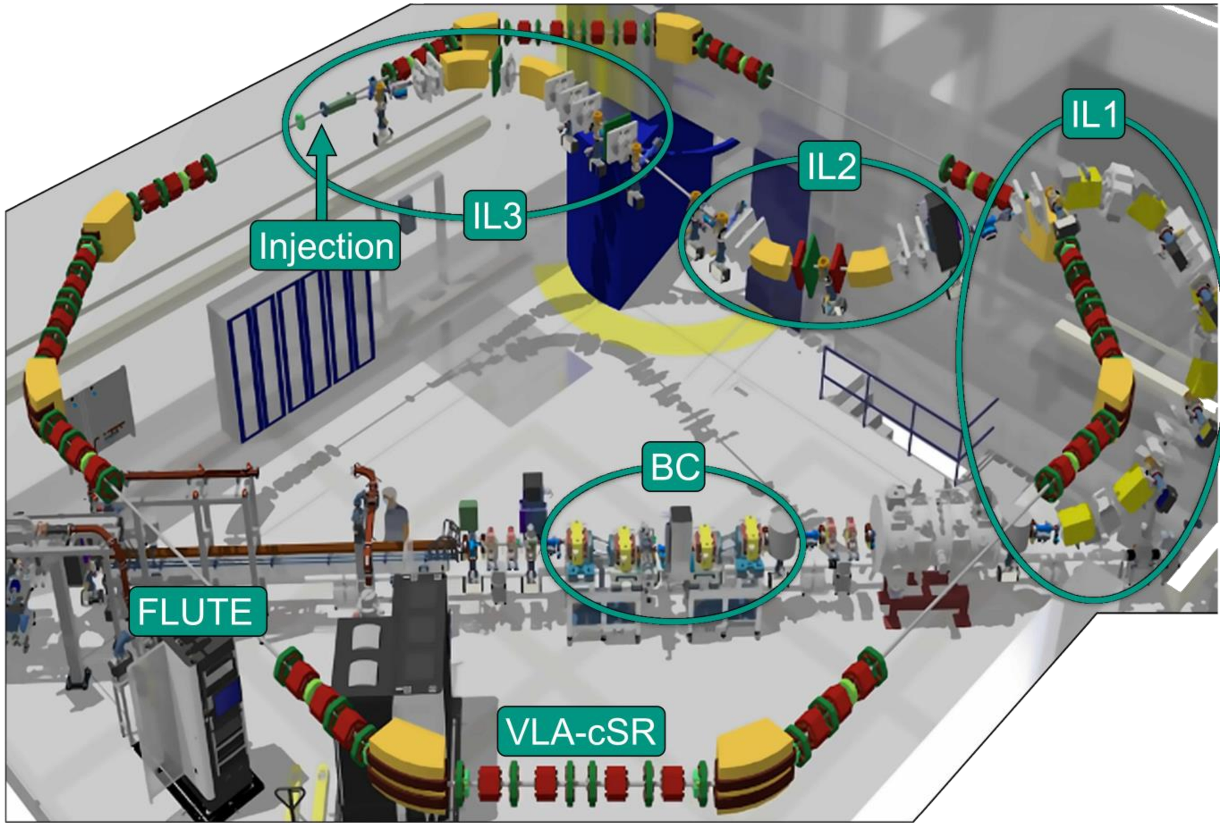
Simulation-based optimization of the injection of ultrashort non-Gaussian electron beams into a storage ring



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Content

1. Motivation cSTART and Injection Line (IL)
2. Challenges and solving strategies
3. Longitudinal compression
4. Transverse Matching

cSTART motivation

compact **ST**orage ring for **A**ccelerator **R**esearch and **T**echnology

- Injection and storing of ultrashort **LPA beams**
- Opportunity to study non-equilibrium beam physics
- FLUTE as 2nd injector for comparison

cSTART:

LPA's

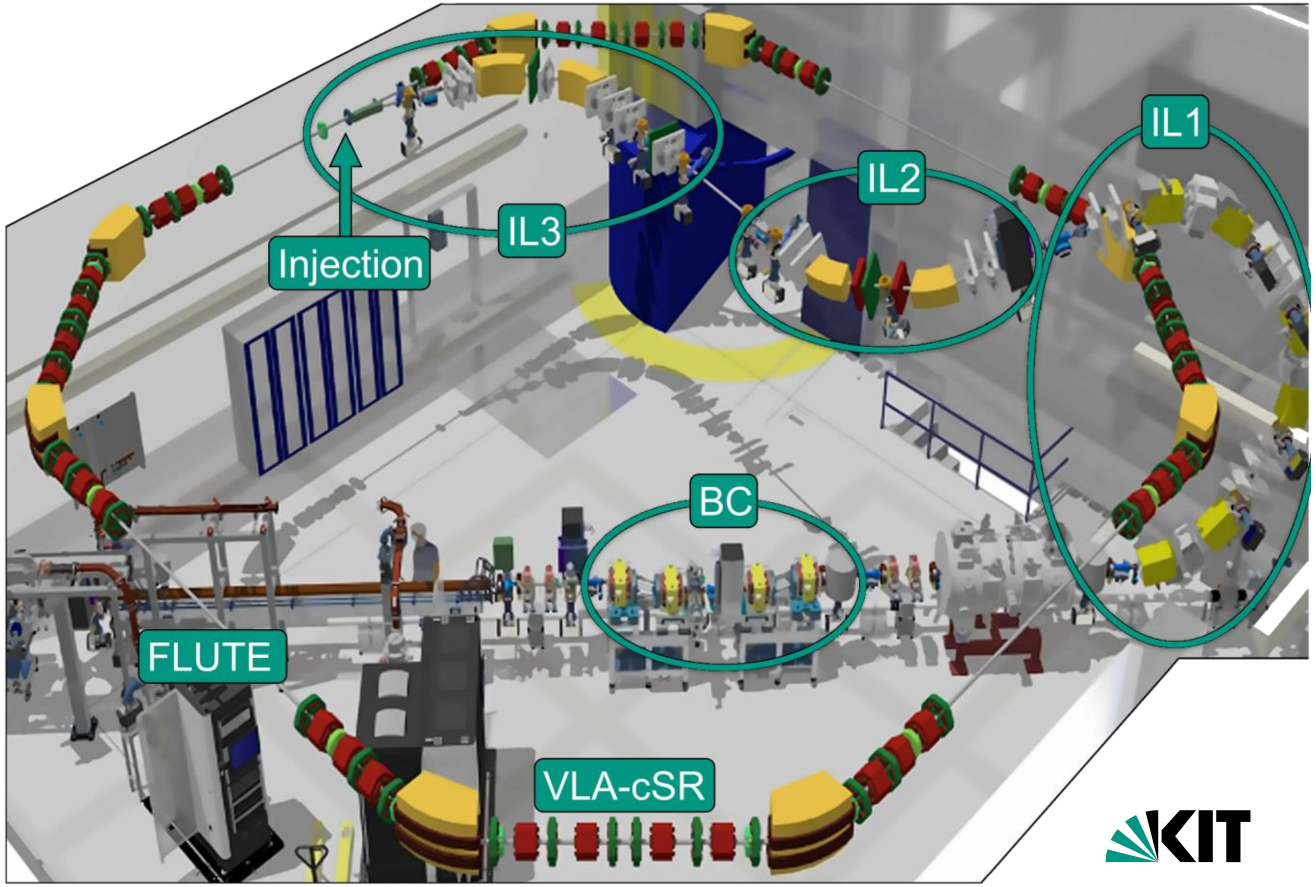
FLUTE

Injection Line (IL)

Storage ring (VLA-cSR)

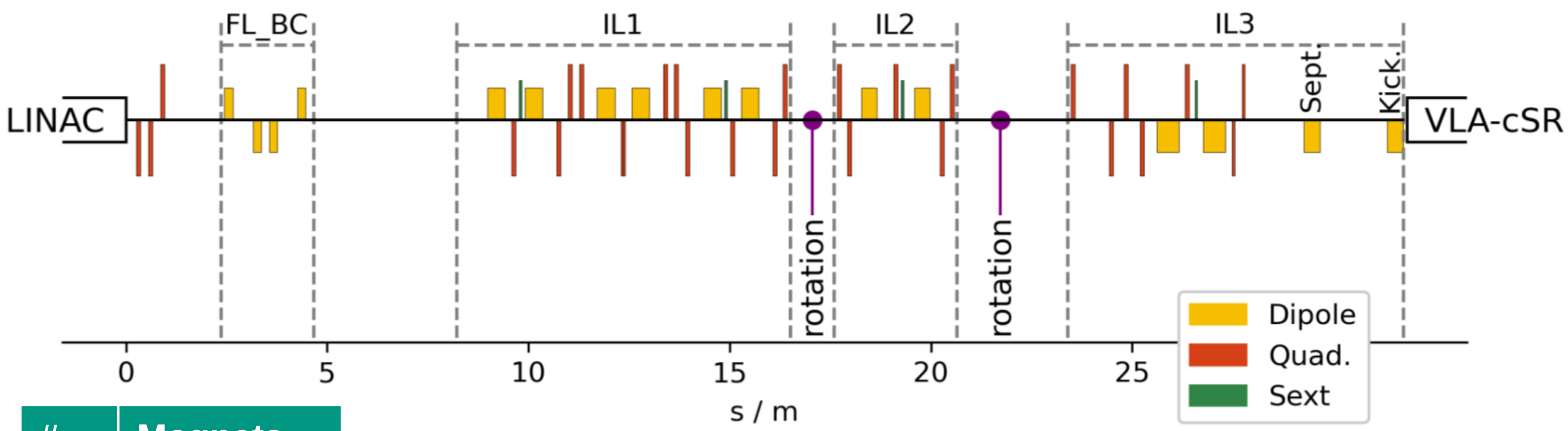
Development since initial IL design

- Conceptual initial design laid the foundation of IL
- cSTART advanced towards Final Design Report stage
- Advanced IL simulations required:
  - Addressing technical constrains (space claims)
  - Solutions for different beam parameter and optics
  - Speed up simulation time from months to days

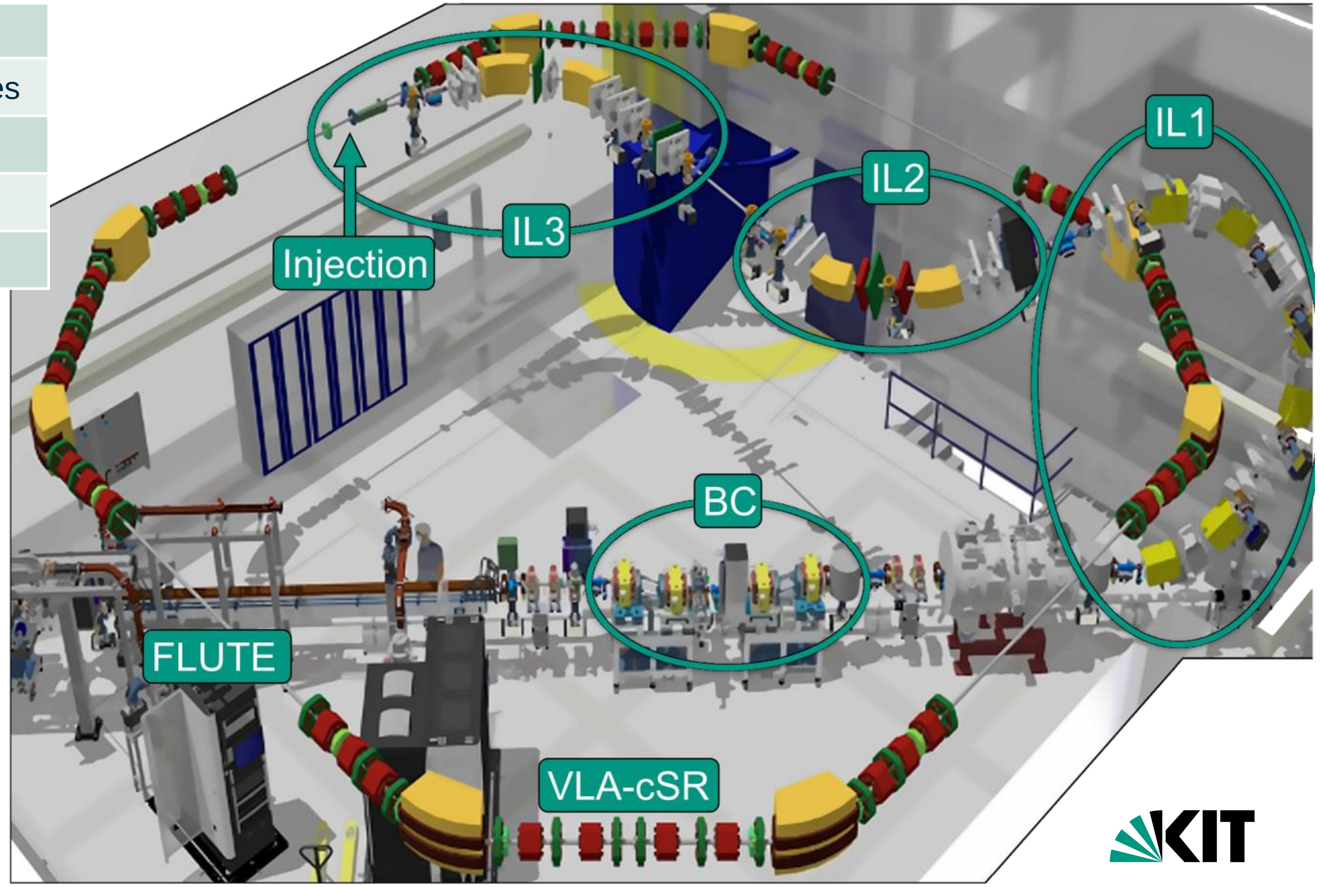


Overview

- FLUTE: bunch creation up to 90 MeV
- IL1: vertical arc around storage ring
- IL2: tilted DBA into the horizontal plane
- IL3: matching section and injection
- VLA-cSR: cSTART **storage ring**



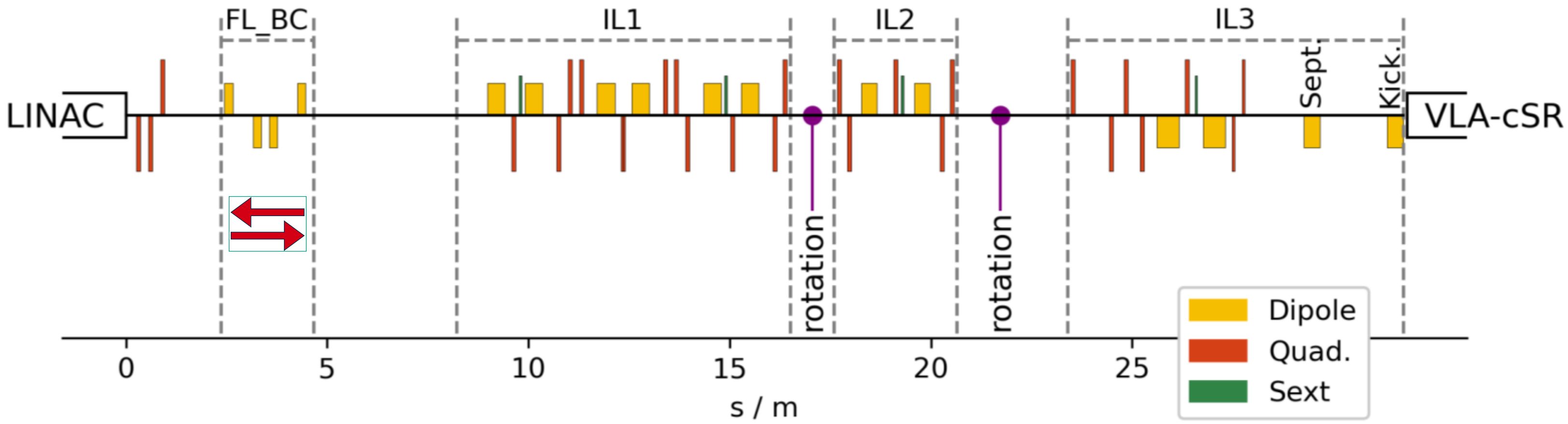
#	Magnets
14	Dipoles
32	Quadrupoles
4	Sextupoles
1	Septum
1	Kicker



Injection Line Challenges

- Tight geometrical constrains
- Handling vertical, horizontal and tilted deflections
- Longitudinal bunch compression to femto-seconds!
- Transverse matching to storage ring
- Coping with non-linear effects and xy-coupling
- Adaptable for a parameter range (q, E, chirp …)

Bunch compressor



- FLUTE Bunch compressor (FL_BC) delayes low-energy electrons
- The BC “shears” the long. phase space counter-clockwise by $\mathbf{R_{56}}$

$$R_{56} = \int \frac{\eta_{xy}(s)}{\rho_{xy}(s)}\ \mathrm{ds}$$

- A bunch with a positive chirp *h* compresses

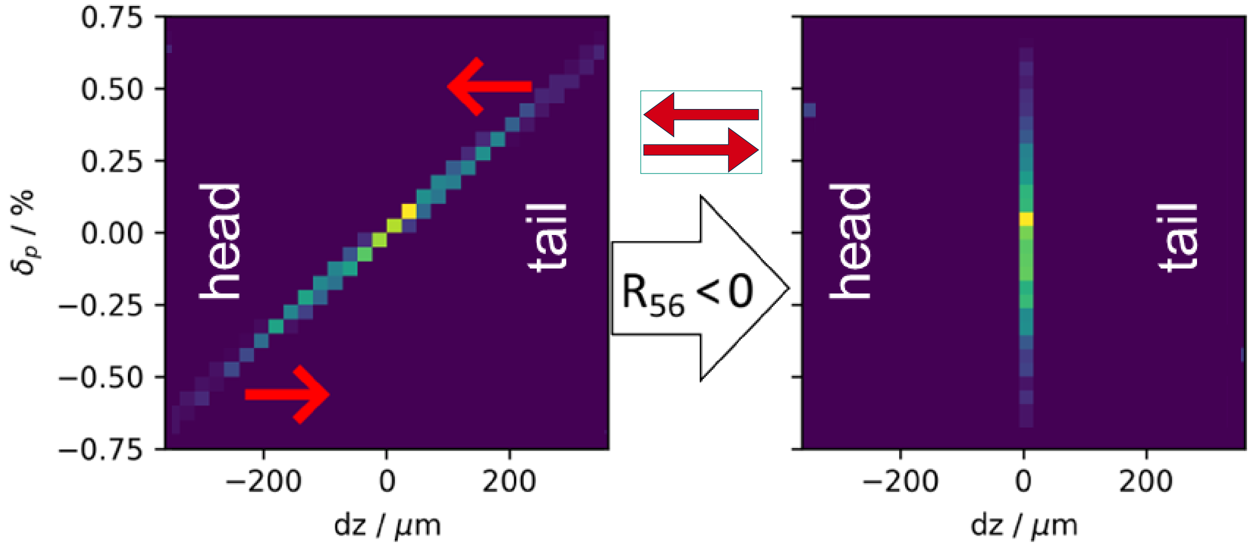
$$h = \partial\delta_p/\partial z$$

$$h^{-1}(S_2) = h^{-1}(S_1) + R_{56}$$

positive

chirp

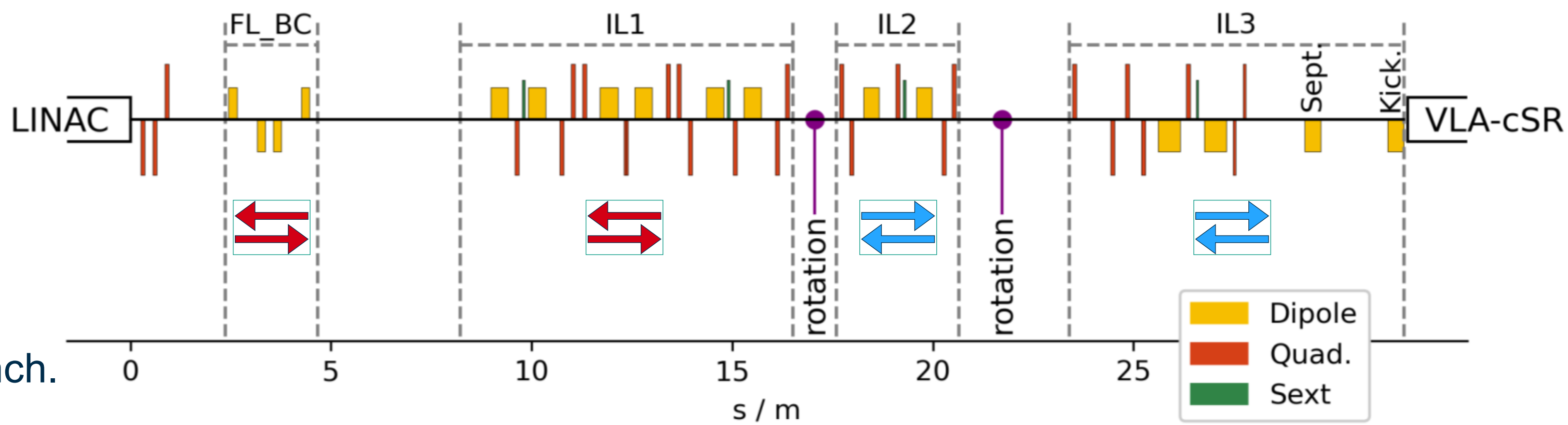
$h > 0$

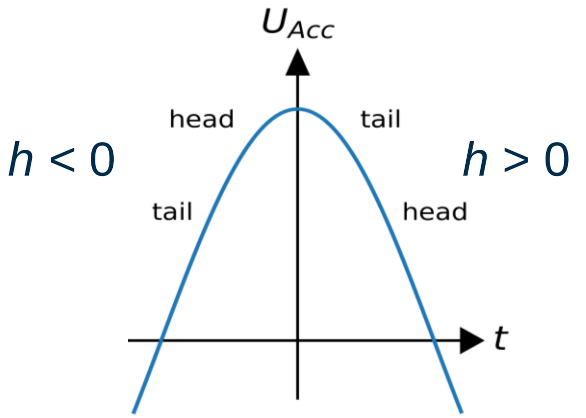


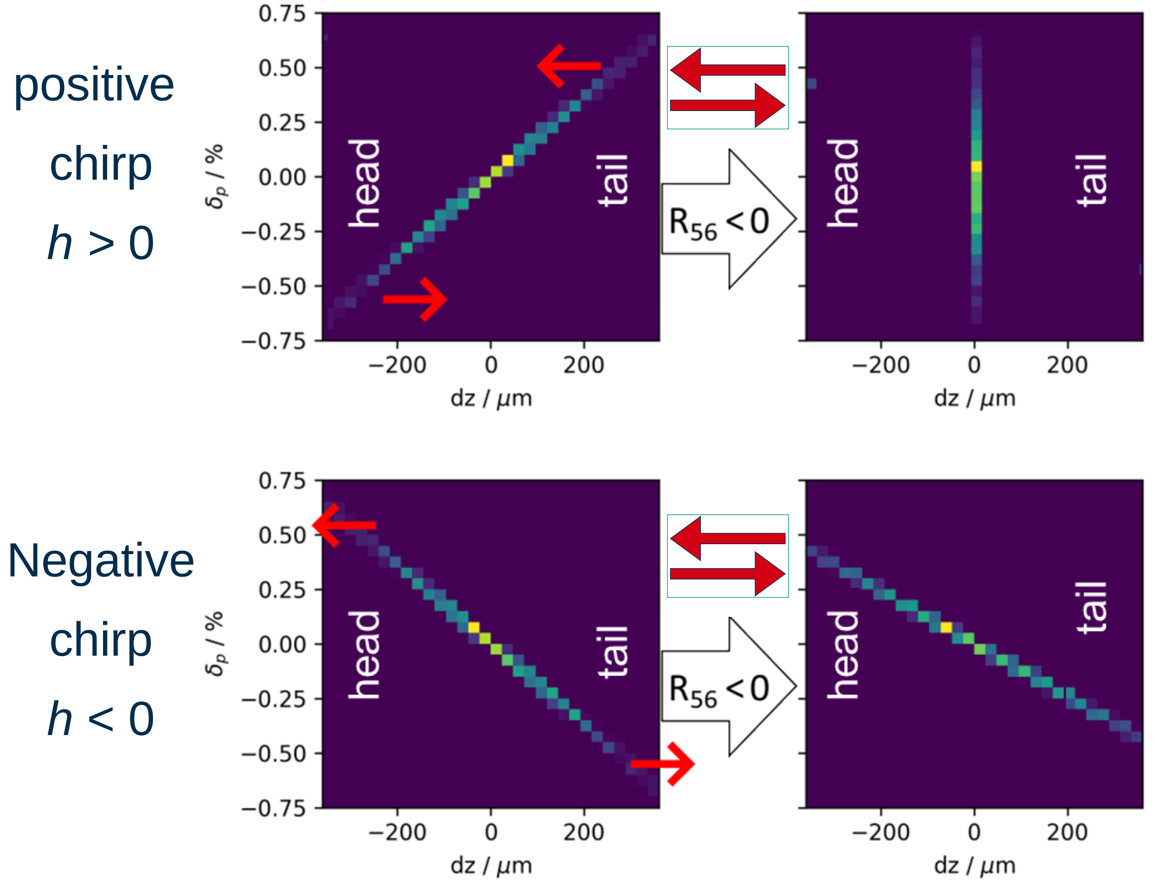
- Transporting ultrashort bunches leads to intense CSR bursts, energy loss and particle losses.
- A fs-bunch cannot be transported through the IL!

Initial chirp

- IL designed to compress the bunches just at the septum.
- FLUTE linac operation on "opposite flank" for a negative chirped bunch.







IL phase space operation

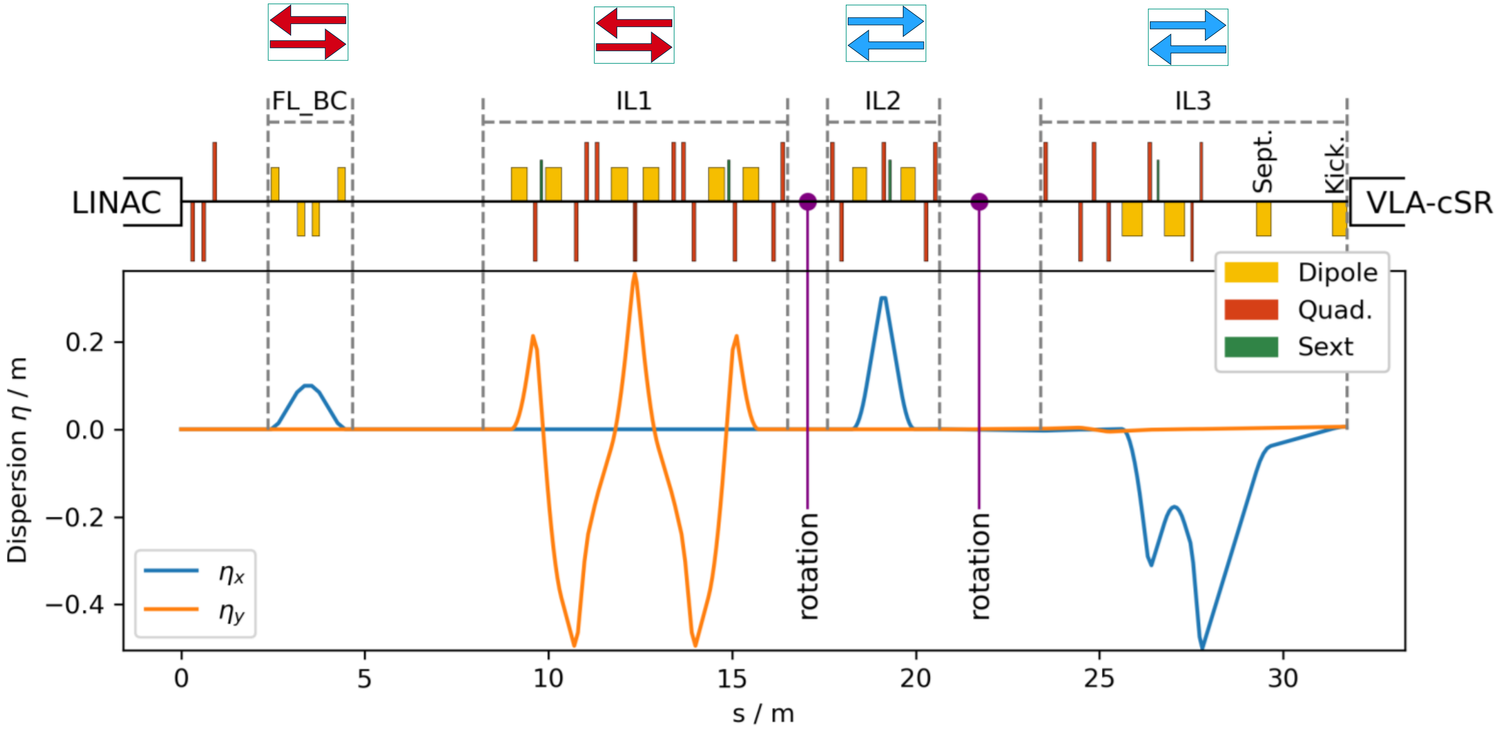
- Starting with a negative chirp
- Bunch elongates first in BC & IL1 (**R_{56}<0)**
- and compresses in IL2 & IL3 (**R_{56}>0)**

→ **No ultrashort bunches during transport**.

Strategy towards an optics solution

- Compose the TL out of achromatic sections: η=0 before/after section

- Only Quads at η≠0 influence long. Dynamics
- All Quads influence transverse dynamics



Optics discussion:

- **1.** solve **long. compression** in η≠0 sections
- **2.** solve **transverse matching** in η=0 sections

Full compression condition

- Bunch chirp transforms by R_{56}

$$h^{-1}(S_2) = h^{-1}(S_1) + R_{56}$$

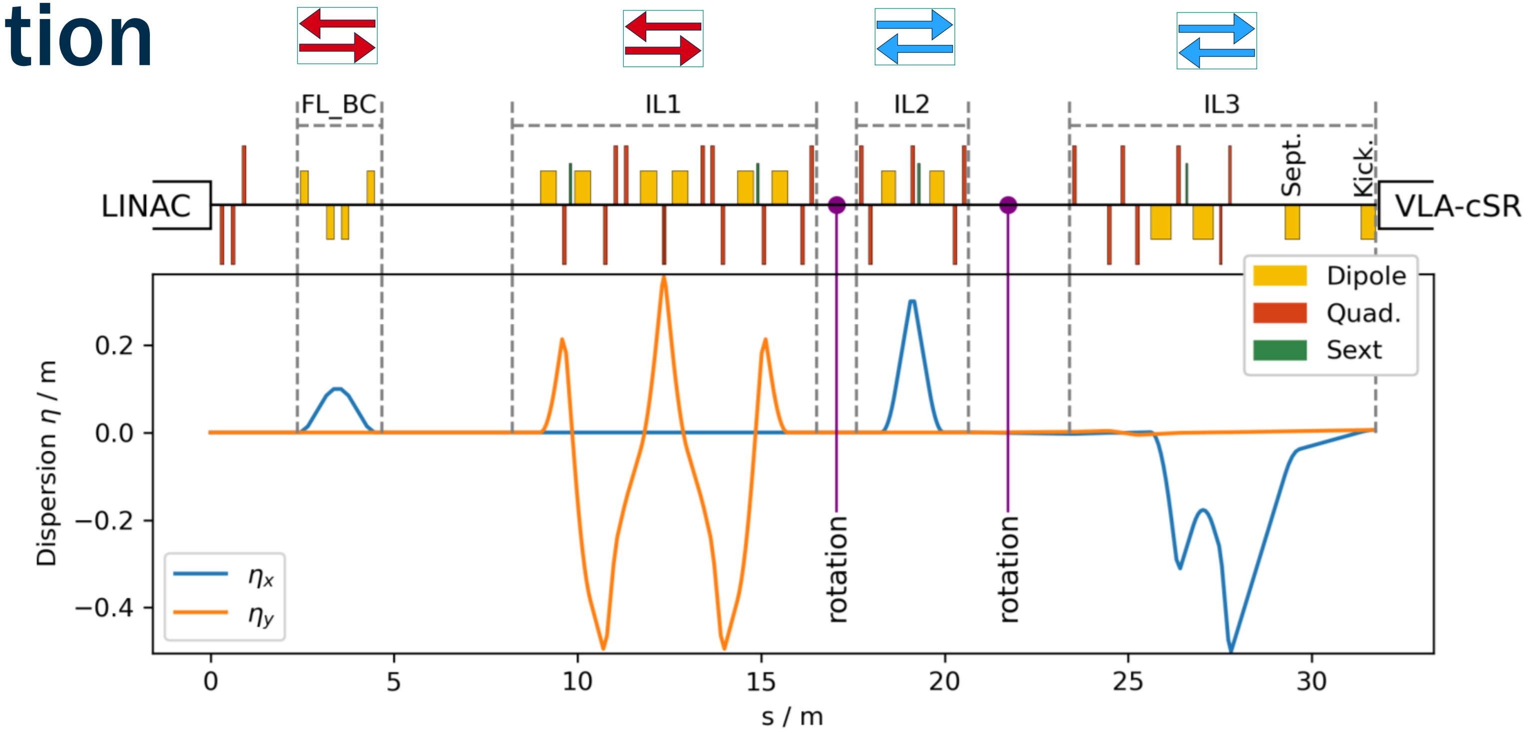
- Initial chirp: $h^{-1}(S_1) = -2.8\ \mathrm{cm}^{-1}$
- Full compression: $h^{-1}(S_2) = 0\ \mathrm{cm}^{-1}$
- **Full compression condition (FCC):**

$$\sum_i R_{56,i} = -h^{-1}(S_1)$$

- The sum of all R_{56} values have to counteract the initial chirp
- BC, IL2 & IL3 have limited margin in R_{56}
- IL1 designed for **flexible R_{56}** value

$$R_{56,\mathrm{IL1}} = -h^{-1}(S_1) - R_{56,\mathrm{BC}} - R_{56,\mathrm{IL2}} - R_{56,\mathrm{IL3}} - R_{56,\mathrm{ToF}}$$

$$R_{56,\mathrm{IL1}} = -17.7\,\mathrm{cm}$$



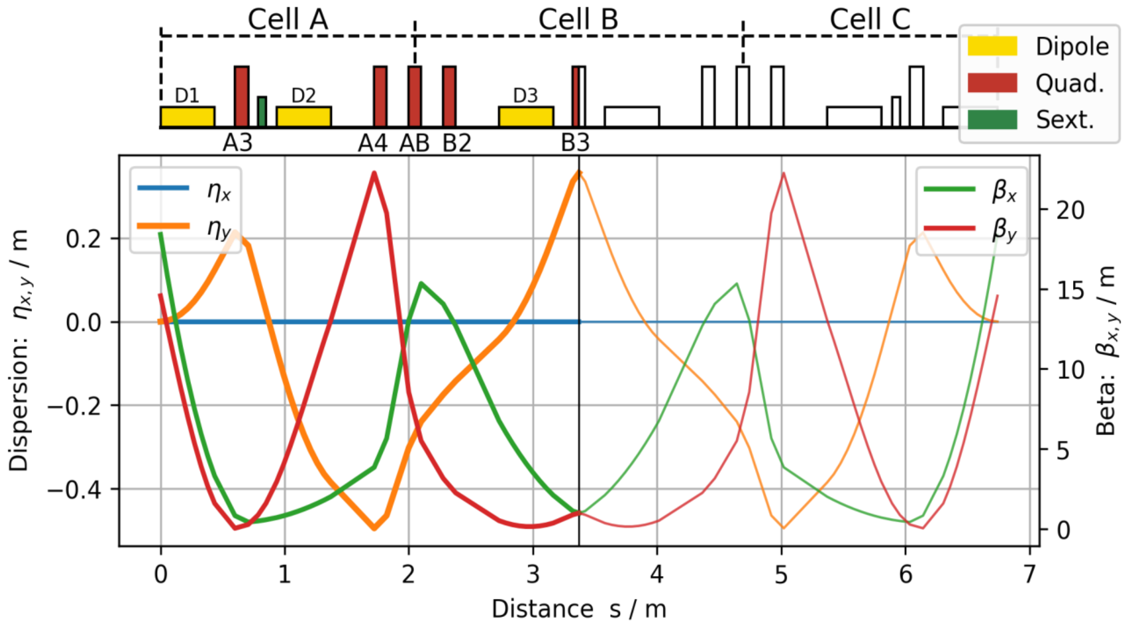
Section	Structure	R56 / cm
BC	BC	-2.5
IL1	HBA	[-420; +130]
IL2	DBA	+3.4
IL3	DBA	+20.1
ToF		-0.4

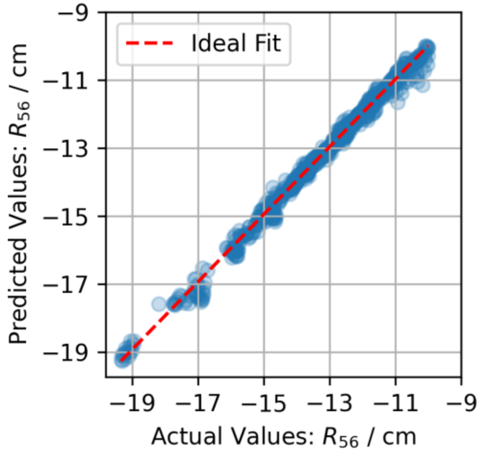
IL1 optics with NN

- Investigating the full parameter volume of possible optics
  - IL1 optics serves 9 quadrupoles
  - 5 individual quadrupoles, considering mirror symmetry
  - 4 open DoF, considering achromaticity

- **4 input** parameter: K_1-values of quadrupoles: A3, A4, B2, B3
- For one set of inputs, several optic functions are calculated, e.g. R_{56} and Twiss functions max values → **10 outputs**
- Repeated for different input combinations
  → created ~ **16.000 different input/output pairs**

- This data is used for training a NN* and constructing a surrogate model (SM).
- SM prediction has high accuracy:
  Pearson correlation coefficient > 0.99 for 6/10 outputs, e.g. R_{56}
- SM allows for an investigation of complete parameter volume with **only 16.000** simulations, taking **minutes instead of days!**

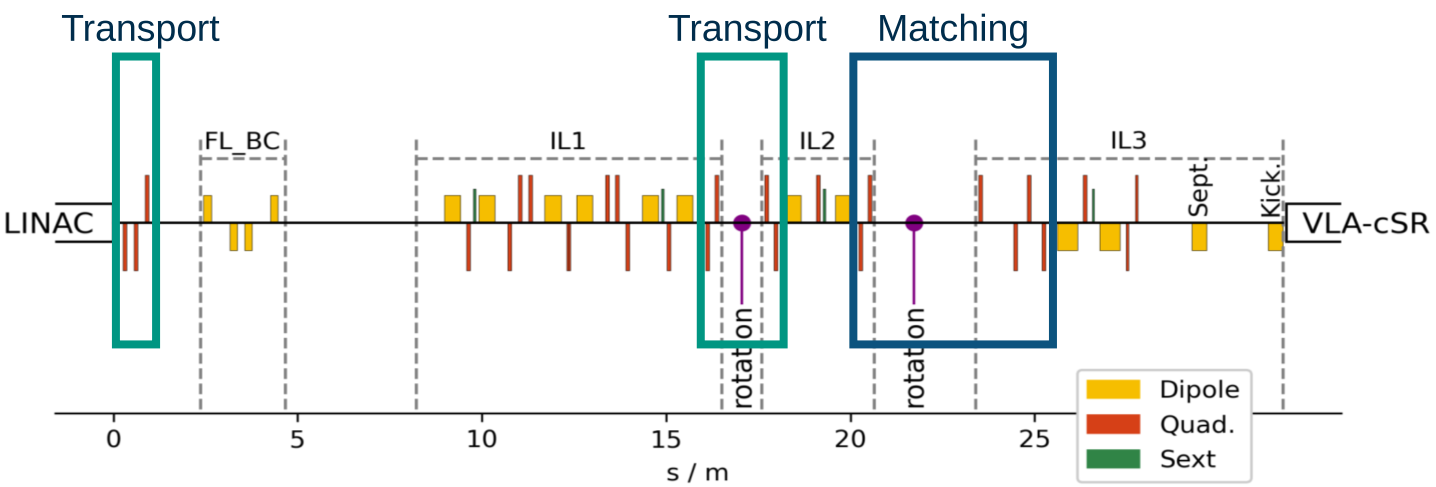




*PyTorch: 6 layers, 32 neurons fully connected, feedforward, min-max-normalized, rectified linear unit (ReLU) activation function, Adam optimizer, 9:1 training:evaluation

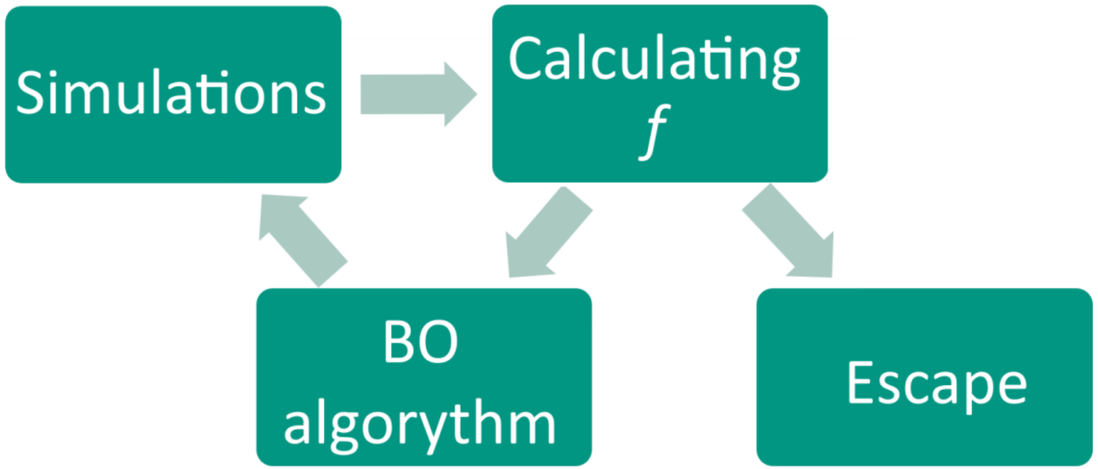
Transverse Optics

- Remaining quadrupoles utilized for
  - Beam transport (FLUTE, IL1, IL2)
  - Matching (IL2, IL3) with 6 quadrupoles



- 6D tracking shows non-gaussian bunch shape at injection point due to IL2 rotation and higher order effects
  → Matching optimization based on expensive 6D tracking,
  → NN training not feasible
  → Ideal for Bayesian Optimization (BO)

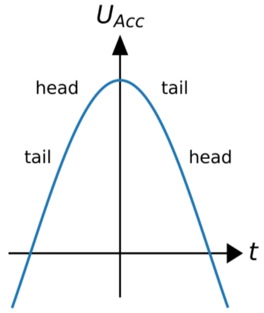
- BO implementation in python with *xopt*
- Fully customizable optimization function *f*
  - Calculation of matching parameter : ($\beta_{x,y}$, $\alpha_{x,y}$, $\eta_{x,y}$) directly from 6D particle distribution
  - trimming of long non-gaussian tails

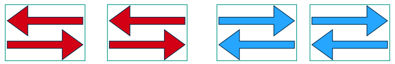


Work in progress…

Summary

No ultra-short bunches during transport

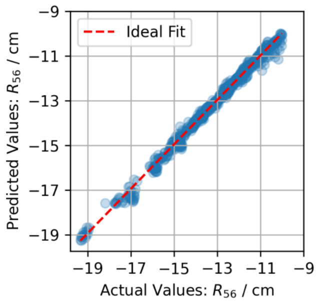




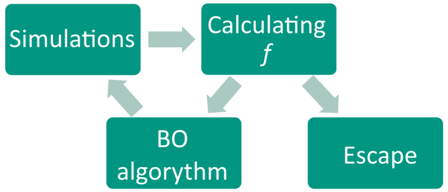
Full compression condition (FCC)

$$R_{56,\mathrm{IL1}} = -17.7\,\mathrm{cm}$$

- NN & SM make IL1 optics for entire parameter volume accesible
- Allows fast investigation and finally formulating for optimization criterions

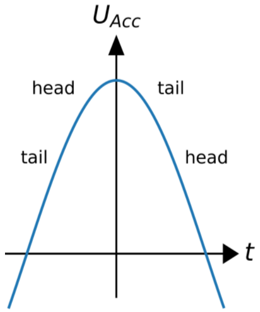


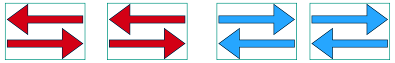
- BO implemented for Matching
- Approach for coping with non-linearities



Summary & Outlook

No ultra-short bunches during transport





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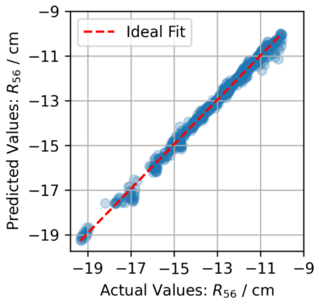

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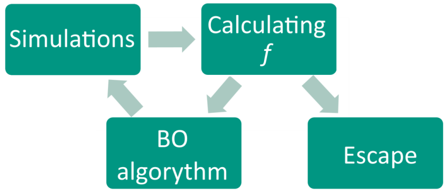


- **Adding higher order dynamics to the SM**
- **Further ingeneering on optimization function f required**

Backup Slides

Backup: IL1 optics

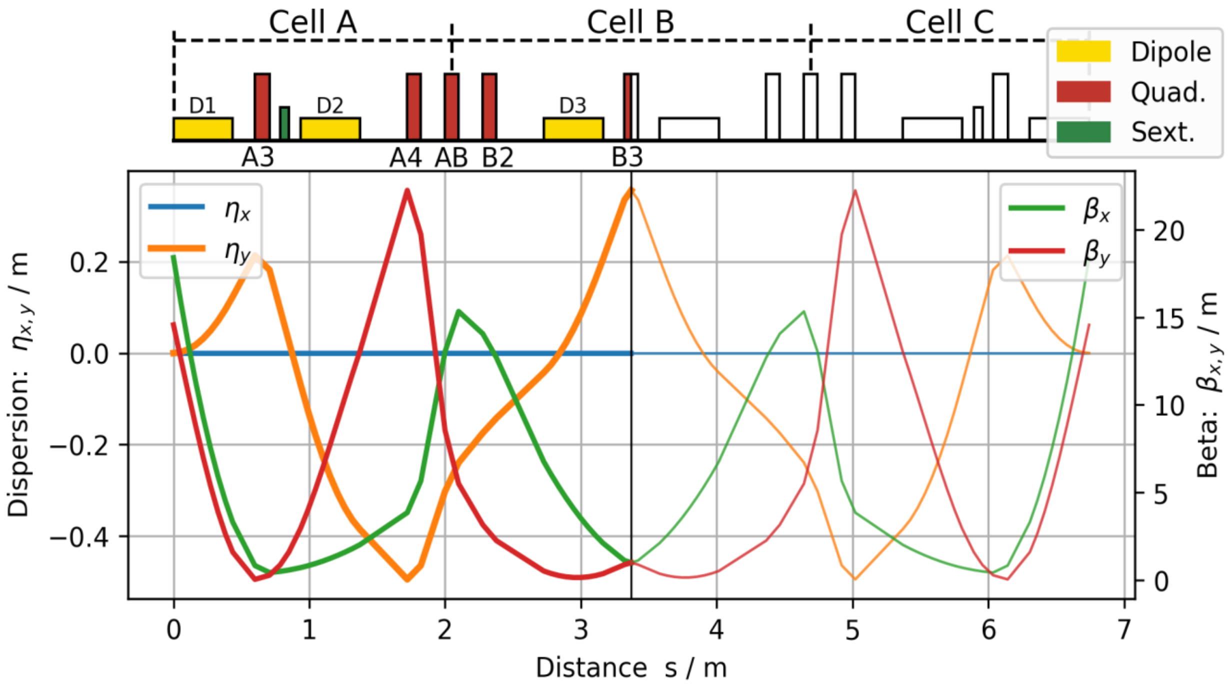
- IL1 optics are calculated independent of surrounding IL.
- Considering Mirror symmetry, IL1 optics have 5 open DoF: K_1-strengh of quadrupoles: A3, A4, AB, B2 and B3.
- For a given set of K_1-values, the twiss parameter and dispersion are defined by:

$$\alpha_{(x,y)}(s_{sym}) = 0$$
$$\beta_{(x,y)}(s_{sym}) = 1$$
$$\eta_{(x,y)}(s_0) = 0$$
$$\eta'_{(x,y)}(s_0) = 0$$

- 1 DoF (quadrupole AB) is set to met achromaticity:

$$\eta'_{(x,y)}(s_{sym}) = 0$$

- Remaining DoF are considered **Input**: A3, A4, B2, B3
- A set of **output** parameters is calculated:
  - Required quadrupole AB strength (K_1)
  - R_{56} of the IL1 section
  - Entrance Twiss parameters: $\alpha_{x,y}, \beta_{x,y}$
  - Integrated product $\int \beta_y(s) \cdot \eta_y(s)\, ds$ inside the sextupole and each of the three dipoles.



These instructions are used to create a dataset of ~16.400 input/output pairs.

A data selection is applied: $-20\,\mathrm{cm} < R_{56} < -10\,\mathrm{cm}$

The remaining 6,400 input/output pairs are used to train a feedforward Neural Network*.

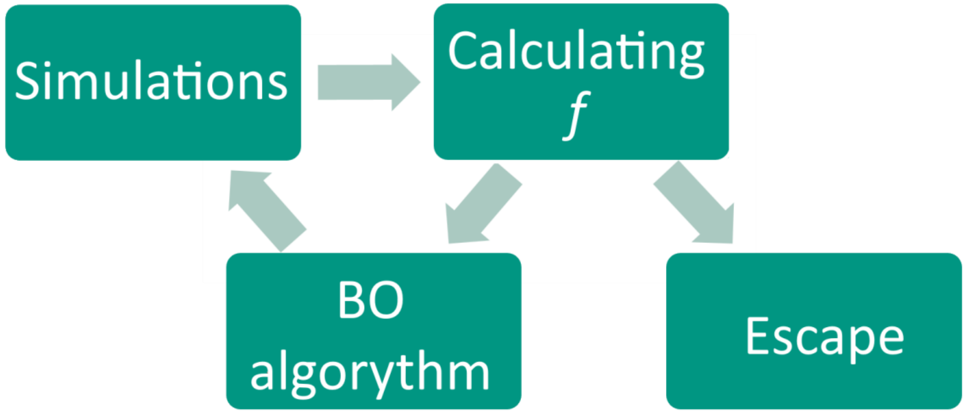
*PyTorch: 6 layers, 32 neurons fully connected, min-max-normalized, rectified linear unit (ReLU) activation function, Adam optimizer

Backup: BO optimization function

- BO Implementation in python with *xopt*
- allows for a custom optimization function:

  minimization of $f = L \cdot \sum_i m_i$

1. L: beam losses in %
2. m_i: Matching metric for each parameter V_i: ($\beta_{x,y}$, $\alpha_{x,y}$, $\eta_{x,y}$)
   – m_i = sene(V_1, V_2) (soft-edge not equal), sensitivity function
   – Distance between V_1 (desired value in VLA-cSR) and V_2 (injected)
   – V_2 calculated directly from macro particle distribution
   – Allows for advanced pre-processing, e.g. outlier handling



$$\mathrm{sene}(V_1, V_2) = \frac{|V_1 - V_2|}{\tau |V_1|} \cdot H\left(|V_1 - V_2| - \tau |V_1|\right)$$