MASSACHUSETTS GENERAL HOSPITAL
CANCER CENTER

Imaging Needs for Protons

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Propositions

- Imaging serves to ensure the correct fraction dose
  - … and, in current practice, assumes geometry equals dosimetry.
    - *True for γ – Geometry does not affect dosimetry*
    - *False for p – Geometry strongly affects dosimetry*
  - Not all observables are image-based
  - DGRT: Dose-Guided RT
- p RT requires different implementations
  - … thus, equipment has different effectiveness between γ and p
- p physics offers novel capabilities
  - … in-vivo, chemical, control-feedback at the delivery level

$\vdash$

- Identify p-specific requirements & deployments
- Identify p workflow requirements

Active Goals in RT

- Image-guided therapy for improved targeting
- Increase target to healthy tissue dose ratio
- Reduce treatment time and/or increase fraction size
- *Reduce cost for patient, society, and caregiver*

Requires

- Registration – Common reference of data
- Adaptive RT – Adjust delivery pattern
- Motion tracking – In-vivo
- *Performance – Computations, Feedback & Control*
- *Connectivity – Data backbone & Logic*

Claim: p can outperform γ

The p is an instrument

- A narrow p beam is a concise information package
  - $E_{in} - E_{out}$ — dE/dX(x,y,z)
  - Bragg peak localization — (x,y,z)
  - Charged — Ionizing, count, control / ion
  - Nuclear interactions — γ
  - Highly redundant — Effective use of prior knowledge
- Immediate control feedback
  - Parameters into the system – (E,Q,x,y) – are the ones observed
    - We also need ‘t’
    - Unlike IMRT where D = *f*(leaf position)
  - High-speed controls
    - Limited, typically, by E switching

PBS Control

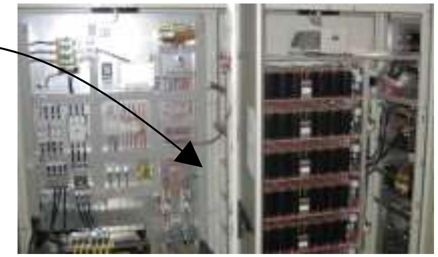
PYRAMID Technical Consultants, Inc.

iba

Jay Flanz
Ben Clasie

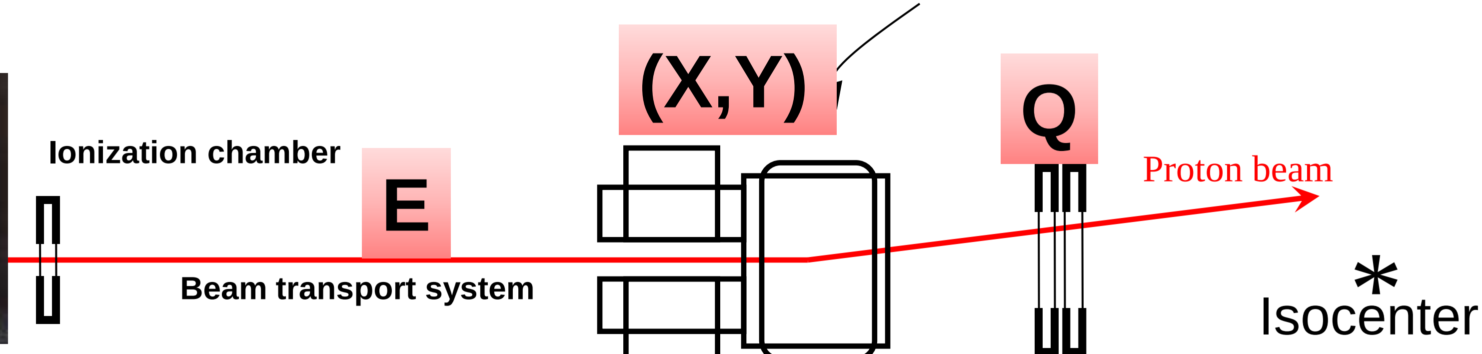
TP SpotMap
(Q, E, X, Y)

Scanning controller, Pyramid Technical Consultants PTC



Scanning magnet power supply, JEMA

Proton source, IBA



Scanning magnets (nozzle)

Ionization chambers (nozzle)

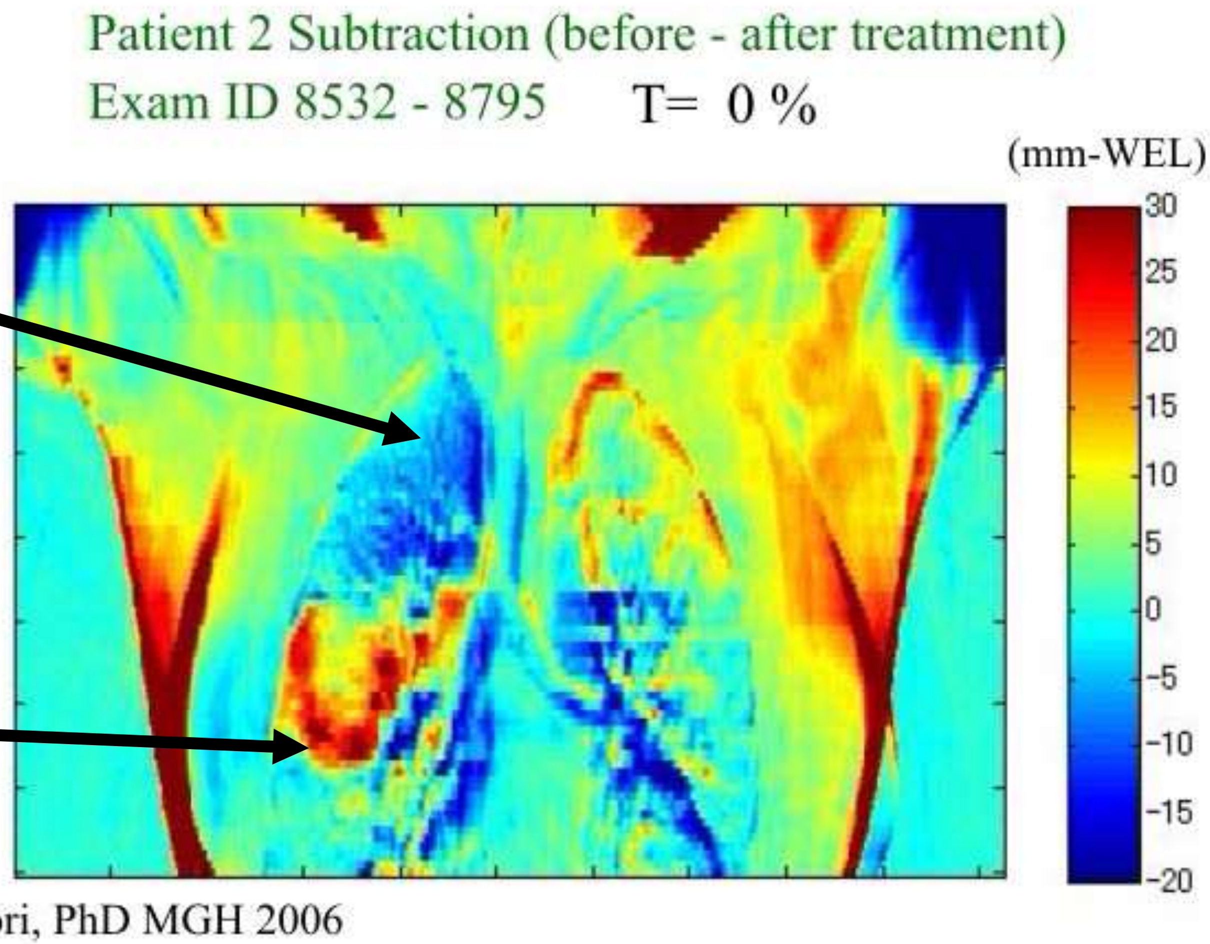
Hall probes, PTC

Electrometers, PTC

- *In PBS: Same variables (Q, E, x, y) throughout in planning, control, and verification*
- *Fully electronic*

Challenge – IGRT

p IGRT: Difference Range Map

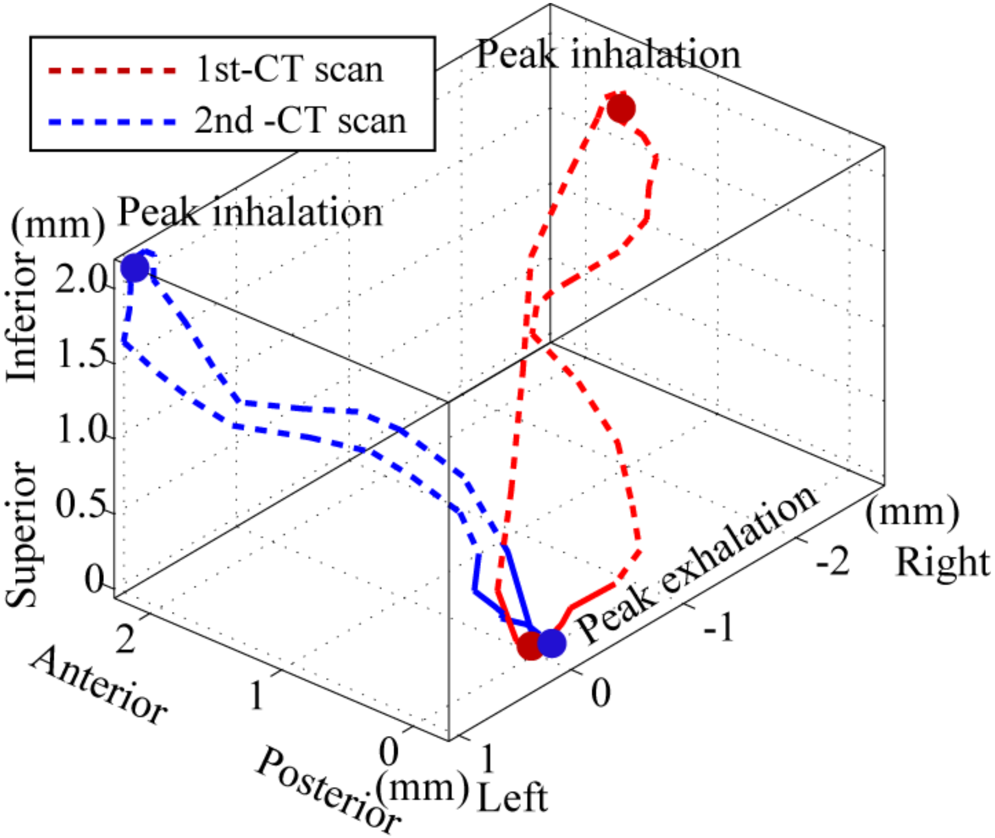


Blue region

Primary changes due to tumor Shrinkage

S Mori & G Chen MGH

p IGRT: Dynamics / ART



Prior Knowledge

- Pre-treatment imaging resolves the set of target positions
- Selective range imaging can rapidly "probe" the patient

PBS time structure is fast

- Energy is slowest (0.5 s ?)
- Q(x,y,E) $\rightarrow$ Q(x,y,E,t)

S Mori & G Chen MGH

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HARVARD MEDICAL SCHOOL

OncoRay – National Center for
Radiation Research in Oncology, Dresden

In vivo dosimetric verification of proton radiation therapy: Biomolecular understanding and application of hepatocyte-specific functional MRI

C. Richter[1], J. Seco[2], O.C. Andronesi[3], R. Borra[3],
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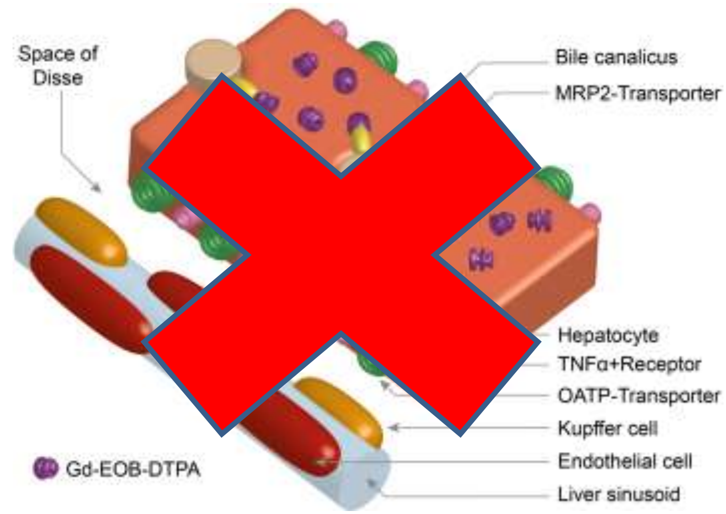
[3] Massachusetts General Hospital, Department of Radiology, Boston

Eovist uptake mechanism



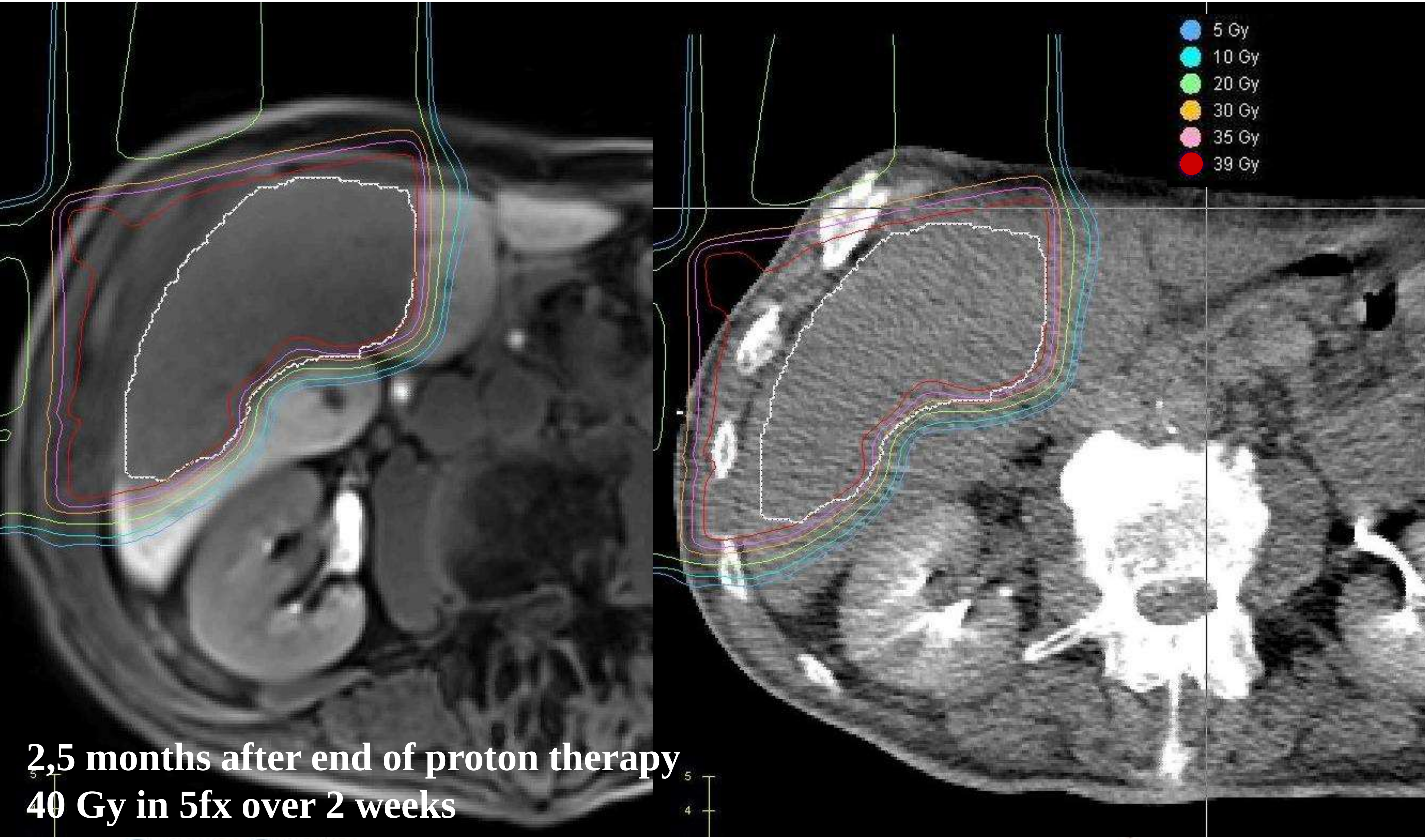
Gd-EOB-DTPA

- Clinical available (Eovist = Primovist)
- 50 % actively taken up in healthy hepatocytes by Organic Anion Transporter Proteins (OATPs)

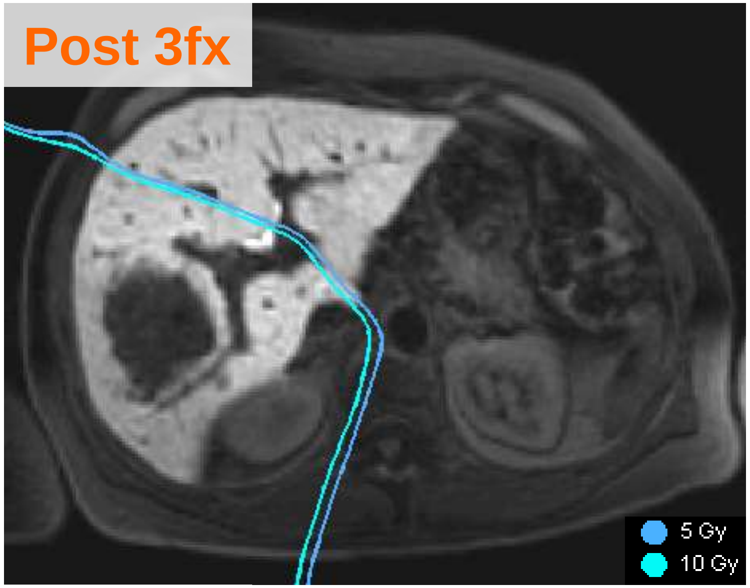
Influence of irradiation

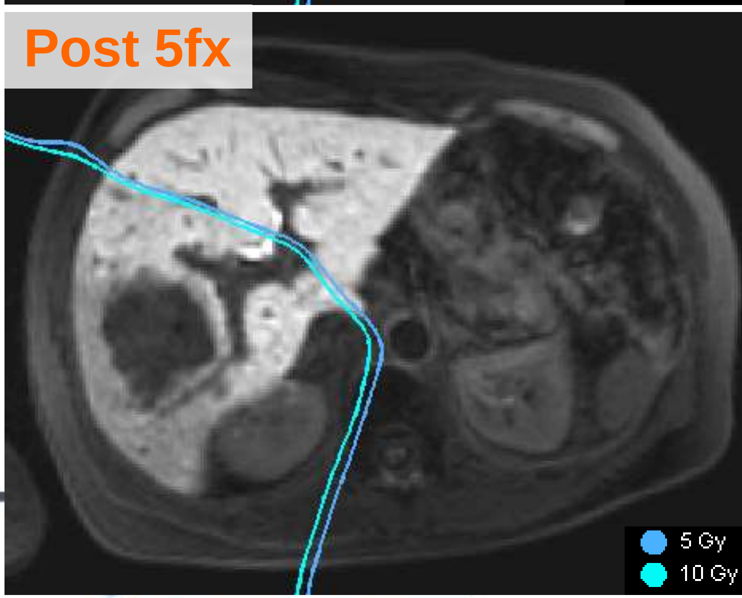
- Irradiation induced release of proinflammatory cytokines (TNF-α, IL-1β, IL-6)
- Proinflammatory cytokines influence hepatocytic function

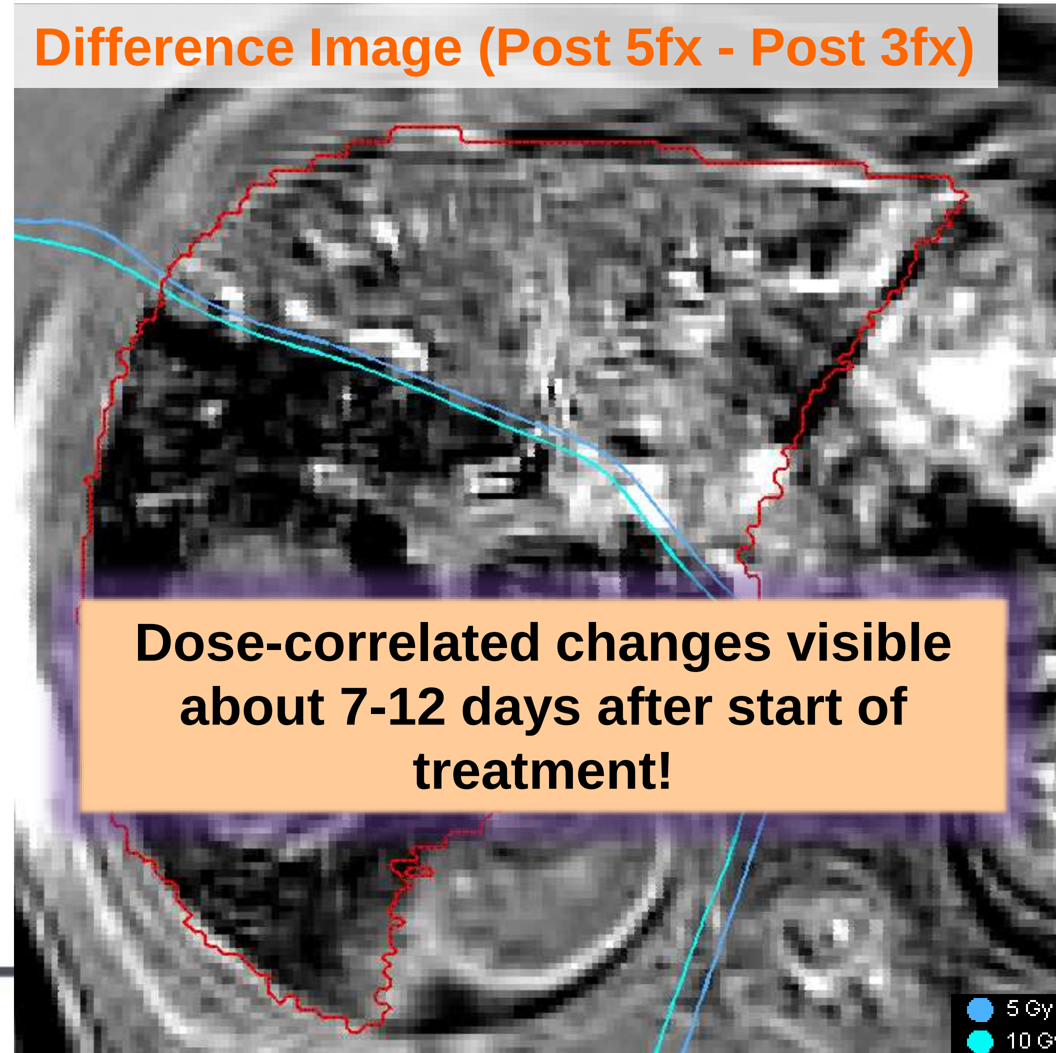
Eovist enhanced MRI post-pRT



Response during treatment?







Dose-correlated changes visible about 7-12 days after start of treatment!

A Detailed Comparison of proton vs. Carbon Ion Computed Tomography

David C Hansen[1], Thomas S Sørensen[1;2], Joao Seco[3]

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2 Department of Computer Science, Aarhus University, Denmark
3 Harvard Medical School and Massachusetts General Hospital, MA, USA
Email contact: dch@ki.au.dk

Ion Tomography

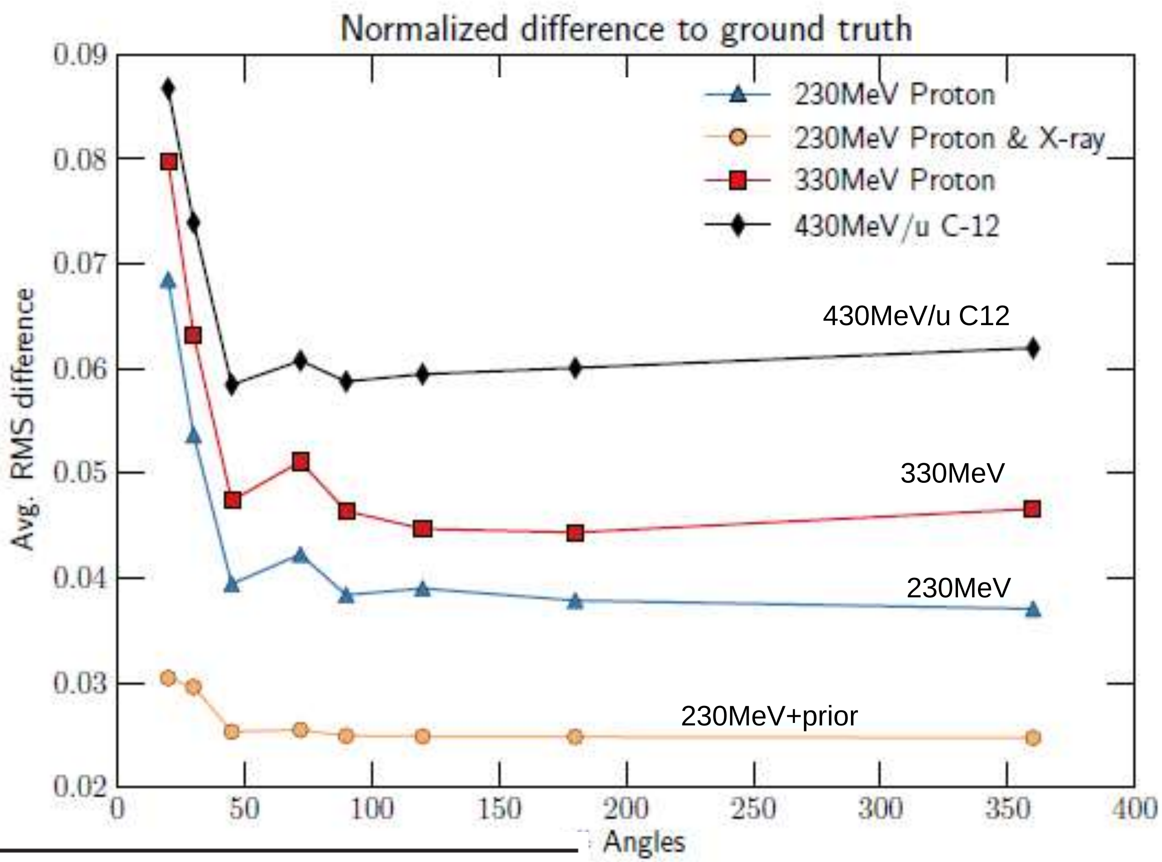
- Stopping Power ratio conversion from HU based on *population average* has a systematic range error (~2%)
- Proton tomography originally proposed by Andy Koehler (1968, *Science*)
  - Experiment: A Cormack & A Koehler (1976, PMB)
- Issues:
  - Proton: Scatter in patient
  - Carbon: Dose in patient
- Use *prior information*

Conventional: $\min \| Ax - b \|^2$ subject to $x_i > 0$

+Prior CT: $\min \| Ax - b \|^2 + \lambda \| x - p \|^2$ subject to $x_i > 0$

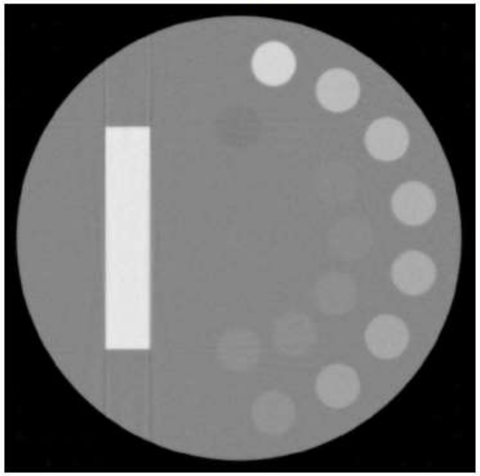
where **A** is the path to ΔE functional, **x** reconstructed density, **b** energy loss, **p** prior CT converted to S

Ion Tomography

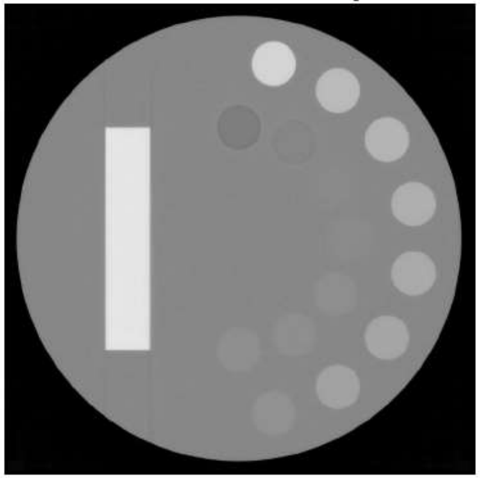


Type	Resolution (mm)
230MeV Protons	1.04
230MeV Protons & X-ray	0.38
330MeV Protons	0.84
430MeV/u C-12	1.12

230MeV



230MeV & X-ray



In vivo proton beam range verification using resolvable prompt gamma lines

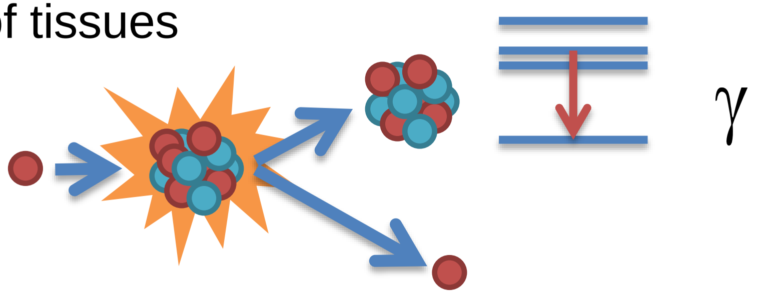
Joost Verburg, Kent Riley PhD, Joao Seco PhD

Harvard Medical School and Massachusetts General Hospital

Resolvable prompt gamma lines

- **Most prompt gamma-rays near end-of-range result from a few nuclear level transitions**
  - $^{16}O(p,p')\,^{16}O^*$ 6.13 MeV γ
  - $^{12}C(p,p')\,^{12}C^* + {}^{16}O(p,p\alpha)\,^{12}C^*$ 4.44 MeV γ
  - $^{16}O(p,p')\,^{16}O^*$ 2.74 MeV γ
  - $^{16}O(p,px)\,^{15}N^* + {}^{16}O(p,px)\,^{15}O^*$ … 5.2 MeV γ

- **Resolving discrete energies allows for novel range verifications methods**
  - Incorporate known nuclear reaction cross sections
  - Improve accuracy in the presence of tissues with unknown compositions

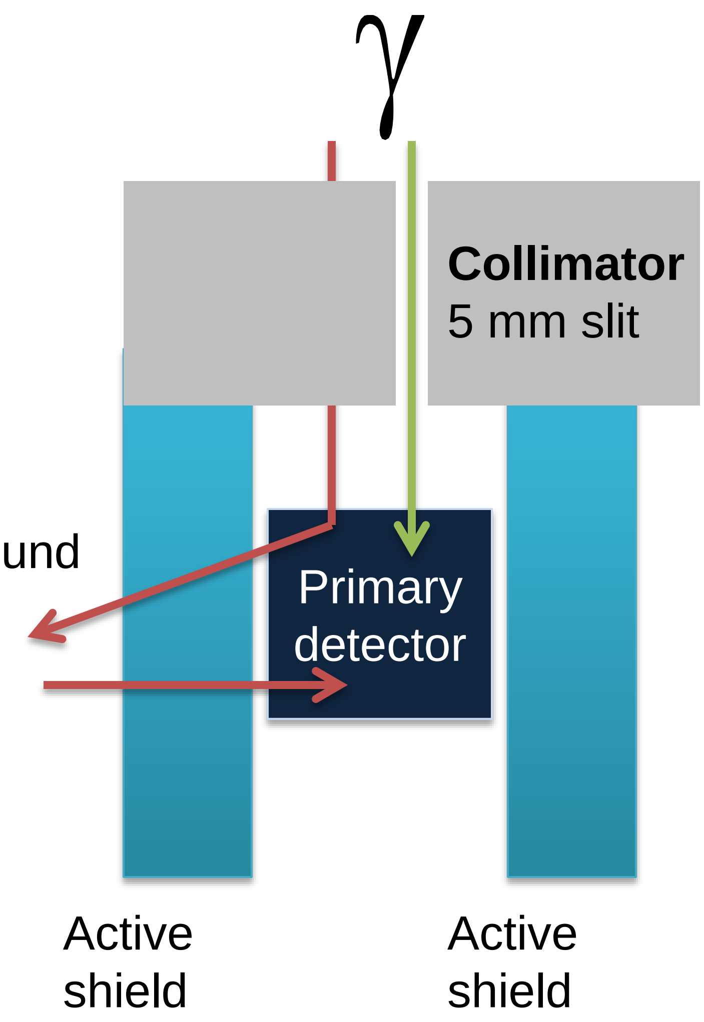


Prototype detector

1. **LaBr$_3$(Ce) scintillator with high energy resolution**

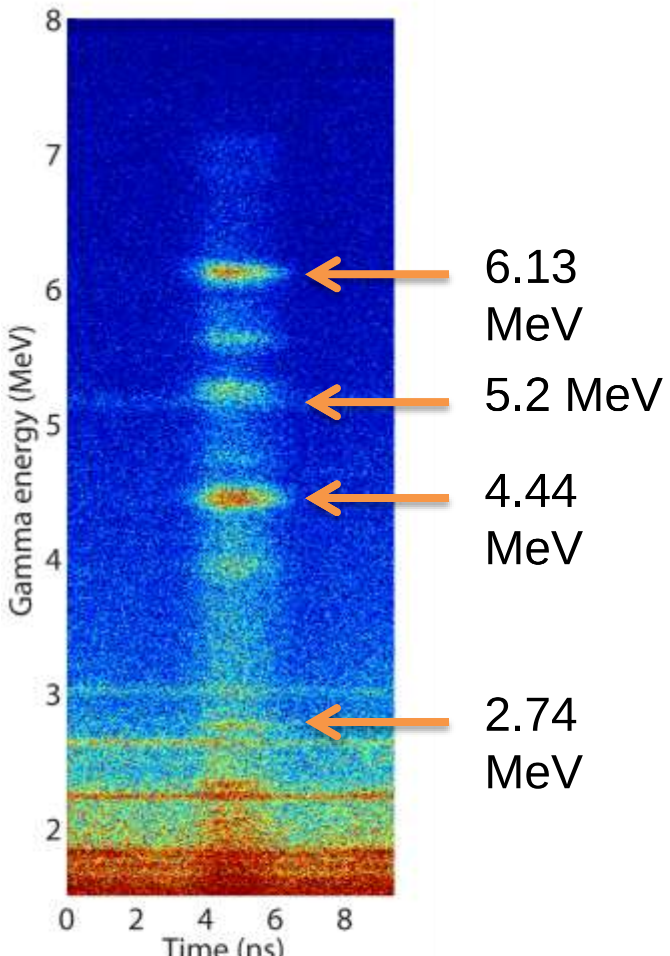
2. **Active anti-coincidence shield**
   - Reduce Compton background
   - Reduce neutron-induced gamma background

3. **Data acquisition system**
   - Synchronized to cyclotron radiofrequency (9 ns period)
   - 200 ps sampling resolution
   - Digital pulse processing

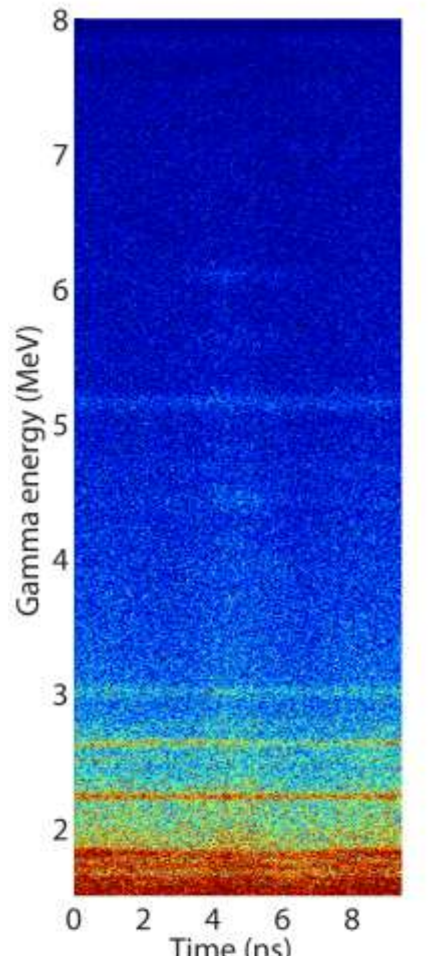


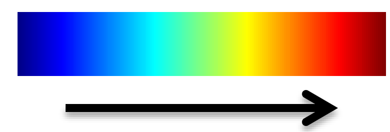
Results: Time/energy histogram

9 mm proximal to end-of-range

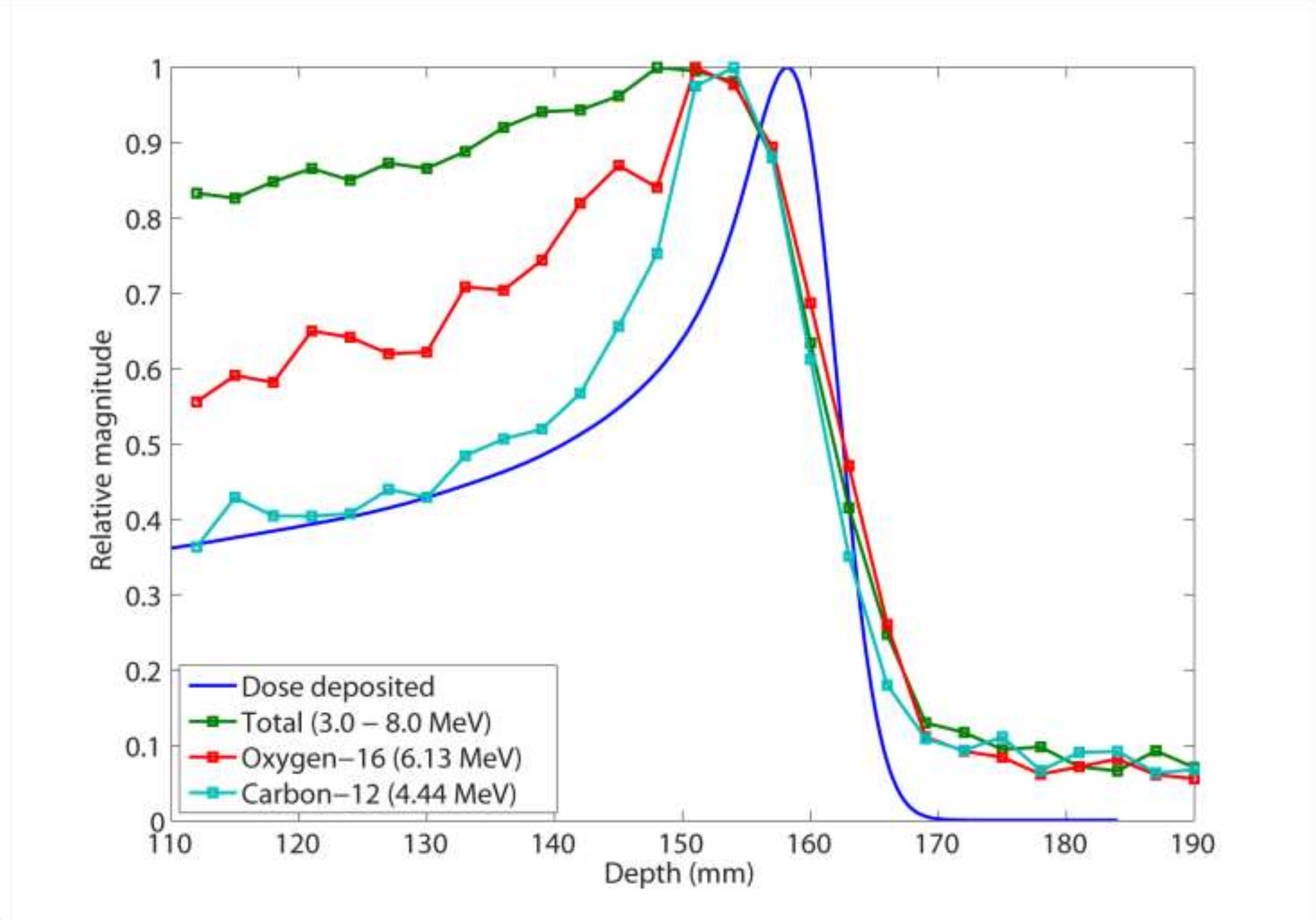


9 mm distal to end-of-range





Results: Range 16 cm



Patient Imaging Requirements

- Geometric setup and stability
  - Multi (1..n) planar X-ray
- Motion tracking
  - Surface tracking (RPM, VisionRT, …)
  - Fluoroscopy of diaphragm / internal markers
  - EM / RF
- Soft-tissue deformation / changes
  - CBCT
- Adaptive planning
  - (4D)CT
- Perform within the treatment session workflow
  - Optimization
  - Connectivity

Workflow

Imaging

- X-ray + CBCT
- CT

Procedures

- Scenarios
  - Outside / Inside room Immobilization / Imaging
  - Optimization
  - Flexibility
- Facility Layout
- Workflow

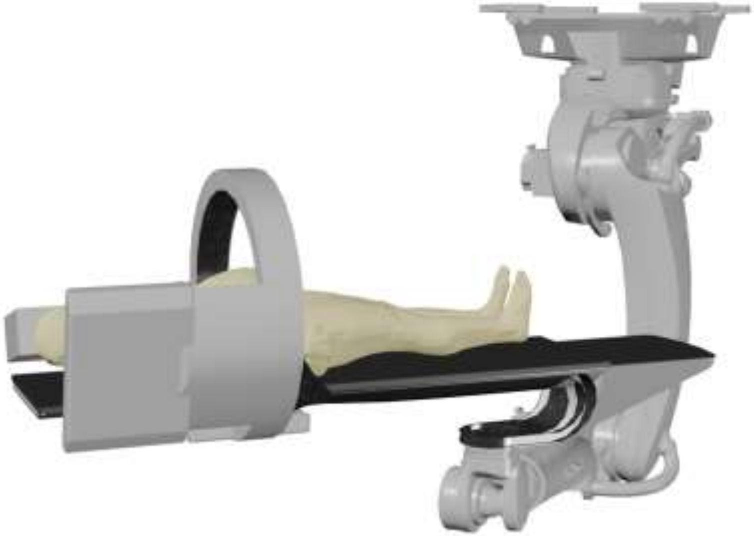
IGRT: Some in-room solutions

CT (on rails) – Off isocenter, space, time

HIT PPS solution

Gantry mounted X-ray systems

PAIR: Integrated imaging ring:



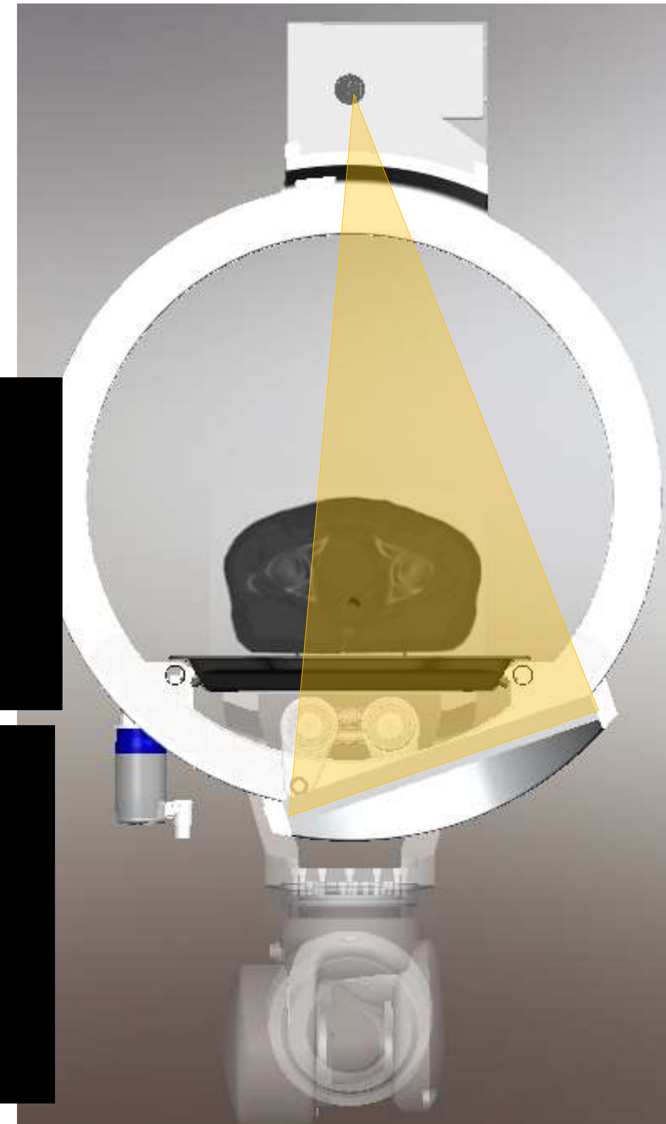
- X-ray / Panel Independent Motion
- Couch CS
- X-ray
- CBCT
- Fluoroscopy

medPhoton GmbH

Ultra-large Field of Views

medPhoton GmbH

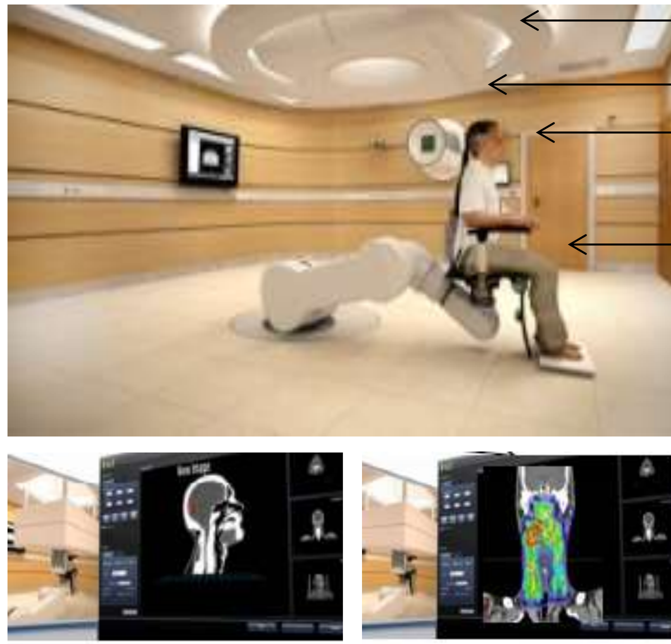
Image auto-stitching



Fixed Beam Setup for Seated Patients

Products

1. P-ART Comprehensive System (all modules but adaptive therapy sw)
2. P-ART Imaging System (all modules, but the robot and the adaptive sw)
3. P-ART Adaptive Therapy System (the adaptive sw)



Product Modules

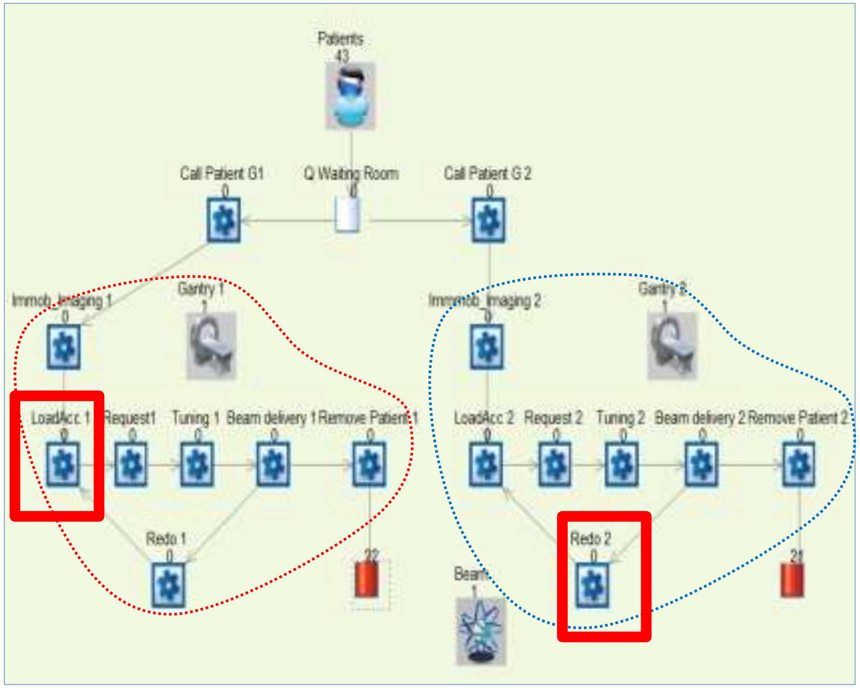
- P-Cure Moving Platform
- CT Scanner
- Camera
- Robotic Chair
- Adaptive Therapy Software
- Positioning Software

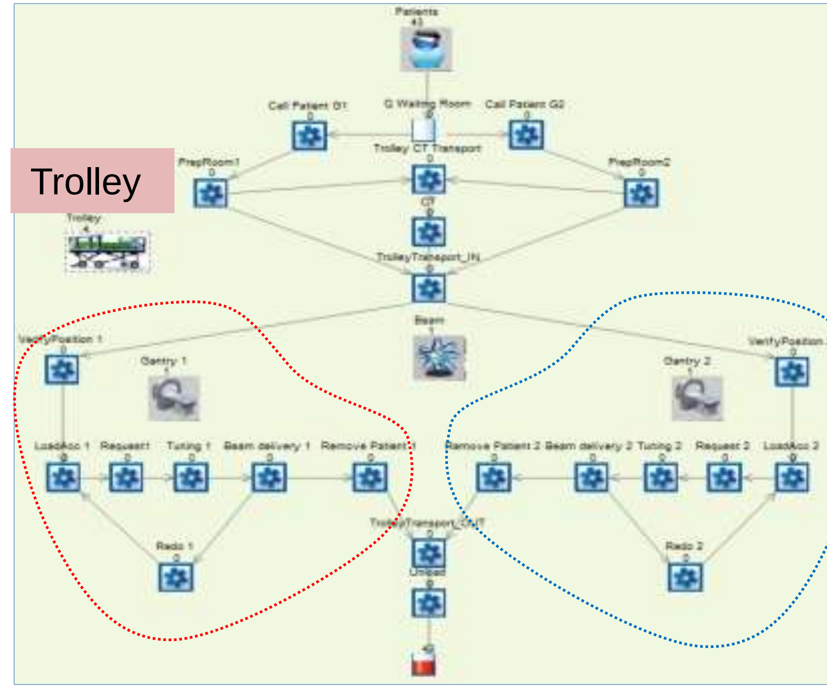
Real-Time imaging + ART can compensate for uncertainties in seated patients

Workflow Simulation

- Analyze
  - Patient flow - are there bottlenecks?
  - Queue locations and sizes – are they blocked or starved?
  - Resources - are they sufficient, do they starve important operations?
  - Failure modes - what are they and what causes them?
  - Check required capacity
- Optimize
  - A stitch in time saves nine – find all the little holes in the process
  - Try before you build
  - Create baseline for performance and improvement
- Discrete-Event Simulation
  - Model system state changes at precise points in simulated time
  - Many commercial packages – Simul8

Workflow Scenarios





- In gantry
  - 1..2 X-ray imaging

- Dedicated per gantry
- Immobilization with either
  - No imaging
  - CT
  - <u>Orthogonal Imaging</u>
- In gantry
  - 1..2 X-ray imaging

Current State – 100 days

Total (min)	553
Gantry (min)	501
Interval (min)	51

Total = End of Last – Start of First patient
Gantry = sum of all patient time in gantry
Request = waiting time in request

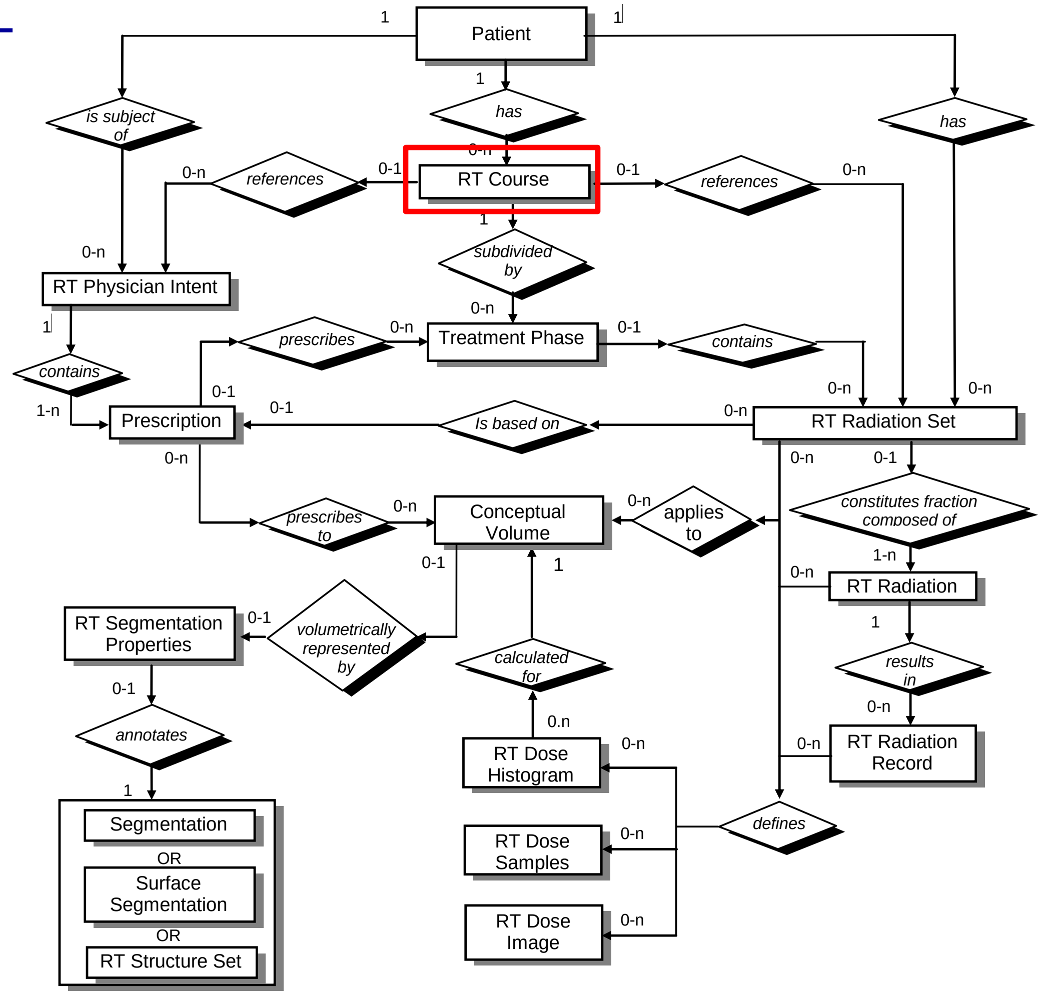
Workflow Connectivity

- The treatment session comprises several discrete tasks combinable in various workflow scenarios
  - Immobilization
  - Volumetric imaging for dose verification
  - Treatment plan adaptation
  - Setup verification
  - Beam-on monitoring
- Requires data model and connectivity for inter-task communication
  - DICOM Gen 2
  - IHE-RO Profiles

Workflow Connectivity

Sup 147: Second Generation RT Radiotherapy

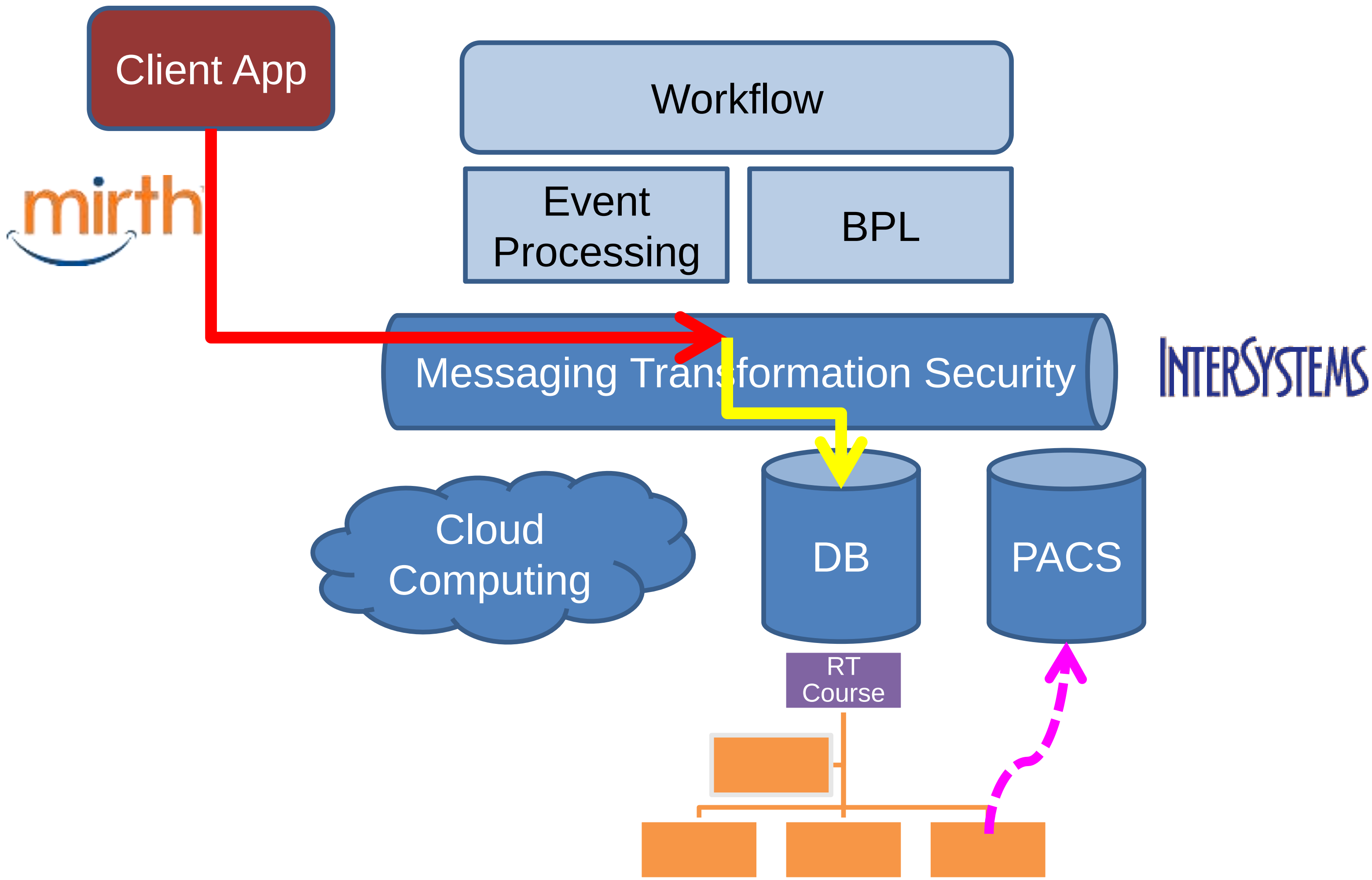
- Existing radiotherapy IODs were designed as containers to <u>communicate</u> radiation therapy data
- Radiation therapy practice and DICOM have evolved.
- In particular, workflow management is now a key aspect of DICOM's domain of application
  - Unified Worklist and Procedure Step
  - Temporal view to map the treatment sequences



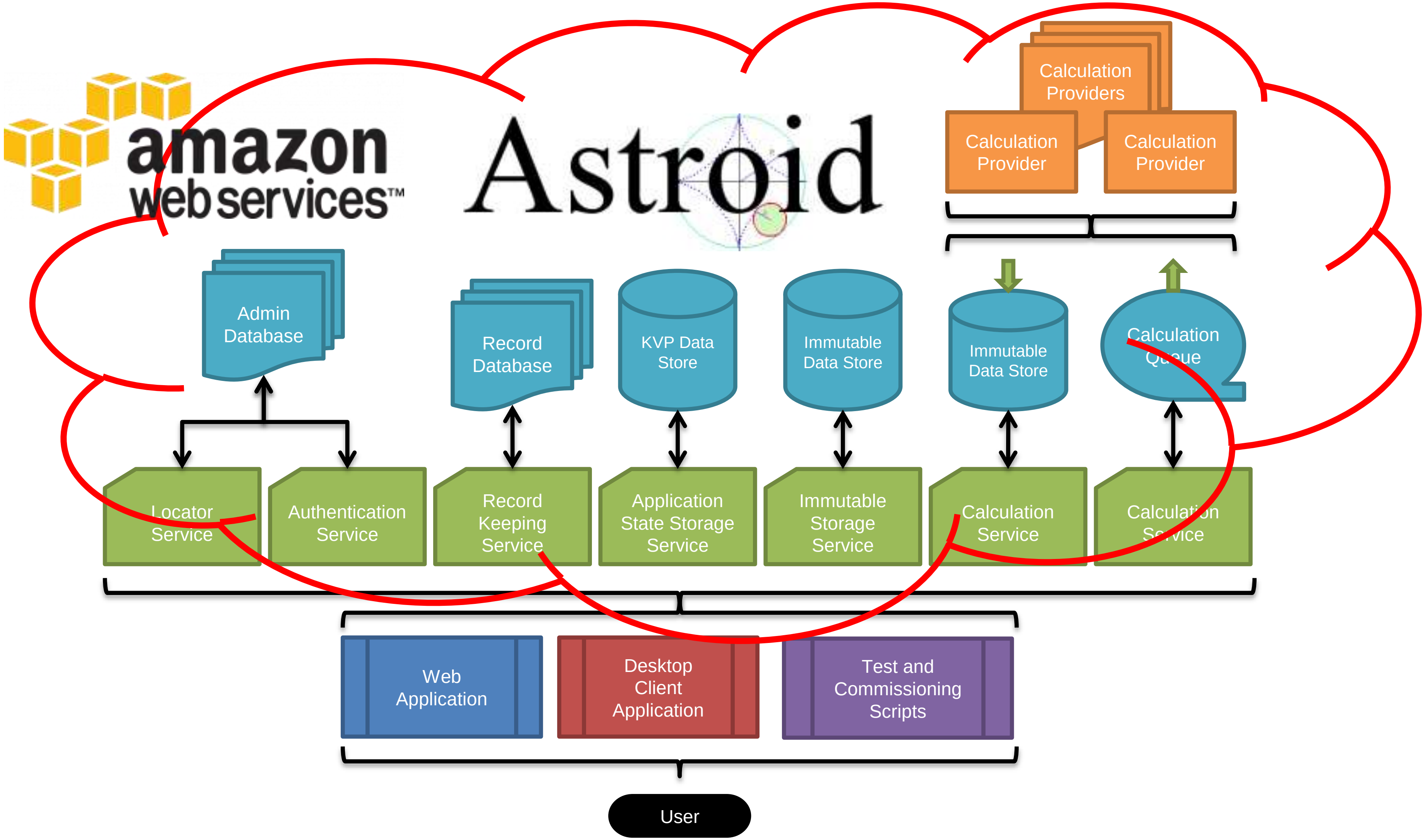
Workflow Connectivity

- MGH uses a “Whiteboard” that manages the data hand-off between tasks
  - Did not find sufficient or efficient support in existing systems
- MGH / ICT are developing an Enterprise System Bus to
  - Capture and coordinate all data transactions between systems (tasks)
    - Build-up DICOM Gen 2 RT Course Record as a function of executed and pending tasks
  - INTERSYSTEMS Ensemble and Cache for ESB
    - Service Oriented Architecture
      - RT systems are, typically, “stand-alone” applications
    - Business Rule Engine to manage task scheduling and execution
  - mirth™
    - DICOM interface and routing

Service Oriented Architecture



Large Scale Computing Architecture



Summary

- p $\neq$ X
  - Same (perhaps) requirements
  - Different Implementation especially where geometry does not suffice for dosimetric feedback (CT vs CBCT)
- p physics offers enhanced feedback
  - Tissue interactions: Prompt γ
  - Immediate dosimetric feedback during delivery
    - Permits control and adaptation during delivery
- Workflow integration and variation
  - “Old” LINAC workflow model must be challenged
  - Do not, ad-hoc, re-use solutions – Look at requirements
- Data & High Performance Computation Backbone
  - Light-weight “point of service” applications
  - Need to capitalize on “modern” computing