HEPHY
INSTITUTE OF HIGH ENERGY PHYSICS

LGAD Performance at Low Energy Proton and Ion Beams for Ion CT

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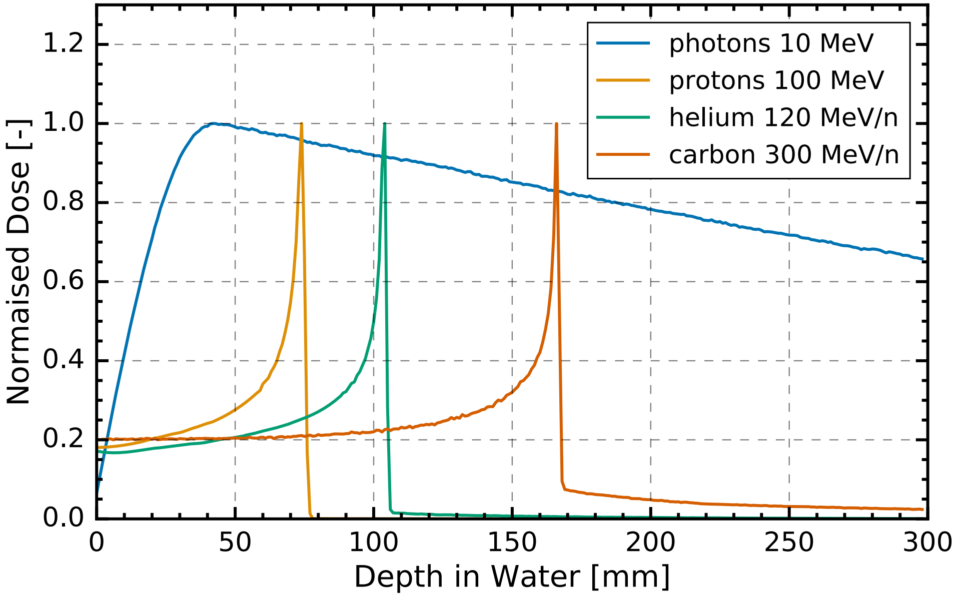
TREDI Workshop Vienna 2020
18.02.2020

Ion Therapy in a Nutshell

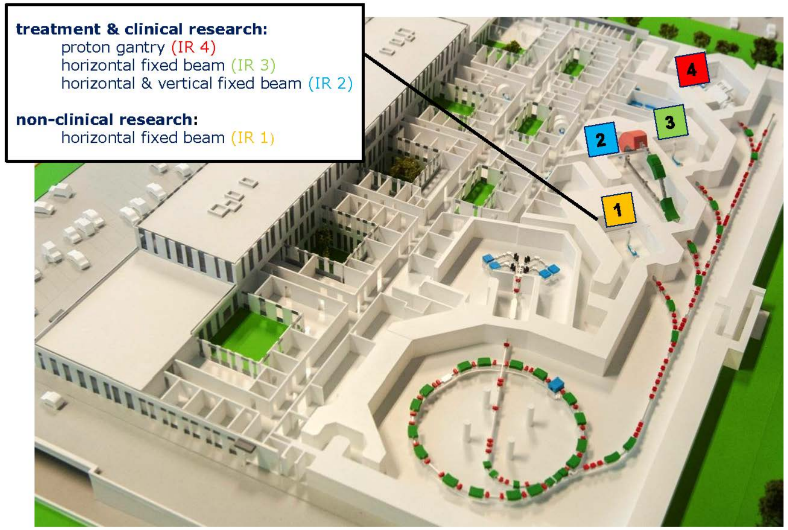
- Cancer treatment with **ion irradiation**
  - Cause **cellular damage**
  - Either via direct ionisation of DNA molecules or indirect via creation of free chemical radicals
- Ion beams allow for a **strongly localised energy deposition**
  - More accurate dose profile compared to photons
  - Allows 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 in a Nutshell

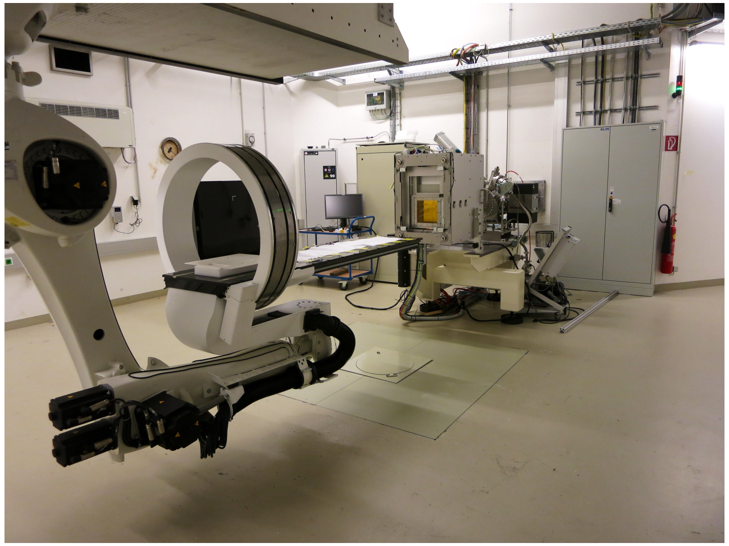
- Ion therapy centre for cancer treatment
  - Synchrotron accelerator complex located close to Vienna
  - Four irradiation rooms:
    - **IR1**: Exclusive to research
      (up to 800 MeV protons, low flux)
    - **IR2**, **IR3**, **IR4**: Clinical use
      (up to 250 MeV protons, GHz rates)
  - Beam 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



treatment & clinical research:
proton gantry (IR 4)
horizontal fixed beam (IR 3)
horizontal & vertical fixed beam (IR 2)

non-clinical research:
horizontal fixed beam (IR 1)

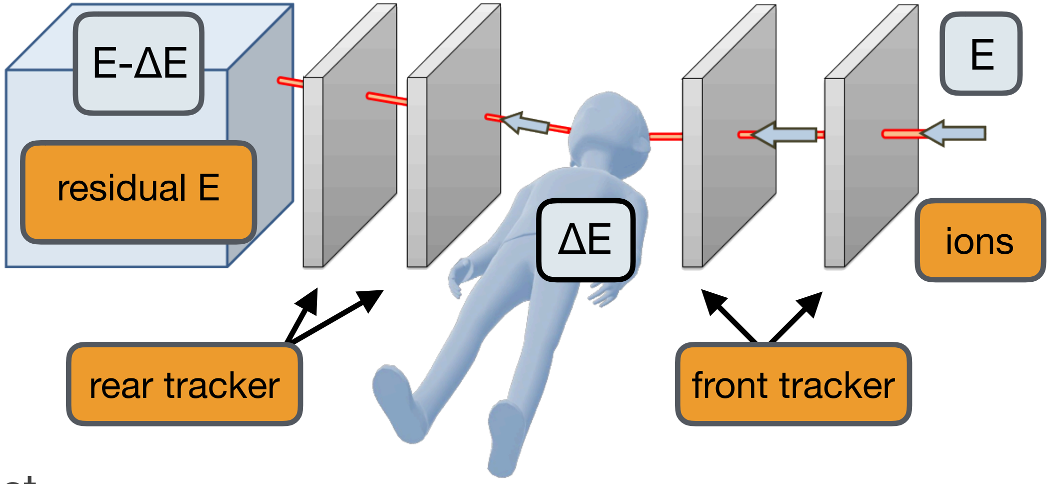
MedAustron accelerator complex



IR1 reserved for research

Imaging with Ion Beams

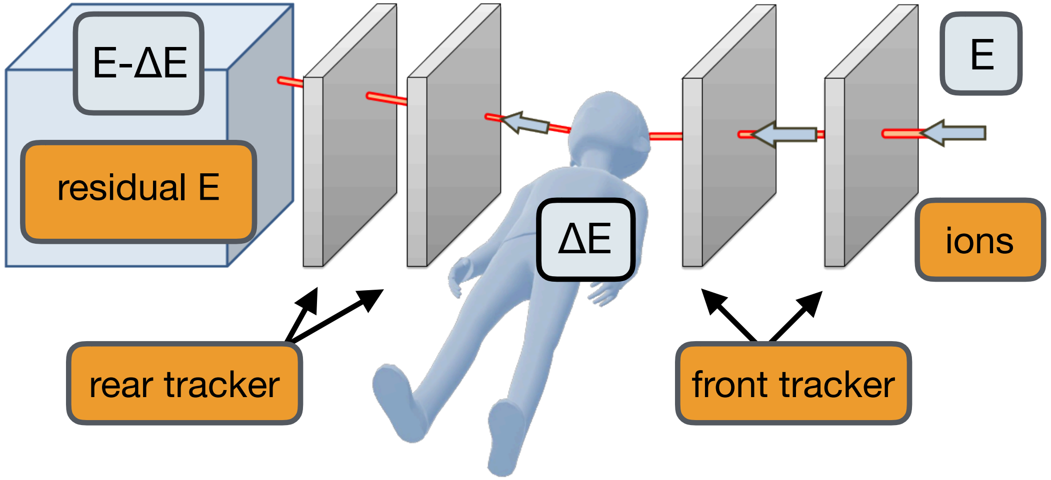
- Aim: **3D map of stopping power** within object
  - Requires ΔE and path estimate
- Particles with energy E
  - Pass front tracker
  - Lose energy ΔE in object
  - Pass rear tracker
  - Deposit energy E-ΔE in calorimeter
- Ion CT
  - **Measure ΔE and path estimate**
  - **Rotate** object and **reconstruct**
  - 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

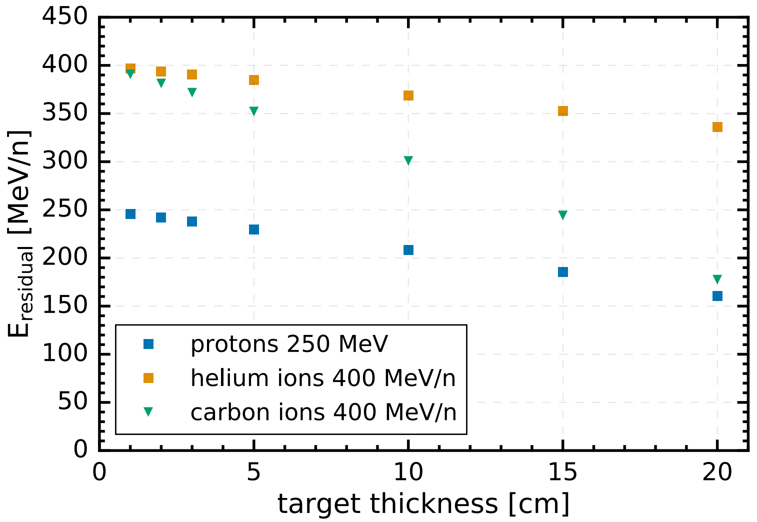
- Requirements
    - Spatial resolution of about 1x1x1 mm^3 (typical voxel size) in the object
    - **Energy resolution of about 1%**
    - Data acquisition rate of >1 MHz
    - **Rad hard to ~1e13 protons** over 10 years of operation
    - Coverage >10x10 cm^2
- Typical Setup
    - Front and rear tracker
        - 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**



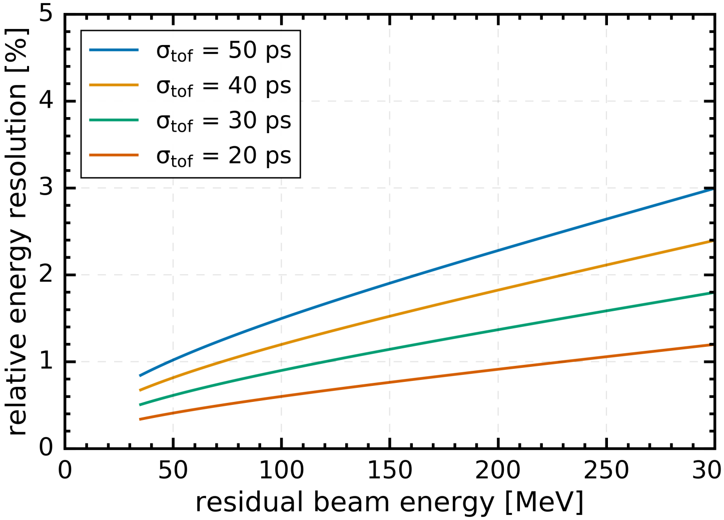
pCT setup sketch

Time-of-Flight for Ion CT

- Typical beam for ion CT is 250 MeV protons
  - Optimal beam energy and species is **tradeoff between MCS and stopping power contrast**
  - Most facilities provide 250 MeV protons as largest available (incident) energy
  - MedAustron also provides carbon and possible helium
- Benchmark case is **20 cm water target**
  - Approximate size of adult head
  - **Residual proton energies** approx. **150 MeV**
- Energy measurement via **ToF competitive**
  - 50 ps via 2 planes á 35 ps (σ_E~1.9% @ 150 MeV)
  - 30 ps via 4 planes á 30 ps (σ_E~1.2% @ 150 MeV)
  - Improves with lower residual energy!



residual energy after passing a water target [GATE simulation]



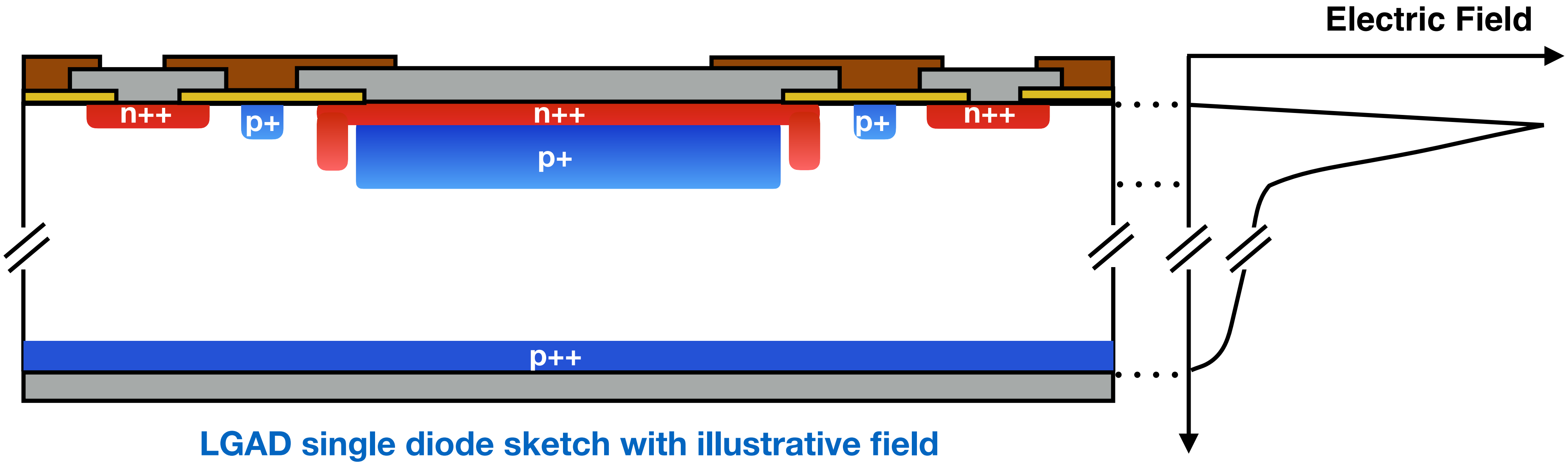
energy resolution with various ToF resolution and 1m flight path [analytical]

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

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

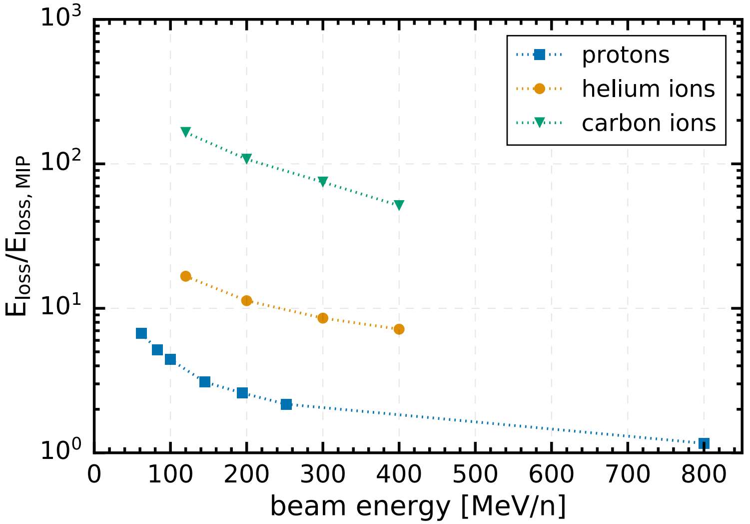
- Gain boosts S/N & t_{rise} and improves time resolution
  - **Jitter term** dominated by t_{rise} and S/N
  - **Constant term** dominated by Landau noise, synchronisation between channels and TDC



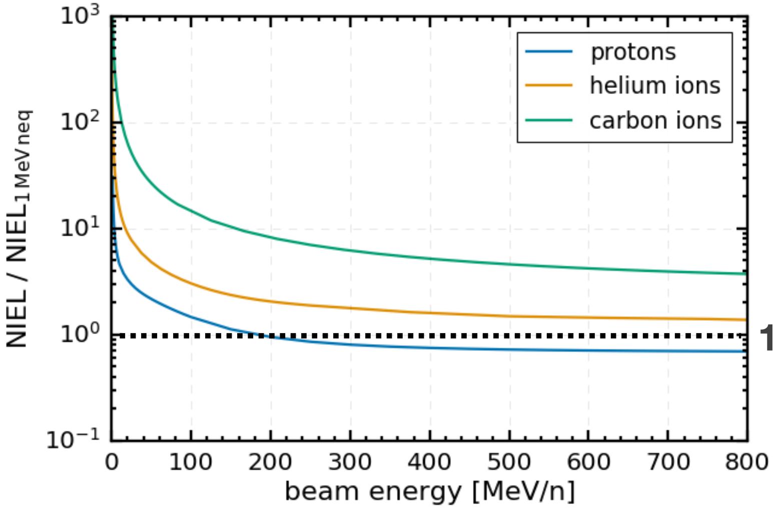
LGAD single diode sketch with illustrative field

LGADs for Ion CT

- 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** [1]
- 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 [2]

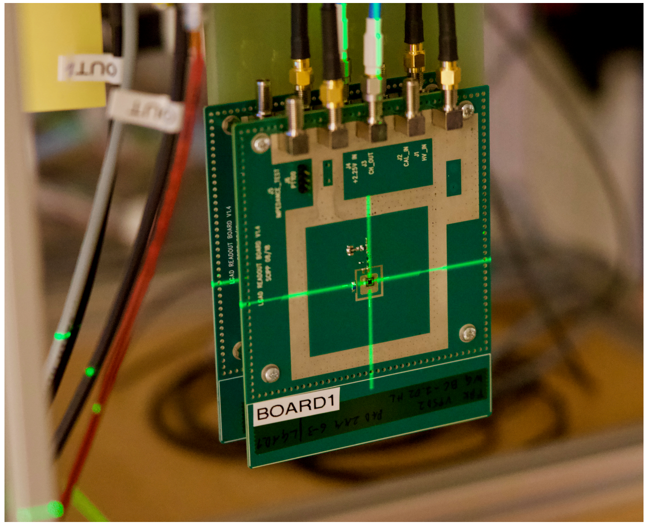
Test Beam Setup

- Sensors: Single diodes
  - FBK UFSD2 production
  - Sensitive area 1x1 mm^2

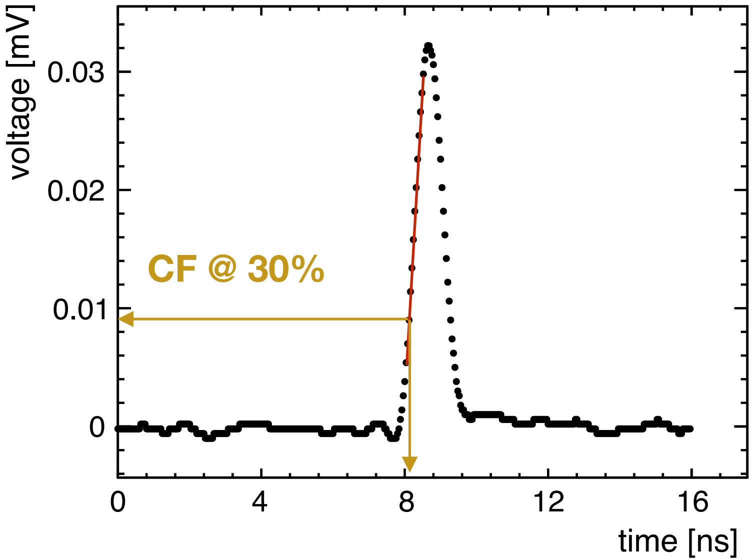
- Frontend: UCSB single LGAD board
  - 1st amplification stage: Infineon BFR840 SiGe
  - 2nd amplification stage: Not needed!
  - Two boards back to back with 2.5 cm spacing

- 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



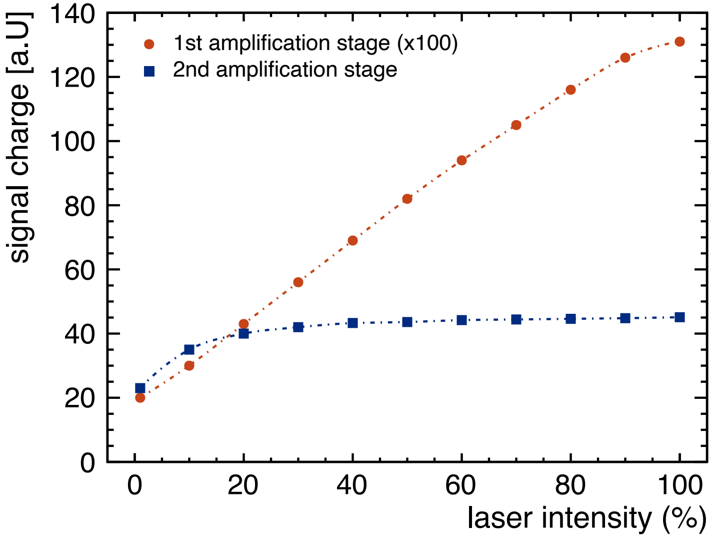
test beam setup



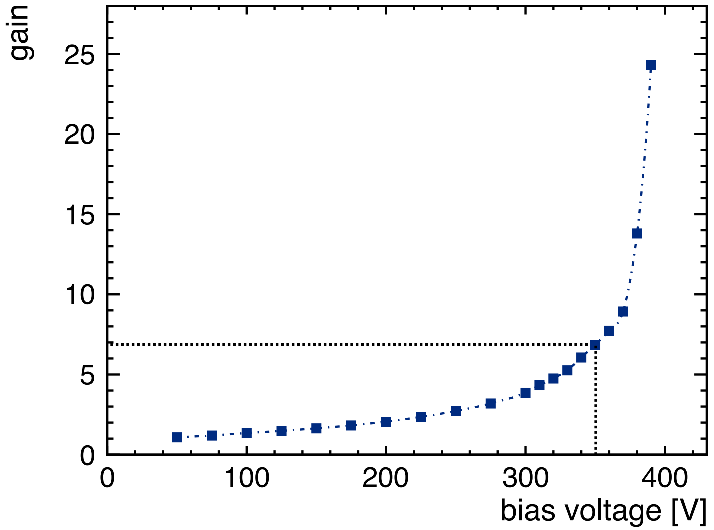
waveform analysis example

Laser Characterisation

- Initial characterisation in typical TCT setup
  - 1064 nm PILAS IR laser
- Saturation of Front End Components
  - UCSB board typically used for MIP detection with 2 amplification stages
  - 2nd amplification stage saturates quickly but is not needed for our application
  - 1st amplification stage more or less linear
- Gain of ~7 at 350V
  - Highest gain used in test beam
    [Keep in mind that we are not detecting MIPs]



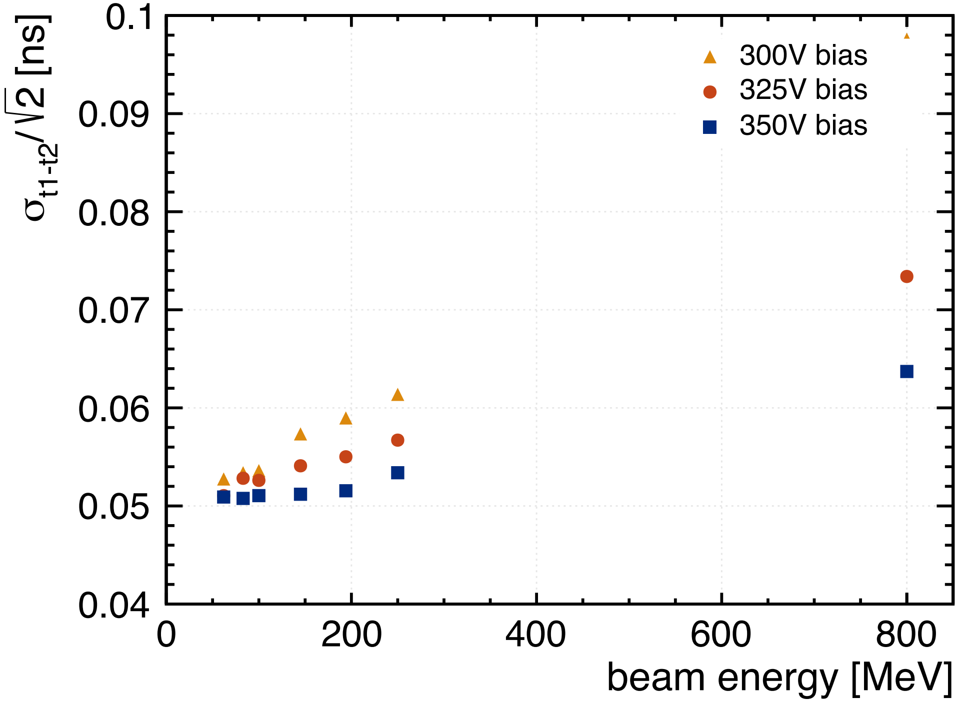
laser response



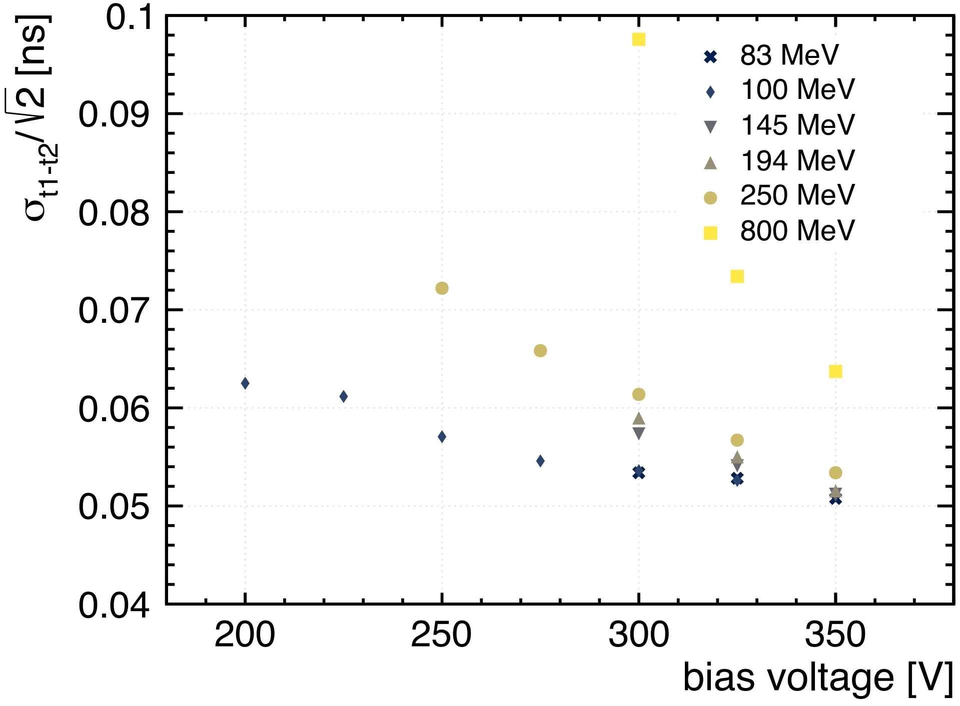
gain extracted from laser measurements

Results for Protons

- Resolutions around 50 ps achieved for beam energies below 200 MeV
  - Not quite the expected 30 ps
  - Higher beam energies could clearly profit from more gain



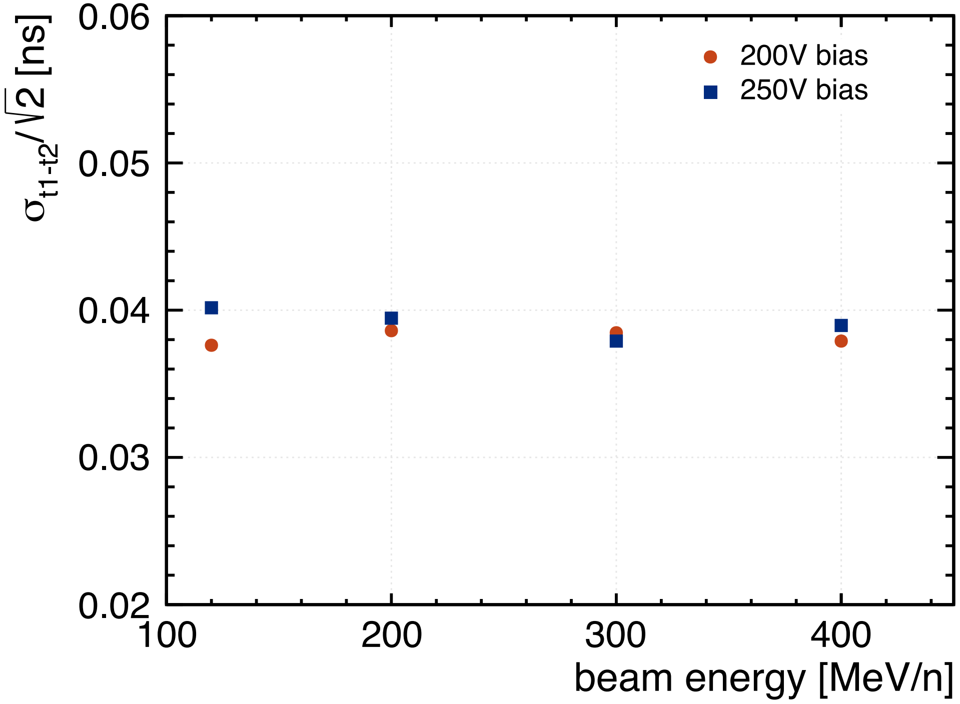
time resolution vs beam energy



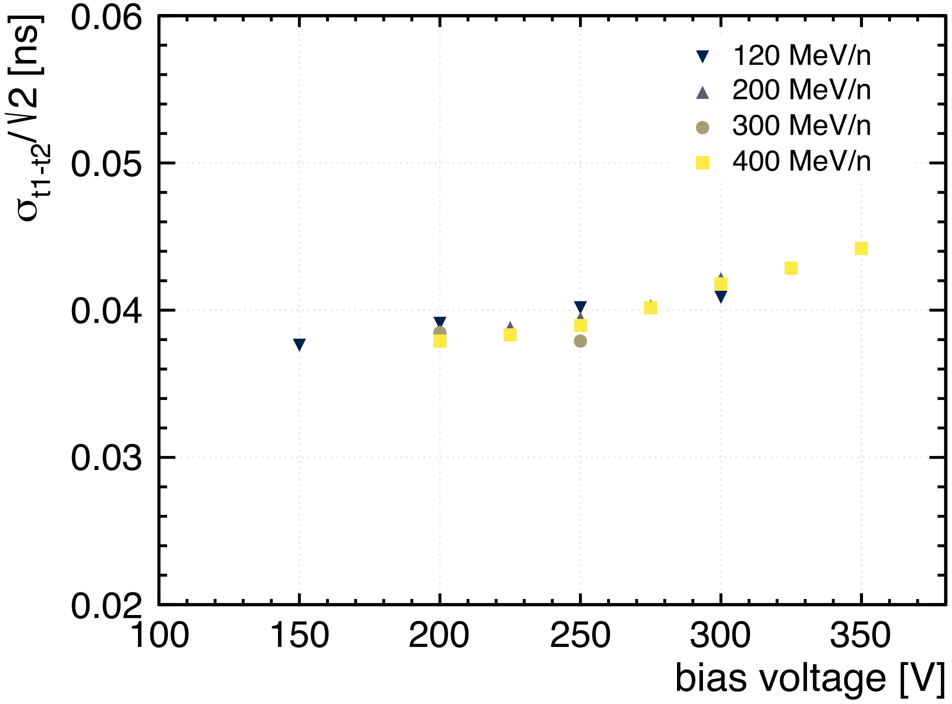
time resolution vs bias

Results for Carbon Ions

- Resolution below 40 ps achieved for all beam energies
  - Better resolution at lower bias voltage hints to shielding effects
  - Gain not really required for carbon imaging
  - Constant term (= Landau noise?) appears to be smaller for carbon ions



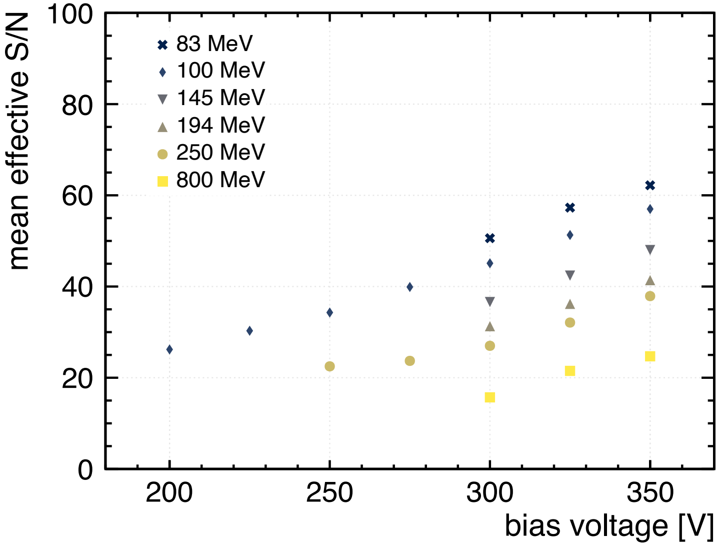
time resolution vs beam energy



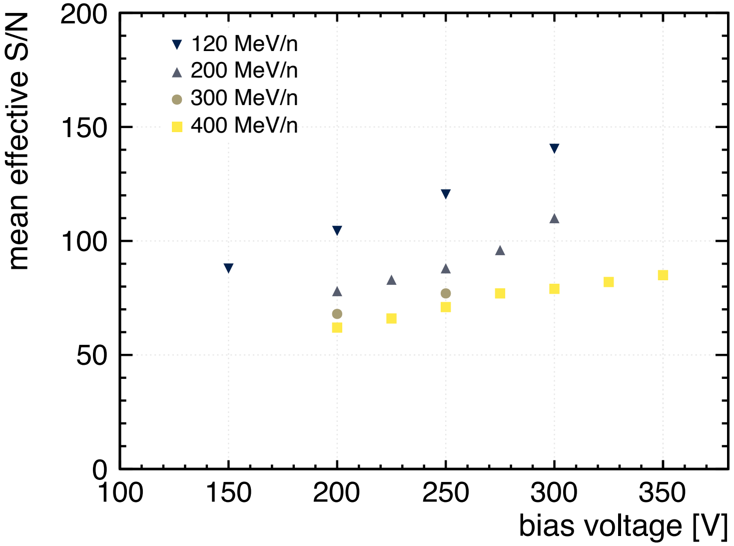
time resolution vs bias

Discussion I

- Jitter contribution
  - Mean system rise time ~ 500 ps
  - Effective values of S/N ~ 20 should allow for ~ 30 ps jitter contributions
  - At same S/N, carbon ions yield better resolution than protons
- Synchronisation
  - Synchronisation uncertainty between oscilloscope channels ~17 ps
- Gain not high enough?
  - Certainly 250 & 800 MeV protons could profit from higher S/N
  - But also the rise time seems to benefit
  - We will have another 8 hours of beam time this weekend with higher bias



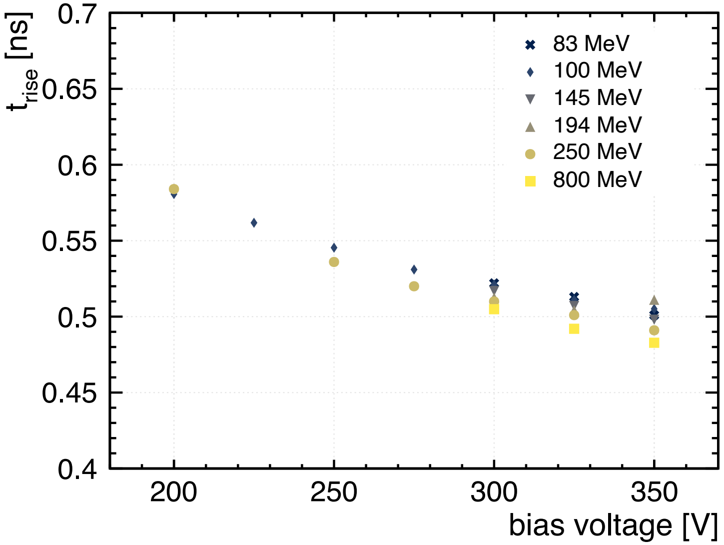
effective S/N for proton runs



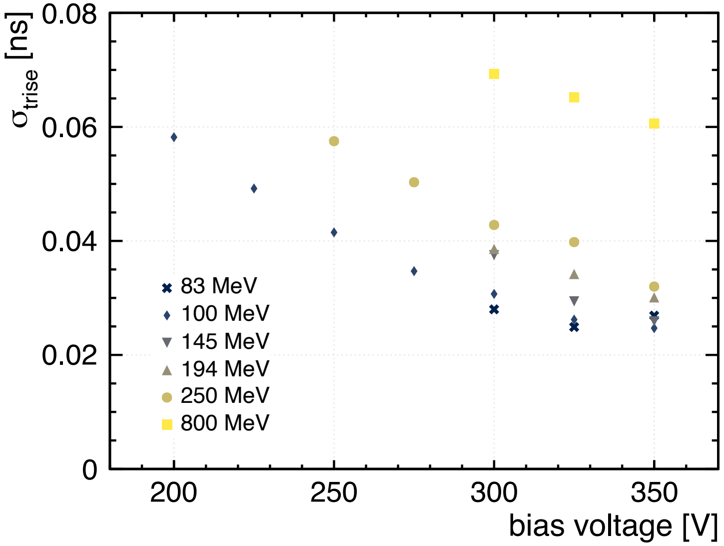
effective S/N for carbon runs

Discussion II

- Jitter contribution
  - Mean system rise time ~ 500 ps
  - Effective values of S/N ~ 20 should allow for ~ 30 ps jitter contributions
  - At same S/N, carbon ions yield better resolution than protons
- Synchronisation
  - Synchronisation uncertainty between oscilloscope channels ~17 ps
- Gain not high enough?
  - Certainly 250 & 800 MeV protons could profit from higher S/N
  - But also the rise time seems to benefit
  - We will have another 8 hours of beam time this weekend with higher bias



mean rise time for protons



RMS of rise time for protons

Summary and Next Steps

- ToF measurements present a viable option for ion CT
    - Many advantages (at least on paper) compared to traditional approaches
    - LGADs are a natural detector candidate that would give the required rad. hardness & rates
    - Utilise the current boost in activity from HEP community
- On LGADs the results are inconclusive
    - 50 ps for protons and 40 ps for carbon ions were reached
    - Encouraging enough to move forward
    - It appears that Landau noise is indeed reduced for carbon ions but more evidence is needed
- The next step needs to include a path towards a larger system
    - Identify the best suited ASIC for a small demonstrator setup
    - SiGe BiCMOS could be an interesting possibility
    - We are open for suggestions!

Acknowledgements

Thank you for your attention!

Contributors:

- Felix Ulrich-Pur
- Thomas Bergauer
- Alexander Burker
- Albert Hirtl
- Christian Irmler
- Stefanie Kaser
- Manuel Ruckerbauer
- Vera Teufelhart

Collaborators:

- EBG MedAustron

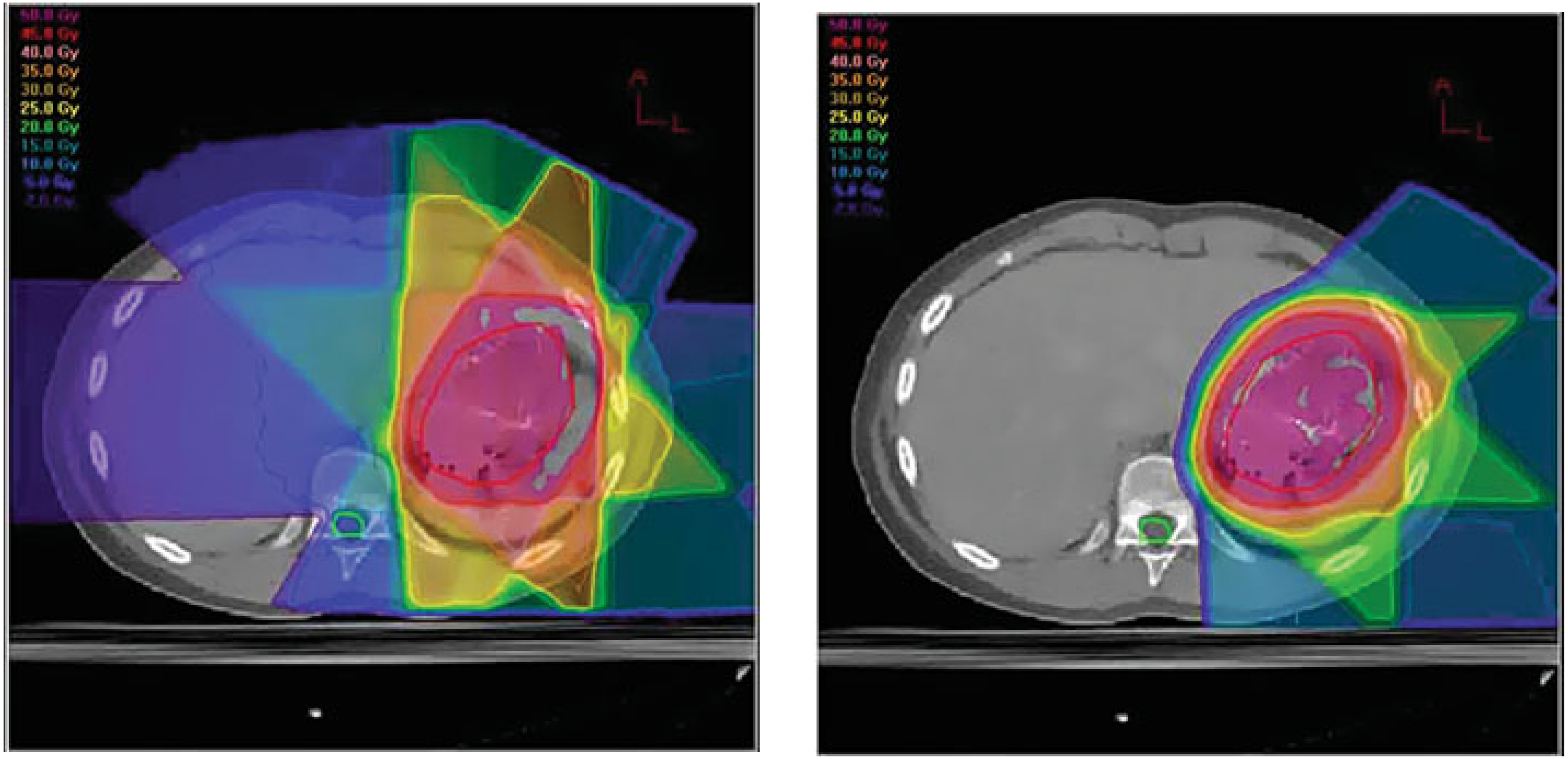
Merci beaucoup also to N. Cartiglia and H. Sadrozinski for providing us with LGAD samples and the readout board design!

References

- [1] M. Ferrero et al. (2019) NIM A 919 p16–26
- [2] http://www.sr-niel.org/index.php/sr-niel-web-calculators/niel-calculator-for-electrons-protons-and-ions/protons-ions-niel-calculator
- [3] Linz U. (2016) Ion Beam Therapy: Fundamentals, Technology, Clinical Applications.

Backup

Proton vs Photon Therapy



Dose comparison for photon (left) and proton (right) treatment plans [3]