Ion Beam Imaging Activities at TU Wien and HEPHY

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MedAustron in a Nutshell

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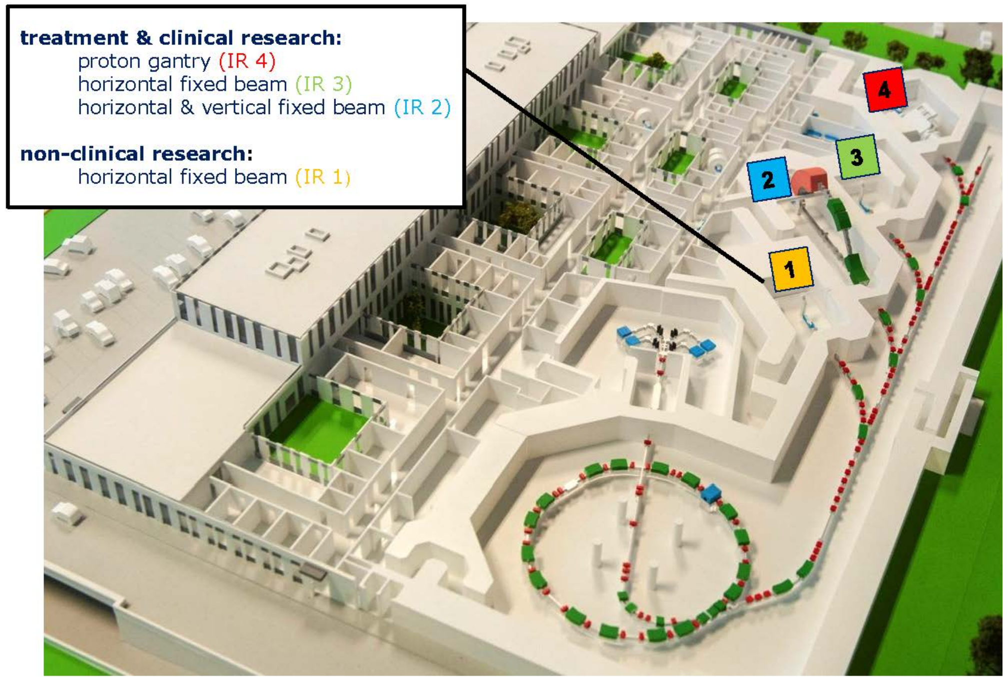
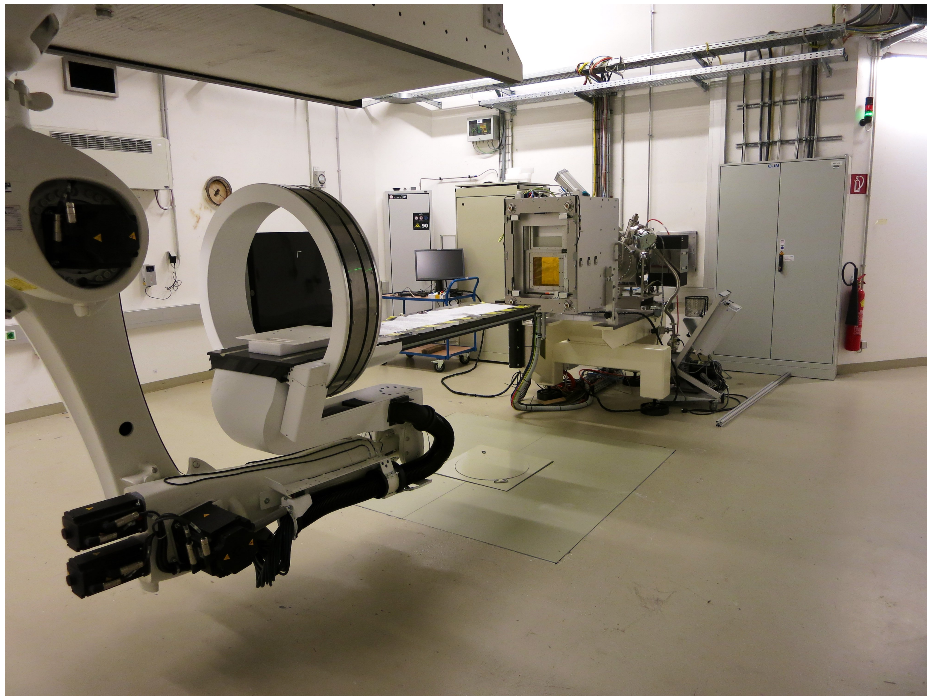
- Ion therapy centre for cancer treatment
  - Synchrotron accelerator complex located close to Vienna
  - Four irradiation rooms:
    - **IR1**: Exclusive to research (up to 800 MeV protons, low flux)
    - **IR2**, **IR3**, **IR4**: Clinical use (up to 250 MeV protons, GHz rates)
  - Beam delivery only in one room at a time
- Beam parameters for IR1
  - **Protons: 60 MeV to 800 MeV**
  - **Carbon Ions: 120 MeV/n to 400 MeV/n**
  - Helium: potential upgrade
  - Particle rates: kHz to GHz
- In operation since end of 2016
  - Carbons since mid 2019



MedAustron accelerator complex



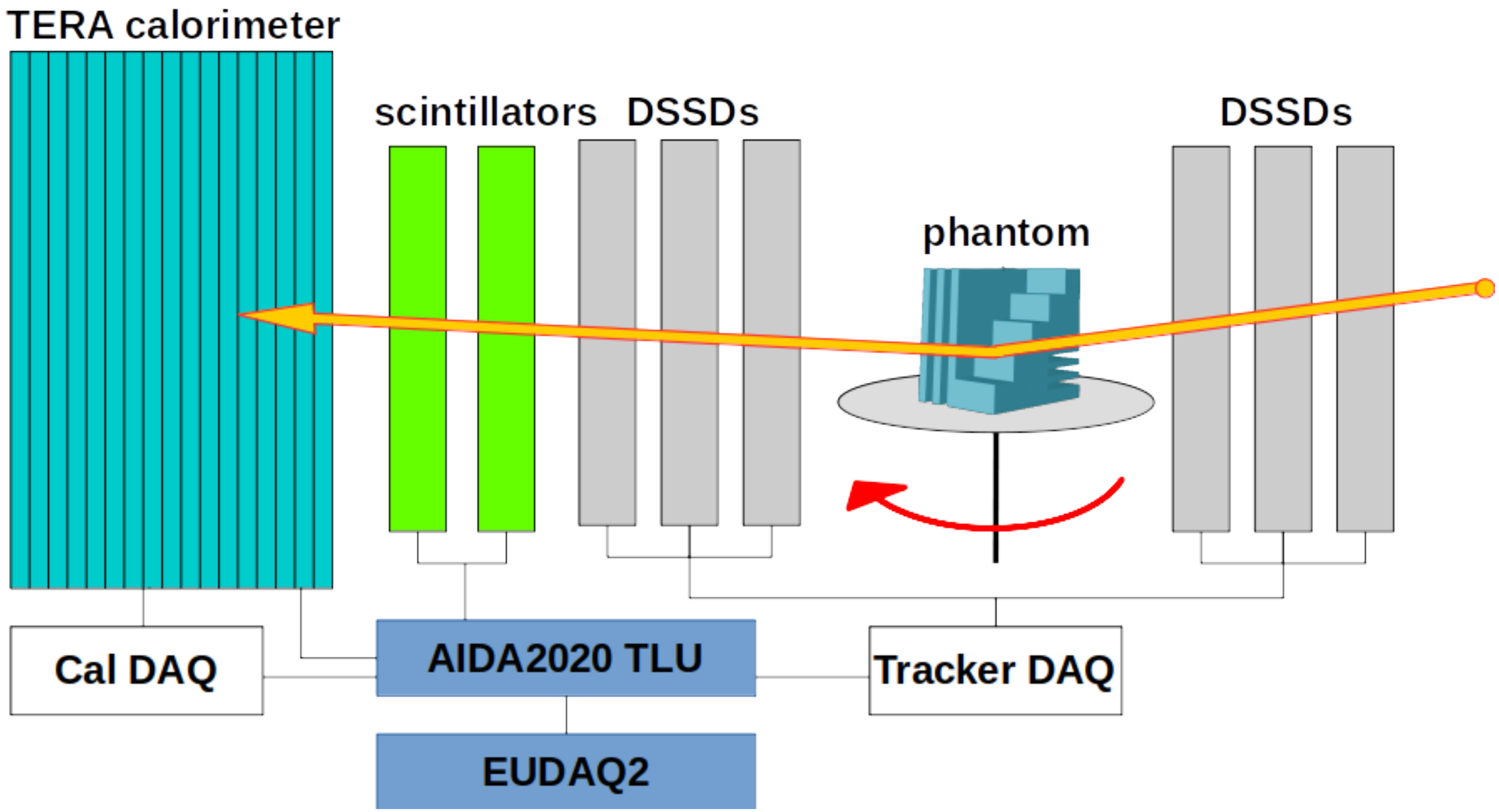
IR1 reserved for research

Overview and Outline

- Joint HEPHY/TU Wien working group for Ion Imaging established in 2017
  - Started with 1 PostDoc and 1 Master Student
  - Now 1.5 PostDoc, 3 PhDs, plus students and HEPHY staff support
- Hardware Part I: Existing detector setup and results
  - First prototype based on Belle II tracker prototype sensors plus former TERA range telescope
  - Performance results and limitations presented in this talk
- Software Part I: Reconstruction
  - First trials with TIGRE framework and OS SART reconstruction
- Software Part II: Detector simulation
  - Establish requirements and guidance for hardware design choices
- Hardware Part II: Future directions

Hardware Part I:
The Present

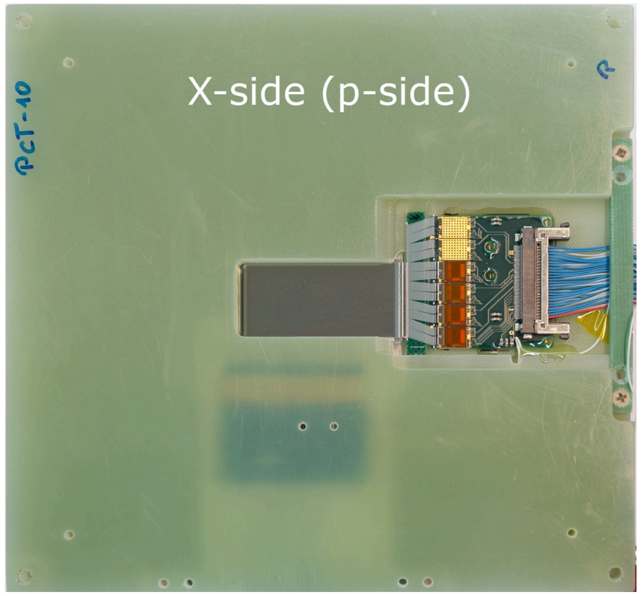
Current pCT Setup

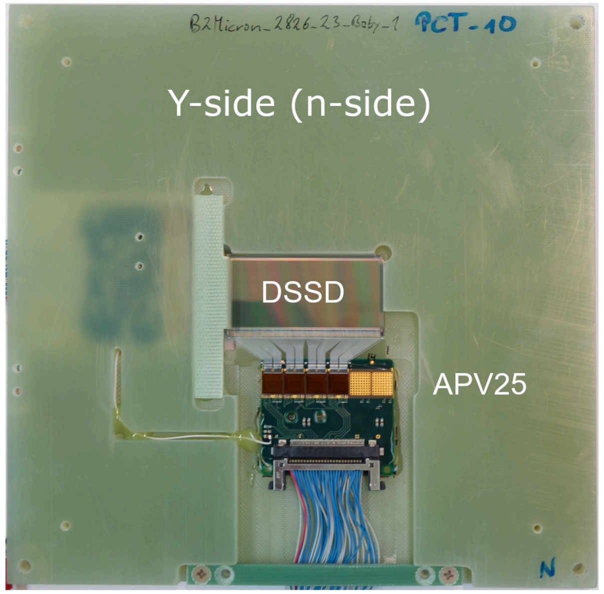


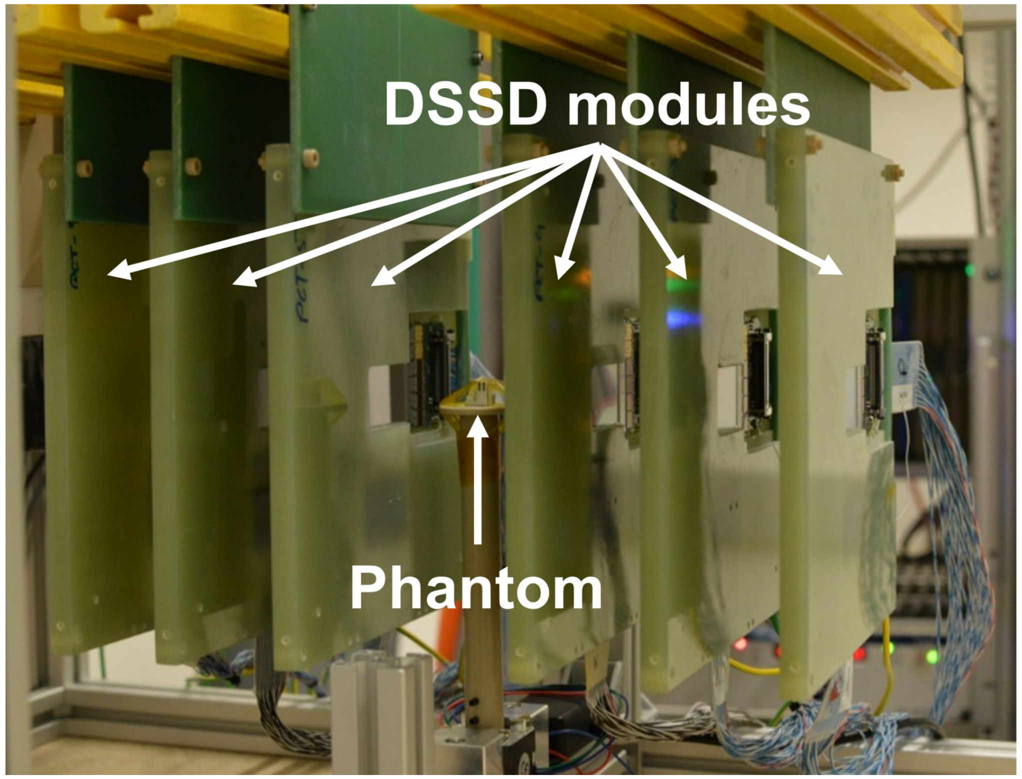
- Rotation table to mount object
- Event synchronisation via AIDA2020 trigger logic unit (TLU)

Tracker: Double Sided Si Strips

- Double sided silicon strip sensors
  - 3+3 planes of ~ 2.5 x 5 cm^2 each
  - Thickness 300 µm thick
    - X side: 512 n-doped strips, 50 µm pitch
    - Y side: 512 p-doped strips, 100 µm pitch
  - Sensors based on Belle II prototypes
  - APV25 ASIC [1]
  - Belle-II SVD readout chain [2]
- Pros:
  - Low material budget
- Limitations:
  - VME based backend limits us to ~ 500 Hz
    - GbE readout implementation ongoing (independent of pCT activities)
  - Sensors limited in size







Existing DSSD tracker

Range Telescope: Plastic Sci Plates

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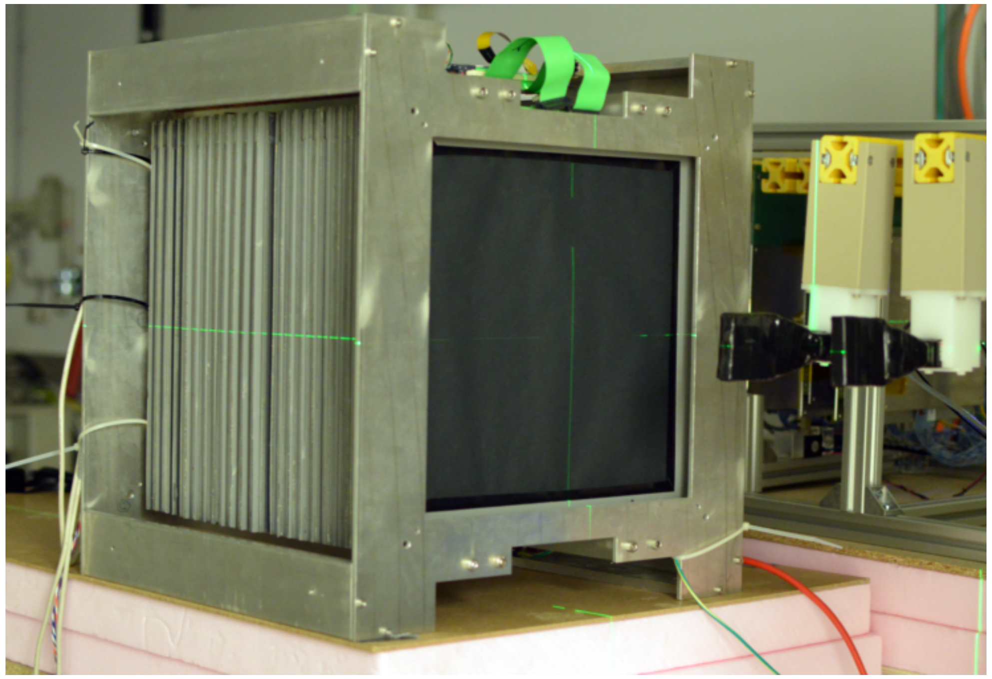
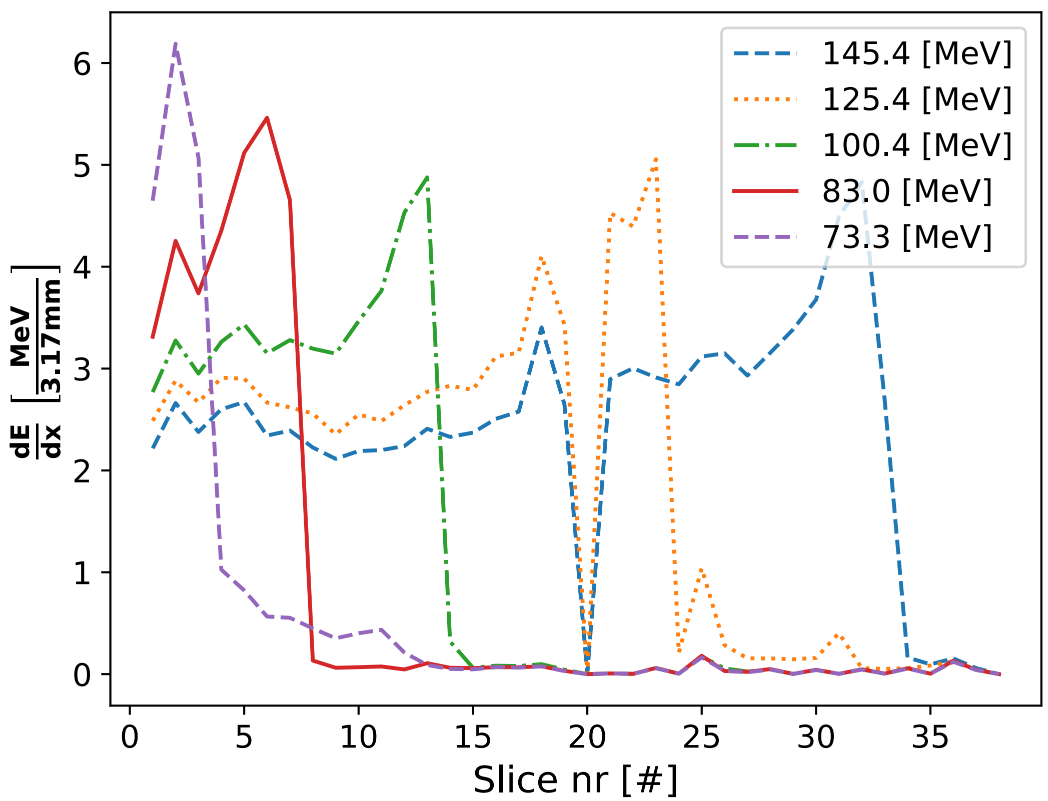
- Range telescope based on 3 mm thick plastic scintillators read by SiPM
  - Formerly TERA
  - 42 layers of 3 x 300 x 300 mm^3 each
  - Can measure protons up to 140 MeV
- Pros:
  - Cheap
  - Can sustain 1 MHz particle rate -> quite ok for prototyping
- Limitations:
  - Dynamic range with 400 pixels per SiPM small -> E_{res} per plane only ~ 8%
  - Accurate energy calibration has proven challenging
  - This thing is old and has seen some wear and tear …



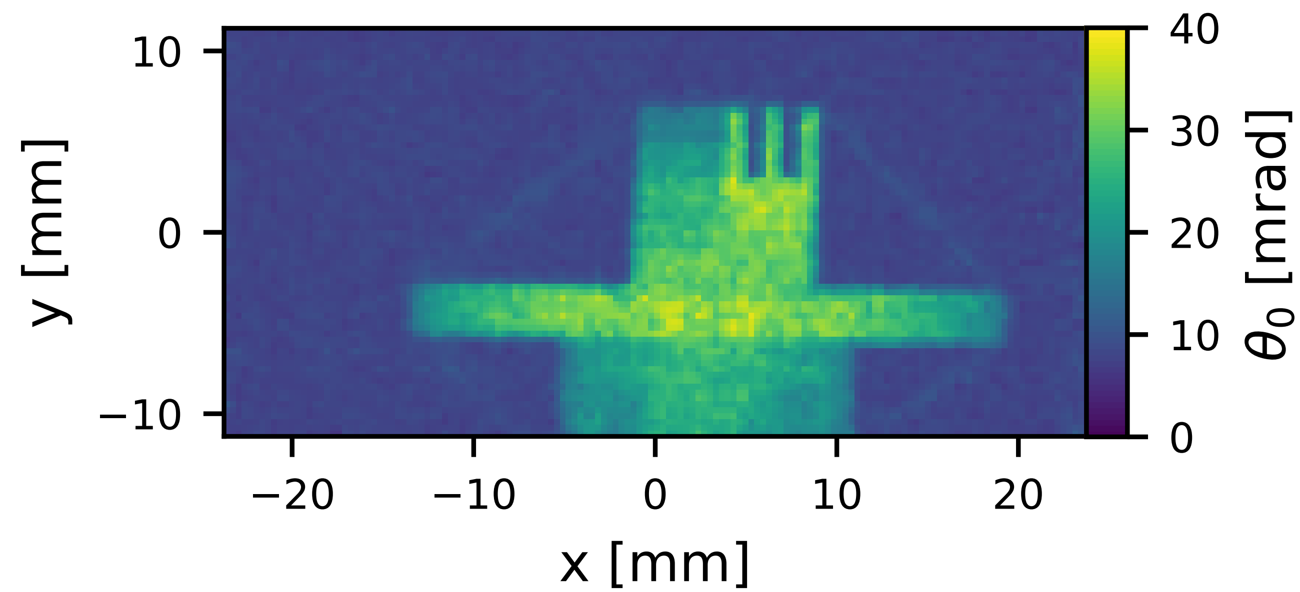
Existing TERA calorimeter

Selected Results

- No full pCT image up to now
  - Recently managed to calibrate the calorimeter and record correct proton range values
  - If no further roadblocks we should be able to record our first pCT in autumn
- Meanwhile only multiple Coulomb scattering results



Proton range profiles



Multiple Coloumb scattering tomography

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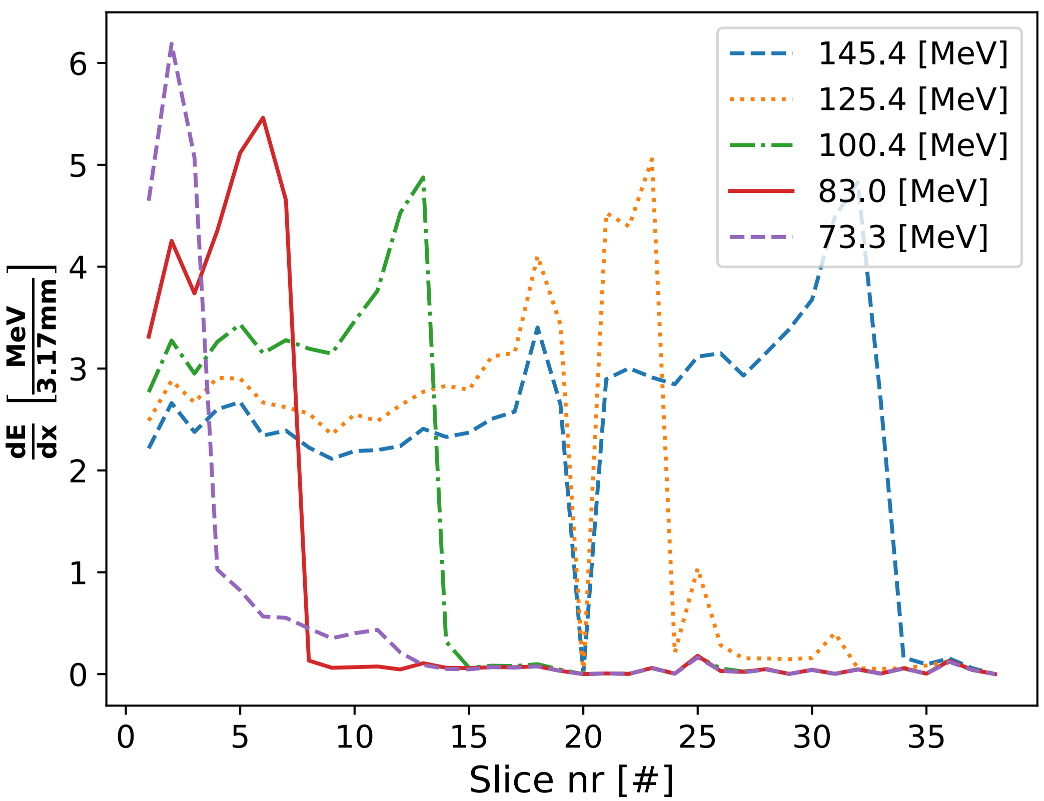
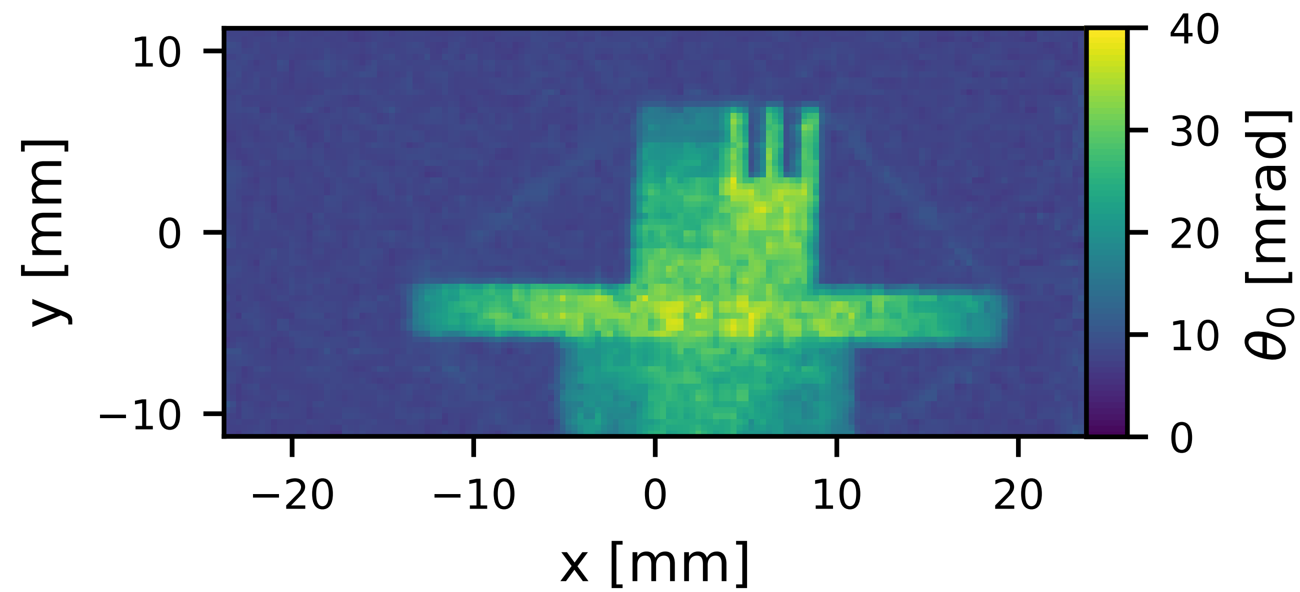


Proton range profiles



Multiple Coloumb scattering tomography

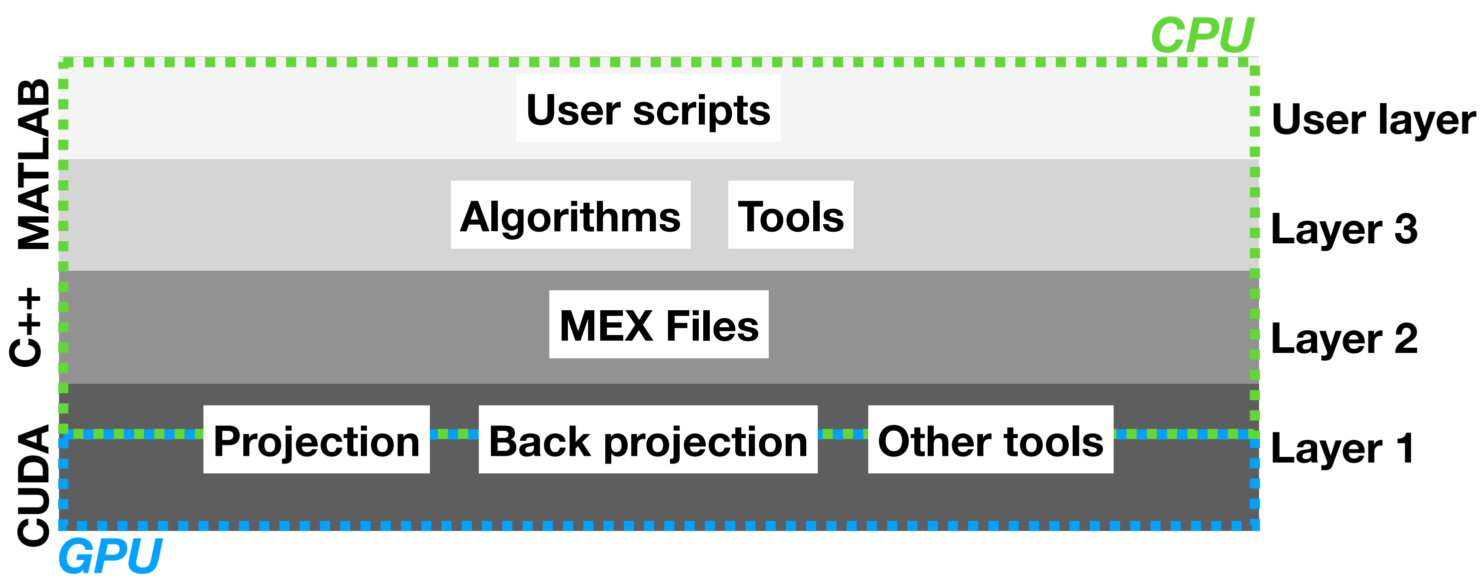
Need new hardware developments!

Software Part I: Reconstruction

TIGRE framework

- TIGRE: Tomographic iterative GPU-based reconstruction toolkit [3]
  - Framework **developed for cone-beam CT** with contributions from our colleagues at Medical University of Vienna
  - Open source MATLAB/CUDA framework
  - Iterative and direct algorithms implemented (**OS-SART** was used)
  - **Should perform well at limited data sets**

- First attempt to adapt the framework to pCT
  - **Straight-line** approximation
  - **Bragg-Kleeman** rule



The TIGRE framework

Simulated Setup

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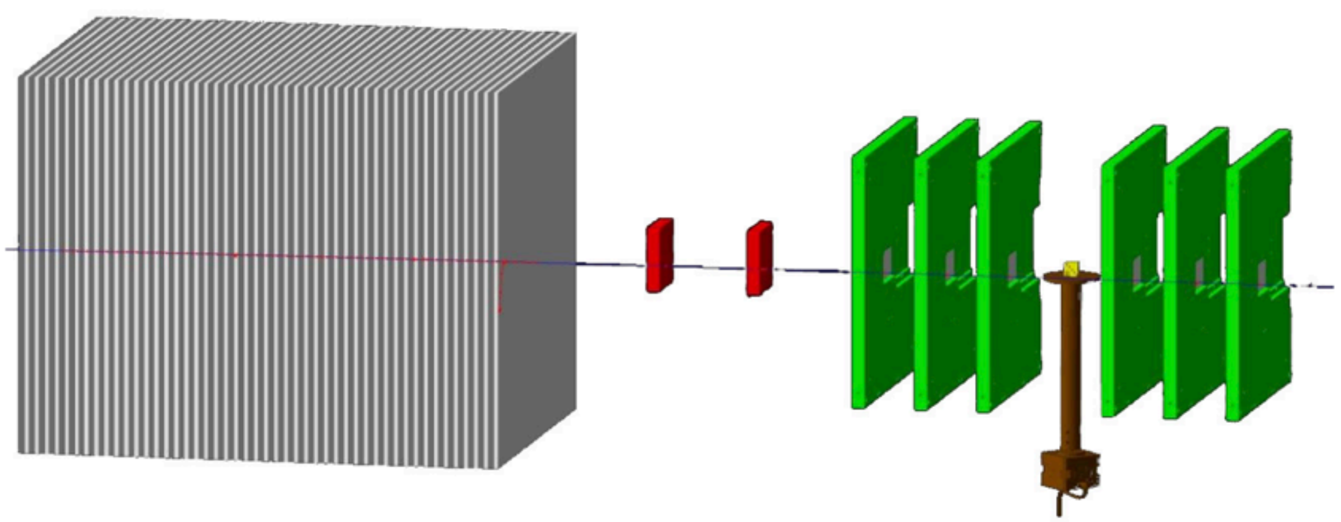
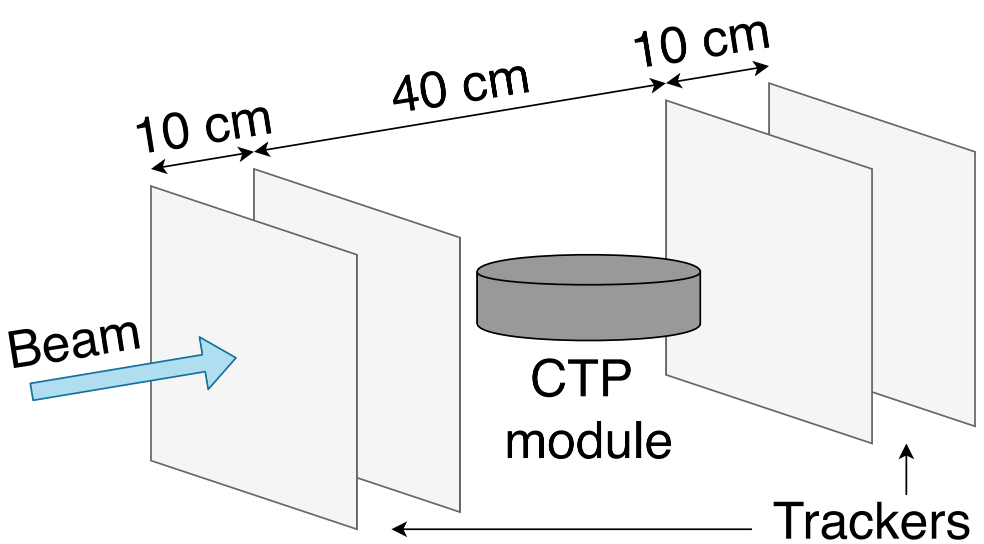
- Geant4 simulation of our experimental setup
  - 'Idealised' with perfect spatial and energy resolution per plane
  - 'Realistic' with resolutions matching existing hardware
    - σ_E = 8% per plane
    - σ_x = 14.4 µm
    - σ_y = 28.9 µm



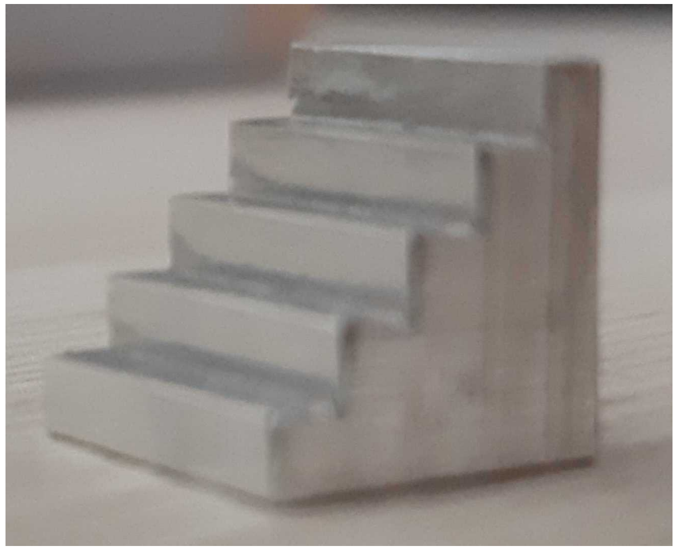
Setup for testbeam validation



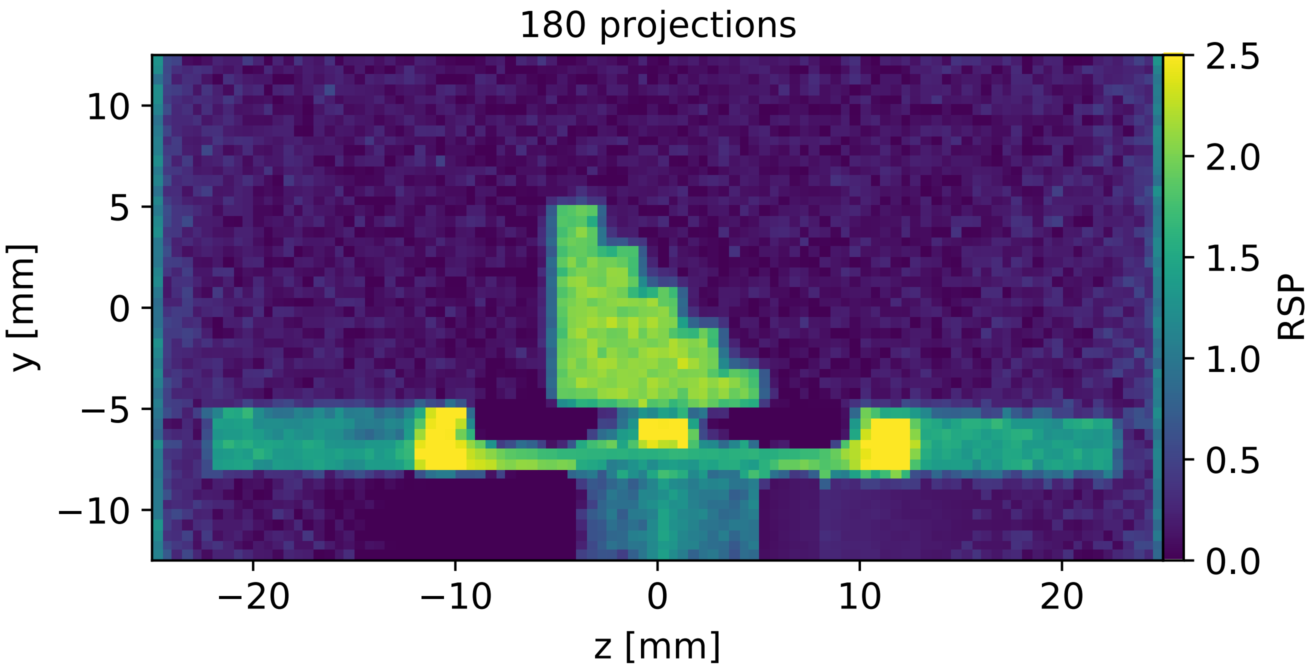
Setup for ideal simulation

Reconstruction Results I

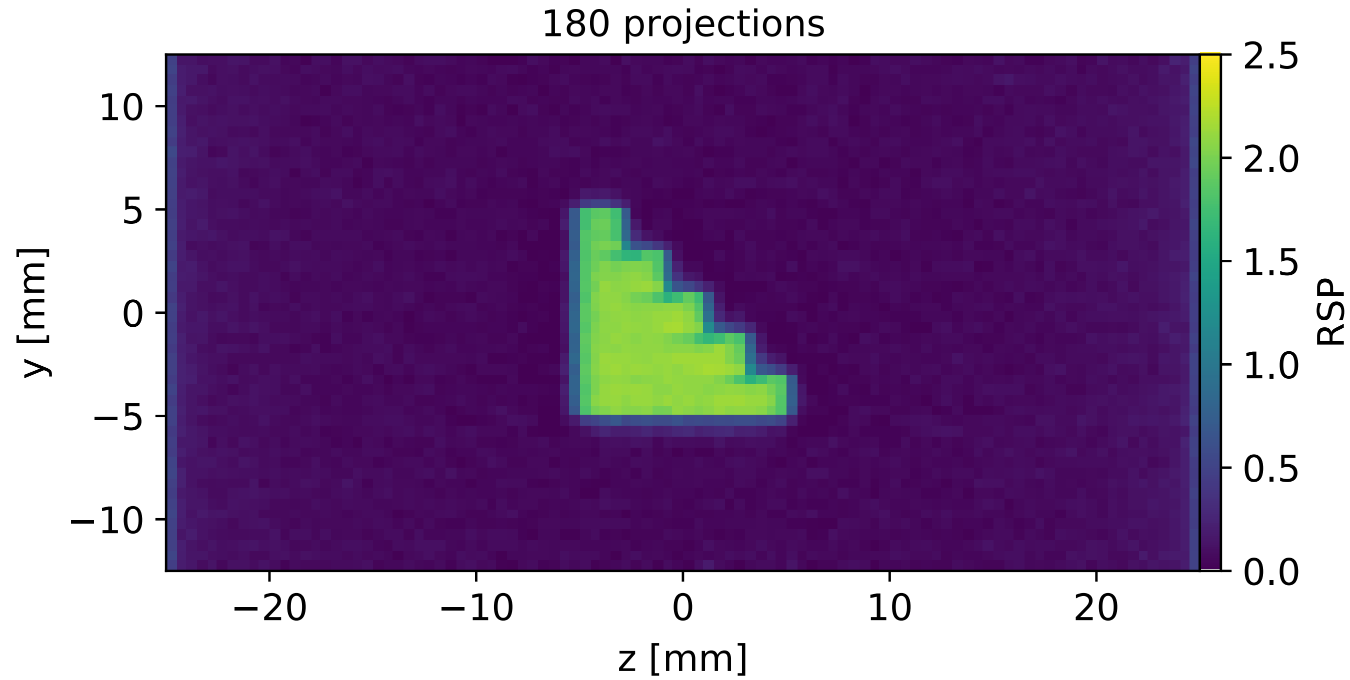
- Small phantom: aluminium staircase
  - Idealised and realistic simulation
  - $E_{init} = 100.4$ MeV
  - N = 800 primary particles mm^{-2}
- Works well but phantom is very small



Real world counterpart



Reconstructed from ‘realistic’ simulation

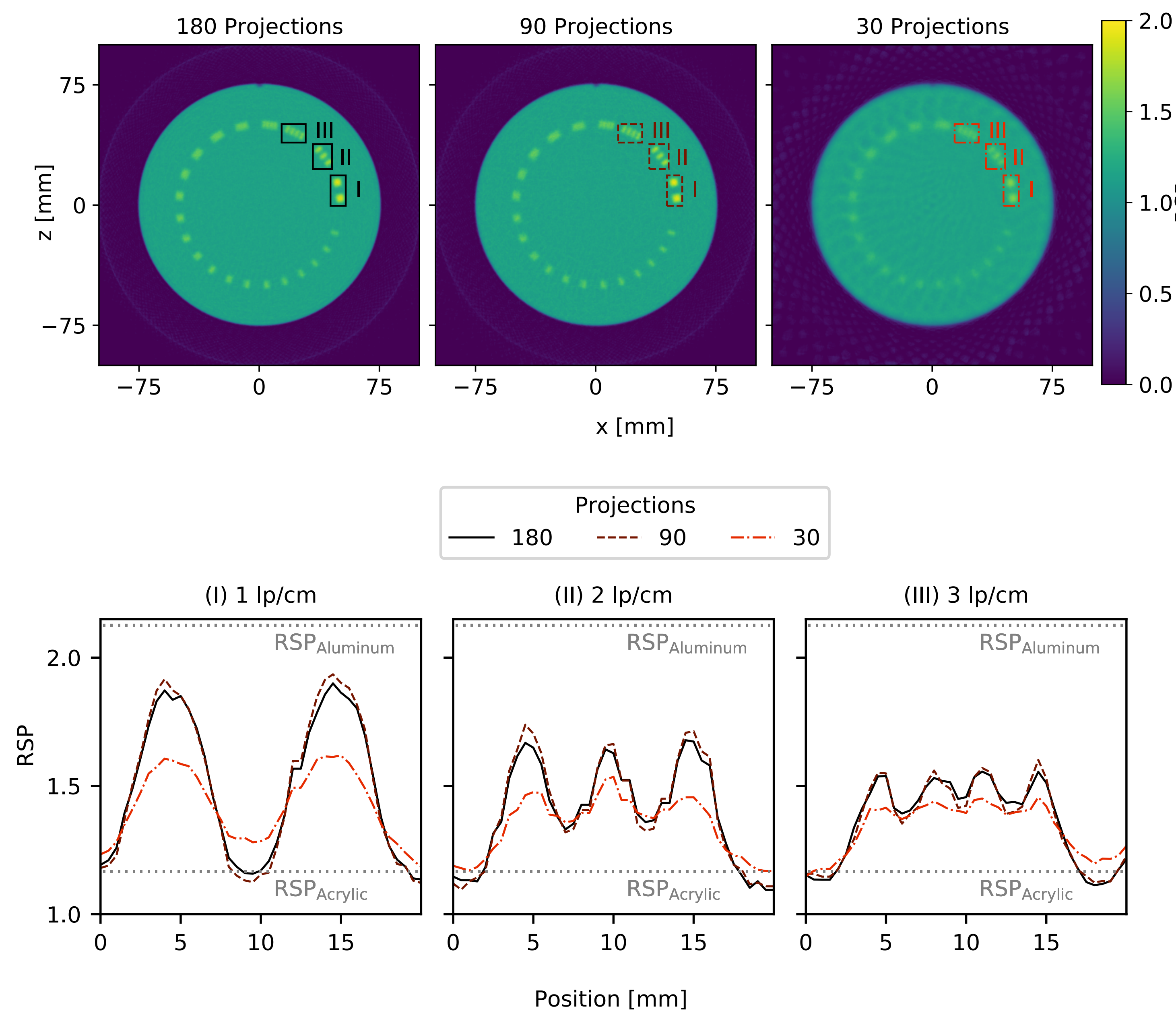


Reconstructed from ‘idealised’ simulation

Reconstruction Results II

- Large phantom: Catphan
  - Idealised simulation only so far
  - E_{init} = 200 MeV
  - N = 800 primary particles mm^{-2} (after cuts)
- Spatial resolution due to straight line approach is clearly limited
  - Cuts on proton paths to improve the spatial resolution amount to data loss
  - MLP has to be added to the framework for further improvement
- Nearly identical results for 180 and 90 projections
- Next step: Integrate MLP in TIGRE
  - Use RTK with distance driven binning as reference

    (Thanks to Simon, Nils and Feriel)



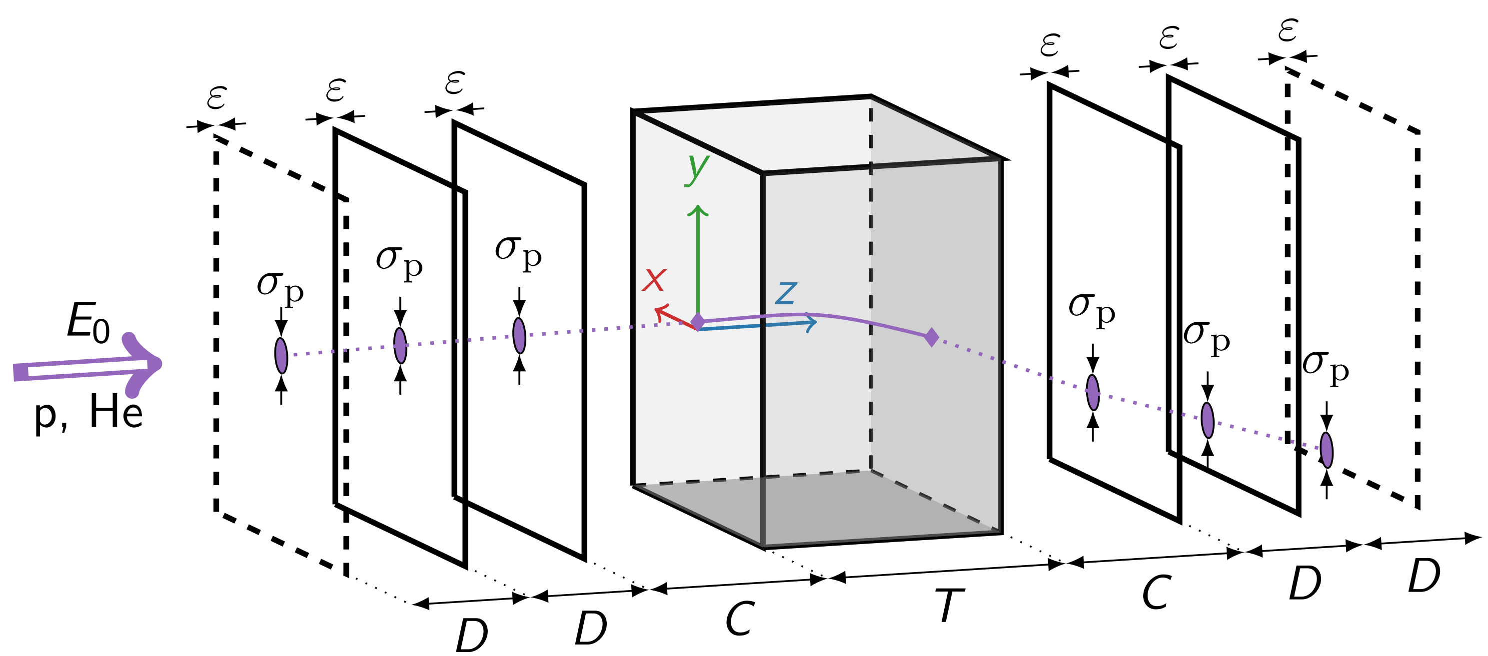
Reconstructed from ‘idealised’ simulation

Software Part II: Design Studies for Future Developments

Guidance for Hardware Design

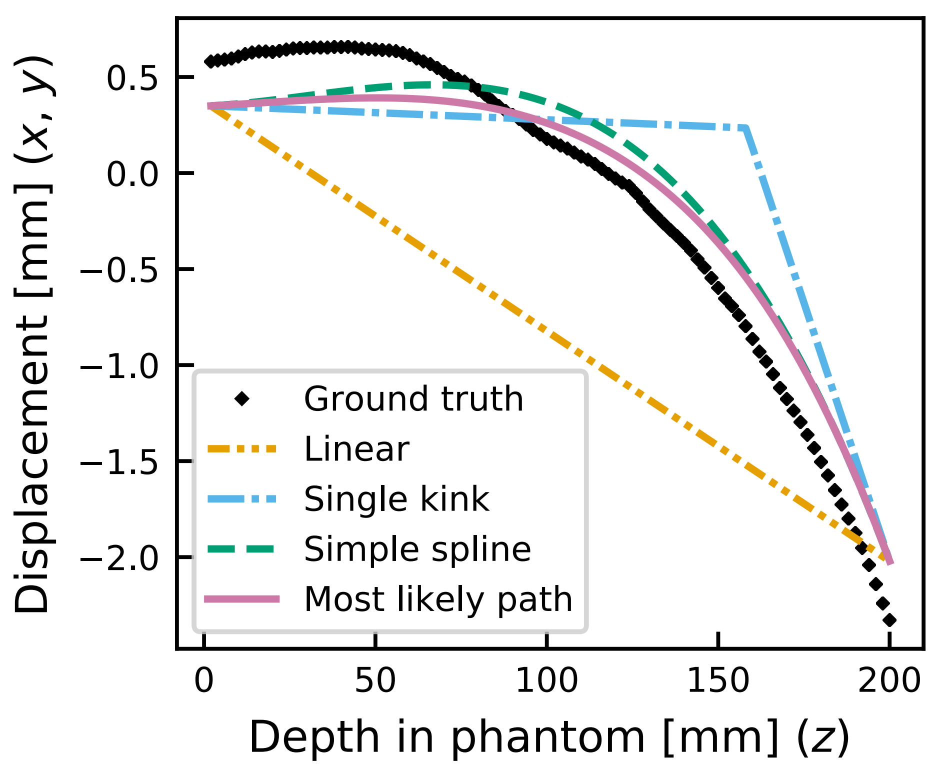
- Future hardware developments needs comprehensive understanding of uncertainty sources
  - Set detector requirements
  - Guide the design choices

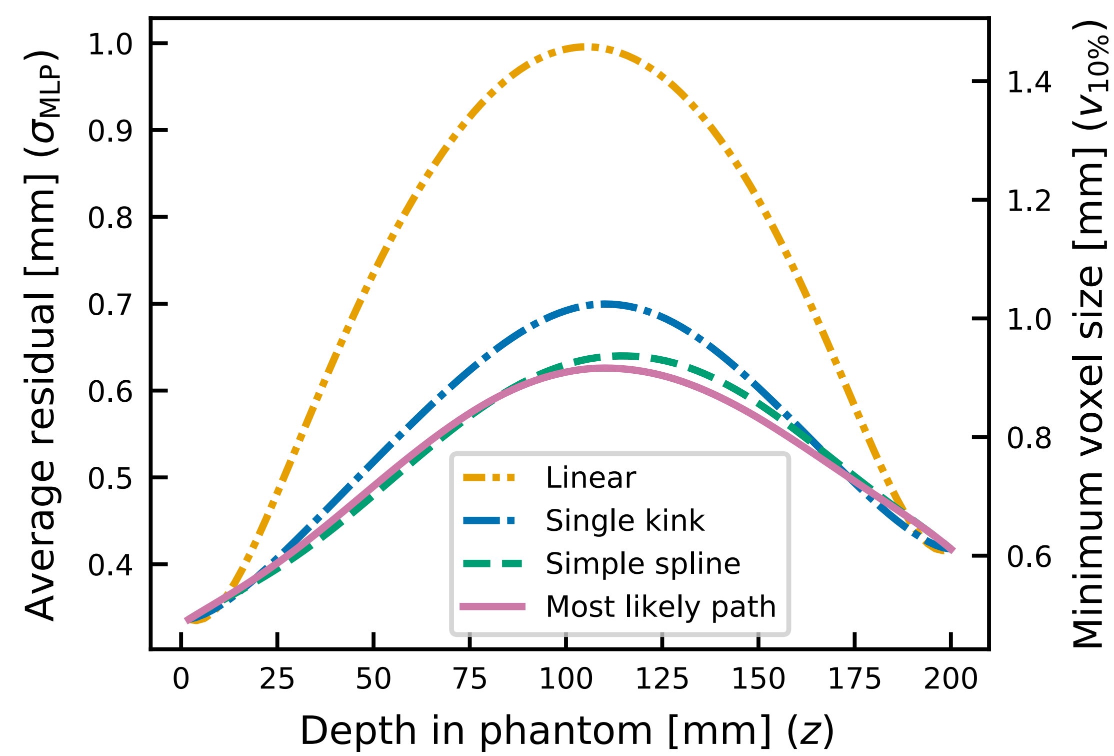
- Geant4 based analysis with many free parameters
  - Single particle tracking setup
  - Detector: material budget ε and position resolution σ_p
  - Geometry: number of planes, distance D, clearance C and thickness T
  - Beam: initial energy E_0 and particle species (proton, helium)
  - Path model: straight line fit or general broken lines (GBL) in air, most likely path (MLP) in phantom



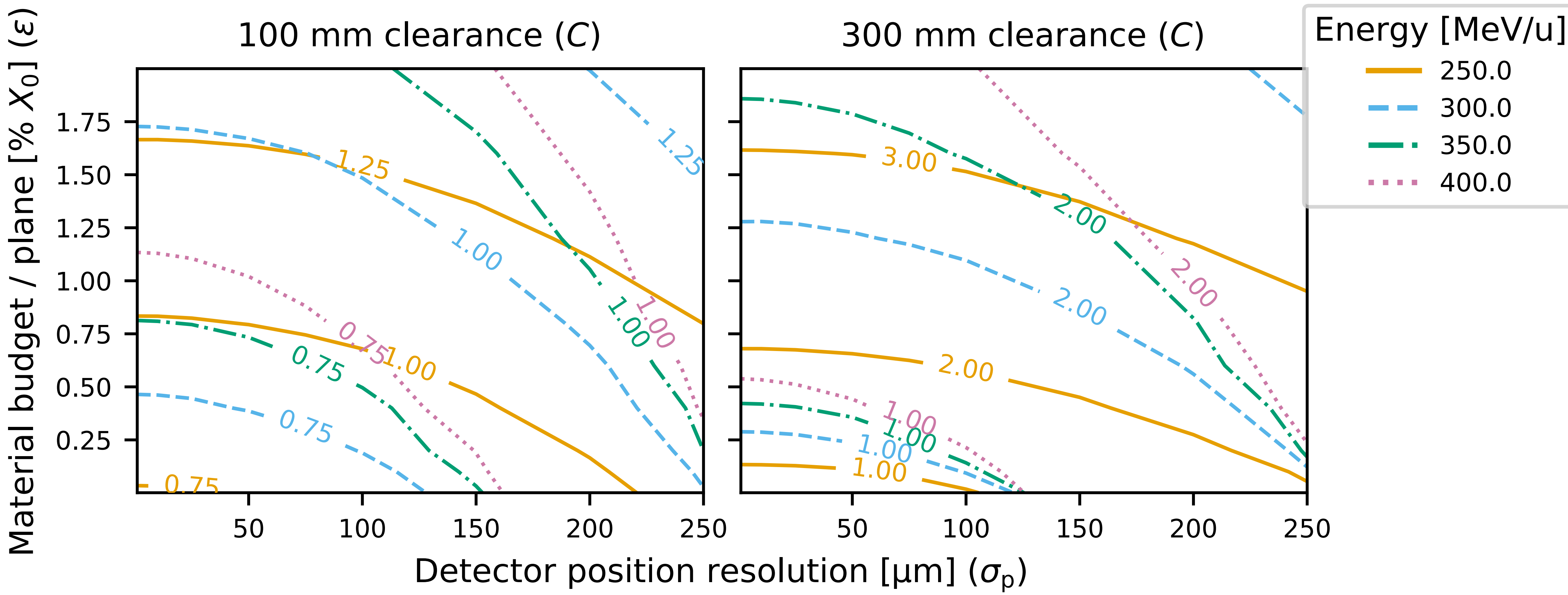
Overview

- Workflow and Figure-of-Merit
  - Track reconstruction in up- and downstream detectors
  - 3σ cuts on scattering angle and energy loss
  - Find phantom entry and exit coordinates and direction
  - Reconstruct most likely path (MLP) in phantom
  - Root-mean-square deviation (RMSD) of lateral MLP position at every depth in phantom
  - Max. RMSD along phantom depth is converted to spatial frequency and minimum voxel size



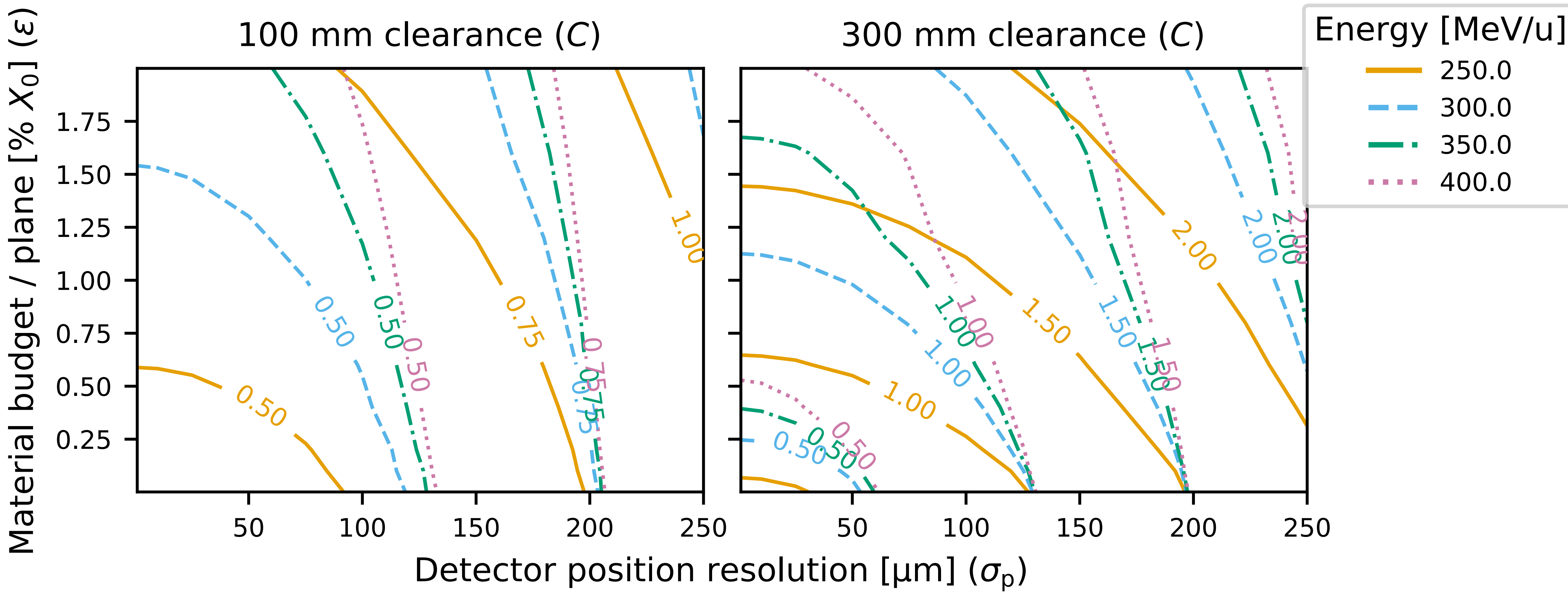


Selected Results for Protons



- Iso-voxel spacing in [mm] for phantom thickness T = 20 cm, detector distance D = 10 cm
- With small air gap, lower limit in voxel spacing is ≈ 0.75 mm
- For a voxel spacing ≤ 2 mm and 300 mm clearance, material budget should be below
  - 0.25% per plane, at $\sigma_p = 200$ µm
  - 0.70% per plane, at $\sigma_p = 50$ µm

Selected Results for Helium



- Iso-voxel spacing in [mm] for phantom thickness T = 20 cm, detector distance D = 10 cm
- Material budget influence ≈ half as large compared to protons
- A lower limit in voxel spacing is just below 0.5 mm
- 2 mm more easily achieved

Number of Detector Planes

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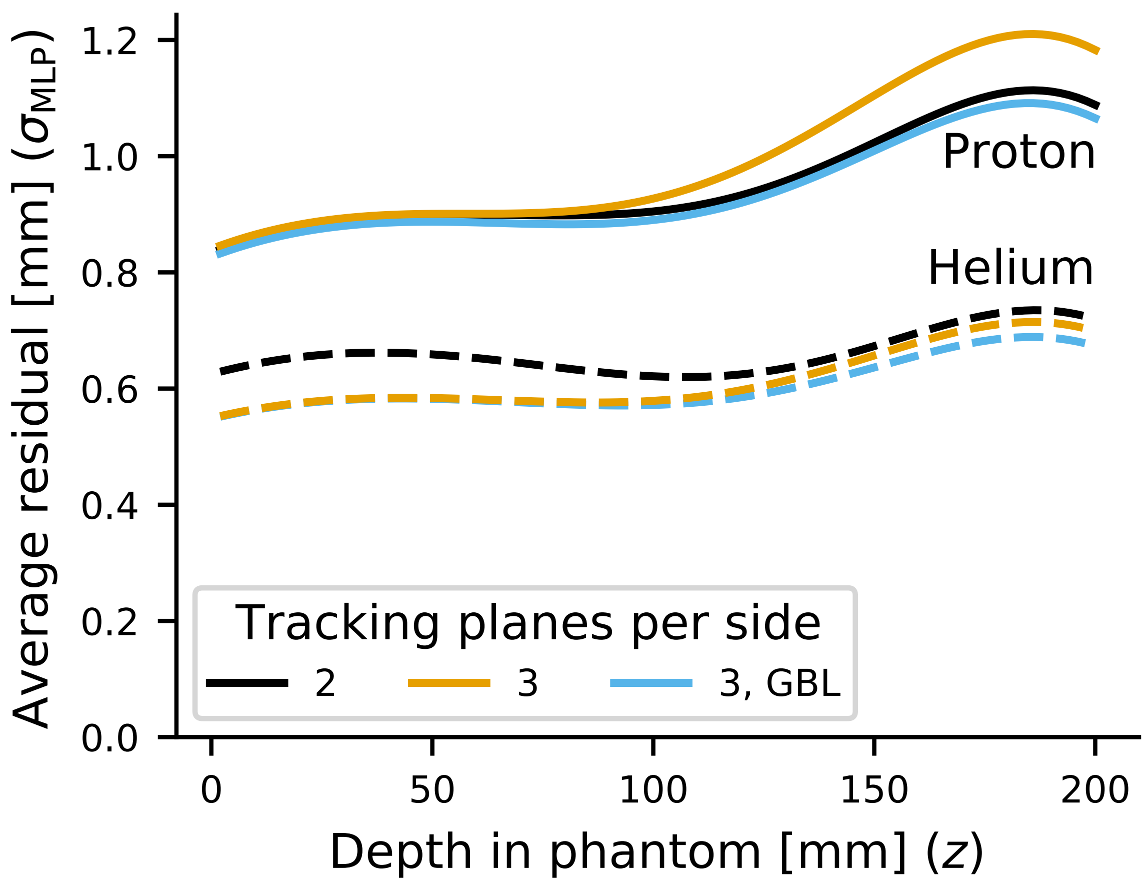
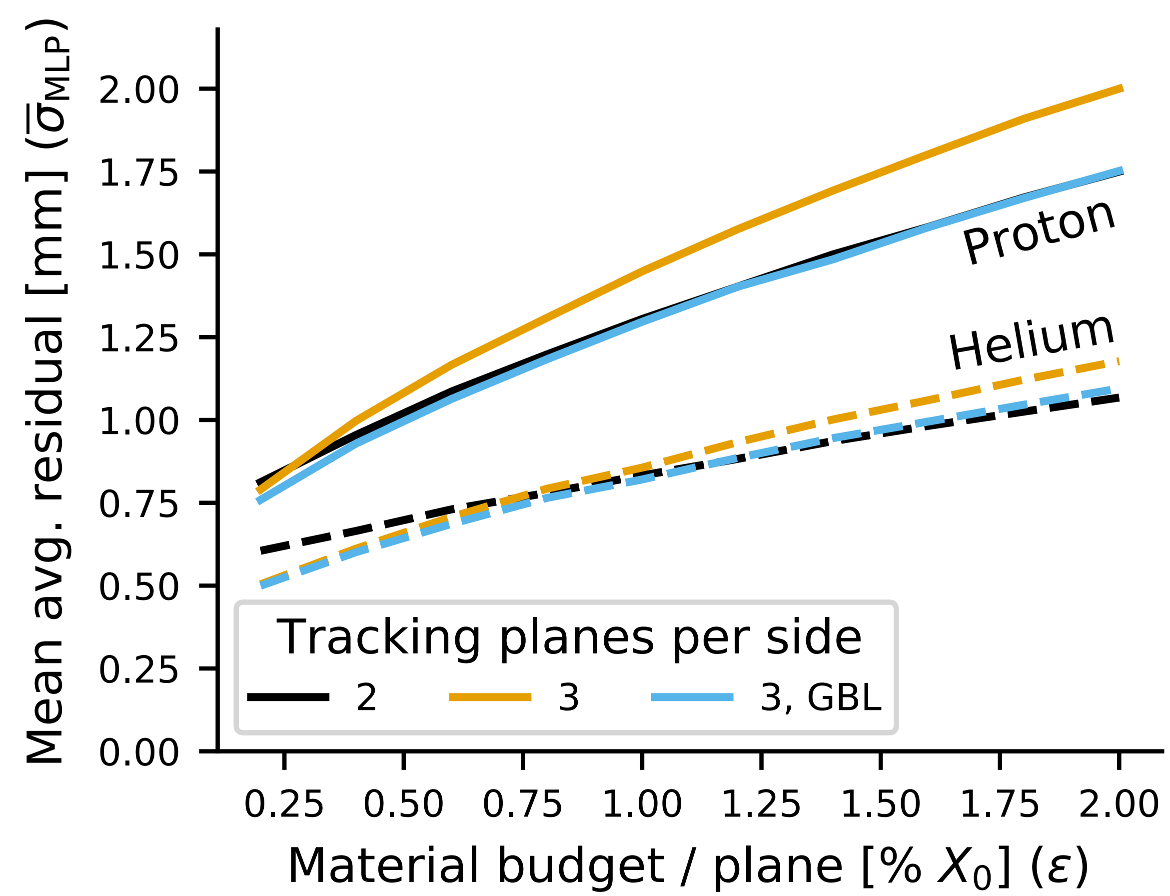


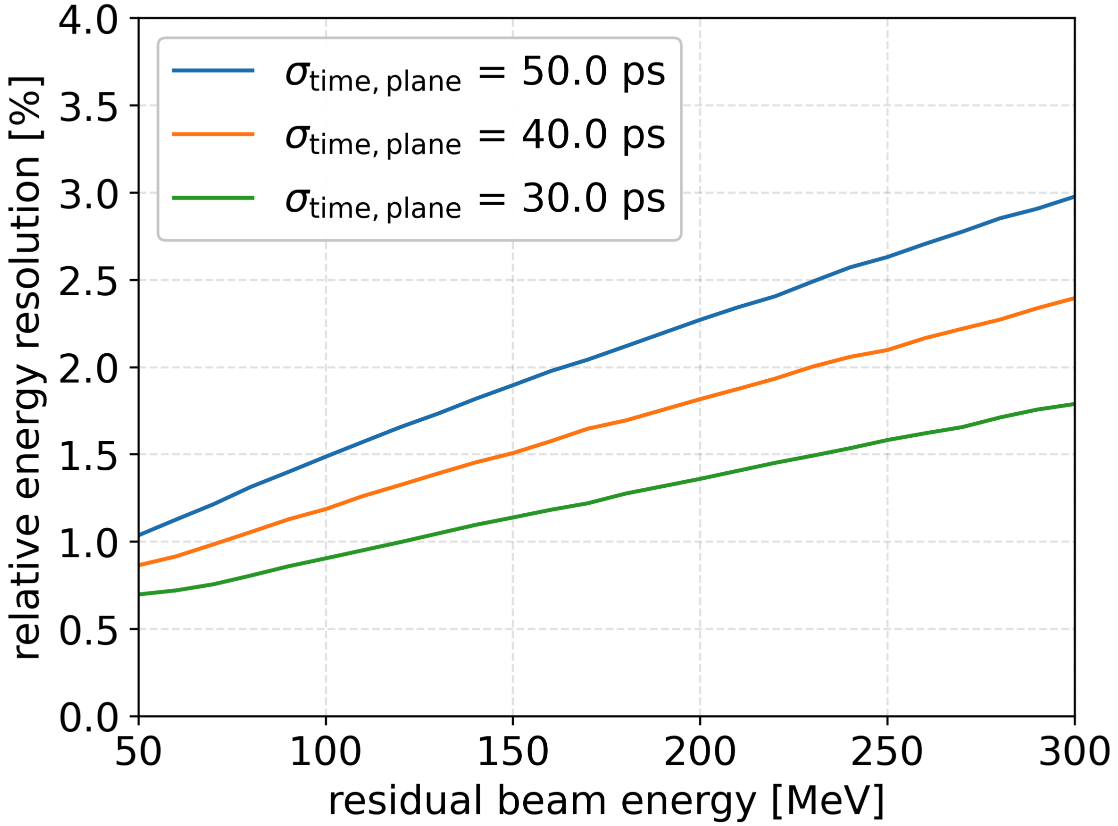


- Test 2+2 planes vs. 3+3 planes with straight line fit and general broken line fit (GBL)
  - For protons and straight line fits, six planes is worse, due to increased downstream scattering
  - For helium, six planes is slightly better, due to reduced upstream angular confusion
- 3 plane GBL performs slightly better than four plane straight line fits
  - Doesn't justify additional investment and integration effort of 2 more planes

Hardware Part II:
The Future

Time-of-Flight based Ion CT

- In the past few years **time resolutions** down to **30 ps** have become accessible
  - Strong interest from HEP community
- Technology of **Low Gain Avalanche Detectors (LGADs)**
  - Allow tracking in time and space
  - Low material budgets
- Energy measurement via **ToF competitive** in this energy regime
  - With 4 planes á 50 ps, σ_E~1.9% @ 150 MeV
  - With 4 planes á 30 ps, σ_E~1.2% @ 150 MeV
- Several advantages
  - Simplifies the detector layout
  - Flexible measurement over a large energy range



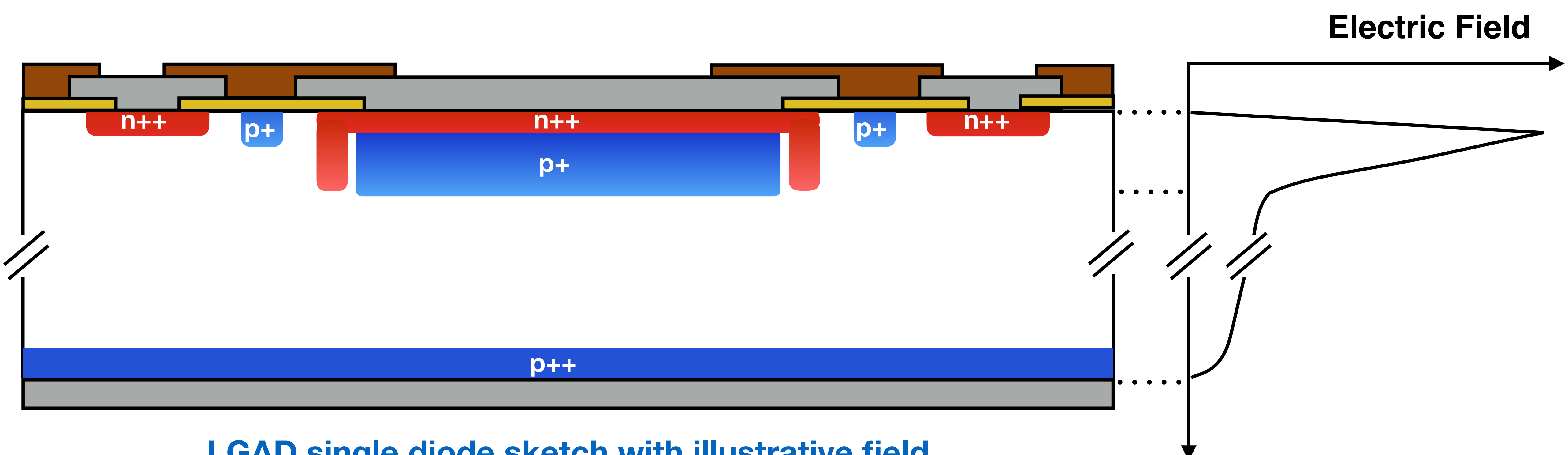
Energy resolution with 2+2 planes at various time resolutions and 1m flight path [Geant4 Sim]

LGADs in a Nutshell

- Thin silicon pad detectors with gain of ~10
  - Additional high **p-doped gain layer** in n-in-p diode to create field in excess of 200 kV/cm
  - *Controlled* impact multiplication

$$\sigma_t^2 \approx \left(\frac{a_{\mathrm{jitter}}}{S/N}\right)^2 + c_{\mathrm{floor}}^2$$

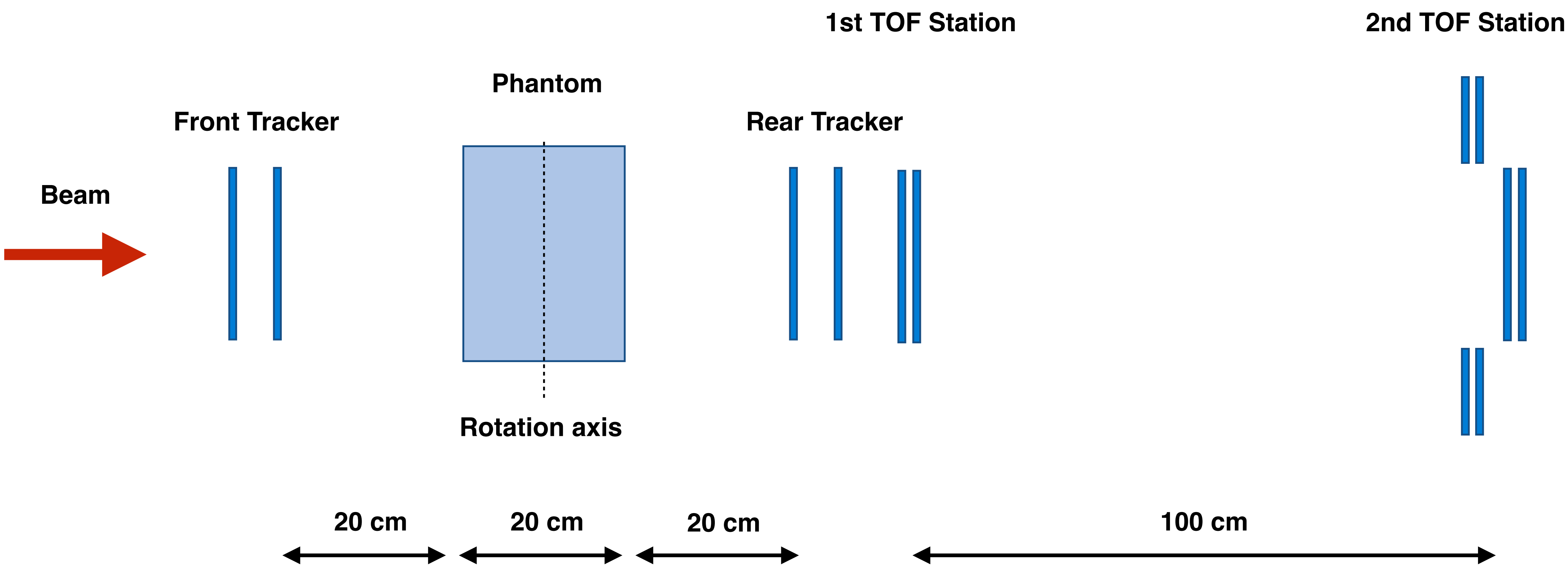
- Gain boosts S/N and improves time resolution
  - **Jitter term** dominated by t_{rise} and S/N
  - **Constant term** dominated by Landau noise, synchronisation between channels and TDC



LGAD single diode sketch with illustrative field

Three Possible Setups

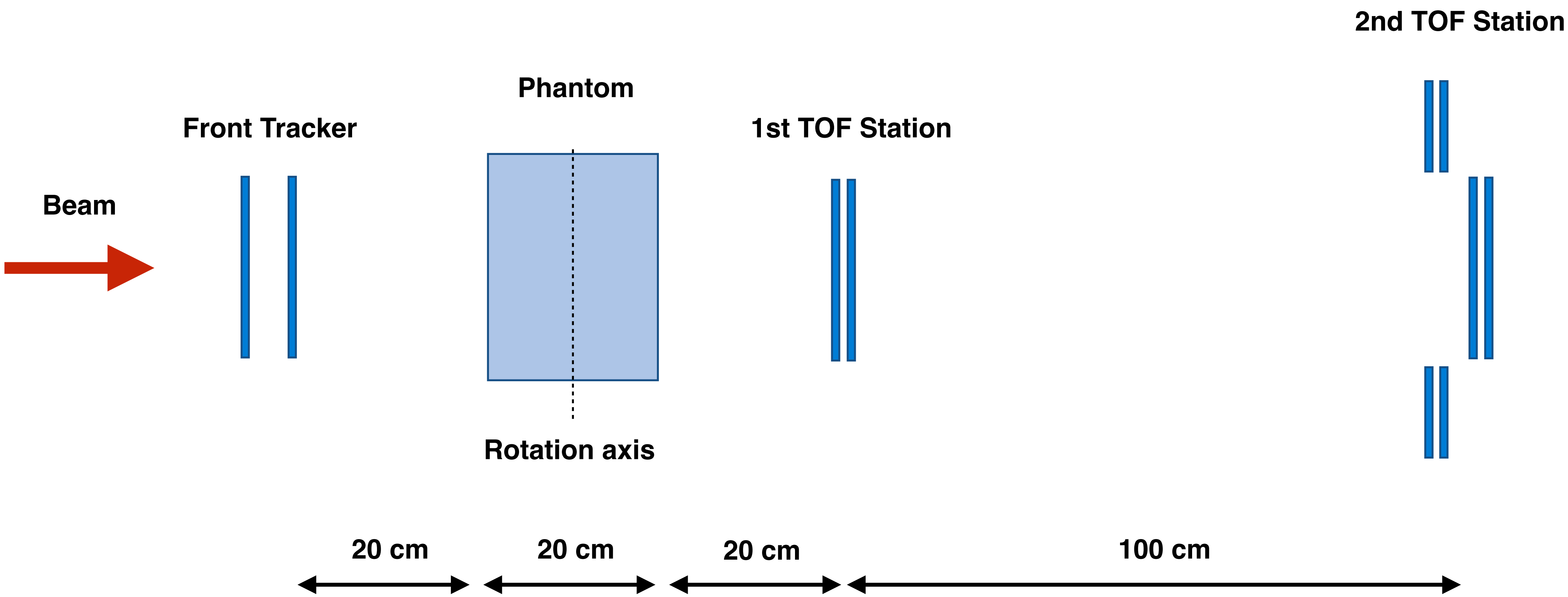
- Option 1: Use TOF only for E-ΔE measurement
  - **Tracker** can use a **different technology** like depleted CMOS
  - **Modest requirements** of $\sigma_{spatial}$ ~ 1 mm, high fill factor easily achieved
  - Can deliver a relatively low cost and flexible calorimeter option



Sketch of TOF E-ΔE setup with separate pixel trackers

Three Possible Setups

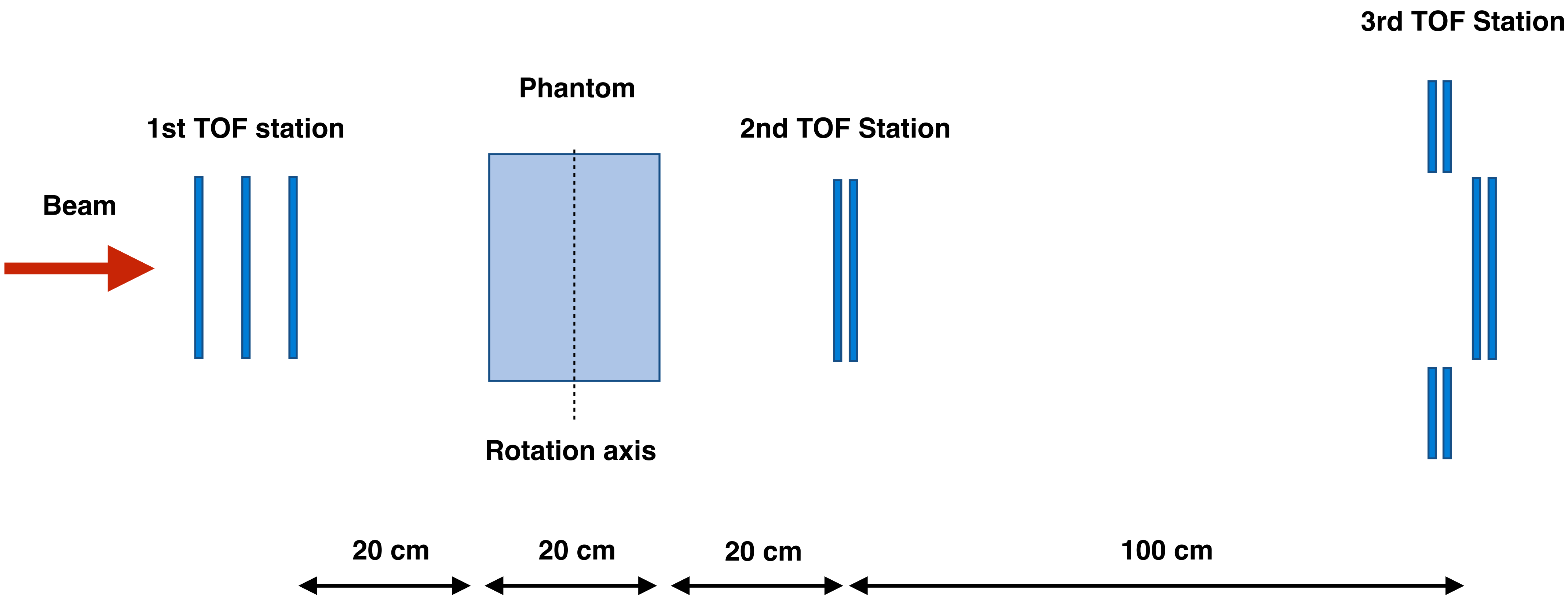
- Option 2: Extend rear tracker based on LGADs over a suitable distance
  - Front tracker can still use a different technology
  - **Stricter requirements** on $\sigma_{spatial}$ and fill factor
  - Sketch assumes LGAD strip sensors



Sketch of TOF rear tracker setup with pixel front trackers

Three Possible Setups

- Option 3: Build a full 4D tracking system
  - Front tracker is also based on LGAD technology
  - **Challenging requirements** $\sigma_{spatial} < 0.1$ mm, high fill factor difficult
  - Reduces development effort by almost a factor ~2
  - Allows to access the TOF through the body which can be used for e.g. filtering in HeCT [4]



Sketch of full 4D tracking setup

What is needed for Realisation?

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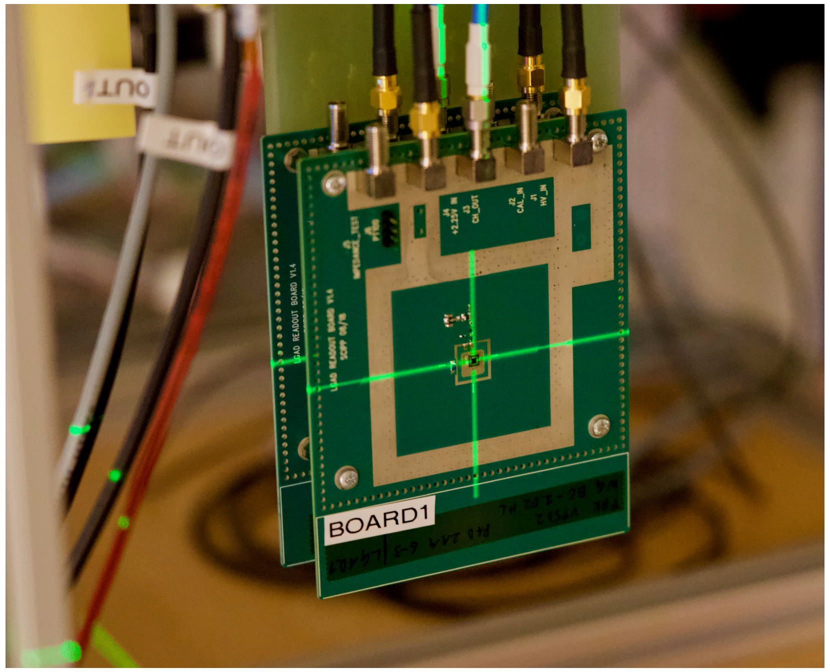
- Construction site I: The **sensor**
  - ★ Need strip geometry with pitch < 150 µm for spatial resolution (< 1 mm for E-ΔE detector)
  - ➤ HADES T0 group has **demonstrated 47 ps with 146 µm pitch** and NINO ASIC [5]
  - ★ Need fill factor > 95% is needed to avoid a third detector layer
  - ➤ FBK has demonstrated **trench isolated LGADs** with 7 µm no-gain area [6]

- Construction site II: The **ASIC**
  - ★ Need a **fully integrated** multi-channel ASIC with amplifier, discriminator and digitisation @ rates of at least O(100 kHz per channel) in data driven readout
  - ➤ Can be achieved by adaptation of existing ASICs
    - Suitable analog and digital front-end **parts exist already** [e.g. 7,8]

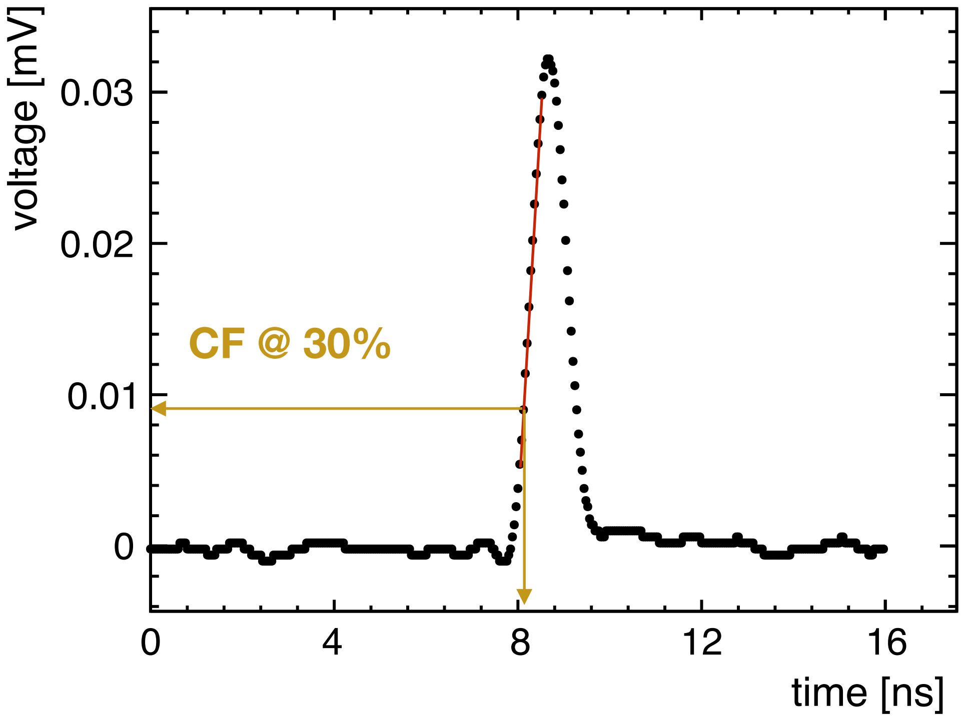
- Construction site III: Low mass, tile-able **module design**
  - ★ Need low material budget < 0.7% X_0 per plane for 4D tracker option (< 1.5% X_0 for E-ΔE option)
  - ➤ Can be done via **adaption from existing designs** e.g. from Belle II SVD
  - ➤ Integrated ASIC including TDC is essential to create a tile-able design for e.g. 30 x 30 cm^2

Test Beam Setup

- Sensors: Single diodes
  - FBK UFSD2 production
  - Sensitive area 1x1 mm^2
- Frontend: UCSB single LGAD board
  - 1st amplification stage: Infineon BFR840 SiGe
  - 2nd amplification stage: Not needed!
  - Two boards back to back with 2.5 cm spacing
- Backend: Tektronix Oscilloscope 25GS/s and 8 GHz BW
  - Diodes have intrinsic rise time of ca. 500 ps
  - Operation at 1 GHz has shown best S/N values
- Offline: Waveform analysis
  - Rising edge fit to extract timestamp at CF=30%
  - RMS of the time difference between two planes



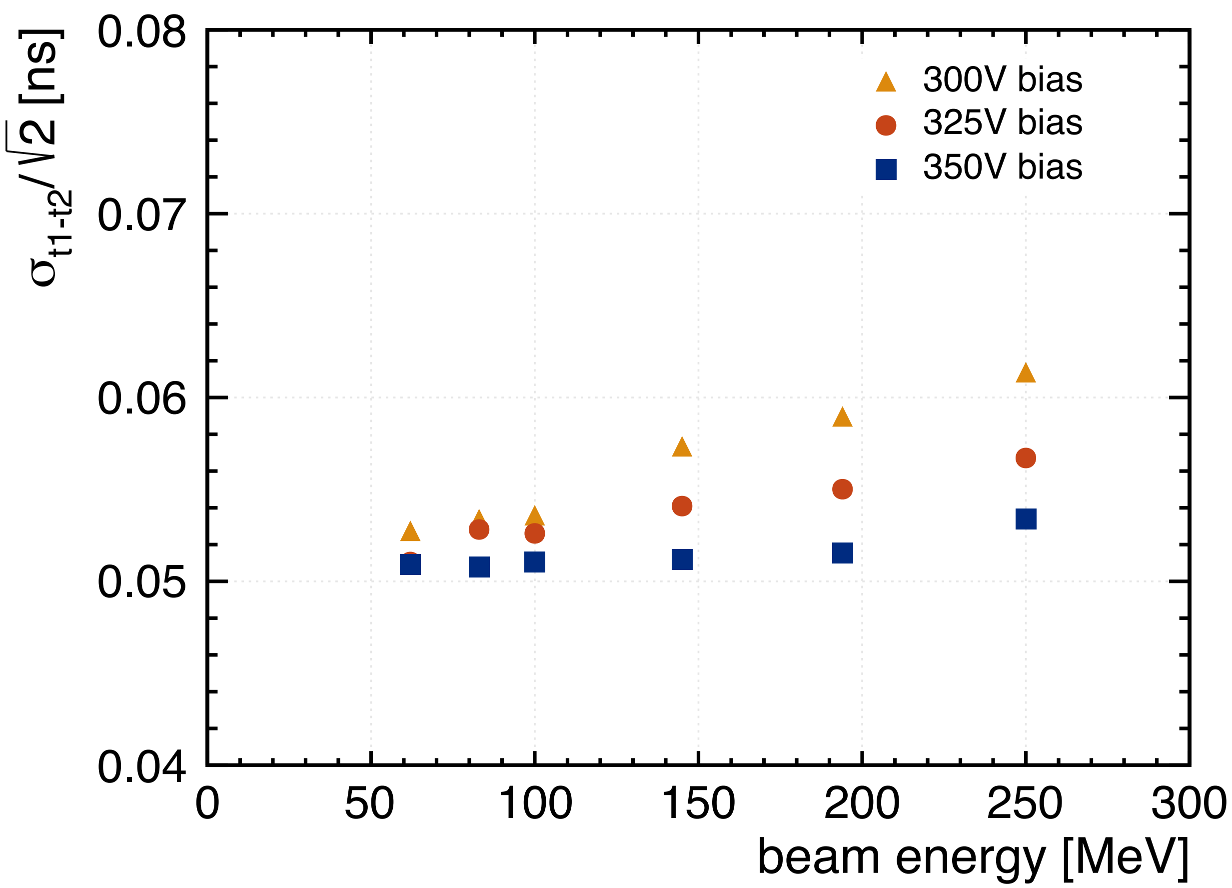
test beam setup



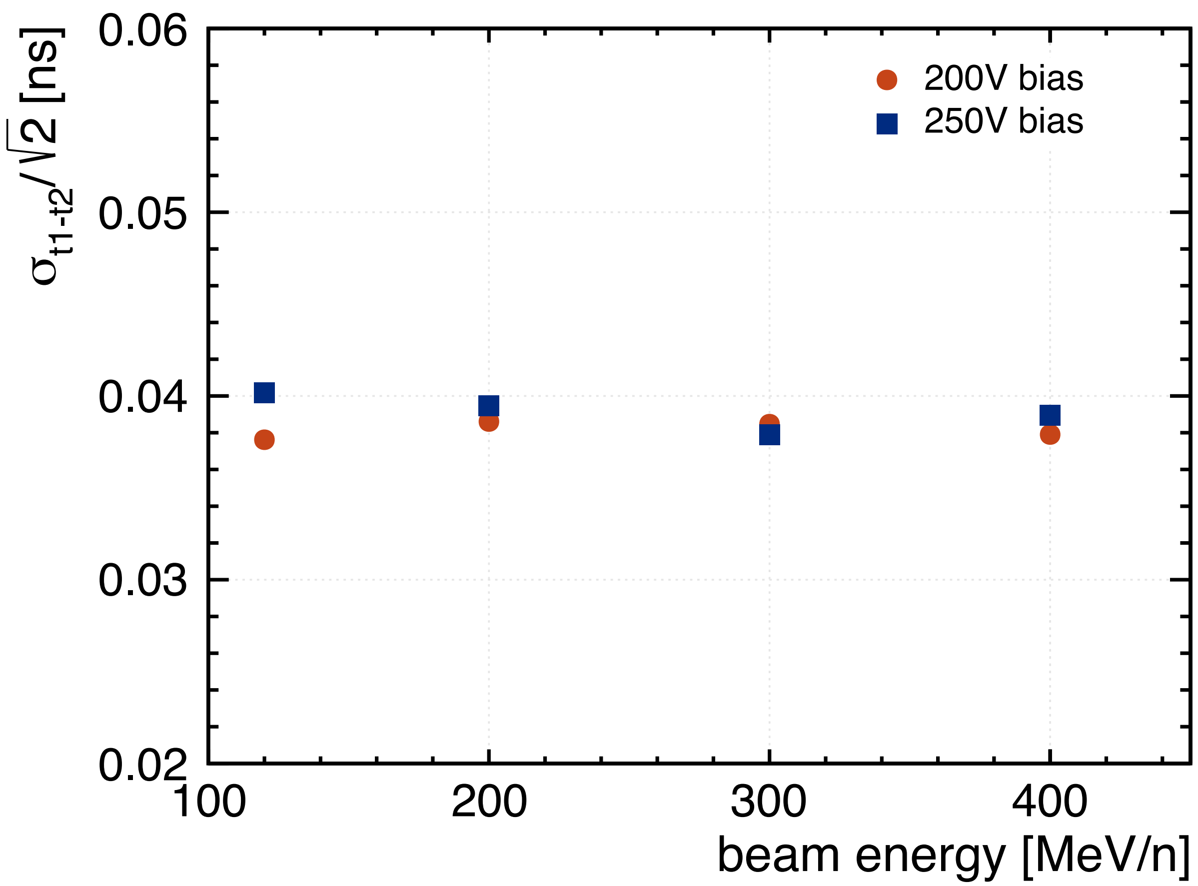
waveform analysis example

Selected Results

- Time resolutions of around 50ps (40ps) achieved for protons (carbons)
  - Improvements towards lower E_{beam} due to higher E_{dep} and better S/N
  - Not quite the expected 30 ps
  - 8bit dynamic range of oscilloscope not ideal
  - Shielding and temperature control might further improve



time resolution for protons



time resolution for carbons

Summary

- Joined HEPHY/TU Wien working group for Ion Imaging has been established
  - Goal is to establish an ion CT setup at MedAustron
- Existing hardware has shown strong limitations
  - Setup based on double-sided silicon strip sensors and range telescope finally working
  - Not suitable for the future
- TIGRE framework using iterative reconstruction is being investigated
  - Currently lacks MLP implementation but appears promising at reduced $N_{projections}$
- New developments towards time-of-flight based system have started
  - Simulation to guide new hardware developments
  - Cooperation with interested partners (FBK, GSI, TU Darmstadt and CREATIS) has been established
  - Currently looking for funding

References

- [1] M. J. French et al. 2001, https://doi.org/10.1016/S0168-9002(01)00589-7
- [2] R. Thalmeier et al. 2017, https://doi.org/10.1016/j.nima.2016.05.104
- [3] https://github.com/CERN/TIGRE
- [4] M. Rovituso et al. 2017, https://doi.org/10.1088/1361-6560/aa5302
- [5] J. Pietraszko et al. 2020, https://dx.doi.org/10.1140/epja/s10050-020-00186-w
- [6] M. Ferroro et al. 2020, https://doi.org/10.1088/1748-0221/15/04/C04027
- [7] R. Kugathasan et al. 2020, https://doi.org/10.22323/1.370.0011
- [8] F. Fausti et al. 2020, https://doi.org/10.22323/1.370.0023

Acknowledgements

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Backup

Ion Therapy in a Nutshell

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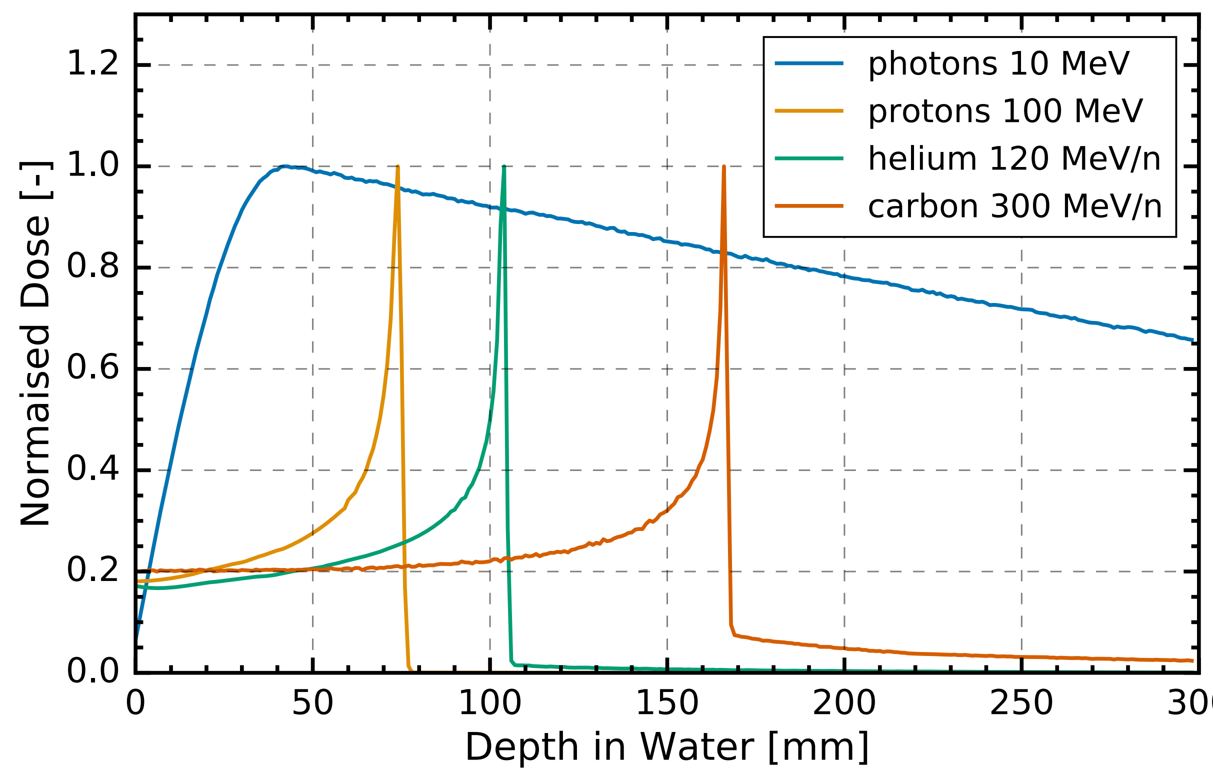
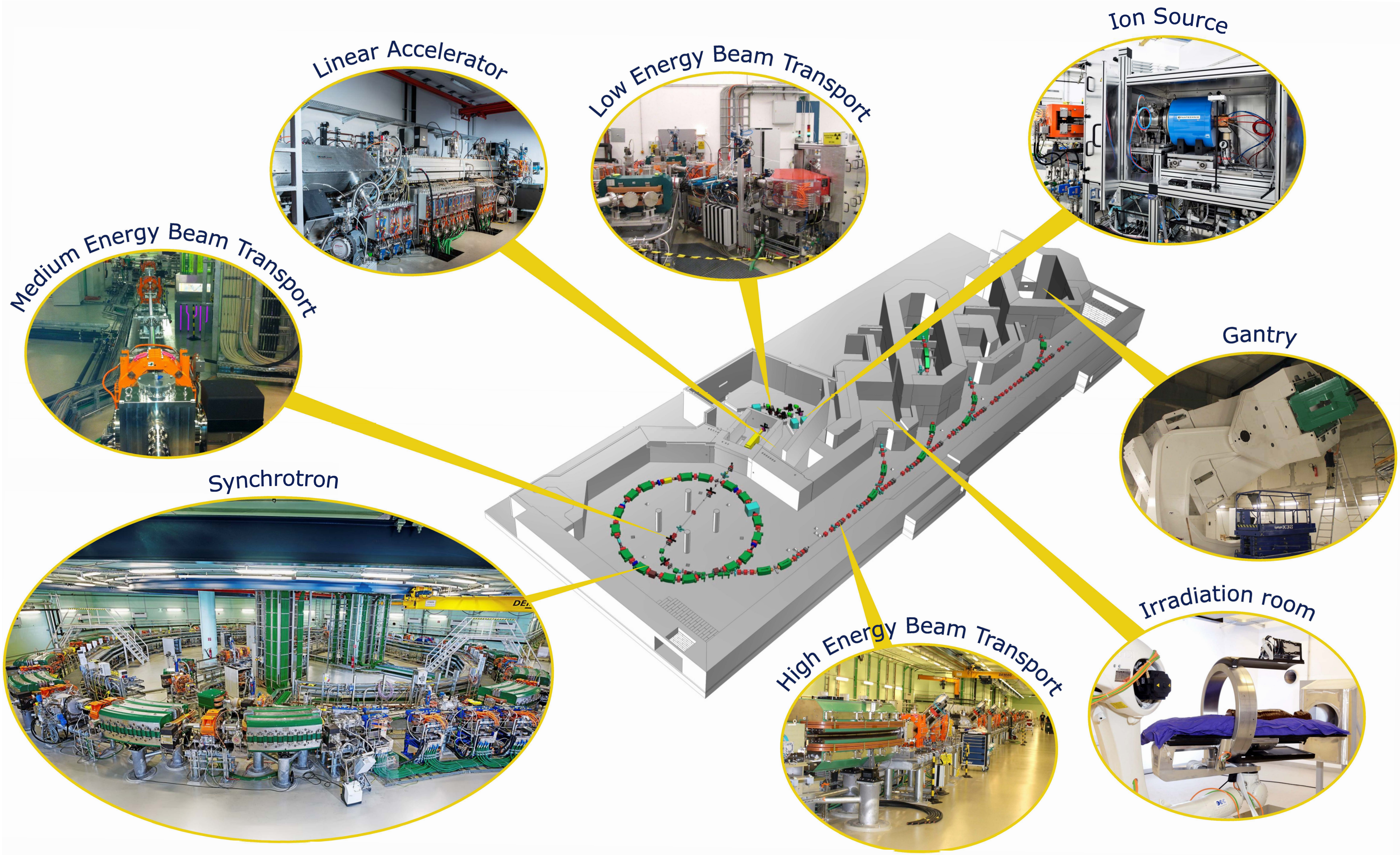
- Cancer treatment with **ion irradiation**
  - Cause **cellular damage**
  - Either via direct ionisation of DNA molecules or indirect via creation of free chemical radicals
- Ion beams allow for a **strongly localised energy deposition**
  - More accurate dose profile compared to photons
  - Allows treatment of tumours close to radio-sensitive tissue, e.g. optical nerve
- Two therapies: Protons and heavier ions
  - Protons allow for sharp distal edge
  - Heavier ions have higher biological effectiveness (RBE) but show a tail dose due to fragmentation
  - Different ions used for different tumours



dose deposition in water [GATE simulation]

MedAustron Accelerator



MedAustron Timeline

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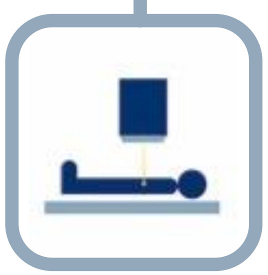
2018 | 2019 | 2020 | 2021 | 2022

p

2 rooms protons



vertical beam line

C

carbon ions

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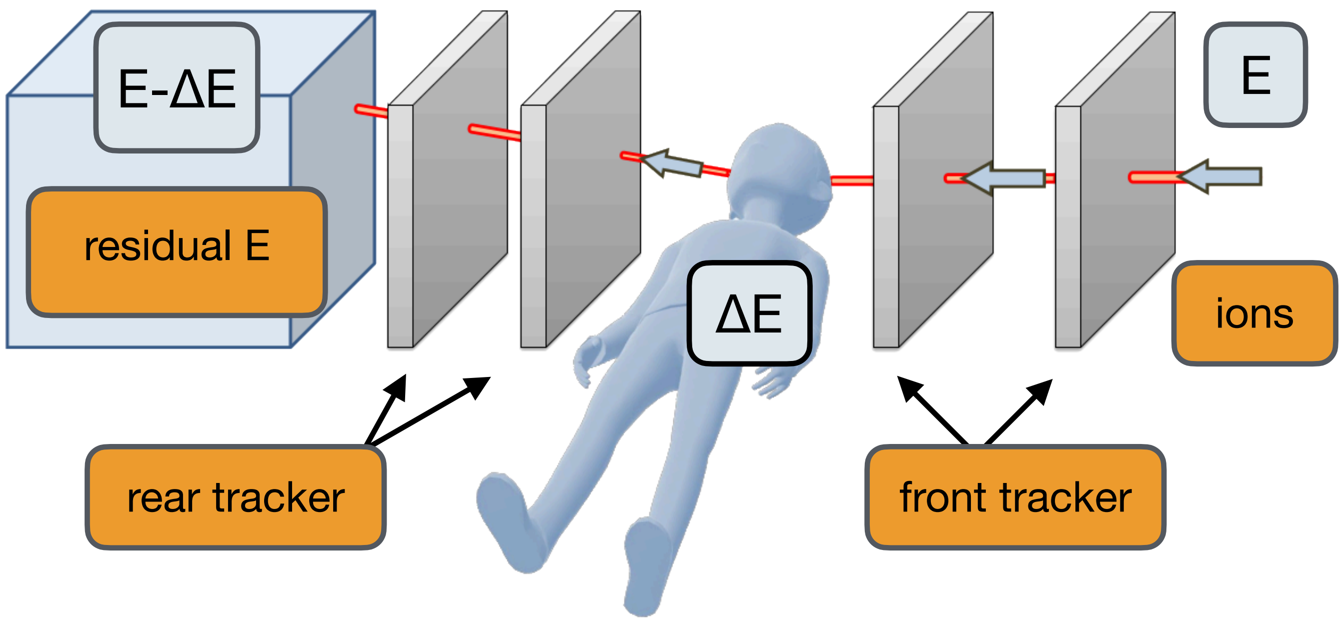
implementation for all beam lines

proton gantry

intended full operation up to 1000 year

Imaging with Ion Beams

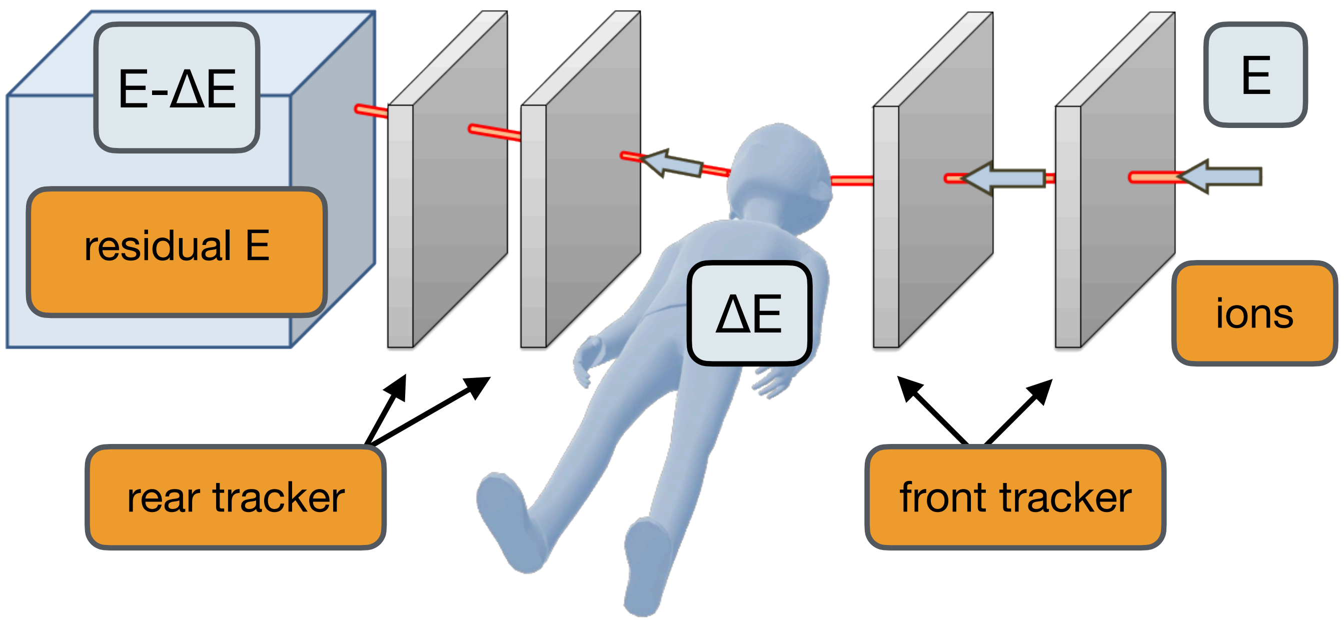
- Aim: **3D map of stopping power** within object
  - Requires ΔE and path estimate
- Particles with energy E
  - Pass front tracker
  - Lose energy ΔE in object
  - Pass rear tracker
  - Deposit energy E-ΔE in calorimeter
- Ion CT
  - **Measure ΔE and path estimate**
  - **Rotate** object and **reconstruct**
  - 3D map of stopping power within object
  - Avoids conversion uncertainties from photon attenuation coefficients (x-ray CT) to stopping power (ion therapy)
  - **Same particle species for treatment and imaging**



pCT setup sketch

An Apparatus for Ion CT

- Requirements
  - Spatial resolution of about 1x1x1 mm^3 (typical voxel size) in the object
  - **Energy resolution of about 1%**
  - Data acquisition rate of >1 MHz
  - **Rad hard to ~1e13 protons** over 10 years of operation
  - Coverage >10x10 cm^2
- Typical Setup
  - Front and rear tracker
    - Scintillating fibres or Si-strip
  - Energy measurement
    - Crystal calorimeter: CsI, YAG:Ce
    - Range counter: stack of thin detector layers made of scintillators or CMOS
    - **Time-of-flight measurement**



pCT setup sketch

LGADs for Ion CT

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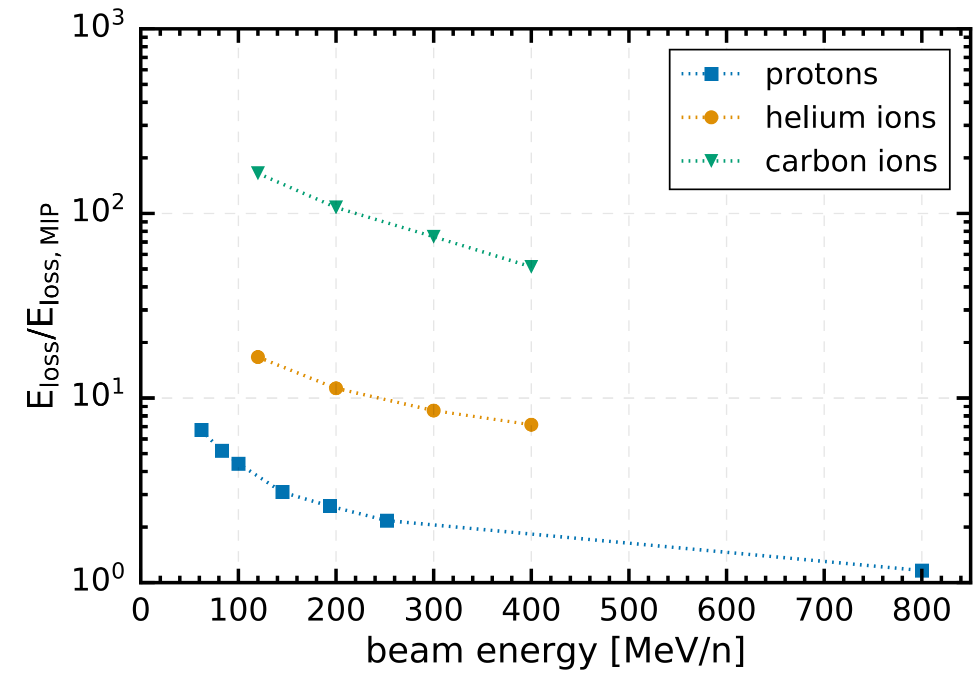
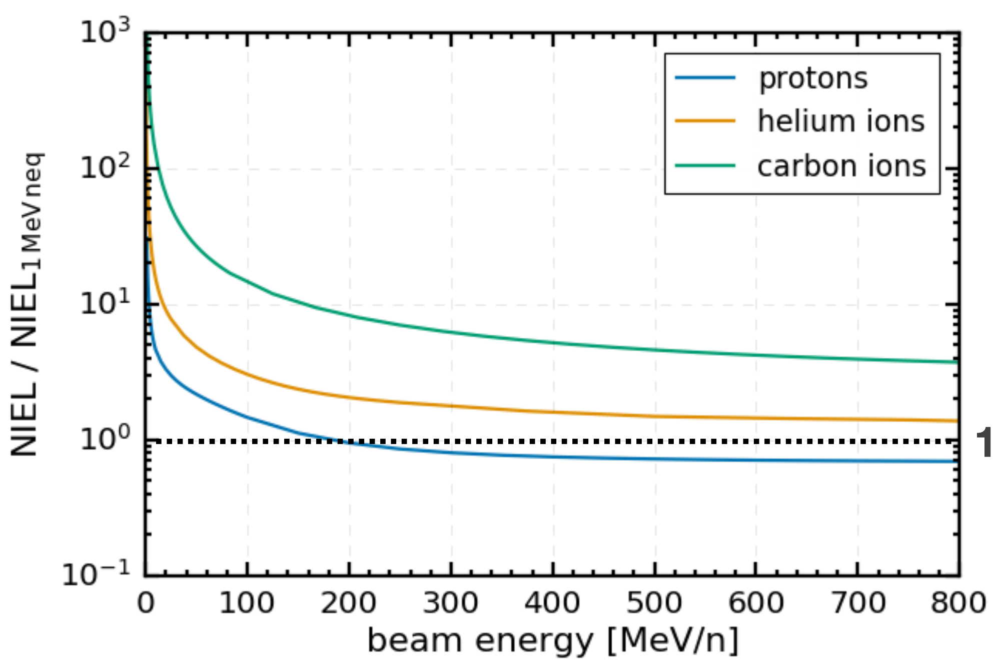
- Excellent time resolution
  - Time resolutions of 30 ps envisaged for CMS/ATLAS timing layer for single MIPs
  - **Energy deposition** in relevant beam range is **several MIPs**
  - Energy deposition of heavy ions is less ‘Landau-like’ and could allow for a reduced Landau noise
- Good radiation hardness
  - **Radiation hardness** shown to above **1e15**
- Could render **rear tracker unnecessary**
  - Required precision driven by MCS limit and varies with object length
  - Spatial resolution of below 1 mm achievable with current LGAD designs
  - Significant efforts for further improvements



energy loss relative to MIPs in 50 µm Si [Allpix² simulation]



displacement damage cross section relative to 1 MeV neutrons