Optimization of hadron therapy beamlines using a novel fast tracking code for beam transport and beam-matter interactions

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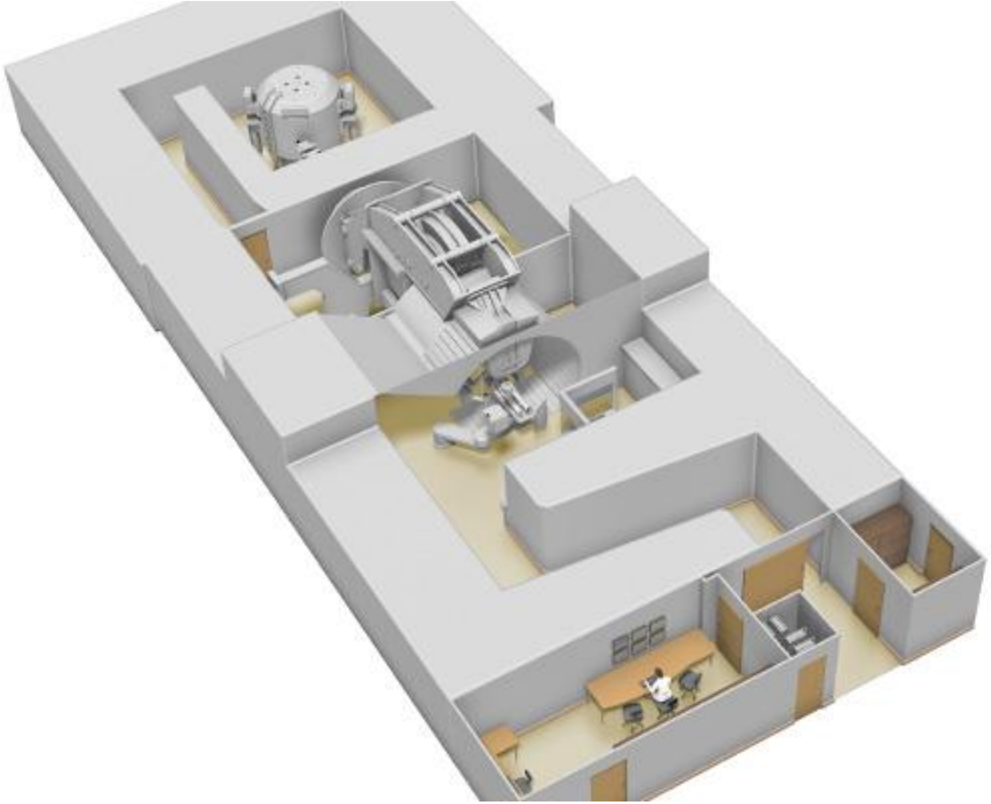
Outline

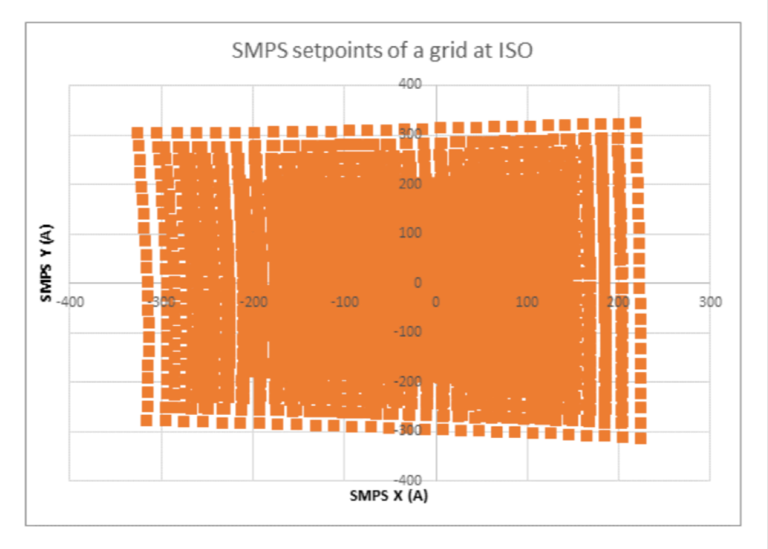
- Challenges for conventional PT beamlines simulations and predictive modeling
- Development of a suite of Python tools and fast tracking code
  - Georges/Manzoni
- Genetic algorithm for design exploration and optimization of PT beamlines
- Summary and next steps

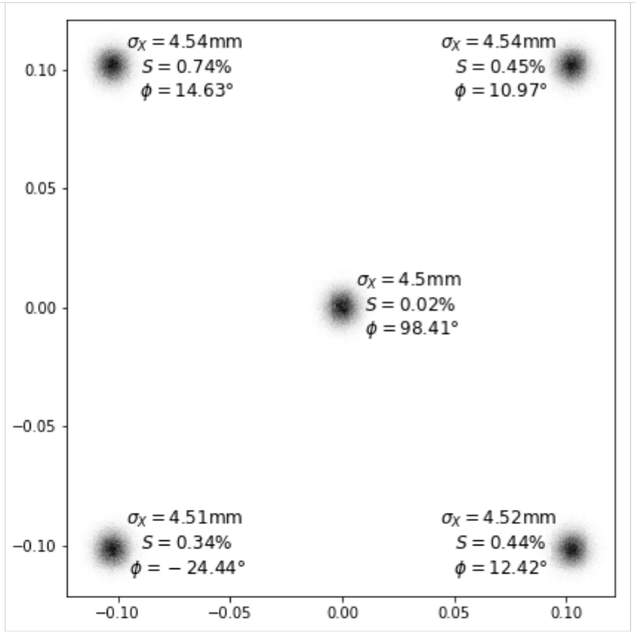
IBA Proteus One

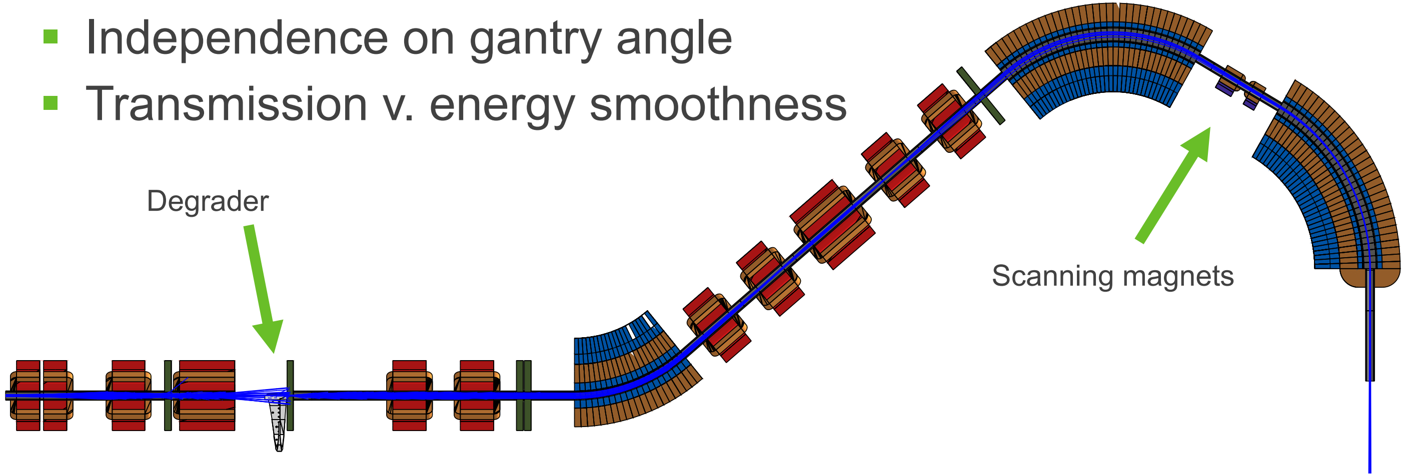


Challenges for PT beamlines simulations

- Cyclotron-based PT beamlines
  - Large emittance (energy degradation), small aperture
  - Fringe fields effects for large amplitude scanning
- Very tight constraints for beam quality at isocenter
  - Beam size: to be minimized, function of energy, independence on scanning
  - X/Y spot symmetry (percent level tolerance)
  - Physical space ellipse orientation (non-round beam at gantry entrance)
  - Independence on gantry angle
  - Transmission v. energy smoothness







Simulation code and model for PT beamline optimization

- IBA Model development: what is required?
  1. Validity of the physical models and methods
     - Need to cross-validate the models with existing and proven codes
  2. Possibility to exchange and contribute to a robust model (Single Source of Truth)
  3. Performance of the numerical methods
     - Suitability to large scale optimization runs

→ **Development of a suite of tools and methods within the Python ecosystem**

Simulation code and model for PT beamlines

- Model development: what did we develop?

- **Georges**: a Python library for beam physics modeling and numerical simulations
  - Allow a unique description of the IBA beamlines to be reused between codes, compared, shared and progressively improved

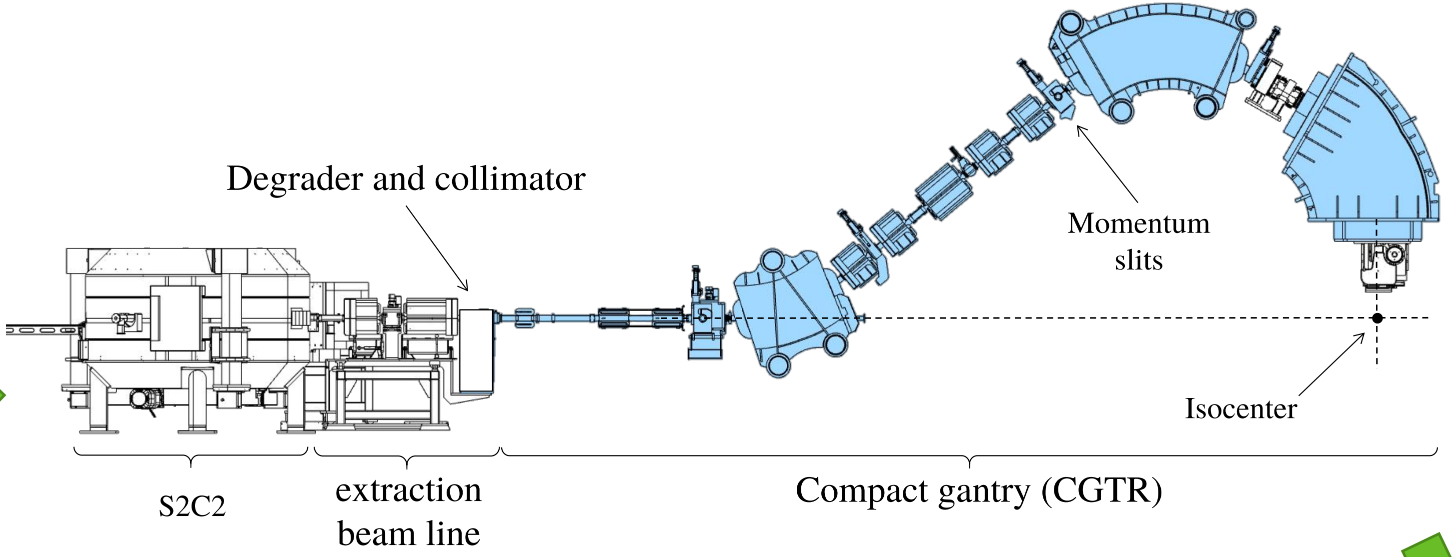
https://github.com/chernals/georges

- **Georges/Manzoni**: a fast tracking code for beam transport and simulation of beam-matter interactions in hadron therapy beamlines

https://github.com/chernals/zgoubidoo

- **Zgoubidoo**: Python 3 interface to Zgoubi (on-going, field maps and ray-tracing)

Simulation tools ecosystem



« gold standard »

- **MAD-X / PTC**

Ad-hoc, fast, optimisation-oriented model

- **Manzoni**

Magnetic models

- **AOC**
- **Zgoubi via Georges and Zgoubidoo**

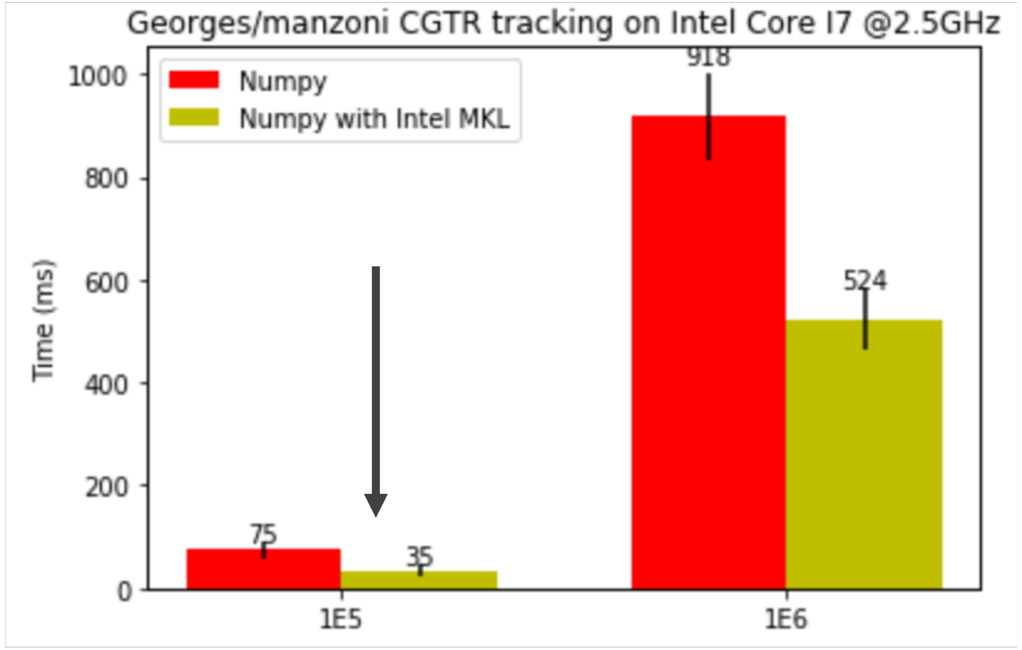
3D realistic model

- **BDSim**
- **See R. Tesse talk this afternoon**

Manzoni fast tracking code

- Manzoni
  - Follows the “kick codes” design principles
    - Linear tracking implemented with fast matrix multiplication (using Intel MKL – BLAS) and second order Taylor expansion of the e.o.m
    - Symplectic integration for nonlinear magnets (in place transformation with Intel MKL – BLAS)
    - Detailed aperture models (numpy + MKL)
  - Semi-analytical multiple Coulomb scattering model

- Fast tracking
  - Multithreaded via Intel MKL
  - Parallel ops. Via Intel MKL
  - Also support PyTorch tensors
    - On CPU (similar performances)
    - On GPU



Manzoni fast tracking code

- Multiple Coulomb Scattering: degrader, air gaps, Titanium foils
- Follow Fermi-Eyges formalism
  - Compute moments of the scattering power

$$T_{dM} \equiv f_{dM}(pv, p_1 v_1) \times \left(\frac{E_s}{pv}\right)^2 \frac{1}{X_S}$$

$$f_{dM} \equiv 0.5244 + 0.1975 \log_{10}(1-(pv/p_1v_1)^2) + 0.2320 \log_{10}(pv) - 0.0098 \log_{10}(pv) \log_{10}(1-(pv/p_1v_1)^2)\,,$$

$$\frac{1}{\rho X_S} \equiv \alpha N r_e^2 \frac{Z^2}{A} \left(2 \log_{10}(33219 (AZ)^{-1/3}) - 1\right)$$

$$A_0(z) \equiv \int_0^z T(u)du\,,$$
$$A_1(z) \equiv \int_0^z (z-u)T(u)du\,,$$
$$A_2(z) \equiv \int_0^z (z-u)^2 T(u)du\,,$$

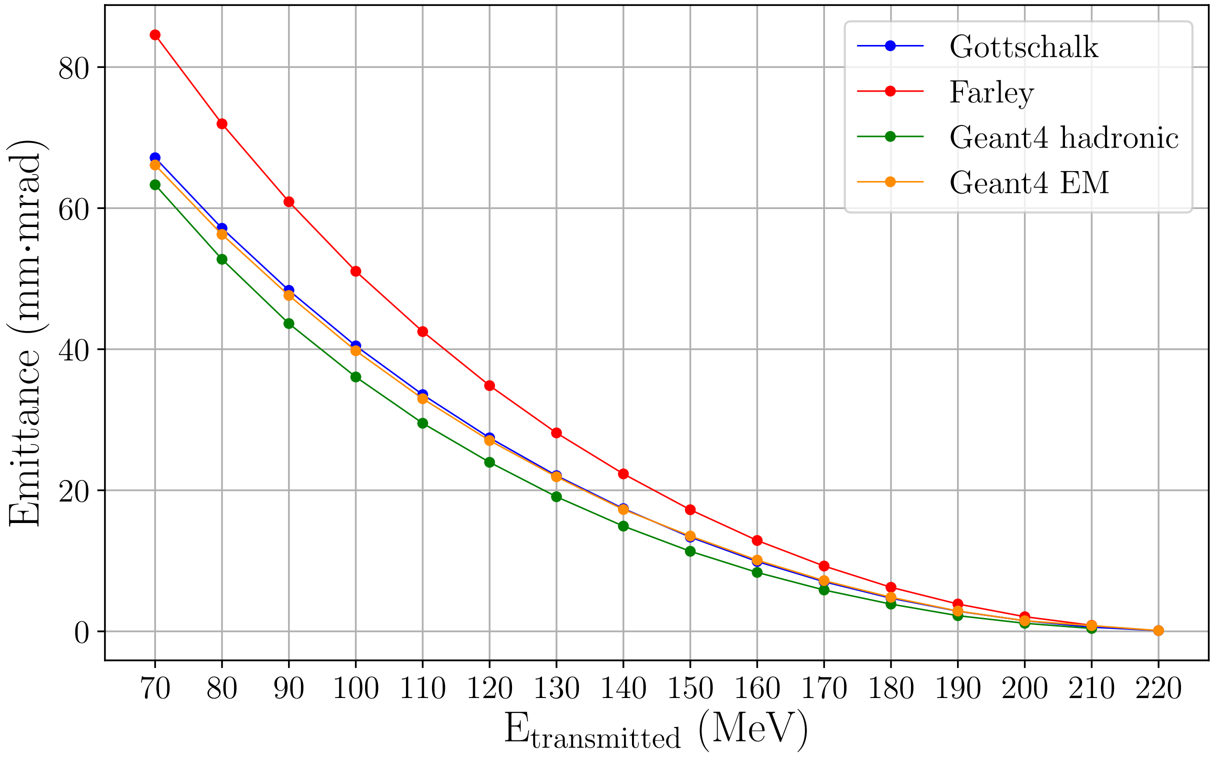
B is given by: $B(z) \equiv A_0A_2 - A_1^2\,.$

$$A_0 = \langle \theta^2 \rangle\,,$$
$$A_2 = \langle x^2 \rangle\,,$$
$$A_1 = \langle x\theta \rangle\,.$$

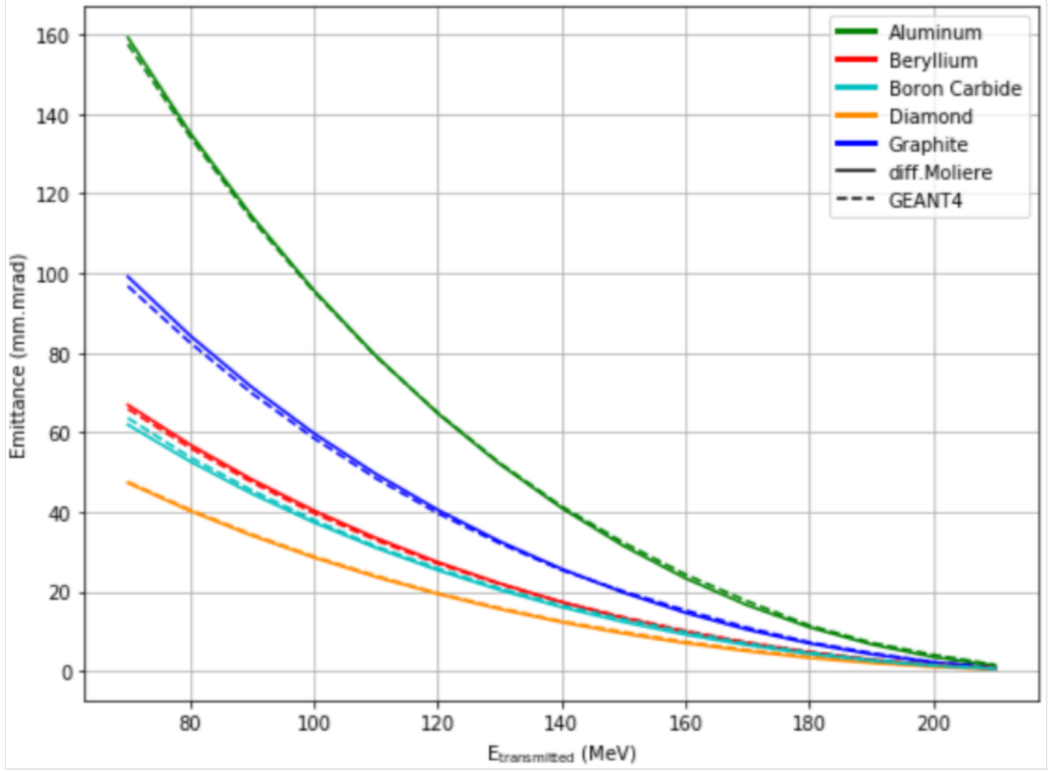
Energy dependency: compute energy loss based on tabulated range data (NIST)

Sample output Gaussian distribution and apply offsets and kicks

Manzoni fast tracking code



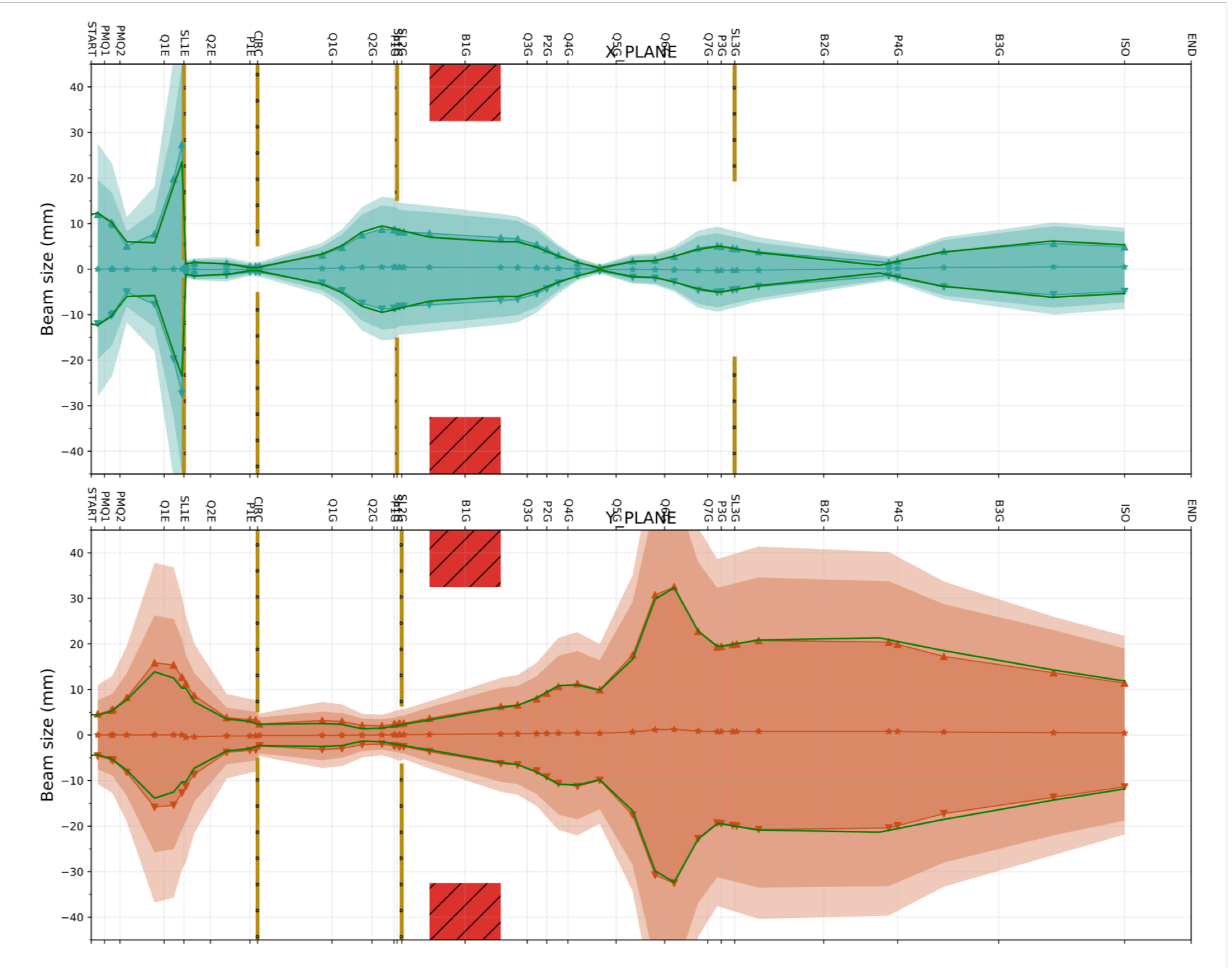
Beryllium degrader



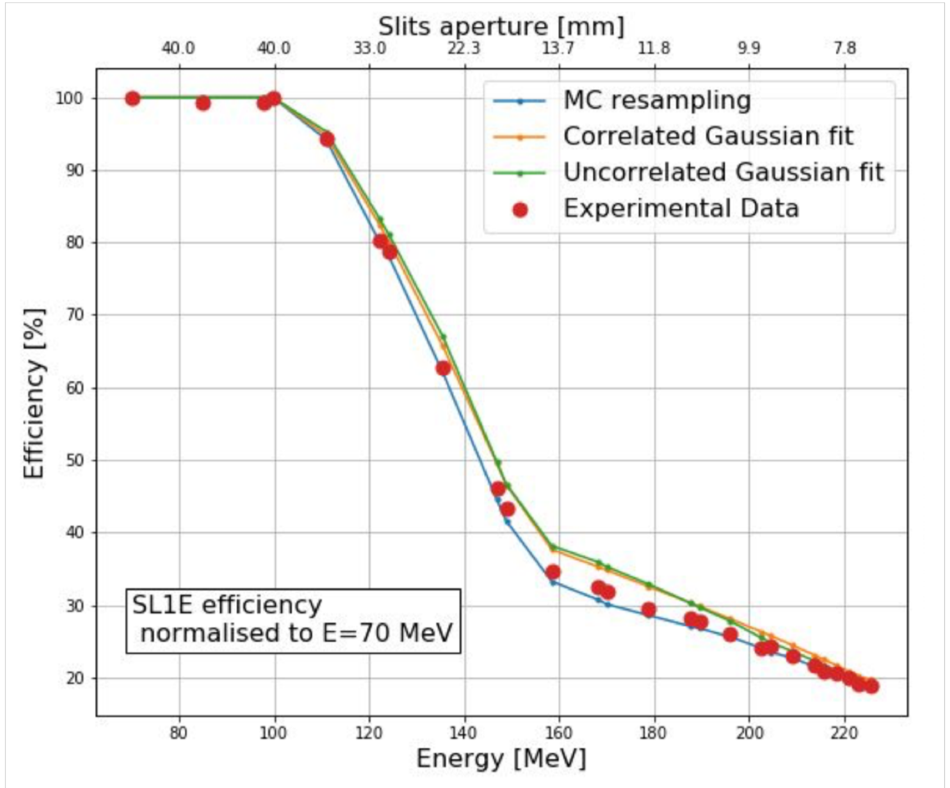
Agreement between FE model and Geant4 (EM only) for different materials

Manzoni fast tracking code

Validation against MAD-X/PTC

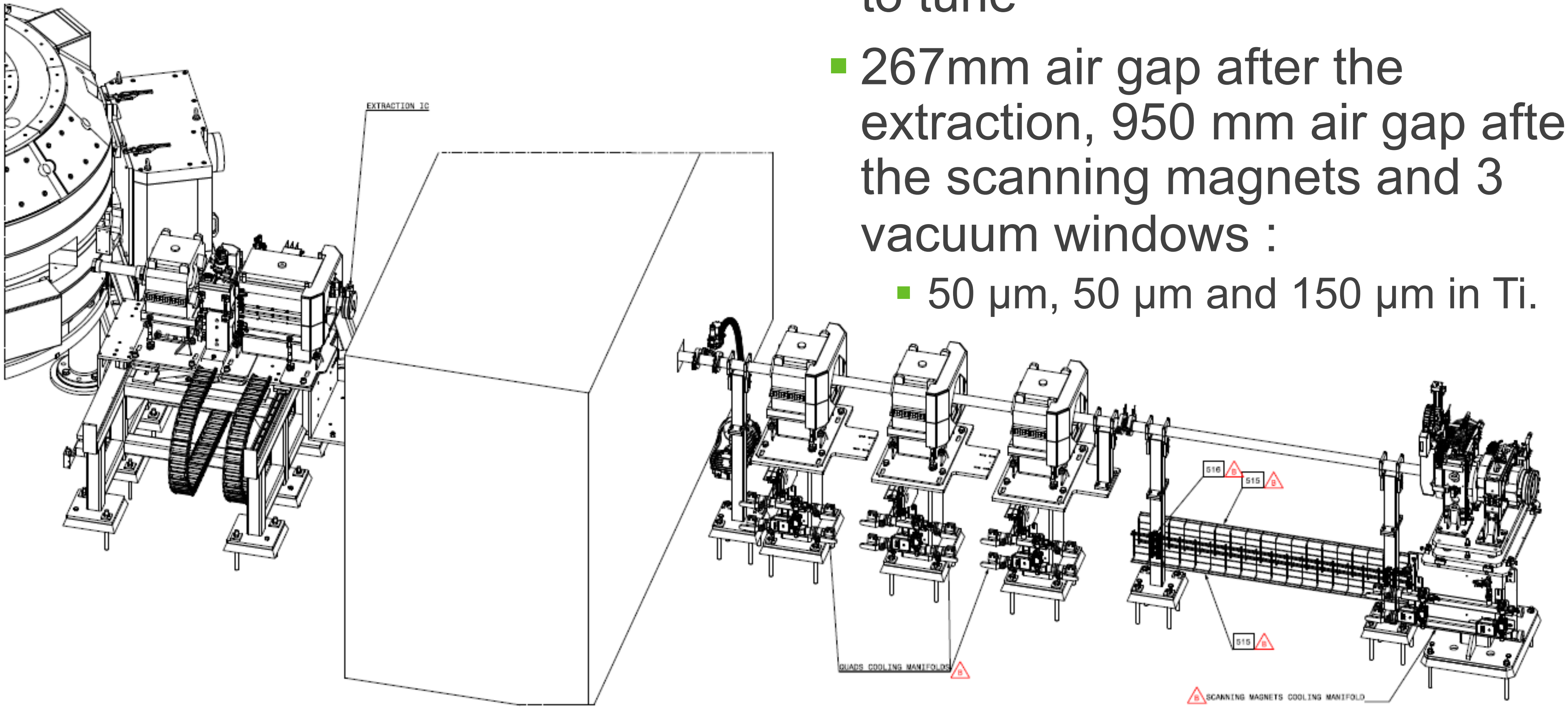


Validation against experimental data



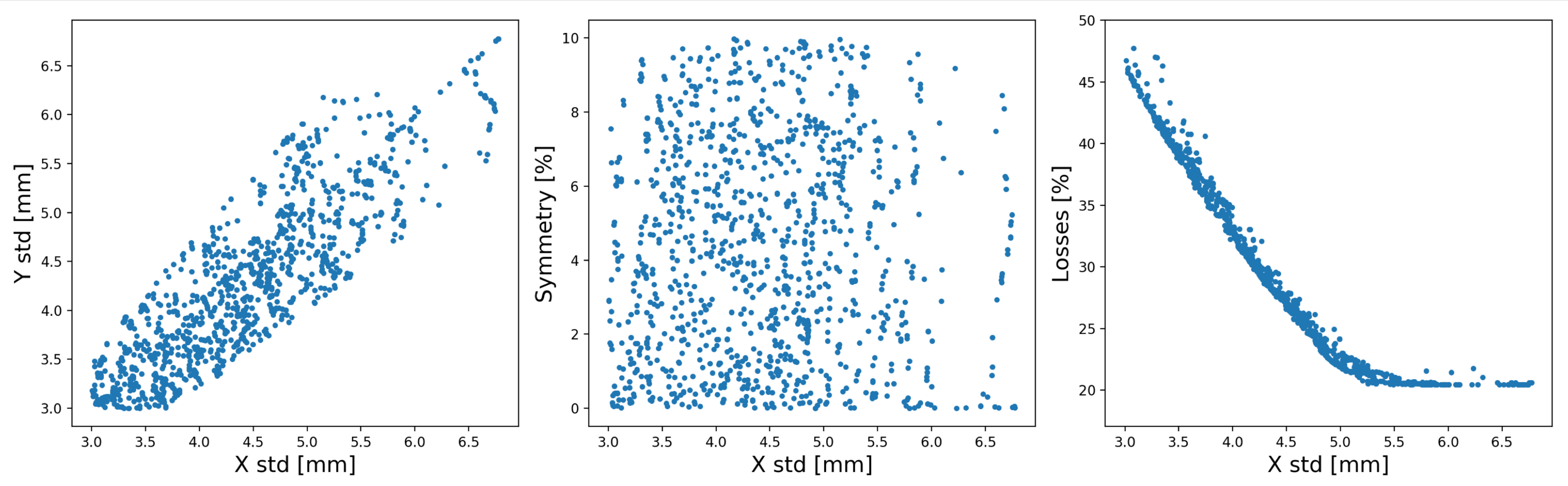
The research beam line

- 5 quadrupoles and extraction slits to tune
- 267mm air gap after the extraction, 950 mm air gap after the scanning magnets and 3 vacuum windows :
  - 50 µm, 50 µm and 150 µm in Ti.



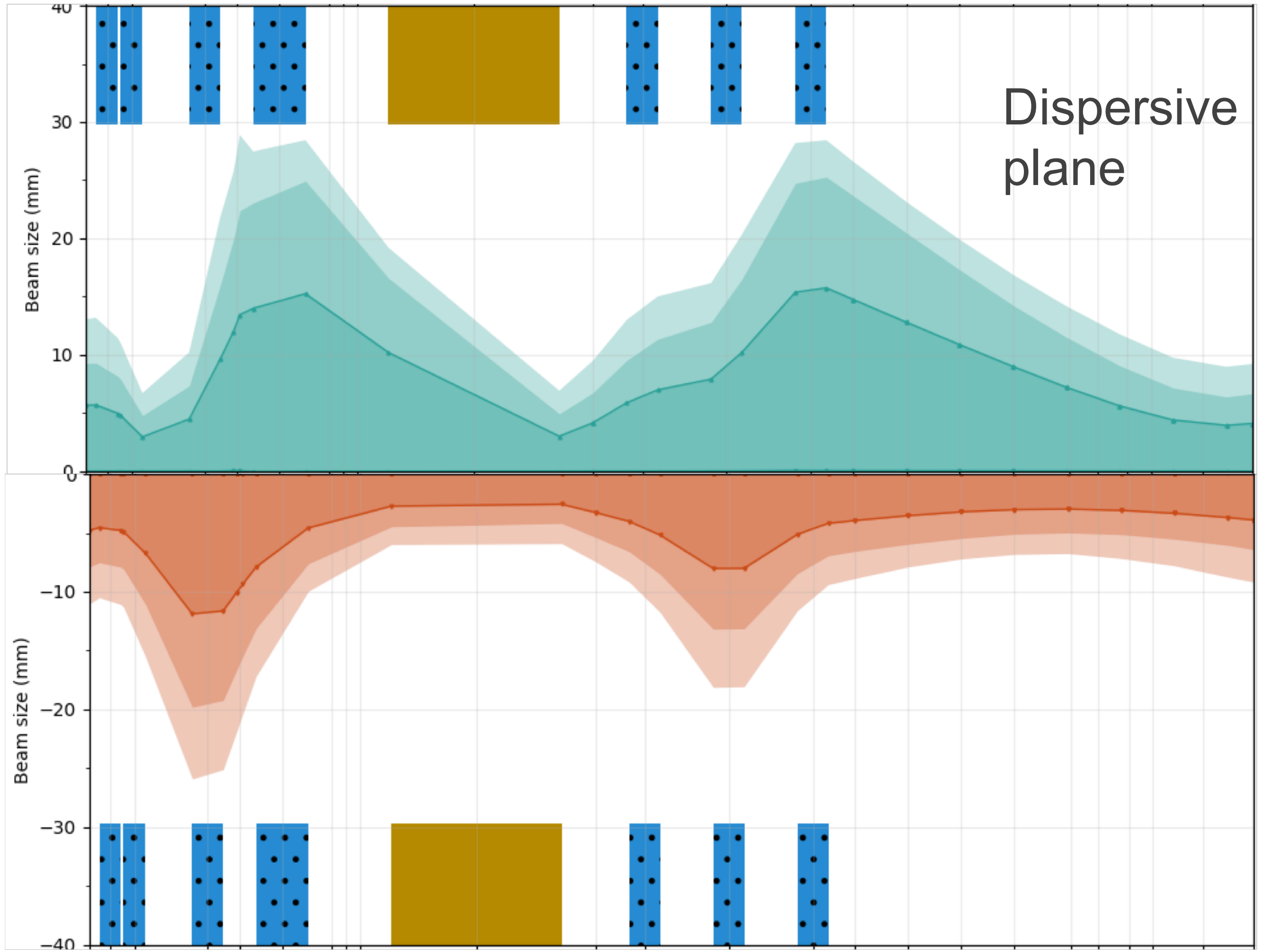
WP1: Automated Optics

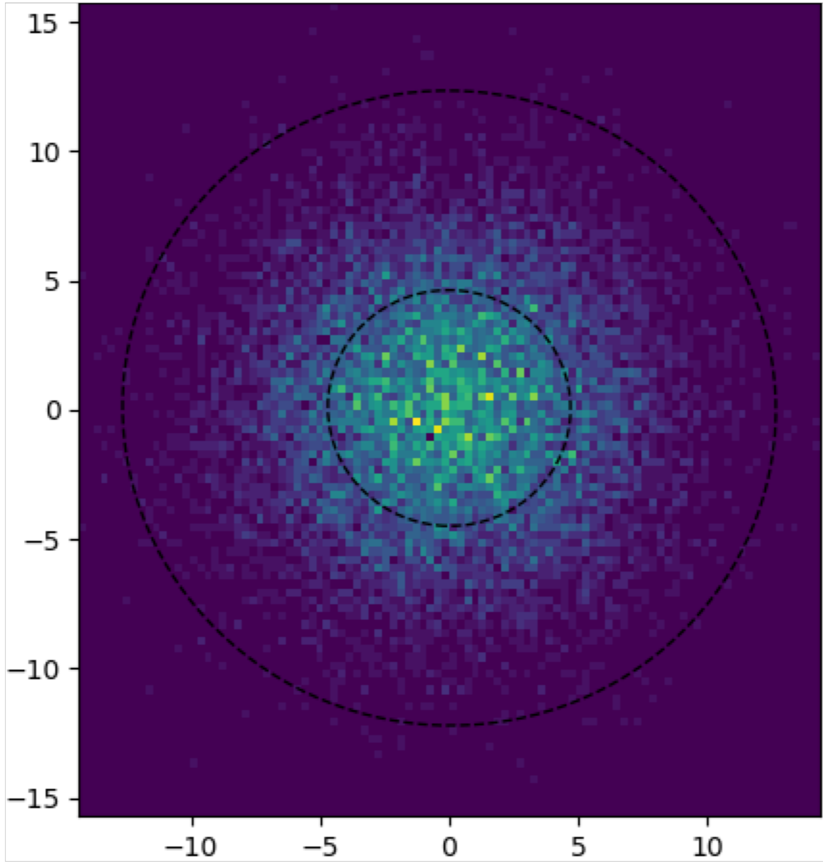
- **Manzoni – Design exploration and Genetic Algorithms**
  - Fast code and efficient algorithms allow detailed exploration of the parameters space



The NSGA-II (Non dominated sorted GA) realization of the MOGA is used and it has been shown to allow large scale search capabilities.

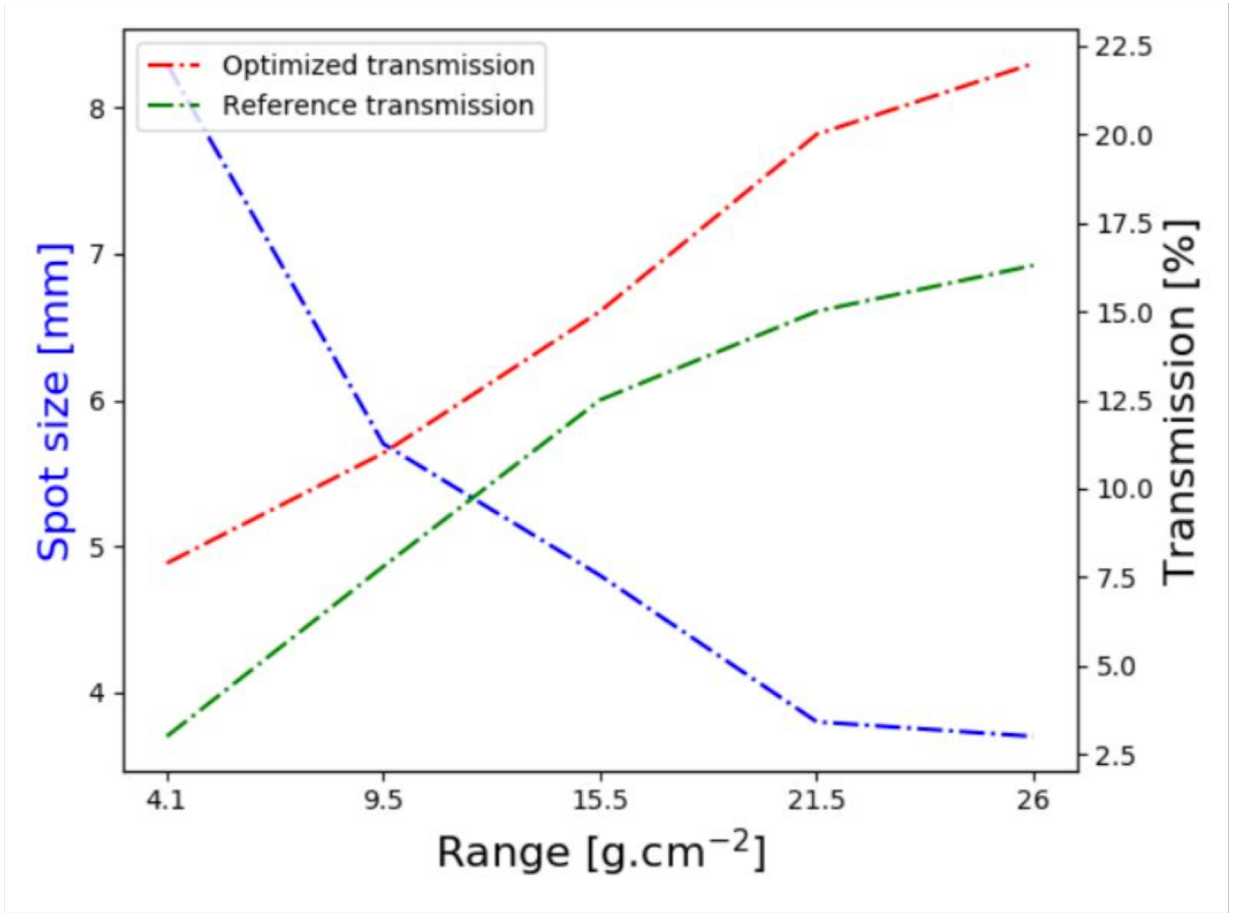
Genetic optimization - Results





Genetic optimization - Results

- Transmission optimization at equal spot size and symmetry for different ranges



Summary and next steps

- A fast tracking code for efficient PT beamline simulation has been developed
  - Modular (e.g. higher order integrators are being progressively added)
  - Benchmarked (MAD-X/PTC and experimental data)
  - Fast implementation using the Intel Python Distribution (MKL and numpy)
- Tools to integrate an NSGA-II implementation into Georges/Manzoni
- A complete model has been tested (including particle-matter interactions) and optimized