August 1, 2023
Loma Linda Workshop

Version 3 of the open-source radiotherapy dose calculation and treatment

matRad

Beyond nominal dose calculation and optimization

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Group Radiotherapy Optimization @ DKFZ

Embedded in the **Department of Medical Physics in Radiation Oncology** (Prof. Jäkel)

- 1 PostDoc
- 5(+2) PhD students
- 1 M. Sc. Student
- 1 B. Sc. Student
- 1 HiWi

Group Picture: G. Stanic, C. Sepulveda, R. Cristoforetti, T. Becher, S. Facchiano, J. Hardt, A.B.A. Bennan, N. Wahl
Not in picture: P. Stammer, T. Ortkamp, L. Bucher

Website: www.dkfz.de/radopt

Research Focus:

- **(Beyond) dose calculation**
  Biological dose calculation for particle therapy, nanodosimetry, uncertainty quantification, etc.
- **Treatment planning / optimization techniques**
  Robust & probabilistic optimization, mixed-modality optimization, (N)TCP-based planning, FLASH/dose-rate optimization
- **Data Science & AI/ML**
  Treatment outcome prediction, AI-driven dose prediction
- Developing/Maintaining the open-source planning toolkit matRad
  www.matRad.org

www.dkfz.de/radopt

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Outline

- What & Who is matRad?
- Previous releases & development
- The Coming Release (v3)
- Going further beyond dose & future developments
- How can you get started with matRad?

Treatment Planning

- is a computerized process in which the dose is numerically simulated and optimized

Commercial solutions are closed systems (Black Box)	Research needs flexible, accessible software

matRad

github SOCIAL CODING

“Basic” research, e.g.,

- Biological Optimization/Planning (RBE, effect, mixed-modality, FLASH)
- “Beyond” dose calculation & optimization (probabilistic, nanodosimetric, etc.)

needs low-level access to dose calculation / optimization!

What is matRad ?

- toolkit for three-dimensional intensity-modulated treatment planning for photons, protons and carbon ions
- Entirely written in Matlab & open source
- matRad implements well-established radiotherapy algorithms for research (prototyping) & 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**

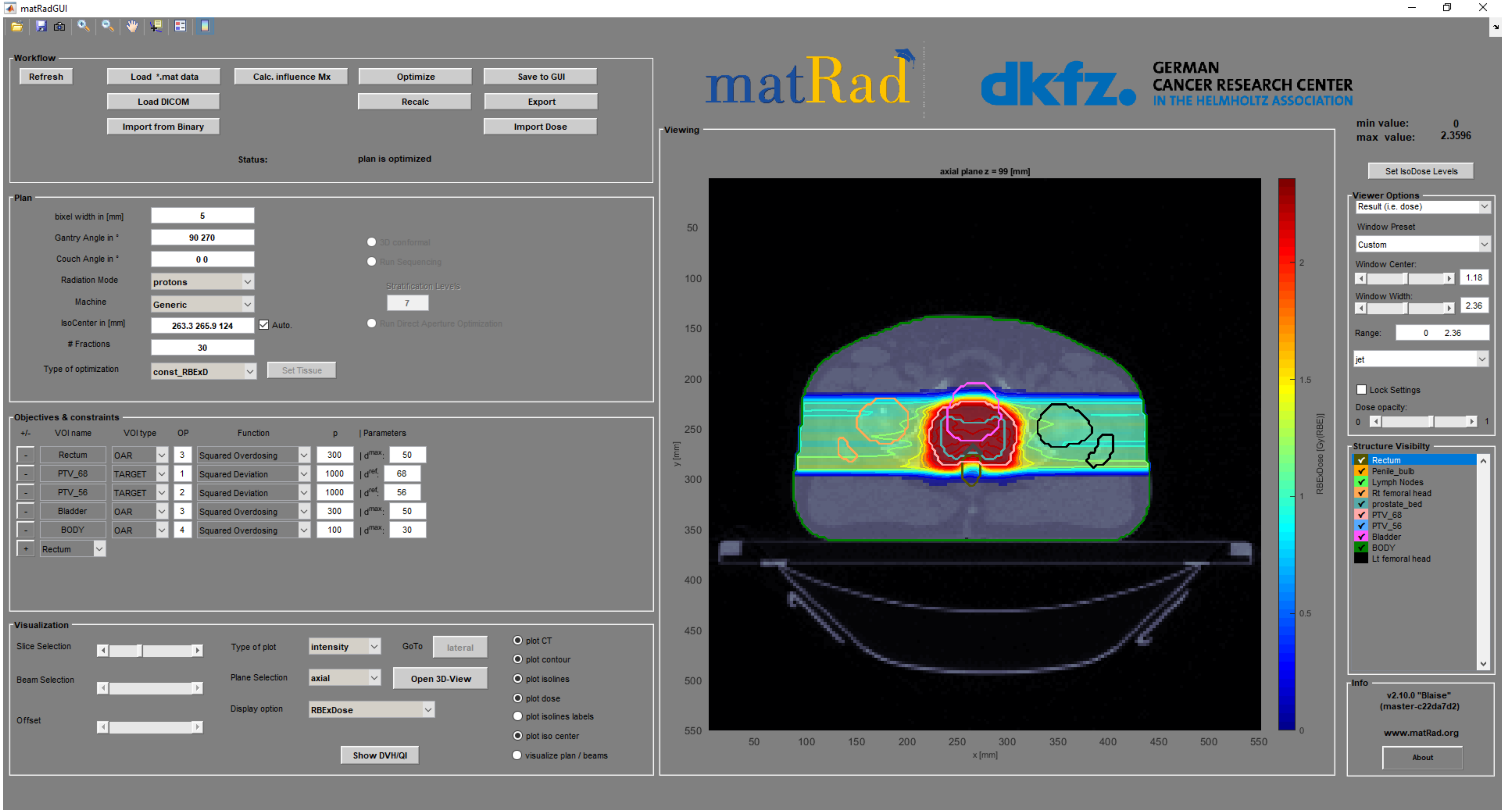
GNU Octave

GPL 3 Free Software
Free as in Freedom

GitHub

Why? Supporting open science, reproducibility and education

www.matrad.org


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 | d^max: 50
PTV_68 TARGET 1 Squared Deviation 1000 | d^ref: 68
PTV_56 TARGET 2 Squared Deviation 1000 | d^ref: 56
Bladder OAR 3 Squared Overdosing 300 | d^max: 50
BODY OAR 4 Squared Overdosing 100 | d^max: 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

Who is matRad ?

DKFZ Development team

Niklas Wahl
Amit Ben Antony Bennan
Jennifer Hardt
Remo Cristoforetti
Simona Facchiano
Tobias Becher
Noa Homolka
Oliver Jäkel

HIT cooperation

Benjamin Ackermann
Swantje Ecker
Malte Ellerbrock
Andrea Mairani

Thomas Tessonnier
Katia Parodi (LMU)

Advisors

Martin Siggel
Peter Ziegenhein

Alumni

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

Other Contributors

Eric Crhistiansen (Carleton University)
Steven van de Water (PSI)

GERMAN CANCER RESEARCH CENTER IN THE HELMHOLTZ ASSOCIATION

HIT Heidelberger Ionenstrahl-Therapiezentrum

DFG Deutsche Forschungsgemeinschaft

Project 265744405
Project 443188743

H.-P. Wieser *et al.* (all authors above in **bold**), “Development of the open-source dose calculation and optimization toolkit matRad,” *Med Phys*, vol. 44, no. 6, pp. 2556–2568, 2017, doi: 10.1002/mp.12251.

All Code Contributors: https://github.com/e0404/matRad/blob/master/AUTHORS.txt

Detailed core features of the first matRad release

- Data I/O:

  DICOM: CT, RTStruct, RTDose (RTPlan import only)
  Binary: *.mat & *.nrrd import & export, *.mha & *.vtk export

- 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

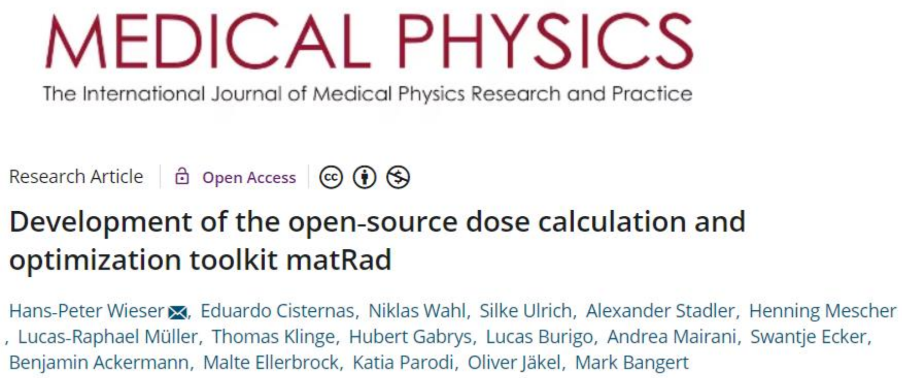
- Inverse planning with new optimization interface

  Photons: Physical dose optimization & DAO

  Protons: + Constant RBE optimization

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

- Scripting &Graphical User Interface
- Standalone executable (GUI only)

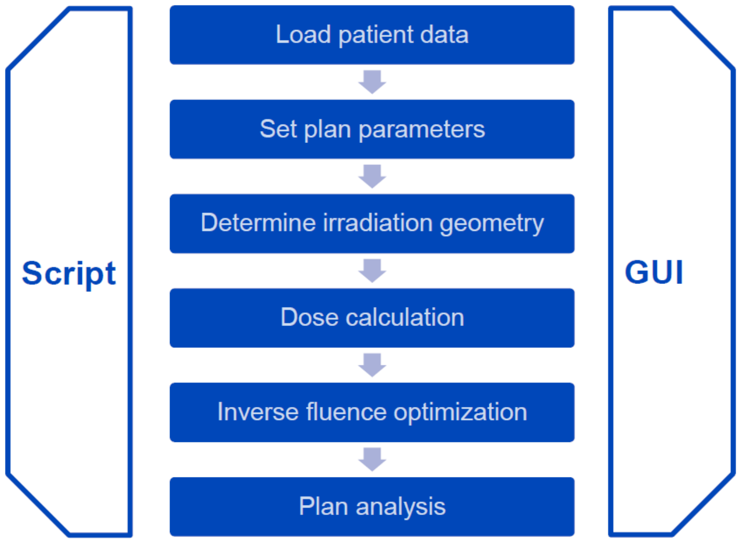

MEDICAL PHYSICS
The International Journal of Medical Physics Research and Practice

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)



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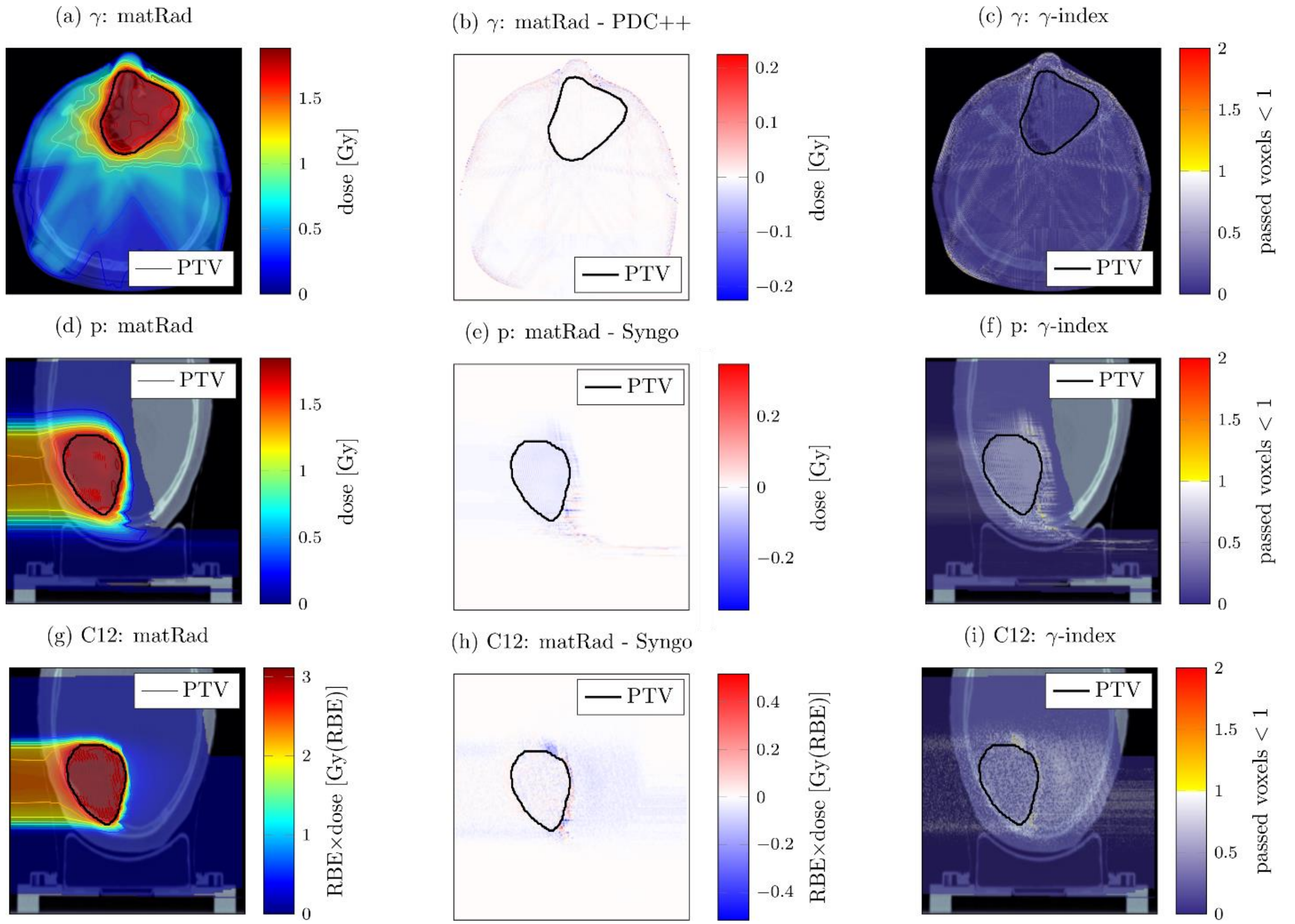
Validation of dose calculation

γ–pass rate (2%/2mm)

		γ–pass rate (2%/2mm)
Photons		99.82%
Protons		99.84%
Carbon ions		99.67%

Wieser et al. *"Development of the open-source dose calculation and optimization toolkit matRad."* Medical Physics (**2017**).

Inverse dose optimization

Non-linear constrained (Quasi-)Newton methods

- `fmincon` (Matlab‘s Optimization Toolbox)
- IPOPT (**I**nterior-**p**oint **opt**imizer for non-linear constrained optimization): https://github.com/coin-or/Ipopt - EPLv2

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

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

$$0 \leq w$$

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

Wieser et al. *"Development of the open-source dose calculation and optimization toolkit matRad."* Medical Physics (**2017**).

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

Wieser et al. *"Development of the open-source dose calculation and optimization toolkit matRad."* Medical Physics (**2017**).

More than 25 confirmed institutes somehow working with matRad

- Github-
- Citation

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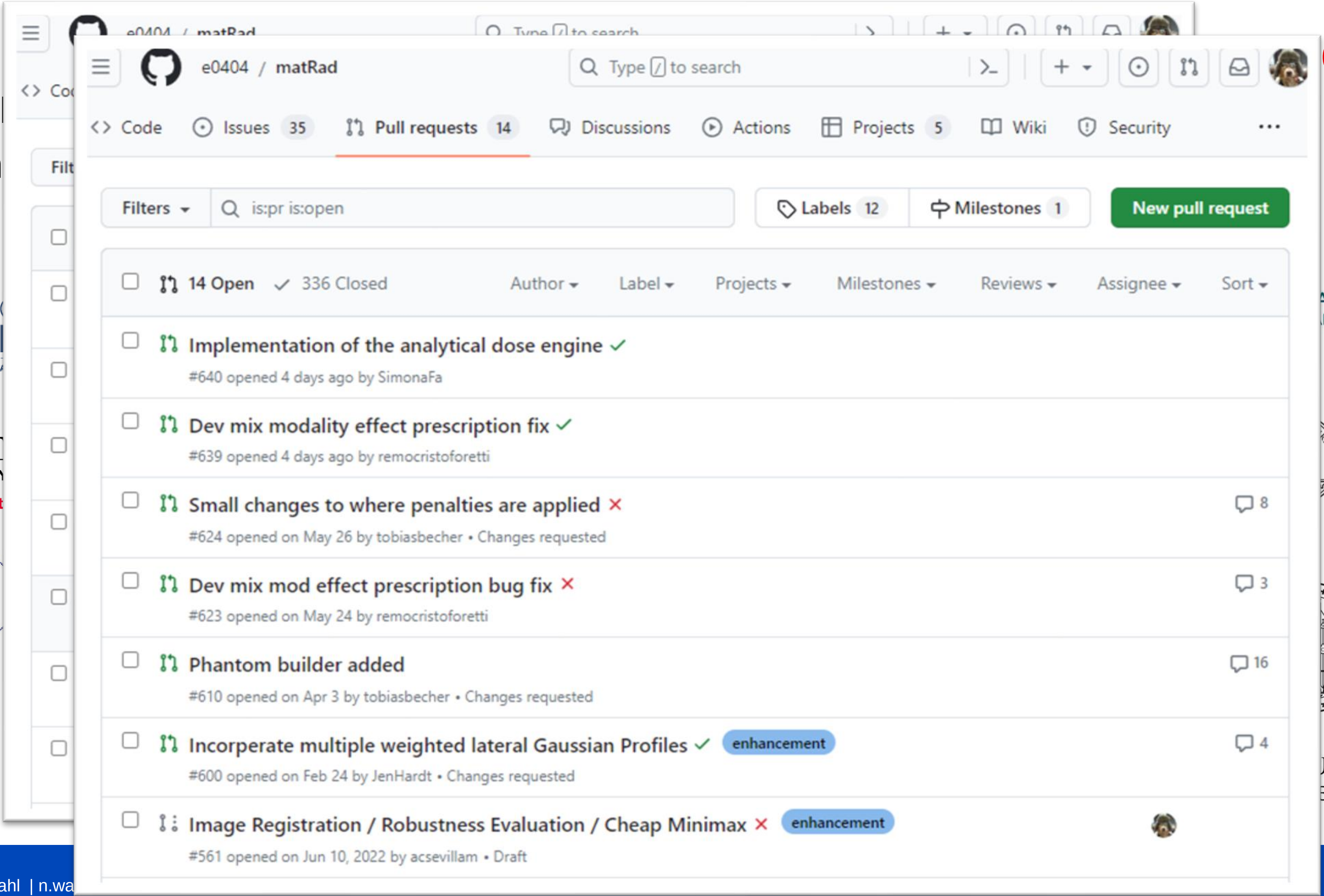

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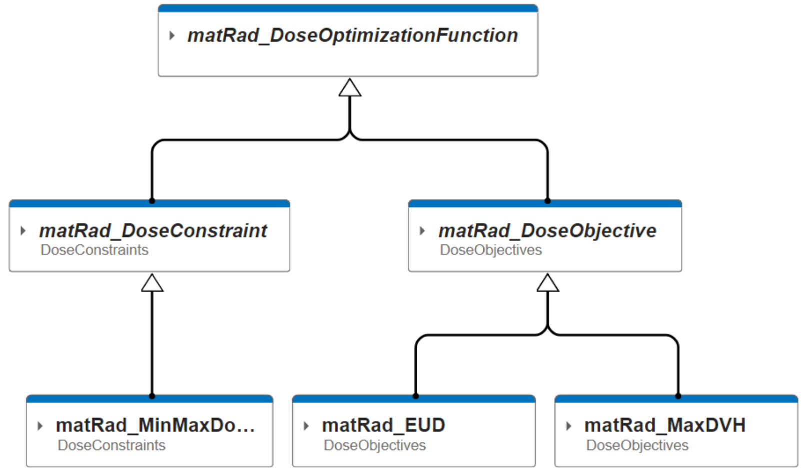
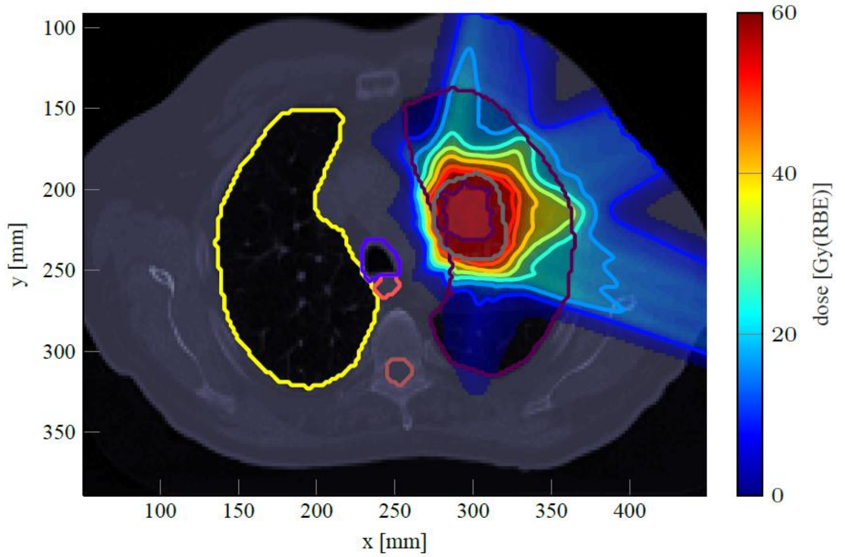
Developments for the last release: 2.10.1 “Blaise” (shown at the Workshop in 2021)

- Bug fixes, additional configuration parameters, etc.
- Independent grids (dose, CT, optimization)
- Extendable object-oriented optimization interface

  → Simple addition of optimizers and objectives / constraints
- Preliminary interfaces to Monte Carlo engines
  - Photons: ompMC - github.com/edoerner/ompMC
  - Protons: MCsquare - openmcsquare.org
- Automated testing (now GitHub Actions)





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

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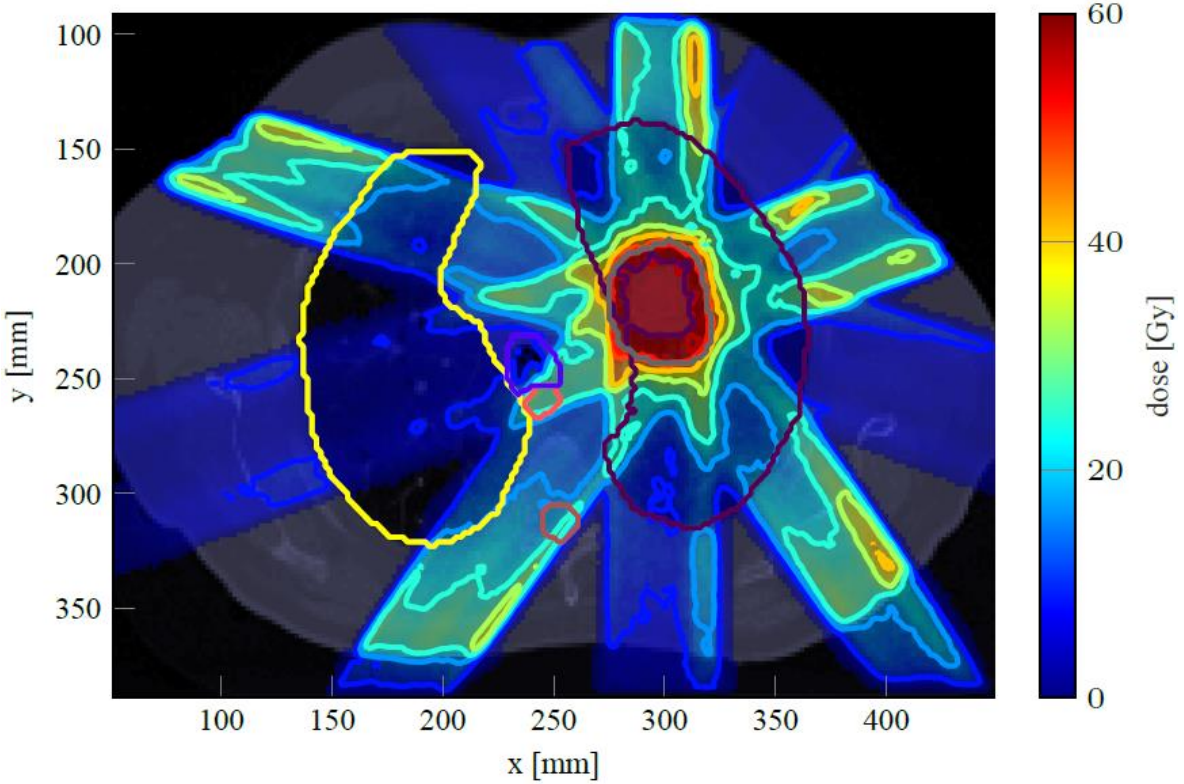
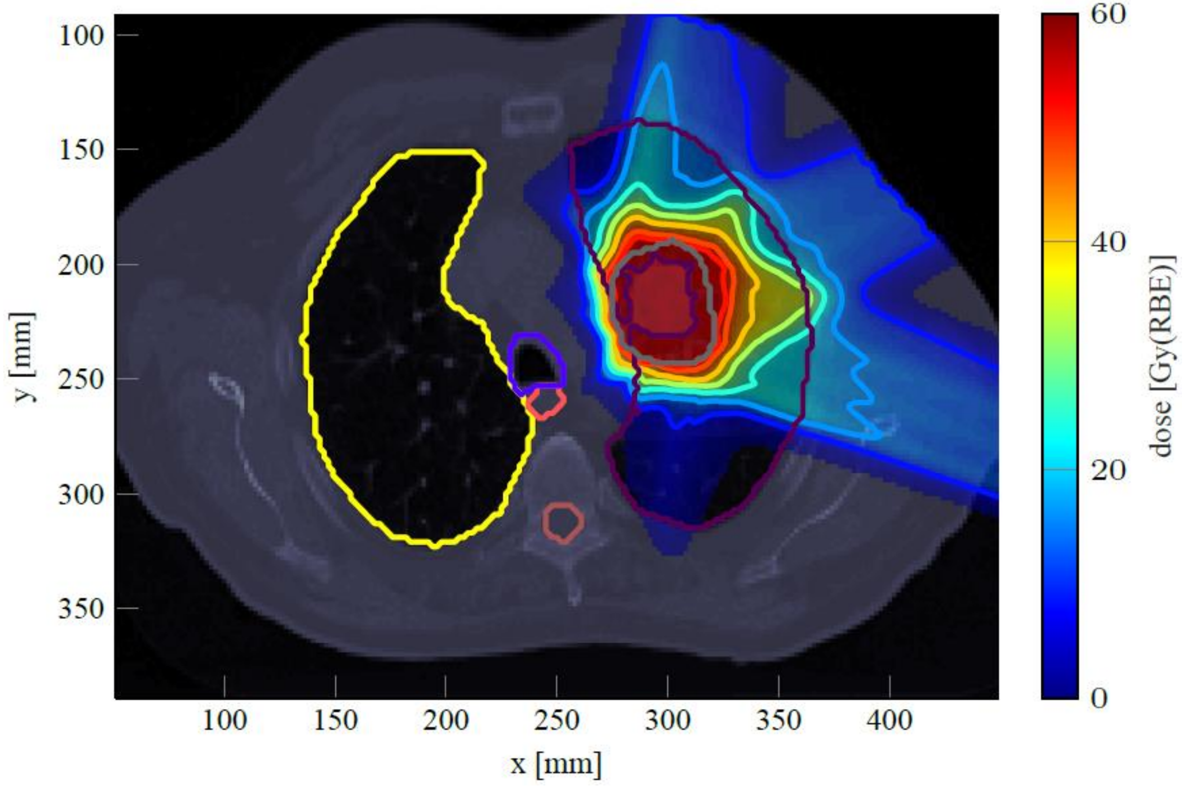
matRad 2.10.1: Novel developments – Basic open-source Monte Carlo Interfaces





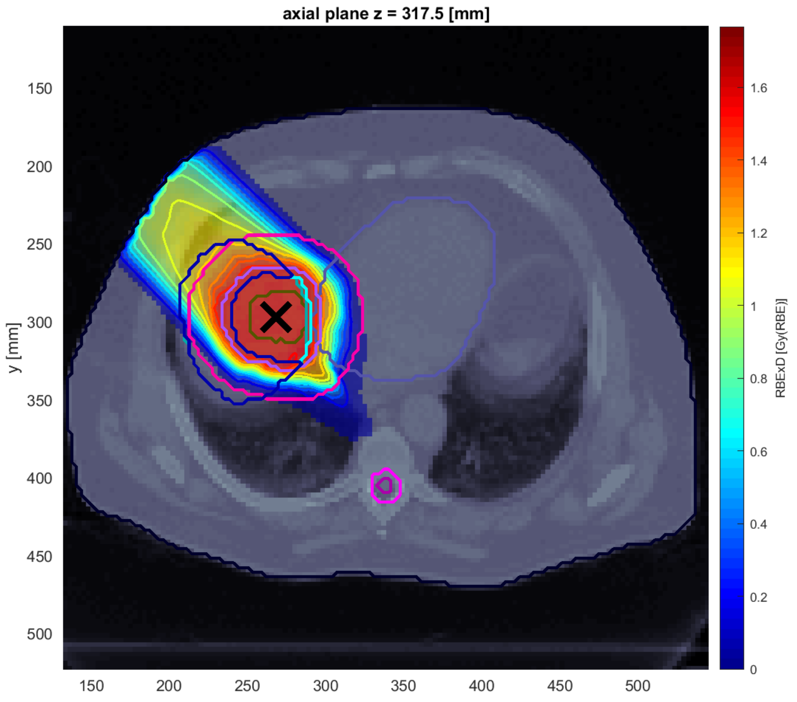
- Photon plan with ompMC
- 1e5 histories/beamlet, 654 beamlets
- 25 min at $(2.5mm)^3$ resolution

- 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)

Post 2020 Development & Research Branches (shown at the Workshop in 2021)

- Helium base data (physical & biological)*
  -dev
- Robust / probabilistic optimization & uncertainty quantification*
  -dev_varRBErobOpt
- Variable RBE & effect for protons*
  -dev_varRBErobOpt
- New GUI (Object-oriented & modular, Octave compatible)*
  -dev_classGUI
- Extended MC interfaces (e.g., TOPAS)*
  -dev_MonteCarlo
- External contributions:
  - VMAT -dev_VMAT(E. Christiansen)
  - optimization -dev_exactOpt (S. van de Water)



Helium Plan

→Sustainable research software call by (German Research Foundation, DFG)
→Funding beginning 2022 enabled us to work towards release of v3 (*)

Deutsche Forschungsgemeinschaft

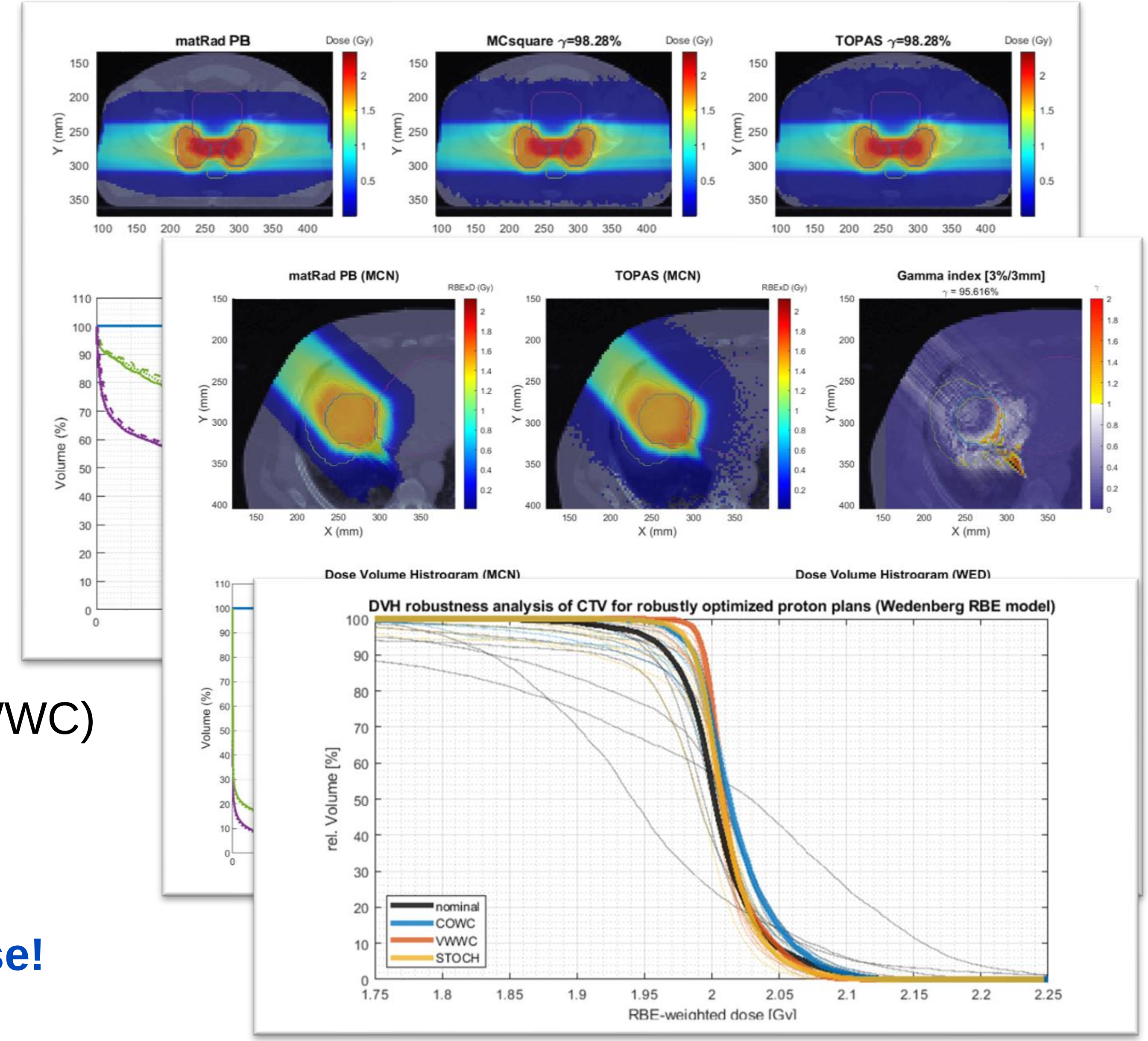
Next Release matRad v3.0.0 – Main features

- **Improved Monte Carlo dose calculation interface**
  - TOPAS + MCsquare (extendable)
  - Protons & Ions (He + C)

- **Variable (Proton) RBE-models**
  - LET-dependent models
  - Tabulated RBE models

- **Robust Optimization methods**
  - Worst-case optimization (COWC, OWC, VWWC)
  - Probabilistic optimization
  - Robustness Analysis

→ **Best Feature: Extend & Combine all of those!**

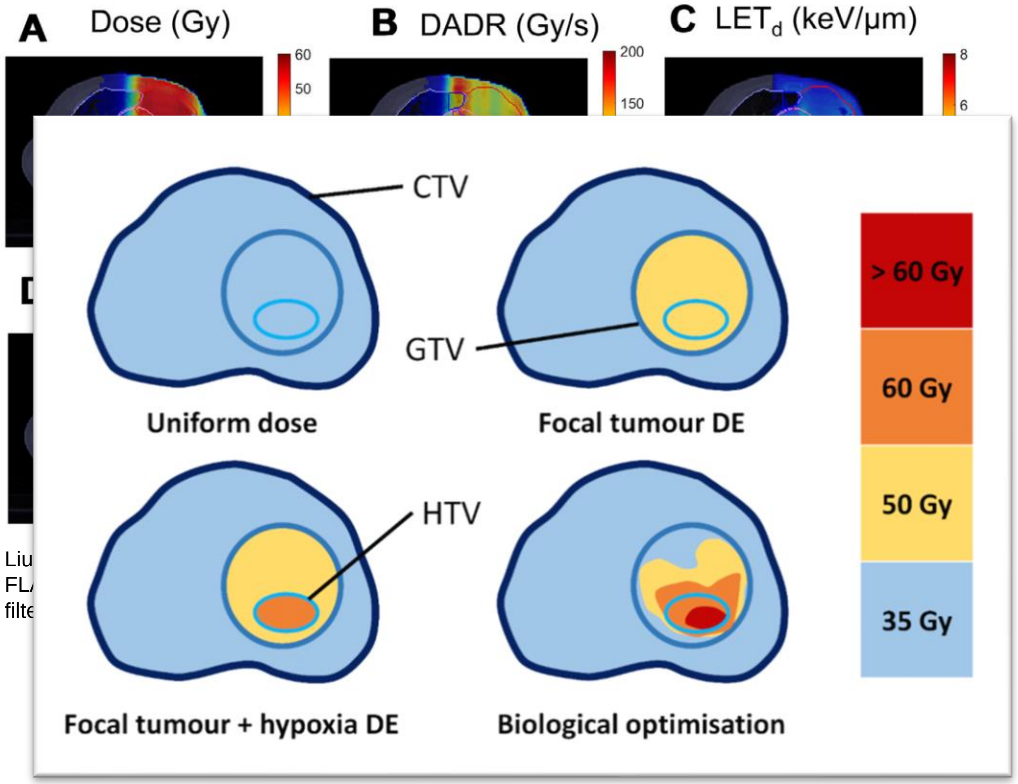


Release Candidate: https://github.com/e0404/matRad/tree/rc/v3.0.0

Current / Future Plans: Going further beyond dose?

Current research on planning with alternative quantities

- FLASH – different dose-rate concepts (DADR, IDR, PBSDR, etc.)
- Reduce sensitiveness to RBE (models)
  - LET-based optimization (LET minimization, dirty dose, etc.)
  - Micro- and nanodosimetric quantities
- Biology-guided planning
  - “dose painting” based on functional imaging
  - (voxel-based) NTCP optimization



Her EJ, Haworth A, Sun Y, et al. Biologically Targeted Radiation Therapy: Incorporating Patient-Specific Hypoxia Data Derived from Quantitative Magnetic Resonance Imaging. Cancers. 2021;13(19):4897. doi:10.3390/cancers13194897

→ matRad facilitates the addition of new quantities q for dose calculation & optimization

- data-structure for dose-like containers/matrices
- Framework for defining new objectives $f(q)$ and constraints $c(q)$
- Framework chaining fluence to the respective quantity & objectives: $\frac{\mathrm{d}f}{\mathrm{d}w} = \frac{\mathrm{d}f}{\mathrm{d}q}\frac{\mathrm{d}q}{\mathrm{d}w}$

Current / Future Plans: What about Python? – pyRadPlan

- Bidirectional Python interface to be published with next subrelease of matRad (probably v3.1)

Call matRad algorithms from Python ⟷ **Call Python algorithms from matRad**

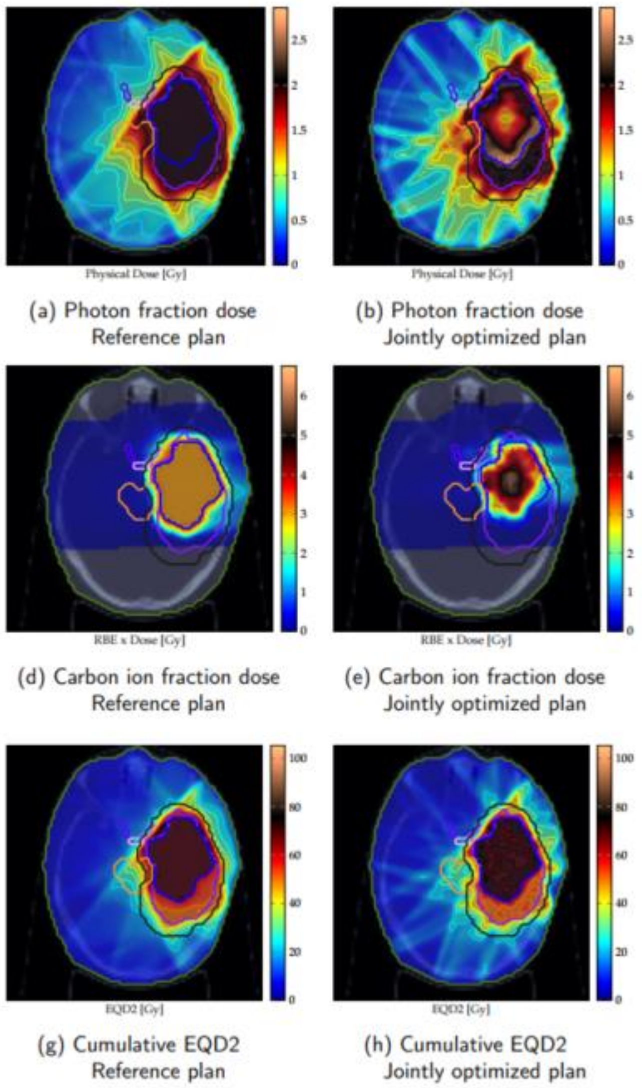
  - ➢ matRad run via MATLAB Engine API for Python, oct2py (Octave), or as compiled Python package
  - ➢ Designed to work on the high-level API of matRad (geometry generation, dose calculation, optimization/superiorization, analysis)

- pyRadPlan will also support Python native planning
  - basic geometry generation possible
  - optimization reimplemented for physical dose & constant RBE using scipy solvers or cyipopt
  - Already used in an internal research project for ML-NTCP-based optimization
  - Exploit Python's flexibility for more performance

pyanno4rt

Example Research Projects

Example Project: Joint mixed-modality planning (A. Bennan, R. Cristoforetti)



- Conventional combined modality treatments are individually optimized and summed up based on RBE weighted dose
  → Not fully exploiting the biological potential

- Simultaneous optimization of the *total treatment effect* based on the LQ-Model:

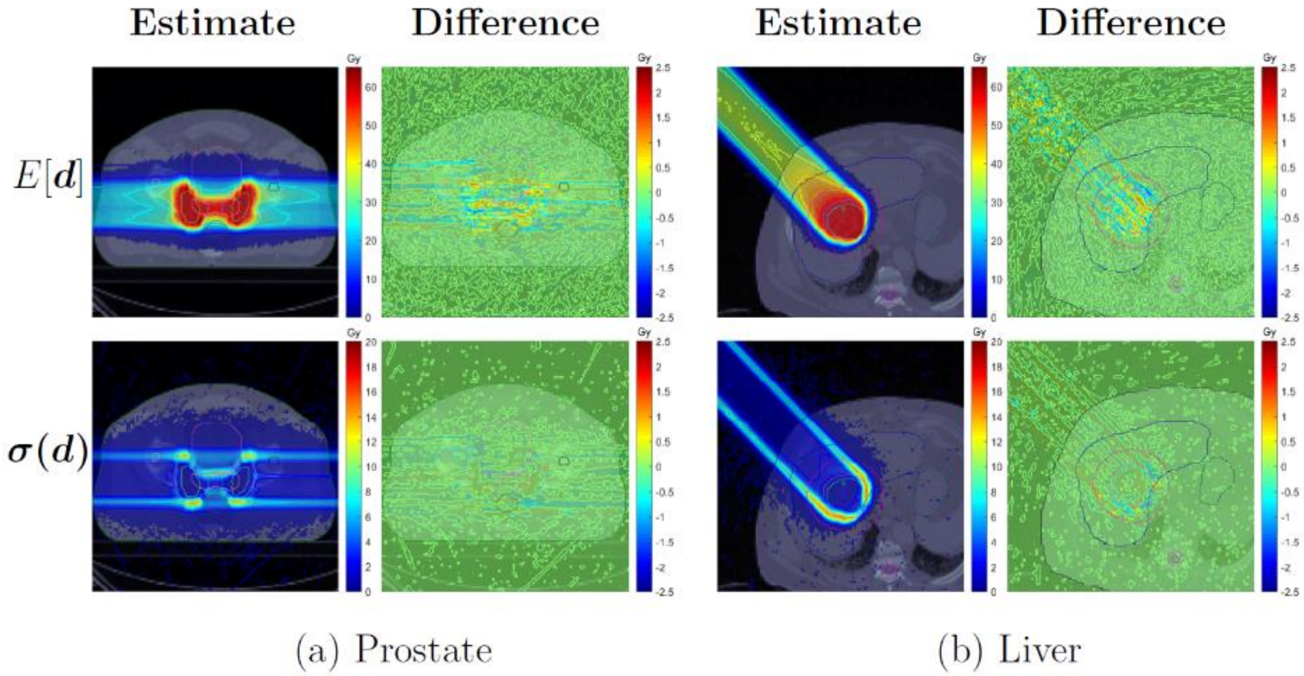
$$\varepsilon = -\ln(S) = \underbrace{n_\gamma(\alpha_\gamma d_\gamma + \beta_\gamma d_\gamma^2)}_{\text{photons}} + \underbrace{n_C(\alpha_C d_C + \beta_C d_C^2)}_{\text{carbon ions}}$$

- **Possibilities:**
  - Exploiting radiobiological properties of the modalities on a voxel-basis
  - improving conformality of biological effect in the adjacent critical structures
  - Exploiting fractionation in mixed (e.g. infiltrated) tissues

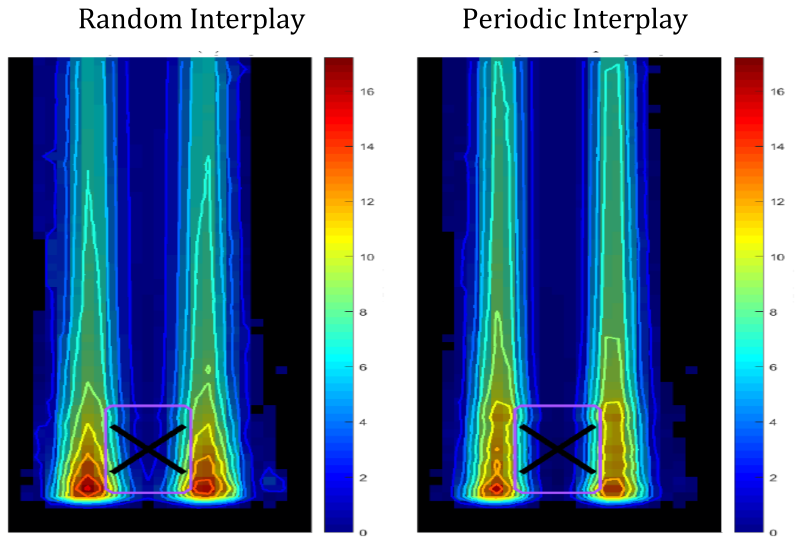
Bennan, A.B.A., Unkelbach, J., Wahl, N., Salome, P., Bangert, M., Joint optimization of photon – carbon ion treatments for Glioblastoma. *Int. J. Radiat. Oncol.*, 2021, https://doi.org/10.1016/j.ijrobp.2021.05.126

Example Project: MC Dose Uncertainty Quantification (P. Stammer, KIT / DKFZ)

- Avoid computation of explicit error / sample scenarios for robustness analysis and robust optimization with Monte Carlo codes
  → Re-weighting of histories of a single simulation for uncertainty estimation
- Input Uncertainty modeling of static & time-dependent beam application/movement patterns using pencil beam correlations



Estimates of expected dose and variance using the reweighting approach and their difference to a reference [1]



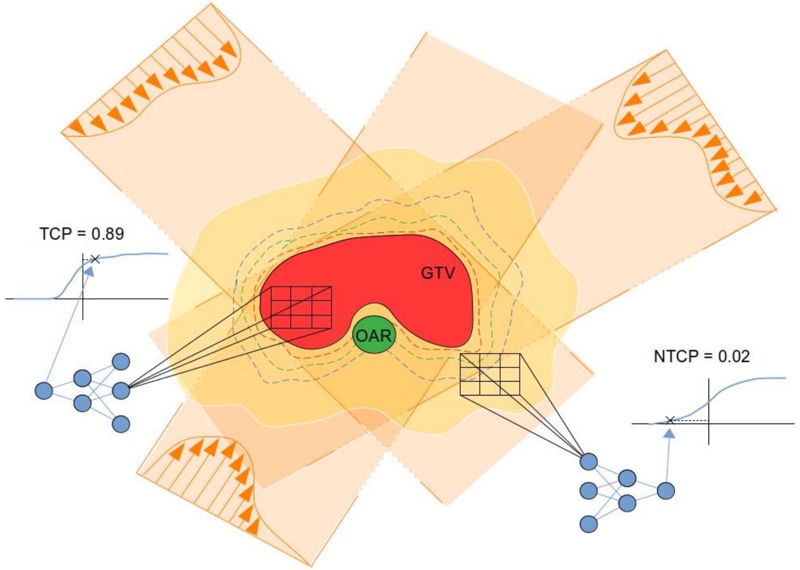
Dose standard deviation in a waterbox for random vs. periodic movement pattern / interplay during treatment

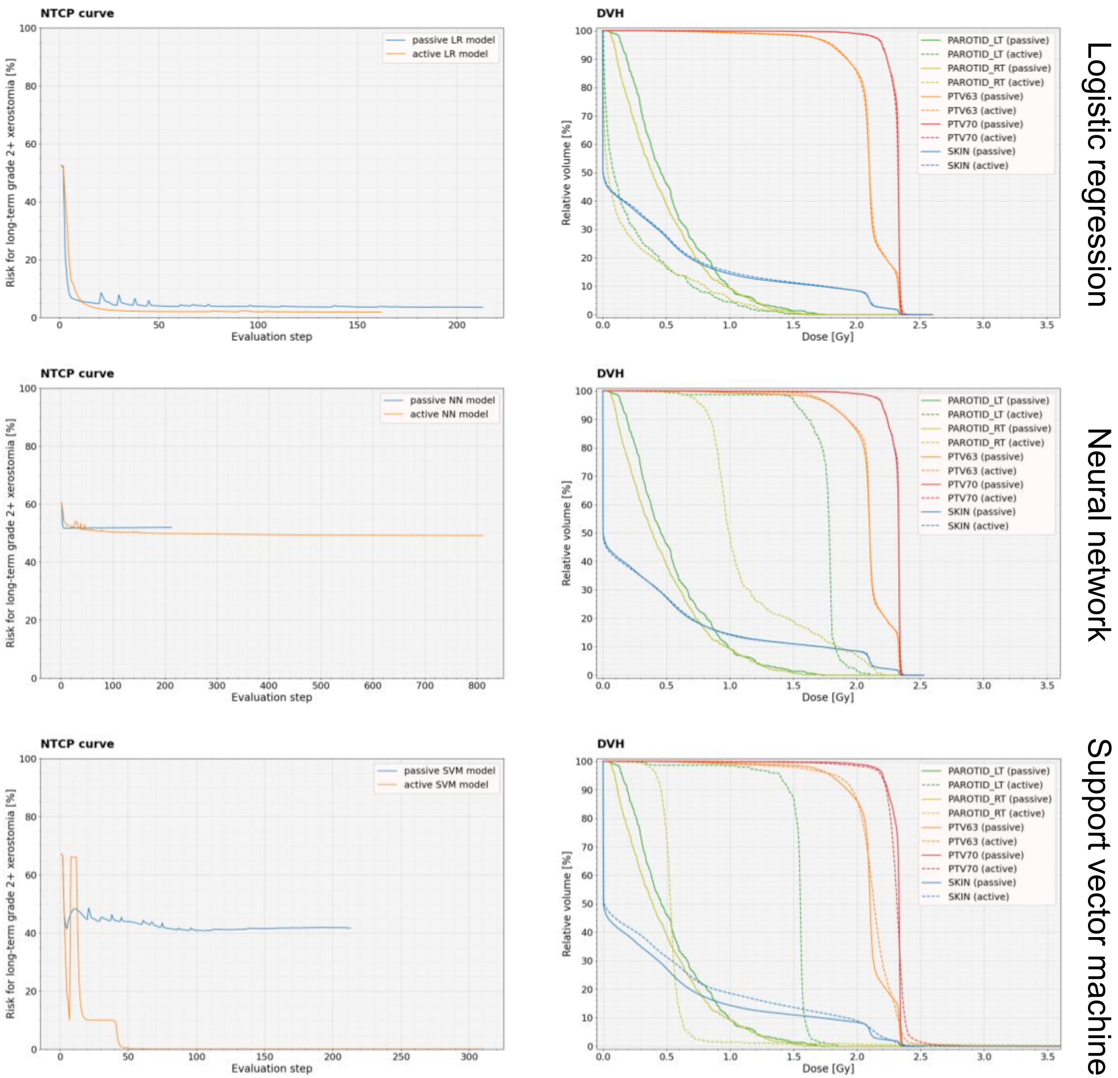
Other Involvements at KIT:

- Development of KiT-RT: A Kinetic Transport Solver for Radiation Therapy (https://github.com/CSMMLab/KiT-RT)
- (Dynamical) low rank methods for more time and space efficient UQ in radiative transport

[1]
P. Stammer, L. Burigo, O. Jäkel, M. Frank, and N. Wahl, "Multivariate error modeling and uncertainty quantification using importance (re-)weighting for Monte Carlo simulations in particle transport," *JCP* 2023;473:111725, doi: 10.1016/j.jcp.2022.111725.
P. Stammer, L. Burigo, O. Jäkel, M. Frank, and N. Wahl, "Efficient uncertainty quantification for Monte Carlo dose calculations using importance (re-)weighting," *Phys Med Biol*, 2021;66(20):205003, doi: 10.1088/1361-6560/ac287f.

Example Project: Inverse Planning using Machine Learning Outcome Prediction Models (T. Ortkamp, KIT / DKFZ)





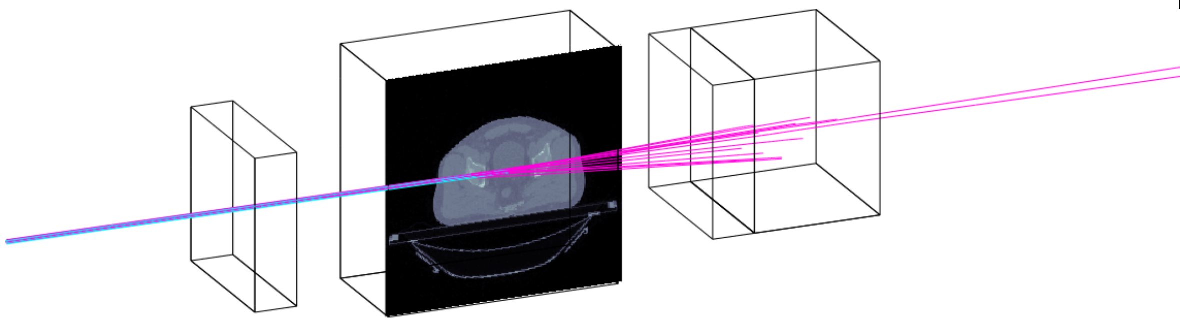
- Explicit integration of machine learning (N)TCP models into the inverse planning problem of radiotherapy optimization
  - Investigation of model stability, i.e. generalization error and uncertainty
  - Efficient fast forward and gradient computations/approximations
- Development of strategies to enable custom model integration and to facilitate the generation of clinically acceptable treatment plans

pyanno4rt

- Python-based advanced numerical nonlinear optimization for radiotherapy (pyanno4rt)
  - Software prototype for machine learning model-based photon & proton treatment plan optimization

Example Project (Following Talk by Jennifer): Developing a HELium Imaging Oncology Scanner for Range Guided Radiotherapy (RGRT)

- (Theoretically) possible to accelerate a mixed beam of carbon / helium ions
- Helium v. carbon range: $R_{He} = 3R_C$
  → He-monitoring?
- How to use in treatment planning / decision making / intervention?

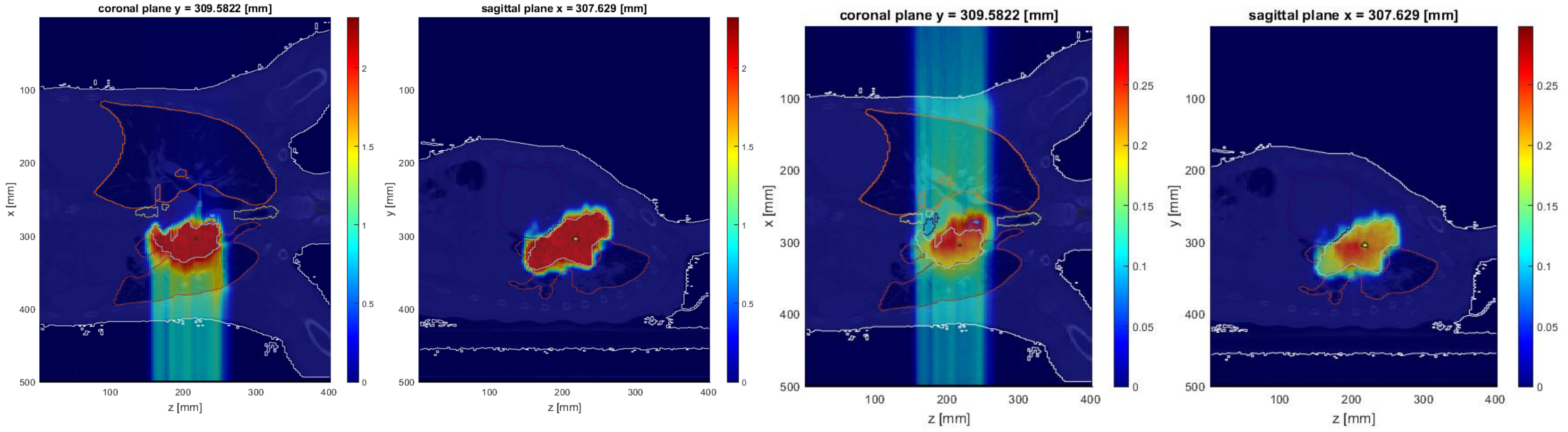


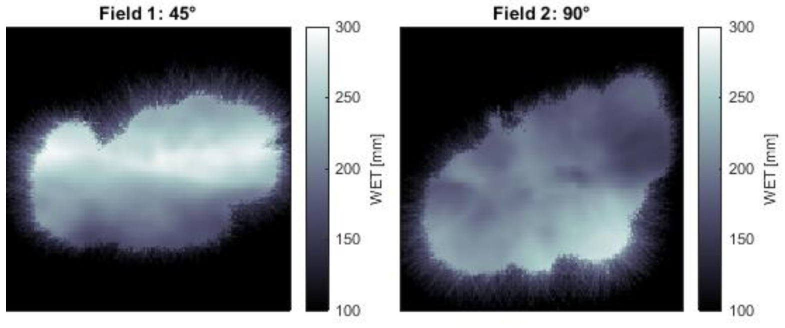
Deutsche Forschungsgemeinschaft

Full dose

He dose → 3x carbon range

WEPL image



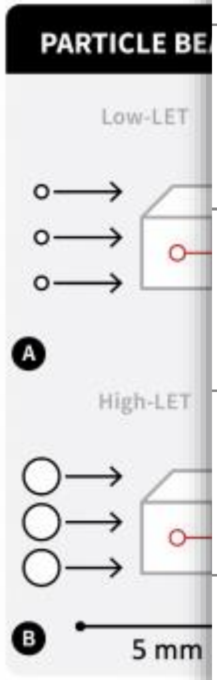


Example P
Nanodosir

Collaborat

- Nanodos

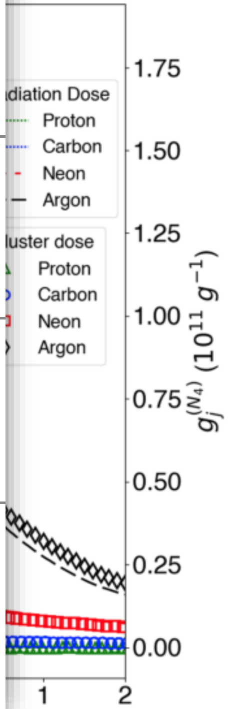
→ impro



- **Goal**: Fa

```
%% Cluster Dose Setup
pln.propDoseCalc.calcClusterDose = true;
pln.propDoseCalc.clusterDoseIP = 'F4';

%% generate steering file
stf = matRad_generateStf(ct,cst,pln);

%% dose calculation
dij = matRad_calcDose(ct,cst,stf,pln);

%% standard optimization without cluster dose
resultGUI = matRad_fluenceOptimization(dij,cst,pln);

%% start gui for visualization of result
matRadGUI

%% cluster dose optimization
cst{16,6}{2} = ClusterDoseObjectives.matRad_ClusterDoseVariance(1e6);
resultGUI2 = matRad_fluenceOptimization(dij,cst,pln);
```

stitutes
alth

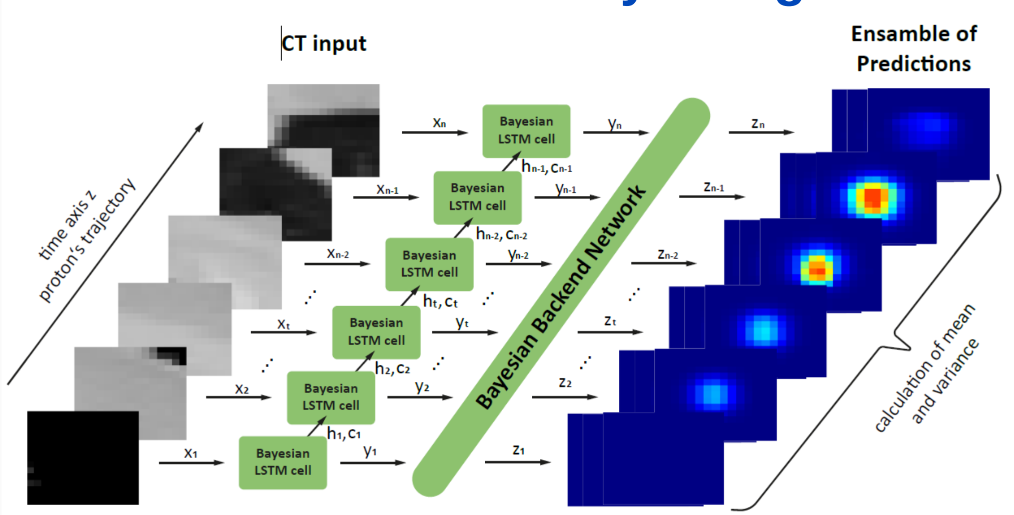


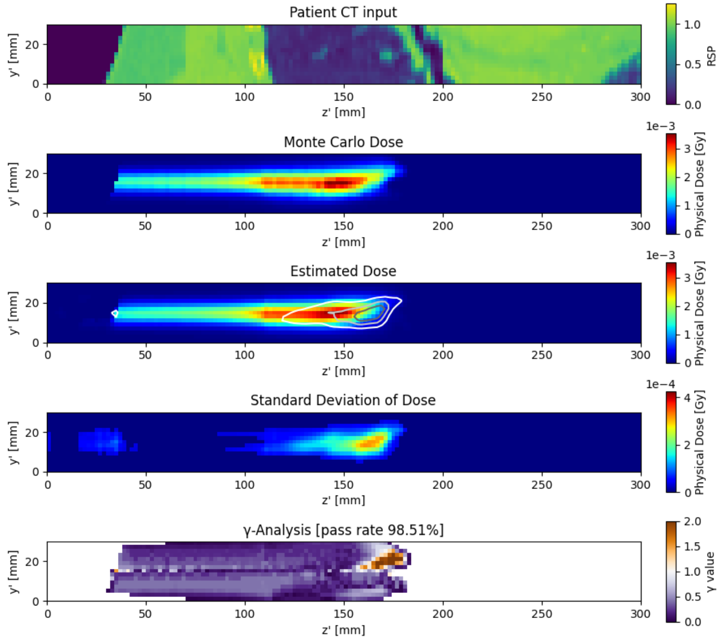
Depth Relative to the Bragg Peak (*cm*)

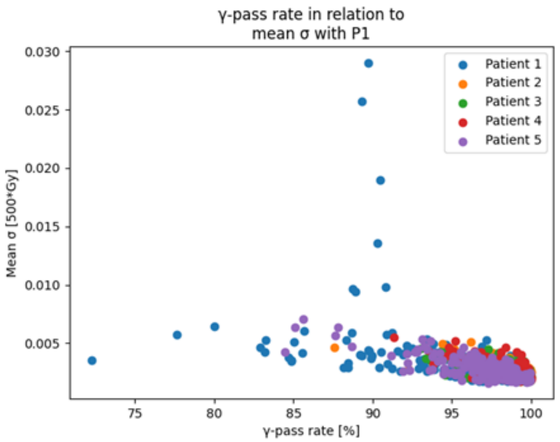
Faddegon BA, Blakely EA, Burigo LN, et al. Ionization detail parameters and cluster dose: a mathematical model for selection of nanodosimetric quantities for use in treatment planning in charged particle radiotherapy. *Phys Med Biol*. Published online 2023. doi:10.1088/1361-6560/acea16

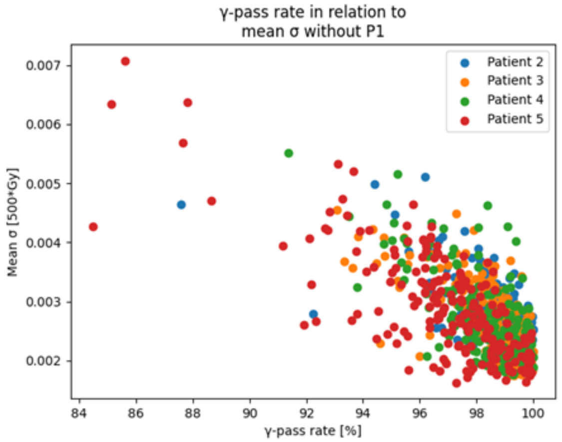
E040-4: BayesDose: Comprehensive proton dose prediction with model uncertainty using Bayesian LSTMs (L. Voss)

- Need for fast and accurate dose calculation techniques with quantifiably uncertainty estimation in proton therapy
- Using a Bayesian Approach to prior LSTM research, the model achieves fast predictions with equal quality compared to the prior deterministic model
- The obtained prediction‘s standard deviation correlates well with dosimetric inaccuracy
  - Models like BayesDose could support decision making and quality assurance in clinic









L. Voss, A. Neishabouri, T. Ortkamp, A. Mairani, and N. Wahl, “BayesDose: Comprehensive proton dose prediction with model uncertainty using Bayesian LSTMs.” arXiv 2023. doi: 10.48550/arXiv.2307.01151.

How to get going with matRad?

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

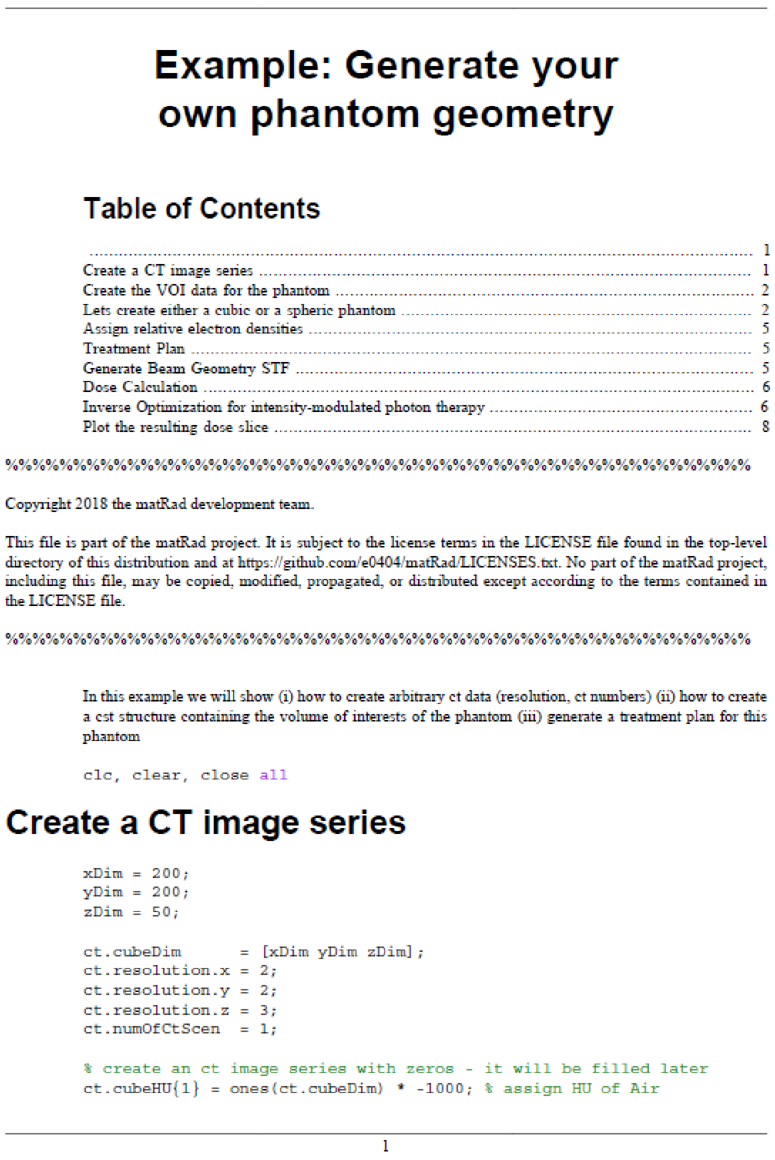
2. Download the Code, or even better: Familiarize with **git** and Clone

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. Profit (and contribute!)
   → Never hesitate to contact us!

How to get going with matRad – Examples

1. How to create your own phantom?
2. How to setup a photon treatment plan?
3. How to perform a direct aperture optimization for photons?
4. How to perform a Monte Carlo dose calculation for photon
5. How to create a treatment plan for protons?
6. How to manipulate stopping powers or to simulate an isocenter shift?
7. How to define carbon ion treatment plan?
8. How to perform robust optimization?



Example: Generate your own phantom geometry

Table of Contents

%%

%%

In this example we will show (i) how to create arbitrary ct data (resolution, ct numbers) (ii) how to create a cst structure containing the volume of interests of the phantom (iii) generate a treatment plan for this phantom

```
clc, clear, close all
```

Create a CT image series

```
xDim = 200;
yDim = 200;
zDim = 50;

ct.cubeDim      = [xDim yDim zDim];
ct.resolution.x = 2;
ct.resolution.y = 2;
ct.resolution.z = 3;
ct.numOfCtScen  = 1;

% create an ct image series with zeros - it will be filled later
ct.cubeHU{1} = ones(ct.cubeDim) * -1000; % assign HU of Air
```

1

www.matrad.org

Data IO

- DICOM
- *.nrrd, *.mha, *.vtk
- CERR
- VOXELPLAN

Dose calculation

- Photons
  - SVD pencil beam
  - ompMC interface
- Particles
  - IMPT pencil beam
  - MCsquare interface
  - TOPAS interface
  - 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
- Superiorization
- 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
- Analytical probabilistic modeling
- VMAT

Base data

- Patient data (CT & RTSS)
- Photon pencil beam base data
  → https://github.com/e0404/photonPencilBeamKernelCalc
- 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!

Features in blue will be available in matRad 3