MASSACHUSETTS GENERAL HOSPITAL
CANCER CENTER℠

QA for Scanned Beams

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Concepts in QA

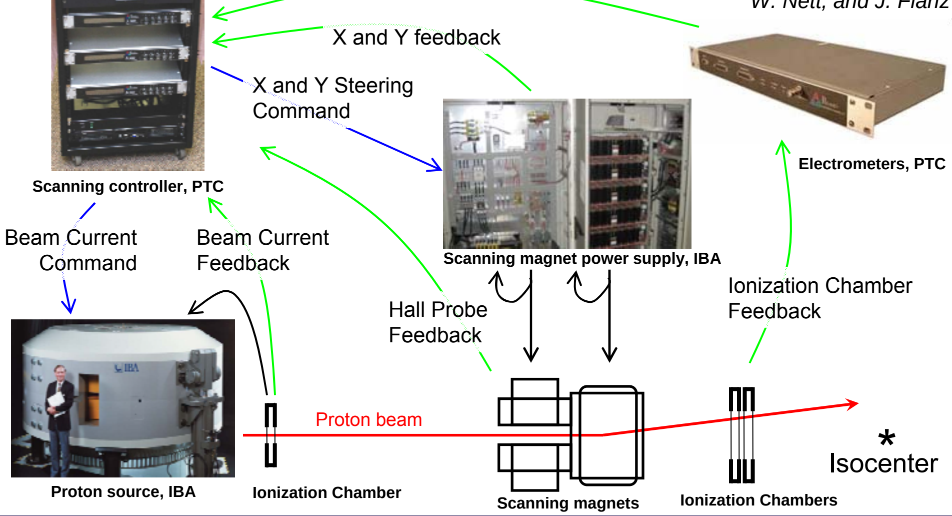
- The set of processes, and their tests, that provide confidence that the "process" and "product" are within the desired parameter phase-space
- Tests should be orthogonal & complete, i.e. yield results that are sensitive to specific underlying process controls
  - Used recurrently against initial baseline & requirements (Validation / Commissioning)
- QA should be based on an operational model that forms the context for tests, analysis, and quality improvement (QI)

Scanned Beams

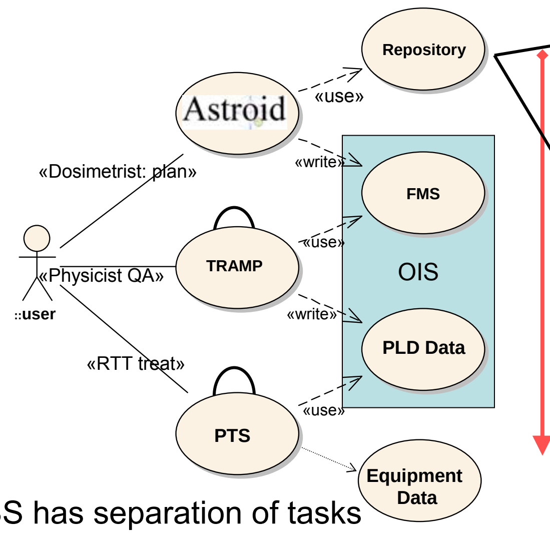
- PBS: dose (in patient) “maps” to control variables
  - D(x,y,z) = F(x,y,Q,E,σ)
- IMRT: dose maps to “leaf-positions”
  - D(x,y,z) = F([xa, xb], [ya, yb], MU)
- Thus in PBS:
  - Clinical variables ≡ Physical observables
    - Allows continuous monitoring of “dose”
    - Establish requirements through variance analysis
  - TPS has direct path to PTS
    - Workflow & QA considerations

PBS Control Flow

P. Boisseau, Y. Claereboudt, D. Demaret, W. Nett, and J. Flanz



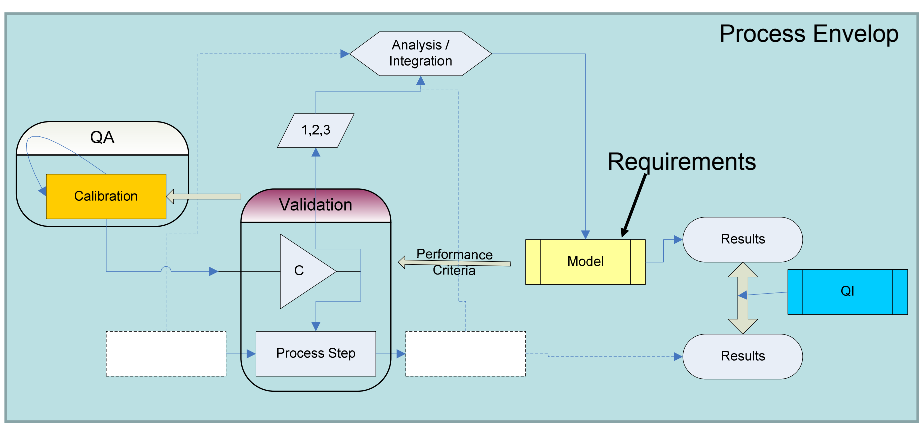
Treatment Workflow



- **Astroid**
  - Data Management
    - Versioning
    - Sign-off
  - Optimize beam(s)
    - Optional RC/AP
  - Produce Flux Map
- TRAMP
  - Read Flux Map
  - Convert to equipment deliverable map
  - Write PLD
  - QA
- PTS
  - Read PLD
  - Deliver treatment

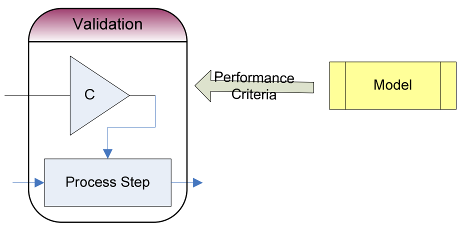
PBS has separation of tasks

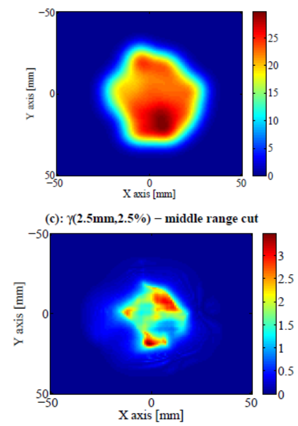
QA Contexts & Semantics



Performance – Analysis

- Desired performance dictates required operation of process component
  - … worse, process can limit achievable & desired result!
- Per treatment site, simulate and vary the control variables and compare to reference
  - PBS: Δ of R, σ, [X,Y], Q
  - Use γ-index for comparison





Performance – Requirements

Base of skull ependymoma - 220 deg

γ	Range Random		Range Systematic		Sigma Random		Sigma Systematic	
parameters	*min*	*max*	*min*	*max*	*min*	*max*	*min*	*max*
δd , δD	[mm]	[mm]	[mm]	[mm]	[%]	[%]	[%]	[%]
1.0mm,2.5%	−0.907	0.856	−0.355	0.363	−10.394	10.982	−7.764	9.258
1.5mm,2.5%	−0.983	0.938	−0.422	0.436	−12.329	13.565	−9.267	12.727
2.0mm,2.5%	−1.026	1.001	−0.495	0.505	−14.602	15.985	−10.458	16.730
2.5mm,2.5%	−1.062	1.045	−0.564	0.577	−16.486	17.758	−11.474	$>$ 20.000

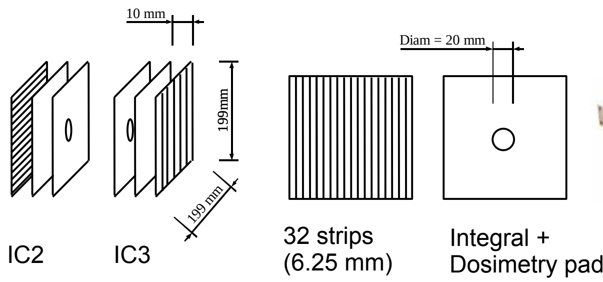
Table 4: 5mm σ fields results - requirements summary table (part II)

- Desired accuracies for γ (2.5 mm, 2.5%)
  - Range ± 0.5 mm
  - σ ± 15% (of nominal σ)
  - [X,Y] ± 0.7 mm
  - Q ± 3-5%
- Systematic errors are of biggest concern

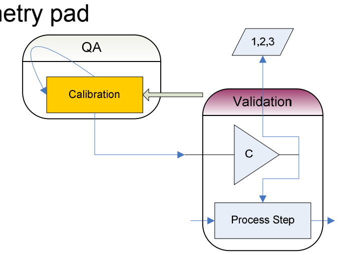
J. Hubeau et al IBA/MGH

Performance – A Control

- IC2 and IC3 each have 3 planes



- The electrometer (Pyramid, MA)
  - Q sensitivity is 0.1 pC
  - Read-out rate is 10 kHz
- Analysis T for σ and [X,Y] is 4 kHz



Performance – Control Calibration

- Screen-detector (BIS*) on nozzle
  - Compare [X,Y] at isocenter — 0.5 mm precision
  - Compare σ at isocenter — ~1.0 mm precision
  - Depends on σ/W
- Absolute [X,Y] calibration
  - BB at isocenter (verified w X-Ray + Beam)
  - Calibrate [0,0] on chamber readout
- Linearity in Q
  - Faraday Cup
  - MU(E) vs Q in cup

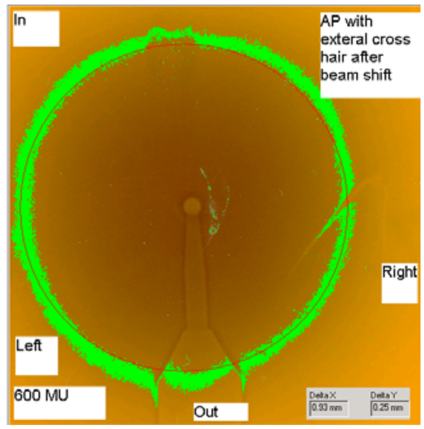
Range stability [mm]	Range accuracy [mm]	Sigma stability [%]	Sigma accuracy [%]	Position stability [mm]	Position accuracy [mm]	Weight stability [%]	Weight accuracy [%]
±1.5	±1.5	±25	±25	±2	±2	±10	±5

σ ~ 10 mm (2 mm, 3%) for current PBS configuration

* Wellhofer

Performance – Control Calibration

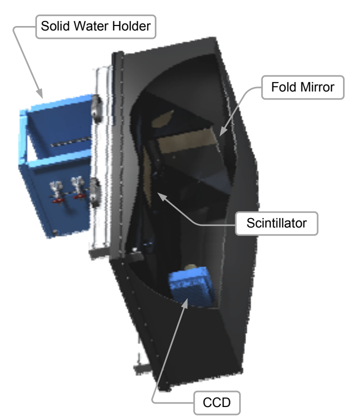
- IC [X,Y] Calibration
  - Center BB @ isocenter
  - Steer beam at BB using IC until centered



Hsiao-Ming Lu

QA Detector

- Mounts to scanning nozzle
- Fast scintillator with high resolution & sensitivity
- Remote focus/aperture, exposure control
- Autocalibration
- Resolution > 1 lp/mm
- No active components simplifies instrumentation
- Minimal scatter of beam

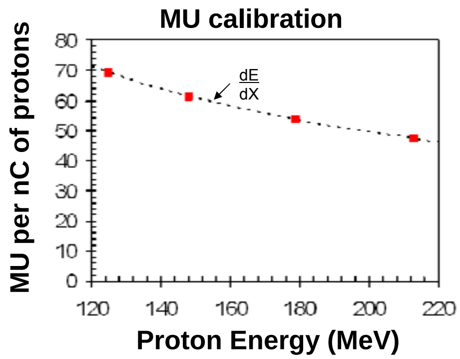


Ebstein et al High-Resolution Scintillation Screen Detectors

Calibration – MU vs Q

Faraday cup

B. Gottschalk

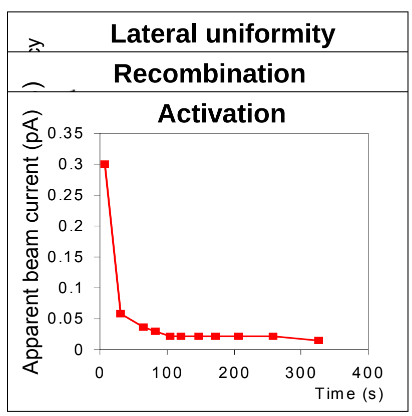


H. Bentefour and B. Clasie

Contributions to Q Uncertainties

Spot Weight (Q/MU) Accuracy

• Dark beam current Can be removed by detuning cyclotron when I=0	2.0%
• IC lateral uniformity	1.0%
• Electrometer	
• linearity (FC)	0.7%
• resolution (spec)	0.01%
• Time response (beam off)	0.5%
• Gantry angle dependence	0.5%
• Recombination	0.2%
• Chamber activation	0.05%
• Total	±2.5%



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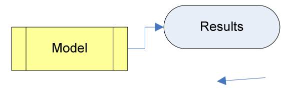
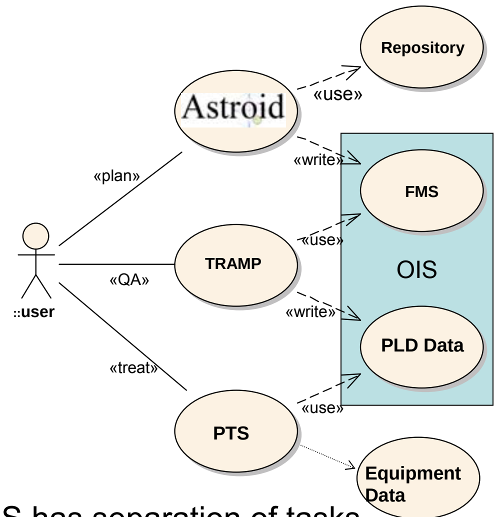
Treatment Workflow





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PBS has separation of tasks

Treatment Workflow

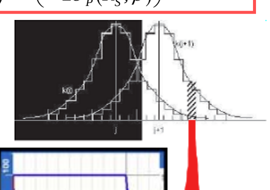
Astroid

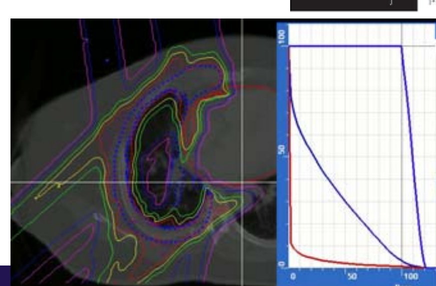
- TPS – Engines
  - Dose Model
    - Spatial accuracy
    - Physical (1b) v Computational (1c)
    - MC vs Algorithmic
    - Apertures & Compensators
  - Optimizer
    - MCO
  - Requirements based validation

$$D(\vec{x}) = \sum_S G_S \quad (1a)$$

$$\times \sum_K \left(\oint \frac{1}{2\pi\sigma_O^2(R_S,z)} \exp\left(-\frac{\Delta_{S,K}^2}{2\sigma_O^2(R_S,z)}\right) dA_K \right) \quad (1b)$$

$$\times \frac{D_{R_S}^{\infty}(\rho)}{2\pi\sigma_P^2(R_S,\rho)} \exp\left(-\frac{\Delta_K^2(\vec{x})}{2\sigma_P^2(R_S,\rho)}\right) \quad (1c)$$





Treatment Workflow

Astroid

- TPS – Data & Commissioning
  - DD – Gy cm^2 Gp^{-1}
  - LUT – Calibrate ESS
  - $\sigma(E)$ – Optics

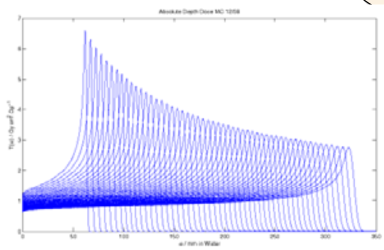


Figure 1: The pencil-beam Bragg peaks generated in GEANT and verified by measurement with the Bragg chamber (Nicolas Depauw).

R90	R80	E
182.61	183.23	162.98
185.54	186.27	164.52
187.86	188.59	165.69
190.27	191.02	166.91
192.58	193.33	168.07
194.79	195.54	169.18
197.09	197.86	170.33
199.38	200.16	171.48
201.57	202.35	172.57
203.76	204.55	173.66
205.94	206.74	174.74
208.12	208.92	175.82
210.19	211.00	176.84
212.26	213.07	177.86
214.32	215.14	178.88
216.47	217.31	179.94
218.53	219.37	180.95
220.48	221.32	181.91
222.43	223.28	182.86
224.37	225.23	183.81
226.89	227.75	185.05
228.82	229.69	185.99

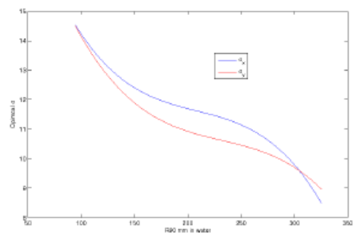


Figure 4: Optical spreads as a function of energy (in R_{90}).

Absolute Dose

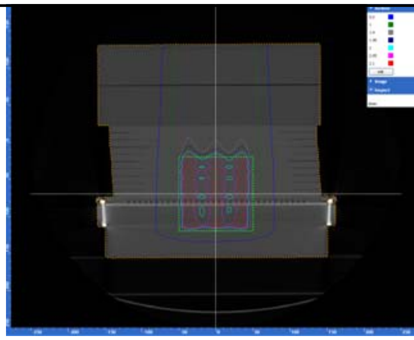
MU ← Optimization ← D(d, E) [Gy cm^2 / MU]

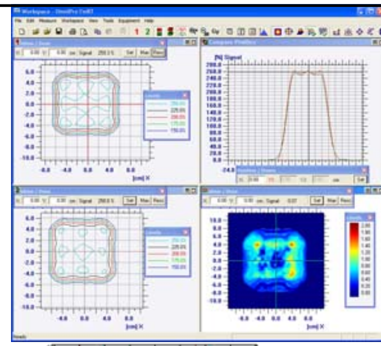
S(E) / Calibrate w Faraday cup

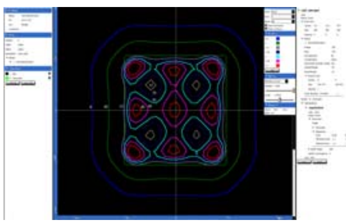
Q [Gp] ← Optimization ← T(d,E) [Gy cm^2 / Gp]

Pure physics
Direct MC model
Intra center communication

Choice impacts our ability to communicate and share treatment plans







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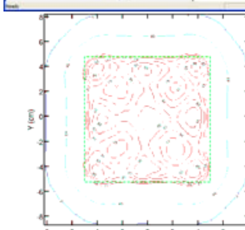
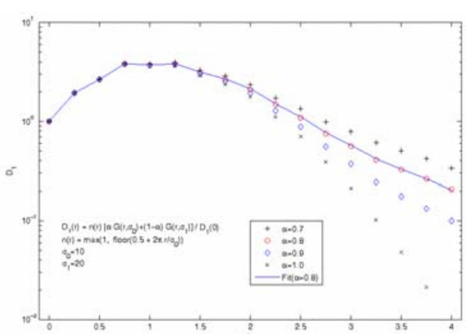


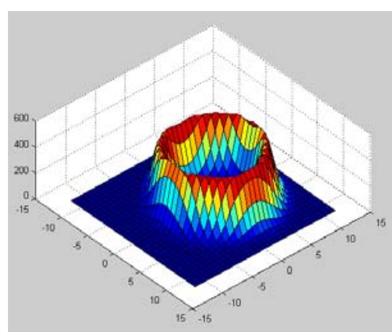
Absolute Dose: For a spot S with Gigaprotons Gs: MU = C dE/dX Gs

Need QA for C = C(x,y)

Repeatability < 1% in output at center

Dose – Perturbations



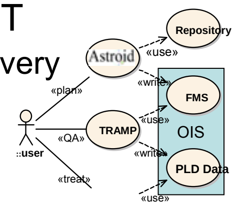


$$D_j = \frac{n_j\left(\alpha G(r_j,\sigma_M) + (1-\alpha)G(r_j,\sigma_H)\right)}{\alpha/2\pi\sigma_M^2 + (1-\alpha)/2\pi\sigma_H^2}$$

Poster 99: B Clasie et al. Dose deposited in the beam halo by a scanned proton pencil beam

Treatment Workflow

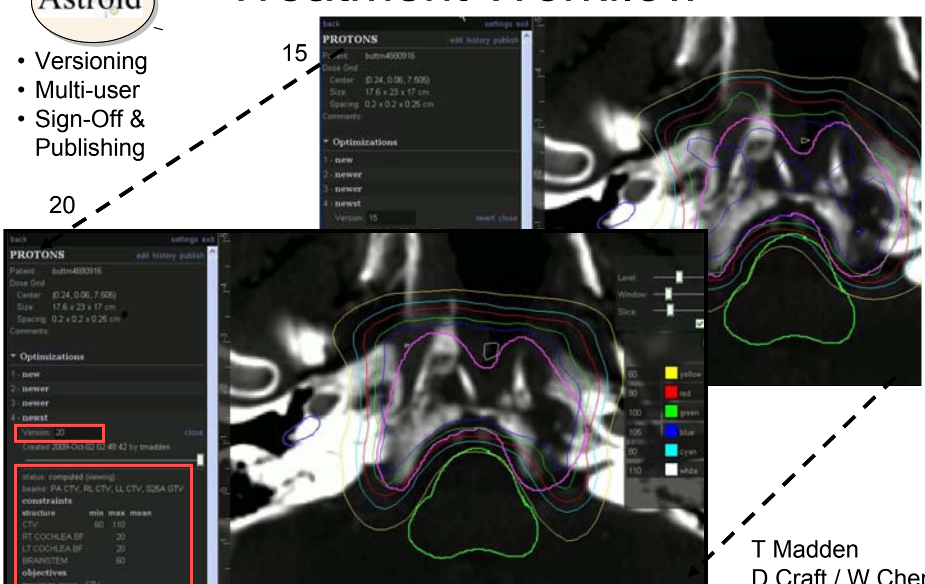
- The Patient: Interfacing with MD & RTT
  - Validation of treatment approach and delivery
    - Robust planning & delivery
      - (Use passive scattered field approaches?)
  - Interfaces to Treatment Planning
    - <u>In</u>: CT / MR / Structures / Prescription
    - <u>Out</u>: Flux Maps
    - <u>In between</u>: TP data management was & is a "black hole"
      - DPLAN (JCRT / Kijewski) Axiom (Siemens)
      - Astroid Repository
  - Documentation & Sign-off at transitions between phases



Treatment Workflow

Astroid

- Versioning
- Multi-user
- Sign-Off & Publishing



T Madden
D Craft / W Chen

Treatment Workflow

- QA TRAMP
  - Trajectory Manipulation
    - FMS is only a shorthand for dose to be delivered
    - Thus, any FMS that delivers that dose is OK
    - Generate optimized trajectories independent of TPS
  - Dose QA
    - Validate FMS for deliverability
    - Verify Q to Dose
      - Include measurements if desired

Summary

- QA is the "tip" of the iceberg – Typically assumed simply the set of recurrent tests.
- These tests must be embedded and interpreted in the "total" system, i.e. complete coverage of system operation, and its intended operation and product.
- "Product" (i.e. "Treat H&N") performance sets requirements for process, its "-lets," and its controls
- Control & Workflow requirements define validation / commissioning / calibration procedures
- Models, and their evolution, provide QI benchmarks
- Not just the technology component