PHENIICS FEST 2024

Lattice Design and Beam Optics Optimization of the PERLE Facility

16 - 17 May 2024

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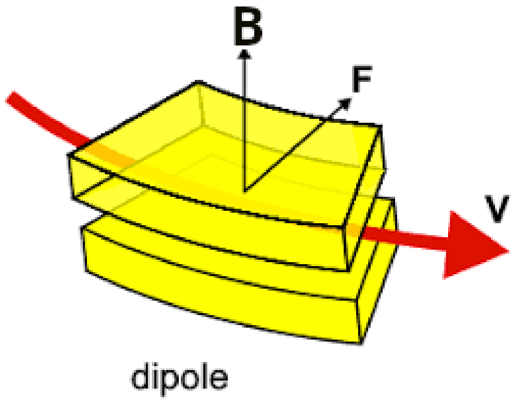
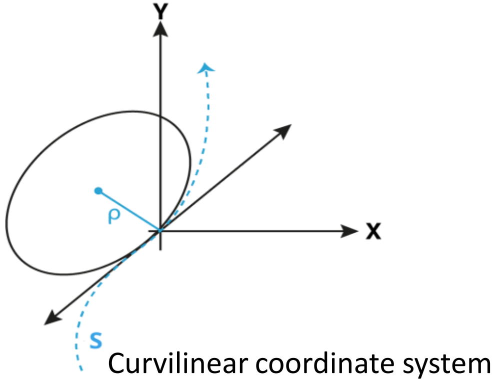
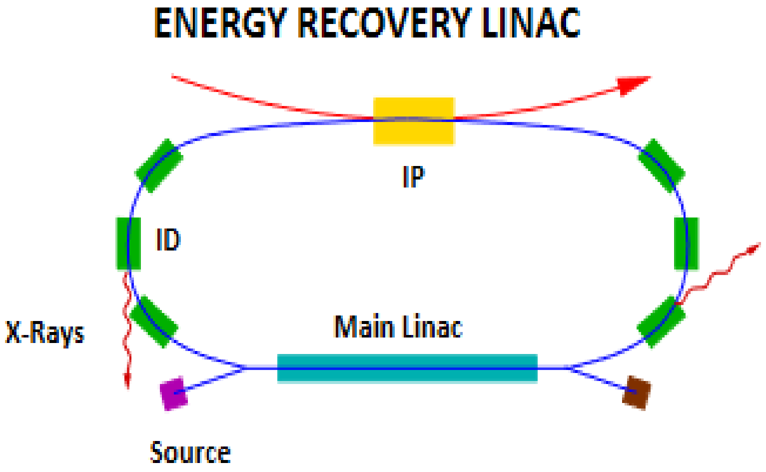
Outline

- **Introduction**
  - ERL and Energy Recuperation
  - PERLE @ Orsay
- **PERLE Lattice and Optics Specifications**
- **Magnet Design**
  - Dipole Magnets
  - Quadrupole Magnets
- **Study of PERLE Lattice Errors**
  - Misalignment Errors
  - Lattice Correction

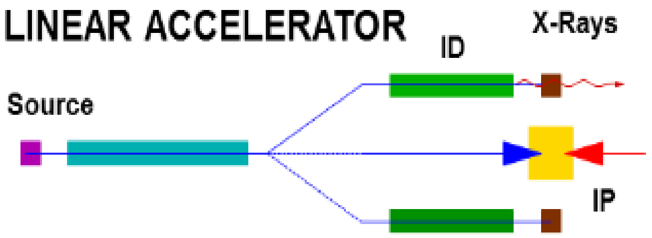




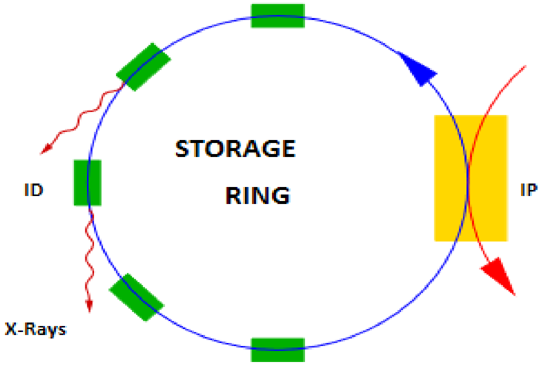
- Energy Recovery LINAC (ERL)



- Particle accelerators:



Dump > 99.9999% of the beam power



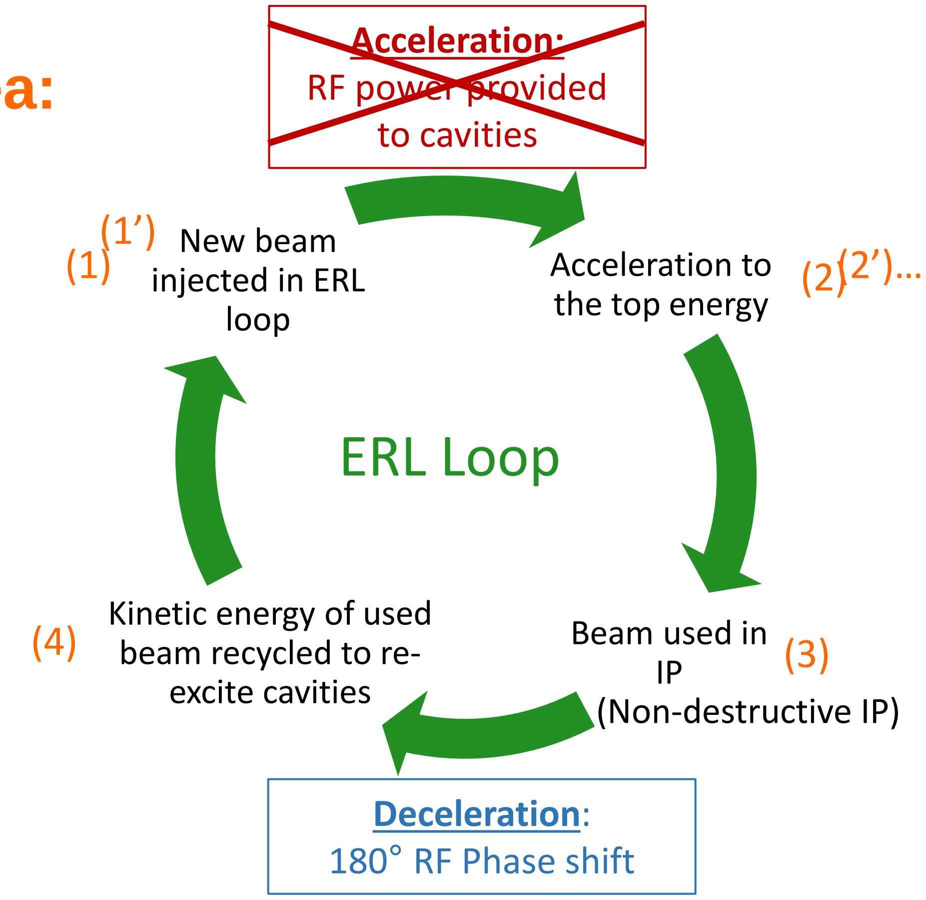
Energy loss due to synchrotron radiation

$$U_{electron}[KeV] = 88.46\ \frac{E^4[GeV]}{\rho\ [m]}$$

- Straight + circular
- Single or multi-turn
- High average beam power in a compact machine

ERL (Energy Recovery Linac) concept

The idea:



The benefits:

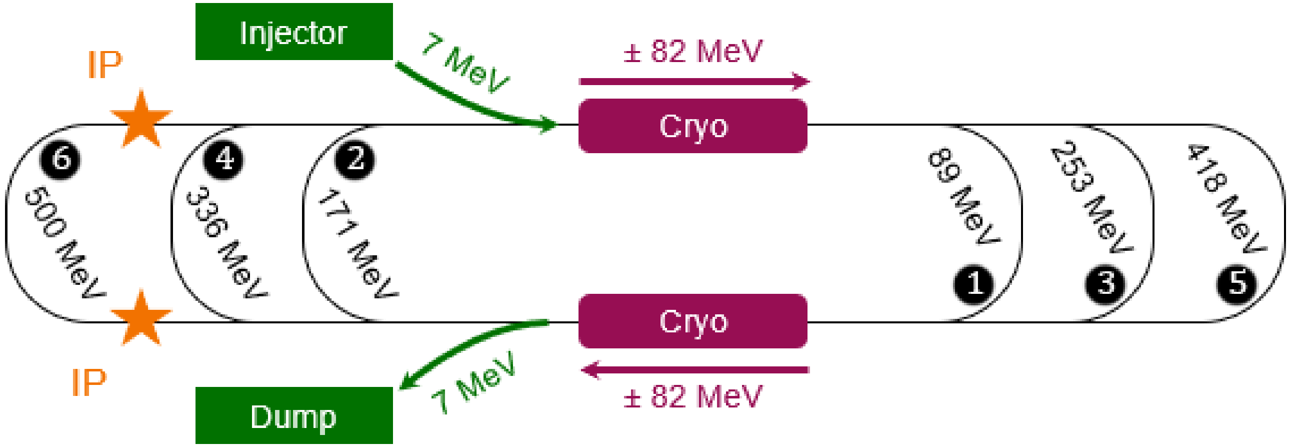
- Energy recovered to accelerate the next bunch
- Beam dumping at low energy
- Beam brightness maintained from the injector
- Multi-pass configuration: High average current + High average beam power

Technology is proven in operational facilities with lower energies and lower beam power

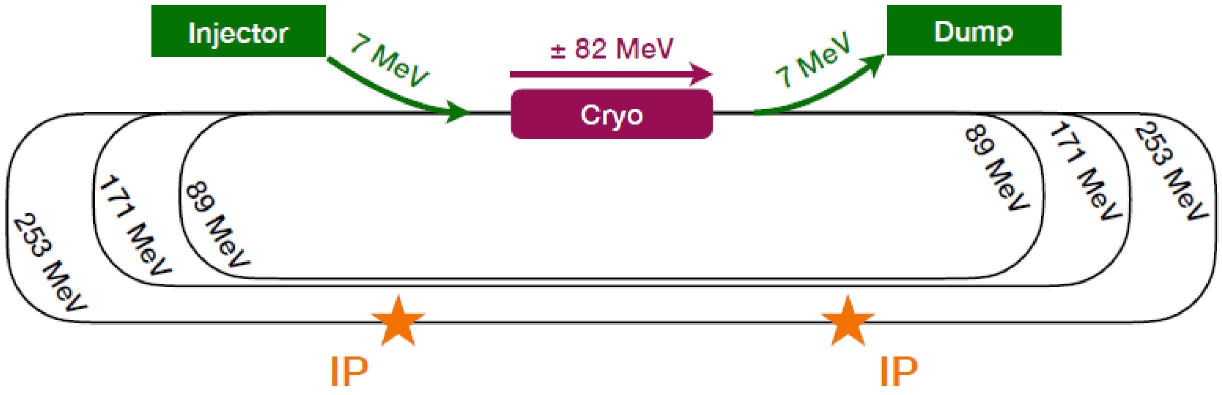
Courtesy of Walid Kaabi

PERLE: Powerful ERL for Experiments

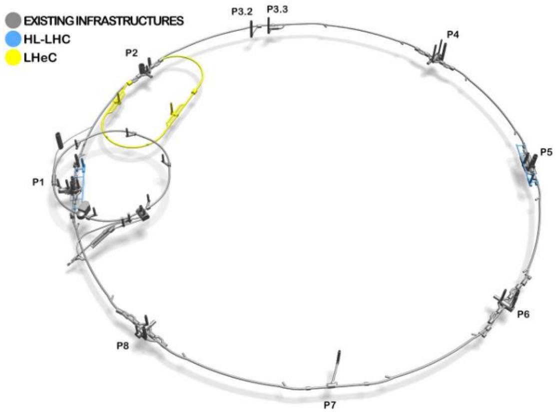
PERLE is the first multi-turn, high-current ERL based on SRF technology to operate at 10 MW power



Staging with 250 MeV version



Parameter	Value	Unit
Injection energy	7	MeV
Max. Beam energy	500	MeV
Average beam current	20	mA
Bunch charge	500	pC
Bunch length	3	mm
Bunch spacing	25	ns
Normalized emittance	6	mm.mrad
RF frequency	801.58	MHz
Duty factor	CW	

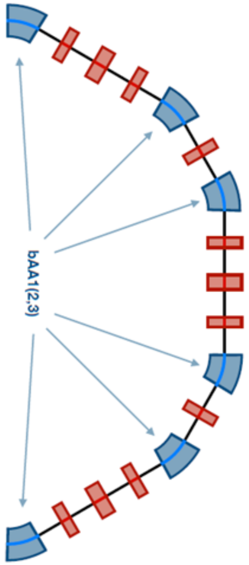


- Demonstration of ERL with 6 passes at high current
- Three straight sections replacing the spreader/recombiner sections, and the second LINAC at one side

- Same technological choices of LHeC
- PERLE will also be a facility platform

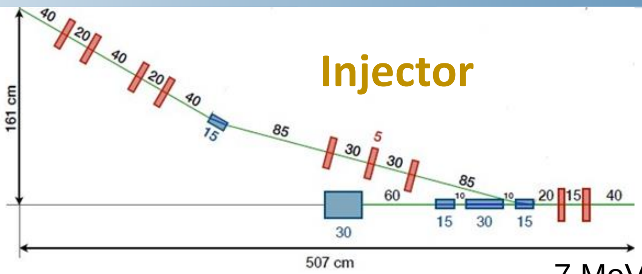
PERLE Layout

6 dipoles with a total bend of 180°



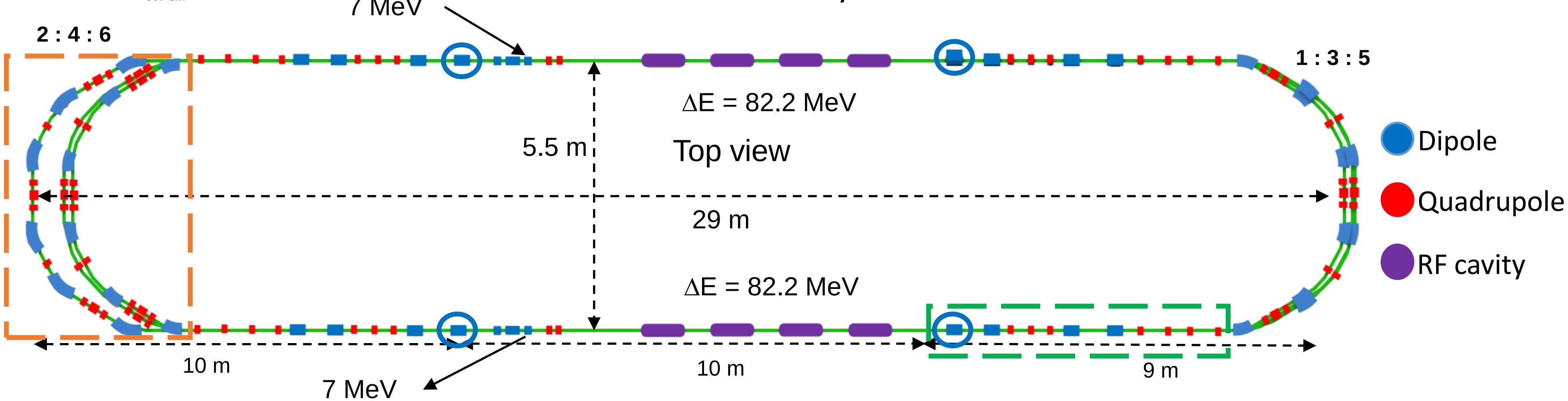
II. **Arcs**

6 arcs for a three-turn configuration



I. **LINAC**

Two cryomodules each of four 5-cell SRF cavities

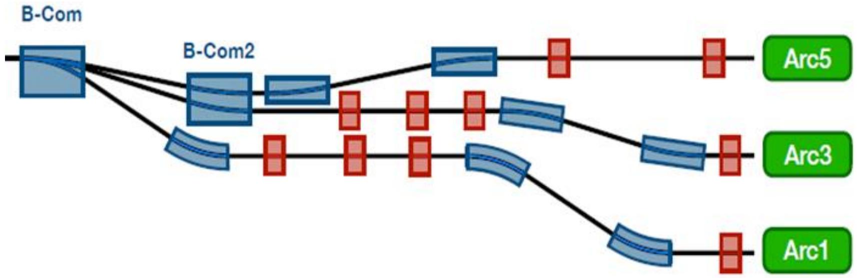


III. **Spreader/Recombiner**

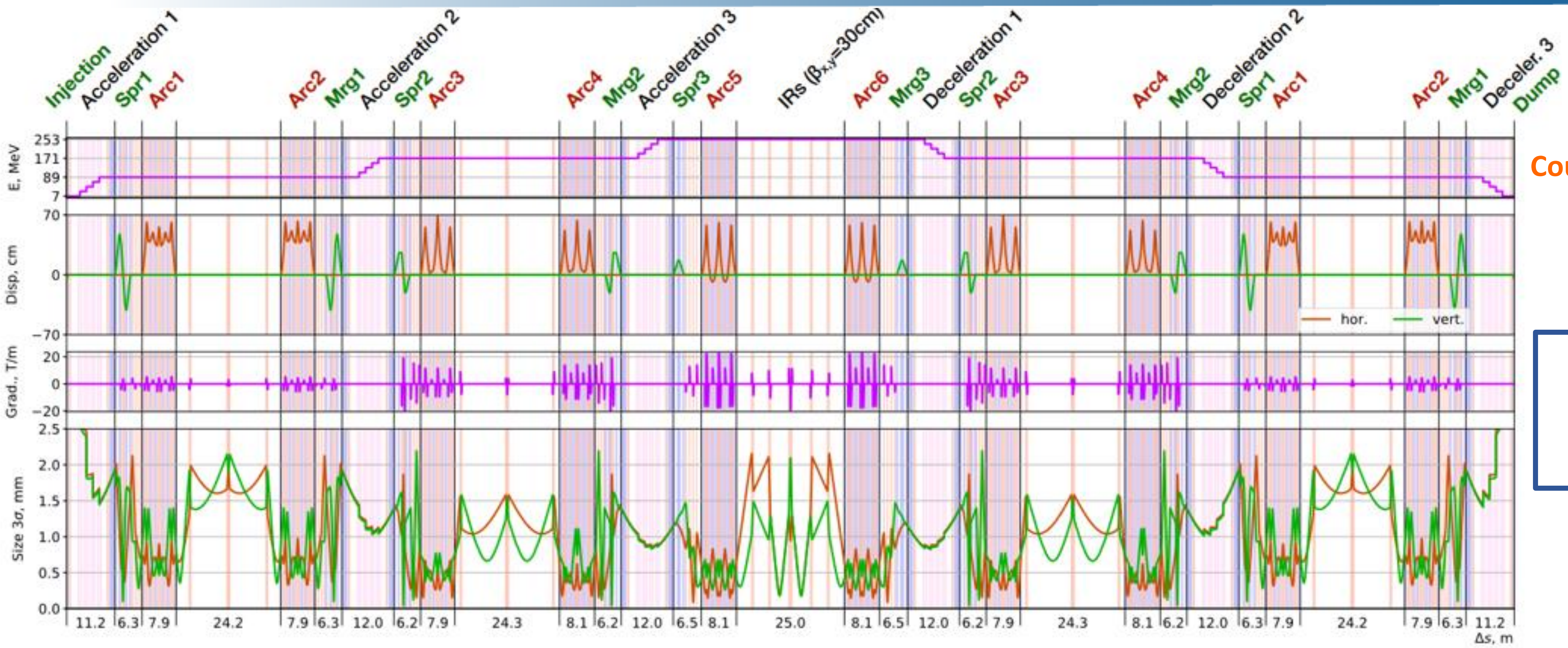
Connect LINAC to the arcs section

One common dipole magnet

Horizontal field magnet → Vertical beam split at three different energies



PERLE Optics – 250 MeV



Courtesy of Alex Fomin

Beam dynamics defines magnet requirements

- Beam rigidity defines the dipole bending angle

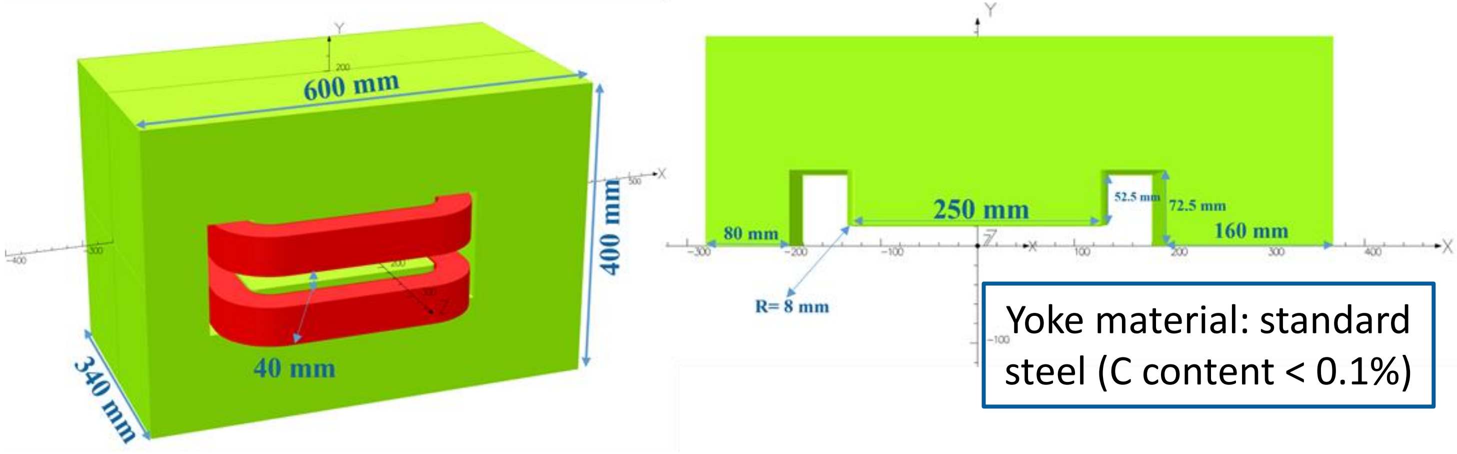
$$\theta = \frac{L}{\rho} = \frac{B.L}{(B\rho)} = \frac{q.B.L}{p}$$

- Quadrupole focusing converge the beam ↔ beam size

$$< x_{rms} > \leftrightarrow \mathrm{kl_q} , \mathrm{k} = \frac{G}{B\rho}$$

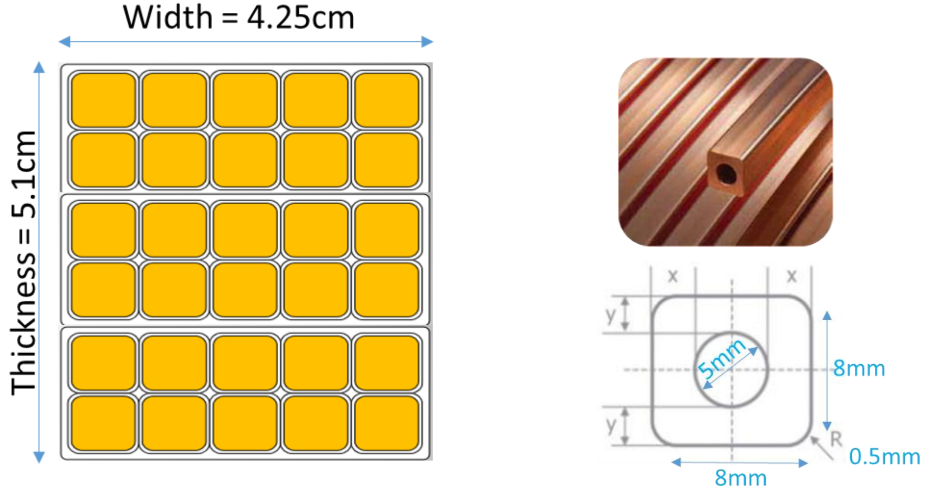
B-com Magnet Design

Tool: Opera 3D

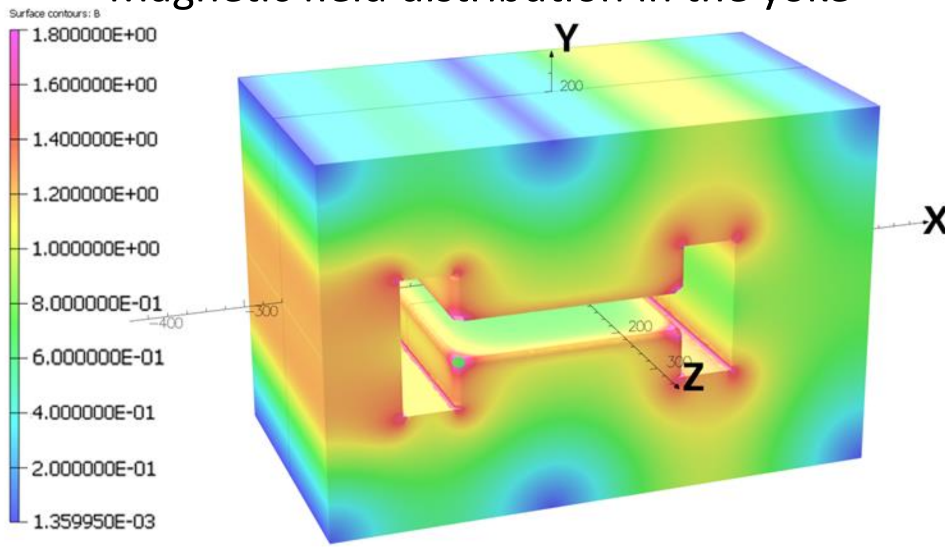


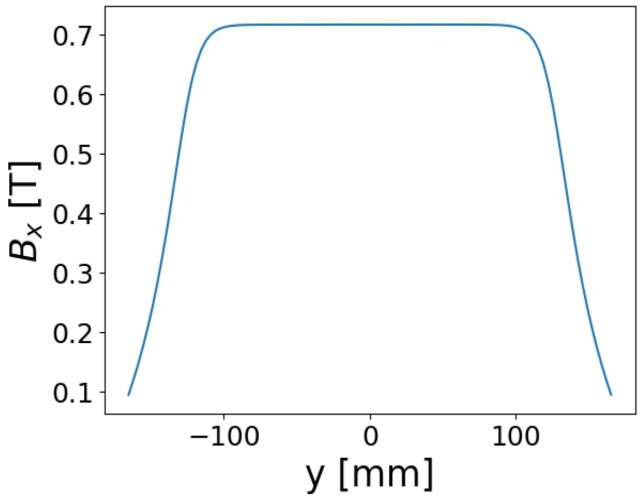
Yoke material: standard steel (C content < 0.1%)

Coil design



Magnetic field distribution in the yoke





$By\ (0,0,0) = 0.716382\ T$

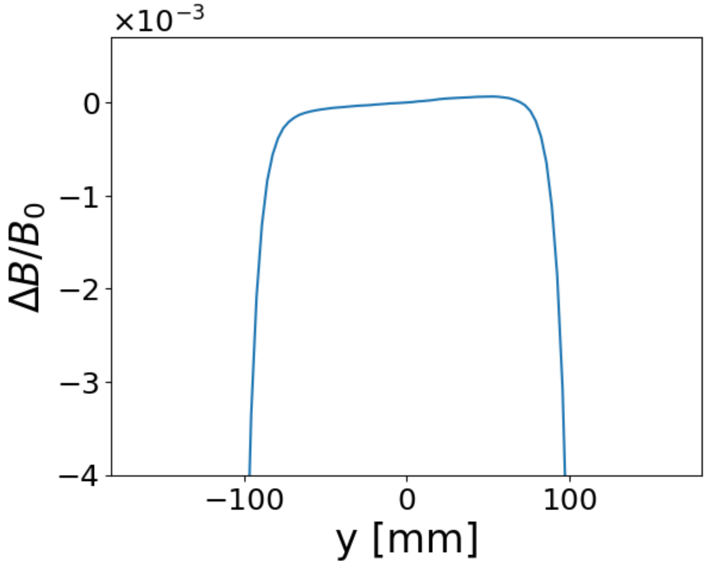
Excitation current calculated for **B = 0.87 T**

$$\mathrm{NI} = \frac{Bh}{2\mu_0}, \mathrm{h} = 40\ \mathrm{mm}$$

0.3 T.m Field integral along beam trajectory of 0.34 m → Nominal $B = 0.88$ T

This work is in collaboration with Jay Benesch from JLab.

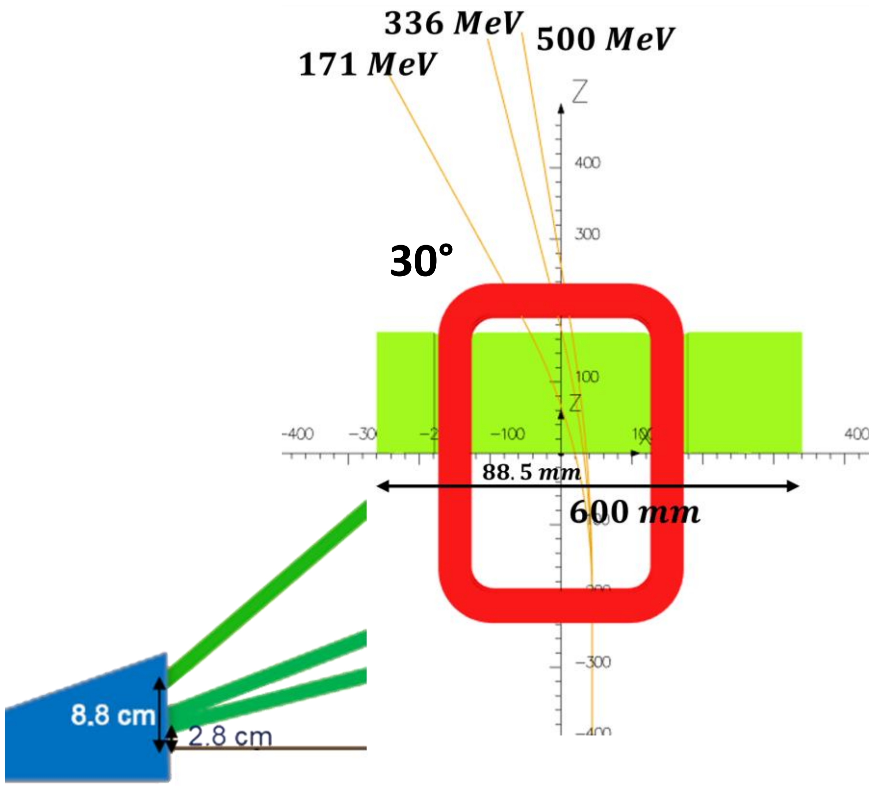
B-com Field Calculation

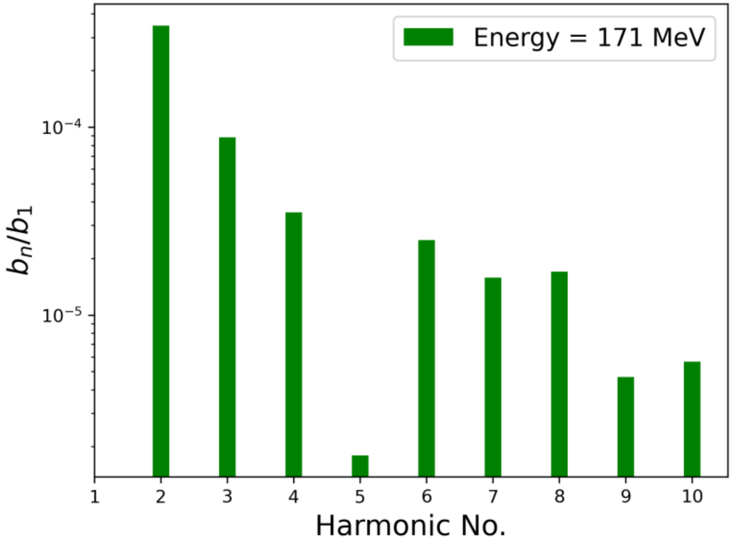


$$\frac{\Delta B}{B_0} = \frac{B(x) - B_0}{B_0}$$

Field uniformity within ±100 mm

Harmonic content
Ensure field quality to guide electrons along a certain trajectory





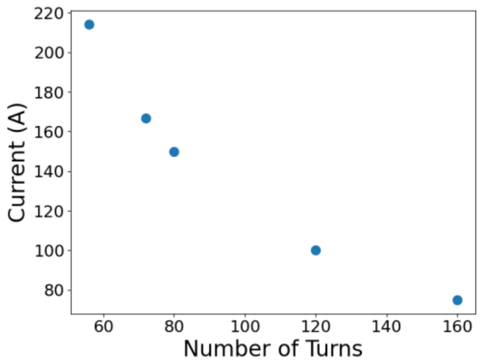
Energy	b1	$\sqrt{\sum_{n=1}^{5} b_n^2} / b_1$
171MeV	-2.90E+01	3.594E-04
336MeV	-2.81E+01	6.79E-05
500MeV	-2.79E+01	1.01E-04

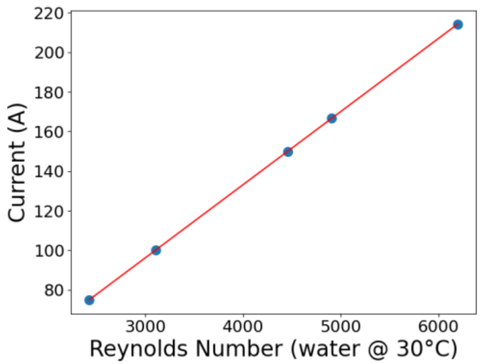
0.036% field homogeneity

Excitation current for **B = 0.87 T**

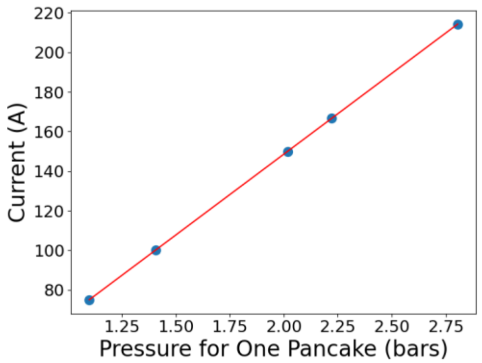
NI = 11520.263 A.turn

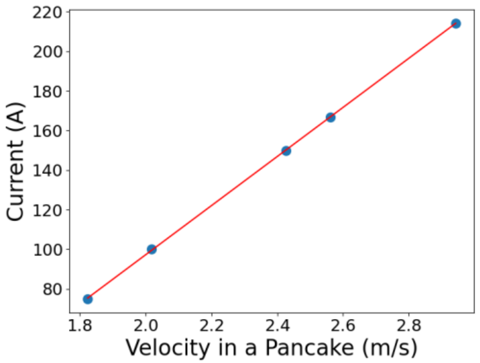
- Goal: achieve the minimum current powering the magnet & ensuring adequate coil cooling.
- Turbulent water flow → Reynolds number > 4000

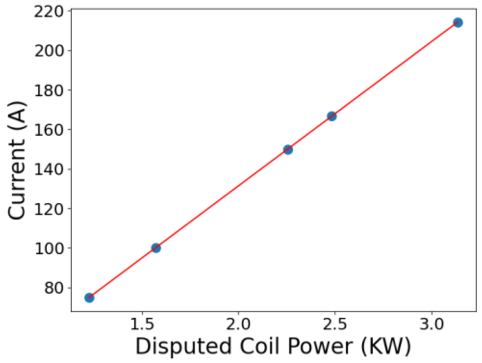




$$I_{min} = 166.67\ A$$



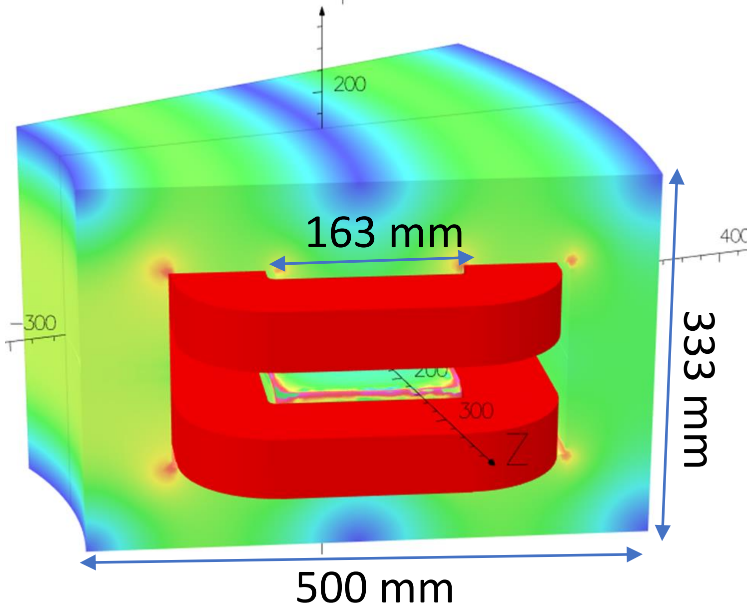


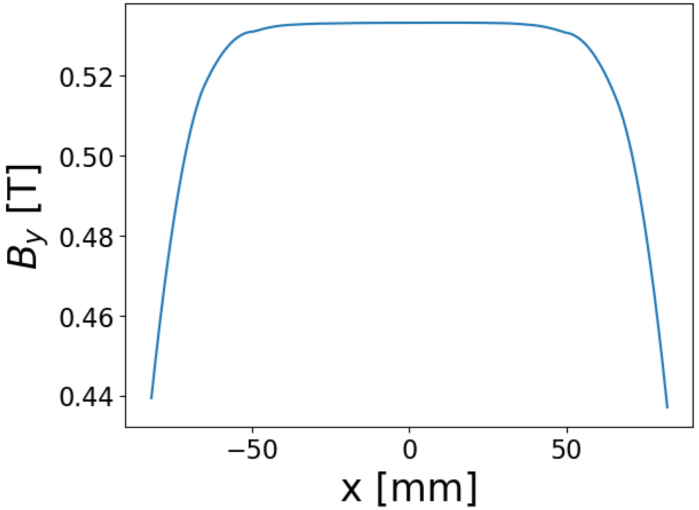


Courtesy of Abdalrhman Marshoud – Internship student from An-Najah University

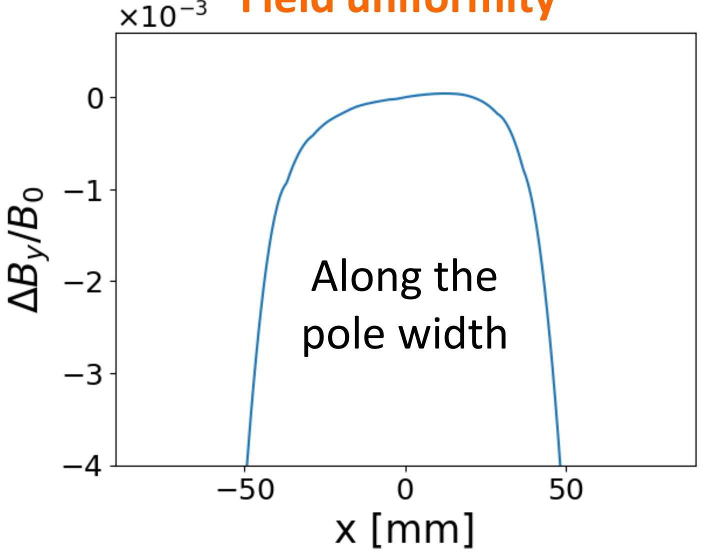
S-bend Magnet (Arcs 1,2)

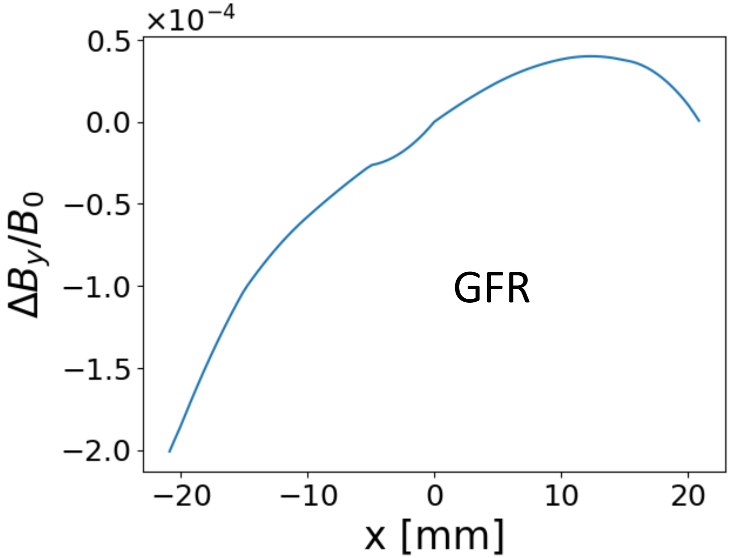
Parameters	Value
Energy [MeV]	89
B [T]	0.472
Ɵ (°)	30
Ɵ (rad)	0.542
L_mag Curved [cm]	33
Bending Plane	Horizontal
J $[A/mm^2]$	2.42





Field uniformity





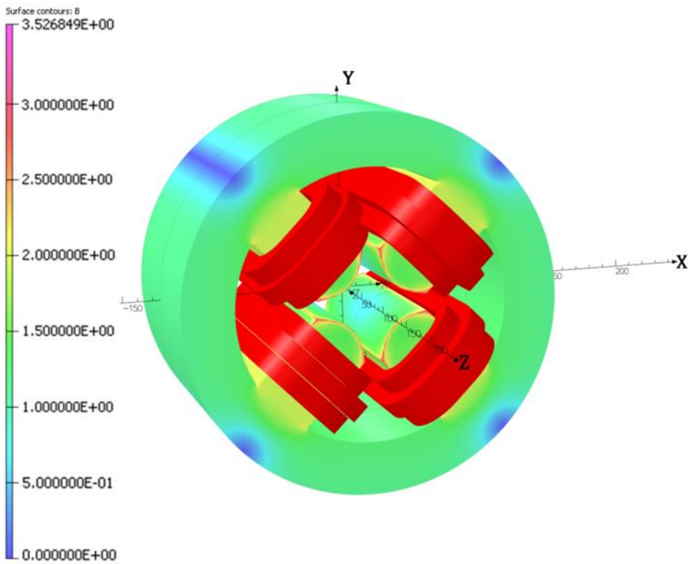
Good Field Region
Field quality within certain tolerances $(10^{-3} - 10^{-4})$

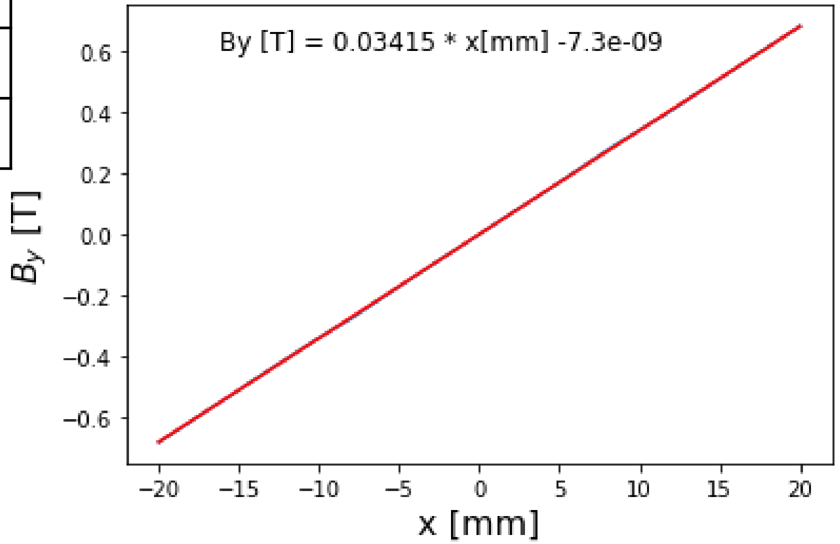
Quadrupole Magnets

Arcs Section

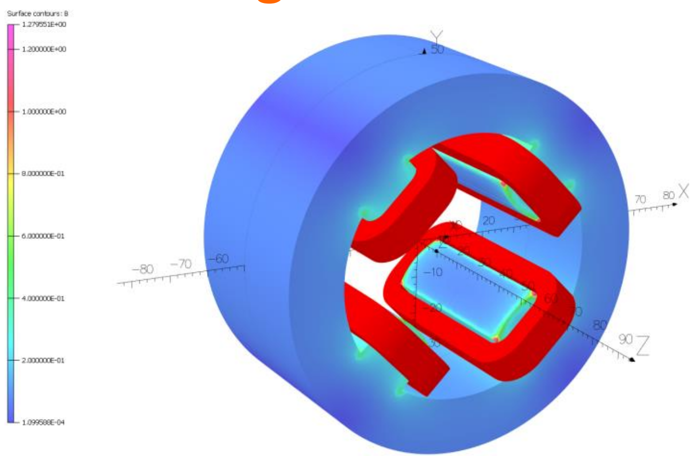
Parameters	Arcs
Height	250 mm
Yoke thickness	35 mm
Length	150 mm
Aperture radius	20 mm
Pole width	44 mm
NI per coil	1750.7 A.turn
Current density J	2.882 A/mm^2
Gradient	34.15 T/m

Max. gradient (250 MeV) = 23 T/m



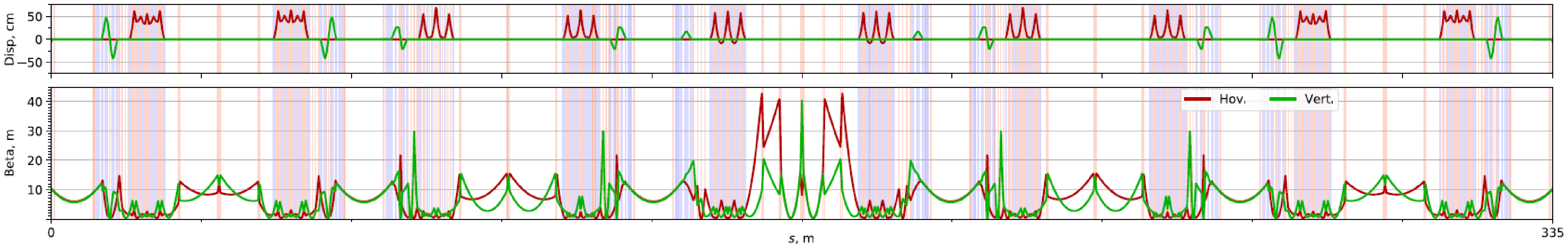


Merger Section



Parameters	Merger
Height	100 mm
Yoke thickness	15 mm
Length	50 mm
Aperture radius	20 mm
Pole width	17 mm
NI per coil	318.31 A.turn
Current density J	2.62 A/mm^2
Gradient	3 T/m

Study of PERLE Lattice Errors



Lattice tuned for

- Zero Dispersion function at the exit of each arc
- Zero difference in Beta function between the entrance and exit of each arc

Imperfections added to the lattice to study their influence on the beam parameters

Effect of optics misalignment:

- Lateral quadrupole misalignment is equivalent to: aligned quadrupole + small dipole

$$B_y = k_1 B\rho \, \Delta x$$

Small offset ~0

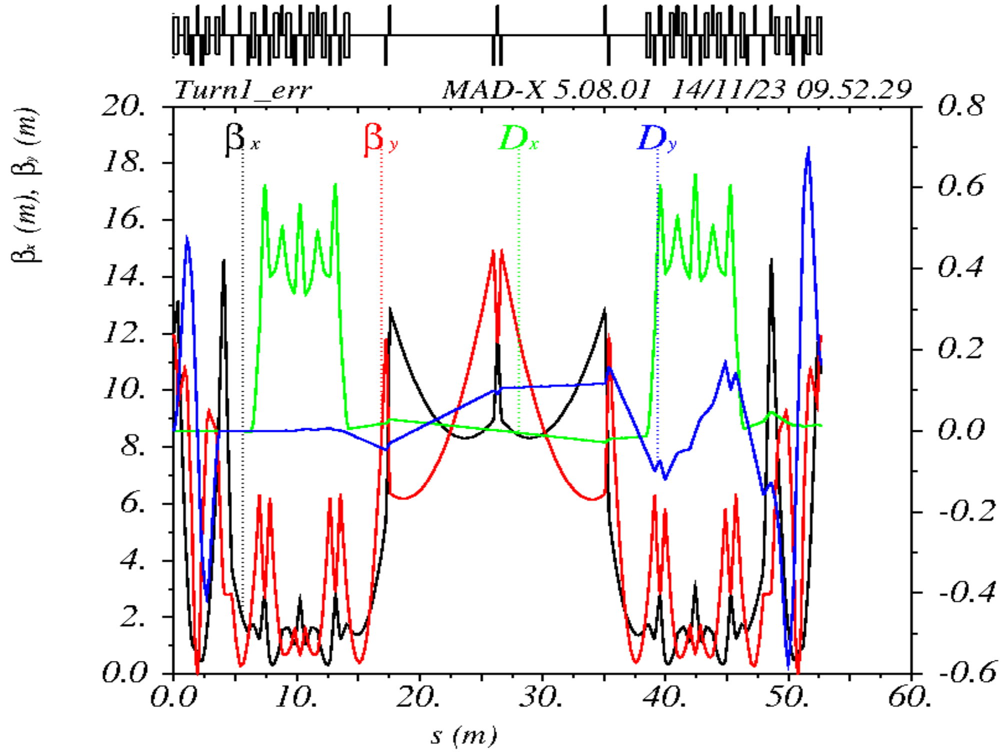
- Additional deflection angle of the beam

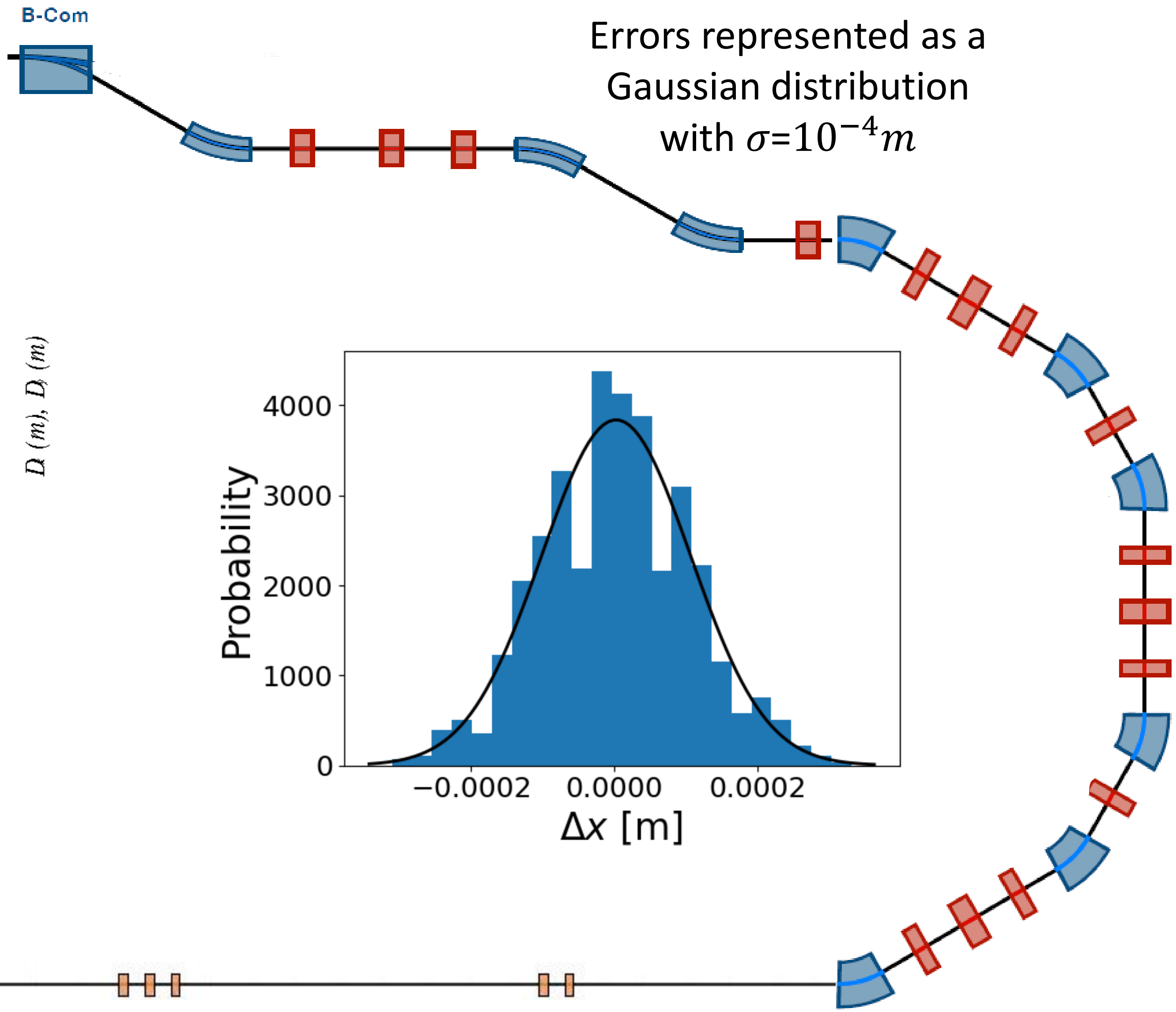
$$\Delta\theta = kl \, \Delta x$$

- Orbit distortion $\propto \beta_{kick\ location}$

Optics misalignments

- Misalignments in all quadrupoles
- 1^{st} Turn only
- $\Delta x, \Delta y$ to the quadrupoles position
- Twiss functions along the lattice were extracted

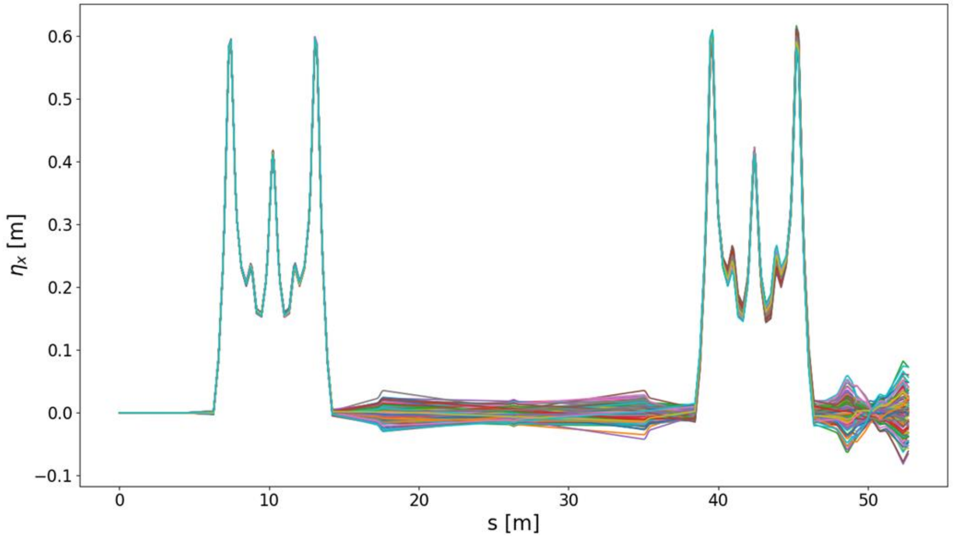


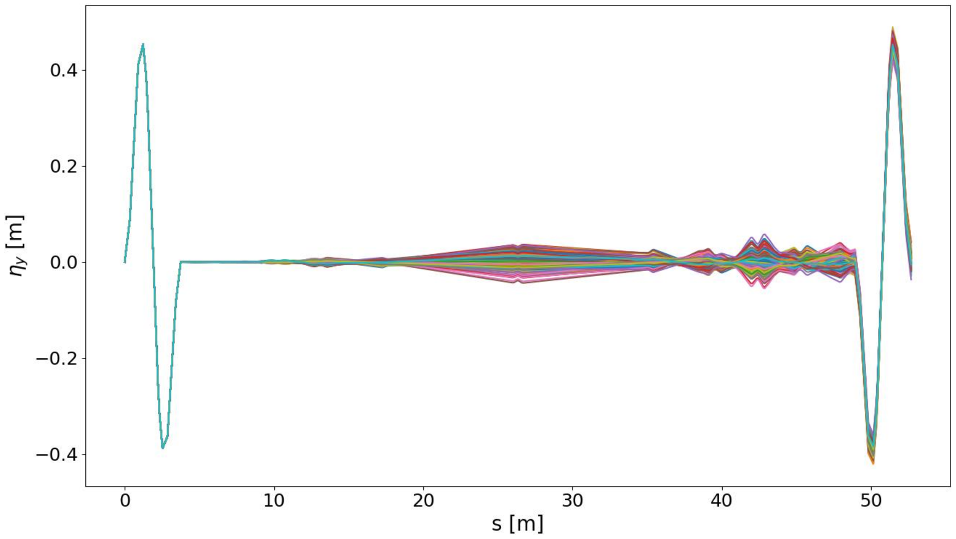


Errors represented as a Gaussian distribution with σ=$10^{-4}m$

BMAD & MADX Simulations

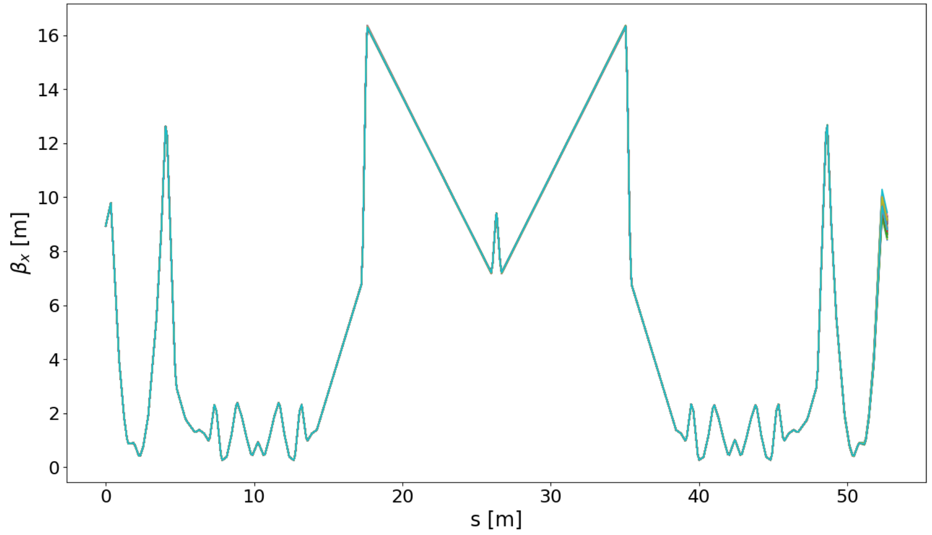
Optics misalignments

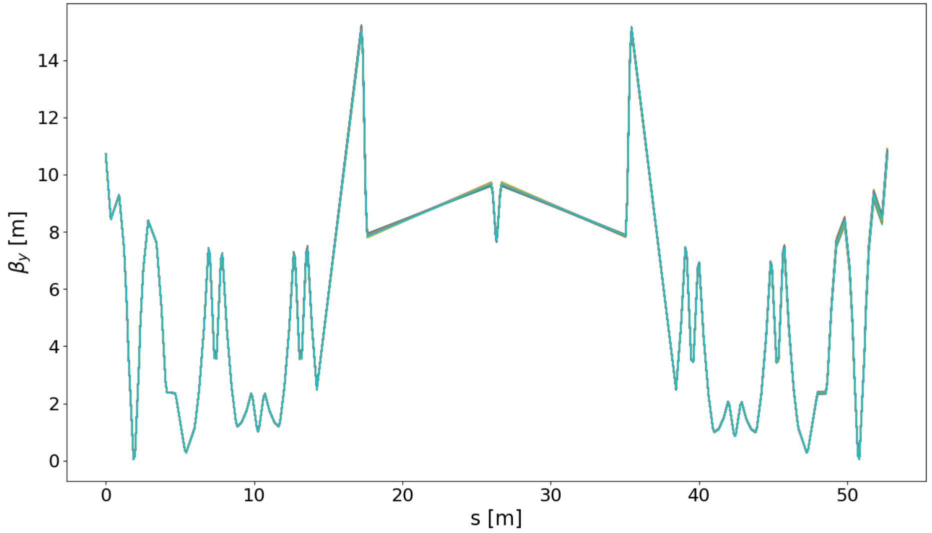




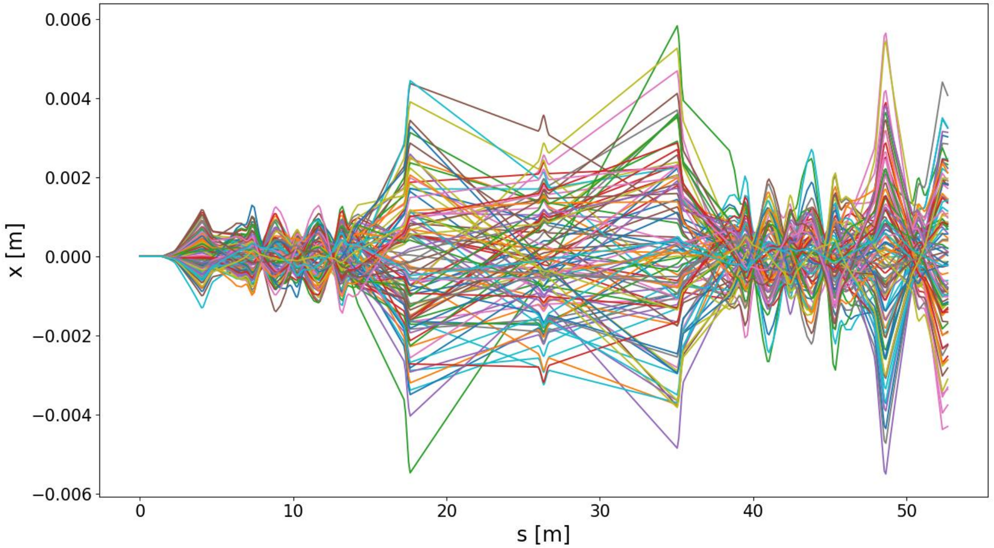
100 simulations

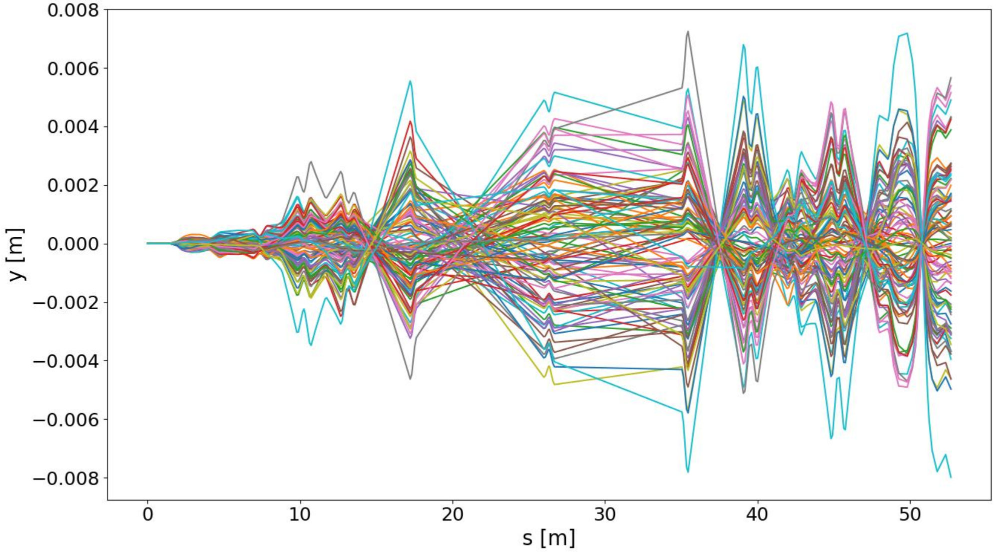
- Misalignment affects dispersion in both planes.
- No effect on Beta function.





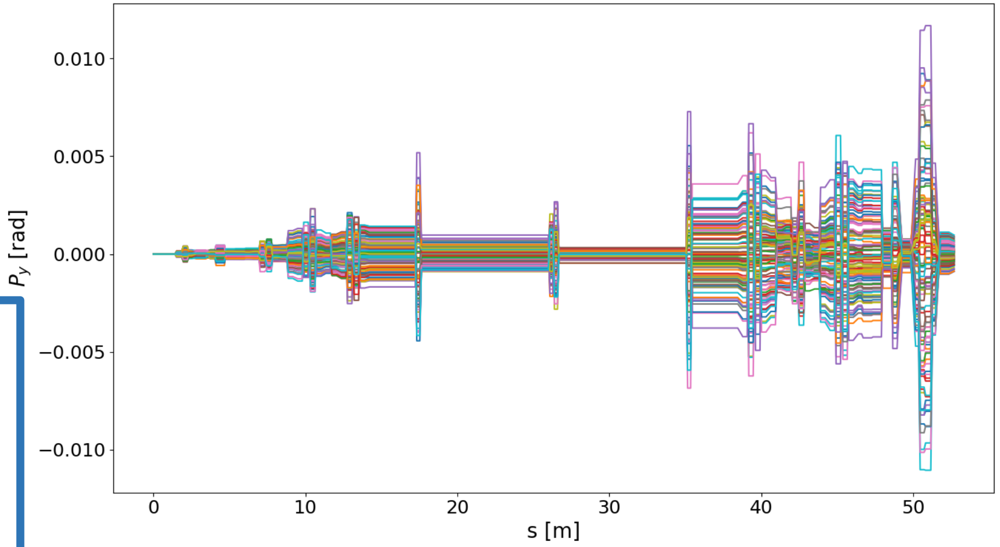
Optics misalignments

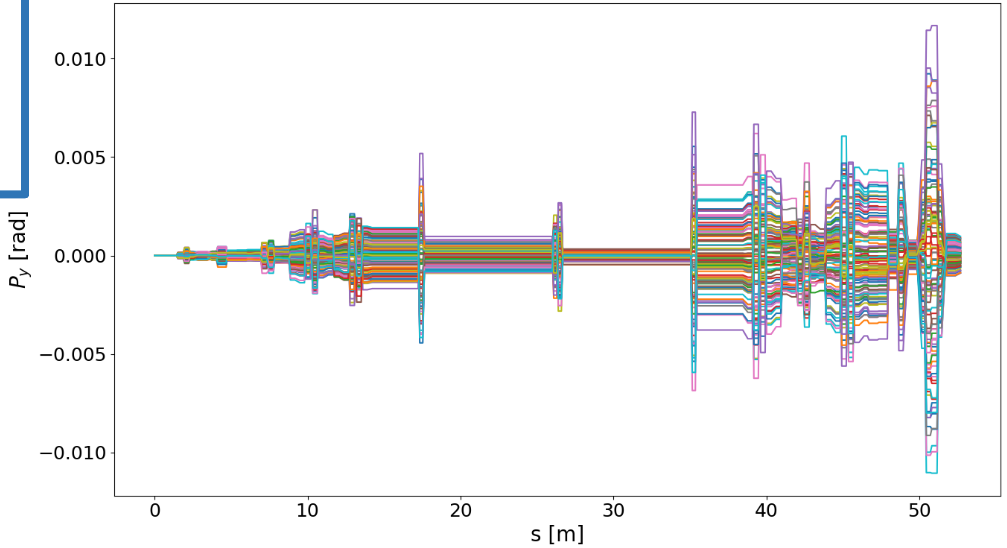




100 simulations

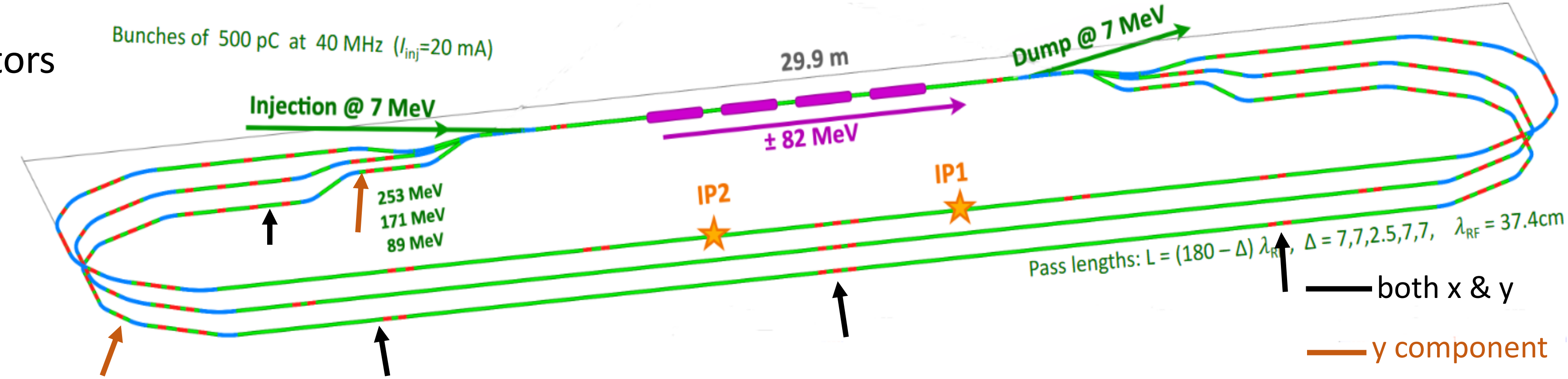
The misalignment affects mostly the particle orbit in both planes.
The effect is seen on the position and also on the momentum x’, y’



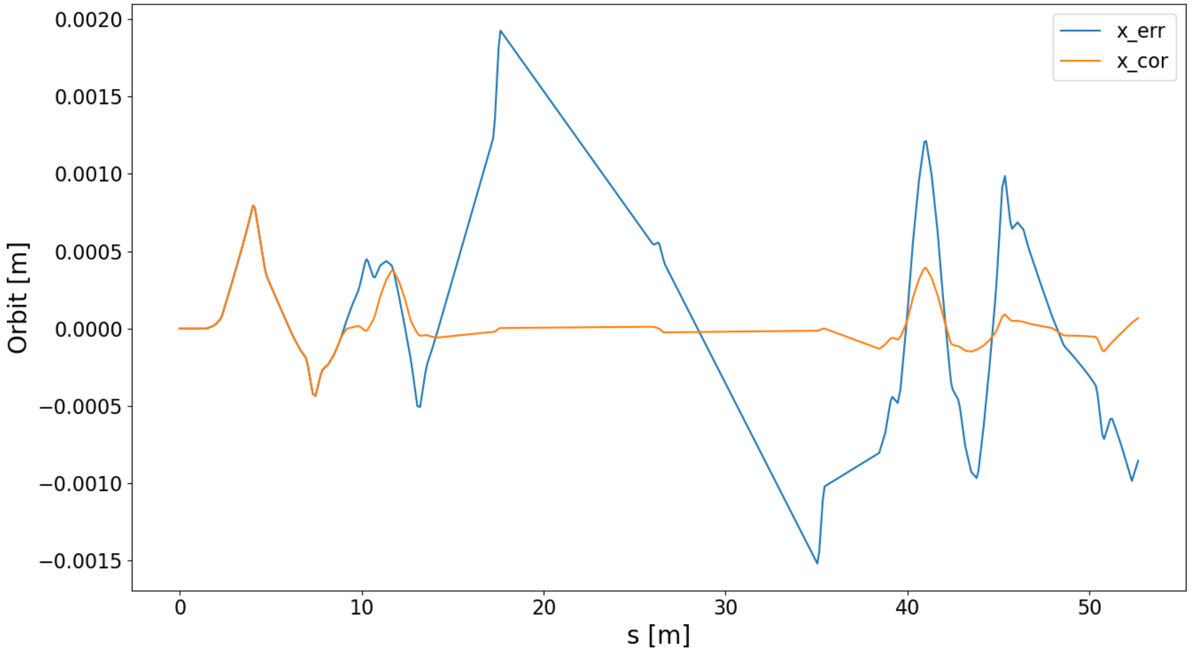


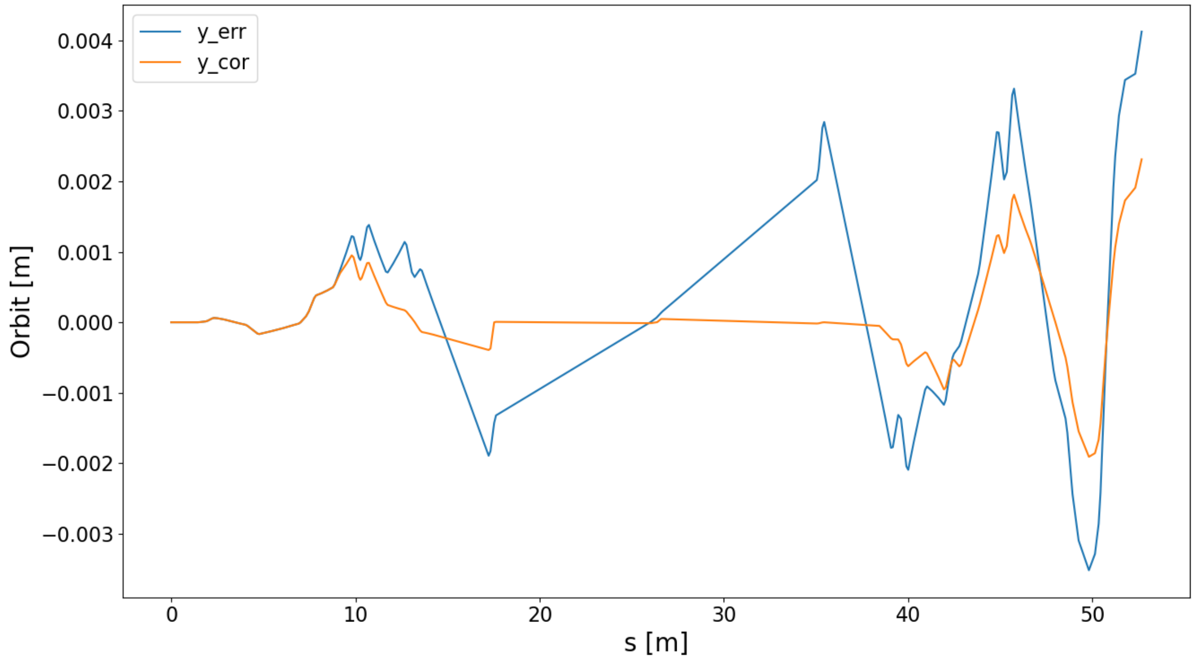
Lattice Correction: Ongoing Study

- Kicker magnets as orbit correctors
- The kick value is the $\delta P = \frac{\delta p_T}{p_0}$
- Positive kick increases p_x, p_y



One simulation





Conclusion

- ERL relies on decelerating the electron beam and using its released energy to the RF cavity to accelerate new fresh bunches.

- The B-com and dipole magnets of Arcs 1,2 designed with their associated cooling circuit parameters.
- Quadrupole magnets of Arcs and injector designed.

- Study of the effect of transverse optics misalignments on Twiss functions (D_x, D_y, β_x, β_y, α_x, α_x, Orbit).
- Quadrupole misalignment affects beam orbit.

- Most critical points were defined → BPMs positions.
- Kicker magnets added for correction *(ongoing).*

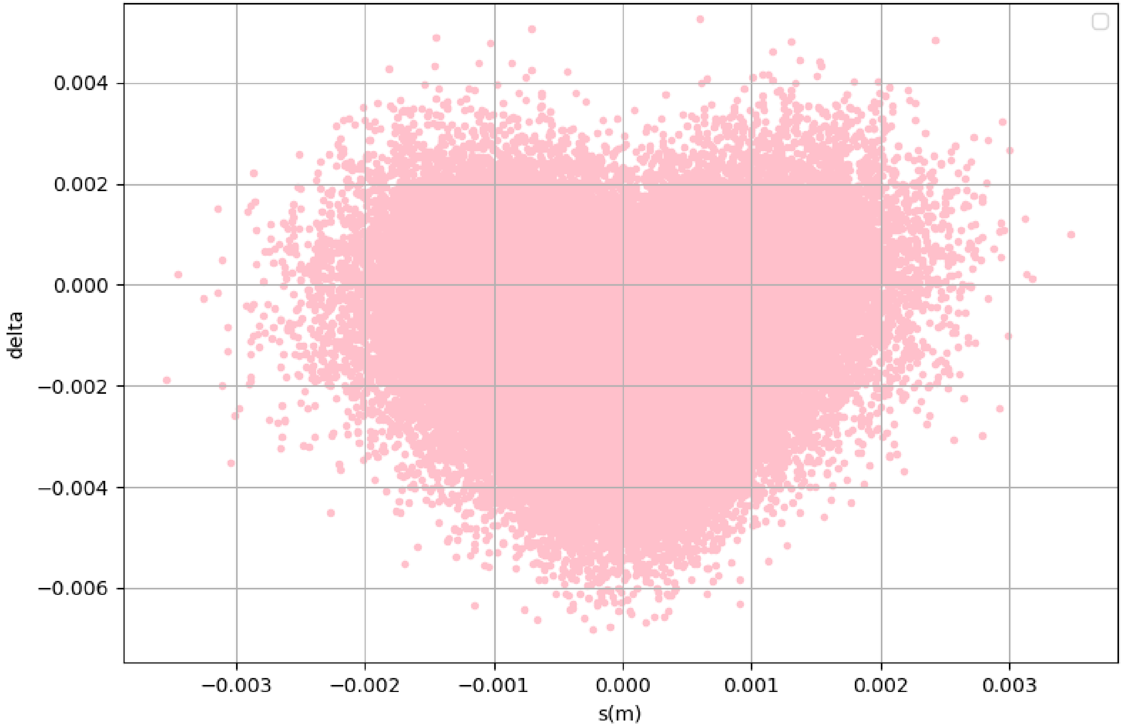
Outlook

- Complete the lattice error study to conclude the orbit stability and lattice acceptance.
- Finalize the design of the magnet elements: dipoles of arcs and spreader (*ongoing*), chicane magnets, and quadrupole families. (maybe sextupoles).

Thank You For Your Attention!

Bonus : Beam at the exit of the merger

(beaucoup d'amour, et surtout, les bons paramètres)

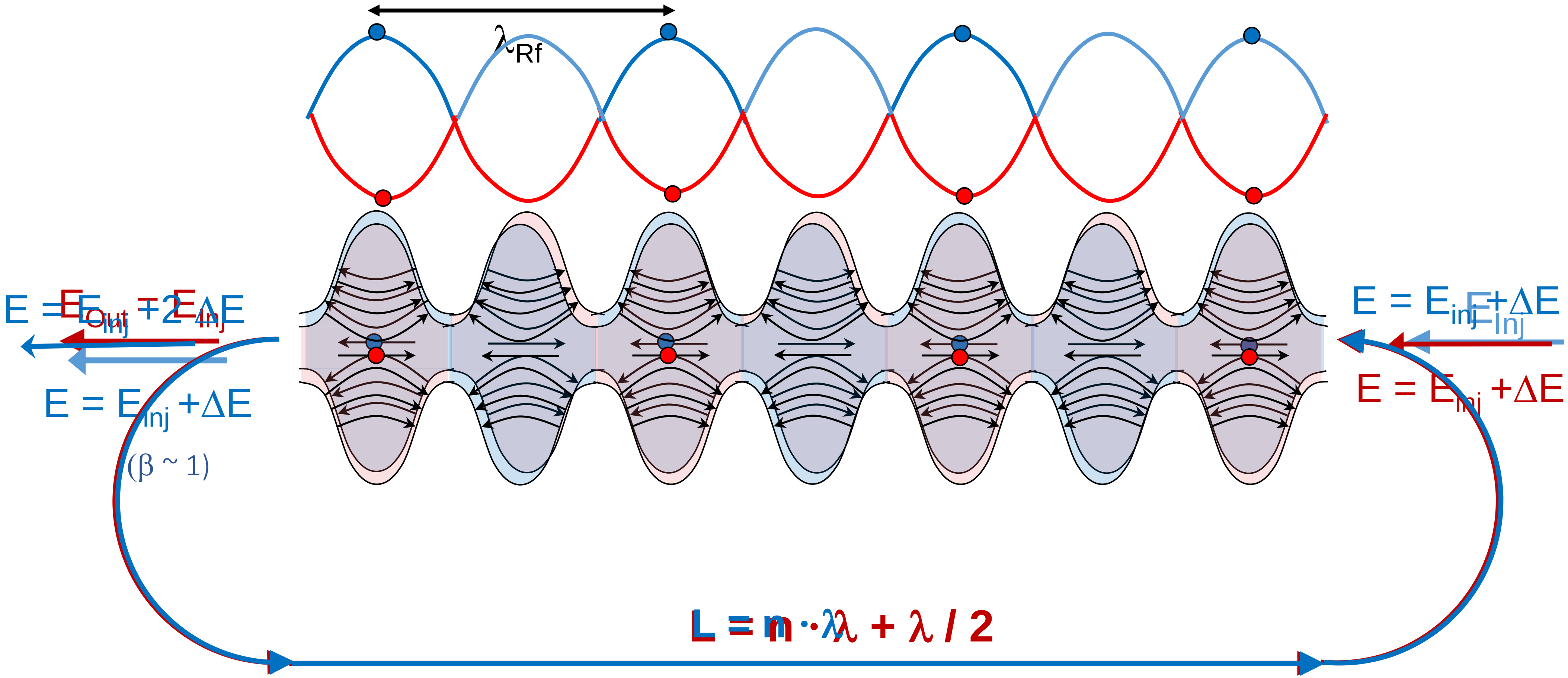


Recipe :

- CSR ON
- Space Charge OFF
- $\sigma_z = 0{,}4$ mm
- $\frac{\Delta P}{P} = 1{,}4e^{-3}$
- $\epsilon_x = \epsilon_y = 5e^{-6}$

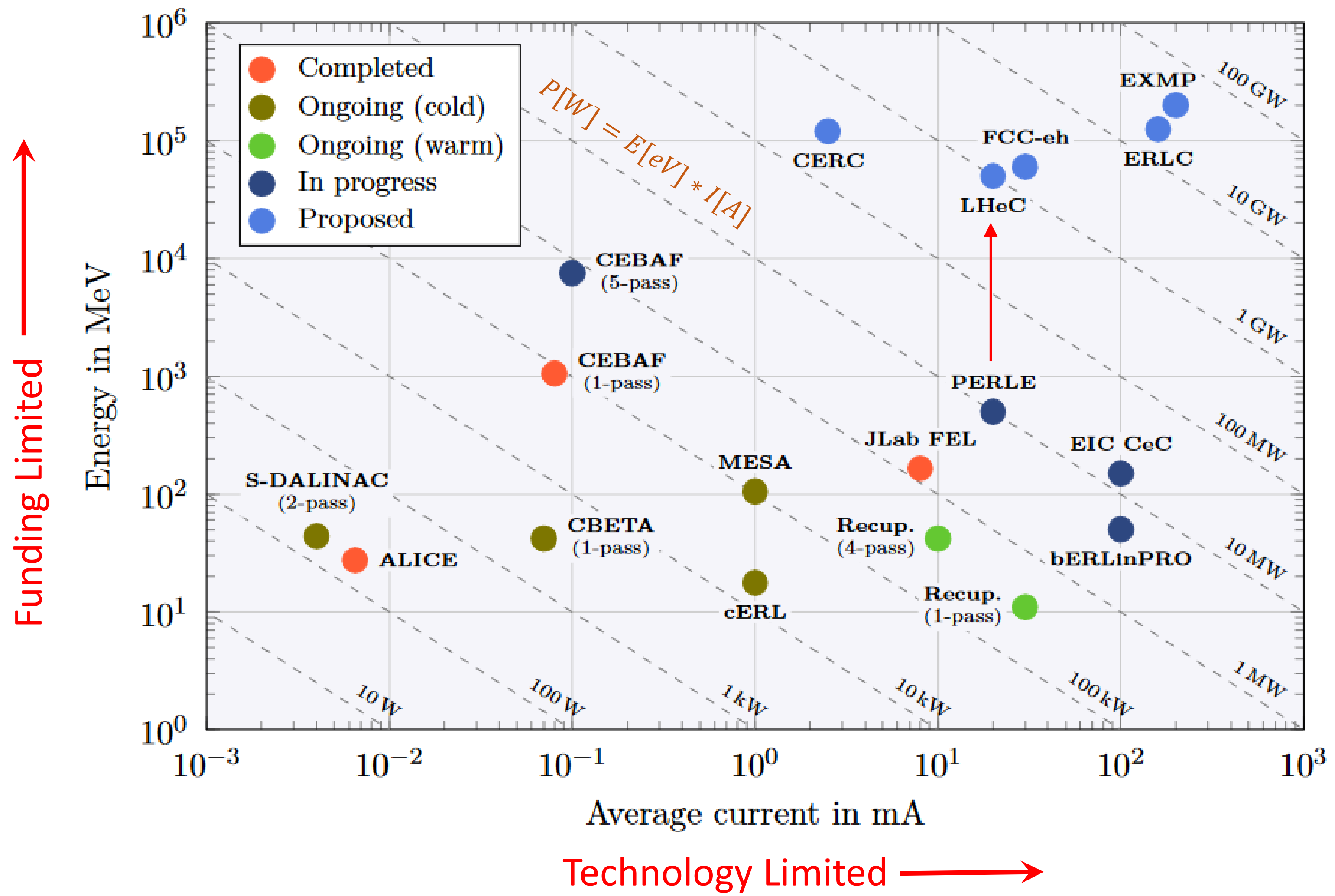
Credit: Julien Michaud

Back-up Slides



- Energy supply → acceleration
- Deceleration = "loss free" energy storage (in the beam) → Energy recovery

ERL Global Landscape



The New Frontier : e-RIB (Radioactive Nuclei Beam) scattering

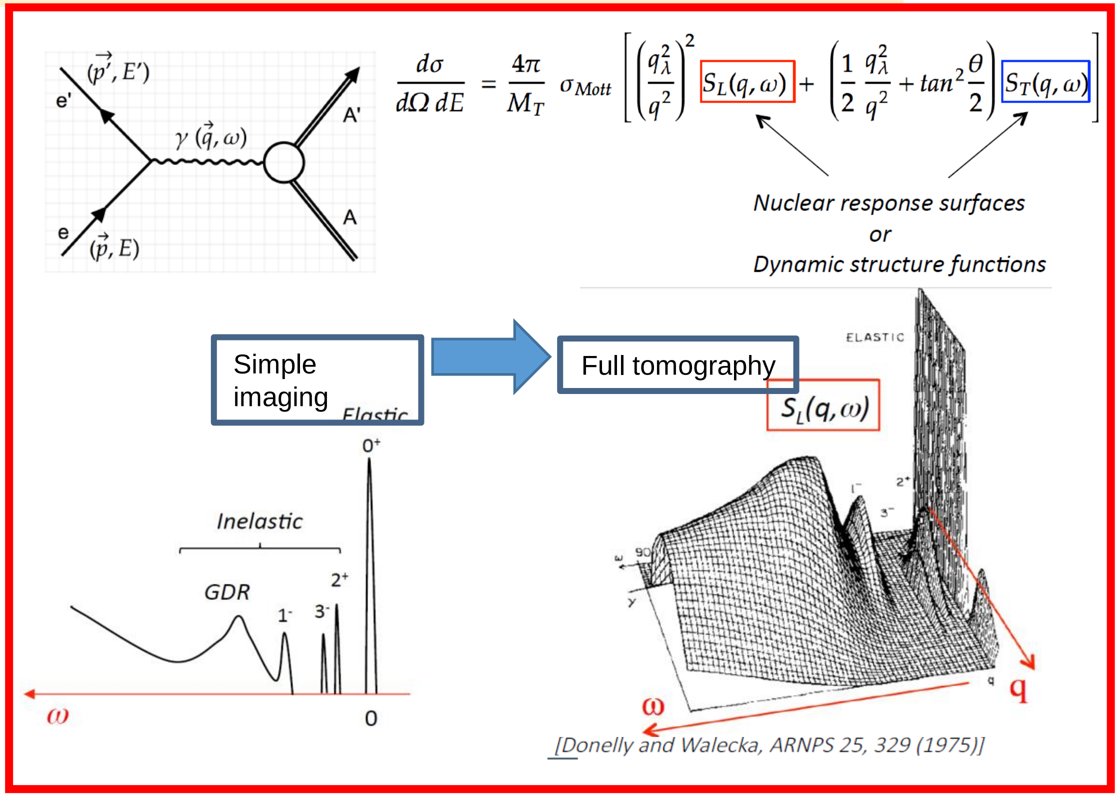
A completely new horizon, explore the interior of exotic nuclei :
charge radius, shape… New properties are emerging (halo, pairing..) !

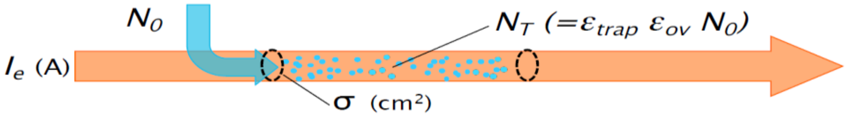
- All interesting phenomena occur at $q \gtrsim 2\text{fm}^{-1}$; the higher the q transferred the lower the cross section; consider previous achievements in this domain
  → **compromise starting at $E_e = 250 \dashrightarrow \simeq 500$ MeV (~0.5fm)**
- Aimed luminosity should be 10^{29} cm^{-2}s^{-1} but much can be already done at
  → **$\mathcal{L} \simeq 10^{27} - 10^{28}$ (with unstable nuclei EVERYTHING is new !)**

A long road ahead before reaching the full tomography of an exotic nucleu
The starting point is :

DESTIN [**DE**ep **ST**ructure **I**nvestigation of (exotic) **N**uclei]

Very challenging
The beam will confine RIB in the longitudinal plane e- with positive ions), and traps have to confine RIB in the transversal plane (à la SCRIT at RIKEN)



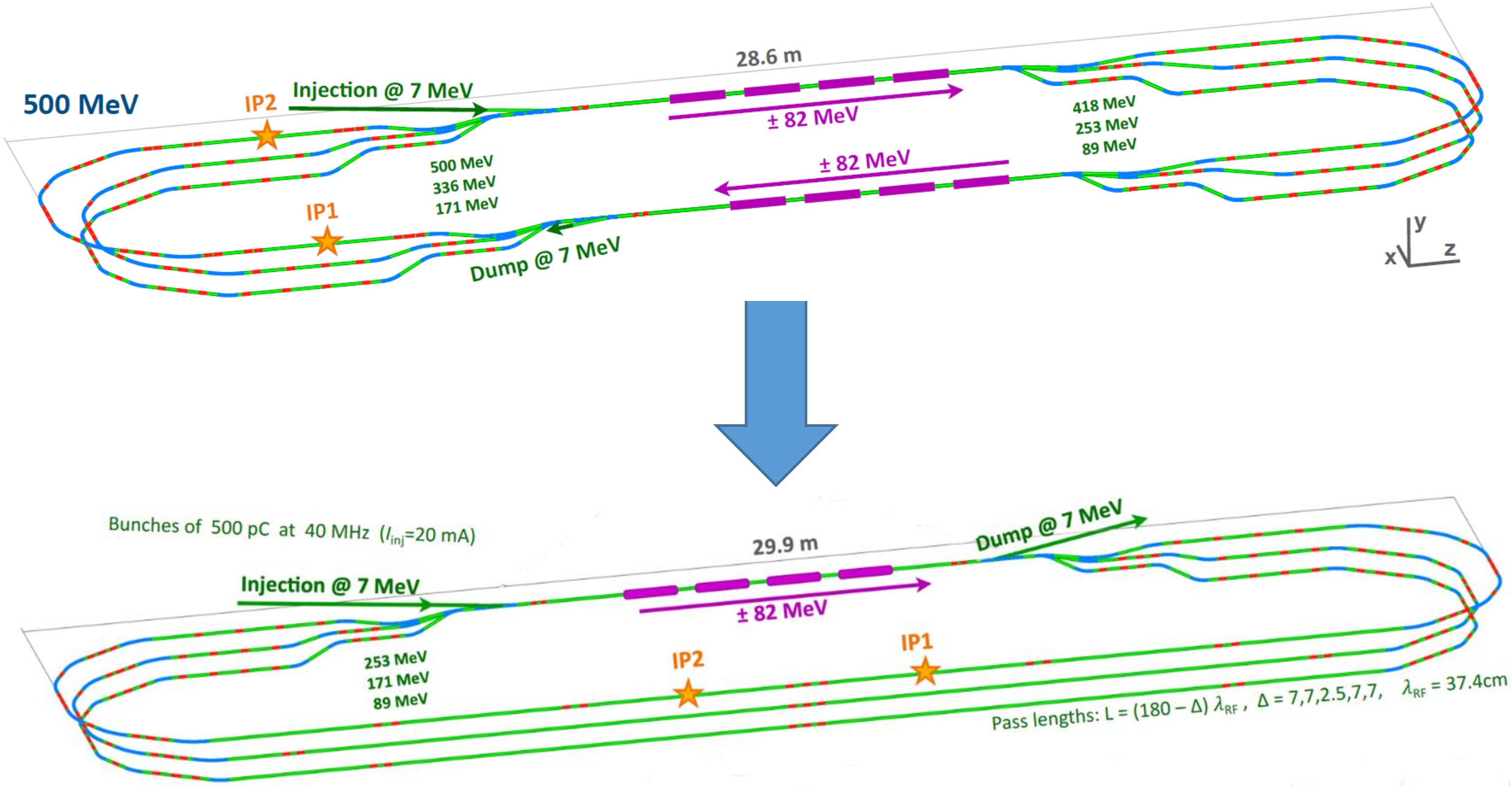


$L \sim \frac{I_e/e \quad N_T}{\sigma}$ /(cm²s)

Collection : from David Verney

Staging with 250 MeV version

- Demonstration of ERL with 6 passes at high current (with half of the power).
- Three straight sections replacing the spreader/recombiner sections at one side, and the second LINAC.
- The Injector and the dump are on the same side leading to a slightly larger footprint.
- More space is available for experimental areas at the interaction points (IP).



Lattice Functions and Optics

- Beta function is related to beam shape and size

$$< x_{rms} >= \sqrt{\epsilon\beta}$$

- Beta function is given by the focusing properties

of the lattice ↔ quadrupoles

- Effect of quadrupole on Beta

$$\beta = \beta_0 \left(1 - \frac{L}{f}\right)^2 - 2\alpha L \left(1 - \frac{L}{f}\right) + \gamma L^2$$

Twiss Parameters

$$\alpha = -\frac{1}{2}\beta'$$

$$\gamma = 1 + \frac{\alpha^2}{\beta}$$

$$L: drift\ length$$

$$\frac{1}{f} = kl_q$$

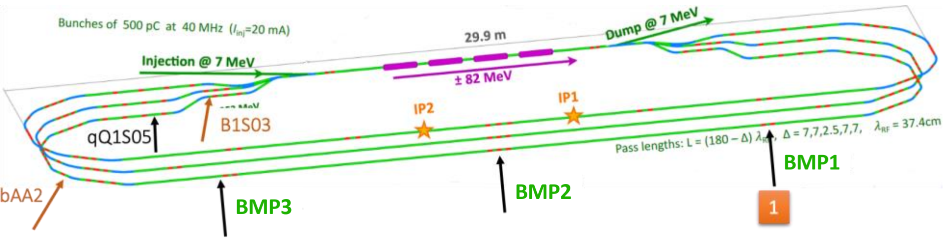
- Bending angle depends on momentum

Dispersion occurs due to momentum change

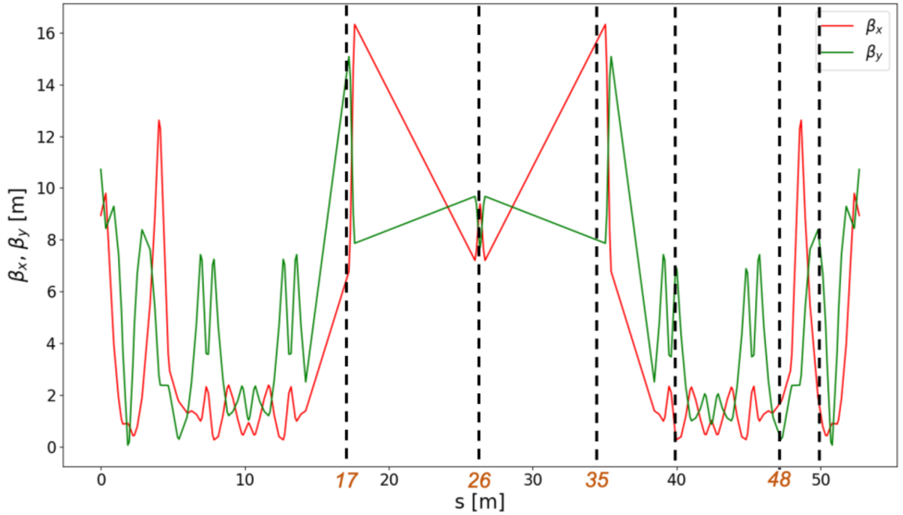
$$D = \frac{\Delta x}{\Delta p/p}, \qquad \frac{\Delta p}{p} = \frac{\Delta \theta}{\theta_0}$$

$$\mathcal{M}_{\text{sector}} = \begin{pmatrix} \cos\theta & \rho\sin\theta & \rho(1-\cos\theta) \\ -\frac{1}{\rho}\sin\theta & \cos\theta & \sin\theta \\ 0 & 0 & 1 \end{pmatrix}$$

- Recalculating the optics of Turn 1 with all (45) quadrupoles misaligned
- Finding the best positions for BPMs and Kickers

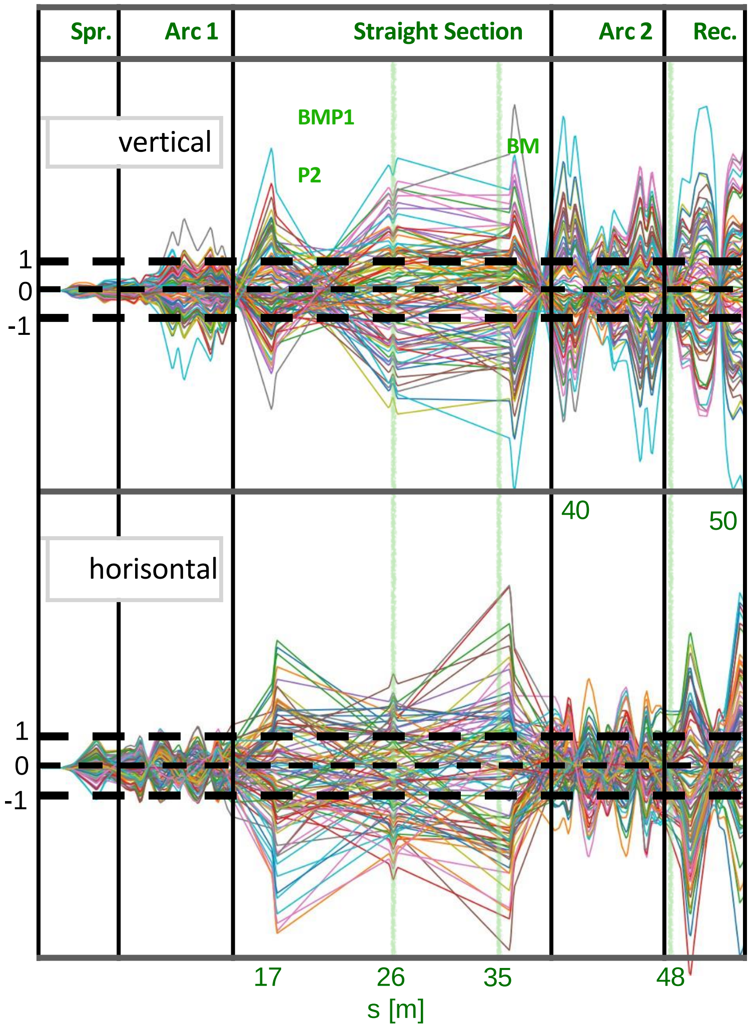


Placement of BPMs on top of betas

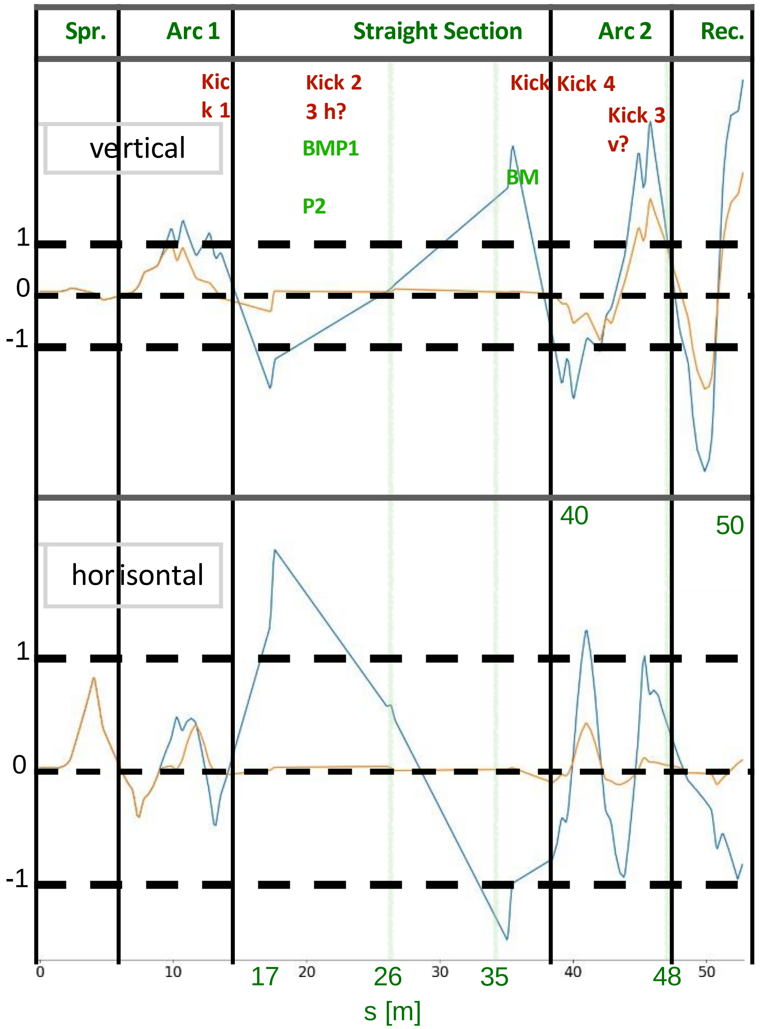


Reference orbit displacement due to quads misalignment [mm] (BMAD simulation)

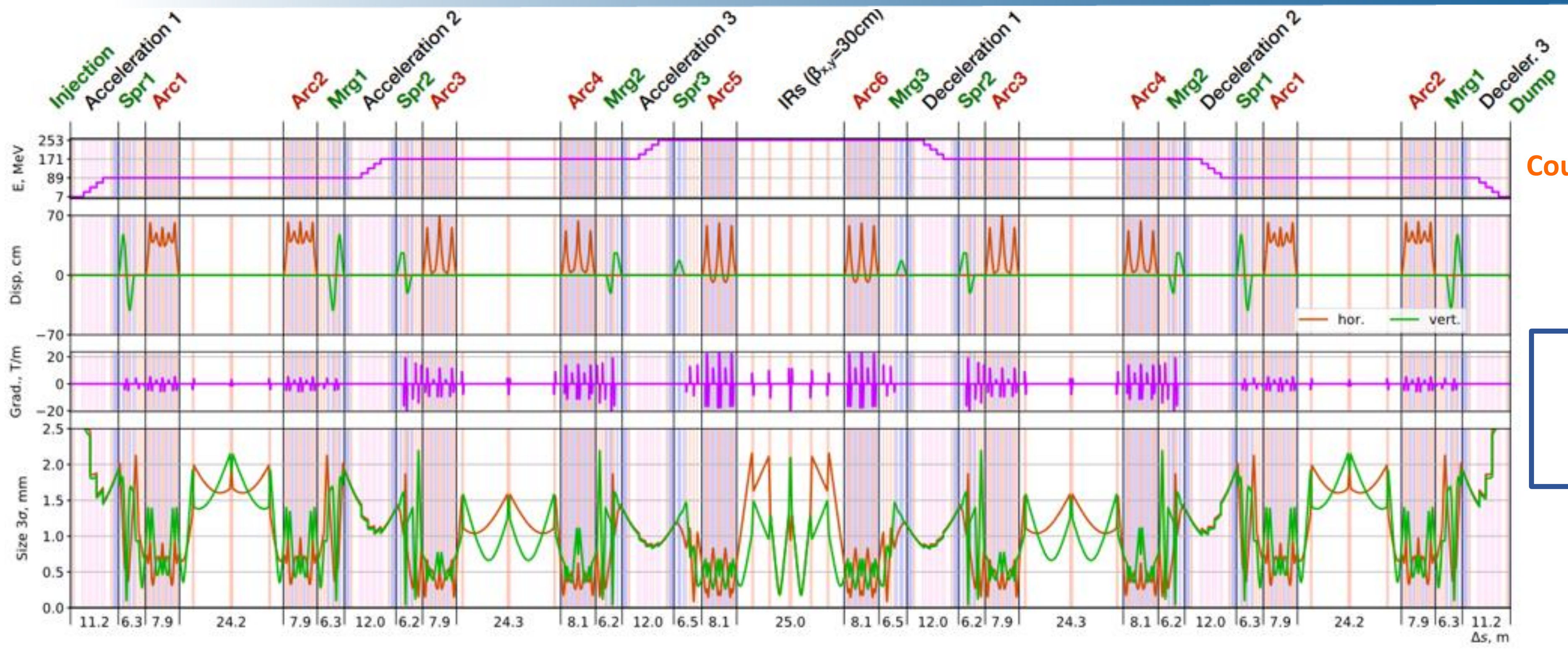
Multiple variants of misalignments



Corrected vs Not corrected (one case)



PERLE Optics – 250 MeV



Courtesy of Alex Fomin

Beam dynamics defines magnet requirements

- The Beta function is given by the focusing properties of the lattice ↔ quadrupoles

A large β-function corresponds to a large beam size and a small beam divergence

$$\beta = 4\pi \frac{\Delta Q}{\Delta k.\, l}$$

- The dispersion is related to the momentum change ↔ dipole bending angle

$$D = \frac{\Delta x}{\Delta p/p}, \frac{\Delta p}{p} = \frac{\Delta \theta}{\theta_0}$$

Lattice Functions and Optics

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- Beta function is given by the focusing properties

  of the lattice ↔ quadrupoles

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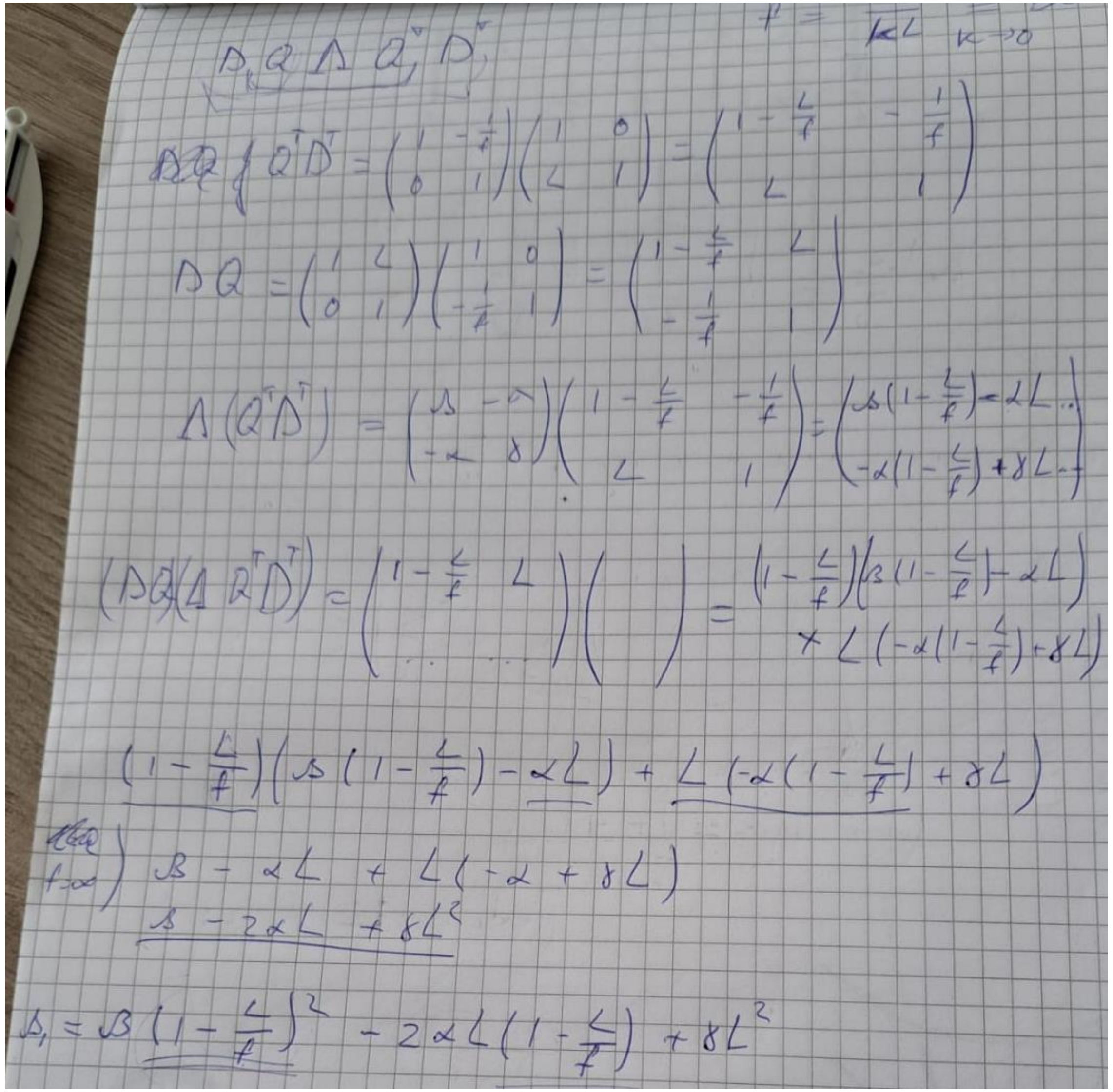
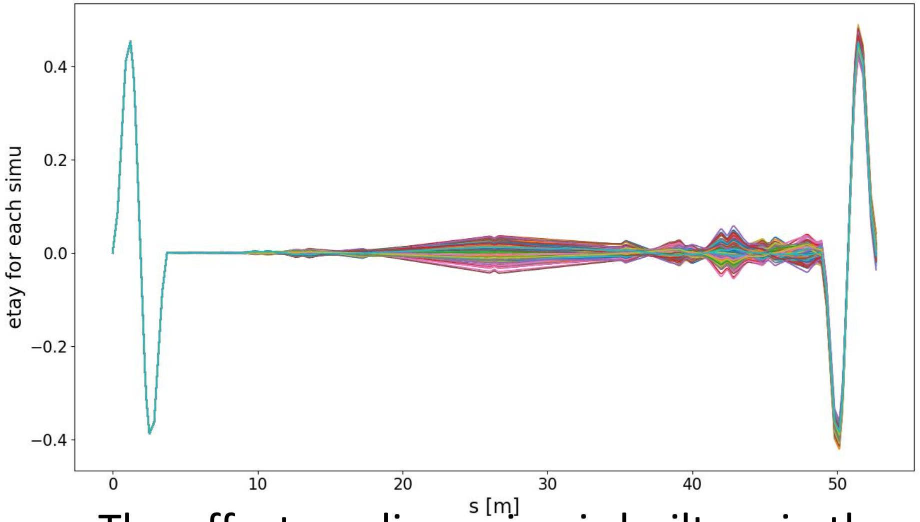
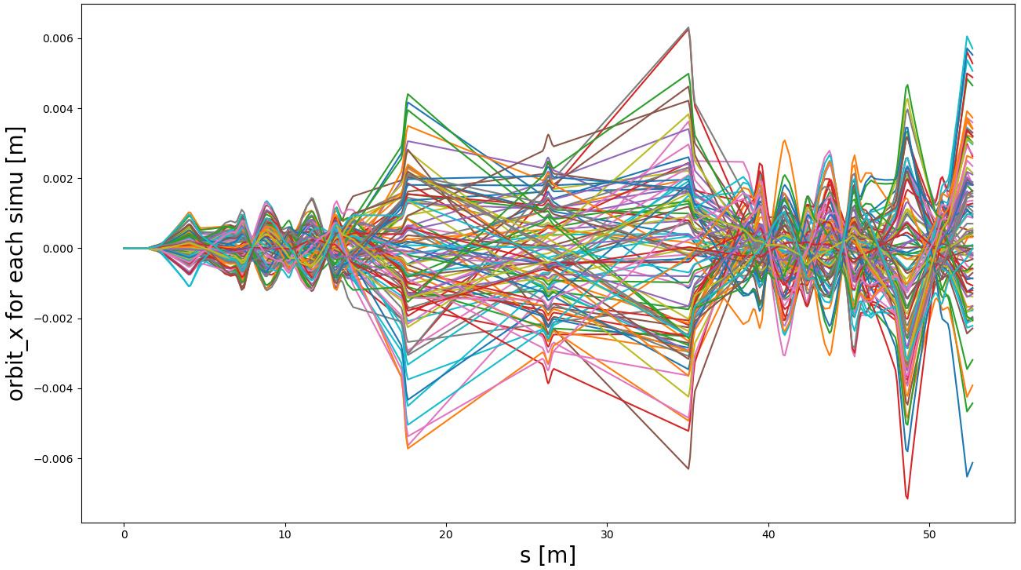
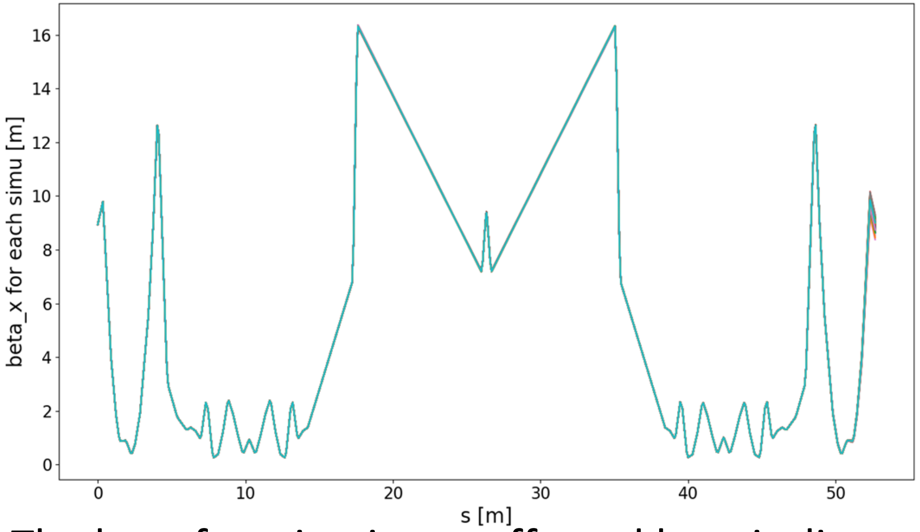


Optics misalignments

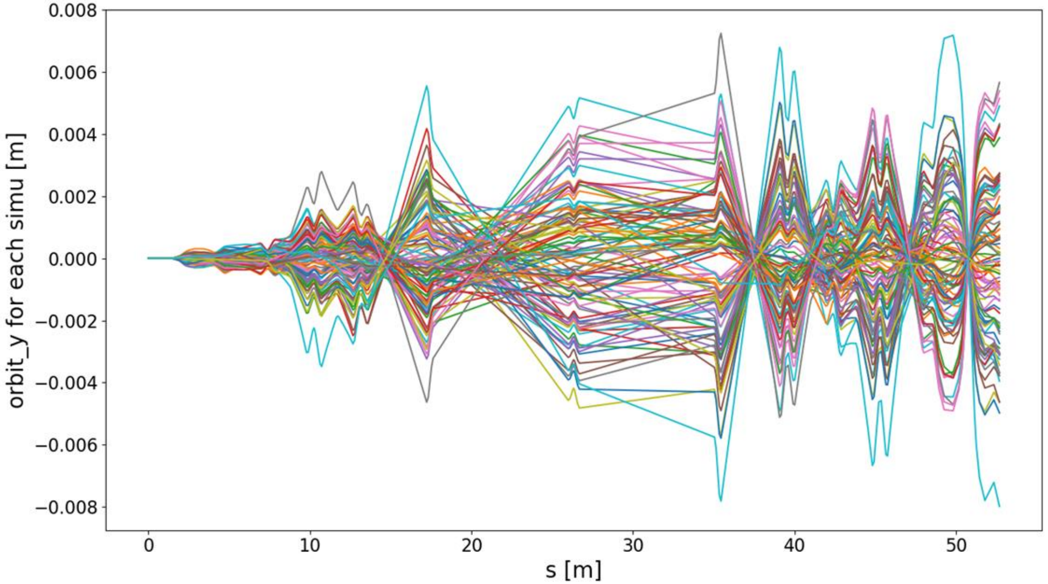


The effect on dispersion is built up in the straight section





The beta function is not affected by misalignment



The misalignment affects mostly the particle orbit in both planes.
The effect is seen on the position and also on the momentum x’, y’

Lattice Correction: Ongoing Study

- Kicker magnets are the orbit corrector elements in BMAD
- The kick value is the momentum change $\delta P = \frac{\delta p}{p_0}$
- Positive kick increases p_x, p_y

Correctors Optimization Procedure:

I. Add 2 kickers near the points of interest (with zero kick)

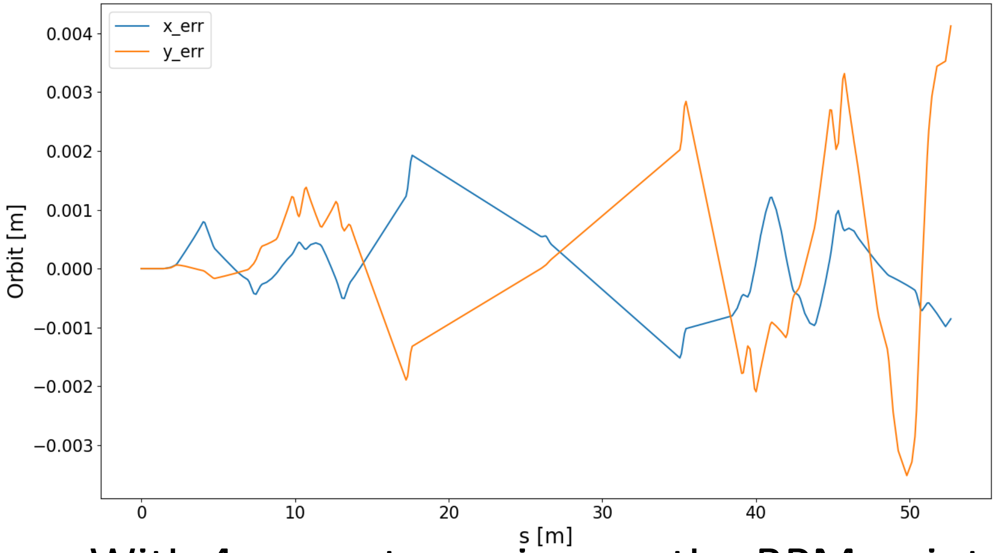
II. Introduce offsets to the Quadrupoles

III. Define the lattice requirements (zero particle orbit)

IV. Define the variable to be optimized (the kick value)

V. Run the optimizer to correct the orbit

Horizontal & Vertical misalignments in all quads



With 4 corrector-pair near the BPM points