MEDICAL PHYSICS AND QUALITY ASSURANCE IN PARTICLE THERAPY

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MedAustron Ion Therapy Center

OVERVIEW

- Introduction
  - Differences to photons

- Particle Therapy Treatment Planning
  - Differences
  - LET and RBE
  - Guidelines

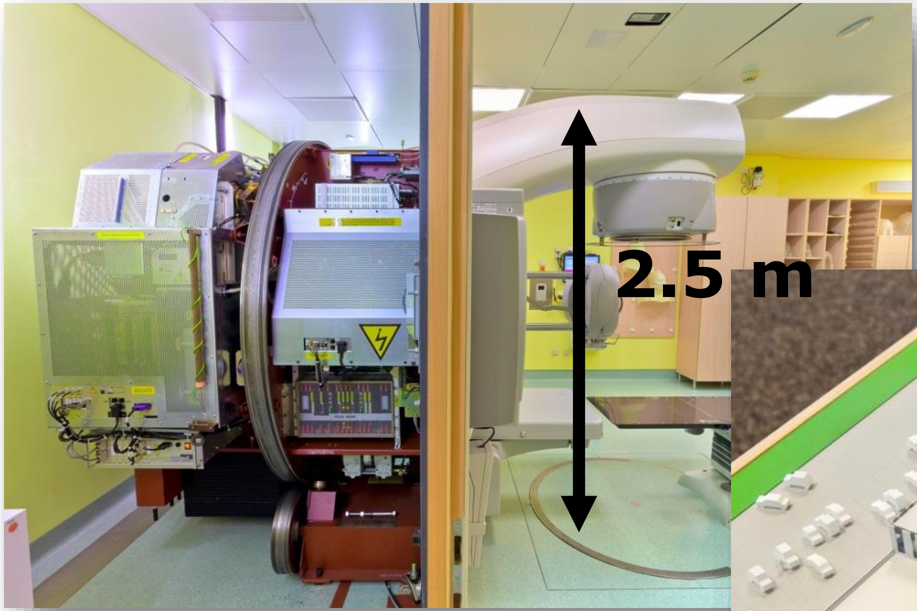
- Quality Assurance
  - Beam Delivery and other equipment

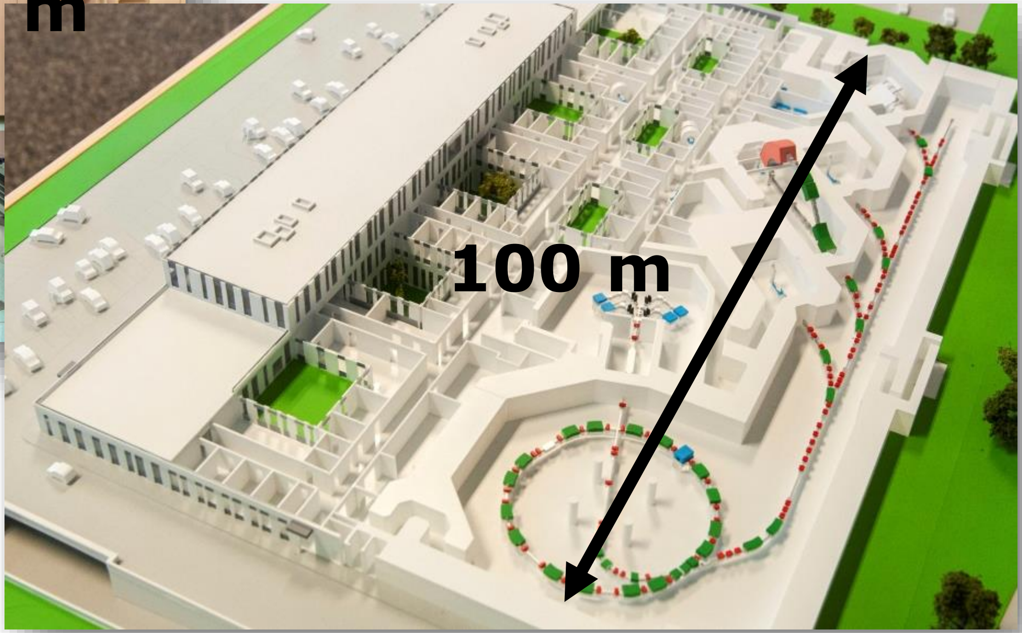
- Conclusion

INTRODUCTION

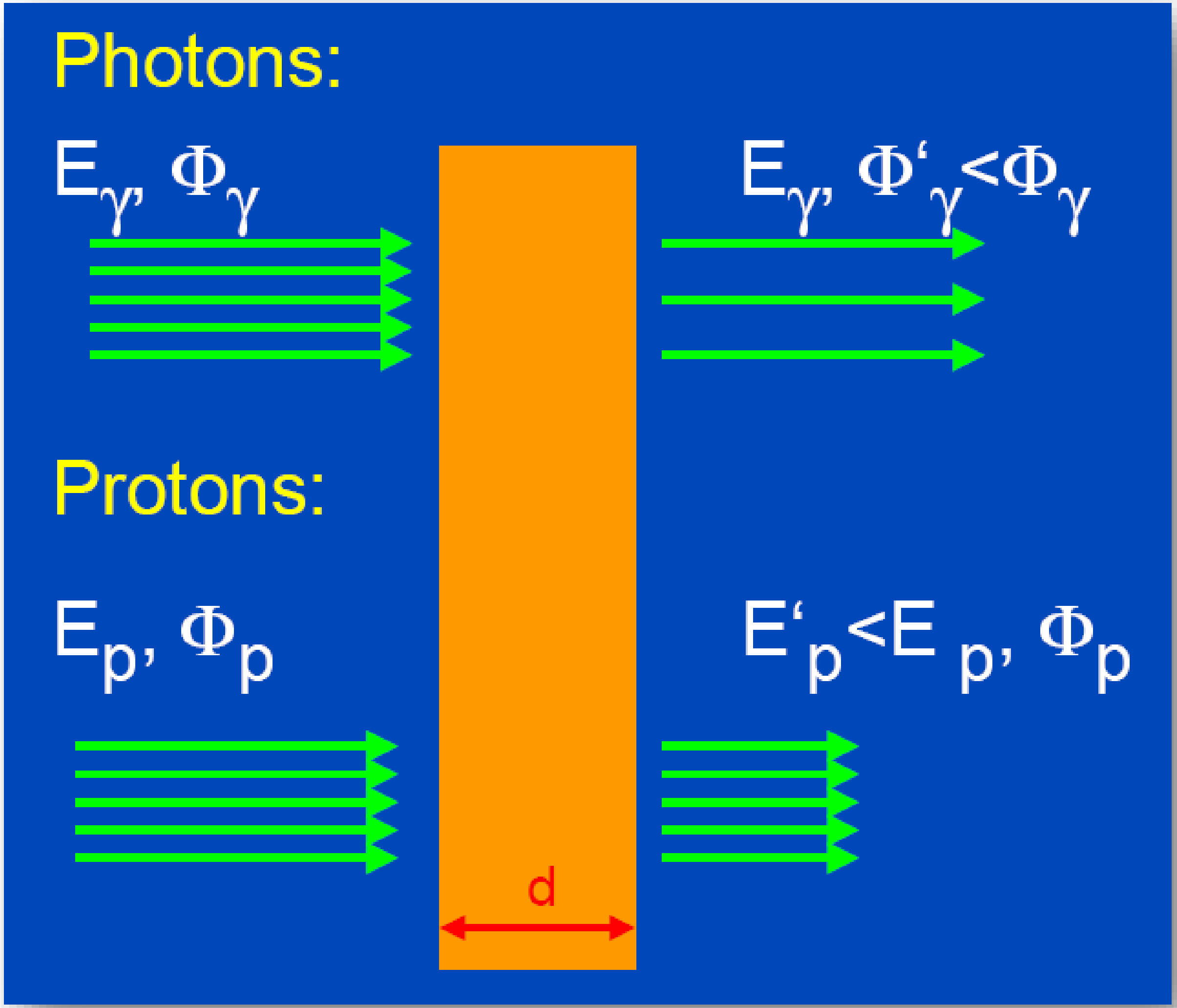
BEAM PRODUCTION

- Electron Linear Accelerator vs. p, C Synchrotron

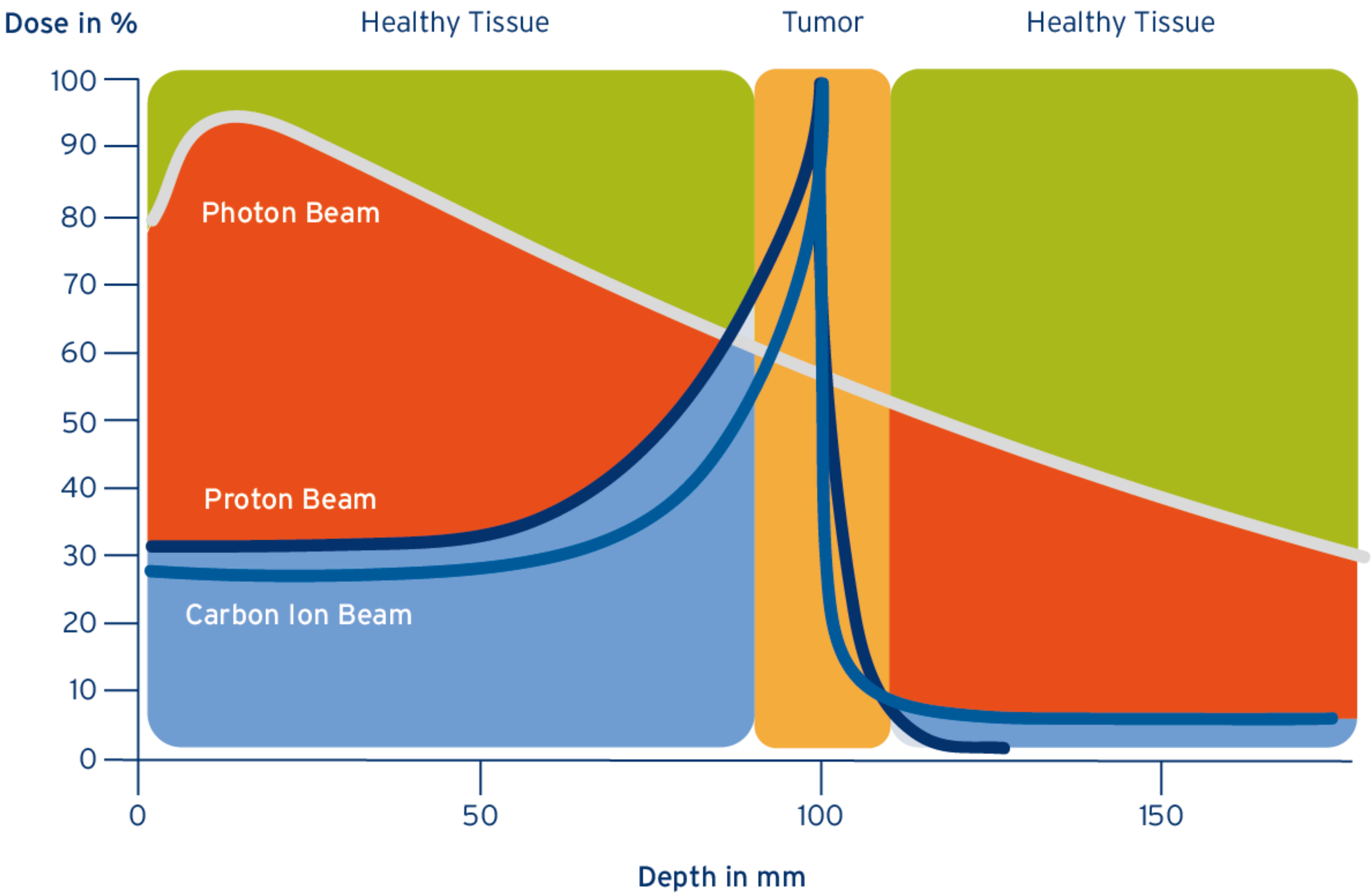




FUNDAMENTAL DIFFERENCE IN PENETRATION



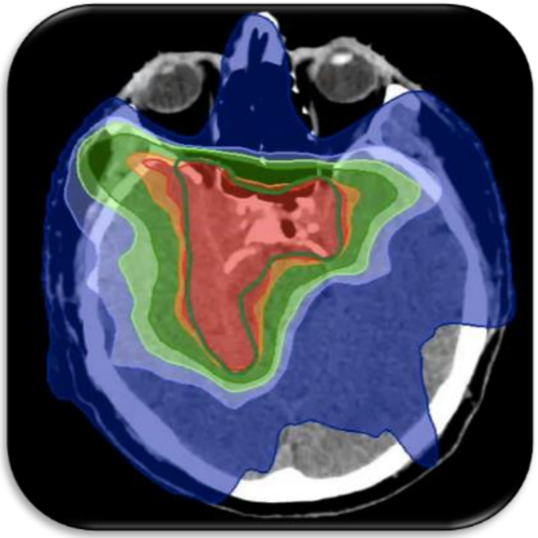
THE PRINCIPLE OF PARTICLE THERAPY



TREATMENT PLANNING - COMPARISON

PHOTONS

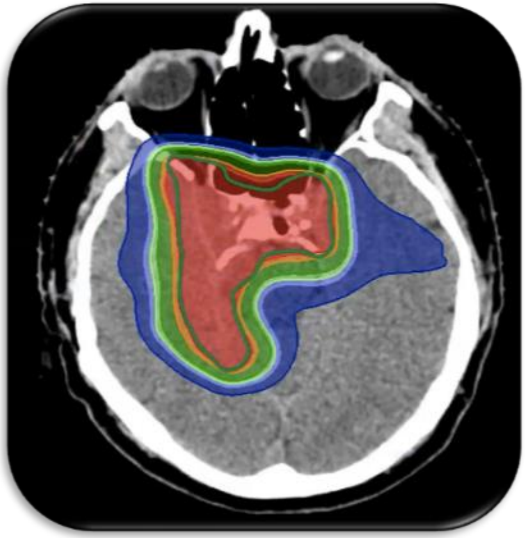
IMRT, VMAT, SBRT



Several fields, entry and exit dose

PROTONS

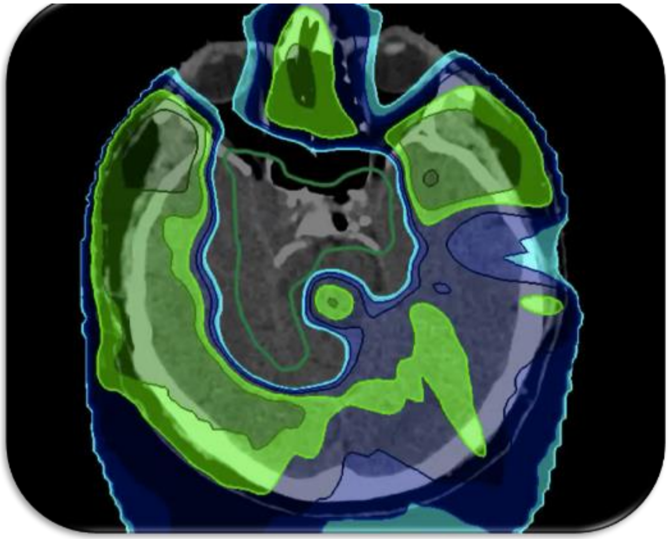
IMPT



Fewer fields, reduced entry dose, no exit dose

DOSE DIFFERENTIAL

Photons minus Protons



TREATMENT PLANNING

PRESCRIBING AND REPORTING
ICRU REPORT 78: DOSE QUANTITIES AND UNITS

- Absorbed (physical) dose:
  - Symbol: ***D*** (total absorbed dose)
    d (aborbed dose per fx)
  - Unit: **1 Gy**

- RBE-weighted absorbed dose:
  - Symbol: $\boldsymbol{D}_{\mathbf{RBE}}$ (total RBE-weighted absorbed dose)
    $\boldsymbol{d}_{\mathbf{RBE}}$ (RBE-weighted absorbed dose per fx)
  - Unit: **1 Gy (RBE)**

PRESCRIBING AND REPORTING
ICRU REPORT 78: DOSE QUANTITIES AND UNITS

- RBE-WEIGHTED ABSORBED DOSE (DRBE)

Relation between absorbed dose (D) and RBE-weighted absorbed dose (D_{RBE}) for protons:

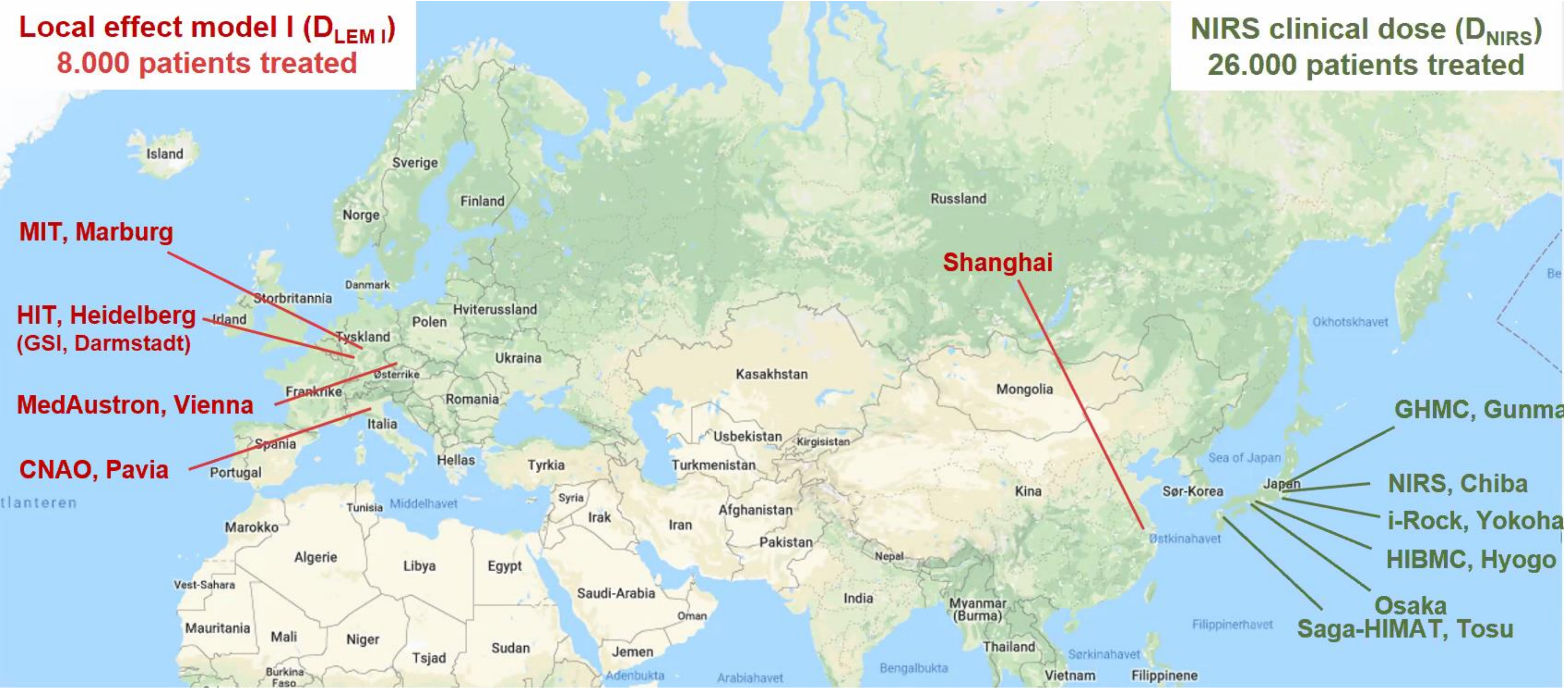
$$\boldsymbol{D_{RBE} = 1.1 * D}$$

- RBE is a dimensionless quantity. Therefore, both D and D_{RBE} share the unit Gy.
- To avoid confusion, it is recommended that the quantity D_{RBE} shall be expressed in Gy, followed by a space and the parenthetical descriptor '(RBE)'.

TWO RBE MODELS APPLIED CLINICALLY FOR C

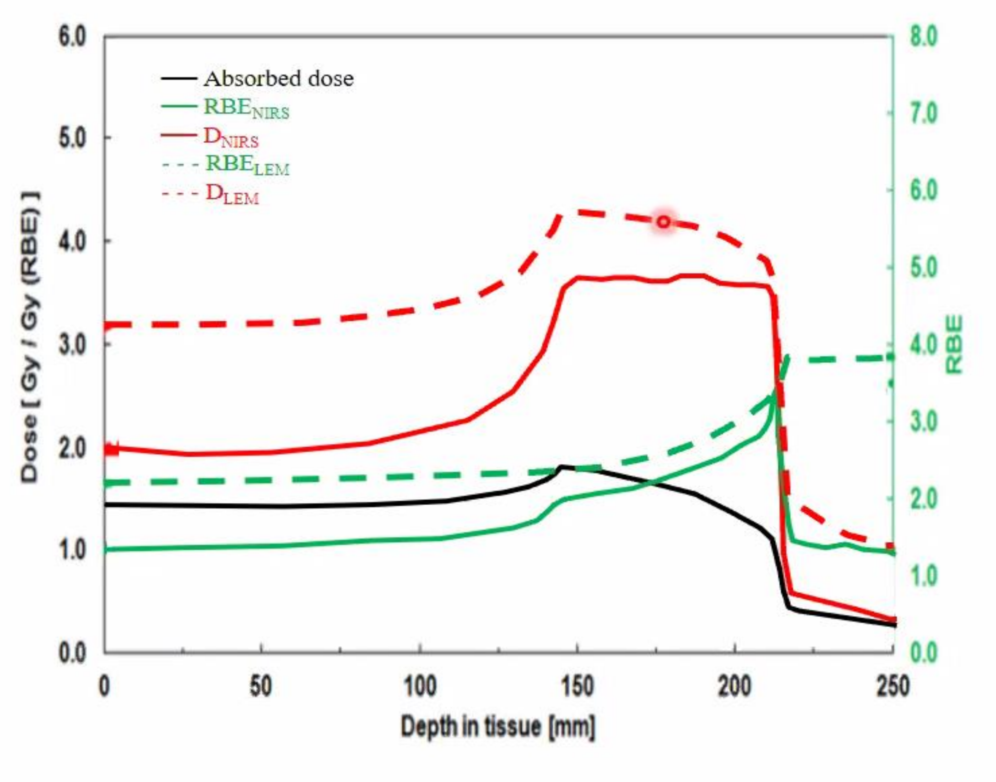
	NIRS Clinical dose	Local effect model I (LEM I)
Developed at	NIRS, Chiba, Japan	GSI, Darmstadt, Germany
Developed for	Passive scattering beam delivery	Active scanning beam delivery
1st patient treated	1994	1997
Total no. Treated, Dec-19	26.000	8.000
Purpose	Predict tumor response (acute effect)	Predict late side effects
Cell type	HSG cell line	Chordoma cell line
Ref. Radiation	(Photons) – indirectly via neutron experience	Photon
Dose dependent RBE	No	Yes

TWO RBE MODELS APPLIED CLINICALLY FOR C



NIRS CLINICAL DOSE VS. LEM I

In Japan:
D_{NIRS} = 3.6 Gy (RBE)



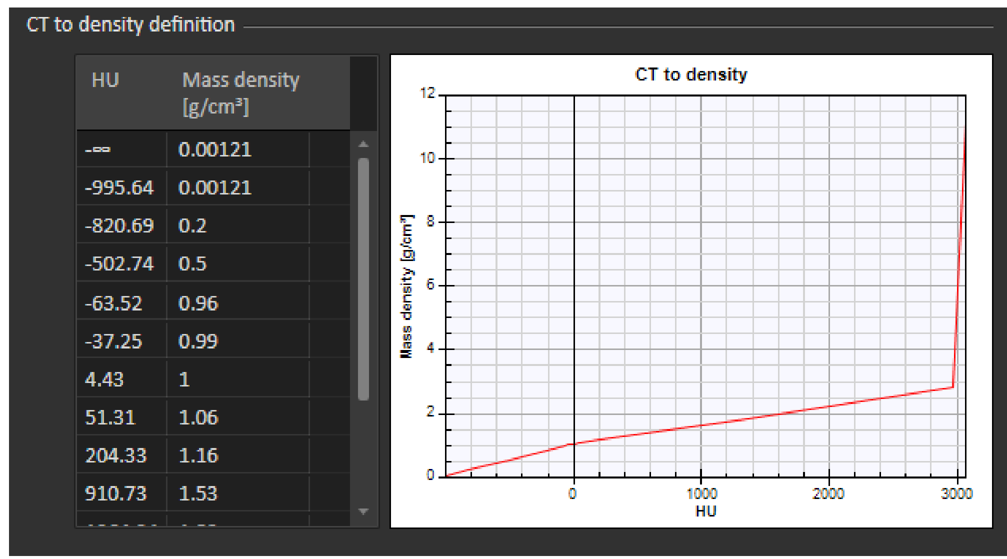
Adapted from G Magro et al. PMB (2017)

TREATMENT PLANNING SOFTWARE
CT CALIBRATION

CT – Basis for dose calculation

- HUs depend on CT imaging protocol parameters
- HU (to MD) to WET: Conversion table need to be selected
- Imaging protocol specific calibration required

CT



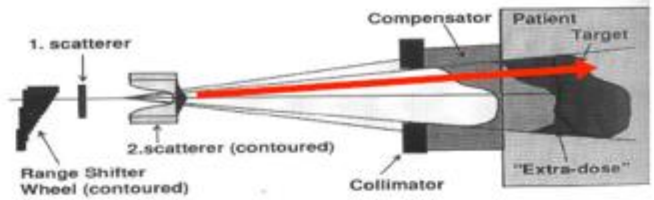
HU	Mass density [g/cm³]
-∞	0.00121
-995.64	0.00121
-820.69	0.2
-502.74	0.5
-63.52	0.96
-37.25	0.99
4.43	1
51.31	1.06
204.33	1.16
910.73	1.53

Example of HU to MD conversion table.

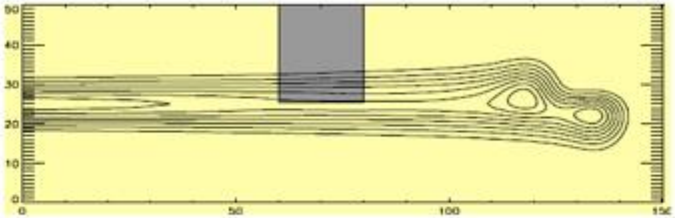
TREATMENT PLANNING SOFTWARE
DOSE CALCULATION

- 3 families :

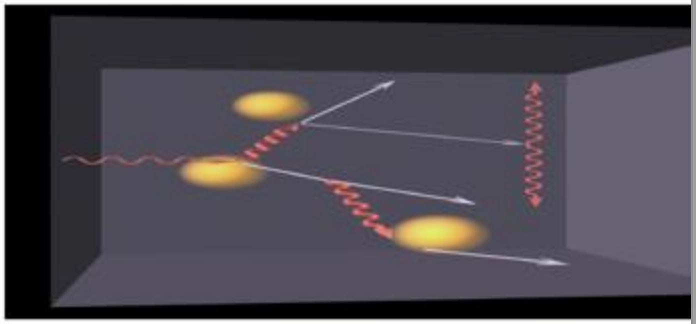
1) Ray tracing



2) Pencil beam



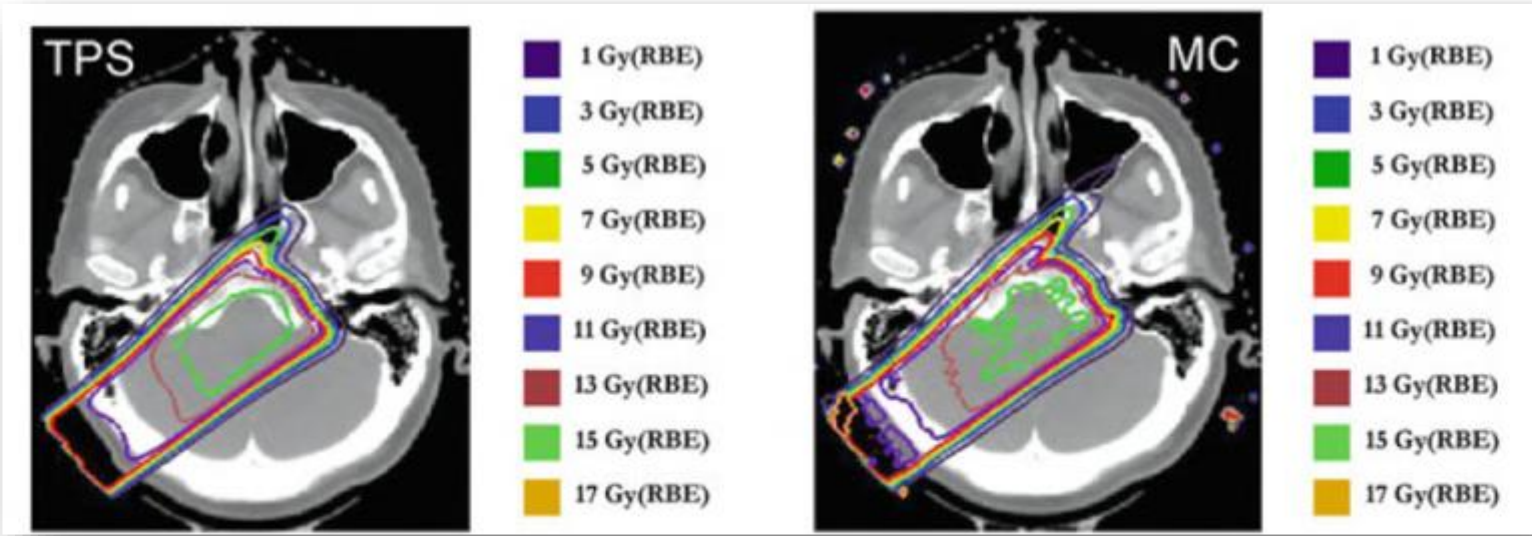
3) Monte Carlo



A. Mazal Utrecht 2016

TREATMENT PLANNING SOFTWARE DOSE CALCULATION ALGORITHMS

Pencil beam algorithm | Monte Carlo algorithm



Paganetti, Parodi, Linz 2012

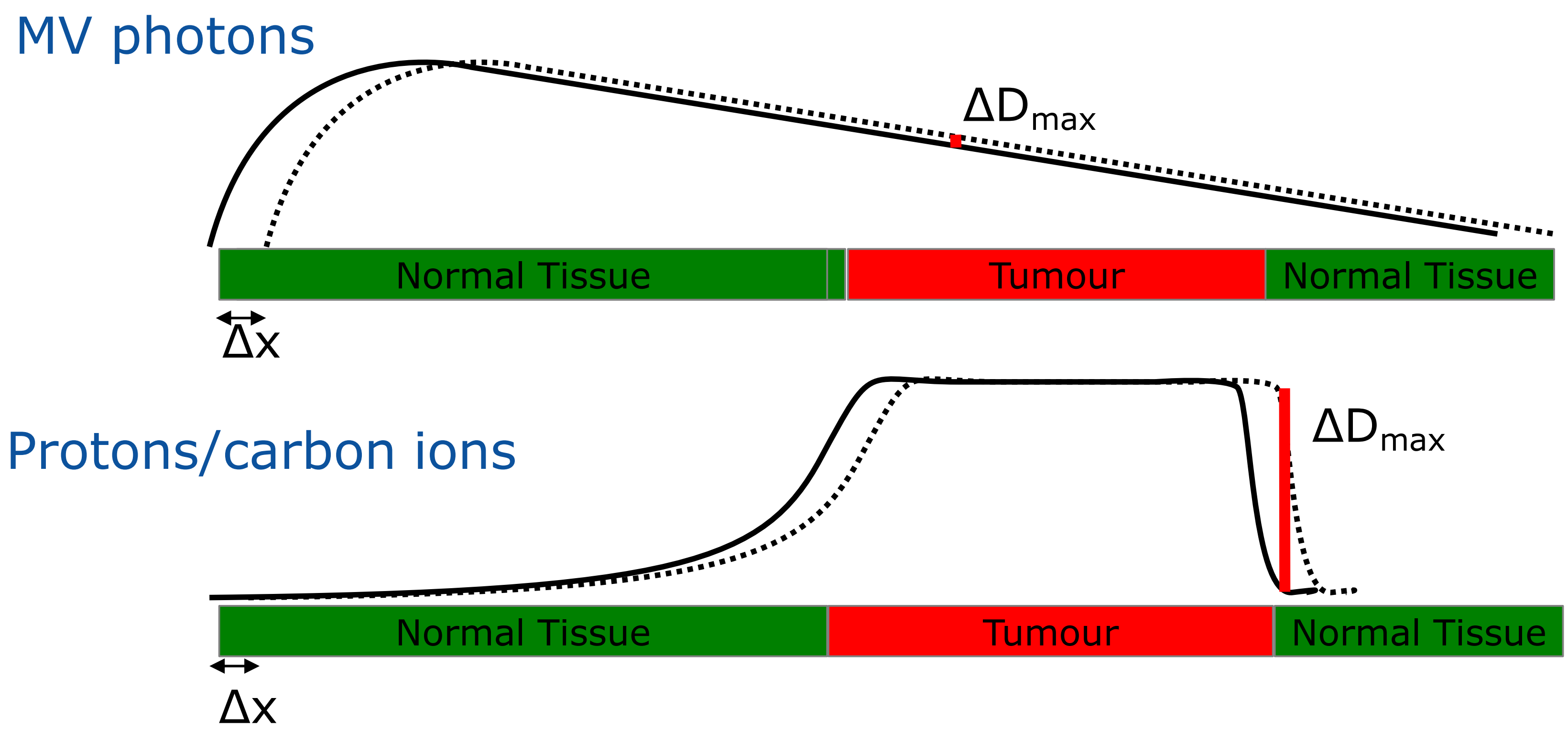
Pencil beam algorithm

- ✓ **Fast, pragmatic**
- Less sensitive to complex geometries
- Weaknesses in the presence of lateral heterogeneities
- Weaknesses in the modelling of nuclear halo
  - ➢ *Attention: combination of larger air gaps, range shifter, lateral heterogeneities and oblique surfaces (H&N, lung)*

Monte Carlo algorithm

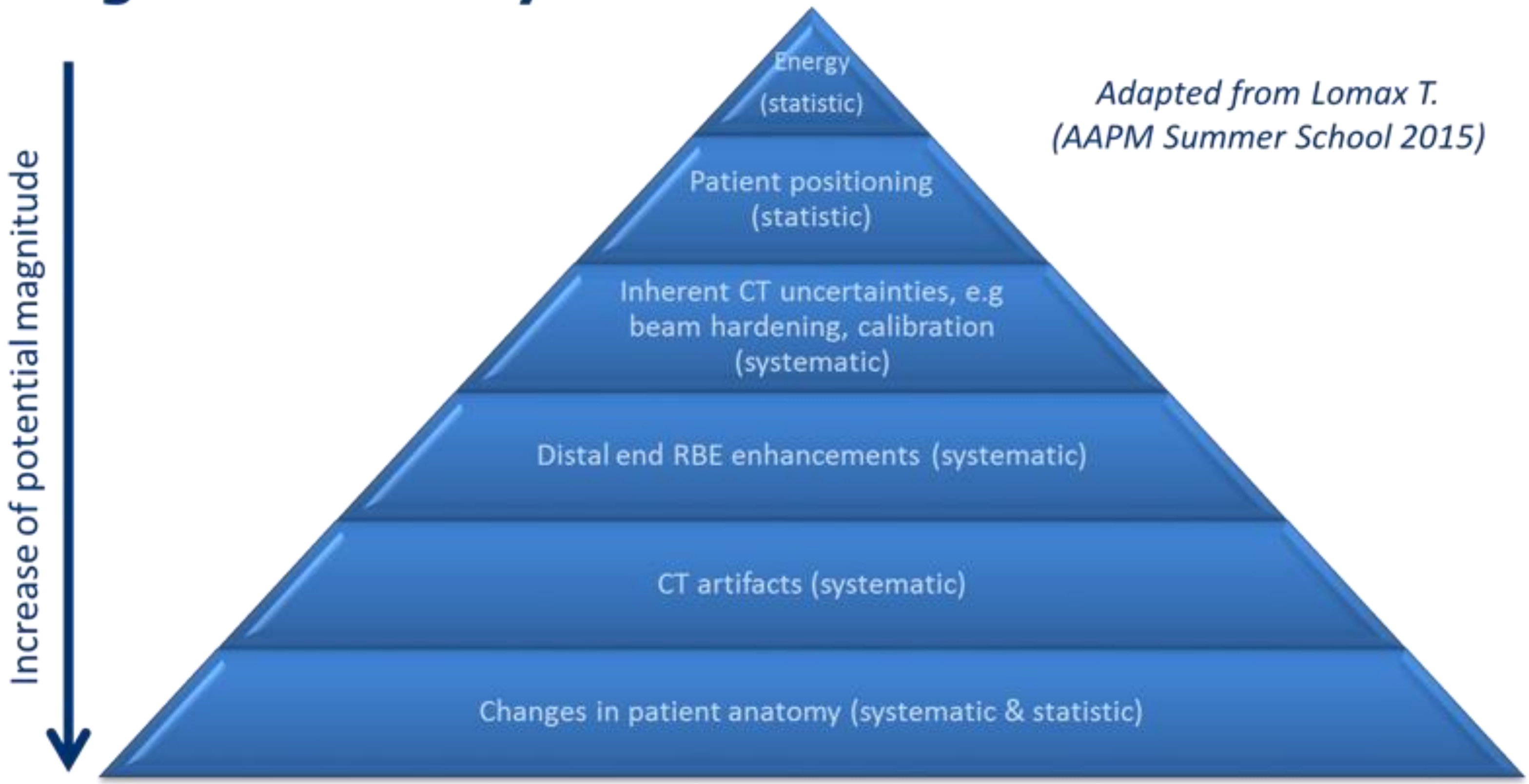
- Time consuming
- ✓ **High accuracy**
- Semi-analytic implementations in commercial TPS
  - ➢ Pre-calculated beam model
  - ➢ Scoring starts e.g. at patient surface

RANGE UNCERTAINTIES
EFFECTS



RANGE UNCERTAINTIES
SOURCES

Range uncertainty

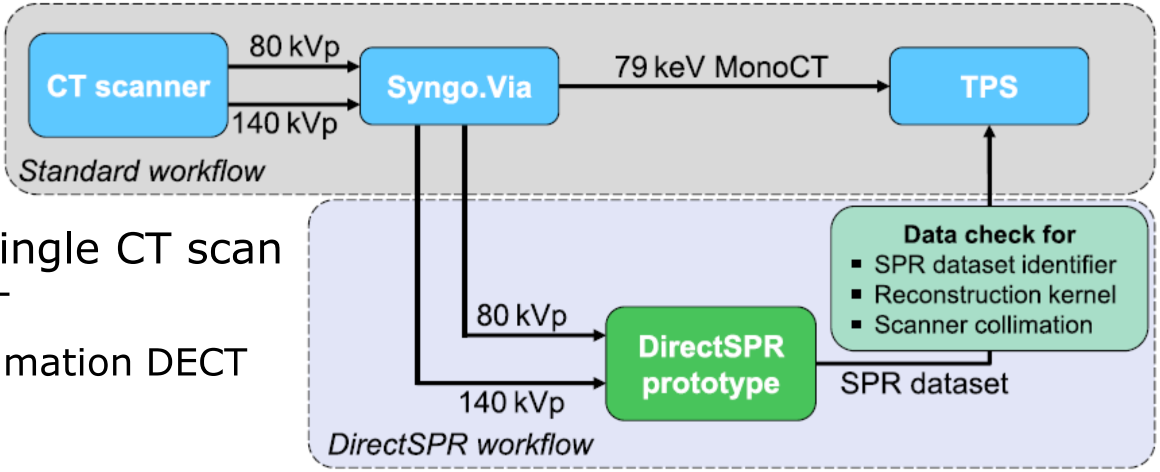


Adapted from Lomax T. (AAPM Summer School 2015)

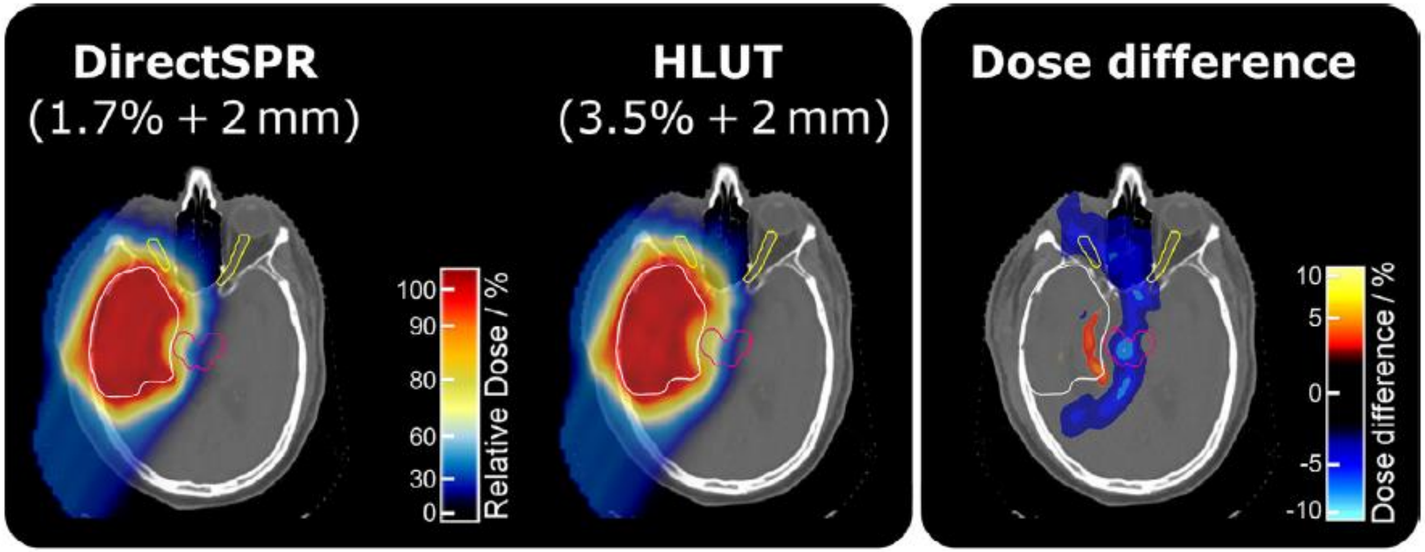
- Estimated sum of range uncertainties: ~3 - 5%
- Range uncertainties are likely to be systematic.

RANGE UNCERTAINTY

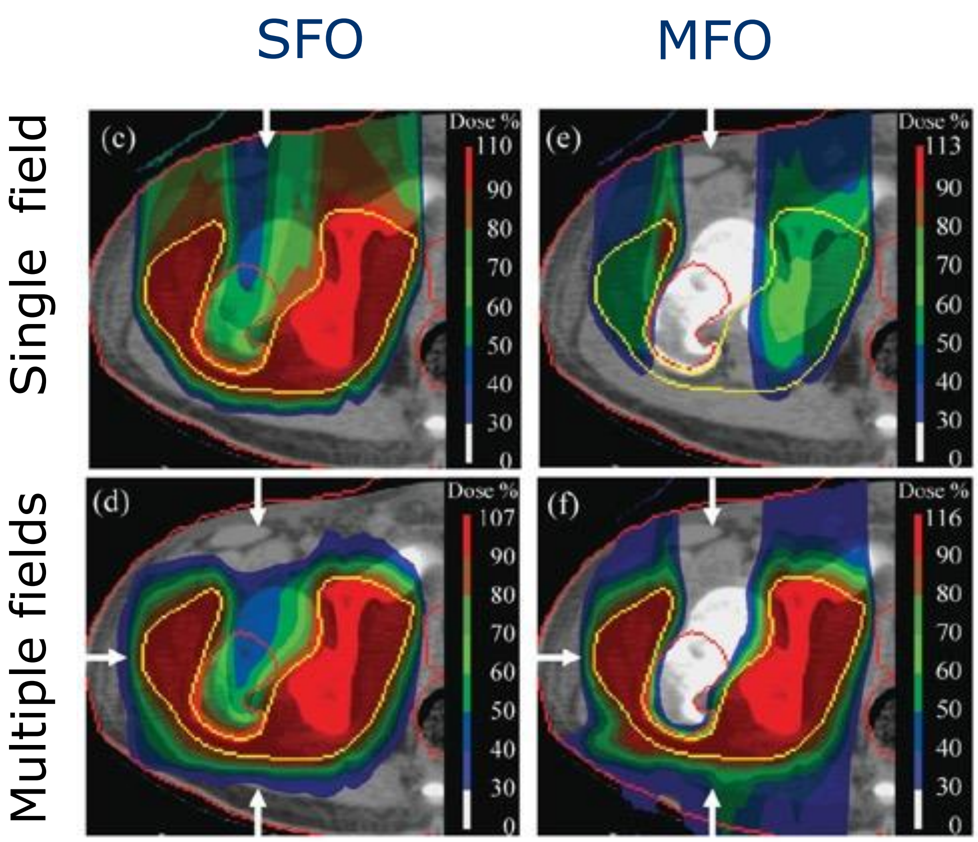
- SPR dependency on RED and mean ionization potential cannot be fully resolved by a single CT scan
  - Direct SPR estimation via DECT
  - Algorithms for RED/I value estimation DECT



- Remaining uncertainty due to:
  - Artefacts
  - Size dependent calibration
  - I-value
  - SPR energy dependency



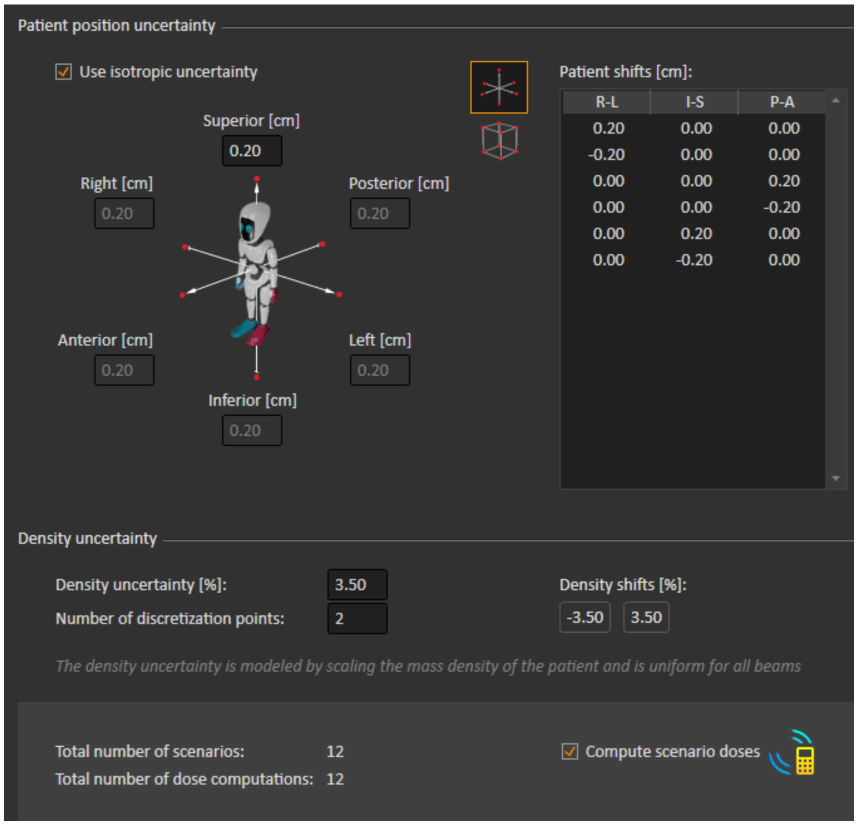
PLAN GENERATION STRATEGIES
SFO vs MFO: ISODOSE DISTRIBUTIONS



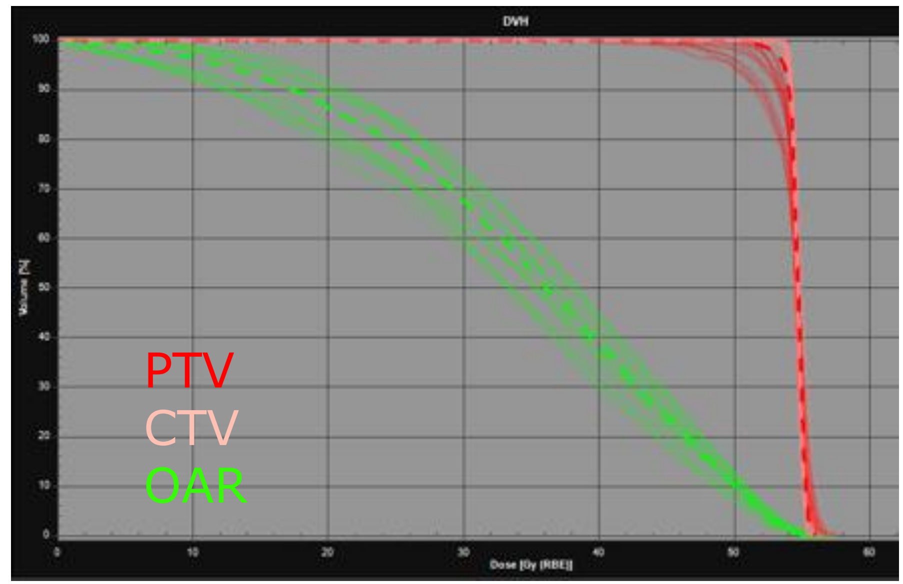
ICRU Report 78

PLAN GENERATION STRATEGIES

ROBUSTNESS EVALUATION



Scenario definition

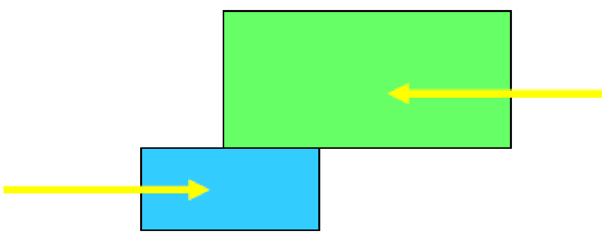


DVHs for all scenarios

PLAN GENERATION STRATEGIES

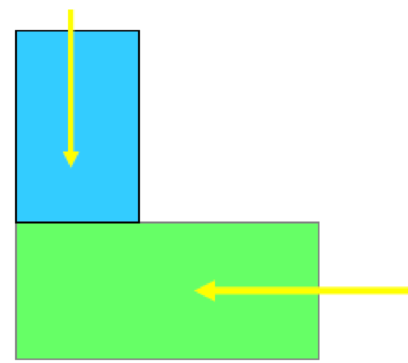
ROBUST OPTIMIZATION & FIELD MATCHING / PATCHING

Match fields



Lateral penumbra
+
Lateral penumbra

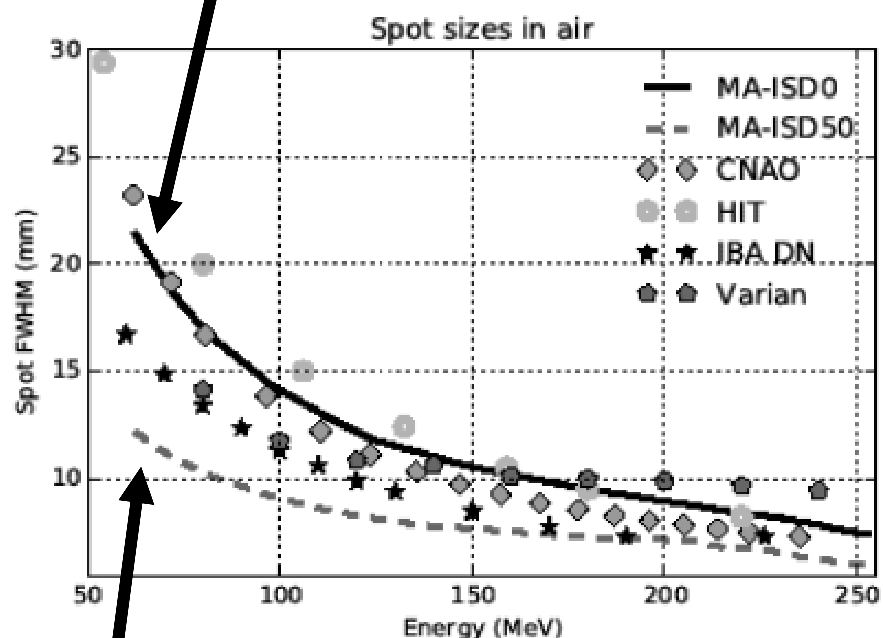
Patch fields



Distal penumbra
+
Lateral/distal penumbra

NON-ISOCENTRIC PROTON TREATMENTS

Isocenter



Non-Isocenter – 50 cm closer to nozzle

Non-isocentric proton treatments allow reducing proton penumbras!

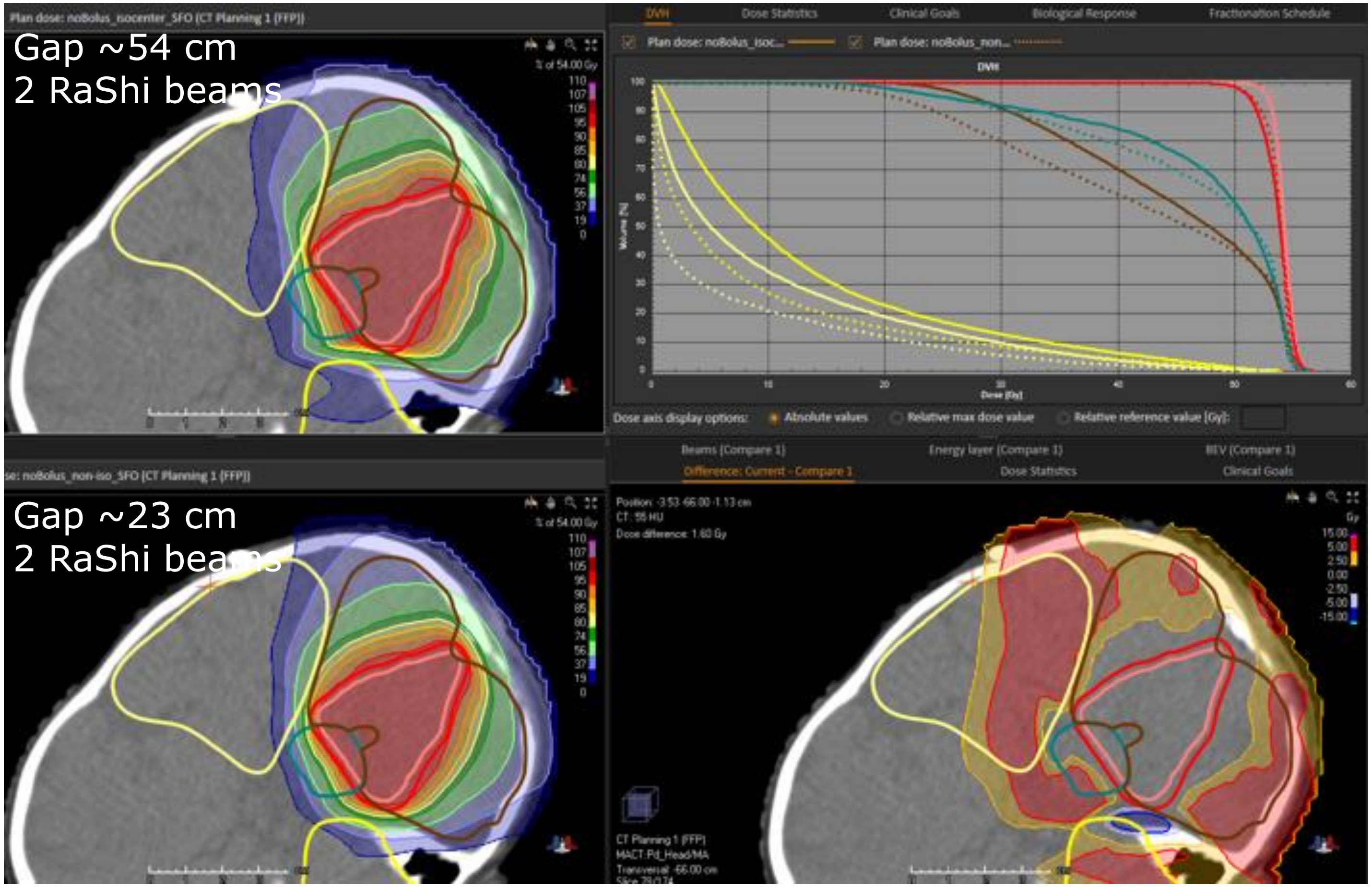
Up to 30-40% penumbra reduction clinically!

Grevillot et al MedPhys 2020

PHYSICAL BEAM PROPERTIES

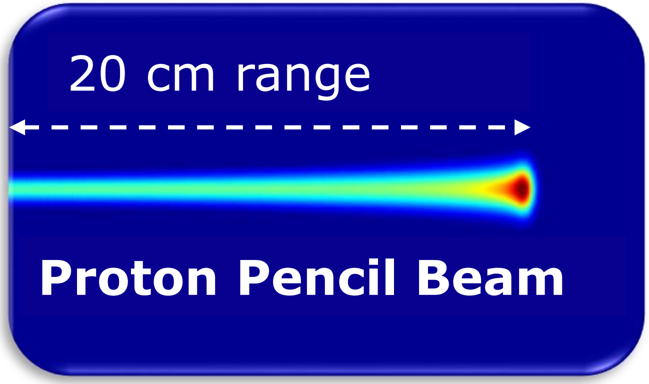
SPOT SIZE / PENUMBRA

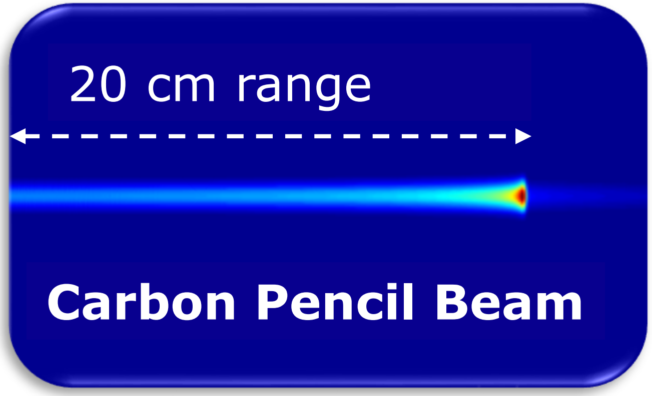
- dosmetric impact of air gap reduction

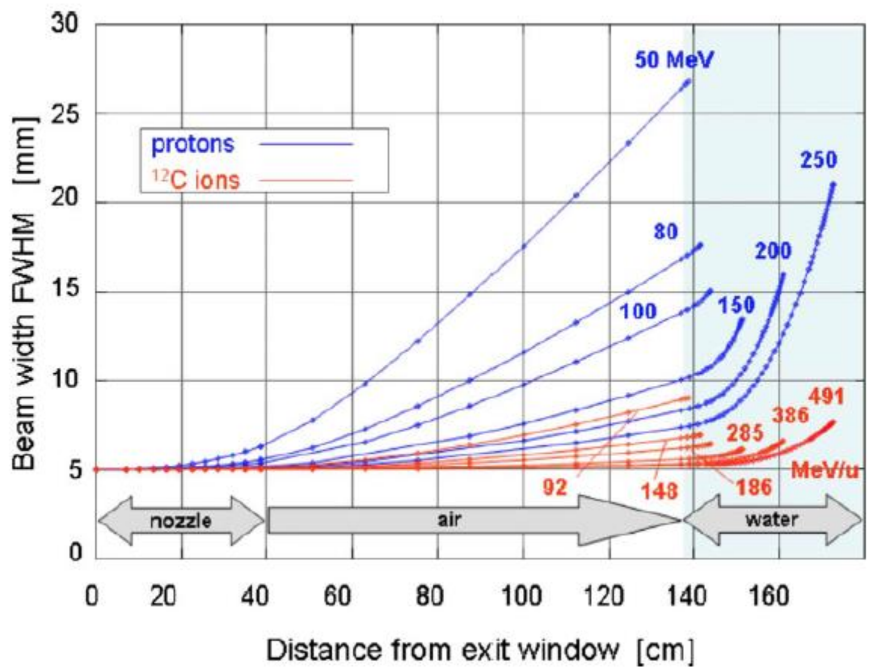


DIFFERENCE BETWEEN PROTONS AND CARBONS

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







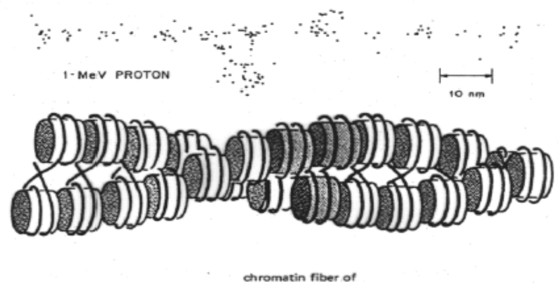
Weber and Kraft, Cancer J 2009

RE-IRRADIATION SCENARIO

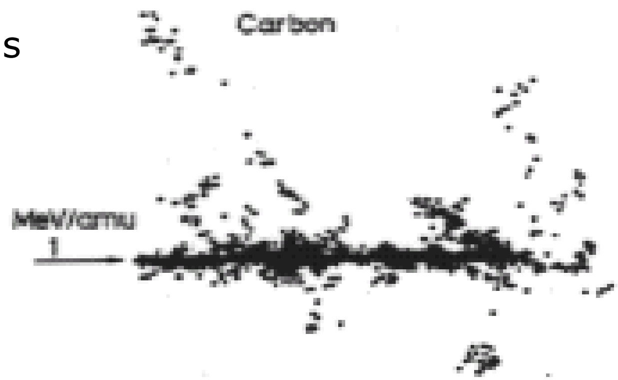
From 78 to 16 Gy RBE in 10 mm (> 6 Gy RBE per mm)

BIOLOGICAL IMPACT

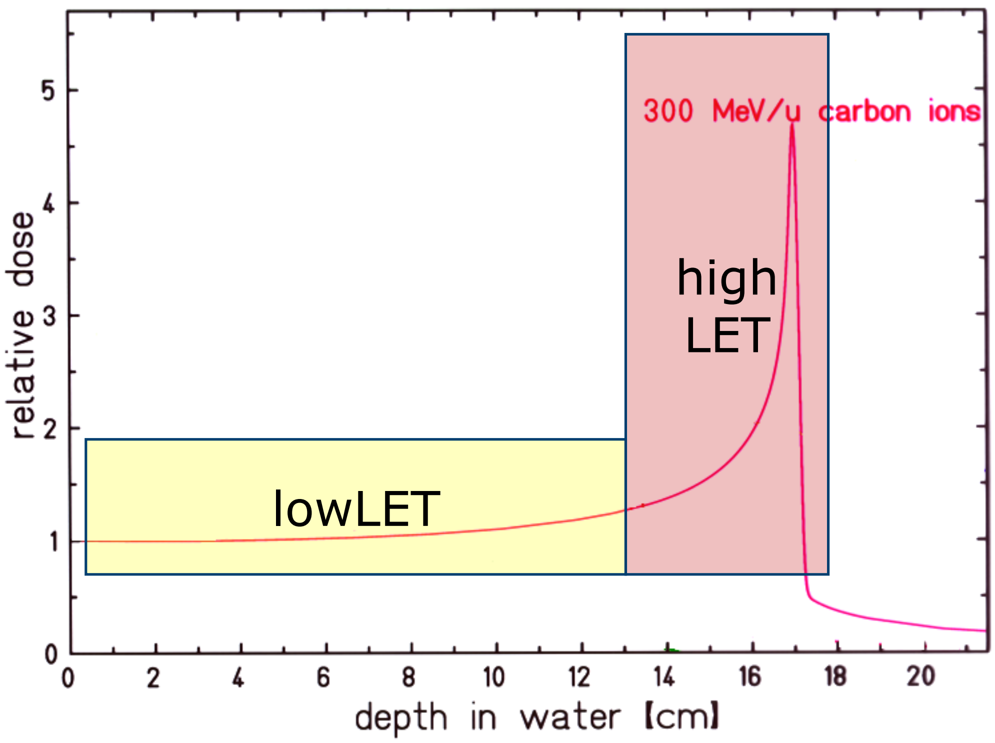
Photons



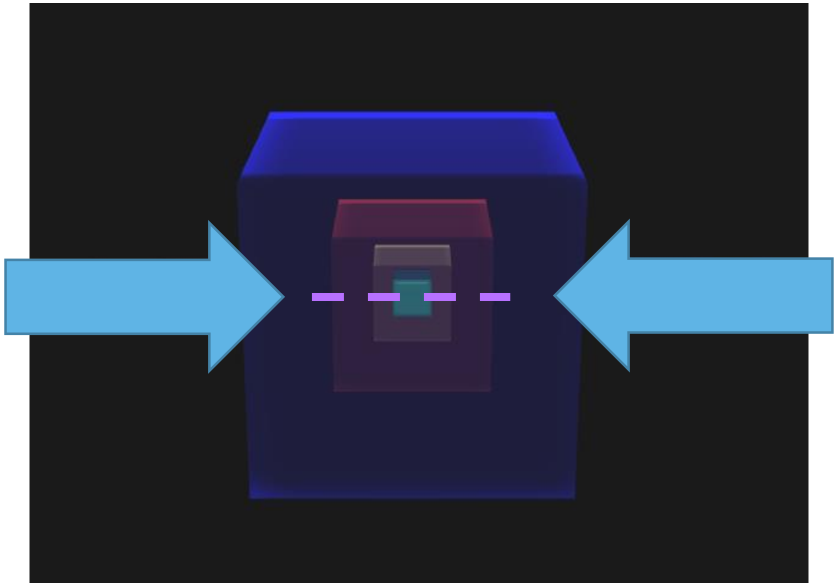
Carbons

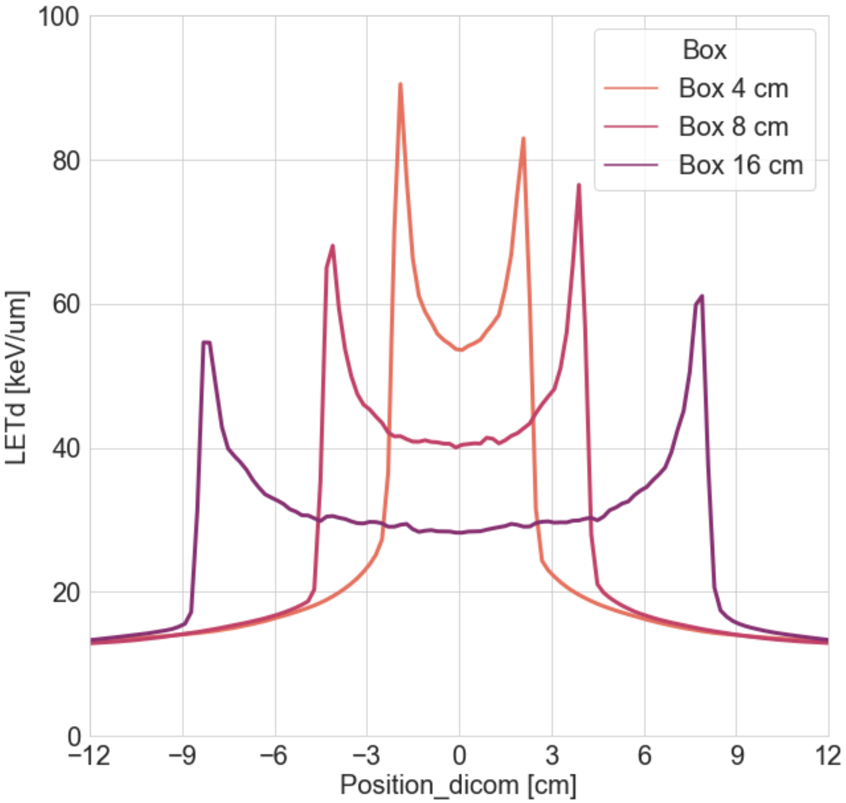


CARBON IONS HIGH LET - ONLY WHERE YOU NEED IT?



Is CIRT dealing with high LET_d?

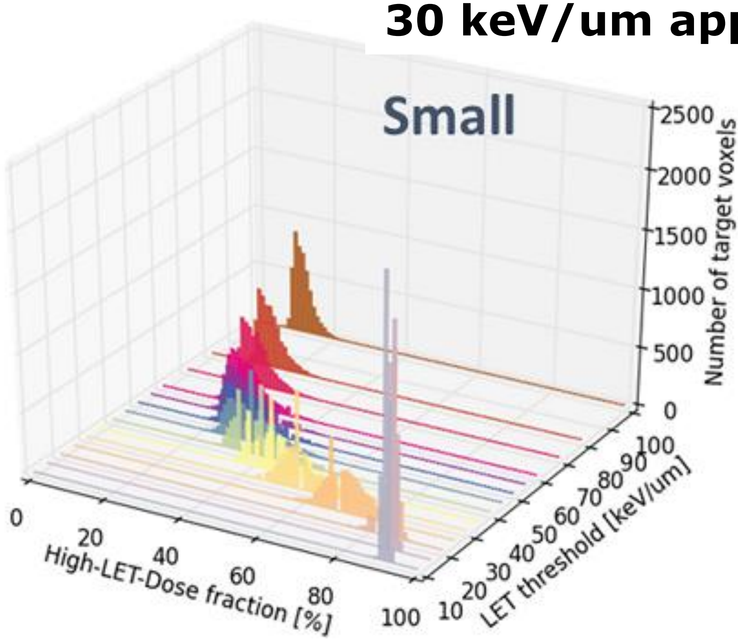


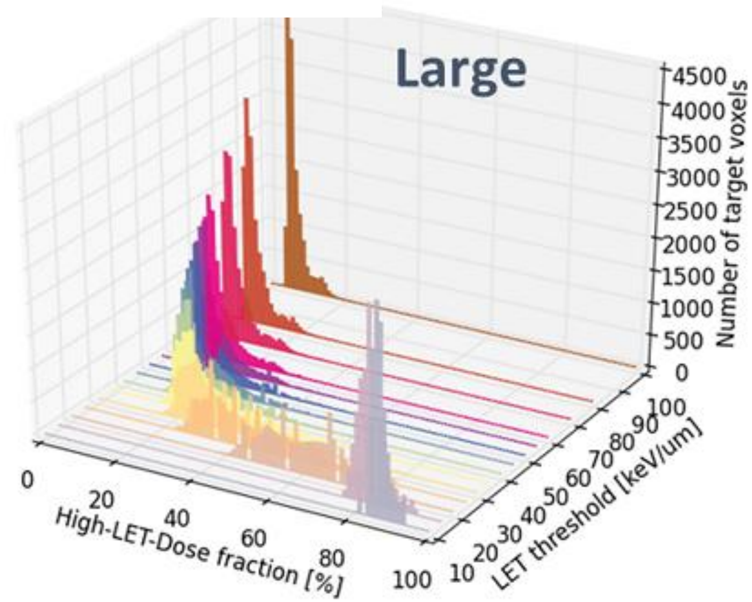


NOVEL TREATMENT PLAN EVALUATION CONCEPT IN CIRT BASED ON HIGH-LET-DOSE

- High-LET-dose (hLD physical dose filtered on LET) quantity with potential to be additional evaluator in TP
- compared the hLD distribution in small and large tumors
- 10 patients having either <500 cm^3 small (n=5) or ≥500 cm^3 as large tumor
- voxel-based evaluation of fraction of hLD to physical dose (hLDf) as a function of LET threshold was performed

30 keV/um appropriate threshold?



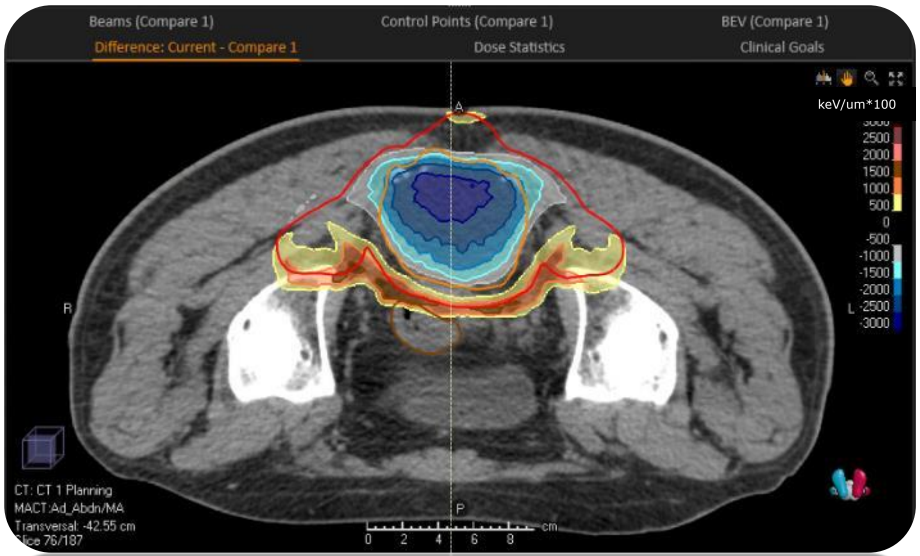


HIGH LET dose objective

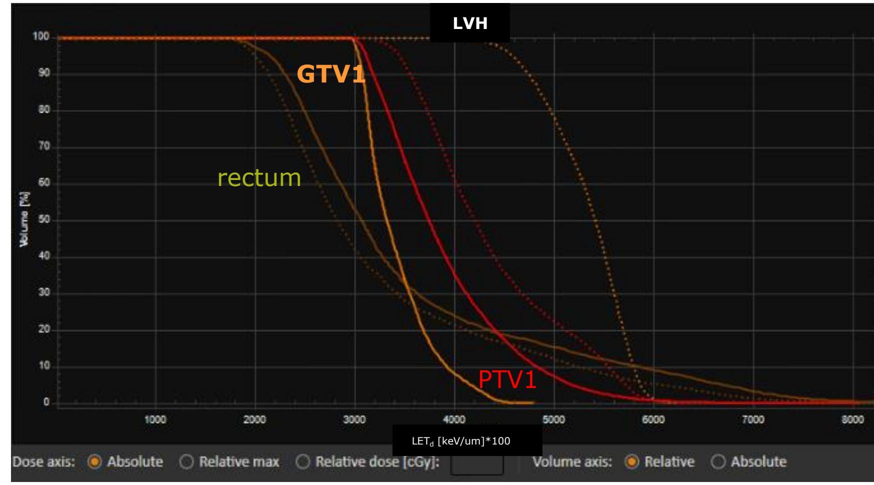
LET_d distribution: what can be achieved?

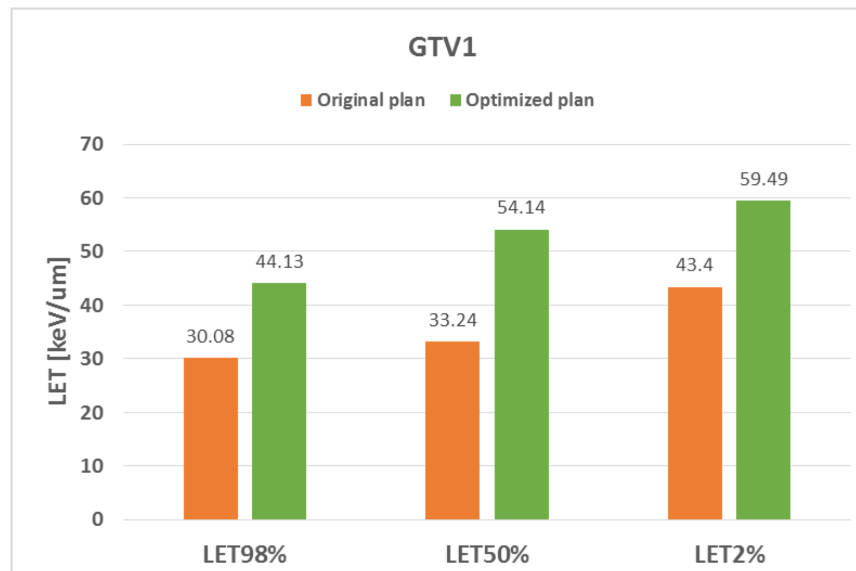
Research collaboration with RSL

Original – LET optimized



increase high LET dose – e.g the dose which has a LET beyond 40 keV/μm should be more than 15 Gy





QUALITY ASSURANCE

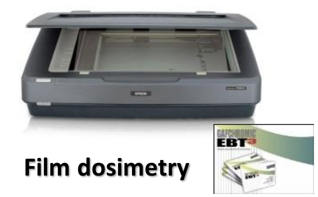
QA EQUIPMENT/MEASURMENT DEVICES

For Beam-commissioning

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

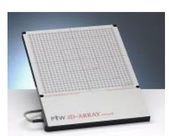




Daily QA and Patient specific QA

Giraffe → Octavius → CIRS phantom → Daily-QA PTW phantoms → PAS Phantoms

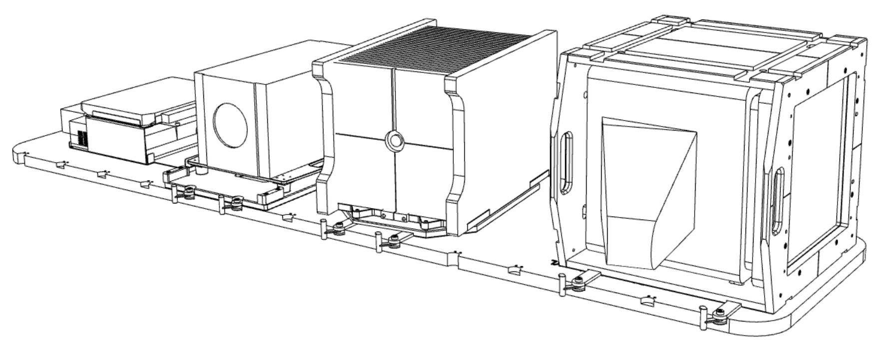




Grevillot et al Med Phys. 2018 Jan;45(1):352-369

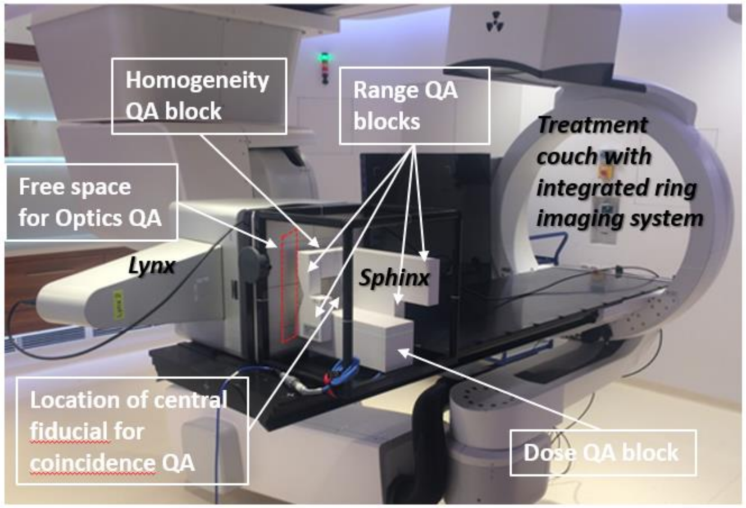
QA TABLE

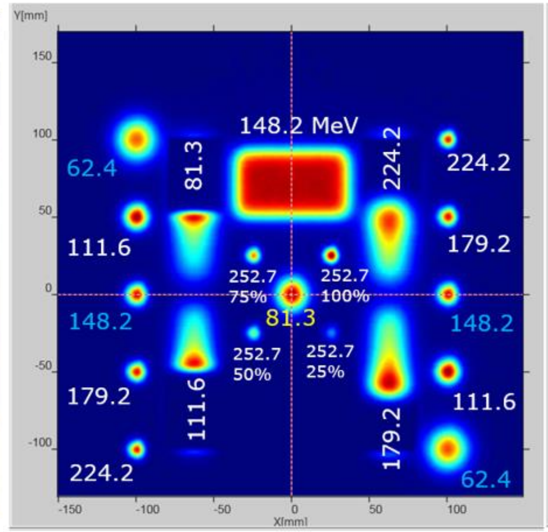
- Faster
- Easier

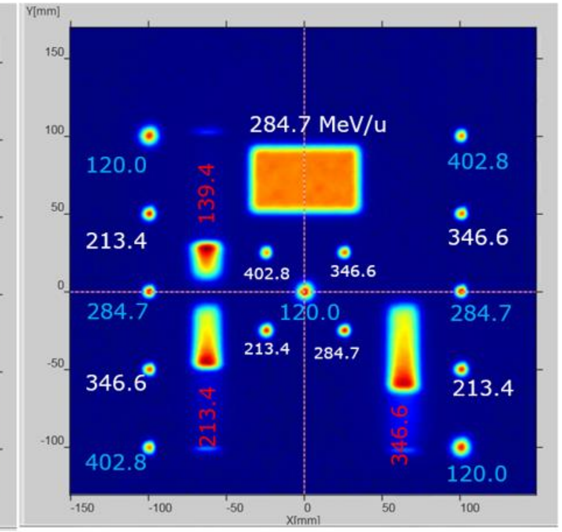
- Prototype



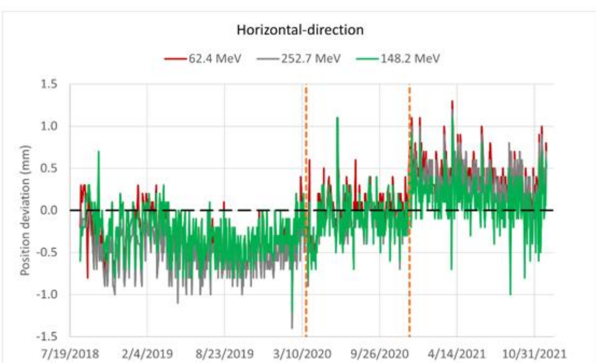
ESTABLISH OPTIMIZATION OF QA







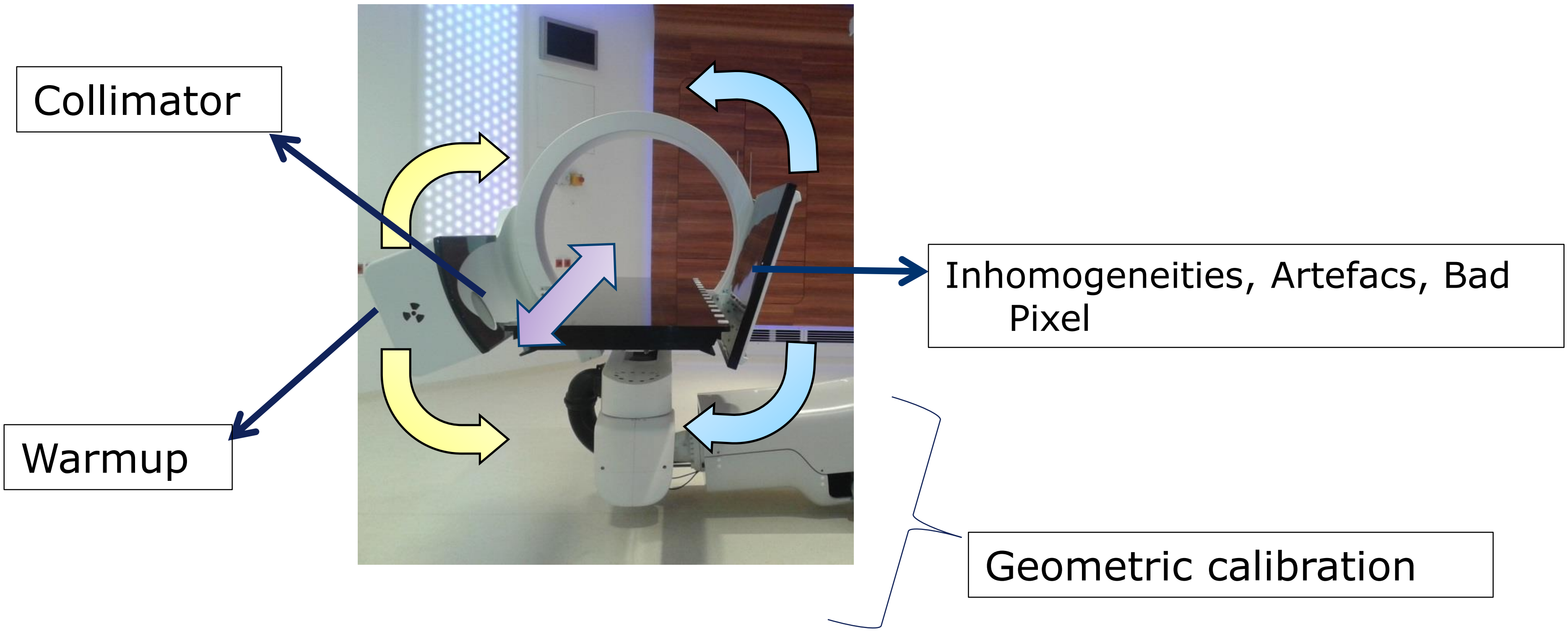
- Integrated system for both proton and carbon ions and generate trendlines



		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%

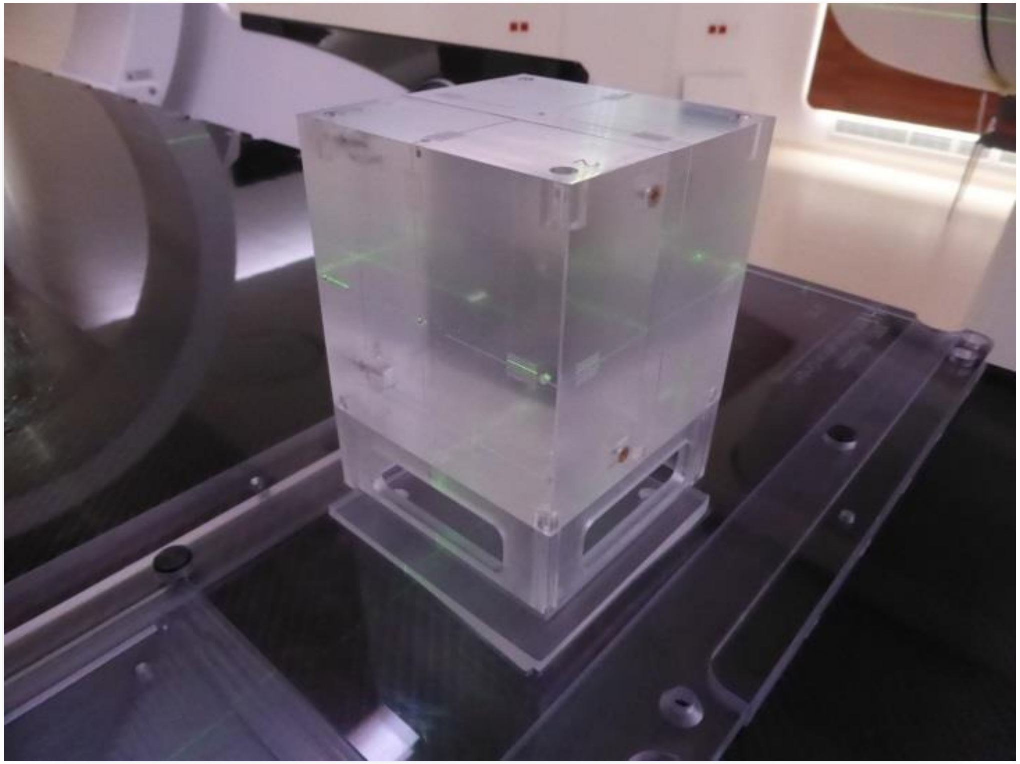
Grevillot et al J Appl Clin Med Phys. 2023;24:e13896

PPVS DAILY QA



PAS WHOLE WORKFLOW

- IGRT accuracy



Daily check

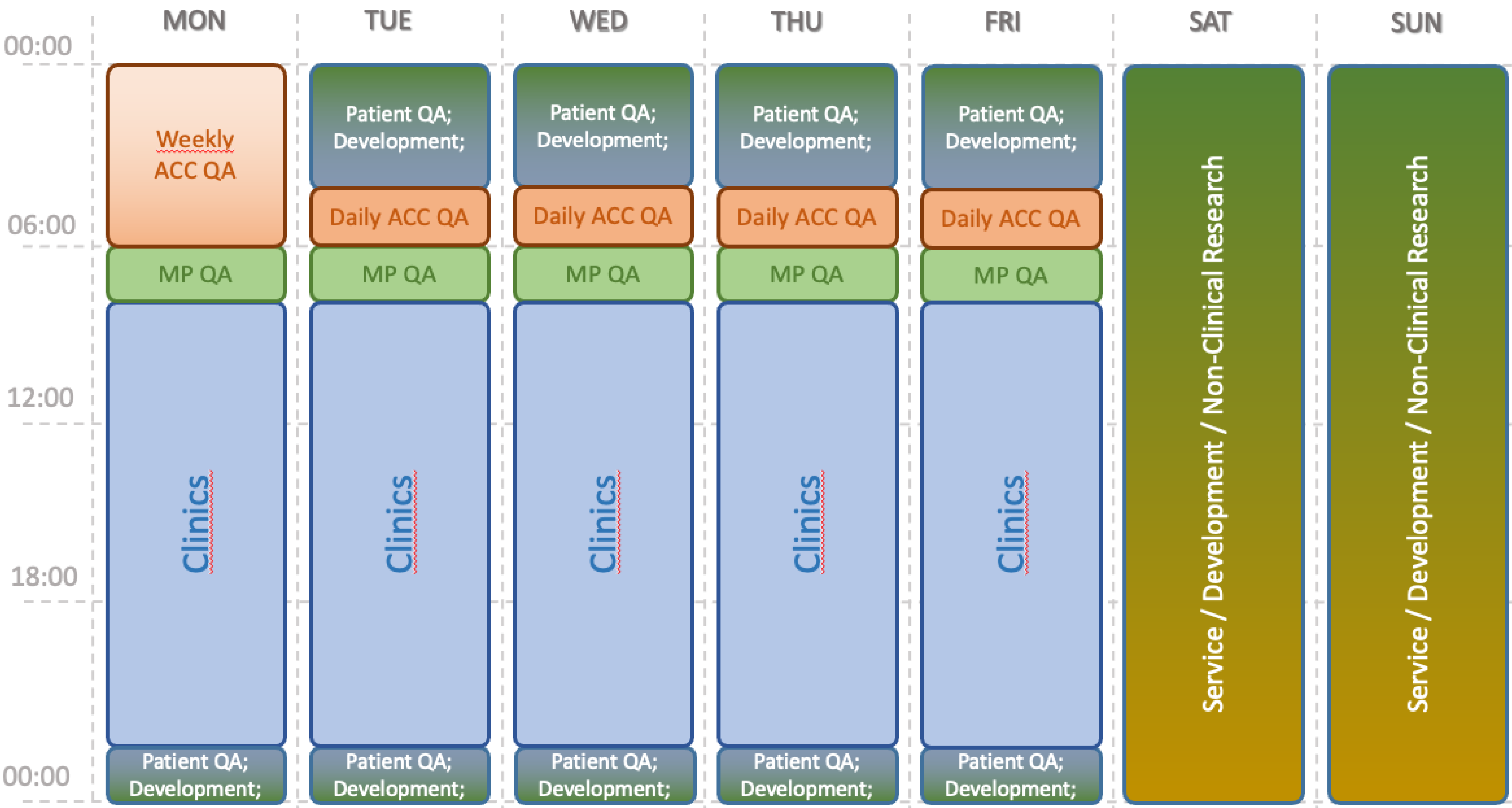
With whole clinical workflow with intended wrong position

Check of markers on the cube with laserlines after registration and alignment

1 Position: T180°

- **Tolerance level: 0.5 mm**
- **Action level 1: 1.0 mm**
- **Action level 2: 2.0 mm**

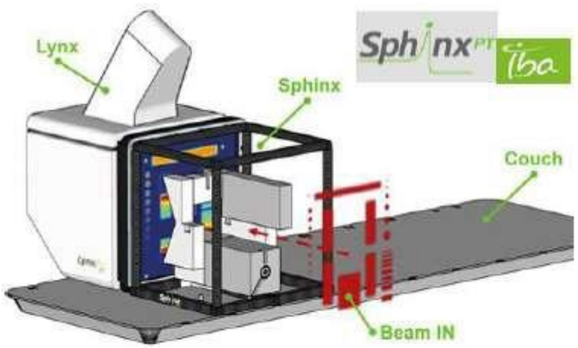
OPERATION SCHEDULE



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!

MOTIVATION TOWARDS INDEPENDENT DOSE CALCULATION

- **Rationale**
  - expQA (experimental QA) requires a lot of beam time!
  - expQA is performed in a homogeneous geometry – not representative of the patient!
  - **expQA is less sensitive in detecting treatment failures than IDC!**

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

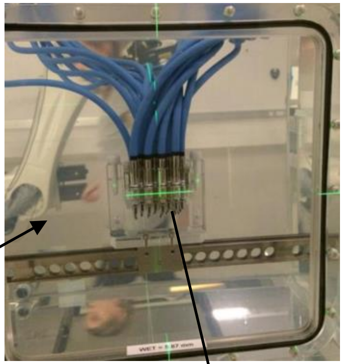
- **Cyberknife**:
  similar findings in terms of sensitivity. **Milder et al, J Appl Clin Med Phys, 2020**

- **Protons**:
  "The 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 measurement-based PSQA." **Jhonson et al, PloSOne 2019**

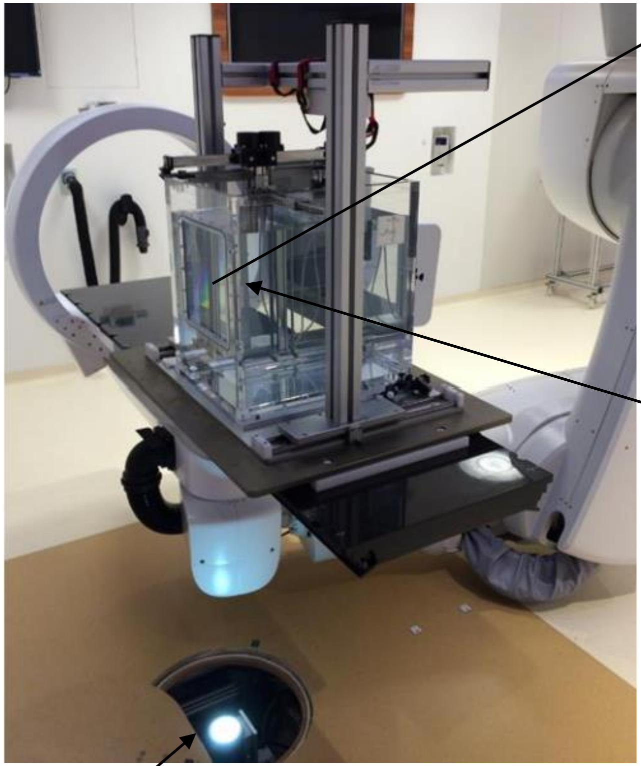
PSQA AT MEDAUSTRON

- **PSQA set-up for horizontal beam**

Entrance window



Horizontal beam



24 pinpoints block
(placed at the treatment position in water)

Positionning via tracking camera

PROTON INDEPENDENT DOSE CALCULATION

- **MyQA iON (IBA-Dosimetry)**

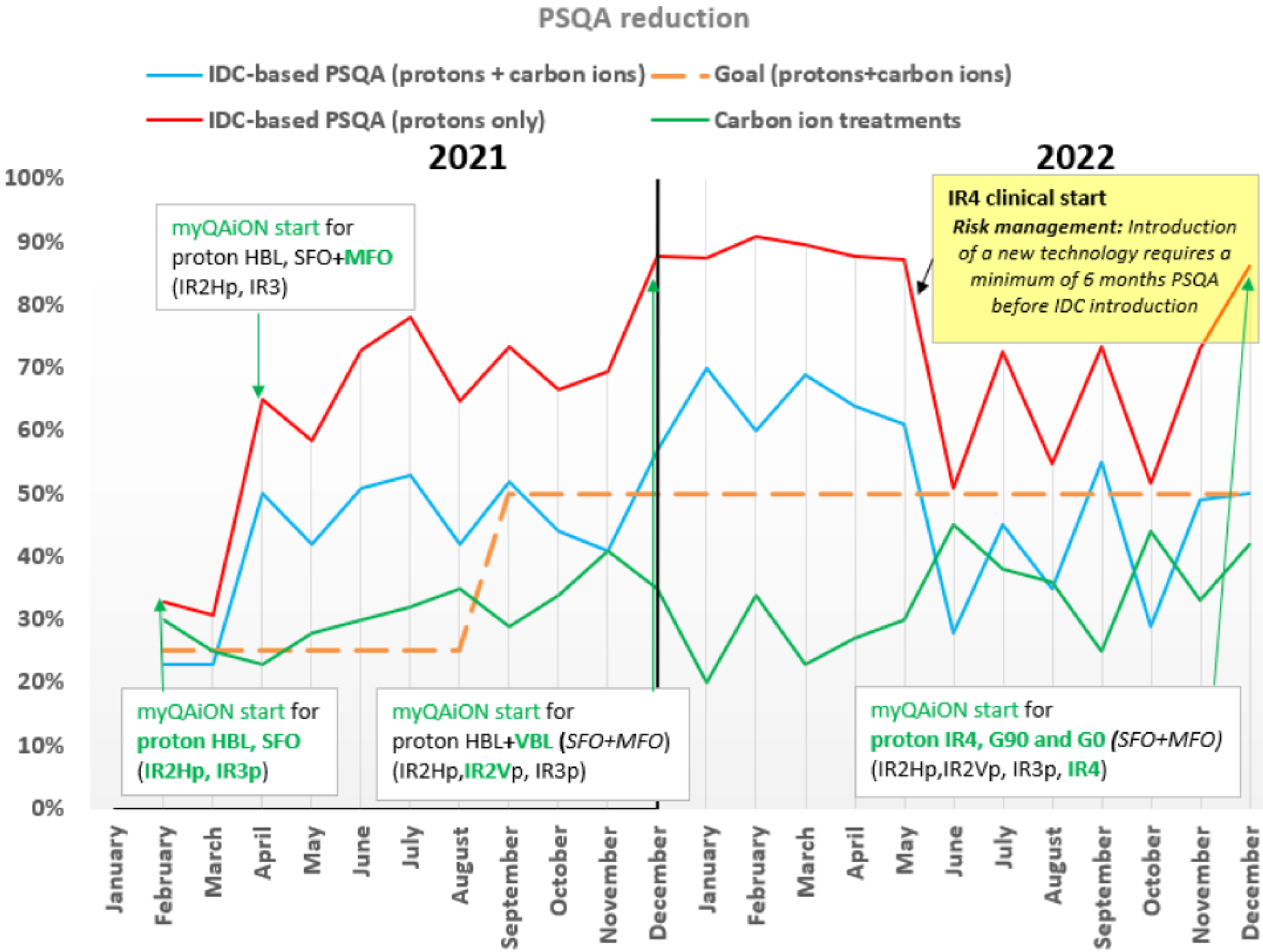
Workflow

- TPS plan exported to MyQAiON
- **Automatic** IDC recalculation *(Monte Carlo algorithm)* & gamma evaluation in the background
- After **10min-1hr**, IDC analysis review and IDC report generated to approve the treatment *(**web-browser-based** technology)*

3D Dose and Gamma verification of the TPS plan dose vs. independent MC plan dose on patient anatomy: 3D Gamma map (upper left), dose difference map (upper right), TPS plan dose (lower right), independent MC plan dose (lower left).

https://www.iba-dosimetry.com/product/myqa-ion-pt

PROTON INDEPENDENT DOSE CALCULATION



OPTIMIZATION OF MACHINE QA

Goal

REDUCING QA BEAM TIME

- INCREASING MP QA EFFICIENCY
- SUBSTITUTING BEAM QA BY OTHER MEANS

Boundaries

KEEP QUALITY

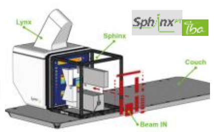
- NO SAFETY COMPROMISES

SUMMARY ON QA OPTIMIZATION

I. OPTIMIZATION

2019

- Ultra-Fast Morning QA V1!



2021

- Ultra-Fast Morning QA V2!

  VBL QA speed-up (~10 min saved daily)

2023

- Ultra-Fast Morning QA V3!

  1-energy dose QA

  Sphinx compact

2024

- Ultra-Fast Morning QA V4?

II. SUBSTITUTION

- IDC HBLp + VBLp (myQAiON)!
- IDEAL v1.0!

- IDC IR4 (myQAiON) – preponed!
- myDEAL (HBLc + VBLc) – *alpha/beta?*

- myDEAL (HBLc + VBLc) – *clinical?*

2024+ : Log-file based QA ?

AREAS OF RESEARCH AT MEDAUSTRON

Clinical • Translational

RESEARCH AT MEDAUSTRON

CLINICAL RESEARCH

- **Registry study**
- **Clinical studies**

Creating more evidence in particle therapy

INTERDISCIPLINARY ONCOLOGY RESEARCH

- **Radiation Oncology**
- **Medical Physics**

Teaching and research site of the Karl Landsteiner Private University

TRANSLATIONAL & SCIENTIFIC RESEARCH

- **Radiation Biology**
- **Med. Radiation Physics**
- **Accelerator Physics**
- **Particle Physics**

In cooperation with Medical Universities Vienna & Graz, Technical University Vienna, HEPHY and FH Wr. Neustadt

INTERDISCIPLINARY ONCOLOGY RESEARCH

At the Department of General and Translational Oncology and Hematology at Karl Landsteiner University

KARL LANDSTEINER
PRIVATUNIVERSITÄT FÜR GESUNDHEITSWISSENSCHAFTEN

Prof. Markus Stock

Division:

Medical Physics

Development/optimization of medical physics methods including dosimetry and microdosimetry, MC simulations, Big Data, radiation plan optimization, software development and process management

Prof. Piero Fossati

Division:

Radiation Oncology

Optimization of patient treatments with radiotherapy by applying the best standards of care and by performing clinical research and fostering the translation of preclinical research in a clinical setting

VACANCIES
KARL LANDSTEINER UNIVERSITY OF HEALTH SCIENCES/MEDAUSTRON

- **POSTDOCTORAL RESEARCH FELLOW (POST DOC) DIVISION „RADIATION ONCOLOGY" -** UNIV. PROF. DR. PIERO FOSSATI MD
- 40 Hours (F/M/D)

- **PHD Position - DIVISION „RADIATION ONCOLOGY"** - UNIV. PROF. DR. PIERO FOSSATI MD
- 30 Hours (F/M/D)

- **PHD Position - DIVISION „MEDICAL PHYSICS"** - UNIV.-PROF. PD DI MARKUS STOCK, PHD
- 30 Hours (F/M/D)

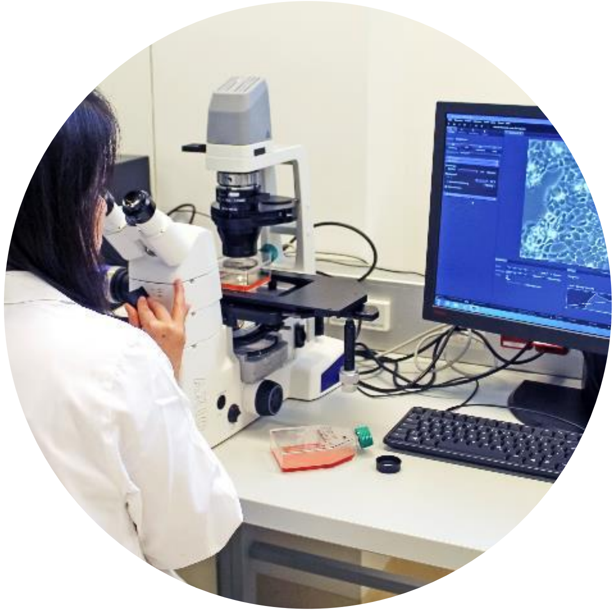
- Workplace: MedAustron in Wiener Neustadt

- For more details contact: markus.stock@medaustron.at

TRANSLATIONAL RESEARCH
RESEARCH STRATEGY 2022 - 2024

Applied Particle and Medical Physics

- Particle Imaging
- Instrumentation
- Dose Determination
- Microdosimetry
- Laboratory Course



Technological Innovations and Clinical Implementation

- Clinical Implementation and Validation
- MRI in Particle Therapy
- Quality Assurance

Biophysics and Molecular Radiobiology

- Pre-clinical Animal Research
- Translational Radiobiology

Exploratory Studies and Emerging Topics

Accelerator Physics

- Implementation of Helium Ions
- Extraction Mechanisms
- Novel Developments

SUMMARY

- Particle Therapy requires **<u>additional specialization</u>** of at least 6 months in medical physics (TP, special equipment, QA)
- Synchrotron possibility to take advantage of **<u>Multi-Ion treatment</u>** at one single site
- Effort in design and requirements definition to get **<u>best of several particles</u>**
- Many **<u>optimization efforts</u>** still ongoing (organizational, expansion of indications, dosimetric uncertainty, LET, beamline design, …) and a lot of **<u>research possibilities</u>**

MANY THANKS FOR YOUR ATTENTION