The Intersection of High Energy Physics and Medicine

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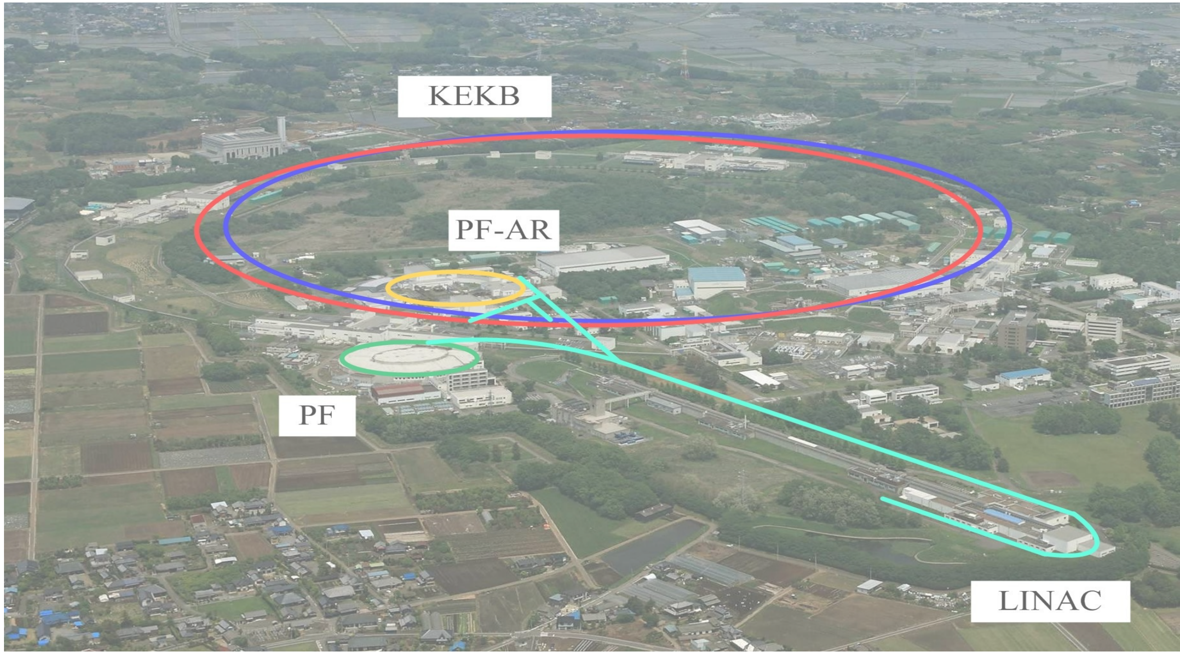
The Belle II Experiment & Detector

- This experiment is at KEK, Tsukuba, Japan
- It is designed to collide 4 GeV positrons (e^+) with 7 GeV electrons (e^-) with the world’s highest luminosity ever

Belle II at KEK, Tsukuba, Japan

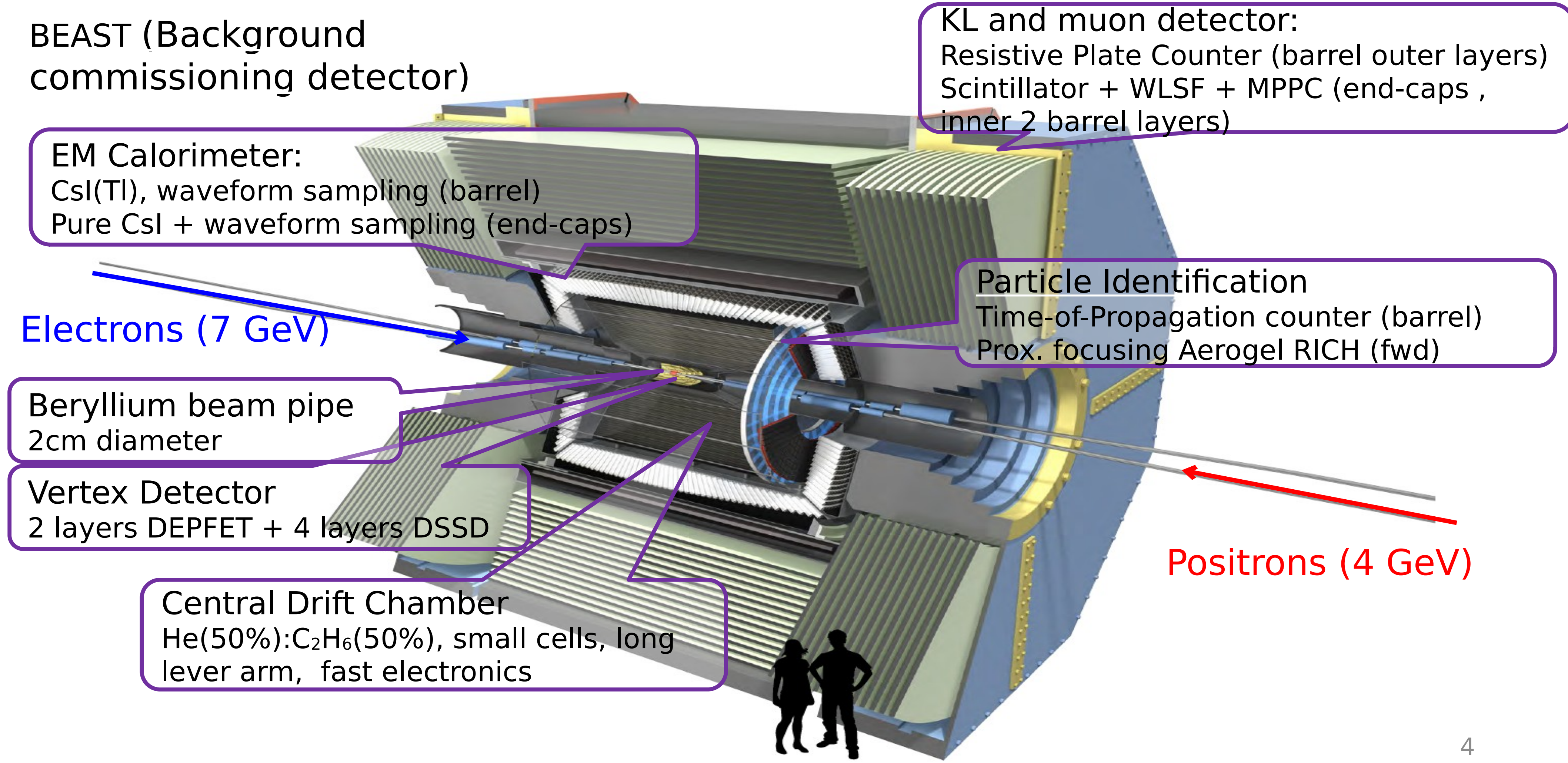
- The Belle II experiment is part of a broad-based search for new physics in the intensity frontier
  - Precisely measuring particle collisions and comparing with theory



- The SuperKEKB accelerator
- upgrade will provide 40x the
- luminosity of KEKB and 50x
- the data taken with Belle

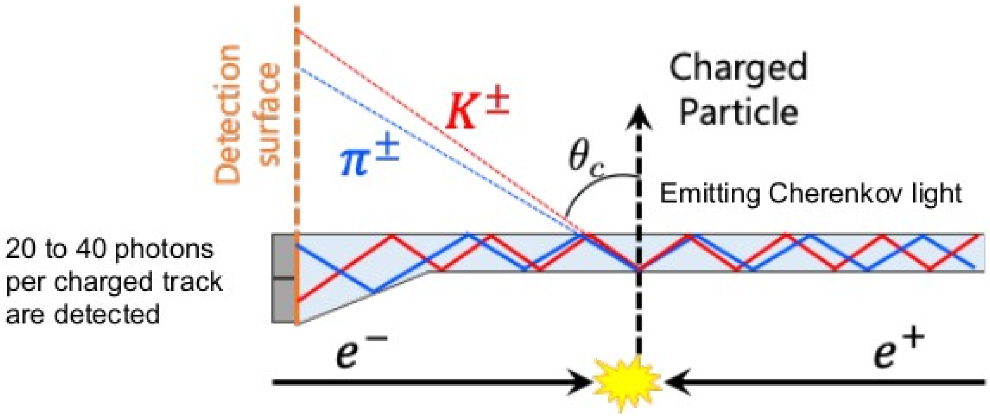
  - Electrons and positrons will collide to provide useful events >30,000 times per second. The detector needs to detect the resulting particles, send the data to server farms, and store it for analysis. [In figure: PF-AR = Photon Factory Advanced Ring]

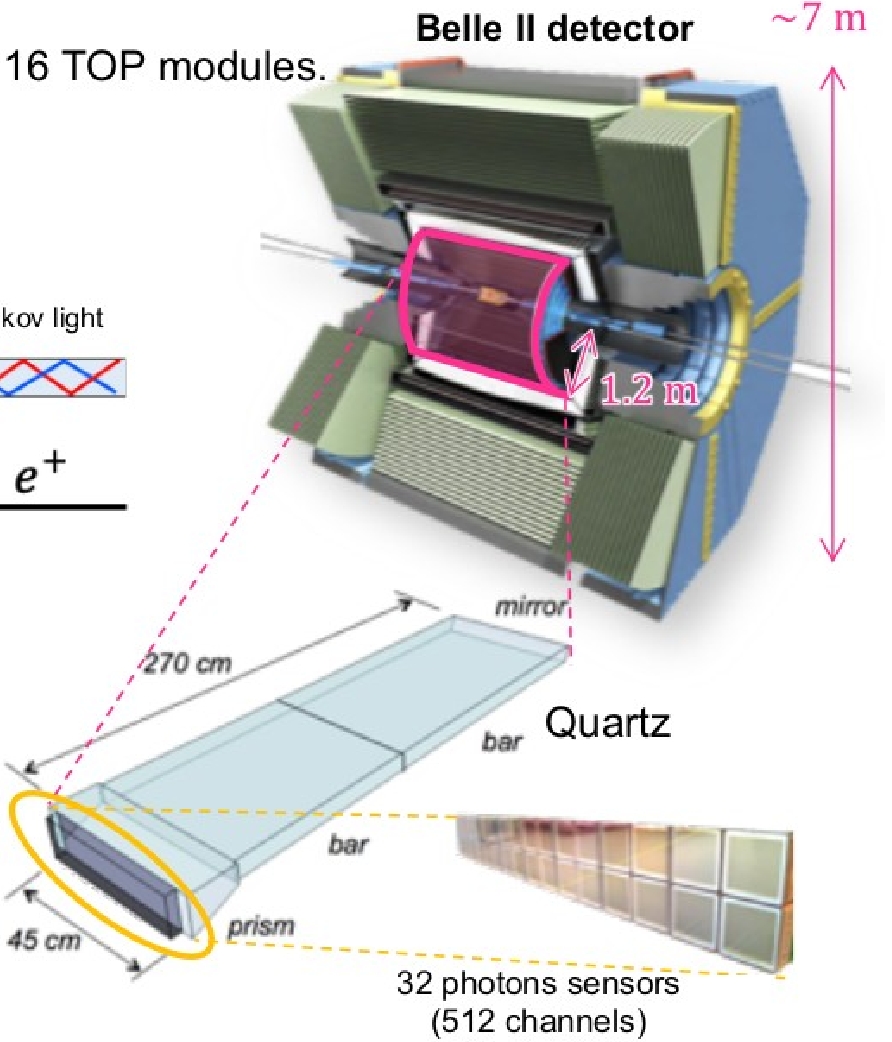
Belle II Detector



The Time-Of-Propagation (TOP) Detector

Belle II barrel particle identification system
with Cherenkov ring imaging, which consists of 16 TOP modules.





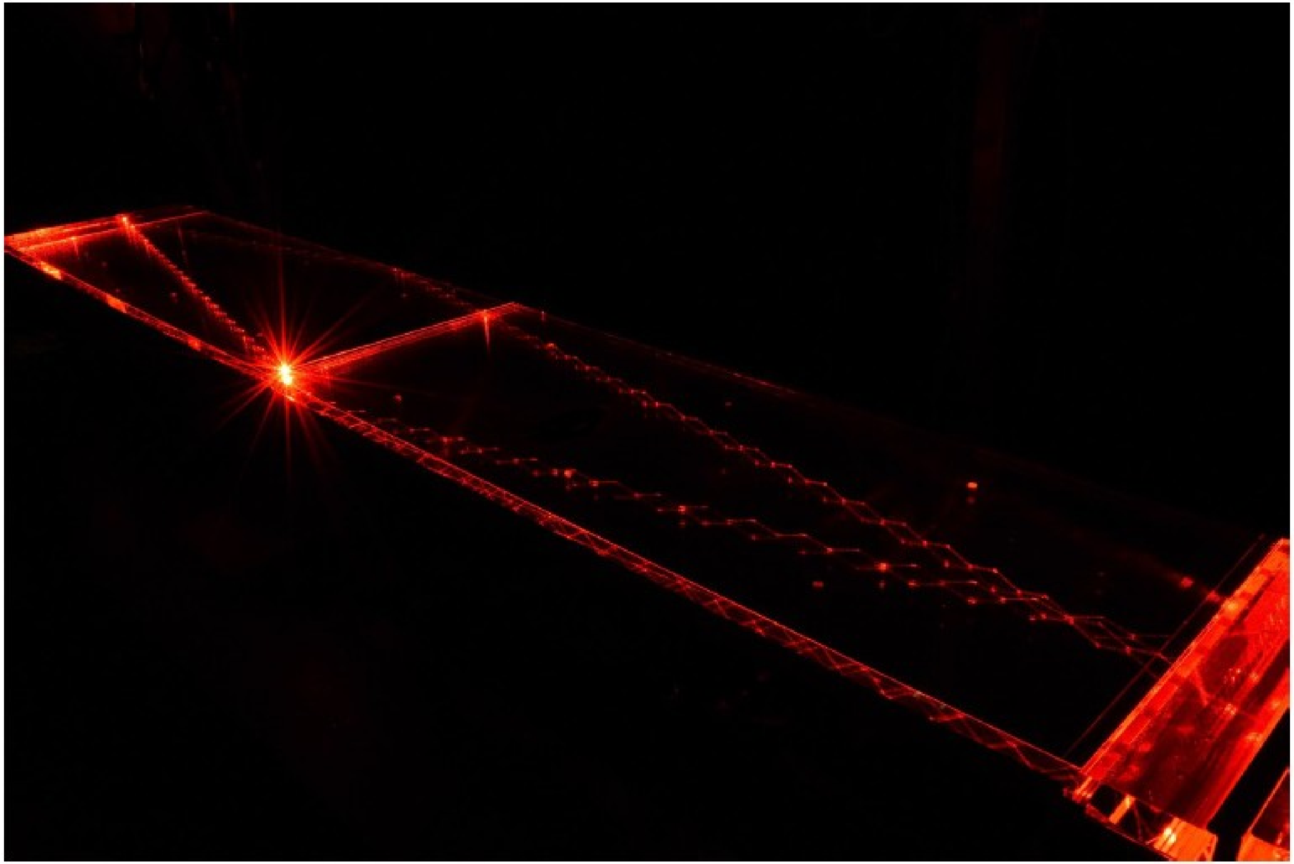
$$\cos\theta_c = \frac{1}{n\beta} = \frac{\sqrt{m^2+p^2}}{np}$$

$$p = 3\ \mathrm{GeV}\ \pi/K$$
$$\Delta\theta_c \simeq 0.6^\circ \Longrightarrow \Delta t = \mathcal{O}(100)\ \mathrm{ps}$$

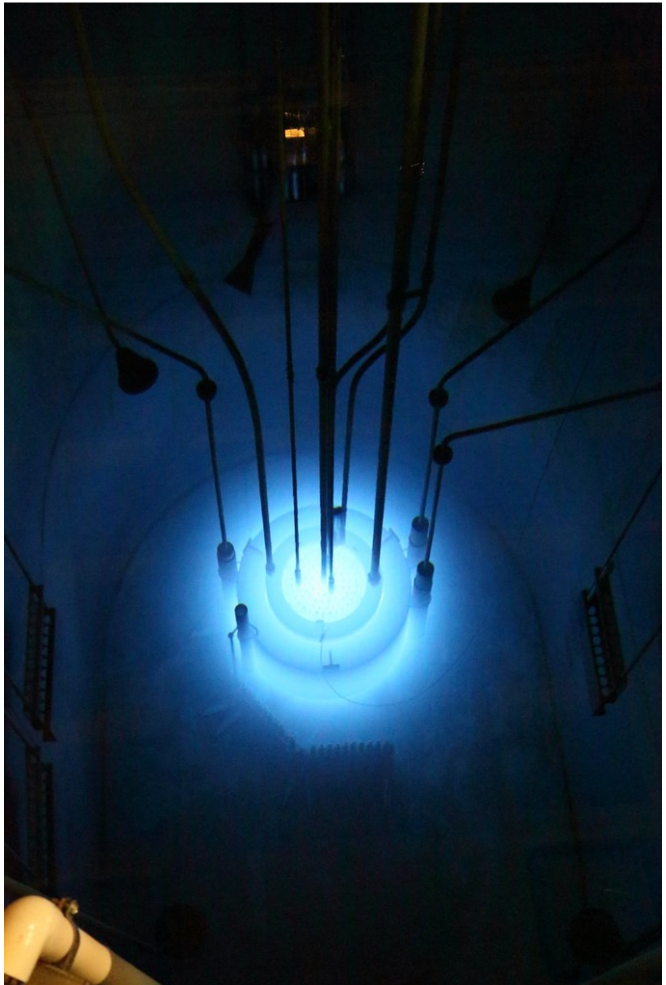
$$\boxed{\text{Performance} \propto \frac{\sqrt{\#\text{ of photons}}}{\text{Time resolution}}}$$

The Time of Propagation Detector (TOP)

- Charged particles produced in Belle2 emit Cherenkov radiation as they traverse quartz bars in the TOP



Properties of Cherenkov Radiation



- Since the emission angle is given by

$$\cos\theta = \frac{1}{n\beta}$$

- and $n \approx 1.33$ for water at 20 °C.

- For high energy particles, the angle is 41 degrees

- In practical terms, the number of photons collected is small, typically around 50 / cm

- Belle2 uses precision timing (resolution better than 100 ps) to distinguish photons from K and π

- The radiation is polarized in the plane containing the

Measuring Beam Dose with Cherenkov Emissions (CE)

- “Direct in-water radiation dose measurements using Cherenkov emission corrected signals from polarization imaging for a clinical radiotherapy application”, by

- Émily Cloutier, Luc Beaulieu, & Louis Archambault [Université Laval, Québec]

- Scientific Reports (2022) 12:9608
- https://doi.org/10.1038/s41598-022-12672-w

The Setup

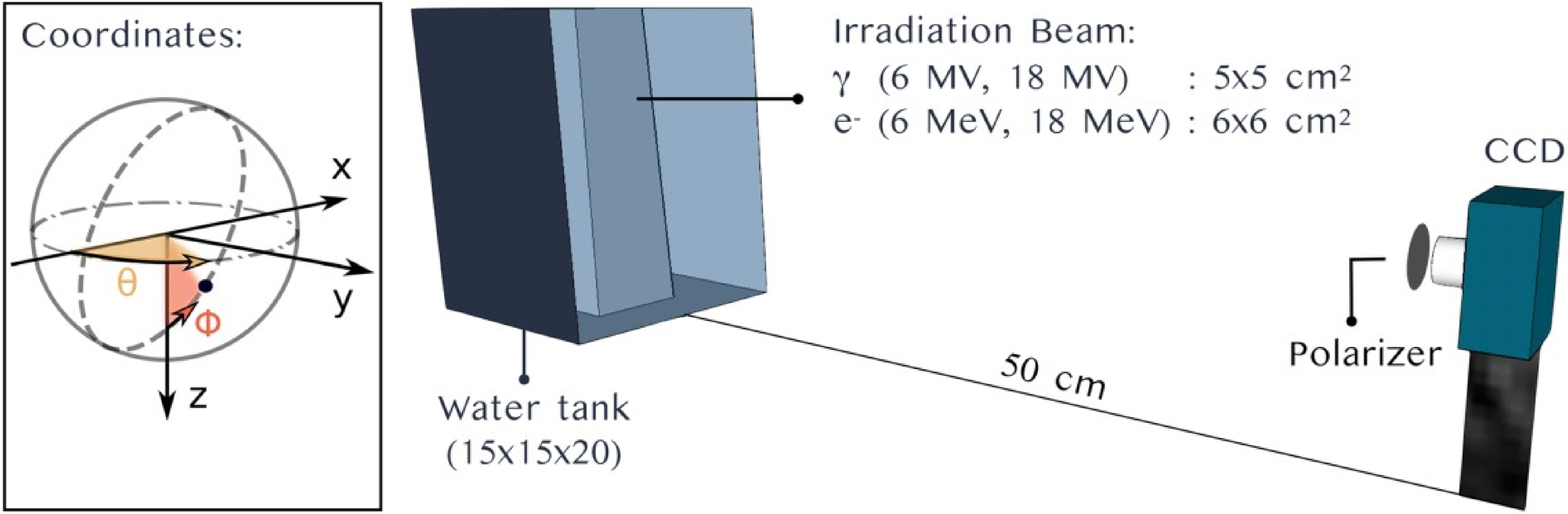


Figure 8. Representation of the measurement setup together with the irradiation conditions for PPDD and profile measurements. The setup image was created using SketchUp[35].

Emission Angle vs Beam Energy

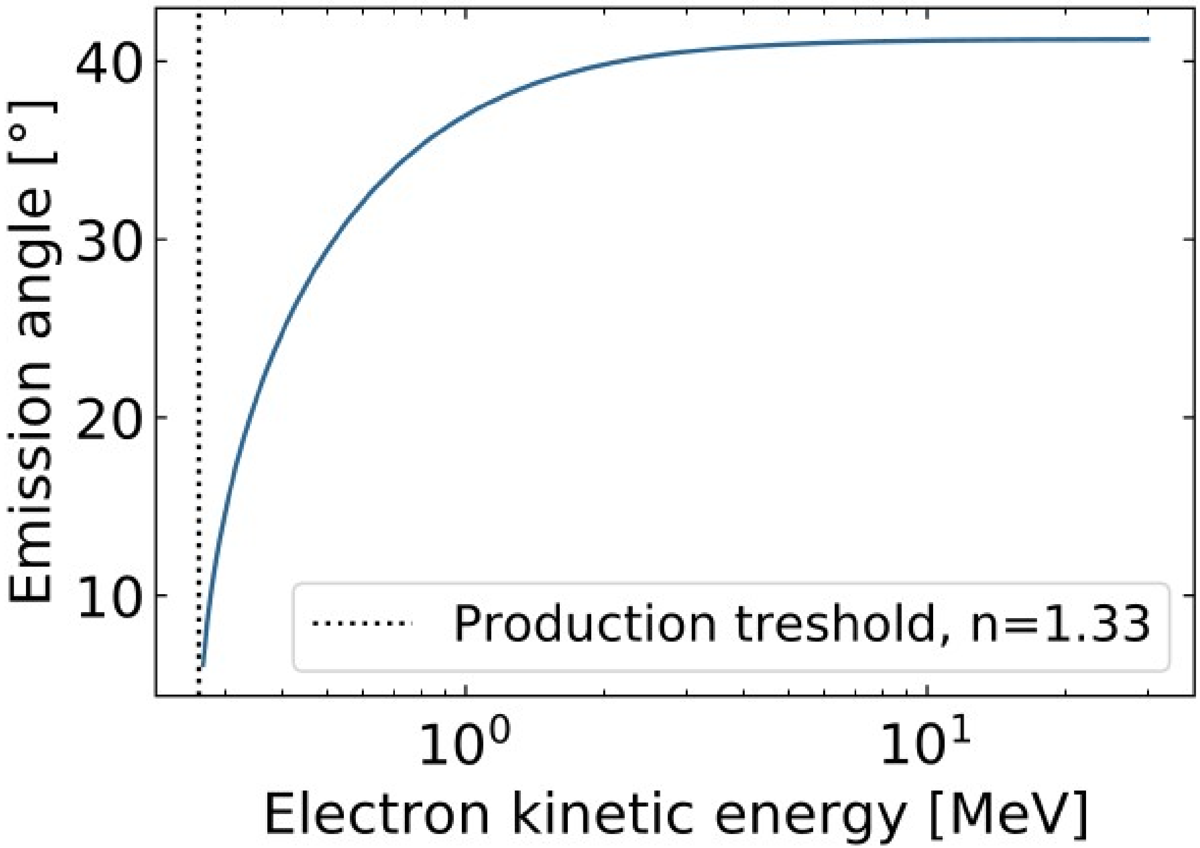


Figure 7. Cherenkov signal emission angle as function of a charged particle kinetic energy, an electron in that case, in water ($n = 1.33$).

Images for Four Polarizations

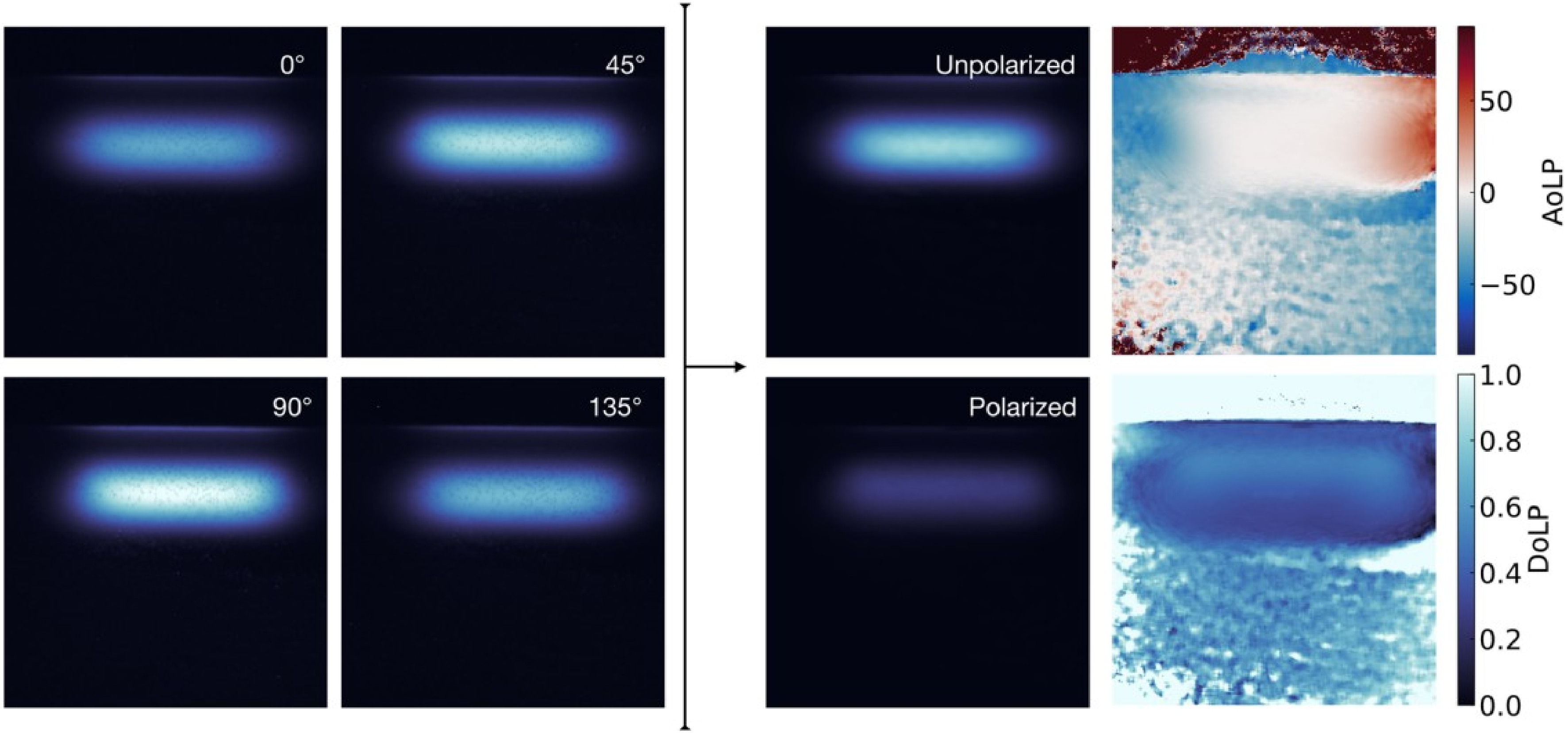


Figure 6. On the left are presented the four images acquired from the four polarization states (0°, 45°, 90°, 135°) for a 6MeV beam. The right panel presents the resulting images following the polarization imaging formalism. The unpolarized and polarized portions of the signals are presented along with the degree and angle of linear polarization extracted from each pixel.

Angle and Degree of Polarization

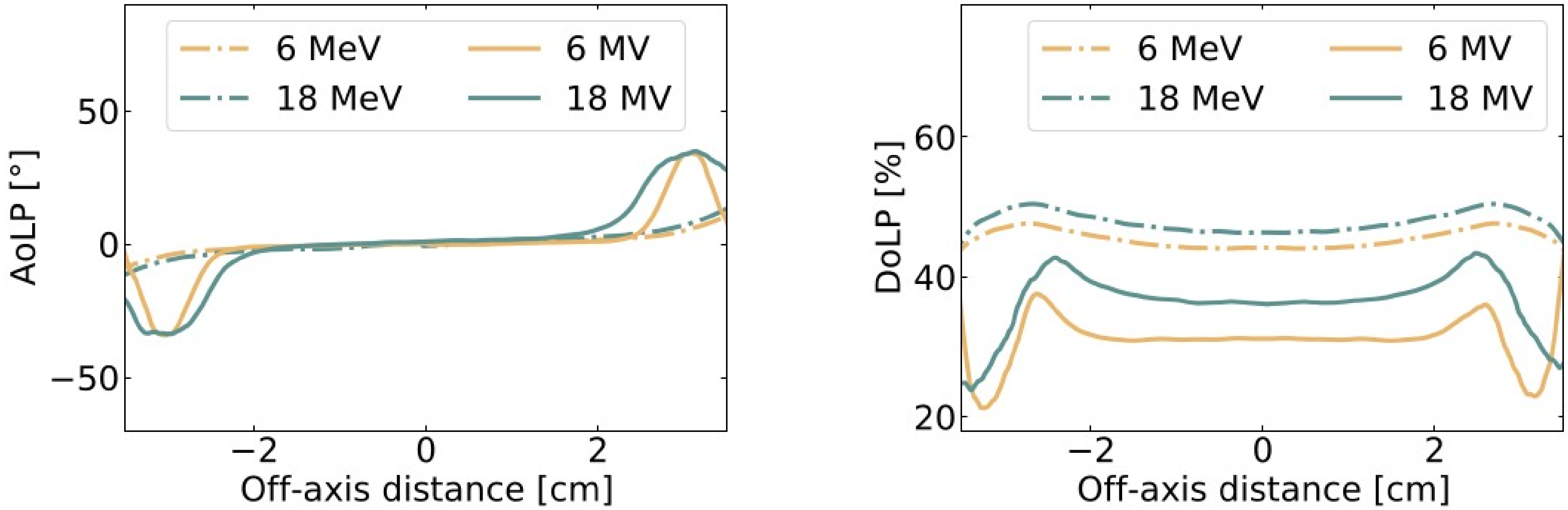
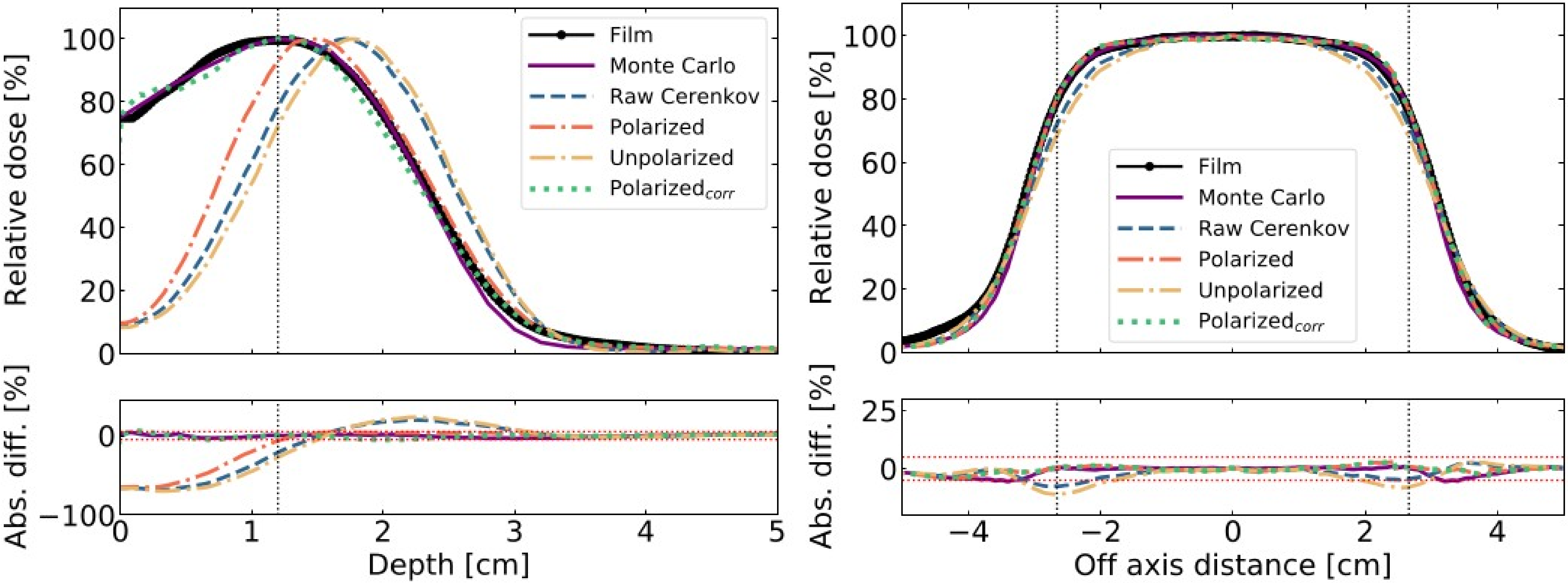


Figure 5. Angle (left) and degree (right) of linear polarization along profiles for the 6 MeV, 18 MeV, 6 MV and 18 MV beams. The profiles are taken at the depth of maximum dose for each energy.

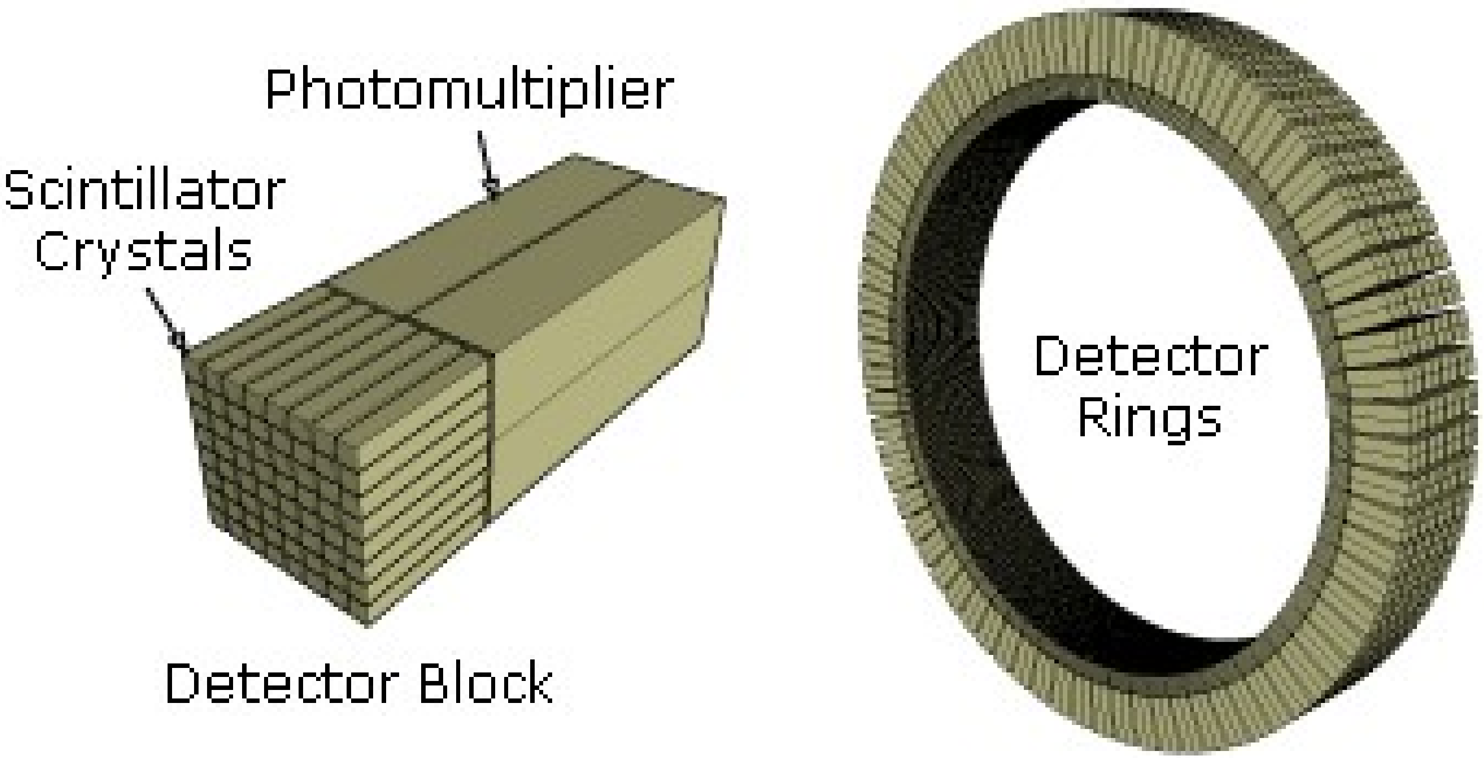
Reconstructed Doses



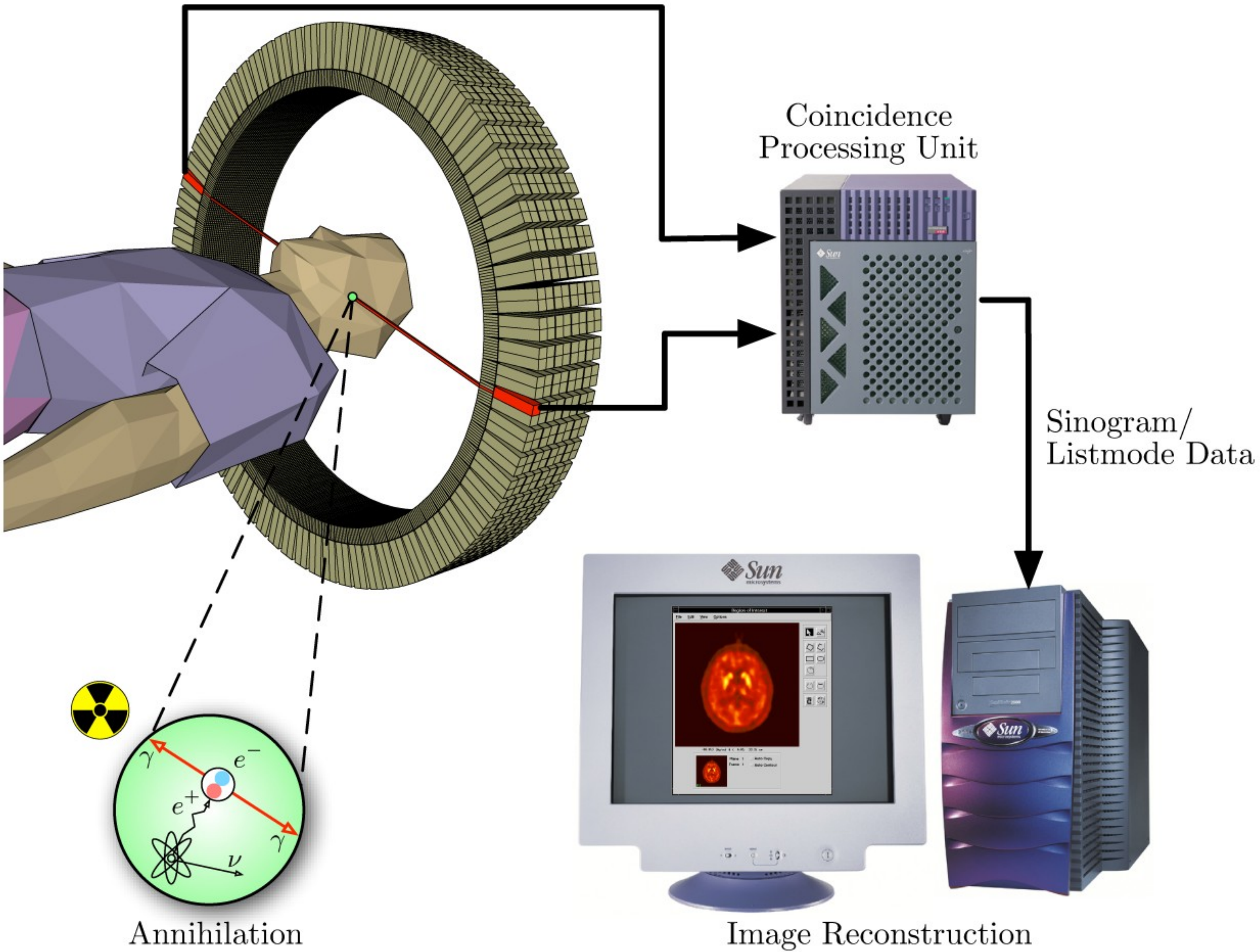
Comparison with HEP

- Coordinate system is different
- One paper says > 180 MeV is “high energy”
- Speed at which dose is delivered is increasingly important. Want patient to remain still for not too long. Hence “FLASH” radiotherapy.
- Timing of 50 ps not used (yet)
- Counting of 50 photons would be too low (?)
- Use GEANT for detector simulation, ELEGANT for accelerator simulation
- Use terms like “phantom”

Positron Emission Tomography (PET)




MAVIC
Discovery


Coincidence
Processing Unit
Sinogram/
Listmode Data
Annihilation
Image Reconstruction

Positron Emission Tomography (PET)

- A radionuclide that emits positrons (β^+) is injected; it accumulates in the region of interest; gamma-ray pairs emanate from e^+e^- annihilation; the line of response or point of emission resolution can be improved from a few ns to ~10 ps.
- Better time resolution also helps greatly in 3D reconstruction.
- However, as temporal and spatial resolution improve, the need for detailed simulation of particles as they pass through a variety of matter in the patient becomes more important

CT Scans

- Wikipedia (where the PET pictures are from) has a great video of CT scan reconstruction:
- https://en.wikipedia.org/wiki/File:Tomographic_reconstruction-_Projection,_Back_projection_and_Filtered_back_projection.webm
- Seems perfect for Machine Learning applications

Accelerators

- Hospitals need compact devices to accelerate charged particles needed for irradiation.
- The Compact Linear Collider (CLIC) is a TeV-scale high-luminosity linear e^+e^- collider under development at CERN; the total length will be in the 11-50 km range.
- However, it accelerates particles with a gradient of 72 MV/m, which should allow for compact generation of electron beams in the 100-300 MeV energy range.

From US DOE's "Basic Research Needs for High Energy Physics Detector Research & Development Report"

- In this report we summarize the need for new technologies in terms of four Grand Challenges. The technologies envisioned to address them are described in the body of the report. The Grand Challenges are:

1. Advancing HEP detectors to *new regimes of sensitivity*
2. Using integration to *enable scalability* for HEP sensors
3. Building next-generation HEP detectors with *novel materials and advanced techniques*
4. Mastering *extreme environments and data rates* in HEP experiments

Acknowledgements

- Thanks to many Belle 2 physicists whose talks I borrowed from, including Tom Browder (Univ. of Hawaii), Kazuki Kojima (Nagoya Univ.), … and to the authors of the various articles cited and Wikipedia!
- CLIC information is from CERN's 2018 report:
- https://arxiv.org/pdf/1812.06018.pdf
- US DOE's "Basic Research Needs" report

- I would also like to thank Dr. Audrius Stundžia, of Tomographix Ltd. in Toronto, Canada for discussions on these topics.

Extra Slides

- Text

Title

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