Monte Carlo Simulations in Ion Beam Therapy at MedAustron

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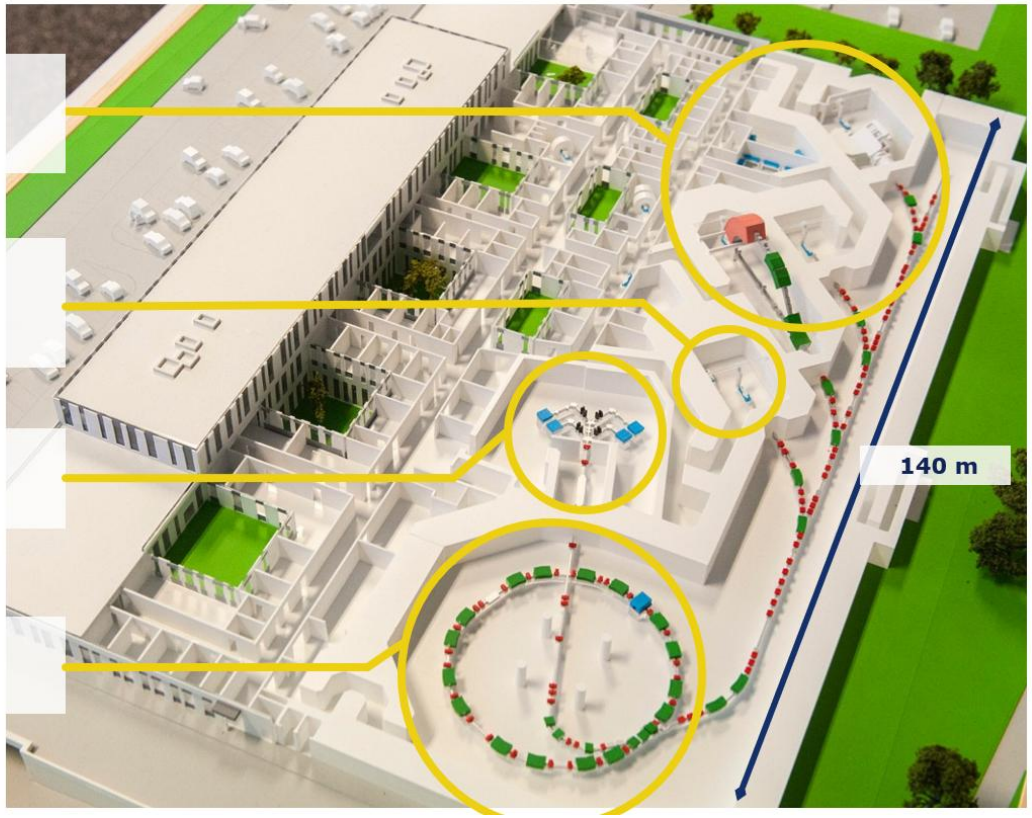
MedAustron Ion Therapy Center Overview

Irradiation Rooms
Three rooms for patient treatments

Research
Irradiation room for non-clinical use

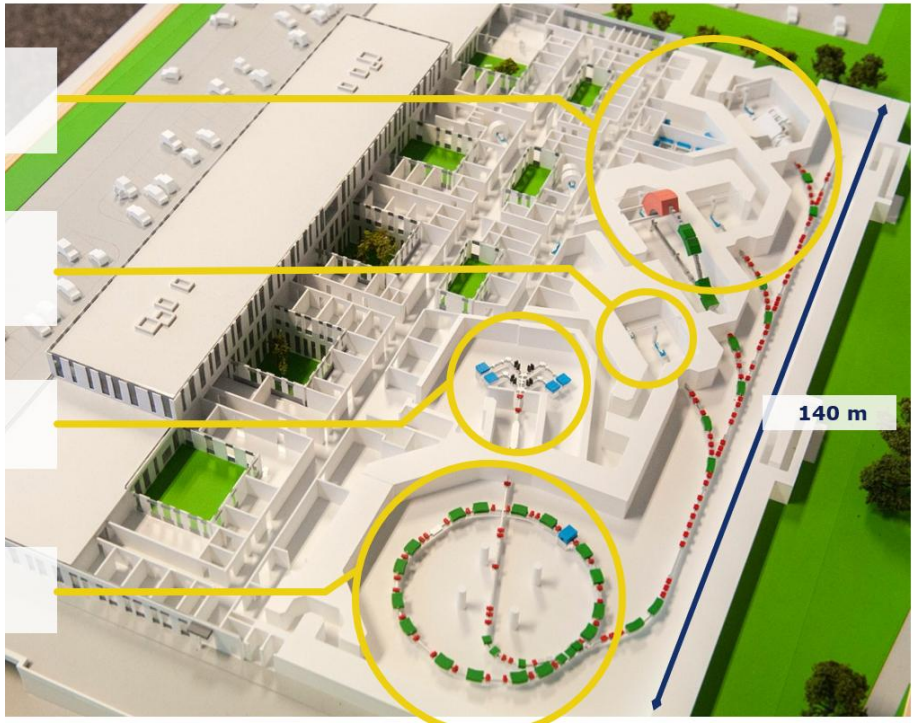
Ion Sources
and linear accelerator

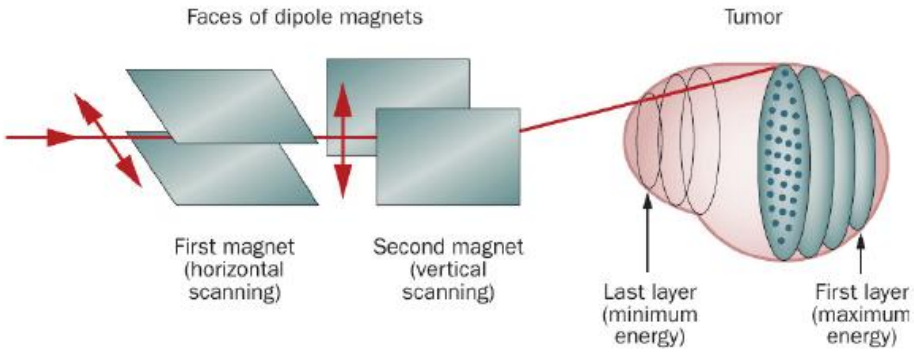
Synchrotron
proton/carbon/helium accelerator



- Wiener Neustadt, Austria
- Synchrotron based
- **Protons** and **carbon ions** clinical, **helium** commissioned for research
- Pencil beam scanning

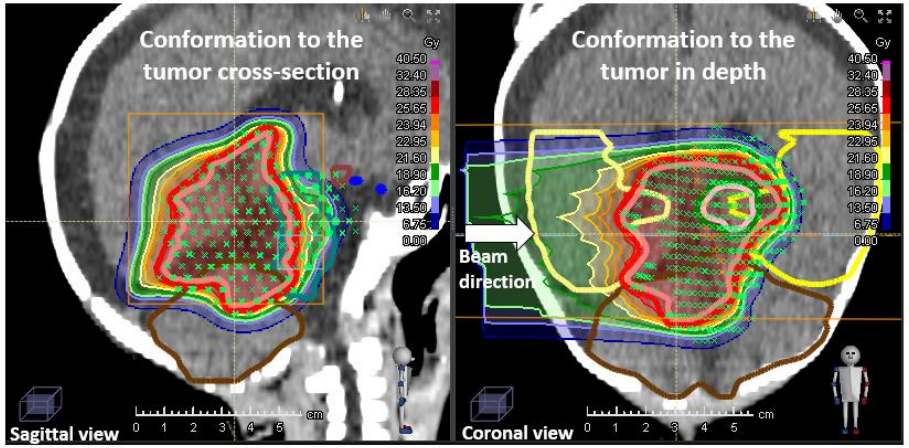
Pencil Beam Scanning





[1]

Pencil beam scanning



[2]

Treatment plan example

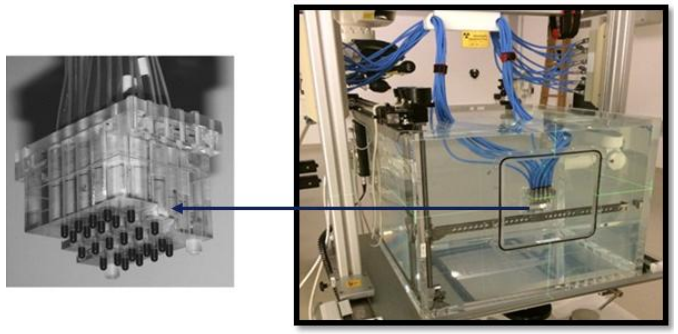
[1] M. Durante and J. S. Loeffler. "Charged particles in radiation oncology"

[2] Grevillot 2021, Monte Carlo Modelling of Scanned Ion Beams in Radiotherapy, eBook ISBN9781003211846

Patient Specific Quality Assurance (PSQA)

Up to 55 fractions treated every day!

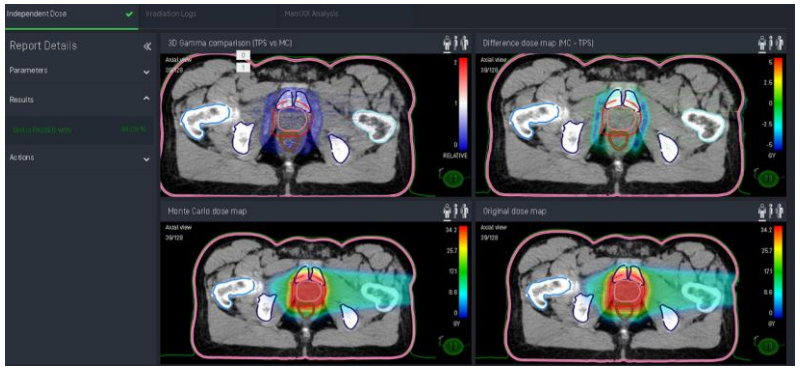
Measurement based PSQA



Measurement set-up using 3D-block

- Treatment plan delievered in water and dose measured at the plan position
- 24 pin-point measurements "only"
- Limited to low gradient dose regions
- Beam time required

Independent Dose Calculation (IDC)



IDC using myQAiON (IBA-dosimetry)

- Treatment plan is simulated with an independent dose engine in the CT of the patient
- Full 3D geometry
- Account for high gradient dose regions
- Save beam time and man power

Patient QA at MedAustron:

- **Proton:** ~ 100% IDC with **myQAiON-MCsquare** since 2021 – CE marked IDC product
- **Carbon:** 100% plans measured, soon replaced with **myQAiON-IDEAL** – CE marked IDC product (2025)

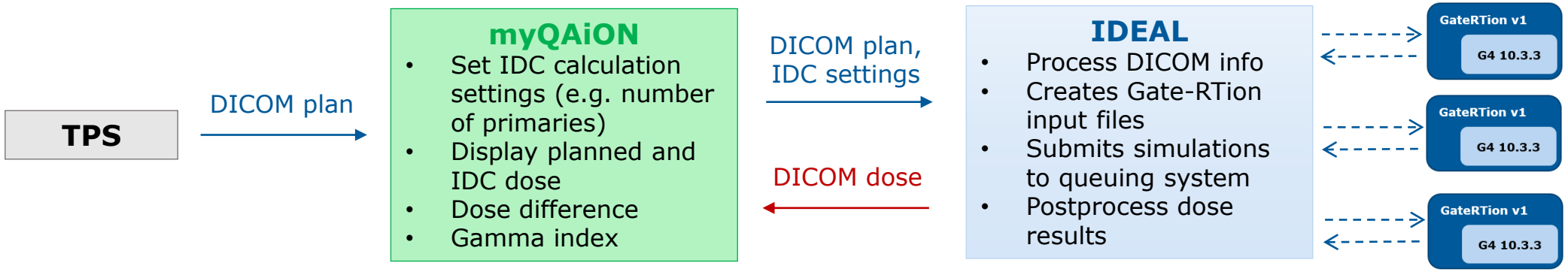
The IDEAL Project

IDEAL: **I**ndependent **D**os**E** c**A**lculation for **L**ight ion beam therapy using Geant4/GATE

- Based on **Gate-RTion** (Gate with G4 10.3.3) -> validated Gate version for ion beam therapy
- Gate wrapper, with a DICOM in – DICOM out framework
- Open source, part of Opengate collaboration, developed at MedAustron
- Project Start: 2018

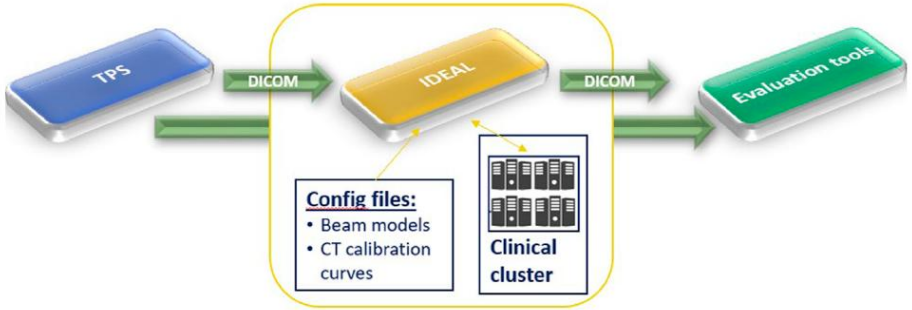
myQAiON-IDEAL:

- CE medical product, licensed



IDEAL: let's get into details

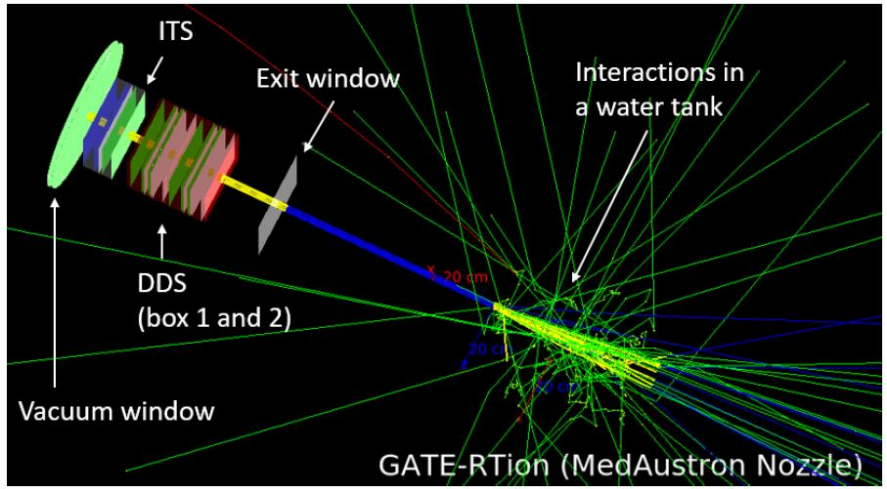
DICOM info:
- **CT** -> patient geometry, HU map, CT scan protocol, scoring grid
- **Structures** -> External structure used to remove dose outside
- **RT plan**
  - Energies, beam positions and intensities -> treatment plan source
  - Isocenter position and couch angle -> patient positioning in the simulation
  - Beamline -> correlates with beam model and nozzle geometry
  - Passive elements
- **RT doses** -> dose is simulated in the CT grid and re-sampled on the plan dose grid



Configuration files:
- CT calibration curves: density and composition curves, for each CT protocol
- Beam models: energy-dependent source parameters, scanning magnets positions
- Nozzle geometry

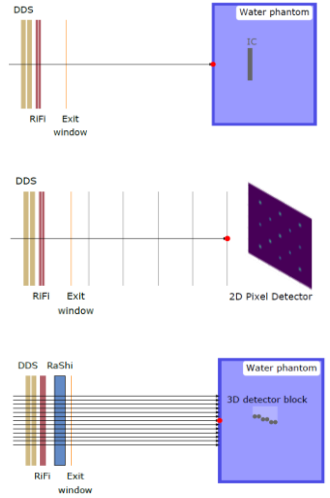
Parallelization of simulation splits -> HT Condor queuing system

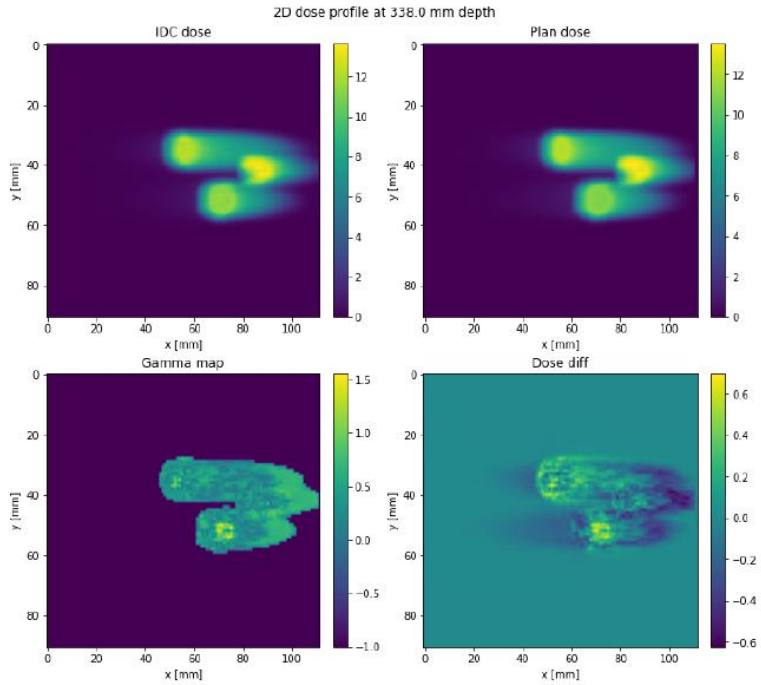
User interfaces:
- Command line
- Python script -> can be integrated your python program!
- API -> HTTP/HTTPS frameworks



IDEAL v1 Validation

- **Dosimetric commissioning** (MedAustron beam model validation, for carbon ions) [1]
  - Depth dose profiles in water
  - Pencil beam sizes and positions in air
  - Reference dose in water
  - Dose in SOBPs in water
- **Clinical commissioning:**
  - Simulation of patient cases in water against PSQA measurements
- **HU to material conversion**
  - rWET of calibration tissue equivalent material
  - rWET of animal tissue
- **Functional tests**
  - Alignment (CT, beam, dose grid)
  - Selection of correct settings (HU to material, beamline, …)





Grid resolution: [1, 3, 2] mm
Couch angle: 15 degrees
Gamma index pass rate: 98.58%
(global gamma, 3% 3 mm, simulations with 1% statistical uncertainty)

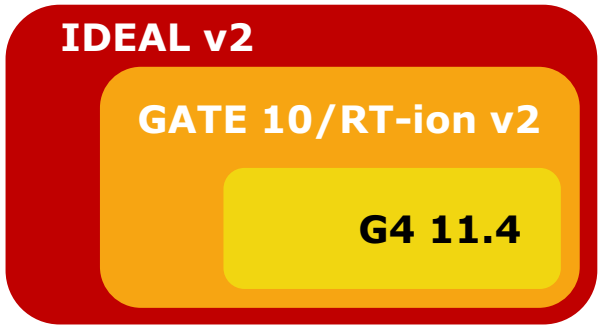
[1] Experimental validation of Geant4 nuclear interaction models in dose calculations of therapeutic carbon ion beams - Jia - 2025

IDEAL v2 – Gate-RTion v2

IDEAL v2: source code

Start simulation in **Gate 10**

- Enables **MT** -> Optimize use of computational resources
- Additional LIBT features (e.g. dose uncertainty calculation, DICOM reading)
- Calculation of **LET** and **RBE weighted dose** available
  -> results presented during Gate 10 scientific meeting 2025
- Replace ancient G4 version (10.3.3) with more recent one



Gate-RTion v2:

Goal: release in 2026

- Advanced validation with **G4 11.3.0** for carbon ions
  - results presented during Gate 10 scientific meeting 2025
- Current issues:
  - ~~Calculation time overhead (under investigation)~~
  - Bug in transversal profiles QMD -> fixed in **G4 11.4**
- Collaboration driven by MedAustron:
  - Several LIBT centers in Europe
  - Regular update meeting
  - Define test and criteria for the validation
- Next steps at MedAustron :
  - ~~Work on calculation time issue~~
  - Validation for protons and carbon ions

Gate For Ion Beam Therapy

From research tools to first medical applications at MedAustron!

- **Development of MC dose engines for IDC**
  - 2012: **GATE/Geant4** for proton IDC (Grevillot et al, *Phys. Med. Biol.* **57** (2012) 4223–4244)
  - 2016: **MCSQUARE**, a fast proton MC code (Souris et al, *Med. Phys. 43 (4)*, April 2016)
  - 2020: **GATE-RTion v1.0**: a GATE release for clinical use (Grevillot et al, *Med. Phys. 47 (8),* August 2020)

- **Development of home-made IDC systems for clinical use**
  - 2020: **AUTOMC/GATE-RTion v1.0** – protons (Aitkenhead et al, *Br J Radiol* 2020; 93: 20200228)
  - 2021: **IDEAL/GATE-RTion v1.0** – protons & carbon ions
    (Grevillot & Boersma et al, *frontiers in Physics,* August 2021 | Volume 9 | Article 704760)

- **Implementation of medical products for proton & carbon ion IDC at MedAustron**
  - 2021: **myQAiON/MCSQUARE** (IBA-dosimetry, CE marked IDC product) - for protons!
    (Dreindl et al, PTCOG2021, Grevillot et al, ESTRO 2021)
  - 2025: **myQAiON + IDEAL/GATE-RTion v1.0** (IBA-dosimetry, CE marked IDC product) -for carbon ions!
    (MedAustron/IBA collaboration)

- **Future perspective:**
  - **myQAiON + IDEAL v2/GATE-RTion v2.0** -> Biological dose for carbon ions is available
  - **IDEAL v2/GATE-RTion v2.0** standalone for advanced research purposes:
    - LET distribution, new RBE models…
    - MRI-guided LIBT (Hermann Fuchs)
    - Mixed beam irradiations
    - Prompt-gammas/PET imaging
    - Etc.

Gate For Ion Beam Therapy

Next steps

- **GATE-RTion V2/IDEALV2/Geant4.11.4 validation**
  - Particles: Protons / Carbon / Helium
  - Features: LET, RBE-weighted dose, new LUT source features
  - Applications: IDC, mixed beam applications
  - Publication: New Reference paper for GATE-RTion

- **IDEAL V3/European collaboration**
  - HIT/CNAO/MIT: many shared topics
    - IDEAL as the open-source platform
    - GATE-RTion as the reference MC code
    - MonteRay as a faster dedicated ion therapy MC code
  - IBA-Dosimetry provides the CE platform
  - Could we make GATE faster?
    - Denoising techniques?
    - Variance reduction techniques?
    - Any other idea?
    - Potential collaboration for further AI-application?

PHYS. REV. ACCEL. BEAMS **28,** 111001 (2025)
MATTHIAS KAUSEL *et al.*

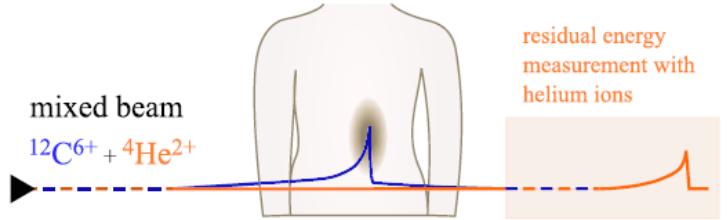


FIG. 1. Schematic mixed beam irradiation. The carbon beam is used for tumor treatment while the residual helium energy is measured downstream of the patient for diagnostic purposes.

Thank You For Your Attention!