Status Update on Proton CT

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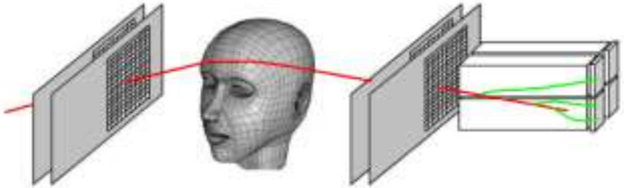


Technologies addressing Range Uncertainties in
Proton Therapy, AAPM 55th Annual Meeting

Outline

- What do we gain by developing proton CT (pCT)?
- pCT principles & development
    - Principles & concepts
    - pCT collaboration
    - pCT development & first results
    - Status update
- Future developments

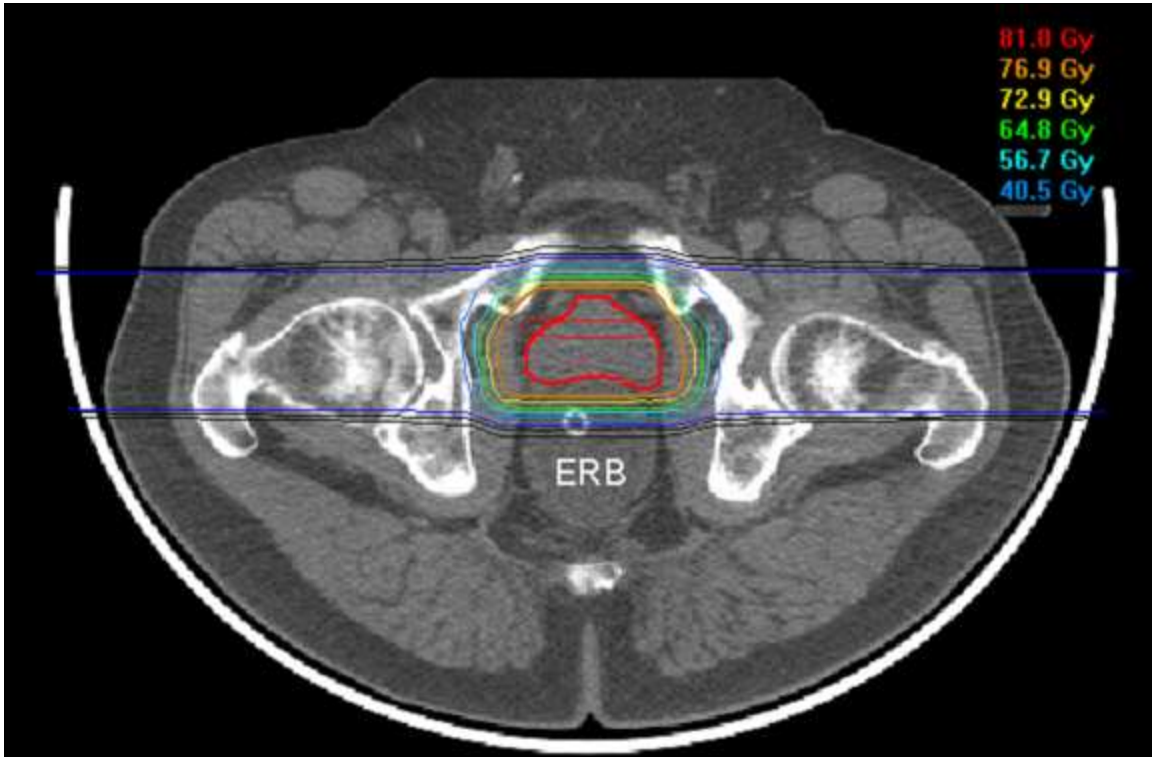
WHAT DO WE MISS AND WHAT CAN WE GAIN?

Current Limitations Related to Range Uncertainty

- The ability to place a Bragg peak at a planned location is the major advantage of protons and ions; unfortunately, our ability to do this within ~1% of range is limited by a combination of factors related to incomplete knowledge about physical tissue properties & their position relative to the beam.
- Range uncertainty frequently creates a conflict between healthy tissues sparing and need to completely cover tumor tissue.
- The higher RBE in the distal 3rd of an SOBP further complicates the situation.

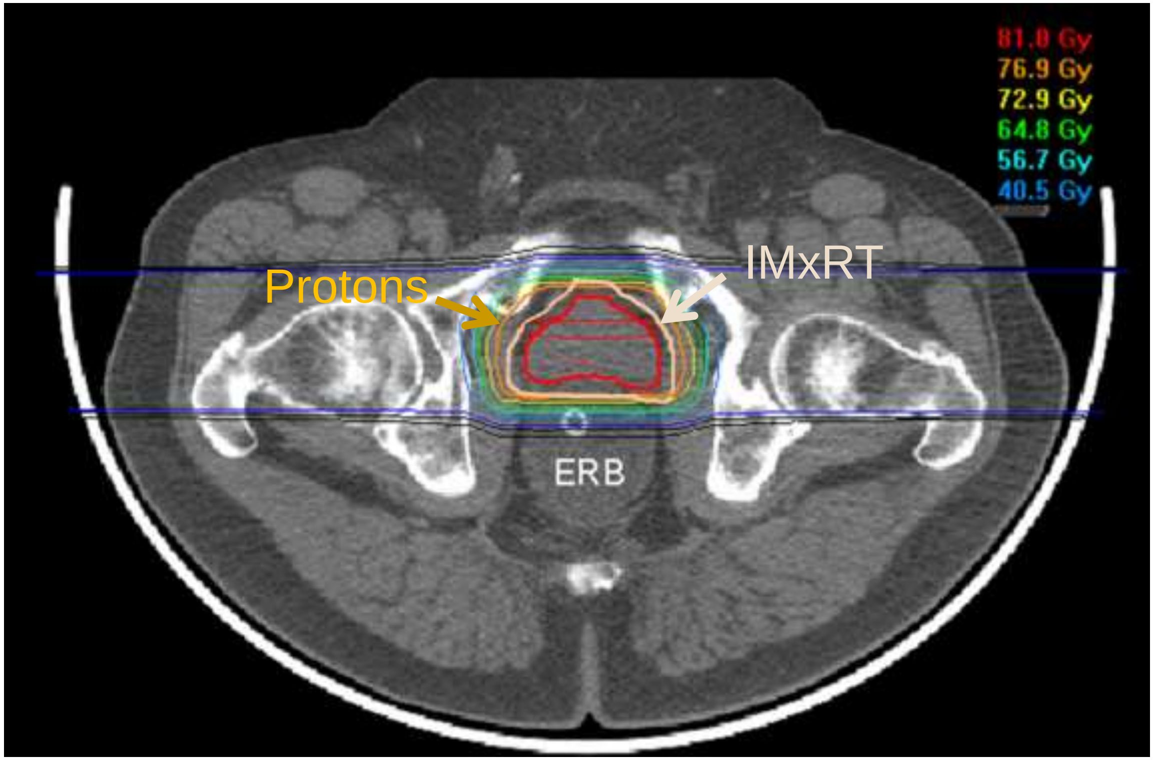
Example, Prostate Cancer

- CTV is expanded in a beam-specific way according to internal motion, set-up error, and distal range uncertainty

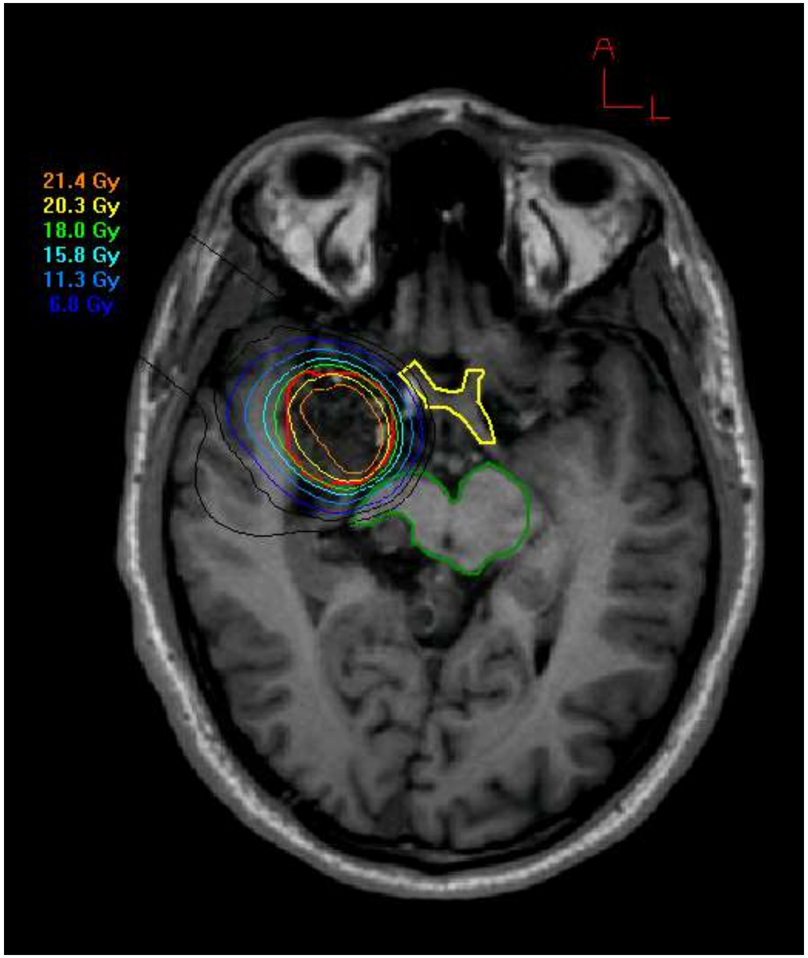


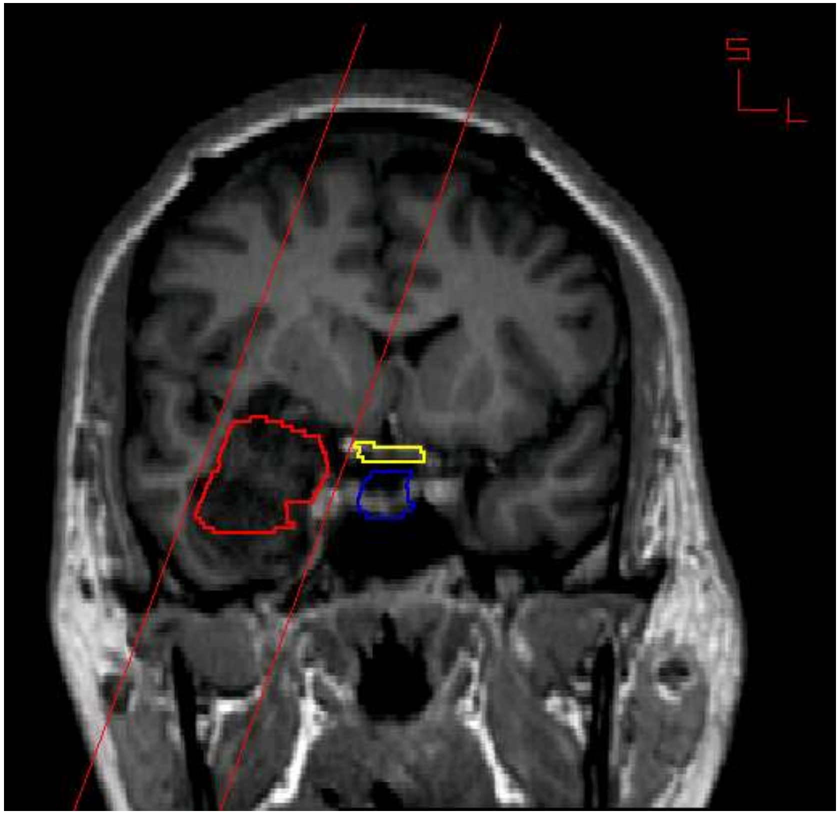
Example, Prostate Cancer: Wider Lateral Margins compared to IMRT

- IMxRT with image guidance applies uniform PTV margins, that are smaller laterally compared to a typical proton plan
- For a meaningful comparison, one should aim at IMpRT plans with reduced range error



Example, Target in Difficult Anatomical Location





Example, Artifacts from High-Z Materials

- The presence of artifacts, here from embolization material in this AVM patient makes proton treatment planning very challenging
- Dental artifacts are common in head and neck cancer plans

Potential Gain from Proton CT for Treatment Planning and Pretreatment Verification of Proton & Ion Therapy

- Improved definition of physical tissue properties (e.g., relative stopping and scattering power)
- Avoidance of artifacts
- Low-dose in-room imaging for plan verification / treatment adaptation
- Reduced range uncertainty, more accurate dose calculation

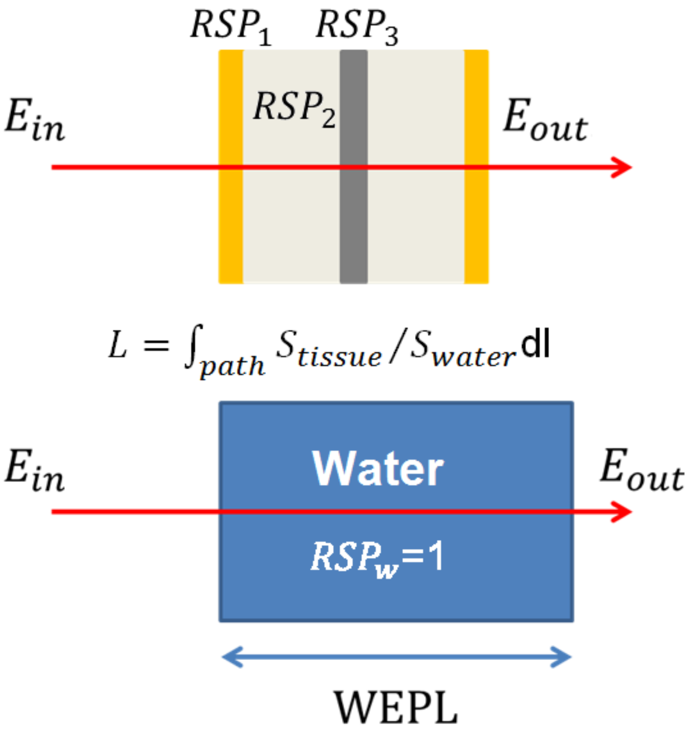
PROTON CT: CONCEPTS AND TECHNOLOGY UPDATE

The Proton CT Collaboration

- A group of individuals with interest in proton imaging first met at BNL in Jan 2003 and LLUMC in Feb 2003 to develop a conceptual design for a modern pCT scanner based on single proton registration
- 2003 – 2007: Conceptual design, Geant4 simulations, most likely path concept, small prototype experiments
- 2008 – 2010: Phase 1 scanner for proof of principle
- 2011 – 2015: Phase 2 scanner development with NIH funding

Conceptual Approach to Proton CT (Cormack, 1963)

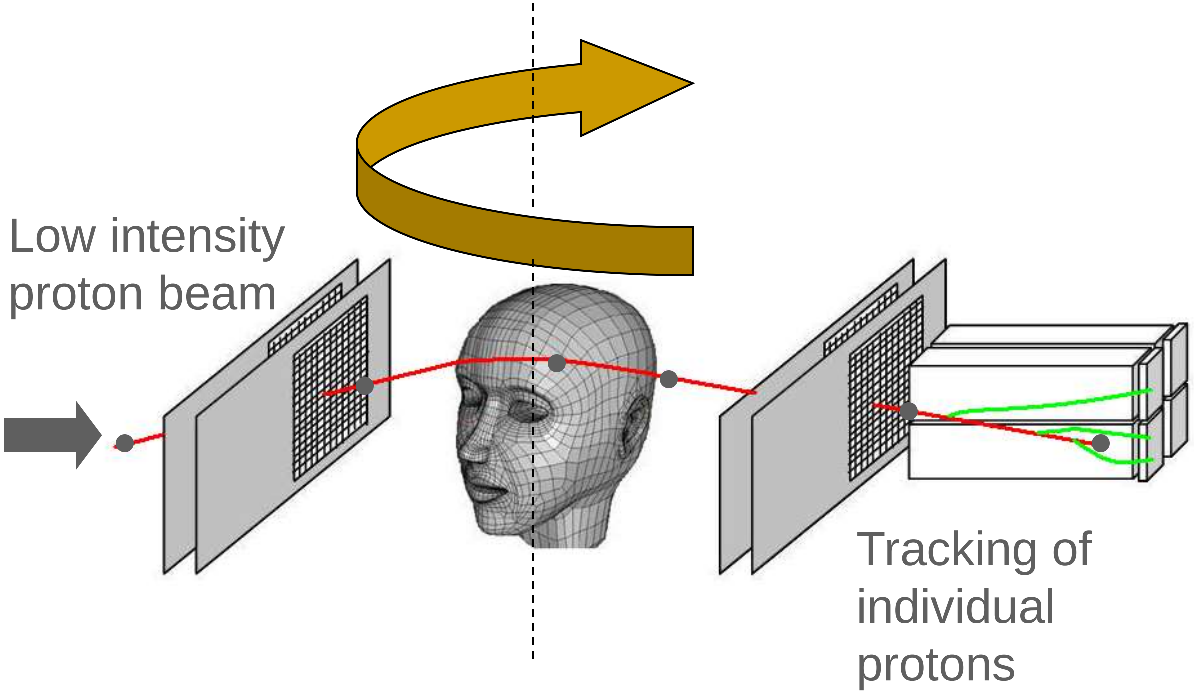
- Protons mostly lose energy via electronic interactions
- Measured residual energy loss of protons can be used to determine the path length through water with the same average energy loss (WEPL)
- Mathematically, WEPL is the path integral of relative stopping power (RSP) through inhomogeneous tissues
- Collecting WEPL data from many directions allows (tomographic) reconstruction of RSP in 3D, which is (practically energy independent
- A similar concept applies to relative scattering power (angular variance) and proton fluence attenuation due to inelastic nuclear interactions
- Thus one can reconstruct material properties important for proton energy loss, scattering, and nuclear interactions



$$L = \int_{path} S_{tissue} / S_{water}\, \mathrm{dl}$$

Proton CT Scanner: Conceptual Design

- Protons of sufficient energy to penetrate the human body part to be imaged
- Protons are tracked on the entry and exit side using position-sensitive detectors
- Residual energy / range detector to measure energy loss of individual protons
- Isocentric detector arrangement in synchrony with proton gantry



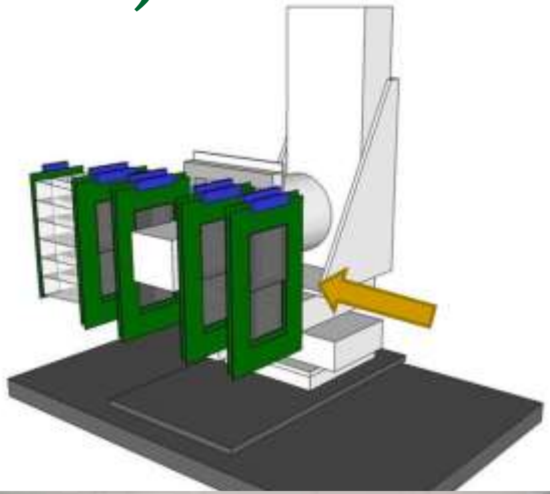
Conceptual design of a stand-alone proton CT scanner rotating with the proton gantry

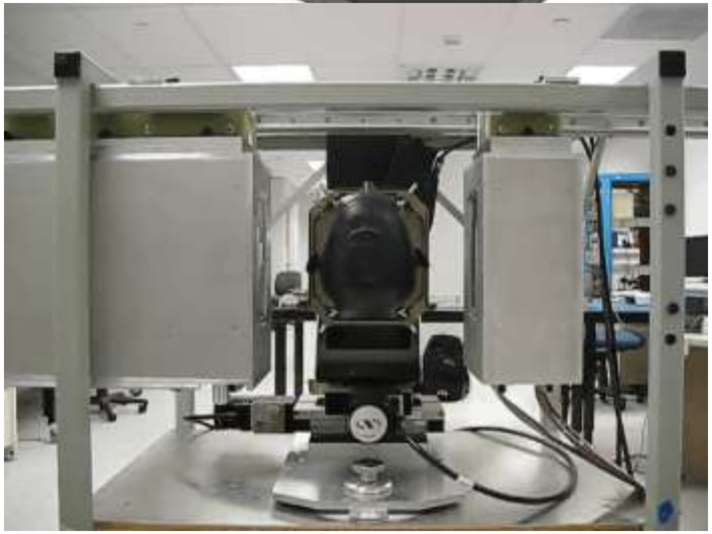
Single Proton CT: Advantages and Challenges

- Single proton detection allows
  - rejection of events not fitting the physical model (“data cuts”)
  - estimation of individual proton paths
  - use of algebraic (iterative) reconstruction algorithms based on individual proton histories
- Challenges of proton detection
  - Requires very high data rates (fast DAQ systems),
  - and computation tools using massive parallelism for fast reconstruction

First Modern Proton CT with Single Particle Detection – Phase 1 Scanner (2011)

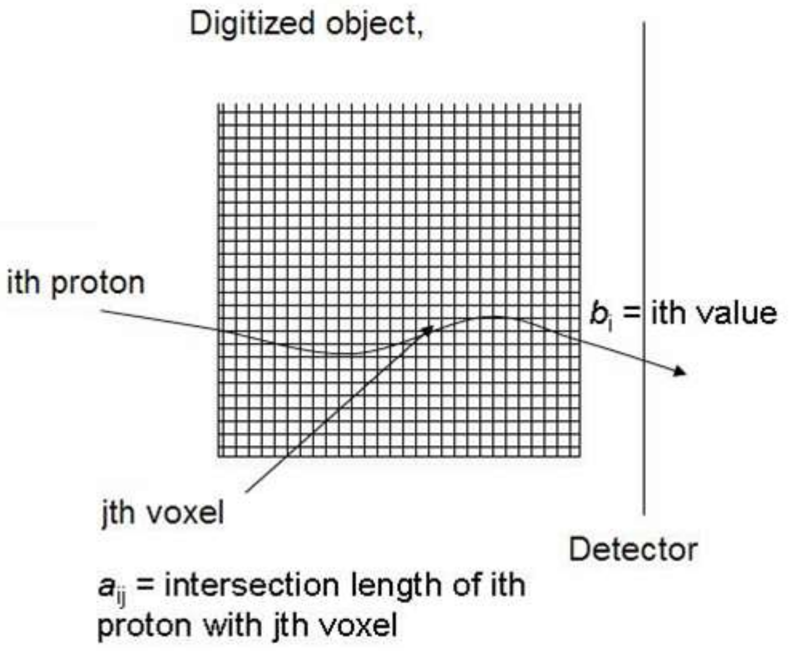
- Employed existing tracking sensors (silicon strip detectors and data readout for Fermi Space Telescope, NASA GLAST Mission)
- Energy measurement with multi-segmented crystal calorimeter
- FPGA-based DAQ & GPU based reconstruction





Proton CT Reconstruction: Solution Concept

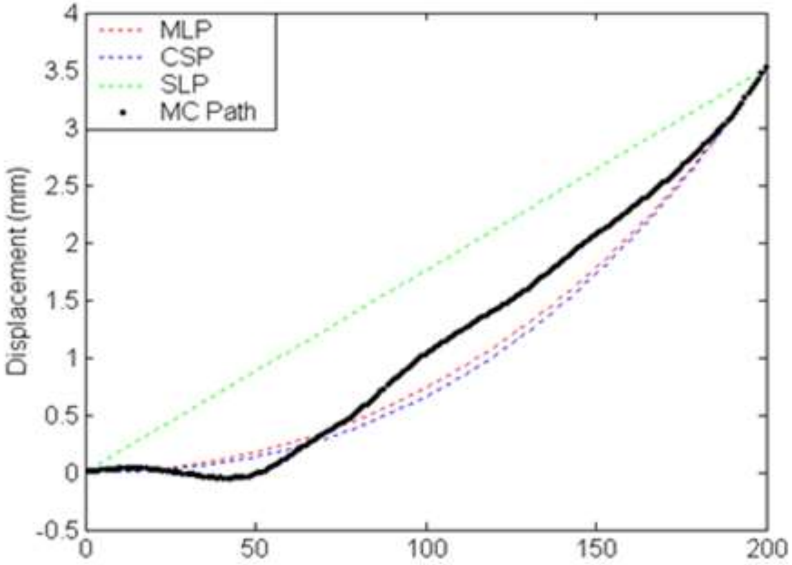
- With registration of single particle histories, the object solution can be found by solving a very large, sparse linear system
- Iterative reconstruction algorithms exploit massive parallelism

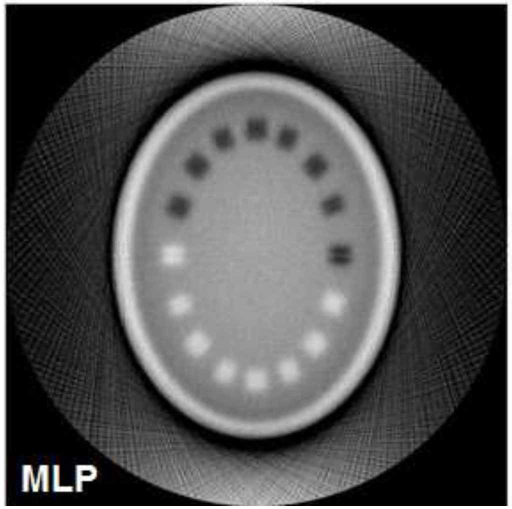


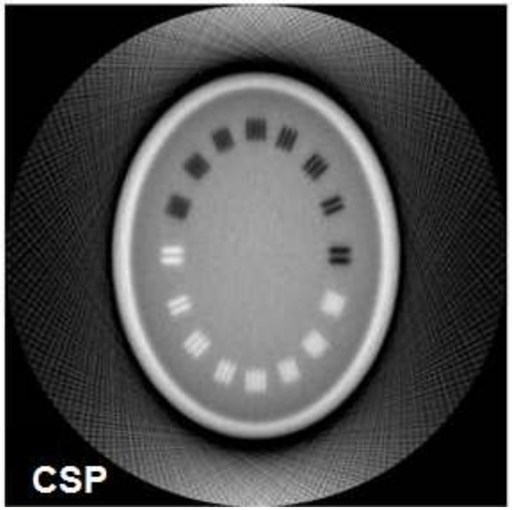
$$Ax = b$$

Proton CT Reconstruction: Path Concepts

- Different path reconstruction concepts were tested
- Most likely path performs best

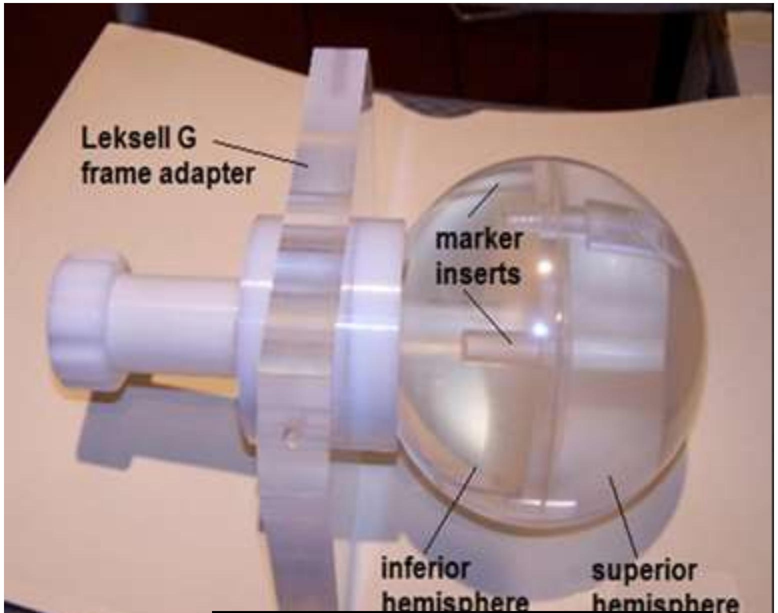


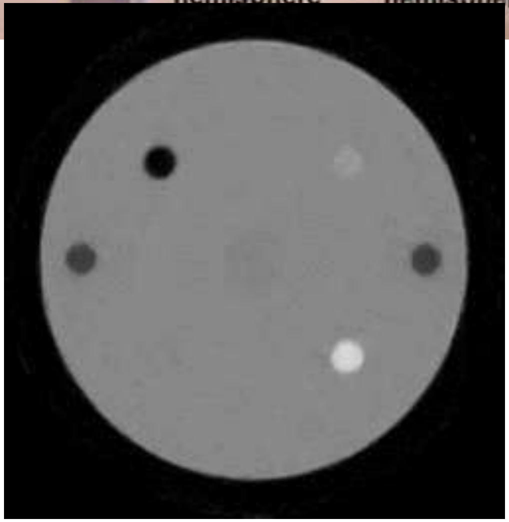




Phase 1 Scanning Results

- First pCT scans were performed with the Lucy phantom QA phantom (made from polystyrene) with different cylindrical inserts
- Quantitative RSP comparisons gave agreement with expected values to better than 1%

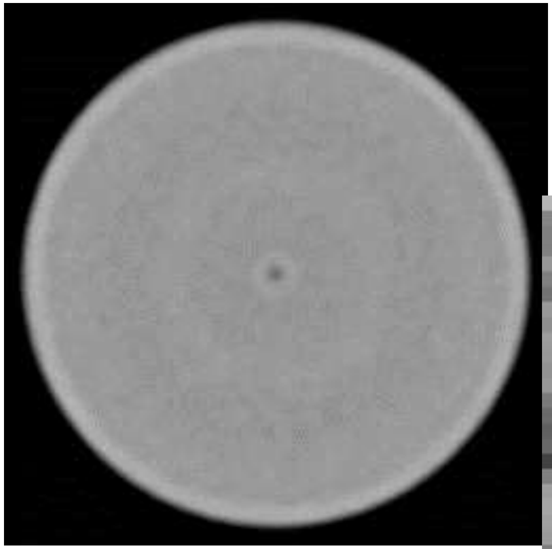


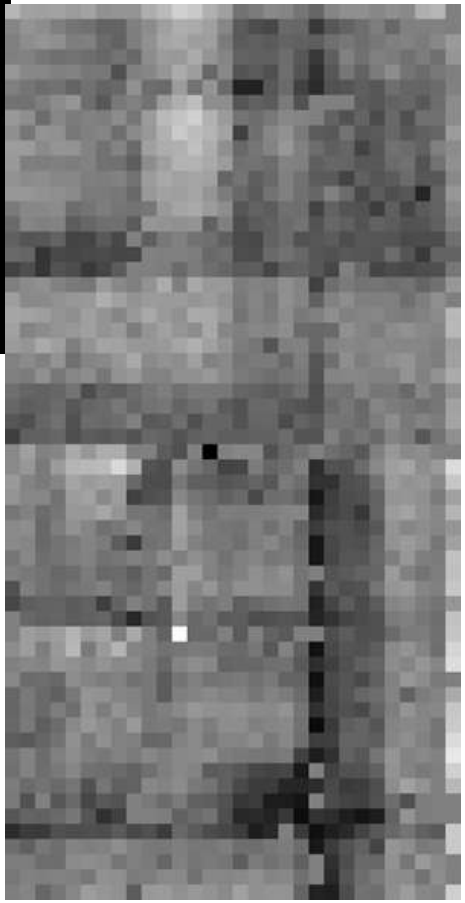


Proton Radiography with the Phase 1 Scanner

- Proton radiographs based on energy loss of a realistic hand phantom were obtained with 200 MeV protons
- More faithful representation of relative bone and soft tissue electron densities compared to x-ray radiographs
- pRadiographs can be used for QA and fast verification purposes (before treatment)

Lessons Learned from the Phase 1 Scanner

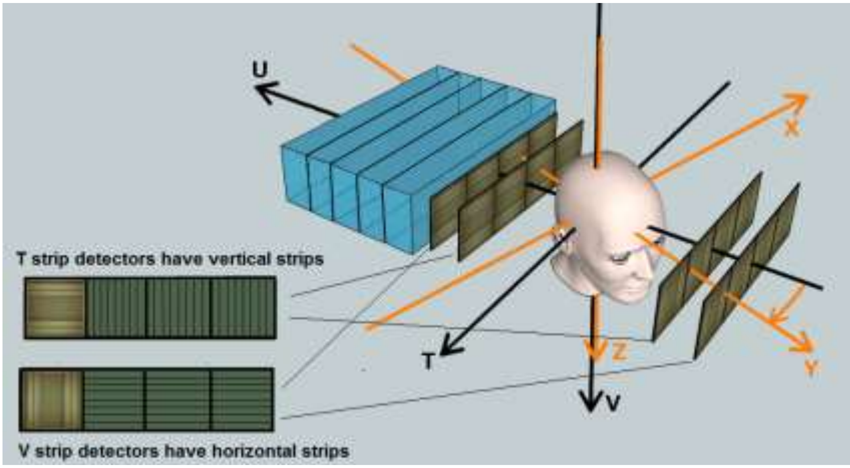


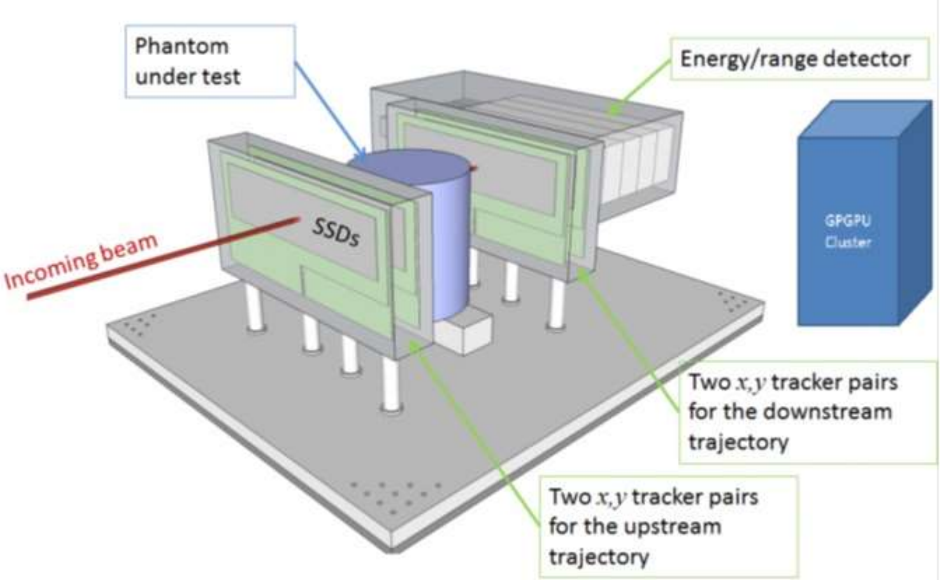


- The DAQ system (readout ASIC borrowed from Fermi) was not designed for speed, Lucy scans took many hours to acquire at kHz data rates
- Overlap of silicon tracker planes (tiling) causes central artifact
- The segmented calorimeter was difficult to calibrate and created insensitive interfaces

Phase 2 Scanner Upgrades

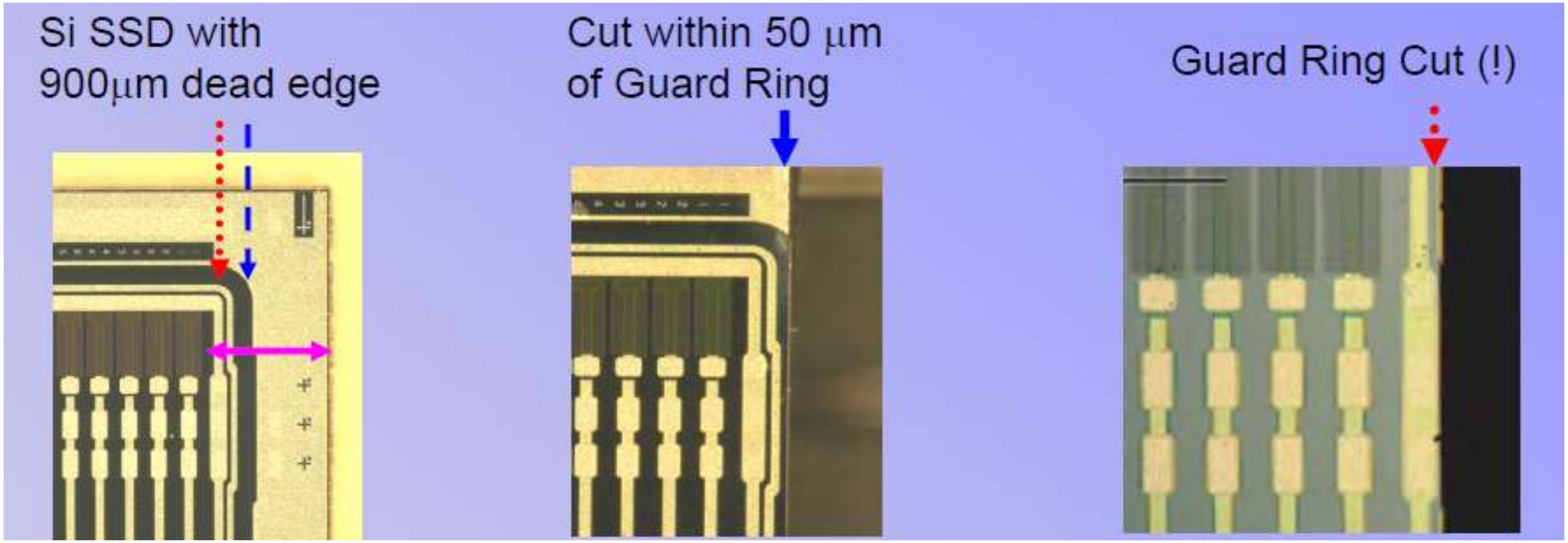
- Larger sensitive detector area (9 cm x 36 cm)
- New sensors with slim edges
- Simplified energy detector (5-stage scintillator with PMT readout)
- Dedicated ASIC for high data rates (2 MHz nominal rate) – acquisition times < 5 min
- Reconstruction in under 10 minutes on GPU cluster





Novel Si Sensors with “Slim” Edges

Courtesy Hartmut F-W Sadrozinski, UCSC



Si SSD with 900μm dead edge

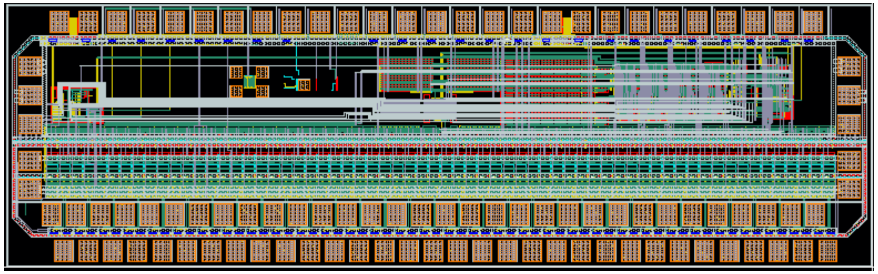
Cut within 50 μm of Guard Ring

Guard Ring Cut (!)

- The corner of a sensor manufactured by Hamamatsu Photonics for the Fermi space telescope mission is shown on the left with the planned cut indicated by the red line
- The sensor was etch-scribed with XeF2, cleaved and passivated with nitrogen plasma-enhanced chemical vapor deposition (PECVD)
- The slim edge with strips and bias ring is shown on the right; only traces of the guard ring are visible.

Phase 2 Scanner Time Line & Status

- Design of new scanner, including layout of ASIC was completed in 2011
- ASCIC was received in Sep. 2012 and was found to be fully functional in lab tests
- Proto-type tracker board for DAQ development completed in Dec 2012
- Prototype (3-stage) energy detector completed in Jan. and tested in March 2013
- Tracker PCBs completed in June 2013
- New 5-stage detector completed in July 2013



Phase 2 pCT ASIC

Robert Johnson (UCSC) with pCT tracker printed circuit board

FUTURE DEVELOPMENTS

The Promise of Proton CT

- Modern proton CT is the product of recent developments in particle physics, computing, and mathematics applied to advance medicine (reducing range uncertainties)
- There is much potential in this technology because it promises to be an accurate quantitative, low-dose imaging modality
- Proton CT is applicable to ion therapy as well, because RSP is independent of ion species.

Challenges Ahead

- The full development of proton CT for applications in proton and ion therapy as well as potential ultra-low-dose diagnostic applications requires a new generation of high-energy, low-intensity, compact accelerators and gantries
- Since funds for medical research are limited, developments have to “piggyback” on large-scale technology-driven scientific developments (e.g., high energy physics, NASA projects, etc.) starting from existing prototypes
- Transfer to medical applications requires a team of researchers from medical and physical disciplines willing to work together and understand each other

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- Current collaborators & graduate students from UCSC, California State University San Bernardino, University of Haifa, and University of Wollongong
- Medical physics and accelerator support team at LLUMC

Thank you!

Loma Linda University Radiation Research Laboratories (in front) and Medical Center in the background