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PROTON THERAPY INSTITUTE

Quality Assurance of Systems.

Roelf Slopsema MSc.

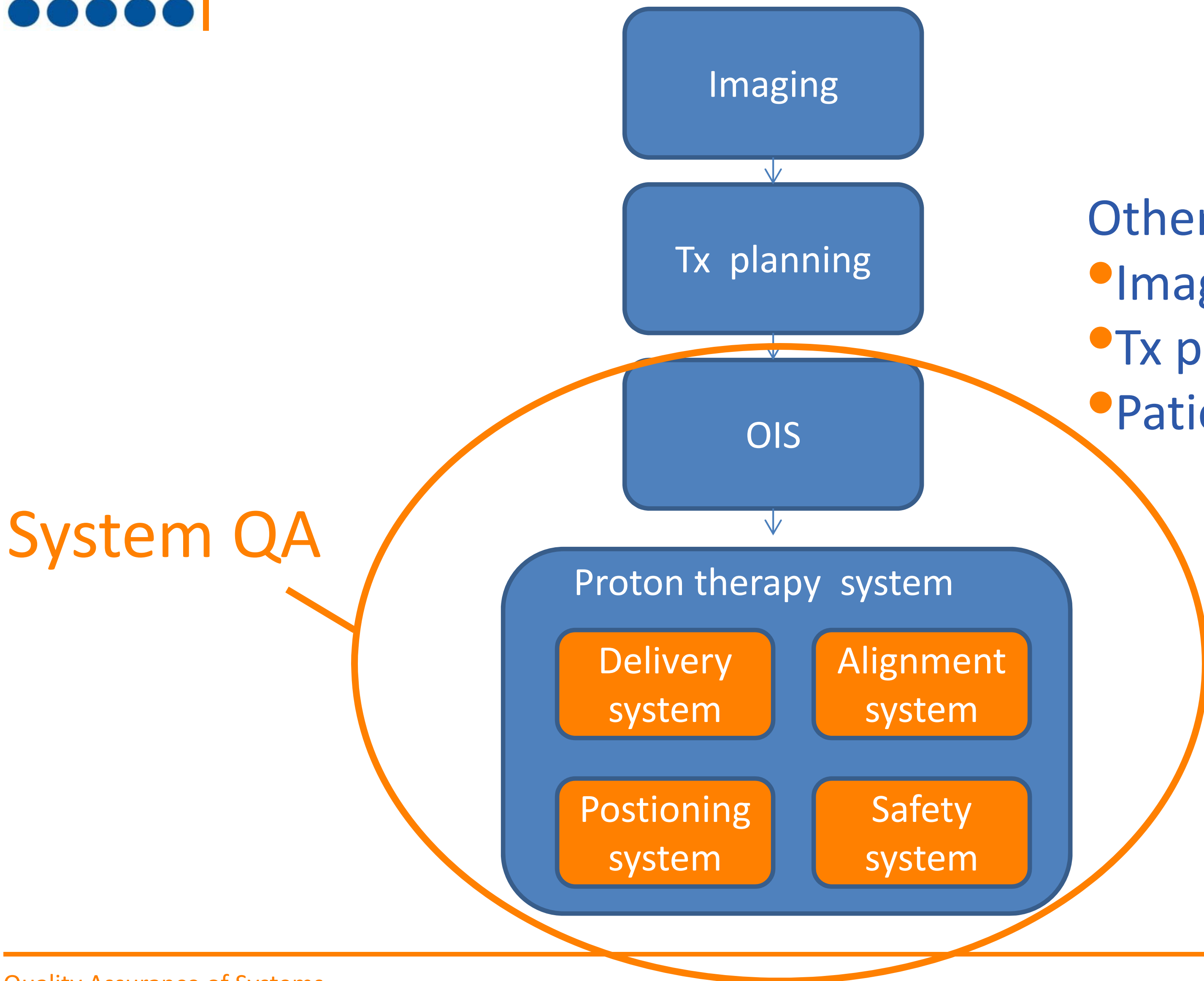
Disclosures

- UFHPTI has IBA equipment
- I have worked for IBA
- Examples in this presentation are not intended to suggest superiority of one system/facility over another

Overview of this lecture

- Introduction
- Examples of system QA procedures and protocols
  - Daily
  - Weekly & monthly
  - Yearly
- Setting up a new QA program
  - Guidelines and references
  - General approach
  - Staffing and scheduling

System QA



Other types of QA
- Imaging systems
- Tx planning
- Patient-specific

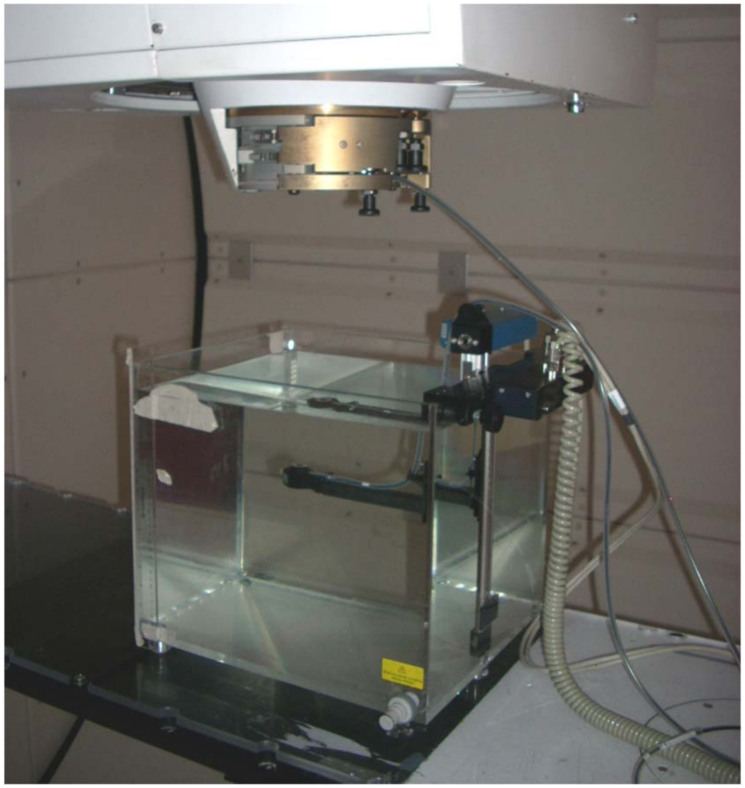
Different delivery techniques

	Using patient-specific collimator and compensator to conform the beam	Using small beam to conform the beam
Using high Z materials to spread beam (**scattering**)	**Double Scattering (DS)**	
Using magnetic fields to spread the beam (**scanning**)	**Uniform Scanning (US)**	**Pencil Beam Scanning (PBS)**

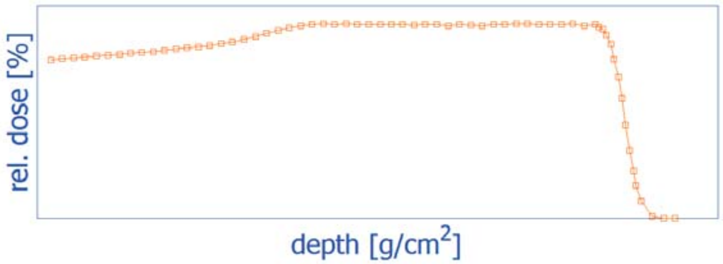
Daily QA - standard dosimetry DS

Parallel-plate chamber in water phantom

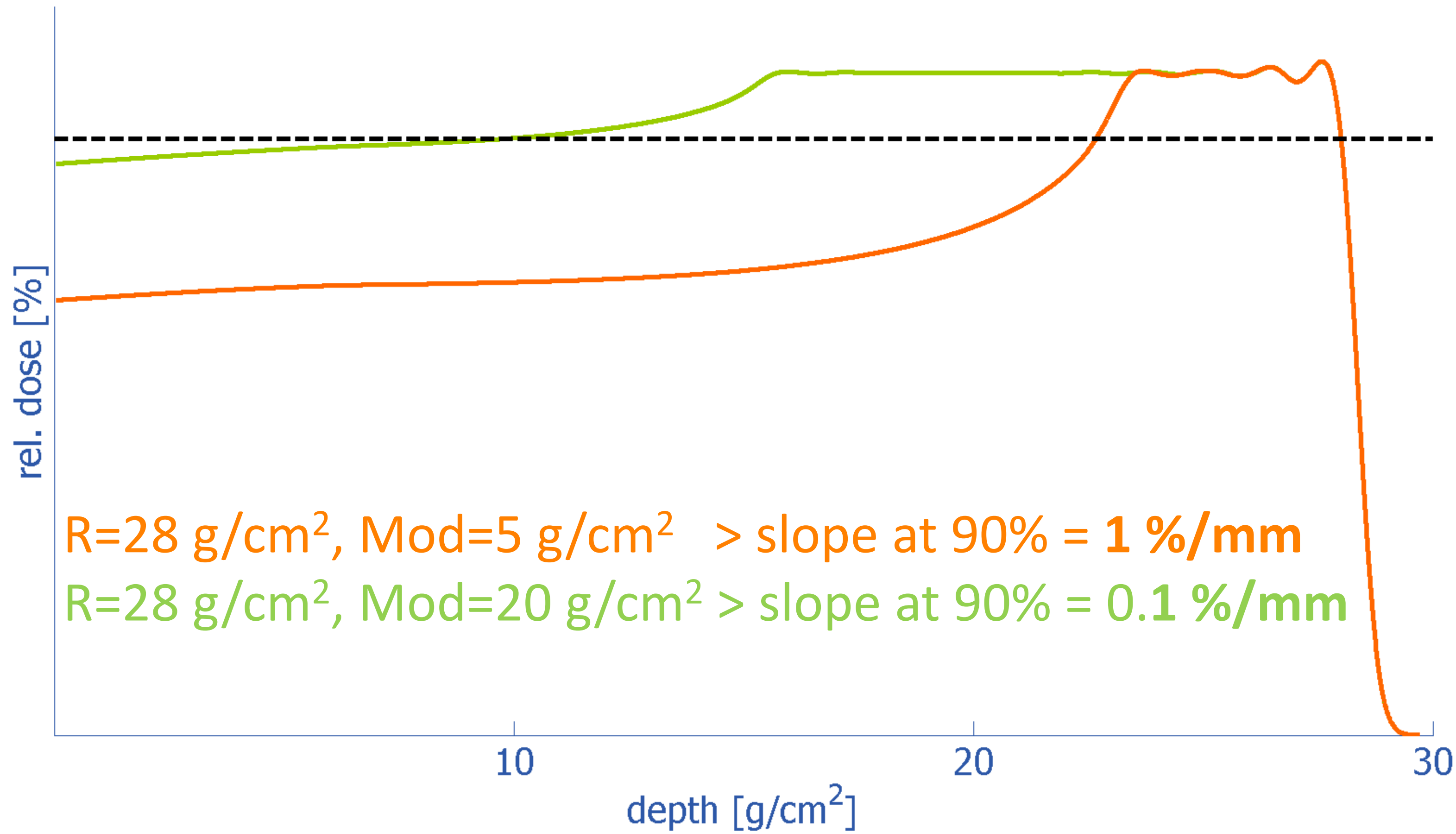
- Range
- Modulation width
- Shape SOBP
- Output (dose/MU)
- Dose rate [Gy/min]



+ can verify range, modulation width, shape SOBP
- cumbersome setup
- fairly long measurement
- cannot be used for scanned beam (interplay scanning / energy switching and detector motion)



Practical considerations SOBP measurement: modulation tolerance



Define tolerance both in distance and dose: e.g. modulation width should be within 3 mm of requested **or** dose at expected proximal 90% point should be between 88 and 92%

Zebra

- Stack of 180 ionization chambers
- 2 mm water-equivalent spacing
- 1 mm print boards, 1 mm air gap
- 2.5 cm diameter electrode
- Max range 33 cm in water

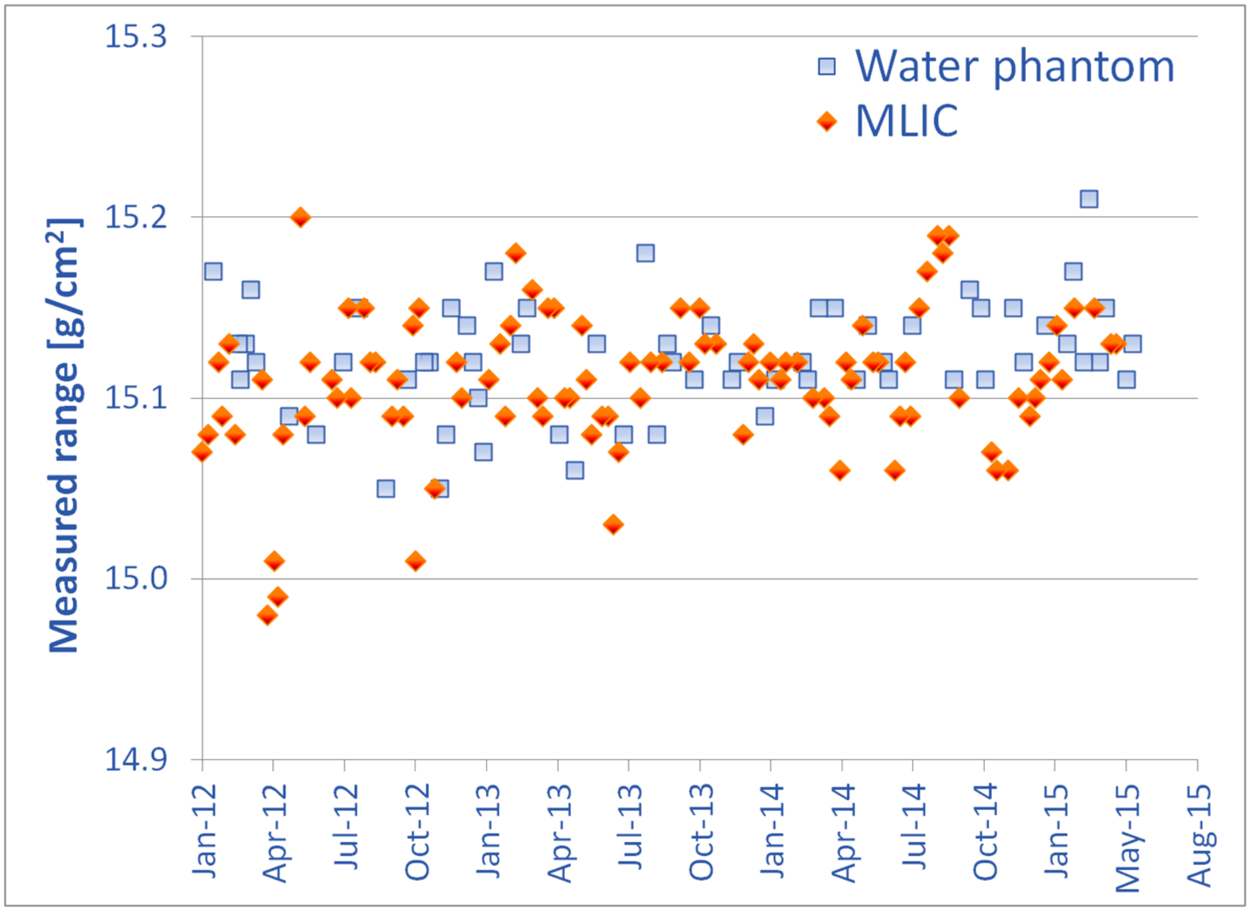
Practical considerations

- diameter of eletrode requires proton field to be large enough to have equilibrium (i.e. not for small apertures, or pencil beams)
- need to limit field size to avoid irradiating electronics
- channel thickness is on the large size > range accuracy, pristine peak measurements
- absolute dose calibration fairly stable; relative needs periodic re-calibration

Source: http://www.iba-dosimetry.com/sites/default/files/RT-BR-E-Zebra-OP-Incline-0211_Rev.2_0813.pdf

Comparing MLIC to Water Phantom: range

Measured range for DS reference field 1 (R=15.10 g/cm^2, Mod=10.4 g/cm^2) in Gantry 1 UFHPTI



	WP	MLIC
average	15.12	15.11
st. dev	0.03	0.04
min	15.05	14.98
max	15.21	15.20

Source: UFHPTI weekly QA in G1

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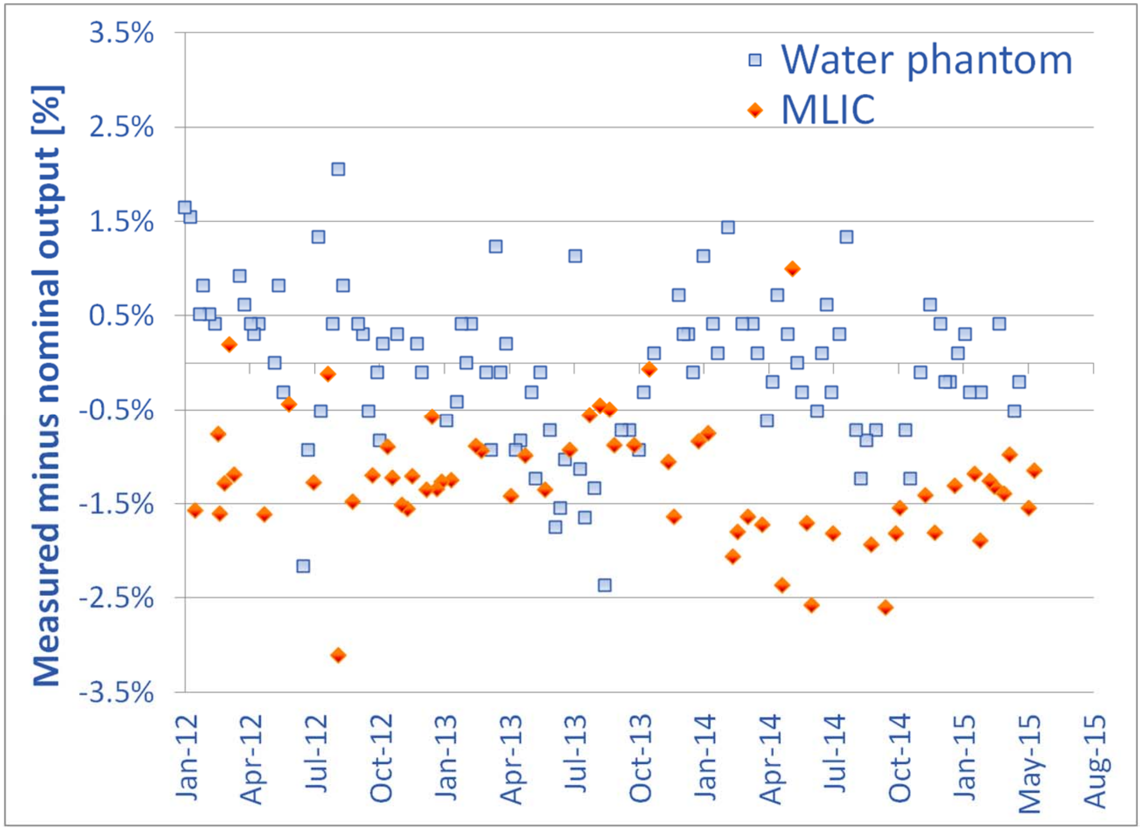
Comparing MLIC to Water Phantom: dose

Measured output for DS reference field 1 (R=15.10 g/cm^2, Mod=10.4 g/cm^2) in Gantry 1 UFHPTI



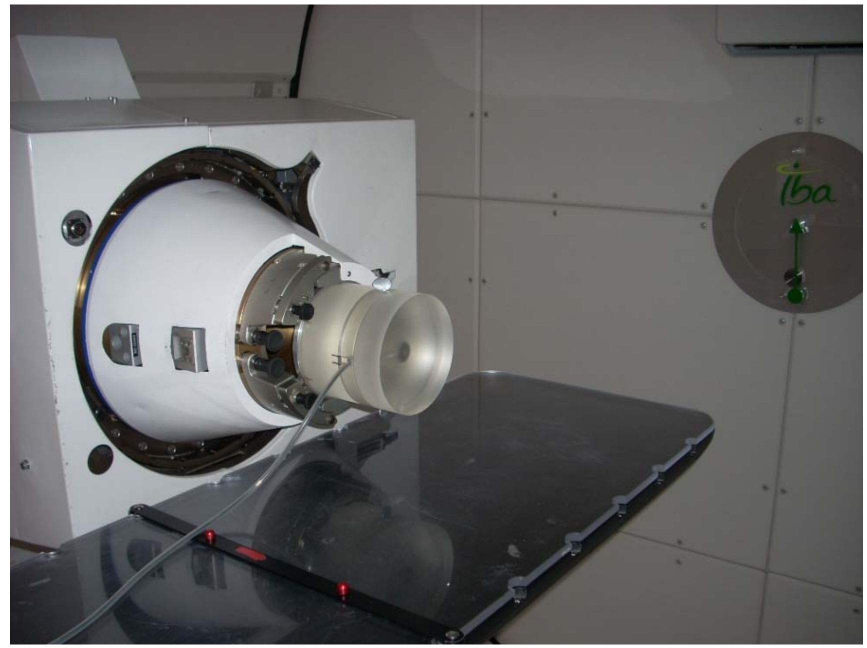
	WP	MLIC
average	0.0%	-1.2%
st. dev	0.8%	0.7%
min	-2.4%	-3.1%
max	2.1%	1.0%

Source: UFHPTI weekly QA in G1

DS / US / PBS (dose cubes)

Daily QA DS/US/PBS: output & range only

- Output
  - In solid water
  - In snout-mounted phantom
  - Central detector of 2D array

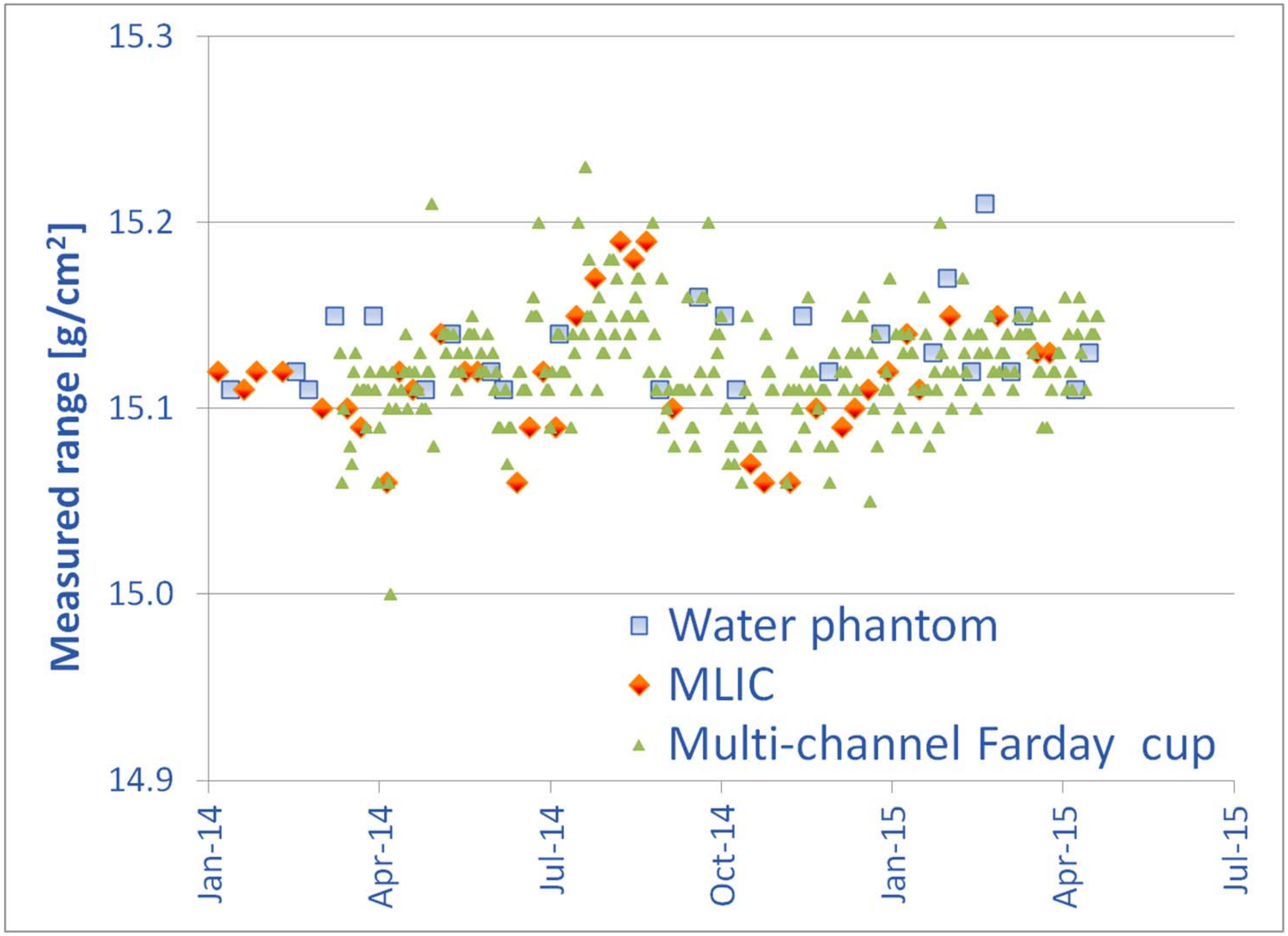


Parallel-plate chamber in 'range-compensator phantom' for output check

- Range
  - ratio of two detectors with different buildup: one in uniform region, one in distal fall-off
  - Use of PT system's 'multi-channel Faraday cup'

Comparing multi-chnnel Faraday cup to water phantom and MLIC

Measured range for DS reference field 1 (R=15.10 g/cm^2, Mod=10.4 g/cm^2) in Gantry 1 UFHPTI



	WP	MLIC	Far
Av.	15.12	15.11	15.12
Std.	0.03	0.04	0.03
Min	15.05	14.98	15.00
max	15.21	15.20	15.23

Source: UFHPTI weekly QA in G1

UFHPTI – Daily QA DS/US

Duration: ~20 minutes

Test	Device	Tolerance	Comments
Output check 1 ref field[α]	Daily QA 3[β] plus plastic buildup	±3%	Recording other detectors
Range 1 ref field	Multilayer Faraday cup in collimators	± 1.5 mm	Simultaneous with output
X-ray alignment & couch	Image of indexed Daily QA 3 device	± 1.5 mm	Drive couch to predefined position
Lasers	Markers on Daily QA 3	± 1 mm	
Safety interlocks & communications	Door, backup counter, neutron detector, intercom, video	N/A	

[α] Ref field: R=15.1 g/cm2, M=10.4 g/cm2 (15cmx15cm)
[β] Sun Nuclear

ProCure Oklahoma – Daily QA US

Source: X. Ding et al, A novel daily QA system for proton therapy, J Appl Clin Med Phys. 2013 14(2):115

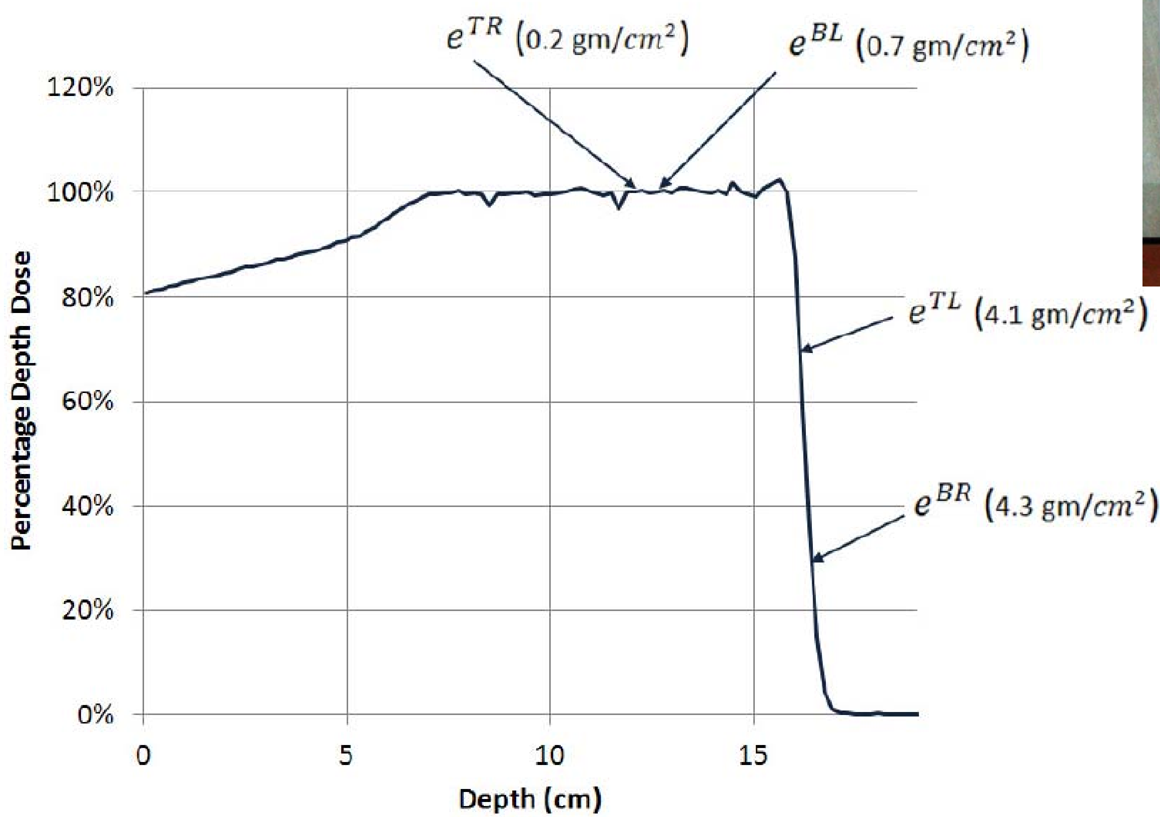
Test	Device	Tolerance	Comments
Output constancy ref field[α]	Daily QA 3 (CAX chamber)	±3%	Use of compensator to put in mid sobp
Range constancy	Daily QA 3 (electron energy chambers)	±1 mm	Use of compensator to put in distal sobp
Beam symmetry	Daily QA 3 (2 electron energy ch)	<3%	2 energy chambers @mid sobp
X-ray alignment	4 metal bb's in Daily QA 3 holder	1 mm	Indexed to couch
Lasers		2 mm	
Couch motion		1 mm	
Safety interlocks & communications	Door, beam/x-ray light, audio/video	N/A	

[α] Ref field: R=16.0 g/cm2, M=10.0 g/cm2 (15cmx15cm)

ProCure Oklahoma: Daily QA 3

Source: X. Ding et al, A novel daily QA system for proton therapy, J Appl Clin Med Phys. 2013 14(2):115

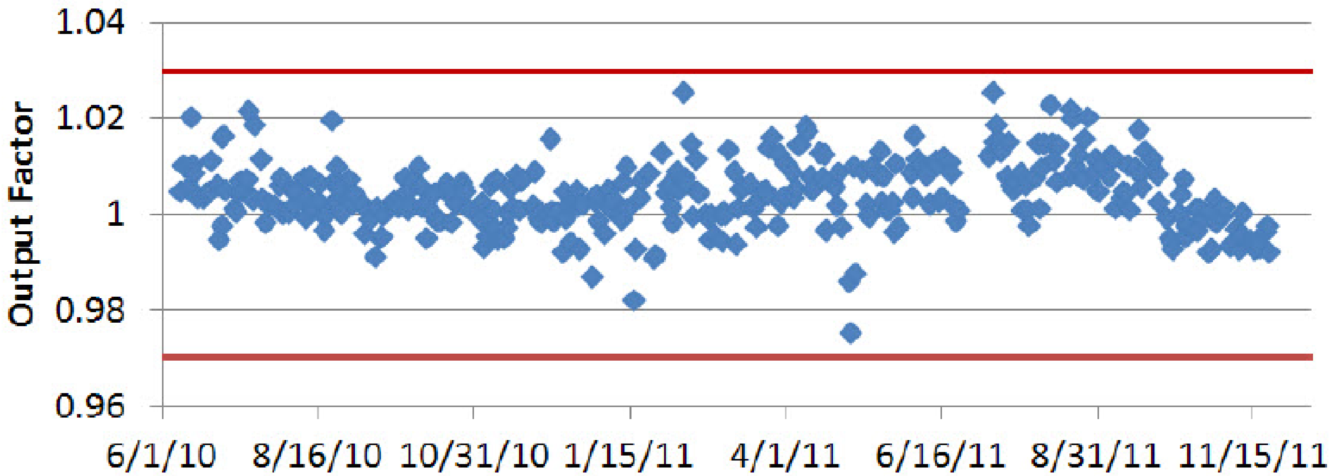
Use of ‘electron energy’ diodes to verify range

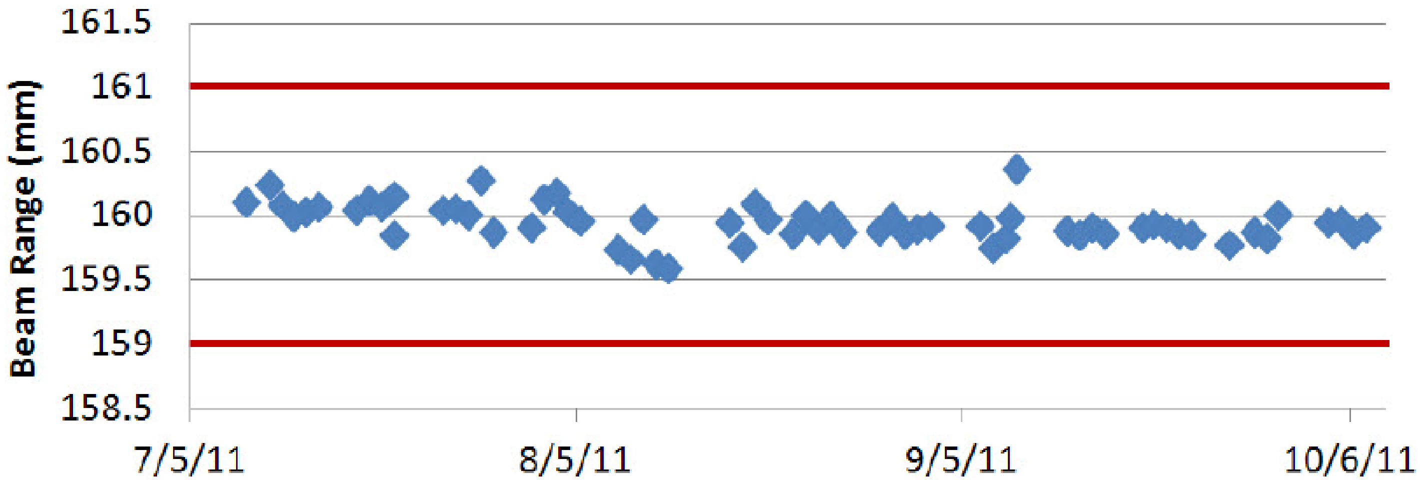


Change in range of 1 mm leads to about 30% change in ratio eTR&eTL or eBL&eBR

Source: X. Ding et al, A novel daily QA system for proton therapy, J Appl Clin Med Phys. 2013 14(2):115

Output and range variation ProCure US





Source: X. Ding et al, A novel daily QA system for proton therapy, J Appl Clin Med Phys. 2013 14(2):115

Daily QA Pencil Beam Scanning

- Compared to US/DS:
  - Less hardware, but more sophisticated (electronic) control
  - Larger 'equipment-setting space'
  - Larger risk of (major) delivery error
  - newer technology
- Individual pencil beam properties vs. clinical 3D dose distribution
  - Pencil beam: building blocks, more sensitive to system changes, easier to determine error causes,….
  - 3D dose: closer to clinical delivery, clinical relevant tolerances, sampling more of equipment-setting space

UPenn – Daily QA PBS (2013)

3D dose distribution approach

Test	Device	Tolerance	Comments
Output for dose cube	Matrixx[α] and solid water	Output: ±3%	Average of four central chambers
Range constancy for dose cube	Matrixx and solid water	Range: ±1mm	Matrixx placed in distal end SOBP
Field size & alignment for dose cube	Matrixx and x-ray bb's	Field center: ±1 mm	Matrixx aligned using x-ray system
Imaging system			
Safety interlocks			

α IBA Dosimetry

Source: site visit July 2013

UPenn – Daily PBS QA with Matrixx

- Ion chamber array
- 1020 chambers
- 24.4 x 24.4 cm^2 active area
- Detector spacing: 7.62 mm
- Chamber diameter: 4.5 mm
- Stable enough for constancy checks

Sequence of irradiations:

1. R=20 g/cm^2, distal layer , 20x20cm^2, no buildup → field size & dose
2. R=20 g/cm^2, Mod=10 g/cm^2, 10x10cm^2, buildup 20 cm → range (distal fall-off)
3. R=20 g/cm^2, Mod=10 g/cm^2, 10x10cm^2, buildup 10 cm → field alignment & size, dose

Alignment included by setting up Matrixx with x-ray system

Source: site visit July 2013

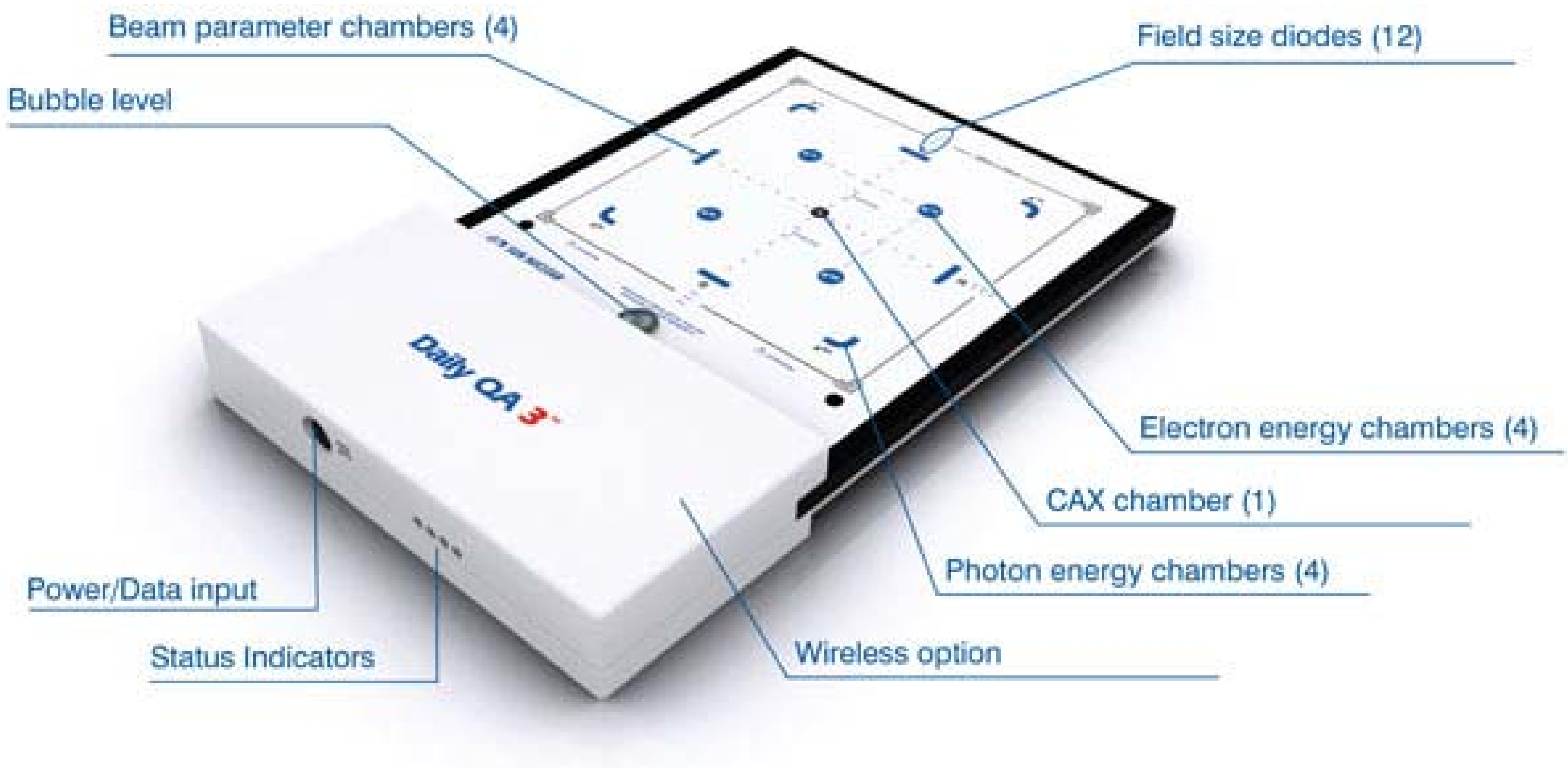
WPE – Daily QA PBS

Individual pencil approach

Test	Device	Tolerance	Comments
Output constancy (3cmx3cm @ 159MeV)	Daily QA 3 with plastic buildup (CAX chamber)	±2%	Buildup of 1 g/cm^2
Range constancy (187 MeV and 201 MeV)	Daily QA 3 (electron energy chambers)	±1 mm	Different buildup (entrance&distal fall-off)
Spot position & sigma (4 spots @ 220 MeV)	Daily QA 3 (field size diodes)	Position: ±1.5 mm Sigma: ±10% from baseline	Position determined from x-ray iso
Imaging and alignment system	Daily QA 3 indexed on couch, x-ray markers		

Source: J. Lambert, C. Baumer, B. Koska, X. Ding, Daily QA in proton therapy using a single commercially available detector, J Appl Clin Med Phys. 2014 Nov 8;15(6):5005

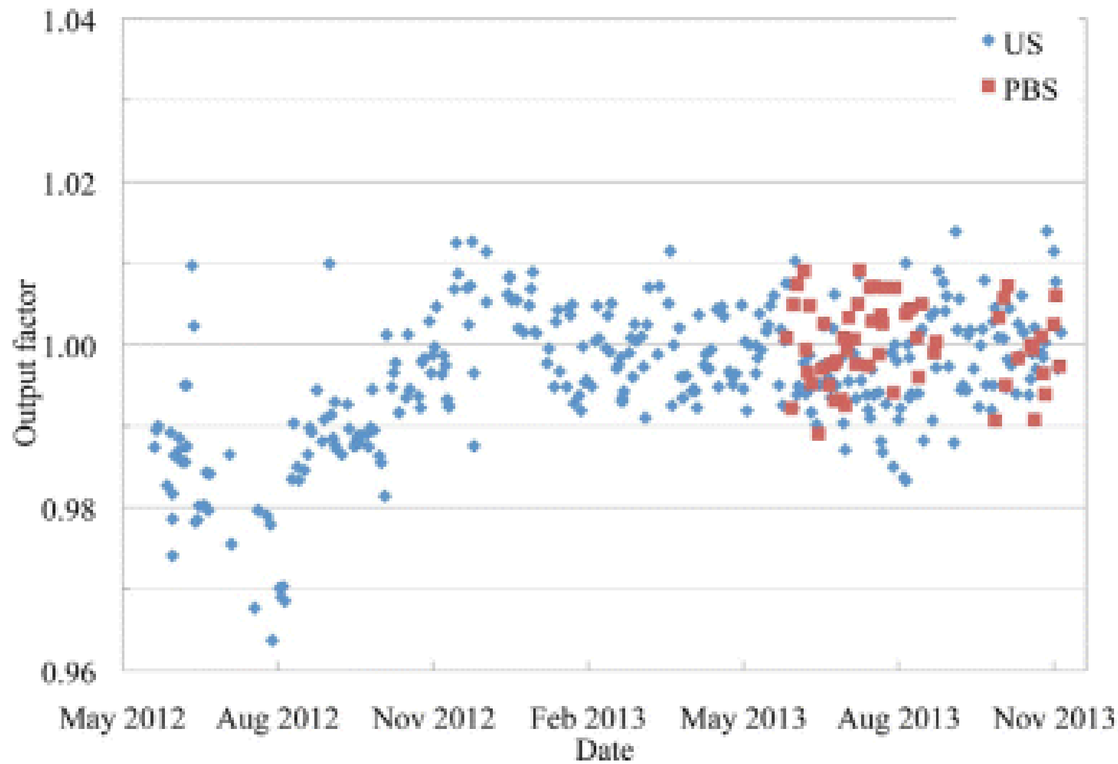
WPE – Daily QA PBS



Source: J. Lambert, C. Baumer, B. Koska, X. Ding, Daily QA in proton therapy using a single commercially available detector, J Appl Clin Med Phys. 2014 Nov 8;15(6):5005

WPE – Daily QA PBS/US

Daily output as measured with QA3 central ionization chamber

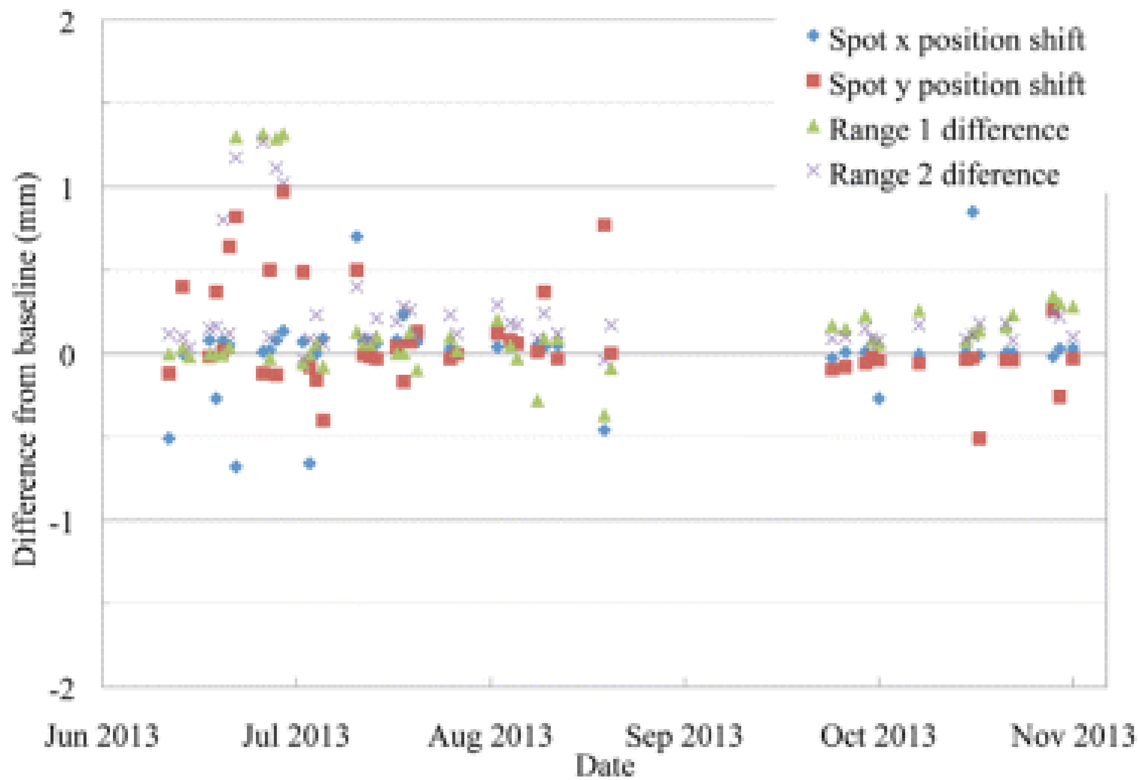


The output factor of the proton beam measured with the central ionization chamber of the QA3 device for both the US and PBS gantries.

Source: J. Lambert, C. Baumer, B. Koska, X. Ding, Daily QA in proton therapy using a single commercially available detector, J Appl Clin Med Phys. 2014 Nov 8;15(6):5005

WPE – Daily QA PBS/US

Daily range and spot position of WPE PBS as measured with QA3 device.

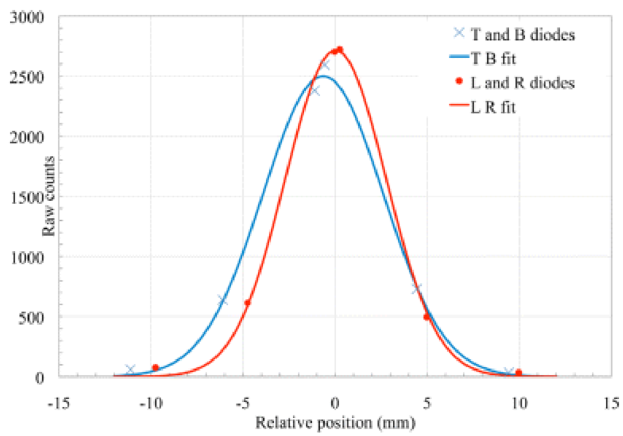


The range accuracy of a 187 MeV and a 201 MeV PBS proton beam, and the spot position accuracy of a 220MeV beam.

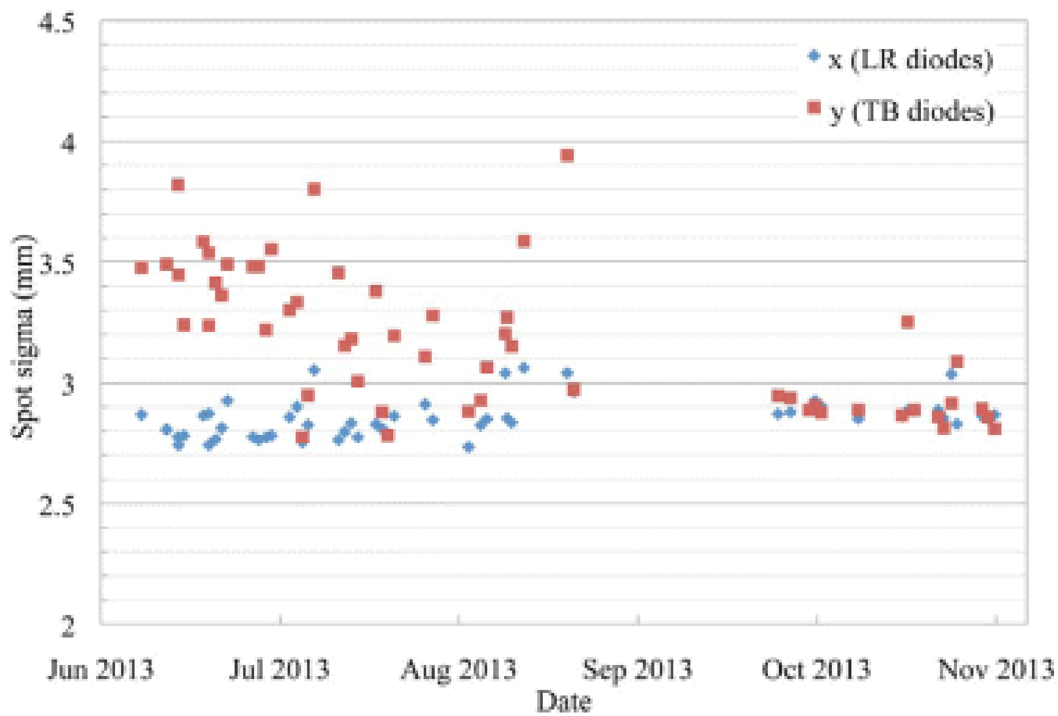
Source: J. Lambert, C. Baumer, B. Koska, X. Ding, Daily QA in proton therapy using a single commercially available detector, J Appl Clin Med Phys. 2014 Nov 8;15(6):5005

WPE – Daily QA PBS/US

Daily spot size of WPE PBS as measured with QA3 device.



Fit of four diode readings in L/R and top/bottom directions with gaussian to determine position and sigma



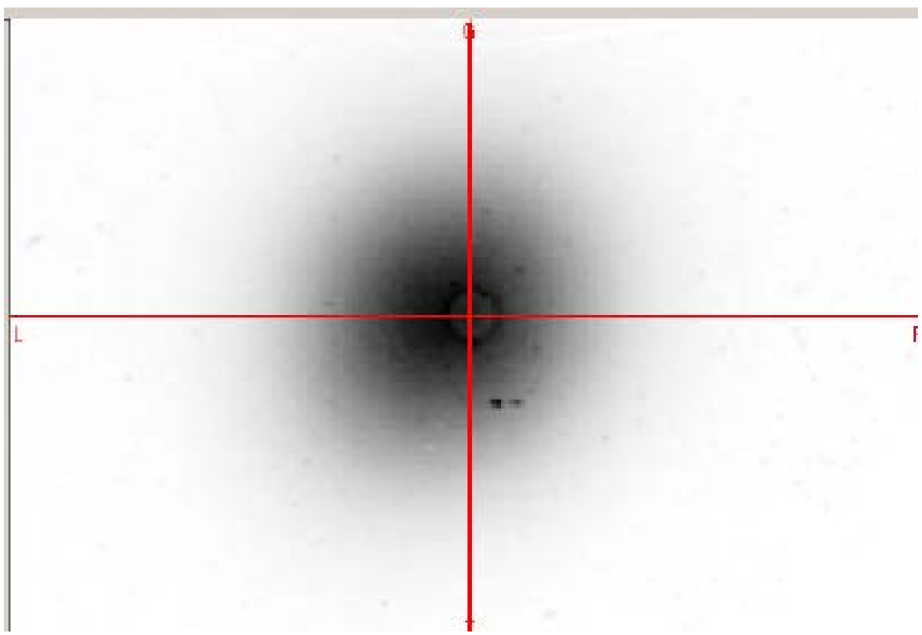
The spot sigma of a single 220 MeV proton beam spot, shown in the X and Y directions, measured by the 12 diodes on the QA3 device

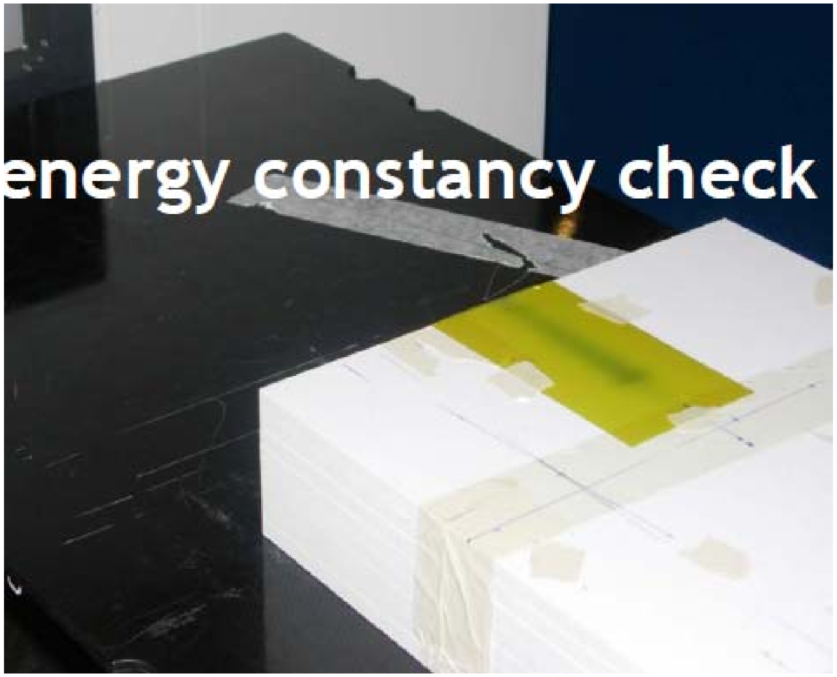
Source: J. Lambert, C. Baumer, B. Koska, X. Ding, Daily QA in proton therapy using a single commercially available detector, J Appl Clin Med Phys. 2014 Nov 8;15(6):5005

CNAO – Daily QA PBS

Individual pencil approach

Use of gafchromic film to verify spot size & position and energy





Source:

UFHPTI – Weekly QA DS/US

Duration: ~60 minutes

Test	Device	Tolerance	Comments
PDD & output for 2 ref fields + 1 rotating field	MLIC	Range: ±1.0 mm Mod: ±3.0 mm or ±3% Output: ±2.5%	Not in water
X-ray – proton alignment & light field	X-ray exposure of crosshair and aperture	Crosshair: ±1.5 mm LF: ±1.5 mm	Rotation of different snout sizes
Couch isocentricity	X-ray system and IsoAlign device	±1.5 mm	Align target at rot 0, rotate to 90 and check
Fixed scatterer lollipop check	System's multilayer Faraday Cup	±2.0 mm	Compare range 'all in' to 'all out'

UFHPTI – Monthly QA DS/US

Duration: ~60 minutes

Test	Device	Tolerance	Comments
PDD & output for 2 ref fields + 1 rotating field	PPC05 in water phantom	Range: ±1.5 mm Mod: ±3.0 mm or ±3% Output: ±2.5%	Same tolerances as MLIC
Lateral profiles for 2 ref fields	Matrixx multi-ionization chamber array	Symmetry: 2% Flatness: 3%	1 gantry angle
X-ray – proton alignment	Double-exposure x-ray and proton on film	±1.5 mm	
Comprehensive alignment system check	Plastic box with bb's	±1.5 mm	Set up phantom at setup angle, go to tx angle, verify

MD Anderson – Monthly QA DS

Test	Device	Tolerance	Comments
Lateral profile	Matrixx	Flatness: ≤2 % Symm: ≤2 %	1 angle, 8 energies, 3 sizes
Gantry-angle dependence output	Farmer chamber in snout-mounted phantom	2%	4 angles, 8 energies, 3 sizes
Couch isocentricity	LF projection of crosshair	≤1 mm	
Gantry isocentricity	LF projection crosshair & pointer	≤1 mm	
Couch translation	Markings on couch-mount	≤1 mm	
Snout horizontal motion trueness	LF projection of crosshair	≤1 mm	

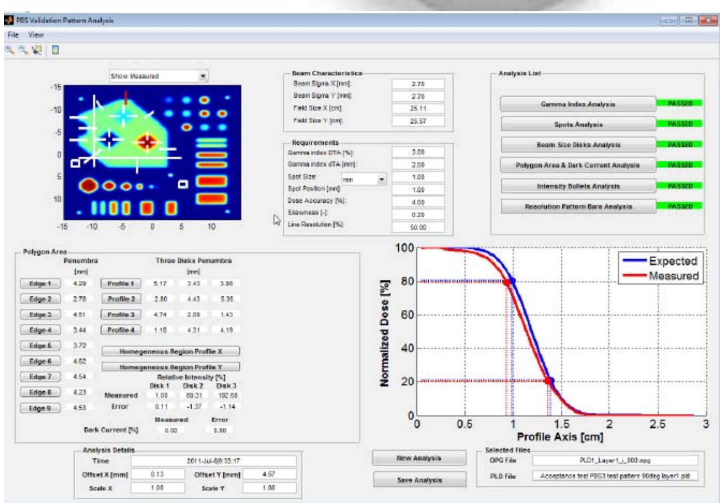
Source: B. Arjomandy et al, An overview of the comprehensive proton therapy machine quality assurance procedures implemented at The University of Texas M. D. Anderson Cancer Center Proton Therapy Center-Houston. Med Phys. 2009 Jun;36(6):2269-82.

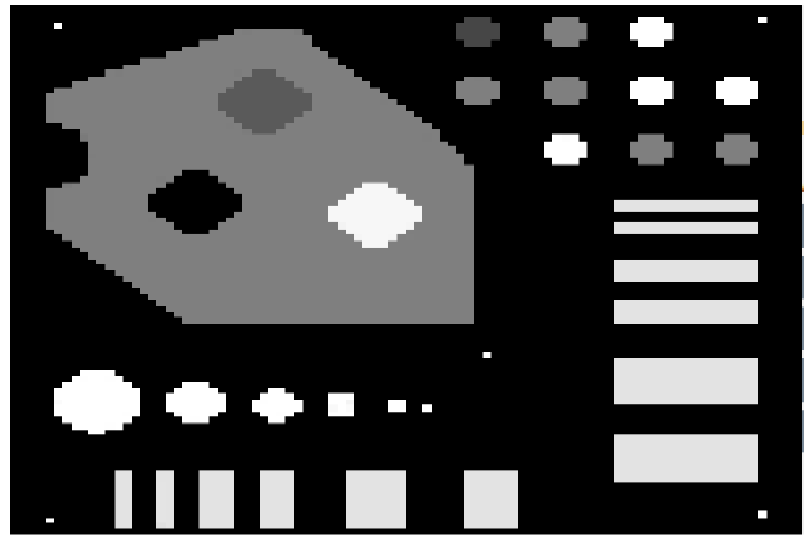
PBS weekly & monthly QA tests

- Additional fields: low/high energies, field size
- Mono-energetic pristine peaks
  - 3-4 energies
  - MLIC (scanned)
  - Range accuracy, shape
- Spot position, shape, size
  - 2-4 energies
  - various gantry angles
  - Lynx, film
- Absolute dose in water
- Mechanical / Imaging similar to DS/US

Few (none) tests of more clinical, non-uniform fields

ProCure – Weekly QA PBS





- Delivery of pbs ‘test pattern’
- Scintillator measurement (Lynx)
- Spot position, size, shape, intensity
- DTA 1.5% and 1.5mm for 95% of the points
- 2 energies at 2 gantry angles

Source: http://www.aapm.org/meetings/2013AM/documents/Scripps.pdf

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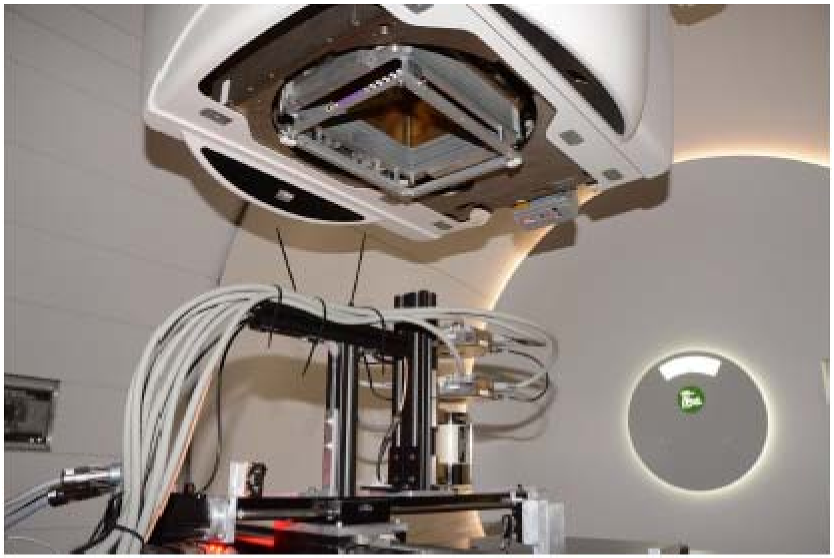
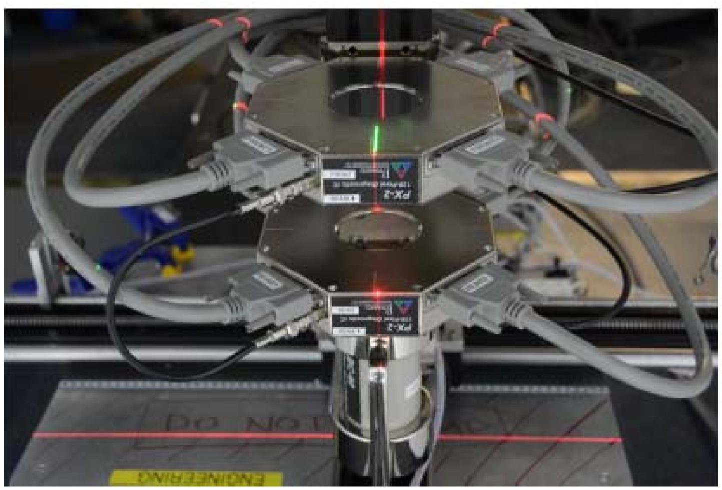
MGH – Weekly/Monthly QA Device





Two pixel ionization chambers followed by a (multi-layer) Faraday cup

Whole assembly mounted on a high-precision motion stage

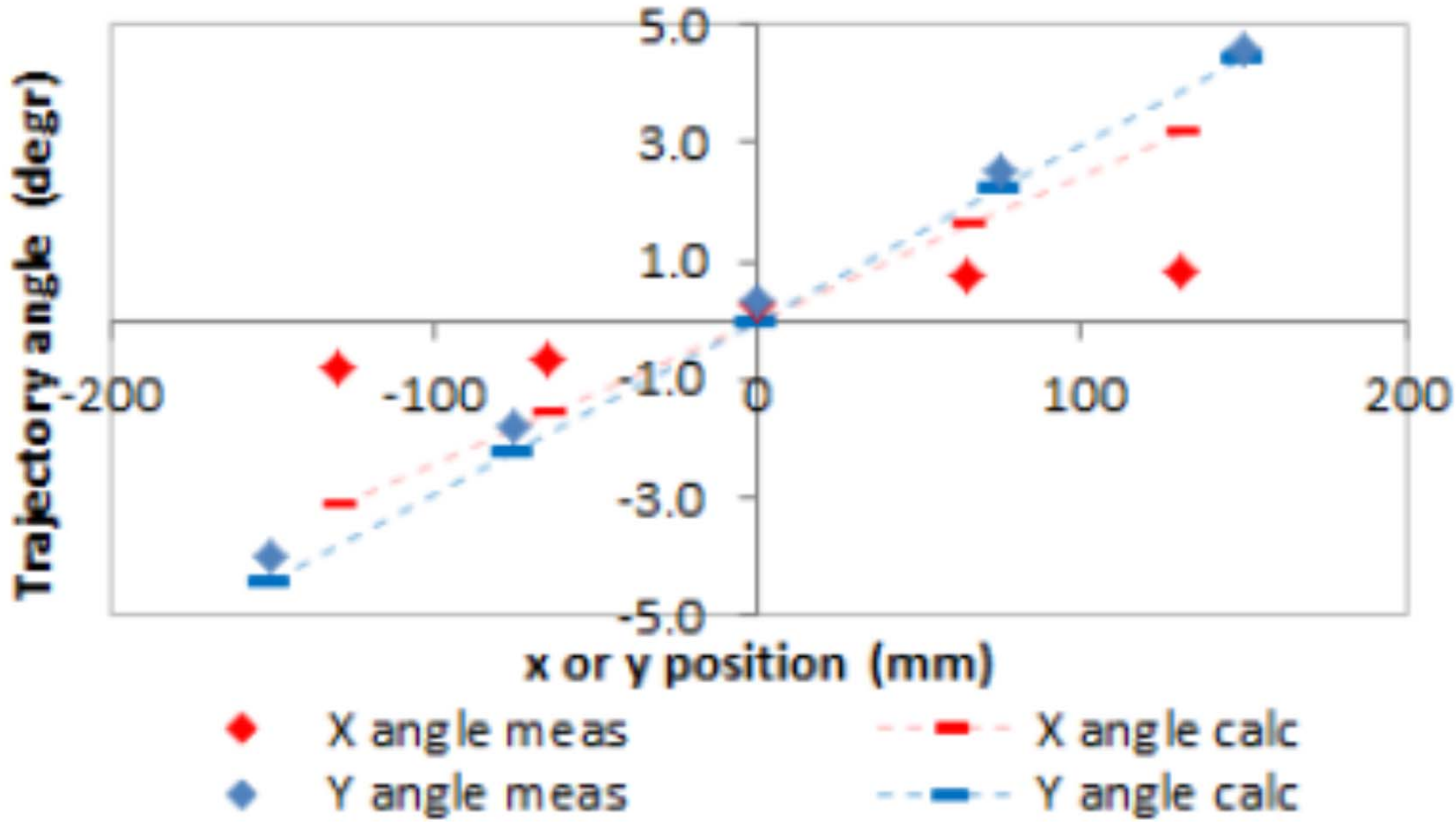
Deliver spot map and between spots move assembly to nominal spot position

Measure properties individual spots
- shape/size
- position and direction
- dose (total charge)

Source

MGH – Weekly/Monthly QA Device

Measurement of pencil beam angle as function of pencil position.



Source:

UFHPTI – Yearly QA DS/US (1)

Duration: 12 hrs per room

Test	Device	Tolerance	Comments
Machine output (reference field)	Farmer chamber in water; IAEA TRS 398 protocol	Output: ±1.0%	If out of tolerance adjustment MU chamber gain
MU linearity	Farmer chamber	Offset: ±0.5 MU Max diff from linear fit: ±0.2%	MU: 25, 50, 100, 150, 200
Dose-rate dependence output	Farmer chamber	Max variation: ±1%	1 – 3 Gy/min
Output and DR for one field per option (8 total)	Parallel-plate chamber in water phantom	Diff to baseline: ±2.5% Diff to model: ±2.0% DR: ±30%	

UFHPTI – Yearly QA DS/US (2)

Duration: ~12 hrs per room

Test	Device	Tolerance	Comments
Gantry-angle dependence output	Parallel-plate chamber in snout-mounted phantom	Max. var: ±0.5%	
PDD for one field per option	Parallel-plate chamber in water phantom	Range: ±1.5 mm Mod: ±3mm or ±3% Min/Max: ±3%	
Lateral profile for one field per option	Matrixx detector array with solid water	Symm: ±2% Flatn: ±3% Min/Max: ±3%	Profile measured at middle SOBP
Gantry-angle dependence lateral profile	Matrixx detector	Var. symm: ±0.5% Var. flatn: ±0.5%	Cardinal angles plus one in-between

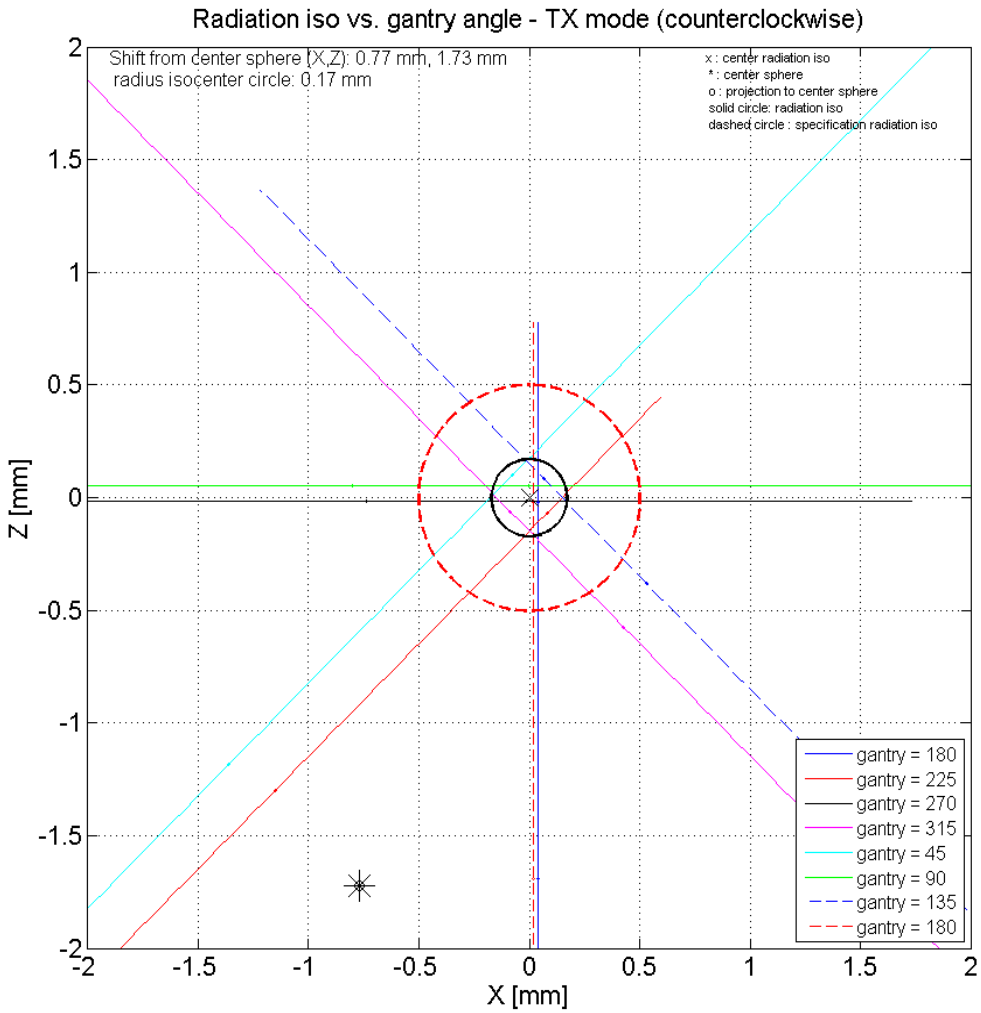
UFHPTI – Yearly QA DS/US (3)

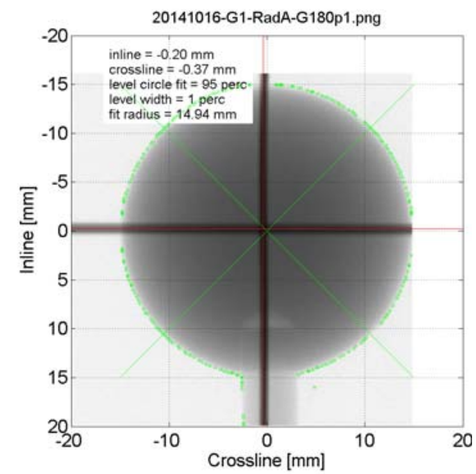
Test	Device	Tolerance	Comments
Gantry angle accuracy	Digital level	0.5 deg	
Gantry isocentricity	Plastic sphere and x-ray system	Radius cross plane: ≤0.5 mm Variation inline: ±0.5mm	
Alignment perpendicular x-ray to isocenter	Plastic sphere and x-ray system	Max distance to beam iso: ±0.75mm	
Couch positioning accuracy	Ruler and level	±0.5 mm ±0.2 deg	
Couch isocentricity	Plastic sphere and x-ray system	Rot center to iso: ≤0.5 mm Radius rot. center: ≤0.5 mm	

UFHPTI – Yearly QA DS/US (4)

Test	Device	Tolerance	Comments
Snout positioning accuracy	Ruler and x-ray system	Position: ≤5 mm Motion in plane: ≤0.5 mm	
Proton-to-xray alignment	Film	≤1 mm	Performed for all 4 snouts, 3 gantry angles per snout
Light field alignment	Film	≤1 mm	
Laser alignment	Isoalign device plus x-ray	≤1 mm	
X-ray image dose and quality	kVp&mAs meter and Leeds phantom		
Safety interlocks			

UFHPTI Gantry isocentricity: verification method





Radius of isocenter sphere in crossplane with correction:
0.2 mm

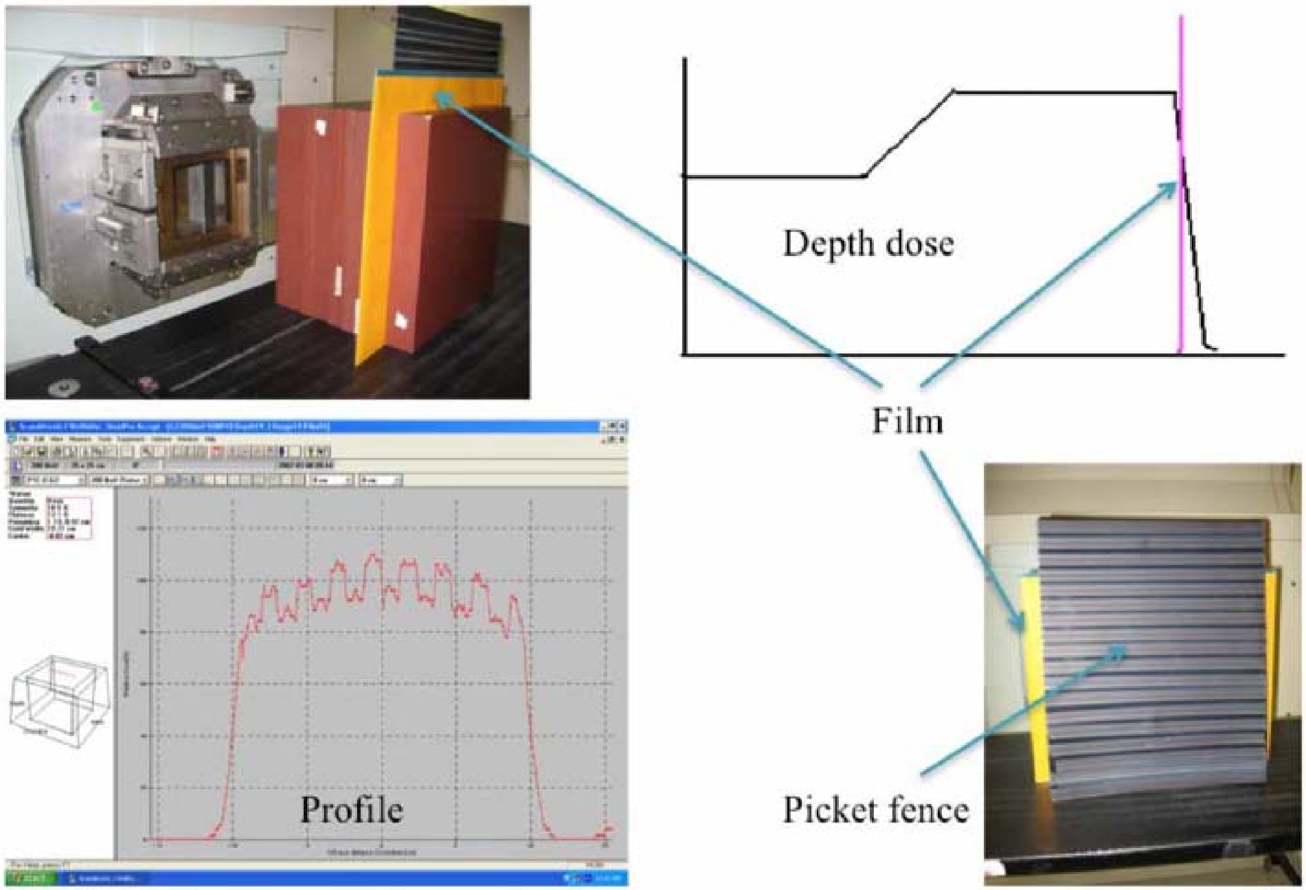
QA tolerance:
≤0.5 mm

MD Anderson Yearly – gantry isocentricity

- Metal ball aligned at iso
- Two micometers on surface ball
- for 'beam iso' : star shot film

Source: B. Arjomandy et al, An overview of the comprehensive proton therapy machine quality assurance procedures implemented at The University of Texas M. D. Anderson Cancer Center Proton Therapy Center-Houston. Med Phys. 2009 Jun;36(6):2269-82.

MD Anderson Yearly – range uniformity DS



1 cm strips at 1 cm spacing provide small range shift

Film behind 'picket fence'

Solid water to place film in distal fall-off

Strips cause 20%-25% variation in dose

Source: B. Arjomandy et al, An overview of the comprehensive proton therapy machine quality assurance procedures implemented at The University of Texas M. D. Anderson Cancer Center Proton Therapy Center-Houston. Med Phys. 2009 Jun;36(6):2269-82.

System QA - overview

- DS/US daily QA is fairly consistent between different facilities:
  - Output constancy single field
  - Range verification using two-chamber or multi-layer Faraday cup
  - Quick check alignment and imaging system
- PBS daily QA methods vary quite a bit between facilities, although parameters checked are fairly uniform
  - Output constancy for single field / energy
  - Energy / range for single field / energy
  - Spot position or 2D profile position/size for single field / energy
  - Alignment, imaging, and safety similar to DS/US
- DS/US weekly, monthly, yearly QA procedures shows variation in measurement methods and frequency, but not parameters
- PBS weekly/monthly/yearly QA shows large variations in parameters and methods, but mostly checking individual pencils

Setting up a Proton QA program

- Guidelines?
  - AAPM 142: Quality assurance of medical accelerators
  - ICRU 59, 78
  - AAPM TG 224: Proton Machine QA ??
- Proton treatment systems
  - few centers
  - wide variety of delivery, positioning, imaging systems
  - technology is still rapidly evolving
  - most systems have been used clinically for <<5 years
- Treatment protocols
  - number of tx sites still increasing
  - planning, positioning, treatment protocols evolving

No cookie cutter approach to proton system QA……

12 step approach to setting up QA

STEP 1 Identify treatment variables

dosimetric: range, modulation, SOBP uniformity, skin dose, distal fall-off, lateral profile flatness, symmetry, lateral penumbra, field size, dose, dose rate, …..

Mechanical: beam angle, snout position, couch position, couch rotation, ….

Imaging / setup: imaging-beam alignment, lasers, light field alignment, x-ray image quality, ….

Safety: interlocks, crash buttons, ….

Accessories: immobilization mechanical integrity, immobilization dosimetry, range shifter, range compensator, …..

12 step approach to setting up QA

STEP 1 Identify treatment variables

STEP 2 Evaluate impact of error for each variable

e.g. range: high, modulation: moderate, skin dose: low

e.g.: x-ray alignment: high, x-ray image quality: moderate, x-ray kVp: low

→ consider clinical protocols:

-Imaging each treatment field: impact couch isocentricity moderate, else high

-Using light-field to match fields: impact misalignment LF high

12 step approach to setting up QA

STEP 1 Identify treatment variables

STEP 2 Evaluate impact of error for each variable

STEP 3 Determine system components affecting each variable and determine likelihood of failure/drift

Know your system!

e.g.: PBS energy set using achromatic bending magnet system → magnets prone to drift

e.g.: In DS/US field size determined by aperture → small likelihood of error

e.g.: PBS spot size determined by cyclo extraction & beamline quadrupoles → moderate chance of drift

12 step approach to setting up QA

STEP 1 Identify treatment variables

STEP 2 Evaluate impact of error for each variable

STEP 3 Determine system components affecting each variable and determine likelihood of failure/drift

STEP 4 Determine frequency and accuracy with which each variable needs to be tested

Based on impact and likelihood of error determine frequency

Based on acceptable variation (clinical tolerance) determine accuracy with which test needs to be performed.

Also determine subset of equipment settings for which test needs to be done: e.g. spot position for what energies, positions, ….

12 step approach to setting up QA

STEP 1	Identify treatment variables
STEP 2	Determine impact of error for each variable
STEP 3	Determine system components affecting each variable and determine likelihood of failure/drift
STEP 4	Determine frequency and accuracy with which each variable needs to be tested
STEP 6	Establish test procedures

Required accuracy > measurement accuracy & sensitivity

Device selection

Efficiency (combining tests in single measurement)

12 step approach to setting up QA

STEP 1	Identify treatment variables
STEP 2	Determine impact of error for each variable
STEP 3	Determine system components affecting each variable and determine likelihood of failure/drift
STEP 4	Determine frequency and accuracy with which each variable needs to be tested
STEP 6	Establish test procedures
STEP 7	Set tolerances for each test procedure

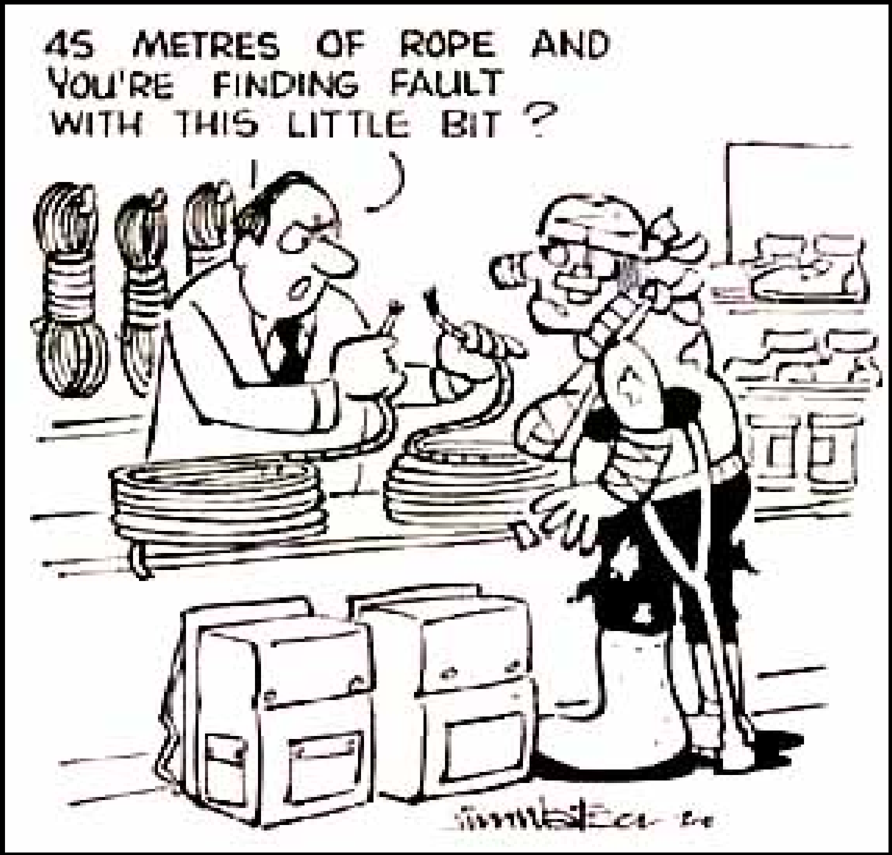
Taking into account: desired accuracy, expected machine variation, measurement accuracy

STEPS 8-12 Keep updating QA program

- Start with elaborate QA and slowly reduce frequency
  - initially 3 PBS fields per day, later reduced to 2 then 1
- Based on issues identified by QA consider increasing frequency of certain tests / implementing new tests
  - e.g. couch isocentricity showed drift > moved from monthly to weekly
- When implementing new clinical protocols review of system QA is needed
  - e.g. large, matched lymphoma tx: pps motion, LF, uniformity large fields
  - e.g. SRS: recombination at high dose rate, alignment accuracy

QA scheduling and staffing at UFHPTI

- Equipment
  - 3 gantry rooms (2 DS only, 1 DS&US(&PBS)), 1 proton eyeline
  - 2 linacs, 1 VERO machine
- Clinical operations
  - 90-100 proton
  - tx days 6:30AM – 10 PM Mon-Fri
- Staffing
  - 3 'QA coordinators' full time on QA
  - 2 physics residents part time on QA
  - Faculty physicists do yearly QA and data review / program development
- Scheduling
  - Daily QA: 5:45 – 6:20, two physicists
  - Weekly & Monthly: 8-12 hrs on Sunday (weekday nights if needed)


45 METRES OF ROPE AND YOU'RE FINDING FAULT WITH THIS LITTLE BIT ?