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

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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 radiosensitive 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

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**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
Imaging with Ion Beams

- **Aim:** 3D map of stopping power within object
  - Requires $\Delta E$ and path estimate

- **Particles with energy $E$**
  - Pass front tracker
  - Lose energy $\Delta E$ in object
  - Pass rear tracker
  - Deposit energy $E-\Delta E$ in calorimeter

- **Ion CT**
  - **Measure $\Delta E$ 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**

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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**
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 ($\sigma_E \sim 1.9\% @ 150$ MeV)
  - 30 ps via 4 planes á 30 ps ($\sigma_E \sim 1.2\% @ 150$ MeV)
  - Improves with lower residual energy!
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

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

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

**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

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**Energy loss relative to MIPs in 50 µm Si**

[Allpix$^2$ simulation]

**Displacement damage cross section relative to 1 MeV neutrons**

[2]
Test Beam Setup

- Sensors: Single diodes
  - FBK UFSD2 production
  - Sensitive area 1x1 mm²

- 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
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 Graph]

![Gain Graph]
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

![Graph showing time resolution vs beam energy and bias voltage](image)

- Time resolution vs beam energy
- Time resolution vs bias voltage

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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

- \[ \frac{\sigma_{t_1-t_2}}{\sqrt{2}} \] vs beam energy [MeV/n]
- \[ \frac{\sigma_{t_1-t_2}}{\sqrt{2}} \] vs bias voltage [V]

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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
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
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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!
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References


Backup
Proton vs Photon Therapy

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