

From Hadron Therapy to the LHC: Modelling Accelerators Across Energy Scales



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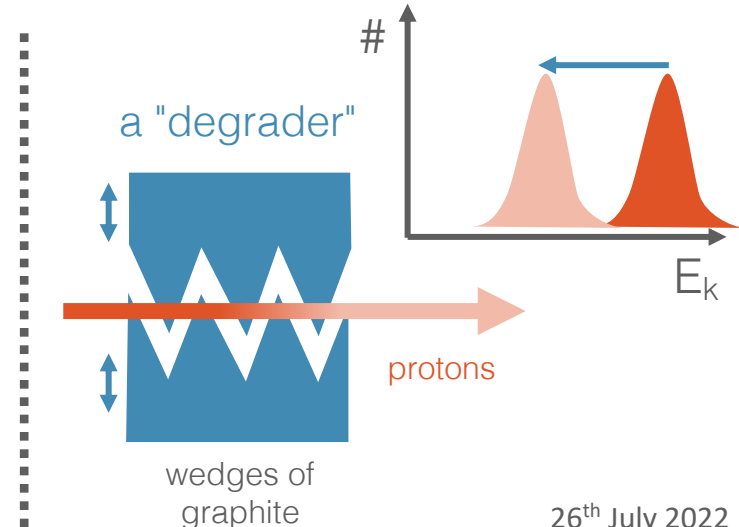
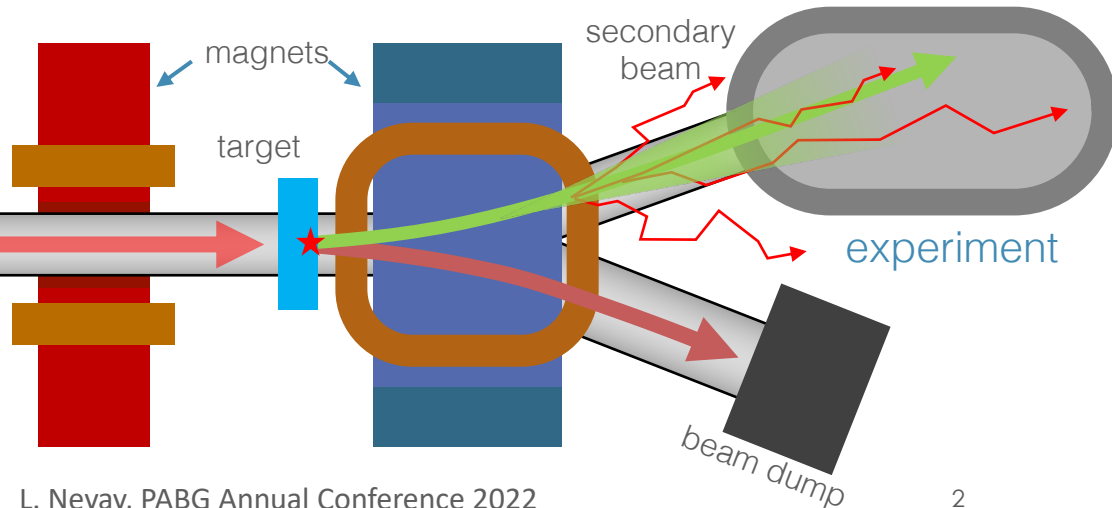


PABG Annual Conference

25th - 26th July 2022 | Liverpool

Beam Losses & Particle-Matter Interaction

- No accelerator contains *all* particles - there will be beam loss
- Consequences can be: *none* / *intended* / *catastrophic*
- Many physics experiments in the vicinity of accelerators experience charged particles from the accelerator as unwanted 'background'
- Many (medical) beam lines use particle-matter interaction



The Machine Detector Interface

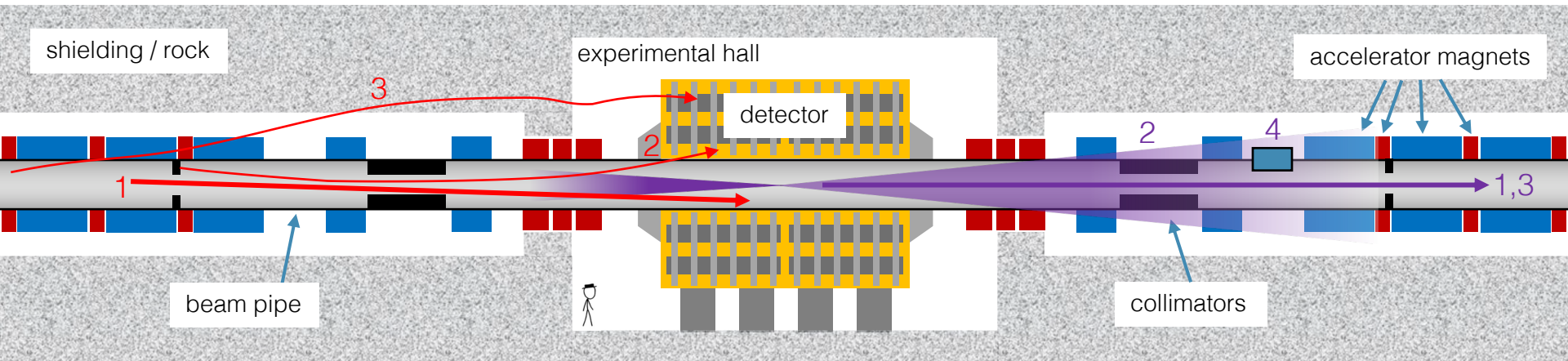
- Radiation / particles in both directions - *both* are interesting

Incoming:

1. products from residual gas interaction
2. leakage from the collimation system
3. general secondaries from beam loss

Outgoing:

1. lightly scattered primaries
2. physics debris
3. forward physics
4. forward experiments

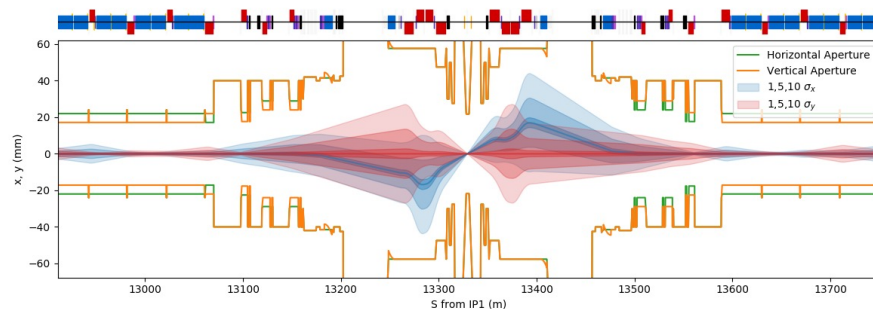


Goal: simulate far reaching particles *in* and *out* of experiment and understand them

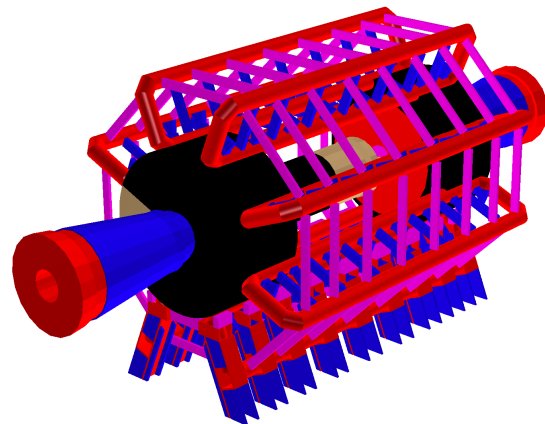
Need: accurate magnetic particle tracking *and* interaction with matter

Accelerator Tracking vs Radiation Transport

- Accelerator tracking accurately models motion of particles in the specific fields in an accelerator
 - typically 1x type of particle in a bunch going forwards with a specific energy
 - most often in *curvilinear* coordinate system for accuracy
- Radiation transport models all particles and their processes in an arbitrary field
 - requires a complex 3D model for an accurate result
 - numerical integration for particle motion can be inaccurate
 - uses *Cartesian* coordinate system
- Need **both, together**



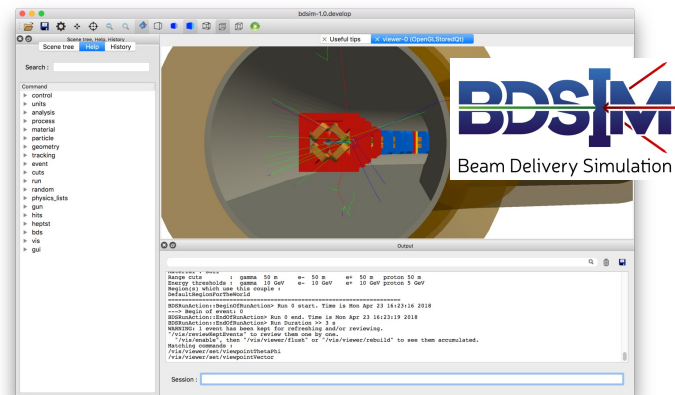
versus



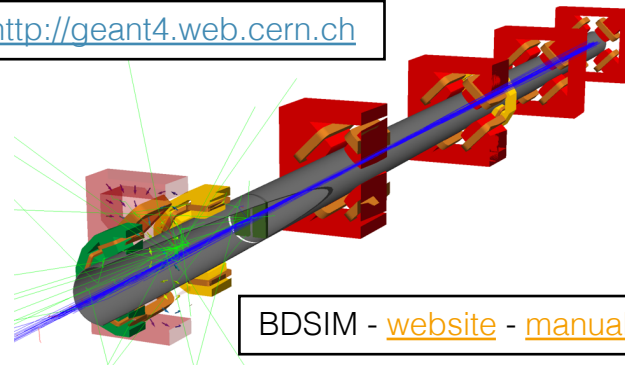
BDSIM - Beam Delivery Simulation



- BDSIM code joins the two seamlessly
 - all particles, all energies
- Automatic **Geant4** models of accelerators
 - rewritten and modernised since 2013
- Library of scalable accelerator components
 - make a model in **minutes to weeks**, not **years**
 - convert from other accelerator codes easily
- Applied to many experiments and machines
 - *FASER, KLEVER, NA62, PS at CERN, ATLAS non-collision backgrounds, FCC-ee, FCC MDI, ILC / CLIC, AWAKE, XFEL, LHC collimation, ICS & H Laserwires, MAGIX at MESA, PSI HIPA*
- Benefit from community-driven Geant4
 - physics models constantly updated and improved



<http://geant4.web.cern.ch>

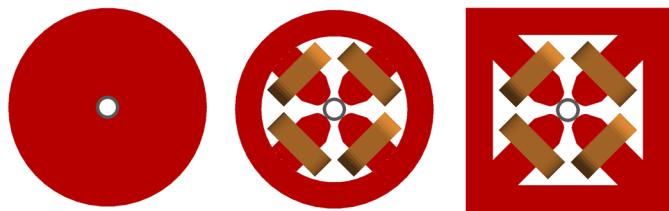


BDSIM - [website](#) - [manual](#)

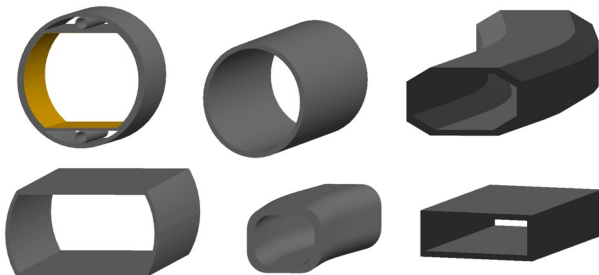
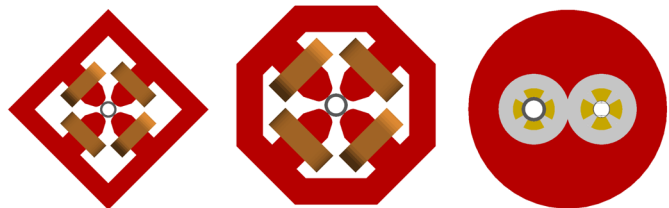
[Comp. Phys. Comm. \(252\), July 2020, 107200](#)

How It Works: Geometry

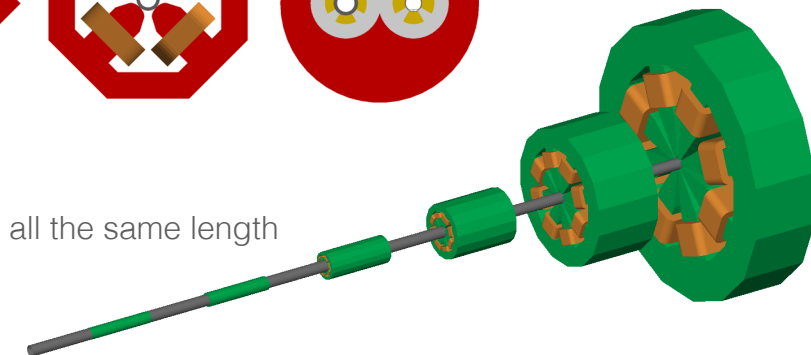
- Provide library of typical accelerator components with adjustable proportions



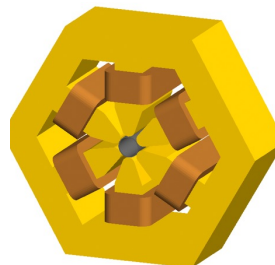
different yoke styles



different apertures



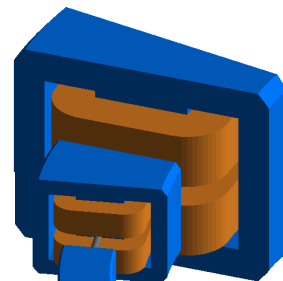
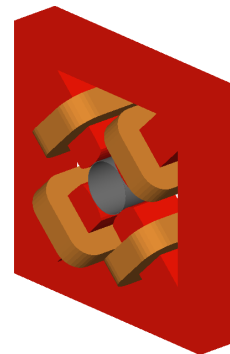
all the same length



sextupole

quadrupole

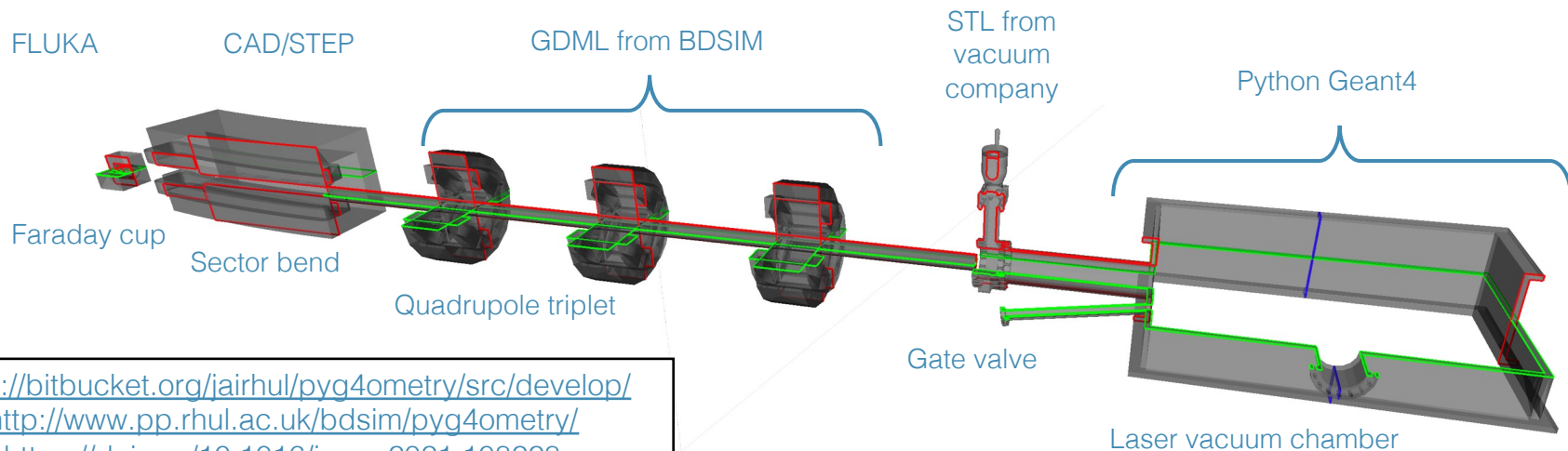
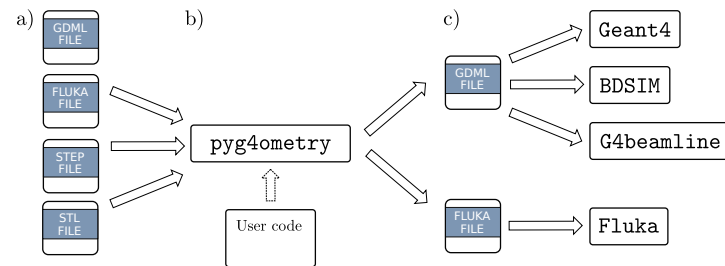
all the same length



scalable geometry

Custom Geometry - pyg4ometry

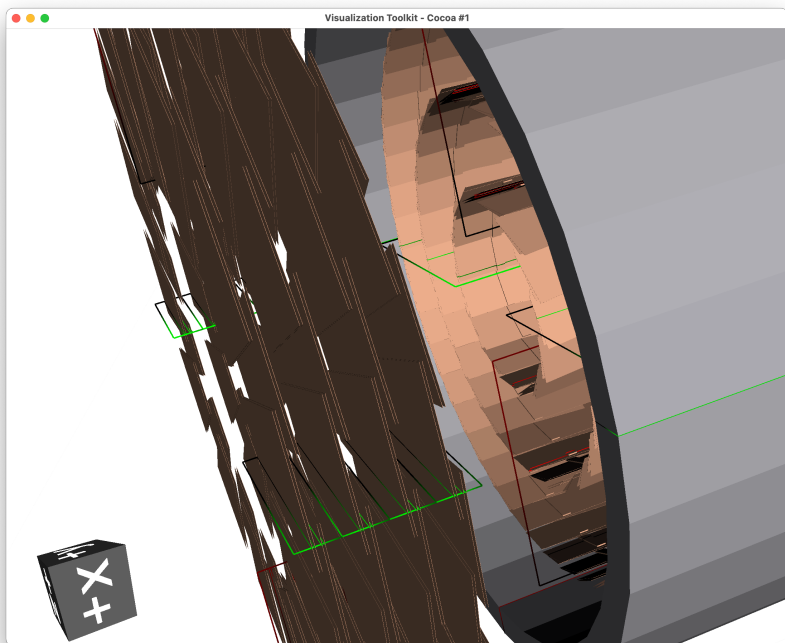
- Python geometry package:
 - create, convert, composite, compare, validate
- Place custom components in Geant4 / BDSIM
- Have parity with models in Geant4 & FLUKA



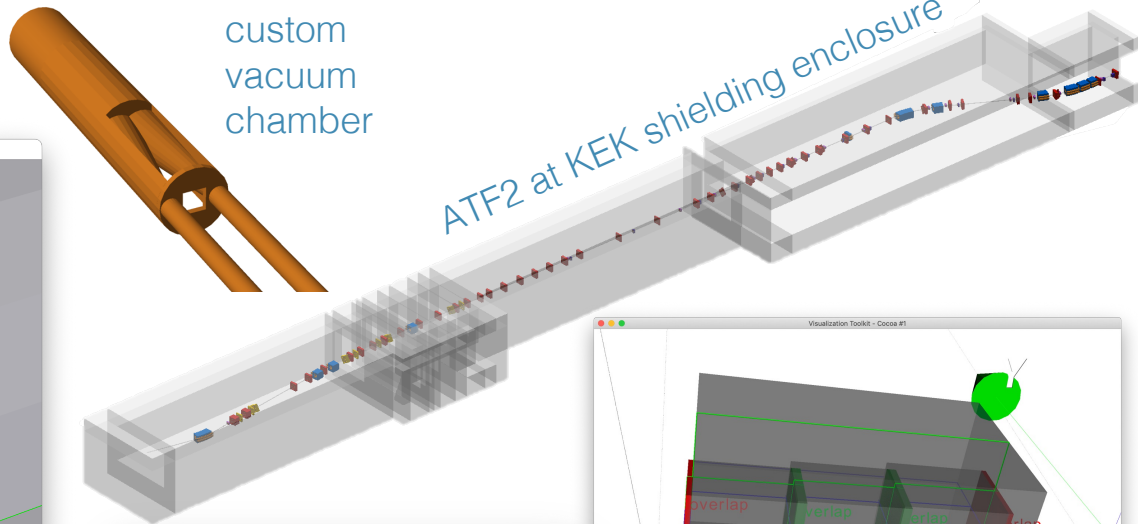
<https://bitbucket.org/jairhul/pyg4ometry/src/develop/>
<http://www.pp.rhul.ac.uk/bdsim/pyg4ometry/>
<https://doi.org/10.1016/j.cpc.2021.108228>

Geometry Examples

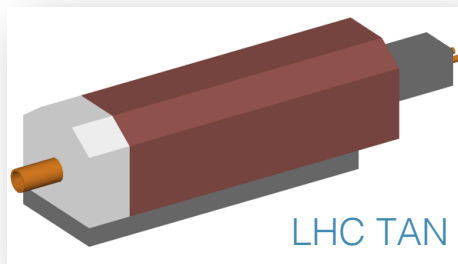
silicon tracker detector written in Python



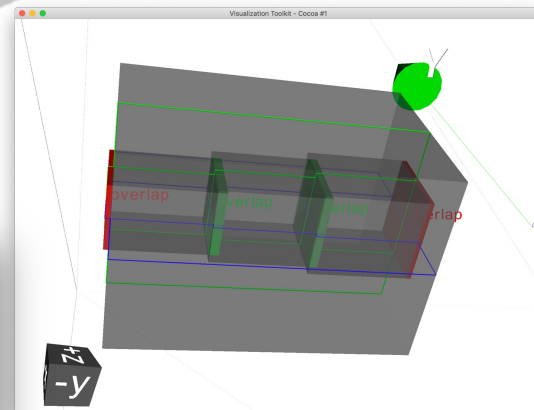
custom
vacuum
chamber



ATF2 at KEK shielding enclosure



LHC TAN

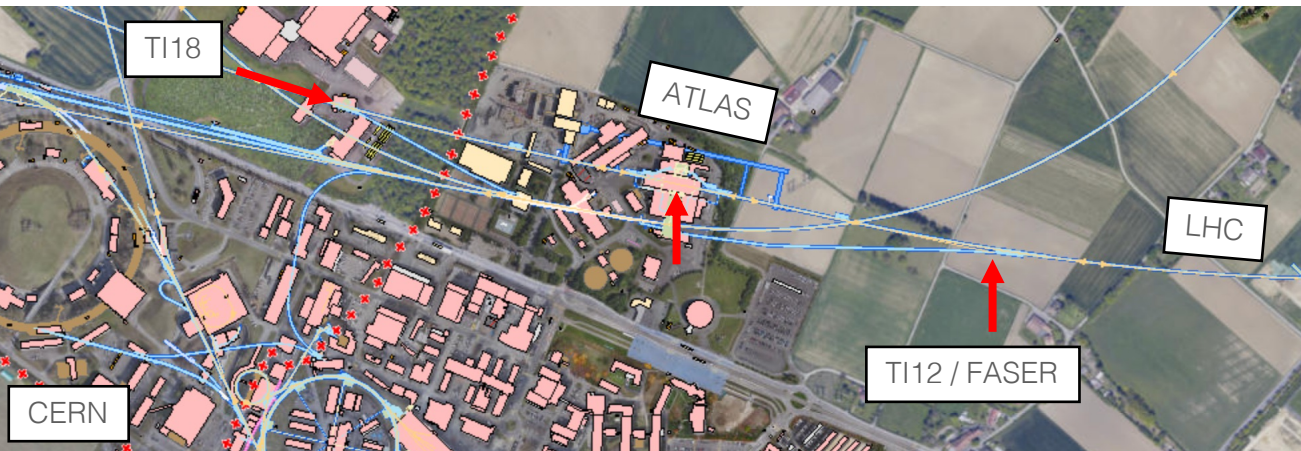


overlap checking and
identification

FASER - ForwArd Search ExpeRiment at the LHC



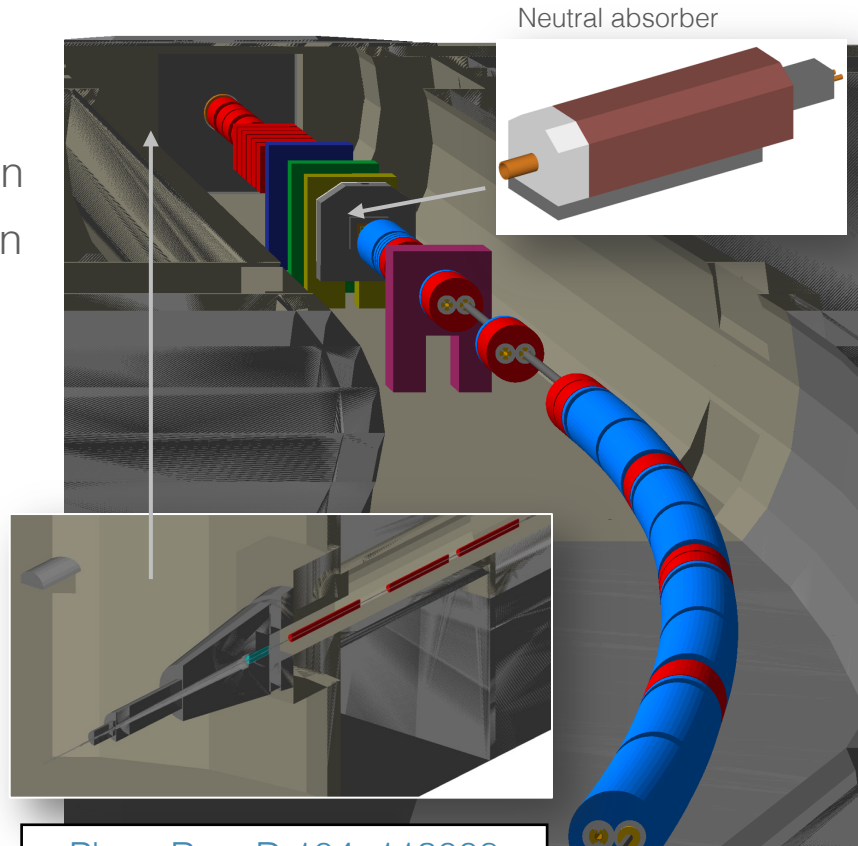
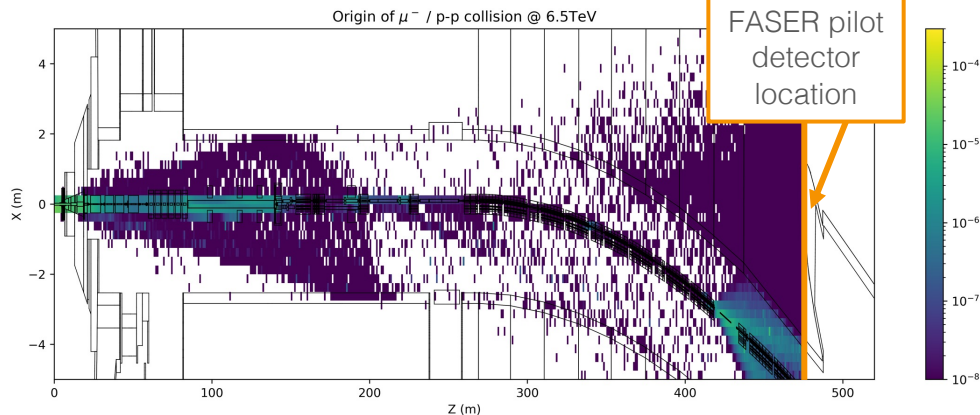
- New search for axion-like dark matter at the LHC
- Look in the very far forward direction along line of sight
 - $Z = 475$ m from IP1 (ATLAS) collision point
- Conception in 2017, designed and built -> just starting!
- Also study neutrinos in a unique energy range
 - higher E_k than reactor sources and lower than astrophysical sources



FASER - A Simulation Challenge



- Want to understand backgrounds muons and neutrino (signal!) origins [v: Phys. Rev. D 104, L091101](#)
- Need precision of 1 particle in 10^{12} per p-p collision
- Full "detector-like" model made of the accelerator in Geant4 using BDSIM from IP1 (ATLAS)
 - can simulate the various beam optics during the run such as beam crossing-angle and divergence
 - luminosity levelling will be used in Run III

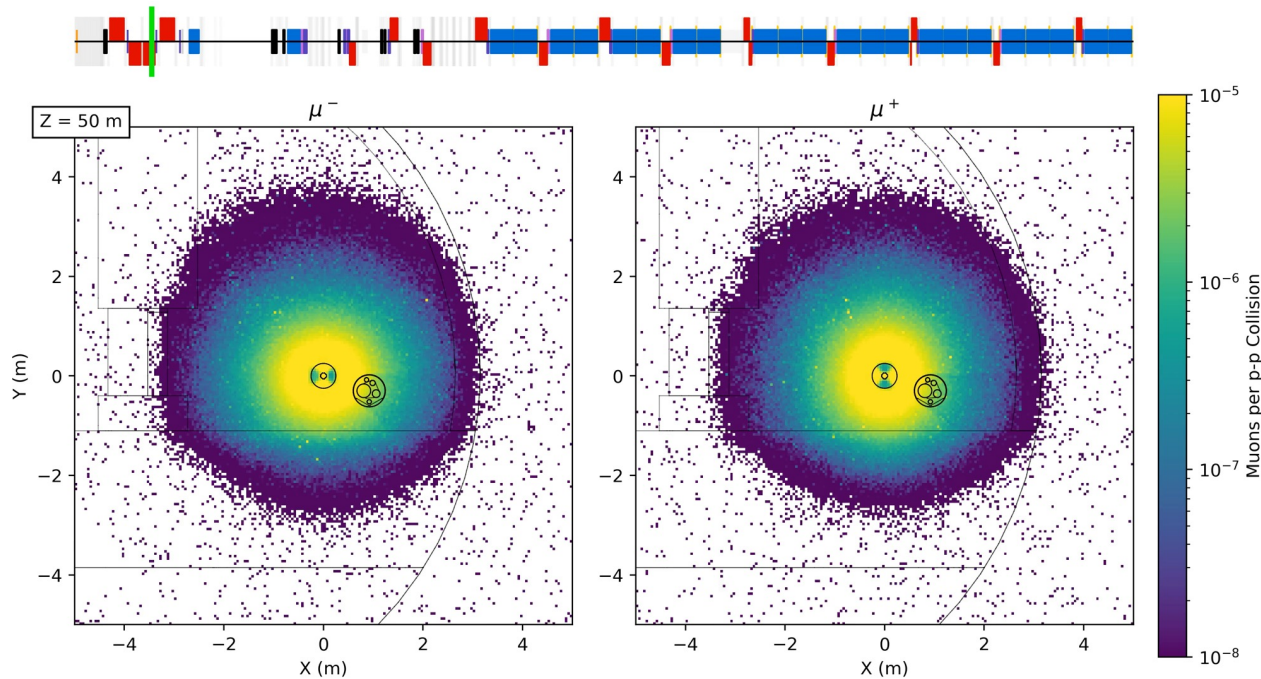
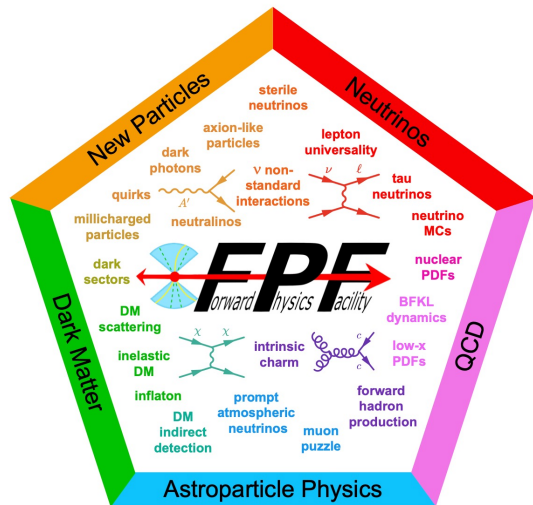


[Phys. Rev. D 104, 113008](#)

Forward Physics Facility



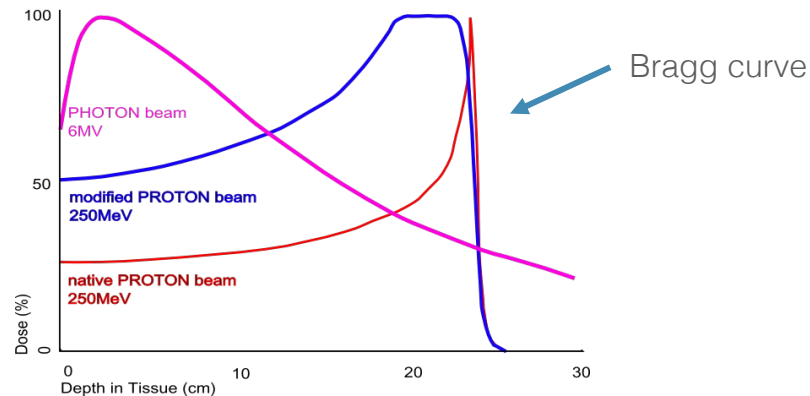
- Proposed dedicated facility in new tunnel ~ 600 m from IP1
 - for HL-LHC era
- Studying sweeper magnet design and location



Snowmass 2022 Paper <https://arxiv.org/abs/2203.05090>

Medical Hadron Therapy

- Protons and ions are used to treat cancers
 - greater relative biological efficiency (RBE)
- Accelerator must move around patient
- Large national-level therapy centres
- Modern facilities are increasingly *compact*
 - cheaper and more accessible! but closer to patient



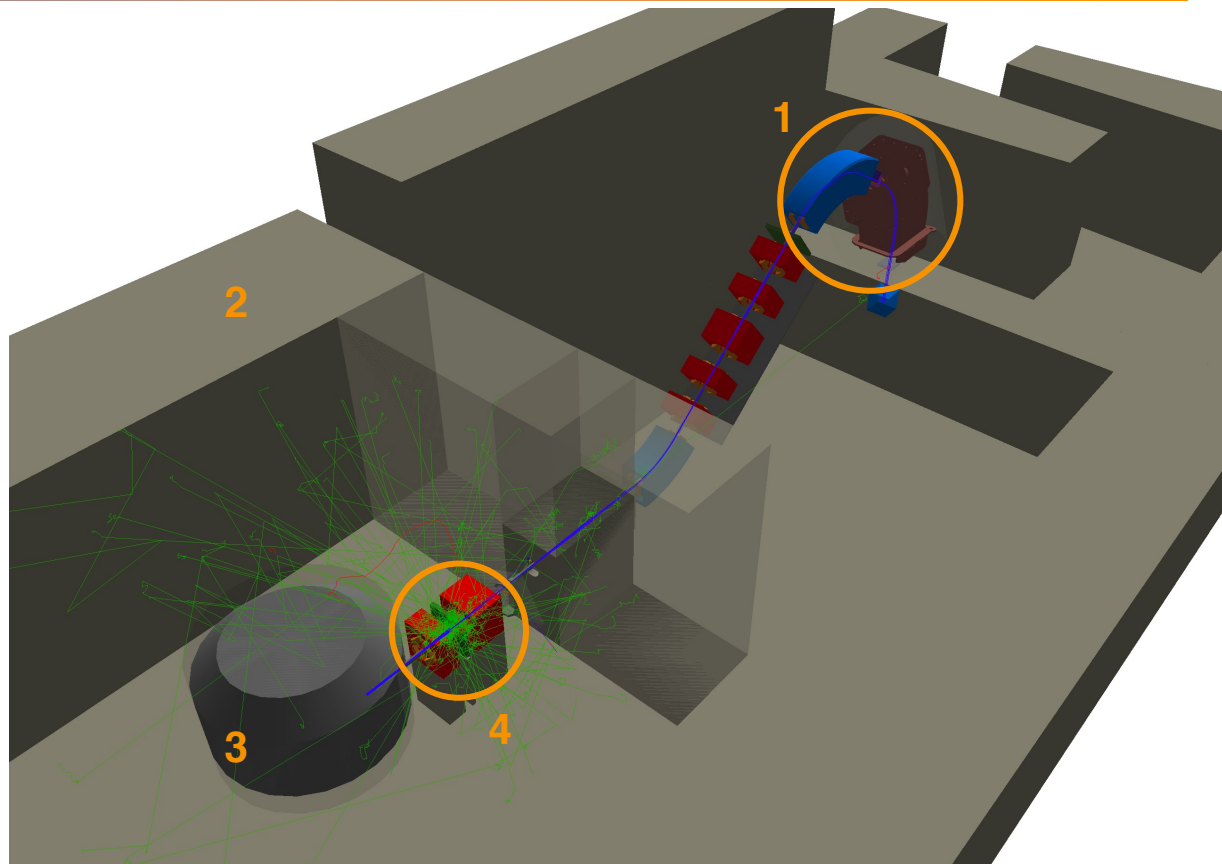
D. A. Miller,
<https://commons.wikimedia.org/wiki/File:BraggPeak.png>



H. Owen et al., International Journal of Modern Physics A (29), 14, 1441002 (2014)

Building a Complete Model

- Start with optical model
 - e.g. MADX Twiss
- Customise magnets
 - CAD converted - 1
- Use select field maps
- Composite geometry
 - shielding - 2
 - cyclotron - 3
 - degrader - 4
- Optical agreement and rotating gantry

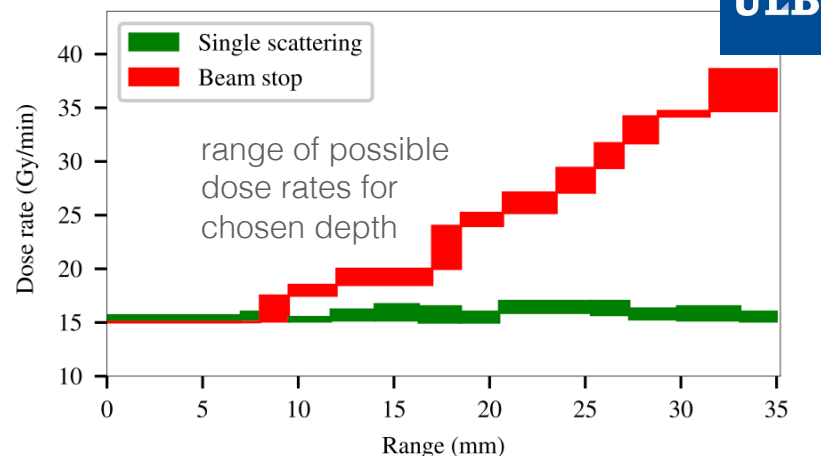
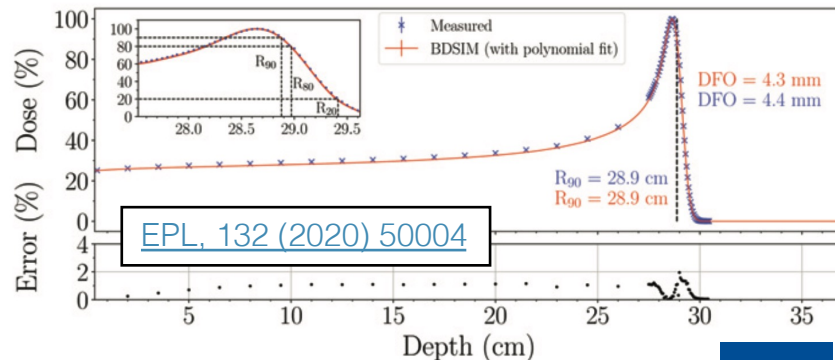
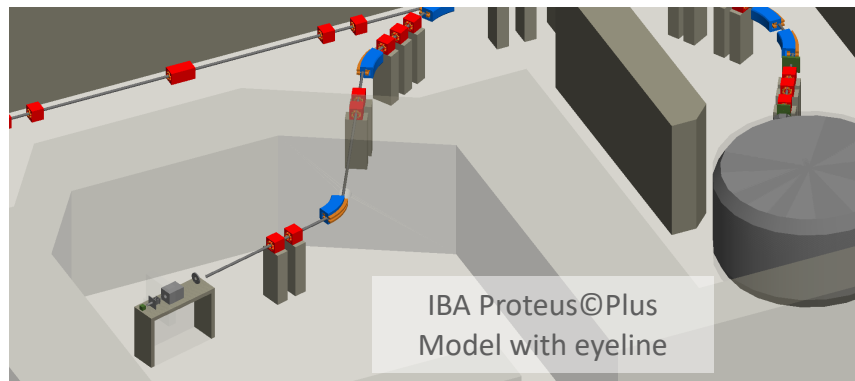


IBA Proton Therapy Facility Simulations



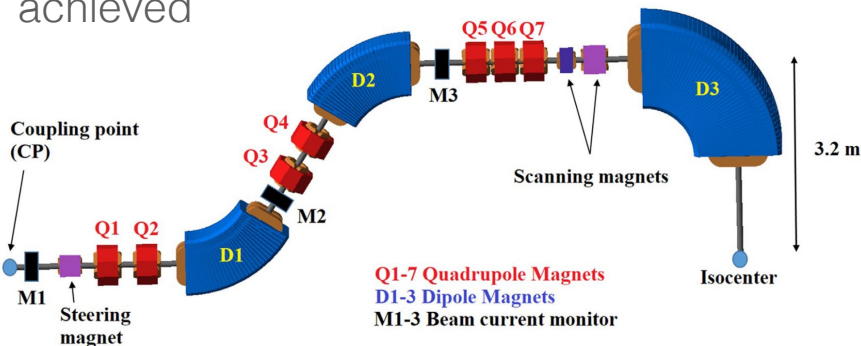
- First start-to-end gantry simulation with particle-matter interaction - from cyclotron to Bragg Peak
 - excellent experimental agreement
- Recent study on increasing dose rate in eyeline

[Phys. Rev. Research 4, 013114 \(2022\)](#)
- Results: reduce distal fall-off and reduce treatment time by factor of 3: treatment in < 30s
 - huge improvement for patient holding still

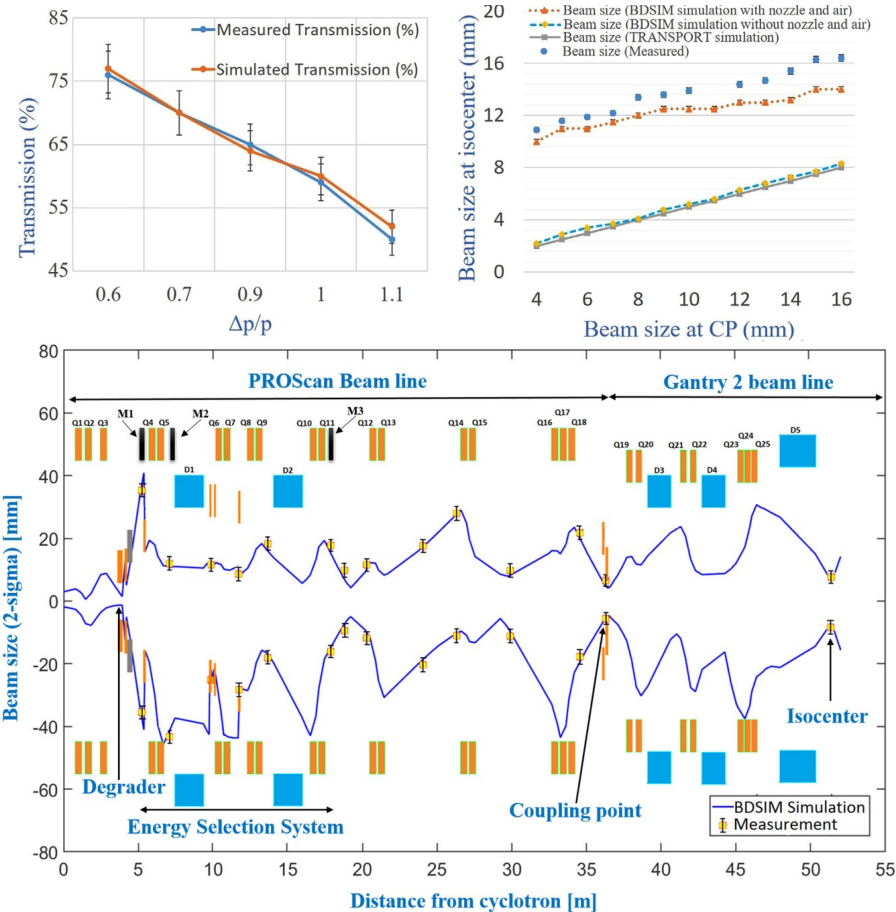


An Example of Recent Results at PSI

- PSI designed a new emittance selection system to increase transmission by a factor of 6 for the goal of FLASH therapy
 - <https://doi.org/10.1002/mp.15278>
- Also, new optics for PSI Gantry 2 for greater acceptance
 - <https://doi.org/10.1002/mp.15505>
- Excellent agreement with experiments achieved



PSI Gantry2 Model



- Many current and future experiments are not in an isolated environment and link with the accelerator
- The same techniques are equally applicable at low and high energy
- Tools presented for creating accurate 3D models
 - 1 person can achieve and learn something quickly!
 - it is possible to have parity between FLUKA & Geant4 models
- Geant4 physics models are constantly being updated by the community
- Validated medical models act as a testbed for new treatment modalities
- Upcoming challenges:
 - addition of [collective effects](#) - combining single and multi-particle dynamics
 - multiple beam lines - splitting and recombination



Thank you & Questions?

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BDSIM - [website](#) - [manual](#) - [paper](#)

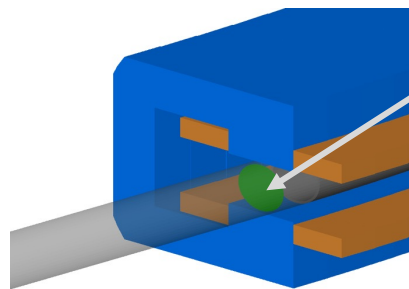
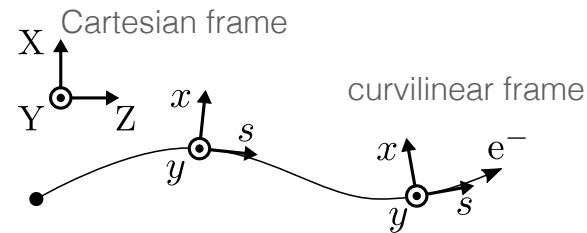
pyg4ometry - [website](#) - [paper](#)

[1] Title slide image credit; CERN + BDSIM model

Backup

How It Works: Tracking

- Convert between coordinate systems
- Use *parallel geometry* for transforms
 - cylinders that correspond to the beam line axis
 - parallel means just another set of geometry
- Include 'thin' elements as very short elements with 1 tracking step across the 3D volume



thin element for
dipole fringe fields

