OMA Advanced School on Medical Accelerators and Particle Therapy

Treatment Planning

Gabriele KRAGL

CONTENTS

- **Part I General aspects**
  - Introduction and motivation
  - Particle therapy delivery techniques
  - Treatment planning software
  - Prescribing and reporting

CONTENTS

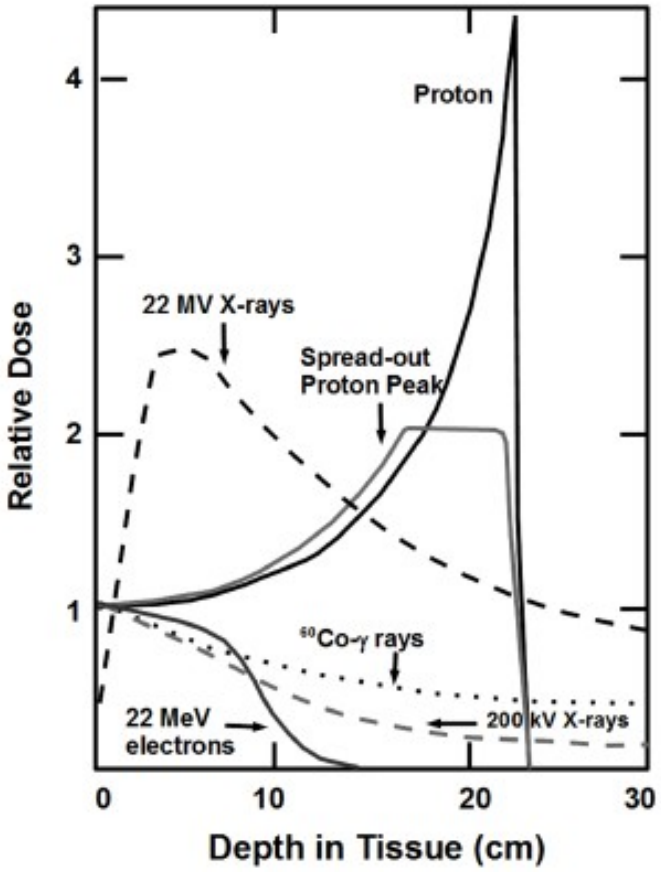
- **Part II Proton PBS treatment planning**
  - Physical beam properties & Penumbra
  - Range uncertainties
  - Plan generation strategies and concepts
  - Adaptive treatment planning
  - 4D treatment planning

CONTENTS

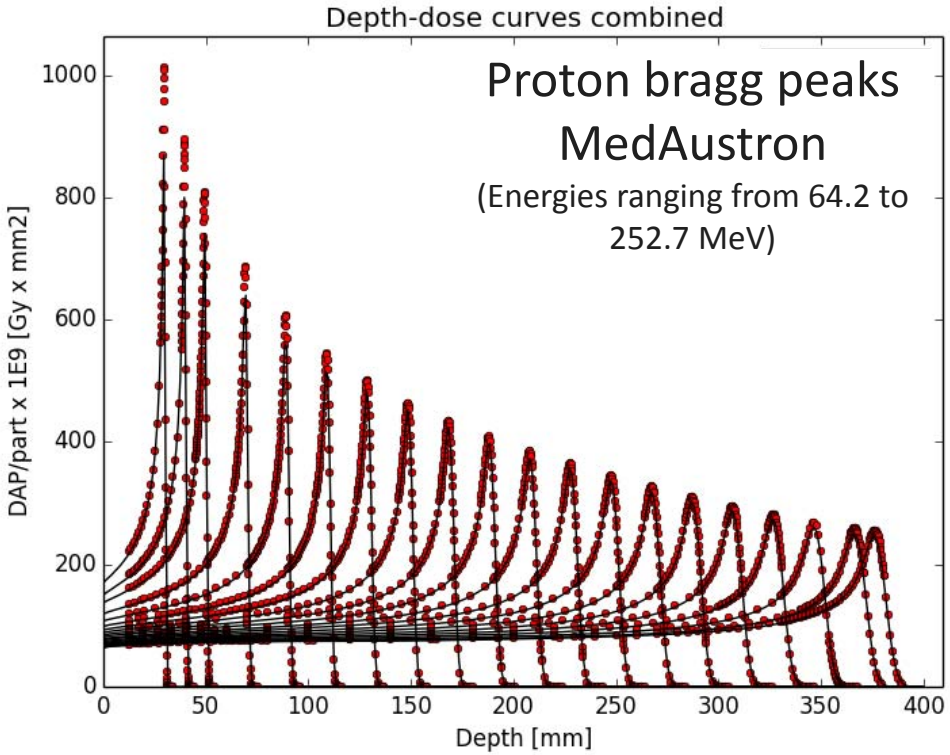
- **Part I General aspects**
  - **Introduction and motivation**
  - Particle therapy delivery techniques
  - Treatment planning software
  - Prescribing and reporting

INTRODUCTION & MOTIVATION

DEPTH DOSE DISTRIBUTIONS



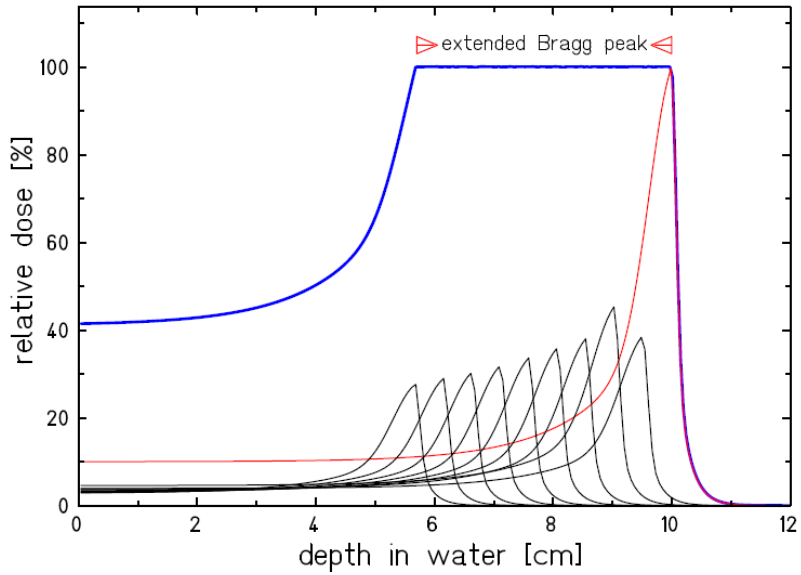
[Levy & Schulte TCR 2012 Vol1 No3]



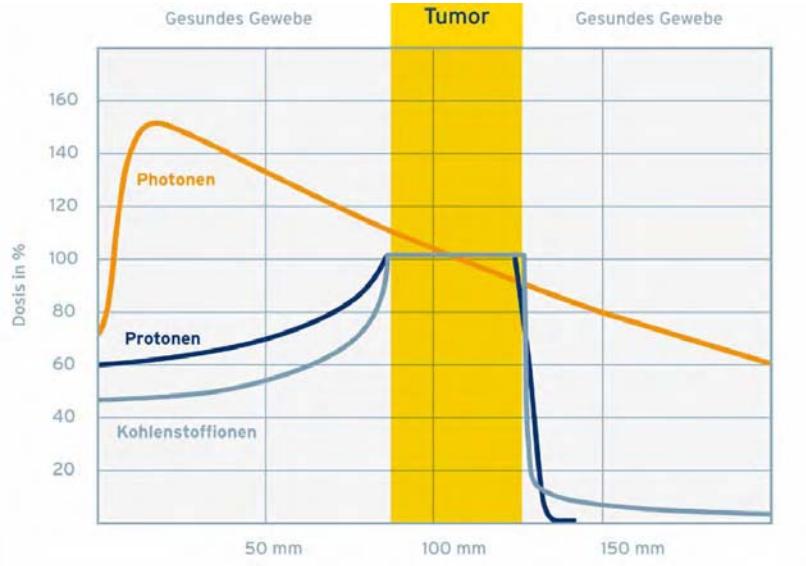
INTRODUCTION & MOTIVATION

DEPTH DOSE DISTRIBUTIONS

- **Spread-out Bragg peak (SOBP)**



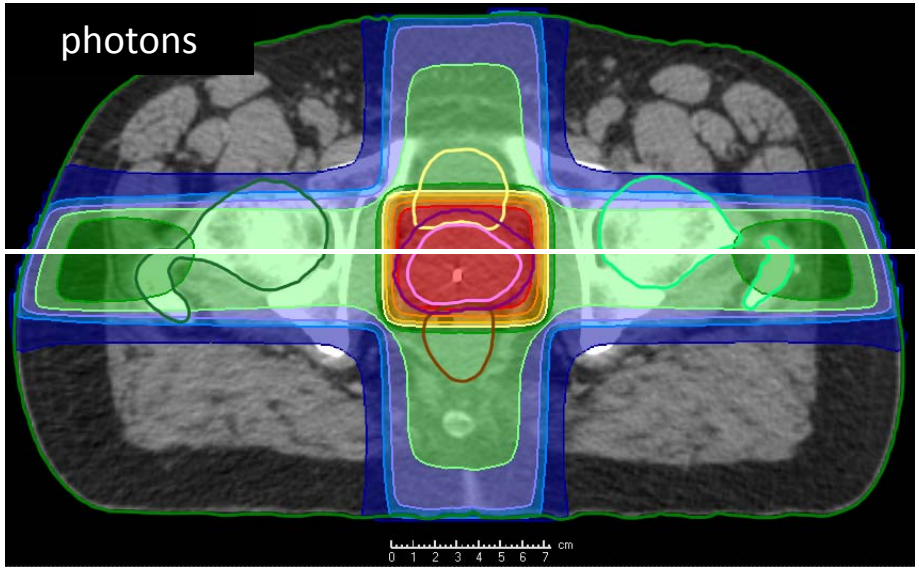
[Weber 1996]

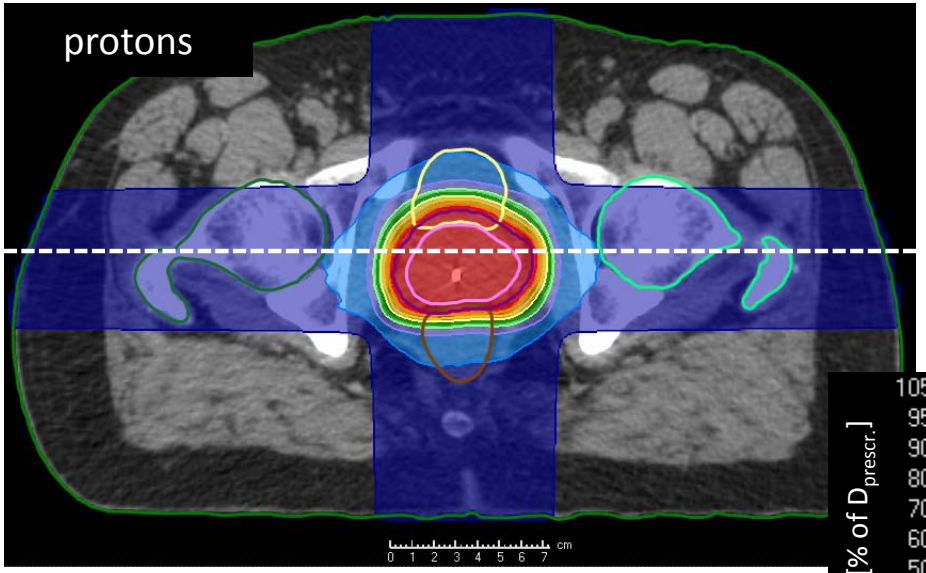


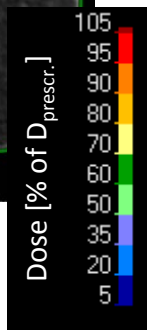
Depth dose distribution: Photons vs. Particles

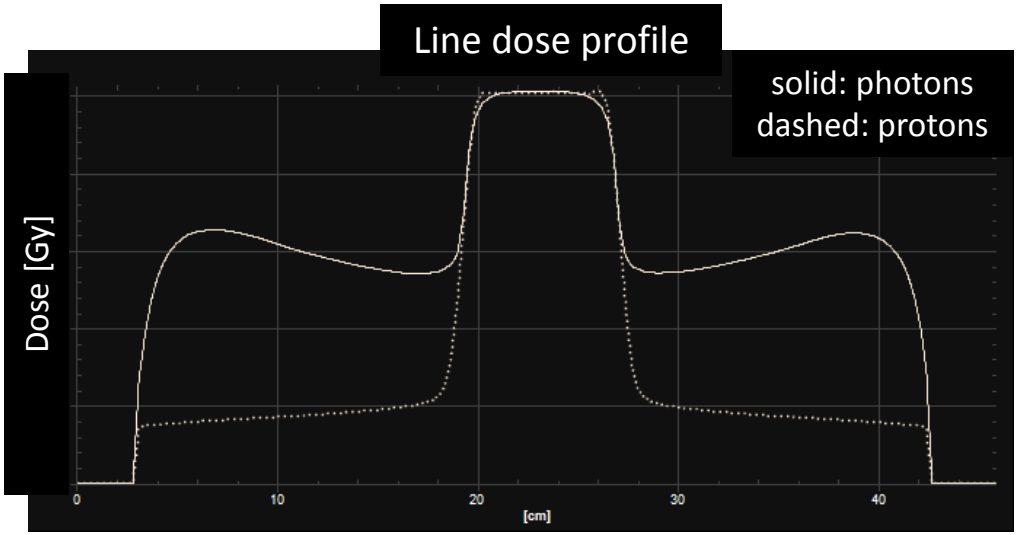
INTRODUCTION & MOTIVATION

ILLUSTRATION: EFFECT OF MULTIPLE FIELDS



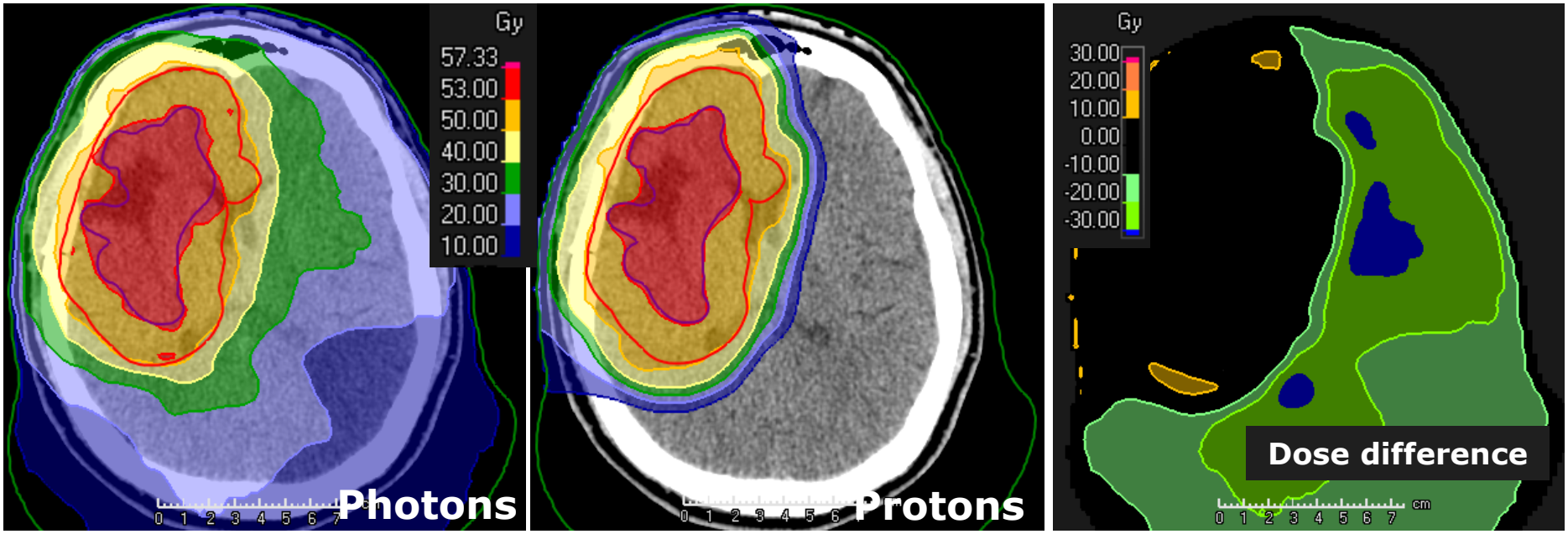






INTRODUCTION & MOTIVATION

INTEGRAL DOSE

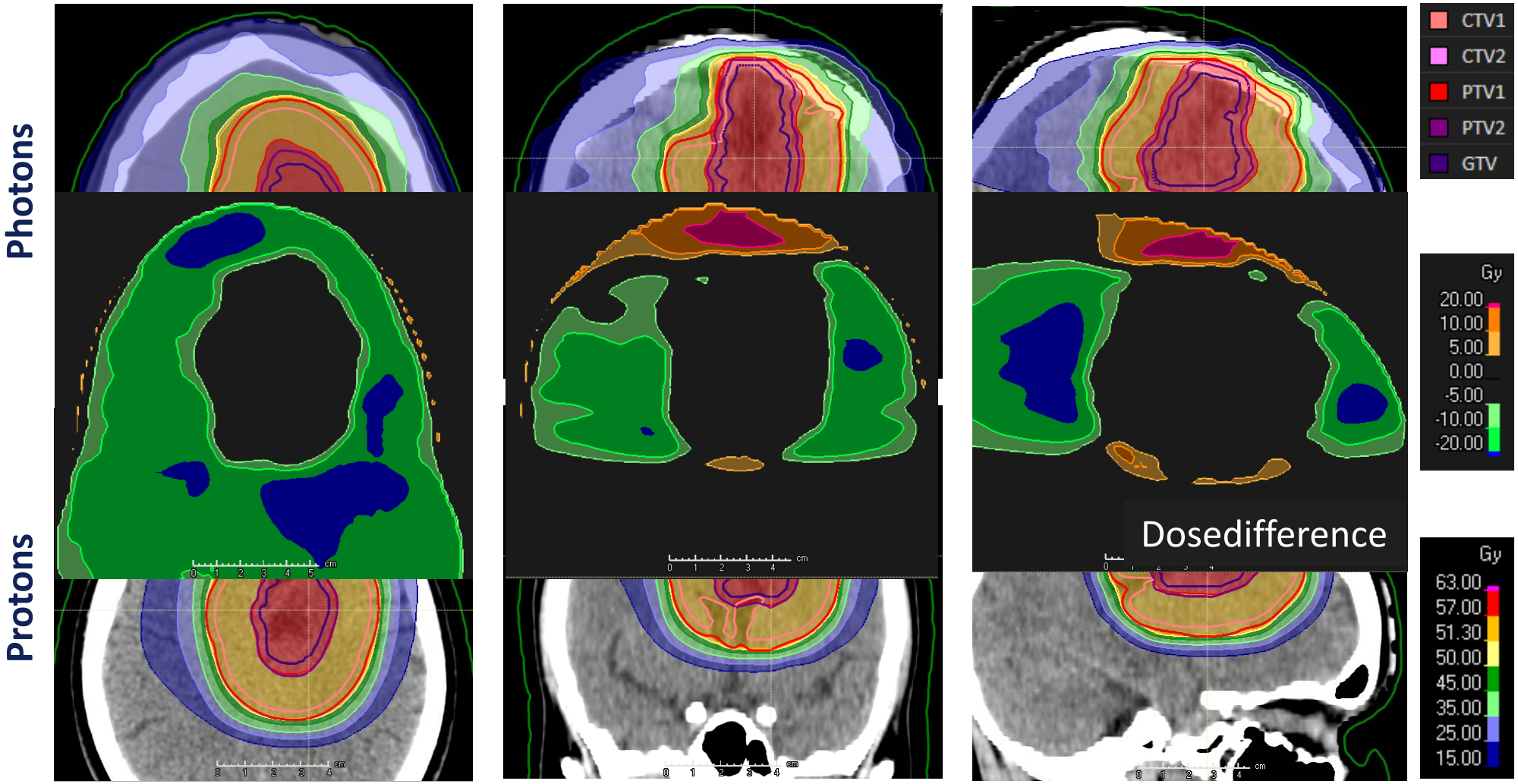


Depth dose distribution: Photons vs. Particles

Major motivation for the use of particles: Reduced dose to normal tissues.

INTRODUCTION & MOTIVATION

INTEGRAL DOSE - QUANTIFICATION



Kragl et al. ÖGRO 2018

INTRODUCTION & MOTIVATION

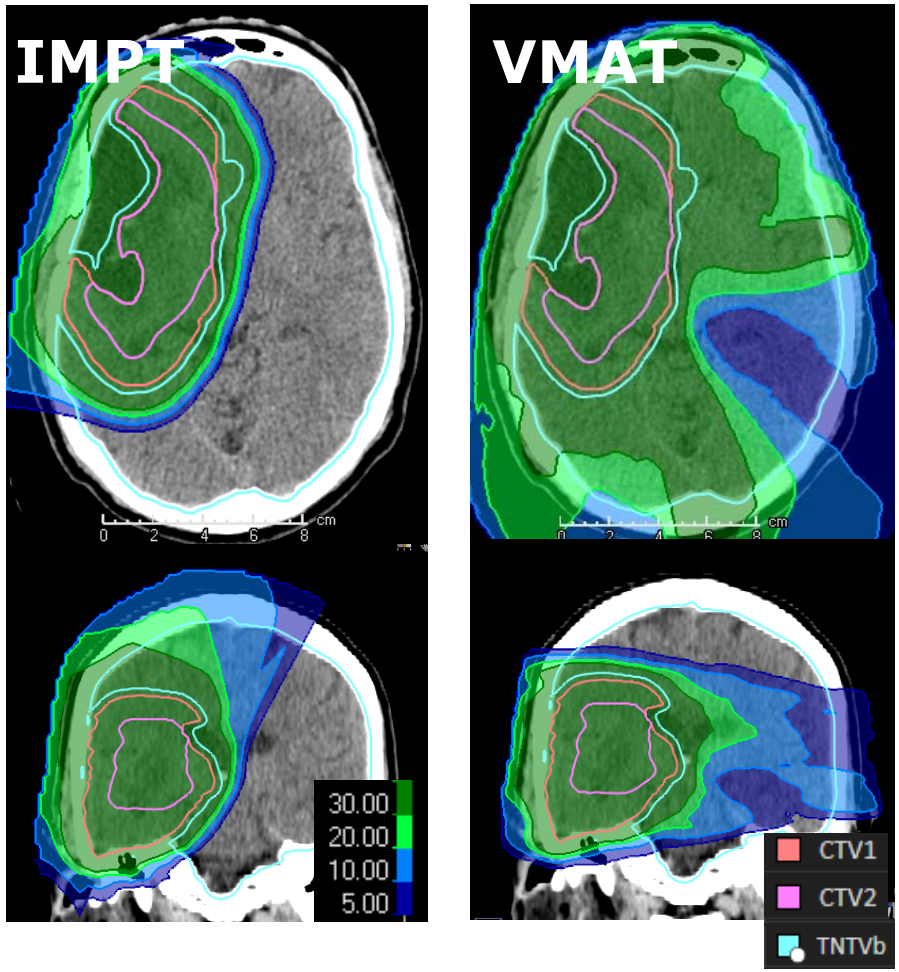
INTEGRAL DOSE: BRAIN-PTV

N = 7

		VMAT	IMPT	Av. Diff%
$V_{TNTVb,5Gy}$ [%]	Median (Range)	83% (62-94)	41% (27-57)	**-43%**
$V_{TNTVb,10Gy}$ [%]	Median (Range)	76% (57-89)	33% (23-49)	**-42%**
$V_{TNTb,20Gy}$ [%]	Median (Range)	50% (42-65)	24% (17-34)	**-25%**
$V_{TNTVb,30Gy}$ [%]	Median (Range)	27% (18-40)	17% (12-29)	**-10%**

Median V_{TNTVb} = 1126 ccm (887 - 1369 ccm)

$D_{TNTVb,50\%}$ [Gy]	Median (Range)	19,7 Gy (16,7-26,0)	1,5 Gy (0,1-9,5)	**-18,2 Gy**



Kragl et al. ÖGRO 2018

INTRODUCTION & MOTIVATION

INTEGRAL DOSE: PEDIATRIC CSA

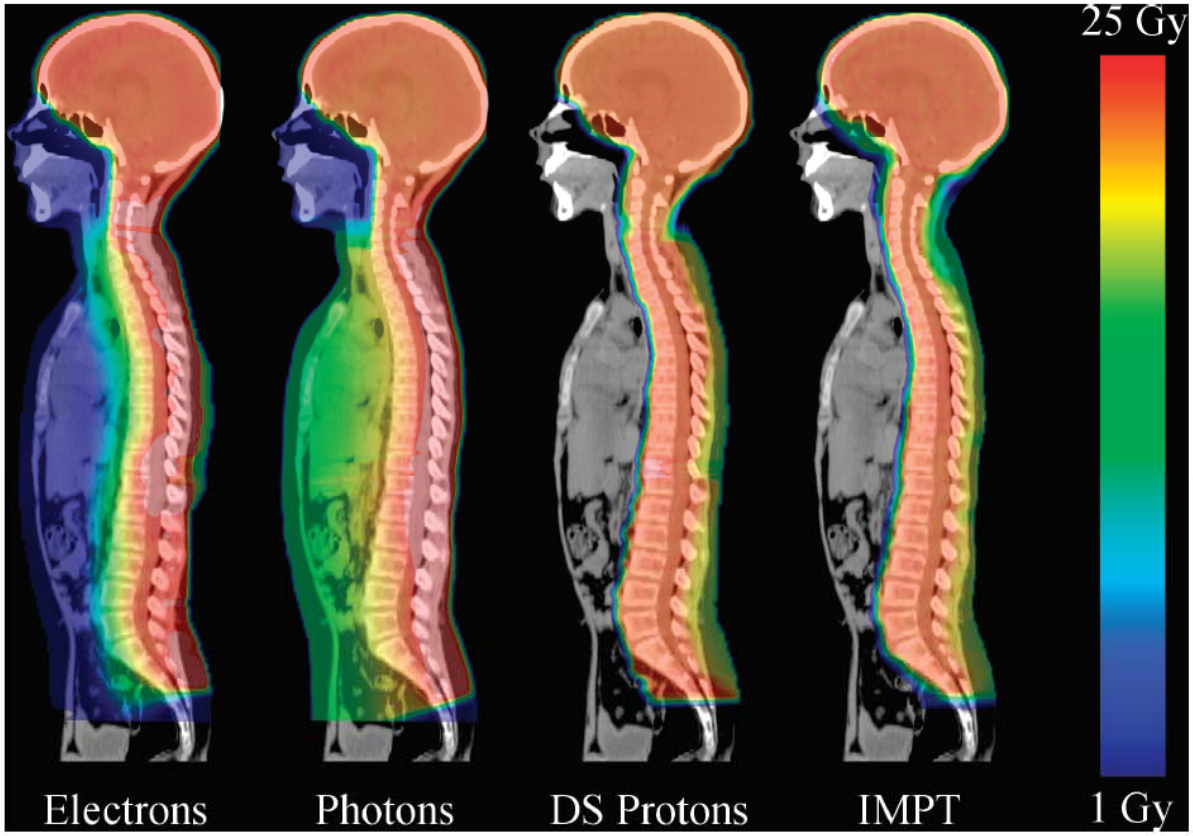


Figure 1. Dose distributions for an 11-year-old male patient from CSI technique applying electrons, photons, DS protons and spot scanning IMPT.

[Stokkevåg et al. Acta Oncol. 2014 Vol53]

CONTENTS

- **Part I General aspects**
  - Introduction and motivation
  - **Particle therapy delivery techniques**
  - Treatment planning software
  - Prescribing and reporting

DELIVERY TECHNIQUES

PASSIVE VS. ACTIVE BEAM DELIVERY SYSTEMS

Passive beam delivery

- Passive energy variation
  - Cyclotron
    - Exchangeable modulator wheels
    - Range shifter plates
  - Field specific compensators
- Lateral scattering
  - Single / Double scattering
  - Field specific collimators

Active beam delivery

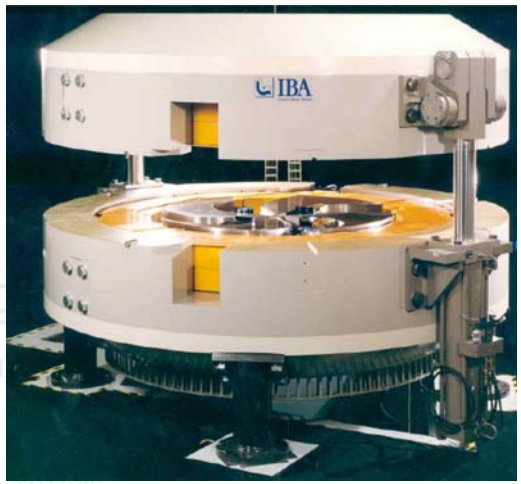
- Active energy variation
  - Synchrotron
    - Range shifters
    - Ripple filters
  - No field specific passive devices
- Pencil beam scanning
  - Spot-, Line-, Raster-scanning
  - No passive devices essential

DELIVERY TECHNIQUES

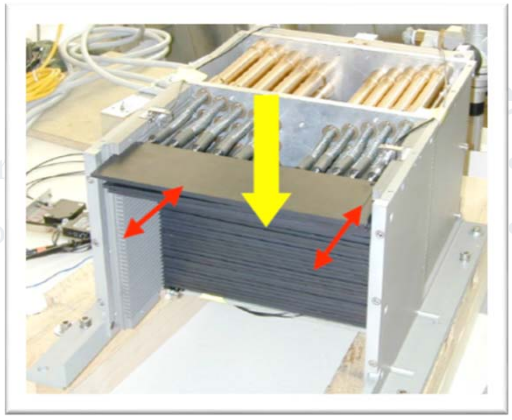
PASSIVE VS. ACTIVE BEAM DELIVERY SYSTEMS

Passive beam delivery

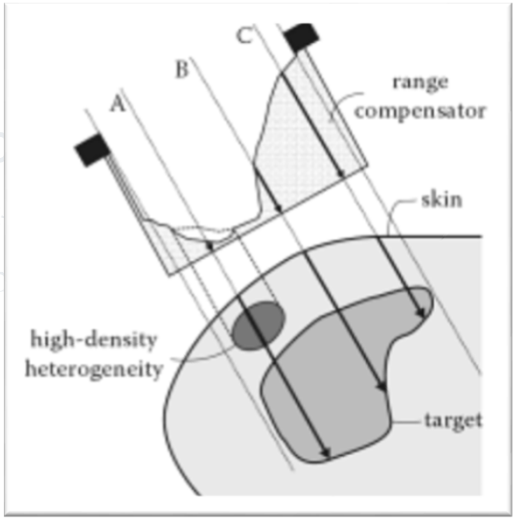
- Passive energy variation
  - Cyclotron
    - Exchangeable modulator wheels
    - Range shifter plates
  - Field specific compensators



Example of a cyclotron.
Source: www.researchgate.net



Example of range modulator wheel and range shifter plates.
Paganetti. Proton Therapy Physics 2012, Pedroni PTCOG 2008.

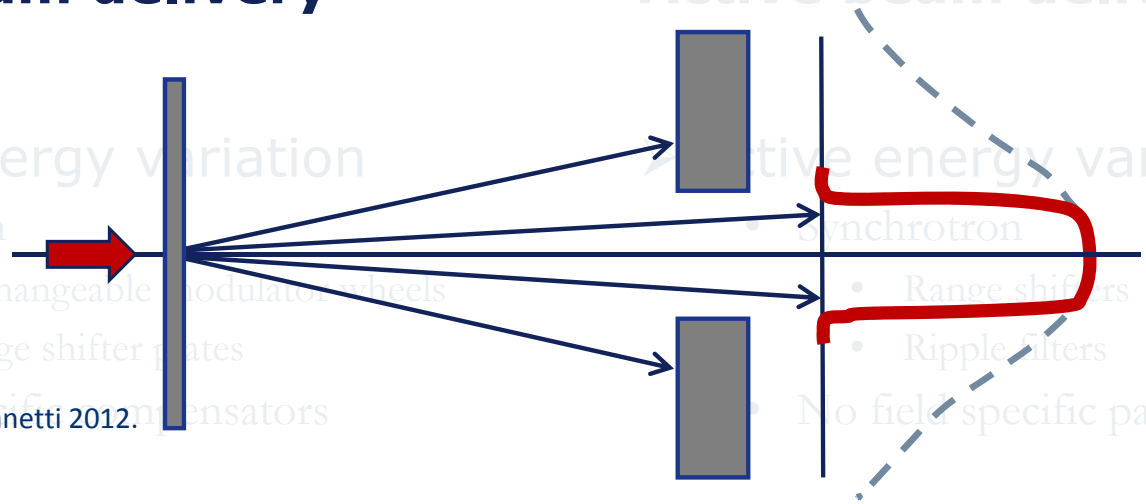


Paganetti 2012

DELIVERY TECHNIQUES

PASSIVE VS. ACTIVE BEAM DELIVERY SYSTEMS

Passive beam delivery



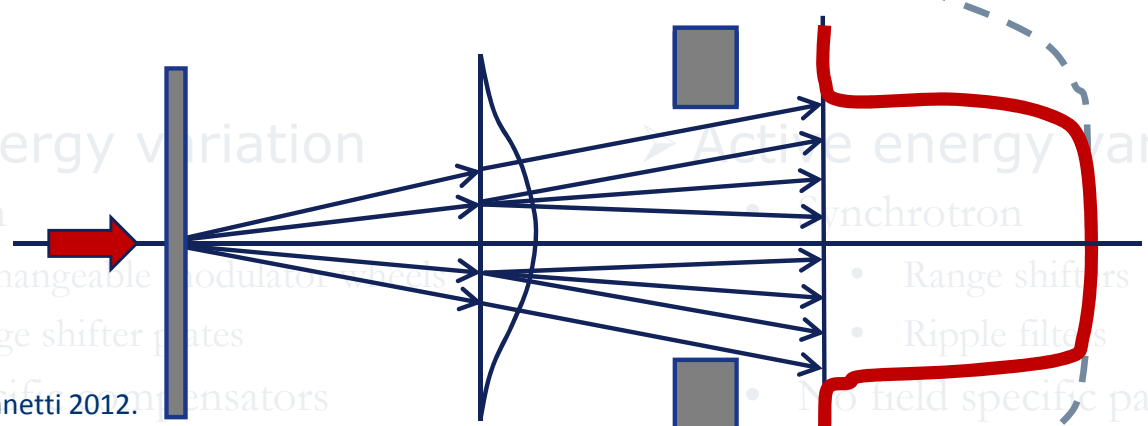
Graph adapted from Paganetti 2012.

- Lateral scattering
  - **Single** / Double scattering
  - Field specific collimators

DELIVERY TECHNIQUES

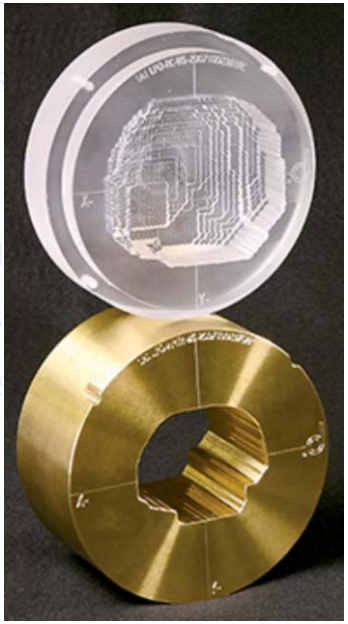
PASSIVE VS. ACTIVE BEAM DELIVERY SYSTEMS

Passive beam delivery



Graph adapted from Paganetti 2012.

- Lateral scattering
  - Single / **Double** scattering
  - Field specific collimators



Source: www.oncolink.org/treatment

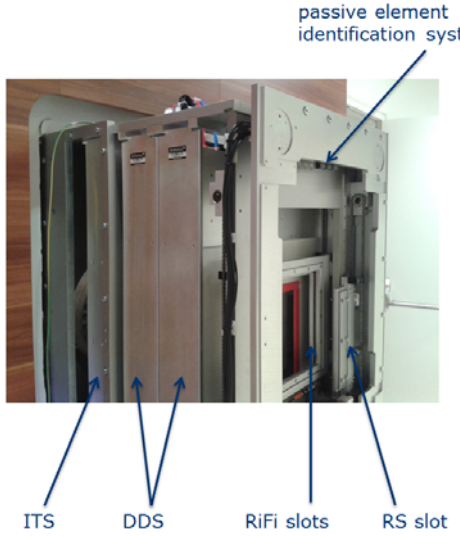
DELIVERY TECHNIQUES

PASSIVE VS. ACTIVE BEAM DELIVERY SYSTEMS

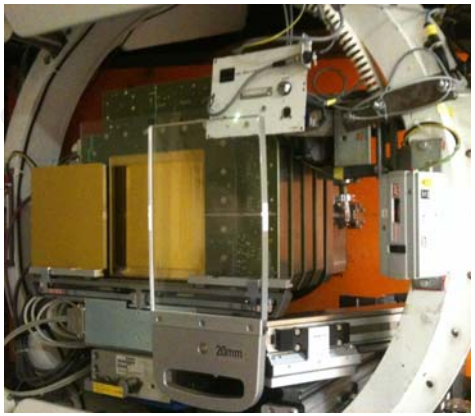
MedAustron synchrotron.

Active beam delivery

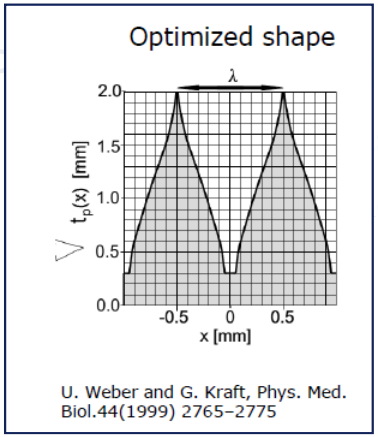
- Active energy variation
  - Synchrotron
    - Range shifters
    - Ripple filters
  - No field specific passive devices



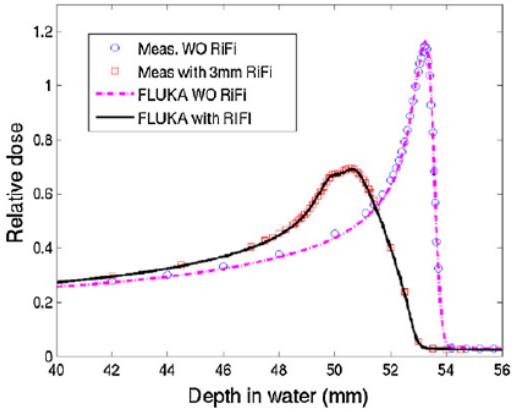
MedAustron nozzle.



Nozzle of HIT Ionengantry with Range Shifter



RiFi design.



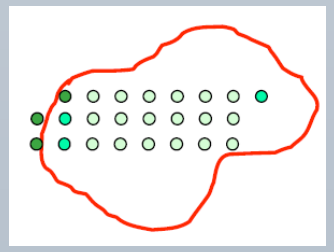
Parodi et al. PMB 2012

DELIVERY TECHNIQUES

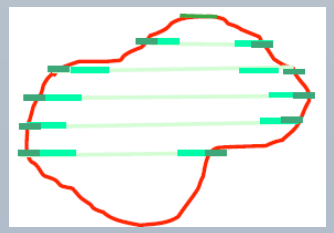
PASSIVE VS. ACTIVE BEAM DELIVERY SYSTEMS

Definitions PBS [Pedroni PTCOG 2008]:

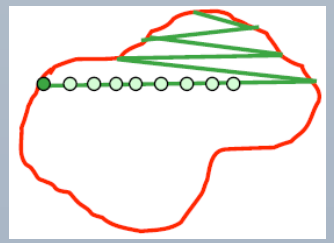
(1) Discrete (Spot-) Scanning



(2) Continuous (Line-) Scanning



(3) Quasi-discrete (Raster-) Scanning



Active beam delivery

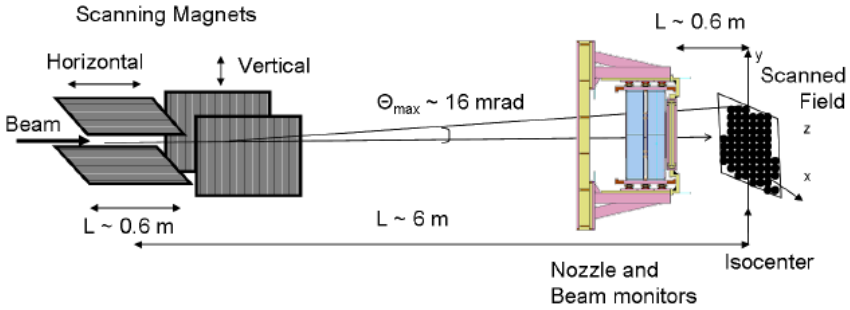


Figure 3.9: The CNAO horizontal beam line setup

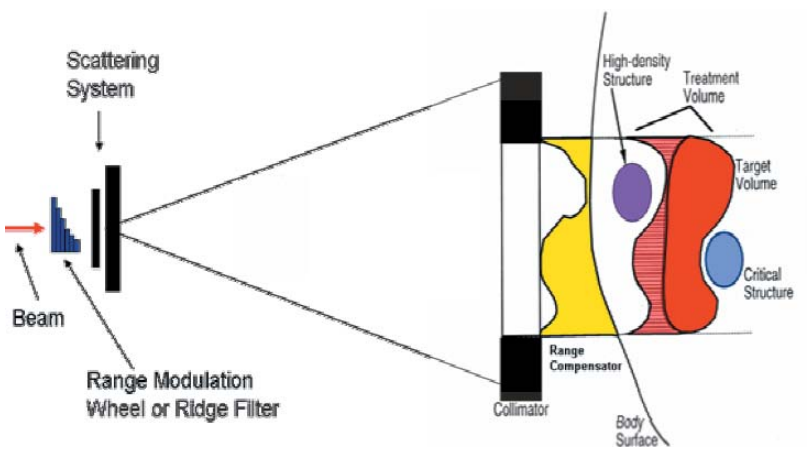
Giordanengo PhD Thesis 2009.

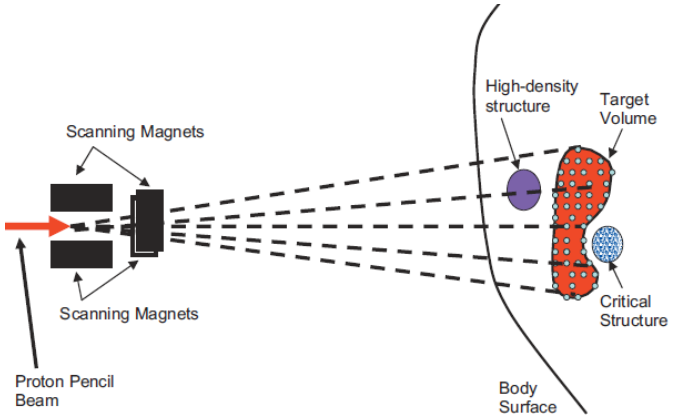
- Pencil beam scanning
  - Spot-, Line-, Raster-scanning
  - No passive devices essential

DELIVERY TECHNIQUES

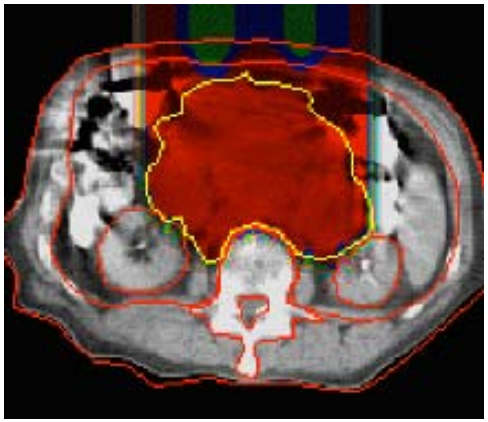
PASSIVE VS. ACTIVE: ISODOSE DISTRIBUTIONS

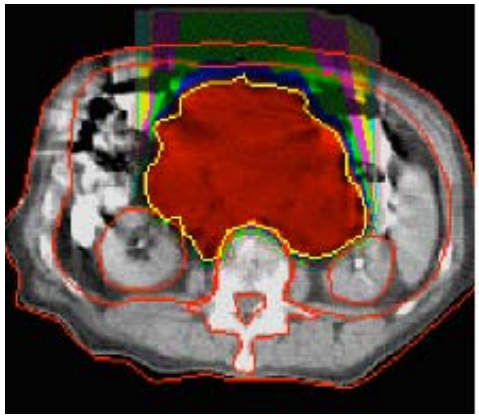
Passive delivery vs. Active delivery





Smith MP 36 2009

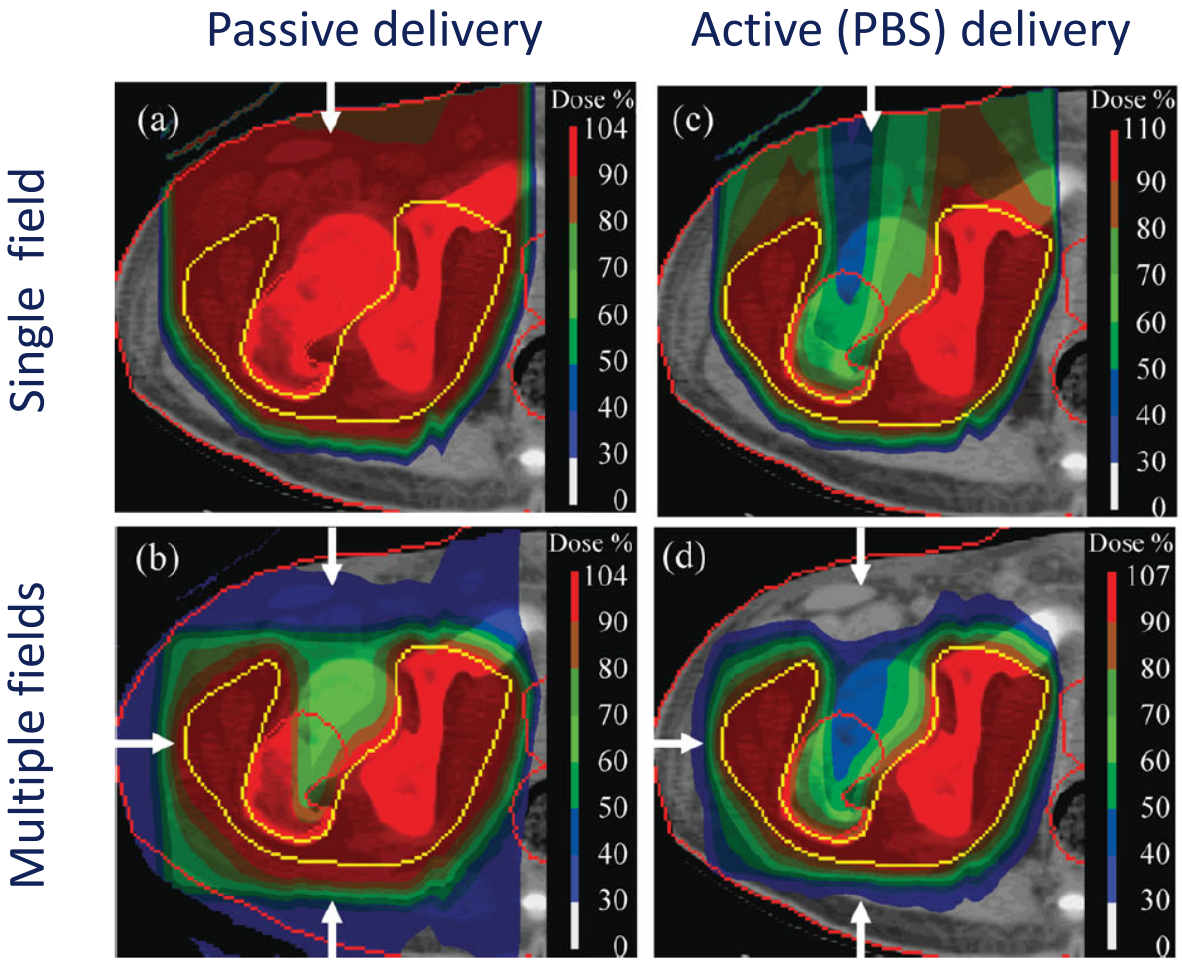




Pedroni PTCOG 2008

DELIVERY TECHNIQUES

PASSIVE VS. ACTIVE: ISODOSE DISTRIBUTIONS

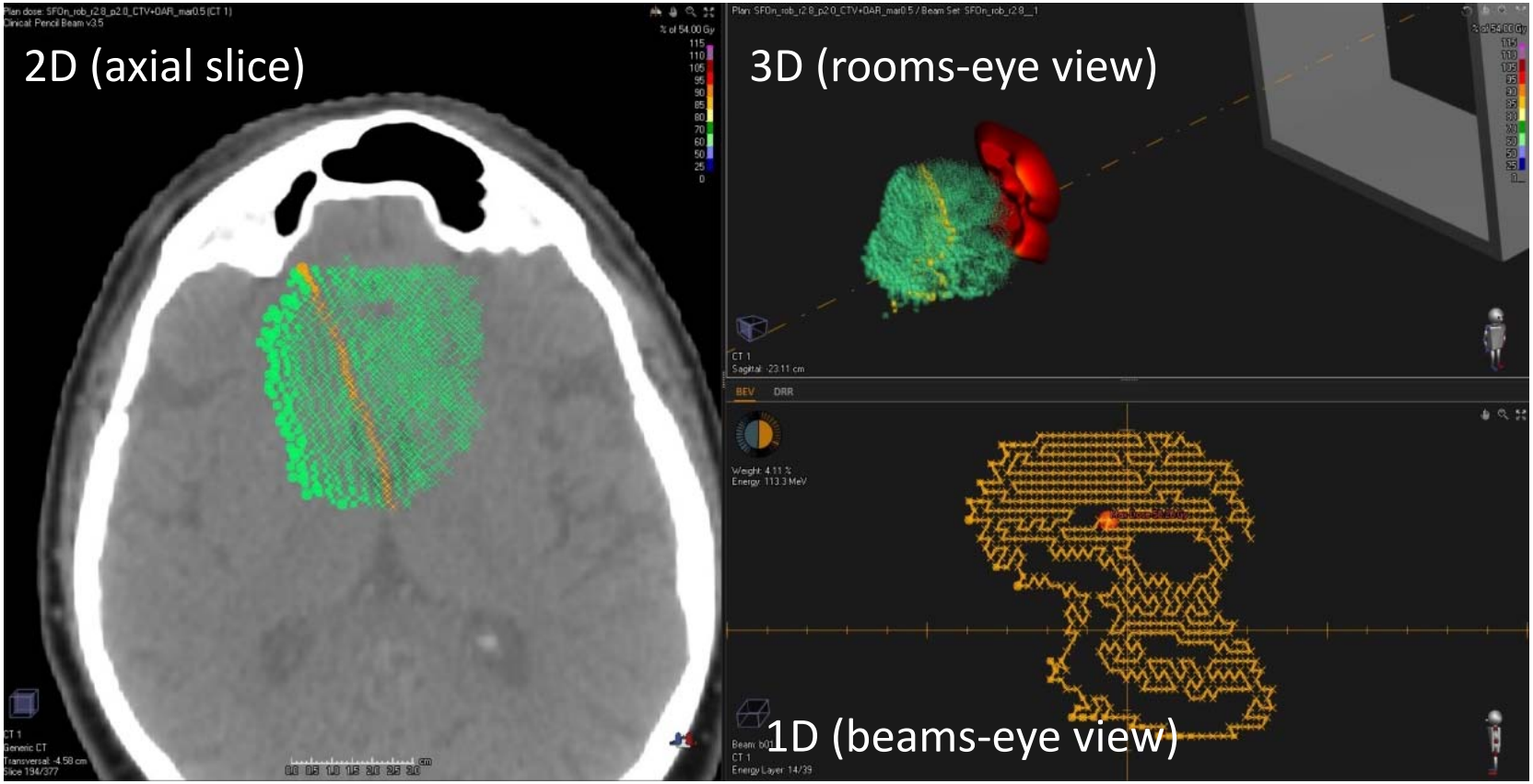


ICRU Report 78; PSI

DELIVERY TECHNIQUES

MEDAUSTRON APPLIES SYNCHROTRON BASED PBS

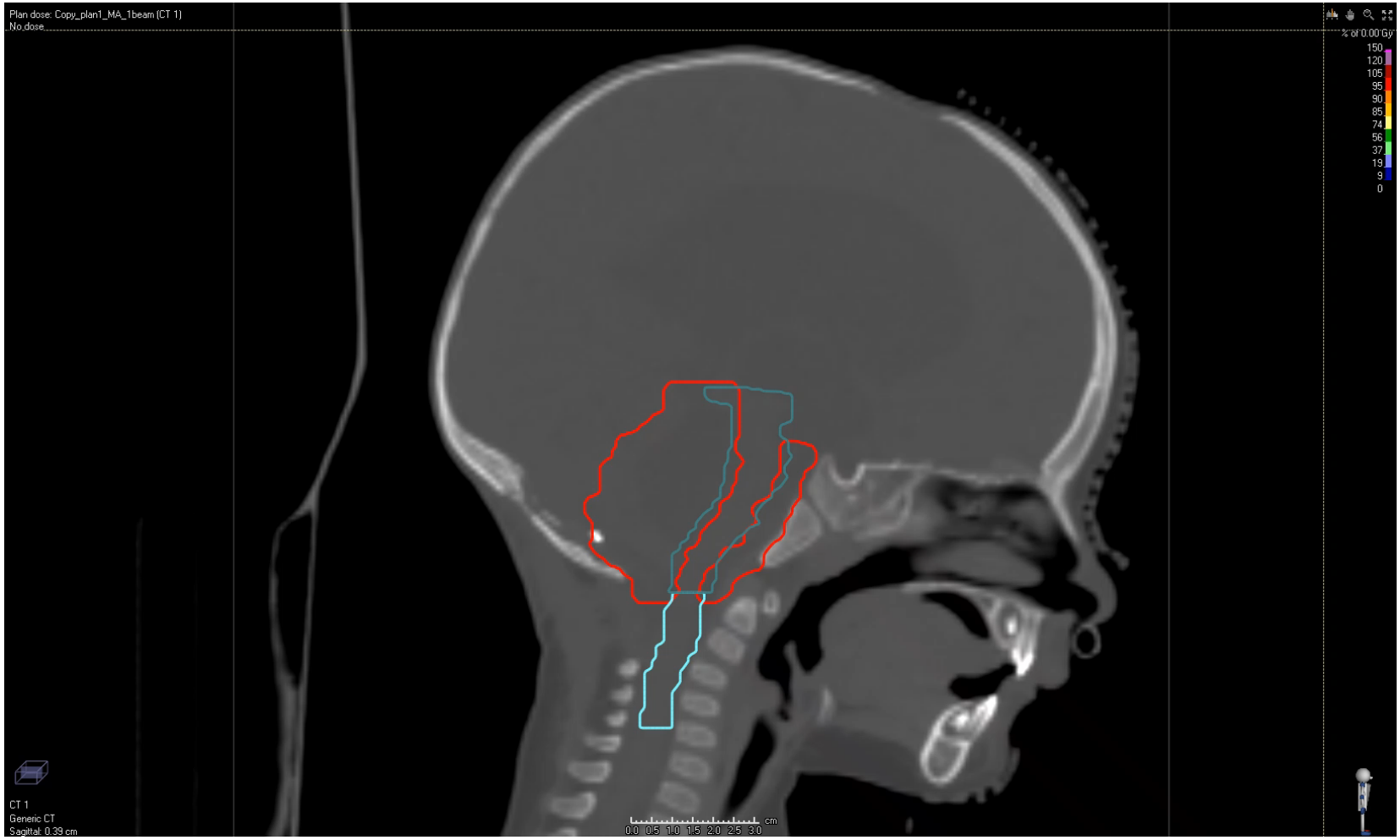
Display of 1 iso-energy layer



DELIVERY TECHNIQUES

MEDAUSTRON APPLIES SYNCHROTRON BASED PBS

Active energy modulation

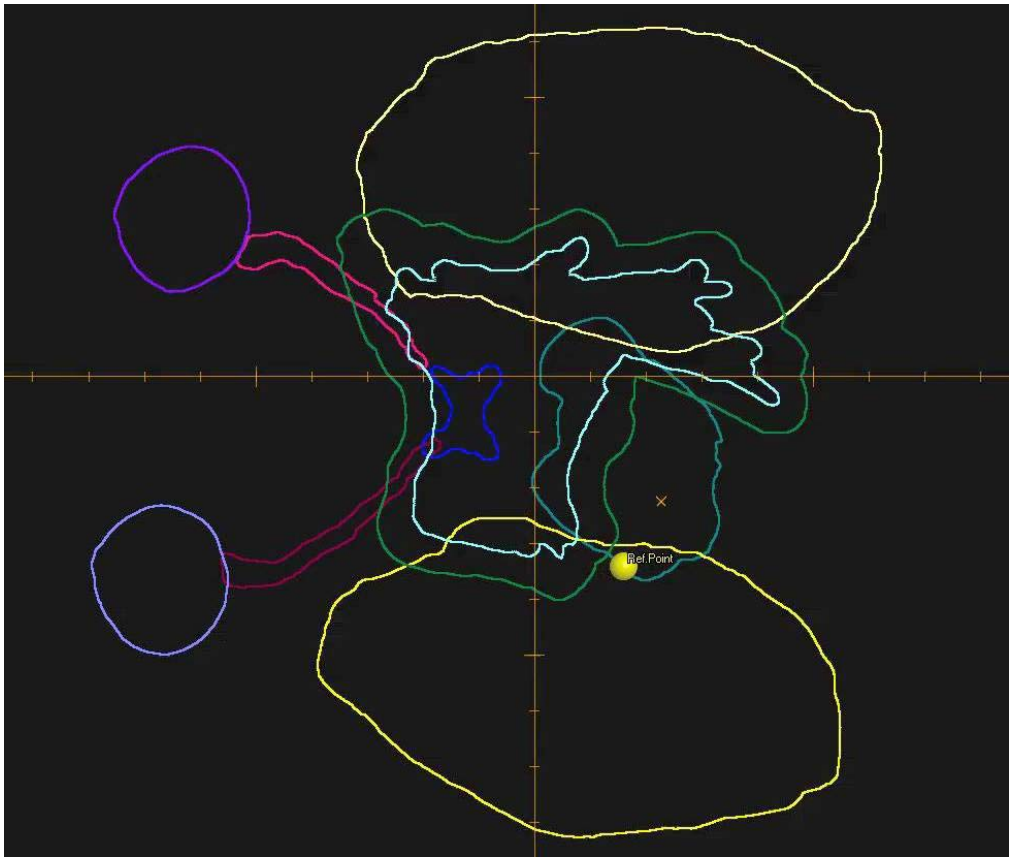


DELIVERY TECHNIQUES

MEDAUSTRON APPLIES SYNCHROTRON BASED PBS

Pencil beam scanning

Traveling salesman problem



No preferred scan direction

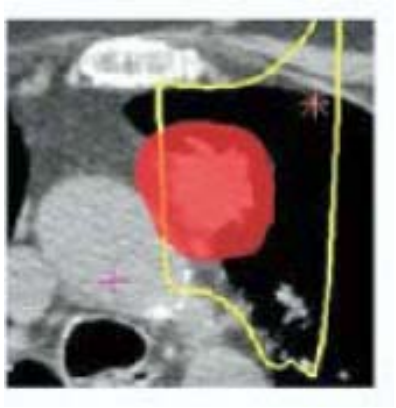
DELIVERY TECHNIQUES

PASSIVE VS. ACTIVE: PROs AND CONs

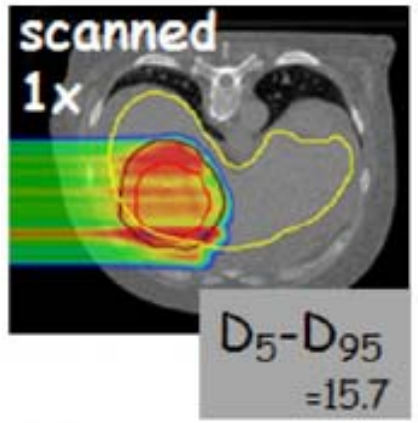
- **Mono-energetic pencil beam scanning (PBS) is widely considered superior to passive techniques.**

PBS - PROs	PBS - CONs
• less passive elements in the beam line	• penumbra
• no patient customized passive elements	• (without mitigation strategies) less robust to organ motion
• reduced neutron dose	
• superior dose distribution	
• less fields required	

Tumor motion: Scattering vs. Scanning



Engelsmann, IJROBP 2006



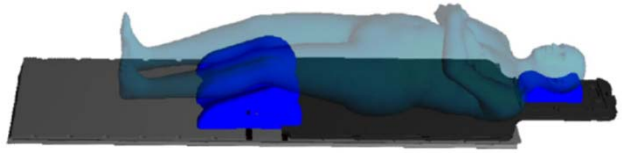
Knopf, PMB 56, 2011

CONTENTS

- **Part I General aspects**
  - Introduction and motivation
  - Particle therapy delivery techniques
  - **Treatment planning software**
  - Prescribing and reporting

TREATMENT PLANNING

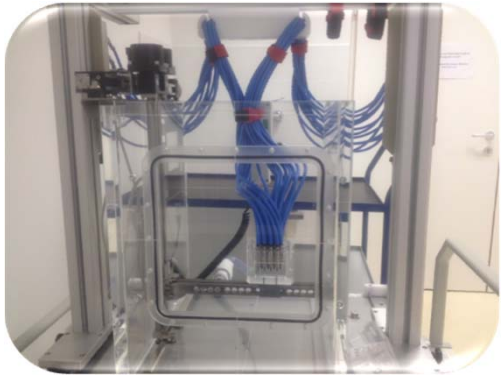
@ MEDAUSTRON (SIMPLIFIED)



OIS / R&V

Oncology Information System / Record & Verify System

medPhoton GmbH

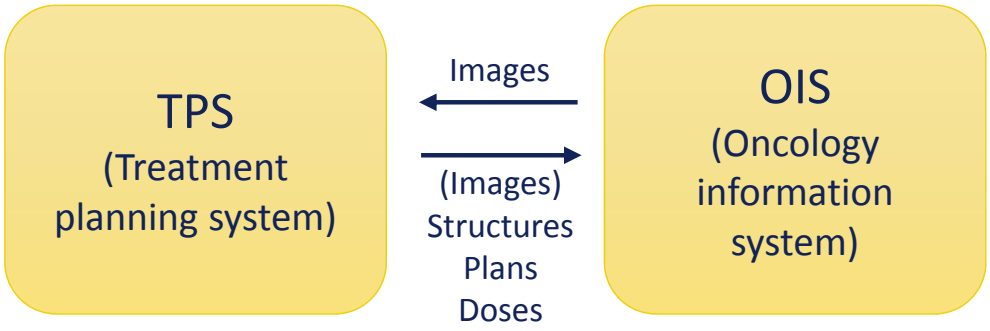


TREATMENT PLANNING SOFTWARE

COMMUNICATION FORMAT: DICOM

- **Digital Imaging and Communications in Medicine**

  - Standardized communication format
  - The American College of Radiology (ACR) and the National Electrical Manufacturers Association (NEMA)
  - https://www.dicomstandard.org/
    - Supplement 102: Radiotherapy Extensions for Ion Therapy
    - Site specifics: private DICOM agreements
  - TPS vendors have to declare conformance
  - Most relevant objects for RT:
    - DCM images
    - (DCM RT images)
    - DCM RT structures
    - DCM RT plans
    - DCM RT dose files (RBE&phys)
    - …



TREATMENT PLANNING SOFTWARE

COMMERCIAL PROTON TPS

- **Purpose**
  - Estimate patient dose
  - Dose calculation typically based on CT-images (HU values)

- **Commercial systems**
  - RayStation (RaySearch Labs)
  - Eclipse (Varian)
  - XiO, Monaco (Elekta)
  - Pinnacle (Philips)
  - …

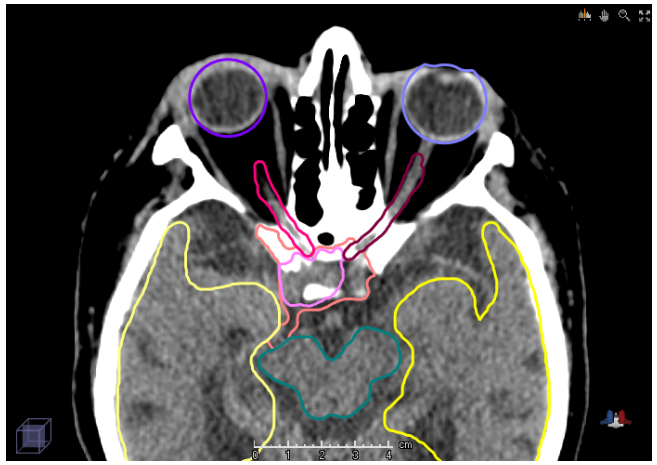
- **Common modules**
  - Patient data management
  - Image registration
  - Contouring
  - Plan setup
  - Dose calculation
  - Plan optimization
  - Plan evaluation

  - Physics commissioning tool
  - Database management

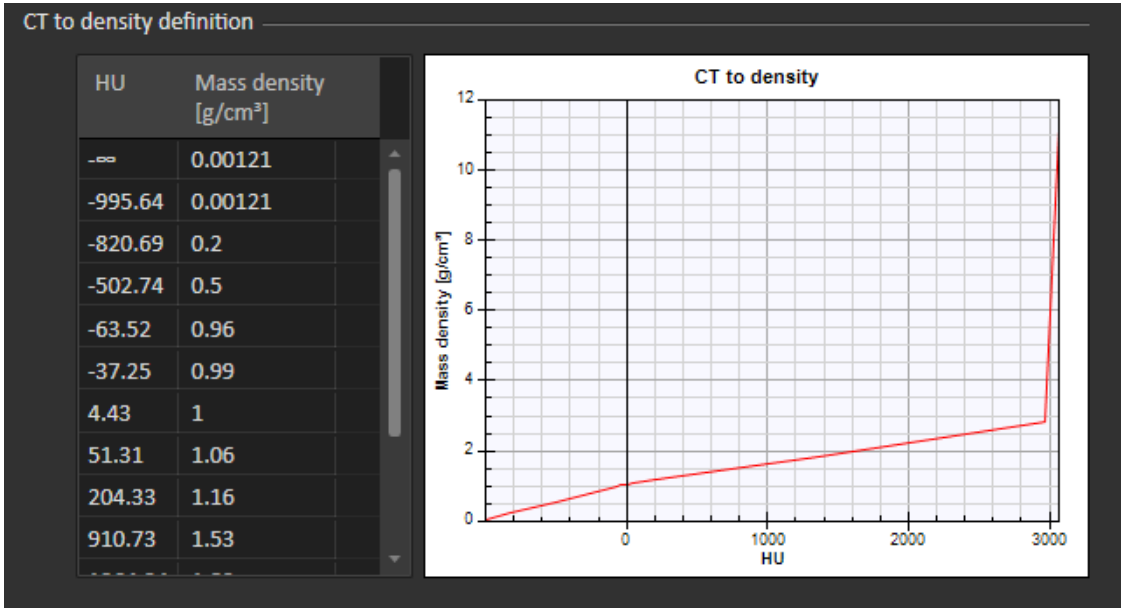
TREATMENT PLANNING SOFTWARE

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
  - ➢ **Talk by J. Gora on Friday.**



CT

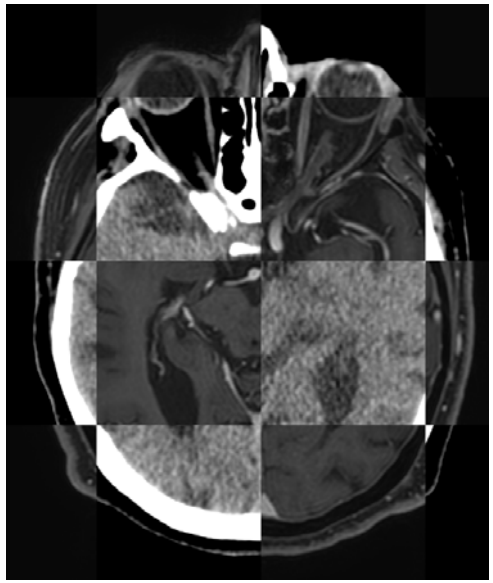


Example of HU to MD conversion table.

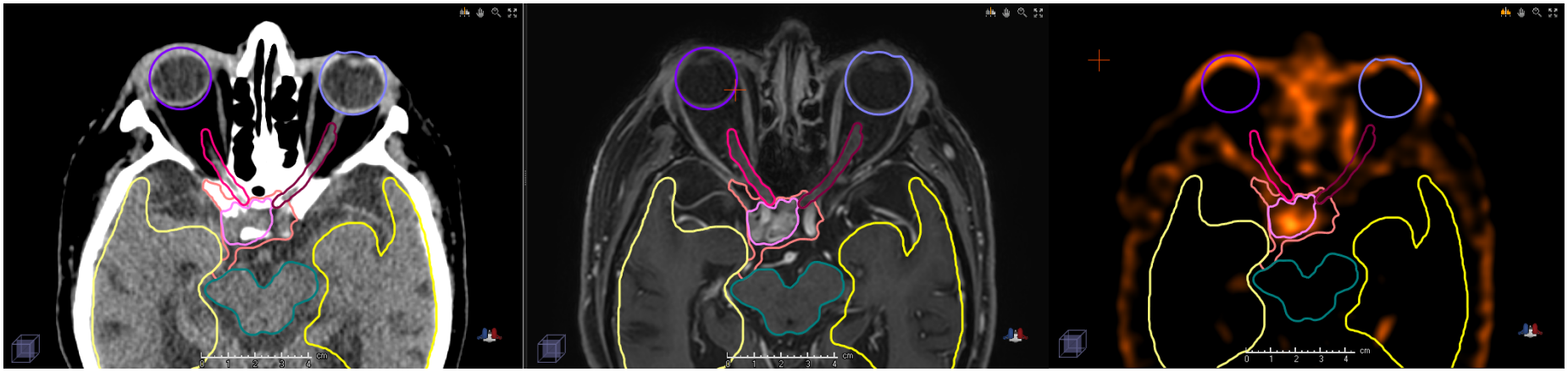
TREATMENT PLANNING SOFTWARE

IMAGE REGISTRATION & CONTOURING

- **Image registration**
  - Rigid registration
  - Deformable image registration
  - Fusion tools



- **Contouring**
  - Variety of contouring tools
  - ABAS
  - (Machine learning)

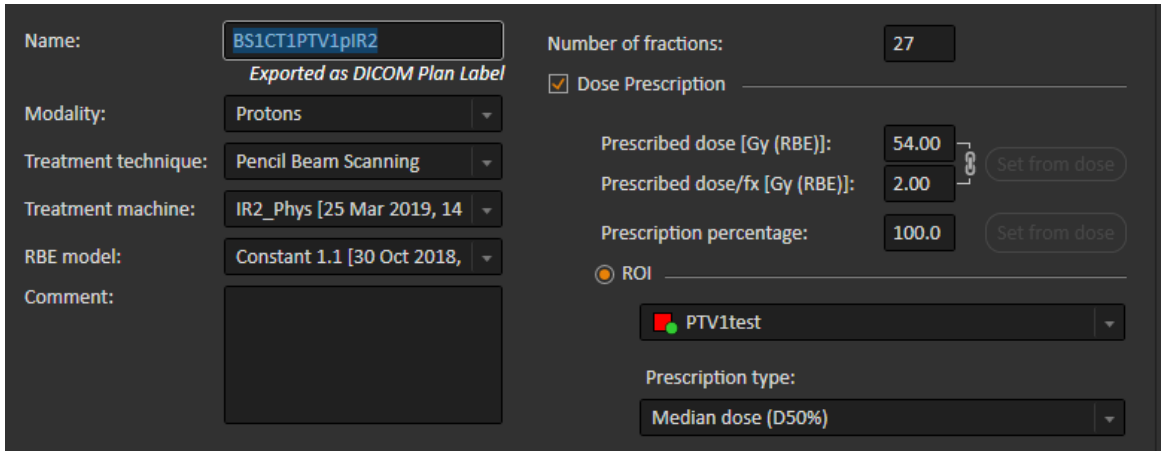


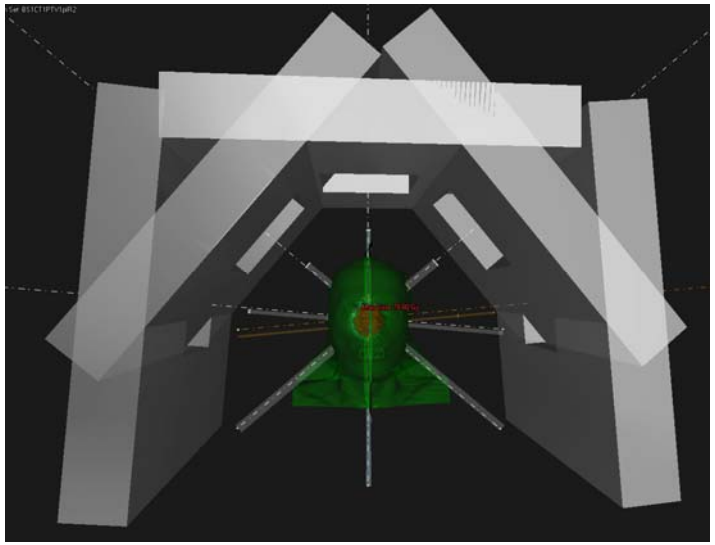
CT MR PET

TREATMENT PLANNING SOFTWARE

PLAN SETUP

Choose modality, machine and setup prescription:





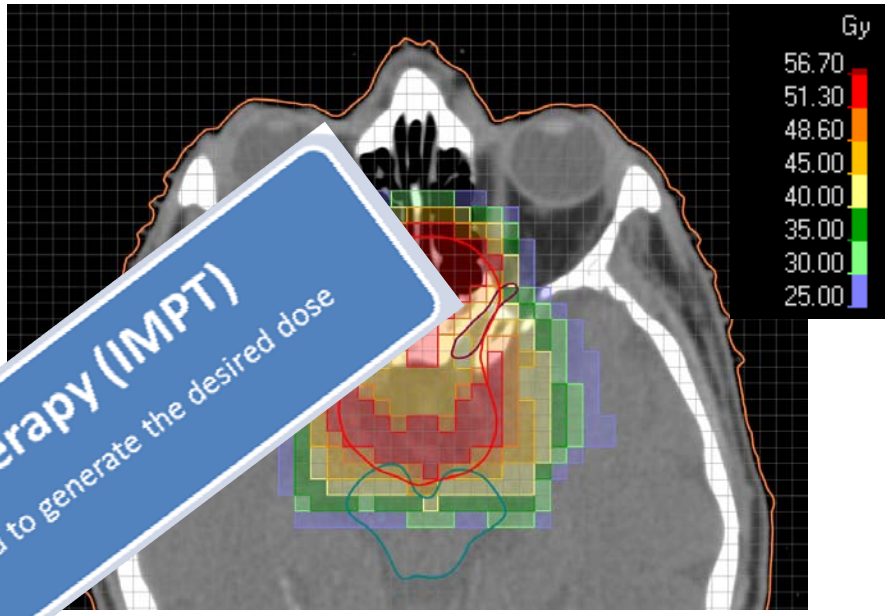
Define beams/fields:

No.		Name	Description	Isocenter [cm] Name	R-L	I-S	P-A	Snout Name	Position [cm]	Air gap [cm] Min	CAX	Gantry [deg]	Coll. [deg]	Couch [deg]	Range shifter
1		b1g0c180		BS1 b1_moved 4	-4.59	14.51	-39.83	VBL_Nozzle	64.23	20.00	21.97	0.0	0.0	180.0	(None)
2		b2g90c180		BS1 b2_moved 2	27.25	14.51	-1.57	HBL_Nozzle	64.80	20.00	28.76	90.0	0.0	180.0	(None)

TREATMENT PLANNING SOFTWARE

PLAN OPTIMISATION

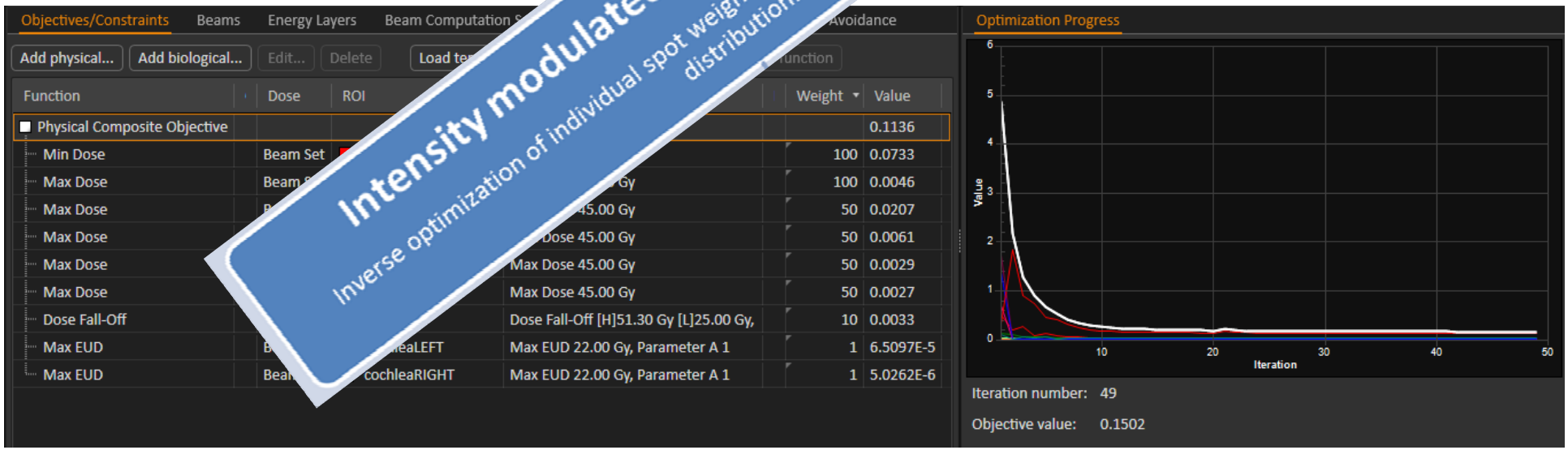
- Inverse optimization of spot positions and spot weights.
- Setup optimization parameters:
  - Number of iterations
  - Machine limitations
  - Optimization tolerance/stop criteri



Intensity modulated particle therapy (IMPT)

Inverse optimization of individual spot weights required to generate the desired dose distribution.

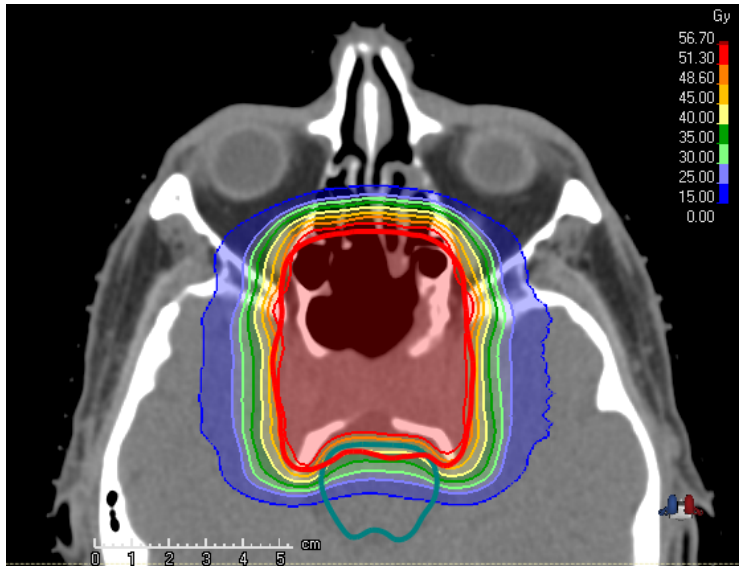
Select objective functions:

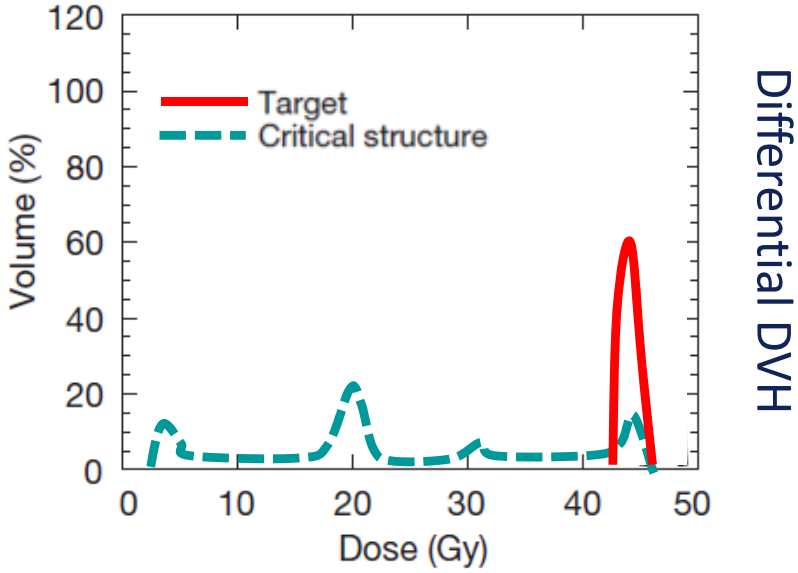


TREATMENT PLANNING SOFTWARE

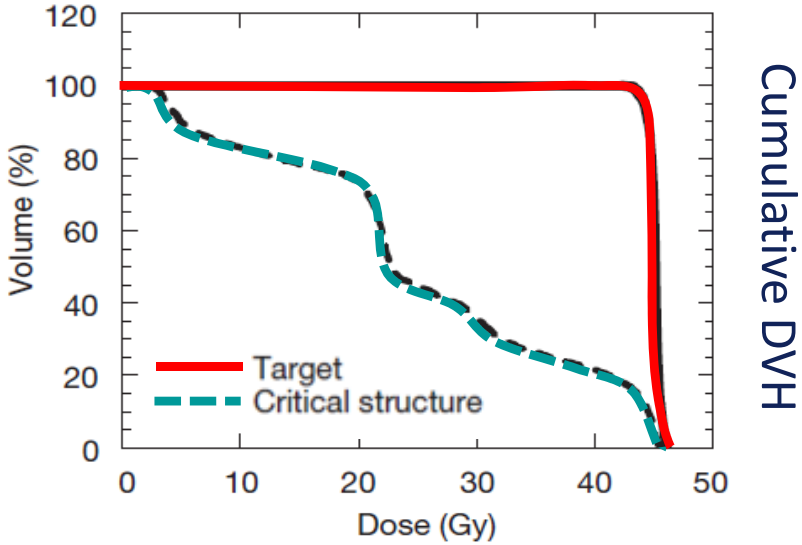
PLAN EVALUATION

- **Tools for plan evaluation & comparison**
  - Isodose distributions
  - Dose volume histograms
  - Dose statistics
  - Dose difference plots
  - …





Differential DVH



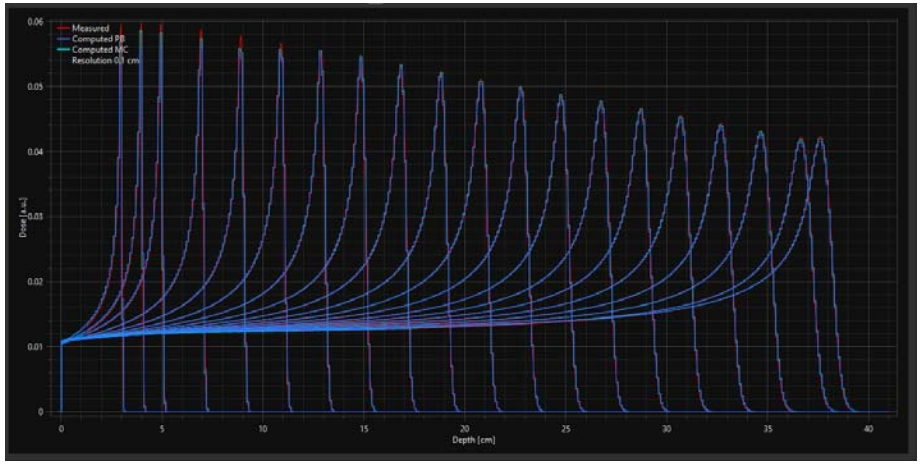
Cumulative DVH

adapted from IAEA Handbook Radiation Oncology Physics 2005

TREATMENT PLANNING SOFTWARE

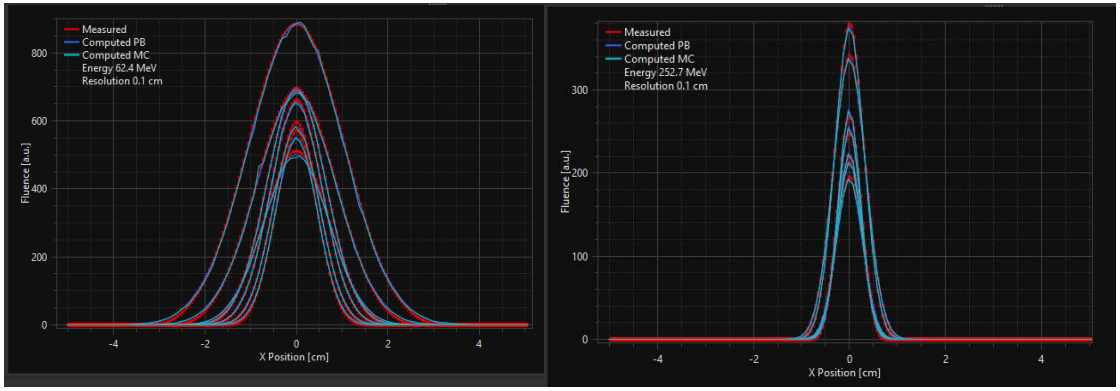
PHYSICS COMMISSIONING TOOLS

- **Input data**
  - measured IDDs
  - measured spot distributions @ various air gaps
  - absolute dose @ reference geometry
  - machine specific beam parameters and geometry



measured vs. computed IDDs for a selection of energies

- **TPS commissioning module**
  - tune model parameters to the site specific beam lines
  - ➢ e.g. adjust range, beam divergence, spot size, dose per meterset, etc.



measured vs. computed spot profiles for various air gaps

TREATMENT PLANNING SOFTWARE

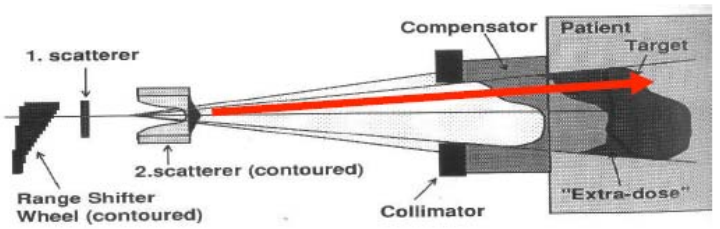
DOSE CALCULATION

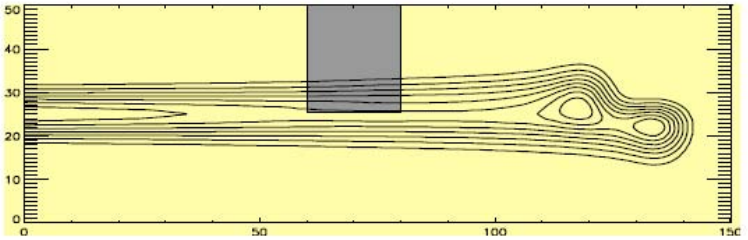
- 3 families :

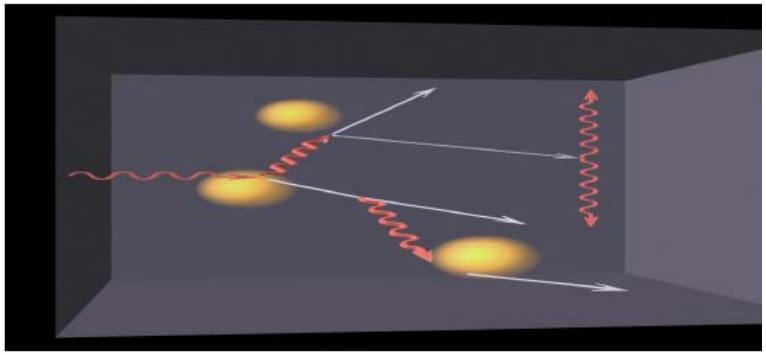
1) Ray tracing

2) Pencil beam

3) Monte Carlo





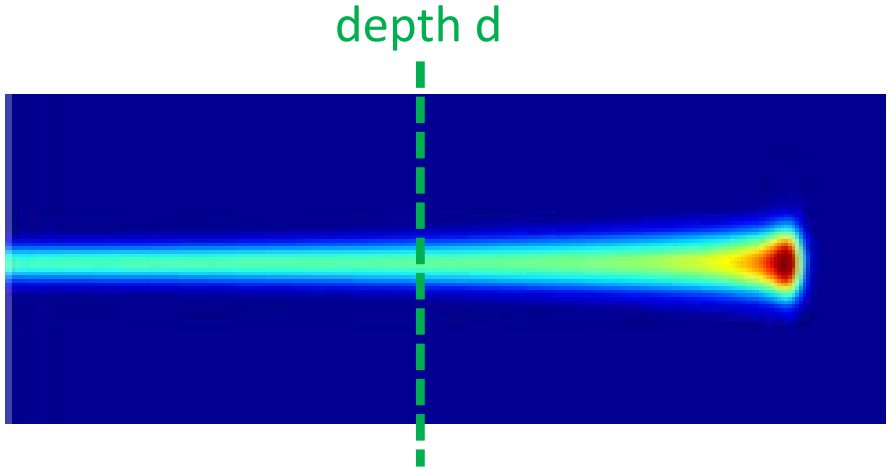


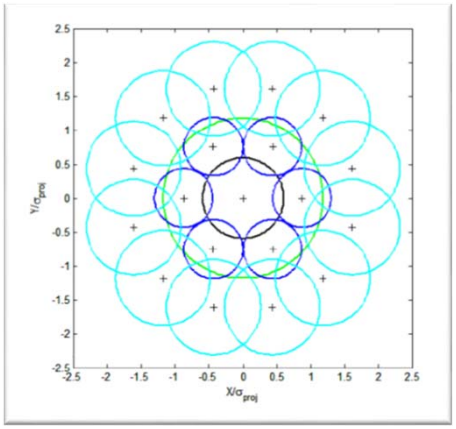
A. Mazal Utrecht 2016

TREATMENT PLANNING SOFTWARE

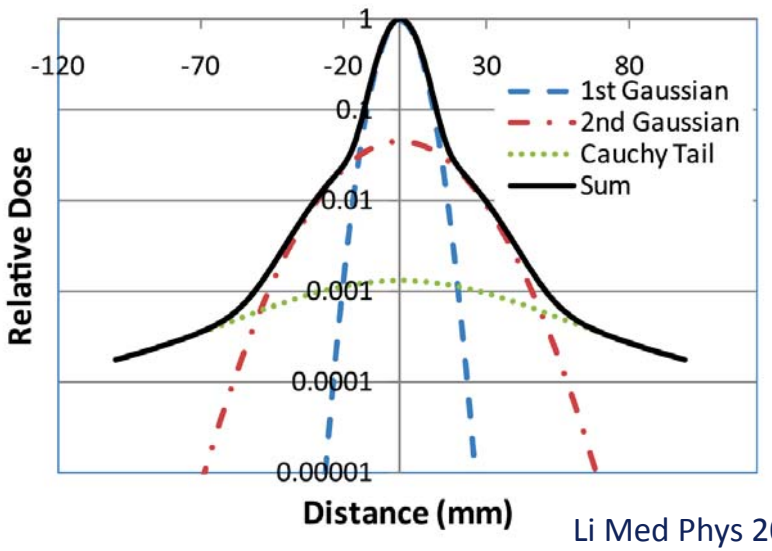
DOSE CALCULATION: PENCIL BEAM ALGORITHM

- $D(x,y,z) = I(d(z)) \times LAT(x,y,d(z))$
  - I(d) is integral depth dose
    - HU to WET
  - LAT(x,y,d) is lateral dose profile
    - Multiple Coulomb Scattering (1st and 2nd Gaussian)
    - Nuclear Interaction (Halo) due to large angle inelastic nuclear fragments (3rd Gaussian)
  - Usually multiple sub-PB





RSL reference manual

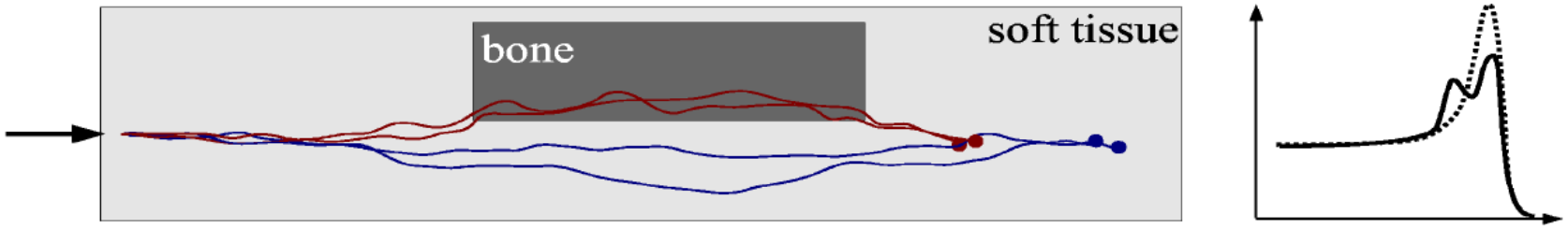


Li Med Phys 2012

TREATMENT PLANNING SOFTWARE

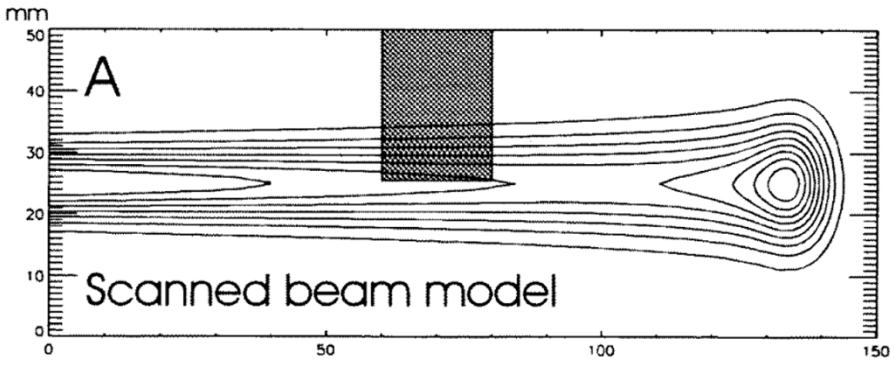
DOSE CALCULATION: PENCIL BEAM ALGORITHM

- Heterogeneities orthogonal to the beam incidence

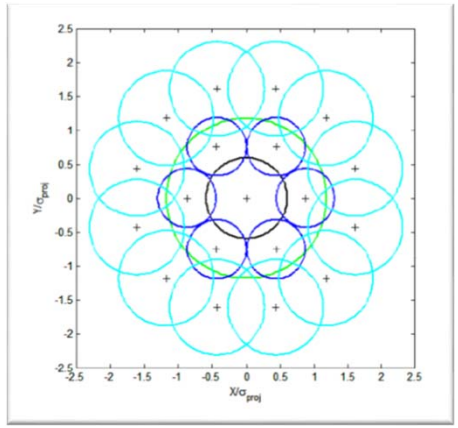


Lomax, PMB 2008

- Limitations of PB algorithm (per subspot)



Goitein

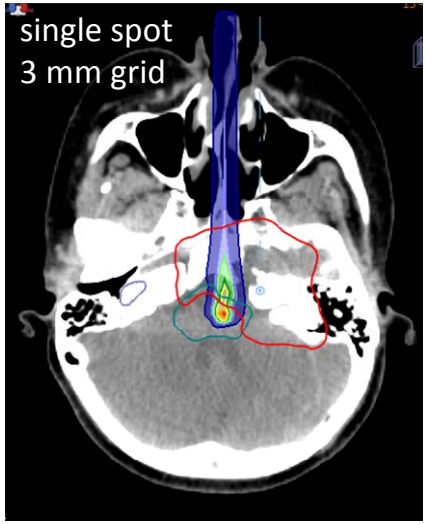


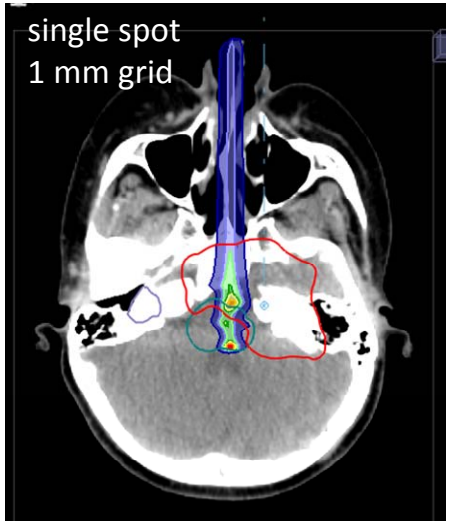
RSL reference manual

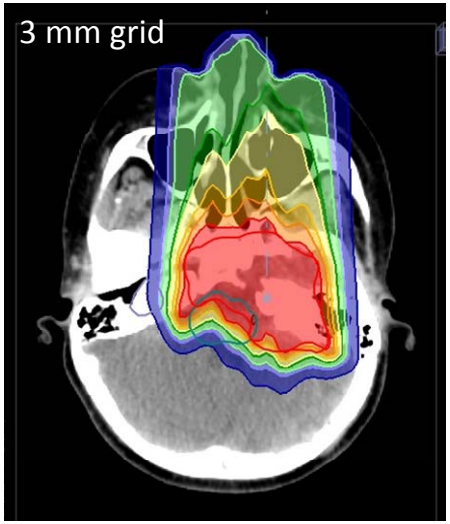
TREATMENT PLANNING SOFTWARE

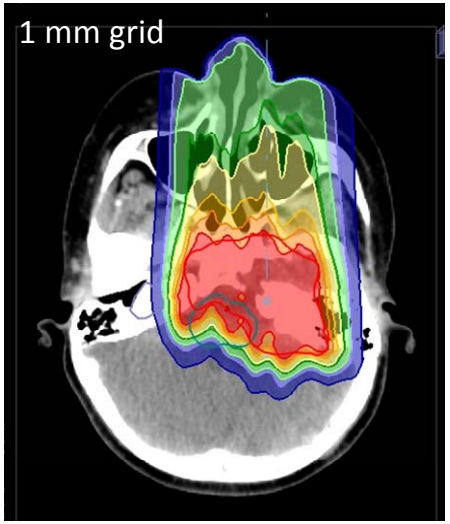
DOSE CALCULATION: PENCIL BEAM ALGORITHM

- PB algorithm: dose grid size matters





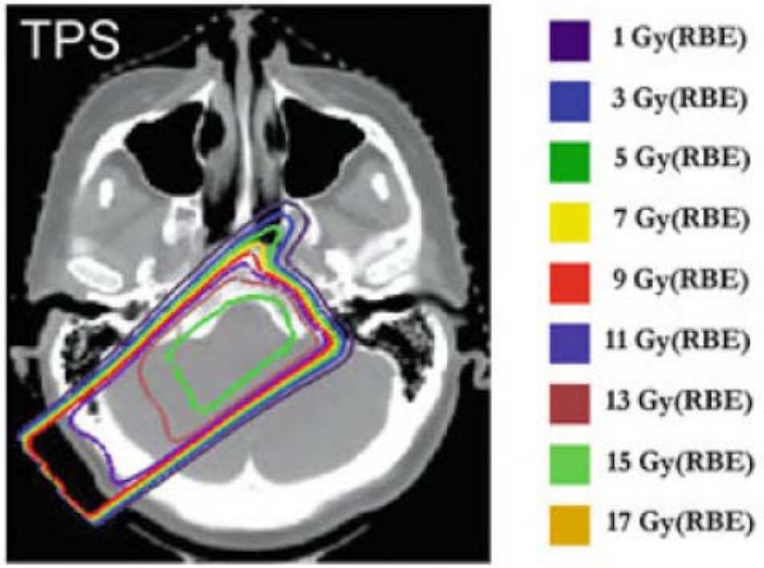




TREATMENT PLANNING SOFTWARE

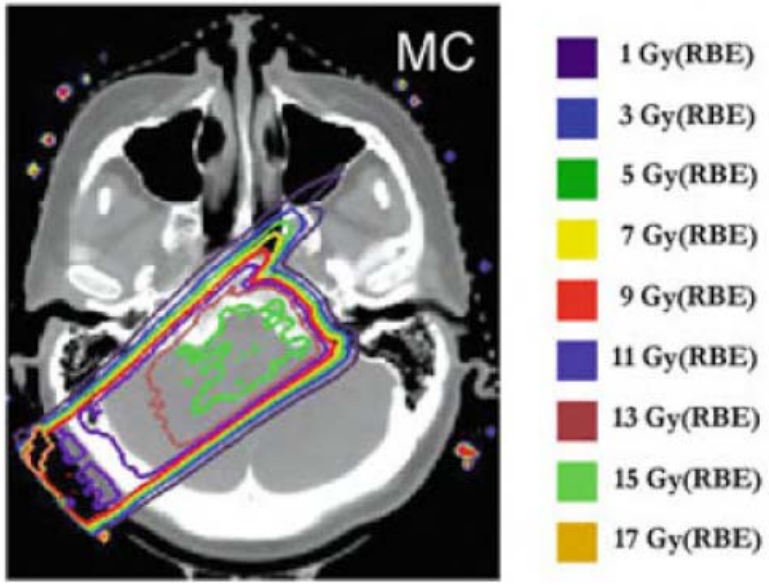
DOSE CALCULATION ALGORITHMS

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



Paganetti, Parodi, Linz 2012

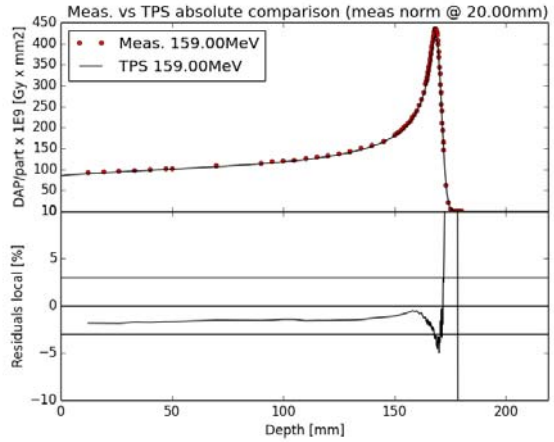
- Time consuming
- ✓ **High accuracy**
- Semi-analytic implementations in commercial TPS
  - ➢ Pre-calculated beam model
  - ➢ Scoring starts e.g. at patient surface

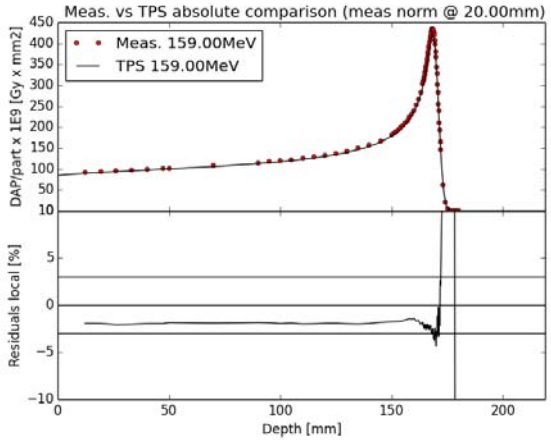
TPS COMMISSIONING

1D/2D @ MEDAUSTRON

PB4.1 MC4.0

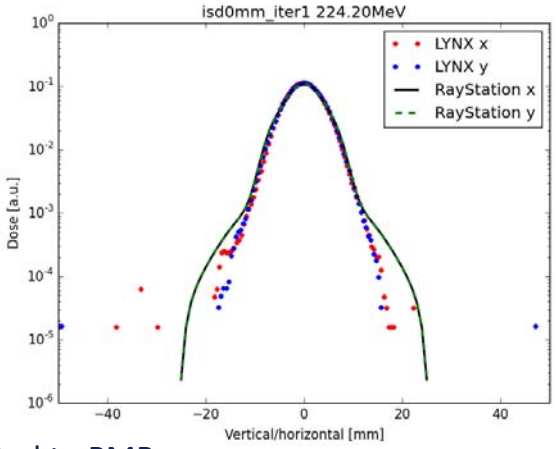
159.0MeV

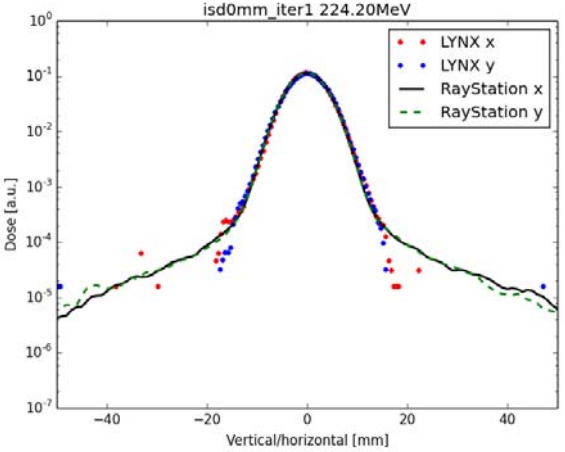


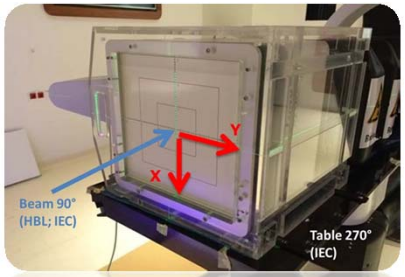


IDDs in water @ ISD0

224.2MeV





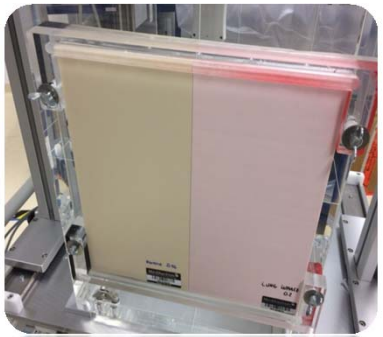


Lateral spot profiles in air @ ISD0

Carlino et. al submitted to PMB

TPS COMMISSIONING

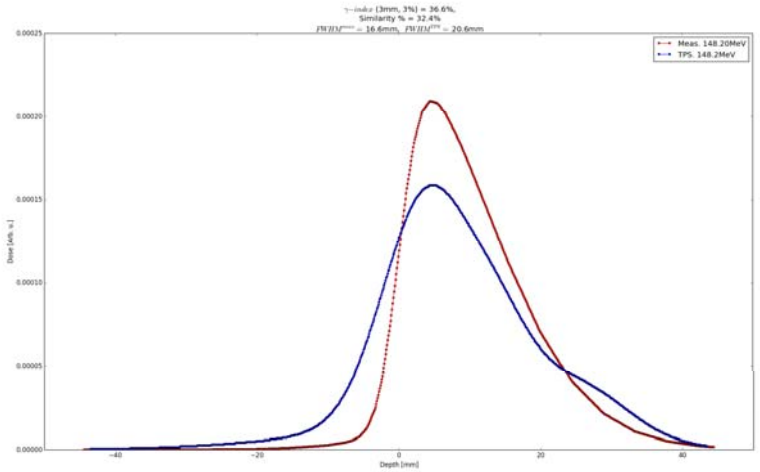
1D/2D @ MEDAUSTRON

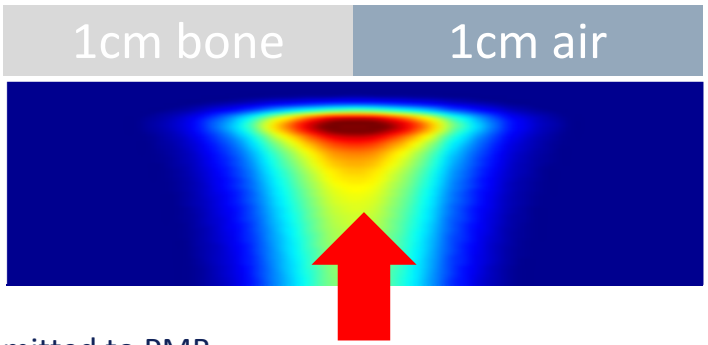


- **Lateral profiles**

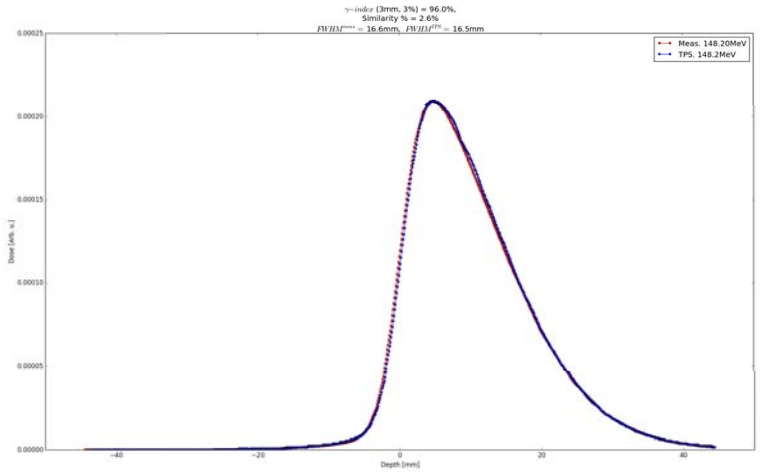
148.2 MeV, with RaShi

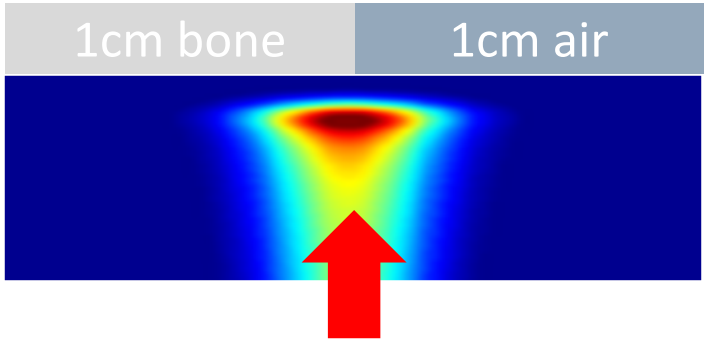
PBv4.1





MCv4.0

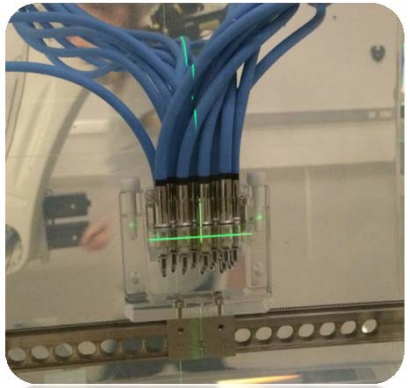


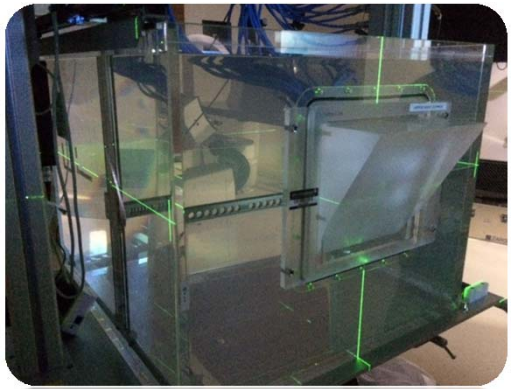


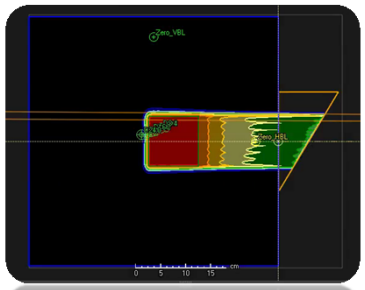
Carlino et. al submitted to PMB

TPS COMMISSIONING

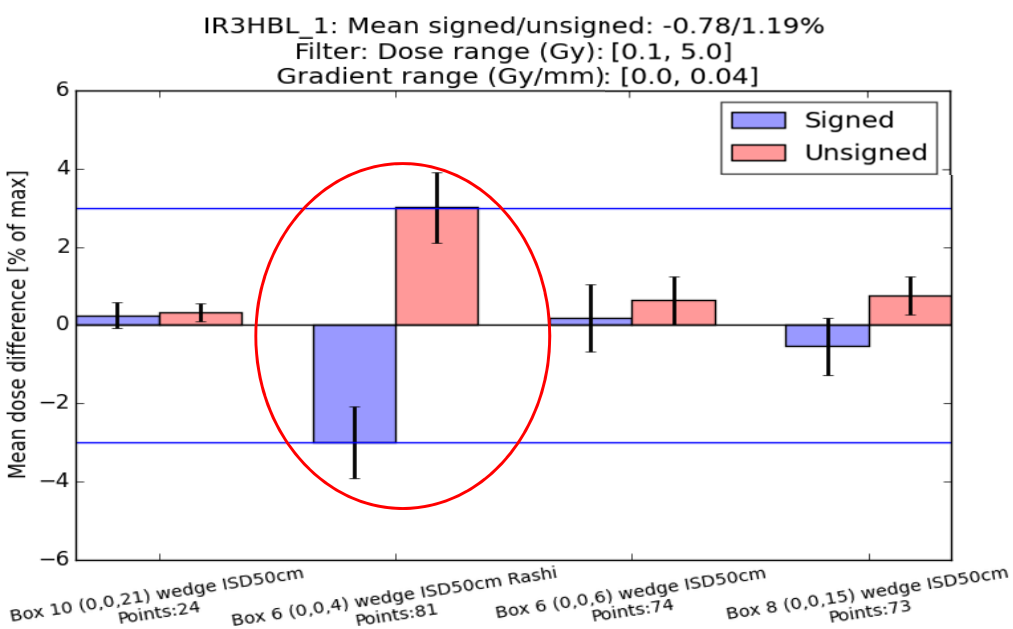
3D @ MEDAUSTRON



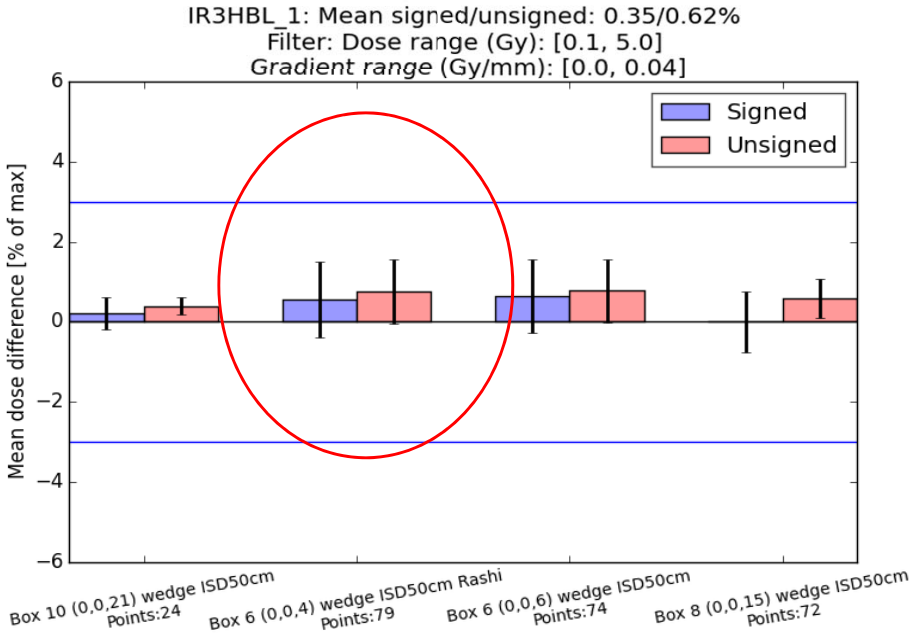




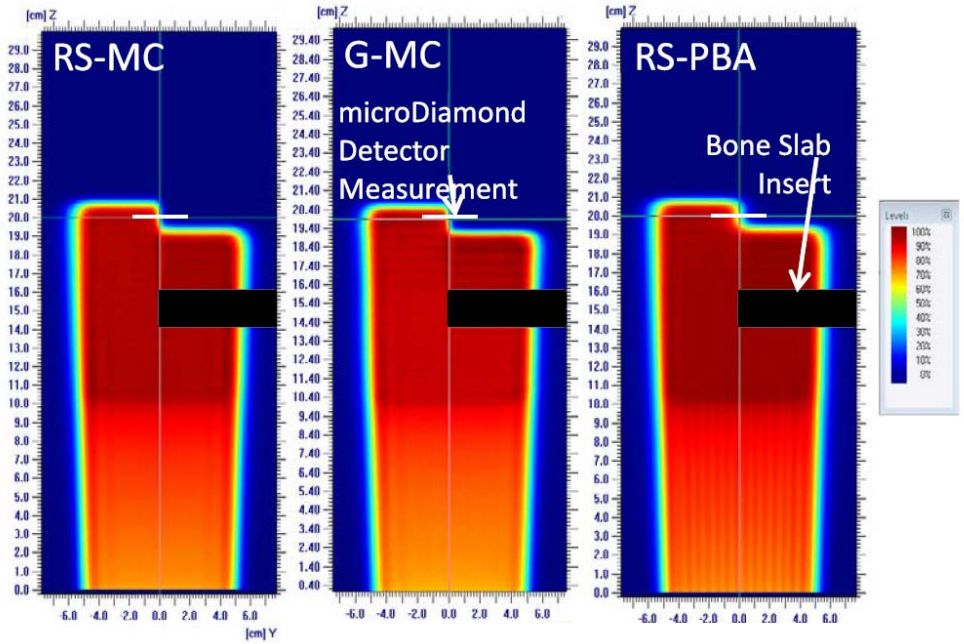
PBv4.1



MCv4.0



Carlino et. al submitted to PMB



IOP Publishing | Institute of Physics and Engineering in Medicine
Physics in Medicine & Biology
Phys. Med. Biol. 62 (2017) 7659–7681
https://doi.org/10.1088/1361-6560/aa82a5

Dosimetric evaluation of a commercial proton spot scanning Monte-Carlo dose algorithm: comparisons against measurements and simulations

Jatinder Saini[1], Dominic Maes[1], Alexander Egan[1], Stephen R Bowen[1,2], Sara St James[2], Martin Janson[3], Tony Wong[1] and Charles Bloch[1,2]

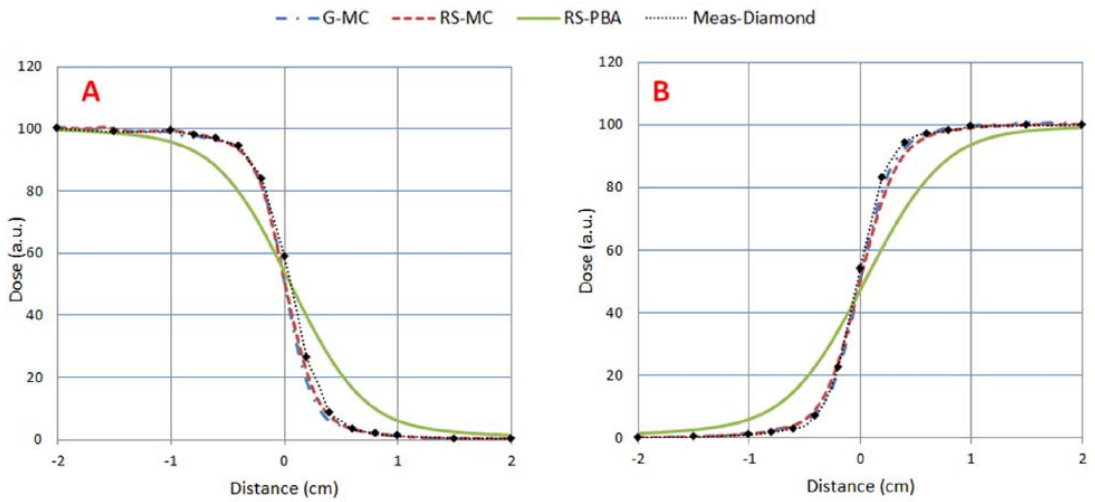


Figure 11. 1D dose profiles at the distal side of the inhomogeneity (see figure 8). Measurements (black dotted) were performed by a microDiamond detector. Calculated dose profiles are G-MC (blue dash dot), RS-MC (red dash), and RS-PBA (green solid). Panel (A) 2 cm bone slab at 15 cm depth, panel (B) 2 cm lung slab at 15 cm depth.

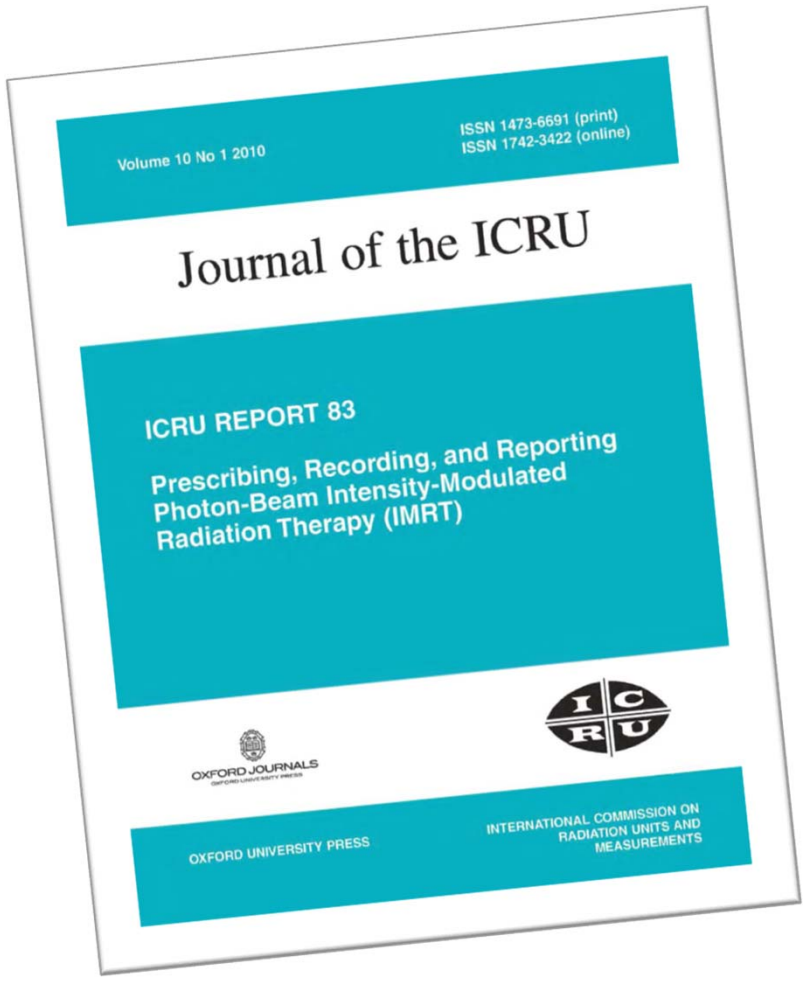
CONTENTS

- **Part I General aspects**
  - Introduction and motivation
  - Particle therapy delivery techniques
  - Treatment planning software
  - **Prescribing and reporting**

PRESCRIBING AND REPORTING

ICRU REPORTS #50, #62, #78, #83

- International Commission on Radiation Units and Measurements



PRESCRIBING AND REPORTING

ICRU REPORT78: 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: D_{RBE} (total RBE-weighted absorbed dose)
    d_{RBE} (RBE-weighted absorbed dose per fx)
  - Unit: **1 Gy (RBE)**

PRESCRIBING AND REPORTING

ICRU REPORT78: DOSE QUANTITIES AND UNITS

RBE-WEIGHTED ABSORBED DOSE (DRBE)

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

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

- 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)'.

PRESCRIBING AND REPORTING

TARGET VOLUME DEFINITION

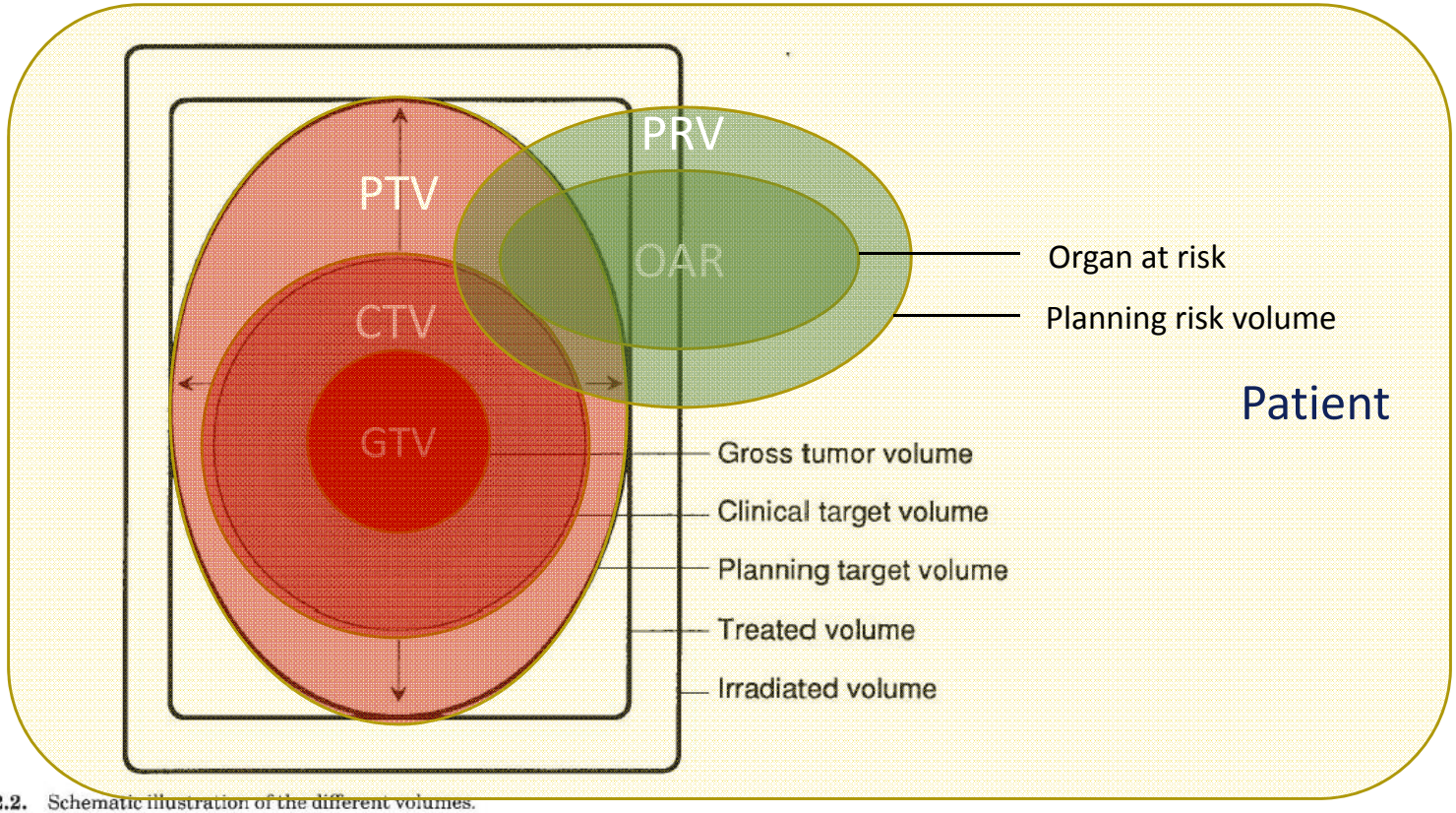


Fig. 2.2. Schematic illustration of the different volumes.

Gross Tumor Volume (GTV) denotes the demonstrated tumor.

Clinical Target Volume (CTV) denotes the demonstrated tumor (when present) and also volumes with suspected (subclinical) tumor (e.g., margin around the GTV, and e.g., regional lymph nodes, NO (according to the TNM-classification [UICC, 1987]), considered to need treatment). The CTV is thus a pure anatomic-clinical concept.

Planning Target Volume (PTV) consists of the CTV(s) and a margin to account for variations in size, shape, and position relative to the treatment beam(s). The PTV is thus a geometrical concept, used to ensure that the CTV receives the prescribed dose, and it is (like the patient/tissues concerned) defined in relation to a fixed coordinate system. Note that in the example shown the magnitude of foreseen movements of the CTV is different in different directions.

Treated Volume is the volume that receives a dose that is considered important for local cure or palliation.

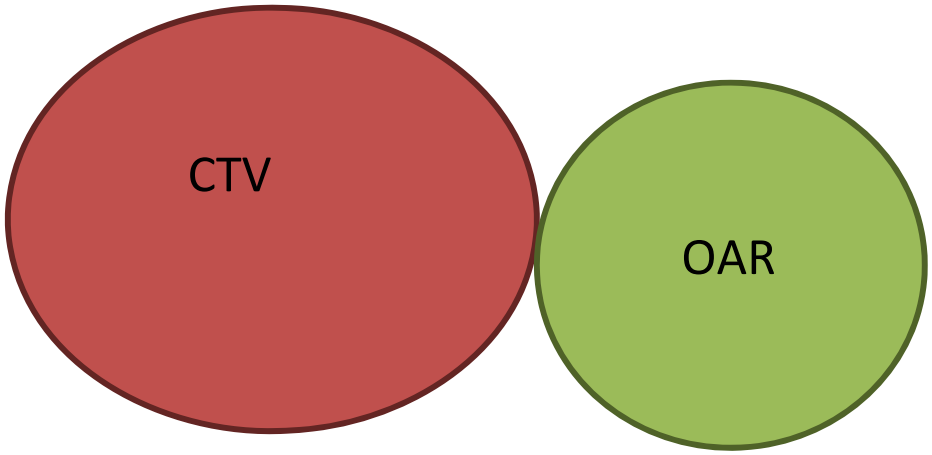
Irradiated Volume is the volume that receives a dose that is considered important for normal tissue tolerance (other than those specifically defined for organs at risk).

ICRU 50

PRESCRIBING AND REPORTING

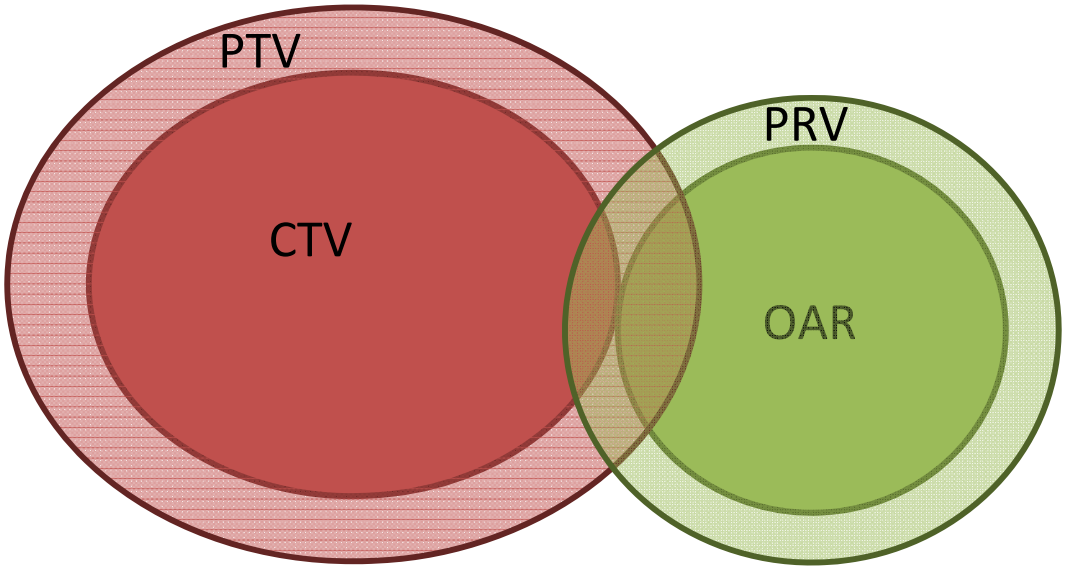
STRUCTURE CONFLICTS

Non-moving targets



PRESCRIBING AND REPORTING

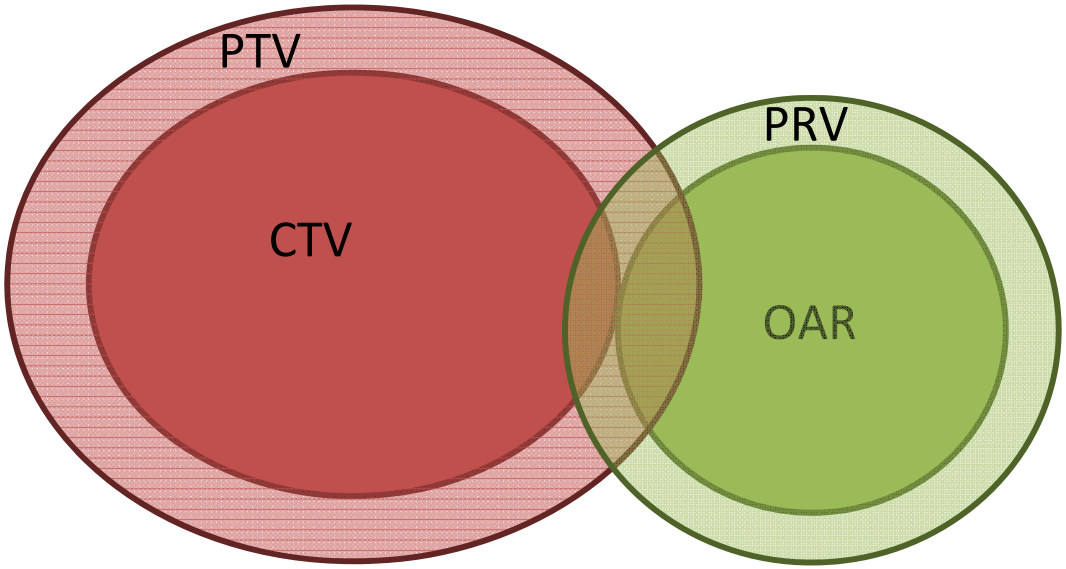
STRUCTURE CONFLICTS



PRESCRIBING AND REPORTING

STRUCTURE CONFLICTS

ICRU 83



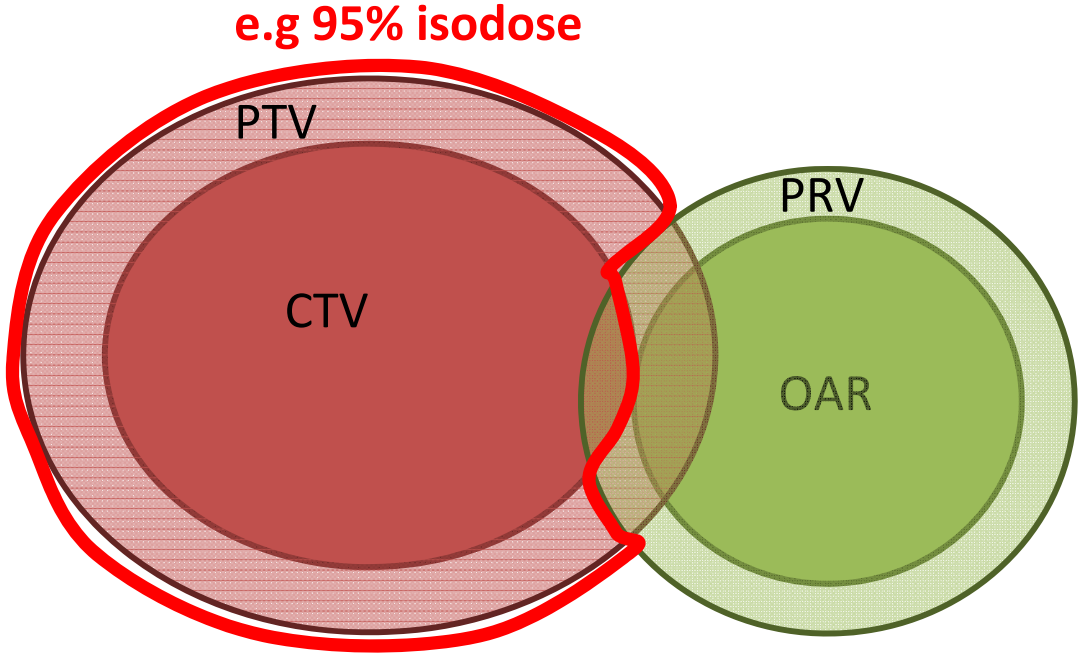
*Define **prioritities**, e.g.:*

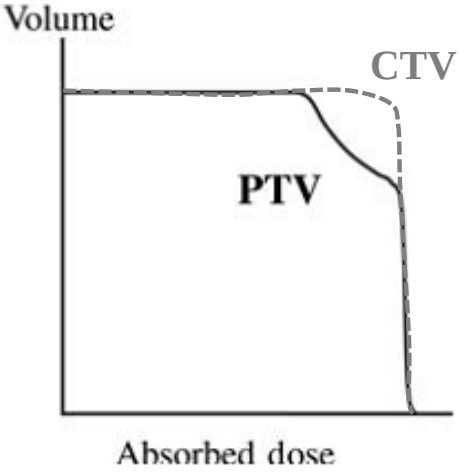
1. *CTV coverage*
2. *PRV/OAR sparing*
3. *PTV coverage*

PRESCRIBING AND REPORTING

STRUCTURE CONFLICTS

ICRU 83





*Define **prioritities**, e.g.:*

1. *CTV coverage*
2. *PRV/OAR sparing*
3. *PTV coverage*

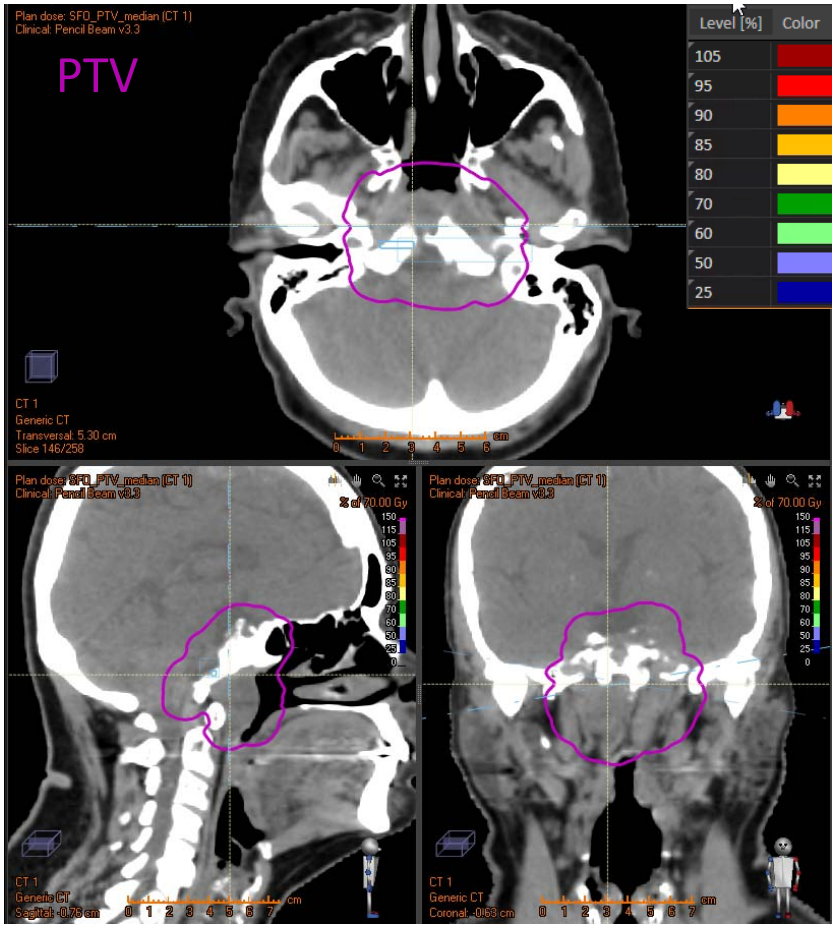
PRESCRIBING AND REPORTING

ICRU REPORT 83: DOSE NORMALISATION

Simple hypothetical case to illustrate the effects

Hypothetical target prescription:

- $D_{RBE,pres}$ = 60 Gy (RBE)



PRESCRIBING AND REPORTING

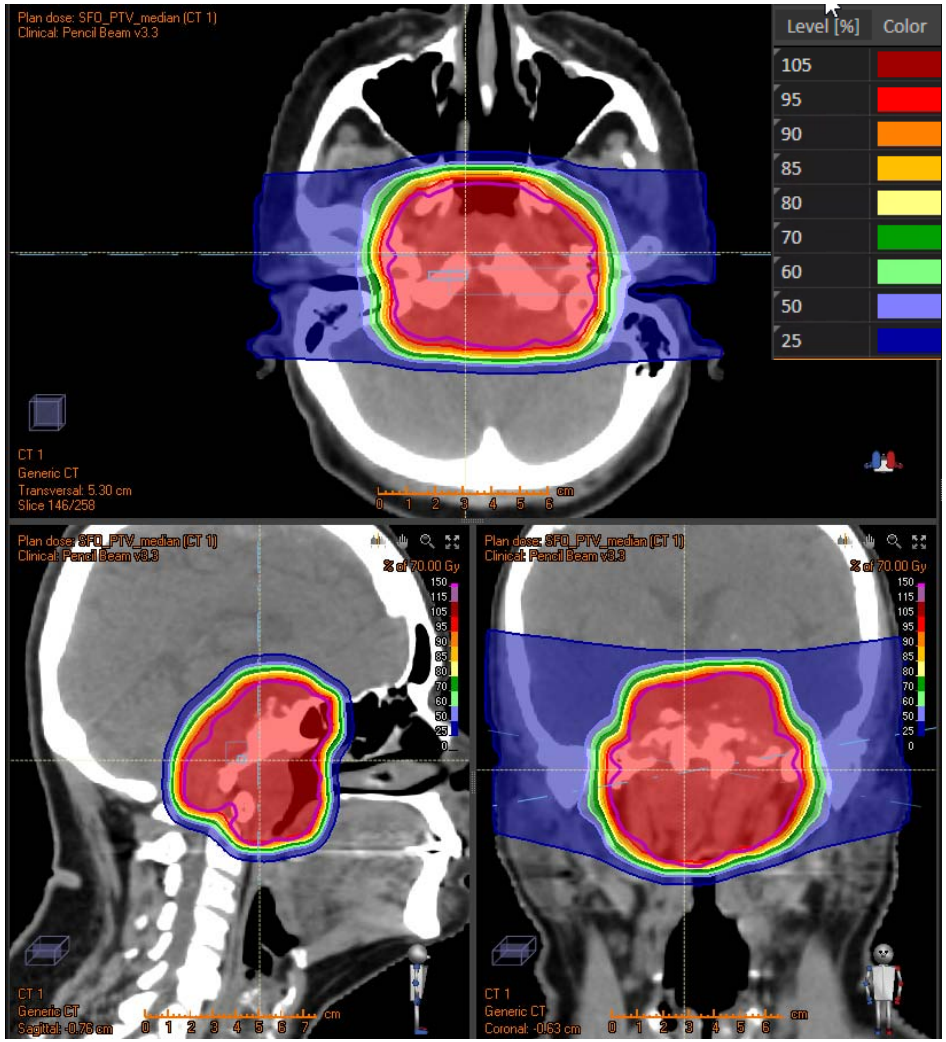
ICRU REPORT 83: DOSE NORMALISATION

Typical prescription

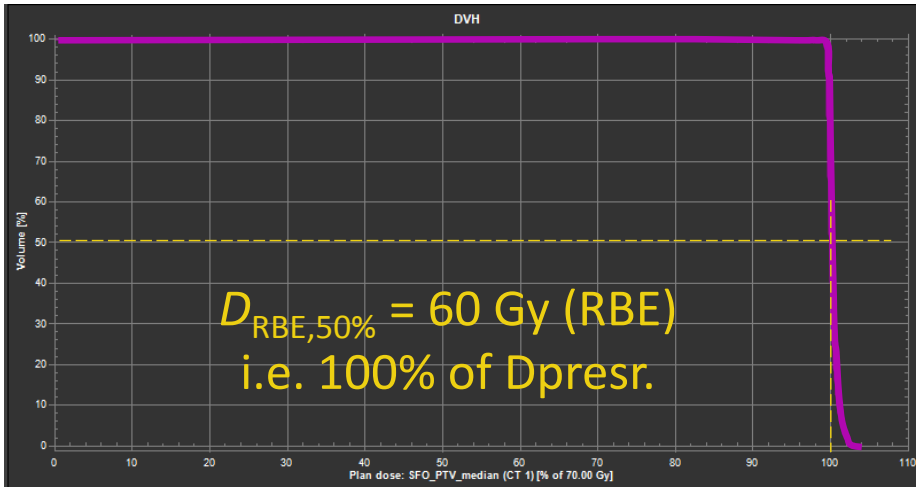
- D_{min} =95% of prescribed dose ($V_{95\%}$ = 100%)
- $D_{RBE,98\%}$ ≥ 98% of prescribed dose
- **$D_{RBE,50\%}$ = 100% of prescribed dose (normalization value)**
- $D_{RBE,2\%}$ ≤ 107% of prescribed dose

PRESCRIBING AND REPORTING

ICRU REPORT 83: DOSE NORMALISATION



95% isodose shall surround the PTV



PRESCRIBING AND REPORTING

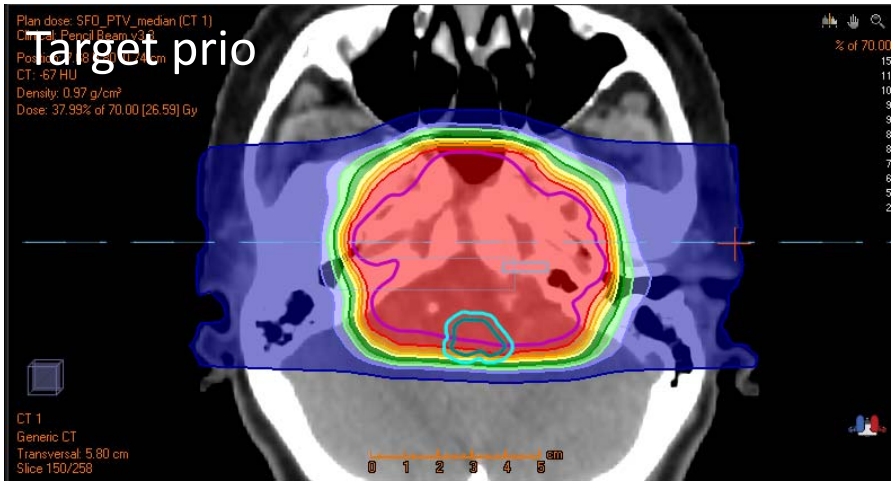
ICRU REPORT 83: DOSE NORMALISATION

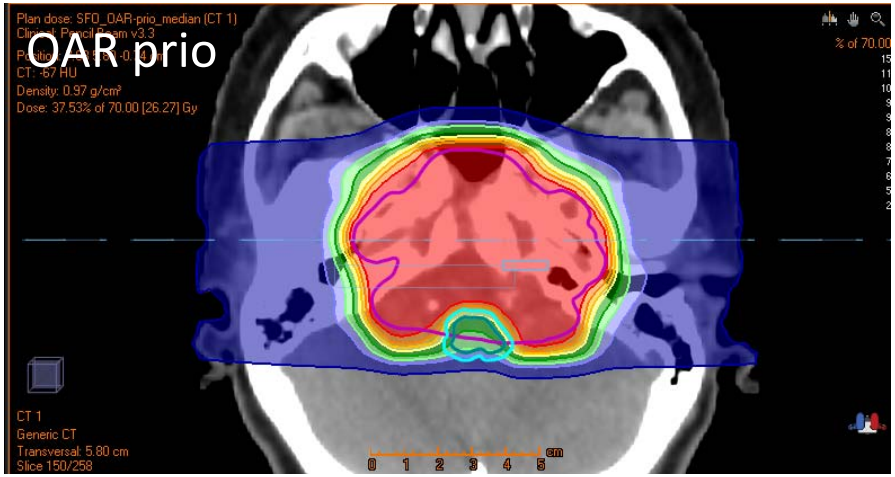
Typical prescription

- D_{min} =95% of prescribed dose ($V_{95\%}$ = 100%)
- $D_{RBE,98\%}$ ≥ 98% of prescribed dose
- **$D_{RBE,50\%}$ = 100% of prescribed dose (normalization value)**
- $D_{RBE,2\%}$ ≤ 107% of prescribed dose

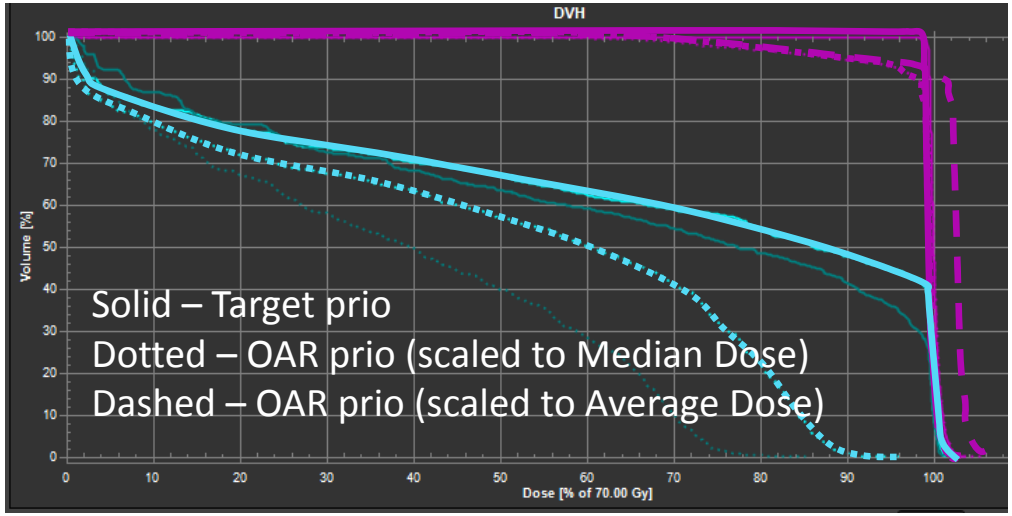
PRESCRIBING AND REPORTING

ICRU REPORT 83: DOSE NORMALISATION





95% isodose shall still surround the PTV (except where we need to make the compromise)



PRESCRIBING AND REPORTING

ICRU REPORT 83: DOSE NORMALISATION

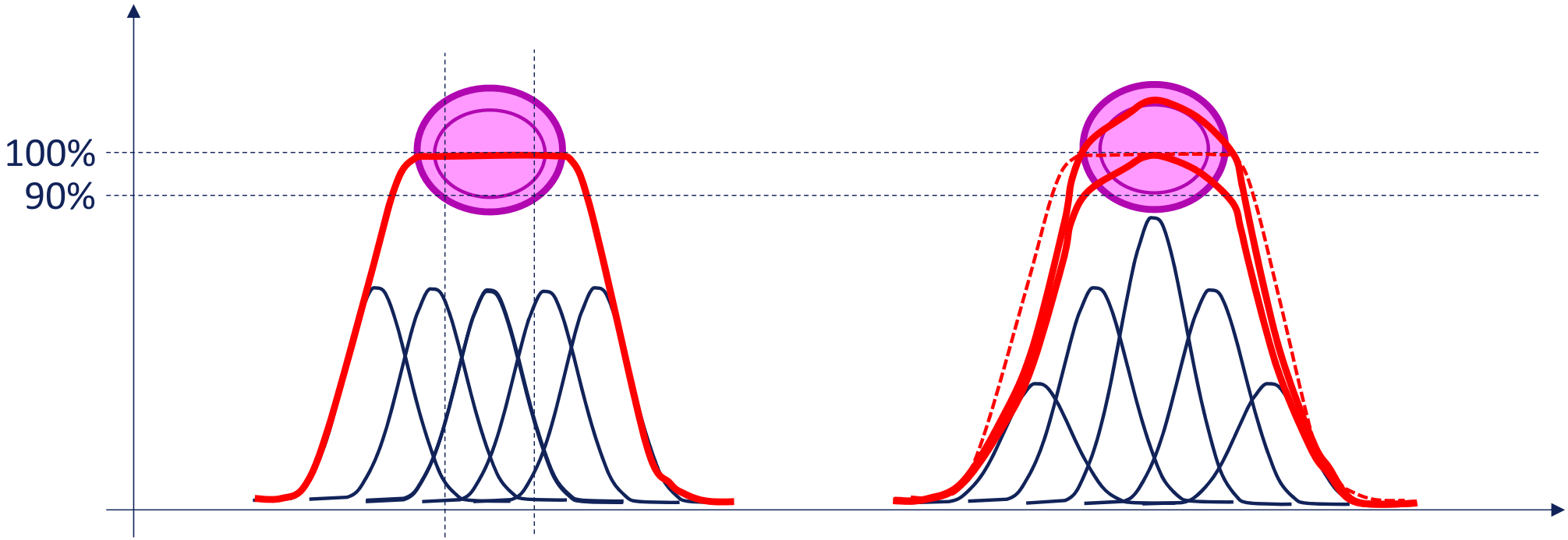
Normalization to **median dose** ($D_{RBE,50\%}$ = 100% of prescribed dose) and definition of priorities ***requires no target help volumes*** (for prescription) and ***no PTV margin compromises***.

Reporting:

- Printed plan information
- Isodose distributions, DVHs
- At minimum: prescribed clinical goals for targets and OARs.

PRESCRIBING AND REPORTING

SMALL TARGETS COMPARED TO SPOT SIZE



Pencil beam scanning (PBS):

- Small hypo-fractionated targets
- Low energies in combination with range shifter
  - ➢ Allow/prescribe heterogeneous dose in the target: **Prescription to isodose**
  - ➢ Collimators, MLCs

CONTENTS

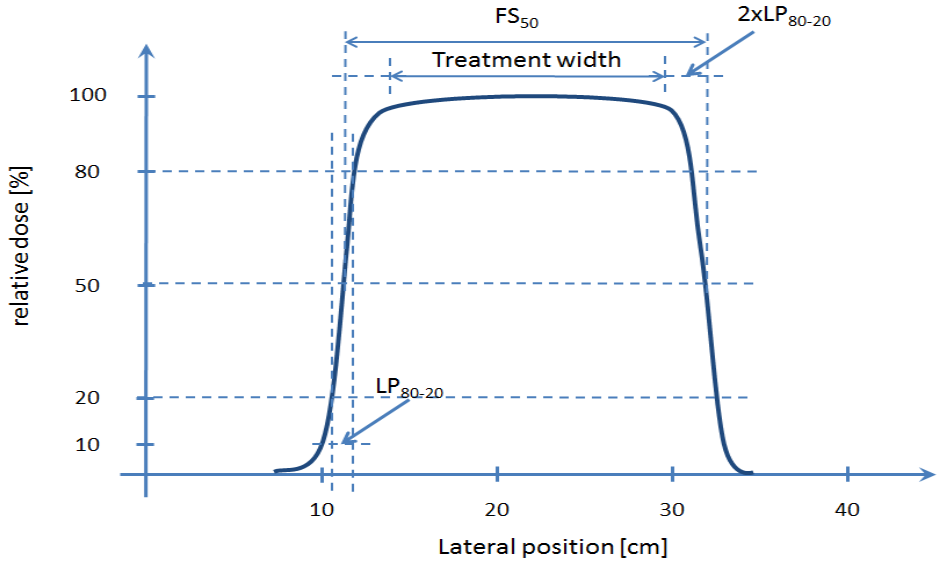
- **Part II Proton PBS treatment planning**
  - **Physical beam properties & Penumbra**
  - Range uncertainties
  - Plan generation strategies and concepts
  - Adaptive treatment planning
  - 4D treatment planning

PHYSICAL BEAM PROPERTIS

SPOT SIZE / PENUMBRA

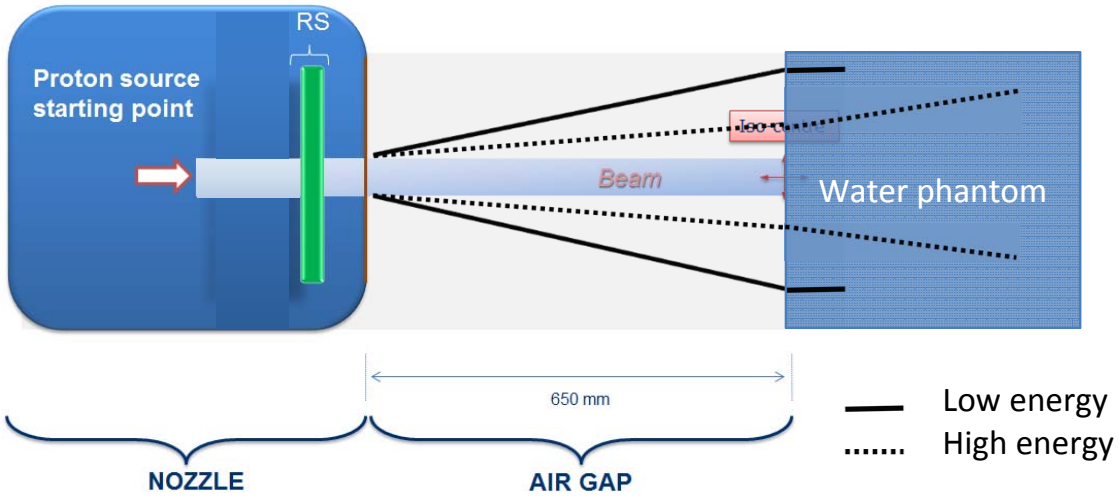
Lateral scattering:

- MCS: penumbra increases with increasing penetration depth.
- Exceeds penumbra of photons at some point.



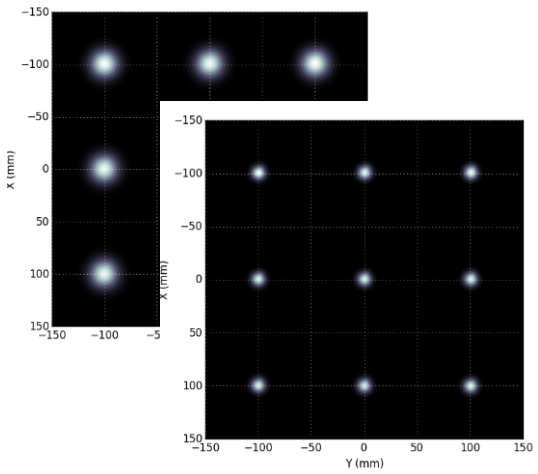
Presence of range shifter (combined with low energies):

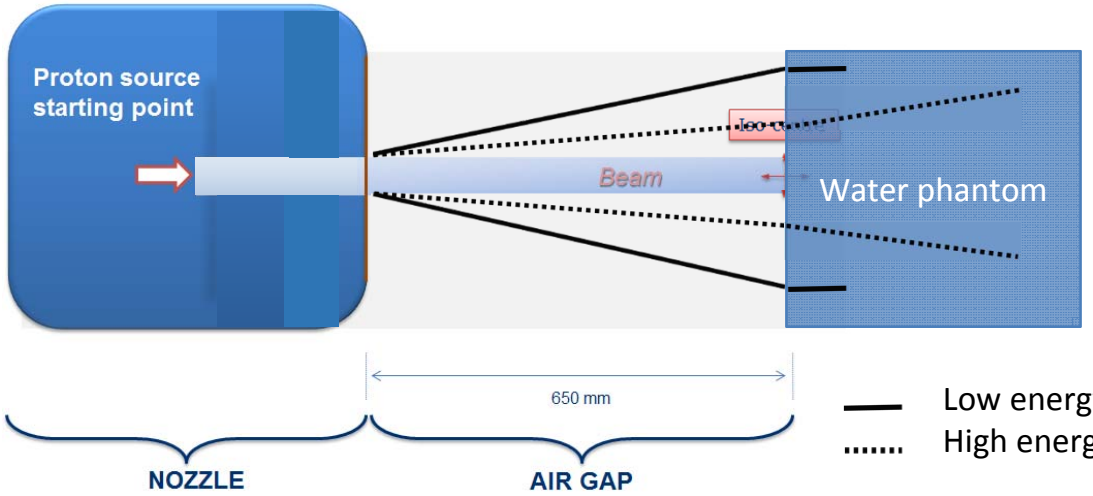
- Substantial increase of spot size.
- Dose calculation accuracy for PB algorithm impaired.
- ***Reduce air gap.***



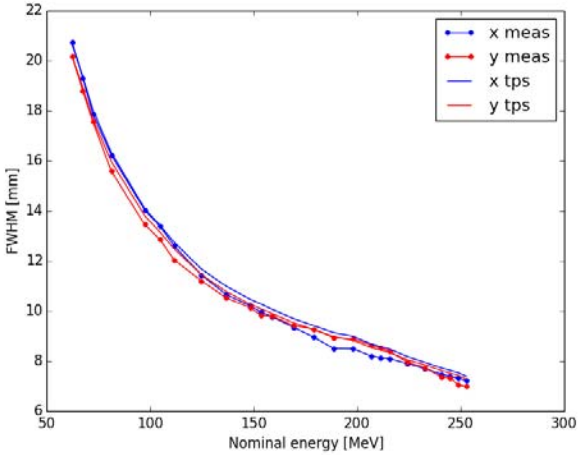
PHYSICAL BEAM PROPERTIES

SPOT SIZE / PENUMBRA

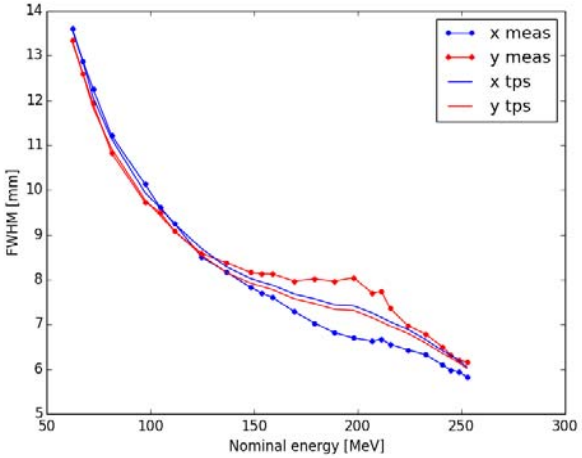




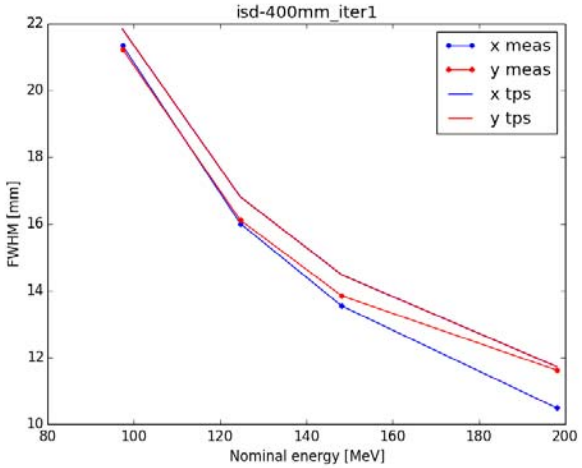
Courtesy Grevillot 2014.



open beam, 65 cm gap



open beam, 25 cm gap



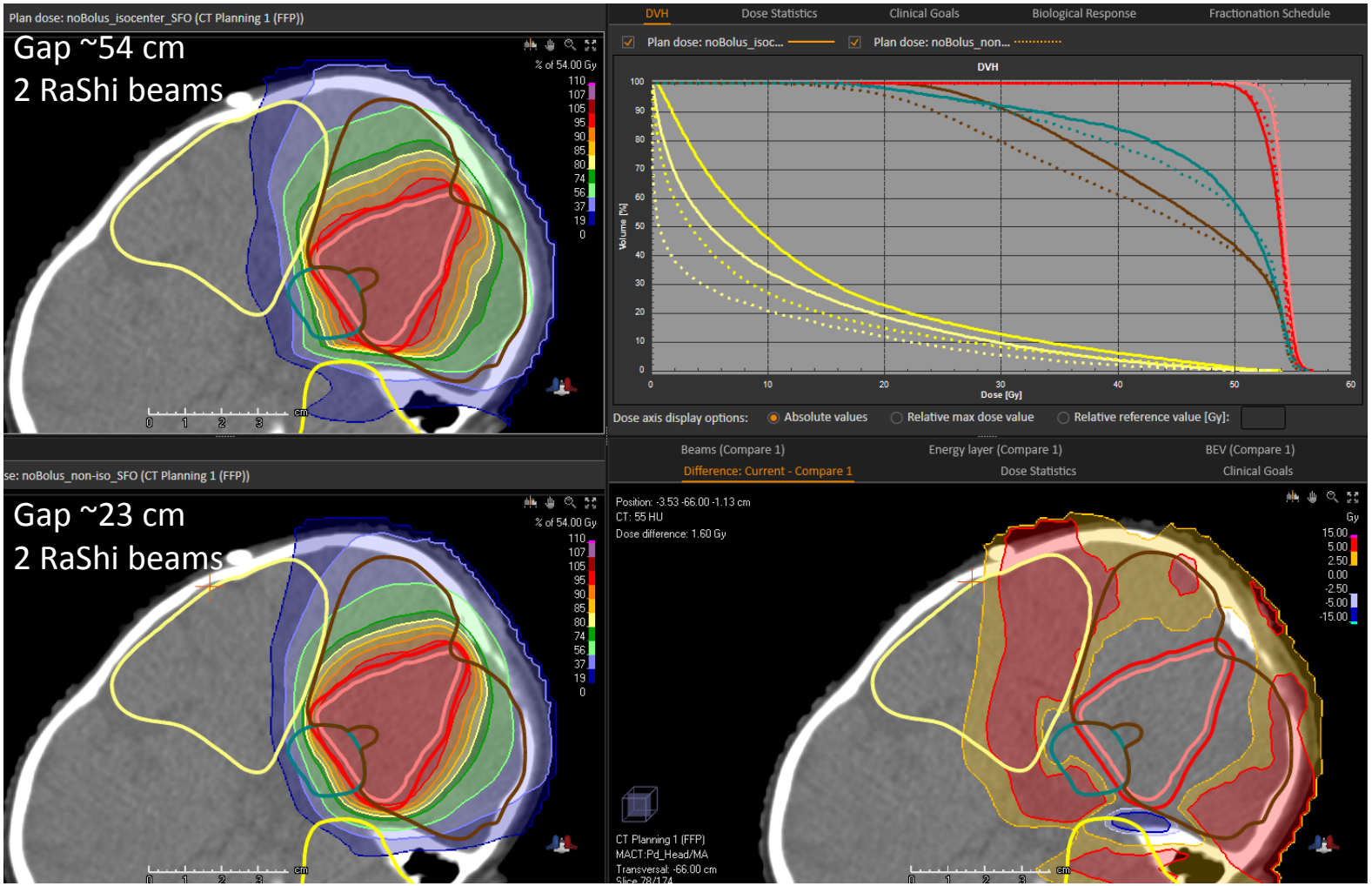
RaShi beam, 15 cm gap

Carlino et. al submitted to PMB

PHYSICAL BEAM PROPERTIES

SPOT SIZE / PENUMBRA

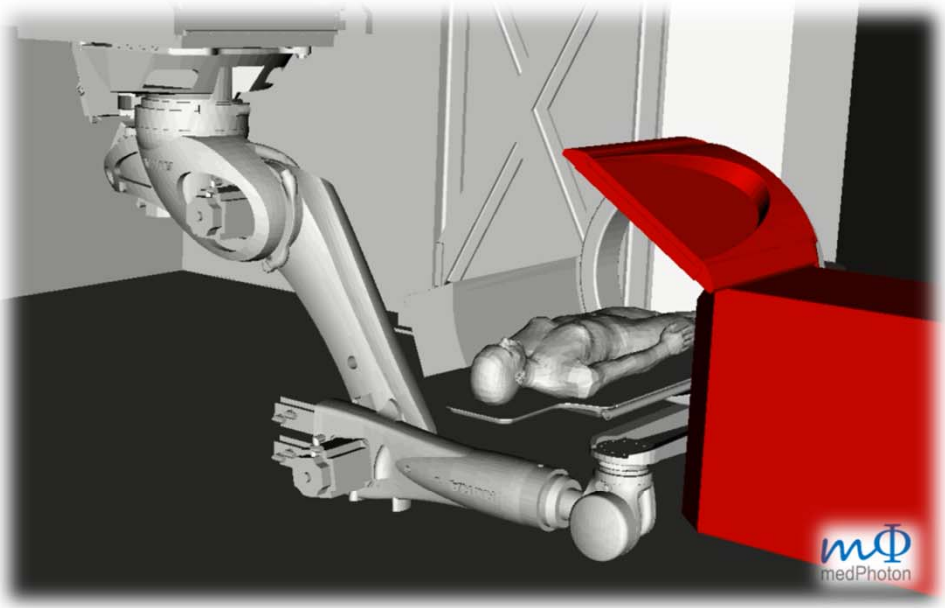
- dosmetric impact of air gap reduction

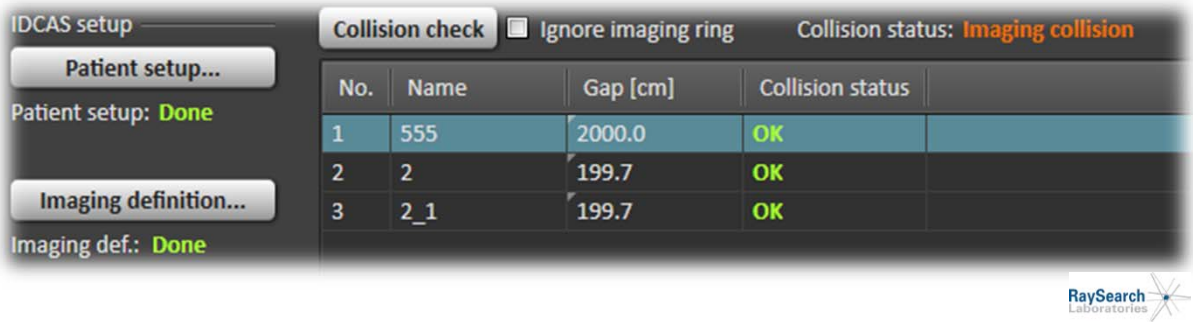


PHYSICAL BEAM PROPERTIES

COLLISION FREE PLANNING

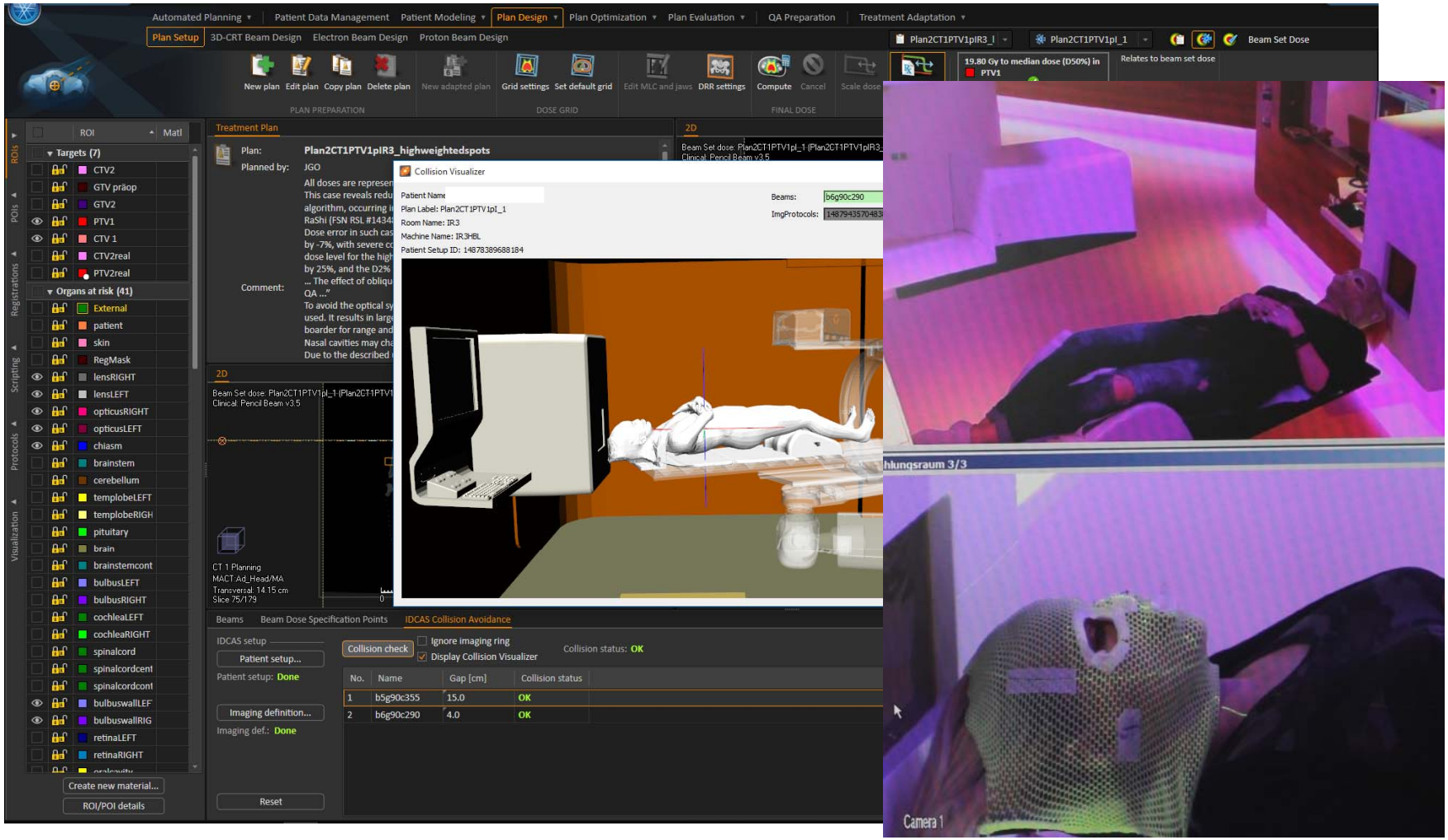
- TPS based interface to collision avoidance software based on modelling of room geometries
- also check imaging protocols





PHYSICAL BEAM PROPERTIES

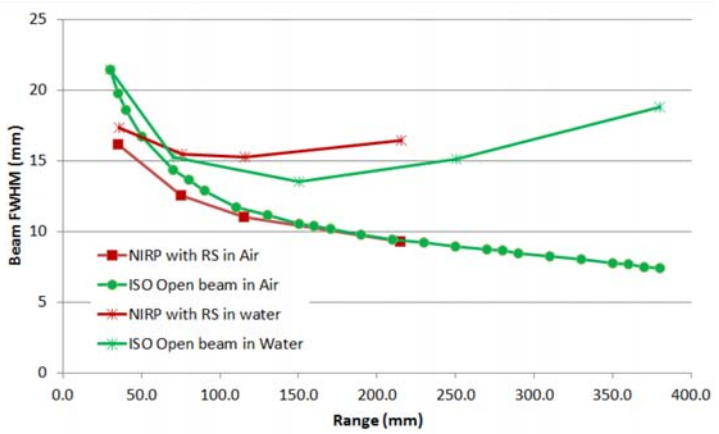
COLLISION FREE PLANNING



PHYSICAL BEAM PROPERTIES

SPOT SIZE / PENUMBRA

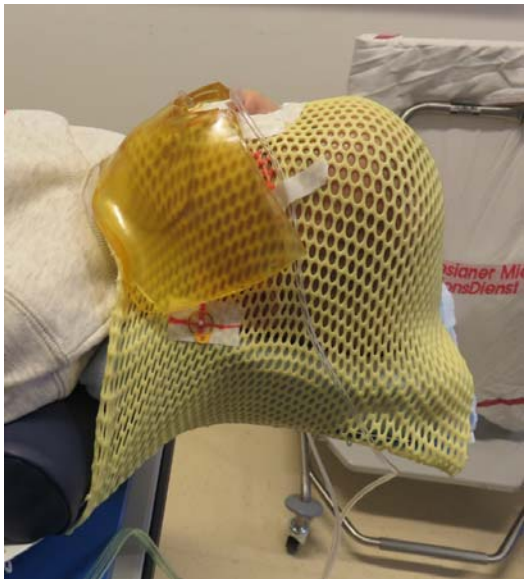
- Best penumbra:
  - @ intermediate depths
  - + air gap reduction
  - no Range shifter



PHYSICAL BEAM PROPERTIES

SPOT SIZE / PENUMBRA

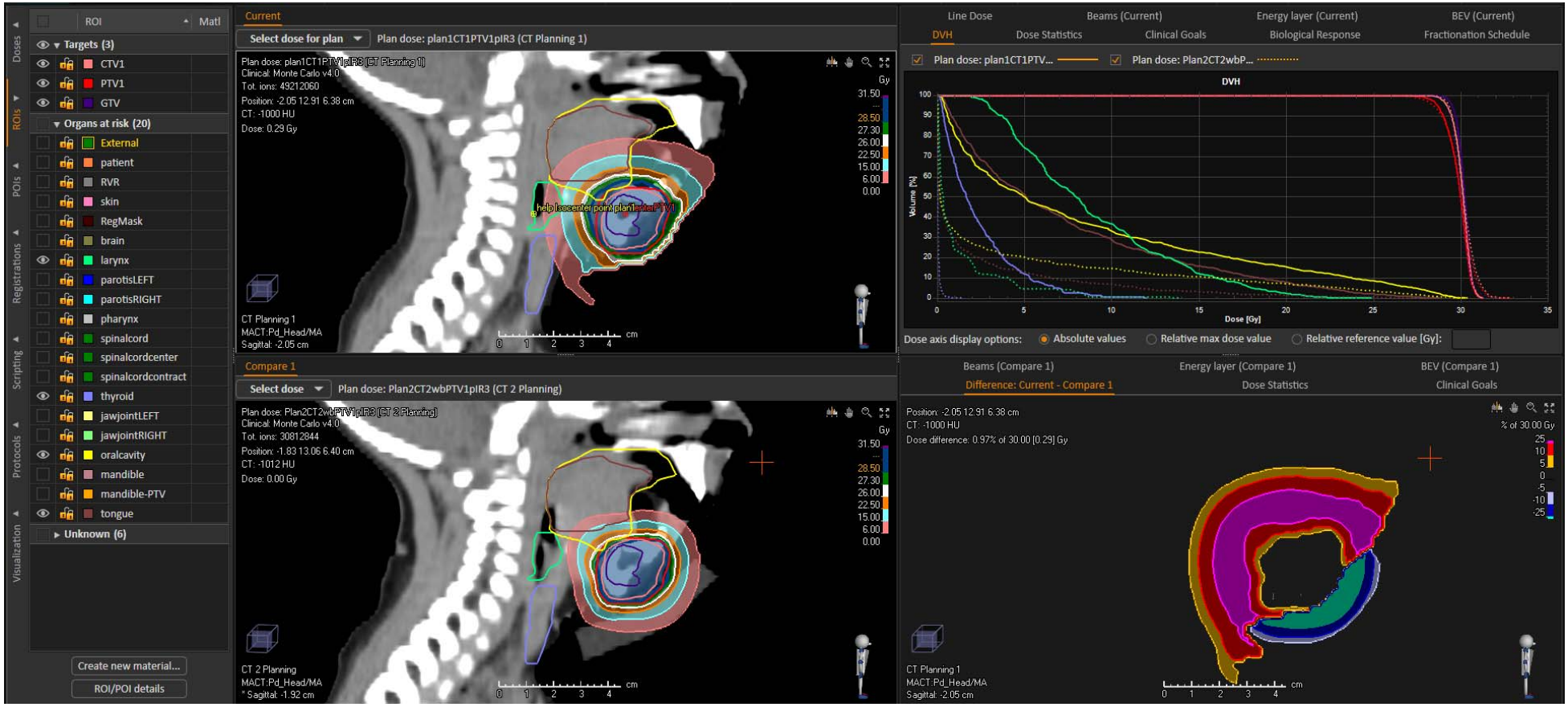
- Avoid RaShi by use of boli



PHYSICAL BEAM PROPERTIES

SPOT SIZE / PENUMBRA

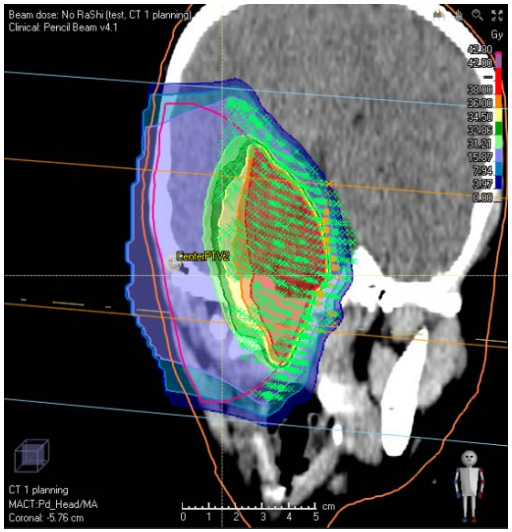
- Avoid RaShi by use of boli



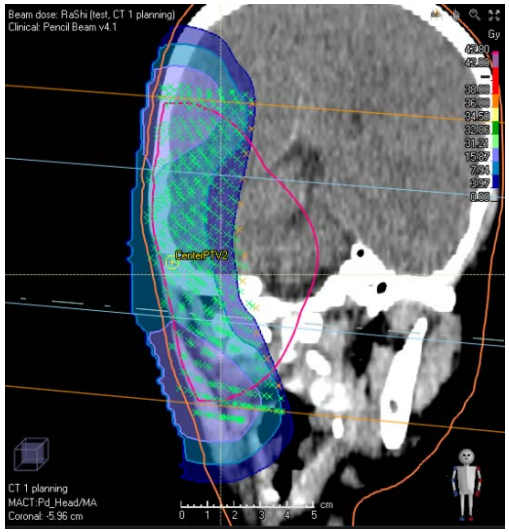
PHYSICAL BEAM PROPERTIES

SPOT SIZE / PENUMBRA

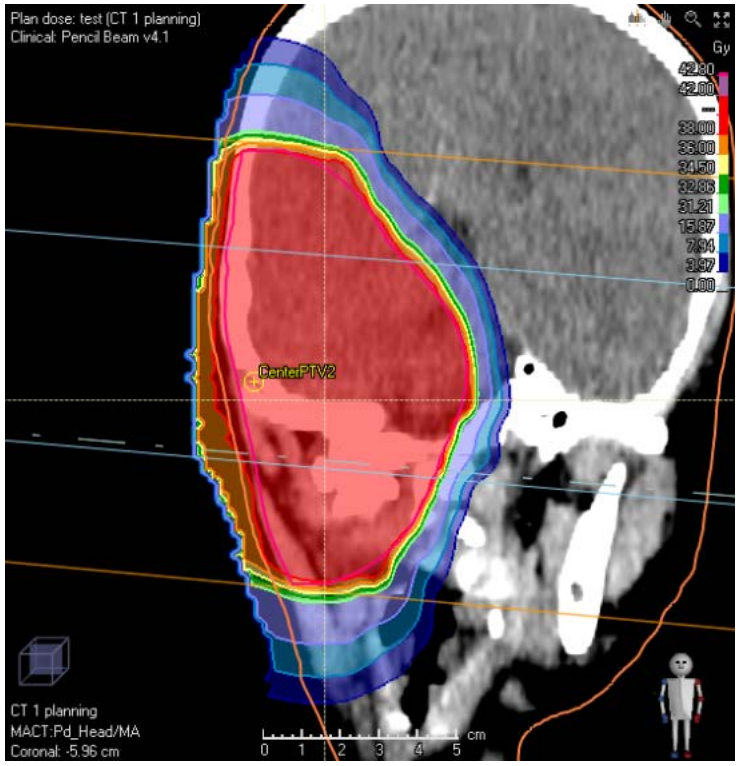
- Subdivision of a beam into part with and without RaShi



without range shifter



with range shifter



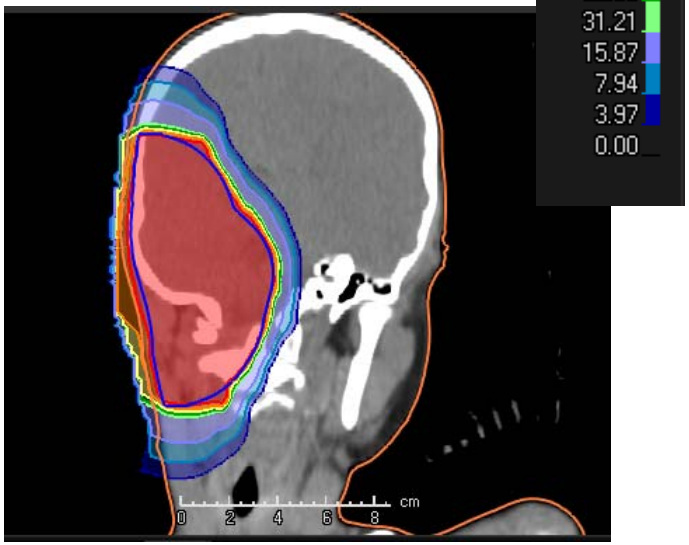
Sum of the two ‚sub-beams‘.

PHYSICAL BEAM PROPERTIES

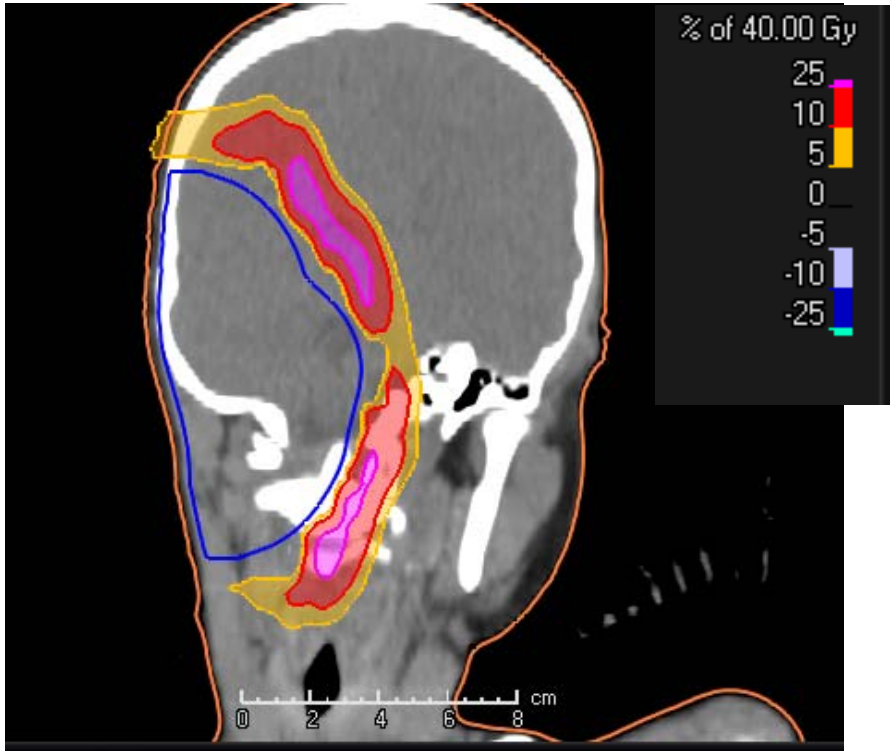
SPOT SIZE / PENUMBRA

no separation

with separation



resulting dose difference

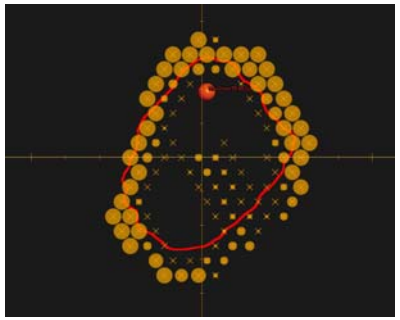


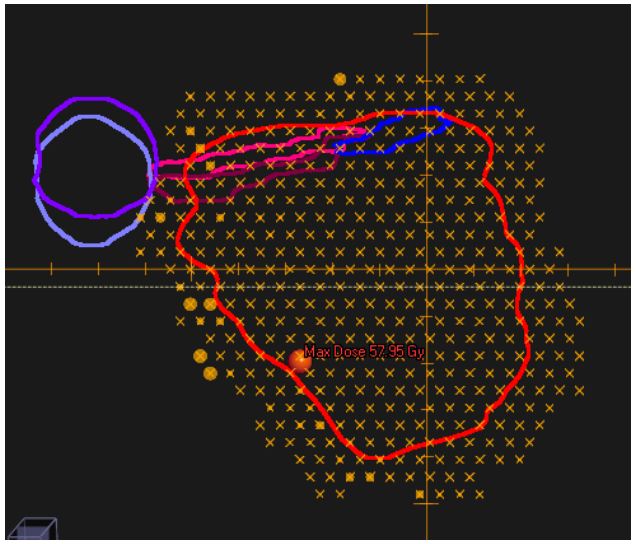
PHYSICAL BEAM PROPERTIES

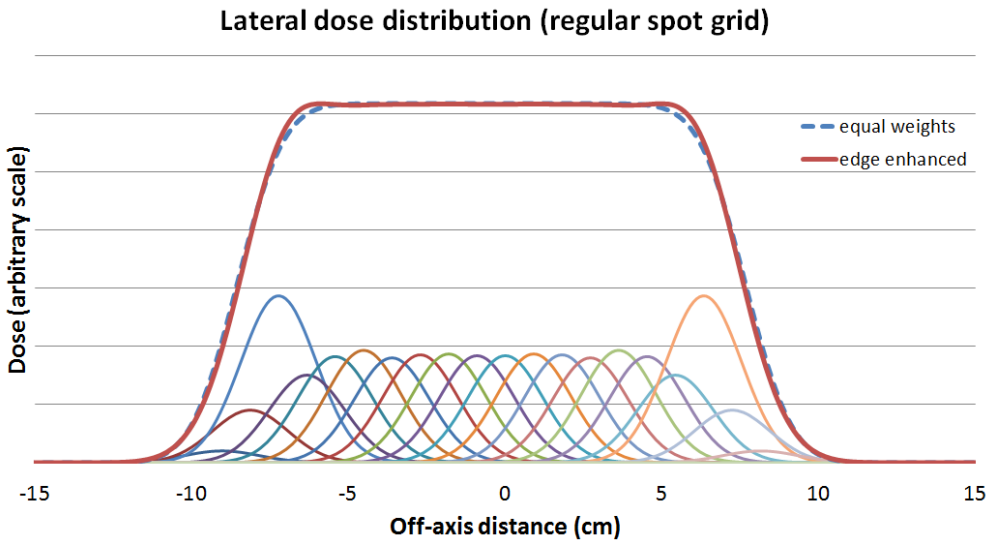
LATERAL SPOT PLACEMENT

- Spot spacing ≤ 1/3 FWHM in water @ BP

- Target margin
  - allow TPS to place additional spots outside the target projection
  - increase target dose homogeneity
  - CAVE: excessive edge enhancement



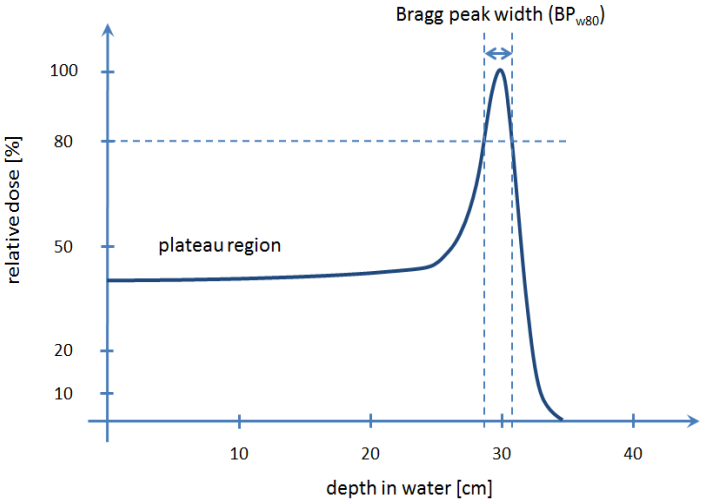


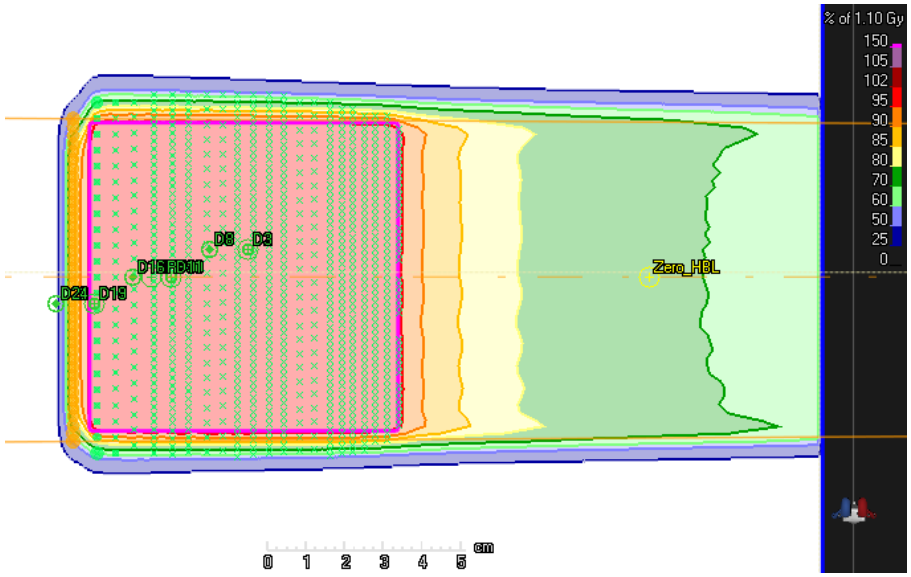


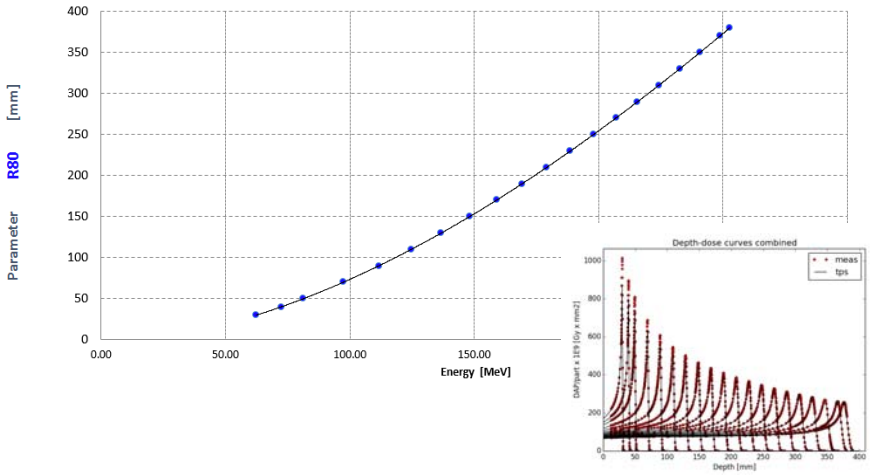
PHYSICAL BEAM PROPERTIES

ENERGY LAYER SPACING

- ≤ Bragg peak width (BPW)
- Options in TPS: constant or relative to BPW

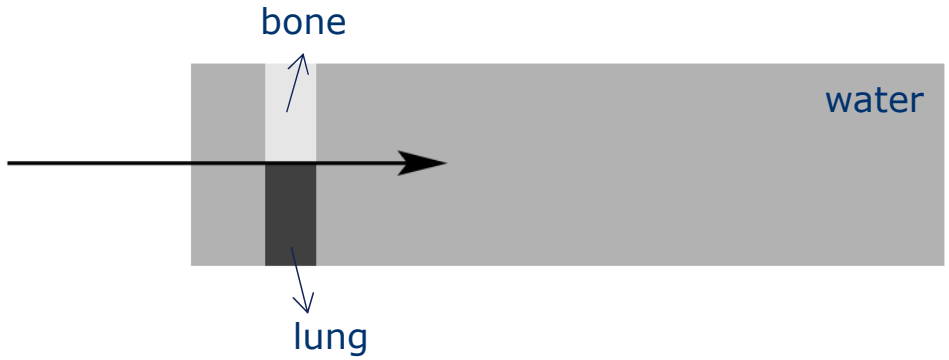


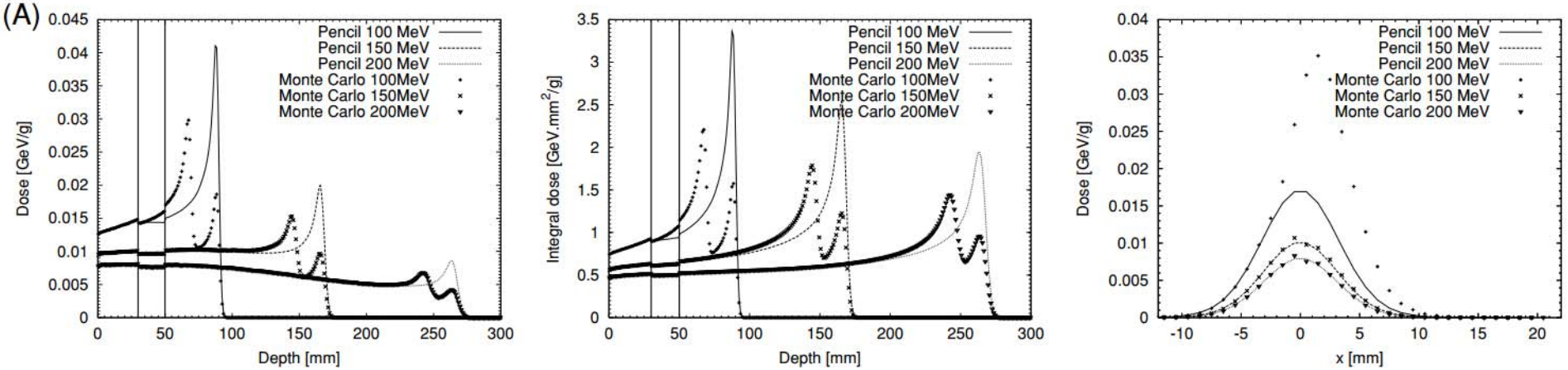




PHYSICAL BEAM PROPERTIES

RANGE DEGRADATION

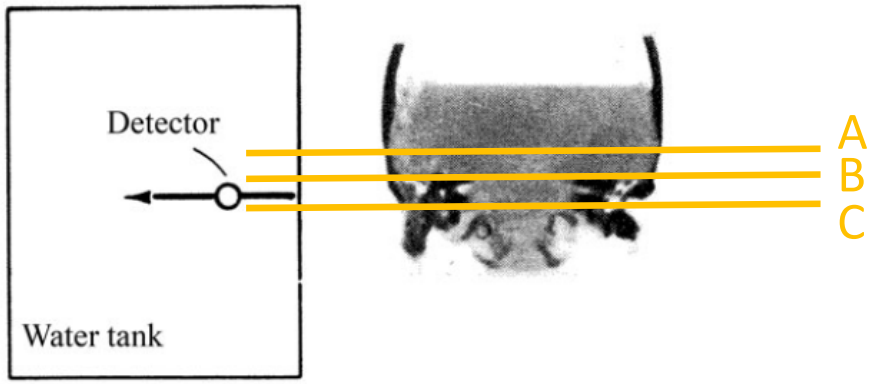


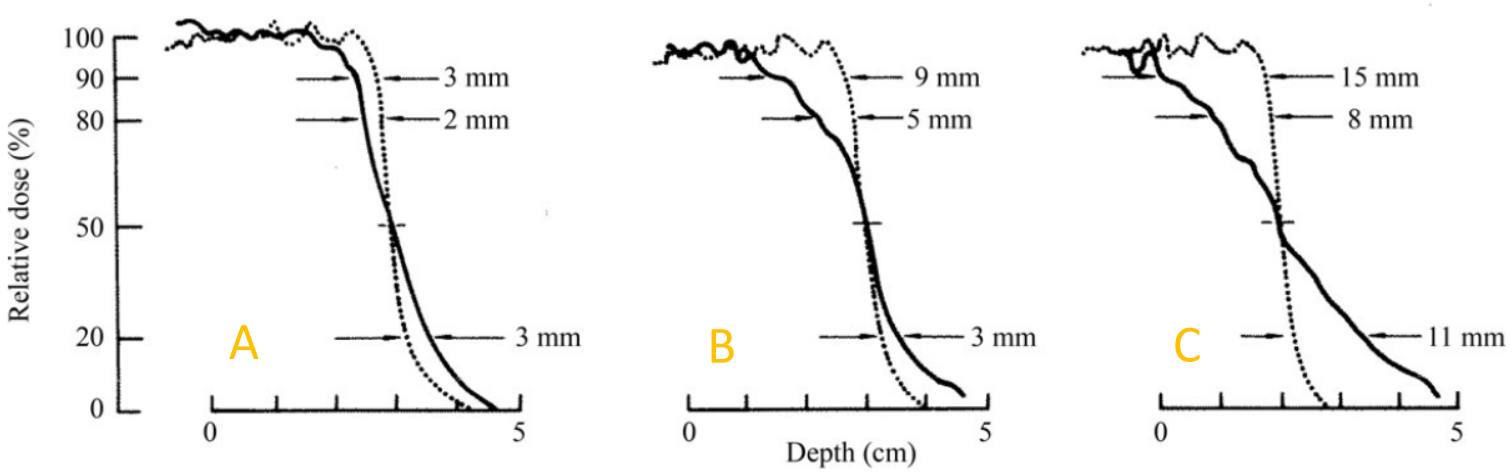


Soukup et al. PMB 52, 2005

PHYSICAL BEAM PROPERTIES

RANGE DEGRADATION



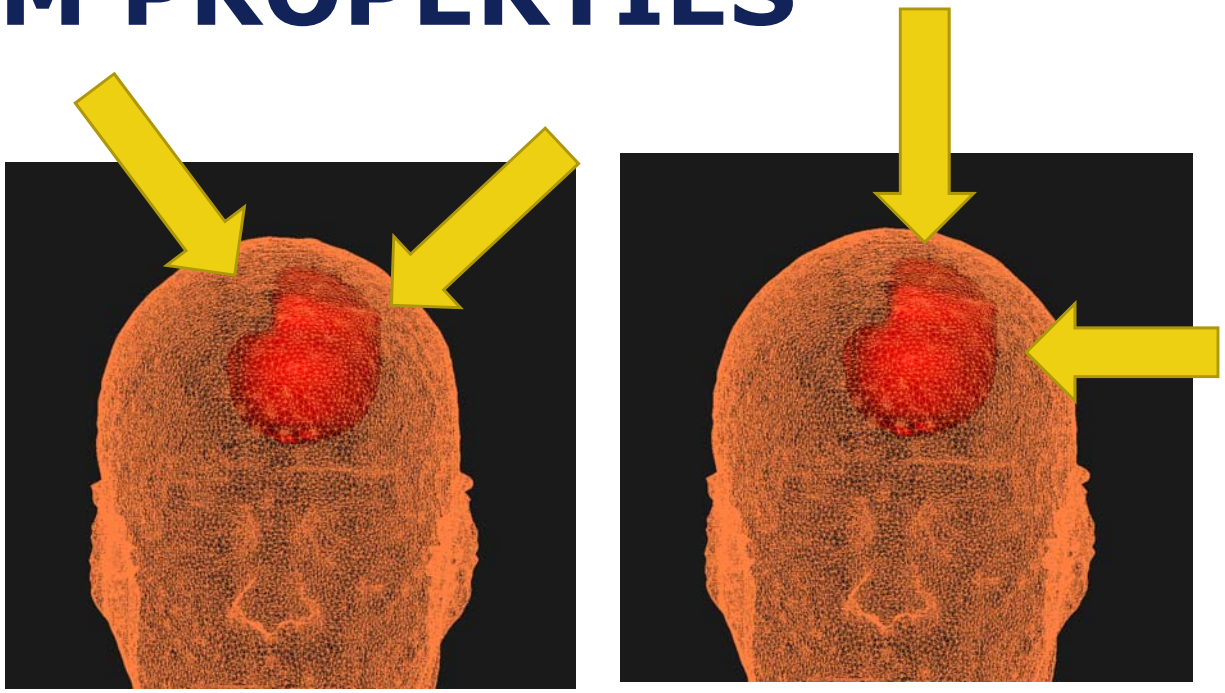


ICRU Report 78

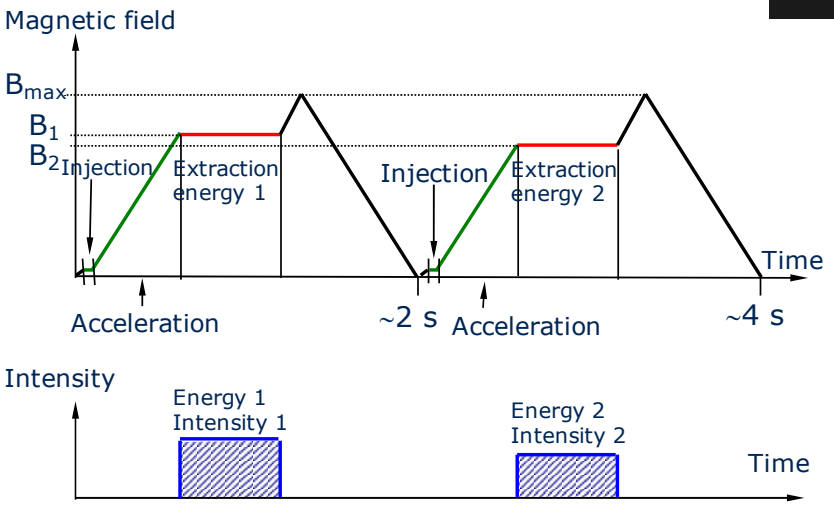
PHYSICAL BEAM PROPERTIES

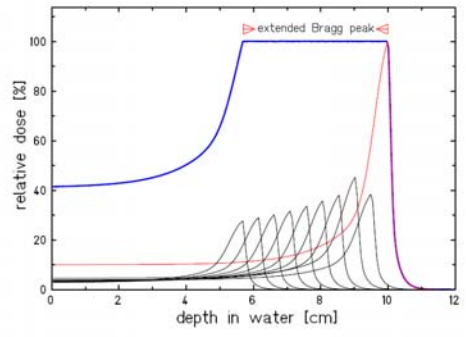
MACHINE PROPERTIES

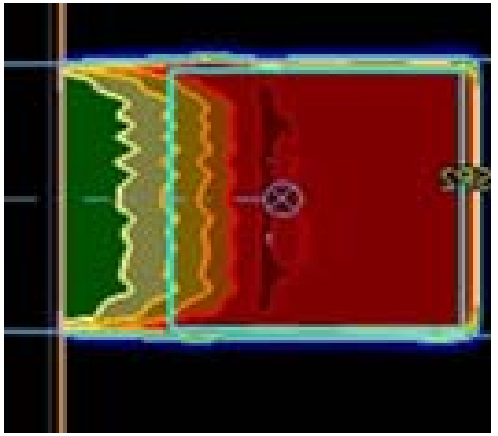
- Geometric parameters: field size etc.
- Min. and max. spot spacing
- Max. layer spacing
- Min. spot weight
- Delivery time structure



alternating plans







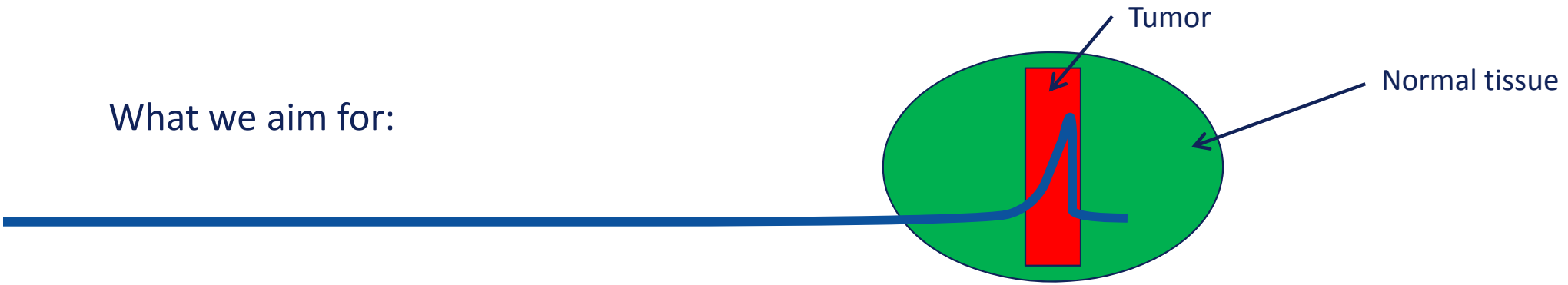
CONTENTS

- **Part II Proton PBS treatment planning**
  - Physical beam properties & Penumbra
  - **Range uncertainties**
  - Plan generation strategies and concepts
  - Adaptive treatment planning
  - 4D treatment planning

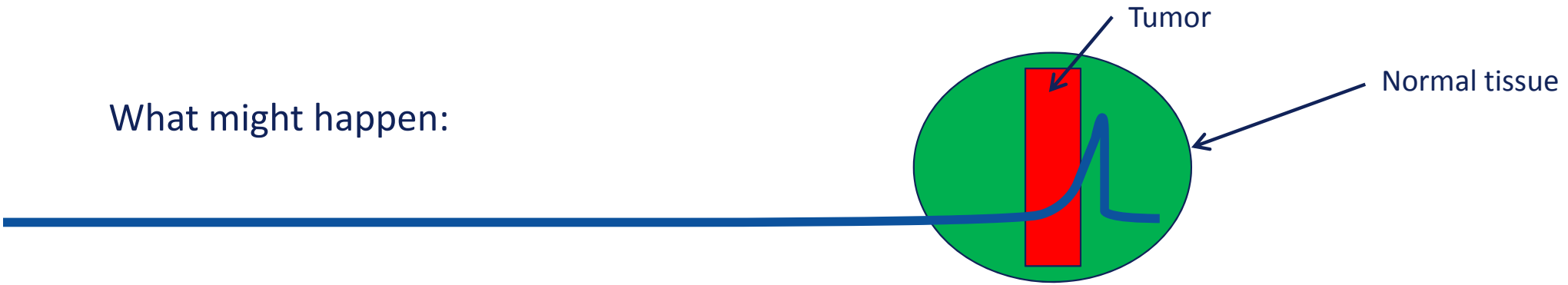
RANGE UNCERTAINTIES

EFFECTS

What we aim for:



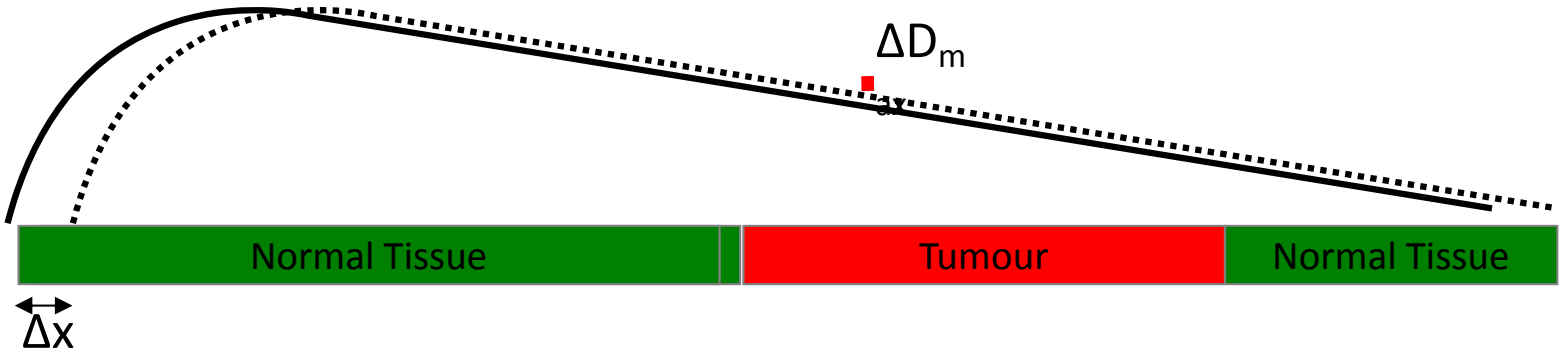
What might happen:



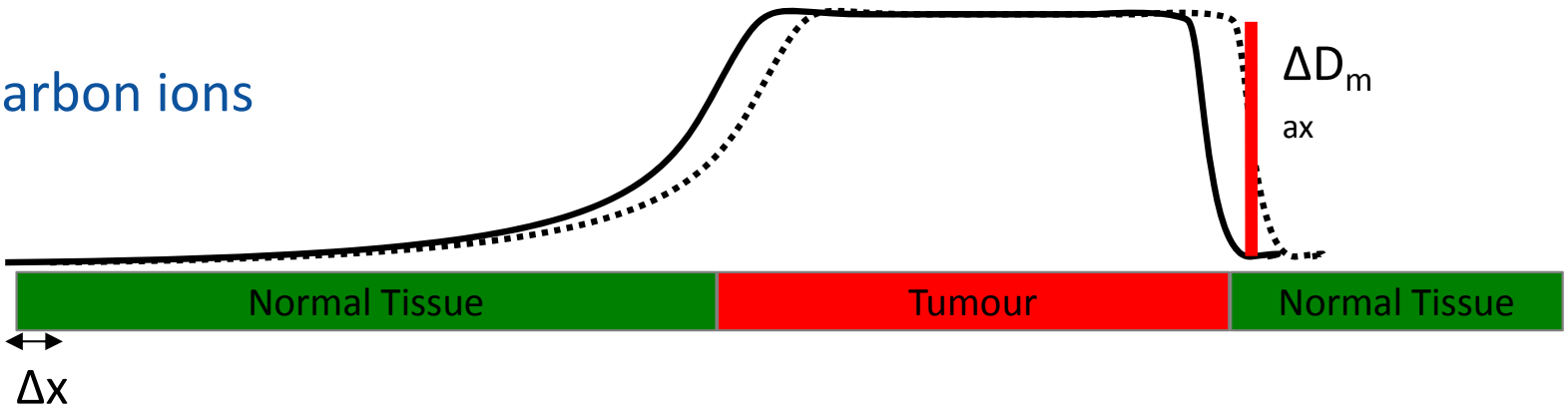
RANGE UNCERTAINTIES

EFFECTS

MV photons

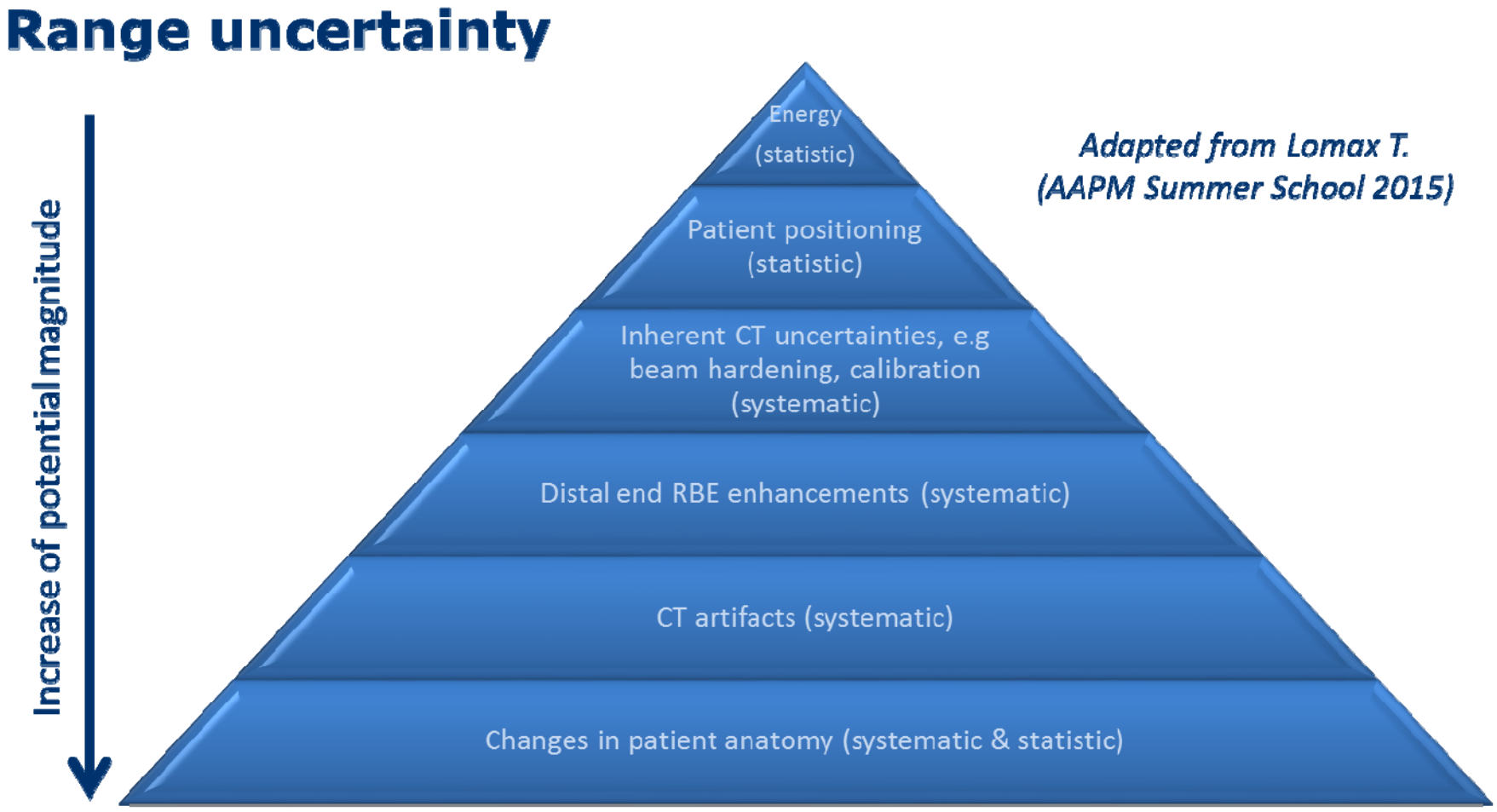


Protons/carbon ions



RANGE UNCERTAINTIES

SOURCES

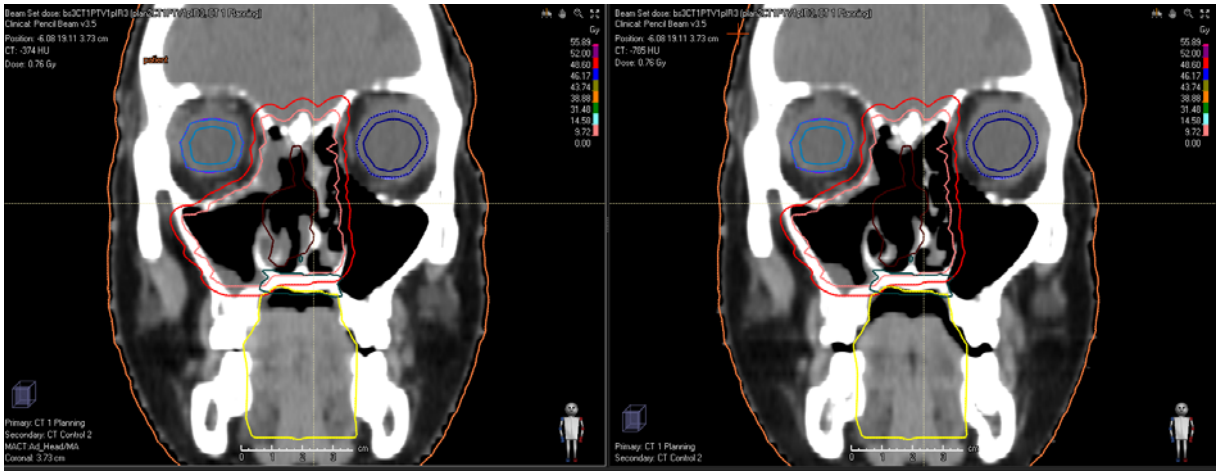


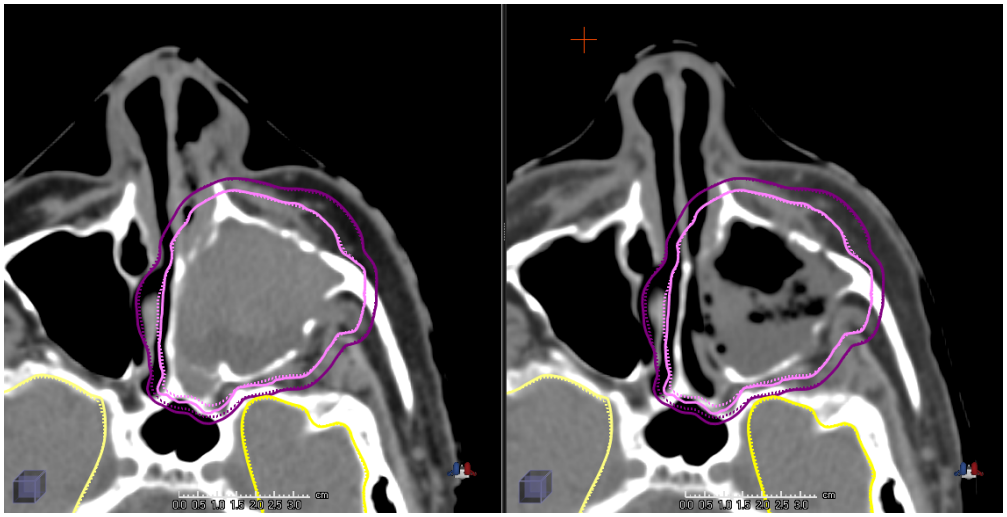
- Estimated sum of range uncertainties: ~3 - 5%
- Range uncertainties are likely to be systematic.

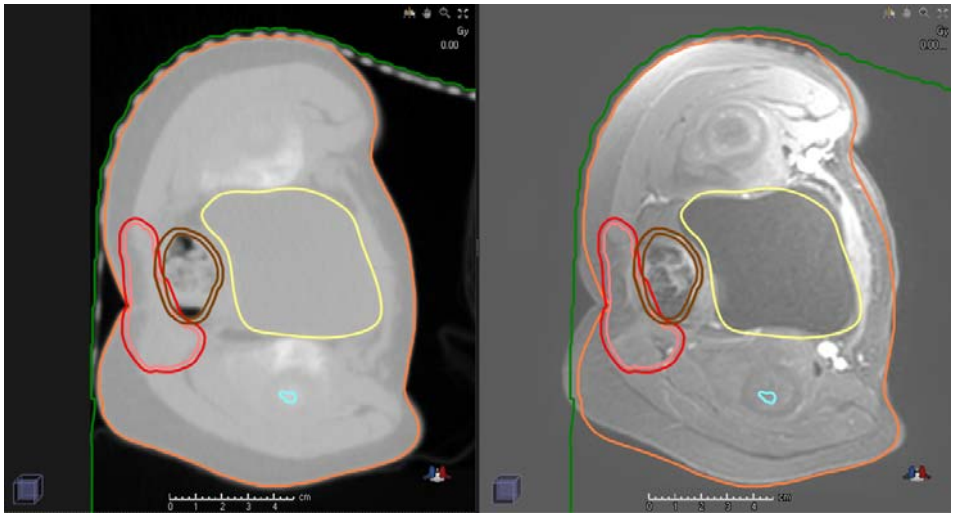
RANGE UNCERTAINTIES

ANATOMICAL CHANGES

- Weight gain / loss
- Changing cavity fillings
- Organ motion
- Tumor shrinkage
- Swelling
- (Repositioning)
- etc.



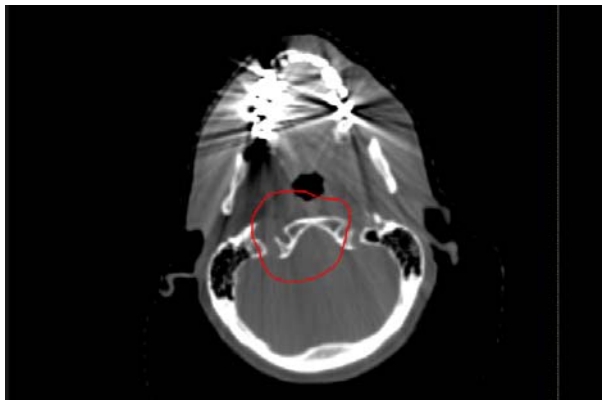


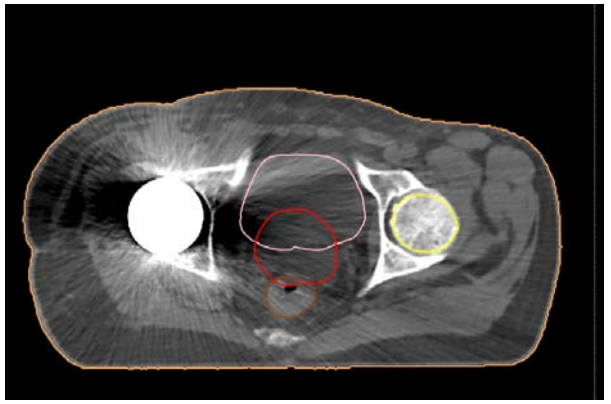


RANGE UNCERTAINTIES

CT ARTEFACTS

- **CT ARTEFACTS DUE TO METALLIC IMPLANTS**
- **Jäkel et al, PMB 2007 reported <5% of patients with neither fillings or prosthesis**
- **Mitigation methods**
  - artefact reduction algorithms (HUs are influenced)
  - delineation of artefacts (and implants) and HU override
  - estimation of related uncertainties required for clinical decisions
- **In case of less pronounced artefacts:**
  - avoid parallel incidence to streak artefacts
  - increase margins or use increased uncertainty in robust optimization
  - use multiple beams





RANGE UNCERTAINTIES

DEALING WITH UNCERTAINTIES

- **Take uncertainties into account during plan generation**
  - Robust beam arrangement, multiple beams
  - Careful choice of plan optimization strategy
  - Robust optimization
  - Use of PRVs
  - Beam specific PTV margins

Evaluation of robustness

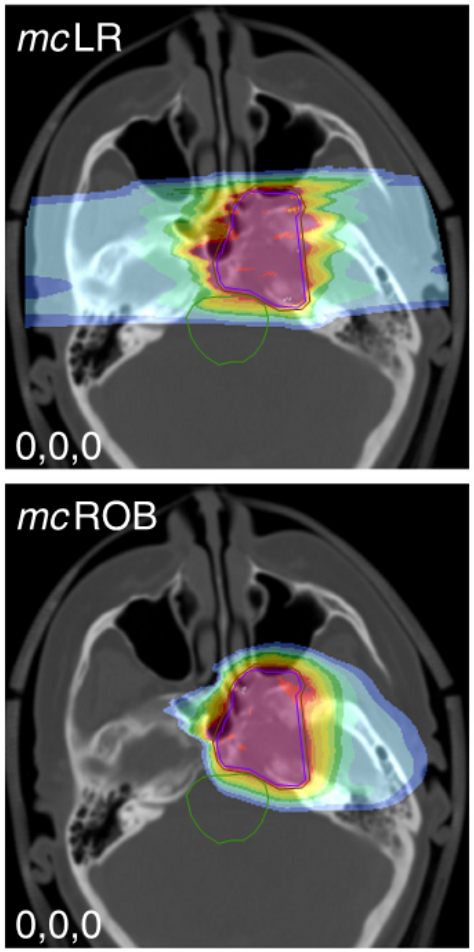
CONTENTS

- **Part II Proton PBS treatment planning**
  - Physical beam properties & Penumbra
  - Range uncertainties
  - **Plan generation strategies and concepts**
  - Adaptive treatment planning
  - 4D treatment planning

PLAN GENERATION STRATEGIES

ROBUST BEAM ARRANGEMENT

- dose homogeneity: **choose beam angles avoiding** large **density interfaces** as well as **'unstable OARs'** along the beam axis
- range uncertainty: **avoid** placing **Bragg peaks proximal to** critical **OARs**
  - beam incidence parallel to OARs
  - spot positioning margins/restrictions around OARs

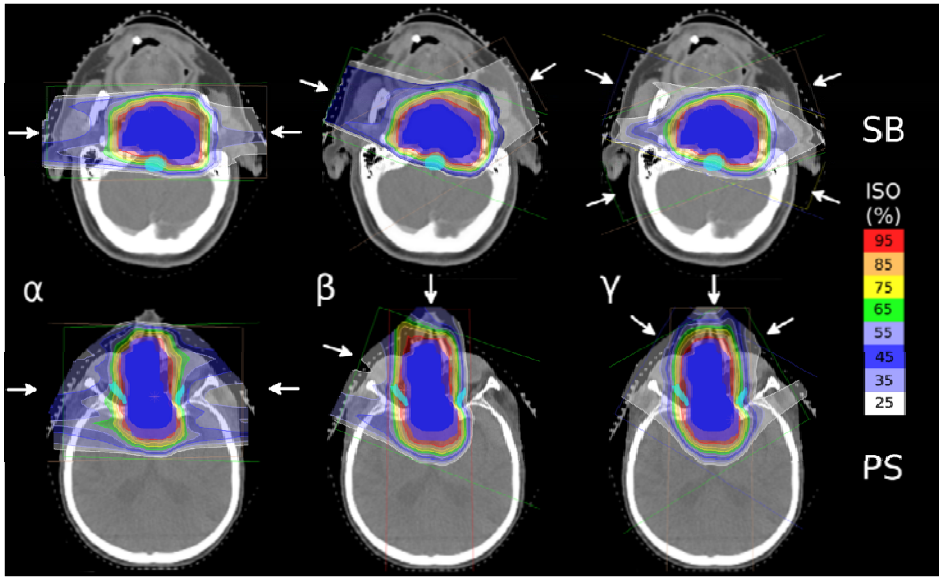


Ammazalorso et al. Radiat Oncol 9 (2014)

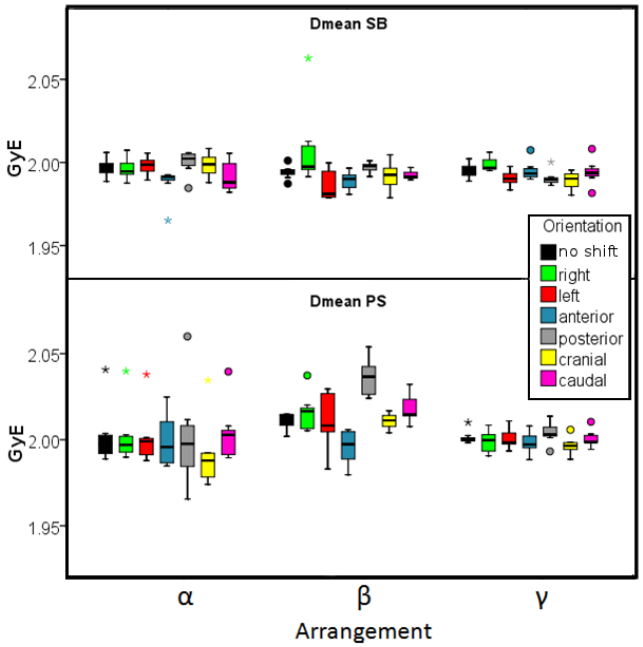
PLAN GENERATION STRATEGIES

ROBUST BEAM ARRANGEMENT

- *use multiple beams*



Hopfgartner & Stock et al (2013) Acta Oncol 52:570-79



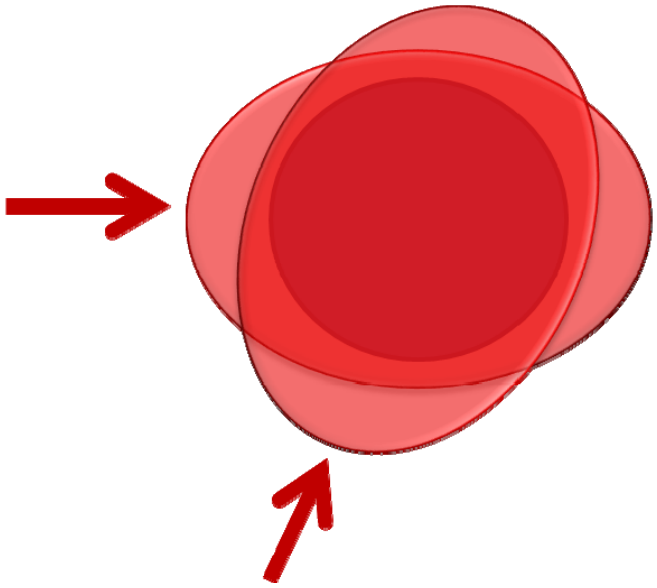
No gantry approach α: lateral opposed beams (2 fields)
Gantry approach β: individually optimized beam angles (2 fields)
Gantry approach γ: multi-beam approach (3 or 4 fields)

PLAN GENERATION STRATEGIES

BEAM SPECIFIC MARGINGS

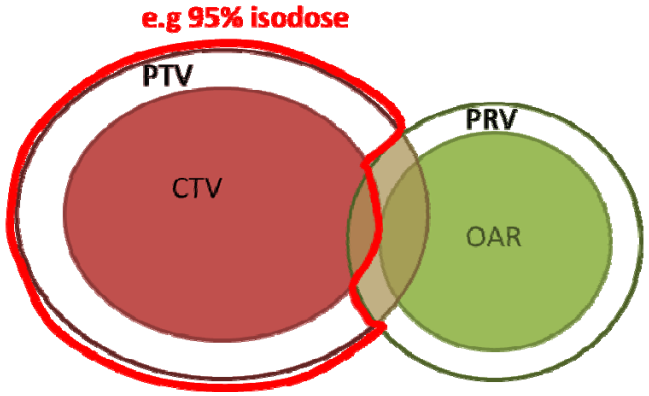
Beam specific margins

Dealing with the range uncertainty separately by ***applying*** additional ***beam specific margin*** on top of positioning uncertainty.



Use of PRVs

(ICRU 83)



PLAN GENERATION STRATEGIES

PLAN OPTIMIZATION STRATEGY

Delivery technique

(monoenergetic pencil beams)

Pencil beam scanning (PBS)

(also called spot scanning particle therapy (SSPT), raster scanning, etc.)

Lateral scanning of a pencil beam without patient specific customized scattering elements, collimators or range modulators.

Optimization strategy

Intensity modulated particle therapy (IMPT)

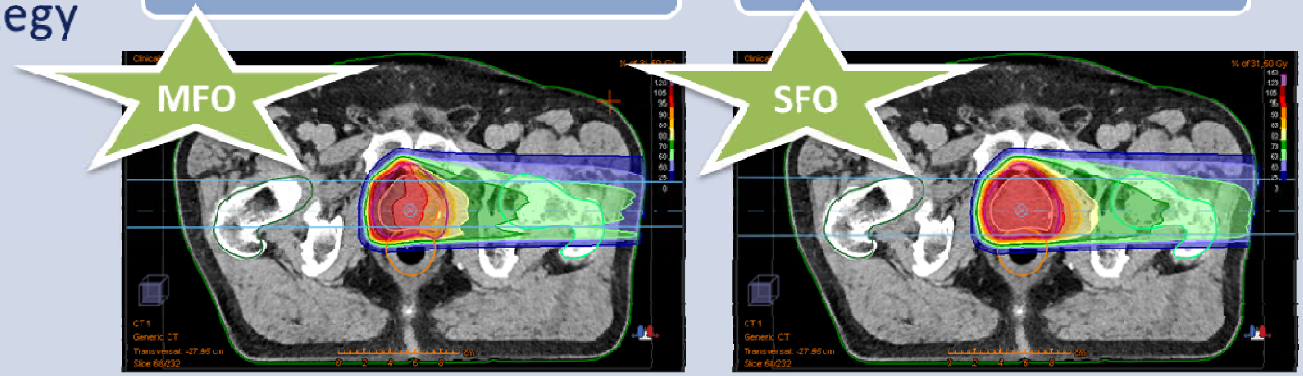
Inverse optimization of individual spot weights required to generate the desired dose distribution.

Multi-field optimization (MFO)

Weights of all spots in all fields are simultaneously optimized.

Single-field optimization (SFO)

Weights of all spots are optimized for each field individually.



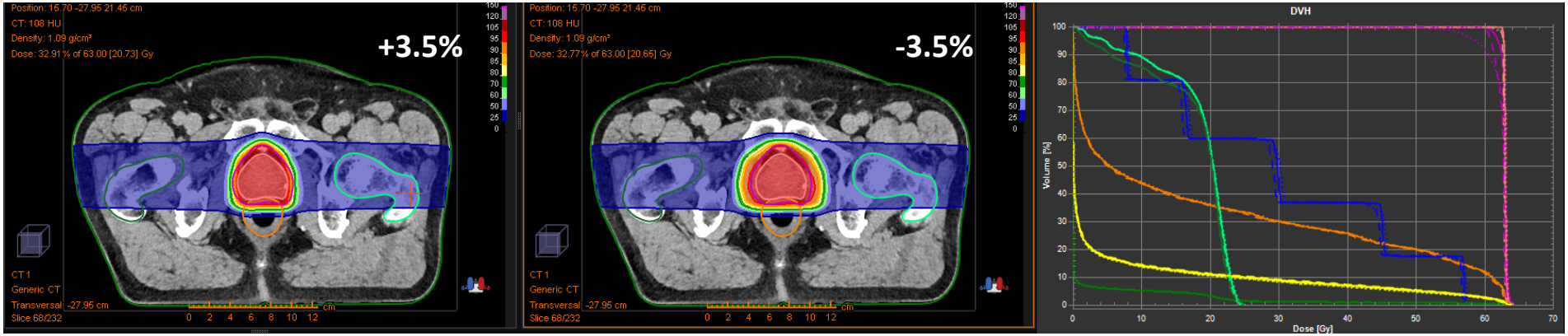
adapted from Zhu et al. Radiation Oncology 2014

PLAN GENERATION STRATEGIES

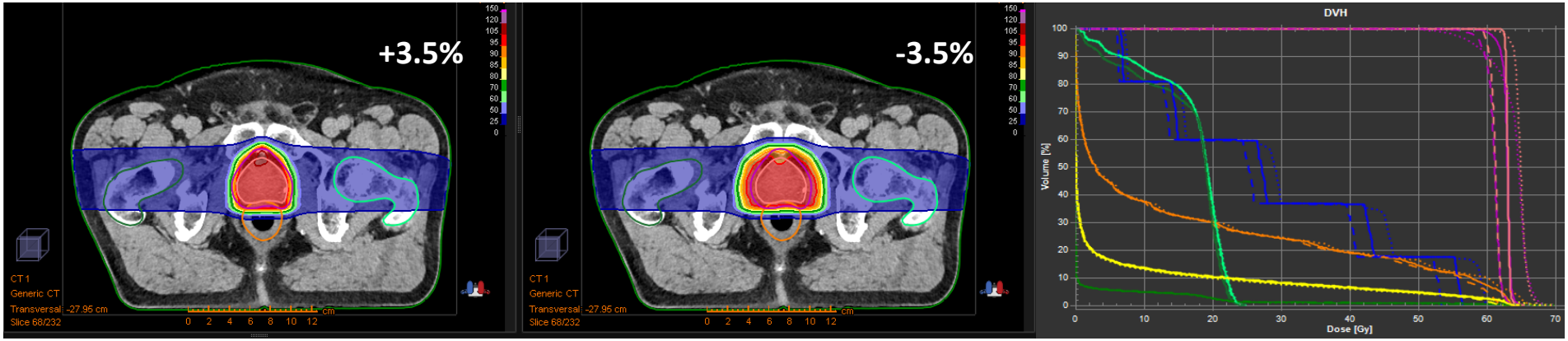
PLAN OPTIMIZATION STRATEGY

Evaluate robustness by simulation of range uncertainty by HU scaling.

SFO

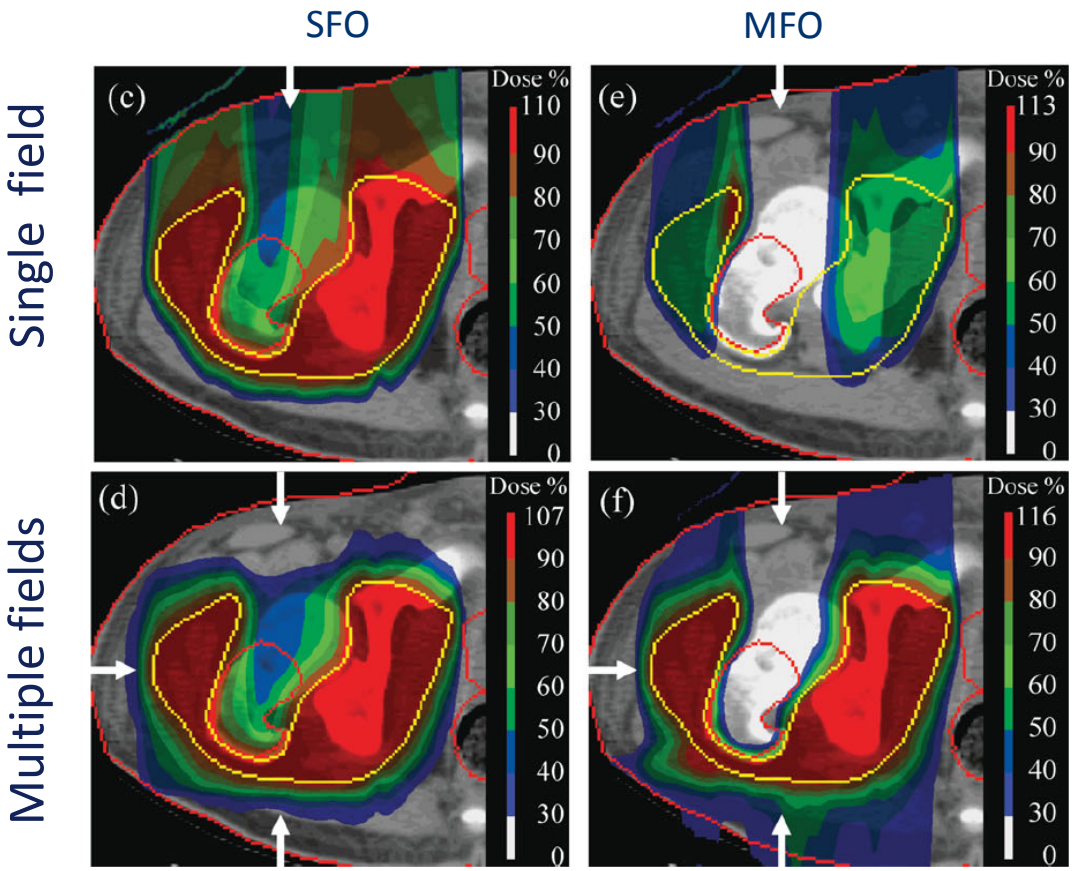


MFO



PLAN GENERATION STRATEGIES

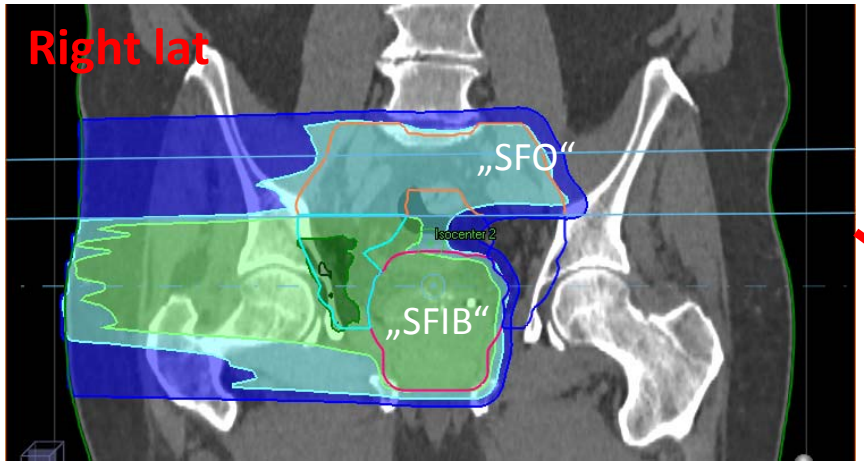
SFO vs MFO: ISODOSE DISTRIBUTIONS



ICRU Report 78

PLAN GENERATION STRATEGIES

PLAN OPTIMIZATION STRATEGY



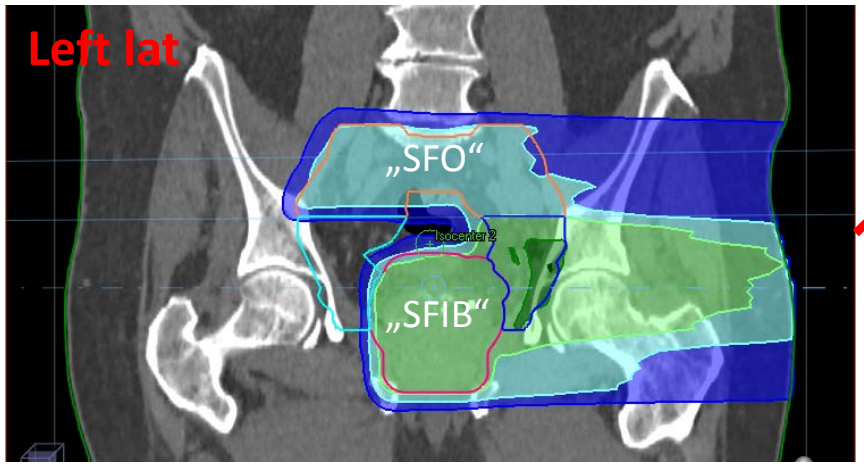
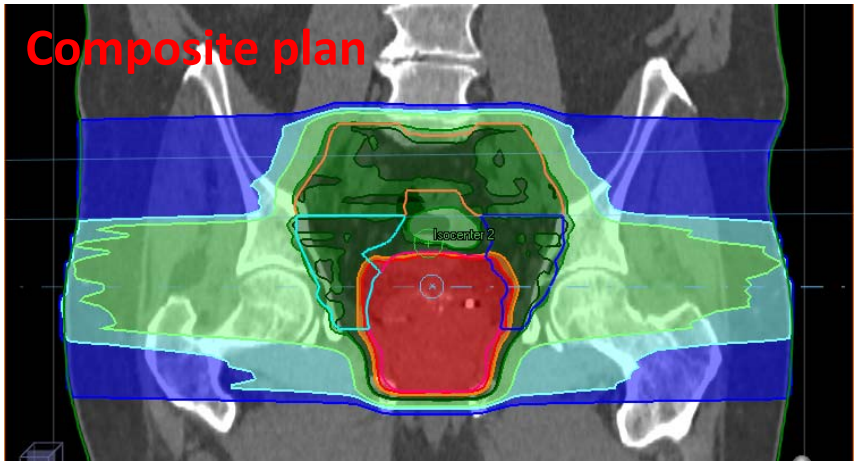
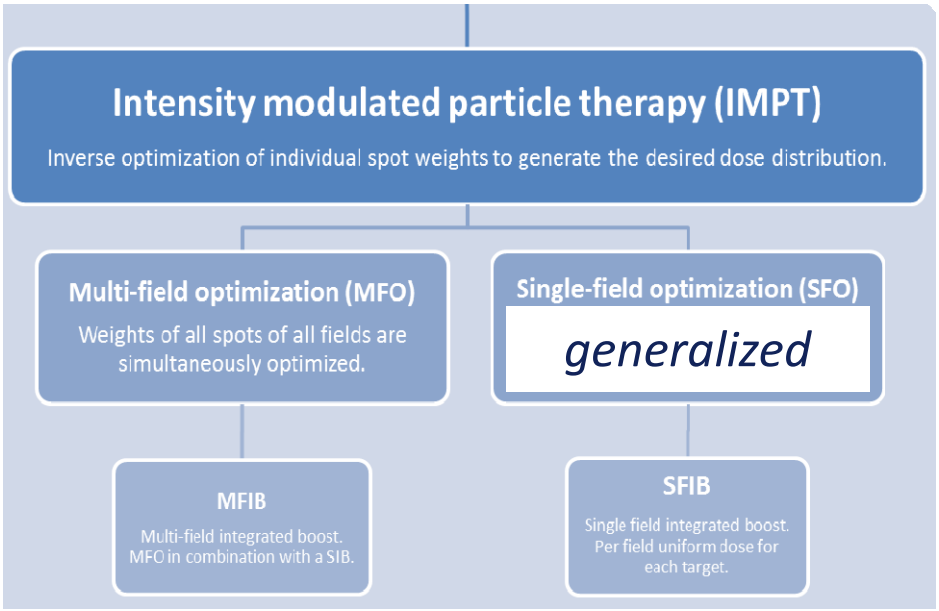


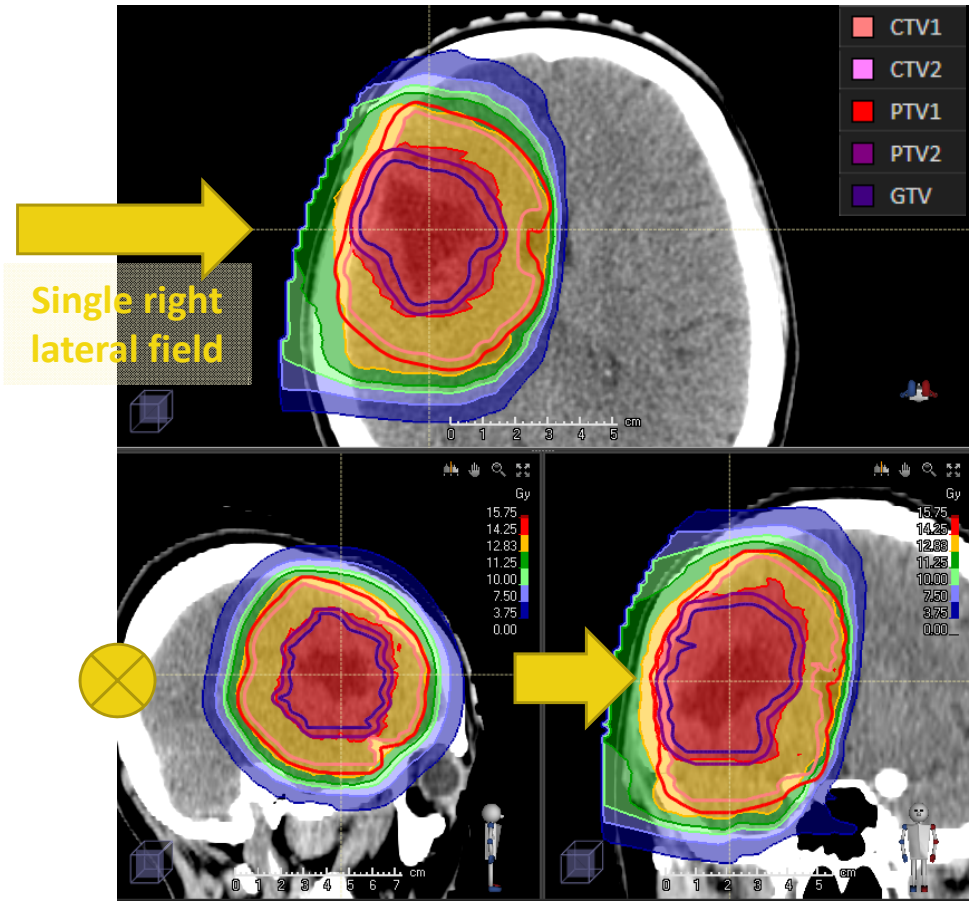
Illustration of potential combinations of optimisation options for complex geometries.



PLANGENERATION STRATEGIES

INTEGRATED BOOSTS



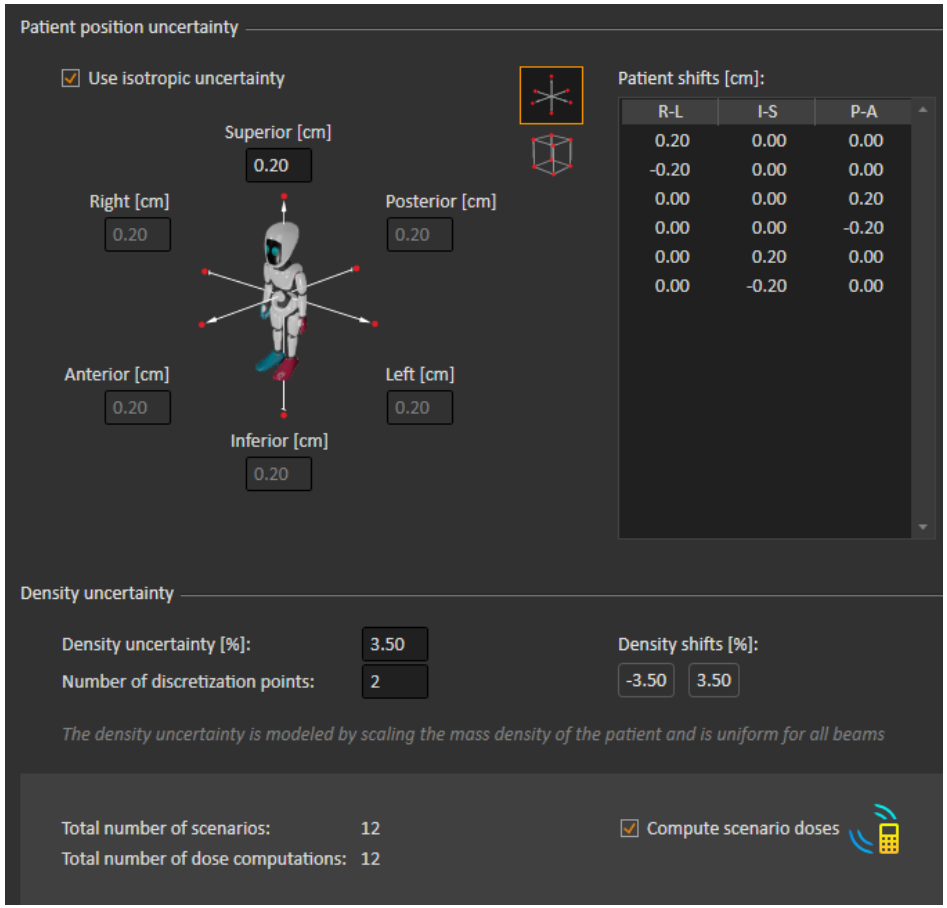


Single Field Integrated Boost (SFIB)

Zhu et al. Radiation Oncology 2014, 9:202

PLAN GENERATION STRATEGIES

ROBUSTNESS EVALUATION



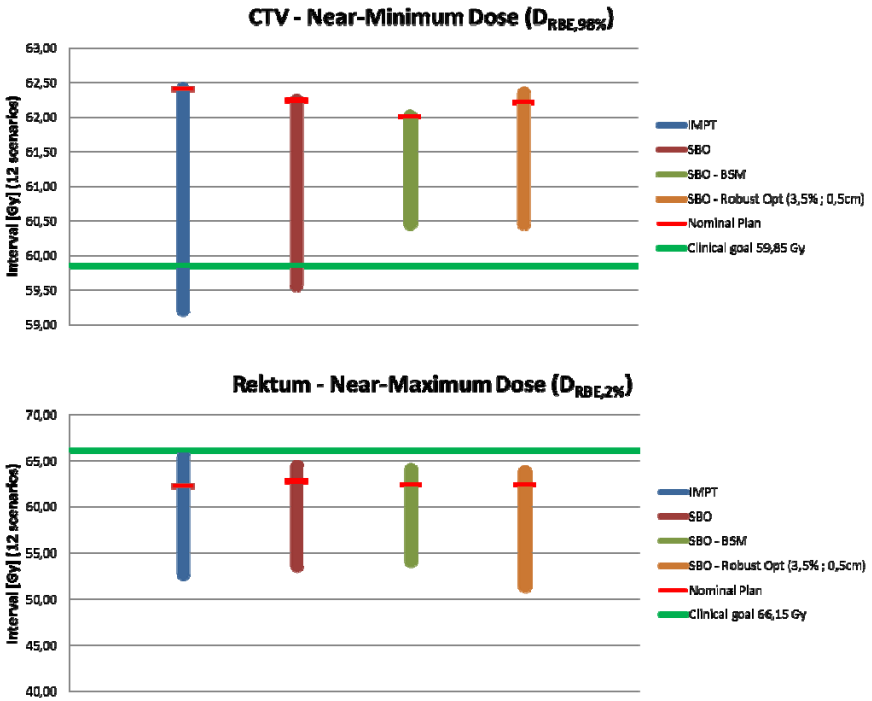
Scenario definition

DVHs for all scenarios

PLAN GENERATION STRATEGIES

ROBUST OPTIMISATION

- **Incorporation of density and setup uncertainty parameters into the optimization**
- **Incorporation of different planning CT**
- **eg. Minimax approach (Frederikson A, Bokranz R. MP 2014)**
    - Compute worst case of each scenarios for selected cost-functions in each iteration step and minimizes the penalty
- **Bears potential** to make the PTV concept obsolete and plan on CTVs only.

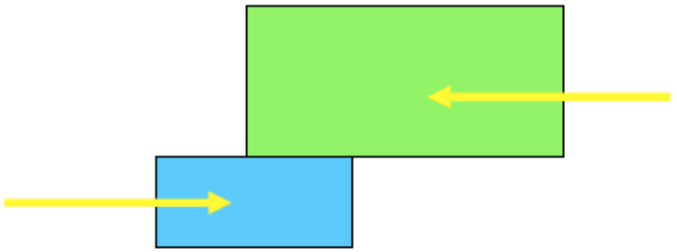


J. Gora, G.Kragl ÖGMP 2015

PLAN GENERATION STRATEGIES

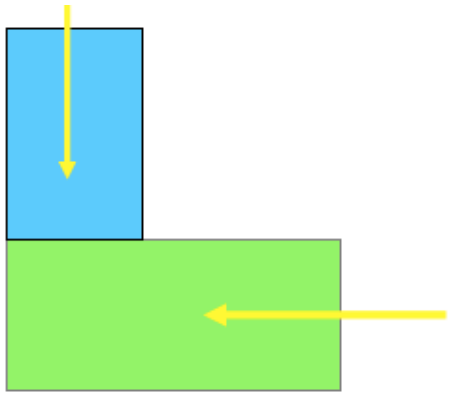
ROBUST OPTIMIZATION & FIELD MATCHING / PATCHING

Match fields



Lateral penumbra
+
Lateral penumbra

Patch fields

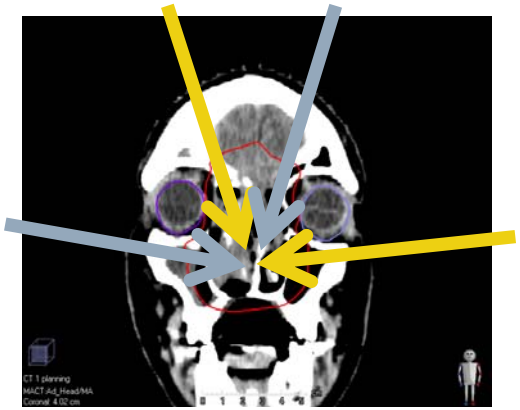


Distal penumbra
+
Lateral/distal penumbra

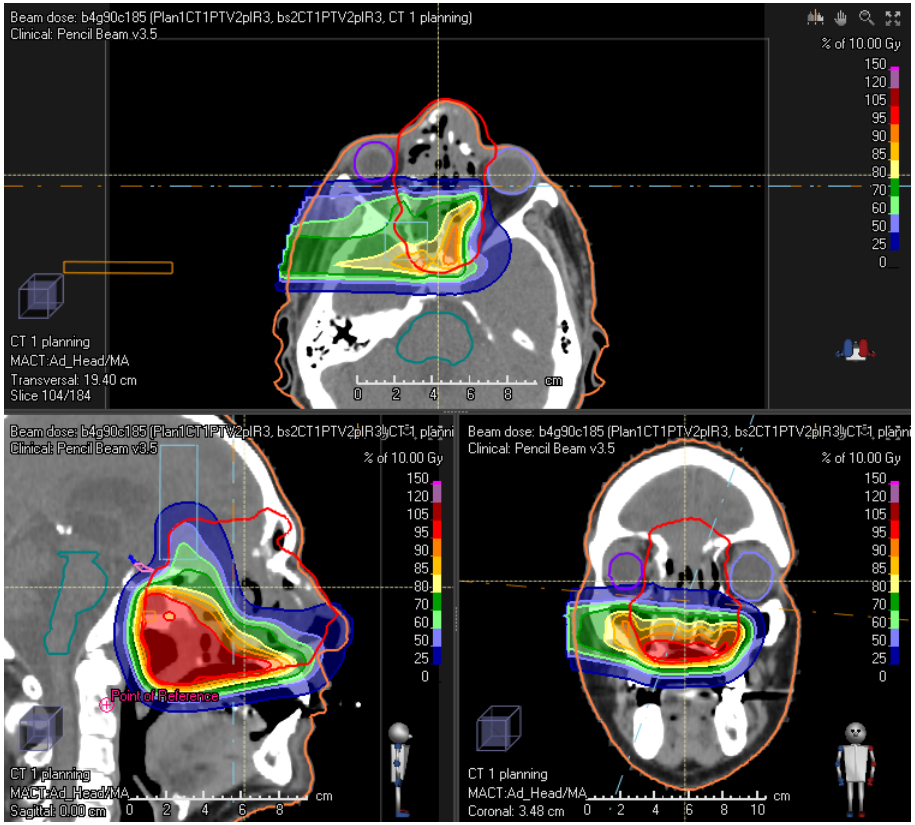
Stock M. Estro school

PLAN GENERATION

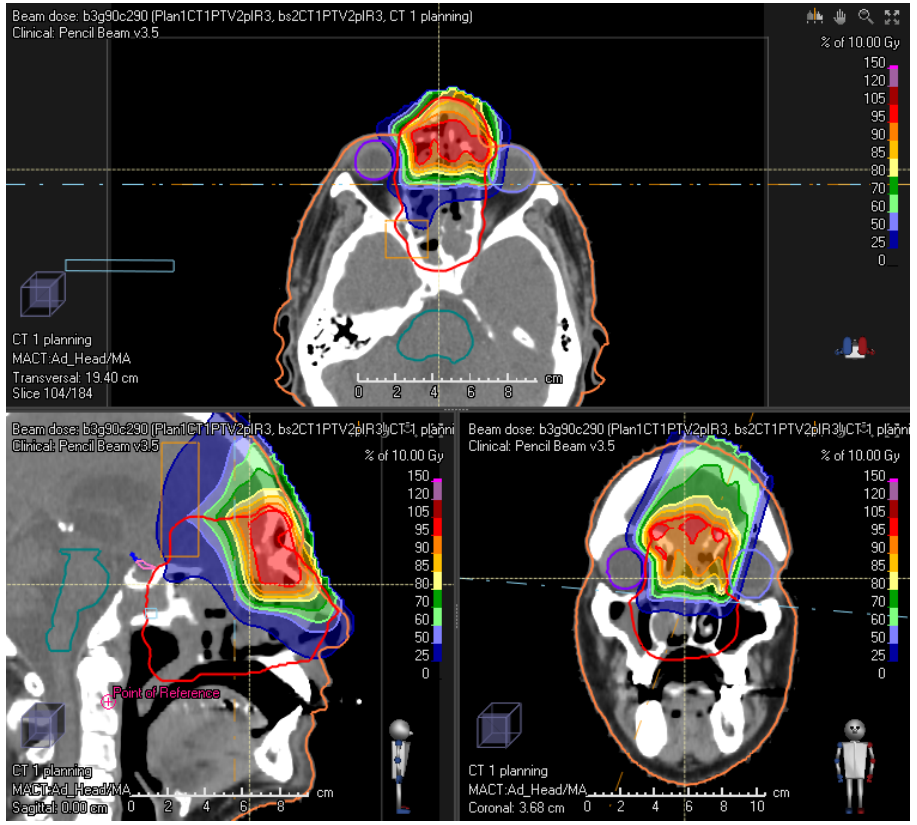
ROBUST OPTIMIZATION & FIELD PATCHING



Produce shallow gradients at the patching boarders.



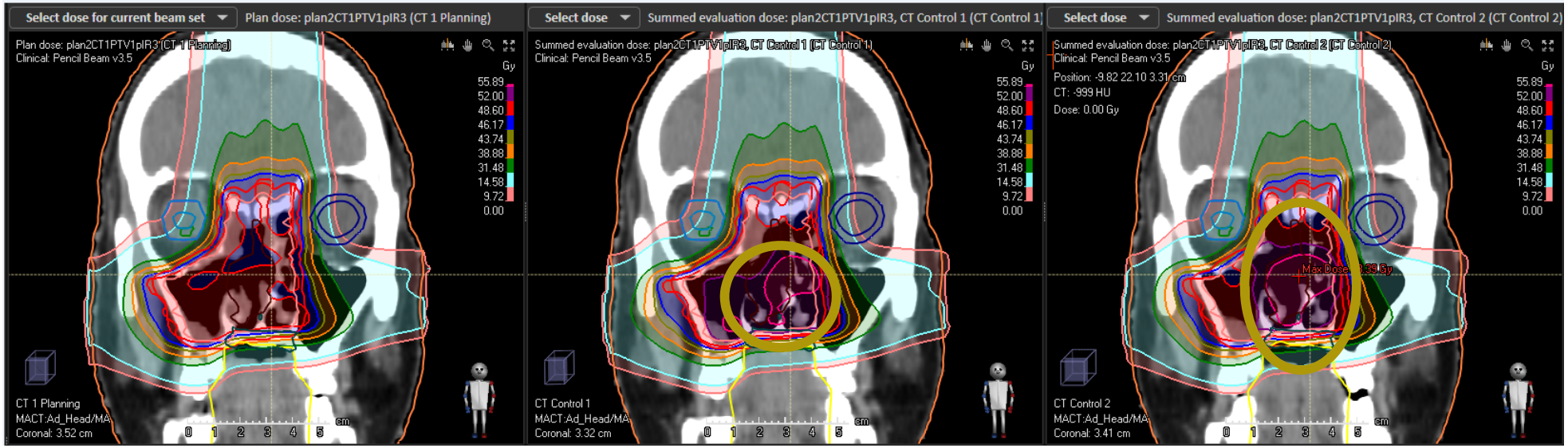
Right lateral



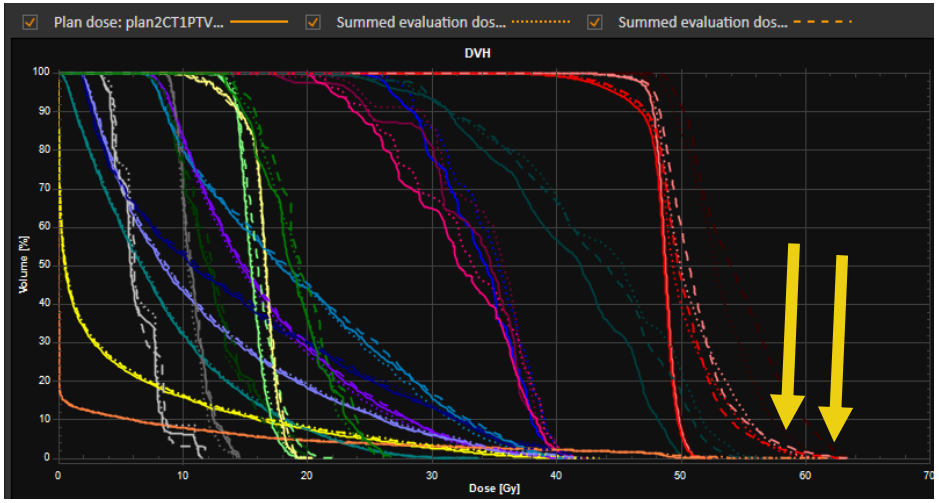
Vertex oblique

PLAN GENERATION

ROBUST OPTIMIZATION & FIELD PATCHING

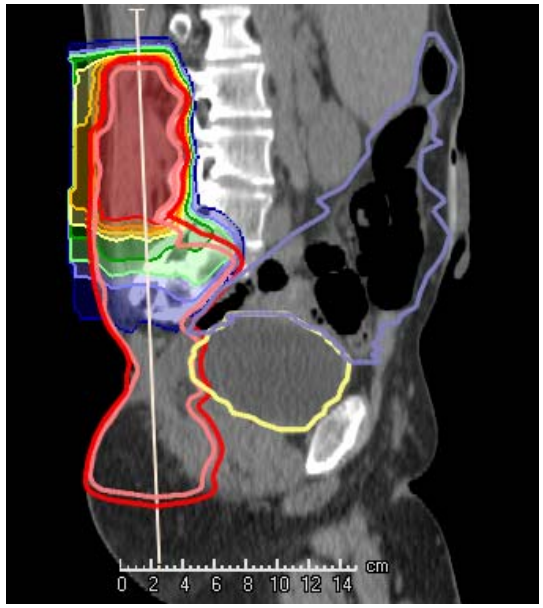


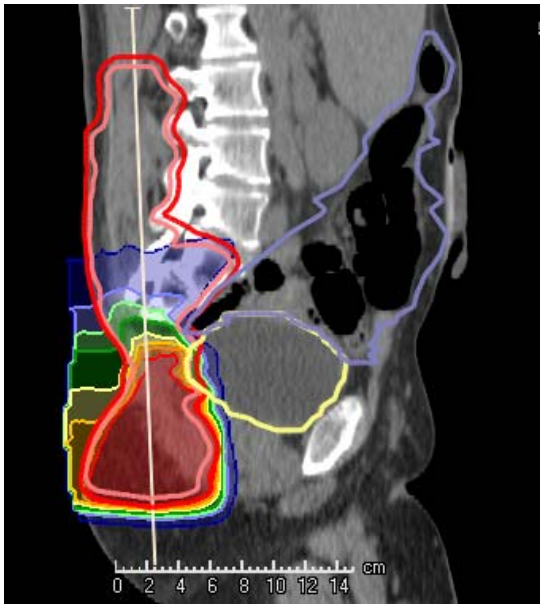
- High prio OARs: stable
- Target: plan adaptation required

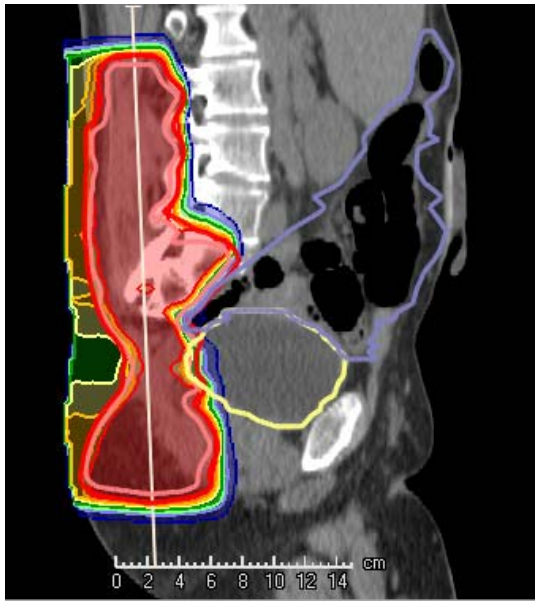


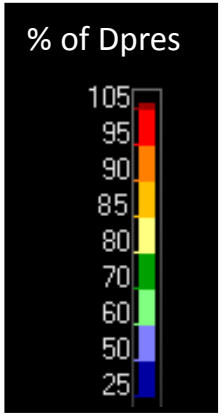
PLAN GENERATION STRATEGIES

ROBUST OPTIMIZATION & FIELD MATCHING

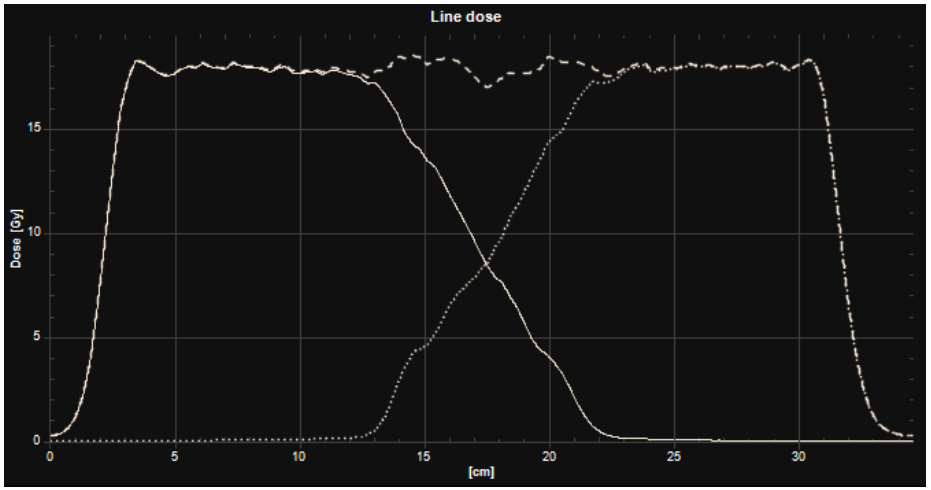






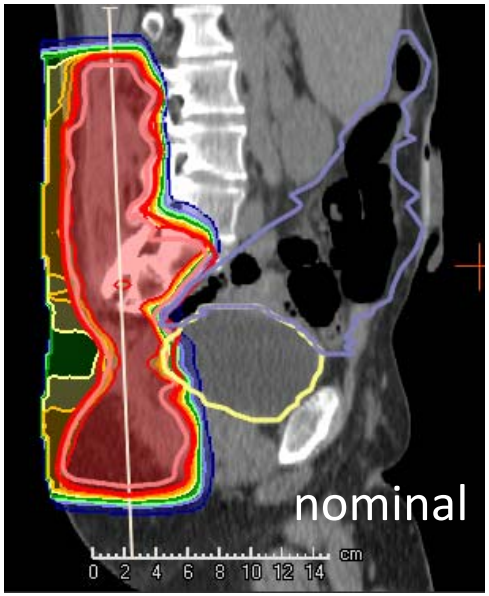


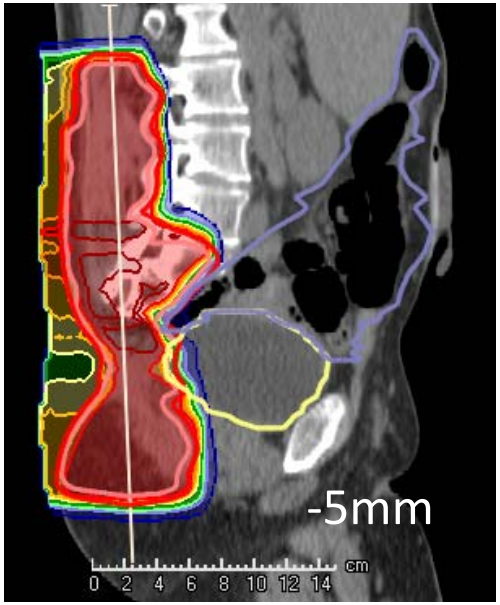
- **Produce shallow gradients at the matching boarders.**

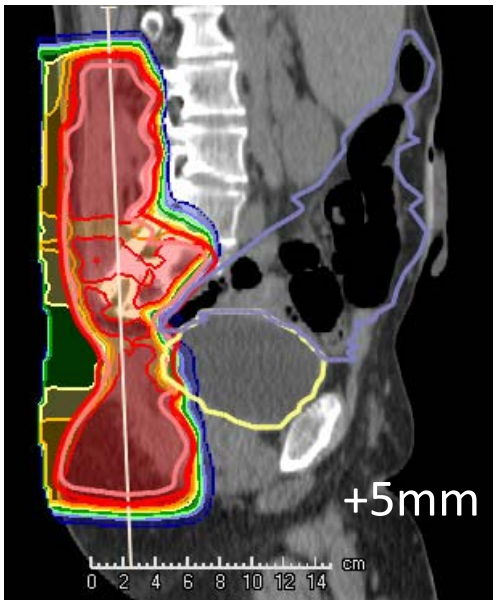


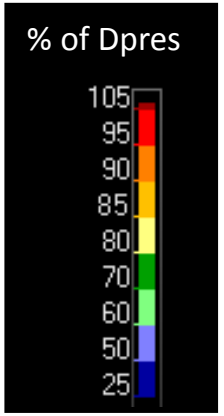
PLAN GENERATION STRATEGIES

ROBUST OPTIMIZATION & FIELD MATCHING

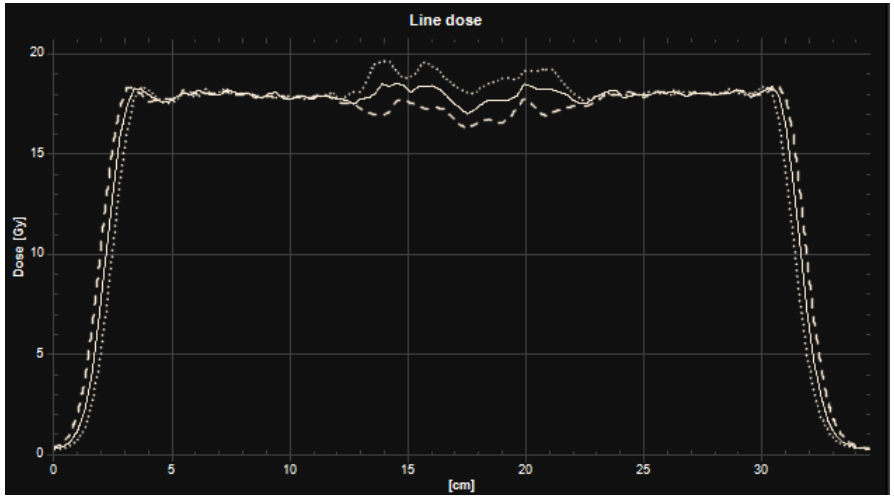






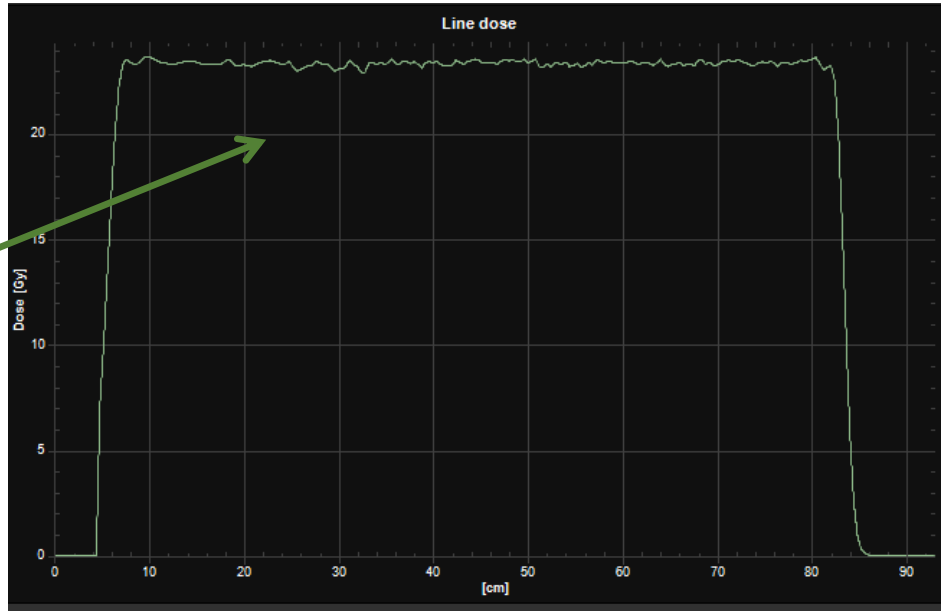


- **5mm isocenter shifts result in moderate over- and underdoses**



PLAN GENERATION STRATEGIES

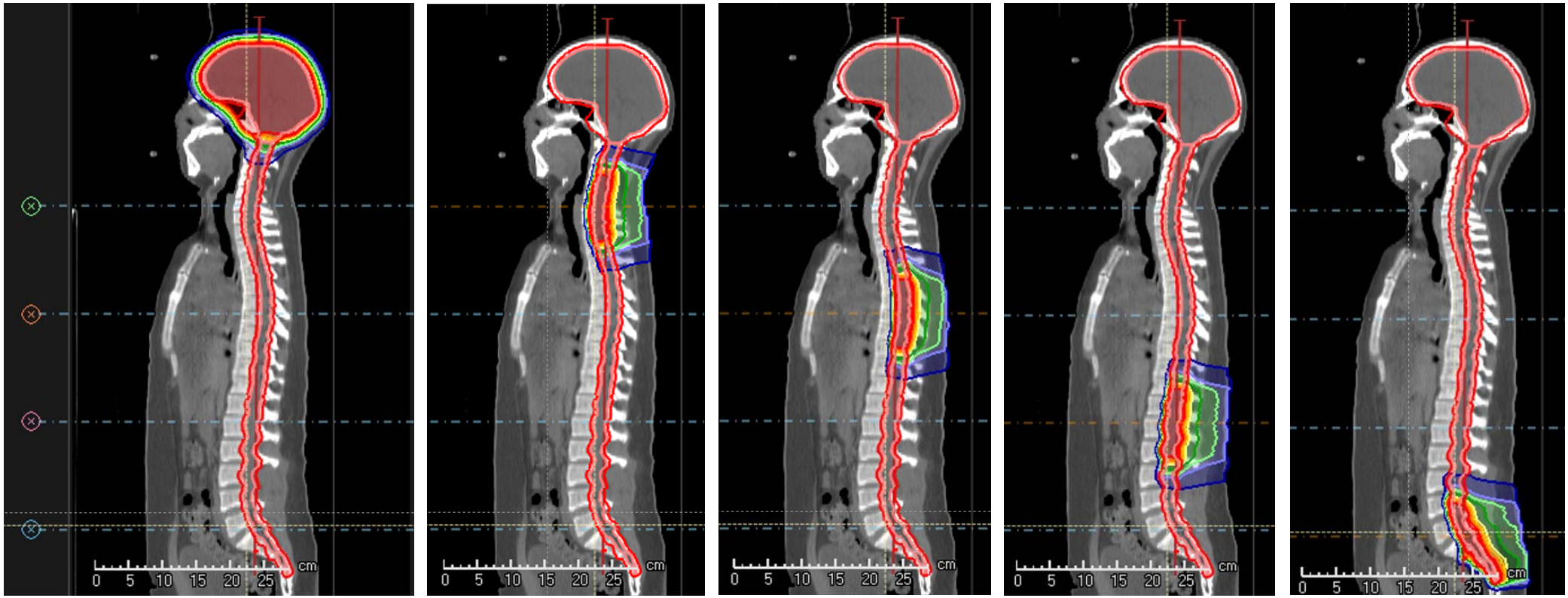
ROBUST OPTIMIZATION & FIELD MATCHING



- I-S PTV dimension: 89 cm

PLAN GENERATION STRATEGIES

ROBUST OPTIMIZATION & FIELD MATCHING

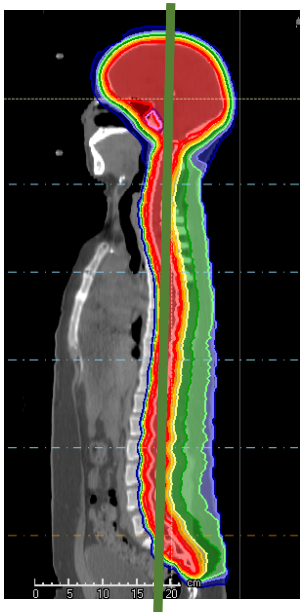


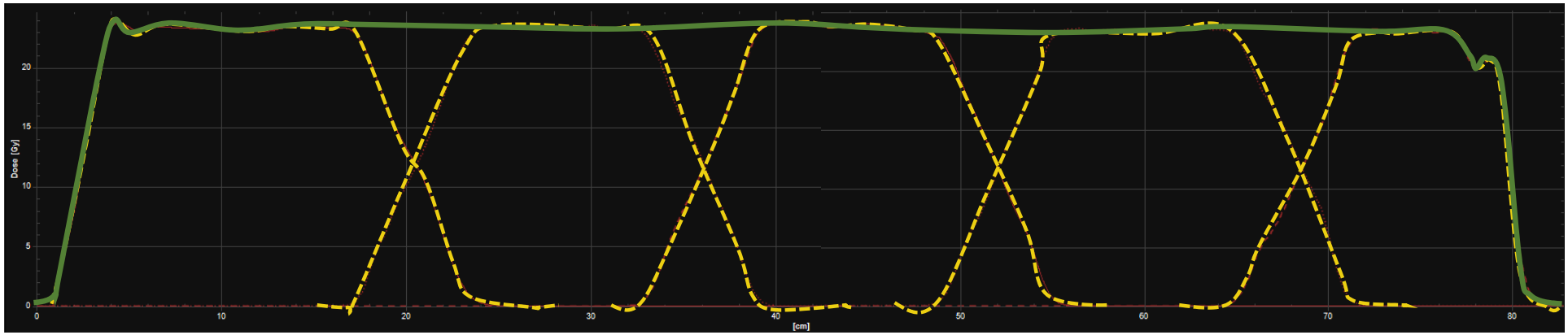
5 isocenters, i.e. 4 junctions

PLAN GENERATION STRATEGIES

ROBUST OPTIMIZATION & FIELD MATCHING

- Min overlap 4 cm

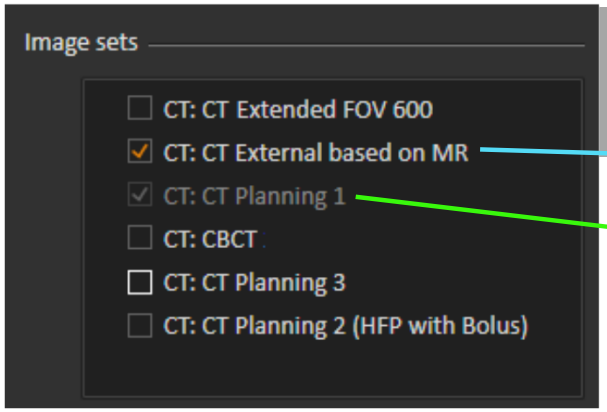




PLAN GENERATION STRATEGIES

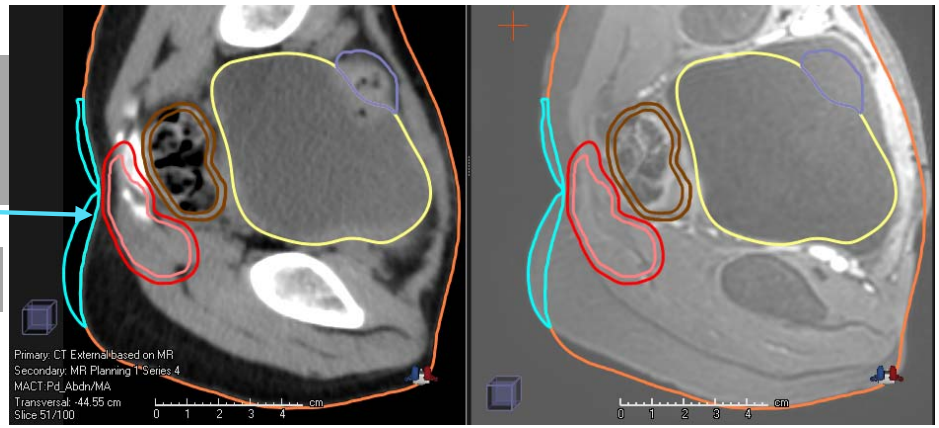
ROBUST OPTIMIZATION: ADDITIONAL PLANNING CTs

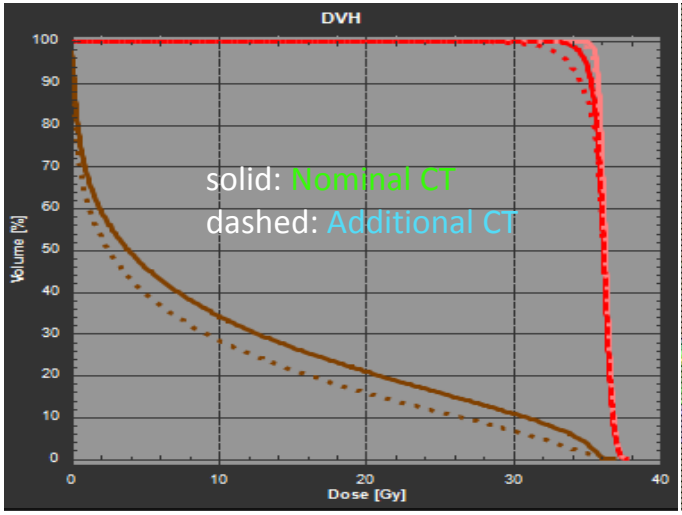
Choose additional planning CTs:

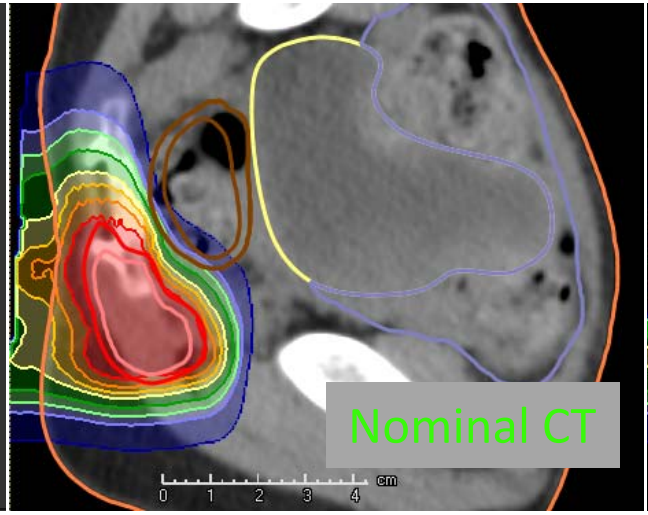


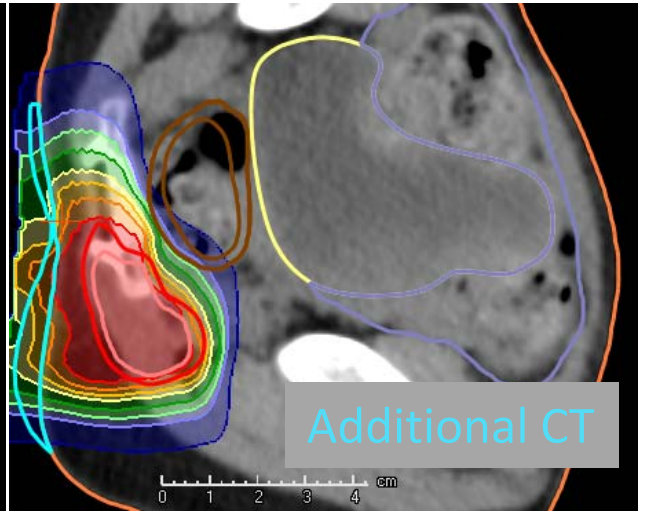
Nominal CT + ‚Unstable' tissue overwritten with adipose tissue

Nominal CT





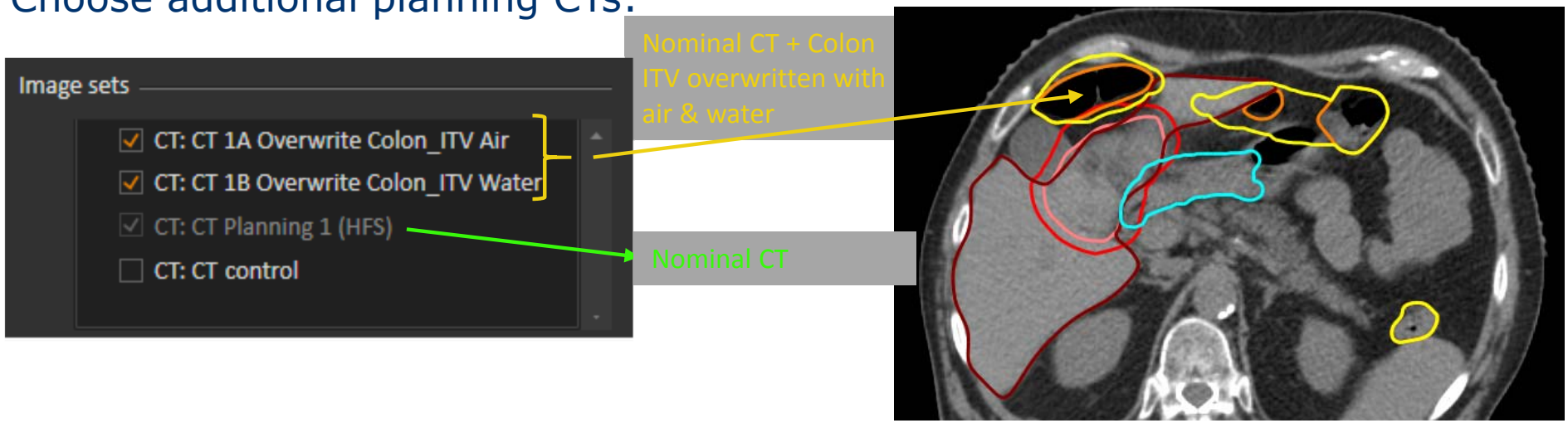




PLAN GENERATION STRATEGIES

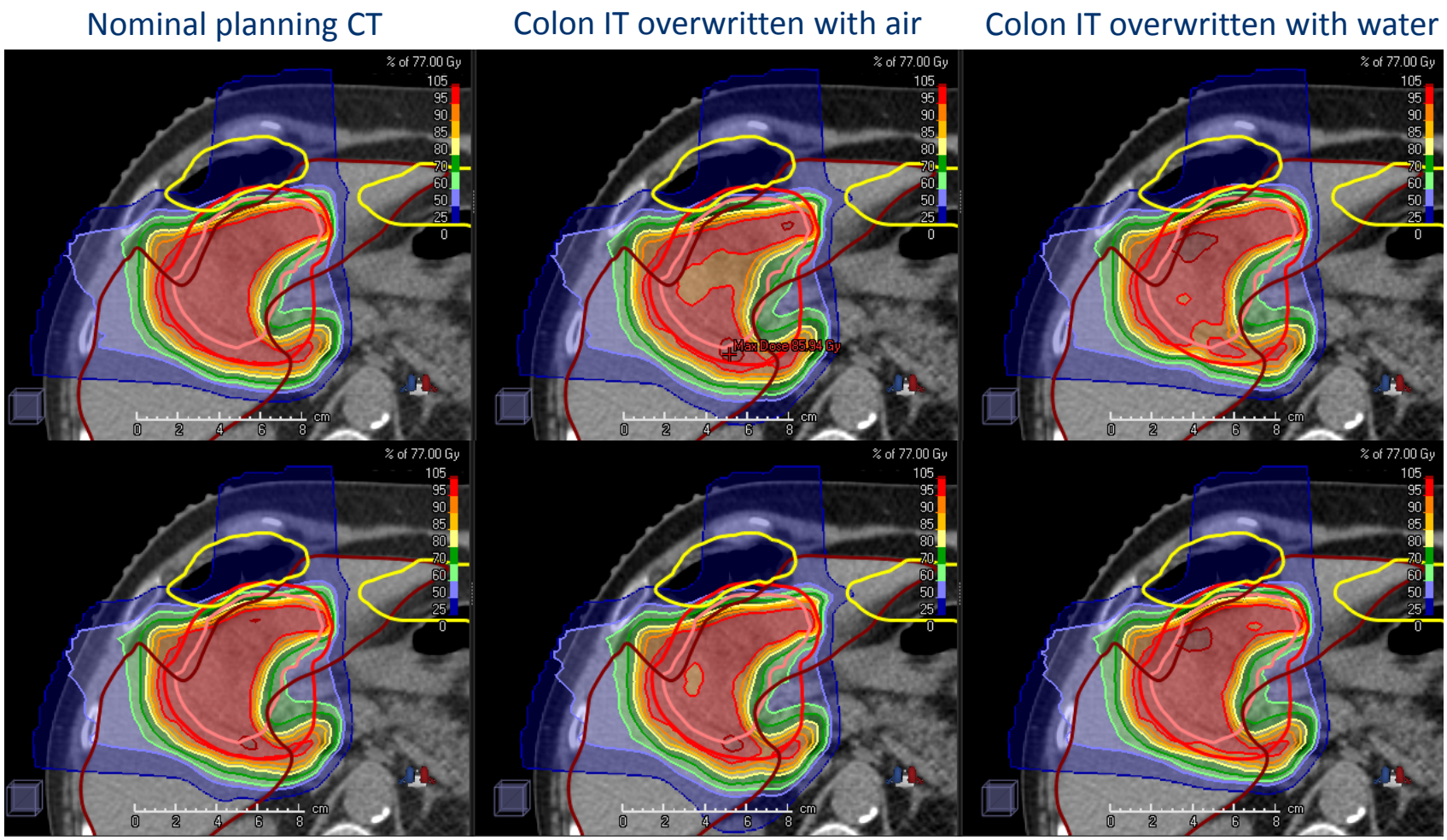
ROBUST OPTIMIZATION: ADDITIONAL PLANNING CTs

Choose additional planning CTs:



PLAN GENERATION STRATEGIES

ROBUST OPTIMIZATION: ADDITIONAL PLANNING CTs



PLAN GENERATION STRATEGIES

ROBUSTNESS AGAINST RBE UNCERTAINTIES

Biological Dose Estimation Model Beam Therapy

Vladimir Anferov[1*], Indra J. Das[2,3]

[1]Pronova Solutions LLC, Knoxville, USA
[2]Indiana University School of Medicine, Indianapolis, USA
[3]IU Health Proton Therapy Center, Bloomington, USA
Email: *Vladimir.Anferov@pronovasolutions.com

Received 14 January 2015; accepted 18 April 2015; published 23 April 2015

INSTITUTE OF PHYSICS PUBLISHING — PHYSICS IN MEDICINE AND BIOLOGY
Phys. Med. Biol. 49 (2004) 2811–2825 — PII: S0031-9155(04)74984-2

A phenomenological model for the relative biological effectiveness in therapeutic proton beams

J J Wilkens and U Oelfke

German Cancer Research Center (DKFZ), Department of Medical Physics, Im Neuenheimer Feld 280, 69120 Heidelberg, Germany

E-mail: j.wilkens@dkfz.de

Received 21 January 2004
Published 11 June 2004
Online at stacks.iop.org/PMB/49/2811
doi:10.1088/0031-9155/49/13/004

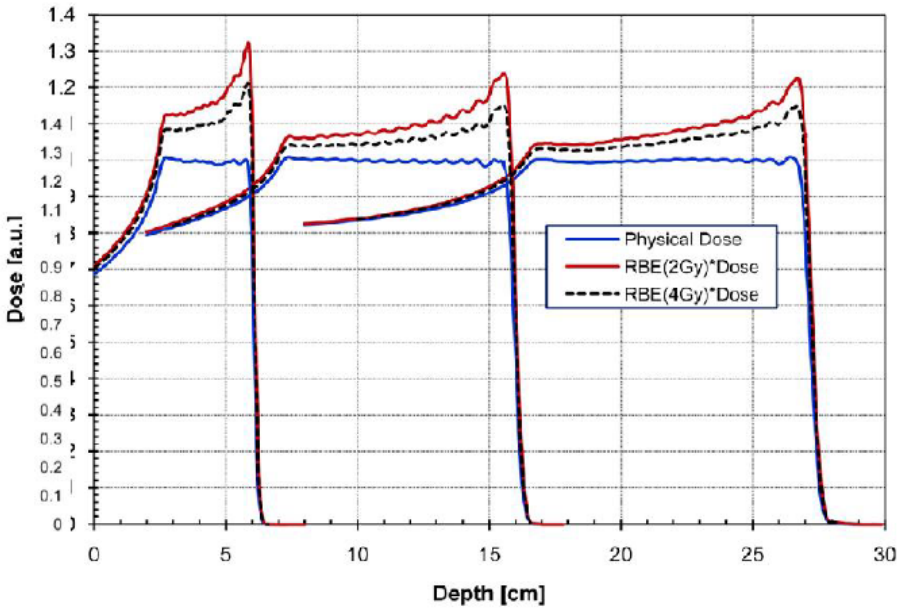


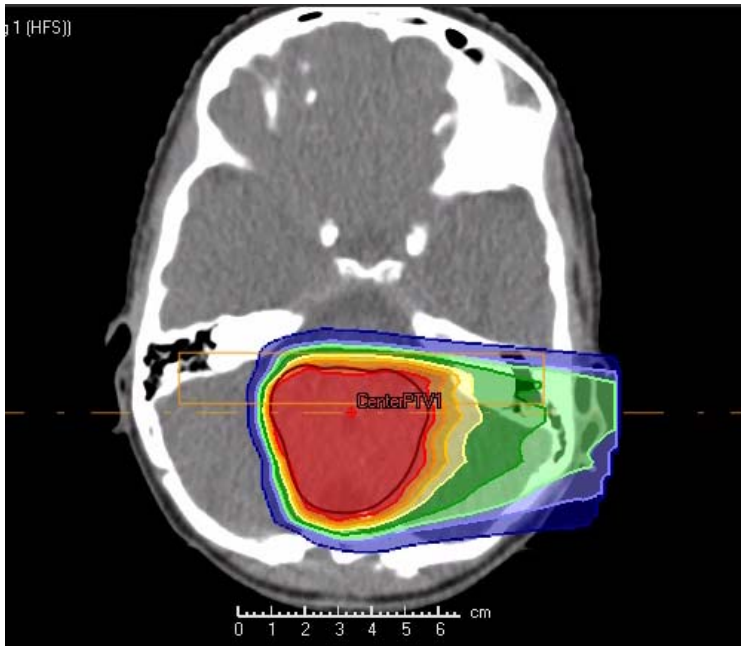
Figure 7. Comparison of the physical dose and RBE-weighted dose in modulated proton beams.

Image courtesy: N. Schreuder

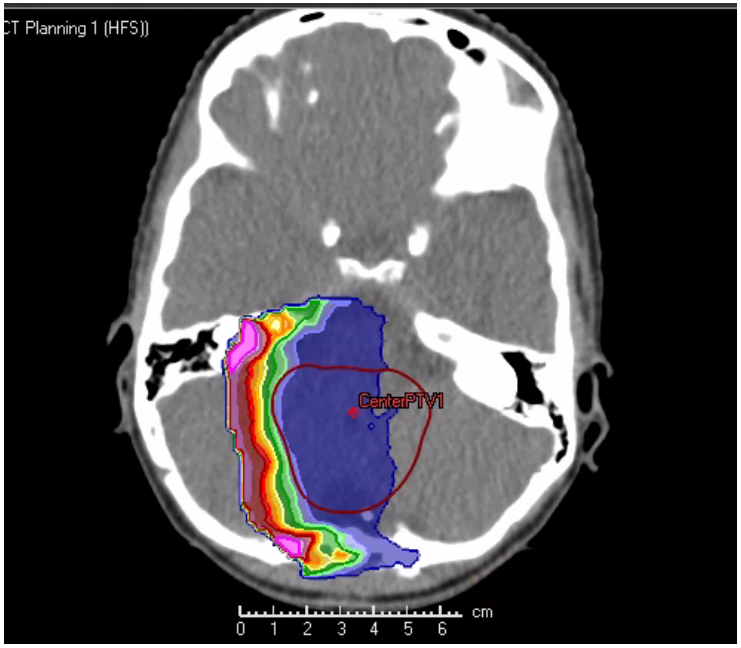
PLAN GENERATION STRATEGIES

ROBUSTNESS AGAINST RBE UNCERTAINTIES

Dose



LET



Optimize LET:

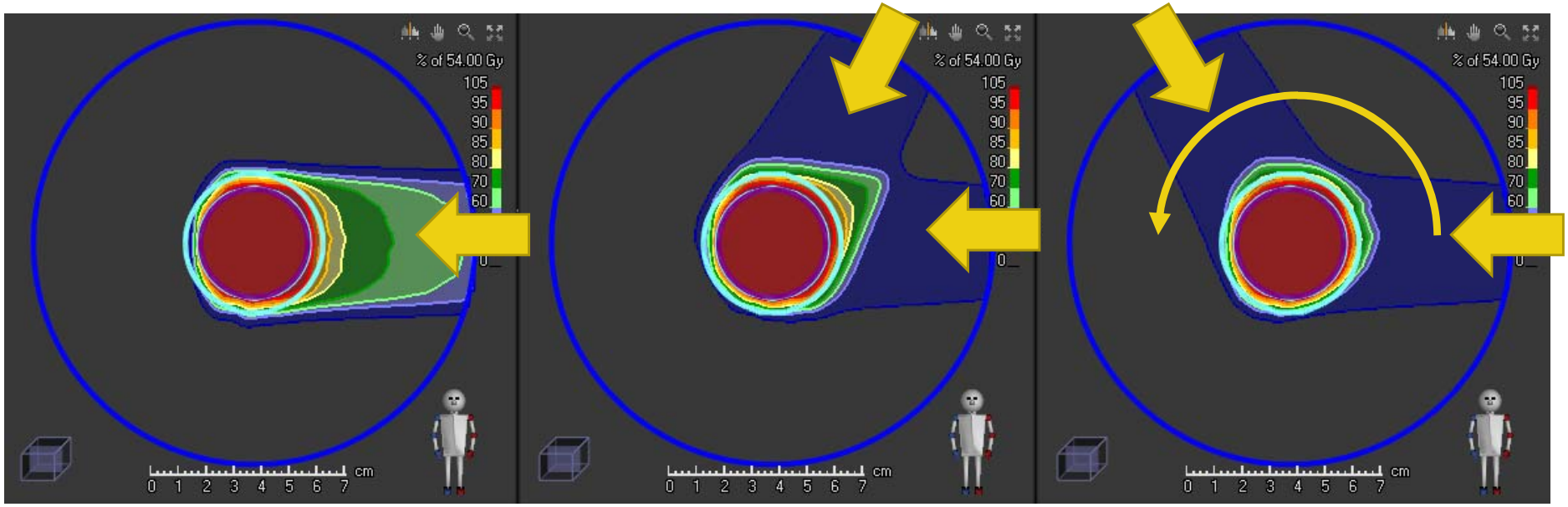
Int J Radiat Oncol Biol Phys. 2019 Mar 1;103(3):747-757. doi: 10.1016/j.ijrobp.2018.10.031. Epub 2018 Nov 2.

Introducing Proton Track-End Objectives in Intensity Modulated Proton Therapy Optimization to Reduce Linear Energy Transfer and Relative Biological Effectiveness in Critical Structures.

Traneus E[1], Ödén J[2].

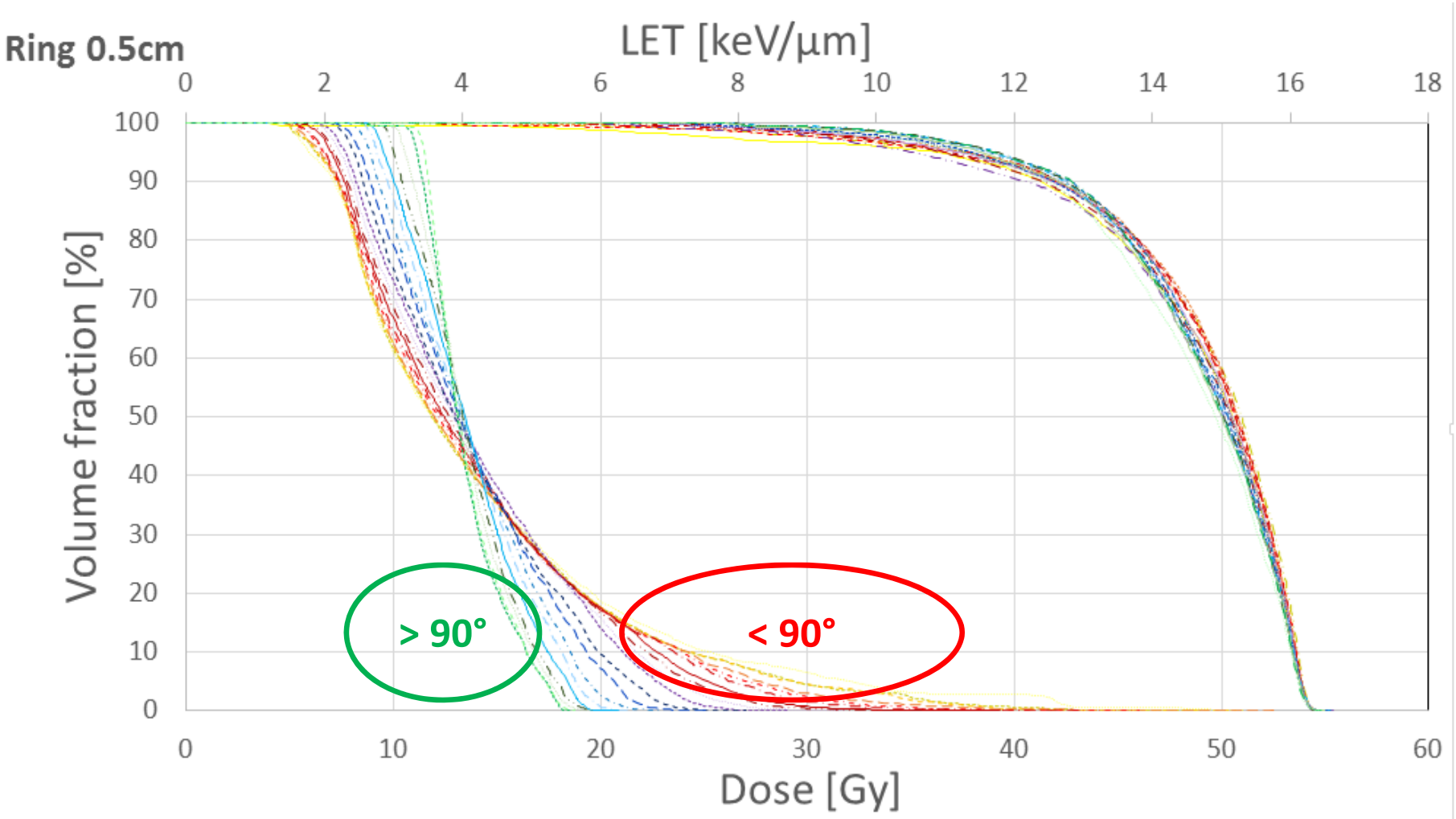
PLAN GENERATION STRATEGIES

ROBUSTNESS AGAINST RBE UNCERTAINTIES



PLAN GENERATION STRATEGIES

ROBUSTNESS AGAINST RBE UNCERTAINTIES



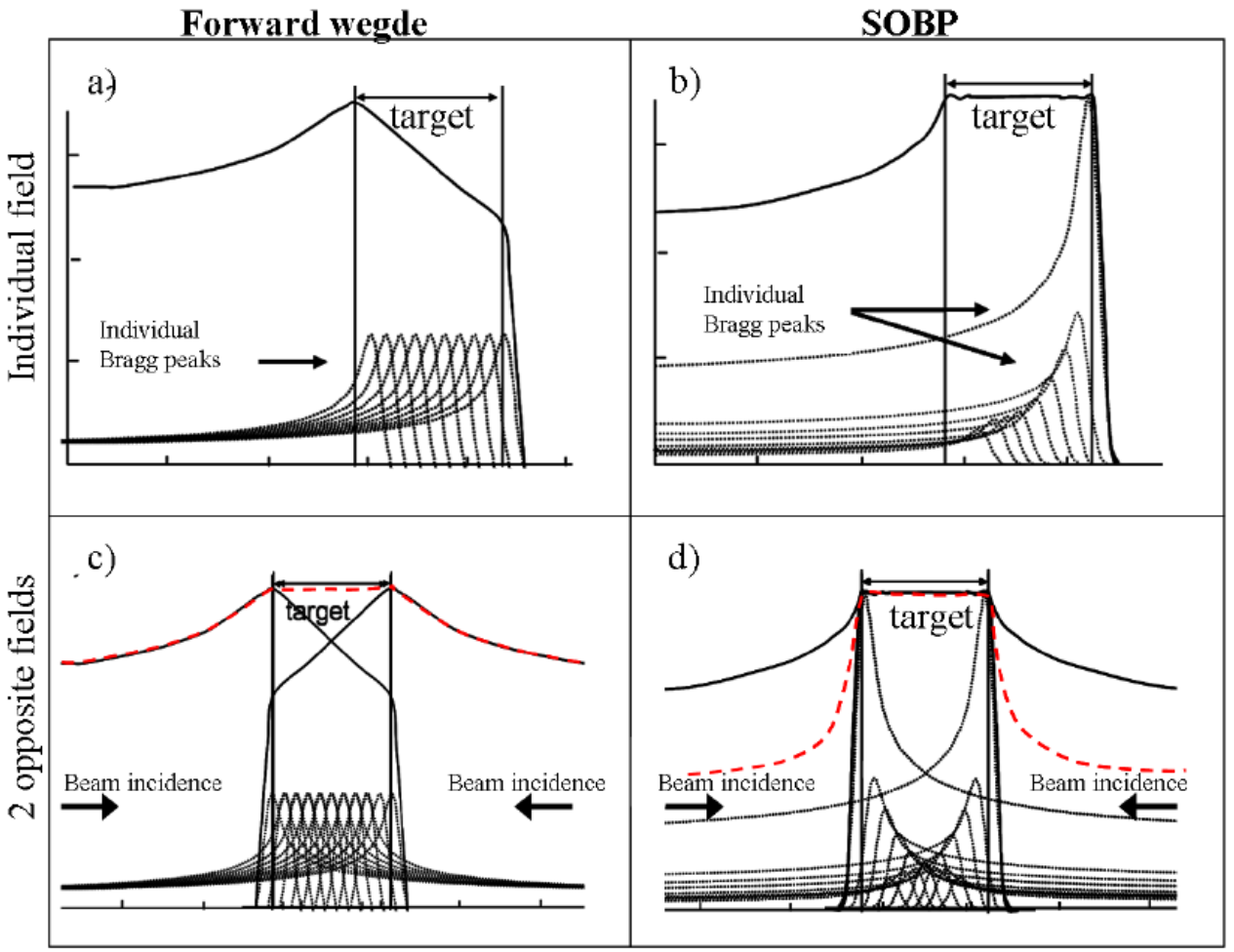
PLAN GENERATION STRATEGIES

COST OF ROBUSTNESS

Increased integral dose

- Reduced modulation
- Robust optimisation on additional CTs

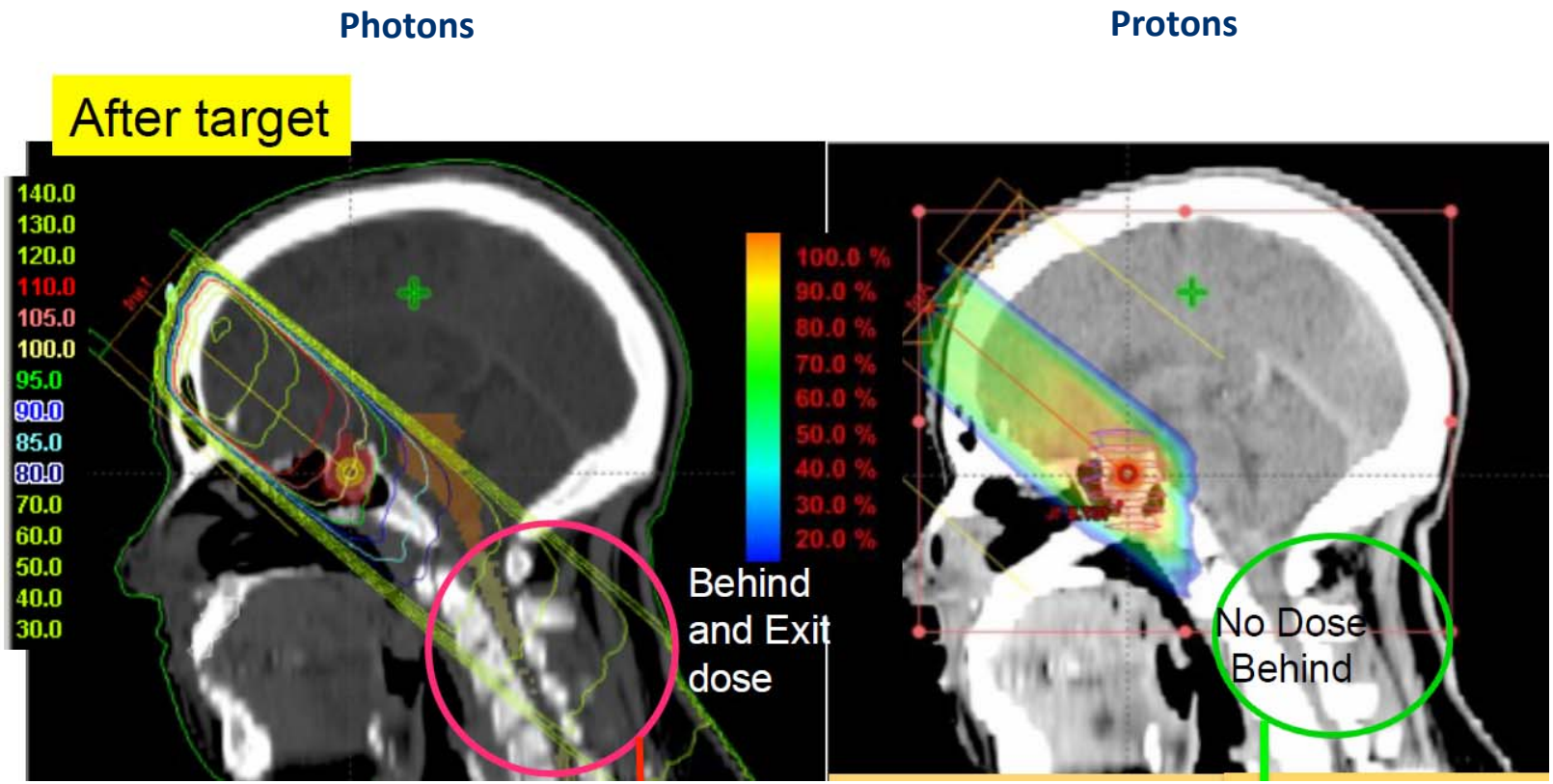
➢ *Cost vs. benefit?*



Dissertation, F. Albertini 2011, PSI Villigen

PLAN GENERATION STRATEGIES

COST OF ROBUSTNESS



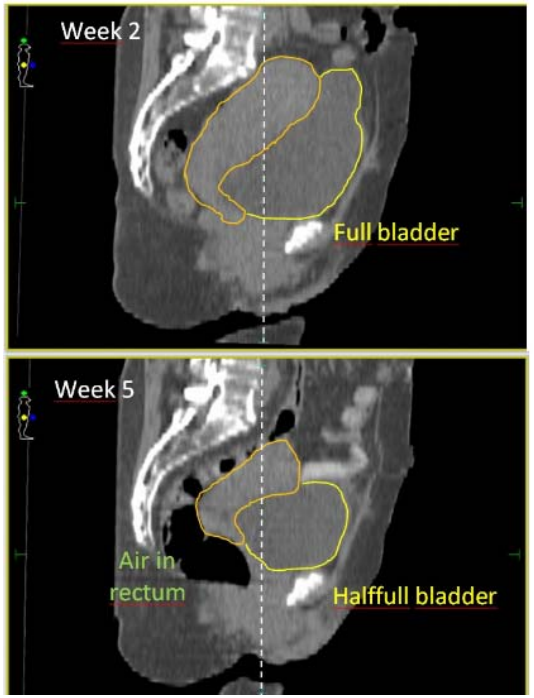
A. Mazal PTCOG

CONTENTS

- **Part II Proton PBS treatment planning**
  - Physical beam properties & Penumbra
  - Patient setup and workflow
  - Optimization strategies
  - **Adaptive treatment planning**
  - **4D treatment planning**

ADAPTIVE RADIOTHERAPY

PRINCIPLES



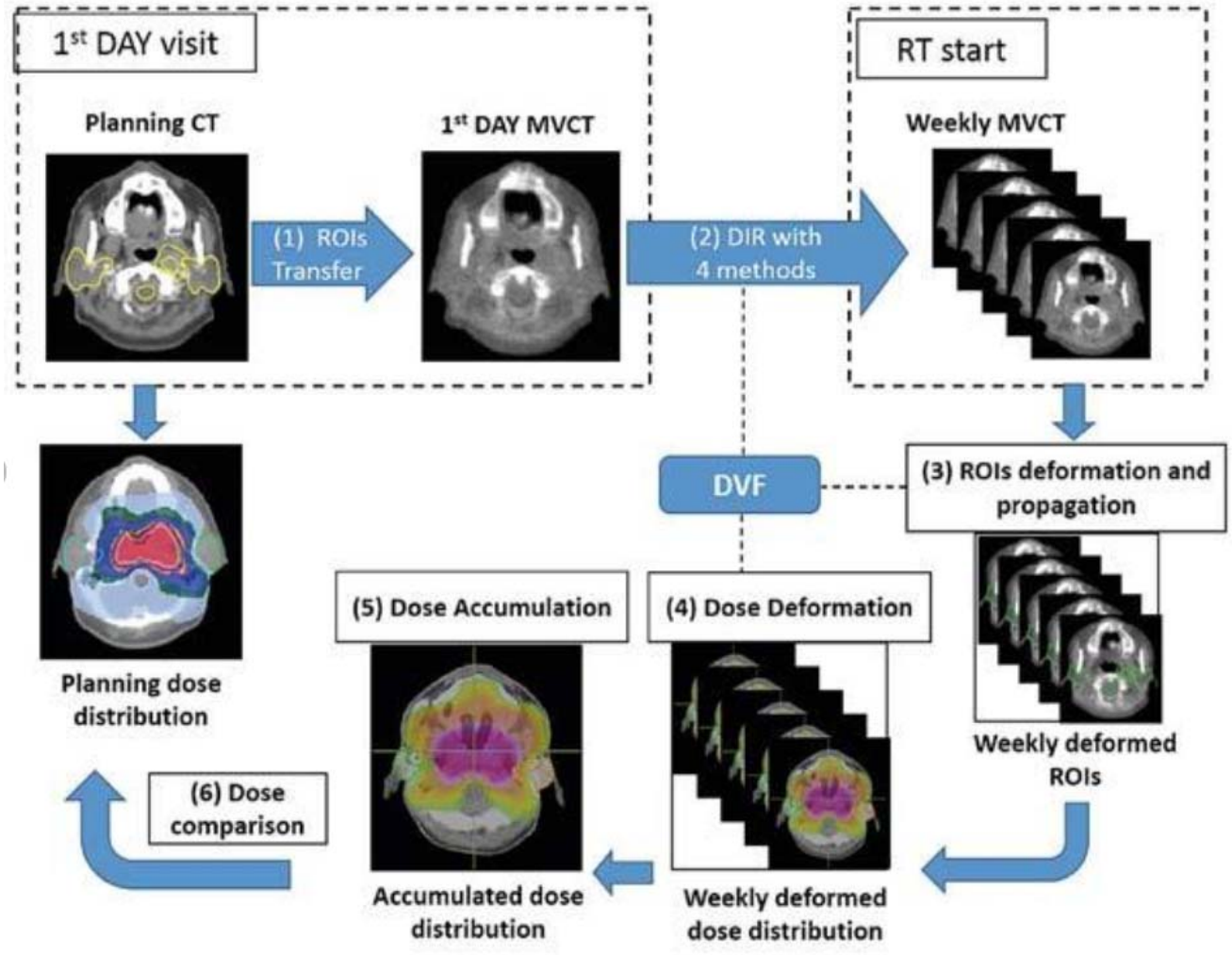
Med. Univ. Vienna, D. Georg.

- **Main reasons for plan adaptations**
  - Tumor shrinkage
  - Weight loss/gain
  - Organ fillings
  - Tumor response
  - Changes in patient position

- **Options for plan adaptation**
  - **Snap shot** → acquire regular re-planning CTs – continue with adapted plan
  - **Offline** → acquire daily images – adapted plan treated in the next fx
  - **Online** → acquire daily images – online daily adaptation and instant treatment of adapted plan
  - **Plan of the day** → acquire images with different organ fillings (e.g. full and half-full and empty bladder) – create respective plans and choose best fitting plan based on daily imaging

ADAPTIVE RADIOTHERAPY

DOSE ACCUMULATION

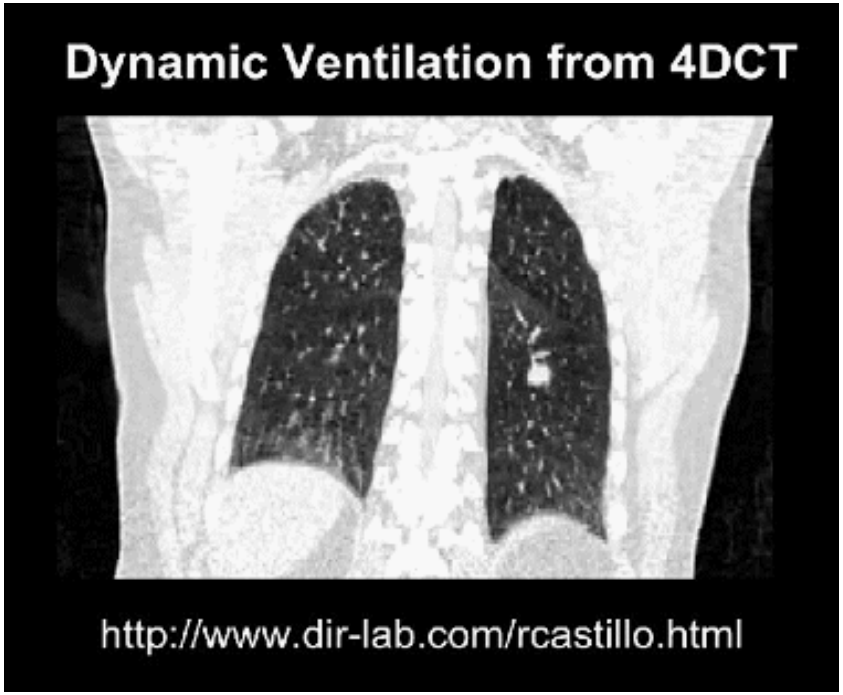


Nobnop W et al. Radiol Oncol 2017; 51(4): 438-446

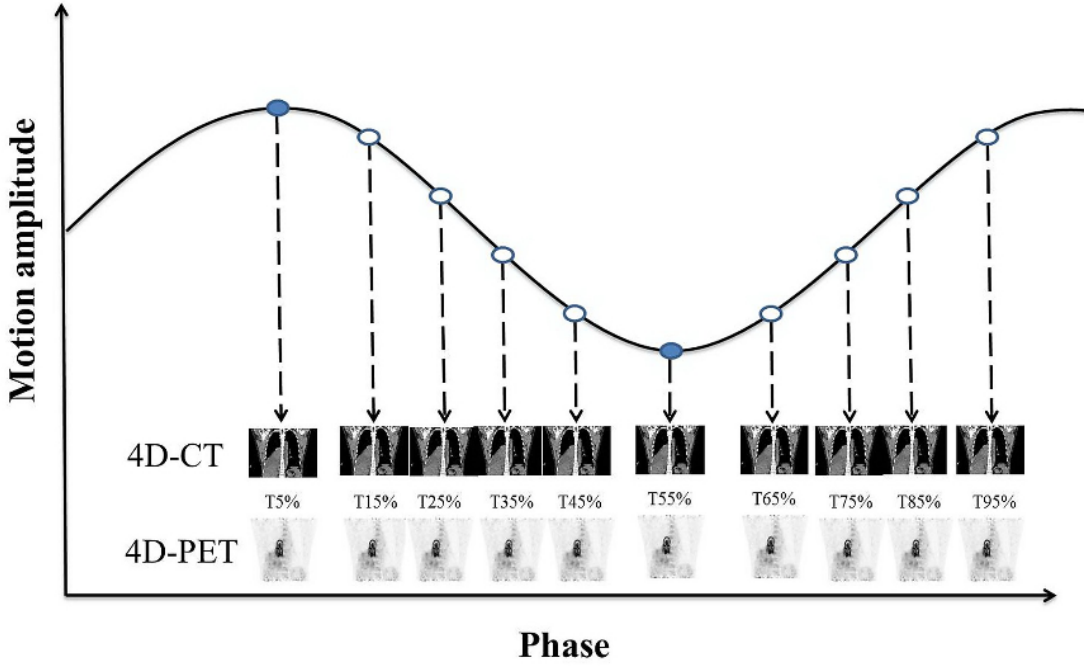
- **Challenges for protons**
  - Calibration of CBCT/4D CT for dose computation
  - Establish efficient workflow
  - Quality assurance

4D TREATMENT PLANNING

4D IMAGE ACQUISITION



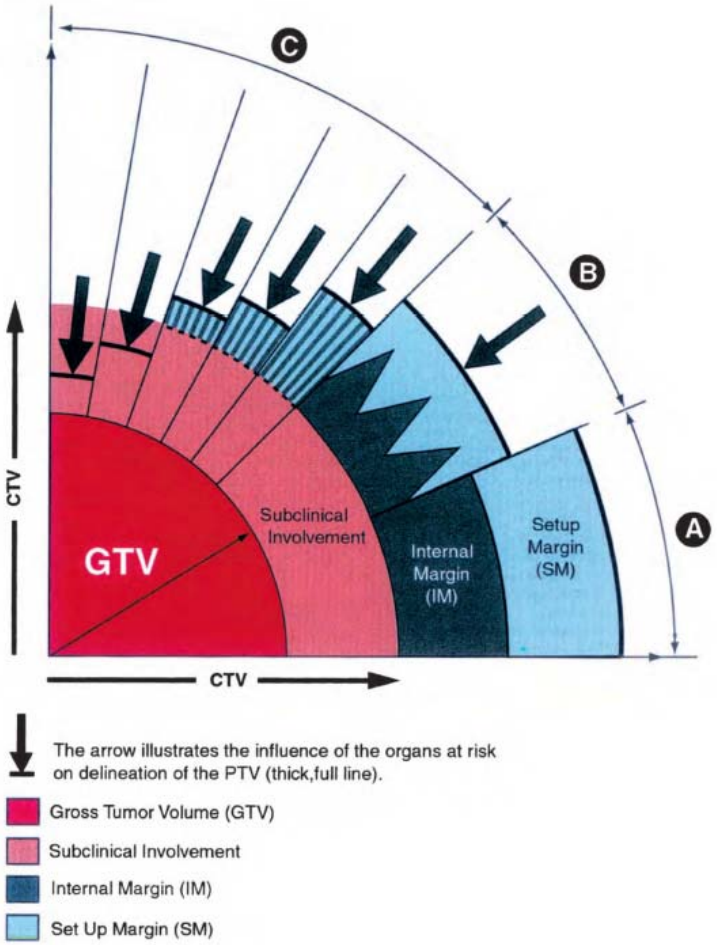
AAPM Summer School 2014



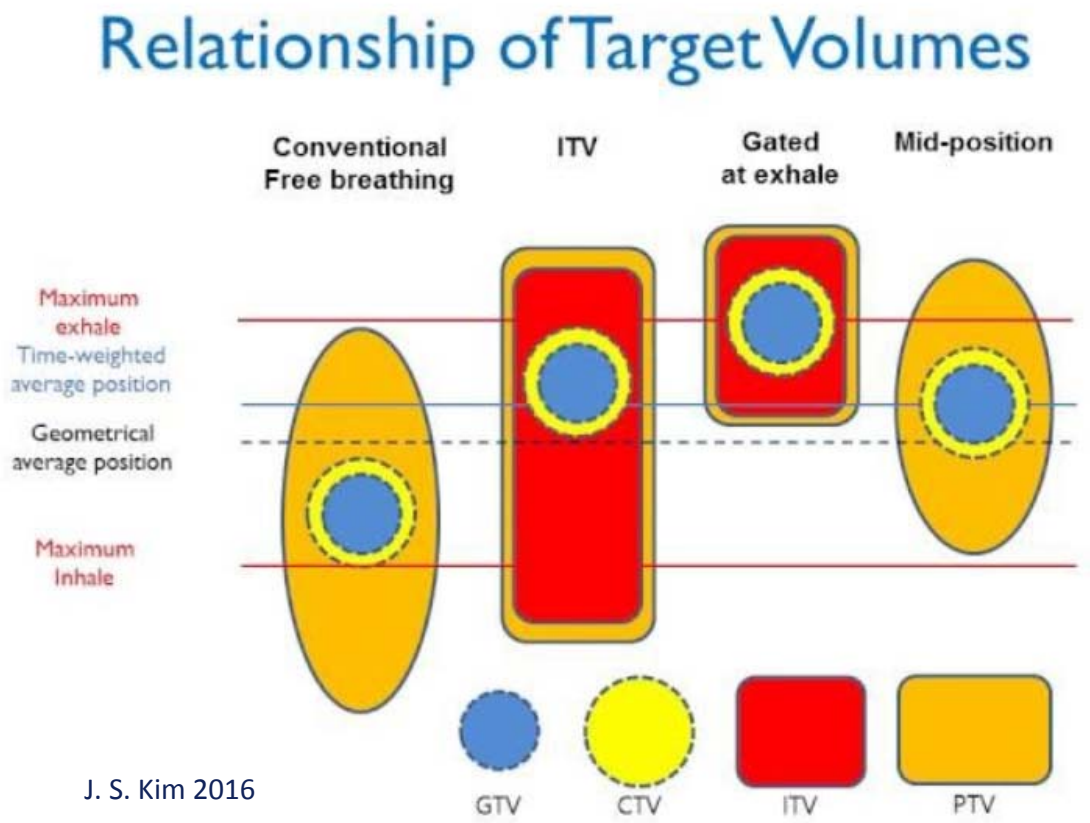
Tzung-Chi Huang et al. PLoS One. 2013

4D TREATMENT PLANNING

VOLUME DEFINITION



ICRU report 62



J. S. Kim 2016

Wolthaus JWH, Schneider C, Sonke JJ et al. Mid-ventilation CT scan construction from four-dimensional respiration-correlated CT scans for radiotherapy planning of lung cancer patients. Int. J. Radiat. Oncol. Biol. Phys.65(5), 1560–1571 (2006)

4D TREATMENT PLANNING

EFFECTS

Main dosimetric effects, when treating moving targets protons:

Scattered and scanned protons:

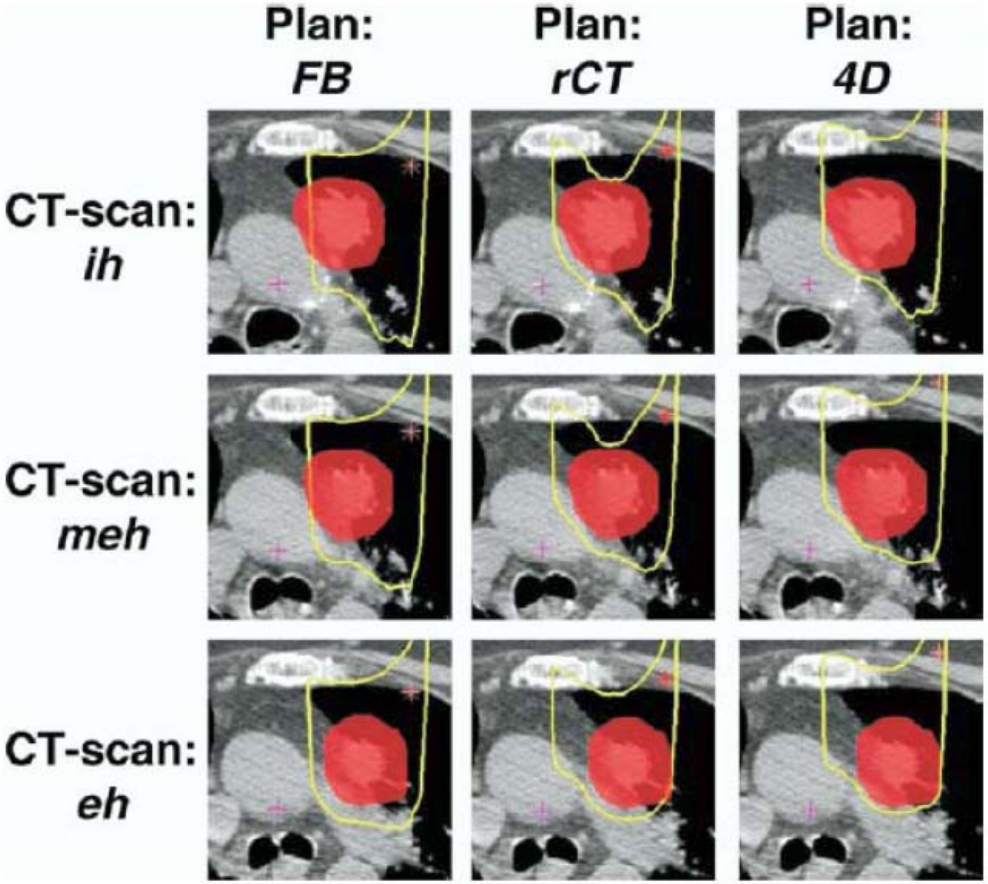
- **Density variations:** Temporal anatomic variations due to motion, e.g. respiration or heart beat, cause temporal density variations (e.g. tumour movement, movement of the ribs) and therefore varying proton ranges.

Scanned protons:

- **Interplay effect:** The intended position of the Bragg Peak is dependent on the actual target position. Therefore, the actual Bragg Peak position can deviate from the planned Bragg Peak position and therefore, unintended over- and under-dosage of the tumour may be the consequence.

4D TREATMENT PLANNING

DENSITY VARIATIONS



Engelsmann, IJROBP 2006

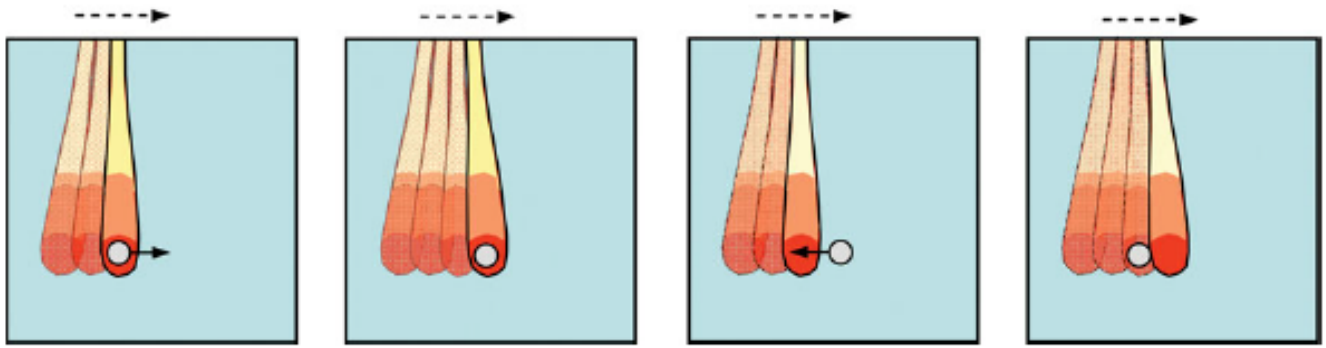
scattered protons; free breathing (FB) vs. representative phase for planning (rCT) vs. compensator based on 4D-CT (4D) recomputed on inhale-, mid-exhale and exhale-CT;

4D TREATMENT PLANNING

INTERPLAY EFFECT

Assume beam scan speed and organ motion speed are comparable.

- **Unintended over- and under-dosage.**



ICRU Report 78

4D TP

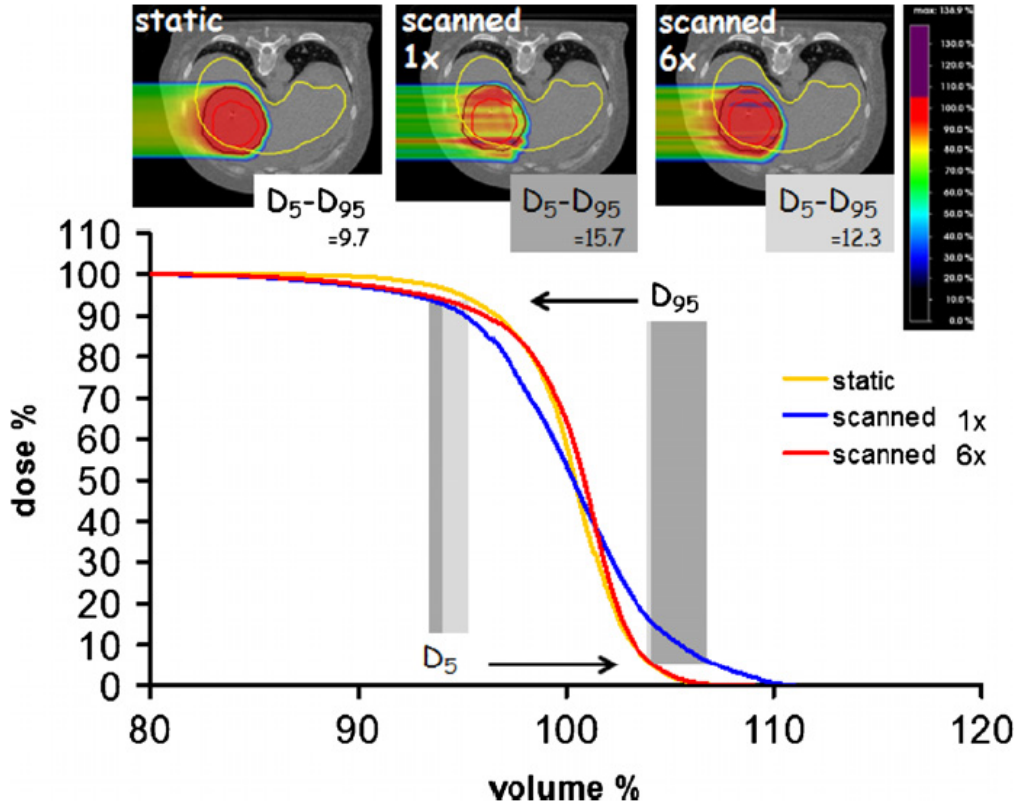
INTERPLAY EFFECT - RESCANNING

IOP Publishing — Physics in Medicine and Biology
Phys. Med. Biol. **56** (2011) 7257–7271 — doi:10.1088/0031-9155/56/22/016

Scanned proton radiotherapy for mobile targets—the effectiveness of re-scanning in the context of different treatment planning approaches and for different motion characteristics

Antje-Christin Knopf[1], **Theodore S Hong**[2] **and Antony Lomax**[1,3]

[1] Center for Proton Therapy, Paul Scherrer Institut, Villigen, Switzerland
[2] Department of Radiation Oncology, Massachusetts General Hospital, Harvard Medical School, Boston, MA, USA
[3] ETH, Zürich, Switzerland



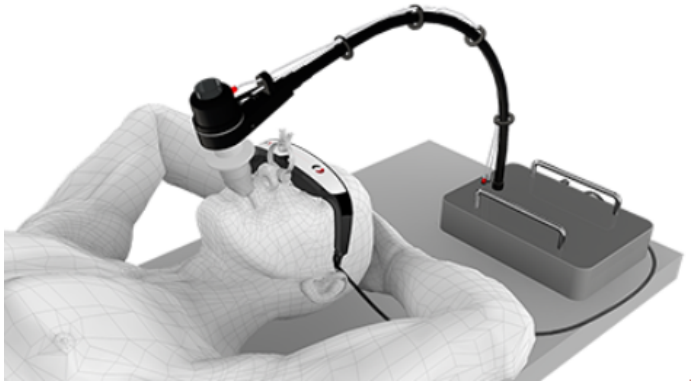
- Moving pattern extracted from 4D CT and/or respiratory curve and delivery time structure
- Potential benefit of rescanning most pronounced for plans with small number of fields and fractions with directions close to orthogonal to the motion direction
- ‘Poor mans rescanning’: Increased # of fields and # of fractions

4D TREATMENT PLANNING

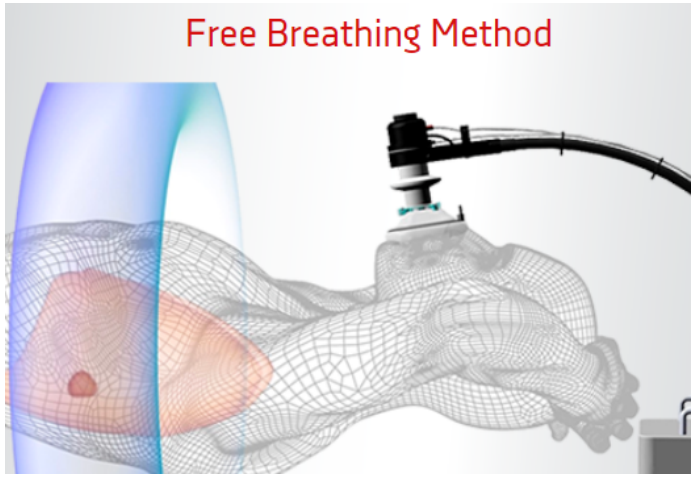
MOTION MITIGATION STRATEGIES

- Motion reduction
  - Abdominal compression
- Breath hold
  - Self-held, active via spirometers and valve breath hold in combination with different respiratory monitoring methods
- Rescanning
- Gating
  - Beam-on only during certain breathing phases „gating window“
- Tracking
  - Beam follows the target trajectory

Voluntary Breath Hold Method



Free Breathing Method



http://www.sdx-gating.com/

4D TREATMENT PLANNING

4D TREATMENT PLANNING STRATEGIES

Plan optimization

- **ITV** generation, ‚OAR-ITVs‘
- **Beam incidence parallel** to tumor motion
- **PBS: Robust optimization**
  - based on 4D-CT
    - ➢ Challenge for protons: HU to WET calibration
  - based on planning CT but with ITV structures and respective over-writes derived from 4D-CT
- **PBS: Tighter spot spacing** ~1/5 FWHM (Bert et al.)
- Consider use of **scattered protons**

Dose calculation

- Challenge: Lung ripple effect
- MC dose calculation

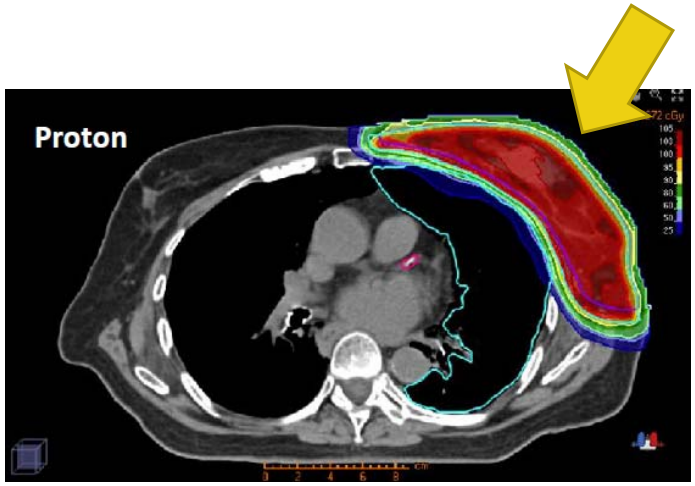
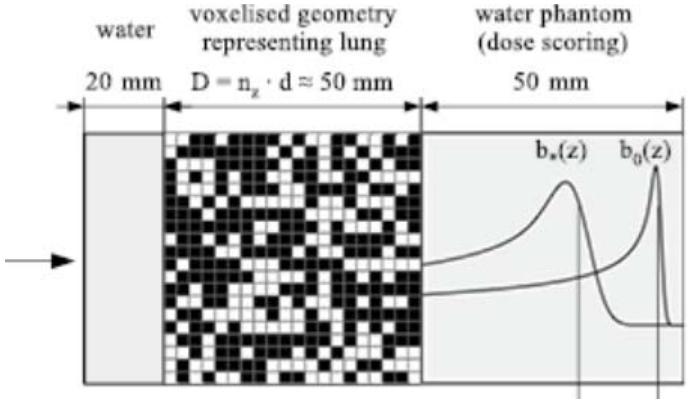


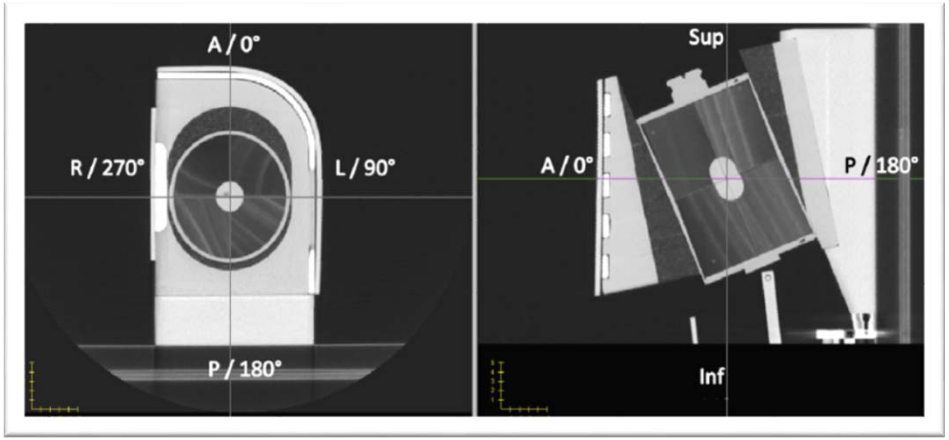
Image courtesy: N. Schreuder



Baumann et al. PMB 62, 2017

4D TREATMENT PLANNING

4D TREATMENT PLANNING STRATEGIES



- **PB**
  - 1 out of 5 centers passed acceptance criteria
- **MC**
  - 4 out of 5 centers passed acceptance criteria

International Journal of Radiation Oncology biology • physics
www.redjournal.org

Physics Contribution

Pencil Beam Algorithms Are Unsuitable for Proton Dose Calculations in Lung

Paige A. Taylor, MS, Stephen F. Kry, PhD, and David S. Followill, PhD

The Imaging and Radiation Oncology Core Houston Quality Assurance Center, The University of Texas MD Anderson Cancer Center, Houston, Texas

Received Jan 23, 2017, and in revised form May 16, 2017. Accepted for publication Jun 5, 2017.

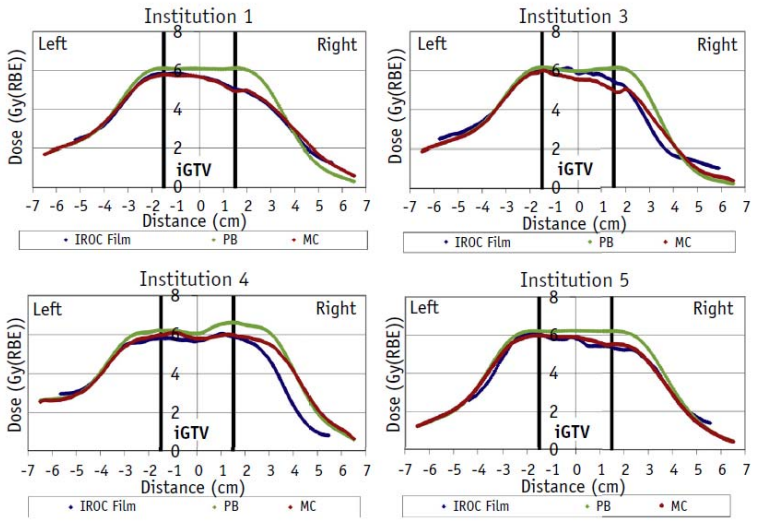


Fig. 4. Dose (relative biological effectiveness [RBE]) profiles through the center of the planning target volume in the left-right direction of the film measurements (blue), analytic pencil beam (PB) algorithm (green), and Monte Carlo (MC) recalculation (red). See Figure 2 for institution 2 profile. *Abbreviations:* iGTV = internal gross target volume; IROC = Imaging and Radiation Oncology Core.

MANY THANKS!

TEAM WORK