The SiFi-CC project – towards online monitoring of proton therapy

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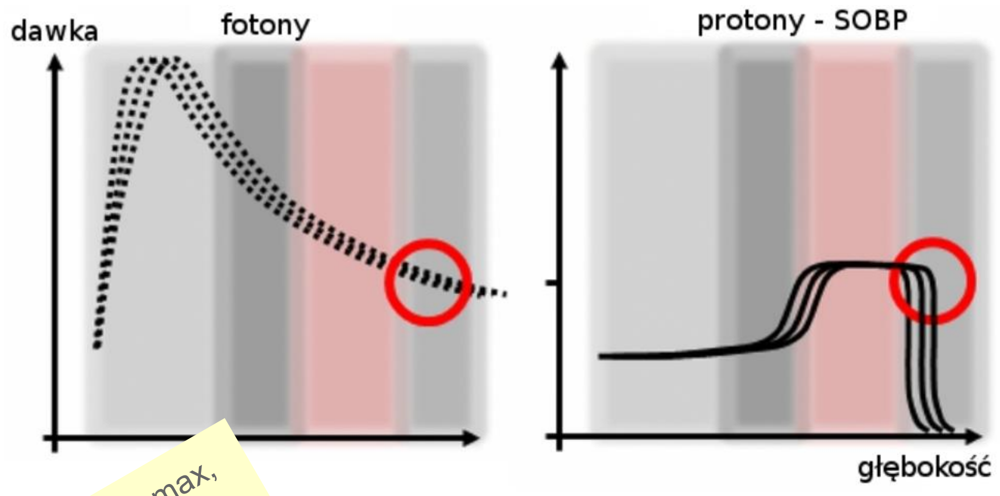
Need for range monitoring



¤ src: Knopf, Lomax, Phys.Med.Biol 2013

Potential causes:

- Planning uncertainties CT→ dE/dx
- Interfractional anatomical changes
  - Weight gain/loss
  - Change of tumour size
  - Full/empty sinuses

Effect of 1-cm air cavity in front of tumour:

- Photons: dose larger by <5%
- Ions: range larger by ~1 cm

Need for range monitoring

- Steep slope of dose distribution – benefit / issue
- Tumours close to critical organs (spinal cord, brain structures) need precision in dose delivery
- Clinical practice: range uncertainties → need to compromise dose conformality and safety
- „ In-vivo range verification methods would represent an optimal solution for full explotitation of the advantages afforded by the ion beam”
  - Reduction of safety margins, better treatment plans
  - Potential to treat new patients categories

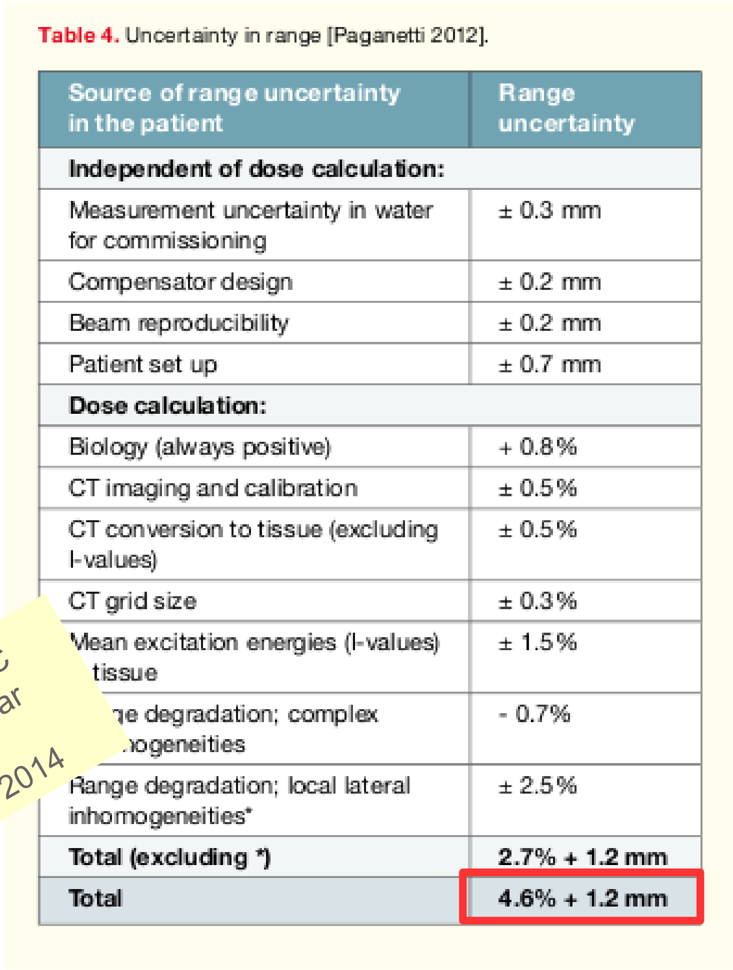
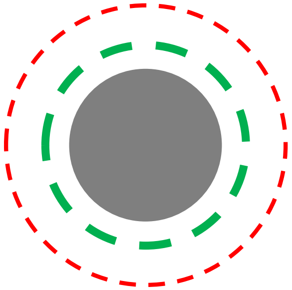


Table 4. Uncertainty in range [Paganetti 2012].

Source of range uncertainty in the patient	Range uncertainty
Independent of dose calculation:	
Measurement uncertainty in water for commissioning	± 0.3 mm
Compensator design	± 0.2 mm
Beam reproducibility	± 0.2 mm
Patient set up	± 0.7 mm
Dose calculation:	
Biology (always positive)	+ 0.8%
CT imaging and calibration	± 0.5%
CT conversion to tissue (excluding I-values)	± 0.5%
CT grid size	± 0.3%
Mean excitation energies (I-values) tissue	± 1.5%
ge degradation; complex nogeneities	- 0.7%
Range degradation; local lateral inhomogeneities*	± 2.5%
Total (excluding *)	**2.7% + 1.2 mm**
Total	**4.6% + 1.2 mm**

src: NuPECC report „Nuclear Physics for Medicine” 2014

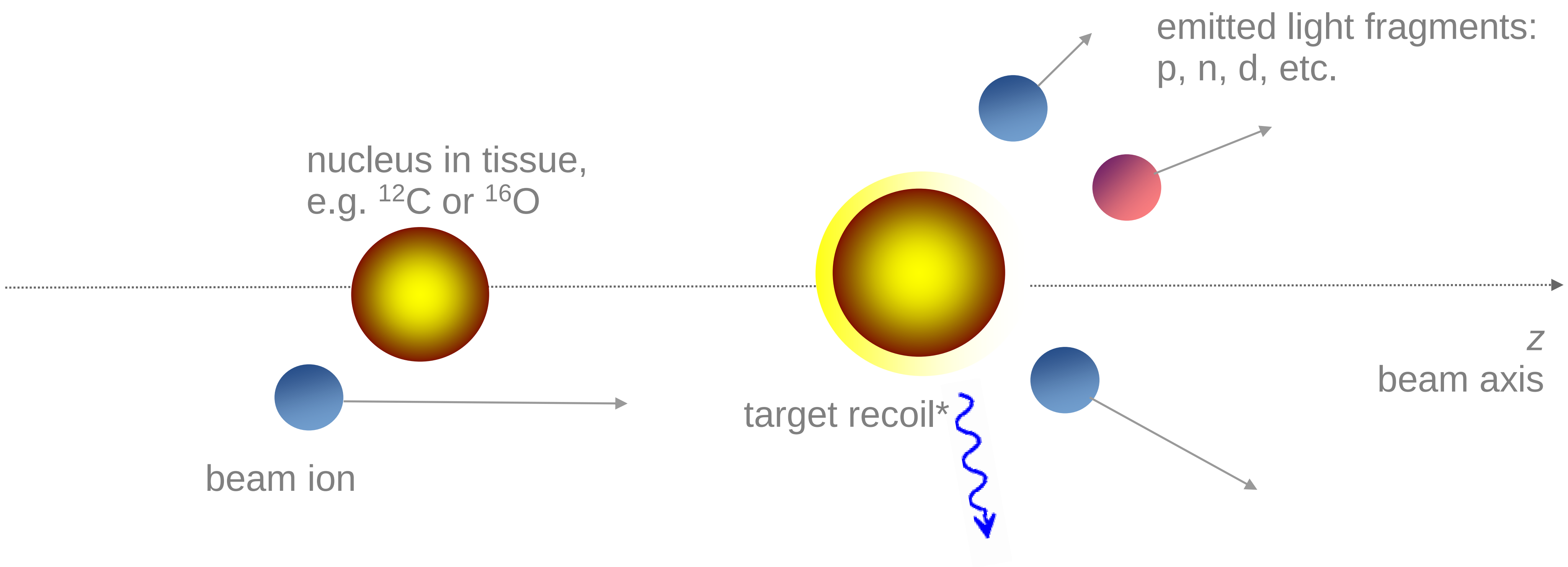


Approaches to range monitoring

Idea: exploit by-products of patient irradiation with ion beam:

- Protons
  - forward-peaked
  - modified by tissue on the way out
- Neutrons
  - forward-peaked,
  - difficult to detect,
  - modified by tissue on the way out
- β+ emitters (consequently 511-keV gamma pairs)
  - PET - well established technology
  - tissue transparent for gamma quanta
  - large detectors, incompatible with gantry
- γ radiation
  - Prompt Gamma Imaging – emerging technology
  - tissue transparent for gamma quanta
  - various options (timing, spectroscopy, imaging, …)

PG emission – microscopic picture



Gamma quanta leaving the patient carry undisturbed information from their place of origin, i.e. interaction region

Reaction channels most relevant for PGI:

- $^{12}C(p, p'\gamma_{4.4\ MeV})^{12}C$, $^{16}O(p, X\ \gamma_{4.4\ MeV})^{12}C$, $^{16}O(p, p'\gamma_{6.1\ MeV})^{16}O$
- Gamma yield depends on proton energy, thus is spatially correlated with depth

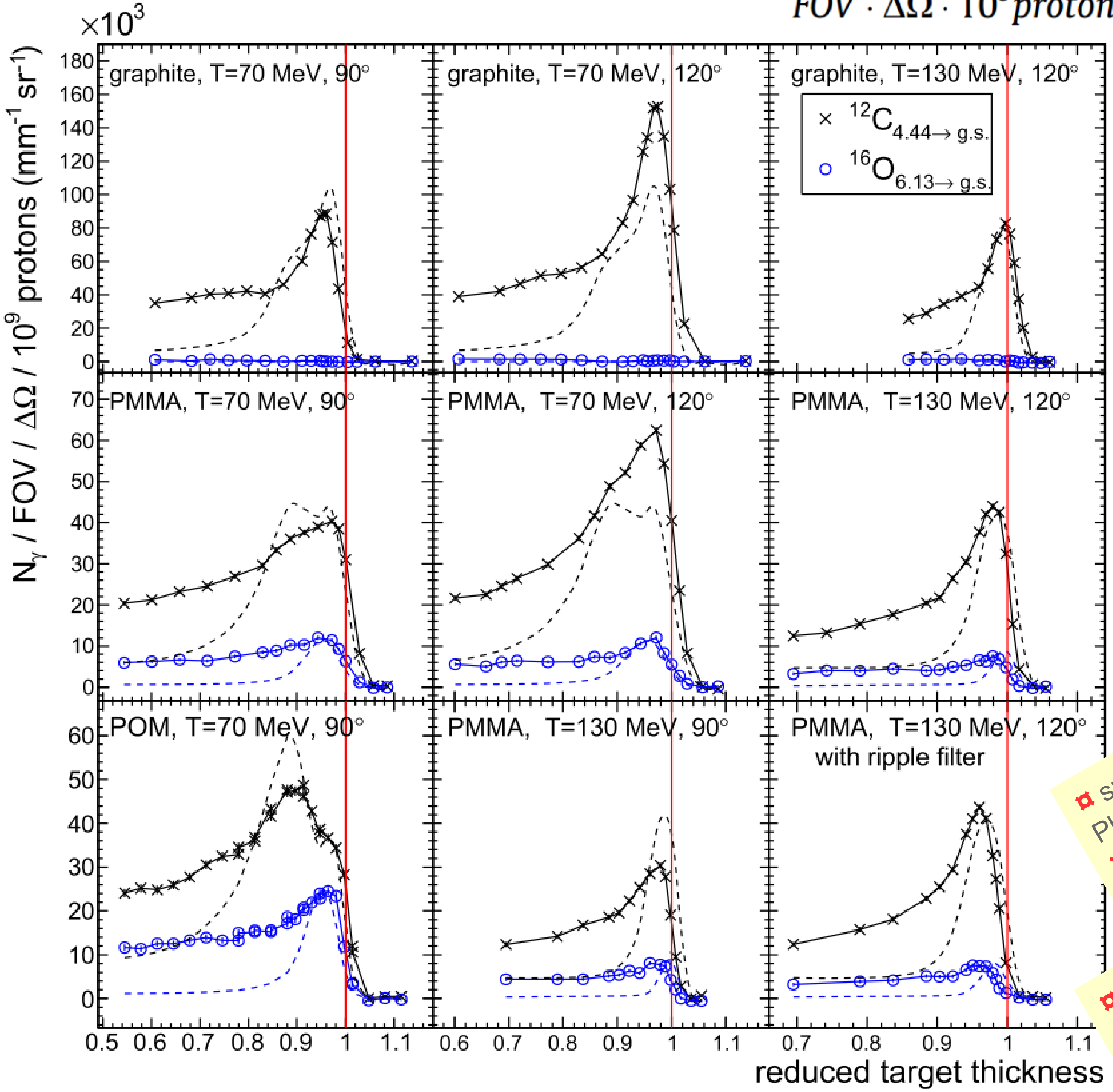
γCCB project - finished

$$\frac{N_\gamma}{FOV\cdot\Delta\Omega\cdot 10^9 protons}(\theta,z)=\frac{\boxed{g(z)}N_t}{FOV}\int\boxed{\frac{d\sigma}{d\Omega}(\theta,E)}\boxed{f(E)}dE$$

Beam attenuation from GEANT

Energy dependent angular distributions **from TALYS**

Proton energy distribution at given depth from GEANT



¤ src: Kelleter, Wrońska et al., Physica Medica 34 (2017)
¤ src: Rusiecka et al., Acta Physica Polonica B 49 (2018)

¤ src: Wrońska et al., Acta Physica Polonica B 48 (2017)

The SiFi-CC project in JU

On-line monitoring of dose distribution in proton therapy using heavy scintillating fibres

SiFiCC = SiPM- and heavy scintillation Fiber-based Compton Camera

Goal: development of a method for on-line monitoring of deposited dose distribution in proton therapy

Technique: imaging exploiting prompt gamma rays emitted during irradiation

Technology: Detector based entirely on new, heavy scintillating materials read out by SiPMs;
DAQ and (partly) image reconstruction based on FPGA → implantation of HEP technologies to medical application;

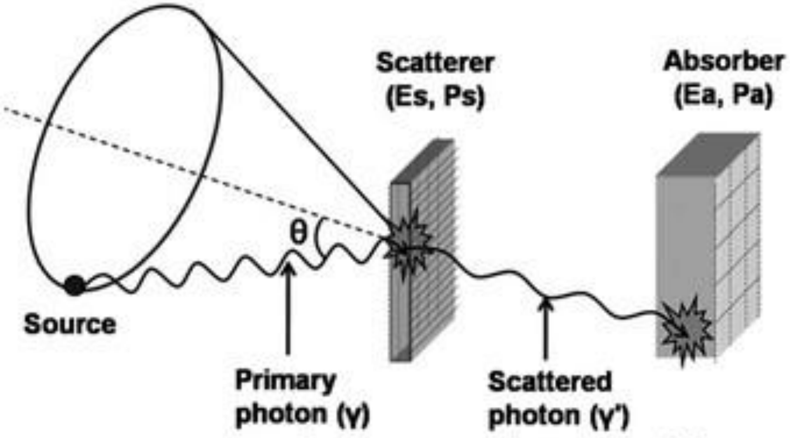
Realization: dual-modality setup

- Coded mask **CM**
- Compton camera **CC**

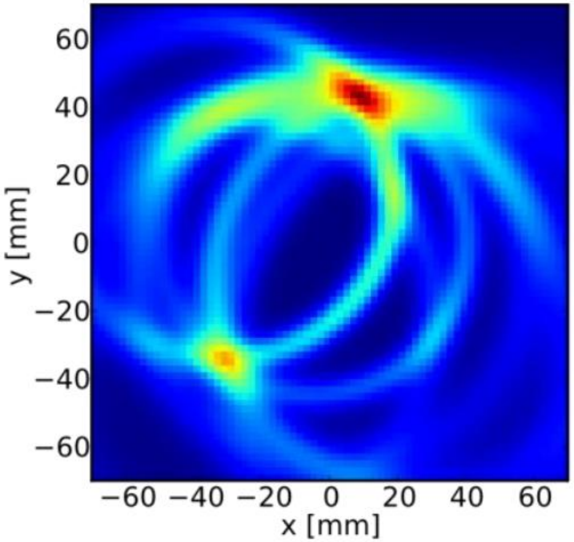
Financed as SONATA BIS by NCN (National Science Centre) **till September 2022**

PGI with a Compton camera

- Detector: scatterer and absorber planes
- Aim: register a Compton-scattering event, positions and energies in both layers, reconstruct Compton cone
- Superimpose intersections of many of such cones → 3d image
- No prototype feasible to work at close-to-clinical beam intensities and exposures
- Many designs, optimization in progress
  - Dresden: CZT + segmented LSO/BGO
  - Munich: double-sided Si strip detectors + monolithic LaBr3
  - Lyon: double-sided Si strip detectors + segmented BGO
  - Valencia: monolithic LaBr3 + monolithic LaBr3
  - Baltimore: multistage CZT based on POLARIS



$$\theta = \cos^{-1}\left[1 + m_0c^2\left(\frac{1}{E_\gamma} - \frac{1}{E_{\gamma'}}\right)\right]$$



Team

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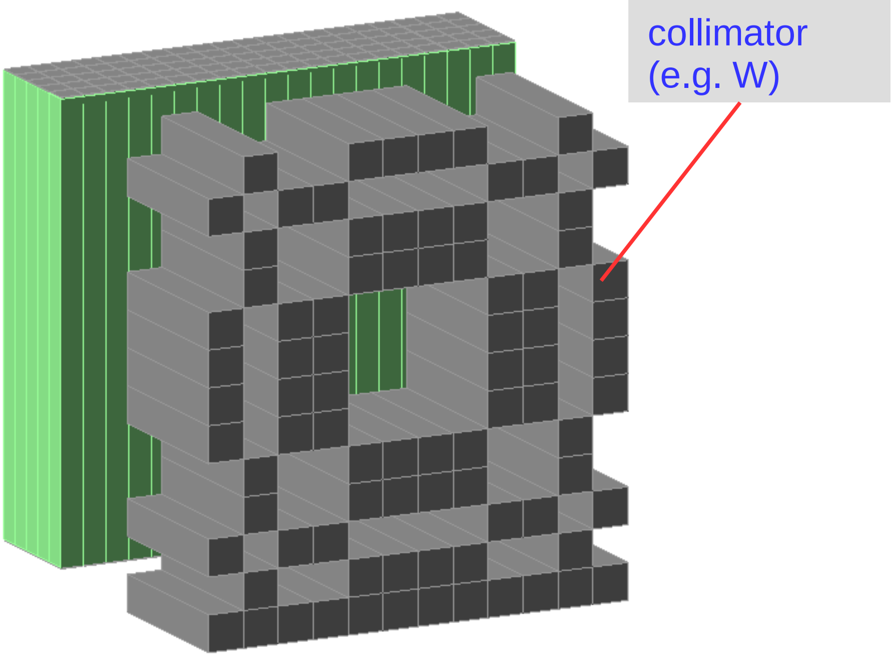
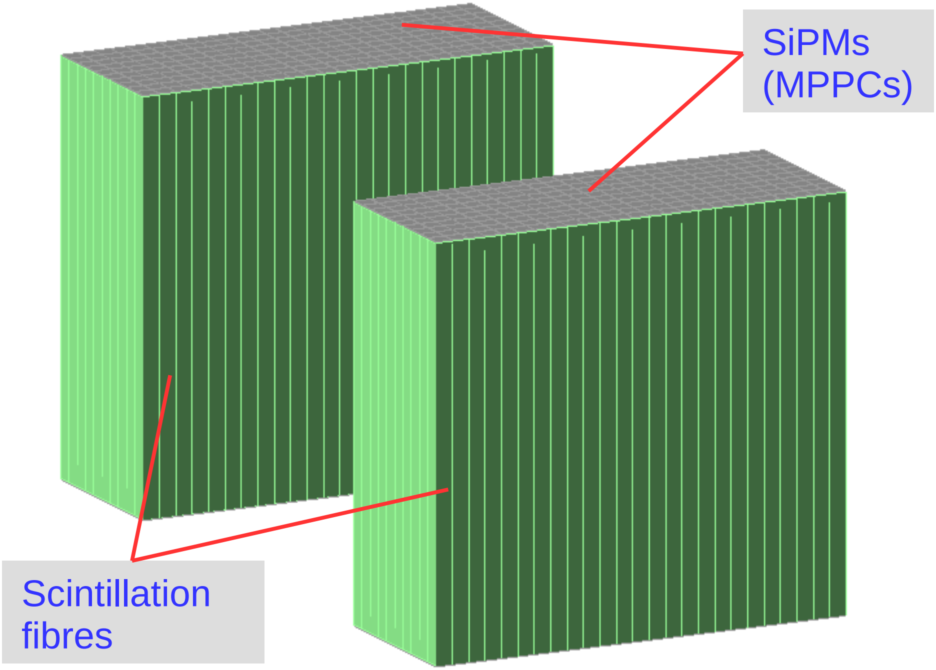
Dual modality - synergy

Coded mask CM



- Technique widely used in astronomy, also for observation of γ sources
- Technique not tested so far for the purpose of proton therapy
- 2d image
- Much larger statistics compared to single-slit detectors without compromising image resolution

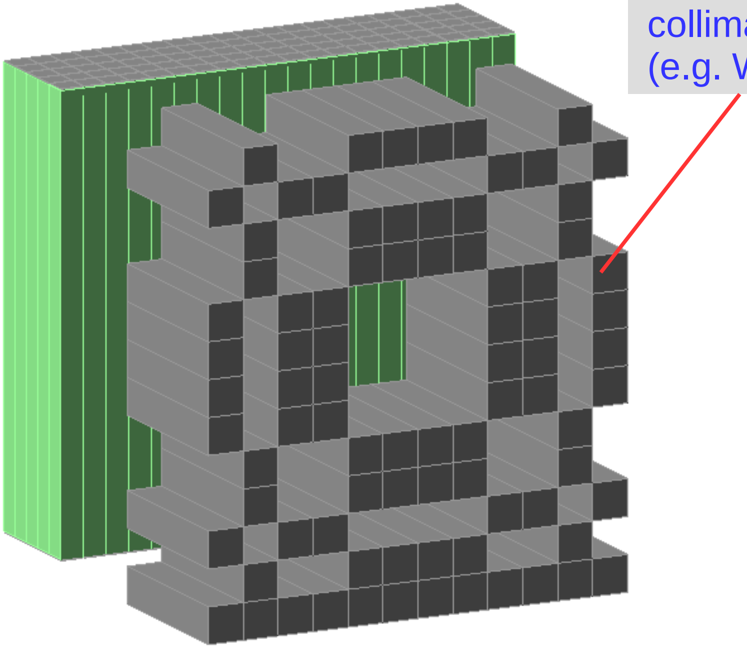
Compton camera CC



- Solution considered and tested for the use in proton therapy
- 3d image
- Problem faced so far: small statistics (efficiency), background from random coincidences
- Proposed solution: detectors of larger efficiency and better time resolution (→electronic collimation)

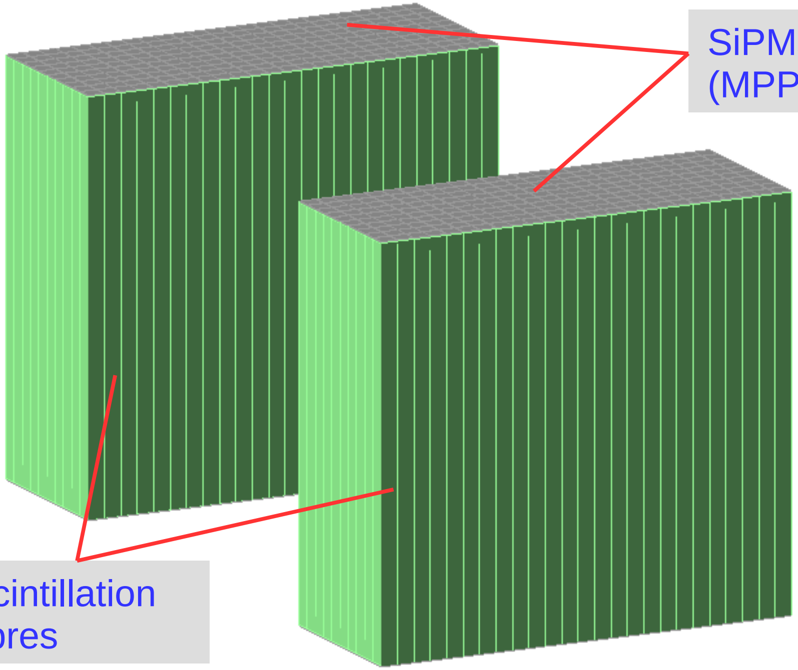
Dual modality - synergy

Coded mask CM



collimator
(e.g. W)

Compton camera CC



SiPMs
(MPPCs)

Scintillation
fibres

Common parts:

- Detection technique
- FEE
- DAQ

→ *expensive hardware*

Modality-specific parts:

- Collimation
- Image reconstruction

→ *mostly software (manpower)*

Lab tests of scintillating fibers

- Test bench constructed
- Tested materials: LuAG:Ce, <u>LYSO</u>, GAGG:Ce:Mg
- Characteristics and criteria:
  - attenuation length
  - signal time constants and resolution
  - light output
  - internal radioactivity
  - price/availability
- Further studies: coating/wrapping, coupling with SiPMs, …

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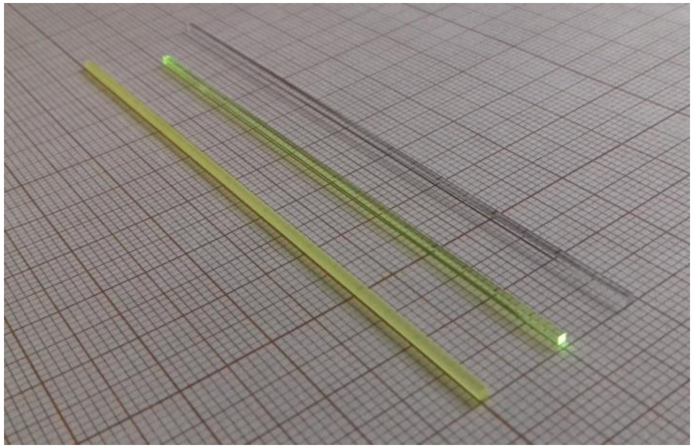

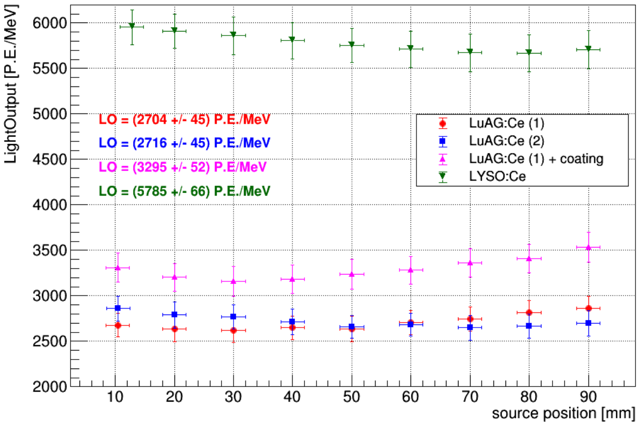

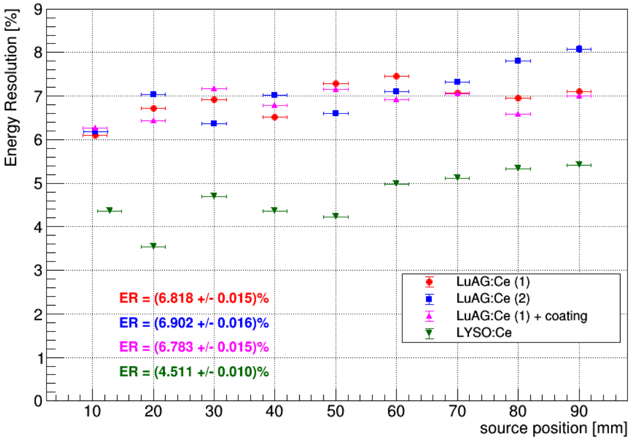

Setup design – MC simulations

- Simulation of different setup versions with GEANT4
- Efficiency, position- and energy resolution studied for different geometries and materials
- Low-level (E, x, y, z) reconstruction algorithms developed
- Results confronted with lab measurements

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PhD student
RWTH Aachen

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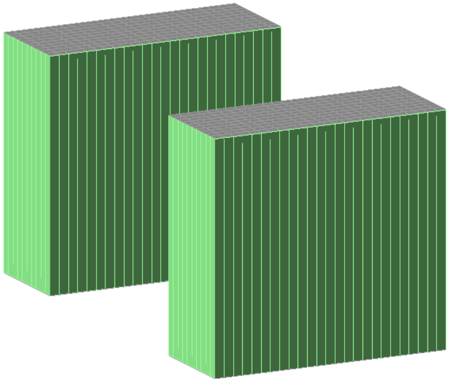

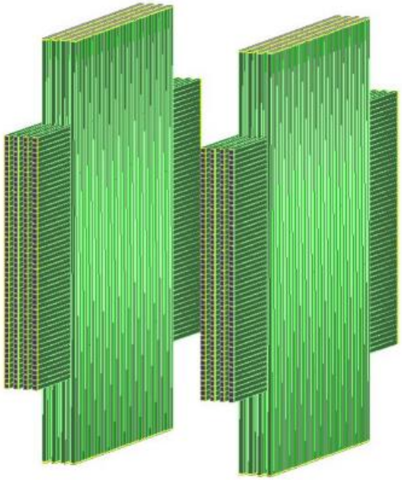

Software framework

- Dedicated software framework to cover
  - image reconstruction
  - data decoding
  - detector calibration
  - ….
- Current status: backprojection and LM-MLEM implemented
- Resolution of σ=2.5 mm obtained for a point-like source in reconstruction (optimization and verification in progress)

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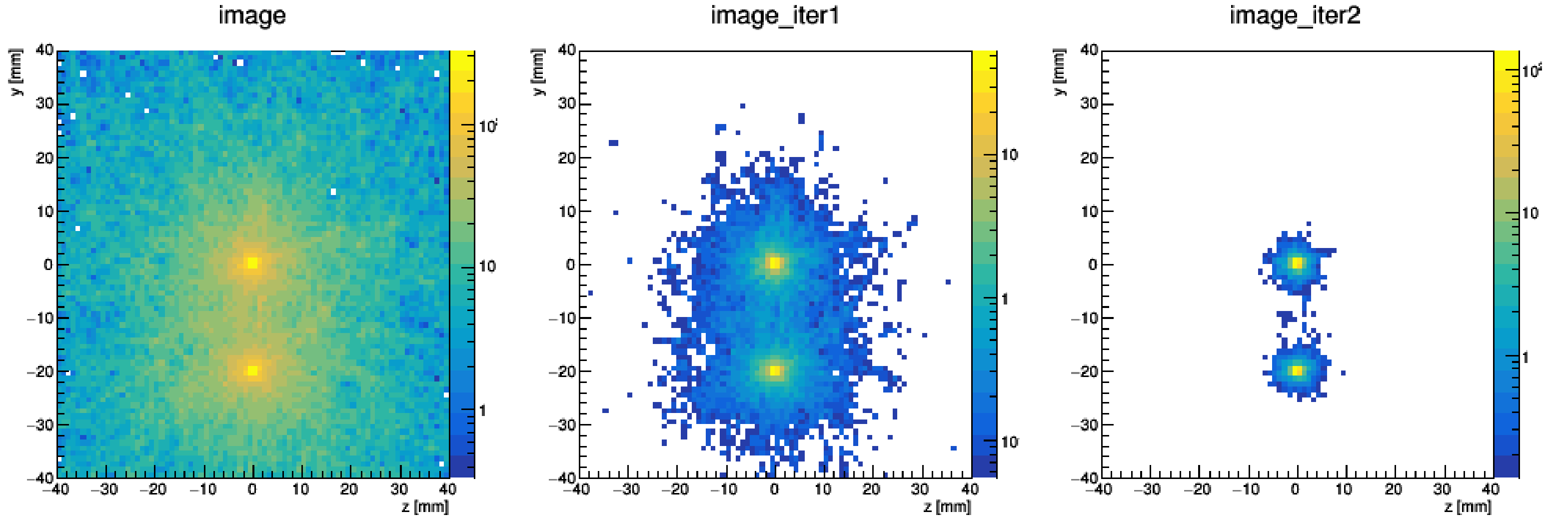
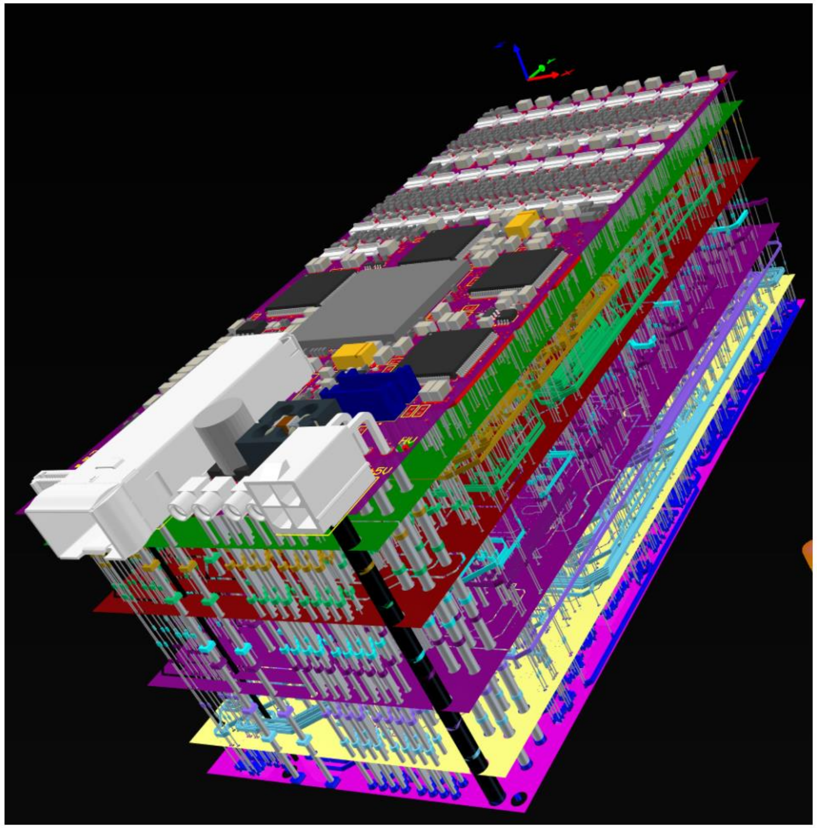


FEE and DAQ development

- FPGA-based DAQ
- FTAB board developed for JPET modified to feature full ADC functionality
- Building coincidences, energy and position reconstruction possible on-board → faster!



Marek Pałka
post-doc
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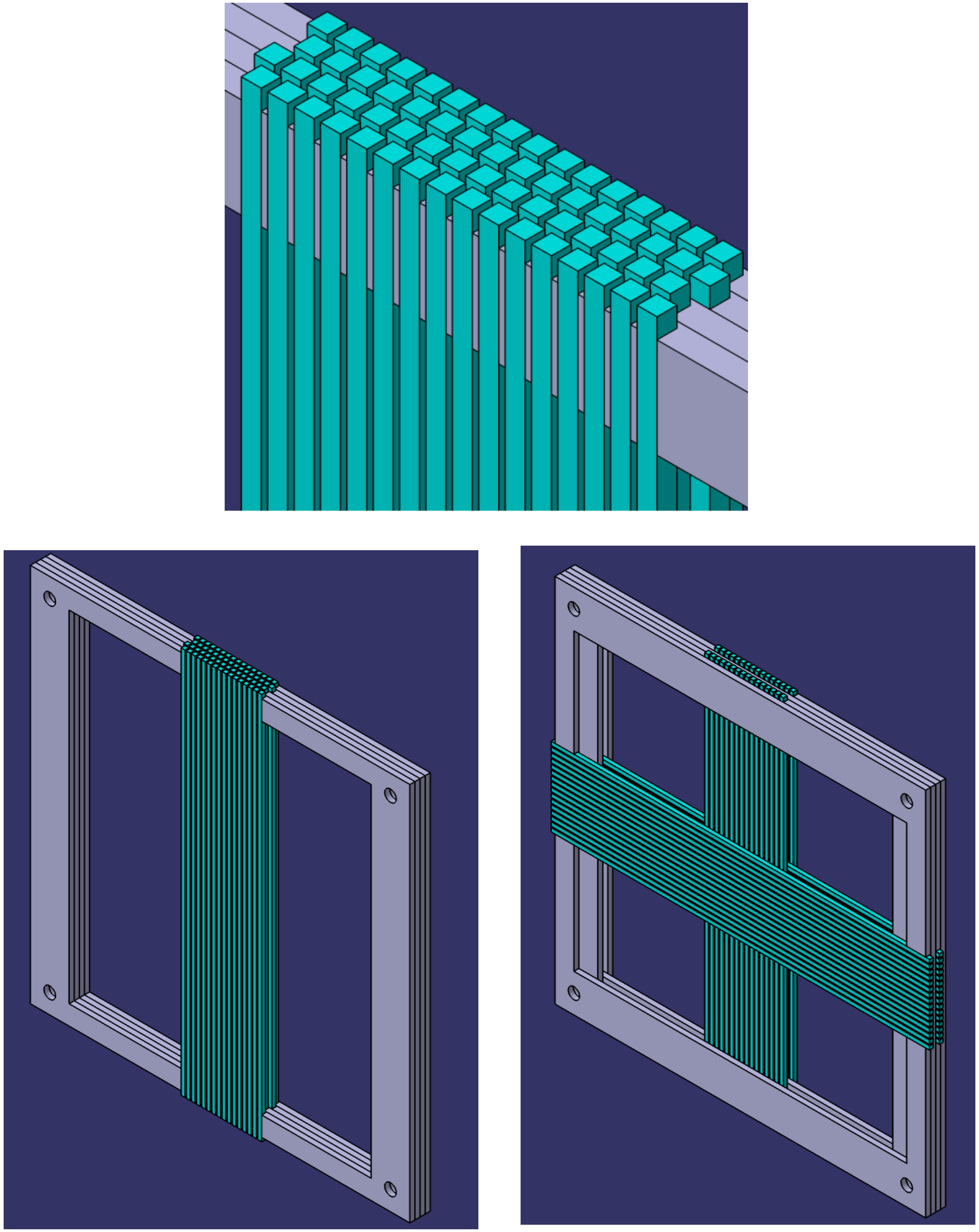
Time-line

- First, small-scale prototype ready this year
- Next year: a full-scale single module ready, to be tested in coded-mask mode
- 2021/2022 – full SiFI-CC
- Stay tuned



Thank you for your attention ❁

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