Heavy Ion Therapy Research Integration

The open-source dose calculation and treatment planning toolkit matRad
An Introduction

NIKLAS WAHL

HANS-PETER WIESER

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Heavy Ion Therapy
Masterclass school

The open-source dose calculation and treatment planning toolkit matRad: An Introduction

Niklas Wahl

Group Radiotherapy Optimization
Department of Medical Physics in Radiation Oncology

DKFZ Heidelberg

Hans-Peter Wieser

Experimental Physics – Medical Physics
Ludwig-Maximilians-Universität München

Treatment Planning

- computerized process
- dose is numerically simulated and optimized

Commercial solutions are closed systems (Black Box)

Research needs flexible, accessible software

matRad

Examples for current projects:

- Biological Optimization
  (RBE, effect, (N)TCP, mixed-modality)
- Probabilistic dose calculation & optimization

→ low-level access to dose calculation / optimization needed

github SOCIAL CODING

What is matRad ?

- toolkit for three-dimensional intensity-modulated treatment planning for photons, protons and carbon ions

- (Almost) entirely written in Matlab & open source

- matRad implements well-established radiotherapy algorithms for research & education

Properties:

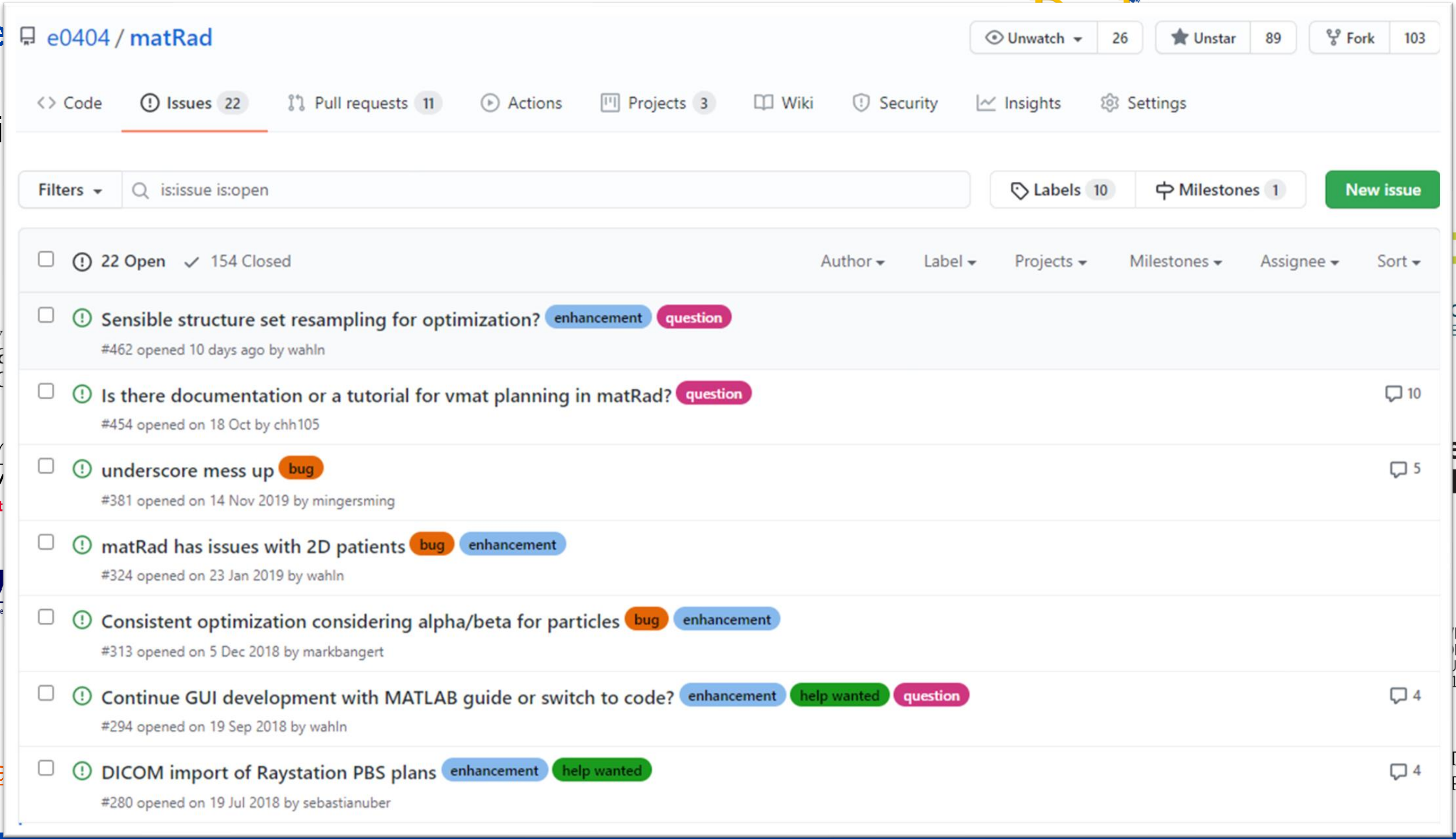
- **open-source code, patients and machine files on GitHub**
- **graphical user interface**
- **Non-linear constrained dose optimization (IPOPT)**
- **Import & export functionalities (DICOM, binary formats)**
- **No Matlab? → Octave compatibility & downloadable standalone**

Why? Supporting open science, reproducibility and education

www.matrad.org

More

- Gi



http://ma

Team

BA 2279/3-1

Development team @ dkfz

Niklas Wahl
Lucas Burigo
Oliver Jäkel
Ahmad Neishabouri
Amit Ben Antony Bennan
Noa Homolka
Paul Meder
Martina Palkowitsch
Pia Stammer
Wael Kheshfeh
Rizka Yulvina
Jeremias Kunz

HIT cooperation

Benjamin Ackermann
Swantje Ecker
Malte Ellerbrock
Andrea Mairani
Thomas Tessonnier

Alumni

Mark Bangert
Hans-Peter Wieser
Eduardo Cisternas
Nelly Abbani
Cindy Herman
Thomas Klinge
Verena Böswald
Henning Mescher
Alexander Stadler
Guiseppe Pezzano
Lucas-Raphael Müller
Hubert Gabrys
Silke Ulrich
Oliver Schrenk

Advisors

Martin Siggel
Peter Ziegenhein

Main features of matRad

- 3D dose calculation (validated)

  Photons: SVD pencil-beam algorithm + sequencing
  Protons: Pencil-Beam algorithm + const. RBE
  Carbon ions: Pencil-Beam algorithm + biol. effect / RBE

- Base data

  Patient data (CORT data set) & DICOM Import

  Physical (& biological) base data for photon LINAC as well as a proton and a carbon machine

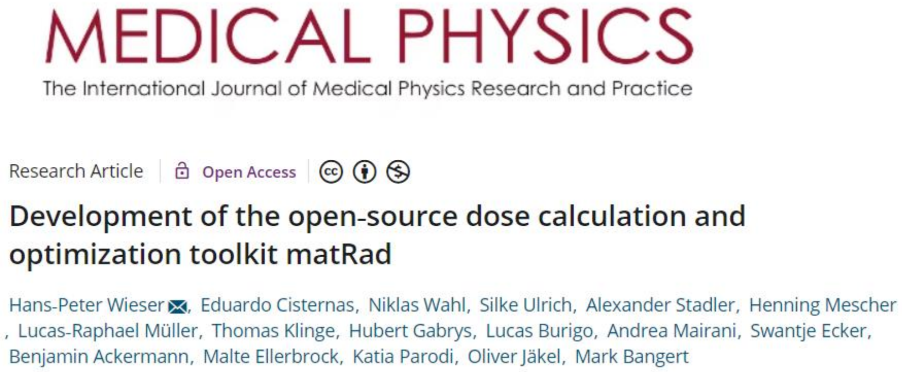
- Inverse planning with new optimization interface

  Photons: Physical dose optimization & DAO

  Protons: + Constant RBE optimization

  Carbon-ions: + RBE (1.1 or variable) or effect optimization

- Scripting & Graphical User Interface
- Standalone executable (GUI only) using the Matlab Runtime for non-Matlab users

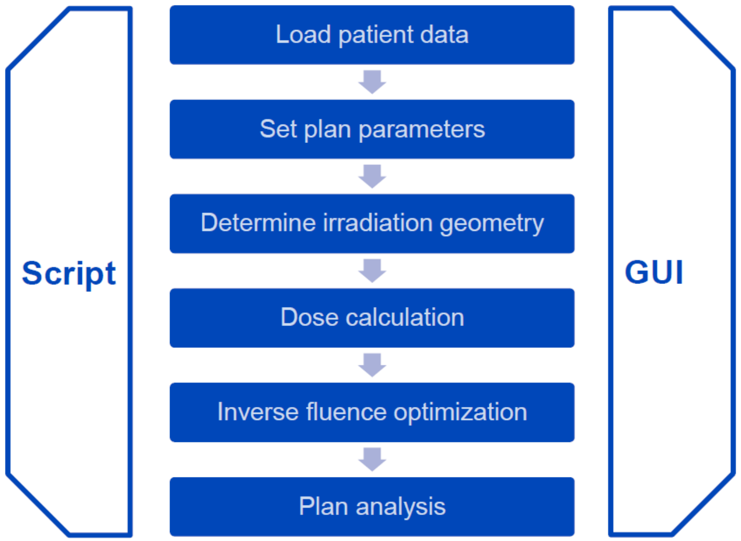

MEDICAL PHYSICS
The International Journal of Medical Physics Research and Practice

Research Article | Open Access

Development of the open-source dose calculation and optimization toolkit matRad

Hans-Peter Wieser, Eduardo Cisternas, Niklas Wahl, Silke Ulrich, Alexander Stadler, Henning Mescher, Lucas-Raphael Müller, Thomas Klinge, Hubert Gabrys, Lucas Burigo, Andrea Mairani, Swantje Ecker, Benjamin Ackermann, Malte Ellerbrock, Katia Parodi, Oliver Jäkel, Mark Bangert

Wieser et al., 2017, Med Phys 44(6)



Inverse dose optimization

$$\min_{w \in \mathbb{R}^B} f(w) = \sum_n p_n f_n(w)$$

$$\text{s.t.} \quad c_k^l \leq c_k(w) \leq c_k^u$$

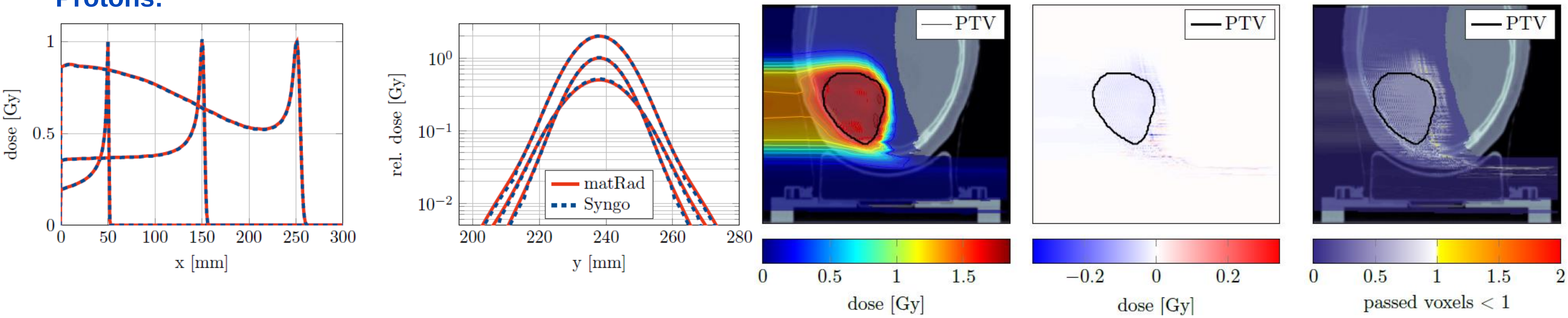
$$0 \leq w$$

- **`IPOPT`** – open-source interior-point optimizer for non-linear constrained optimization
- **`fmincon`** – (Matlab Optimization Toolbox)

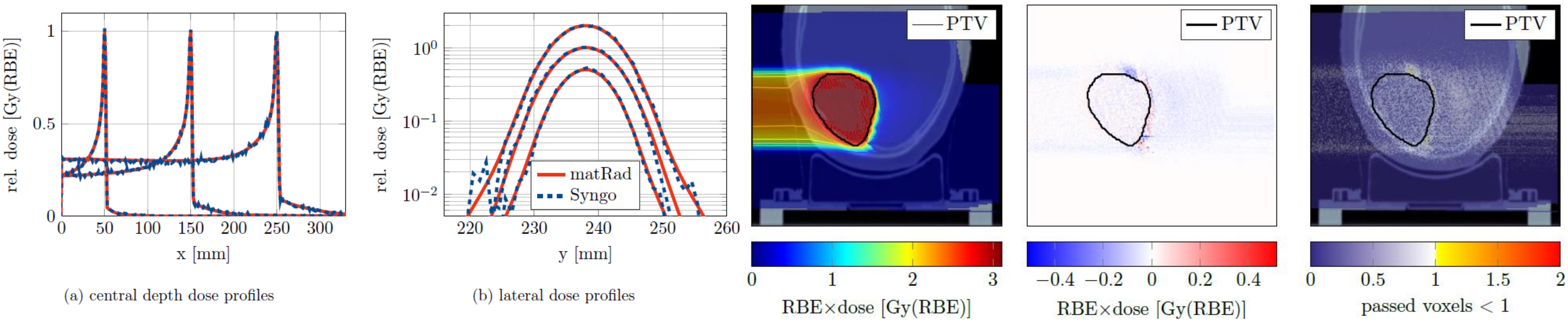
objectives	constraints
$f_{sq\,deviation} = \frac{1}{N_S}\sum_{i\epsilon S}(d_i - \hat{d})^2$	
$f_{sq\,under\,dosage} = \frac{1}{N_S}\sum_{i\epsilon S}\Theta(\hat{d} - d_i)(d_i - \hat{d})^2$	$c_{min\,dose} = d_{min} - \kappa\,log\left(\sum_{i\epsilon S} e^{\frac{d_{min}-d_i}{\kappa}}\right)$
$f_{sq\,over\,dosage} = \frac{1}{N_S}\sum_{i\epsilon S}\Theta(d_i - \hat{d})(d_i - \hat{d})^2$	$c_{max\,dose} = d_{max} + \kappa\,log\left(\sum_{i\epsilon S} e^{\frac{d_i-d_{max}}{\kappa}}\right)$
$f_{mean} = \frac{1}{N_S}\sum_{i\epsilon S} d_i$	$c_{mean} = \frac{1}{N_S}\sum_{i\epsilon S} d_i$
$f_{EUD} = \left(\frac{1}{N_S}\sum_{i\epsilon S} d_i^a\right)^{\frac{1}{a}}$	$c_{EUD} = \left(\frac{1}{N_S}\sum_{i\epsilon S} d_i^a\right)^{\frac{1}{a}}$
$f_{min\,DVH} = \frac{1}{N_S}\sum_{i\epsilon S}\Theta(\hat{d} - d_i)\Theta(d_i - \tilde{d})(d_i - \hat{d})^2$	$c_{min\,DVH} = \frac{1}{N_S}\sum_{i\epsilon S}\Theta(\hat{d} - d_i)$
$f_{max\,DVH} = \frac{1}{N_S}\sum_{i\epsilon S}\Theta(d_i - \hat{d})\Theta(\tilde{d} - d_i)(d_i - \hat{d})^2$	$c_{max\,DVH} = \frac{1}{N_S}\sum_{i\epsilon S}\Theta(d_i - \hat{d})$

Validation against Syngo Siemens - γ-index > 99.67% (2%,2%)

Protons:



Carbon Ions:



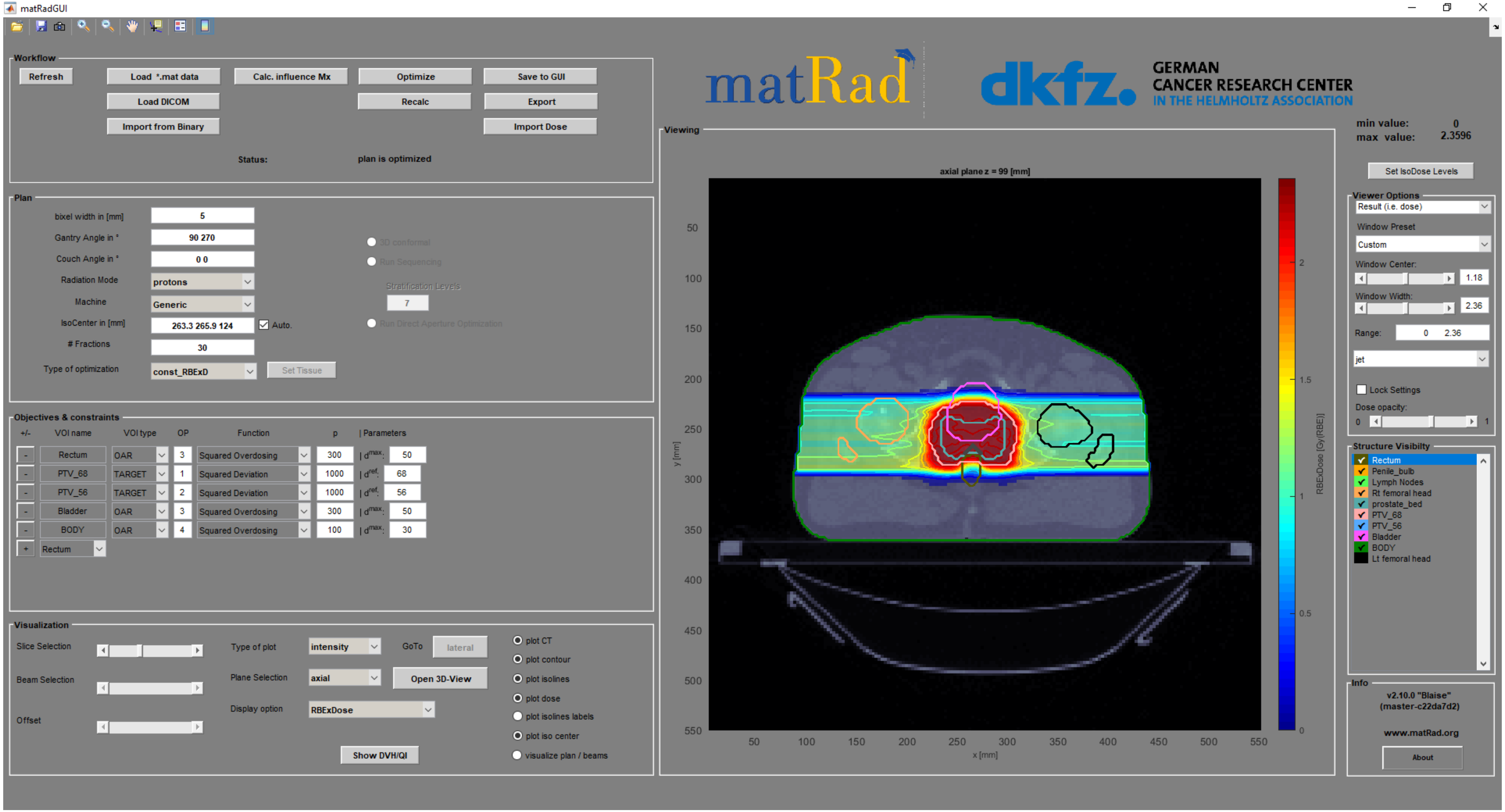
(a) central depth dose profiles

(b) lateral dose profiles

Performance of matRad - Intel Core i7 2.8 GHz, 32 GB RAM

modality -	setting	#beams	#bixel	D_{ij} elem. [1e6]	D_{ij} size [GB]	t_{dose} [s]	#iter.	t_{opt} [s]
photons	82 mm D_{ij} samp.	4	2608	172	2.75	295	145	82
photons	40 mm no samp.	4	2608	99	1.59	101	143	44
photons	82 mm D_{ij} samp.	8	3877	426	6.81	741	51	140
photons	40 mm no samp.	8	3877	236	3.77	226	51	66
photons	40 mm D_{ij} samp.	72	13597	567	9.07	853	147	407
protons	99.75 % SG	1	7797	19	0.29	22	123	41
protons	99.75 % DG	1	5955	87	1.38	46	171	109
protons	99.75 % SG	3	28097	56	0.89	68	67	187
protons	99.75 % DG	3	24137	269	4.30	160	262	330
protons	99.75 % SG	2	45574	116	1.86	97	218	137
protons	99.75 % DG	2	27683	520	8.33	299	197	486
carbon	99.75 % SG	1	11780	160	2.55	67	72	92
carbon	99.75 % DG	1	9963	537	8.61	203	79	225
carbon	99.75 % SG	3	42810	411	6.68	310	117	193
carbon	99.75 % DG	3	31205	756	12.1	560	107	365
carbon	99.75 % SG	2	24612	336	5.88	137	177	273
carbon	99.50 % DG	2	16889	855	17.94	472	134	521

Throughput Optimization: 6 GB/s


matRadGUI
Workflow
Refresh
Load *.mat data
Calc. influence Mx
Optimize
Save to GUI
Load DICOM
Recalc
Export
Import from Binary
Import Dose
Status:
plan is optimized
Plan
bixel width in [mm]
5
Gantry Angle in °
90 270
Couch Angle in °
0 0
Radiation Mode
protons
Machine
Generic
IsoCenter in [mm]
263.3 265.9 124
Auto.
Fractions
30
Type of optimization
const_RBExD
Set Tissue
3D conformal
Run Sequencing
Stratification Levels
7
Run Direct Aperture Optimization
Objectives & constraints
+/- VOI name VOI type OP Function p | Parameters
Rectum OAR 3 Squared Overdosing 300 50
PTV_68 TARGET 1 Squared Deviation 1000 68
PTV_56 TARGET 2 Squared Deviation 1000 56
Bladder OAR 3 Squared Overdosing 300 50
BODY OAR 4 Squared Overdosing 100 30
Visualization
Slice Selection
Beam Selection
Offset
Type of plot
intensity
GoTo
lateral
Plane Selection
axial
Open 3D-View
Display option
RBExDose
Show DVH/QI
plot CT
plot contour
plot isolines
plot dose
plot isolines labels
plot iso center
visualize plan / beams
matRad
dkfz.
GERMAN CANCER RESEARCH CENTER
IN THE HELMHOLTZ ASSOCIATION
Viewing
axial plane z = 99 [mm]
y [mm]
x [mm]
RBExDose [Gy(RBE)]
min value: 0
max value: 2.3596
Set IsoDose Levels
Viewer Options
Result (i.e. dose)
Window Preset
Custom
Window Center:
1.18
Window Width:
2.36
Range:
0 2.36
jet
Lock Settings
Dose opacity:
Structure Visibility
Rectum
Penile_bulb
Lymph Nodes
Rt femoral head
prostate_bed
PTV_68
PTV_56
Bladder
BODY
Lt femoral head
Info
v2.10.0 "Blaise"
(master-c22da7d2)
www.matRad.org
About

dkfz.

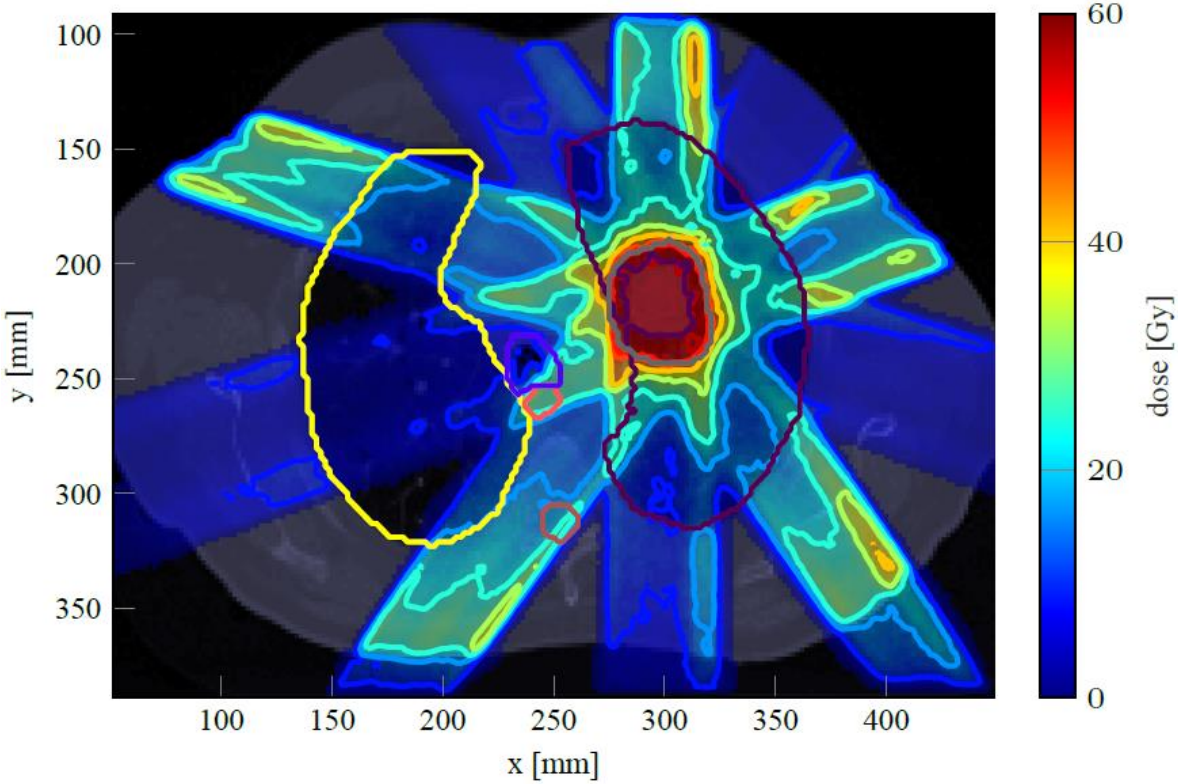
Developments for the last release: 2.10.1 “Blaise”

- Decoupled computation grids

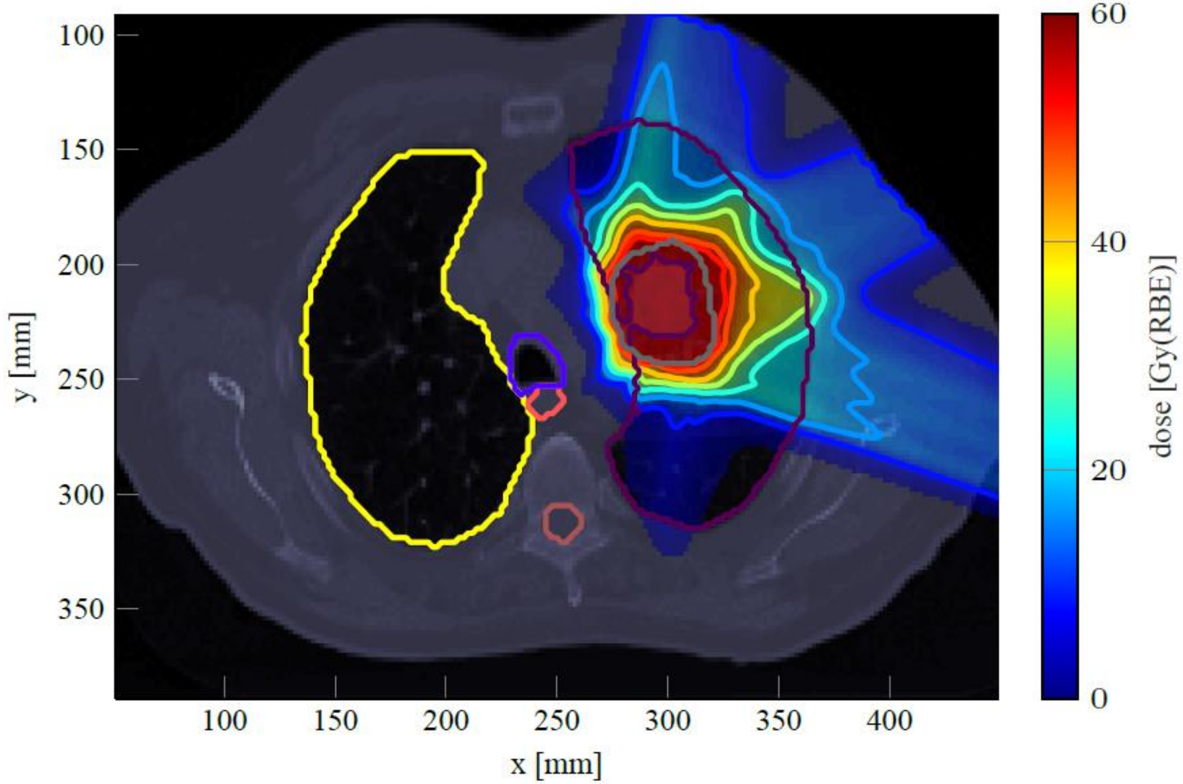
  → Independent resolutions for CT, dose calculation, optimization
- Extendable optimization interface

  → Simple addition of optimizers and objectives / constraints
- Automated testing (TravisCI & Azure DevOps)
- Interfaces to Monte Carlo engines
  - Photons: ompMC
  - Protons: MCsquare
- Bug fixes, additional configuration parameters, etc.

matRad 2.10.1: Novel developments – Basic open-source Monte Carlo Interfaces



- Photon plan with ompMC
- 1e5 histories/beamlet, 654 beamlets
- 25 min at (2.5mm)³ resolution



- Proton plan with MCsquare
- 2e4 histories/beamlet, 4689 beamlets
- 120 min at (2.5mm)³ resolution

Evaluated on Desktop PC, i7-6700 @ 3.4 GHz (4 cores +HT)

Current Developments & Research Projects at DKFZ

“Classical” Software Development:

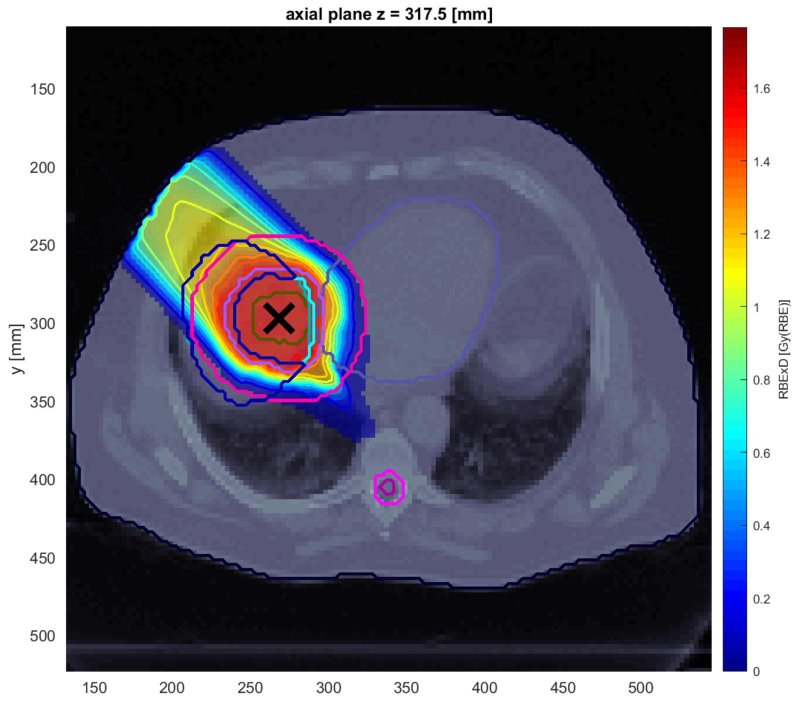
- Unit Testing Framework for Core Functionality
- Comprehensive bi-directional Python Binding
- Refactoring code for modularization

From research:

- NTCP models & optimization
- Carbon Monte Carlo & Lung degradation
- Joint / mixed-modality / spatio-temporal optimization
- Proton FLASH Planning & Tools
- Superiorization for Inverse Planning

Open Development & Research Branches

- Helium base data (physical & biological)
  -dev_varRBErobOpt (Hans-Peter Wieser & Uwe Titt)
- Robust / probabilistic optimization & uncertainty quantification
  -dev_varRBErobOpt (Hans-Peter Wieser et al.)
- Variable RBE & effect for protons (McNamara, Wedenberg, …)
  -dev_varRBErobOpt (Hans-Peter Wieser et al.)
- Pencil-beam fine-sampling
  -dev_fineSampling → -dev (Paul Meder)
- New GUI (Object-oriented & modular)
  -dev_classGUI (Nelly Abbani)
- External contributions:
  - VMAT -dev_VMAT, see Pull Request (Eric Christiansen)
  - optimization recently merged (Steven van de Water)

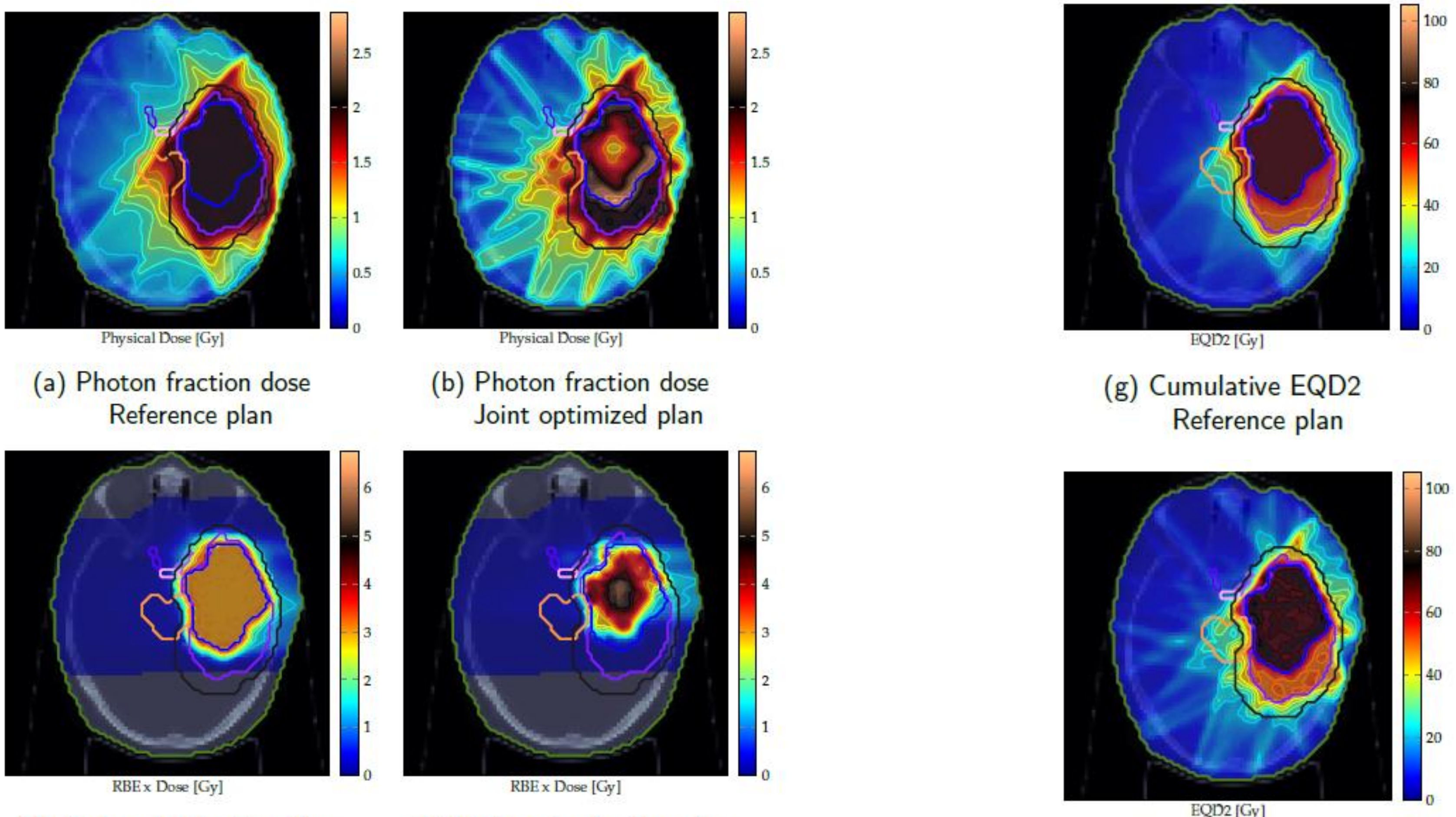


Helium Plan

- **Extended particle MC interface for particles (MCsquare & TOPAS)**
  -dev_MonteCarlo, Master Project (Paul Meder) & Noa Homolka, lot of work by Lucas Burigo

Example matRad Projects

Example Project 1: Carbon/Photon mixed-modality optimization (Amit Bennan PhD Project)



(a) Photon fraction dose Reference plan

(b) Photon fraction dose Joint optimized plan

(g) Cumulative EQD2 Reference plan

(d) Carbon ion fraction dose Reference plan

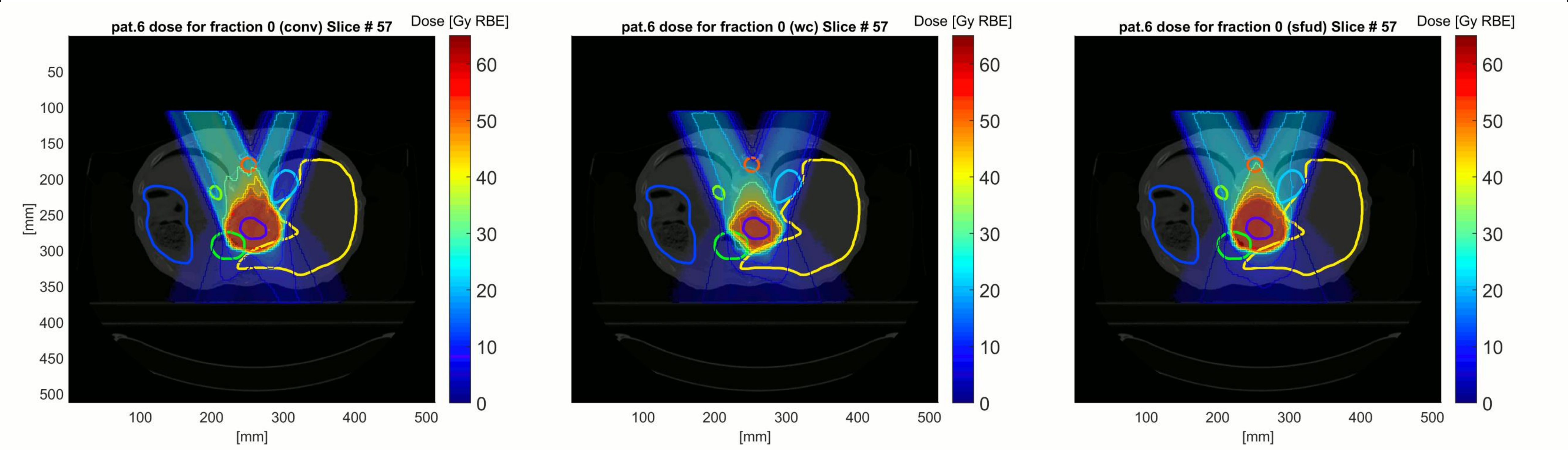
(e) Carbon ion fraction dose Joint optimized plan

(h) Cumulative EQD2 Joint optimized plan

→ Implementation in matRad facilitates adjoint/follow-up student projects

Example Project 2: Robust optimization for interfractional motion

conventional | Worst case | SFUD



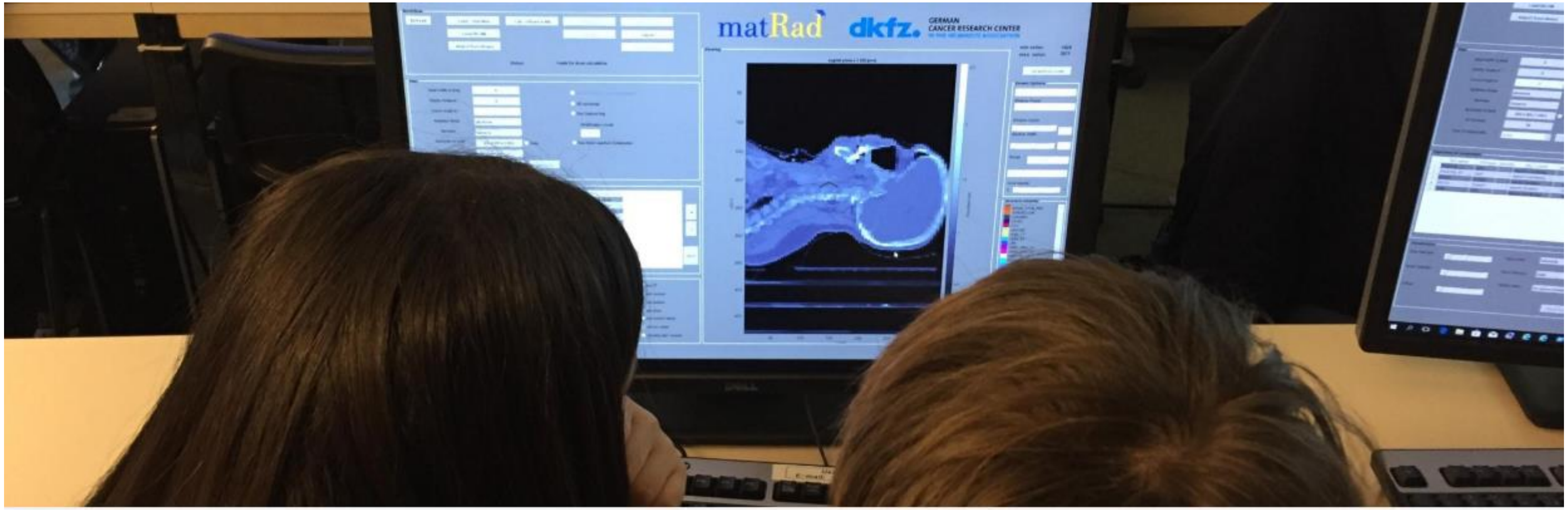
J Steitz, P Naumann, S Ulrich, MF Haefner, F Sterzing, U Oelfke & M Bangert. (2016). Worst case optimization for interfractional motion mitigation in carbon ion therapy of pancreatic cancer. *Submitted to Radiation Oncology*

→ Brought (voxel-wise) worst case optimization to matRad

Example Education & Outreach: Particle Therapy Master Class

- Part of the “International Masterclasses – Hands on Particle Physics” (https://physicsmasterclasses.org/)
- Educational course for school children
- Introduced by DKFZ/GSI/CERN (Main coordination: Yiota Foka)

  → First successful stresstests in April 2019 & 2021



Conclusion

- matRad is an open-source treatment planning toolkit with focus on **research** & **education**
- Used within **internal & external** research projects / collaborations
- **Dose calculation** & **treatment planning** for photons, protons, helium and carbon (including base data & data import)
- **Active development** (internal & external)
  - Monte Carlo interfaces
  - new modalities / optimization techniques
- Efforts in **professionalizing** software development (i. e., continuous integration)

How to get going with matRad?

1. Go to our page on GitHub: **www.matRad.org**

2. Download standalone or code, or even better: Familiarize with **git** and clone

3. Checkout the UI & the code
   - `matRadGUI.m` & `matRad.m`
   - many examples in the `examples/` folder
   - Wiki on GitHub: **https://github.com/e0404/matRad/wiki**

4. Ask for help & join the community on GitHub

5. Use for your research (and contribute)!

www.matrad.org

matRad

Data IO

DICOM

*.nrrd, *.mha, *.vtk

CERR

VOXELPLAN

Dose calculation

Photons

- SVD pencil beam
- ompMC interface

Particles

- IMPT pencil beam
- MCSquare & TOPAS interface
- → incl. phase space approx.
- Analytical probabilistic modeling

Analysis & visualization

GUI CT & dose distribution browser

Dose statistics

DVHs

Dose optimization

Fluence and experimental direct aperture optimization

IPOPT https://projects.coin-or.org/Ipopt

Matlab’s proprietary fmincon

Objectives: Quad. dose deviation, mean dose, EUD, DVH

Constraints: Min, max, mean dose, EUD, DVH

Xia, Engel, Siochi MLC sequencer

Robust and stochastic optimization

Variable RBE optimization for protons

Coverage based optimization

Base data

Patient data (CT & RTSS)

Photon pencil beam base data
→ Can be generated from measurements

Generic proton and carbon ion pencil beam base data

Carbon ion biological base data (LEM IV)

Helium pencil beam base data

Helium biological model

Thank you for your attention!

THANK YOU

Heavy Ion Therapy Research Integration

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