Geant4 applications in MRI-guided x-ray and proton beam therapy

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IV Geant4 International User Conference, Naples, Oct 24-26th 2022

Background: MRI guided radiotherapy (x-ray therapy)

- MRI guided Radiotherapy was first seriously envisaged around 2004
  - 6MV Linac + MRI scanner
  - Geant4 was used to examine the possible dose changes
  - 6MV x-ray beam in a 1.5 T magnetic field

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Phys. Med. Biol. **49** (2004) 4109–4118 PII: S0031-9155(04)80001-0

Integrating a MRI scanner with a 6 MV radiotherapy accelerator: dose deposition in a transverse magnetic field

B W Raaymakers[1], A J E Raaijmakers[1], A N T J Kotte[1], D Jette[2,3] and J J W Lagendijk[1]

Integrated MRI accelerator: dose deposition in a magnetic field 4111

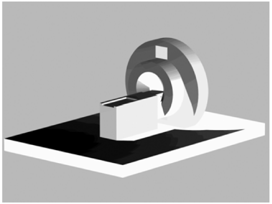
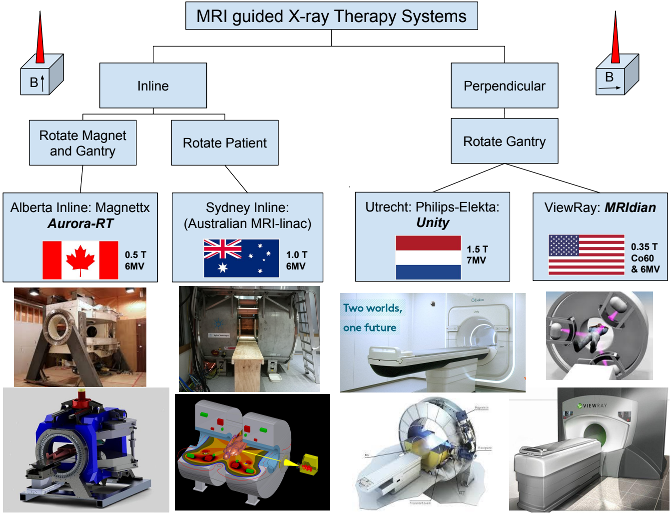


Figure 1. Artistic impression of an integrated MRI accelerator.

Fast forward to now...

- This is a major direction in modern radiotherapy
- There have been a few dosimetry surprises along the way
- Monte Carlo methods have been basically the only option for accurate dose calculations



Background: MRI guided radiotherapy (particle/proton therapy)

- MRI guided proton therapy: 2008
  - Proton + MRI scanner
  - Geant4 was used to examine the possible dose changes
  - Proton beam in 0-3 T magnetic field

IOP PUBLISHING PHYSICS IN MEDICINE AND BIOLOGY

Phys. Med. Biol. **53** (2008) 5615–5622 doi:10.1088/0031-9155/53/20/003

Feasibility of MRI guided proton therapy: magnetic field dose effects

B W Raaymakers, A J E Raaijmakers and J J W Lagendijk

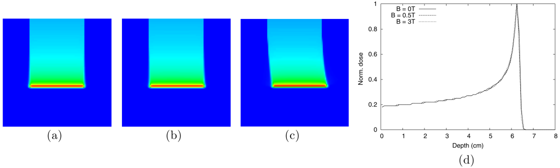
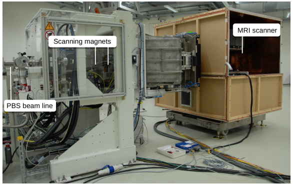


Figure 3. The dose distribution in a homogeneous water phantom for $B = 0$ T (a), 0.5 T (b) and 3.0 T (c) and the central depth dose profiles through the dose distributions (d). Note that there are actually three overlapping lines in (d).

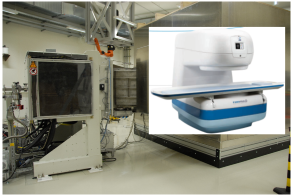
MRPT prototypes and research hardware

1. Dresden (OncoRay):
0.22 T MRI + horizontal PBS beam line (protons)

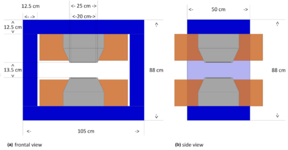


2. Heidelberg (HIT):
0.25 T MRI + horizontal PBS beam line (multi-ions)

3. Dresden (OncoRay):
0.33 T MRI + horizontal PBS beam line (protons)



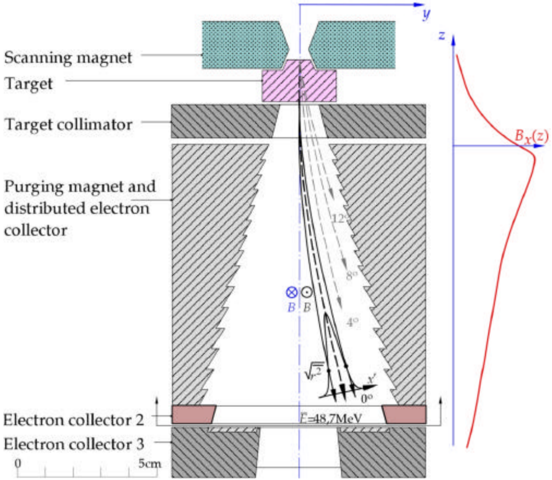
4. Vienna (MedAustron):
small 1 T research dipole magnet + PBS beam line (multi-ion)



- Much more complicated than MRI-linacs
- First patient treatment planned for OncoRay 2023-2024

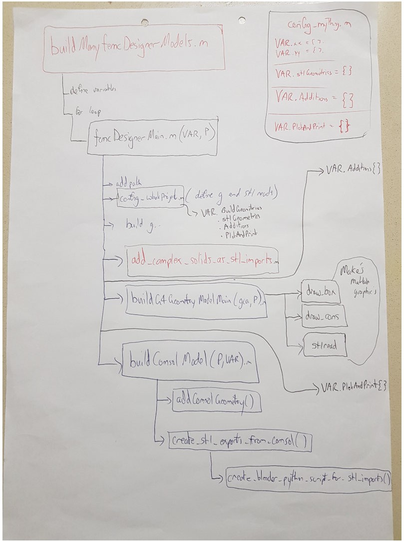
Geant4: Modelling MRI-guided radiotherapy

- Geant4 is a toolkit for radiation transport only
    - No complicated magnetic field modelling
    - Need to import 3D field maps
    - Generate 3D maps in finite element software
- **Purging Magnet** (Advanced Example) ideal for reading in 3D variable magnetic fields
- We are interested in dose changes, beam transport changes
    - SteppingAction class very useful



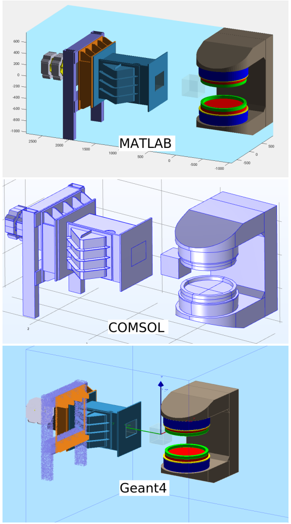
My Modelling tools and workflow

- Matlab
  - overarching toolbox
  - creates COMSOL model
  - creates Geant4 geometry file
  - data analysis
  - visualisation
- COMSOL Multiphysics
  - finite element models
  - magnetic fields
- Geant4
  - Monte Carlo simulations
  - radiation transport
  - B-field data from COMSOL model
- Blender (open source rendering)
  - pretty pictures!

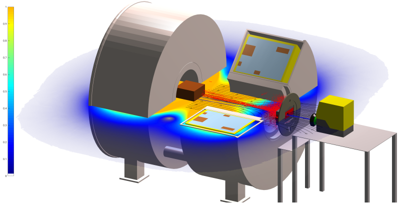


Modelling workflow

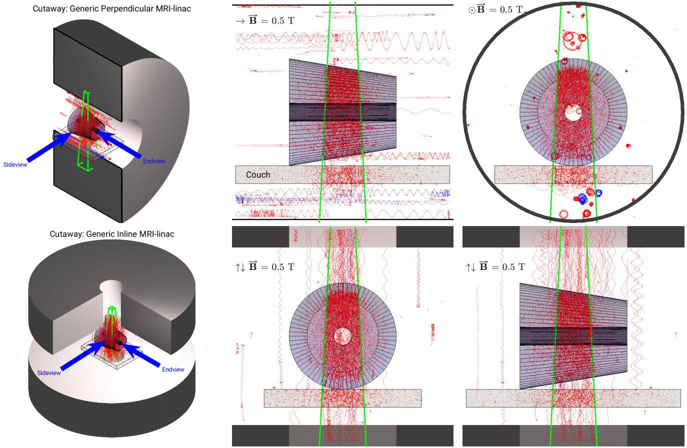
- Geometry registration (Matlab)
  - pdf files, some CAD files
  - mostly manually recreated with in-house definitions
  - fundamental boolean solids
- Magnetic Fields (COMSOL)
  - Non-linear solver
  - B-H or magnetization curves
  - electric current sources
  - steels and coil currents important
- Radiation transport (Geant4)
  - geometry location and composition important
  - magnetic field data from COMSOL
  - tedious process linking static data between codes!



- Australian MRI-Linac Program
  - 1 T split bore MRI
  - 6MV Linac
  - 120 Leaf MLC
- About 4 years part time to develop fully benchmarked model



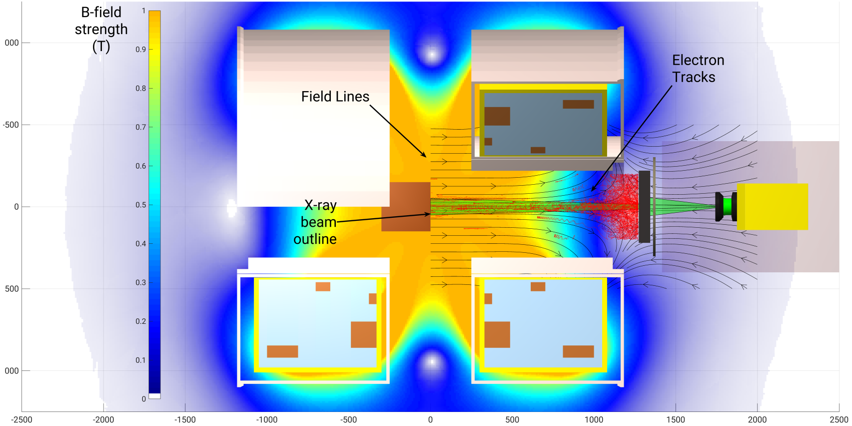
Magnetic field surrounding a phantom: 6 MV beam



Its all about the secondary electrons!

What about the full beam transport: inline orientation system

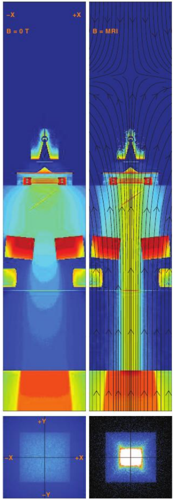
- The fringe field collects and focuses electron contamination
- This was an important discovery with major implications



Electron contamination: inline system

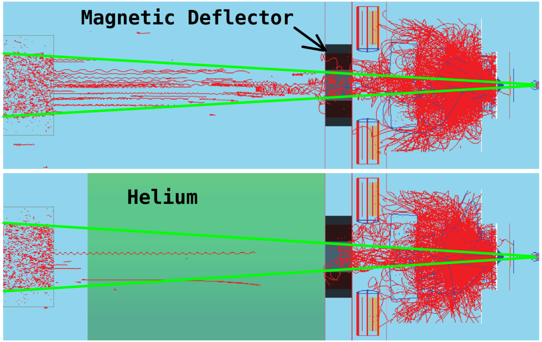
- Skin dose increases of 100-400%
- Various possible workarounds

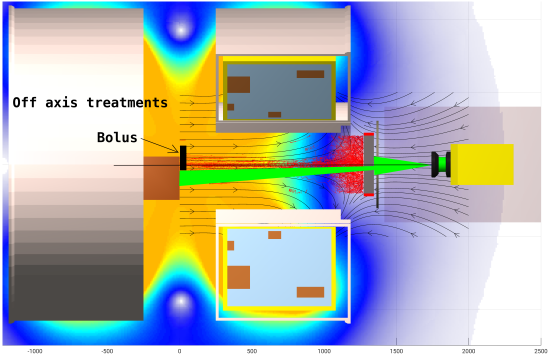
Oborn *et al.*, Med. Phys. 41 (5), May 2014, 051708-1



MRI-Linac: skin dose reduction simulations (PhD student projects)

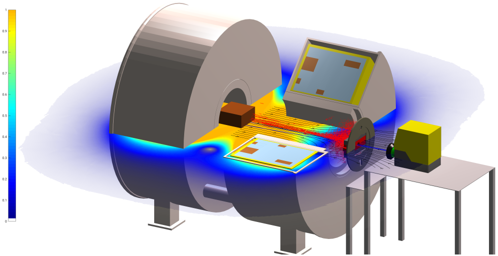
- 1. Bolus above patient and Off-axis treatments
    - Elizabeth Patterson
- 2. Electron deflector and helium zone
    - Madiha Tai





Part 1: MRI-linac modelling - summary

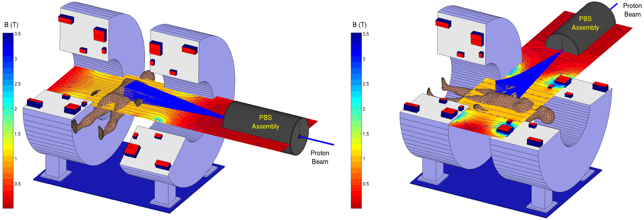
- Geant4 was the first code to be used to investigate the basics of dose changes due to magnetic fields in 2004
    - It has been used extensively at the CMRP over the last 14 years for studying various elements of MRI-Linac radiotherapy
    - It is helping guide the direction taken for the first patient treatments on the Australian MRI-linac system
    - Skin dose predictions very critical
    - Treatment plans will also be checked using Geant4

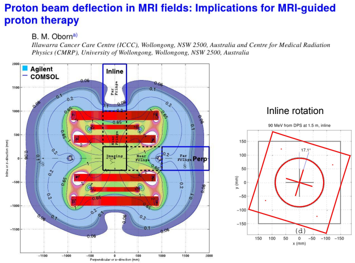


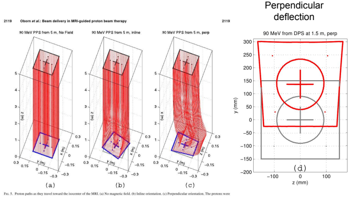
Part 2: MRI-proton modelling

Topic 1: Beam line transport

- Sydney MRI scanner
- First realistic look at beam transport through the MRI fringe field
- Implications: must use pencil beam scanning
- Proton beam deflections are important for treatment planning purposes



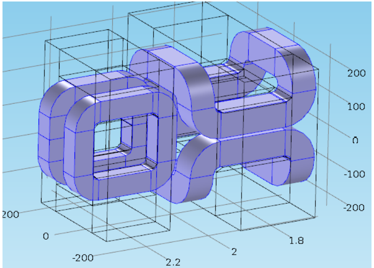


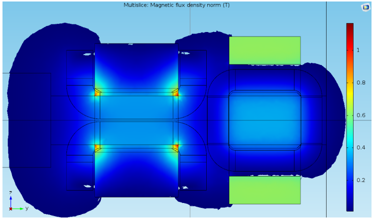


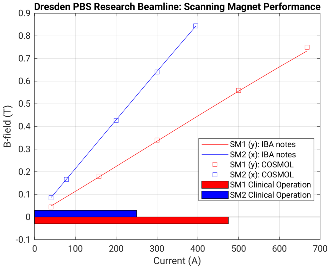
Oborn *et al.*, Medical Physics, Vol. 42, No. 5, 2015

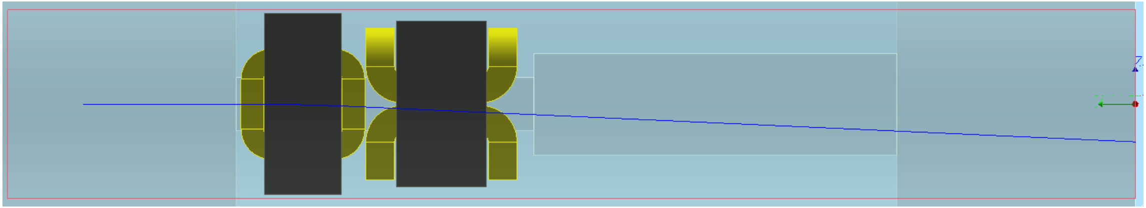
Part 2: MRI-proton modelling

Topic 2: Scanning Magnet Modeling (Full modelling loop)









Inline Orientation Scanning Pattern

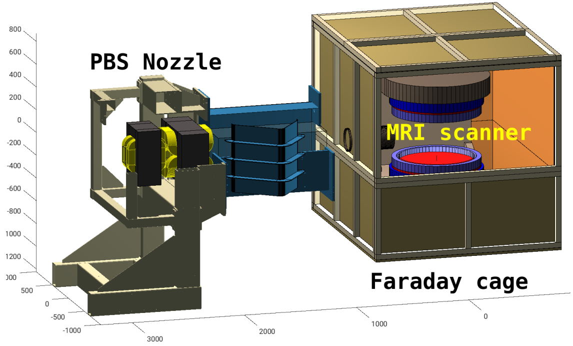
230 MeV pencil beam scanning, scanning magnets in clinical position: (gif)

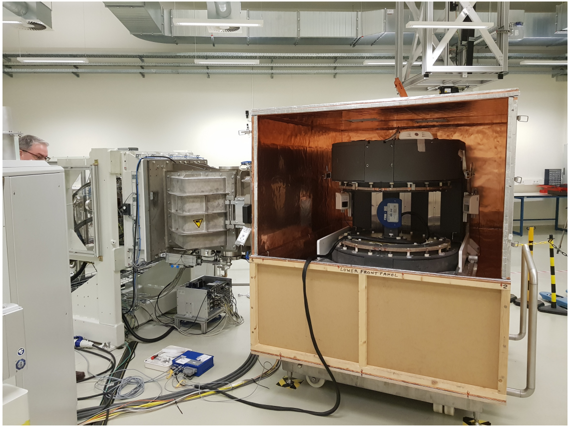
Perpendicular Orientation Scanning Pattern

230 MeV pencil beam scanning, scanning magnets in clinical position: (gif)

Part 2: MRI-proton modelling

Topic 3: Modeling the OncoRay prototype: MRJ2200 + PBS:

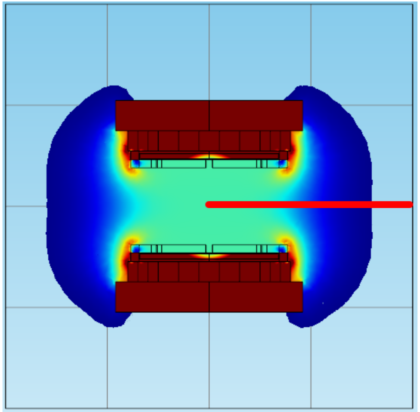


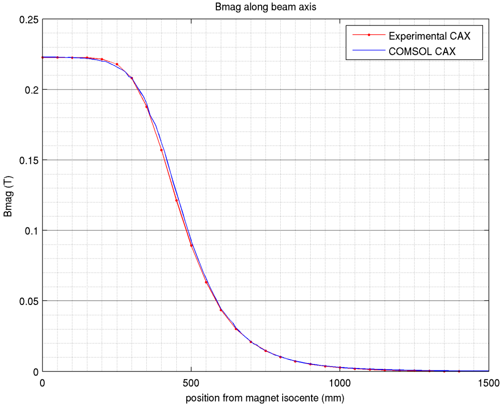


Part 2: MRI-proton modelling

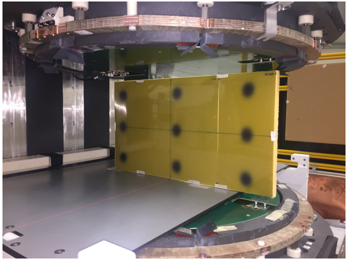
COSMOL magnetic field map

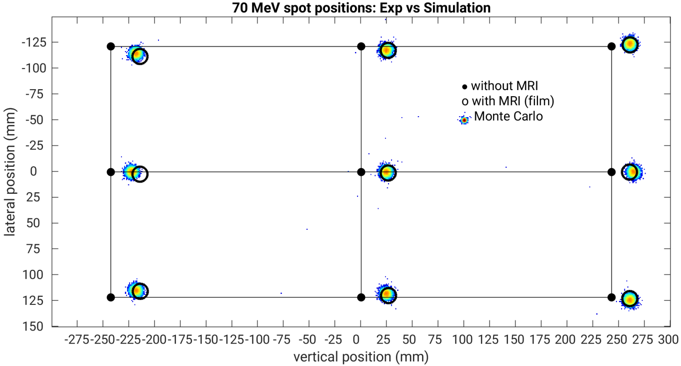
- generally good agreement with experiments along the beamline
- small differences around the shoulder: 2%, 5 mm match





Results: PBS deflection - film vs Monte Carlo



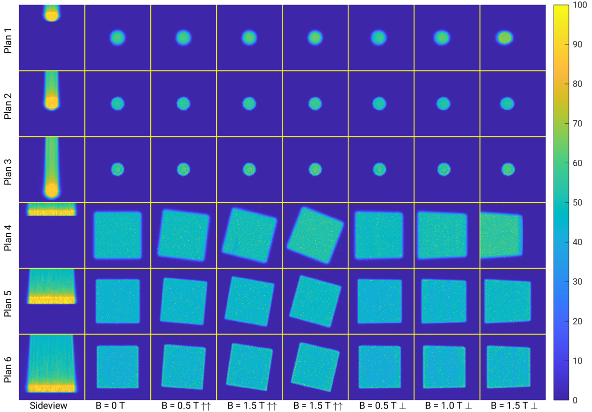


- The errors are related to small inaccuracies in the 3D magnetic field map
- Future work will use full benchmarked MRI models or experimental data for 3D field maps

Part 2: MRI-proton modelling

Topic 4: Electron contamination from proton beams (Entry skin dose)

- Sydney MRI with PBS plans (RayStation)
- 30x30x30 cm water phantom
- 5 cm spherical target
- 20x20x5 cm block target
- 70-213 MeV proton pencil beams
- $<$ 5% dose increases only!
- So why no high skin dose??

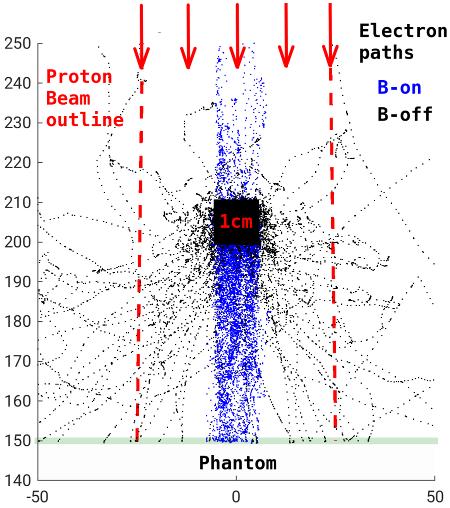


Entry Skin doses at 70 μm depth

Electron contamination from proton beams: Entry skin dose

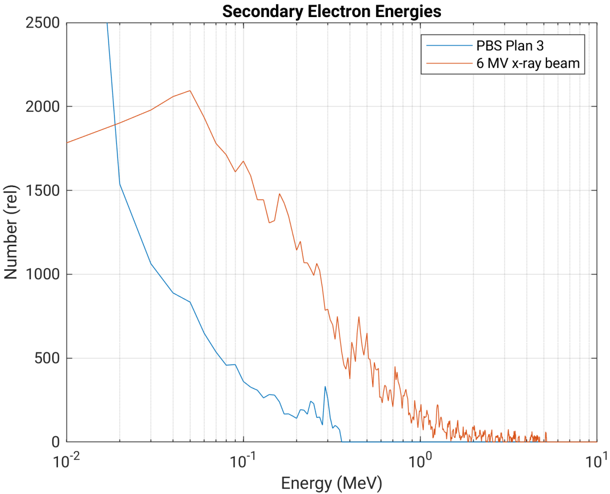
- Extract the electron properties starting from a 1 cm cube above the phantom
- Confirm how electrons travel along the field lines
- Examine their energy spectrum

```
void g4qsmSteppingAction::UserSteppingAction(const G4Step * theStep)
{
...
G4Track * theTrack = theStep->GetTrack();
G4ThreeVector cv = theTrack->GetVertexPosition();
G4ParticleDefinition* particleType = theTrack->GetDefinition();
G4String theParticleName = particleType->GetParticleName();

if (particleType == G4Electron::ElectronDefinition())
   && (cv.x() < 0.5*cm)
   && (cv.x() > -0.5*cm)
   && (cv.y() < 21*cm)
   && (cv.y() > 20*cm)
   && (cv.z() < 0.5*cm)
   && (cv.z() > -0.5*cm)     )

{ then print the info to a text file...
    //- step locations
    //- energy
}
}
```



Electron contamination from proton beams: Entry skin dose

- But what about the electron energies?
- Much lower than those produced by x-ray beams!
- **Conclusion: the secondary electrons simply don't have enough energy to travel long distances in air; no cascade effect towards the surface**



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  - I have used it extensively at the CMRP over the last 8 years for studying various elements of MRI-Linac radiotherapy
  - It is helping guide the prototype development at OncoRay, Dresden
- Future work includes modelling of the next generation 0.5 T MRI system at Dresden

Conclusions

- Geant4 has been used for >15 years to model MRI-guided radiotherapy systems and dosimetry changes
  - Skin dose changes accurately predicted in x-ray therapy
  - Methods to lower skin dose increases modelled, under development at Sydney
  - Important beam transport modelling for MRPT
  - Ongoing modelling with Dresden MRPT development
- Acknowledgements:
  - Geant4 community (and Conference Organizers)
  - Australian MRI-Linac Program and University of Wollongong
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Thanks for your attention!