Let BOIS Steer the Beam: Bayesian Optimization for Ion Steering

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The centroid correction problem

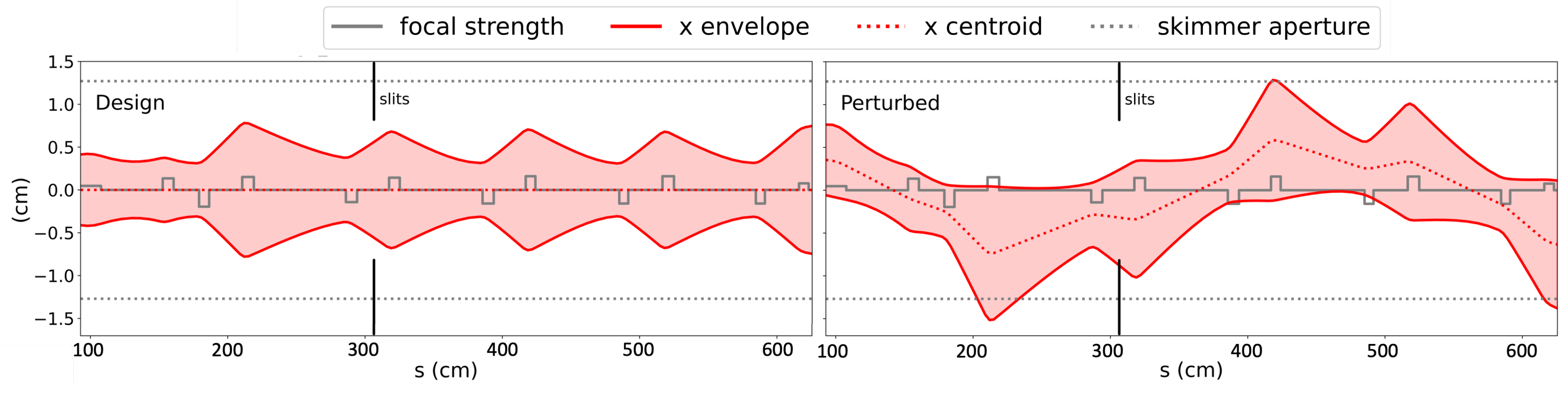


Fig. 2: 2 rms x envelope of an example beam transport. Top shows the designed behavior of the beam, bottom shows the same optics settings with a perturbed beam entering the lattice. Made using TRANSOPTR [4]

- A simplified beam transport problem consists of lenses, apertures and drift spaces. In an ideal system linear segments are free of misalignments.
- However, when a misalignment is introduced, it propagates downstream through the optics (fig. 2) → corrective steerers.

Bayesian Optimization (BO)

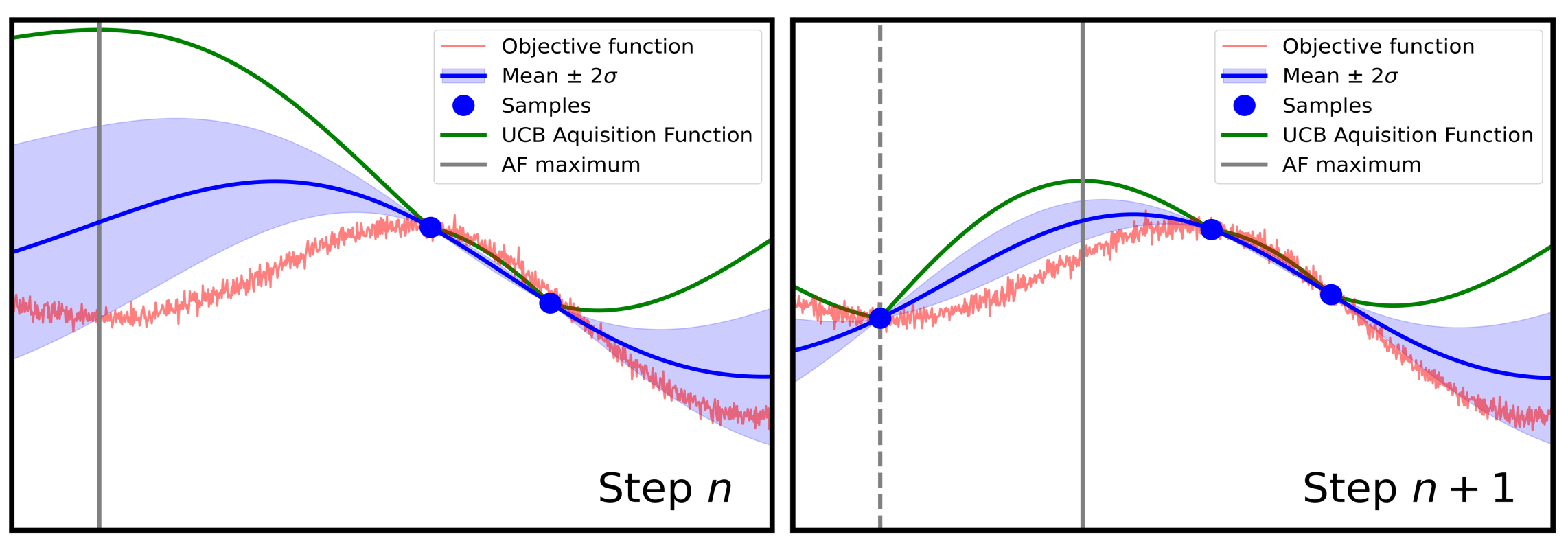


Fig. 3: A toy 1D problem and two consecutive optimization steps with BO. Consider an unknown objective function (noisy red) and some known data samples (blue dots). BO builds an acquisition function α (green) to sample it further and creates a probabilistic model (blue line and shaded area).

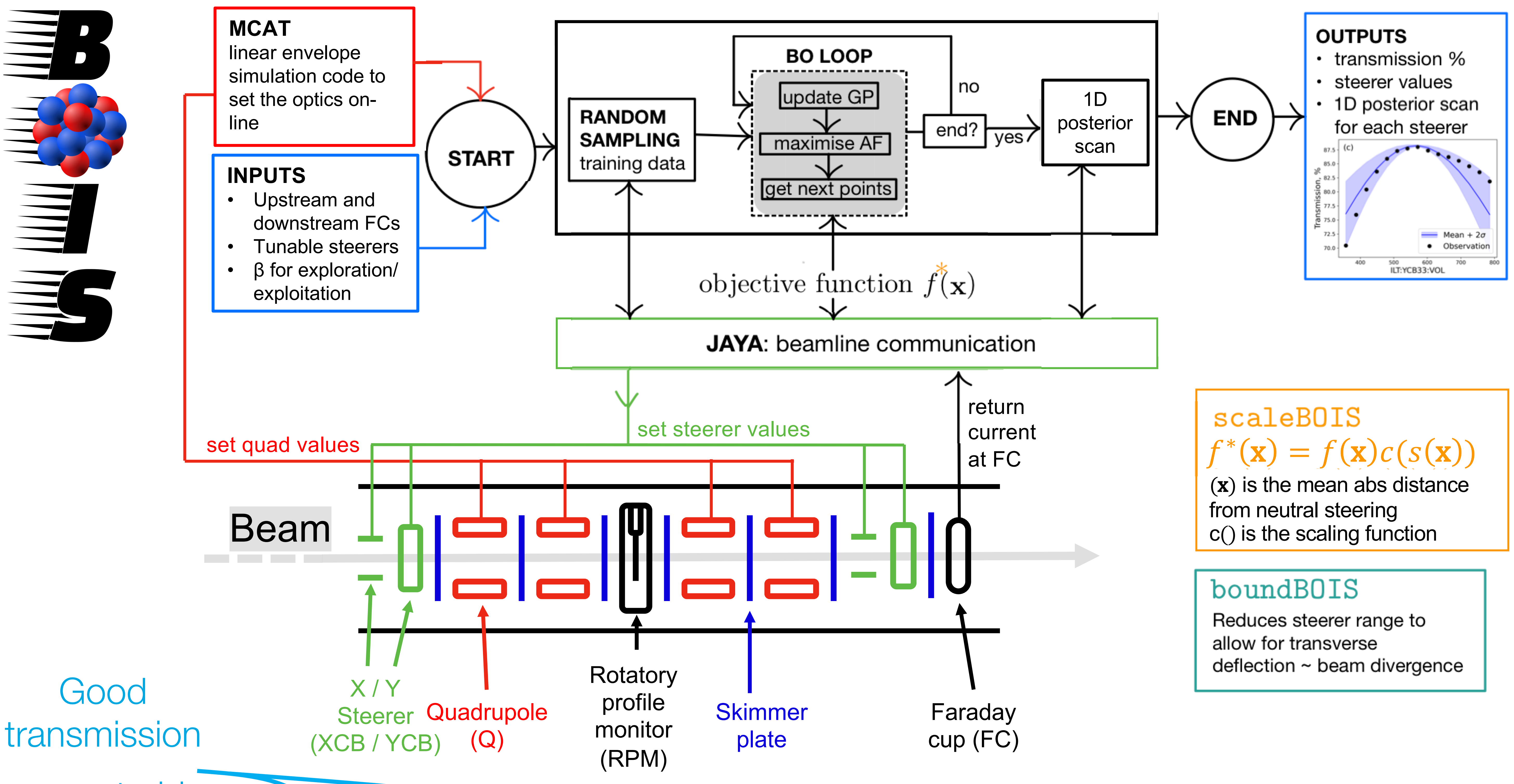
- Black-box optimization algorithm for expensive and noisy systems.

Values of d steerers

$$x^* = \underset{x\in\mathcal{X}^d}{\operatorname{argmax}} f(x)$$

Downstream FC current

- Models the unknown function with mathematical surrogate (prior), usually a Gaussian Process.
- Acquisition function to select the next sampling point, balancing *exploitation* of the expected maxima, and exploration in areas of higher uncertainty:



MCAT
linear envelope simulation code to set the optics on-line

INPUTS
- Upstream and downstream FCs
- Tunable steerers
- β for exploration/ exploitation

START

RANDOM SAMPLING
training data

BO LOOP
update GP
maximise AF
get next points

end?
no
yes

1D posterior scan

END

OUTPUTS
- transmission %
- steerer values
- 1D posterior scan for each steerer

objective function $f^*(\mathbf{x})$

JAYA: beamline communication

scaleBOIS

$$f^*(\mathbf{x}) = f(\mathbf{x})c(s(\mathbf{x}))$$

$(\mathbf{x})$ is the mean abs distance from neutral steering
c() is the scaling function

boundBOIS

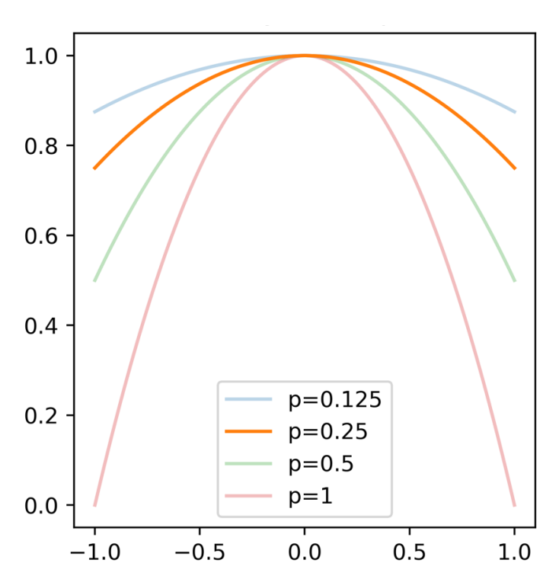
Reduces steerer range to allow for transverse deflection ~ beam divergence

Good transmission

≠ centroid correction

scaleBOIS

- Reduces all objectives to a single scalar value.



$$x^* = \underset{x\in X}{\operatorname{argmax}} f(x)c(x)$$

Scaling function

$$c(x) = -p\underline{s(x)}^2 + 1,$$

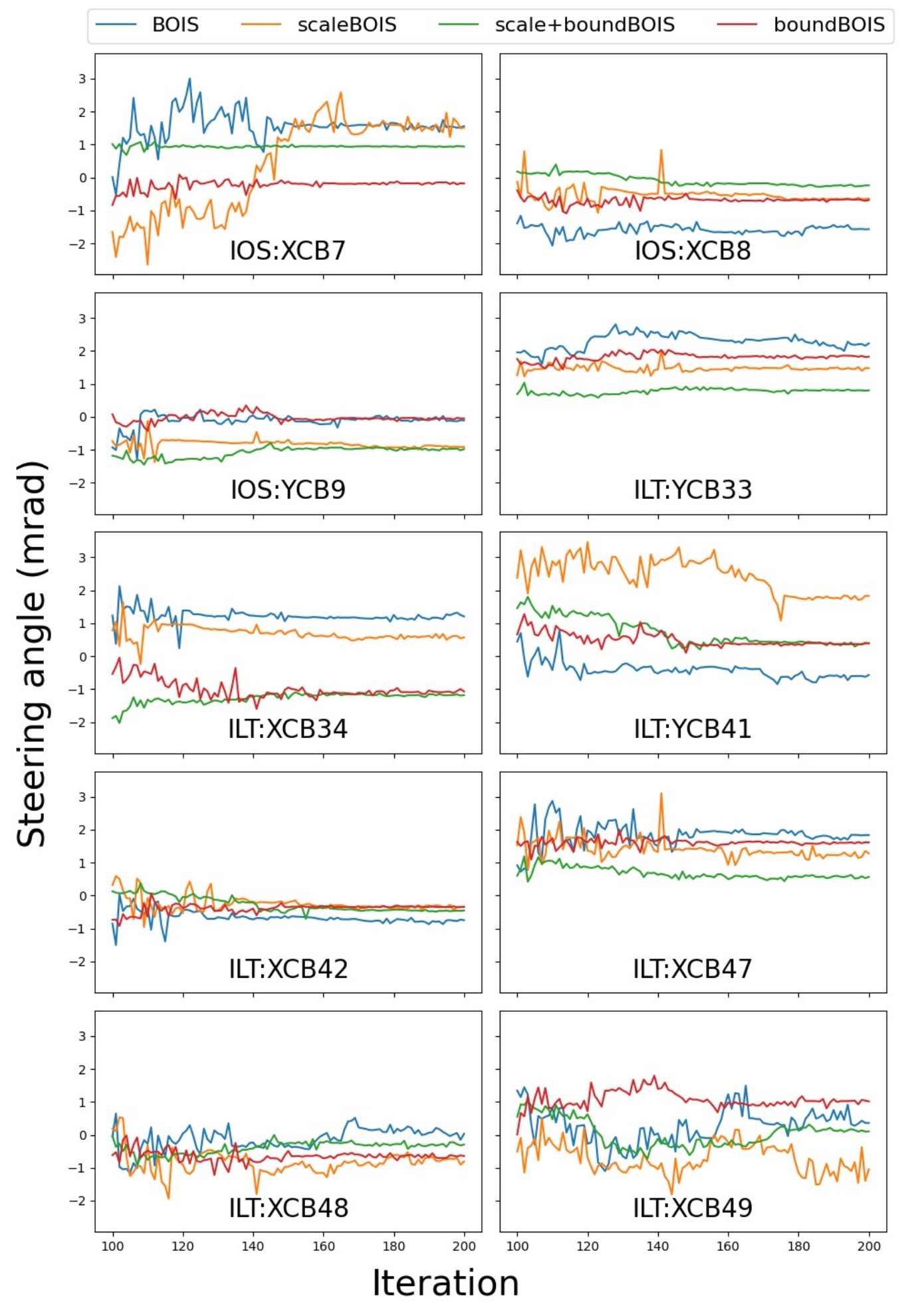
mean deviation from neutral

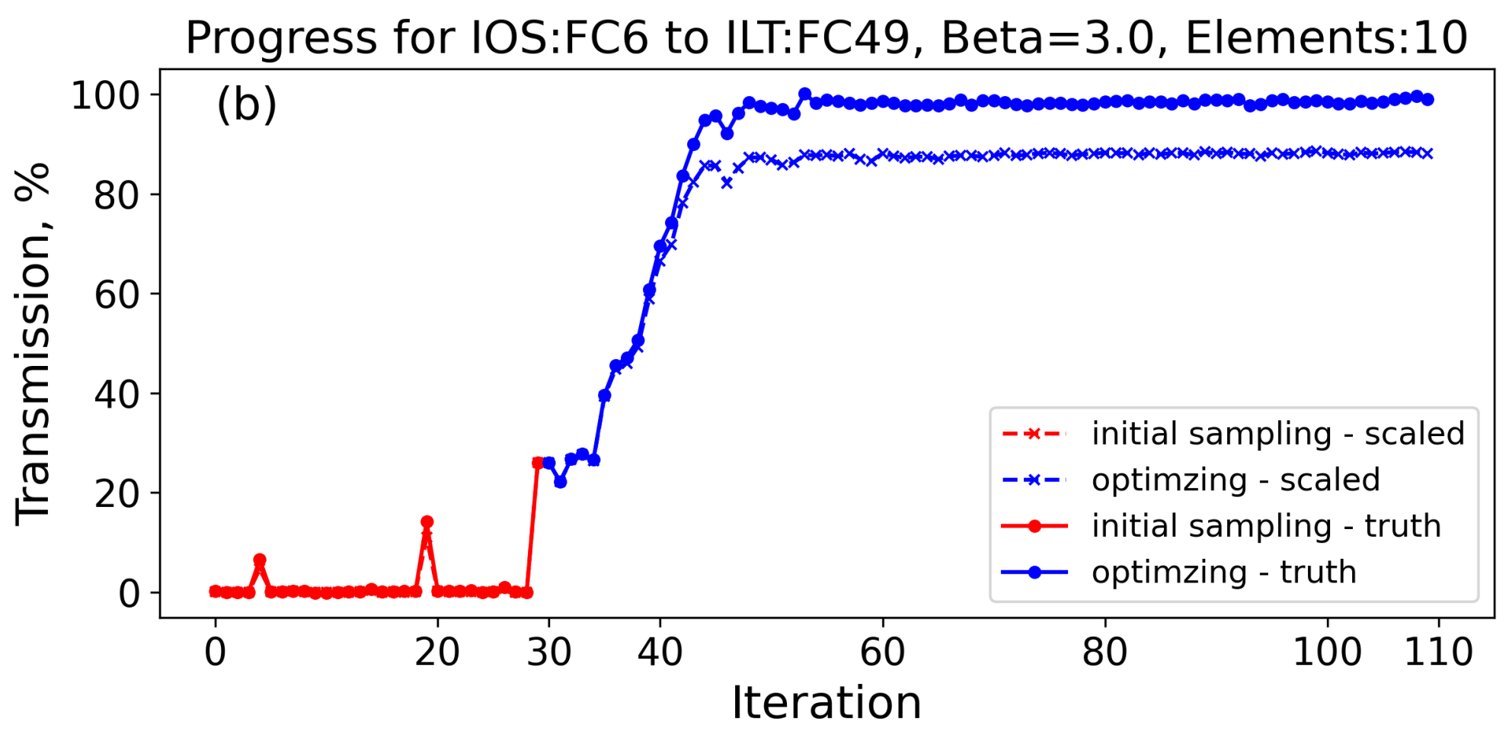
boundBOIS

- Limits the range of steerer settings;
- Scales steerer ranges with beam energy;
- For each steerer allow a maximum transverse beam deflection of 2 mrad:
    - Order of beam divergence
    - More useful input scape

Results

- Beam transported through 30 meters of beamline:
    - From the mass separator through the low-energy transport section and polarizer at ISAC-I,
    - Offline Ion Source (OLIS) beam through the RFQ and accelerated into the MEBT section.
- All methods shown to be effective as operators, in terms of transmission and time.
- boundBOIS reduces mean abs final steering angle by a factor of 0.2, and scale+boundBOIS by 0.4.





Section (FC-FC)	Section Length (m)	Used / tot Steerers	Operator tx (%)	BOIS tx (%)
IMS:14 (a) - IMS:34 (b)	9	13/13	80	73
IMS:14 (a) - IMS:34 (b)	9	4/13	80	89
IMS:34 (b) - ILE2:1 (c)	15	17/21	95	95
ILE2:1 (c) - ILE2:11 (d)	3	4/4	94	91
ILE2:11 (d) - ILE2:19 (e)	4	7/7	73	75

To do list

- ☐ Operational tool
- ☐ Formal multi-objective treatment
- ☐ Hyperparameter optimization
- ☐ Magnetostatics and wider facility deployment

Discovery, accelerated