Evaluation of the GATE-RTion/Geant4 for Independent Dose Calculation in Carbon Ion Pencil Beam Scanning Radiotherapy

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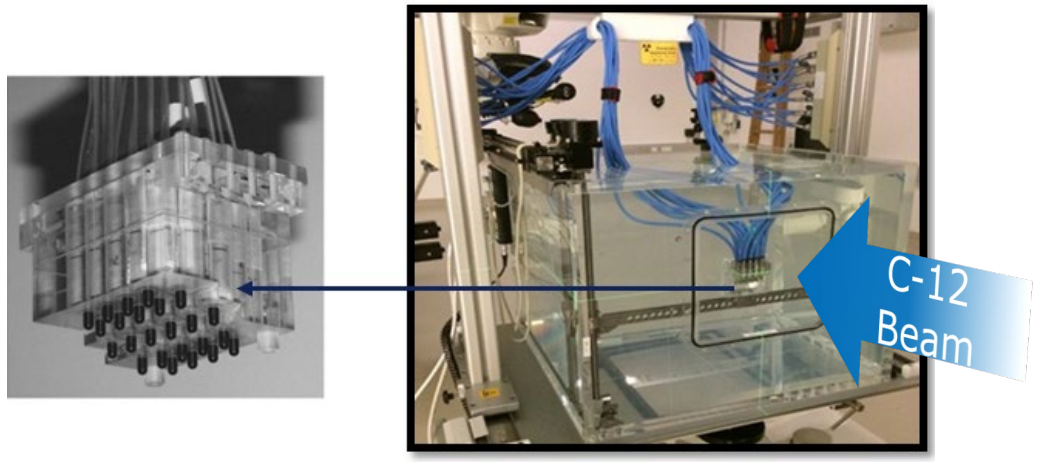
Motivation

- Experimental **patient-specific quality assurance (PSQA)**

  To verify dose calculation in clinical treatment planning system (**TPS**)

  - **Non-human** standardized geometry and material
  - Limited **sensitivity** to errors in planned/delivered dose
  - **Time consuming**



24 PinPoint ICs fixed to the PTW 3D detector block holder
in a PTW MP3-P water phantom

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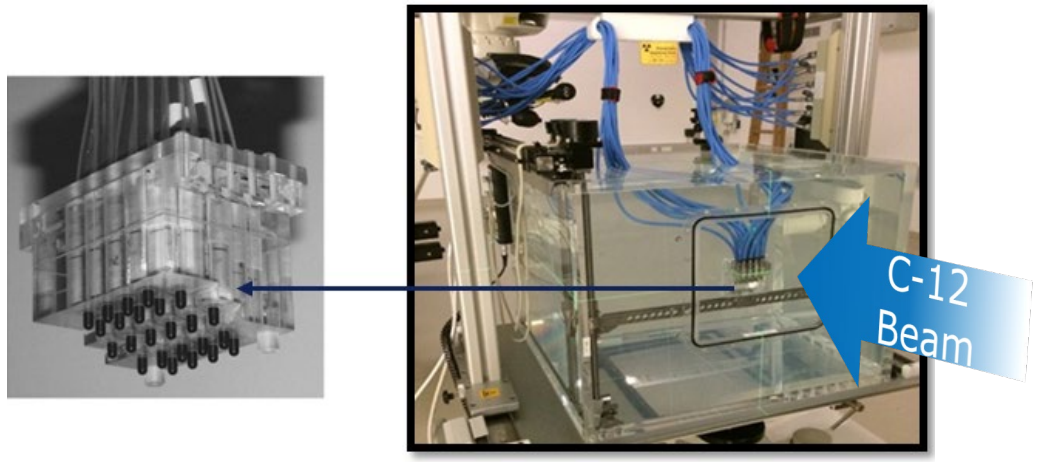

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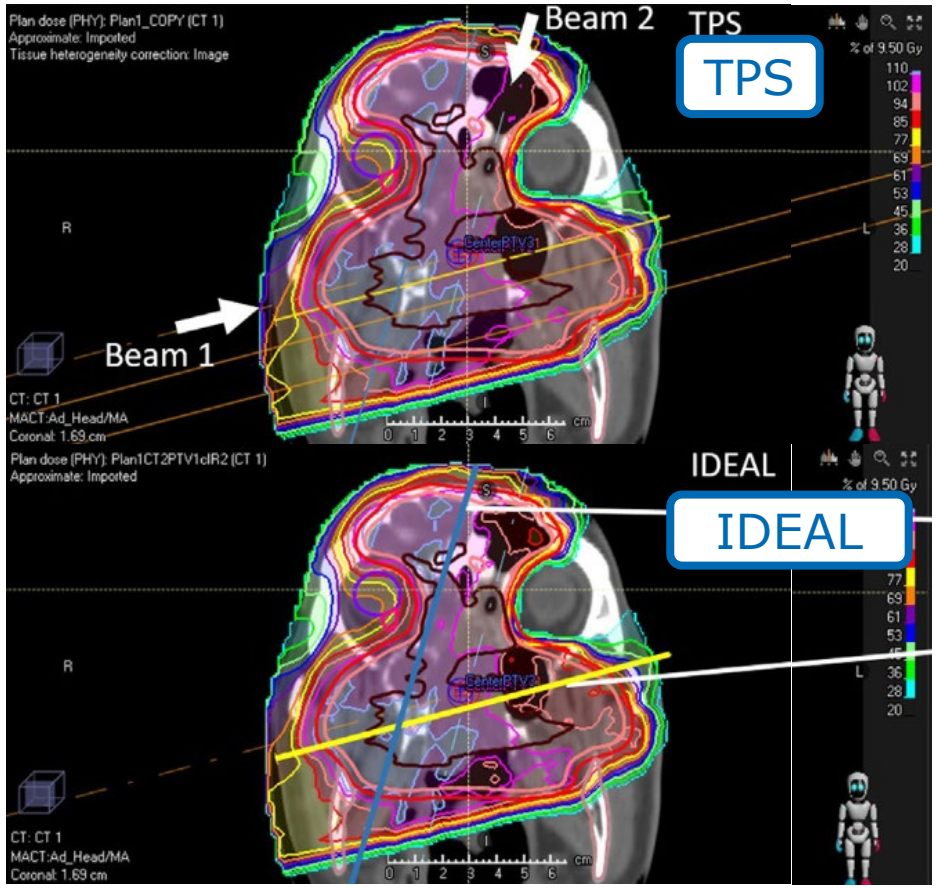
Independent system to recalculate dose in patient geometry

IDEAL

- **Independent** DosE cAlculation system for **Light ion beam therapy**
- Wrapper for GATE-RTion v1.0/Geant4.10.3.p3
  - GATE-RTion: well validated release of GATE for clinical usage, release cycle ~ 5 years [1]
- Designed for **daily clinical usage**
  → automatic workflow

This study aimed to
- optimize the calculation speed and settings of IDEAL
- evaluate dosimetric accuracy of
  QGSP_BIC_EMZ_HP
  QGSP_INCLXX_EMZ_HP
  Shielding_EMZ(_HP)



[1] Grevillot, L., Boersma, D. J., Fuchs, H., Aitkenhead, A., Elia, A., Bolsa, M., ... & Sarrut, D. (2020). GATE-RTion: a GATE/Geant4 release for clinical applications in scanned ion beam therapy. *Medical Physics*, *47*(8), 3675-3681.

[2] Grevillot, L., Boersma, D. J., Fuchs, H., Bolsa-Ferruz, M., Scheuchenpflug, L., Georg, D., ... & Stock, M. (2021). The GATE-RTion/IDEAL independent dose calculation system for light ion beam therapy. *Frontiers in Physics*, *9*, 704760.

Optimization of calculation speed

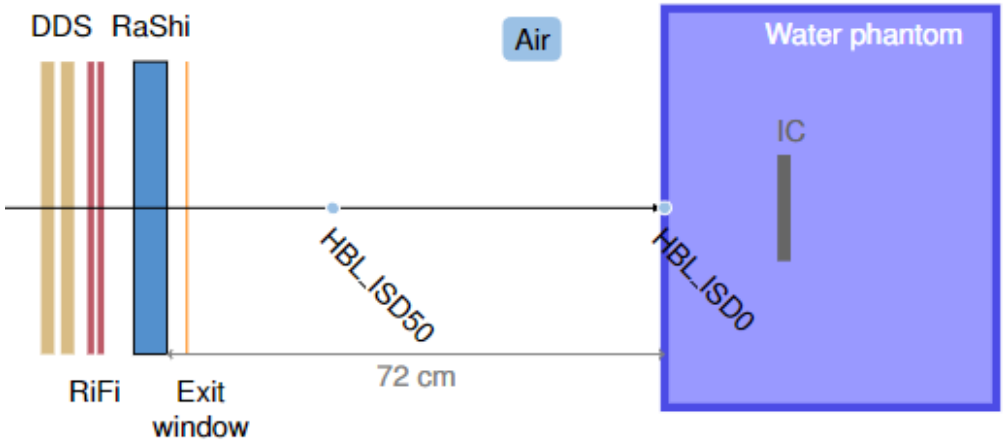
- Calculation time considerably reduced
  - **by about a factor 9** changing**:**
    - Physics list: **Shielding** → **QGSP_BIC**
    - Increasing **electron production cut**
  - Dosimetric accuracy evaluated subsequently
- Computation time of a clinical patient plan
  - Depends on: dose grid size, statistical uncertainty, target volume, energies, number of beams, number of available CPUs, …
  - For typical clinical scenarios on 100 CPU cores: few hours

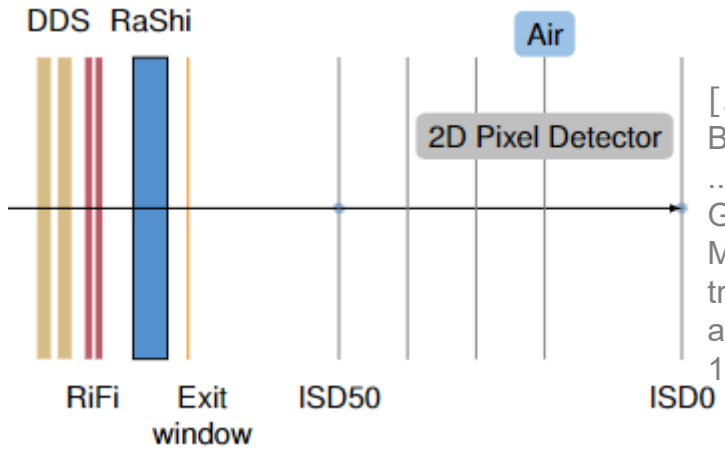
Table 1: Calculation time, t, per primary particle for different physics settings

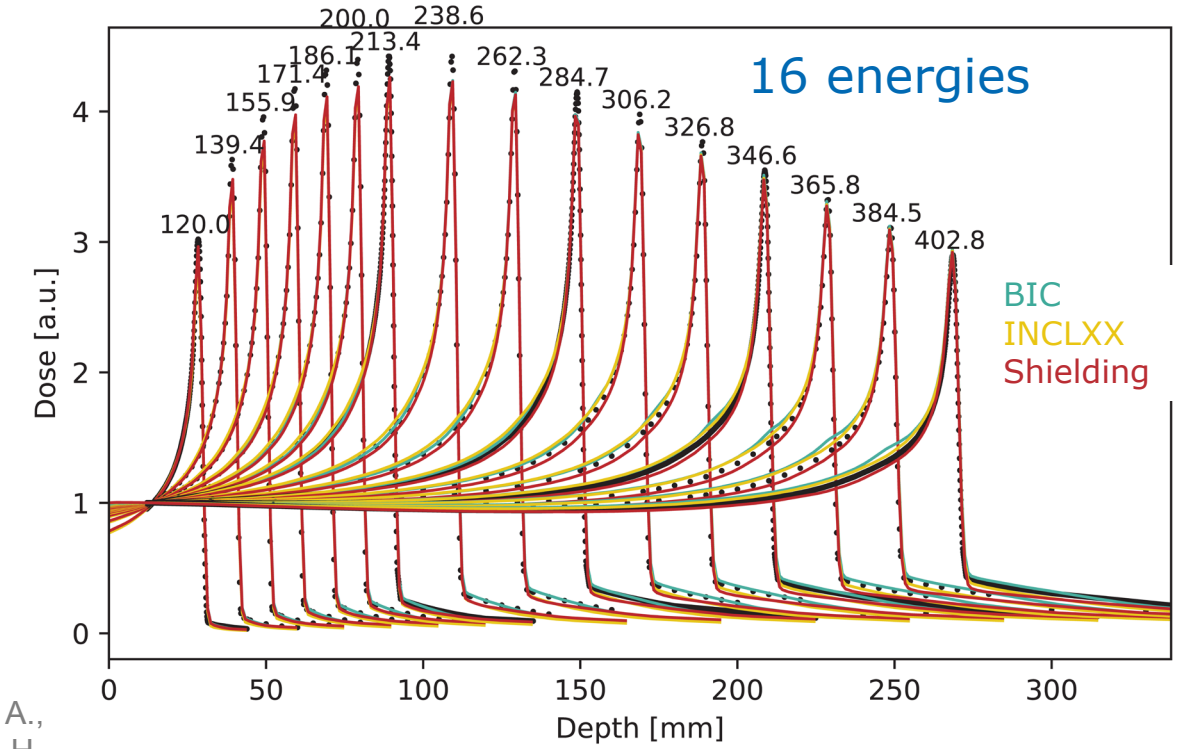
Settings	**t [ms/#]**	**t/t0**
QGSP_BIC_EMZ	42	**0.82**
QGSP_BIC_EMY	40	0.78
QGSP_BIC_HP_EMZ	51	**1.00**
QGSP_INCLXX_HP_EMZ	59	1.16
Shielding_EMZ	84	1.65
QGSP_BIC_EMZ low e- prod cut	417	8.18
Shielding_EMZ low e- prod cut	469	**9.20**

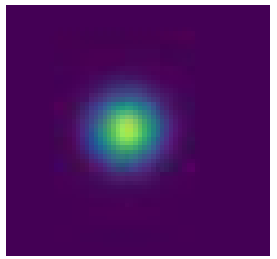
*Note: calculation time may differ for other system/hardware architectures

Characterization of monoenergetic pristine Bragg peak









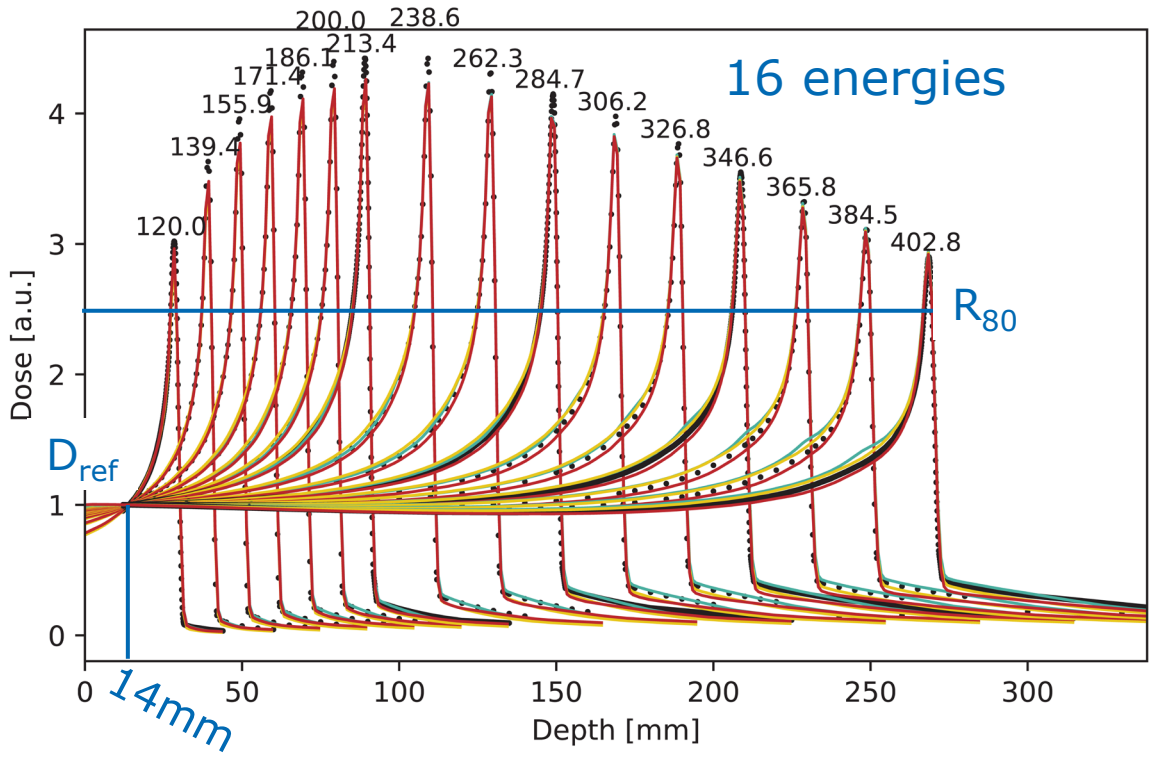
[3] Elia, A., Resch, A. F., Carlino, A., Böhlen, T. T., Fuchs, H., Palmans, H., ... & Grevillot, L. (2020). A GATE/Geant4 beam model for the MedAustron non-isocentric proton treatment plans quality assurance. *Physica Medica*, *71*, 115-123.

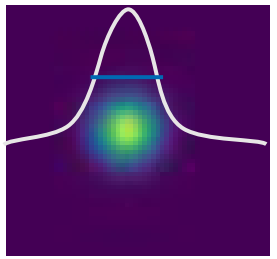
Characterization of monoenergetic pristine Bragg peak

- Abs. diff. of range of 80% BP dose (**R_{80}**) in water
- Rel. diff. of **absolute dose** at 14 mm (**D_{ref}**) in water
- Rel. diff. of full width half maximum (**FWHM**) in air

	QGSP_BIC	QGSP_INCLXX	Shielding
ΔR_{80} [mm]	-0.0±0.1	-0.0±0.1	-0.1±0.1
Δ FWHM [%]	0.0±1.5	0.1±1.5	-0.1±1.5
ΔD_{ref} [%]	0.5±0.6	0.7±1.2	-0.4±0.6

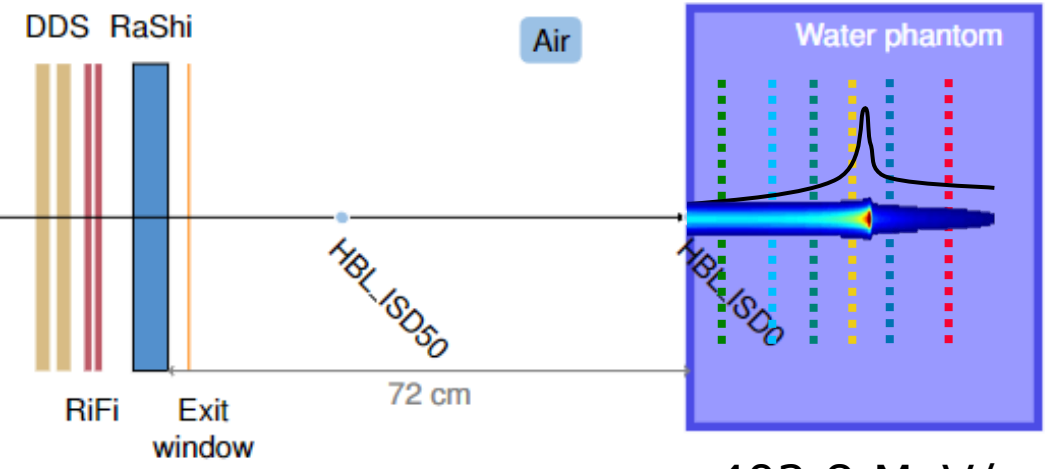
Energy, optics and meterset weight of beam model verified



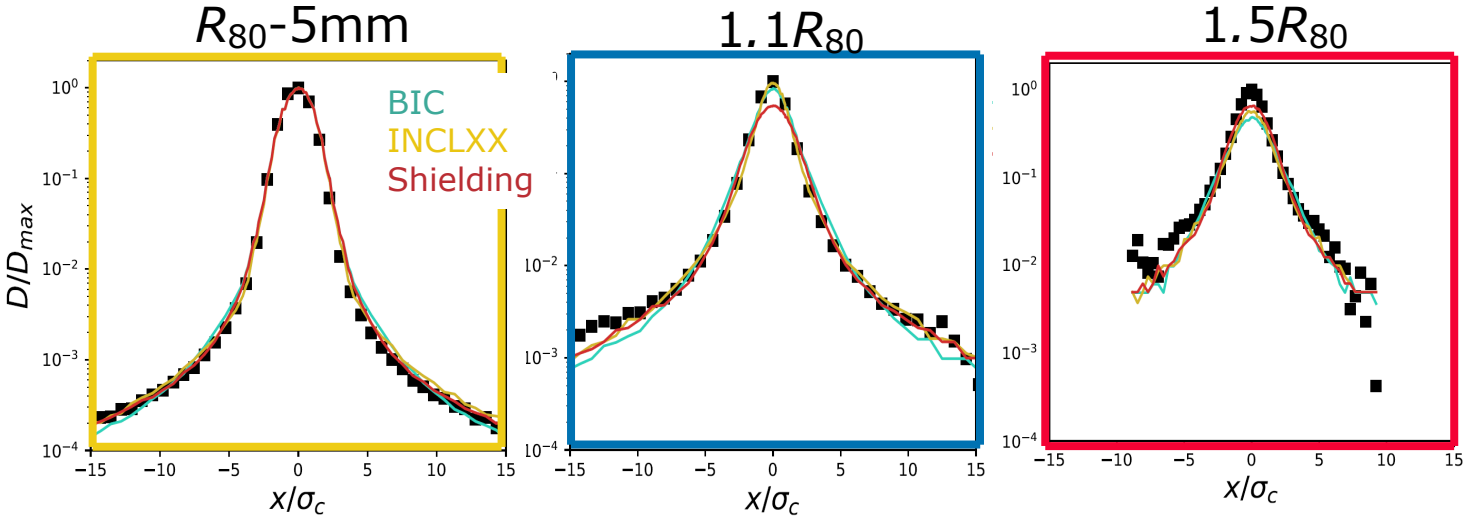


FWHM

Characterization of monoenergetic pristine Bragg peak



402.8 MeV/u

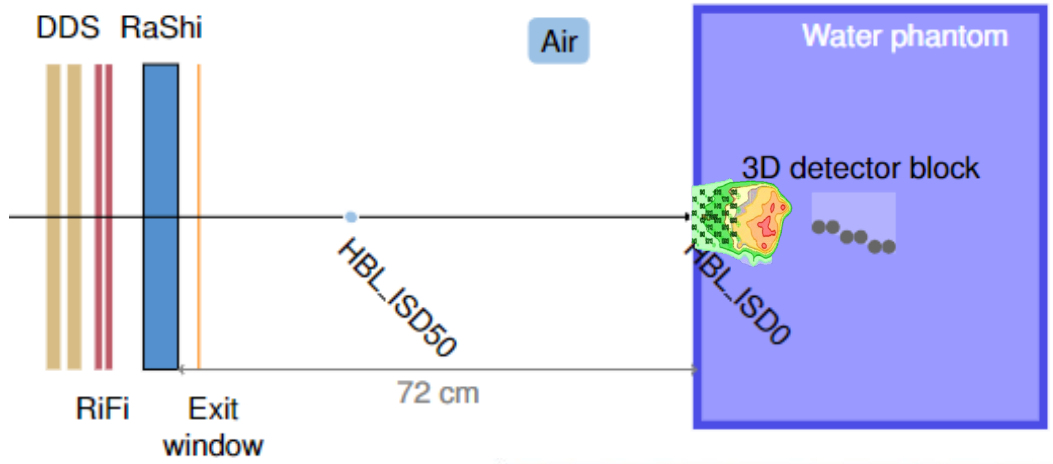


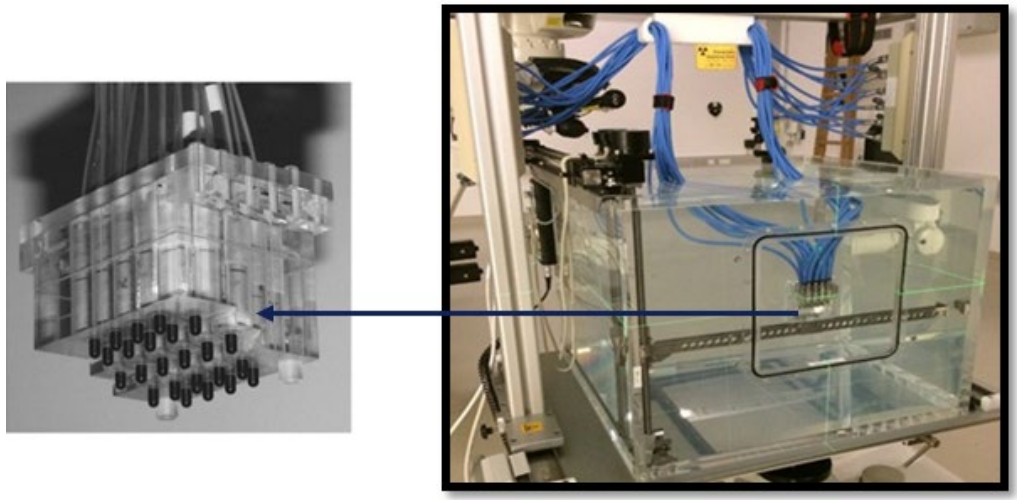
- Overall good agreement to the measured lateral profile before Bragg peak
- QGSP_INCLXX showed best agreement in fragment tail

Low dose halo of pencil beam qualitatively well represented

Dose accuracy in SOBP

- **Negligible intra-target dose gradient**
  - **220** positions in the target region of **8** SOBPs with **uniform absorbed dose** in **water**, 34-248 mm
- **Axial dose gradient**
  - **2007** positions in the target region of **48** SOBPs with **uniform RBE(LEMI)w dose** in **water**, 21.9-265.9 mm
- **Complex dose gradient**
  - **763** positions (measured dose>0.05 Gy, planned dose gradient<0.04 Gy/mm) in **45** patient SOBPs planned with **uniform RBE-weighted dose** in **patient geometry**, recomputed in **water**, 11.9-274.7 mm





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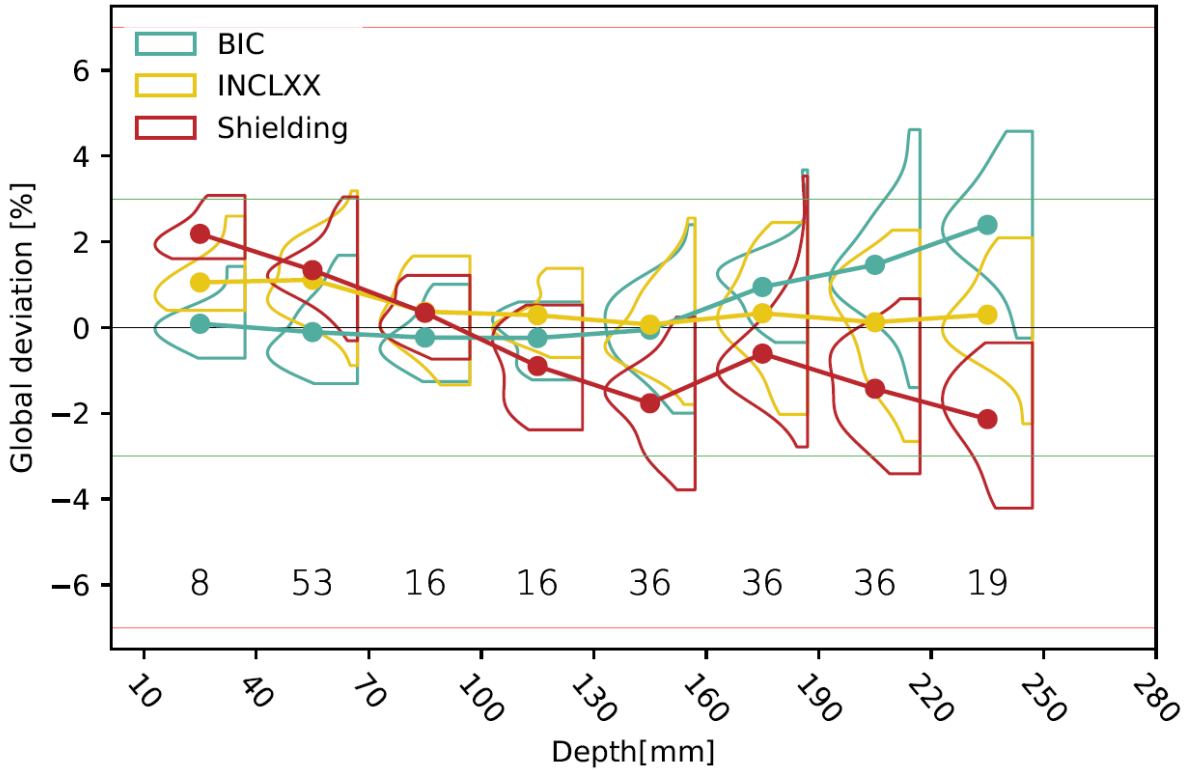
Dose accuracy in SOBP
with negligible intra-target dose gradient

- Intra-target SD/mean <1% for measured and simulated dose
- **Depth-dependent** global dose difference



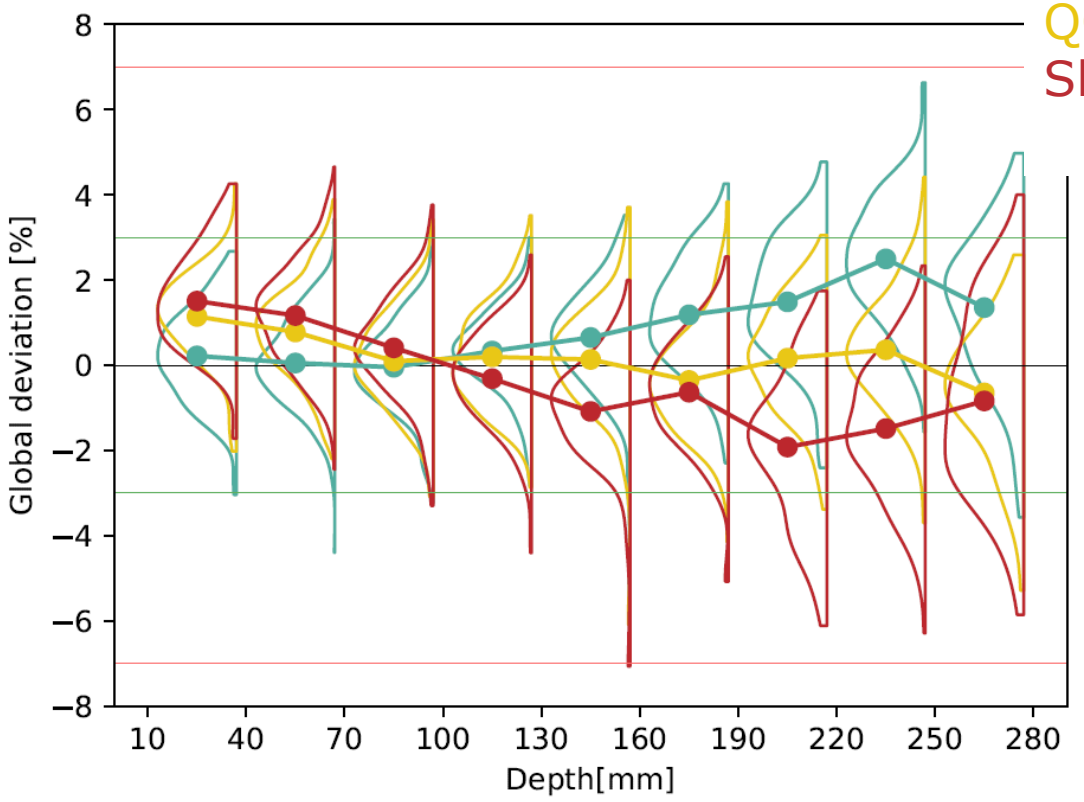
QGSP_BIC ↗
QGSP_INCLXX →
Shielding ↘

Dose accuracy in SOBP

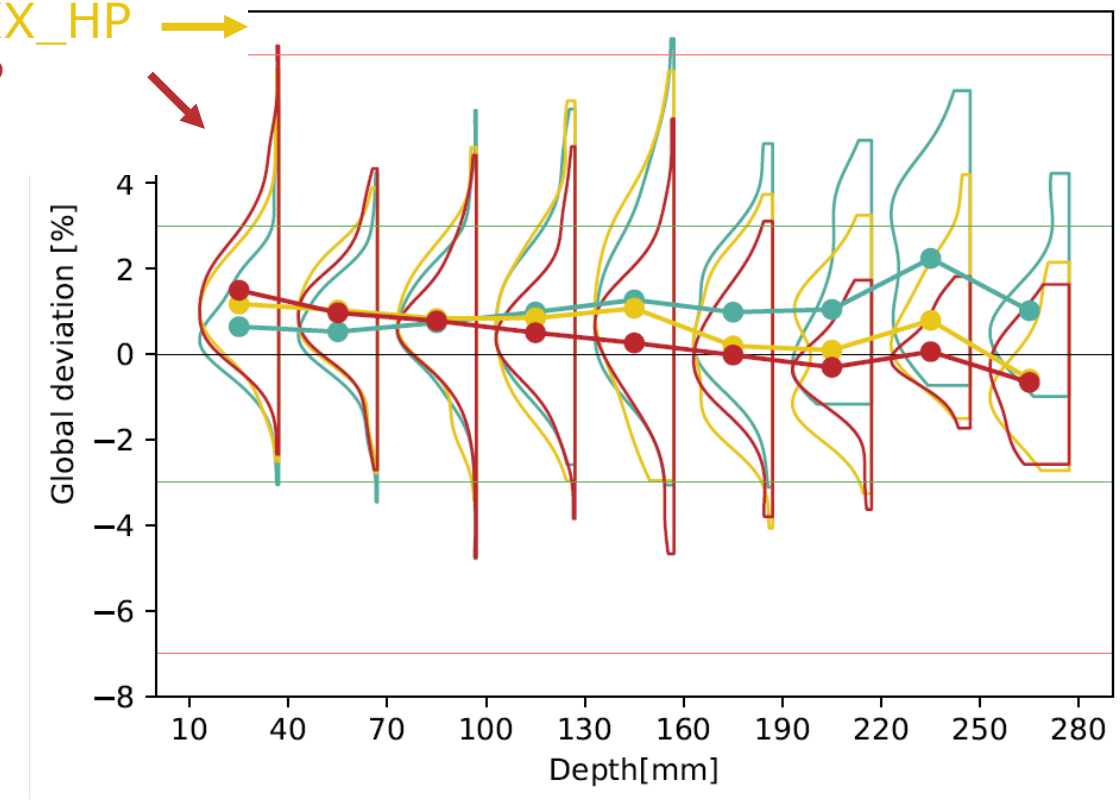
with axial dose gradient

complex dose gradient

- **Depth-dependent** global dose difference persisted

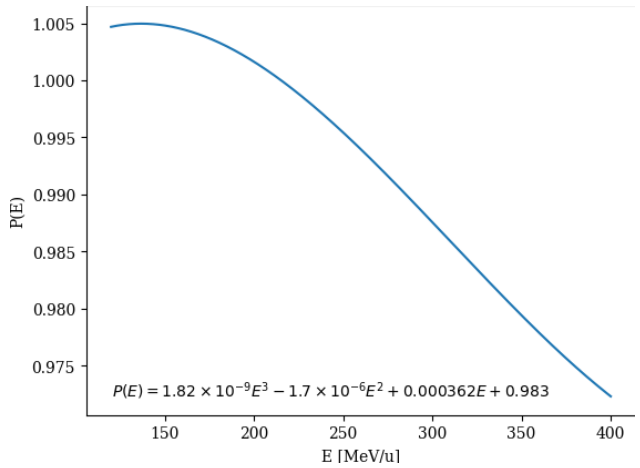


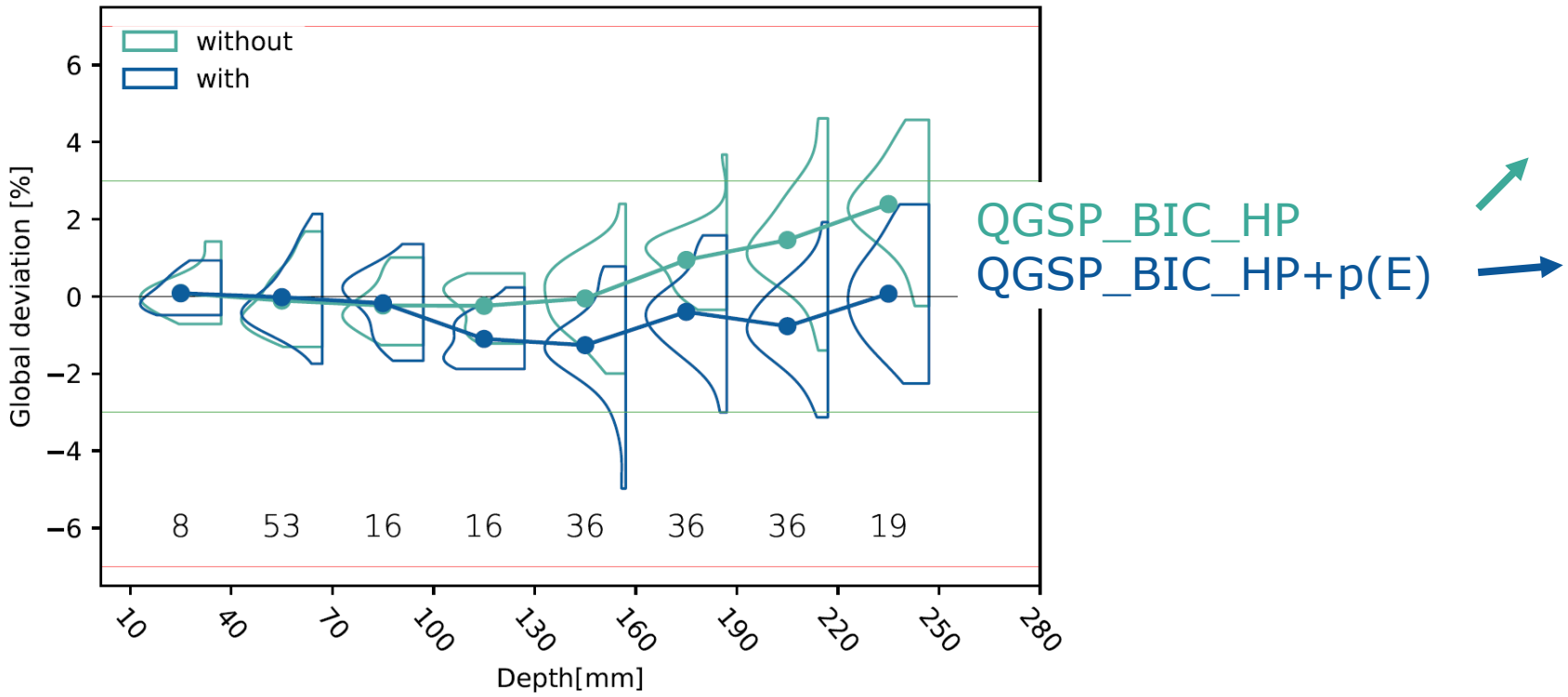
QGSP_BIC_HP
QGSP_INCLXX_HP
Shielding_HP



Compensation of depth dependent accuracy

- Energy-dependent meterset weight scaling correction factor p(E)
- Take QGSP_BIC_HP as an example





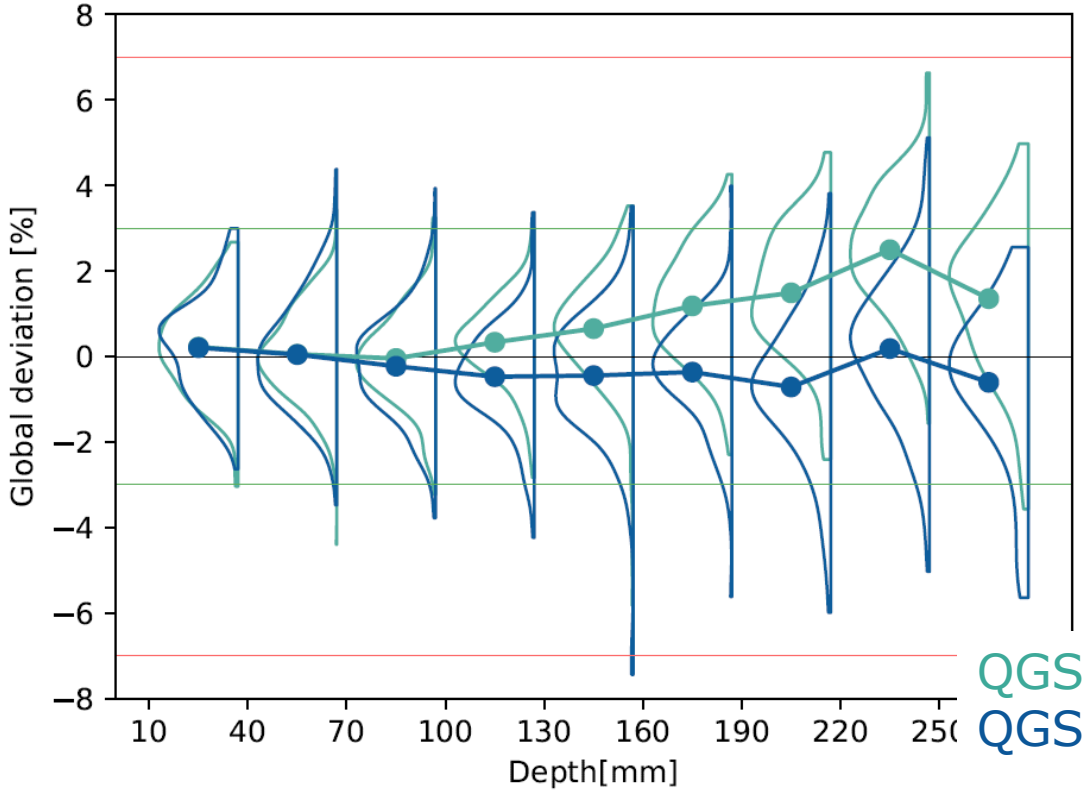
Dose calculation accuracy

with axial dose gradient

complex dose gradient

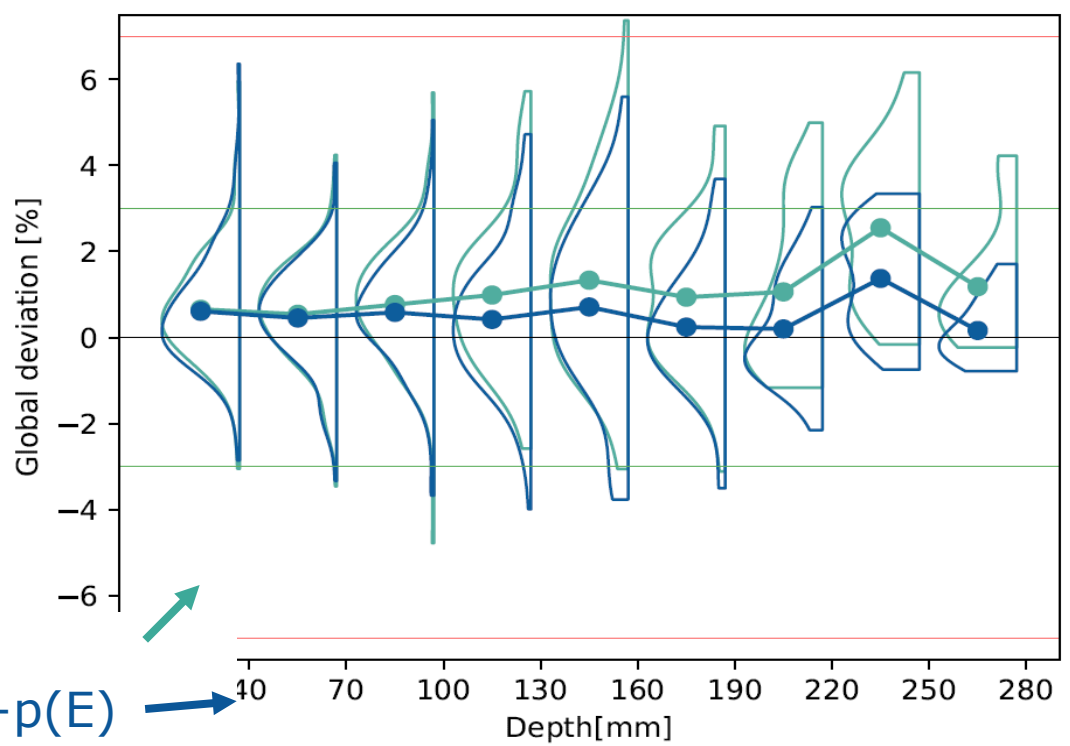
- Global dose difference better than **7%** considering measurement uncertainty

QGSP_BIC_HP with meterset weight scaling is adequate for clinical dose calculation



QGSP_BIC_HP

QGSP_BIC_HP+p(E)

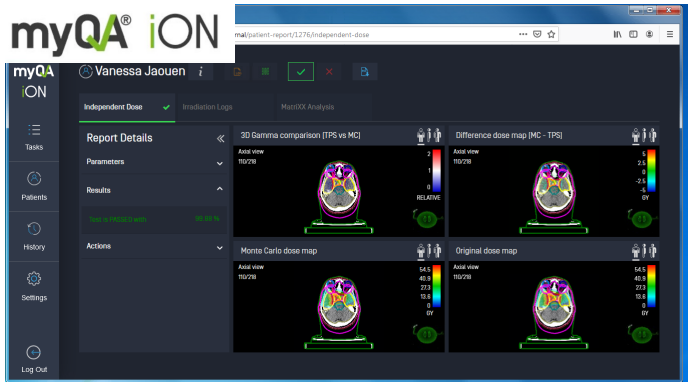


Conclusion

- **IDEAL v1.1 (Gate-RTion v1.0/Geant4.10.3)**
  - Optimized physics settings to improve **simulation speed**
    → clinically acceptable time
  - High **dosimetric accuracy** in water and air for clinical energy range 120-402.8 MeV/u
    → Adequate for clinical dose calculation
- Nuclear interaction models
  - **QGSP_BIC_HP** and **Shielding_HP** demonstrated **depth-dependent** over- and under-estimation of dose in SOBP in water
  - **QGSP_INCLXX_HP** showed good agreement with measurement
    - **Potential candidate** for the dose calculation in carbon ion radiotherapy after further investigation
  - **Meterset weight scaling** mitigated the depth-dependent accuracy effectively

Outlook

- Integration into myQAiON (IBA Dosimetry, Schwarzenbruck, Germany)
  - commissioning in the **clinical workflow** in MedAustron Ion Therapy Center



- Improvements and new features will come with **IDEAL v2.0/GATE-RTion v2 (GATE 10/Geant4.11.2)**
  - New features: **RBE** models for carbon ion beams
  - Reduction of needed computational resources
  - Improving usability & maintainability

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Thank you for your attention!

Please feel free to approach me at coffee break or by:
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