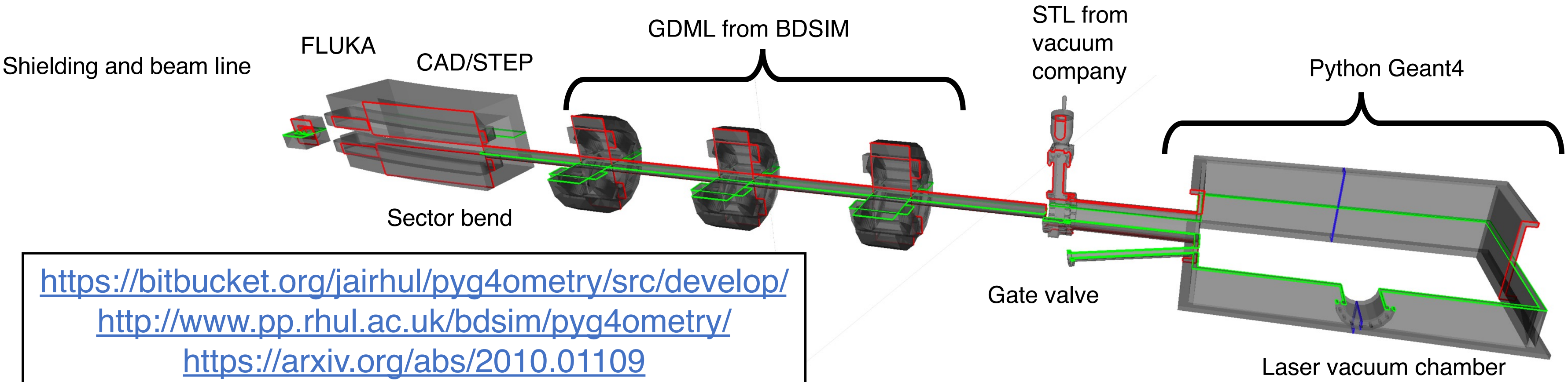
- Access to all of Geant4 physics processes - regularly maintained and updated
- Tracking of all particle types and production of secondary particles
- Custom geometry / beam line elements
  - can be imported geometry or with own C++ class
- Field map support in 1-4D
  - choice of interpolators, choice of dimensions (e.g. z+t or x,y), combinations of E & B
  - choice of numerical integrators - all integrators in Geant4 available (including high order ones)
- Cross-section biasing (particle : process : volumes)
  - e.g. LHC beam gas: in vacuum, bias hadronic inelastic for protons by 10^{10}
  - doesn't affect secondaries, all weights propagated
- Powerful analysis tools and data structure
  - specifically structured for understanding histories and origin mechanisms
  - approachable in Python and ROOT or via provided tools with simple text input files
- Sample planes (i.e. flat) in a 3D model for recording accelerator-code-like distributions
- Collimator-specific information / infinite absorbers -> analyse (combined) effects of collimators
- 6D distribution calculator for optical functions including full statistical uncertainties
  - sigmas, error on sigmas, covariance matrix…

Stewart Boogert

pyg4ometry for Custom Geometry

- Python package to rapidly prepare and convert geometry for Geant4 & FLUKA
  - create / convert / composite geometry
  - validate and ensure safe for tracking (no overlaps etc)
- Place custom components in Geant4 / BDSIM
- Have parity with models in **Geant4 & FLUKA**





https://bitbucket.org/jairhul/pyg4ometry/src/develop/
http://www.pp.rhul.ac.uk/bdsim/pyg4ometry/
https://arxiv.org/abs/2010.01109

email stewart.boogert@rhul.ac.uk

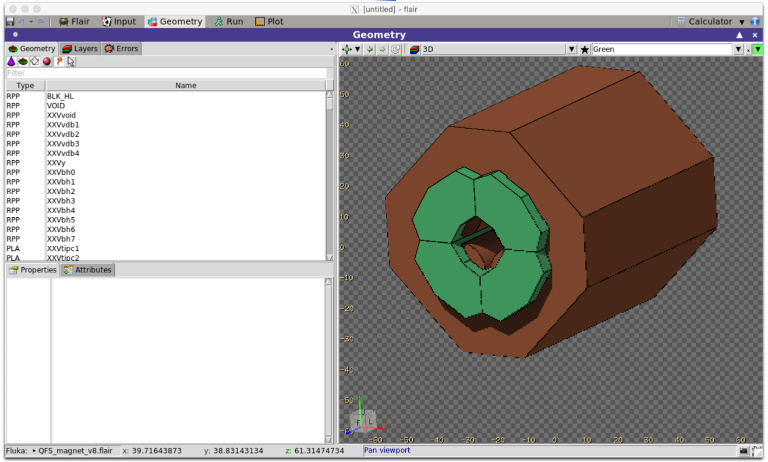
Example Conversion: FLUKA TO GDML

- KLEVER QFS Quadrupole designed in FLAIR and translated to Geant4.

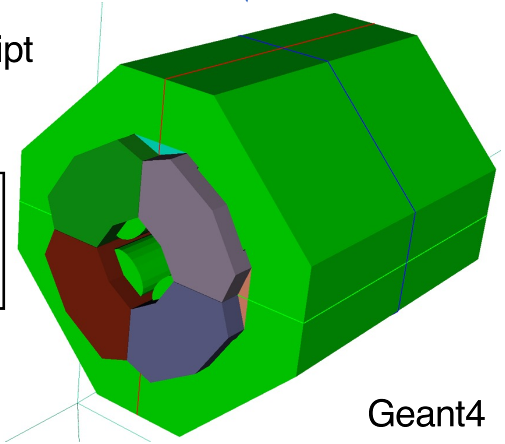
```
import pyg4ometry.fluka as fluka
import pyg4ometry.convert as conver

reader = fluka.Reader("qfs.inp")
greg = convert.fluka2Geant4(reader.flukaregistry)
wlv = greg.getWorldVolume()

v = vi.VtkViewer()
v.addLogicalVolume(wlv)
v.setOpacity(1)
v.setRandomColours()
v.view()
```

Simple Pyg4ometry script

See J. Back's slides (#12) for use of pyg4ometry



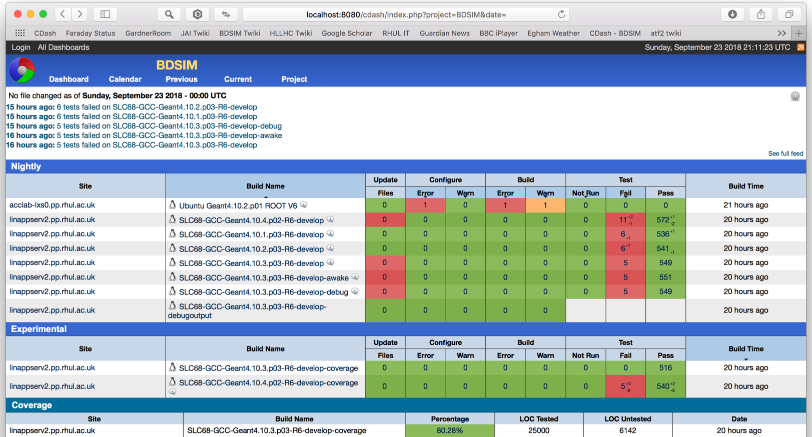
FLUKA (FLAIR)



Geant4

Open Source, Collaboration & Documentation

- BDSIM is open source GPL3
  - public git repository with issue tracker
- Collaboration is very welcome to extend the code
  - via git, pull requests, joint access
- The code is as modular as possible making single piece extensions relatively easy and self contained
  - e.g. new beam line element, new variables in parser, new fields
- BDSIM can be used as a class (library) inside another C++ program / MC chain
- Every example is also a test (> 800)
  - regular nightly testing with CTest, CDash
- Thorough manual and Doxygen
  - regular use by undergraduates for projects
- Ongoing development for several applications
- Symplectic tracker nearly complete



Login All Dashboards
Sunday, September 23 2018 21:11:23 UTC

BDSIM

Dashboard Calendar Previous Current Project

No file changed as of **Sunday, September 23 2018 - 00:00 UTC**
15 hours ago: 6 tests failed on SLC68-GCC-Geant4.10.2.p03-R6-develop
15 hours ago: 6 tests failed on SLC68-GCC-Geant4.10.1.p03-R6-develop
15 hours ago: 5 tests failed on SLC68-GCC-Geant4.10.3.p03-R6-develop-debug
16 hours ago: 5 tests failed on SLC68-GCC-Geant4.10.3.p03-R6-develop-awake
16 hours ago: 5 tests failed on SLC68-GCC-Geant4.10.3.p03-R6-develop

See full feed

Nightly

Site	Build Name	Update	Configure		Build		Test			Build Time
		Files	Error	Warn	Error	Warn	Not Run	Fail	Pass	
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

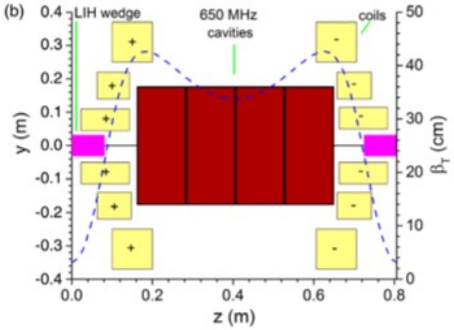
Site	Build Name	Update	Configure		Build		Test			Build Time
		Files	Error	Warn	Error	Warn	Not Run	Fail	Pass	
linappserv2.pp.rhul.ac.uk	SLC68-GCC-Geant4.10.3.p03-R6-develop-coverage	0	0	0	0	0	0	0	516	20 hours ago
linappserv2.pp.rhul.ac.uk	SLC68-GCC-Geant4.10.4.p02-R6-develop-coverage	0	0	0	0	0	0	5^{+3}_{-2}	540^{+2}_{-3}	20 hours ago

Coverage

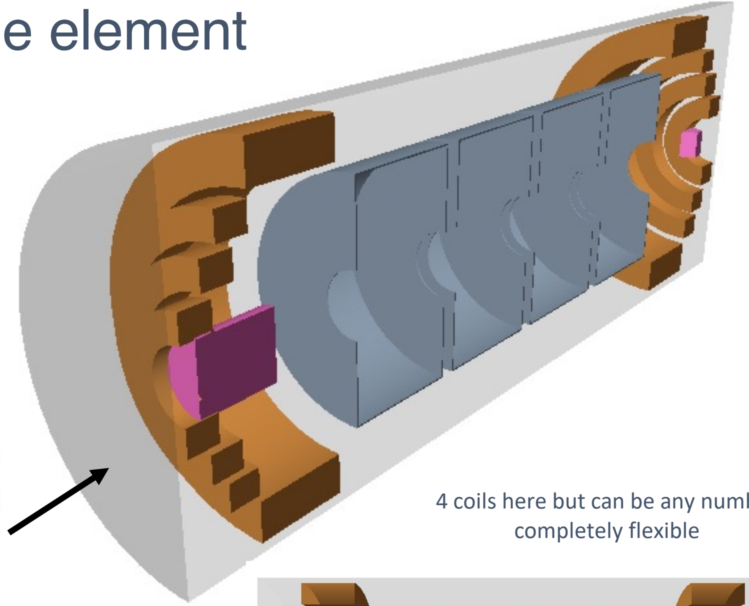
Site	Build Name	Percentage	LOC Tested	LOC Untested	Date
linappserv2.pp.rhul.ac.uk	SLC68-GCC-Geant4.10.3.p03-R6-develop-coverage	80.28%	25000	6142	20 hours ago

Prototype Implementation of Muon Cooler

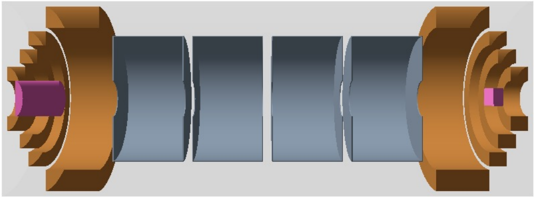
- An example implementation has been started
- New C++ class for muon cooler beam line element
- Variables:
  - absorber type / number
  - RF Cavities / number / field
  - coils / number / shape / current
- To be implemented:
  - 'block' solenoid B field
  - superposition of fields
  - surrounding geometry
  - other cooler designs



Phys. Rev. ST Accel. Beams 18, 031003 (2015)



4 coils here but can be any number
completely flexible



"cooling-channel" branch in git repository

Thank you for your attention

L. Nevay, S. Boogert, A. Abramov[3], G.L. D'Alessandro[3],
S. Alden, S. Gibson, B. LeDroit[1], C. Hernalsteens[2,3],
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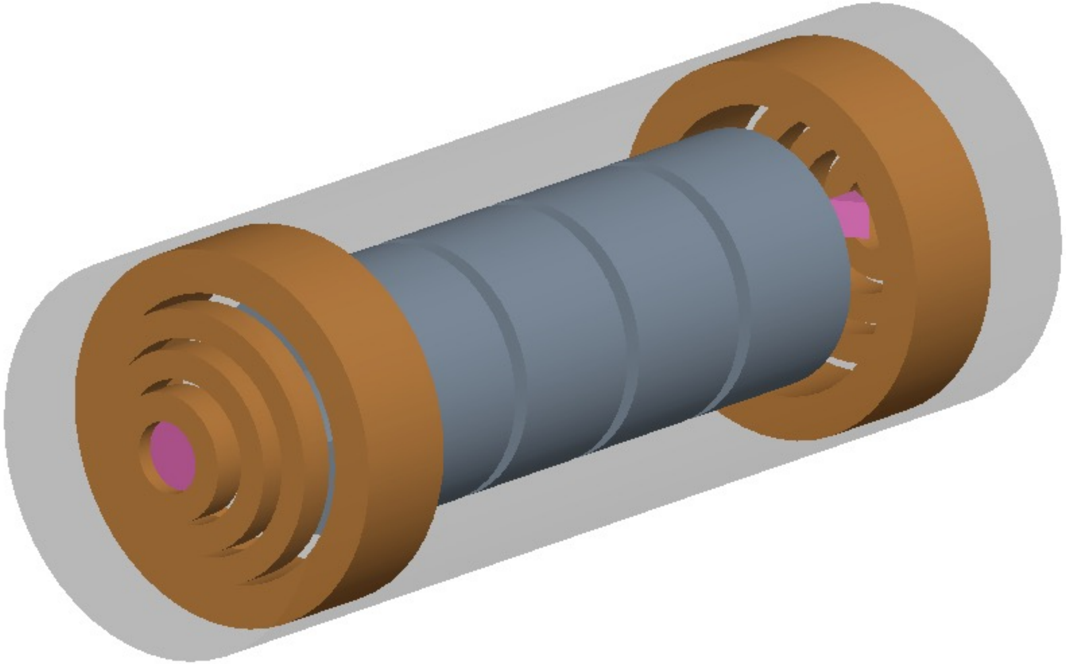
UK Muon Collider and nuSTORM 2nd Collaboration Meeting
27th September 2021

BDSIM - website - manual - paper

BACKUP

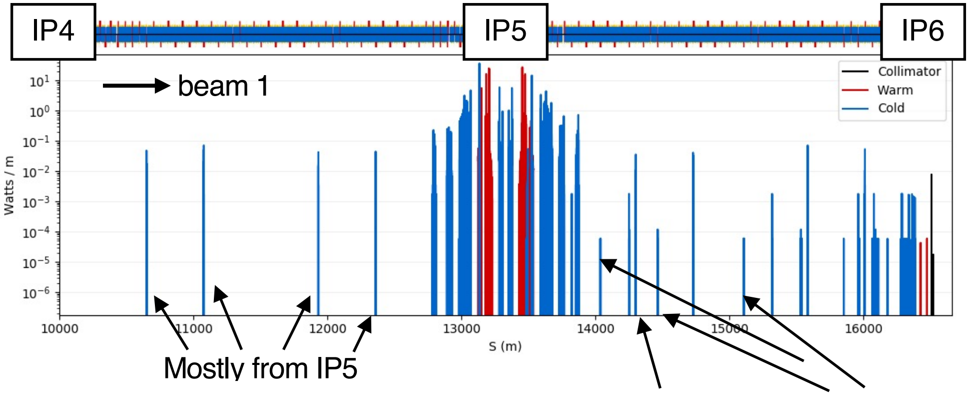
BDSIM Muon Cooler Prototype

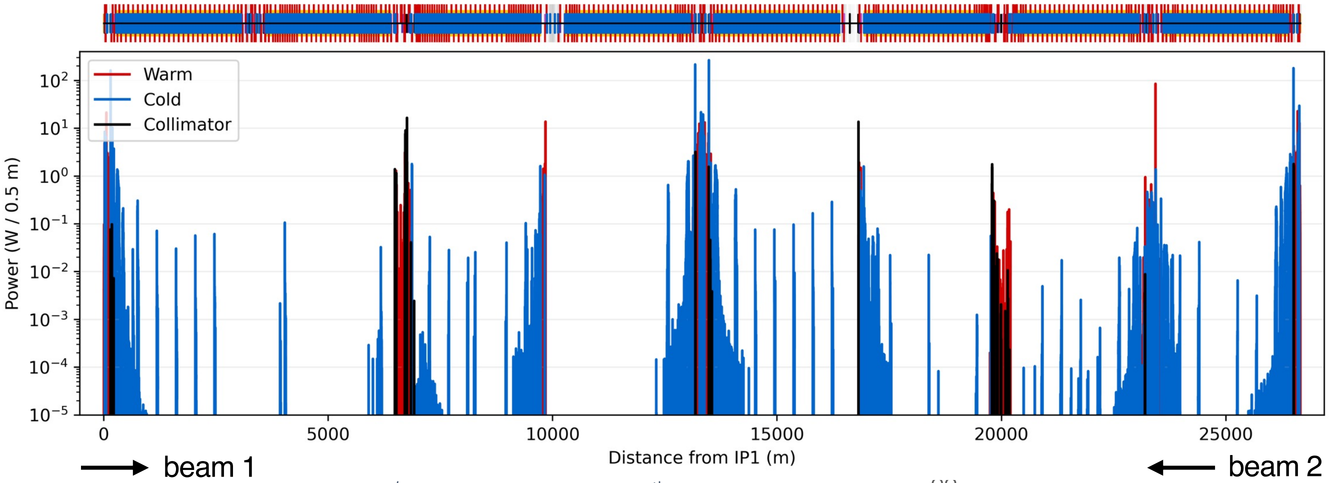


```
cooldef1:  coolingchannel, nCoils=4,
                          coilInnerRadius = {0.1, 0.2, 0.3, 0.4},
                          coilRadialThickness = {0.08, 0.08, 0.08, 0.12},
                          coilLengthZ = {0.1, 0.1, 0.1, 0.3},
                          coilCurrentDensity = {1.2, 1.3, 1.4, 1.5},
                          coilOffsetZ = {-1.42, -1.35, -1.3, -1.1},
                          coilMaterial = {"G4_Cu"},
                          mirrorCoils = 1,
                          nAbsorbers = 2,
                          absorberType = {"cylinder", "wedge"},
                          absorberMaterial = {"G4_Li"},
                          absorberOffsetZ = {-1.3*m,1.3*m},
                          absorberCylinderLength = {25*cm, 0},
                          absorberCylinderRadius = {10*cm, 0},
                          absorberWedgeOpeningAngle = {0, 1*rad},
                          absorberWedgeHeight = {0,10*cm},
                          absorberWedgeRotationAngle = {0, 20*mrad},
                          absorberWedgeOffsetX = {0, 5*mm},
                          absorberWedgeOffsetY = {0, 10*mm},
                          absorberWedgeApexToBase = {0, 10*cm},
                          nRFCavities = 4,
                          rfOffsetZ = {-0.675, -0.225, 0.225, 0.675},
                          rfLength  = {0.4, 0.4, 0.4, 0.4},
                          rfVoltage = {500*kV, 500*kV, 600*kV, 600*kV},
                          rfPhase = {0, 0, halfpi, halfpi},
                          rfFrequency = {0, 0, 2*MHz, 3*MHz},
                          rfWindowThickness = {100*um, 100*um, 100*um, 100*um},
                          rfWindowMaterial = {"G4_B", "G4_B", "G4_B", "G4_Al"},
                          rfWindowRadius = {10*cm},
                          rfCavityMaterial = {"G4_Cu"},
                          rfCavityVacuumMaterial = {"vacuum"},
                          rfCavityRadius = {35*cm},
                          rfCavityThickness = {5*mm};


mc1: muoncooler, l=3*m, horizontalWidth=1.1*m, coolingDefinition="cooldef1";

lat: line=(mc1);

include optionsTest.gmad;
```

LHC Physics Debris Simulations

- Simulate head-on p-p collision with event generator at IPs 1,5 and 8
  - some lightly scattered protons make it into arcs
  - ~2.5kW of debris from collisions
- Record energy deposition throughout
  - individual peaks in arcs agree well with known BLMs to be correlated with luminosity





- Understand which IP each spike comes from
- How these will change with different optics in future