Beam transport, matching and optimization for THz SASE FEL

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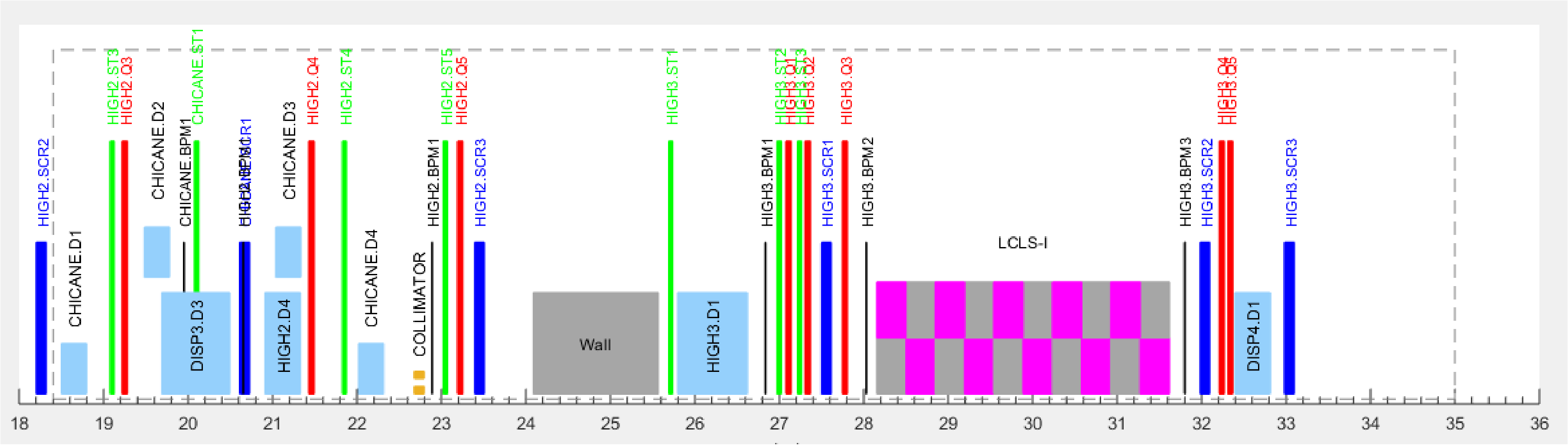
Mini-workshop on THz@PITZ, DESY Zeuthen, 15.03.2023

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Overview of the electron beam preparation

- EM fields, including:
  - Space charge effects; undulator fields (strong vertical focusing);
  - Possibly wakefields in booster accelerator, TDS, undulator vacuum chamber and small apertures from other components along the beamline
- Physical borders
  - Small apertures
  - Small and long vacuum chamber in the undulator
- Limited beam diagnostics: two screen stations

- Smooth and symmetric beam transport from cathode to undulator
- Transverse phase space matching into the undulator


HIGH2.SCR2
CHICANE.D1
HIGH2.ST3
HIGH2.Q3
CHICANE.D2
CHICANE.BPM1
CHICANE.ST1
DISP3.D3
CHICANE.D3
HIGH2.D4
HIGH2.Q4
HIGH2.ST4
CHICANE.D4
COLLIMATOR
HIGH2.BPM1
HIGH2.ST5
HIGH2.Q5
HIGH2.SCR3
Wall
HIGH3.ST1
HIGH3.D1
HIGH3.BPM1
HIGH3.SCR1
HIGH3.Q3
HIGH3.BPM2
LCLS-I
HIGH3.BPM3
HIGH3.SCR2
DISP4.D1
HIGH3.SCR3
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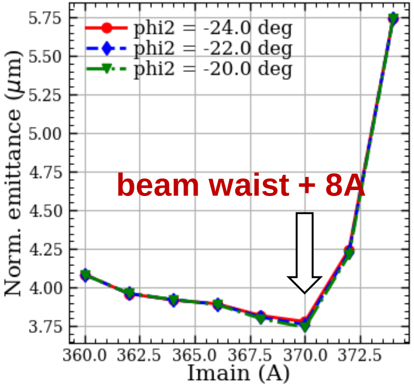
Overview of the electron beam preparation

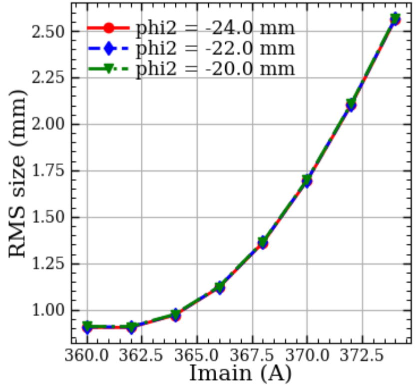
- Photocathode RF gun → **6.3 MeV/c** at MMMG phase
- Booster accelerator → **17 MeV/c** at off crest phase → minimize energy spread
- Solenoids → Focus the beam for approximately minimum emittance at the first emittance station (EMSY1) after the booster
- For smooth focusing from the booster to undulator:
  - First quadrupole triplet after the booster (**5 to 12 m**)
  - Second triplet after the TDS (**12 to 18 m**)
  - Third triplet (new quads) to tunnel 2 (**starting from 25.5 m**)
- For transverse phase space matching into the undulator：
  - Third triplet + one more triplet (new quads) right in front of undulator

Solenoid focusing

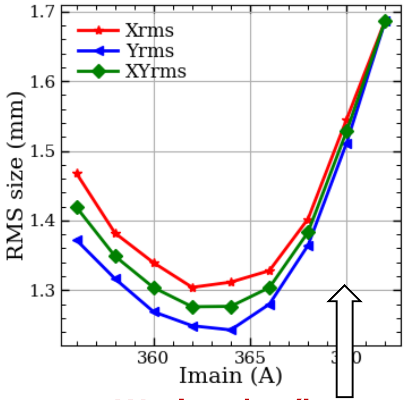
- Solenoids around the RF gun are used to focus the space charge dominated electron beam after emission and compensate the beam emittance

Simulation





Measurement

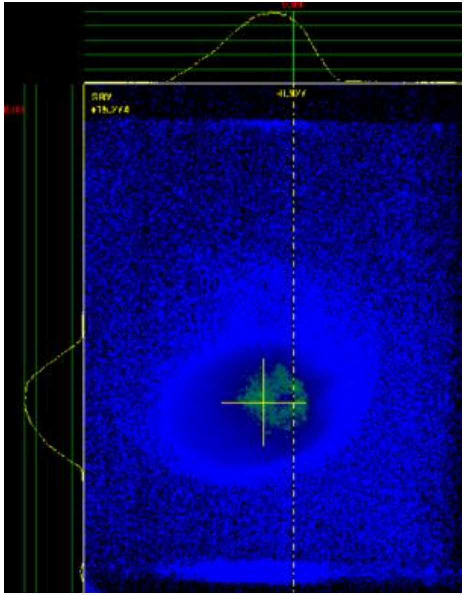


Work point (beam waist + 6A)

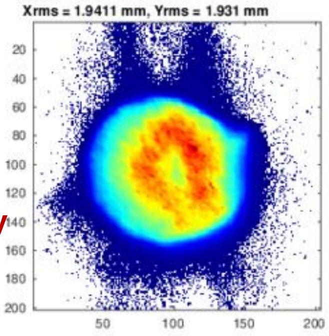
*** phi2 is booster phase w.r.t. maximum mean momentum gain (MMMG); off-crest acceleration in the booster is employed for min. energy spread at the undulator**

Beam trajectory control/correction

- Beam traj. In the booster → Use steerers to symmetrize the distribution downstream the booster after booster BBA

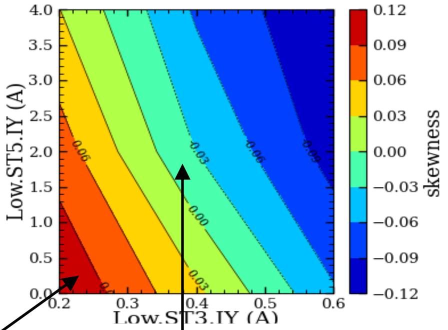


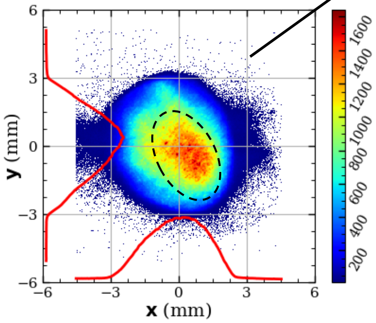
Manually tuning

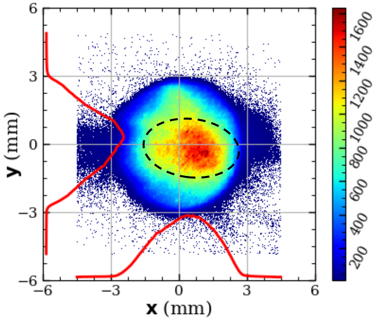


Fine scan of steerers:

$$s = \frac{\mu_3}{\sigma^3} = \frac{\langle (x - x_c)^3 \rangle}{\langle (x - x_c)^2 \rangle^{3/2}}$$

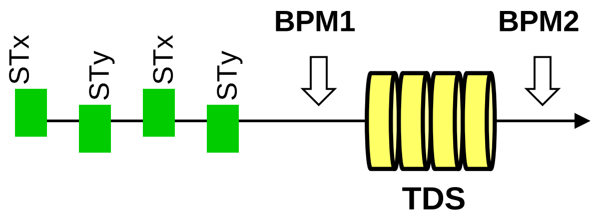


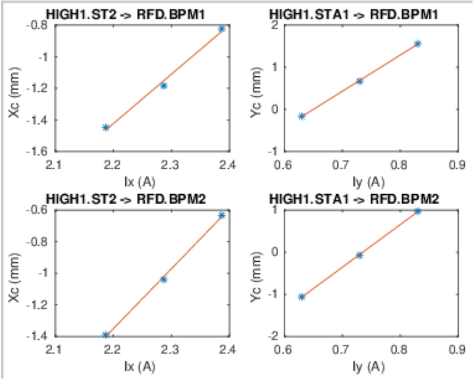


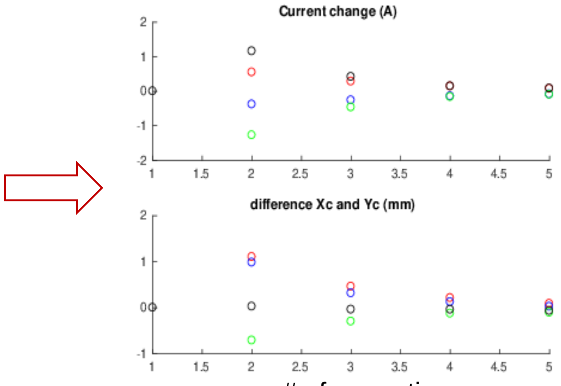


Beam trajectory control/correction

- Around the TDS
  - Iteratively tuning of two pairs of steerers, or
  - Measure response matrix→ correction



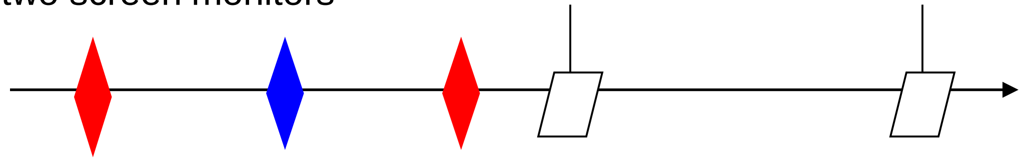




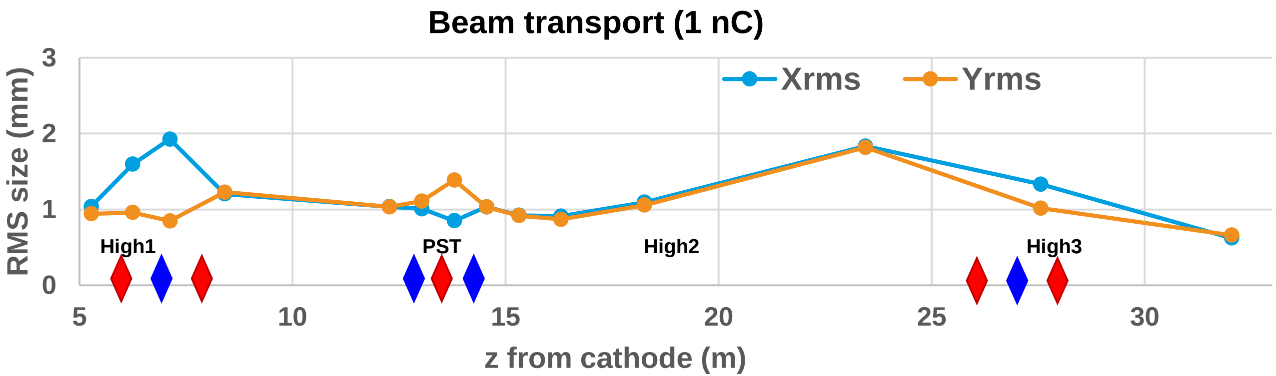
- And also from TDS to undulator and in all quadrupoles (steering free)

Beam transport

- We use quadrupole triplet to focus the beam
  - Iteratively increase the currents of quads after degaussing → reproducible later
    - Quad triplet + two screen monitors



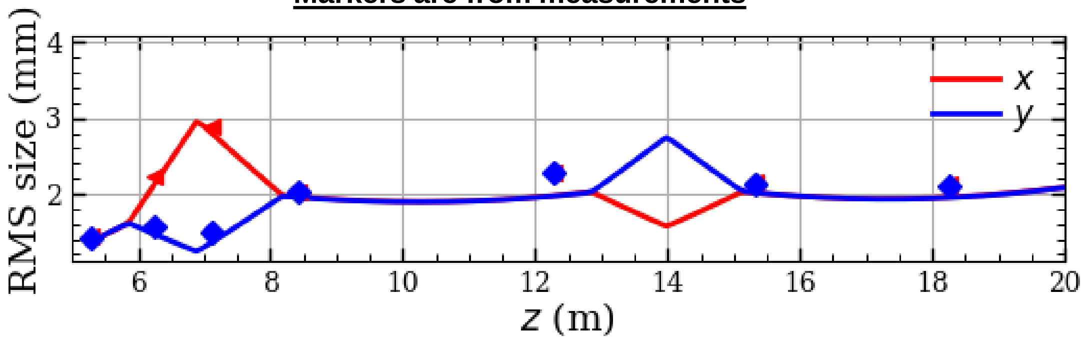
  - Ensure a smooth (and also symmetric) beam transport after the triplet, when cannot be measured everywhere



Beam transport

Another example (2 nC)

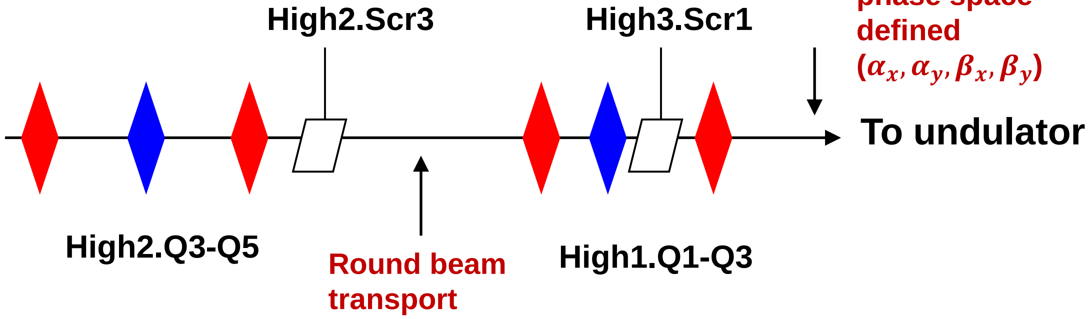
Lines are from simulation;
Markers are from measurements



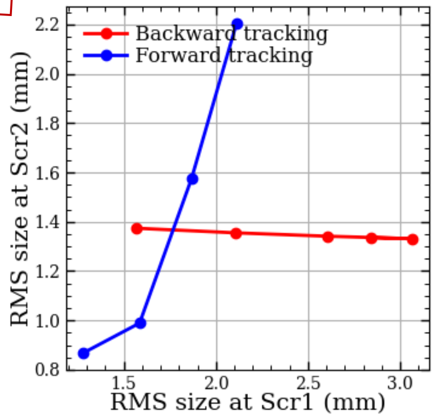
Beam matching into undulator

With two screen stations

- Start-to-end simulations have been performed in advance in order to define the beam envelop needed for the matching procedure
  - Beam envelop development is determined by Twiss parameters + space charge effects
  - Matched beam envelop at the two screen station are obtained by forward tracking (scanning of first triplet) and backward tracking (scanning of second triplet)
  - They are used as references in experiment

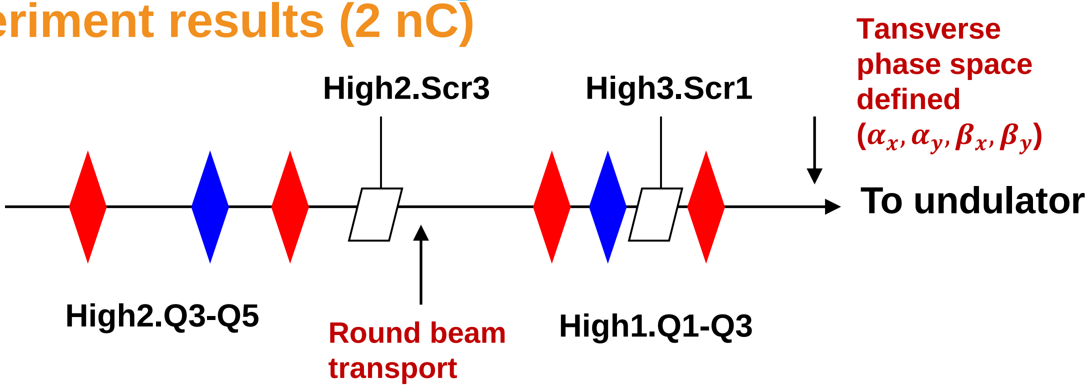


Matching simulation (2 nC)

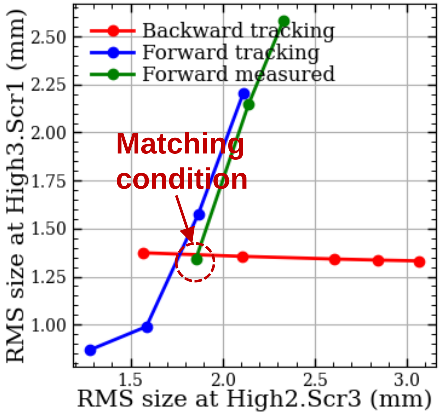


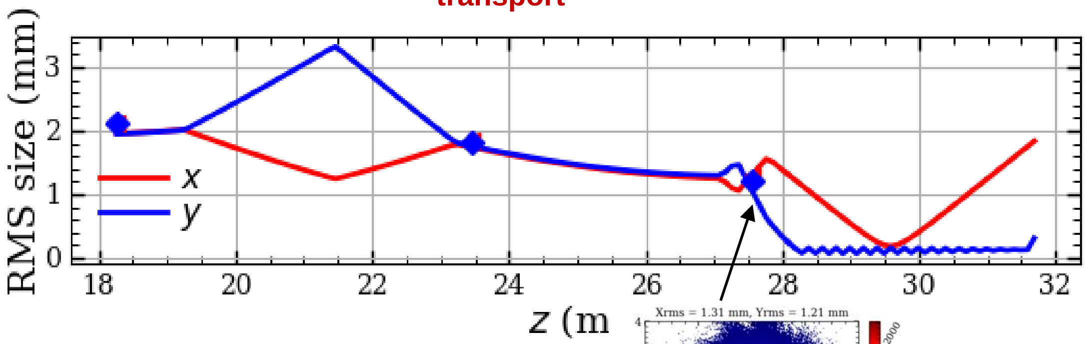
Beam matching into undulator

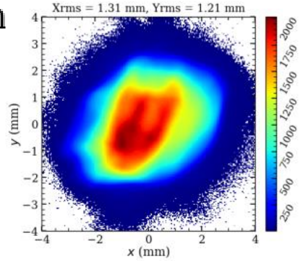
Experiment results (2 nC)



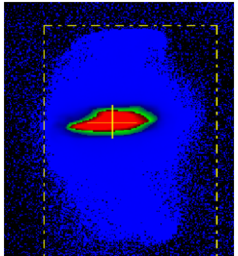
Forward: scanning the first triplet
Backward: scanning the second triplet







After undulator:
Xrms = 1.67 mm, Yrms = 1.12 mm



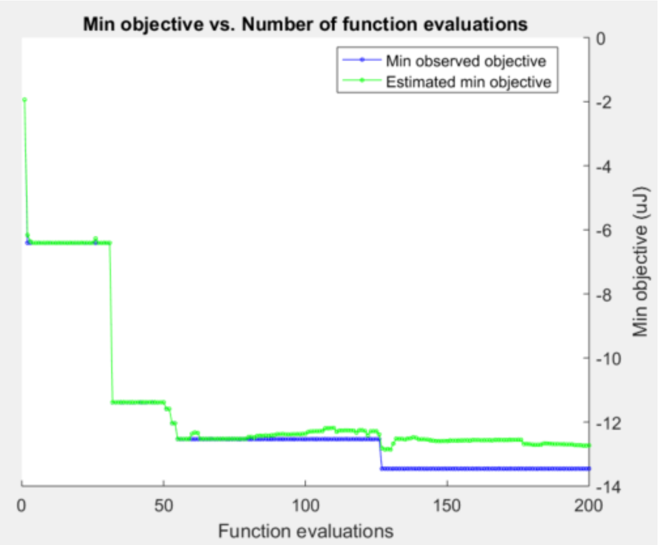
Lines are from simulation;
Markers are from measurements

Bayesian optimization of SASE output

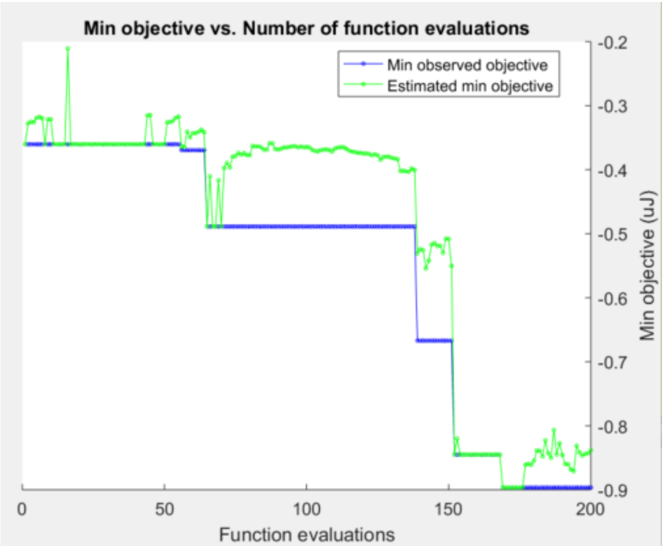
- Usually, we need to tune the 3-6 quadrupoles (for beam matching) and two pairs of steerers (for beam trajectory) in order to optimize the SASE output
- The Bayesian optimization algorithm was considered first because of its capability of handling many variables
  - A Matlab script was developed based on the built-in Bayesian optimizer
  - It works basically, but the final result depends more on the beam itself

Bayesian optimization of SASE output

Examples



A good start may result in quick optimization



Less energy from initial beam
→ cannot help much

Summary

- High charge beam transport from photocathode to the undulator has been established, aiming at smooth beam envelope along the beamline and matching of the beam into the small vacuum chamber of the undulator
- Beam trajectory is found critical to the beam quality, therefore is optimized in the booster, TDS and quadrupoles
- Successful beam transport in the undulator doesn‘t promise a strong lasing; fine tuning of beam phase space and trajectory is necessary
  - Bayesian optimizer developed; Simplex optimizer under development