Reconstruction approaches for TOF-based proton radiography

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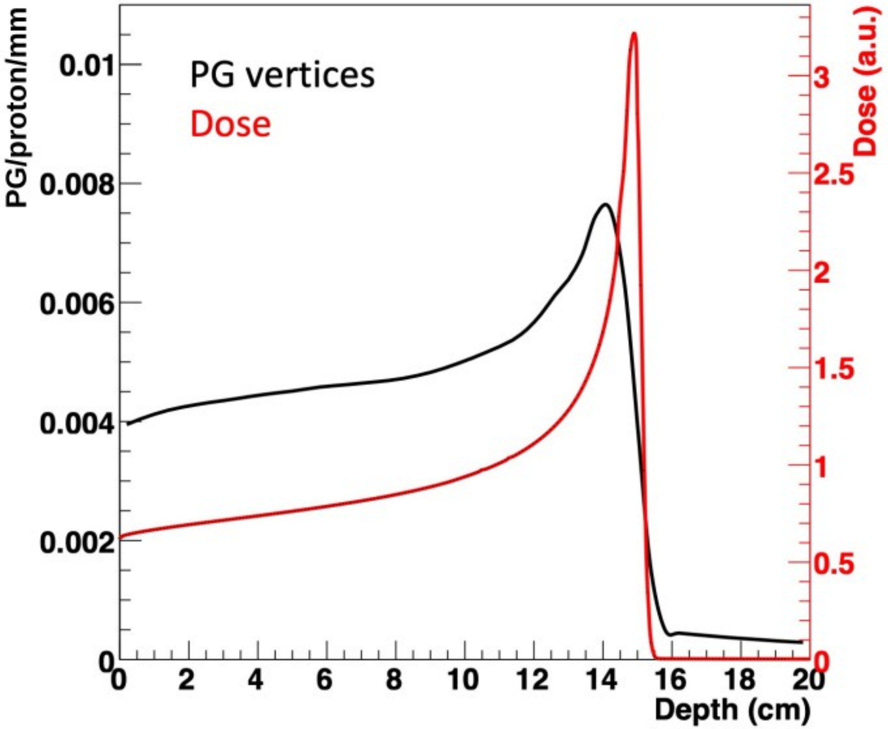
Particle therapy – Range monitoring

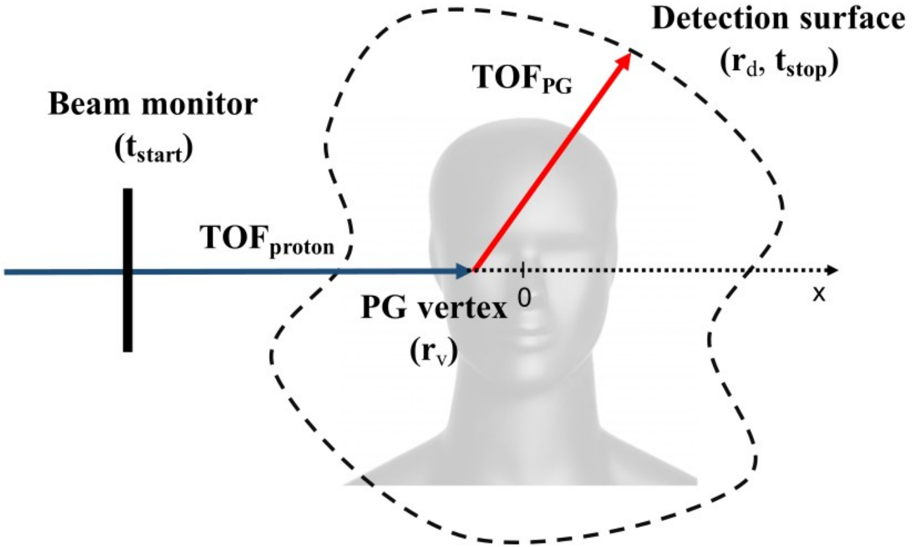


M. Jacquet et al. (2021), A. Andre et al. (2024)

- Hadrontherapy provides high ballistic precision due to **Bragg peak**
- Hadrontherapy requires incident particle **range verification**
- **Prompt-gammas (PG)** are emitted along the path of the incident particle
- PG energy ~ O(MeV), emission time ~ O(ps), vertex density ~ 0.01 [$p^{-1}cm^{-1}$]
- PG vertices are spatially correlated with path of the incident particle

  => possibility of **indirect range measurement**

Prompt-Gamma Time Imaging (PGTI)



M. Jacquet et al. (2021), A. Andre et al. (2024)

- Measure Time-of-flight (**TOF**) = $\mathbf{T_{stop} - T_{start}}$

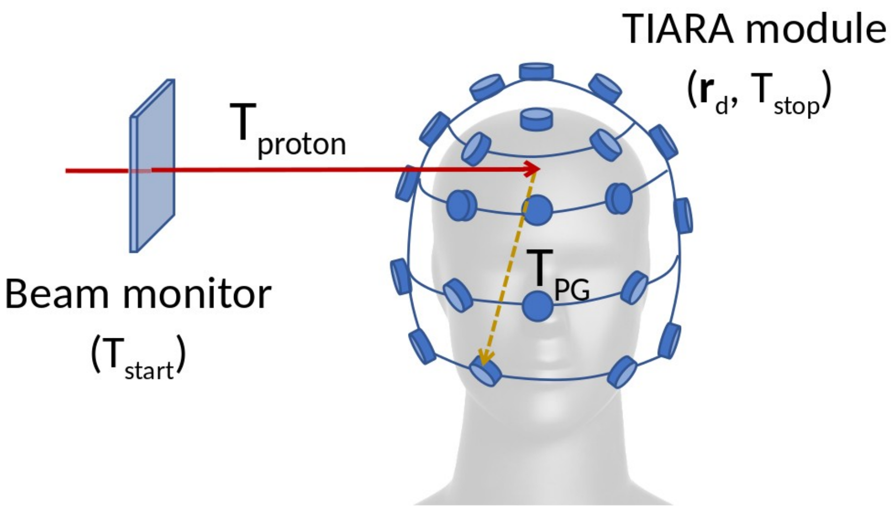
$$T_{proton}(\mathbf{r}_v, \mathbf{v}_p) + T_{PG}(\mathbf{r}_v, \mathbf{r}_d)$$

- Reconstruct PG vertex ($\mathbf{r_v}$) and proton velocity ($\mathbf{v_p}$)
- Combine responses of all PG detectors which increases detection efficiency
- $\mathbf{v_p}$ depends on the materials in the target

$$\frac{dv}{ds} = \frac{dv}{d\gamma}\frac{d\gamma}{dE}\frac{dE}{ds}$$

=> **proton radiography** based on $\mathbf{v_p}$

Time-of-flight Imaging Array (TIARA)



- **Beam monitor** – plastic scintillator (1x25x25 mm^3)

  - 100% detection efficiency
  - time resolution < 120 ps FWHM for 63 MeV protons
  - spatial resolution 1.8 mm σ for 63 MeV protons

- **TIARA module** – array of 30 Cherenkov PbF_2 detectors (2x1.5x1.5 cm^3)

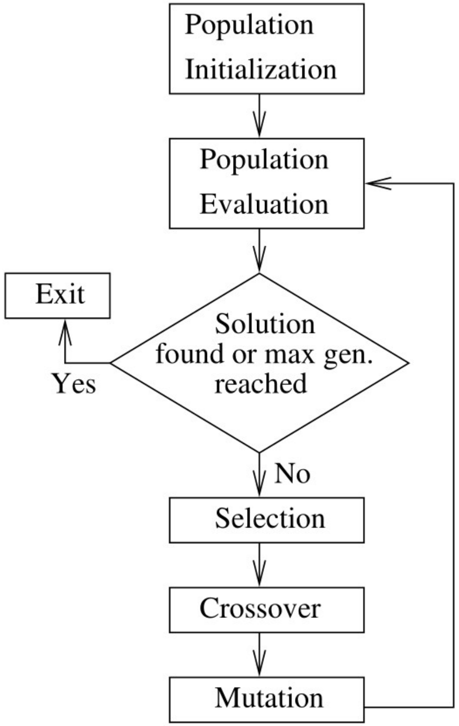
  - time resolution 220 ps FWHM
  - high density => high detection efficiency
  - not sensitive to neutron background

- **Coincidence Time Resolution :** 251 ps FWHM

- **Sensitivity :** 1.65 mm at 2σ for ~10^7 protons

M. Jacquet et al. (2021), A. Andre et al. (2024)

Reconstruction approaches

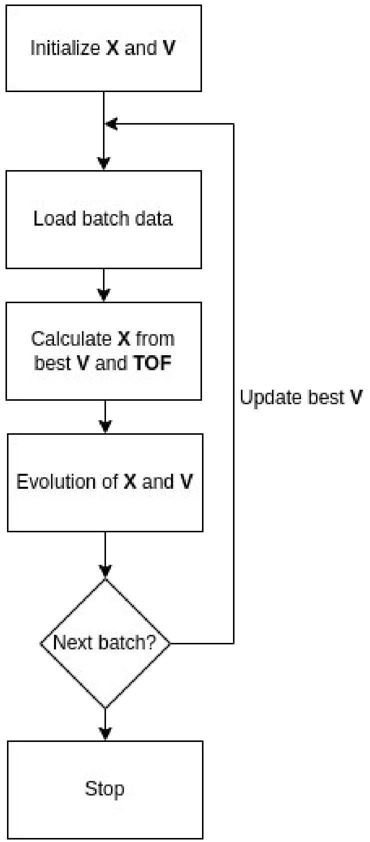


M. Lukac, G. Krylov (2017)

- **Reconstruction** of PG-vertices and proton speed profile:
  - deterministic (e.g. FISTA algorithm)
  - stochastic (e.g. evolutionary algorithm)
  - deep learning

- **Evolutionary algorithm** approach (this work):
  - **Population** is evaluated based on a defined cost function
  - At each iteration best solutions are **selected**
  - Best solutions are combined (**crossover/recombination**)
  - Best solutions are **mutated**
  - **Stochastic** algorithm => relatively slow, needs parallelism

Reconstruction with evolutionary algorithm



- **Evolutionary algorithm implementation:**

  - Input for each PG-vertex is **TOF** and PG-detector coordinates

  - Initial **V** is given by a simulation based on a treatment plan

  - For each data batch the initial **X** is based on current best **V**

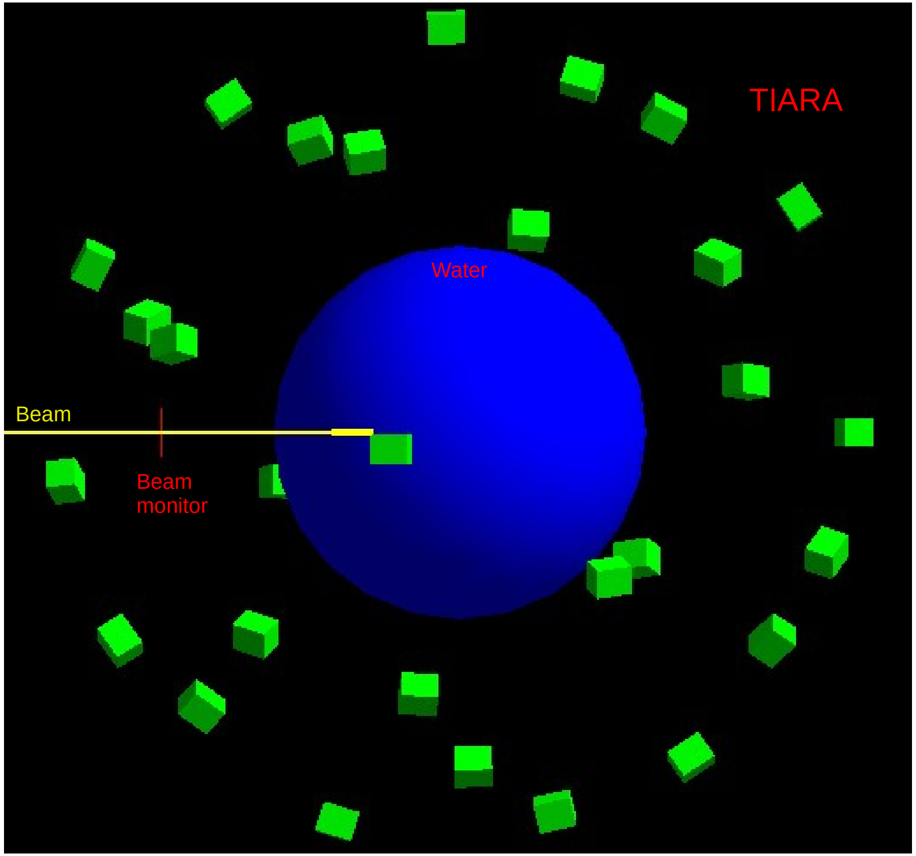
  - Evolution is handled via **scipy.optimize.differential_evolution** with physics-motivated constraints (**V** monotonically decreases)

  - Evolution minimizes the **cost function** (σ=100 ps):

$$\frac{1}{2\sigma^2}(T_{\text{input}} - T_{\text{reco}})^2$$

  - **Termination condition** for a batch - either from a cost function convergence or a limit on the number of evolution iterations

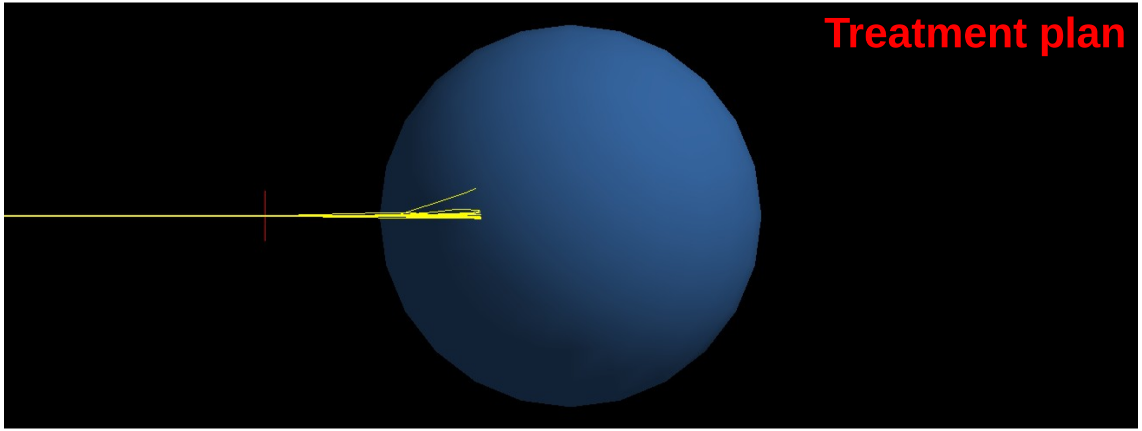
TIARA simulation

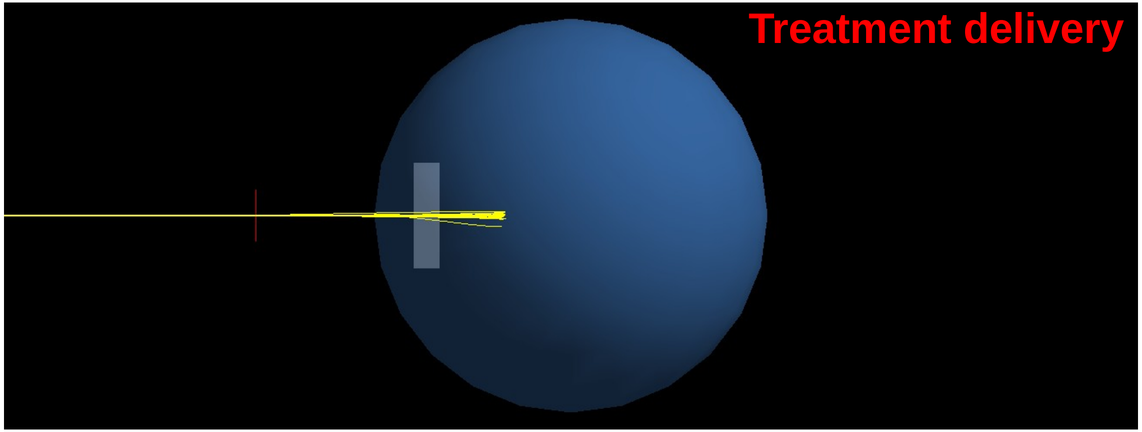


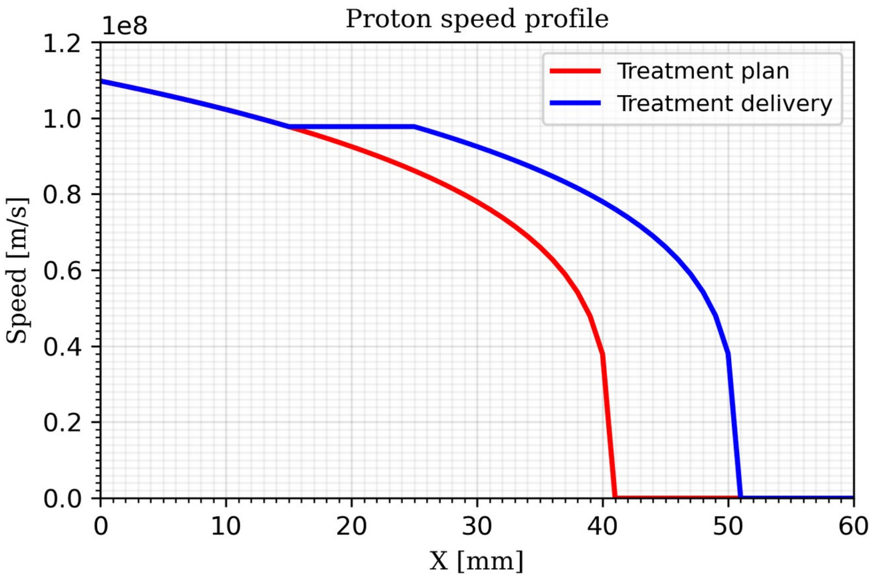
- MC-simulation (GEANT4) of **70 MeV proton beam**
- Water sphere is the target
- Beam monitor records $\mathbf{T_{start}}$
- 30 PG-detectors, spherical arrangement
- Each detector records $\mathbf{T_{stop}}$

- **Treatment plan** – pure water target, proton path length 41 mm
- **Treatment delivery** – adding 10 mm air bubble, proton path length 51 mm

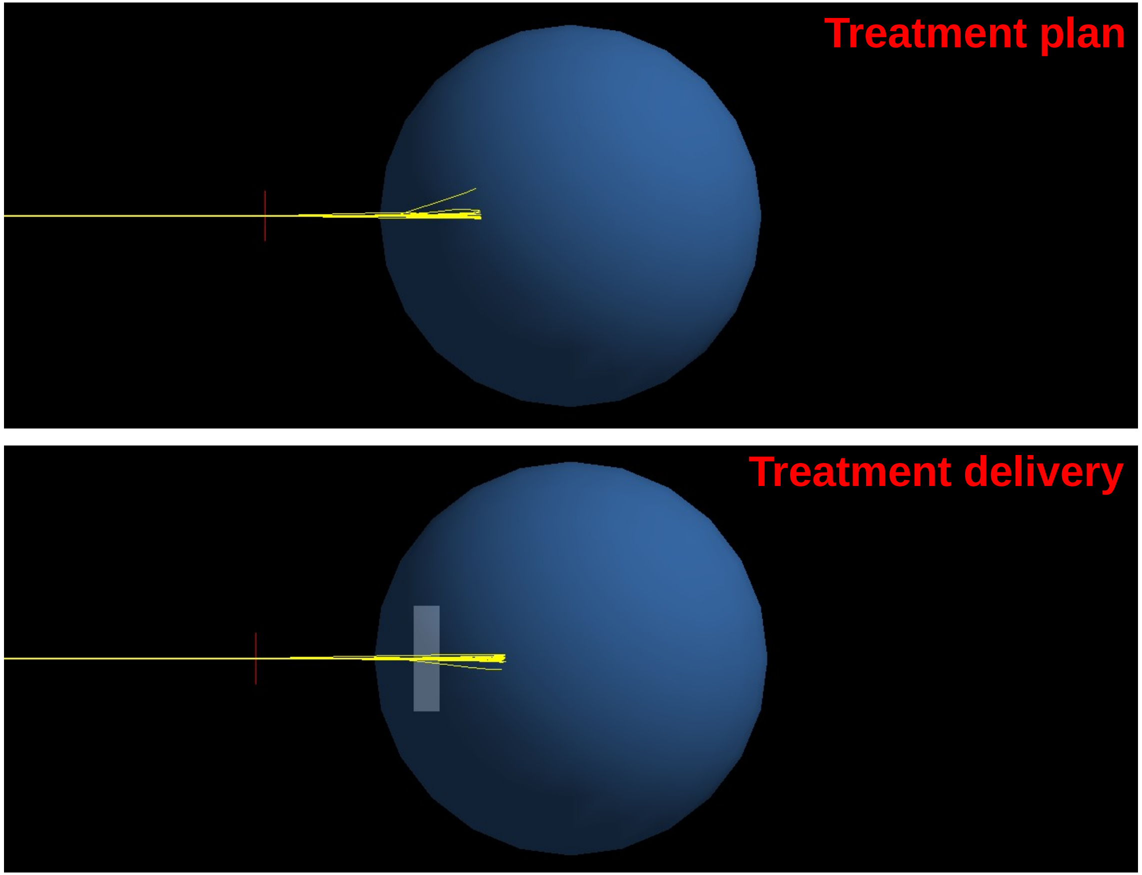
TIARA simulation

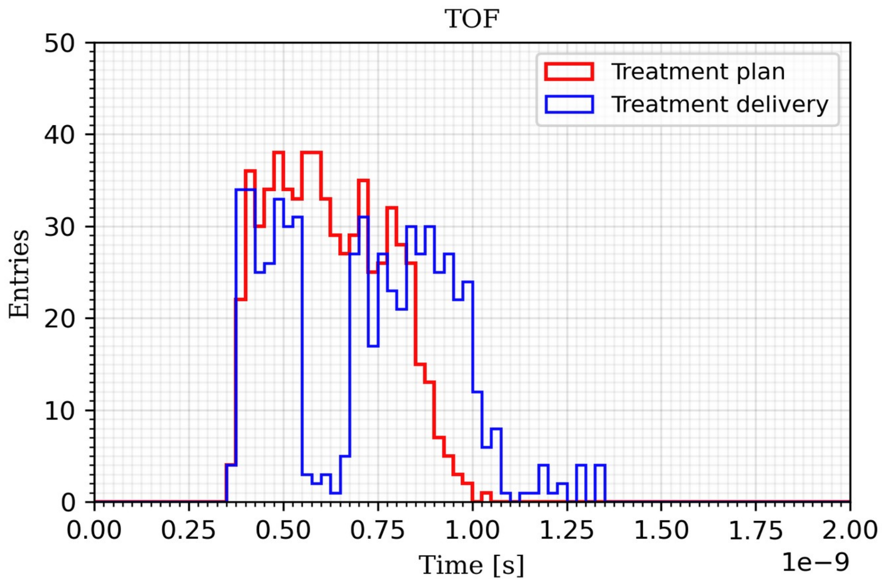




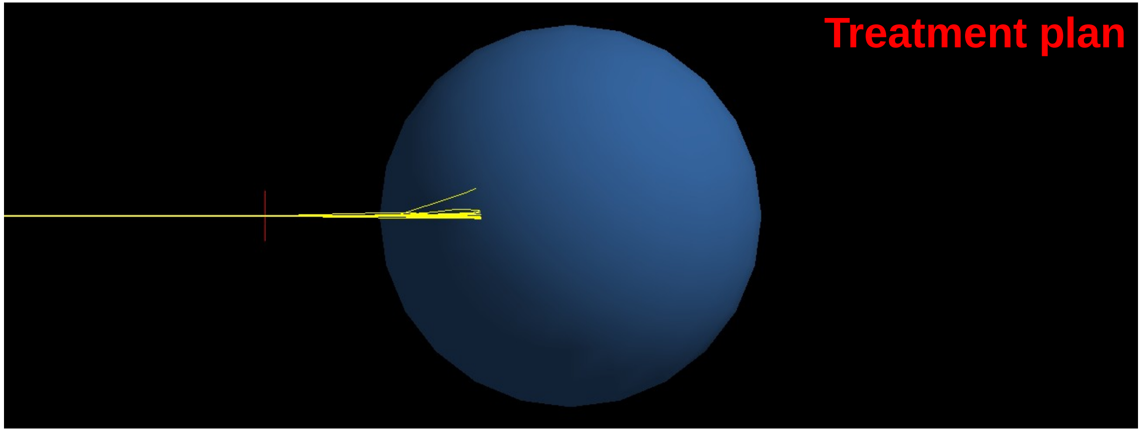


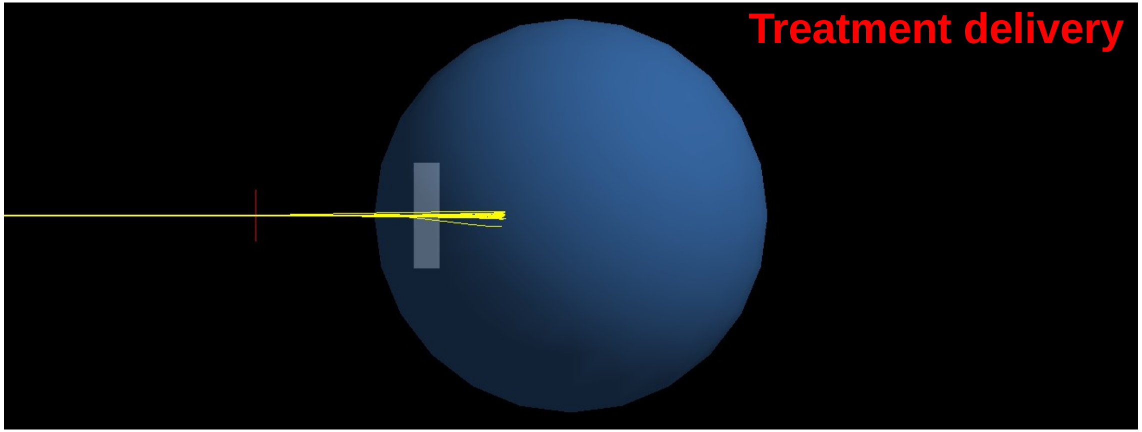
TIARA simulation

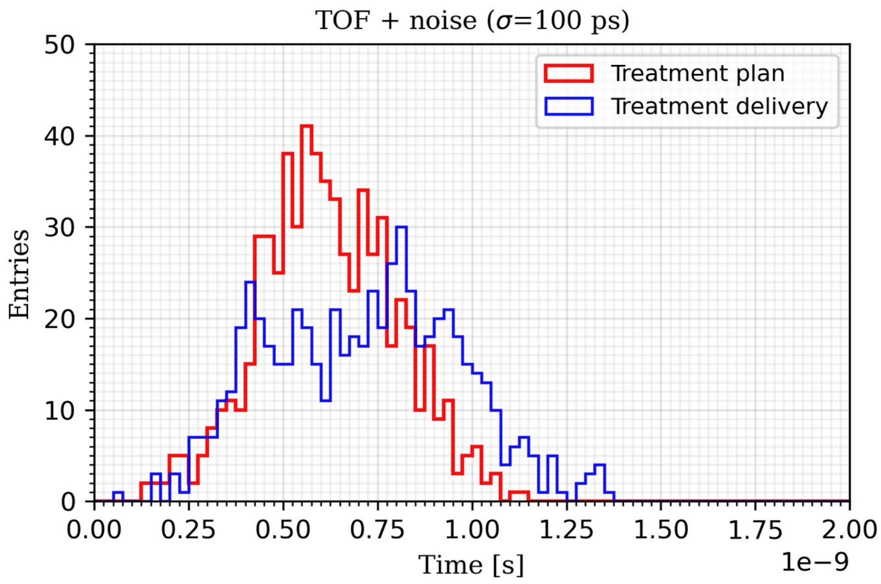




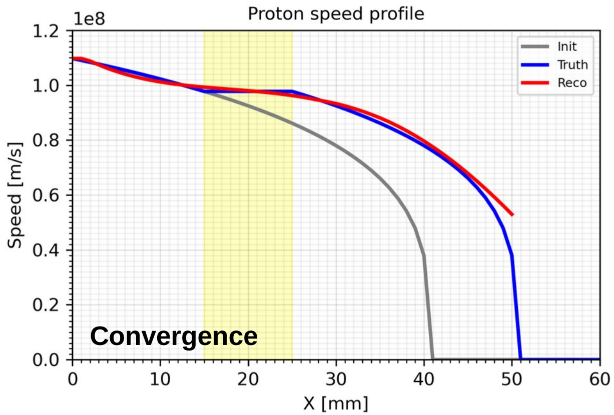
TIARA simulation

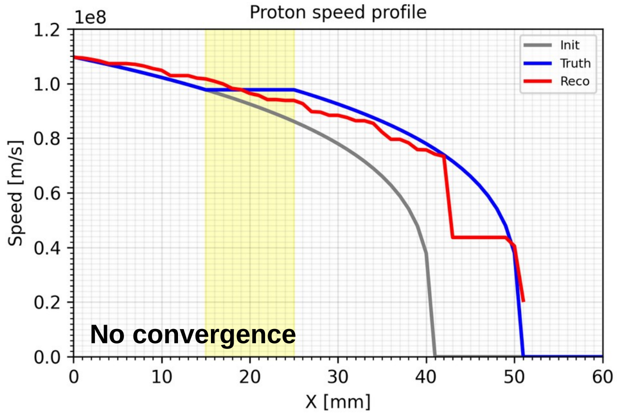






Reconstruction tests

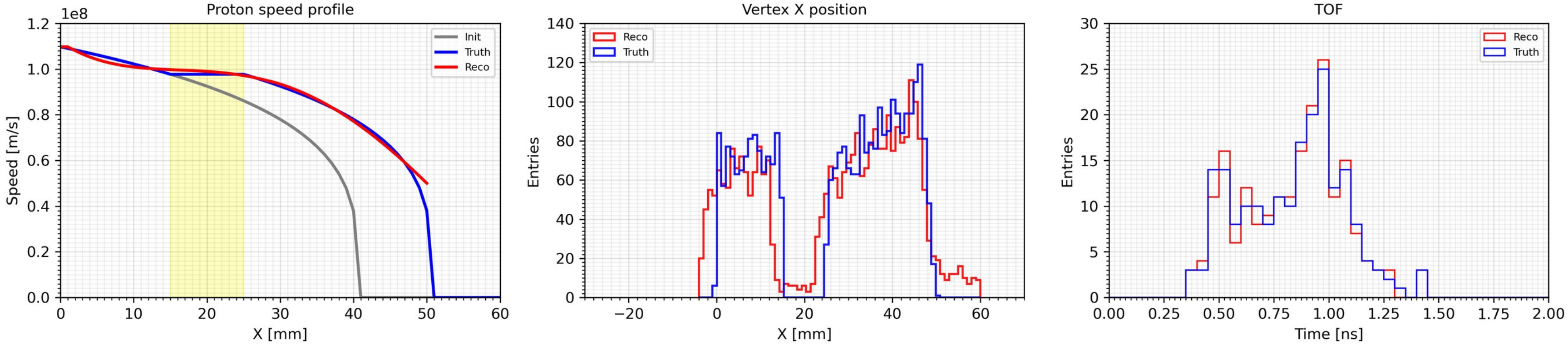




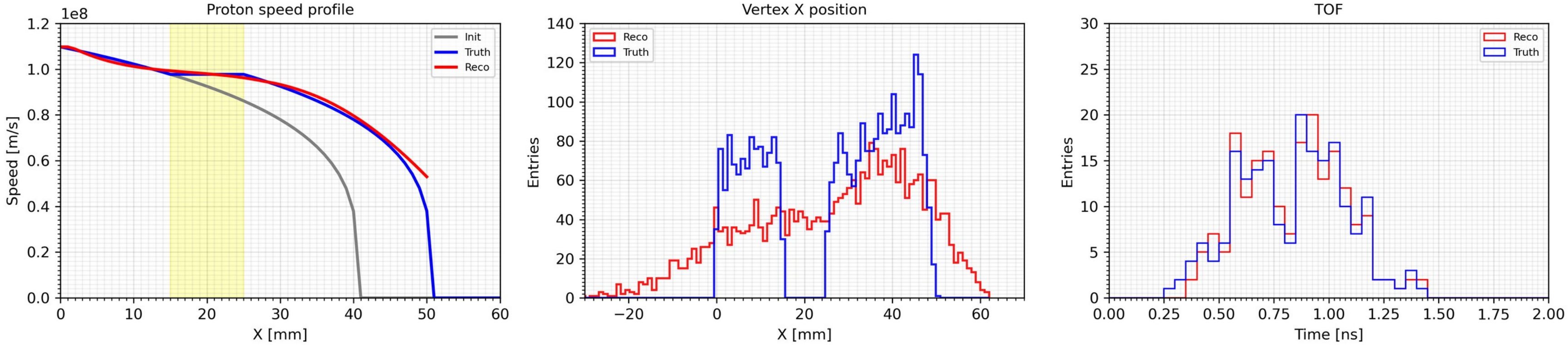
- Initial V is based on the simulation with pure water, i.e. the **treatment plan**
- Reconstruction of the simulation with air bubble => **treatment delivery** monitoring
- Running the reconstruction **with** and **without noise** in the TOF input (noise σ=100 ps)
- Running 100 jobs in parallel with a limit on the number of iterations per batch
- Reconstruction time is **~O(hour) for 5% convergence** => improvement is needed

Reconstruction output

NO NOISE



WITH NOISE



Conclusions

- Data reconstruction for PGTI was implemented using an evolutionary algorithm

- Proton speed profile reconstruction => proton radiography

- The reconstruction was tested using an input from MC simulation of TIARA

- Proton speed profile reconstruction works with a noisy TOF data

- Stochastic reconstruction is slow and requires parallelism

- Next steps: Input TOF denoising, optimizations to decrease the computation time

References

- M. Lukac, G. Krylov, "Study of GPU Acceleration in Genetic Algorithms for Quantum Circuit Synthesis" (IEEE 47th ISMVL, 2017)

- M. Jacquet et al., "A time-of-flight-based reconstruction for real-time prompt-gamma imaging in proton therapy" (Phys. Med. Biol. 66 135003, 2021)

- M. Jacquet et al., "A high sensitivity Cherenkov detector for prompt gamma timing and time imaging" (Scientific Reports vol. 13, 3609, 2023)

- A. Andre et al., "A fast plastic scintillator for low intensity proton beam monitoring" (in preparation, 2024)