CLINICAL DOSIMETRY AND QUALITY ASSURANCE IN HADRON THERAPY

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SLIDE COURTESY

- Loic Grevillot
- Antonio Carlino
- Virgile Letellier
- Jhonnatan Osorio
- Ralf Dreindl
- Stan Vatnitsky
- Hugo Palmans

INTRODUCTION

FACILITY OVERVIEW

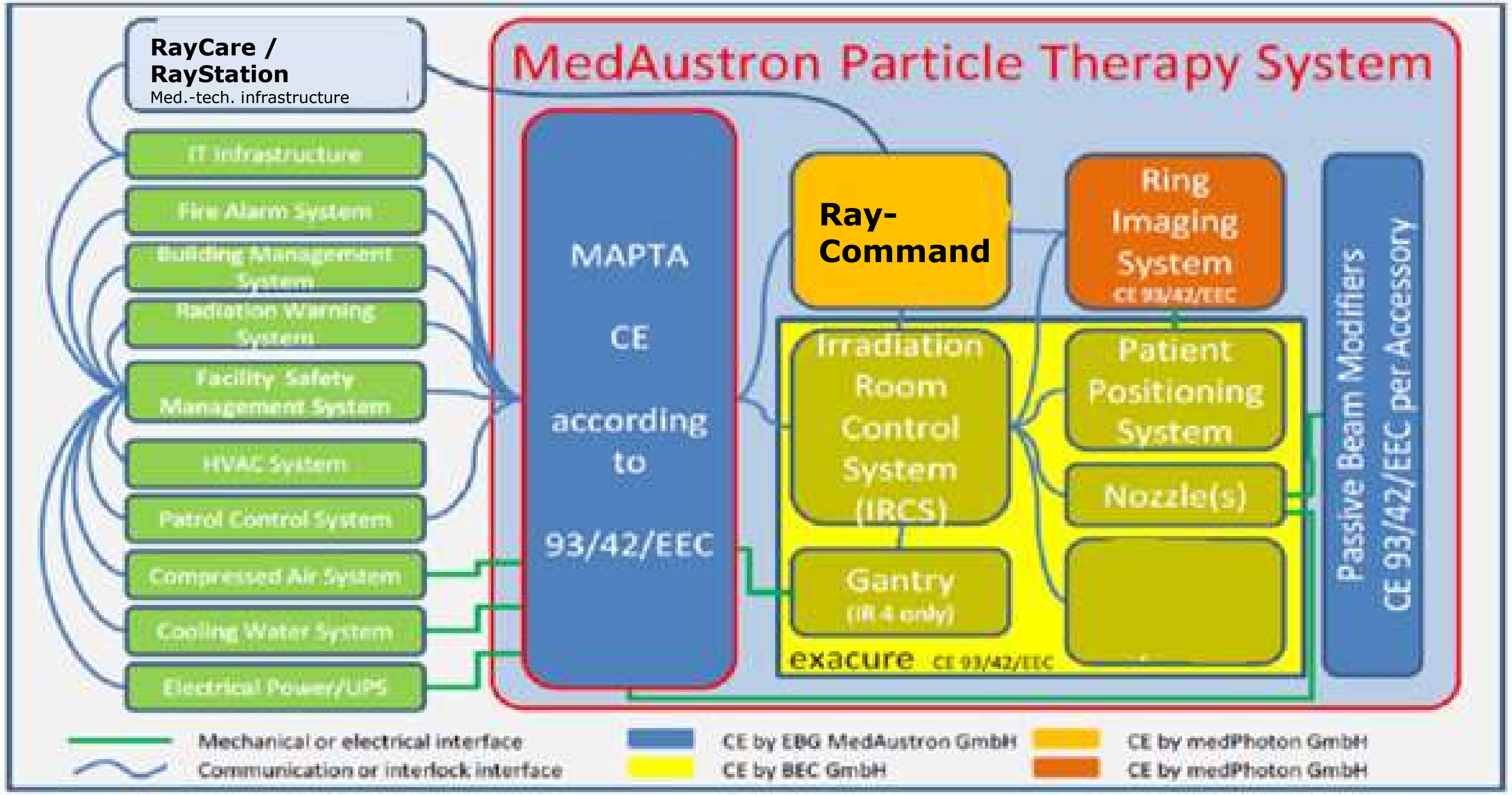
Irradiation Rooms
Three rooms for patient treatments

Research
Irradiation room for non-clinical use

Ion Sources
and linear accelerator

Synchrotron
= circular accelerator

DESIGN OF MAPTS (MEDAUSTRON PARTICLE THERAPY SYSTEM) – CE/MDR CERTIFIED



IMPLEMENTATION OF EQUIPMENT INTO CLINICAL PRACTICE

General steps

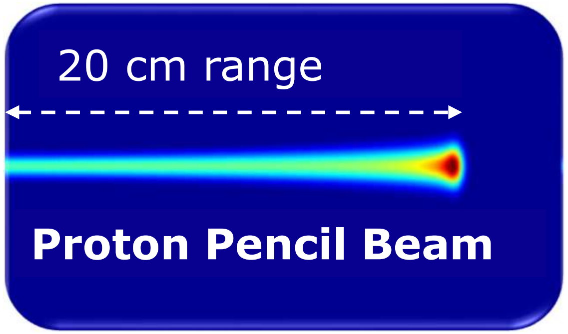
- specifications
- selection and purchase process
- installation
- acceptance testing
- commissioning
- training
- periodic QA
- clinical use

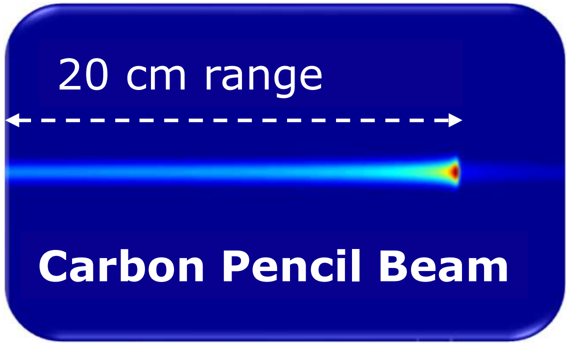
MedAustron steps

- specifications/selection of provider
- **finalization of contract**
- **common development**
- installation
- acceptance testing
- commissioning
- training
- periodic QA
- clinical use
- **new features co-developments**

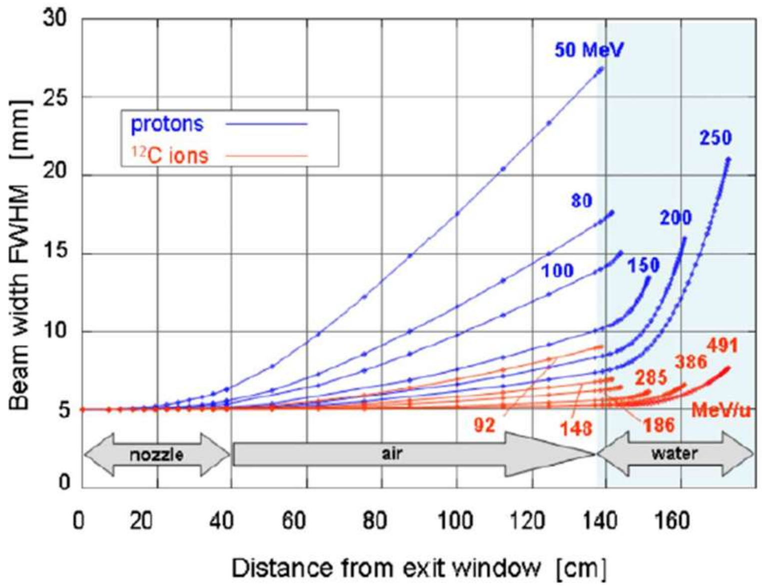
- **Support in CE marking**

DIFFERENCE BETWEEN PROTONS AND CARBONS





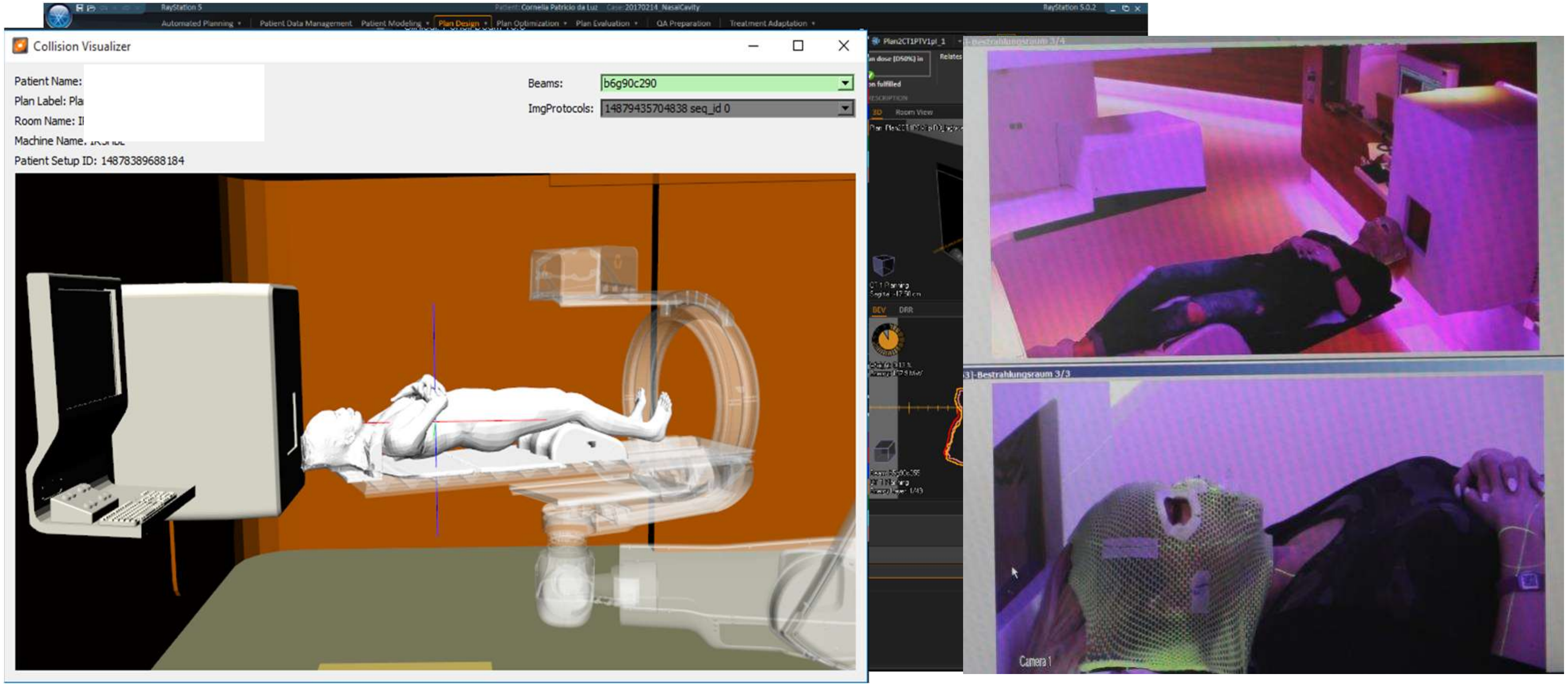
- Sharp penumbra maintained in depth
- Fragmentation tail
- High LET in last part of the path



Weber and Kraft, Cancer J 2009

COMMISSIONING FOR NON-ISOCENTRIC TREATMENT

- Non-isocentric treatment for proton allowed significant reduction of lateral penumbra (30-40%)
- Supported workflow by TPS and in-room components



Grevillot et al, Med. Phys. 47 (2), February 2020

BEAM DELIVERY COMMISSIONING

MedAustron Experience

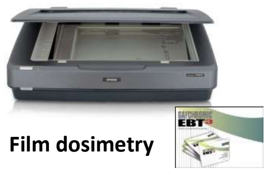
QA/COMMISSIONING EQUIPMENT

For Beam-commissioning

MP3-P → MP3-PL → PeakFinder → Ionization chambers → Lynx → Film dosimetry



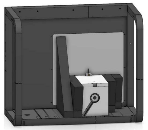
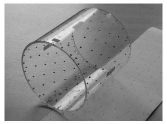
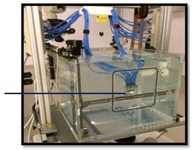


Daily QA and Patient specific QA

Giraffe → Octavius → CIRS phantom → Daily-QA Sphinx Compact → PAS Phantoms → PSQA



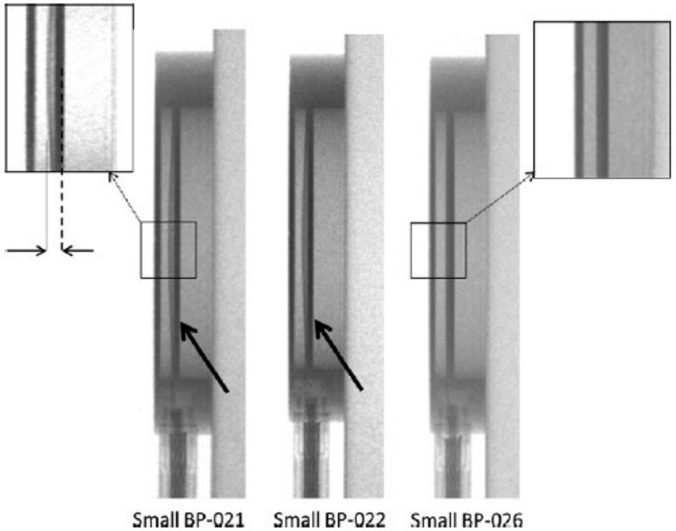





Grevillot et al Med Phys. 2018 Jan;45(1):352-369

DOSIMETRY EQUIPMENT & PHANTOMS

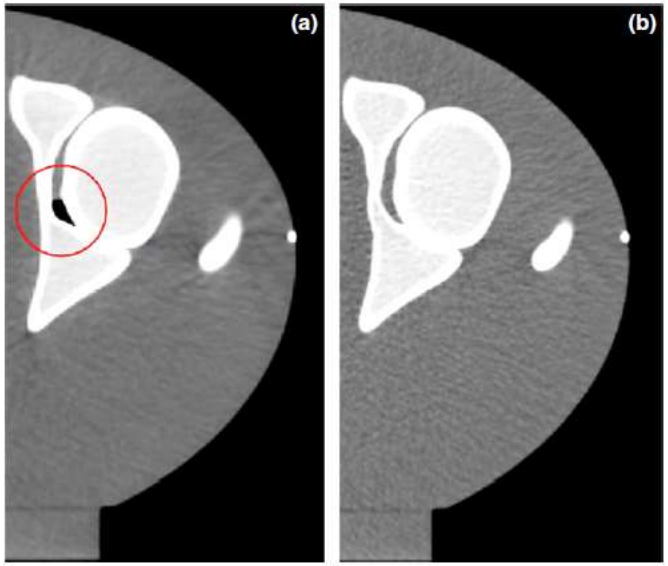
Plane parallel chambers

- X-ray images pointed-out defects in 2 chambers out of 3.
- Dose response was affected by 19%.
- Chambers were exchanged.
- Vendor changed the QA procedure of their equipment.



End-to-end test phantoms

- X-ray images pointed-out defects in the phantom.
- Phantom was exchanged.
- Vendor changed the QA procedure of their phantom.

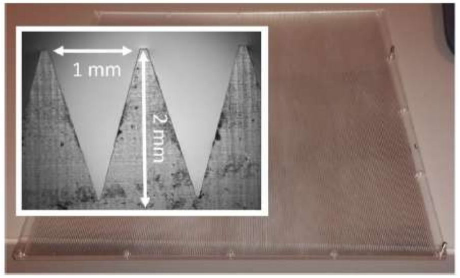


Grevillot et al, 2018, Med. Phys. 45 (1), January 2018 0094-2405/2018/45(1)/352/18

NOZZLE AND PASSIVE ELEMENTS

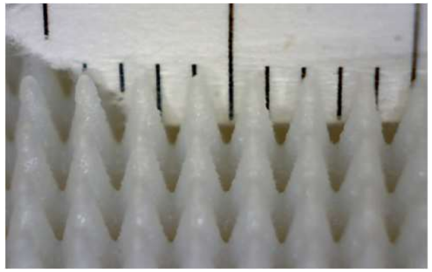
Main Nozzle components

- DDS (Dose Delivery System)
  - Monitoring System
    (beam intensity, position and size)
- ITS (Independent Termination System)
  - Redundant safety system
    (non-expected beam delivery)
- RiFi (Ripple Filters)
  - Static energy spreading device
- RS (Range Shifters)

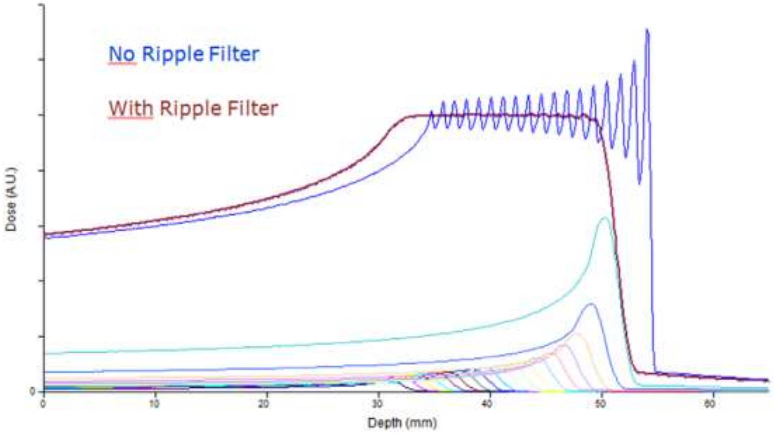


NOZZLE AND PASSIVE ELEMENTS

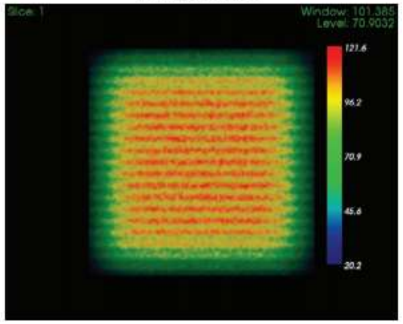
- Design of 1D RiFi for ion beam therapy



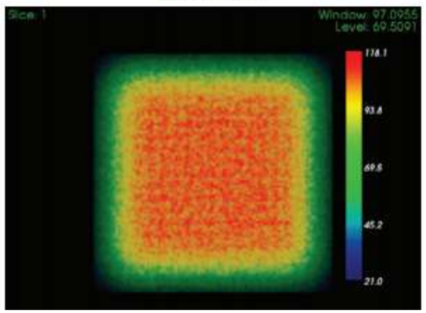
Design of 2D RiFi

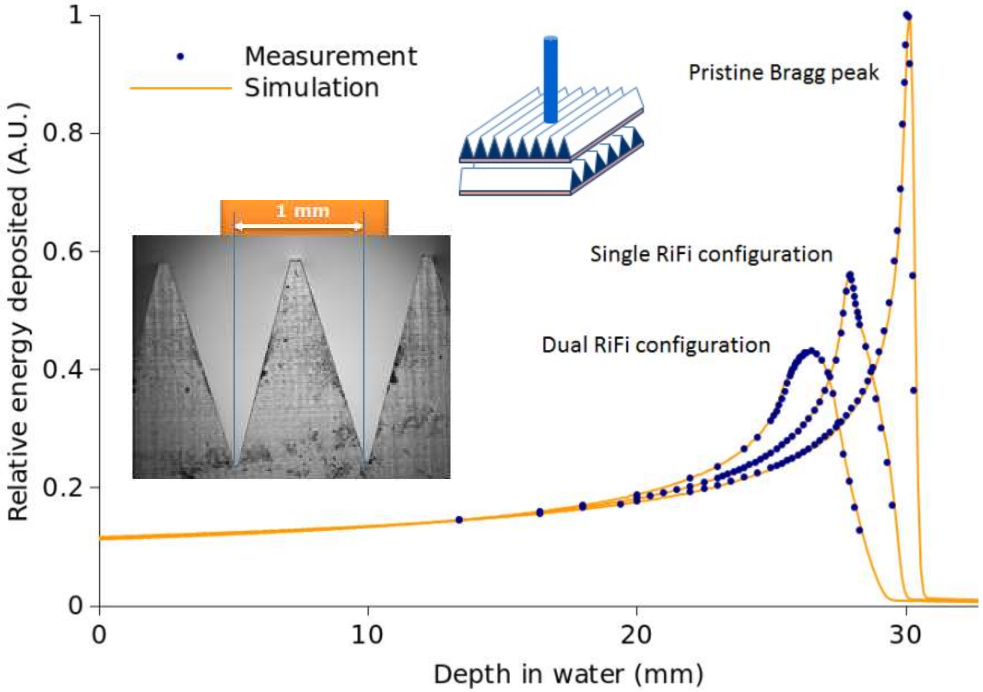


Single RiFi



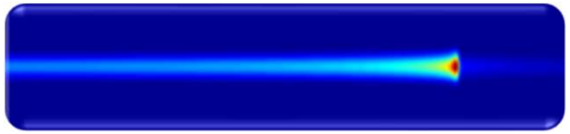
Dual RiFi

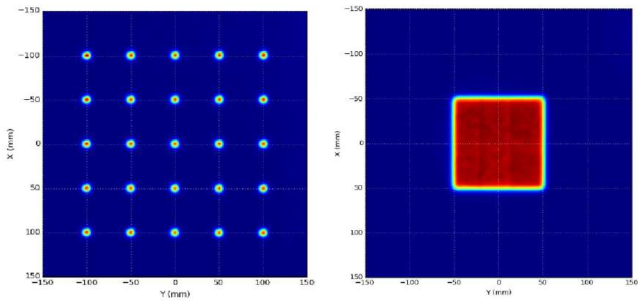




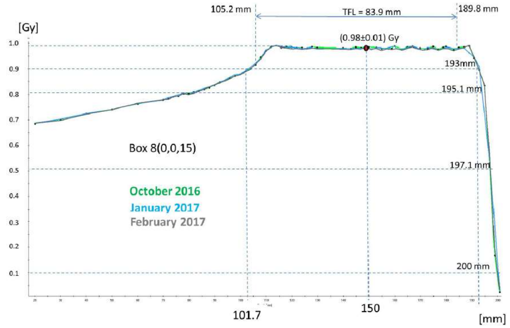
Grevillot et al, PMB 2015

COMMISSIONING CONCEPT FOR BEAM DELIVERY SYSTEM





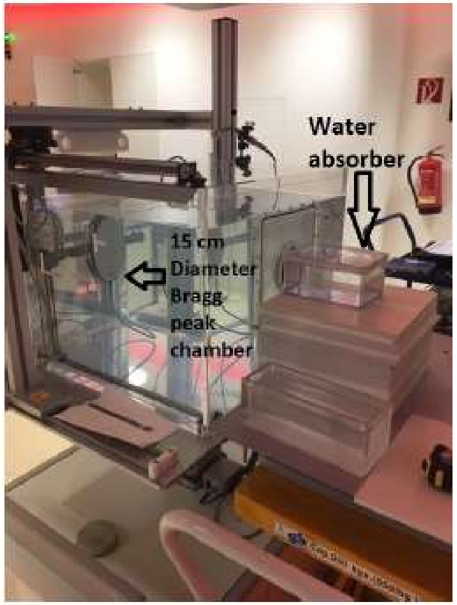
- Baseline Data for TPS and QA (w/wo RS)
  - 1D delivery:
    - IRPD in water at isocenter/non-isocentric (using different detectors)
    - Transverse dose profile for single pencil beam (core and halo)
  - 2D delivery:
    - Spot maps in air at different air gaps
    - Spot maps in RW3
    - Homogeneous square field in air at isocentre/non-isocentric
    - Homogeneous square field in RW3
    - Output factors (field size and frame factor)
    - 2D test pattern
  - 3D delivery:
    - Homogeneous cubic target in water at isocenter/non-isocentric
    - Homogeneous cubic target in RW3 at isocenter/non-isocentric
- System stability

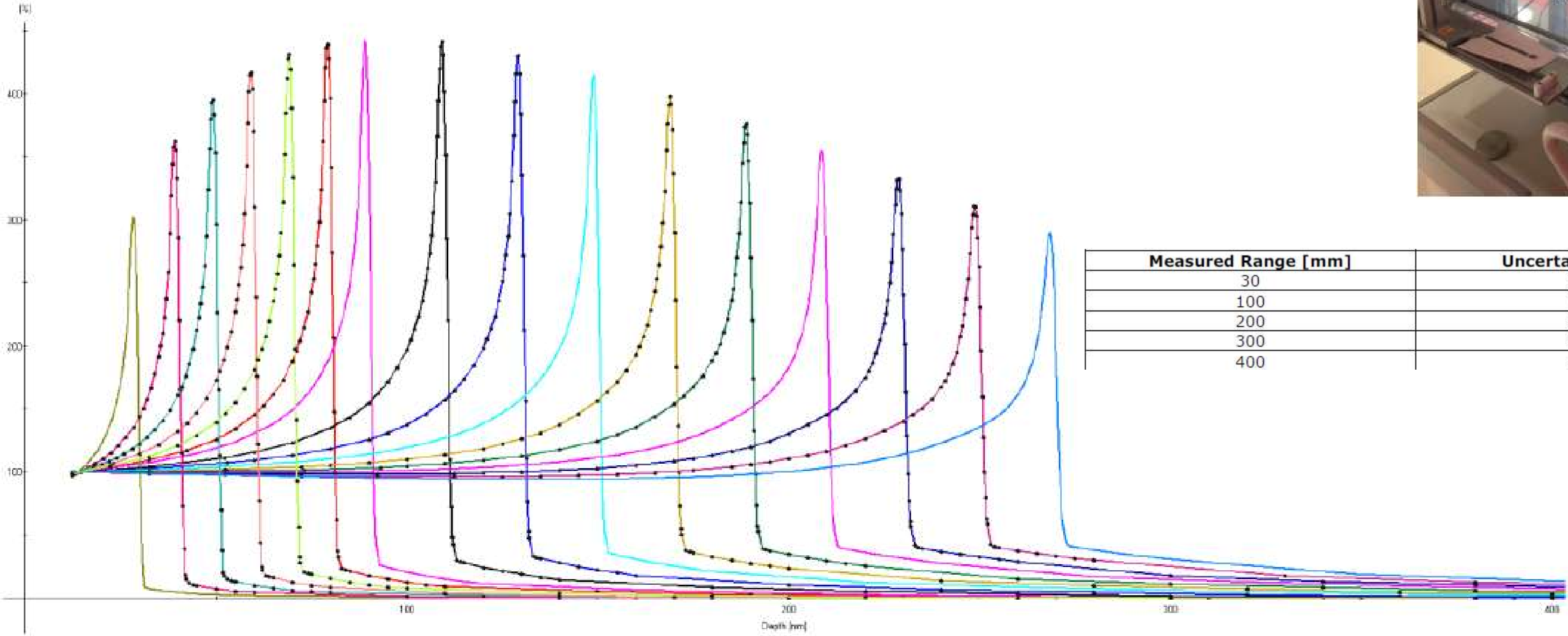


- Dose Monitor Calibration
  - In reference conditions
  - Correction factors for DDS calibration in RW3/Sphinx
  - Verification of monitor calibration in reference conditions/RW3
  - Using redundant method
  - Drift within one day

INTEGRAL RADIAL PROFILE WITH DEPTH (IRPD)

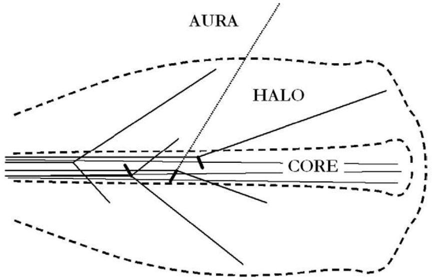
- From 120 MeV/n to 402 MeV/n (2.9 – 27.0 cm in water)
- Measured with PPIC Bragg Peak chamber (normalized to reference calib.)

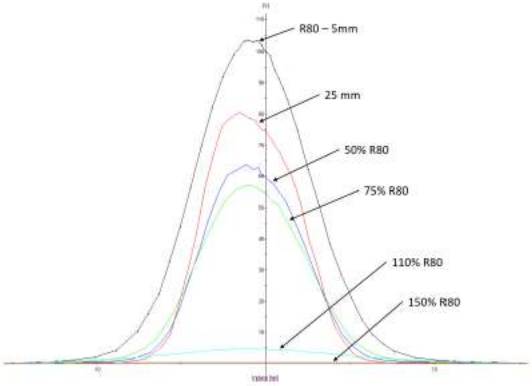


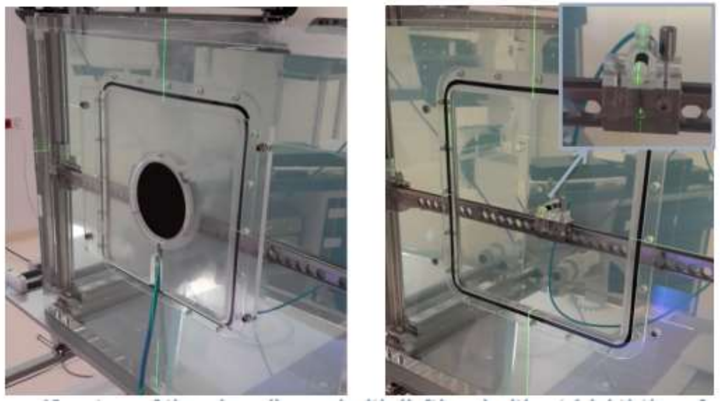


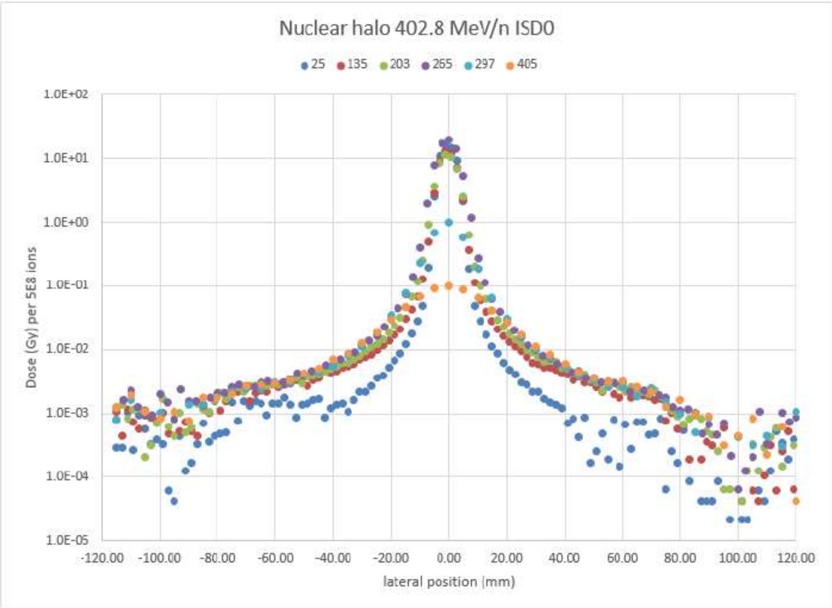
Measured Range [mm]	Uncertainty [mm]
30	0.2
100	0.2
200	0.3
300	0.5
400	0.6

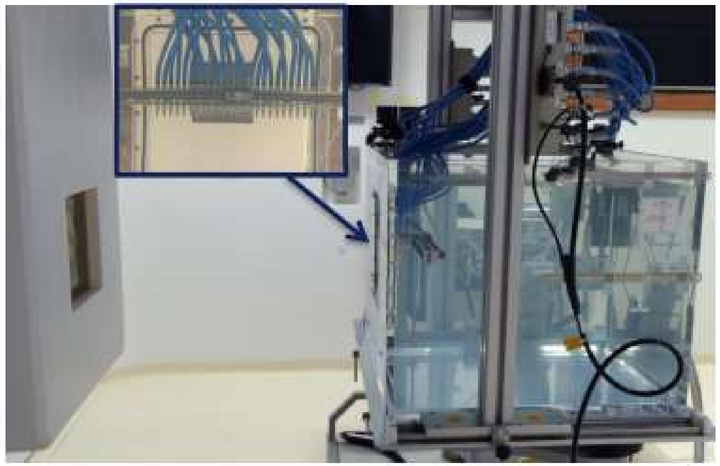
TRANSVERSE DOSE PROFILES – CORE AND HALO



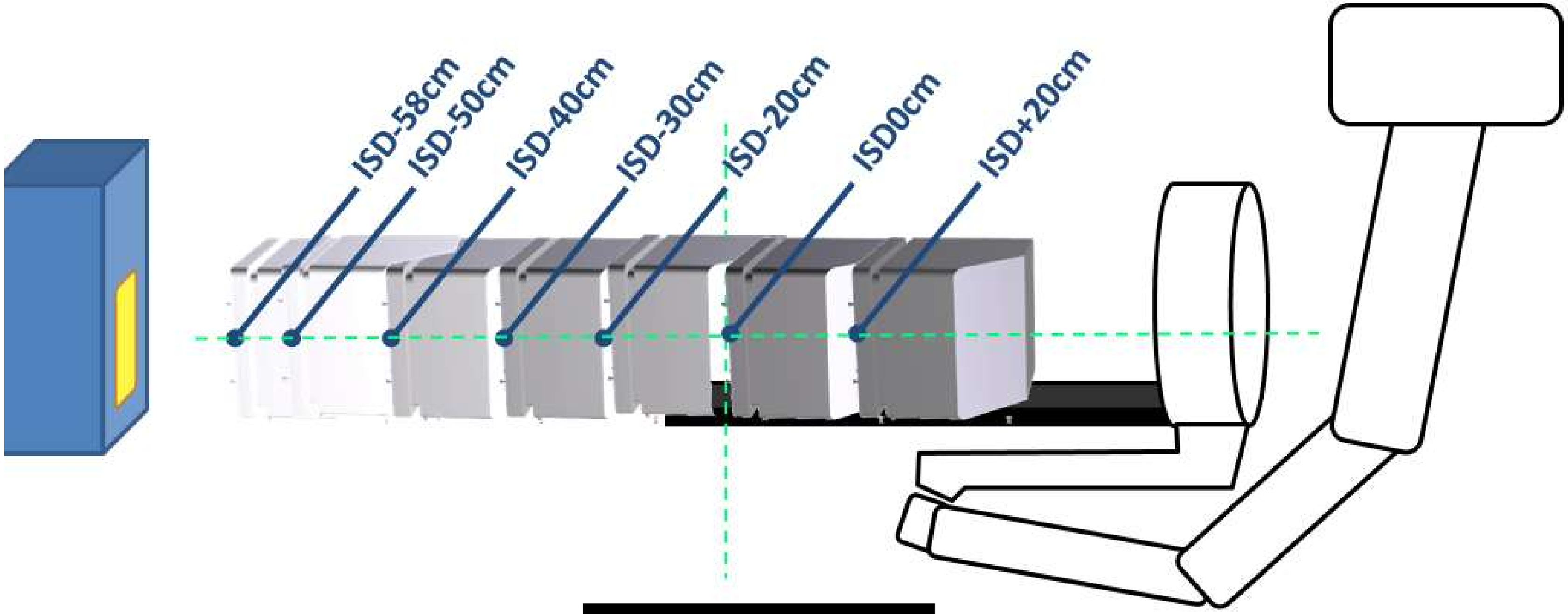


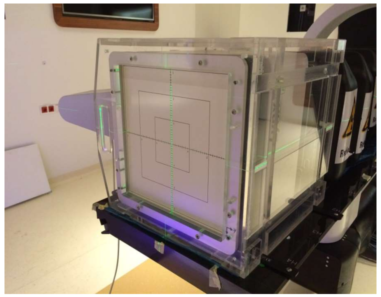


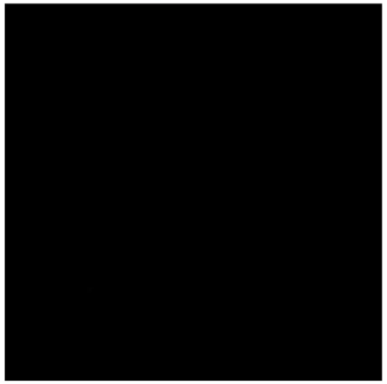




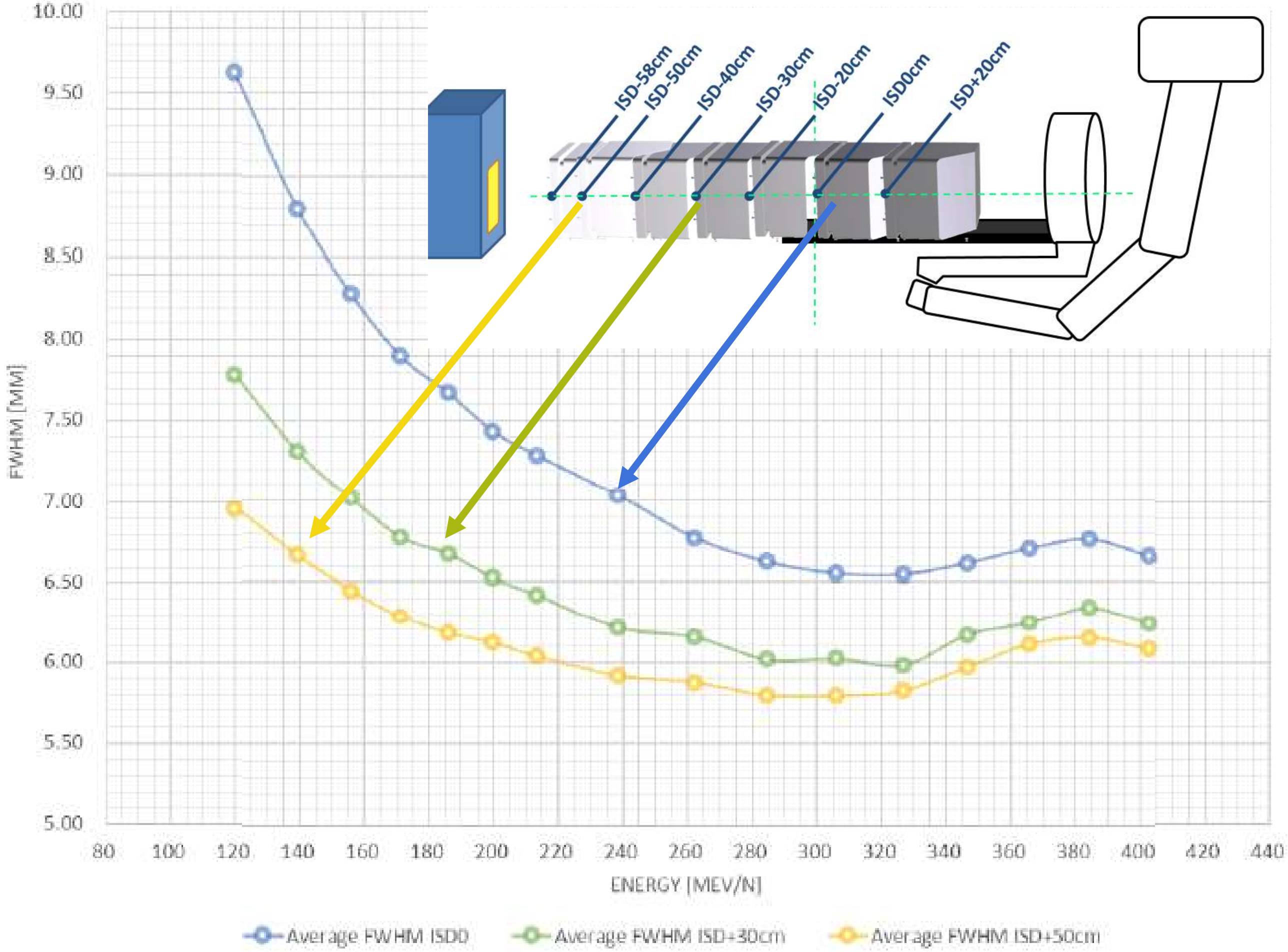
SPOT SIZE IN AIR





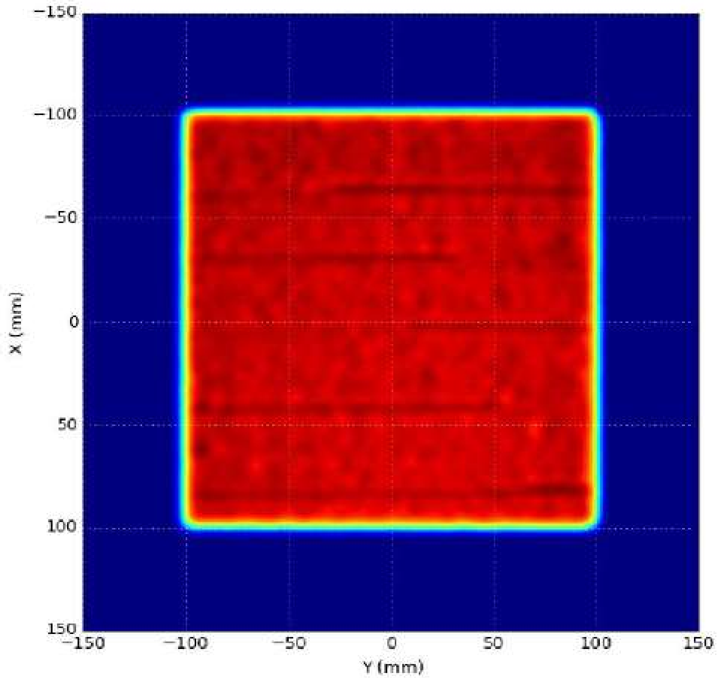


SPOT SIZE IN AIR & HOMOGENEITY



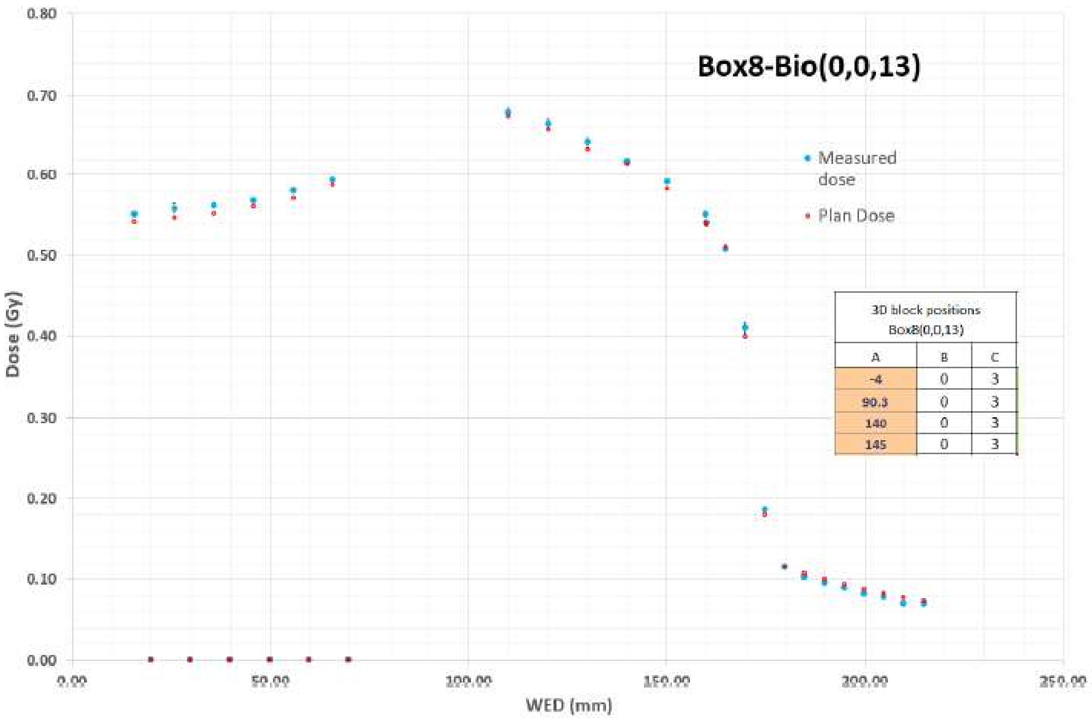
Smaller than protons!

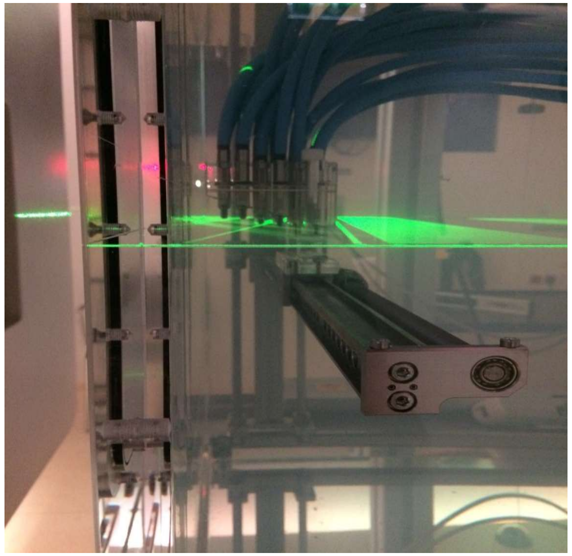
Homogeneity < 5%

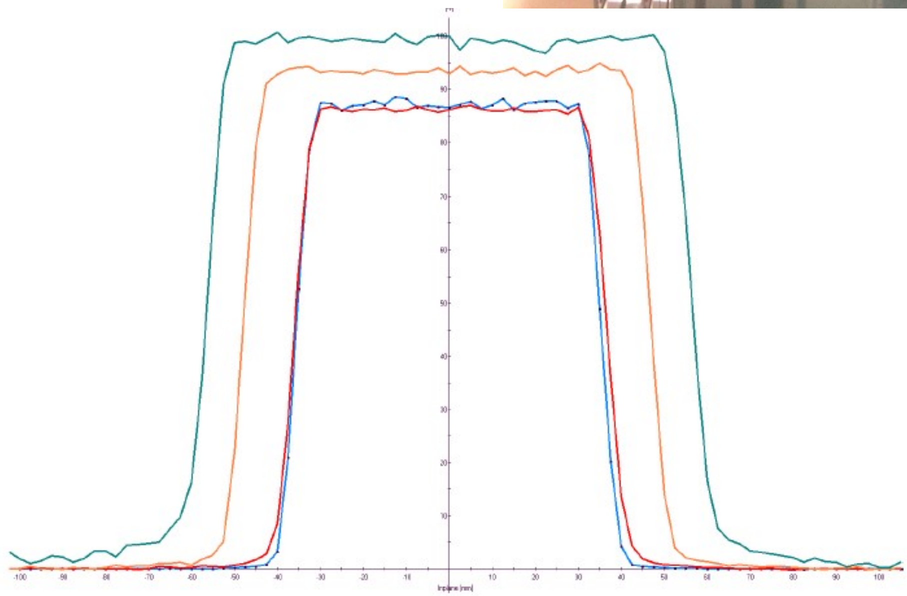


SOBP

Depth-dose + transverse dose profiles







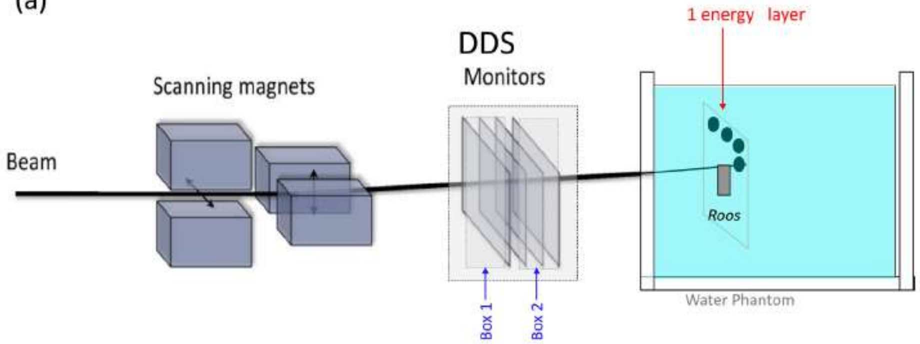
MedAustron

BEAM MONITOR CALIBRATION – SINGLE LAYER/REFERENCE METHOD

- The dose is measured in reference conditions (Isocenter, water, 2 cm depth, 8cm x 8cm field)

$$D_{w,Q} = M_Q N_{D,w,Q_o} k_{Q,Q_o}$$

(a)

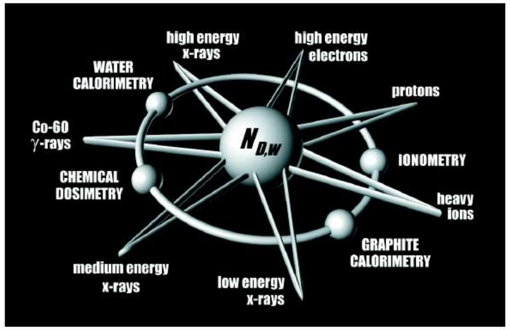


- It is converted into number of particles via relationship to stopping power

$$D[\mathrm{Gy}] = 1.6 \times 10^{-9} \times \frac{dE}{dx}\left[\frac{\mathrm{keV}}{\mu\mathrm{m}}\right] \times F[\mathrm{cm}^{-2}] \times \frac{1}{\rho}\left[\frac{\mathrm{cm}^3}{\mathrm{g}}\right]$$

IAEA TRS-398

Absorbed Dose Determination in External Beam Radiotherapy: An International Code of Practice for Dosimetry based on Standards of Absorbed Dose to Water



Beam monitor calibration in scanned light-ion beams

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(Received 20 June 2016; revised 16 September 2016; accepted for publication 18 September 2016; published 5 October 2016)

Med. Phys. 43 (11), November 2016

UNCERTAINTY BUDGET

Osorio J, et al, 2021

Z Med Phys **31** (2021) 154–165
https://doi.org/10.1016/j.zemedi.2020.06.005
www.elsevier.com/locate/zemedi

Table 3
Uncertainty budget for the determination of the number of particles $n_{Q_{spot}}$ from the absorbed dose to water at a point in a single-layer scanned beam (single-layer method) obtained with the Roos chamber cross-calibrated against the Farmer chamber in a high-energy proton (P) or carbon ion (C) beam.

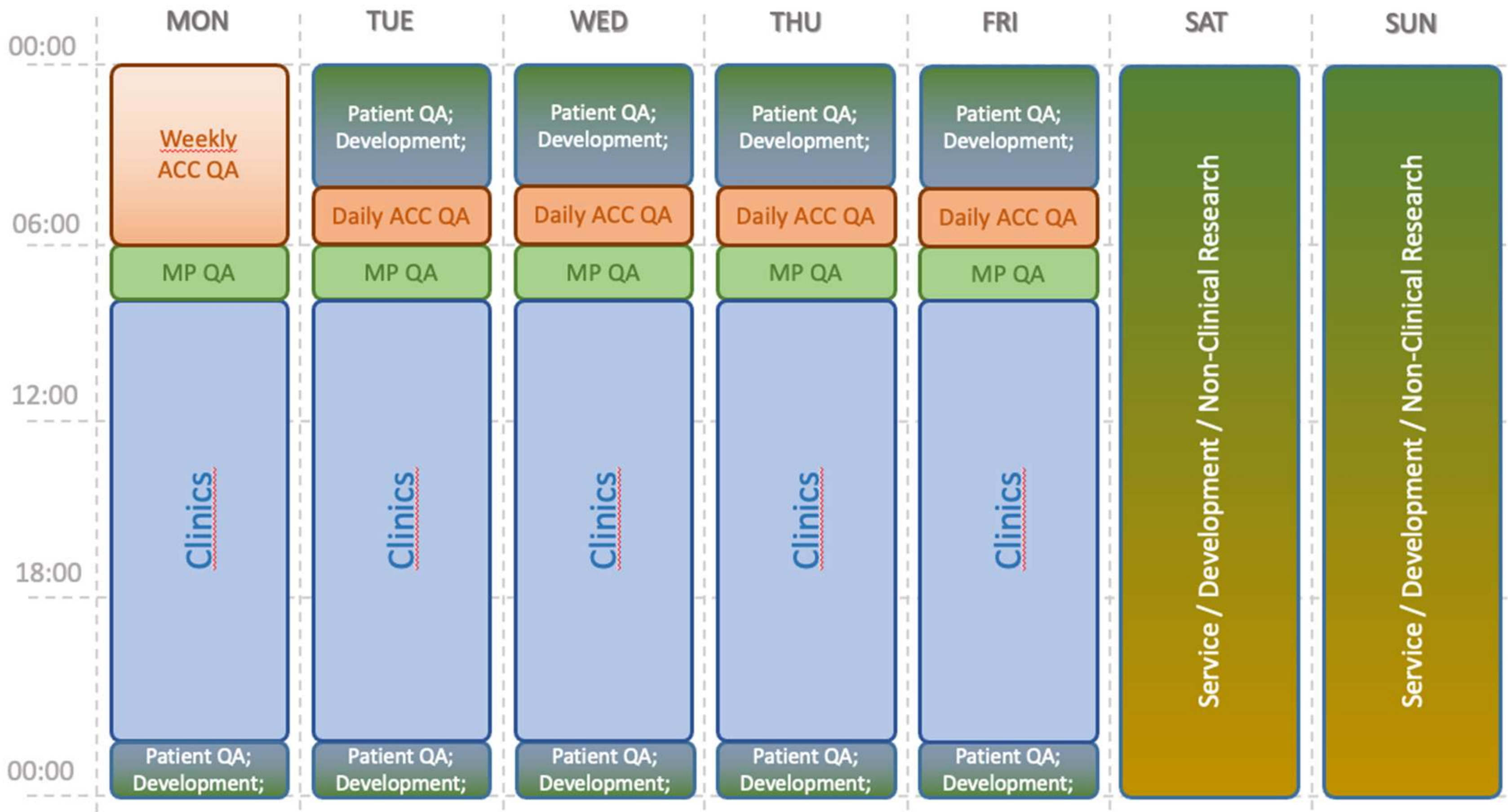
Physical quantity or procedure	Type	%
Step 1: Standards Laboratory		
Combined uncertainty in Step 1		
Calibration coefficient, $N_{D,w}^{Farmer}$, obtained from the standards laboratory	B	0.6
Step 2: Determination of $N_{D,w,Q_{cross}}^{Roos}$ (Eq. (1))		
Long-term stability of Farmer and Roos chambers	B	0.3
Establishment of reference conditions	A	0.3
Ratio of dosimeter readings $M_{Q_{cross}}^{Farmer}/M_{Q_{cross}}^{Roos}$	A	0.2
Correction for influence quantities, $\prod k_i$	B	0.1
Beam quality correction factor, $k_{Q_{cross}}^{Farmer}$ [1]	B	1.7 (P)/2.9 (C)
Combined uncertainty in determination of $N_{D,w,Q_{cross}}^{Roos}$ *(Steps 1 + 2)*		1.9 (P)/3.0 (C)
Step 3: Determination of $DAP_{w,Q}^{Roos}$ (z_{ref}) (Eq. (2))		
Reproducibility of Roos chamber reading	A	0.1
Establishment of reference conditions	A	0.1
Dosimeter reading $M_{Q,raw}^{Roos}$ relative to beam monitor	A	0.2
Correction for influence quantities $\prod k_i$	B	0.2
Beam quality correction factor, $k_{Q,Q_{cross}}^{Roos}$	B	0.6
2D non-homogeneity of the local dose over the area of the Roos chamber resulting from spot position uncertainty	B	0.4
Average spot spacing $\Delta x \Delta y$ at measurement depth (z_{ref})	B	0.5
Combined uncertainty in determination of DAP_w *(Steps 1 + 2 + 3)*		2.1 (P)/3.1 (C)
Step 4 Determination of $n_{Q_{spot}}$ (Eq. (5))		
MC calculation of Cema/fluence	B	1.5
Calibration curve fitting for monitor chamber	B	0.4
Combined uncertainty in Step 4		*1.6*
Combined uncertainty in determination of $n_{Q_{spot}}$		*2.6 (P)/3.5 (C)*

Compared to

- MV photons: 1.2%

QUALITY ASSURANCE

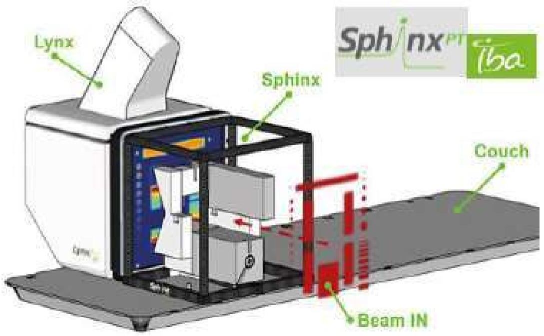
OPERATION SCHEDULE



PILLARS OF BEAM TIME REDUCTION FOR QA

I. OPTIMIZATION

(optimizing QA procedures with beam)



In use since March 2019

First worldwide routine use of Sphinx for carbon ions!

II. SUBSTITUTION

(replacing QA procedures with beam by other means)

Reimagining patient-specific QA in proton and ion therapy facilities

26 May 2021 Sponsored by IBA Dosimetry

Medical physicists from the Austrian particle therapy centre MedAustron explain how – and why – they've put an independent QA solution at the heart of their patient treatment programme

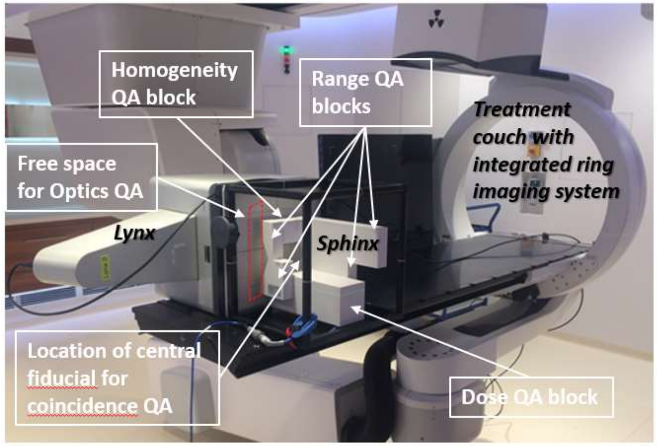
Proton PSQA – 87% in Dec 2021!

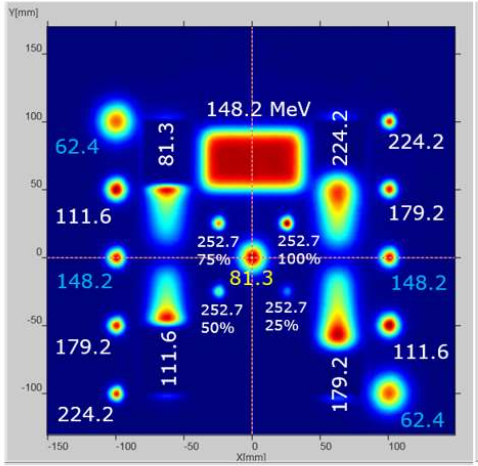
In use since February 2021

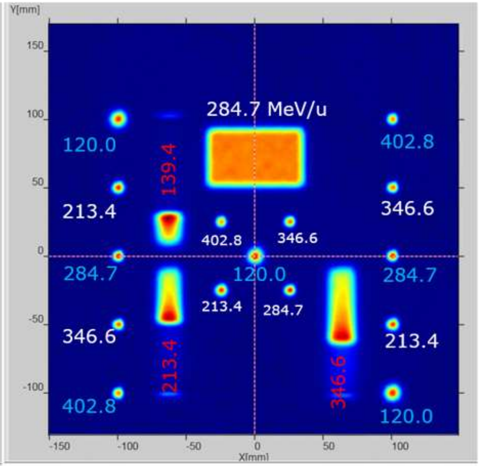
First worldwide clinical user of myQAion!

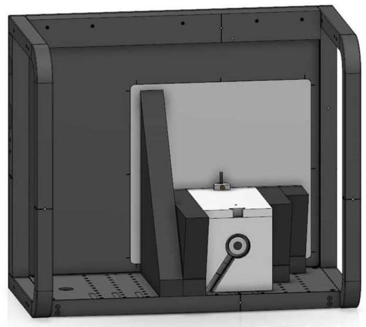
ESTABLISH OPTIMIZATION OF QA

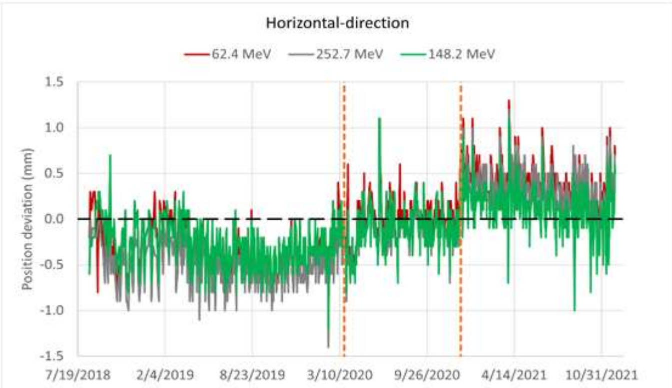
- Integrated system for both proton and carbon ions and generate trendlines











Grevillot et al J Appl Clin Med Phys. 2023;24:e13896

		Protons		Carbon ions	
Sphinx/Lynx region	QA parameter	Warning	Fail	Warning	Fail
Spot	Beam position (x,y)	1.5 mm	3 mm	1.5 mm	3 mm
	Beam size (x,y)	20%/2mm	30%/3mm	20%/2mm	40%/3mm
Bragg peak	Distal range	1 mm	2 mm	1 mm	2 mm
	Proximal range	1 mm	2 mm	1 mm	2 mm
	Width	1 mm	2 mm	1 mm	2 mm
	Fall-off	1 mm	2 mm	1 mm	2 mm
Central fiducial	Coincidence (x,y)	1.5 mm	3 mm		
Homogeneity	Homogeneity (1D)	3%	6%	3%	6%
Dose	Dose	2%	3%	2%	3%

IDC TO REPLACE MEASUREMENT BASED PSQA

- **IMRT:**
  IDC was 12 times more sensitive at detecting treatment failures for IMRT than measurement-based PSQA. **Kry et al, Med Phys 2019**

- **Cyberknife**:
  similar findings in terms of sensitivity. **Milder et al, J Appl Clin Med Phys, 2020**

- **Protons**:
  "implementation of a Monte Carlo (MC) algorithm in an IDC system was shown to illuminate dose computation issues from analytical algorithms implemented in TPS, which would **not** otherwise be **detected using traditional PSQA**." **Jhonson et al, PloSOne 2019**

In the 2020s, there was evidence that MC-based IDC can be good choice in the PSQA process due to limited sensitivity of measurement based PSQA.

FROM EXPERIMENTAL PSQA TO IDC

Journal of Applied Clinical Medical Physics

Commissioning and clinical implementation of an independent dose calculation system for scanned proton beams

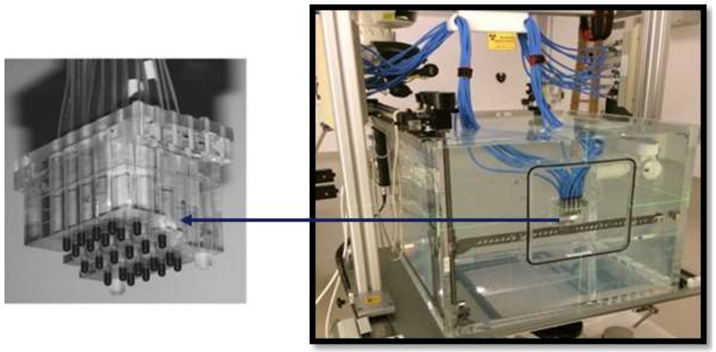
Open Access

Dreindl et al. 2024, JACMP

DOI: 10.1002/acm2.14328

Status: In Production

Measurement based PSQA

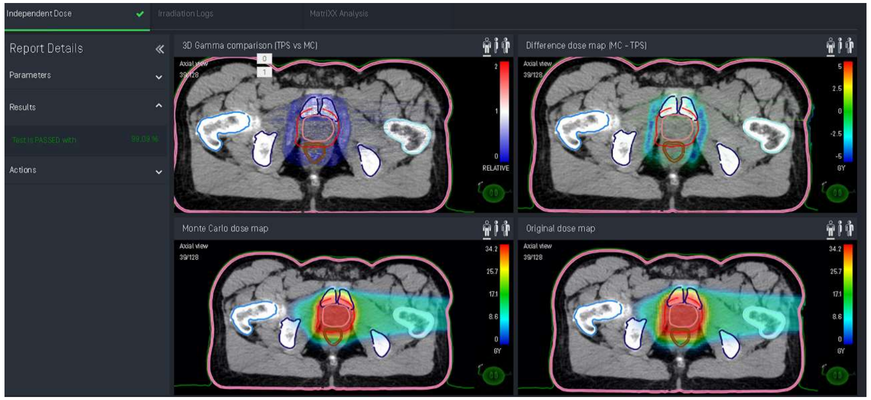


Measurement set-up using 3D-block

- 24 pin-point measurements "only"
- Limited to low gradient dose regions
- **Includes file transfer check**
- **Includes beam delivery check**

⇒ Each beam individually
⇒ Limited to dosimetric check in water *(low dose-gradient only)*

Independent Dose Calculation



IDC using myQAiON (IBA-dosimetry)

- **Full 3D patient geometry**
- **Account for high gradient dose regions**
- Does not include file transfer check
- Does not include beam delivery check

⇒ Full treatment plan
⇒ Independent dosimetric check in full 3D patient geometry

PERSPECTIVE FOR CARBONS

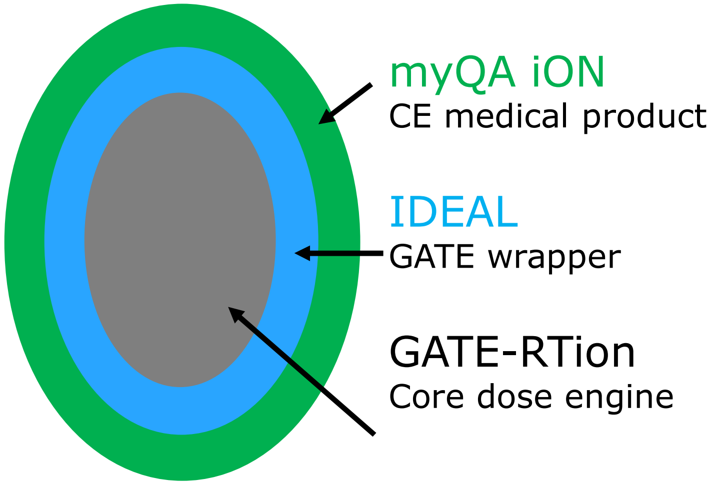
myDEAL = **my**QA iON + **IDEAL**

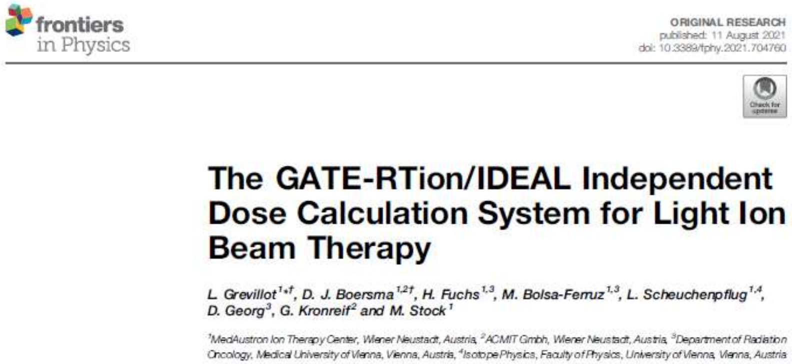
DOSIMETRY

MedAustron

GATE

- Implementing GATE-RTion (GATE/Geant4) within myQAiON for carbon ion IDC.
- Allows proton IDC with GATE also.





frontiers in Physics

ORIGINAL RESEARCH
published: 11 August 2021
doi: 10.3389/fphy.2021.704760

The GATE-RTion/IDEAL Independent Dose Calculation System for Light Ion Beam Therapy

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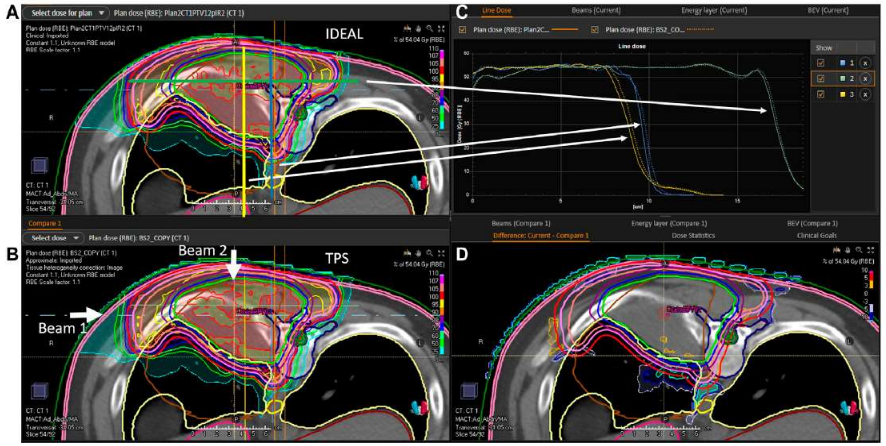

SUMMARY COMMISSIONING

- Equipment does **not necessarily work of the shelf** and needs to be accepted/commissioned as well

- Commissioning includes many measurements in 1D, 2D, 3D and allows to **define a baseline** that can later be used to verify the performance of the equipment (QA of dosimetry equipment) in case of replacement or upgrade.

- Commissioning is necessary to calibrate the equipment and **determine its uncertainty budget** before clinical usage.

- Commissioning steps like **monitor charge collection efficiency, linearity, homogeneity, background, intra-spill range and spot parameters, nozzle WET** not mentioned.

- **Medical equipment** to be commissioned includes, robotic patient positioning system, position verification system, CT scanner, Treatment Planning System (TPS) and auxiliary equipment. **E2E test** for final validation.

SUMMARY QA

- Daily QA of first beamline took 3 hours. Now we QA **4 beamlines** and **2 particle types, PPS/PPVS, safety system** within **1,5 hours. Weekly part of daily QA.**
- **2-3 shifts per week for monthly-, yearly QA and PSQA.**
- **IDC for protons** fully implemented for all beamlines and all CT protocols. This saved a lot of beam time.
- **IDC for carbon ions** currently under development and will be available this year.
- **IDC increases** the **demand on beam delivery QA** program.

MANY THANKS FOR YOUR ATTENTION