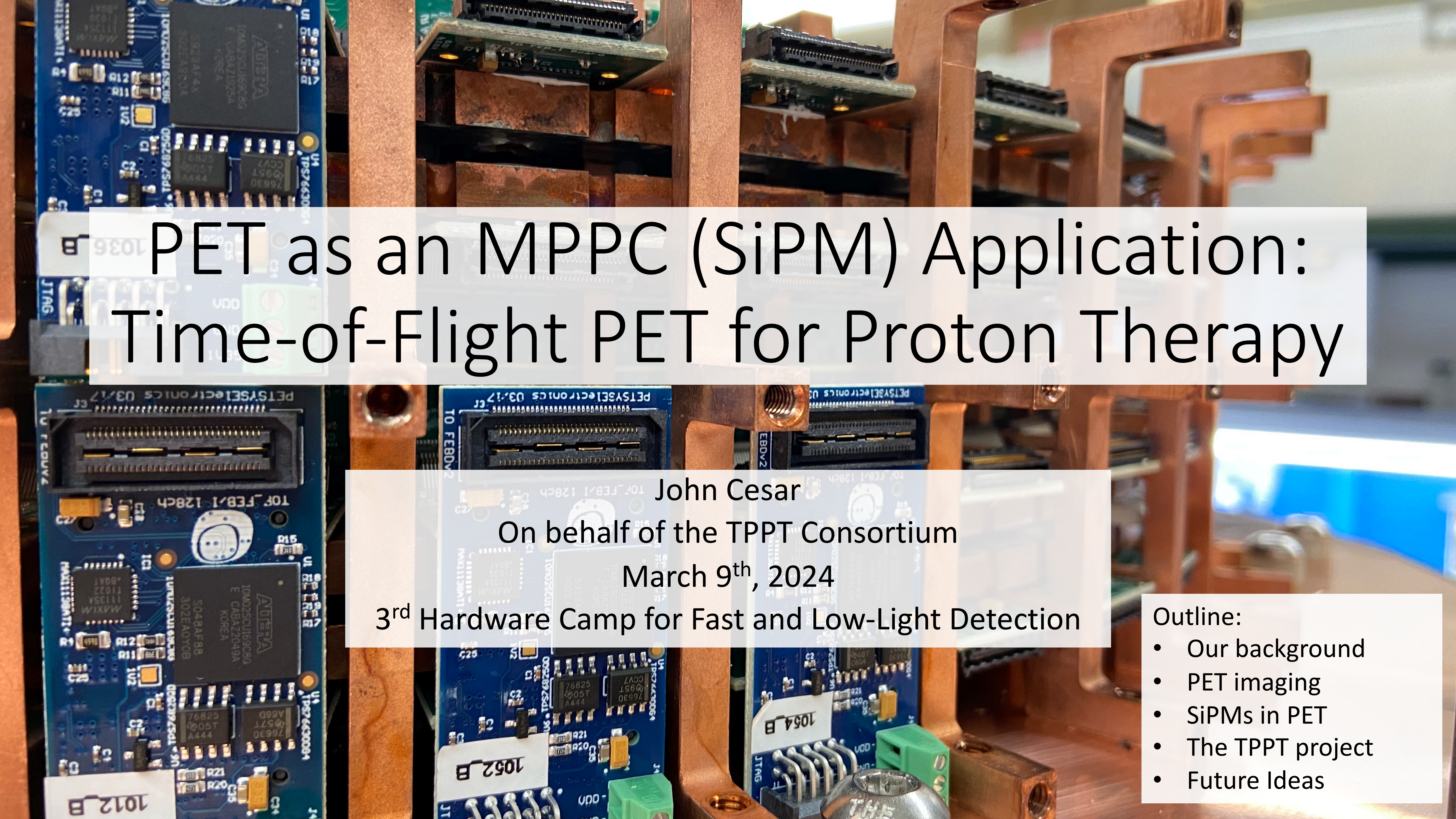


PET as an MPPC (SiPM) Application: Time-of-Flight PET for Proton Therapy

John Cesar
On behalf of the TPPT Consortium

March 9th, 2024

3rd Hardware Camp for Fast and Low-Light Detection

Outline:

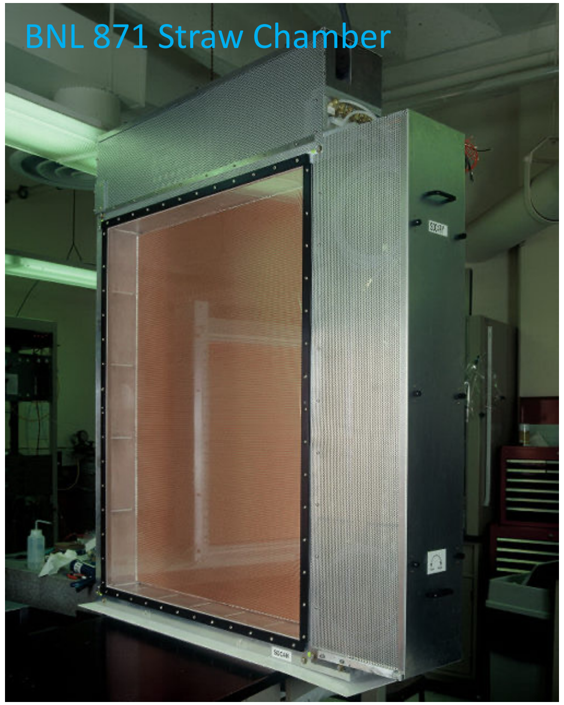
- Our background
- PET imaging
- SiPMs in PET
- The TPPT project
- Future Ideas

Our Background

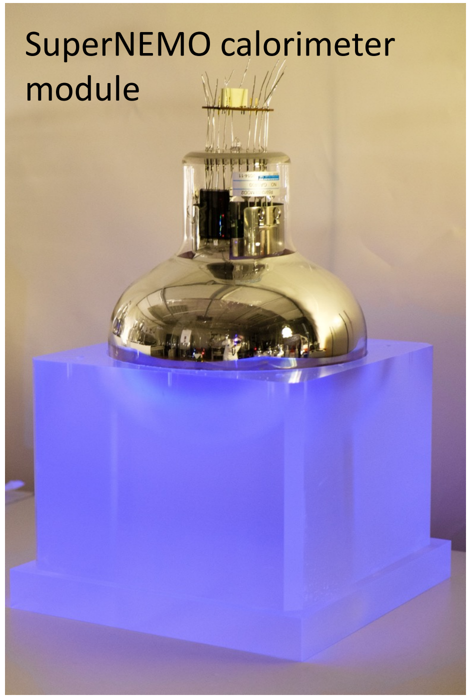
From particle physics to medical physics…(but also still involved in particle physics)

Our Background: The UT Lang Group

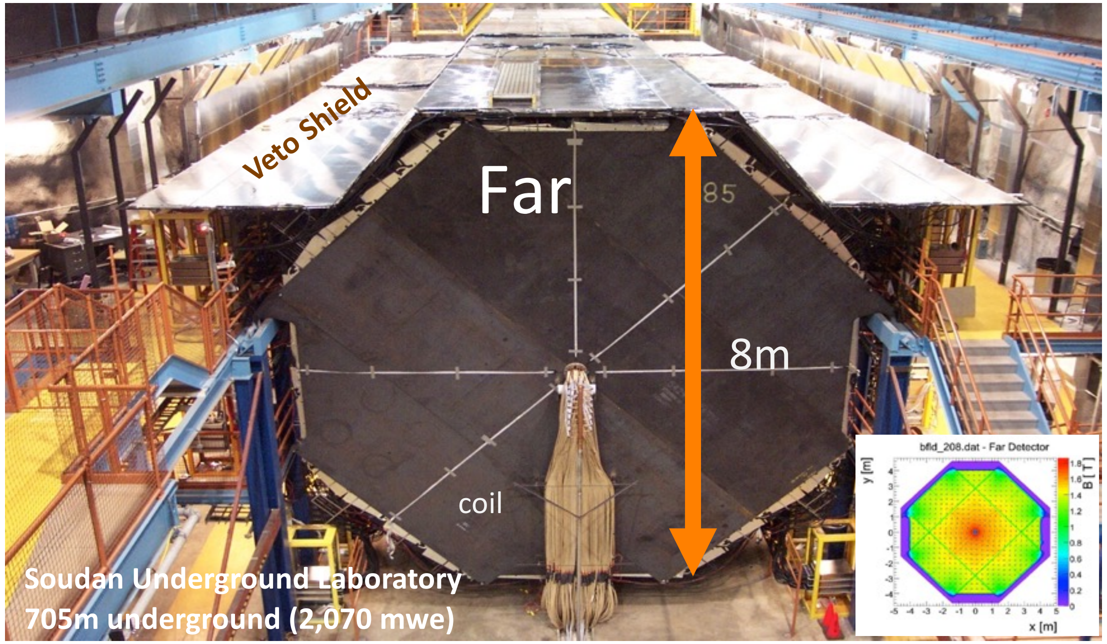
- Historically, our group has been conducting research in high energy physics
  - SSC (Superconducting Super Collider, cancelled in 1993)
  - Rare K_L decays
  - Neutrino oscillations
  - Search for neutrinoless double beta decay
  - Search for coherent neutrino interactions at a reactor
- We have participated in all main aspects of these particle physics endeavors
  - designed, fabricated, deployed new instrumentation
  - developed physics analysis software
- Funded by (over the years)
  - U. of Texas
  - DOE
  - NSF
  - Fermilab
  - URA
  - CNRS (France)
- We have always had interests in contributing to medical physics
  - Turns out that medical imaging is an exciting field to contribute to!

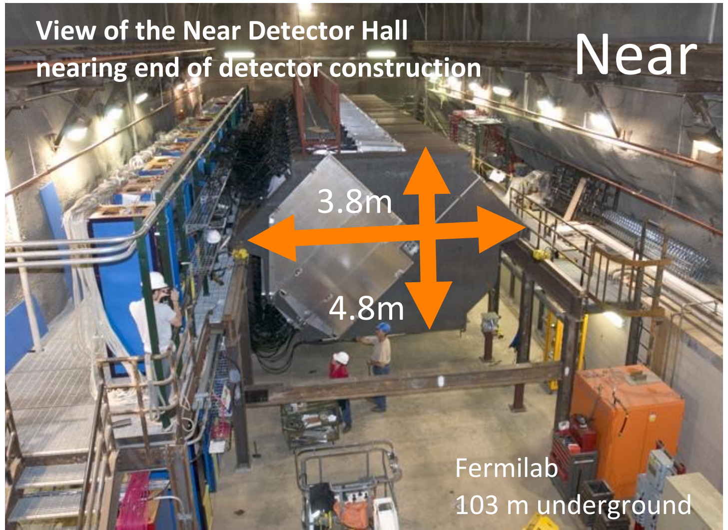

BNL 871 Straw Chamber


MINOS Scintillator strip

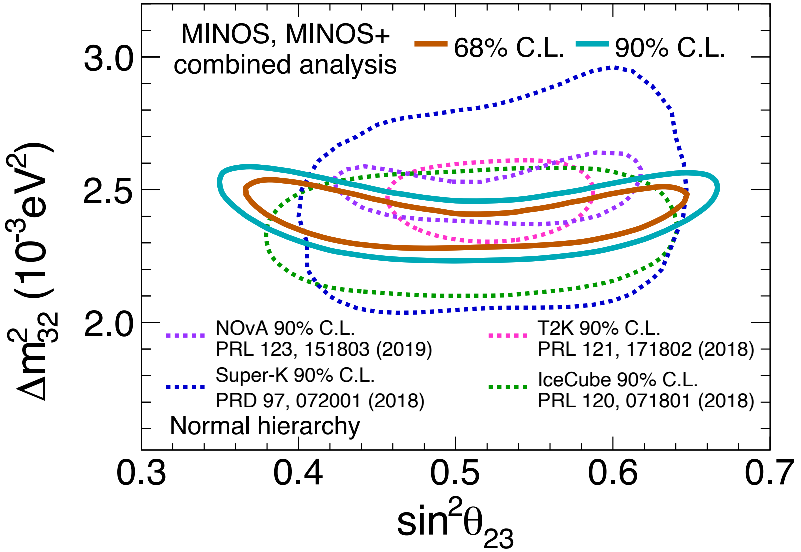

SuperNEMO calorimeter module

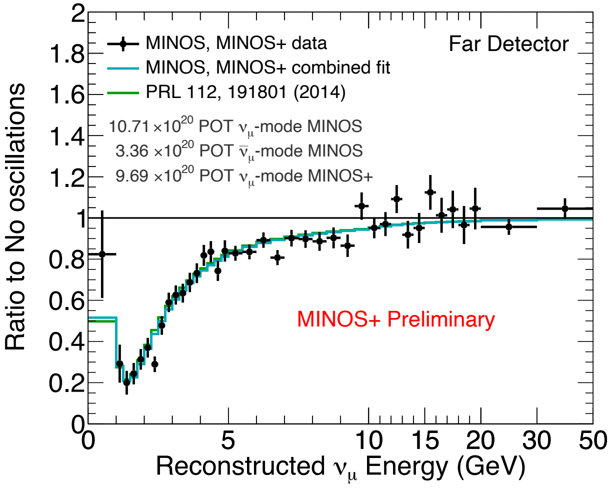
Our Background: MINOS/MINOS+

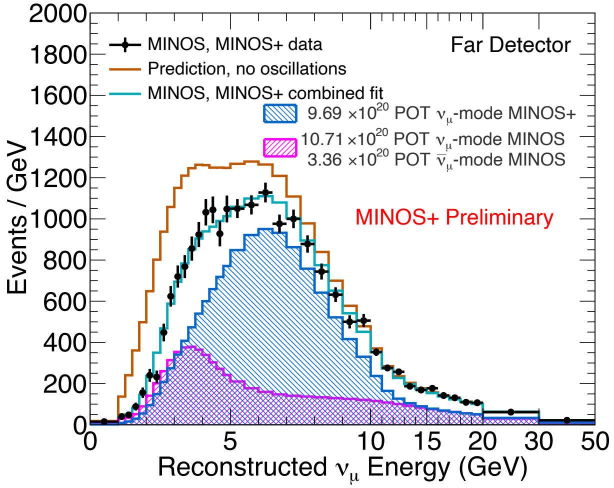




- Large-scale, long base-line neutrino oscillations experiment
- Operated 2005 - 2016
- Precision measurements of mixing parameters



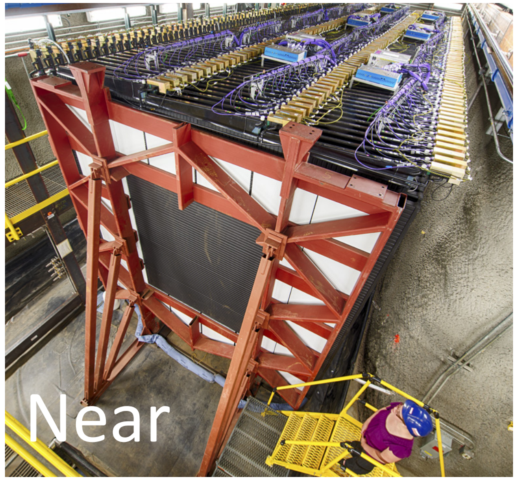


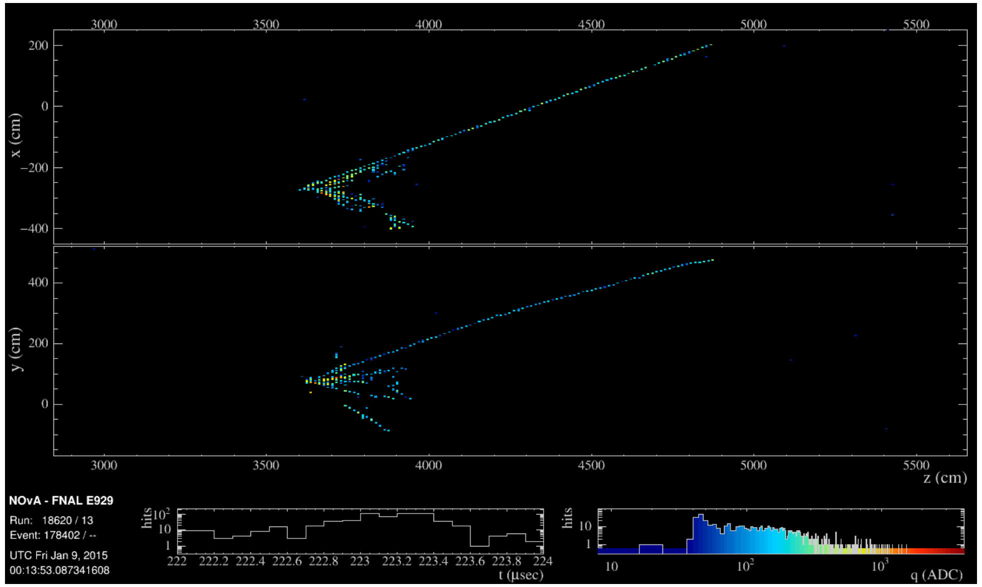


Normal	$\Delta m^2_{32} = +2.41\,^{+0.08}_{-0.08}\ (\times10^{-3}eV^2)$	Inverted	$\Delta m^2_{32} = -2.47\,^{+0.09}_{-0.07}\ (\times10^{-3}eV^2)$
	$\sin^2\theta_{23} = 0.42\ (0.38 \leftrightarrow 0.48)$		$\sin^2\theta_{23} = 0.42\ (0.38 \leftrightarrow 0.48)$

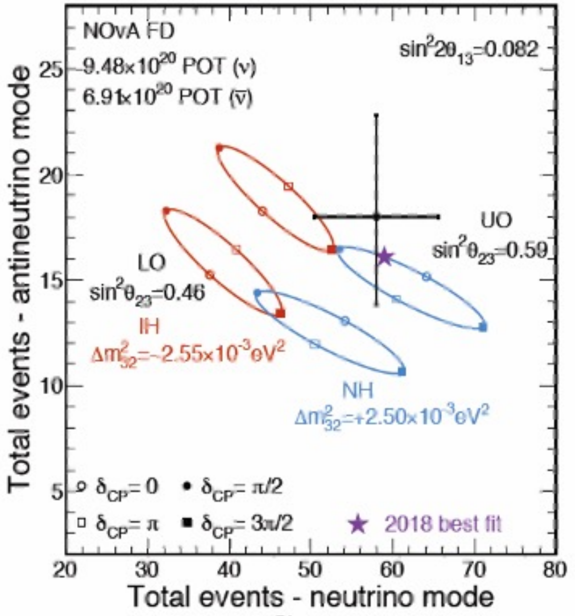
Our Background: NOvA

- Successor to MINOS
- Large-scale, long base-line neutrino oscillations experiment
- Precision measurements of mixing parameters
- Potential mass hierarchy resolution
- Still in operation

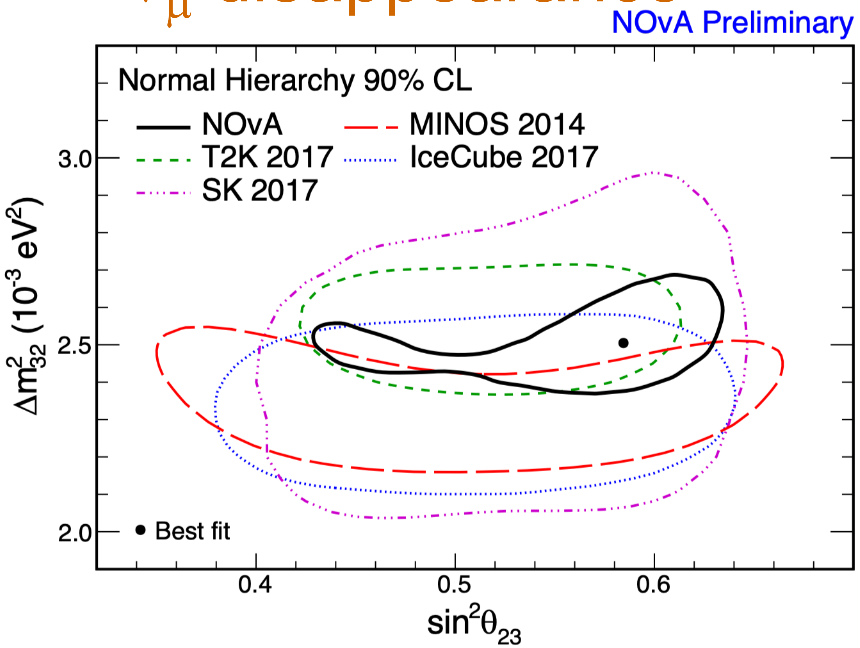




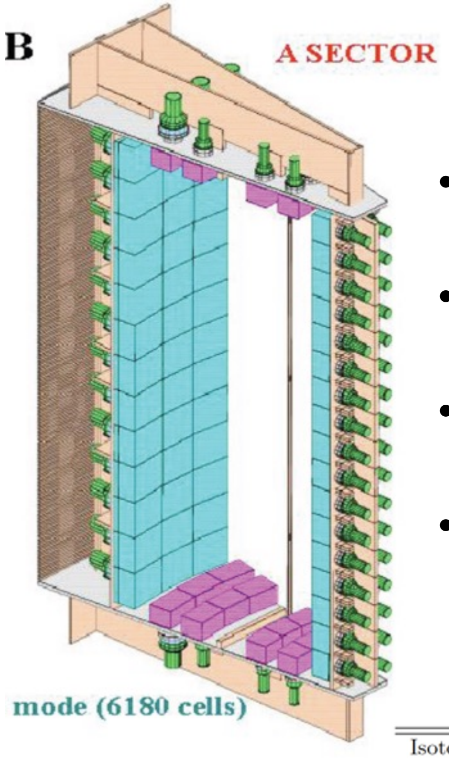
ν_e appearance



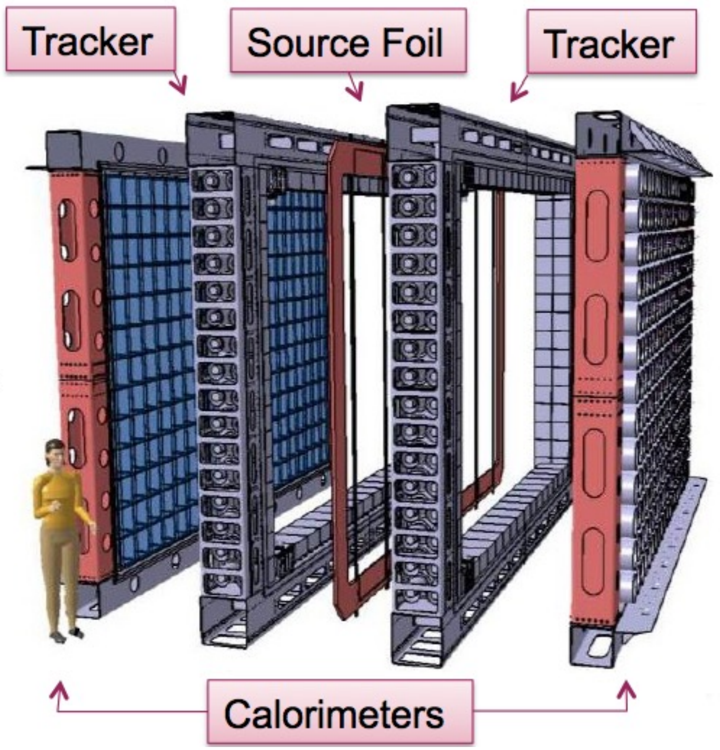
ν_μ disappearance

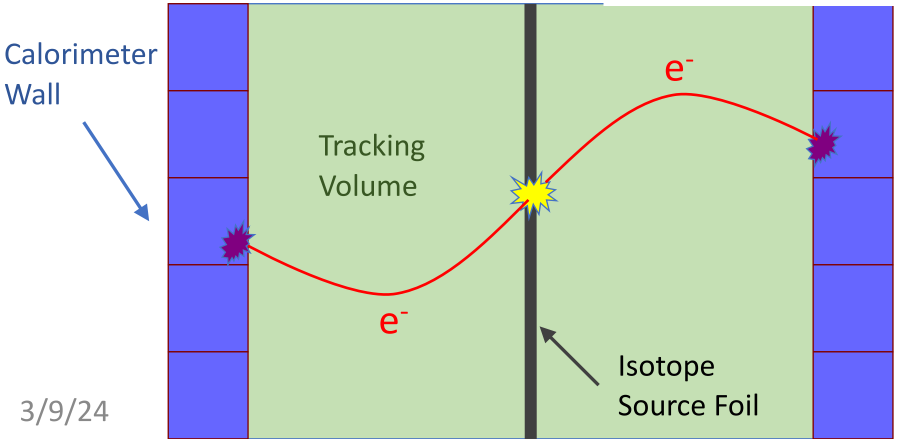


Our Background: NEMO-3/SuperNEMO

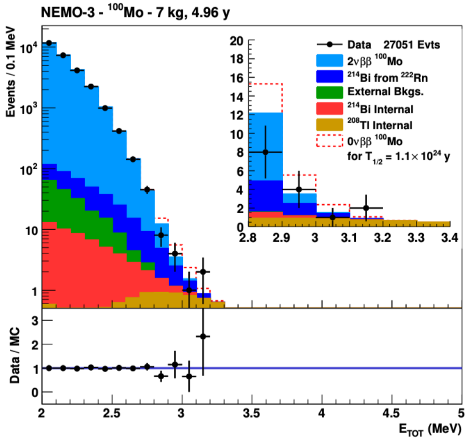


- Neutrinoless double-beta decay search experiment
- Novel multi-observable multi-isotope approach
- NEMO-3 operated from 2003 - 2011
- SuperNEMO demonstrator module currently being commissioned





Isotope	$T^{0\nu}_{1/2}$ ($\times 10^{25}$ y)	$\langle m_{\beta\beta}\rangle$ (eV)	Experiment	Reference
^{48}Ca	$> 5.8 \times 10^{-3}$	$< 3.5 - 22$	ELEGANT-IV	(157)
^{76}Ge	> 8.0	$< 0.12 - 0.26$	GERDA	(158)
	> 1.9	$< 0.24 - 0.52$	MAJORANA DEMONSTRATOR	(159)
^{82}Se	$> 3.6 \times 10^{-2}$	$< 0.89 - 2.43$	NEMO-3	(160)
^{96}Zr	$> 9.2 \times 10^{-4}$	$< 7.2 - 19.5$	NEMO-3	(161)
^{100}Mo	$> 1.1 \times 10^{-1}$	$< 0.33 - 0.62$	NEMO-3	(162)
^{116}Cd	$> 1.0 \times 10^{-2}$	$< 1.4 - 2.5$	NEMO-3	(163)
^{128}Te	$> 1.1 \times 10^{-2}$	—	—	(164)
^{130}Te	> 1.5	$< 0.11 - 0.52$	CUORE	(124)
^{136}Xe	> 10.7	$< 0.061 - 0.165$	KamLAND-Zen	(165)
	> 1.8	$< 0.15 - 0.40$	EXO-200	(166)
^{150}Nd	$> 2.0 \times 10^{-3}$	$< 1.6 - 5.3$	NEMO-3	(167)

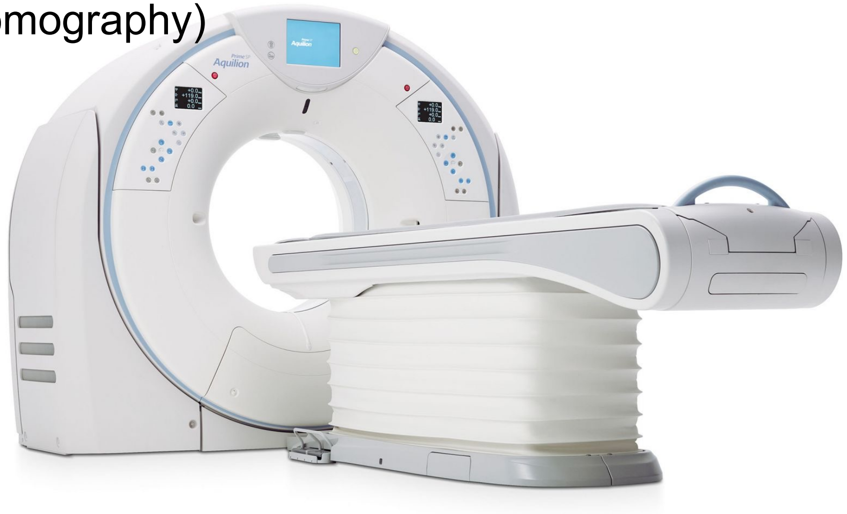


PET Imaging

PET = **P**ositron **E**mission **T**omography and it is a subset of the larger medical imaging field…

PET Imaging: A Subset of Medical Imaging

CT (Computed Tomography)



MRI (Magnetic Resonance Imaging)

PET (Positron Emission Tomography)

And there are others:

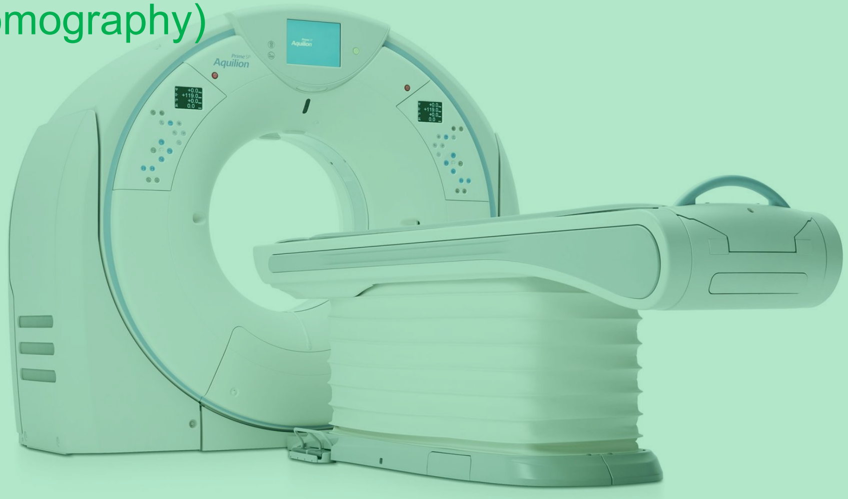
- **SPECT imaging**
- X-ray imaging
- Ultrasound imaging
- …

PET and SPECT are <u>nuclear</u> medical imaging techniques

- Radiation being used/detected is **internal** rather than external
- Employ radiopharmaceuticals
- Emphasis on imaging **<u>function</u>** (metabolism, etc.) not **<u>structure</u>** (anatomy)

PET Imaging: A Subset of Medical Imaging

CT (Computed Tomography)



MRI (Magnetic Resonance Imaging)

STRUCTURAL IMAGING

PET (Positron Emission Tomography)

And there are others:
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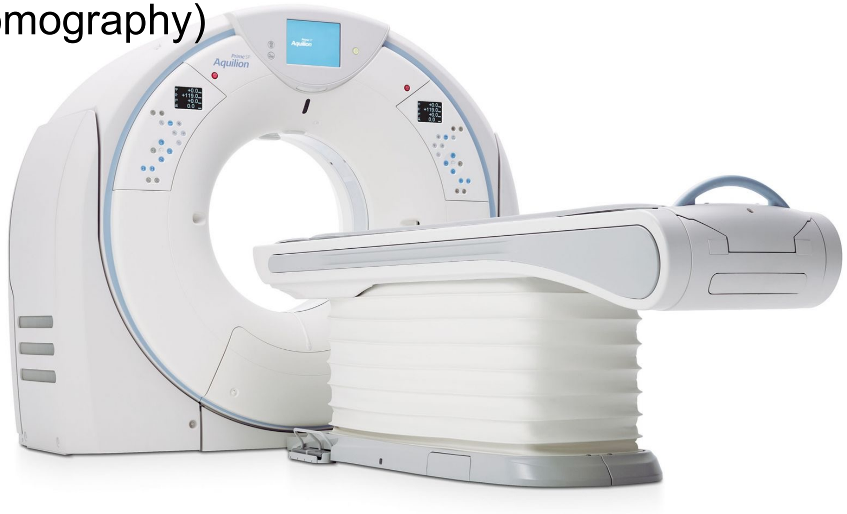

MRI (Magnetic Resonance Imaging)

PET (Positron Emission Tomography)

FUNCTIONAL IMAGING

PET and SPECT are <u>nuclear</u> medical imaging techniques

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- Employ radiopharmaceuticals
- Emphasis on imaging **<u>function</u>** (metabolism, etc.) not **<u>structure</u>** (anatomy)

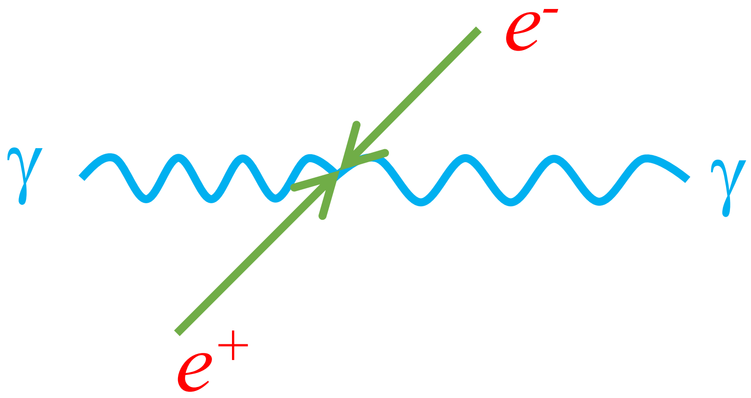
And there are others:

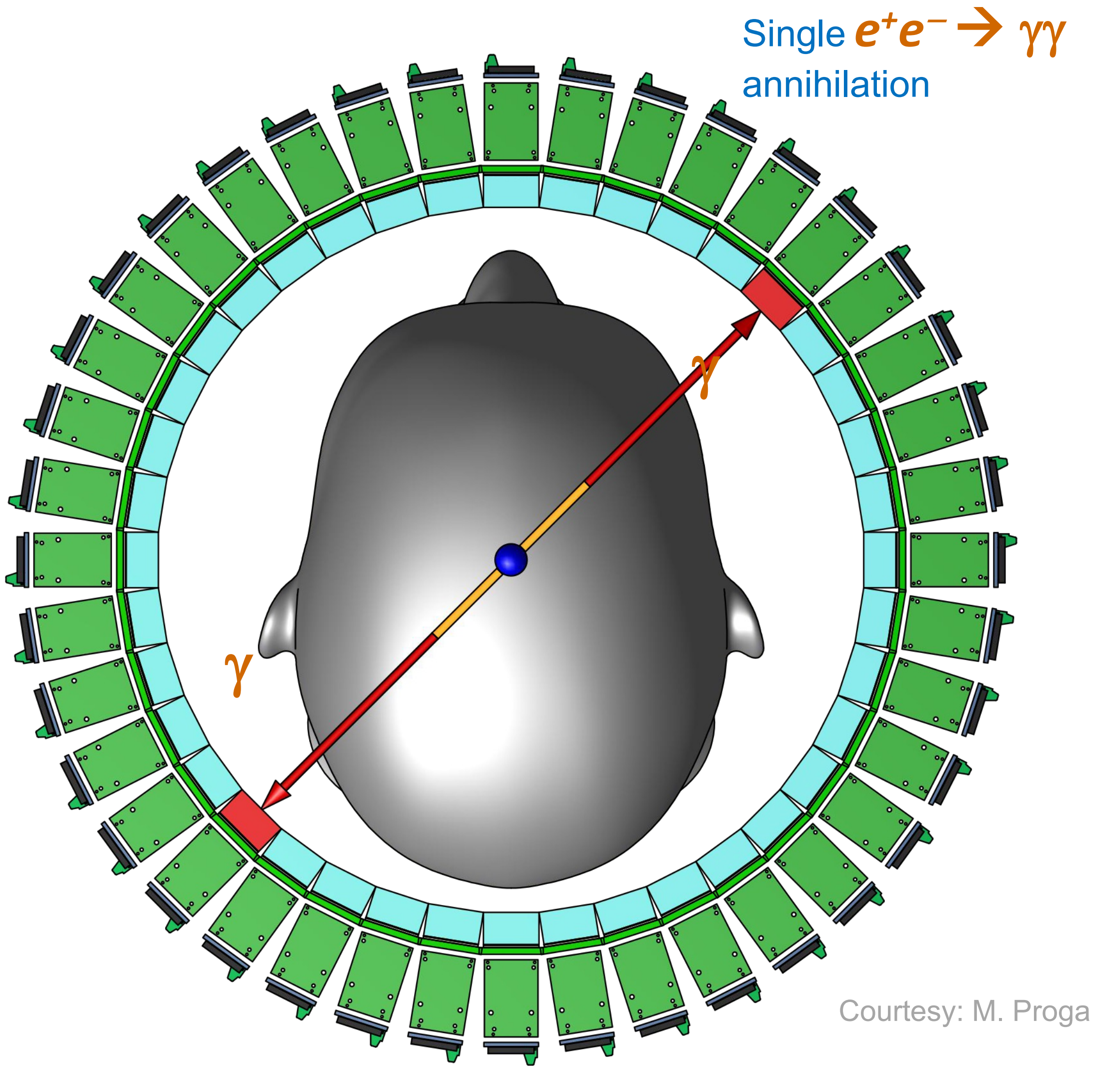
- **SPECT imaging**
- X-ray imaging
- Ultrasound imaging
- …

PET Imaging: Positron Emission

Injection of ^{18}F-fluorodeoxyglucose (^{18}FDG) or other suitable radiopharmaceuticals

$$^{18}F \rightarrow {}^{18}O + e^{+} + \nu_{e}$$





$e^{+} + e^{-} \rightarrow \gamma + \gamma$

$E = mc^{2}$

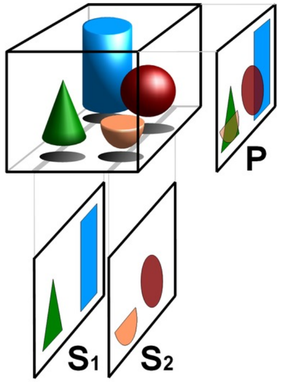
mass of the electron = 511 keV

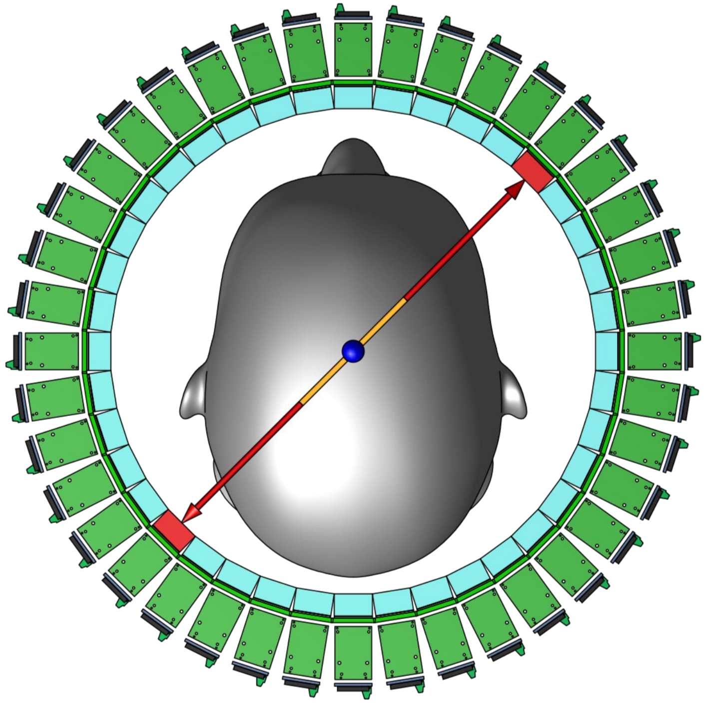
mass of the electron = mass of the positron

$E_{\gamma} = 511\ keV$

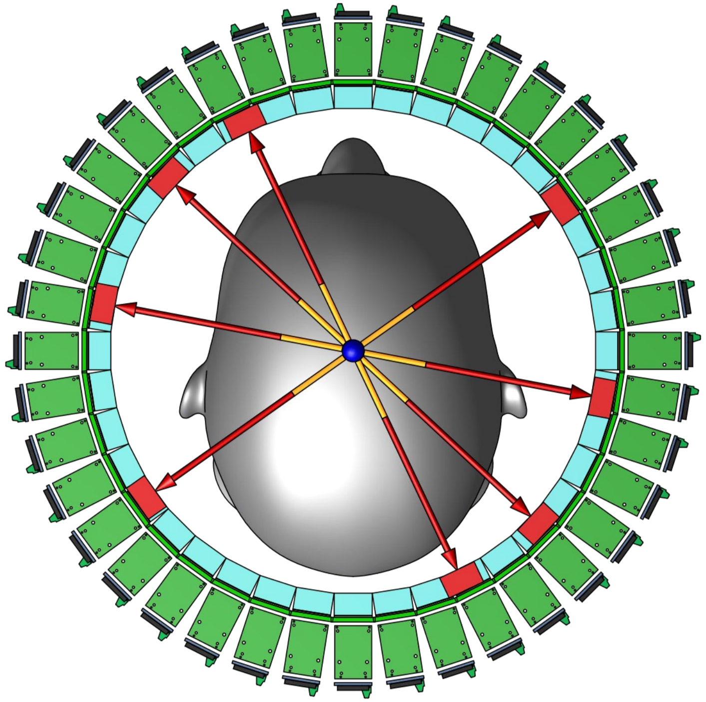
LOR = line of response = the line formed by the trajectories of the two back-to-back gammas

PET Imaging: Tomography

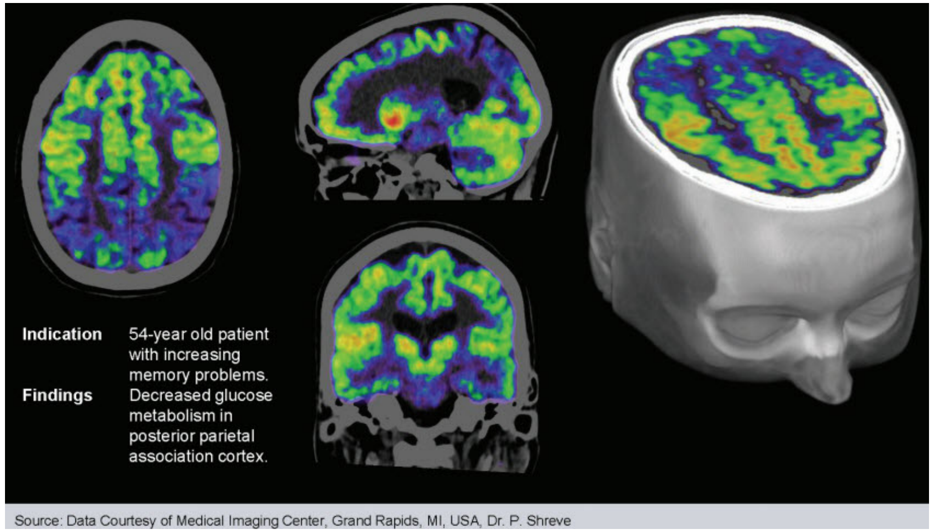




One LOR is not enough, the annihilation could have occurred anywhere along the LOR

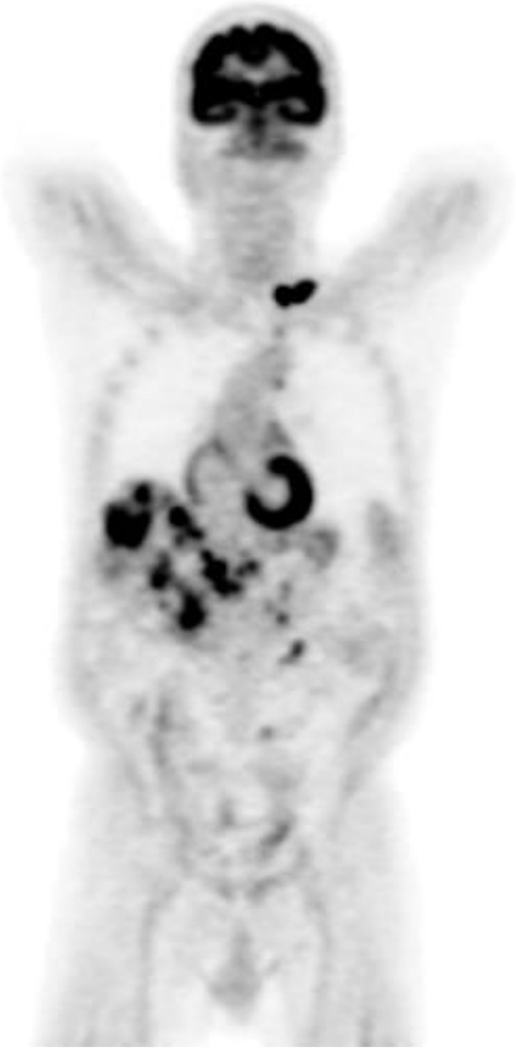


With many LORs from the same region, their intersections can be traced back to a common source



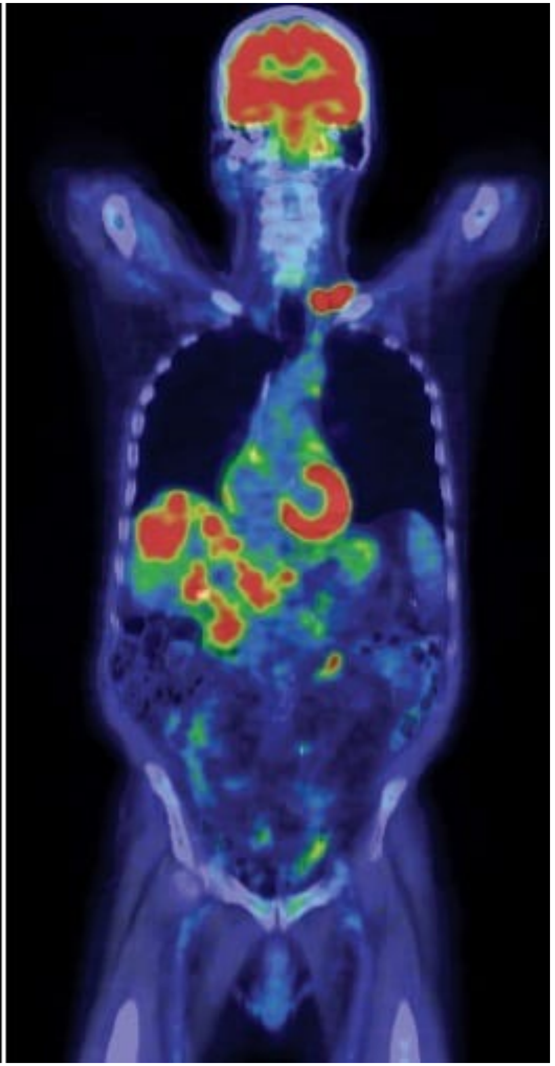
Doing this along different planes then allows for full 3D image reconstruction of activity and/or structure (CT is also tomographic)

PET Imaging: Conventional PET + CT



PET

CT



PET + CT

Recall…

CT = structural
PET = functional

SiPMs in PET

Modern PET scanner technology

SiPMs in PET: Early PMT-based Scanners

- Need to detect and localize emitted gammas
  - Space → gives us LORs
  - Time → Define coincidences
    - Avoid randoms
    - Maybe do more…
- Early scanners used scintillators + PMTs
- But PMTs often had larger surface areas than ideal
  - Needed more pixelization
  - Early designs had to be clever…

A

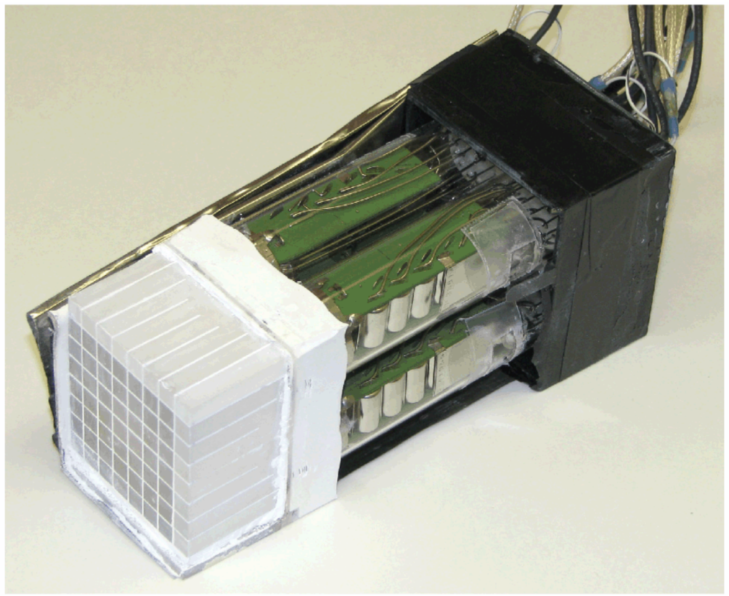
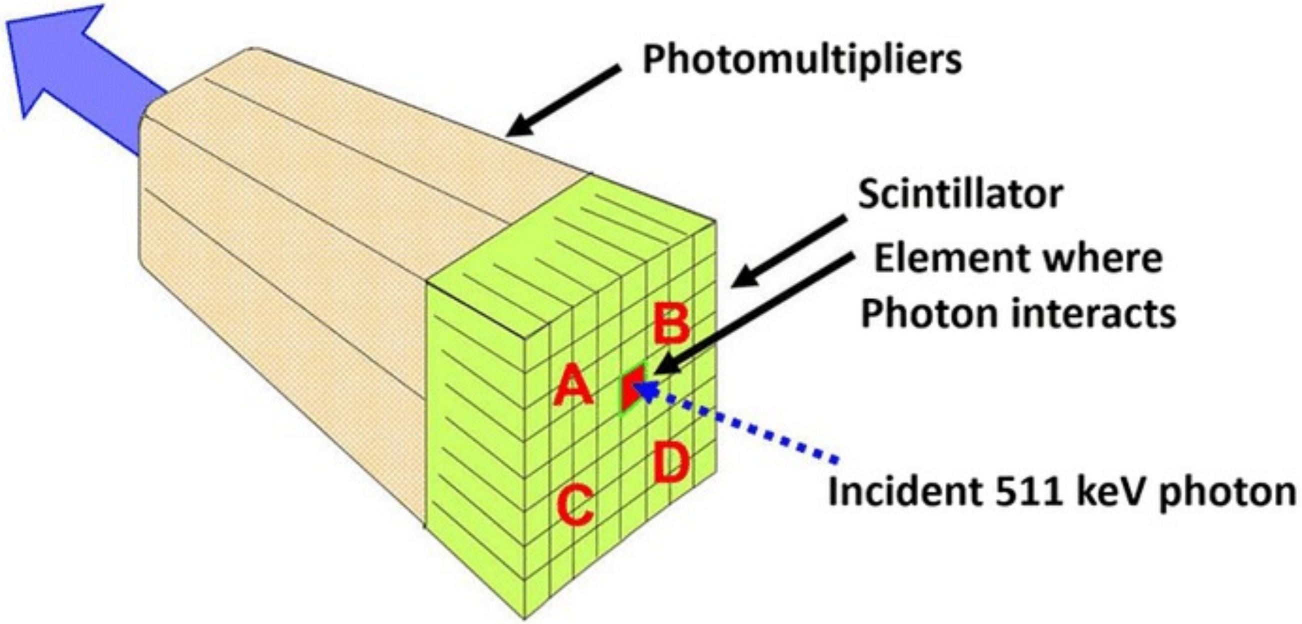
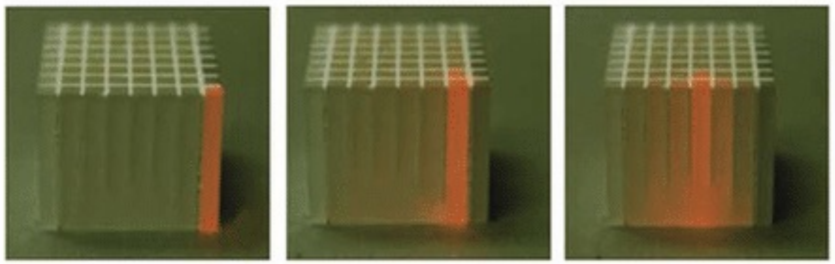


Image courtesy of https://doi.org/10.1017/CBO9781139088268.007



(a)



Light distribution identifies the element

(b)

Image courtesy of doi: 10.1117/1.JMI.4.1.011013

SiPMs in PET: Comparisons

	PD	APD	MPPC	PMT
Gain	1	10^2	to 10^6	to 10^7
Quantum efficiency	Highest	High	Medium	Low
Operation voltage	5 V	100 to 500 V	30 to 60 V	800 to 1000 V
Large area	No	No	Medium	yes
Multi channel with narrow gap	Yes	Yes	Yes	No
Readout circuit	Complex	Complex	Simple	Simple
Noise	Low	Middle	Middle	Low
Uniformity	Excellent	Good	Excellent	Good
Energy resolution	High	Medium	High	High
Temperature sensitivity	Low	High	Medium	Low
Ambient light immunity	Yes	Yes	Yes	No
Magnetic resist	Yes	Yes	Yes	No
Compact & Weight	Yes	Yes	Yes	No

Image courtesy of https://www.hamamatsu.com/eu/en/product/optical-sensors/mppc/what_is_mppc.html

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Compact & Weight	Yes	Yes	Yes	No

Image courtesy of https://www.hamamatsu.com/eu/en/product/optical-sensors/mppc/what_is_mppc.html

Comparable gain to PMTs and better QE

Good for better pixelization (spatial position resolution) and less dead space!

Allows for combined PET + MR (function + structure imaging)

Compactness also open new opportunities for PET…

SiPMs in PET: Fast Timing

- Fast gamma detection opens new opportunities
  - Time-of-Flight (ToF) localization
- Three ingredients:
  - Fast **scintillators**
  - Fast **photodetector**
  - Fast **front-end electronics**
- Leads to improved image reconstruction
  - Less noise in final images

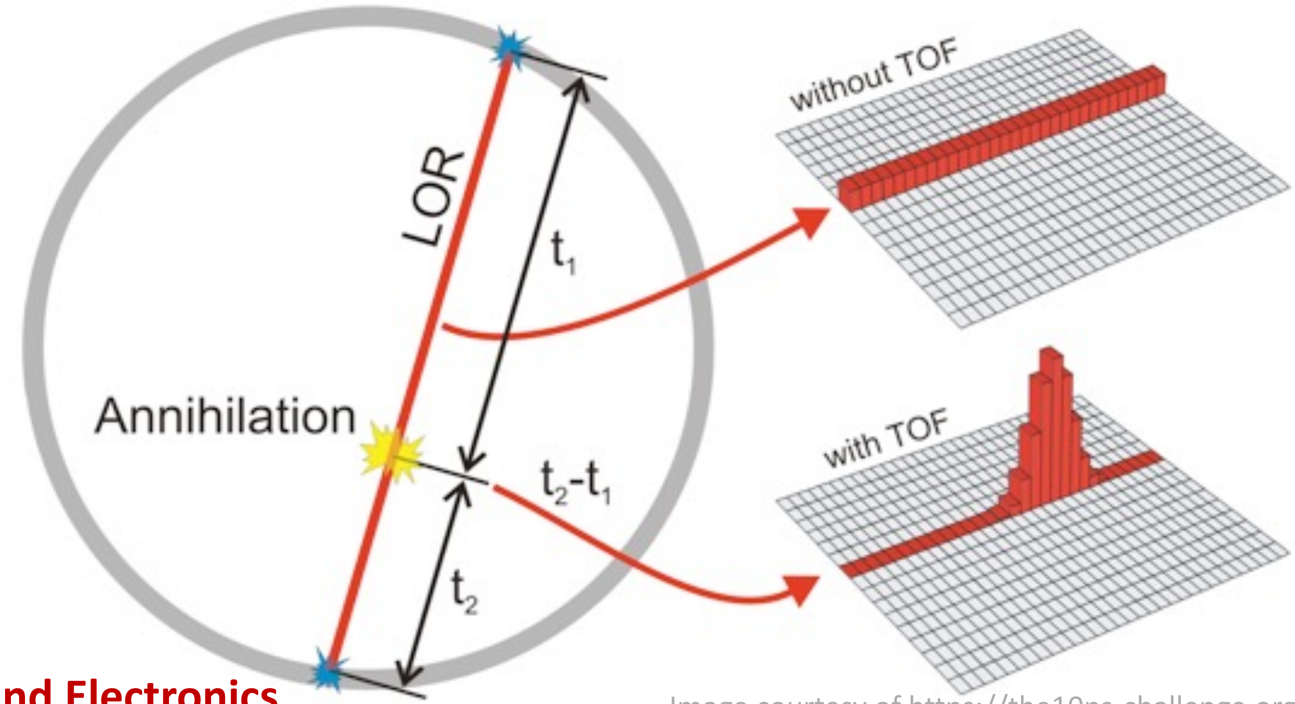
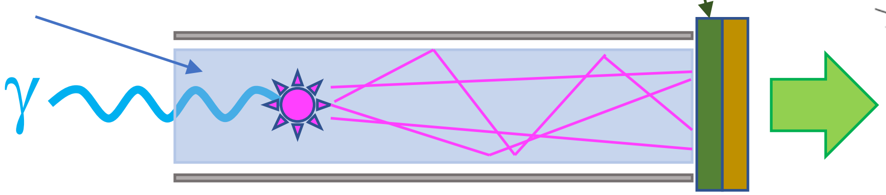
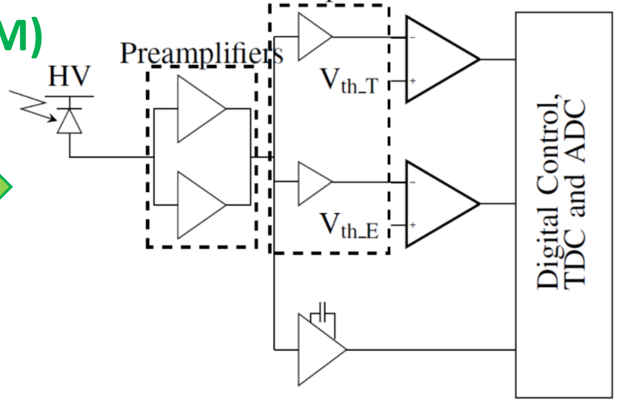


Image courtesy of https://the10ps-challenge.org/



Front-End Electronics

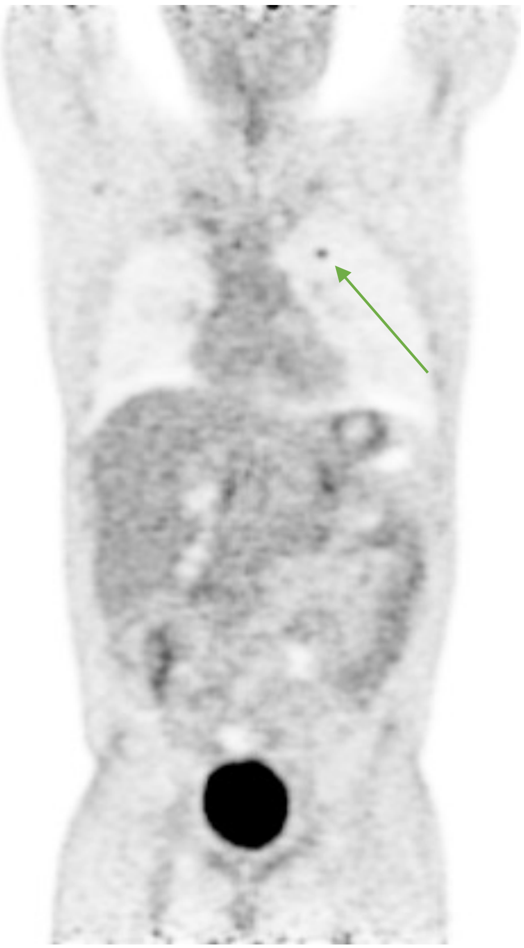


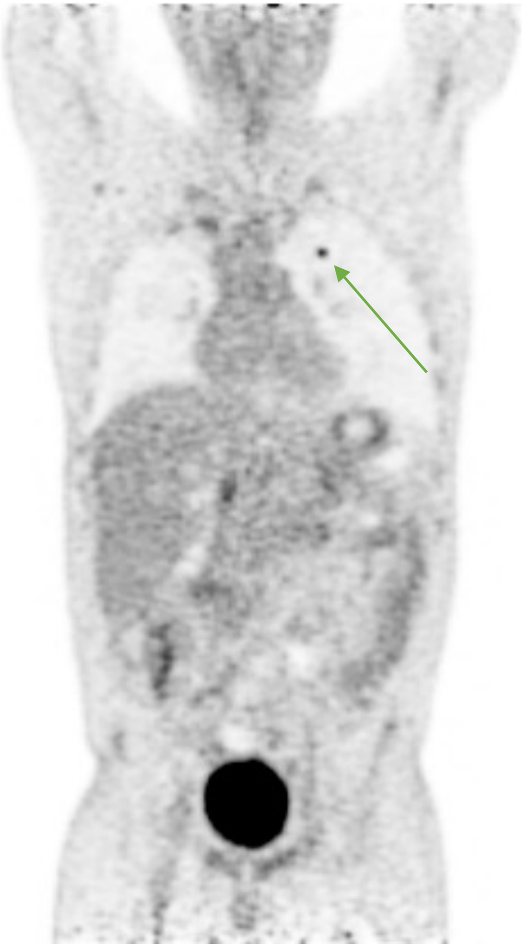
$\Delta X = c\,\Delta T/2$

$\Delta T = t_2 - t_1$

SiPMs in PET: Time-of-Flight PET

Non-TOF





TOF (550 ps)

3 minute/bed
injection of ^{18}F-fluorodeoxyglucose (^{18}FDG)

Borrowed from Dr. Maurizio Conti
Director, PET Physics and Reconstruction
Siemens Medical Solution USA, Inc, Knoxville, TN, USA

SiPMs in PET: Compact Size

- Compactness of SiPMs also present new opportunities
  - Double-ended readout (to be discussed later)
  - In-beam PET imaging
    - Can be used with proton therapy
    - Which leads us to….

Image courtesy of https://www.siemens-healthineers.com/en-us/molecular-imaging/pet-ct/biograph-vision

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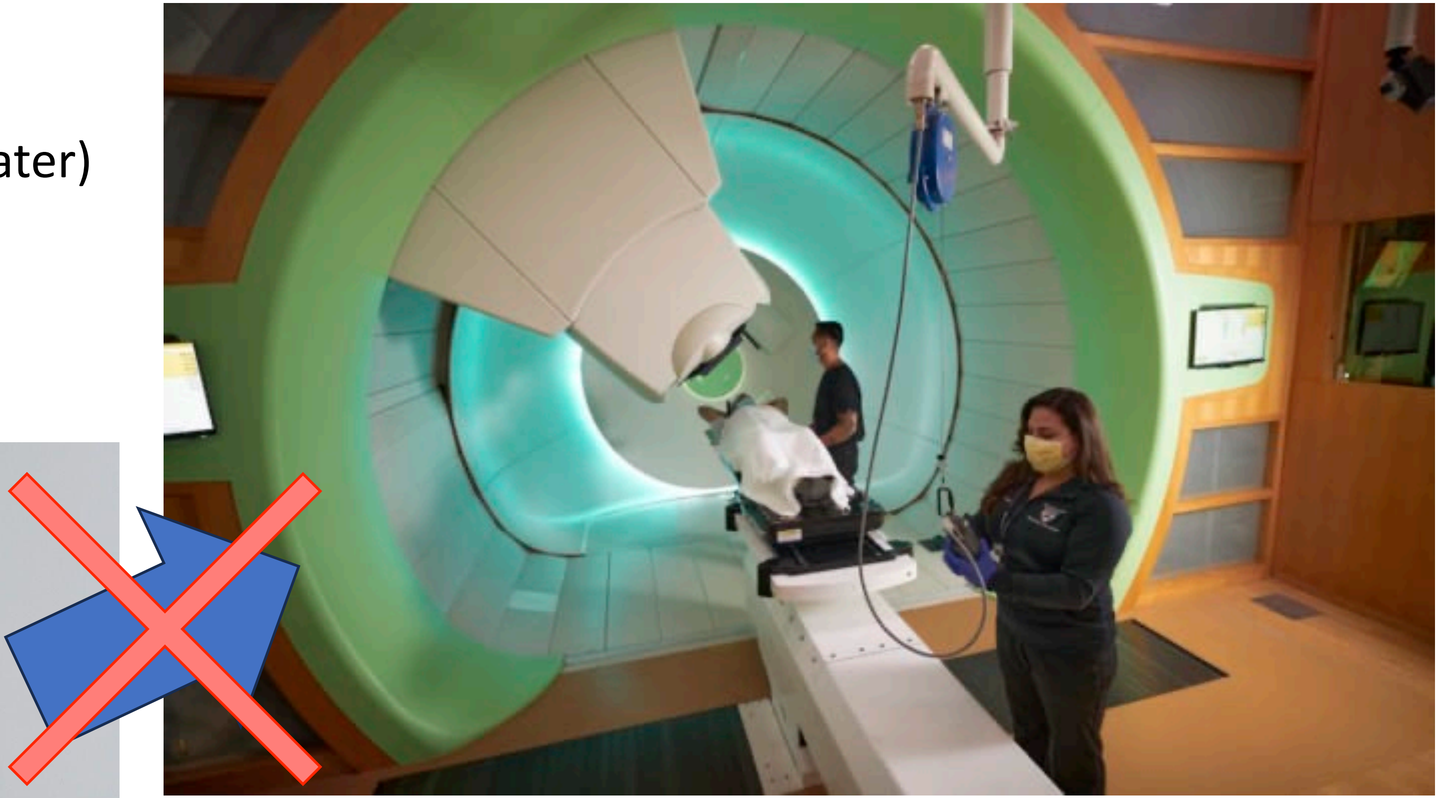


Current conventional PET/CT scanners too large for this because imaging (diagnostics) and treatment (therapy) don't mix…yet

The TPPT Project

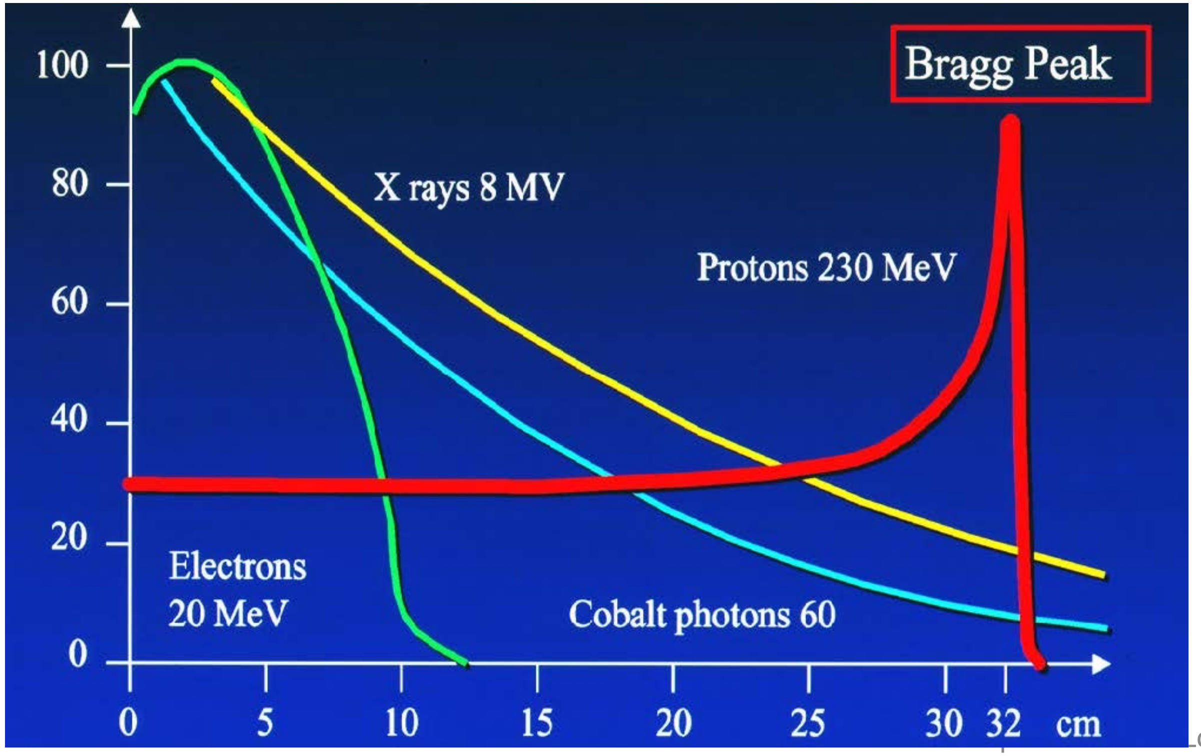
Time-of-Flight PET for Proton Therapy:
PET feedback to provide image-
guidance during proton therapy

The TPPT Project: Proton Therapy History

``The proton proceeds through the tissue in very nearly a straight line, and the tissue is ionized at the expense of the energy of the proton until the proton is stopped. .... [the] dose is many times less where the proton enters the tissue at high energy than it is in the last centimeter of the path where the ion is brought to rest. [...][in a] **strictly localized region within the body**, with but little skin dose. It will be easy to produce well collimated narrow beams of fast protons, and since the range of the beam is easily controllable, precision exposure of well defined small volumes within the body will soon be feasible.''

Robert Rathbun Wilson, Harvard University

Radiological use of fast protons, Radiology **47**, 487-491 (1946) doi:10.1148/47.5.487.



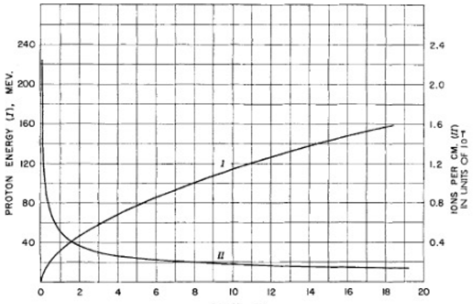


Fig. 1. Curve I is the range-energy relation in tissue. Curve II shows the specific ionization as a function of the residual range of a proton in tissue.

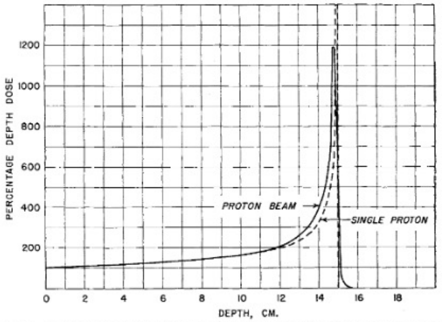
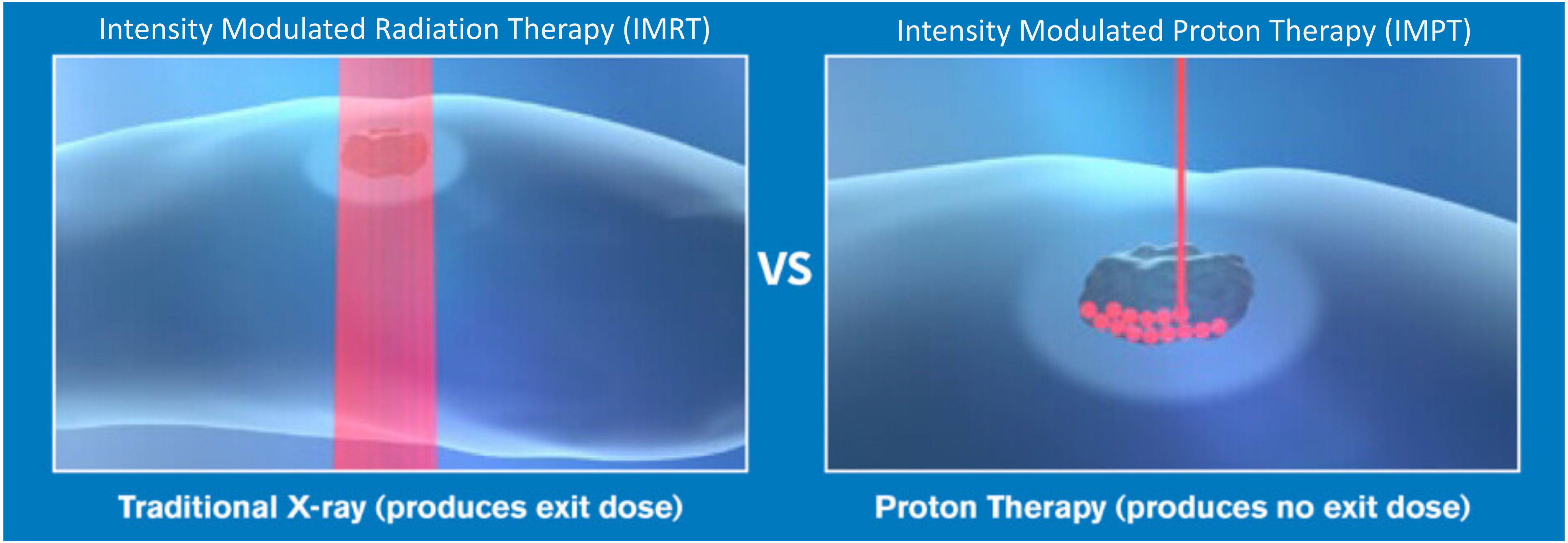
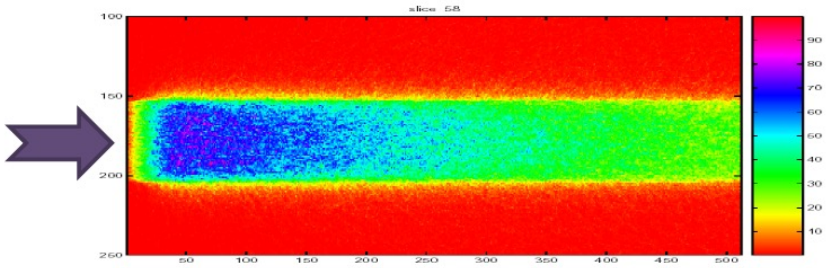


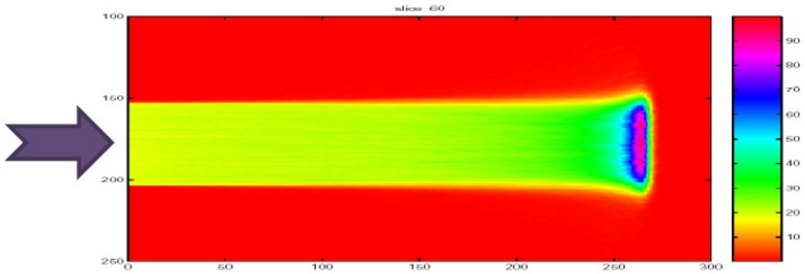
Fig. 2. The dotted curve shows the relative dose due to a single 140 Mev proton. The full curve shows qualitatively the depth dose curve for a beam of 140 Mev protons in tissue.

78 years ago!

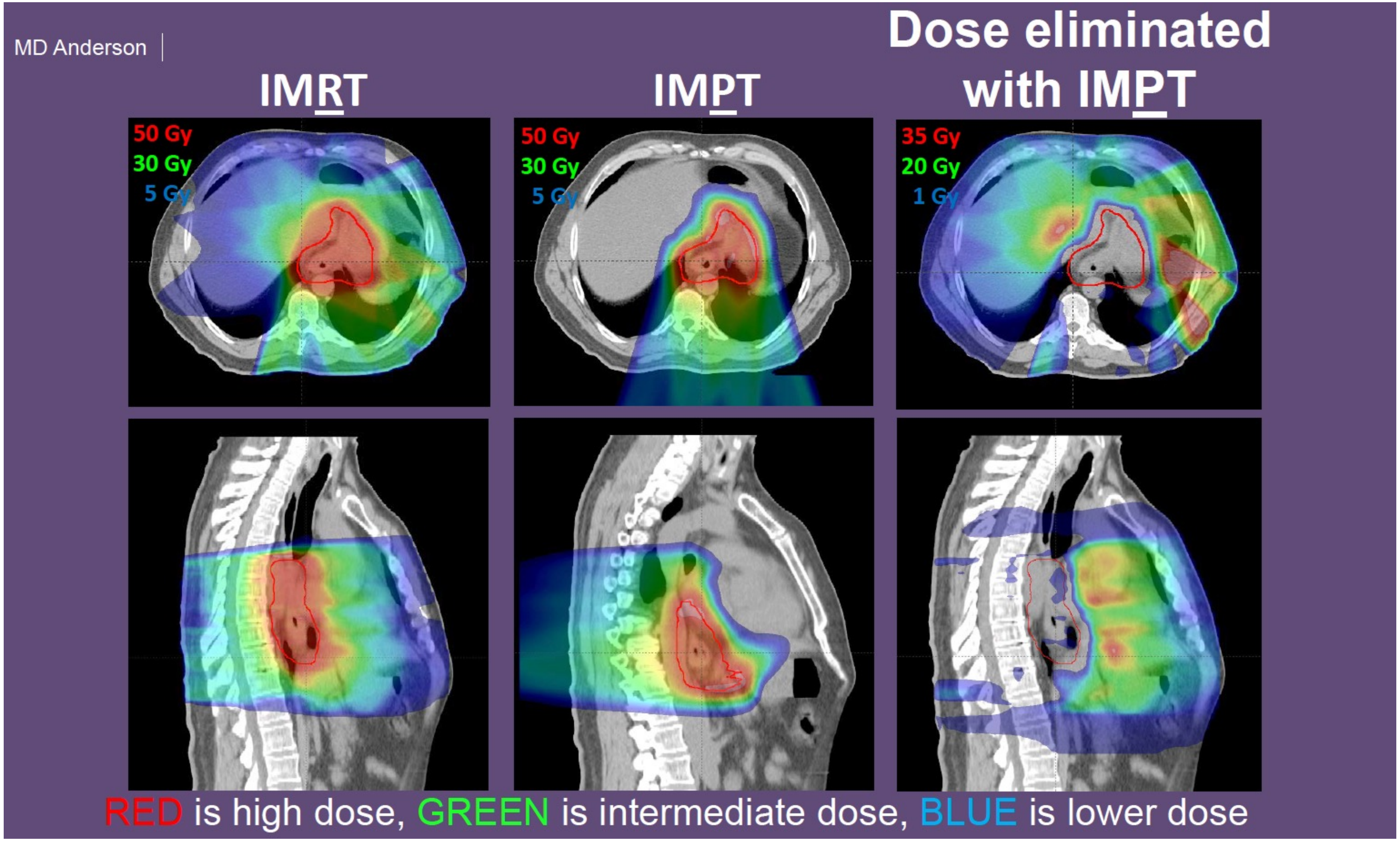
The TPPT Project: Proton Therapy (PT)





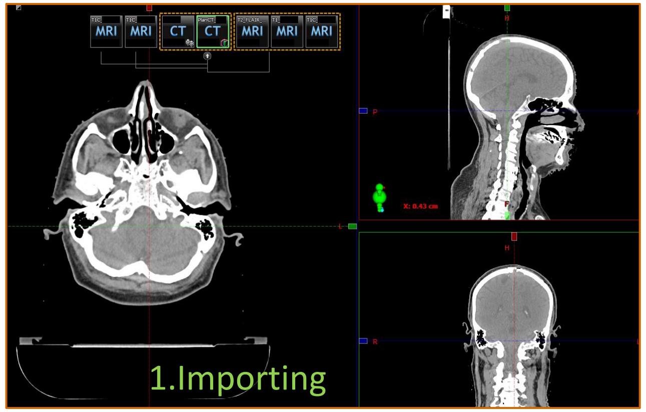


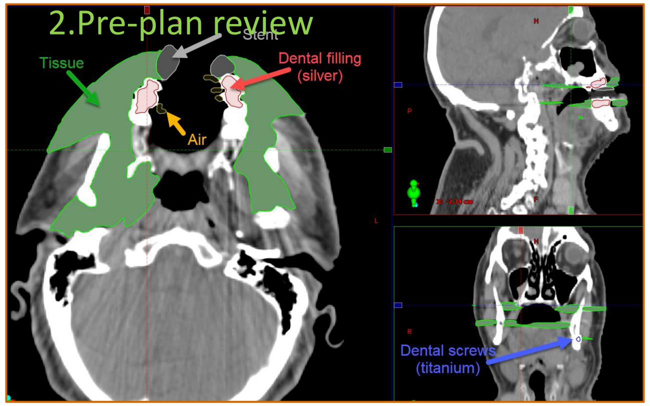
The TPPT Project: Protons vs. Photons

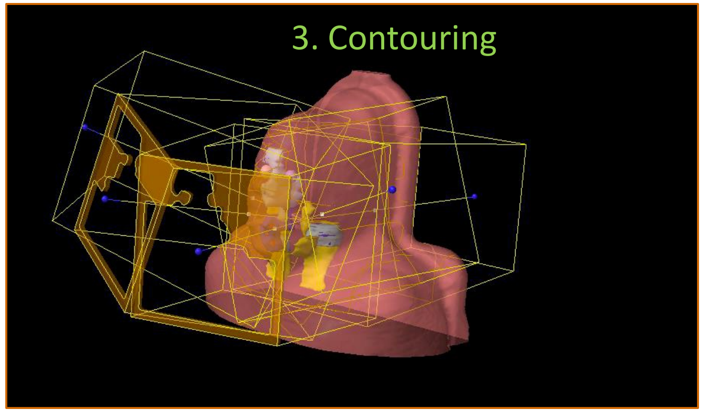


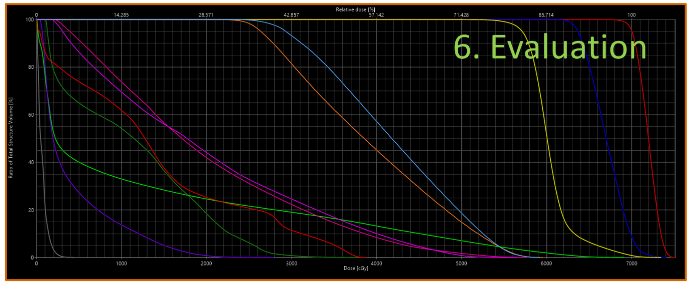
The TPPT Project: Treatment Planning

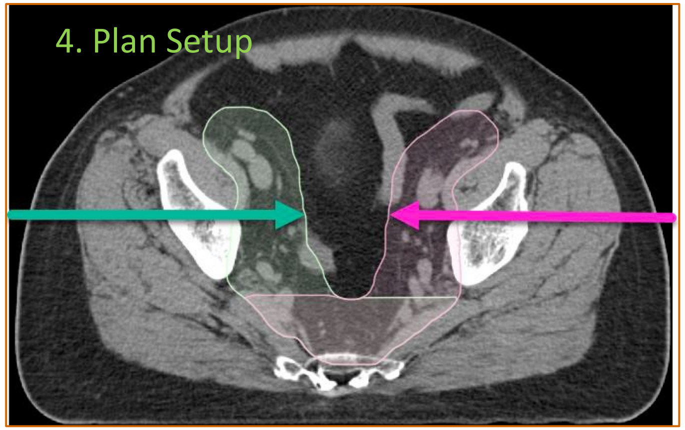
- Meticulous and sophisticated treatment planning ("well-oiled machine") – 5 days of intense preparations
  - 1. Importing
  - 2.Pre-plan Review
  - 3.Contouring
  - 4.Plan Setup
  - 5.Optimization
  - 6.Evaluation
  - 7.Summary

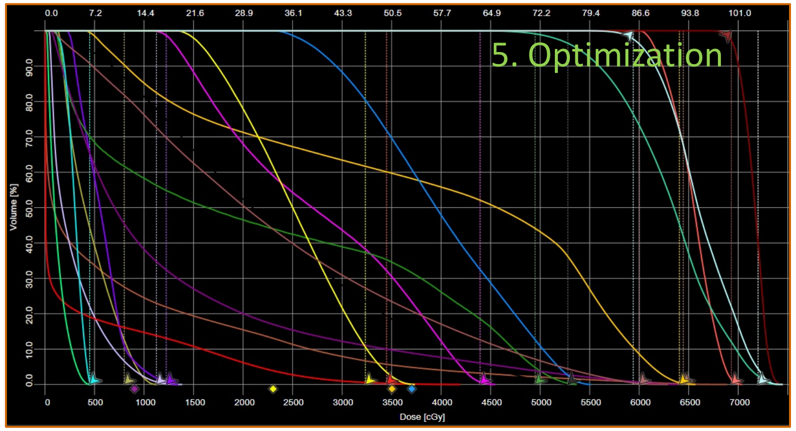


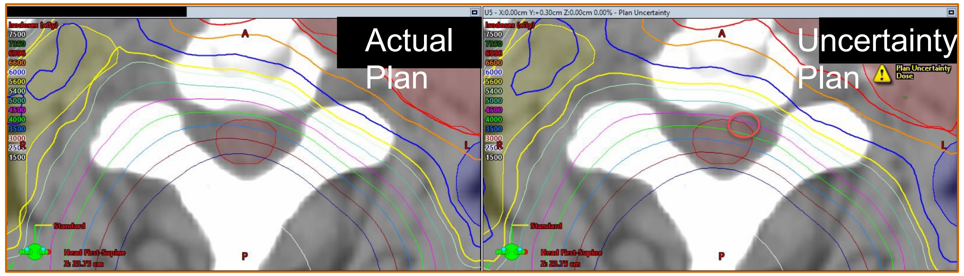












From Christine Chung, MS, CMD, Research Dosimetrist

The TPPT Project: Issues Facing PT

THE UNIVERSITY OF TEXAS
MD Anderson ~~Cancer~~ Center
Making Cancer History®

- **Anatomy changes** may perturb dose distributions to a significantly greater extent for protons than for photons
- **High gradients in proton dose distributions** are very sensitive to anatomy motion and changes, and to set up variations
- **Gaps in the knowledge** of relative biological effectiveness (RBE) of protons
  - Proton RBE is assumed to be a constant of 1.1
- **Heterogeneity in patient population**, tumor characteristics and treatment techniques may be obscuring the potential advantages of protons for subpopulations of patients
- **Evolving treatment delivery** and planning systems and techniques
- **Limits to the applicability of knowledge** and models based on photon therapy experience to protons
- **High cost** of proton therapy

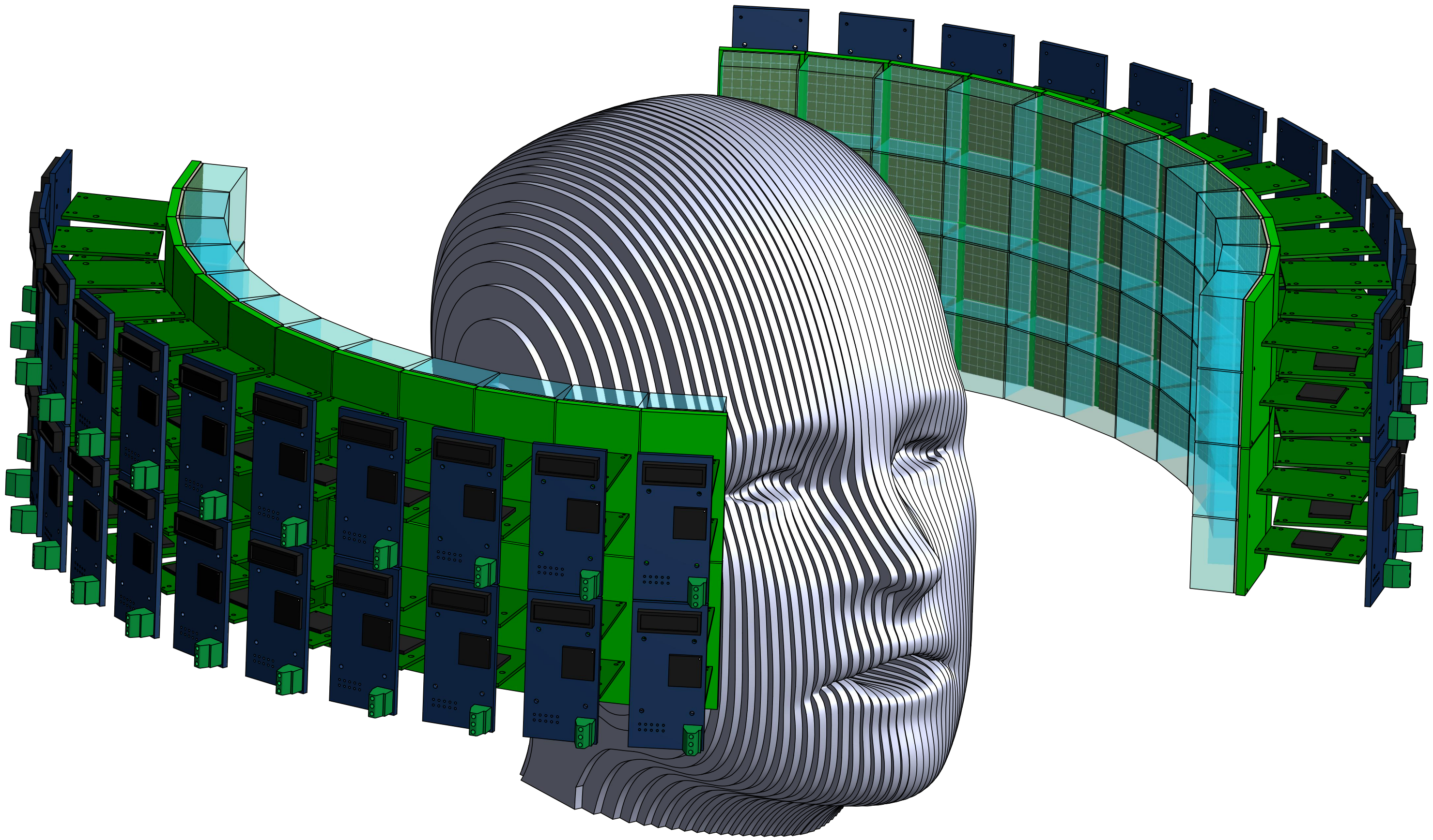
A successful plan requires good communication and multitude of factors that need input from:

– Physician
– Dosimetry team
– Physics team
– Therapy team

Much room for improved feedback of ongoing therapy
(a.k.a. proton range verification)

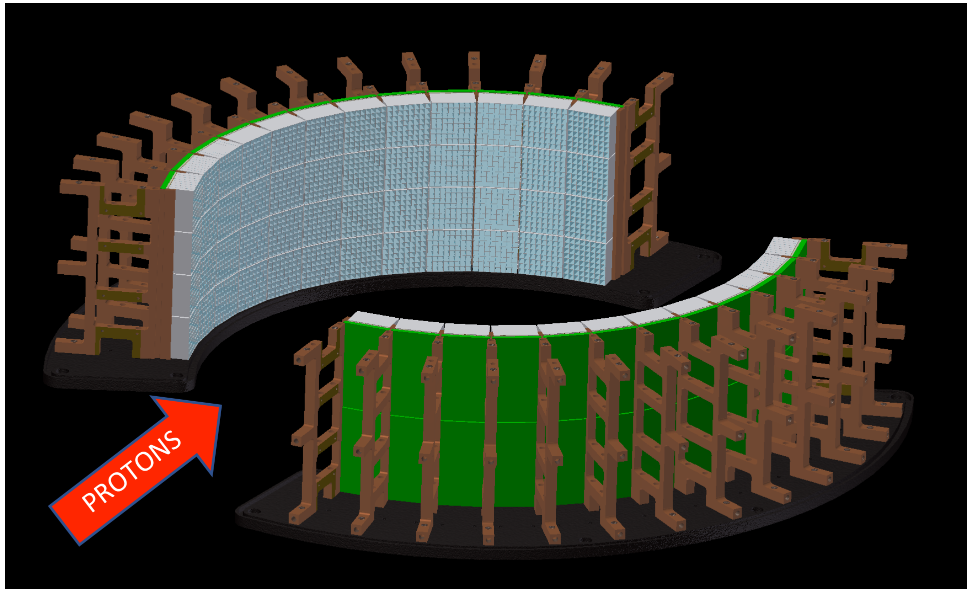
From Radhe Mohan, PhD

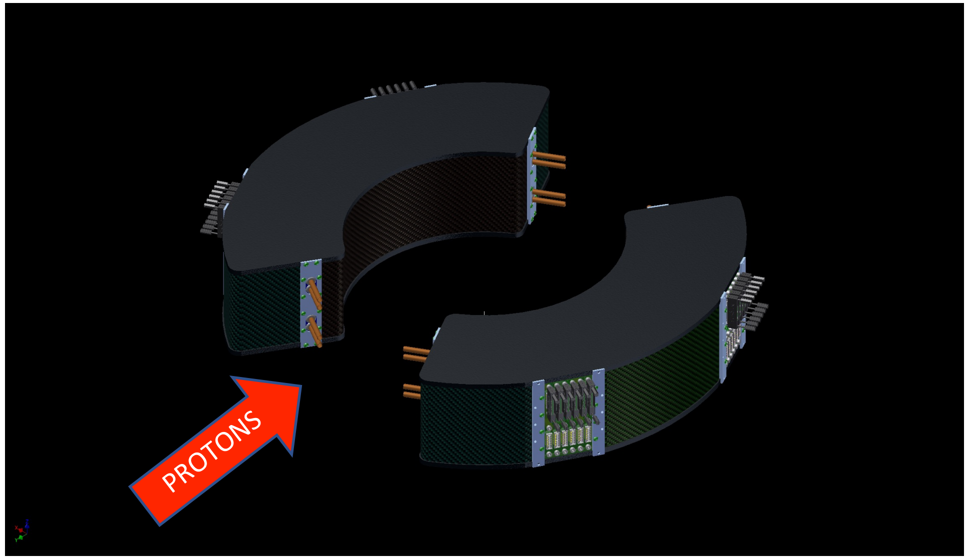
The TPPT Project: Meet the TPPT Scanner



The TPPT Project: Scanner Design

- Design Goal:
  - Detect positron emitting species (PES) activated by beam
    - Short lived, no time for conventional PET scan
      - 15min compared to 30min – 1hr acquisitions
    - Give feedback on where protons are interacting → range verification
    - Bonus: no added dose to patients since using beam activations
- Design Constraints:
  - High sensitivity → “Do more, with less”
    - Shorter acquisition, fewer events
    - ToF greatly helps in this!
  - Beam optimized geometry → gap for proton delivery, detector is “live” during irradiations
    - Veto for beam spill, high-rate environment
  - Needs to be compact to fit into existing infrastructure





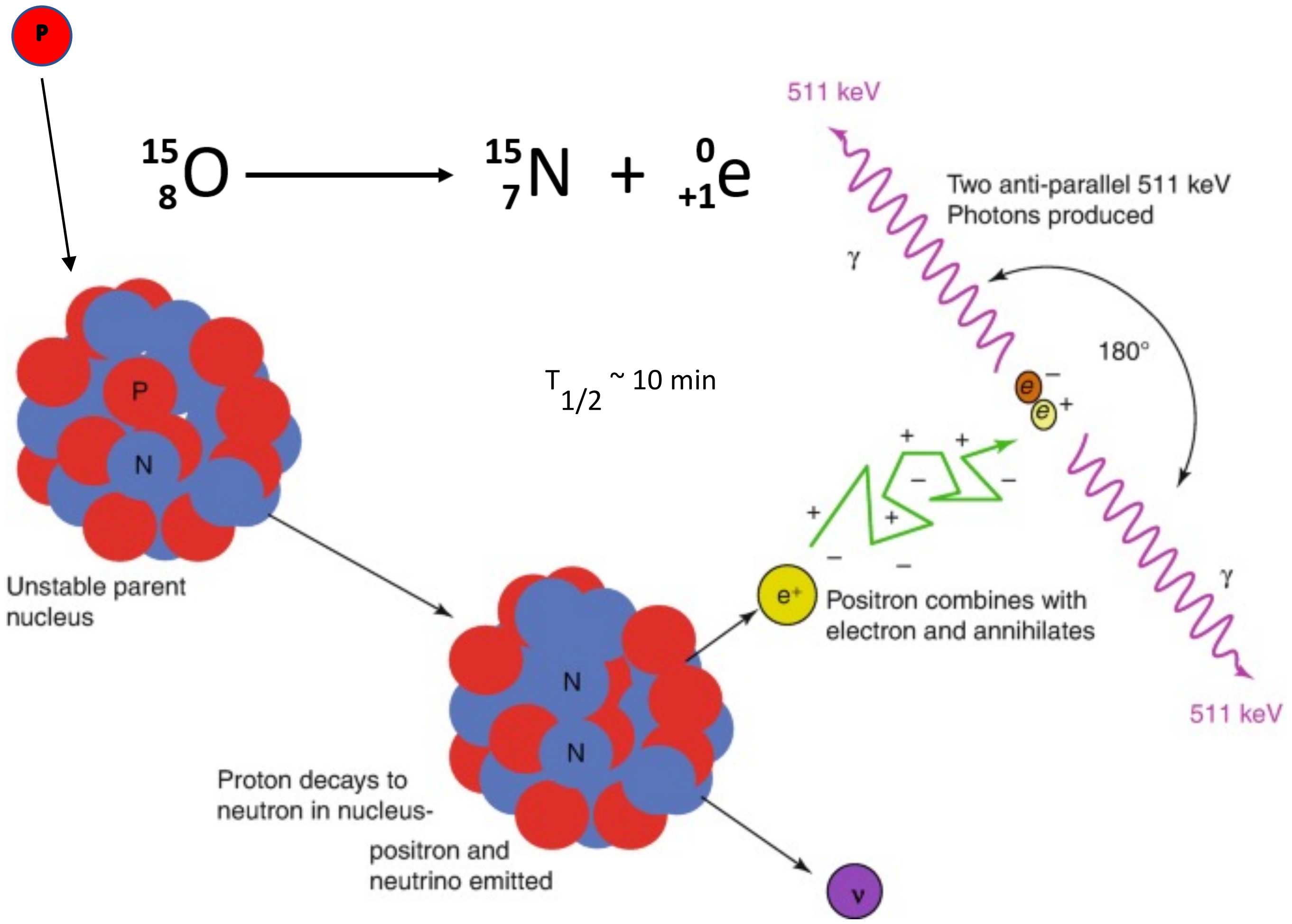
The TPPT Project: PES

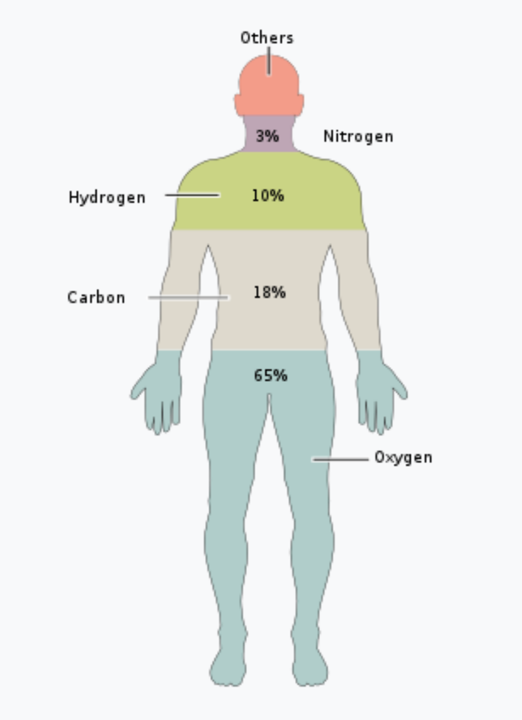
PES = positron emitting species

Proton beam

$$^{15}_{8}O \longrightarrow\ ^{15}_{7}N +\ ^{0}_{+1}e$$

$T_{1/2}$ ~ 10 min





Element	Symbol	percent mass	percent atoms
Oxygen	O	65.0	24.0
Carbon	C	18.5	12.0
Hydrogen	H	10	62.0
Nitrogen	N	3.2	1.1
Calcium	Ca	1.5	0.22
Phosphorus	P	1.0	0.22
Potassium	K	0.4	0.03
Sulfur	S	0.3	0.038
Sodium	Na	0.2	0.037
Chlorine	Cl	0.2	0.024
Magnesium	Mg	0.1	0.015
All others		< 0.1	< 0.3

The main elements that compose the human body molecules (including water) can be summarized as CHNOPS.

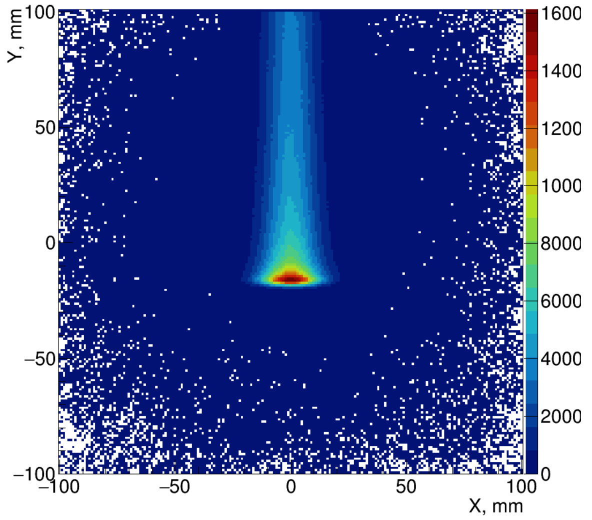
Studenski MT *et al*. Proton therapy dosimetry

Table 1 Relevant positron emitter reactions in tissue from proton therapy

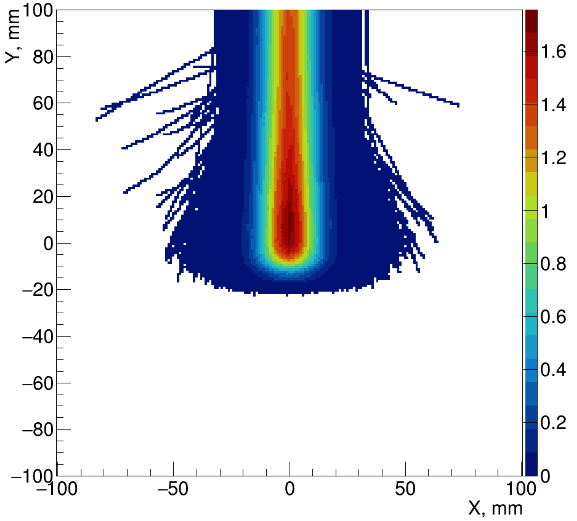
Reaction	Threshold energy (MeV)	Half life (min)	Positron energy (MeV)
$^{16}O(p, pn)^{15}O$	16.79	2.037	1.72
$^{16}O(p, \alpha)^{13}N$	5.66	9.965	1.19
$^{14}N(p, pn)^{13}N$	11.44	9.965	1.19
$^{12}C(p, pn)^{11}C$	20.61	20.390	0.96
$^{14}N(p, \alpha)^{11}C$	3.22	20.390	0.96
$^{16}O(p, \alpha pn)^{11}C$	59.64	20.390	0.96

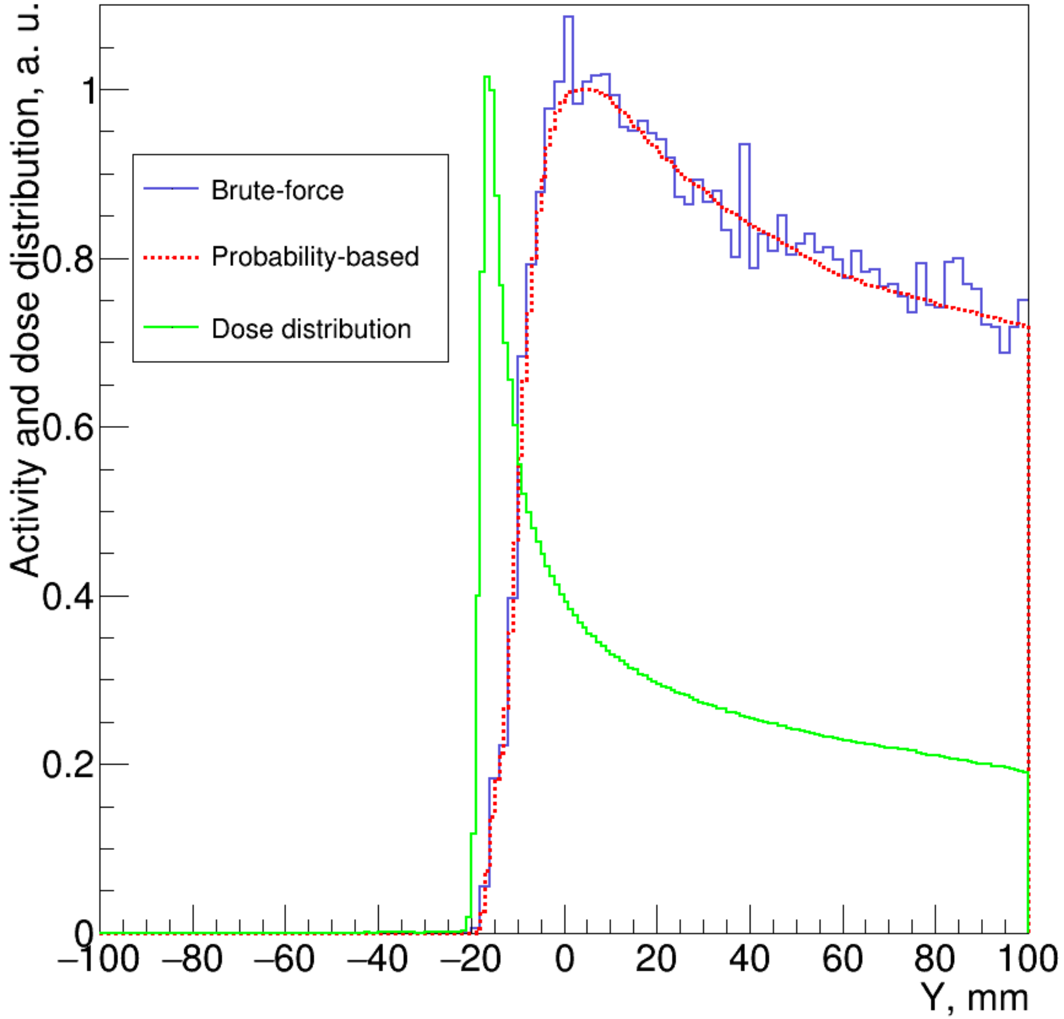
The TPPT Project: Proton Range Verification

2D projection along beam of dose (Bragg Peak) due to **protons**



2D projection along beam of **PES** activity

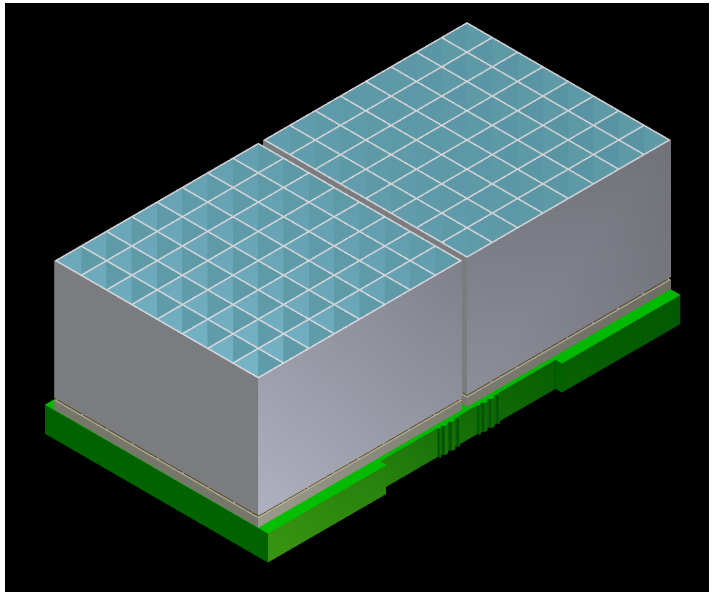




PET imaging of PES relates to proton dose distribution to give feedback on proton range!

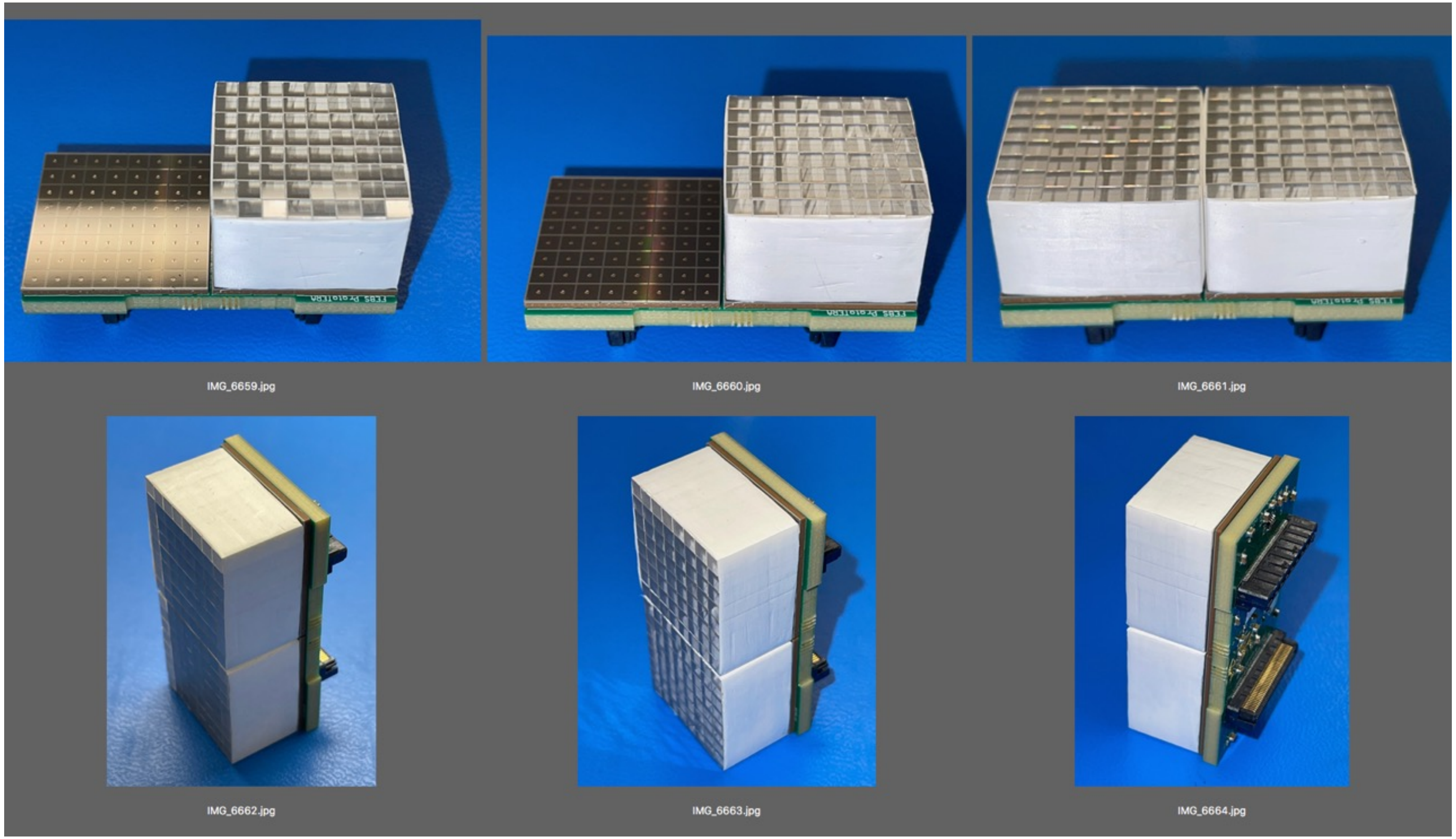
The TPPT Project: The Basic Building Blocks

3 x 3 x 15 mm^3 LYSO* crystals



1:1 coupling to Hamamtsu SiPMs
Two 8 x 8 arrays

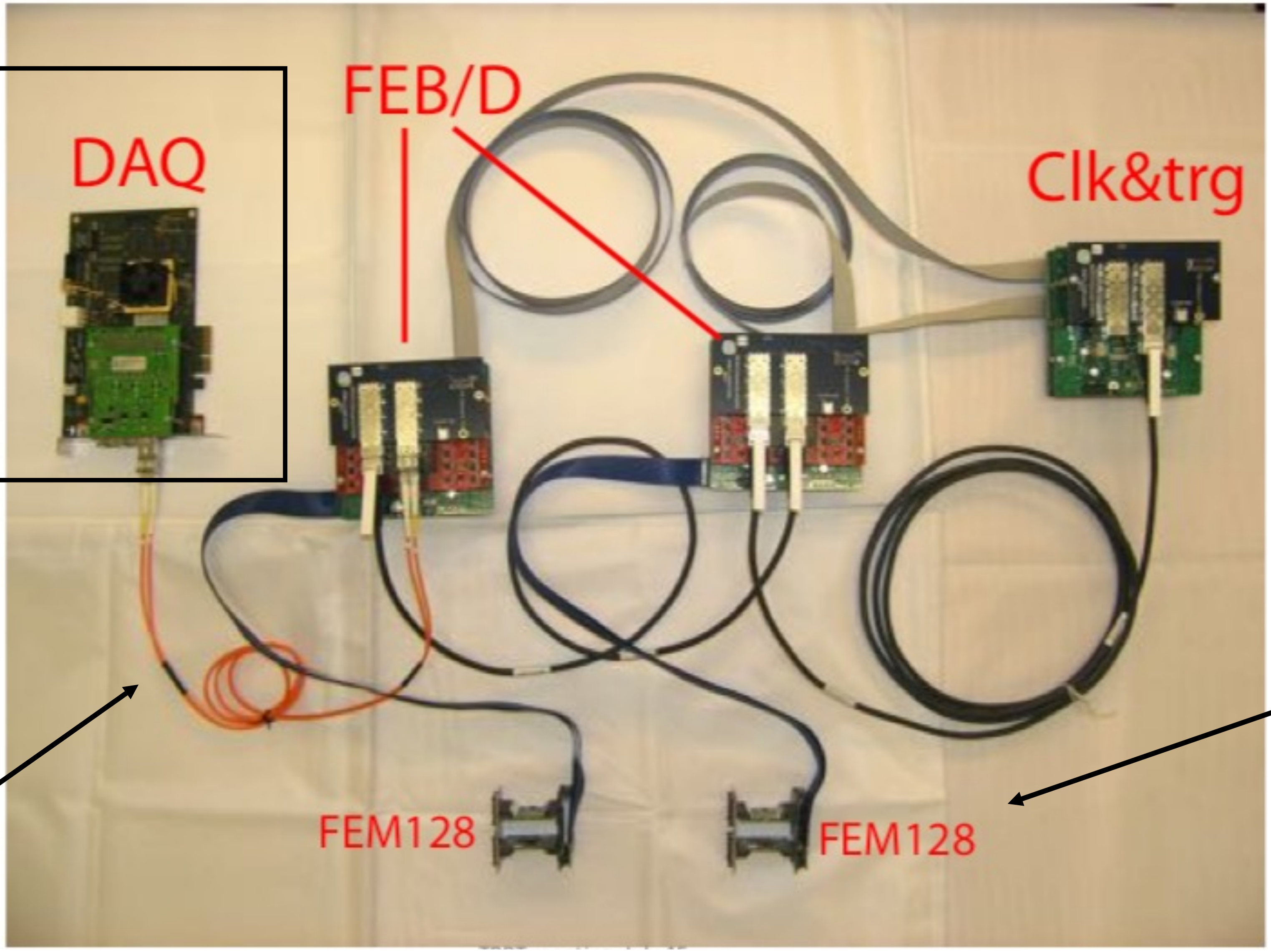
This is a PET optimized MPPC Array



*LYSO (Lu $^{1.8}$Y ^{2}SiO^{5}Ce) is a Cerium doped Lutetium-based scintillation crystal

The TPPT Project: PETsys Electronics

Data Acquisition (DAQ) PC



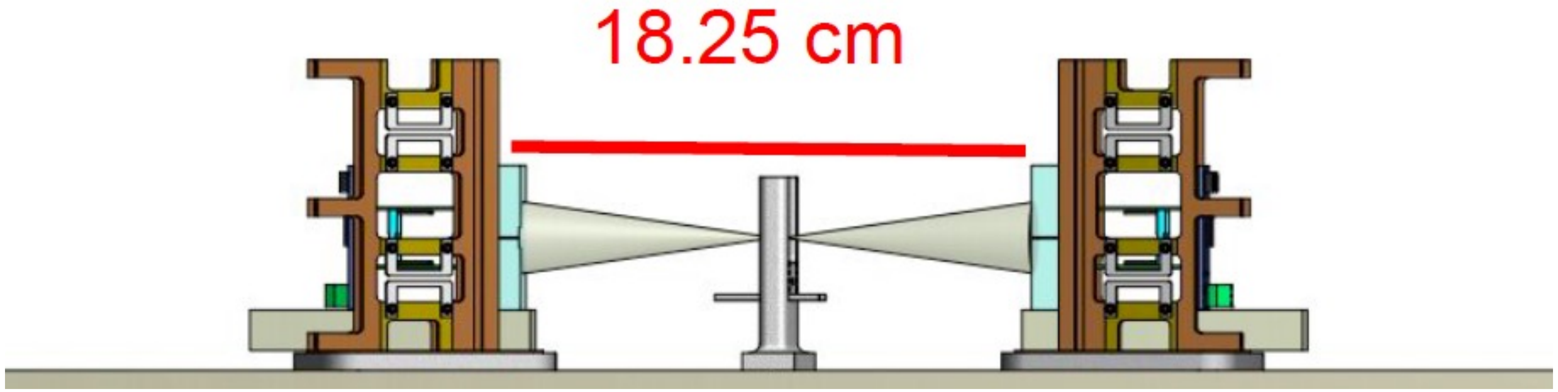
Fiber optic communication between system and DAQ PC

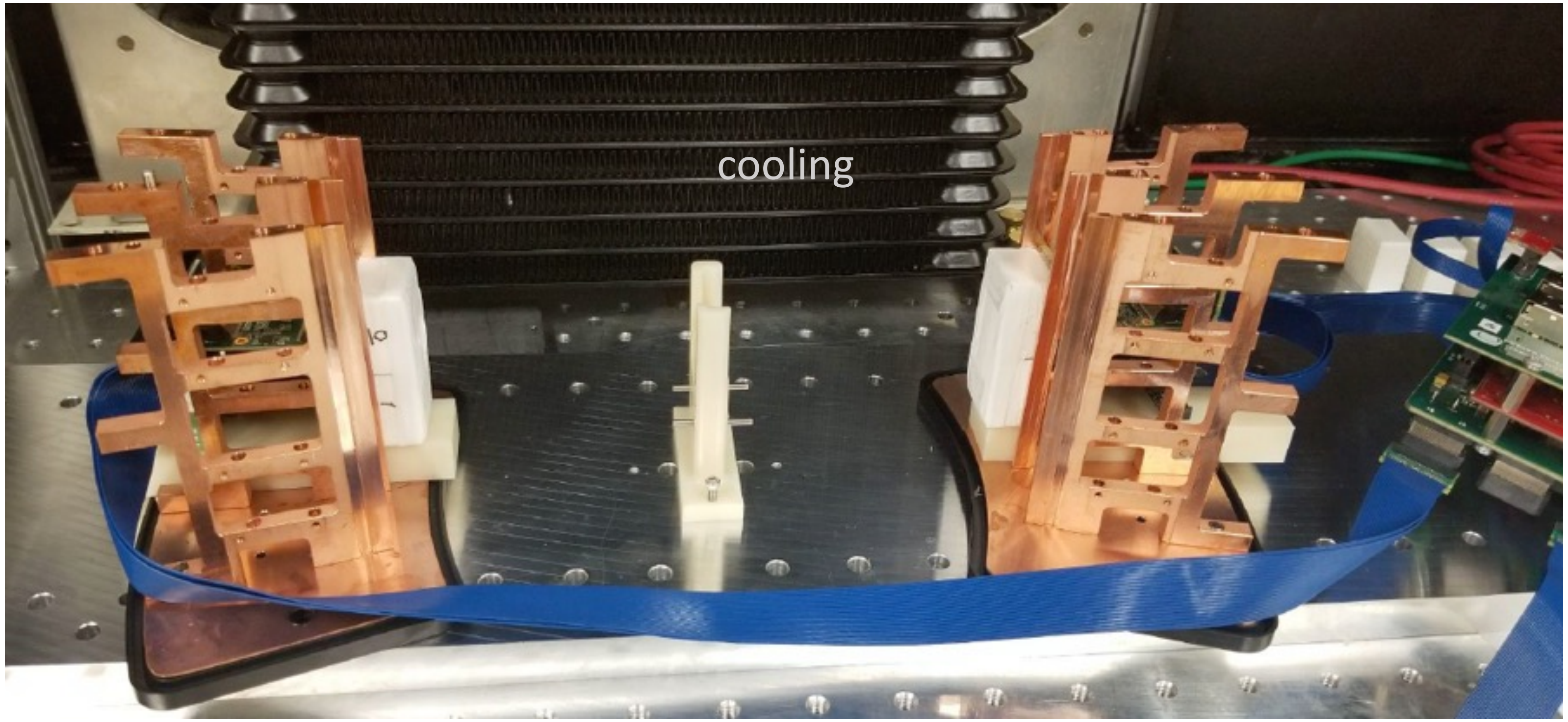
x 48 modules for full scanner

6144 total channels

The TPPT Project: Mini-PET

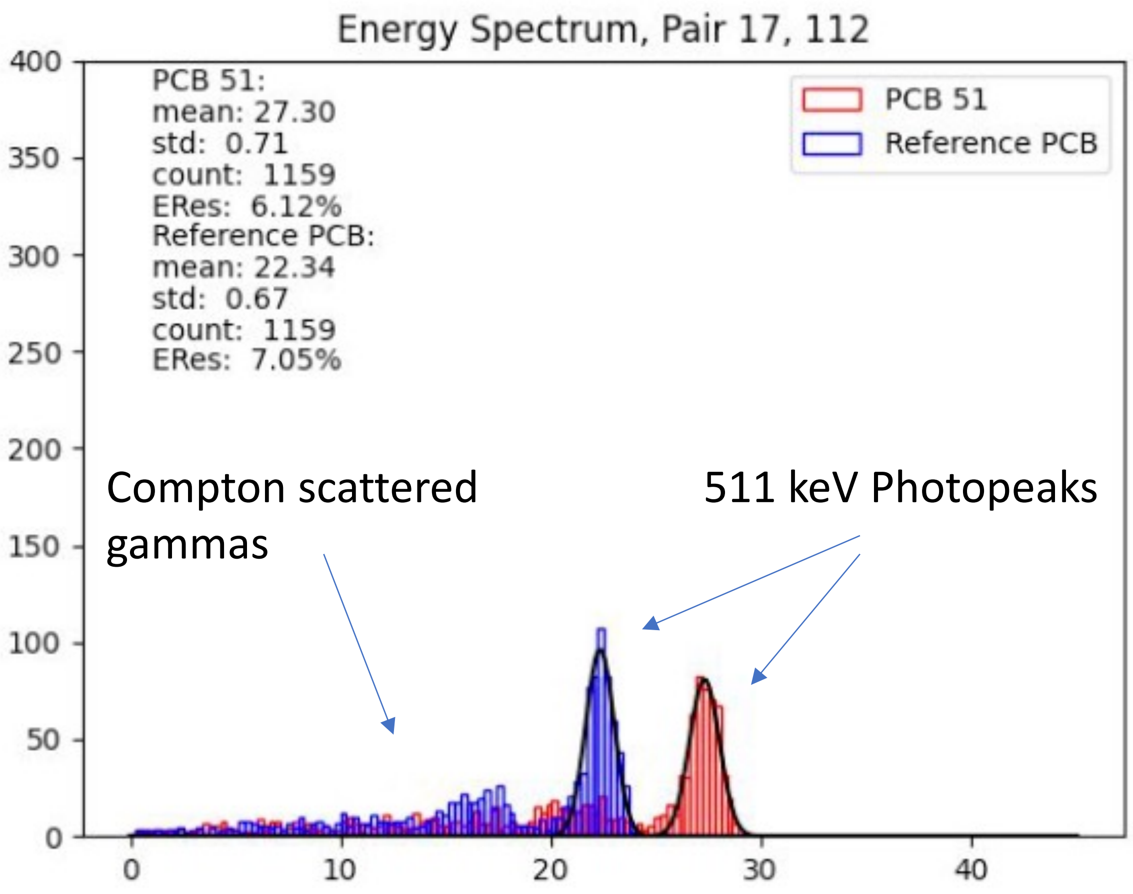
- Characterization and evaluation of all modules after gluing
  - Quality assurance
- Each module placed opposite a reference module
- Na-22 source for coincident gammas
- Extraction of early performance parameters (energy resolution and coincidence time resolution)
  - Next slides



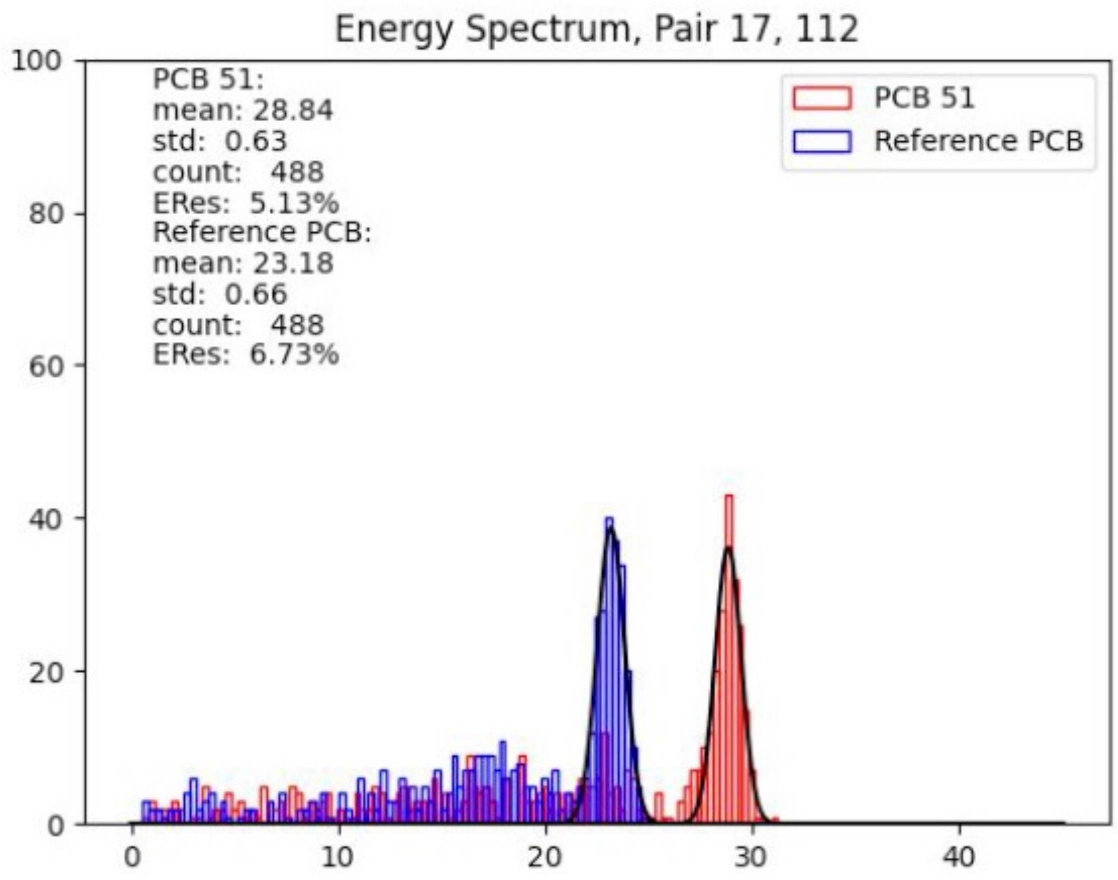


The TPPT Project: Mini-PET Evaluation

Na-22

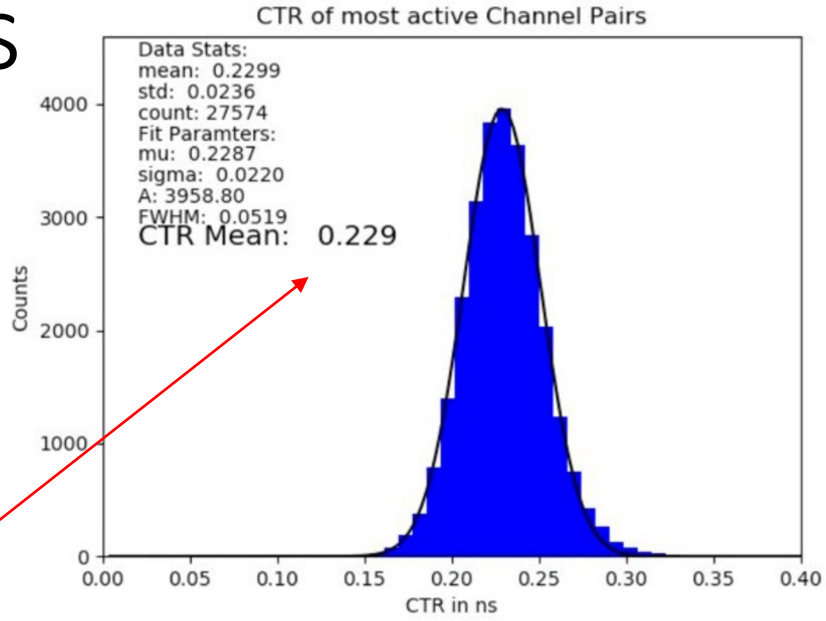


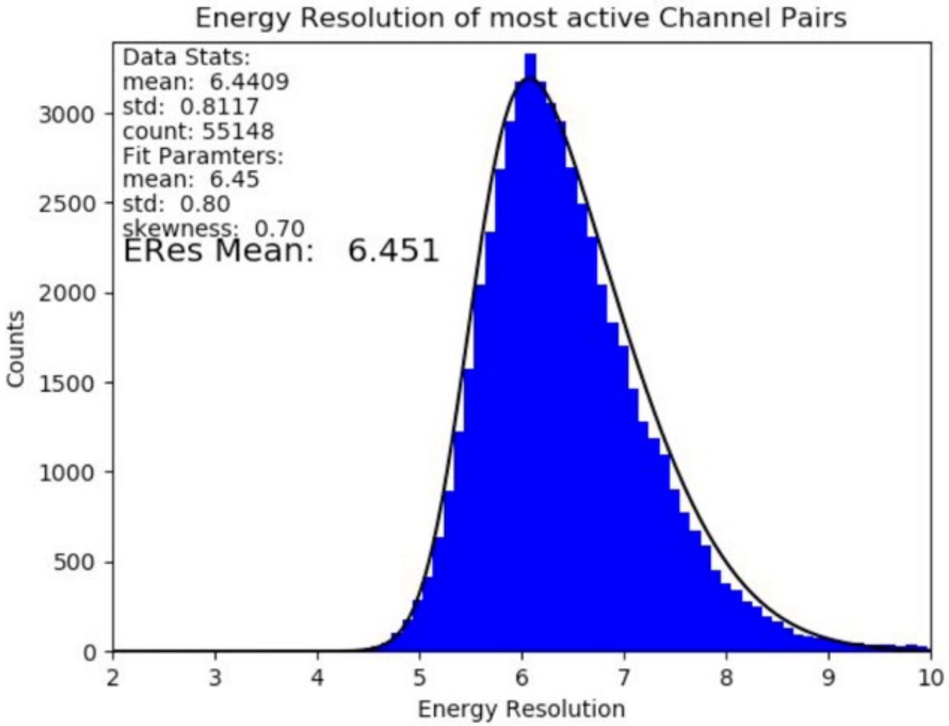
Ge-68



The TPPT Project : Mini-PET Results

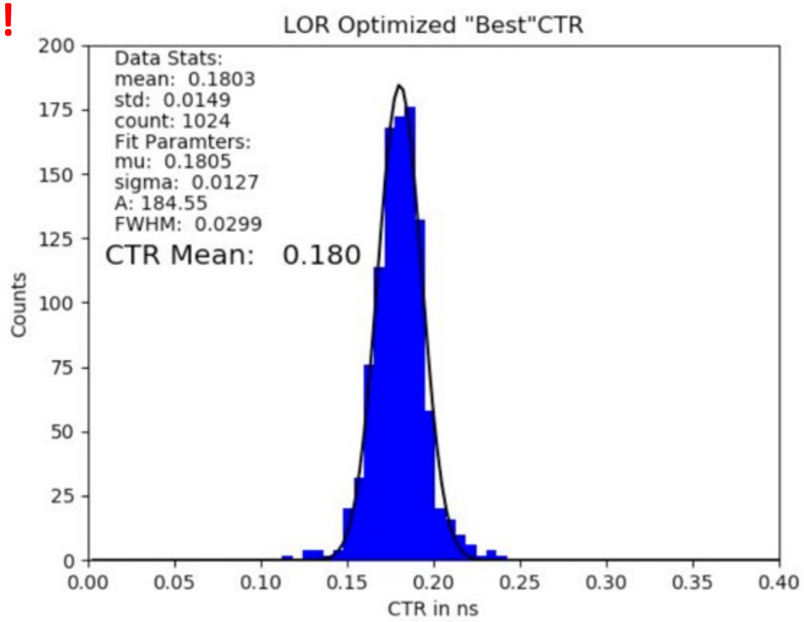
- Select photopeak events from previous energy spectra
  - Estimate energy resolution across pairs of channels
  - Coincidence time resolution (CTR) calculated from time difference between photopeak gammas





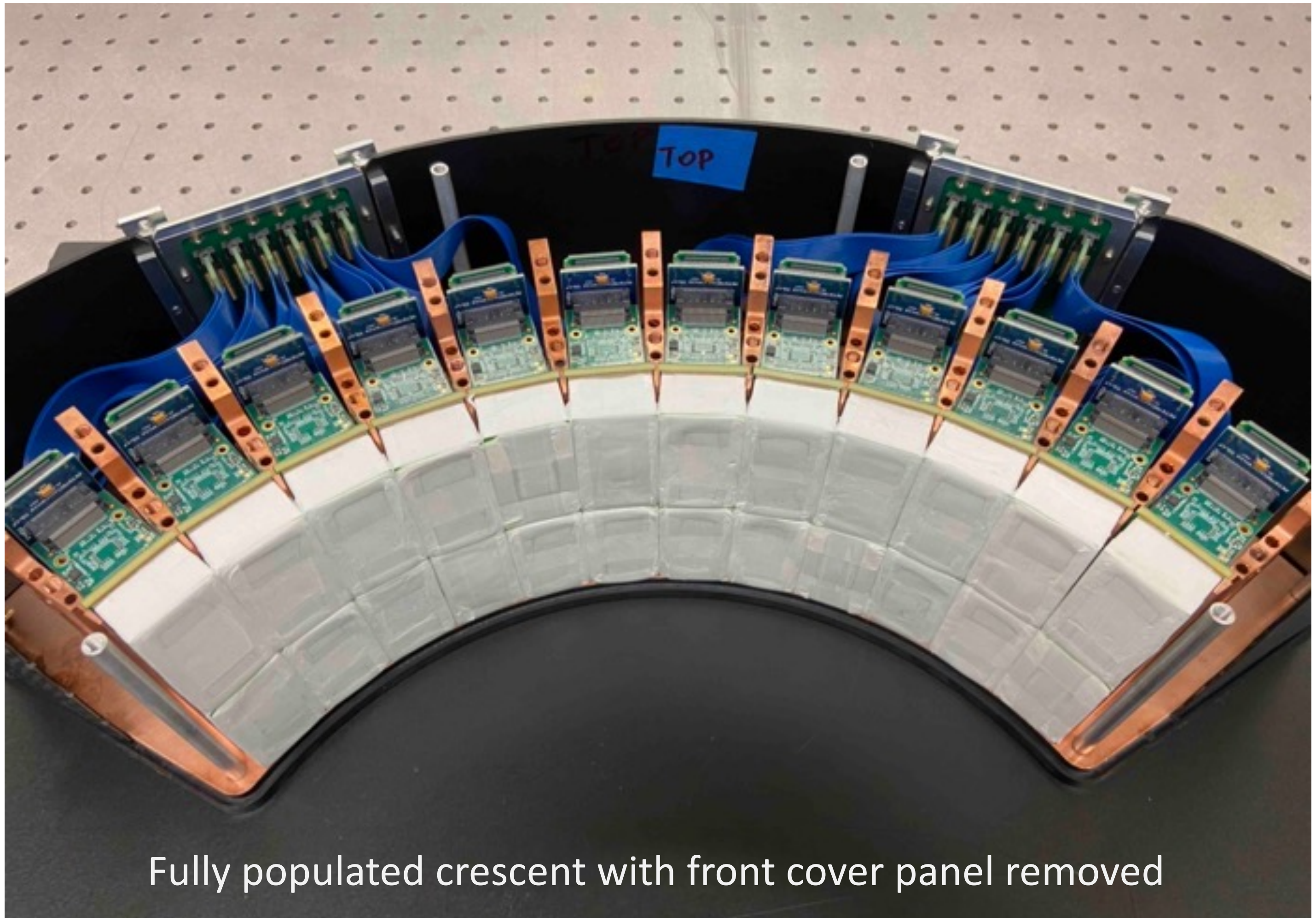
230 ps ToF resolution!

Even better when looking at most optimal lines of response…

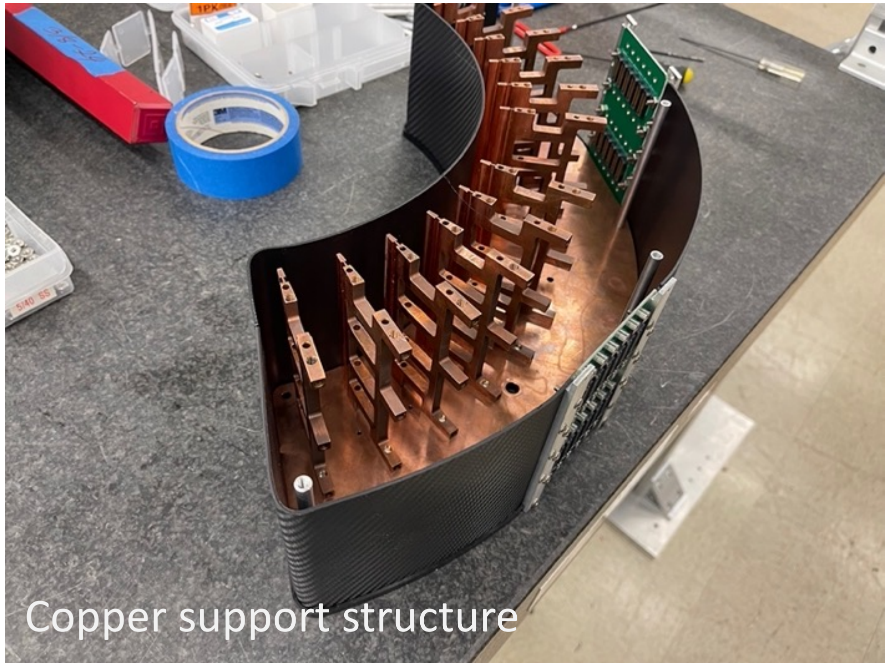


The TPPT Project : Assembly

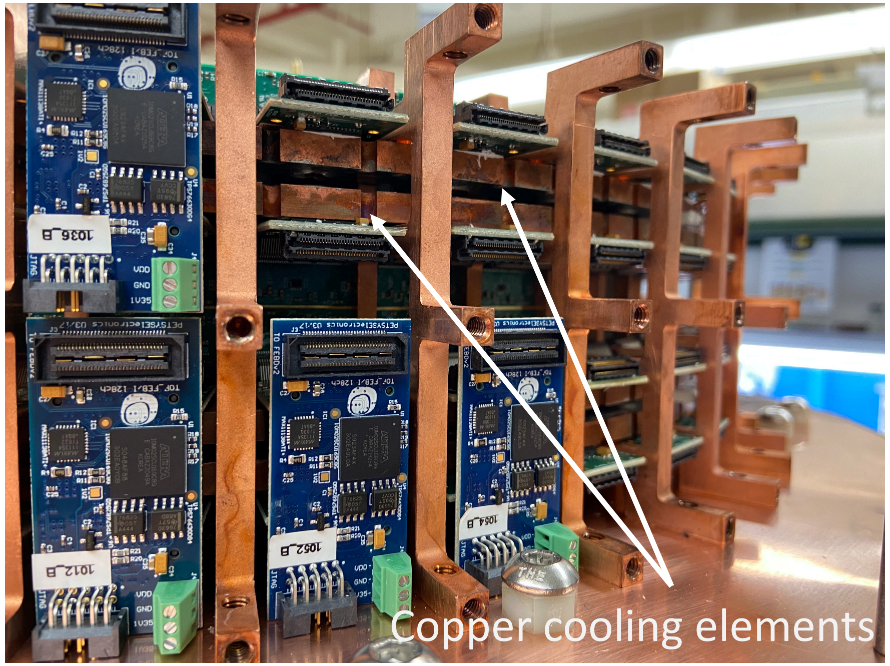
- The scanner at various stages of construction



Fully populated crescent with front cover panel removed

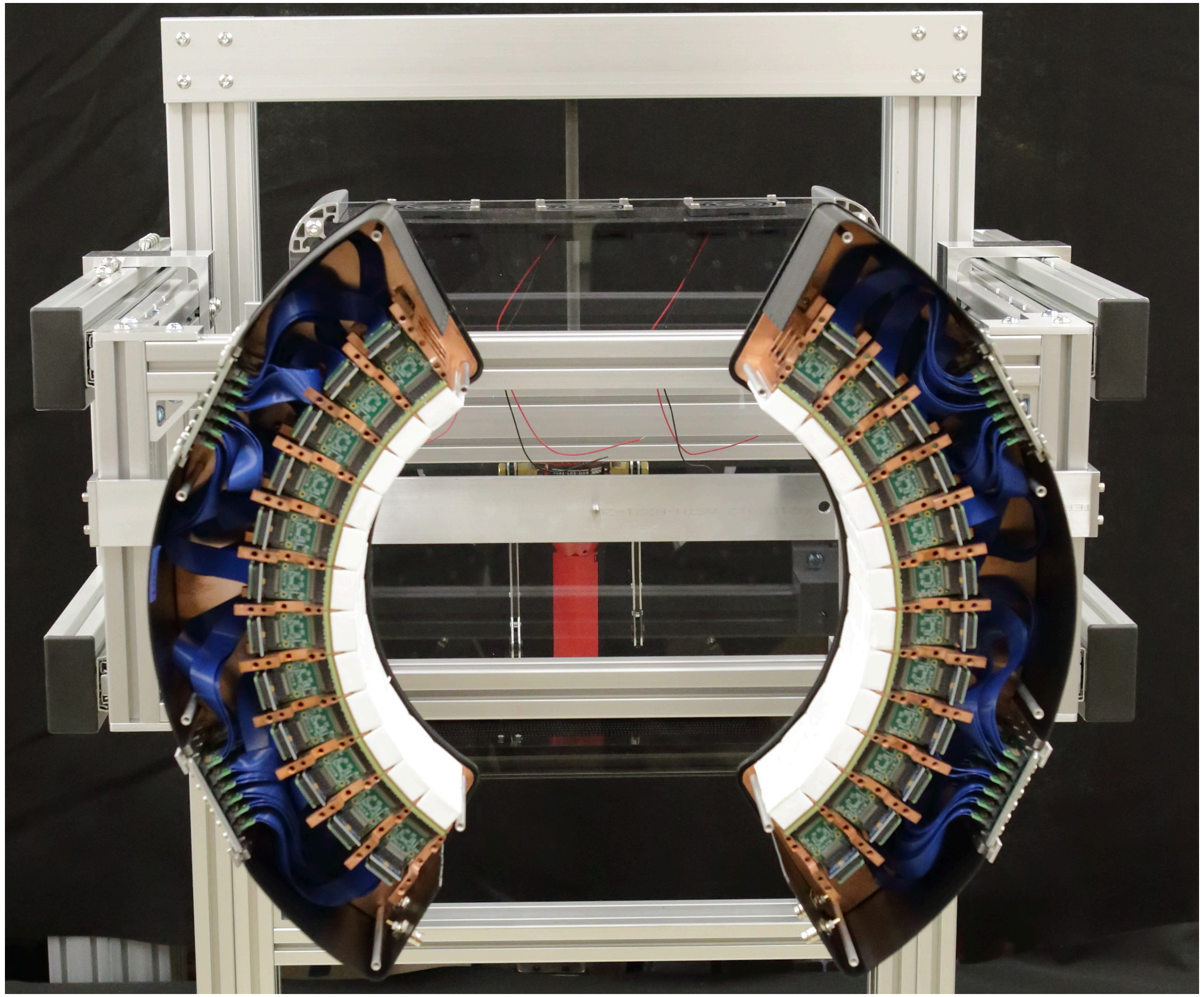


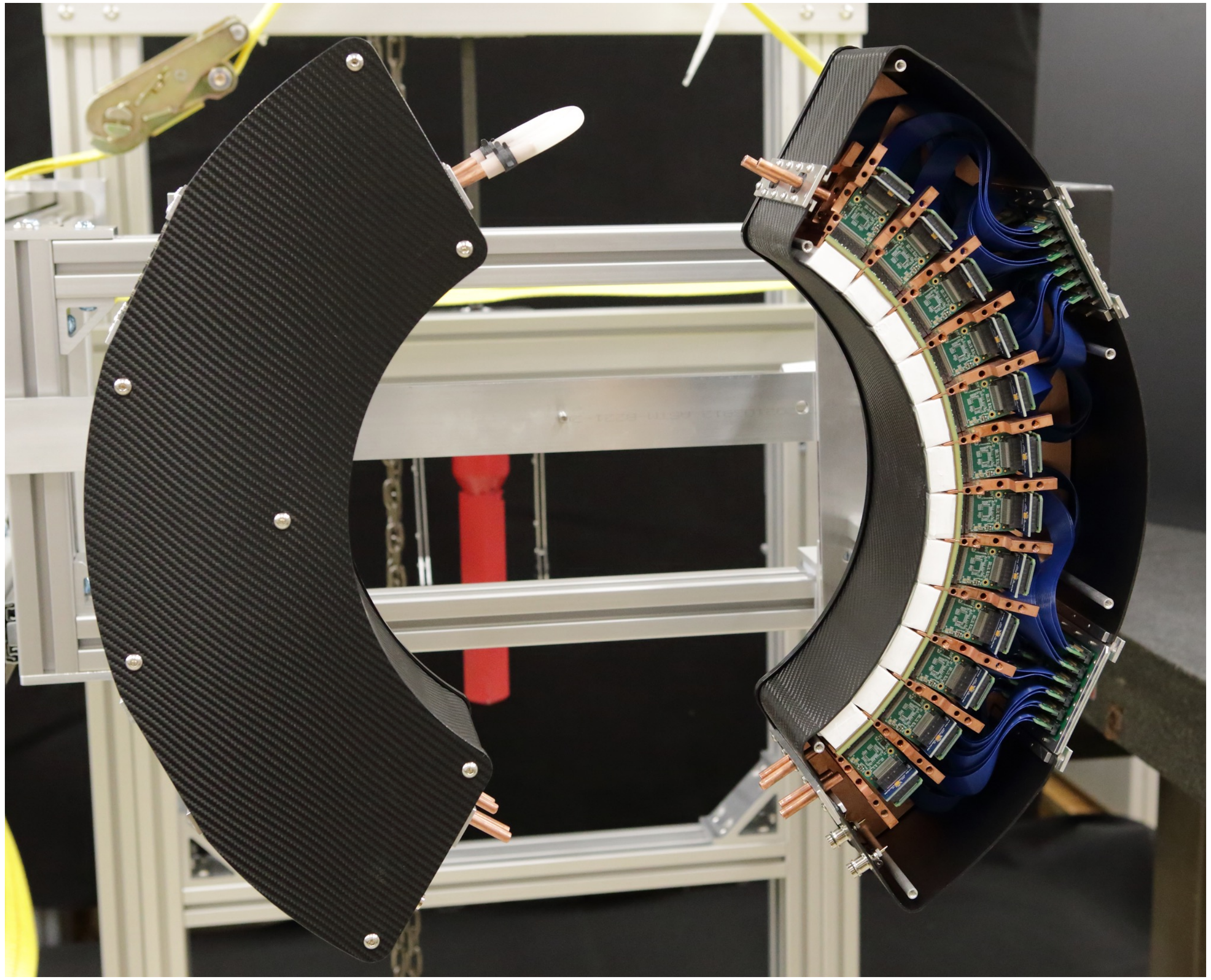
Copper support structure



Copper cooling elements

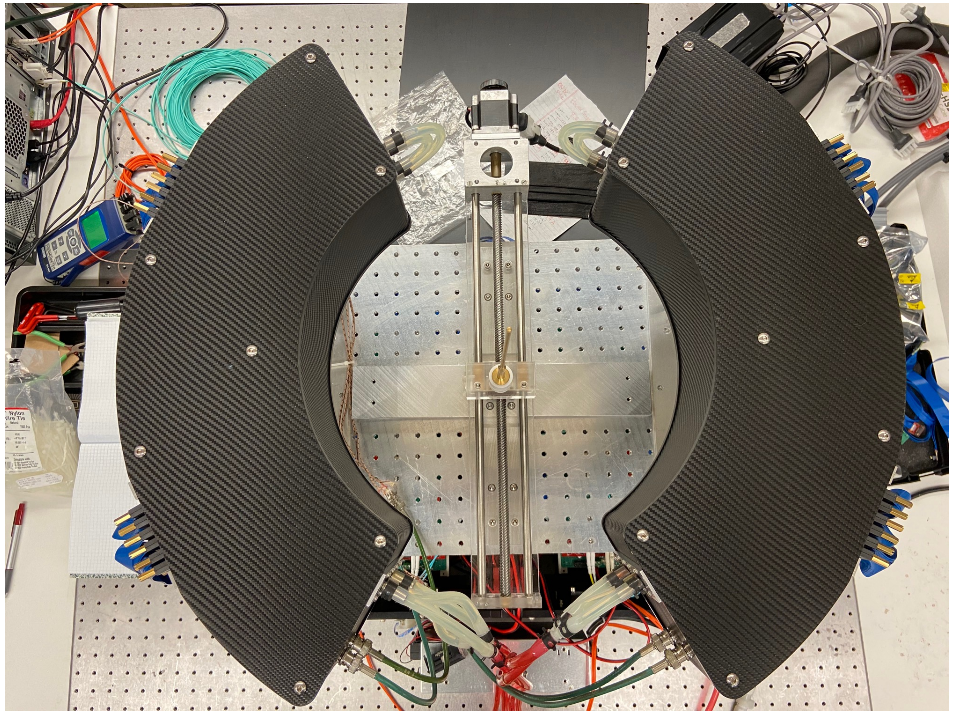
The TPPT Project : Full Scanner on Gantry

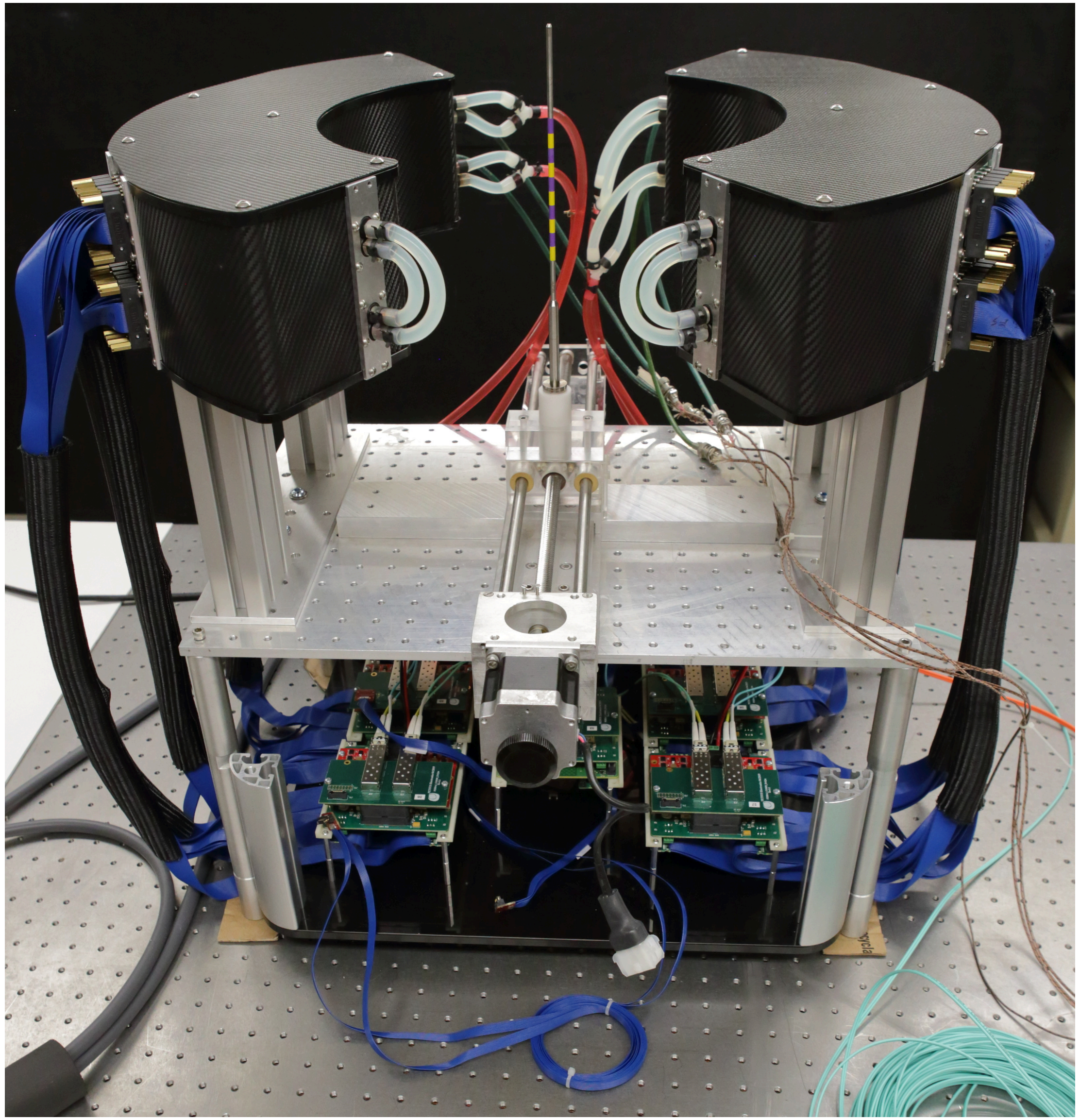




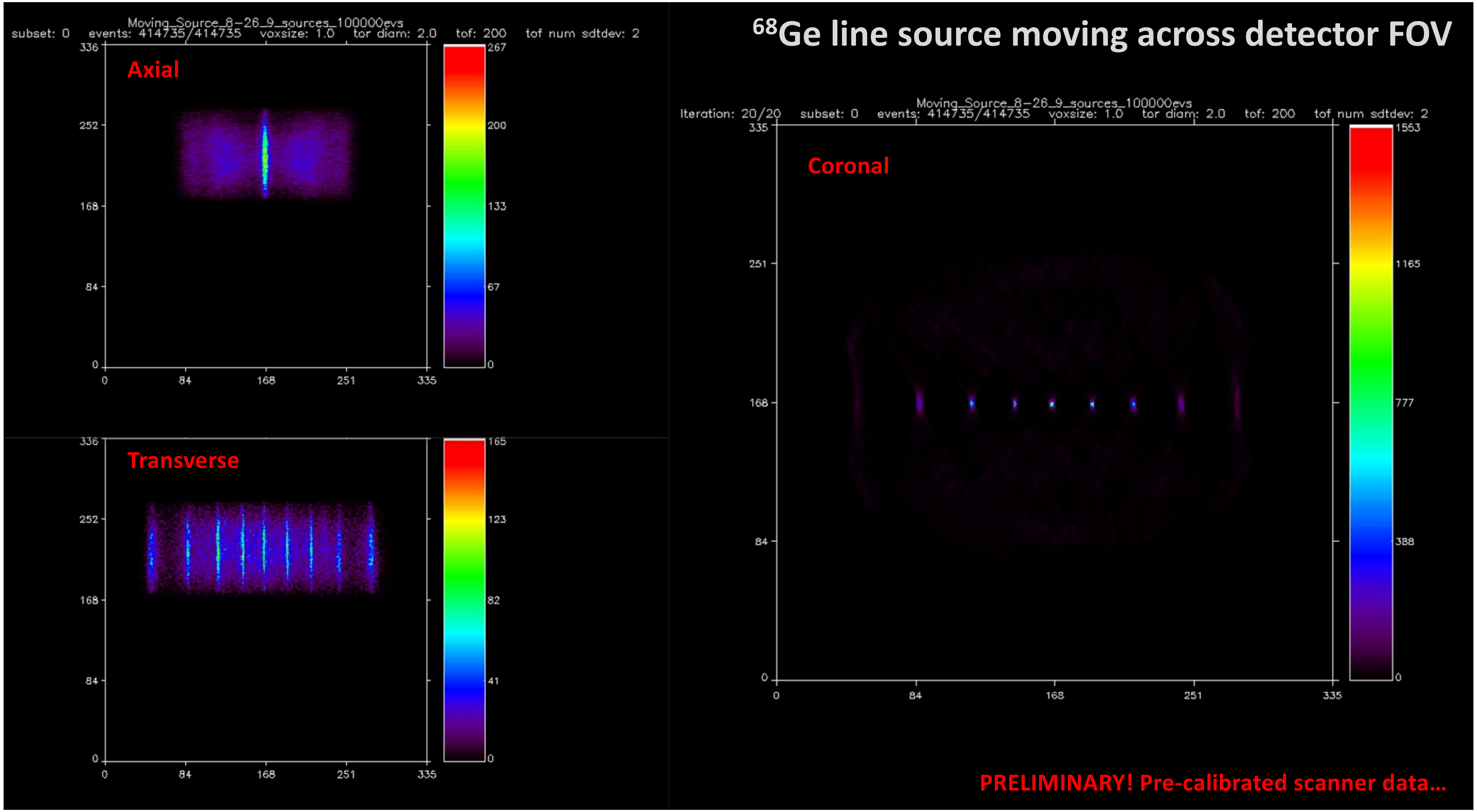
The TPPT Project : Full Scanner on Test Bench

- Various calibrations performed (or in the process):
  - SiPM OV and ASIC threshold scan
  - Normalization + Time alignment
    - Requires moving line source (^{68}Ge)
  - Cooling studies
  - DAQ stress testing
  - Image reconstruction debugging



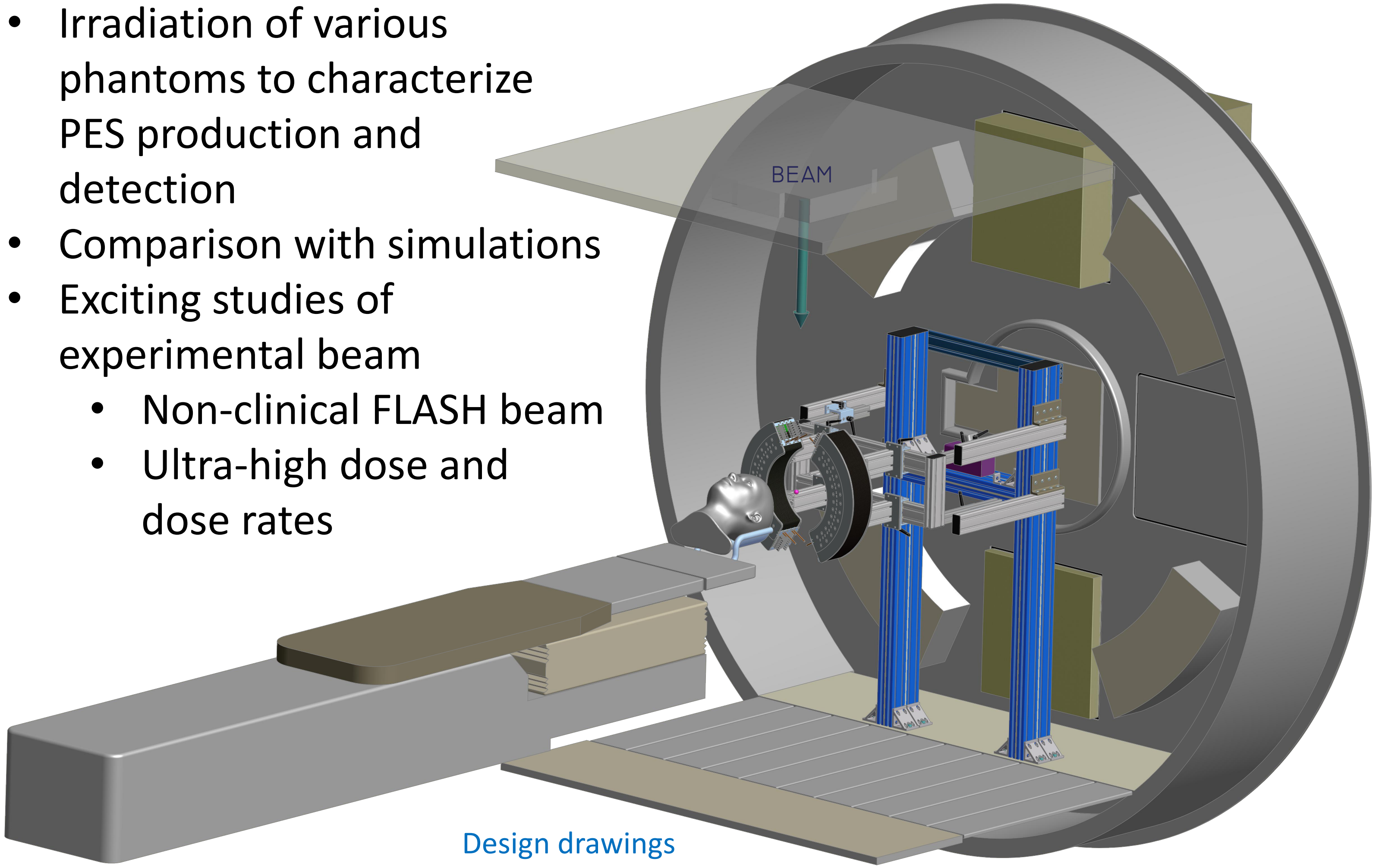


The TPPT Project : First Reconstructed Images!

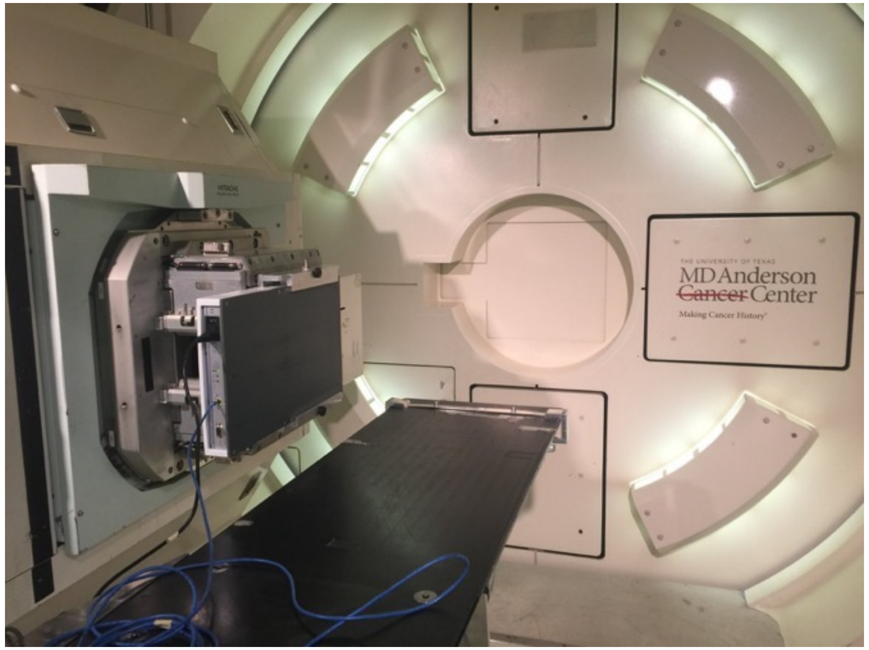


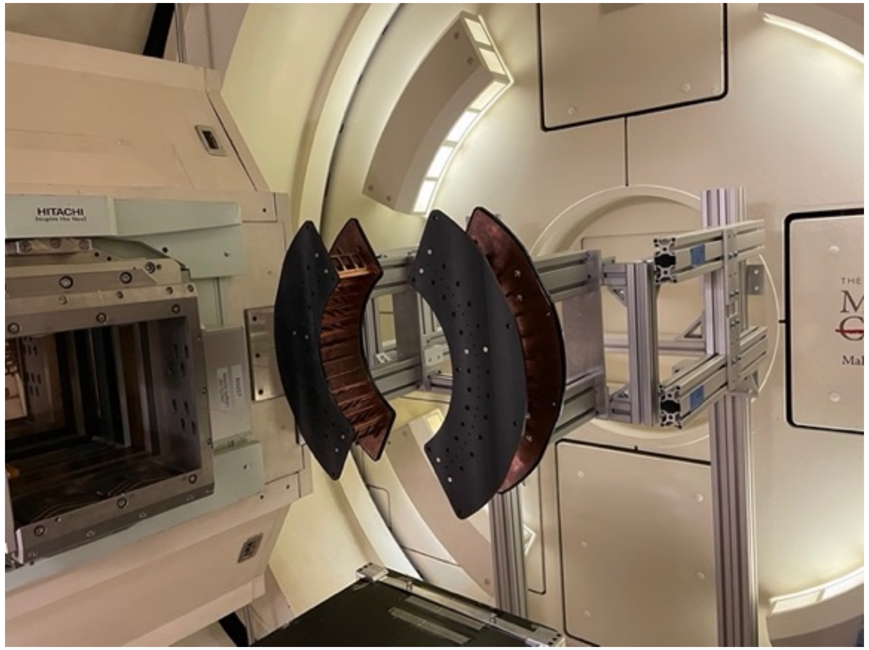
The TPPT Project: The Near Future

- Live in-beam tests at MDACC
- Irradiation of various phantoms to characterize PES production and detection
- Comparison with simulations
- Exciting studies of experimental beam
  - Non-clinical FLASH beam
  - Ultra-high dose and dose rates



Design drawings
by Marek Proga

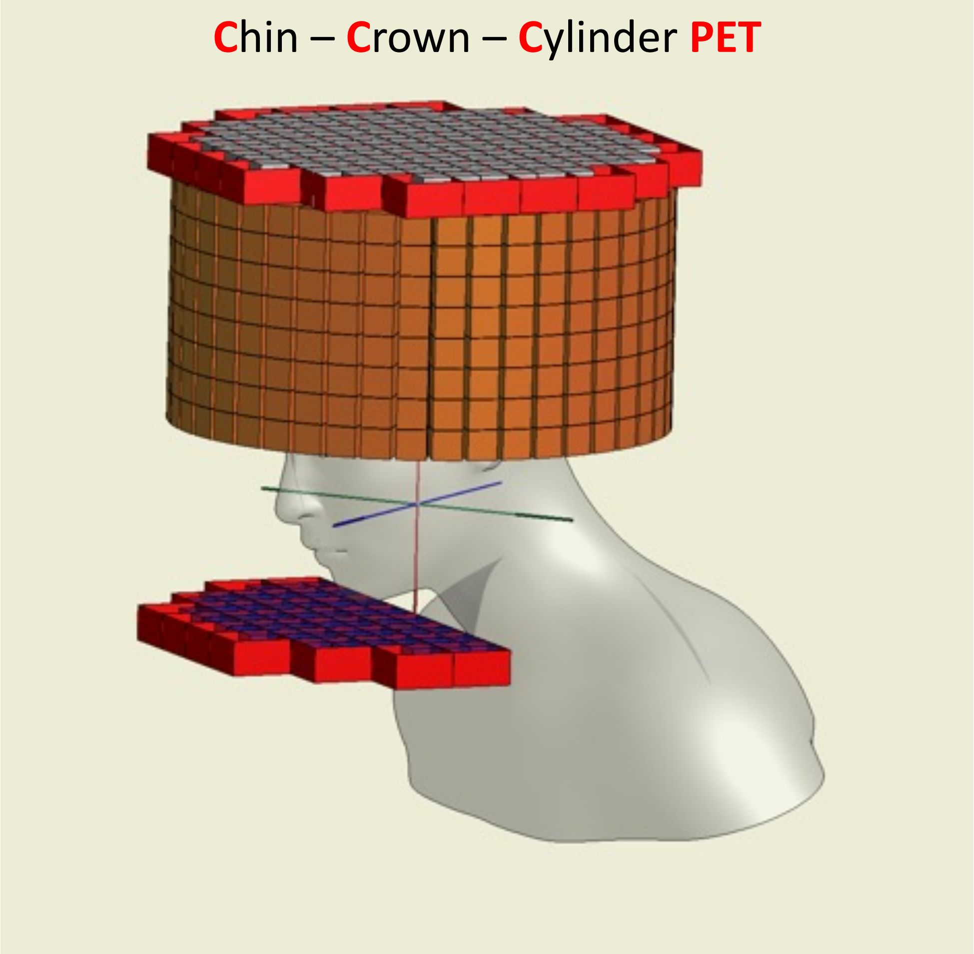




Future Ideas

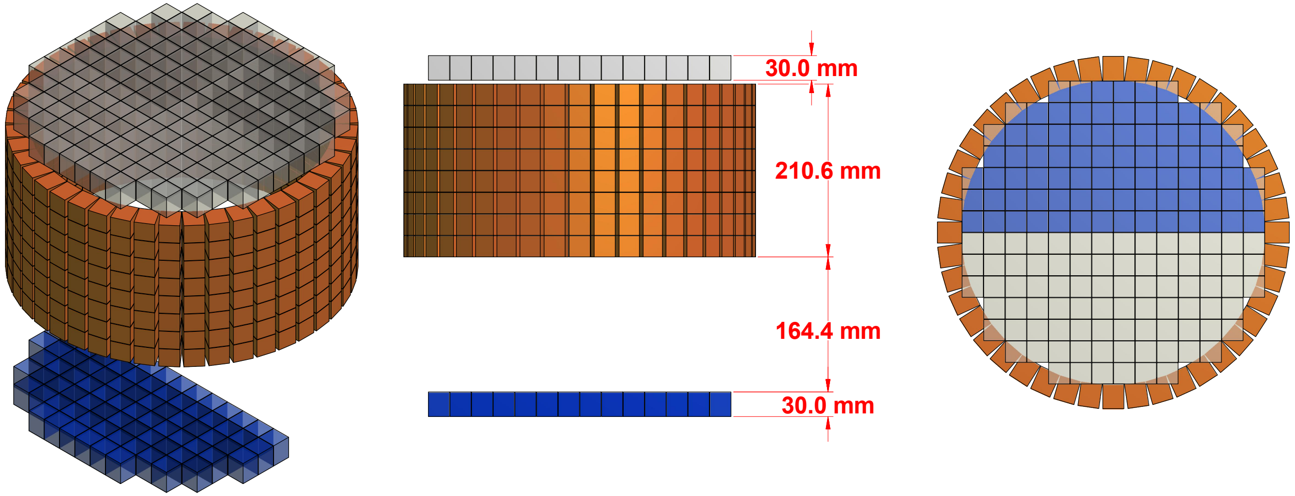
Novel PET ideas only
achievable thanks to SiPMs

Future Ideas: C^3-PET



Design and modeling of a high resolution and high sensitivity PET brain scanner with double-ended readout

Christopher Layden[1,*], Kyle Klein[1], William Matava[1], Akhil Sadam[1], Firas Abouzahr[1], Marek Proga[1], Stanislaw Majewski[2], Johan Nuyts[3] and Karol Lang[1]



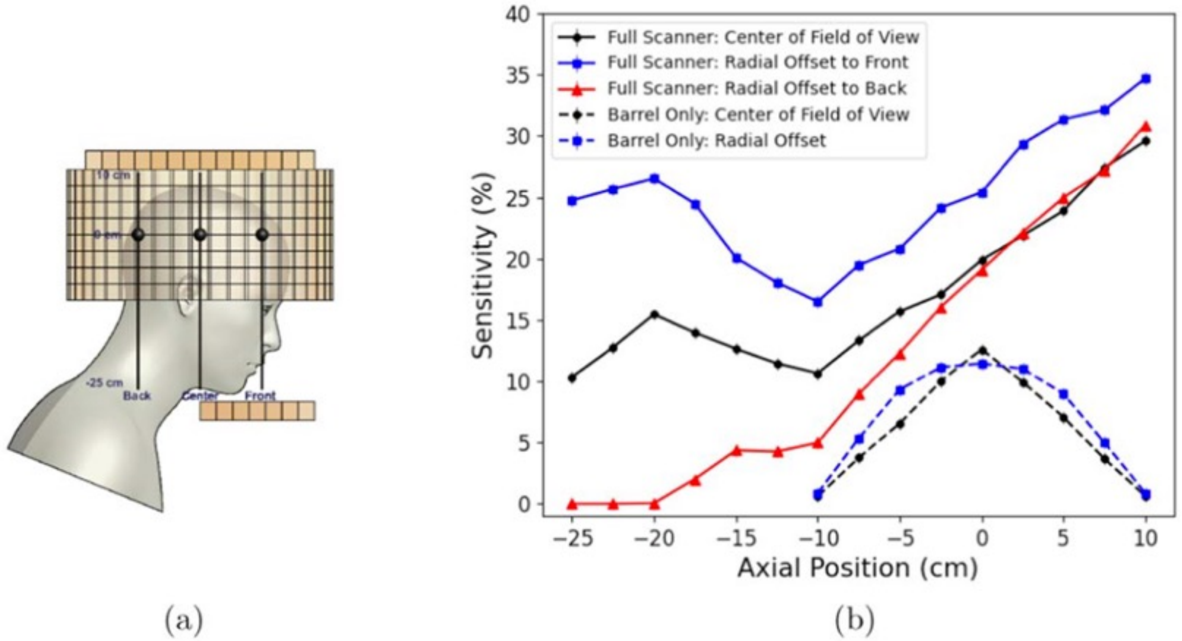
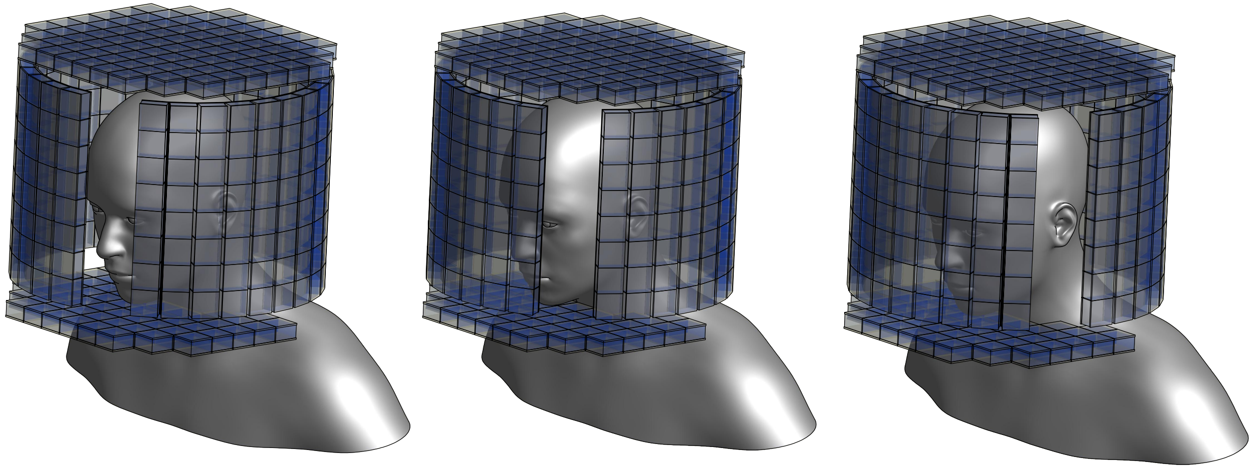


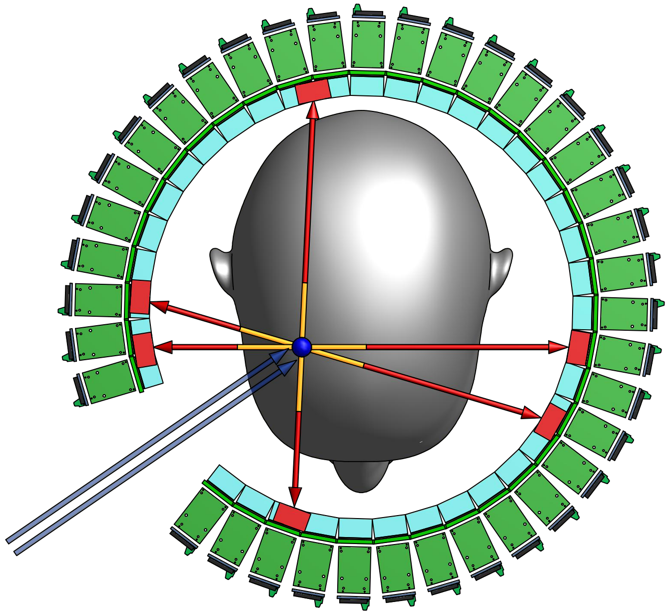
Figure 3. (a) Positions of line sources used for sensitivity predictions. (b) Absolute sensitivities for point sources placed along the line sources, for both the full scanner and barrel module alone, at the center of the radial field of view and at 10 cm radial offsets.

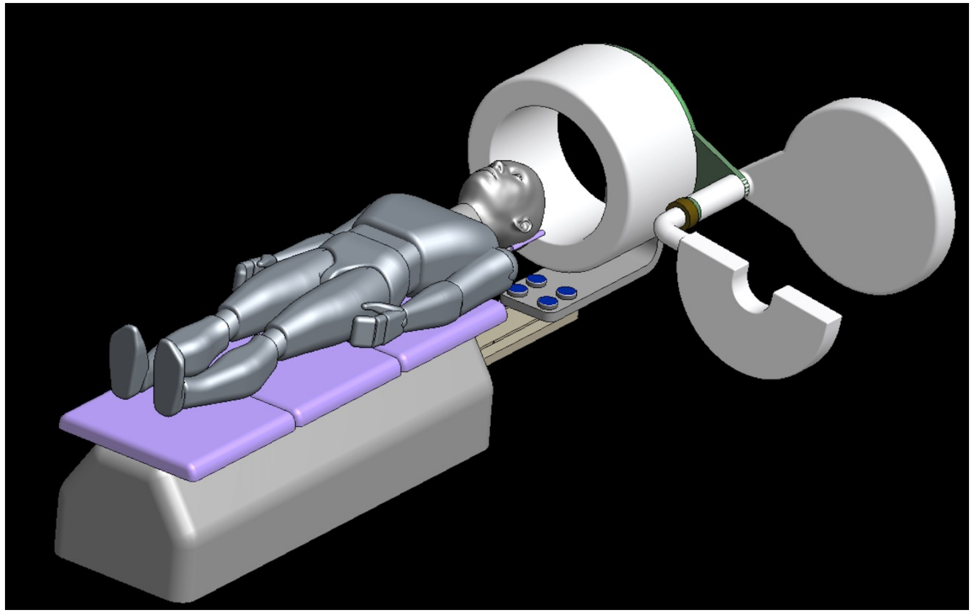
Future Ideas: C^3-PET for Proton Therapy

PET-Image-driven therapy?
PT and radiopharmaceuticals?



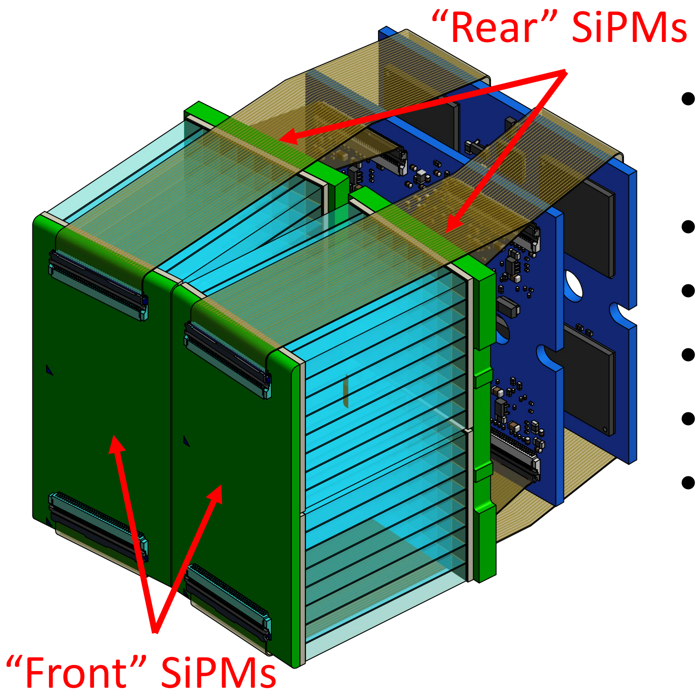
Gapped design for beam delivery



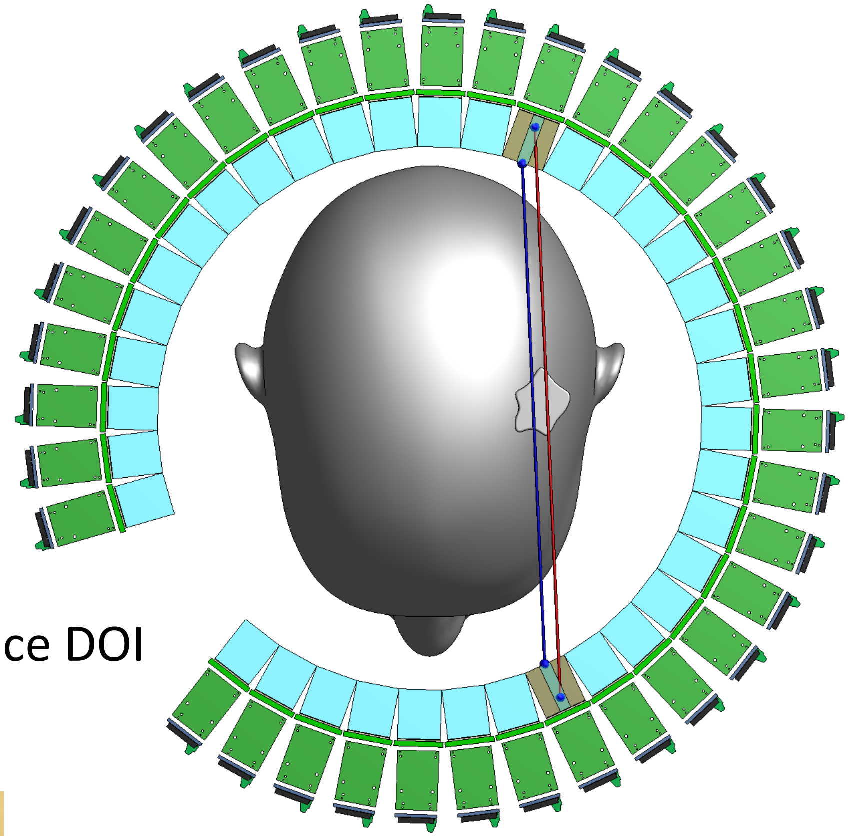


Possible due tothe compactness of SiPMs

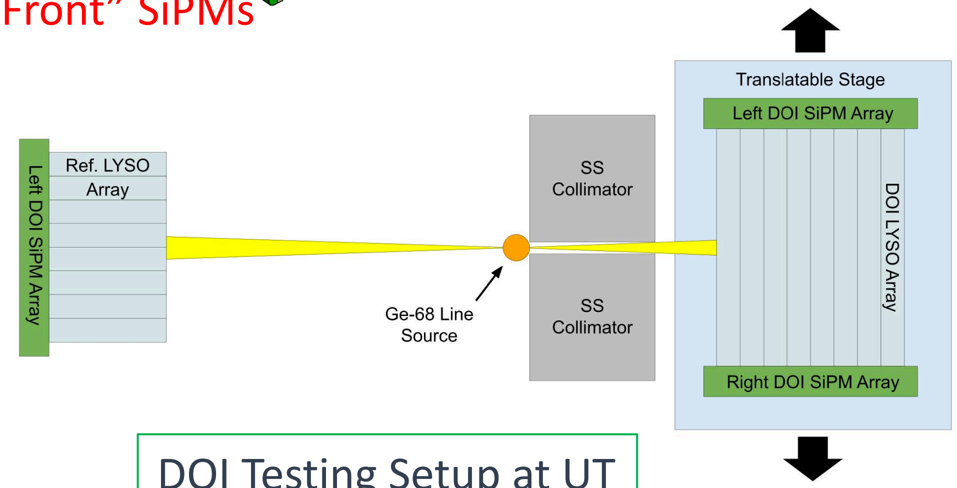
Future Ideas: DOI PET



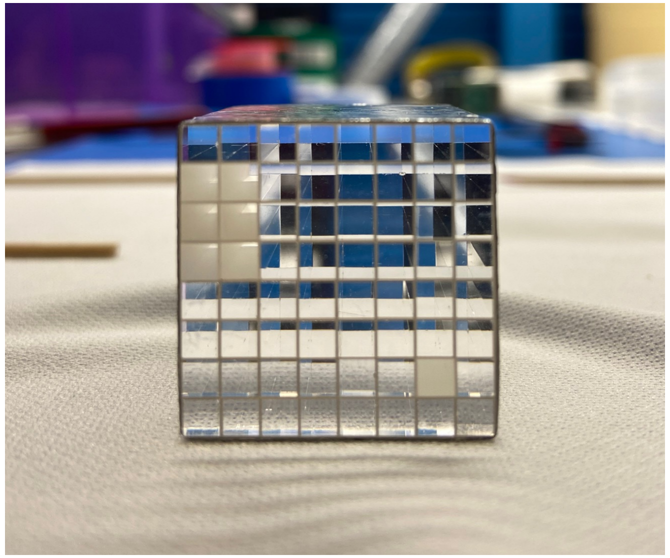
- Goal: Obtaining depth-of-interaction (DOI) information from PET systems
- Sandwich crystals between SiPMs
- Use relative intensities to extract DOI
- Helps eliminate parallax error
- Potential to greatly improve image quality
- Studying optical properties that can enhance DOI

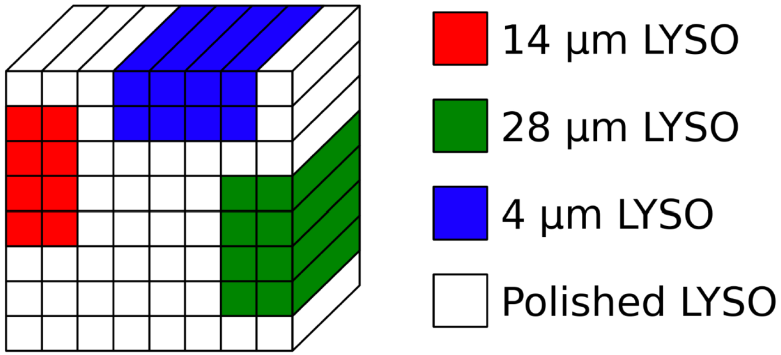


Example of parallax error resulting in shifted LOR



DOI Testing Setup at UT



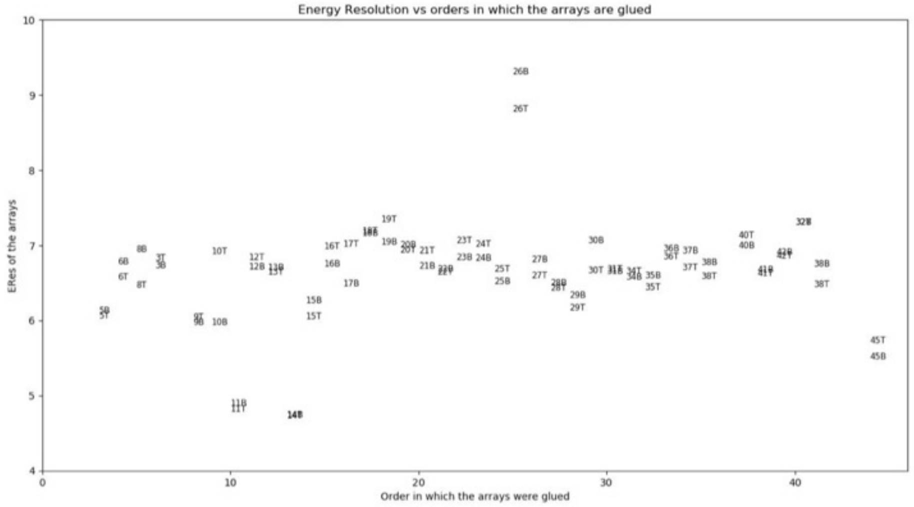


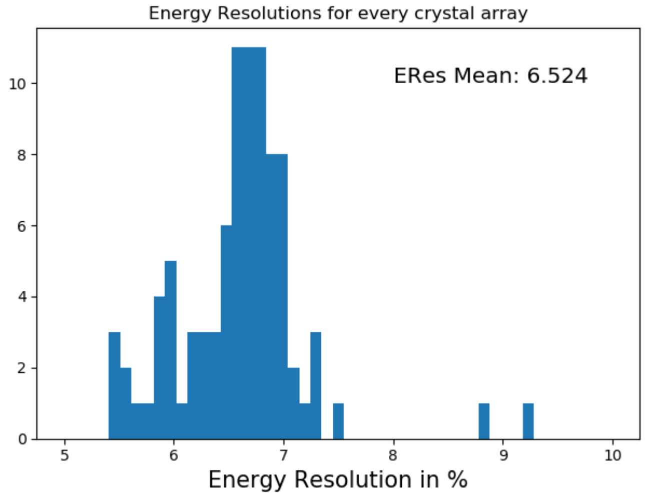
Summary and Conclusions

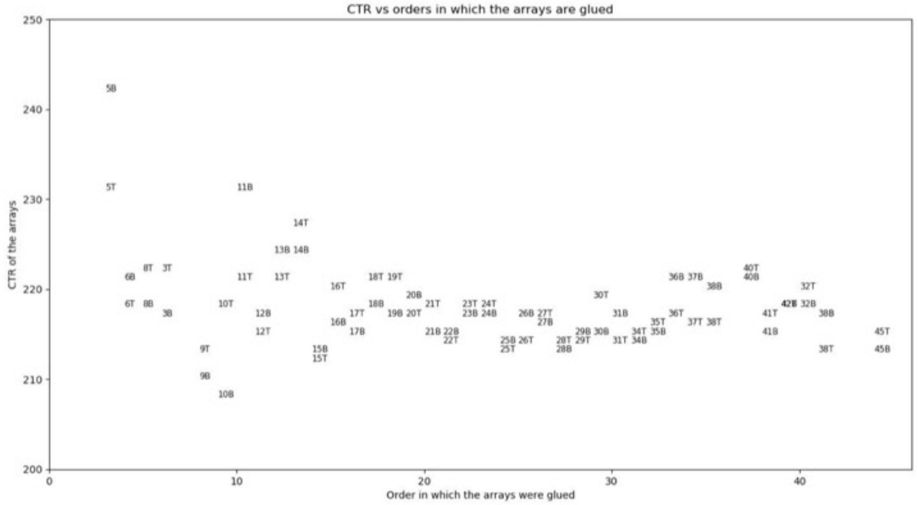
- Physicists **CAN** help fight cancer!
  - Medical professionals are incredibly valuable and talented but also very busy!
  - We can apply our long history and expertise in detector technology to advance the field
  - Help improve treatment outcomes for PT patients
- … And SiPMs have been crucial in this effort!
  - They offer numerous advantages over PMTs in PET imaging:
    - Fast timing, pixelization, compactness, functionality in magnetic fields fields (for integration with MRI)
  - Can be used to create novel scanner designs to push PET into new territory
- The TPPT Scanner is one such example of a next-gen SiPM-based PET system
  - It has been designed, assembled, and almost fully commissioned
    - Just some last calibration steps remaining
  - We will move it to MDACC later this year to begin taking in-beam data
- The project has excited us to continue working in PET and medical imaging

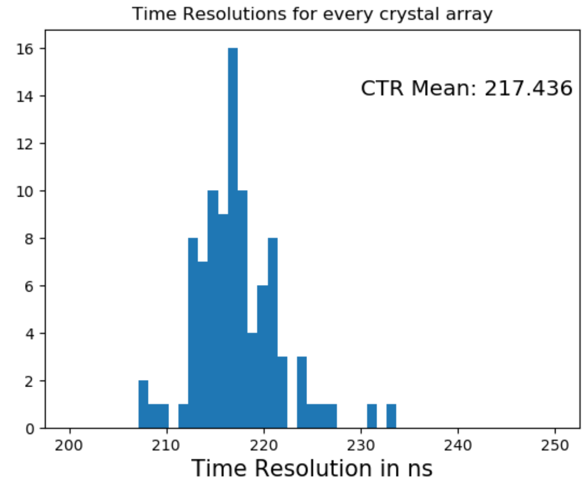
Backup Slides

The TPPT Project : Mini-PET Results



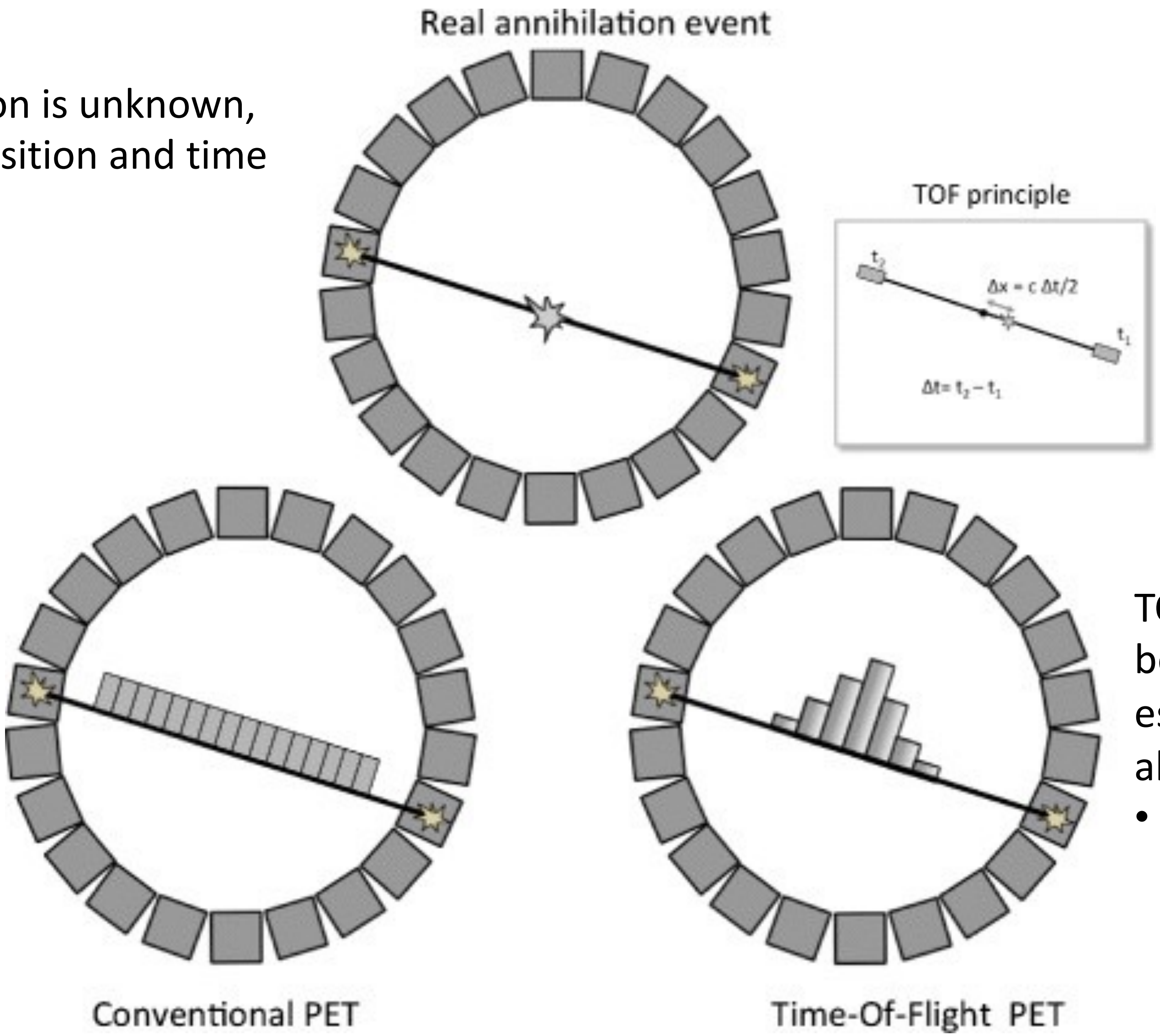






PET Imaging: Time-of-Flight PET

Real event: annihilation location is unknown, what's measured is just the position and time of each hit in the detector

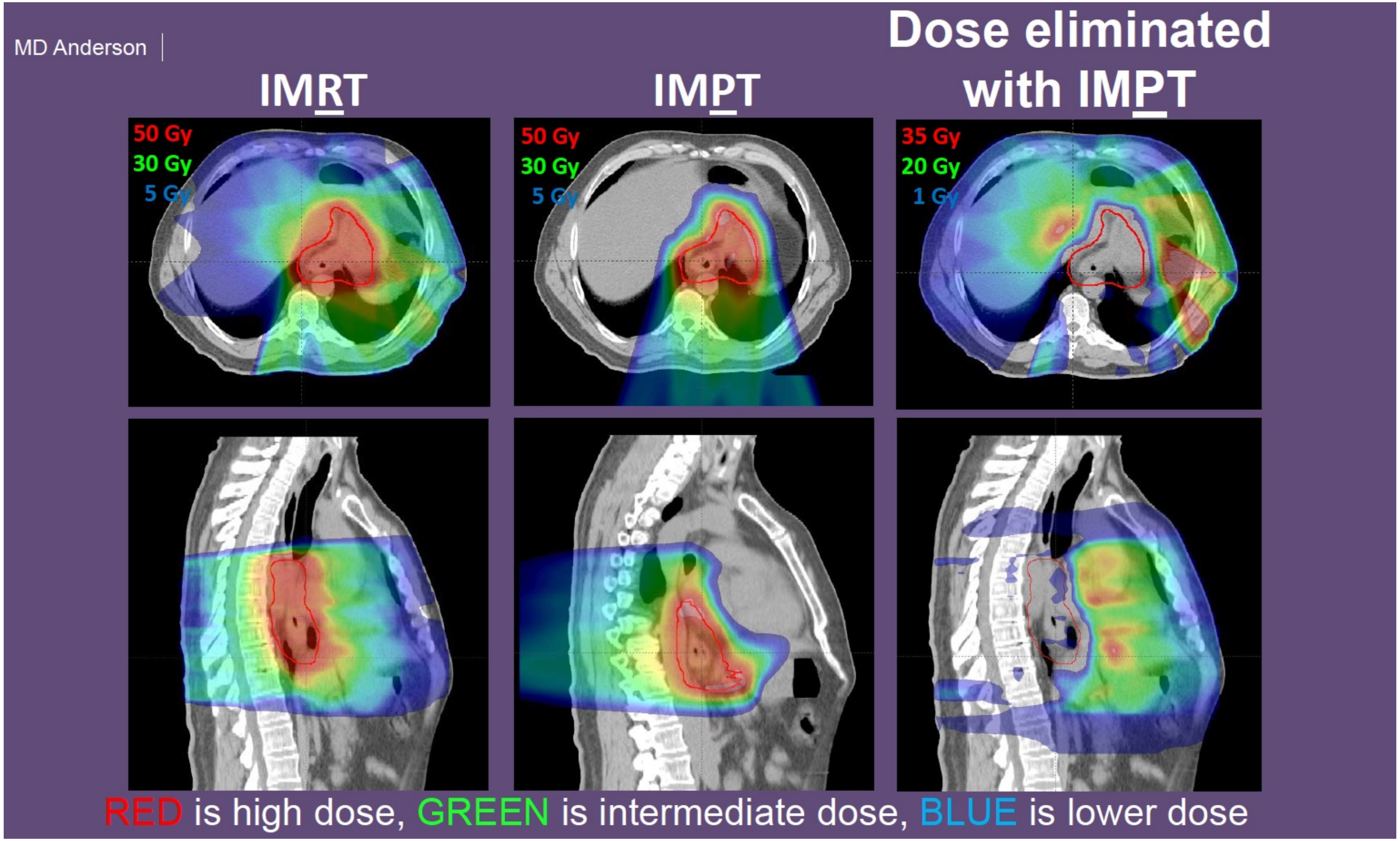


Traditional PET: Annihilation location probabilities uniformly distributed along LOR

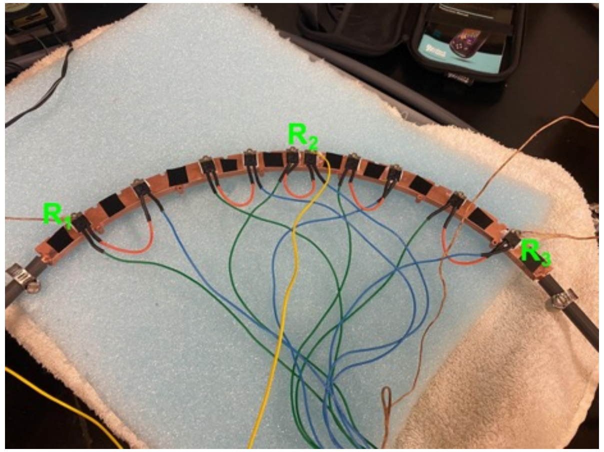
TOF PET: Time difference between detections used to estimate annihilation location along LOR

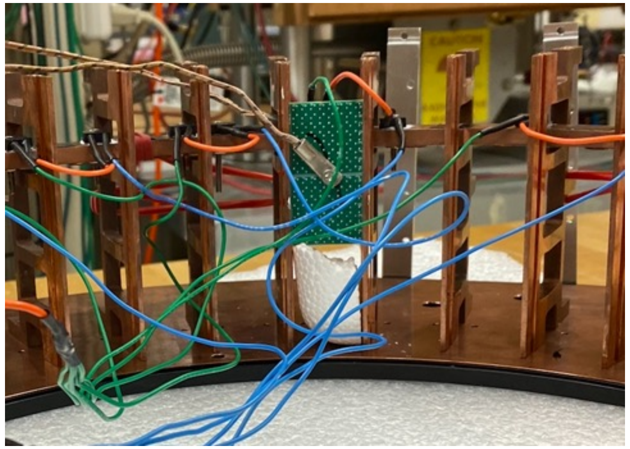
- Gaussian width determined by timing resolution

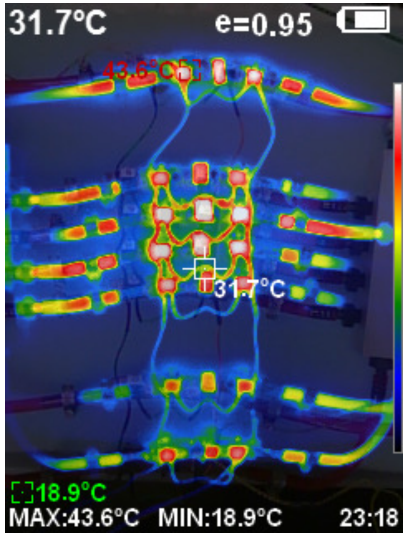
Radiation Therapy: Protons vs. Photons



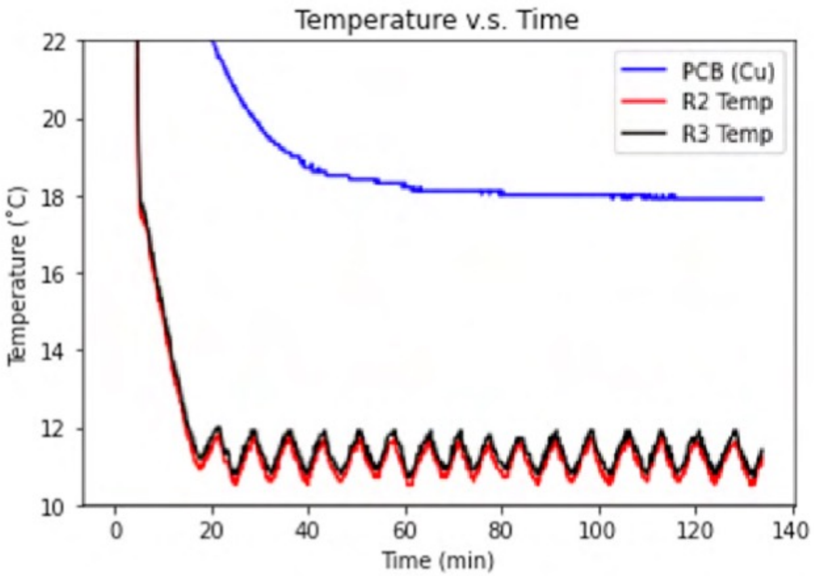
TPPT Hardware: Cooling System



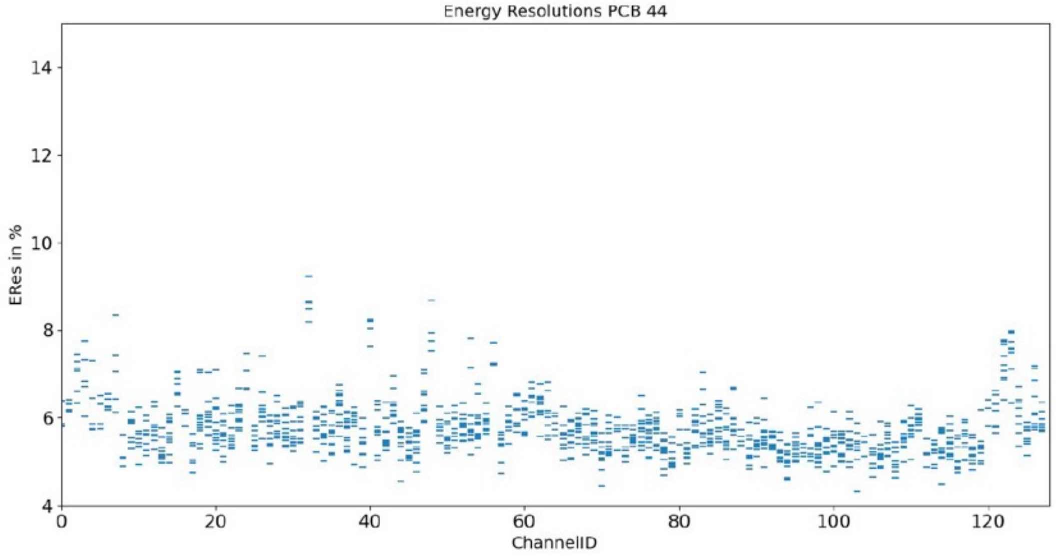


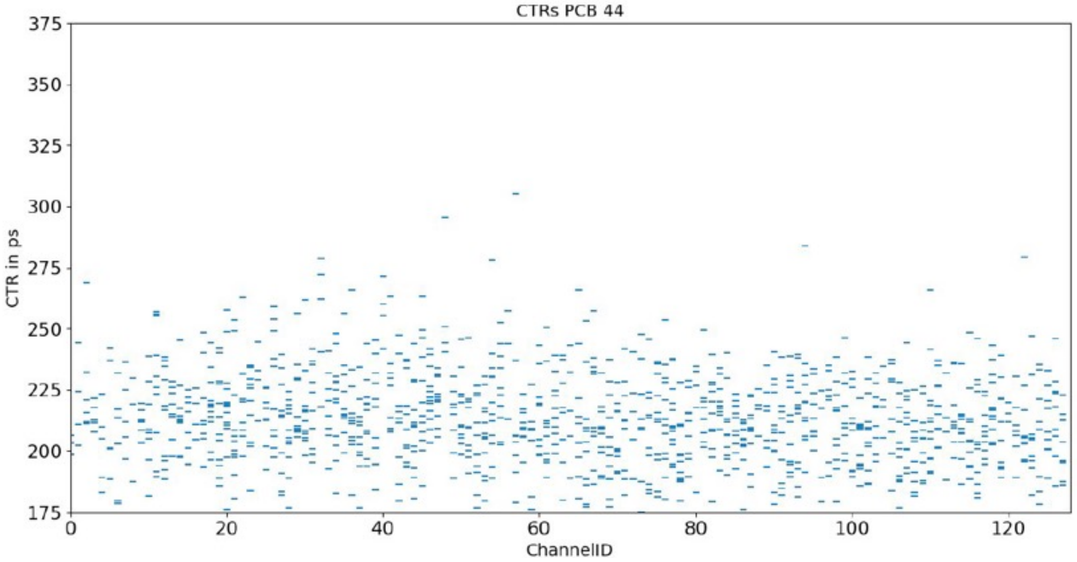


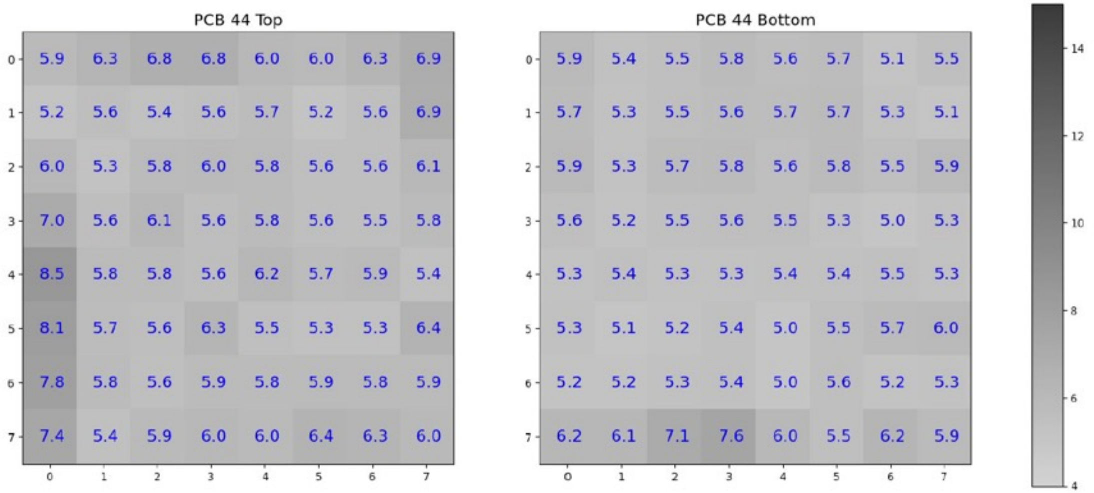
- ~1W dissipation per ASIC (2 x ASIC p module, 96 total)
- ASICs require stable temperature fo calibration and operation
- Developed custom liquid cooling system
  - Copper elements circulate coolant and make thermal contact with ASICS and internal structure

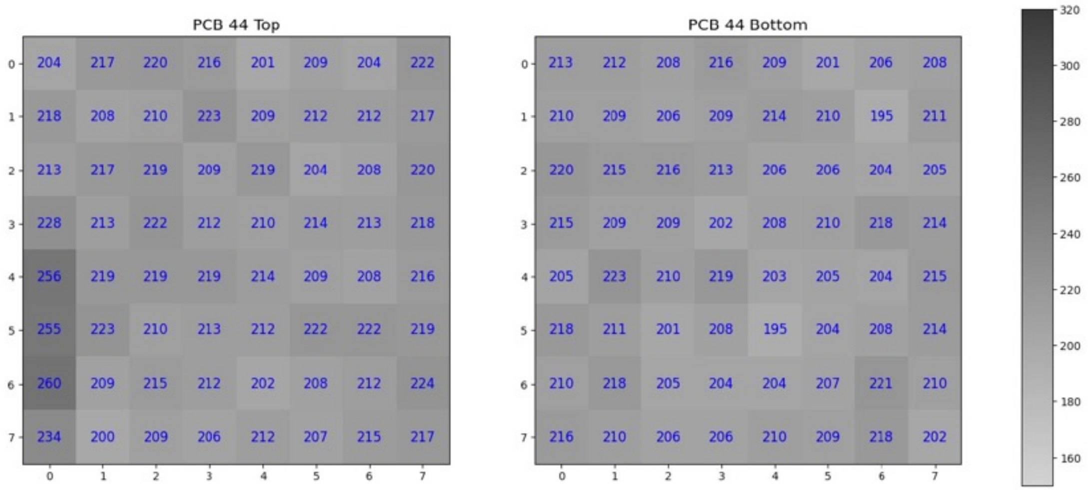


The TPPT Project : Mini-PET Results



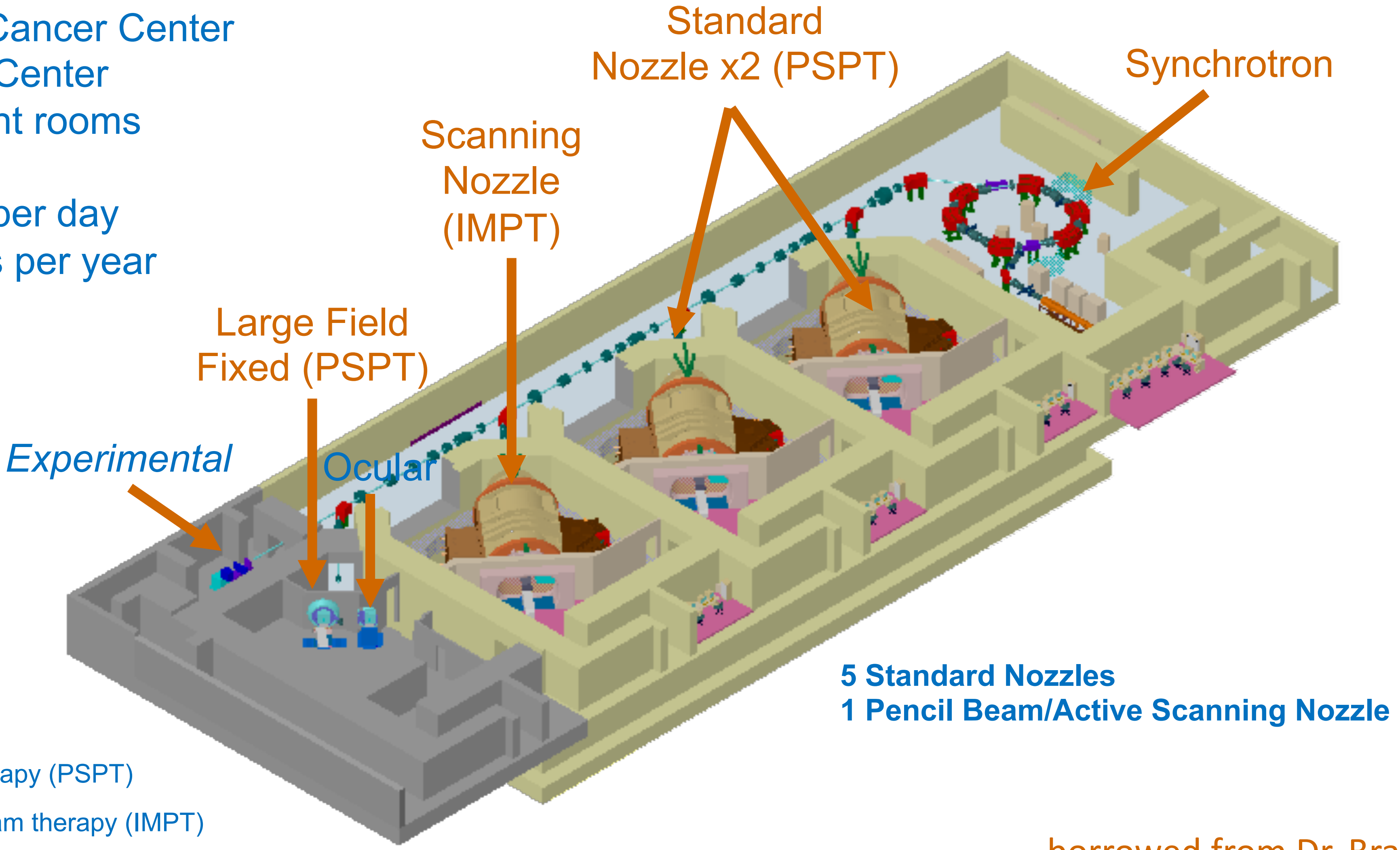






Proton Therapy: MDACC Beamline

- M.D. Anderson Cancer Center Proton Therapy Center
- 4 active treatment rooms
- kV imaging
- 90-110 patients per day
- 700-800 patients per year



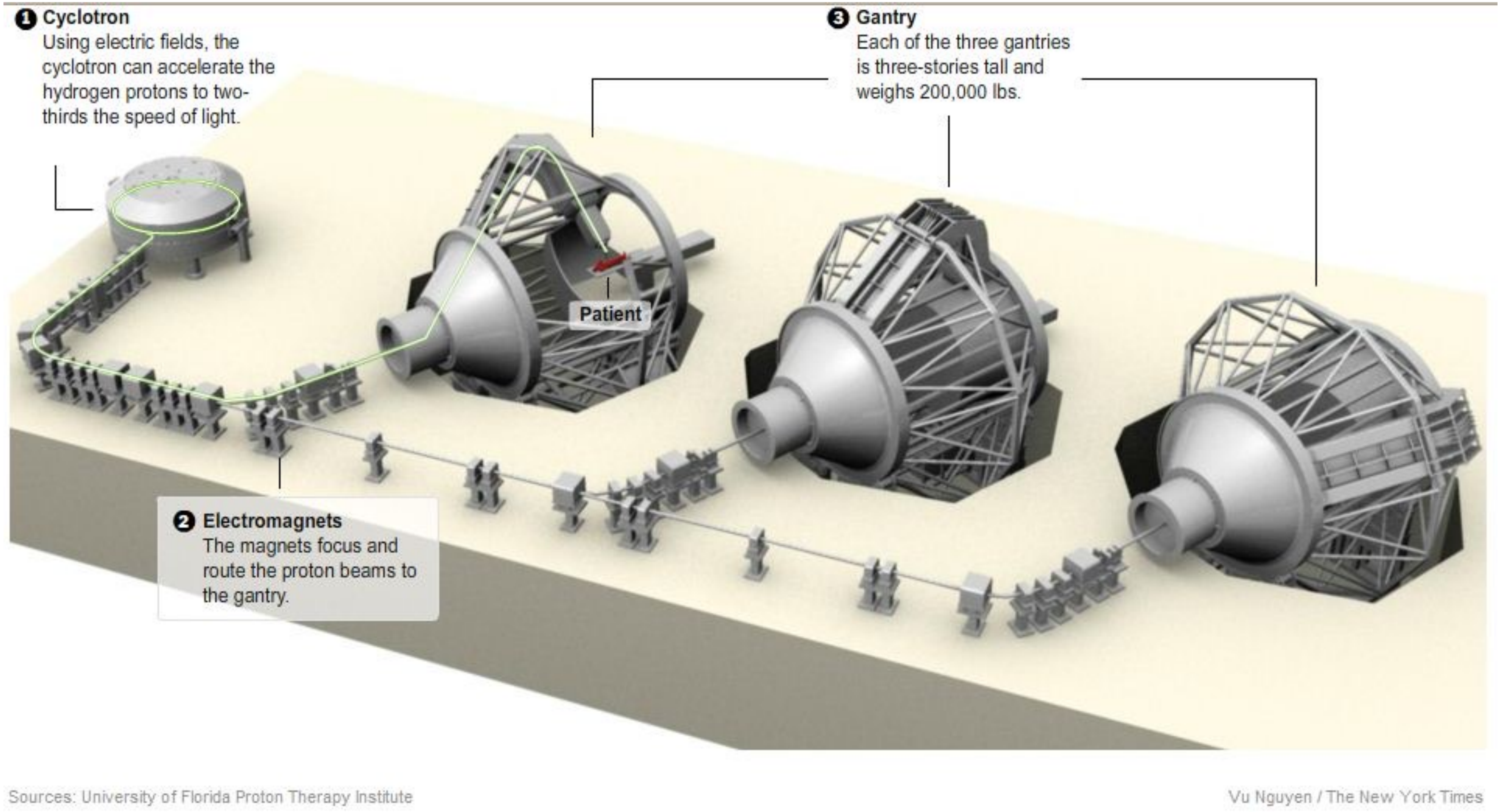
5 Standard Nozzles
1 Pencil Beam/Active Scanning Nozzle

passively-scattered proton therapy (PSPT)

Intensity modulated proton beam therapy (IMPT)

borrowed from Dr. Brandon Gunn

Proton Therapy: The scale ...

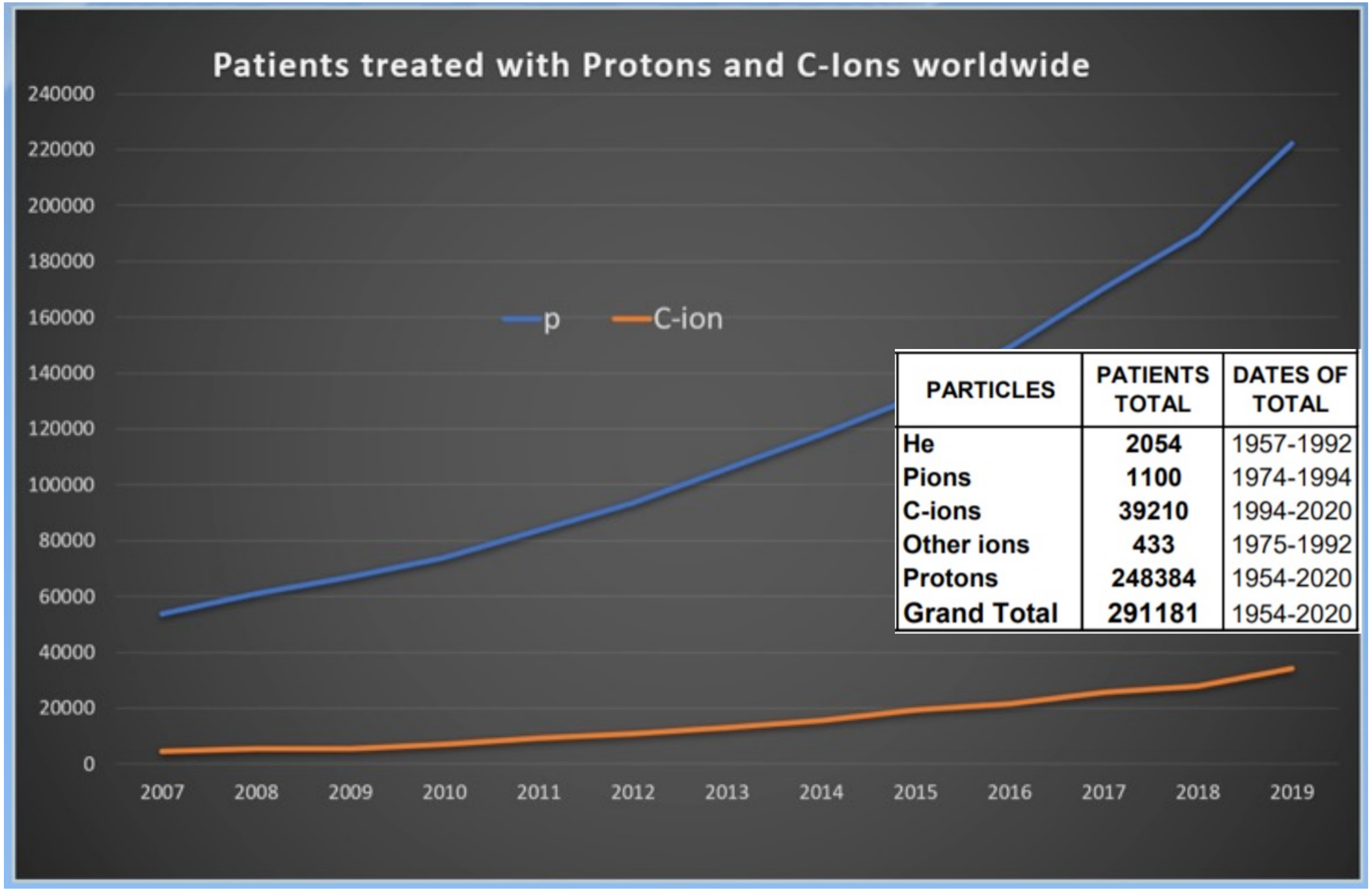


Proton Therapy: On the rise….

112 facilities worldwide, another ~100 in various planning stages

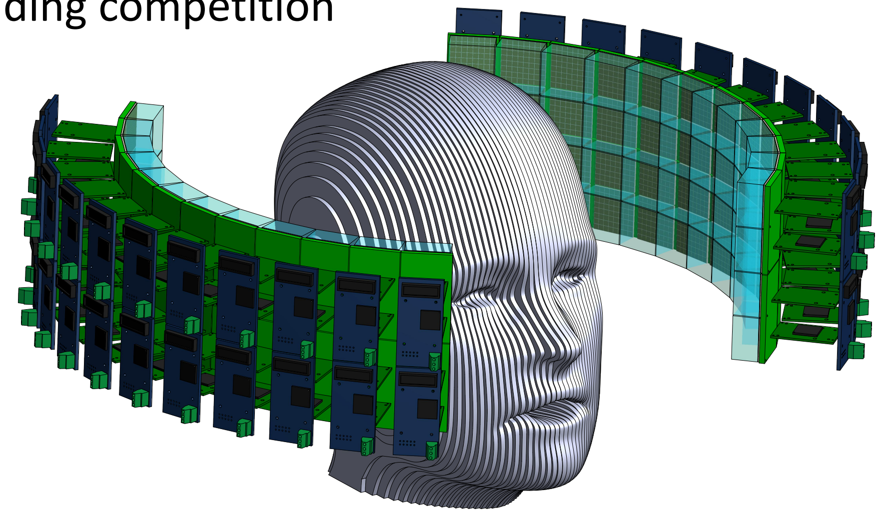
- 42 facilities in the USA …. 26 in Japan … 7 in Germany … 7 in China … (3 Netherlands)
- 2 in Texas: MD Anderson CC and at UT Southwestern Medical Center
- 1 more to open soon at MD Anderson

Proton Therapy: On the rise….



PARTICLES	PATIENTS TOTAL	DATES OF TOTAL
He	2054	1957-1992
Pions	1100	1974-1994
C-ions	39210	1994-2020
Other ions	433	1975-1992
Protons	248384	1954-2020
Grand Total	291181	1954-2020

The TPPT Project: Inception



- 3 years ago we formed a consortium to compete in the UTAustin - Portugal funding competition
- The consortium includes
  - **U. of Texas MD Anderson Proton Therapy Center**

    Sahoo Narayan, Falk Poenisch, David R. Grosshans
  - **U. of Texas at Austin**

    Karol Lang, Marek Proga, +
  - **PETsys Electronics**

    Vasco Varela, João Varela, Stefaan Tavernier, Ricardo Bugalho, Luis Ferramacho, Miguel Silveira, Carlos Leong, Jose da Silva
  - **LIP, Laboratorio de Instrumentação e Fisica Experimental de Particulas (Coimbra)**

    Paulo Crespo, Mario Pimenta, Patricia Goncalves, Hugo Simões, Andrey Morozov
  - **Centro de Ciências e Tecnologias Nucleares (C^2TN), Instituto Superior Técnico (Lisbon)**

    António Paulo, Fernanda Marques, Paula Raposinho, Joana Guerreiro , Filipa Mendes, Salvatore di Maria, Maria Paula Campello
  - **Instituto de Ciências Nucleares Aplicadas à Saúde (ICNAS), Universidade de Coimbra**

    Nuno Ferreira, Francisco Caramelo, Antero Abrunhosa
- We proposed a “feedback” PET scanner to register nuclides activated in proton irradiations:
  - C-11 ($T_{1/2}$=20min), N-13 ($T_{1/2}$=10min), O-15($T_{1/2}$=123sec)

UTAustin Portugal

LYSO vs BGO Crystal Properties

Table 1.

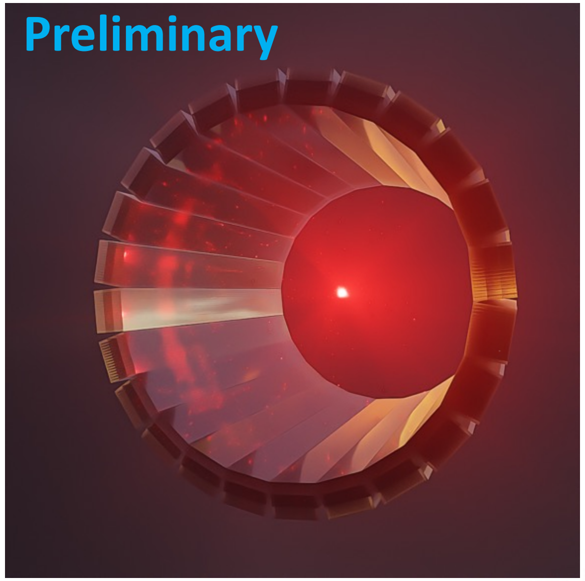
Properties of LYSO and BGO (from Saint-Gobain 2014, 2017).

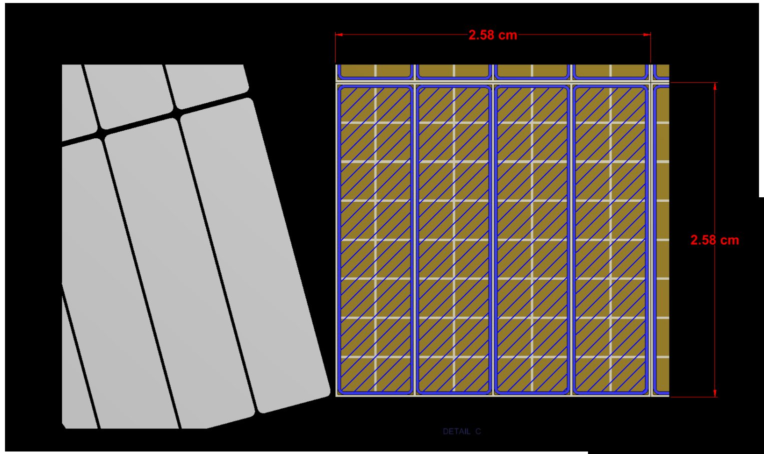
	LYSO	**BGO**
Effective atomic number (Z_{eff})	60	74
Density (g cm^{-3})	7.1	7.13
Attenuation length for 511 keV (cm)	1.2	1.0
Light yield (photons MeV^{-1})	8000–10 000	30 000
Decay time (ns)	37–45 ns	300
Peak wavelength (nm)	420	480

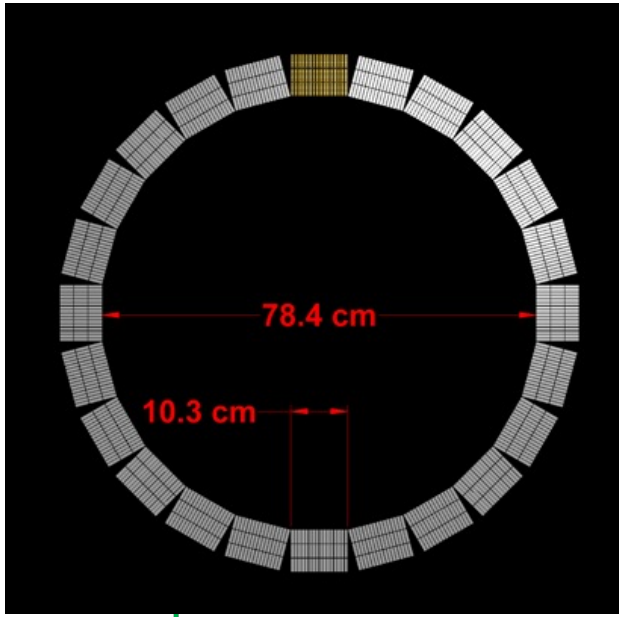
Image courtesy of doi: 10.1088/1361-6560/abc365

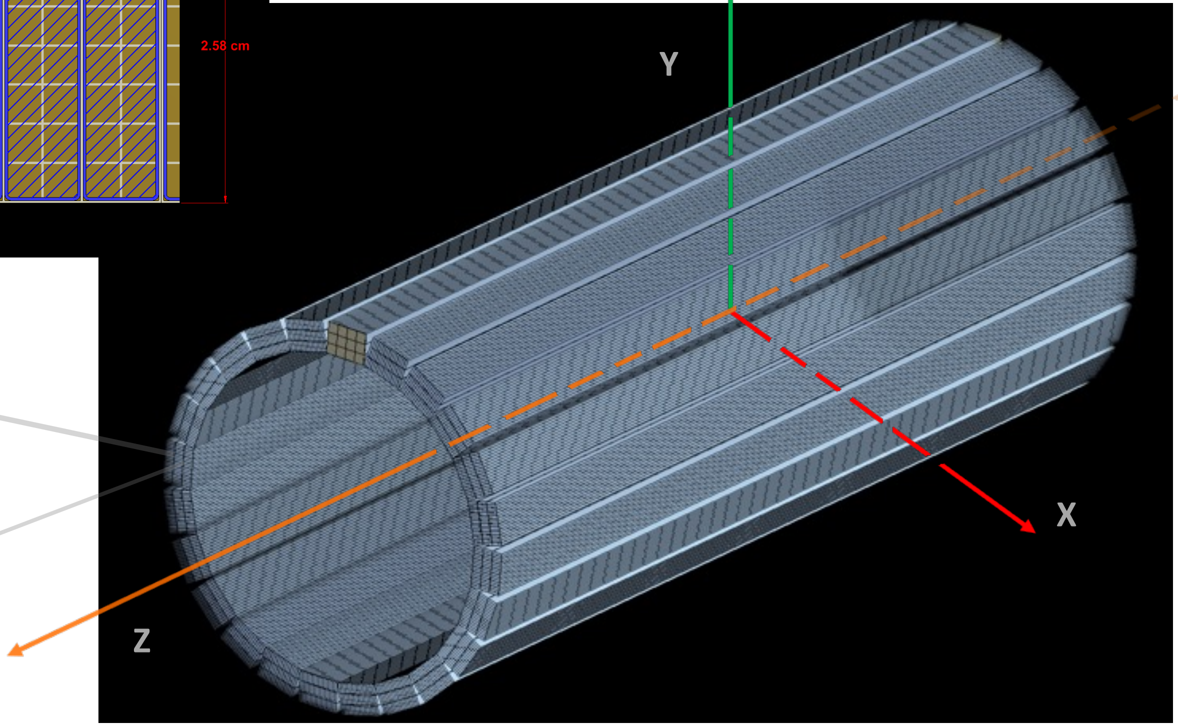
Future Ideas: Full Body PET

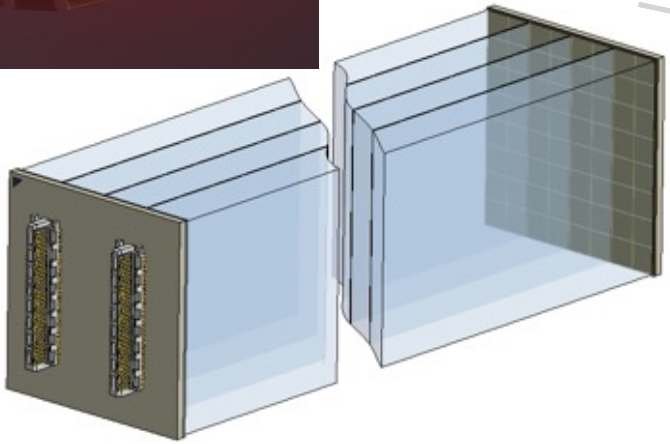
- 1m long barrel PET (2.54 x 0.62 x 100cm scintillator)
- 1152 plastic scintillator strips and 576 SiPMs.
- kNN based reconstruction





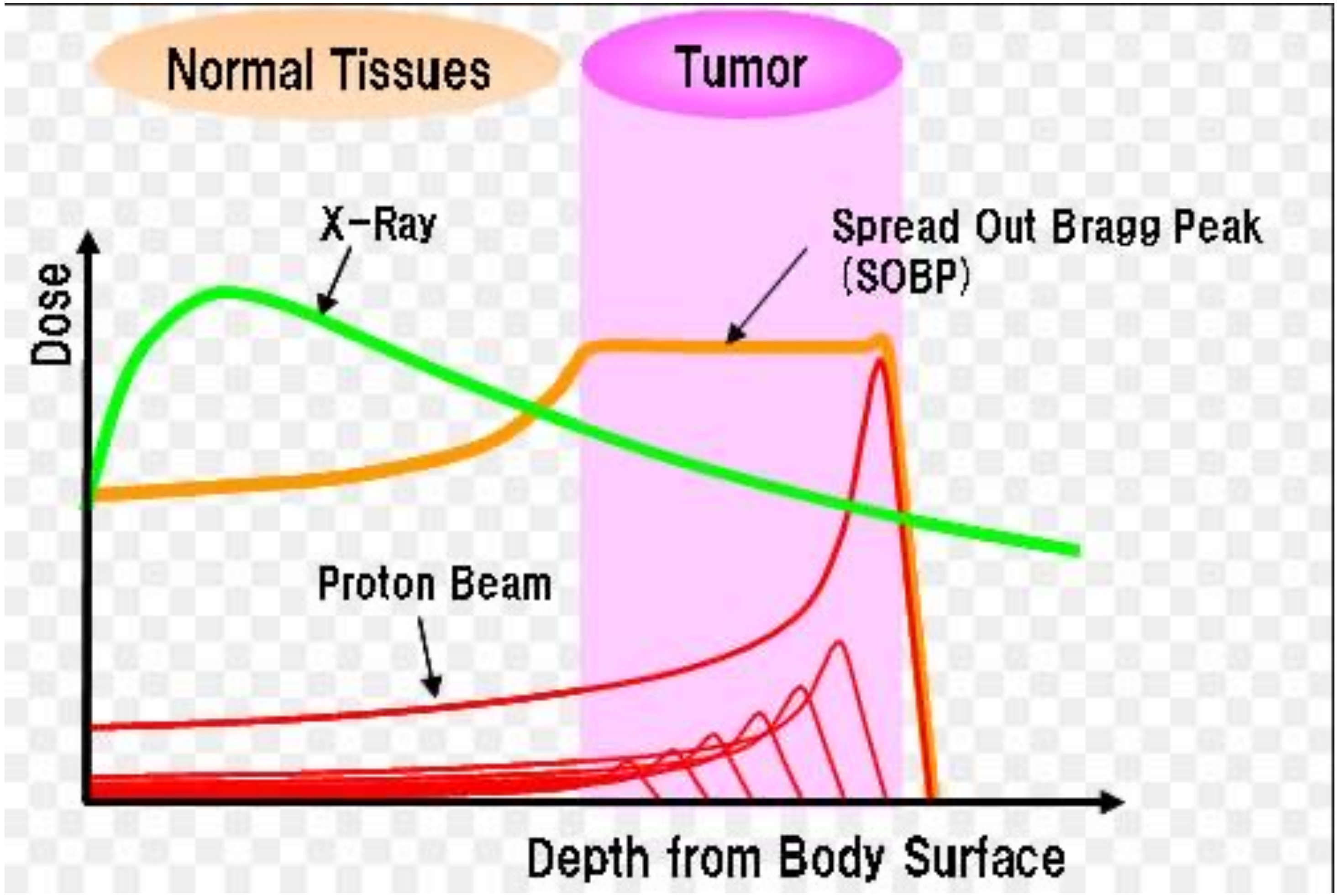




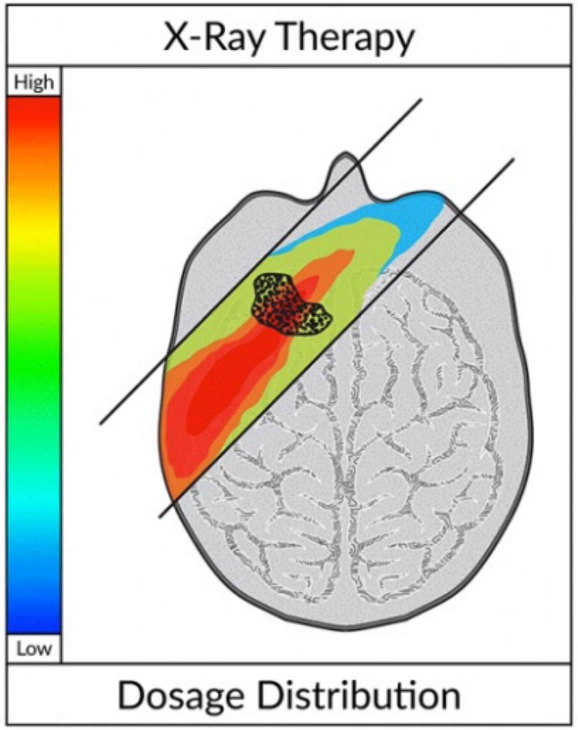


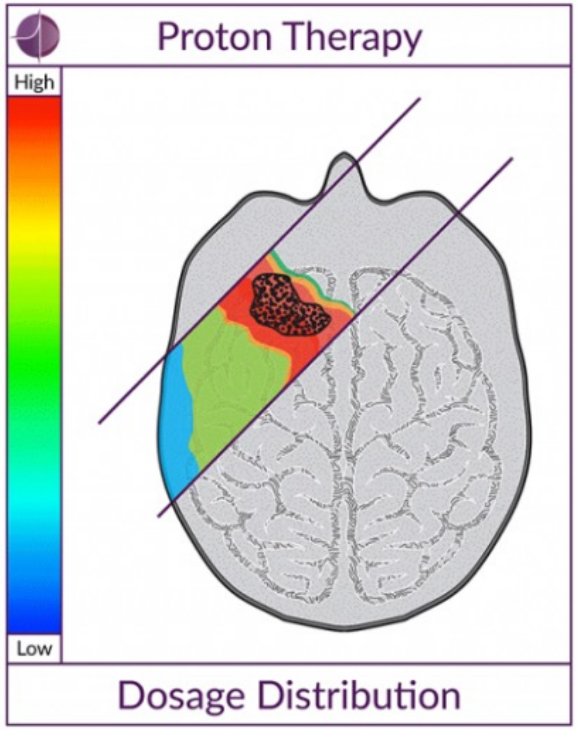
IMPT

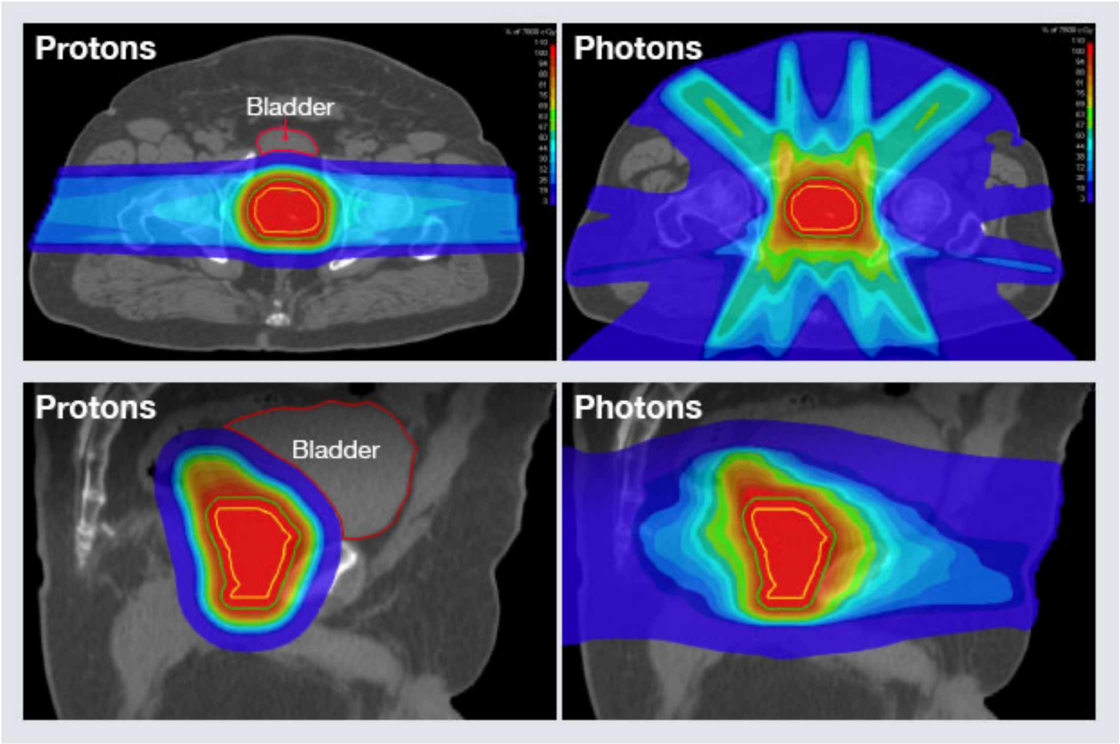
(Intensity Modulated Proton Therapy)



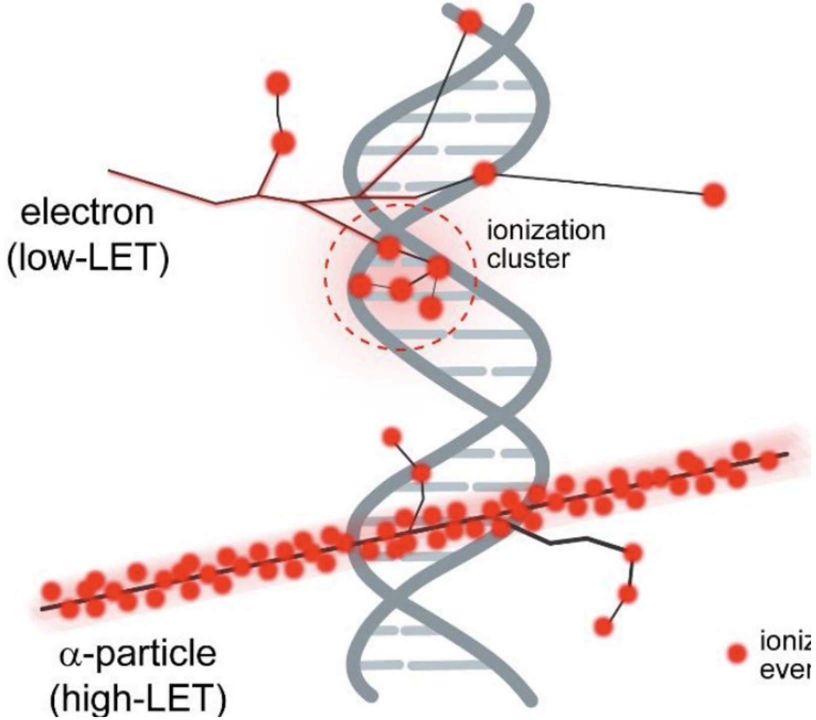
IMRT vs IMPT


X-Ray Therapy
High
Low
Dosage Distribution


Proton Therapy
High
Low
Dosage Distribution


Protons
Bladder
Photons
Protons
Bladder
Photons

Destroying cancer or impeding its growth



oxygen radicals ...