FCC

BOOSTER OPTICS

A. Chance, B. Dalena, T. Da Silva, Q. Bruant (CEA), A Ghribi (CNRS)
A. Mashal (IPM), M. Migliorati (UniRoma), A. Rajabi (DESY)
T. Raubenheimer (SLAC), F. Zimmermann (CERN)

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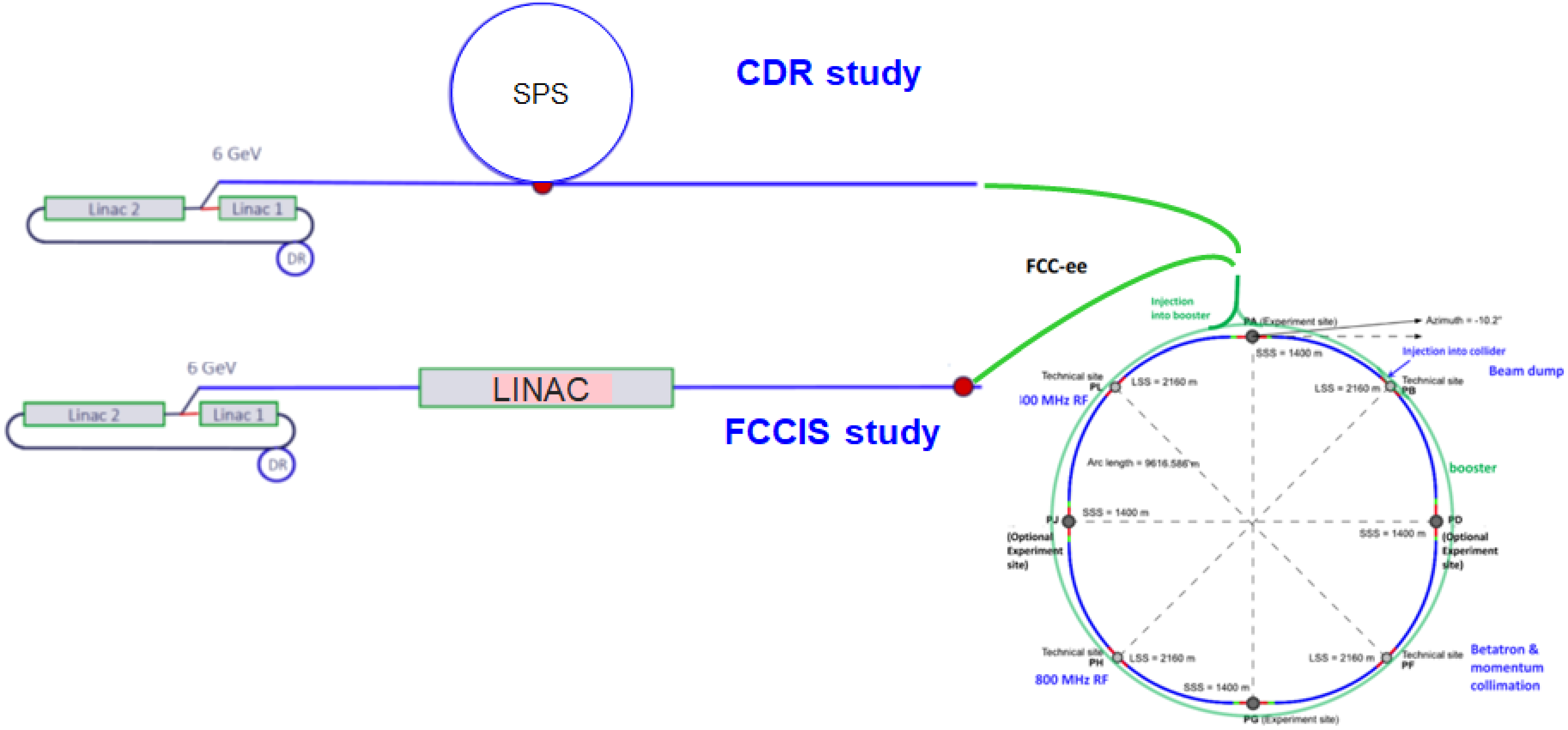
Injector complex

Injection energy into the booster 20 GeV (or lower ?)

Ramping: 80-100 GeV / s (< 1 s)

Alternatives: SPS as Pre Booster Ring (PRB) and a Linac



Booster parameter table (mid-term report)

Running mode		Z	W	ZH	$t\bar{t}$
Injection option		LINAC/SPS			
Circumference	[km]	91.174			
Injection energy	[GeV]	20/16			
Extraction energy	[GeV]	45.6	80	120	182.5
Number bunches / ring		11200	1780	440	60
Maximum particle number / bunch Nmax	[10^{10}]	$\geq$ 2.5 (4 nC)			
Particles / bunch in top-up	[10^{10}]	2.14	0.87	0.69	0.93
RF frequency	[MHZ]	800			
Arc optics FODO		60°/60°		90°/90°	
Momentum compaction		14.9×10^{-6}		7.34×10^{-6}	
Coupling		2×10^{-3}			
Injection horizontal emittance (norm.)	[µm]	10/190			
Injection vertical emittance (norm.)	[µm]	10/4			
Extraction horizontal equilibrium emittance (RMS)	[nm]	0.26	0.81	0.63	1.45
Extraction vertical equilibrium emittance (RMS)	[pm]	0.53	1.62	1.25	2.90

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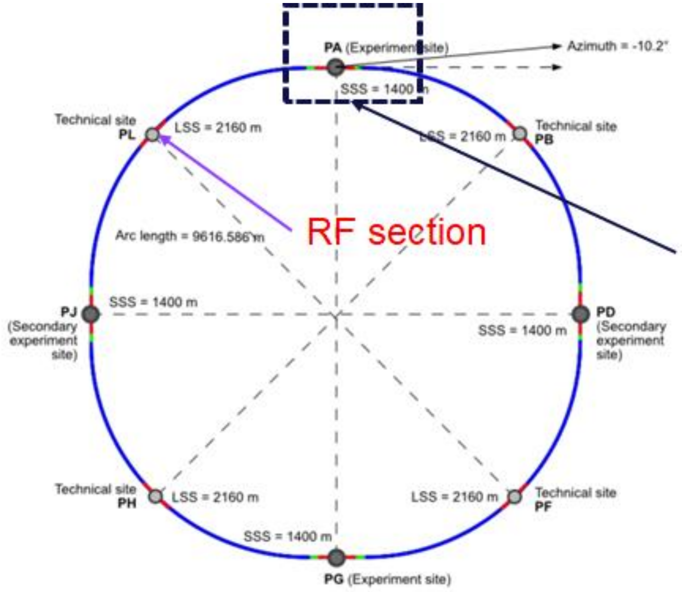
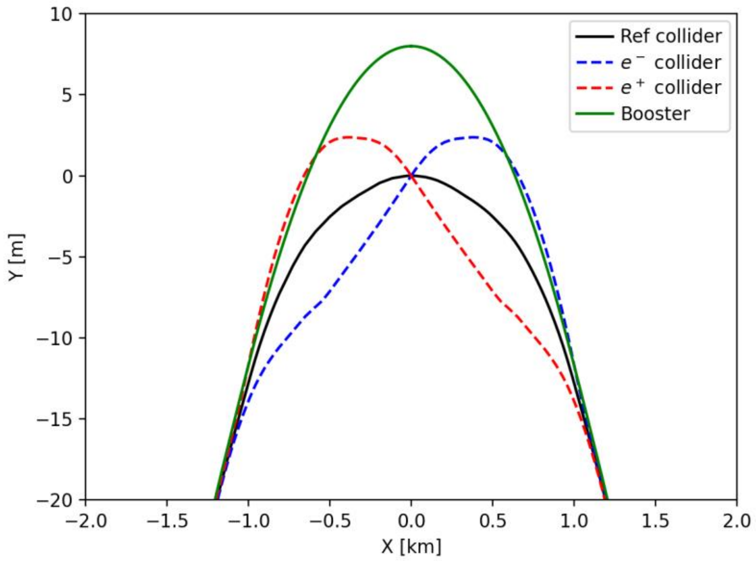
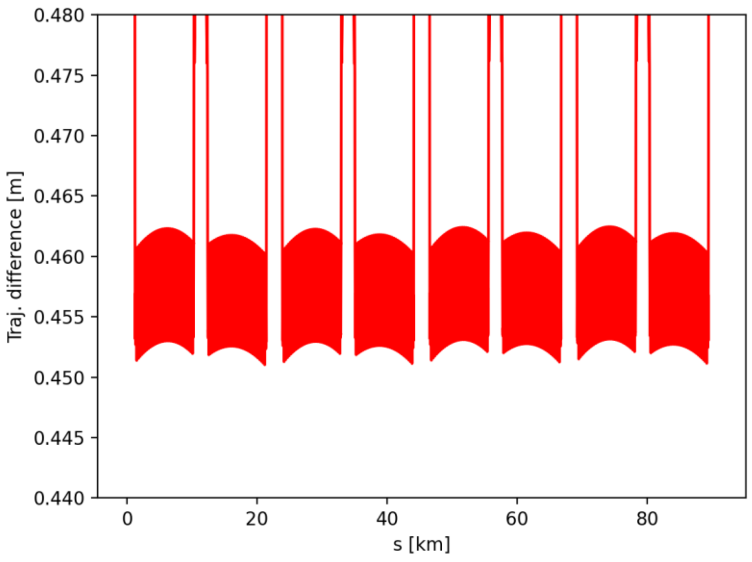
Injection Energy loss / turn	[MeV]	1.514/0.6203			
Extraction Energy loss / turn	[MeV]	40.93	387.7	1963	10500
Injection bunch length	[mm]	4/5.5			
Extraction bunch length	[mm]	4.38	3.55	3.34	1.94
Injection RMS energy spread	[10^{-3}]	1/4			
Extraction RMS energy spread	[10^{-3}]	0.38	0.67	1.01	1.53
Injection Maximum relative energy acceptance	[%]	3			
Extraction Maximum relative energy acceptance	[%]	0.36	0.76	0.49	2.39
Injection RF voltage	[MV]	104.9/82.97		52.85/41.36	
Extraction RF voltage	[MV]	49.48	458.6	2015	11533
Filling time	[s]	28/31.5	8.9/9.6	4.4/4.75	0.6/0.95
Ramp time	[s]	0.32/0.37	0.75/0.8	1.25/1.3	2.03/2.08
Flat top	[s]	1.9	0	0	0
Total cycling time	[s]	30.54/ 34.14	10.4/11.2	6.9/7.35	4.66/5.11

Layout status





- 800 MHz cavities are located in section L.
- The booster is in the outer side of the collider with an offset at the IP of 8 m.
- The total circumference of the booster has been adjusted according to the new tunnel geometry:
  - Collider circumference: 906**58**.7453185 m.
  - Booster circumference: 906**62**.4927239 m
  - **The booster is 3.747 m=10 λ_{RF} longer than the collider.**
- The booster has a transverse shift of 0.456 m +/- 5 mm.



Optics updates

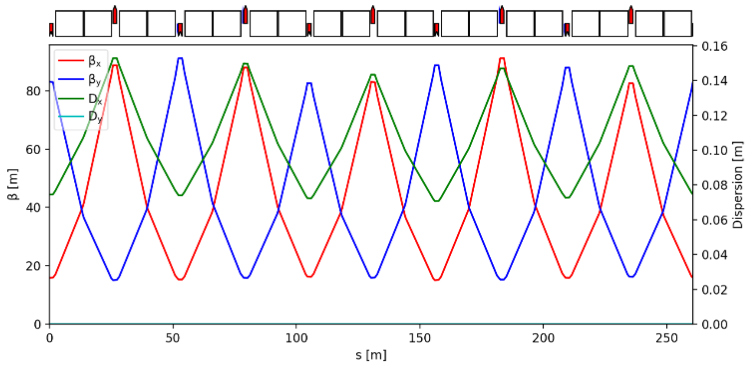
Magnet	Parameter	Unit	Value
Dipole	Min./Max. field	G	64/593
	Length	m	11.1
Quadrupole	Min./Max. gradient	T/m	2.5/23
	Length	m	1.5
Sextupole	Min./Max. gradient	T/m^2	304/2816
	Length	m	0.5

=> Very challenging low dipole field at injection

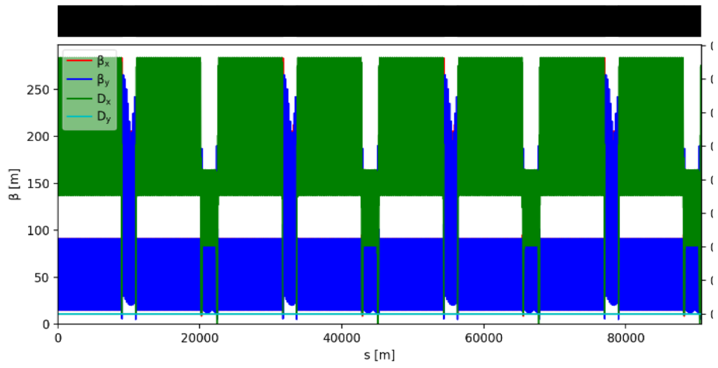
- Group of 5 FODO cells of ~52 m each.
- New tuning procedure to go into the direction of non-interleaved sextupoles:
  - Phase advance of π between 2 sextupoles of one pair.
  - The tune of the arcs is adjusted to get the target tune.
  - All insertions have a phase advance of $(2N)\pi$.
  - The insertions are adjusted to match the Montague functions and second order dispersions (use of an additional sextupole in the dispersion suppressor).
- Needs of 6 quadrupole families.

- Tune Q_x/Q_y: 412.225/416.29
- Momentum compaction: 7.109e-06
- I5: 1.61e-11

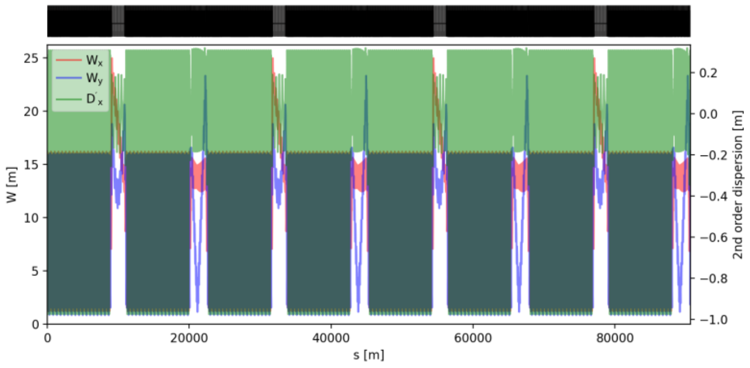
Arc cell: betatron function and dispersion



Optical functions



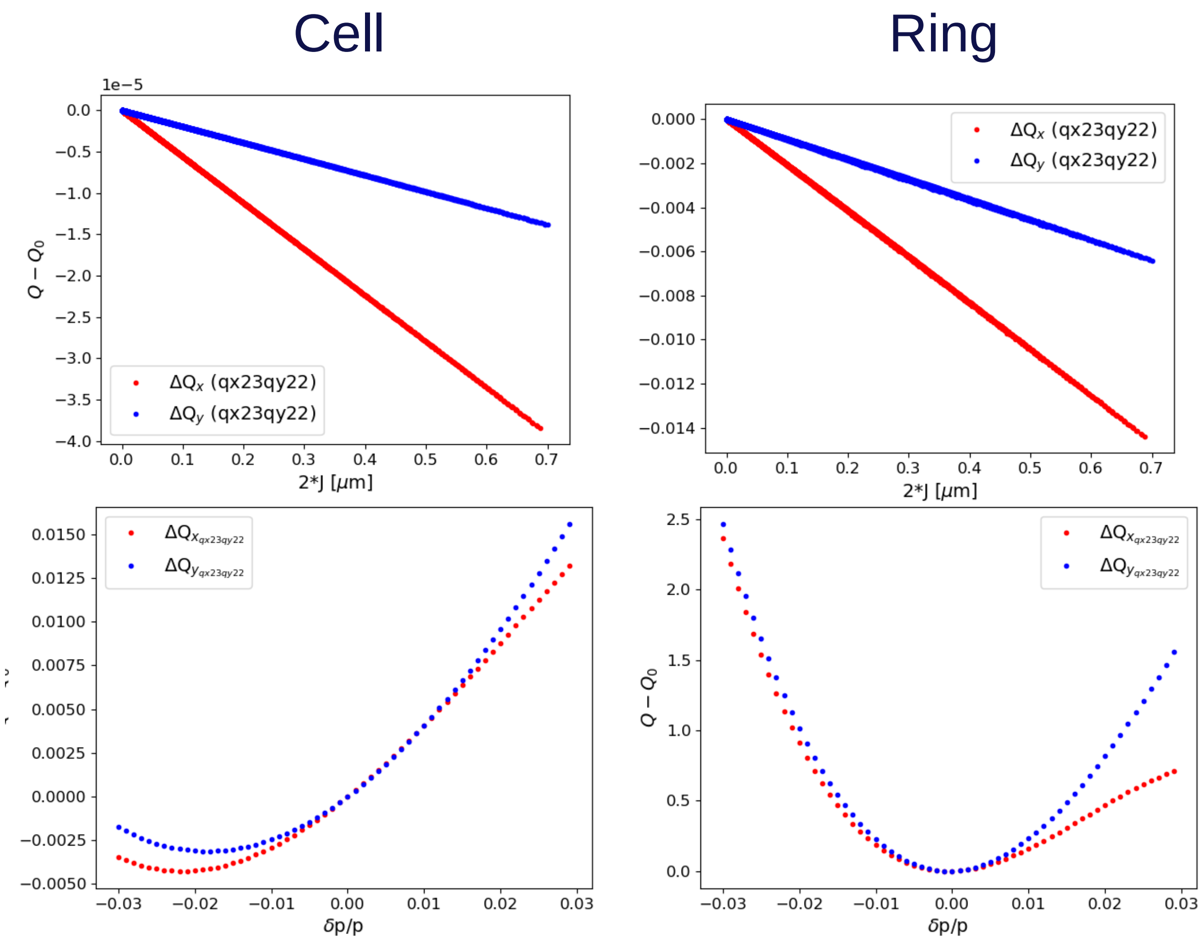
Montague functions Sextupole ON



Motivations for the HFD lattice in the booster

- RMS energy dispersion at linac end a few 0.1%
  → We need a momentum acceptance of more than 1%.
- Second-order chromaticity is driving the momentum acceptance.
- Currently, the momentum acceptance still below 1% with FODO lattice (especially when RF cavities are included).
- To go to higher momentum compaction, we need:
  - 2 optics (60° at Z/W and 90° at HH/ttbar modes)
    - More sextupoles + more quadrupole families
  - Create a dispersion wave to increase the momentum compaction. The price is to modify the high-order chromaticity and to increase the beam size.

Can we improve with HFD optics?



Status HFD optics algorithm for booster

A python script has been written to automatize the cell optimization.

- Knobs: 6 quadrupole strengths and ratio between the dipole lengths
- Sextupole strength calculated to get the target chromaticity
- Constraints:
  - Maximum betatron functions,
  - I5 below an upper boundary,
  - Momentum compaction above a minimum,
  - High-order chromaticity (up to 4th order)
  - Anharmonicity (up to 2nd derivative)
  - Cell tune can be an optional constraint

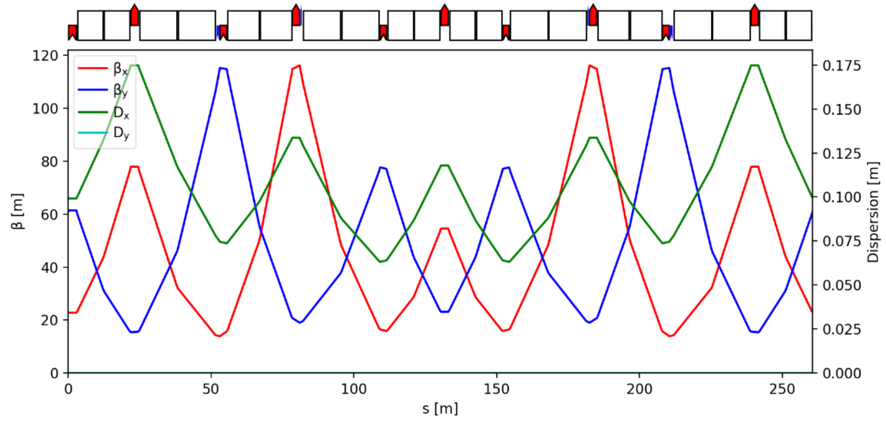
Genetic optimization: optimization takes about one hour.

HFD updates

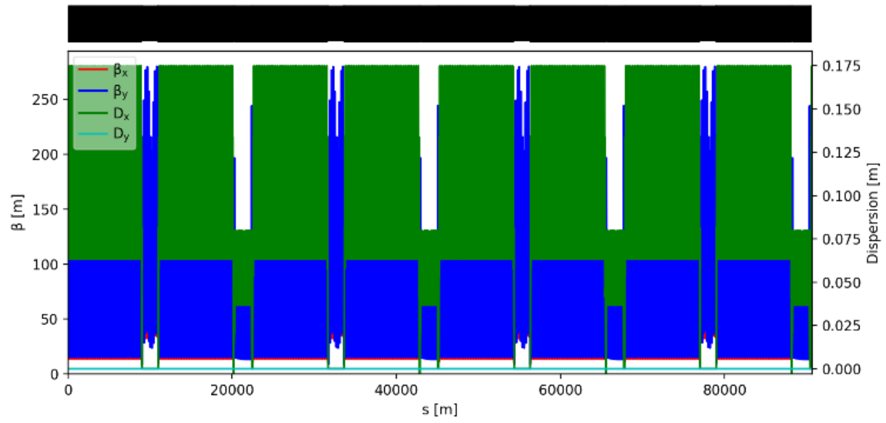
- HFD lattice with a relative dipole length variation of 19%.
- New tuning procedure:
  - Optimum sextupole phase difference (near π).
  - The tune of the arcs is adjusted to get the target tune.
  - All insertions have a phase advance of $(2N)\pi$.
  - The insertions are adjusted to match the Montague functions and second order dispersions (use of an additional sextupole in the dispersion suppressor).
  - **We find an optics very similar to the one of P. Raimondi.**

- Tune Q_x/Q_y: **413**.225/**381**.29
- Momentum compaction: 7.129e-06 (difference of only 0.3% with the FODO one).
- I5: 1.77e-11 (1.1 times the one of FODO)

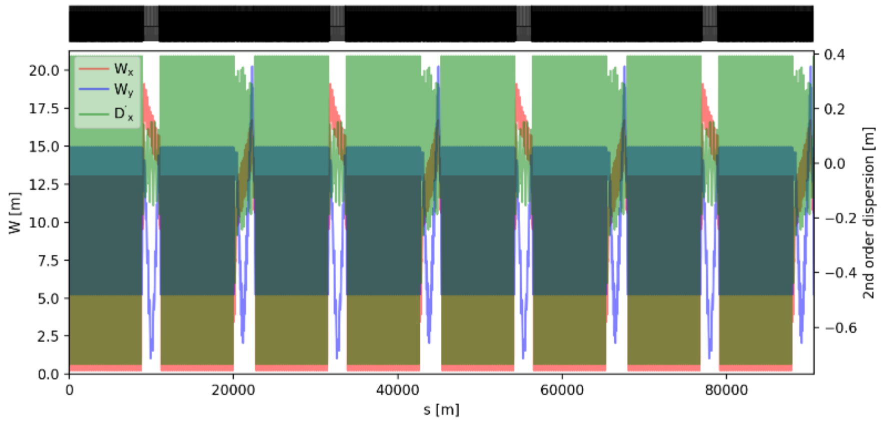
Arc cell: betatron function and dispersion



Optical functions



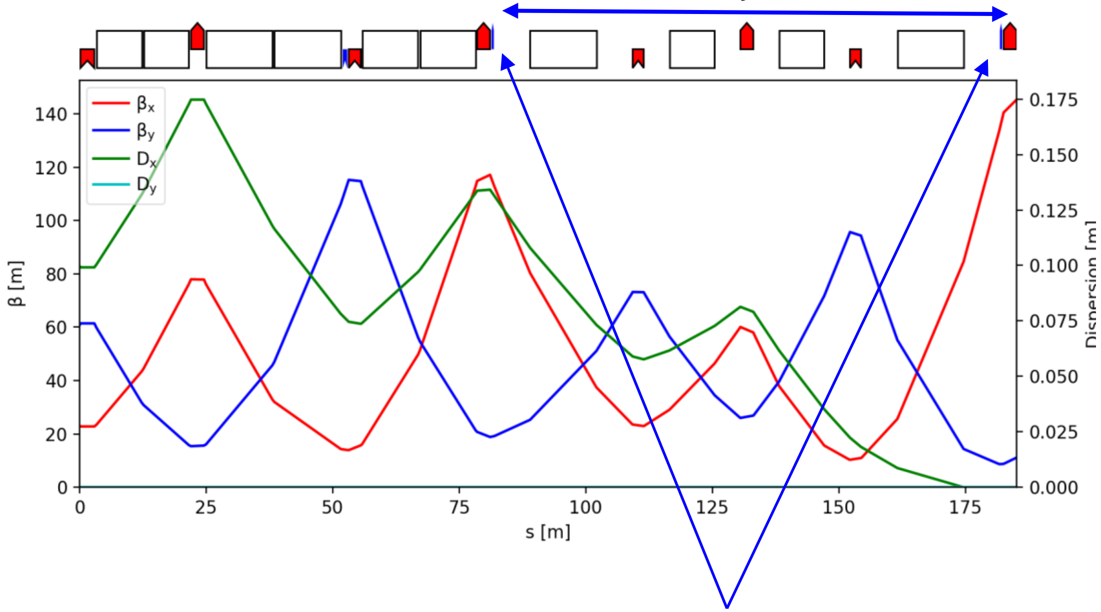
Montague functions Sextupole ON



Transparency + dispersion suppressor

Dispersion suppressor

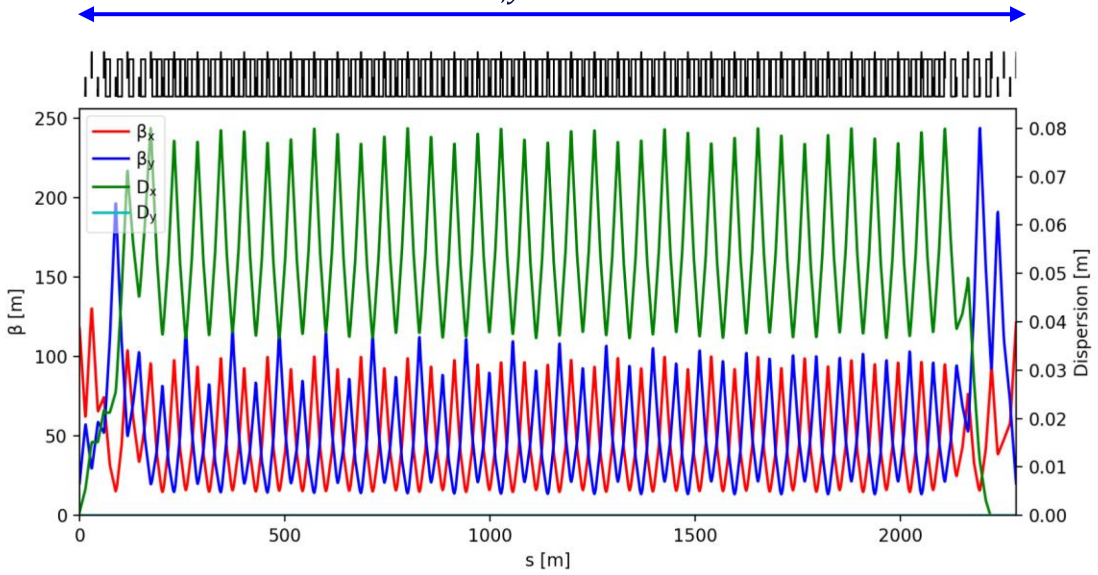
$\Delta\mu_{x,y} \approx \pi$



Sextupole pair used to correct 2nd order chromaticity

Insertion 1

$\Delta\mu_{x,y} = 2\,n\,\pi$



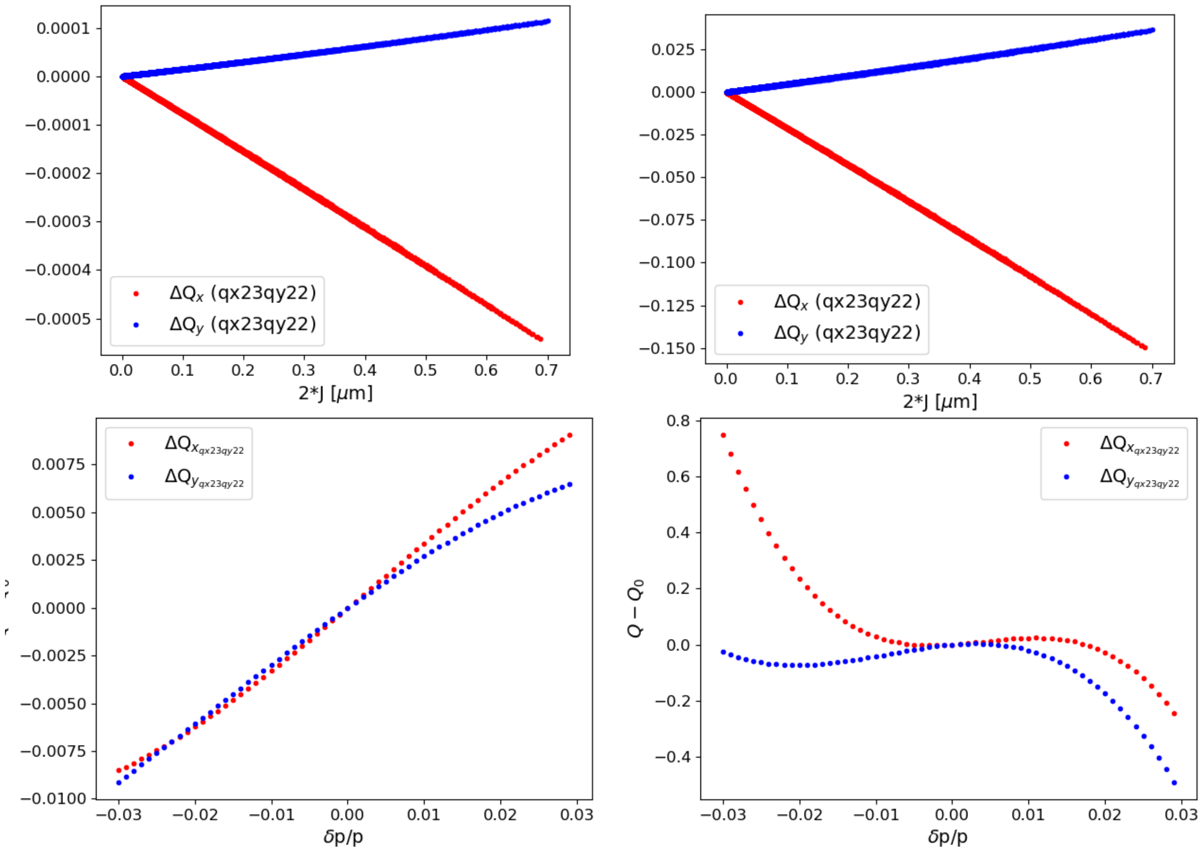
Matching quadrupoles are used to match the Montague functions between the arcs

HFD lattice Anharmonicity and chromaticity

In comparison with FODO lattice, the HFD has a larger anharmonicity (but the sextupoles have a different length).

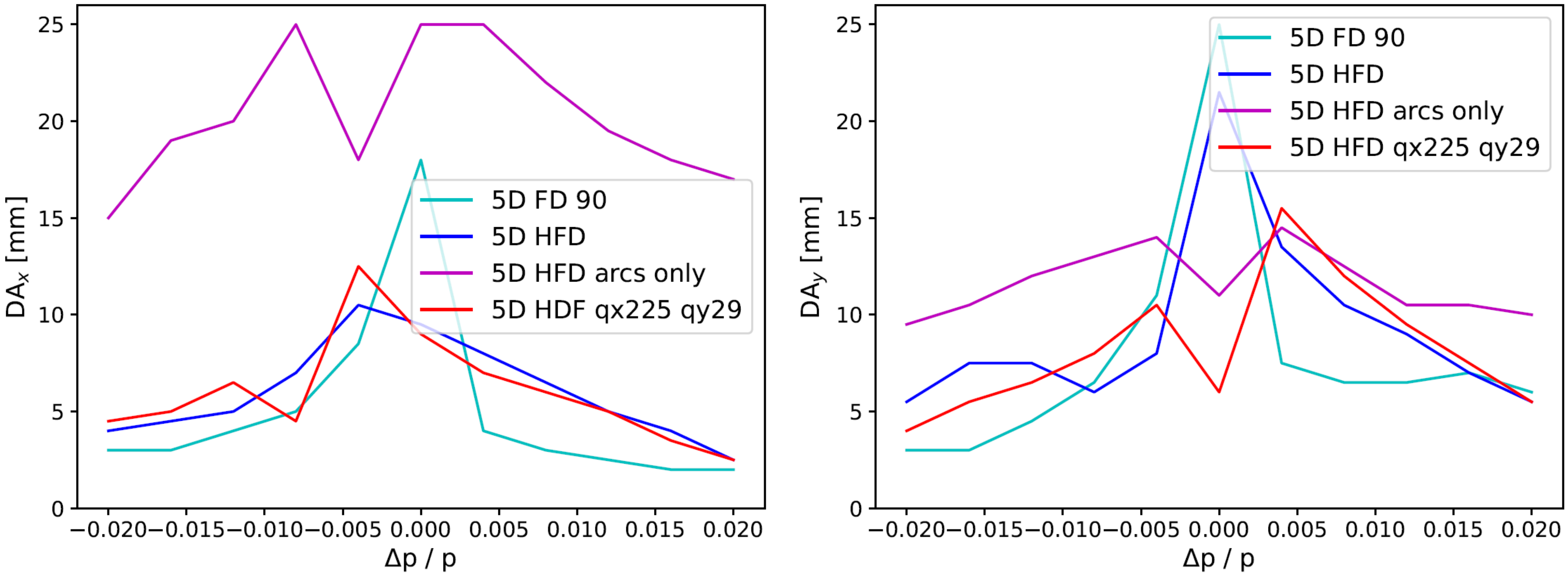
However, we have a better tune variation with momentum: we are driven by the third order chromaticity (whereas the FODO lattice is driven by second order chromaticity).

Cell Ring



HFD and FODO Dynamic aperture

Courtesy: B. Dalena



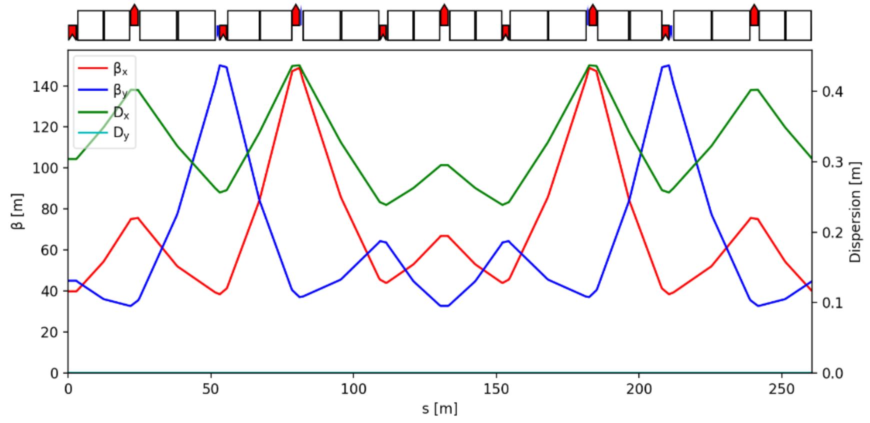
The HFD has a better momentum acceptance as the FODO one.

The insertions have a big impact on the dynamic aperture.

Needs for more investigation.

HFD cells with larger momentum compaction

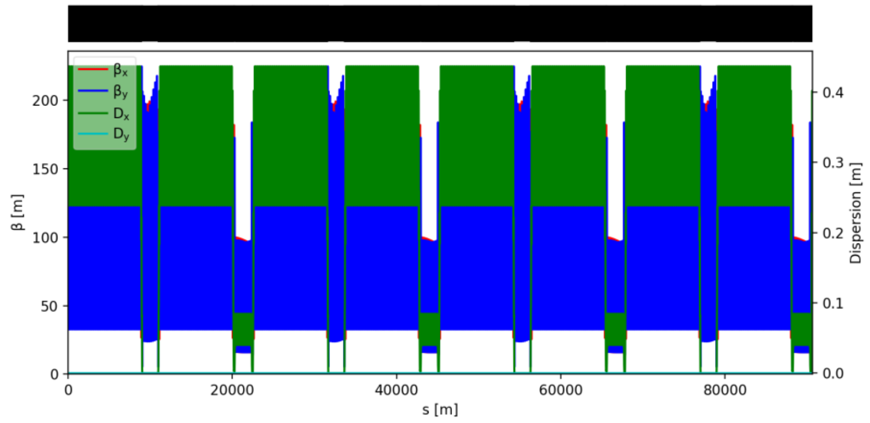
Arc cell: betatron function and dispersion



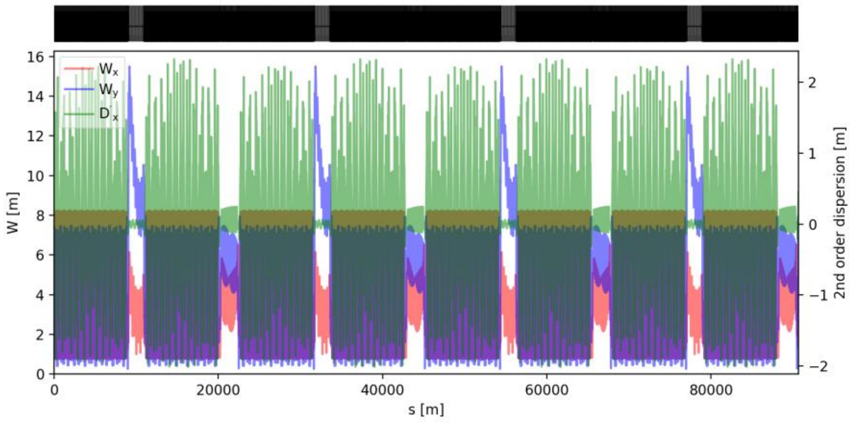
- With the algorithm, we have found another configuration giving a momentum compaction 3 time larger.
  - **Interest for the Z/W operation because that mitigates TMCI instabilities.**

- Tune Q_x/Q_y: **253**.225/**287**.29
- Momentum compaction: 21.27e-06 (3 times the one of FODO)
- I5: **9.36**e-11 (5.8 times the one of FODO)

Optical functions



Montague functions Sextupole ON

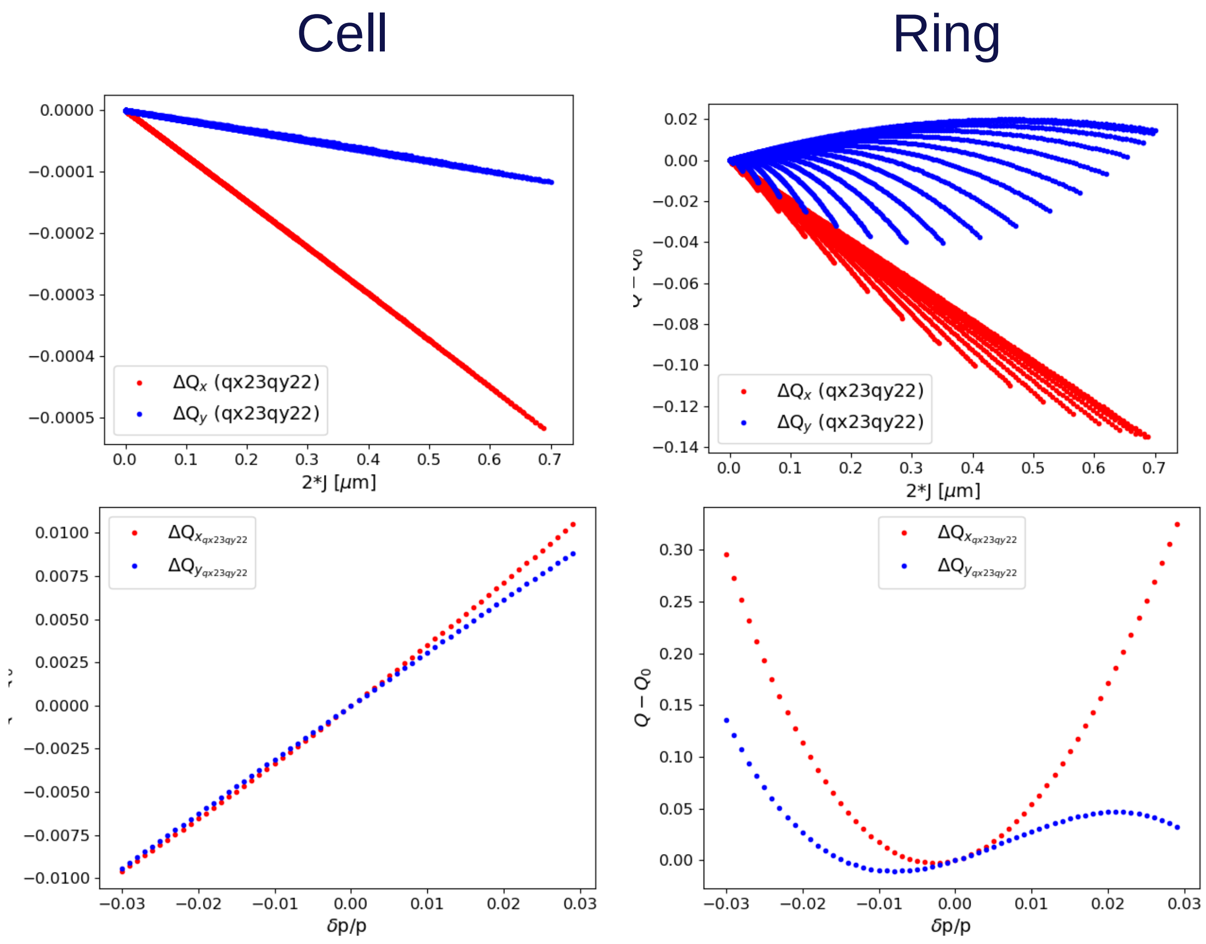


HFD lattice Anharmonicity and chromaticity

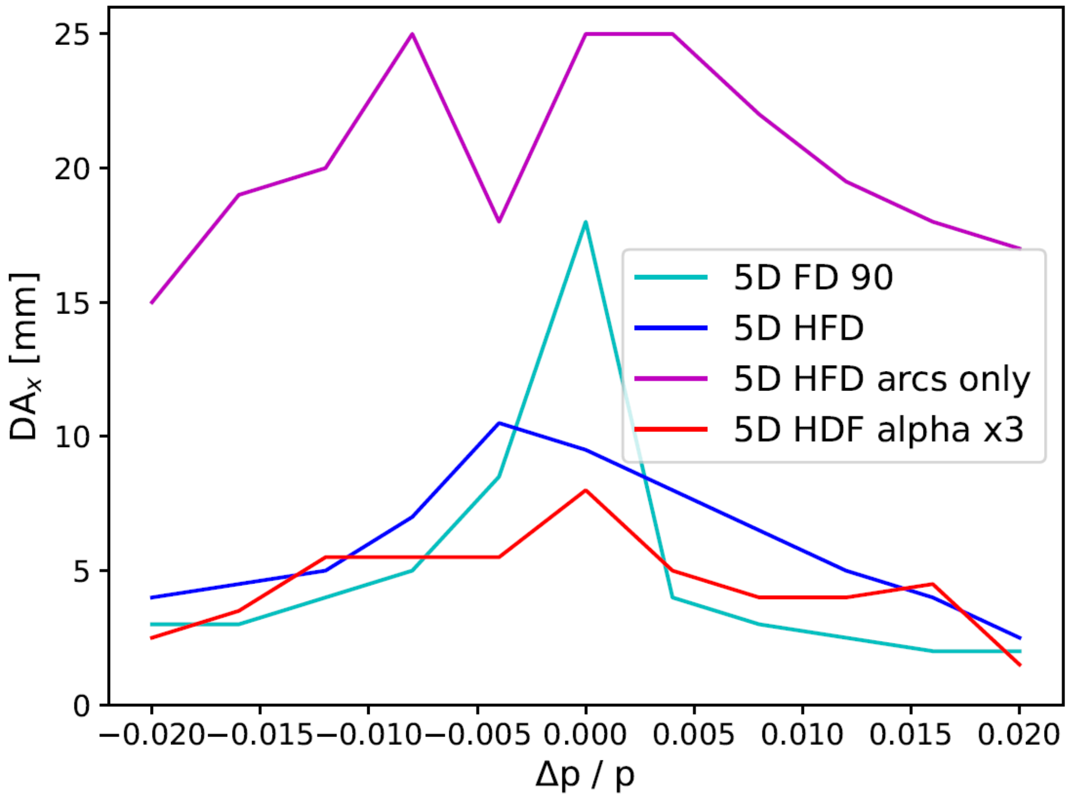
The impact of the insertions is not negligible here.

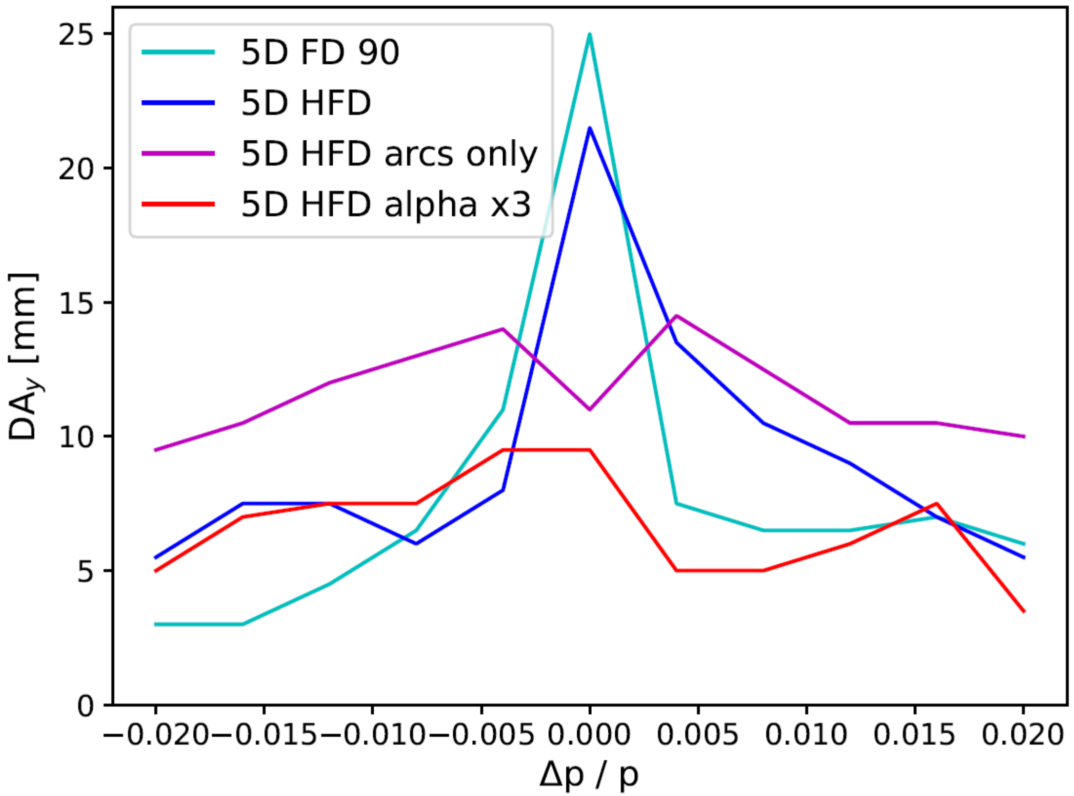
The dispersion suppressors are not optimum here because of the significant change of the arc cell tune.

We need more investigation to understand why the second order anharmonicity becomes strong with this optics.



HFD alpha x 3 and FODO Dynamic aperture





As expected, the degraded anharmonicity due to the insertions implies a strong synamic aperture reduction. Needs for more investigation.

Hardware Booster Arcs
Value per octant

Dipoles	Unit	FODO 90deg	HFD	HFD α_px3
Total angle	rad	0.745	0.745	0.745
Total length	m	7770	7700	7700
Total number	-	700	700	700
Quadrupoles				
Integrated norm. Gradient	m^{-1}	19.6	19.5	12.1
Total length	m	531	877.24	877.24
Total number	-	355	355	355
Sextupoles				
Integrated norm. Gradient	m^{-2}	241.4	179.0	30.90
Total length	m	71	91.736	91.736
Total number	-	142	142	142

Optics summary

- A genetic algorithm has been applied to tune the arcs cells.
- The HFD optics has been compared to the FODO lattice.
  - The momentum acceptance has been enlarged.
  - The insertions have an impact on the dynamic aperture and the transparency condition needs to be investigated deeper.
  - We can find also a lattice with the same pattern as the main HFD optics but with a 3 times larger momentum compaction and a 6 times larger I5, compatible with Z/W operations.
  - But the insertion matching needs more investigation: currently the 2nd order anharmonicity is driving the DA.

We could add sextupoles in the insertions to reduce again the sextupole gradient.

Errors

Courtesy: B. Dalena

old w/o girders

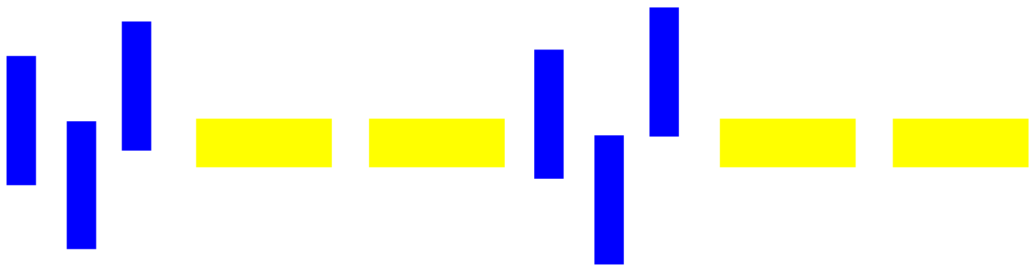
Error type	σ value
Dipole relative field error	$10^{-4}, 10^{-3}$,
Main dipole roll error	300 μrad
Offset quadrupoles (MQ)	150 μm
Offset BPMs	150 μm
Offset sextupoles (MS)	150 μm
BPMs resolution error	50 μm

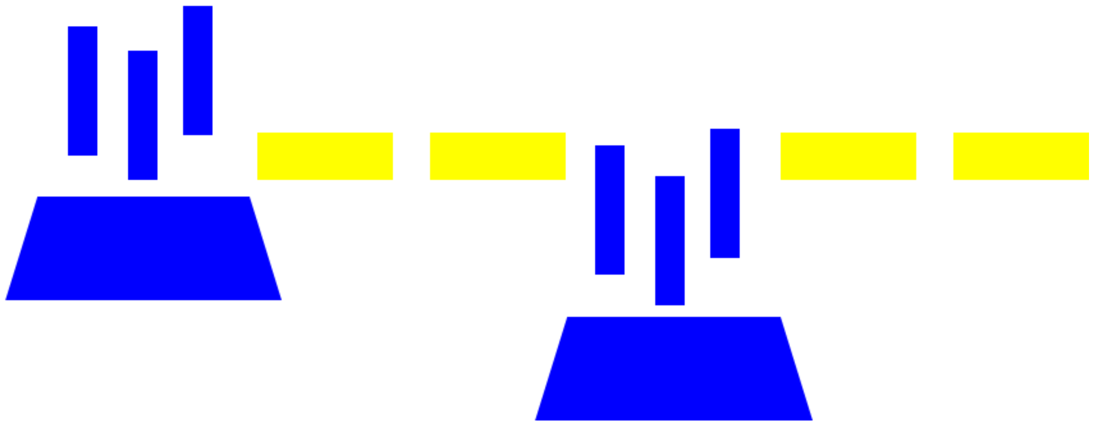
new w girders

Error type	σ value
Dipole relative field error	$10^{-4}, 10^{-3}$,
Main dipole roll error	300 μrad
Offset quadrupoles	200 + 50 μm
Offset BPMs	200 + 50 μm
Offset sextupoles	200 + 50 μm
BPMs resolution error	50 μm

All errors are randomly distributed with ± 3 Gaussian rms.

MS MQ BPM

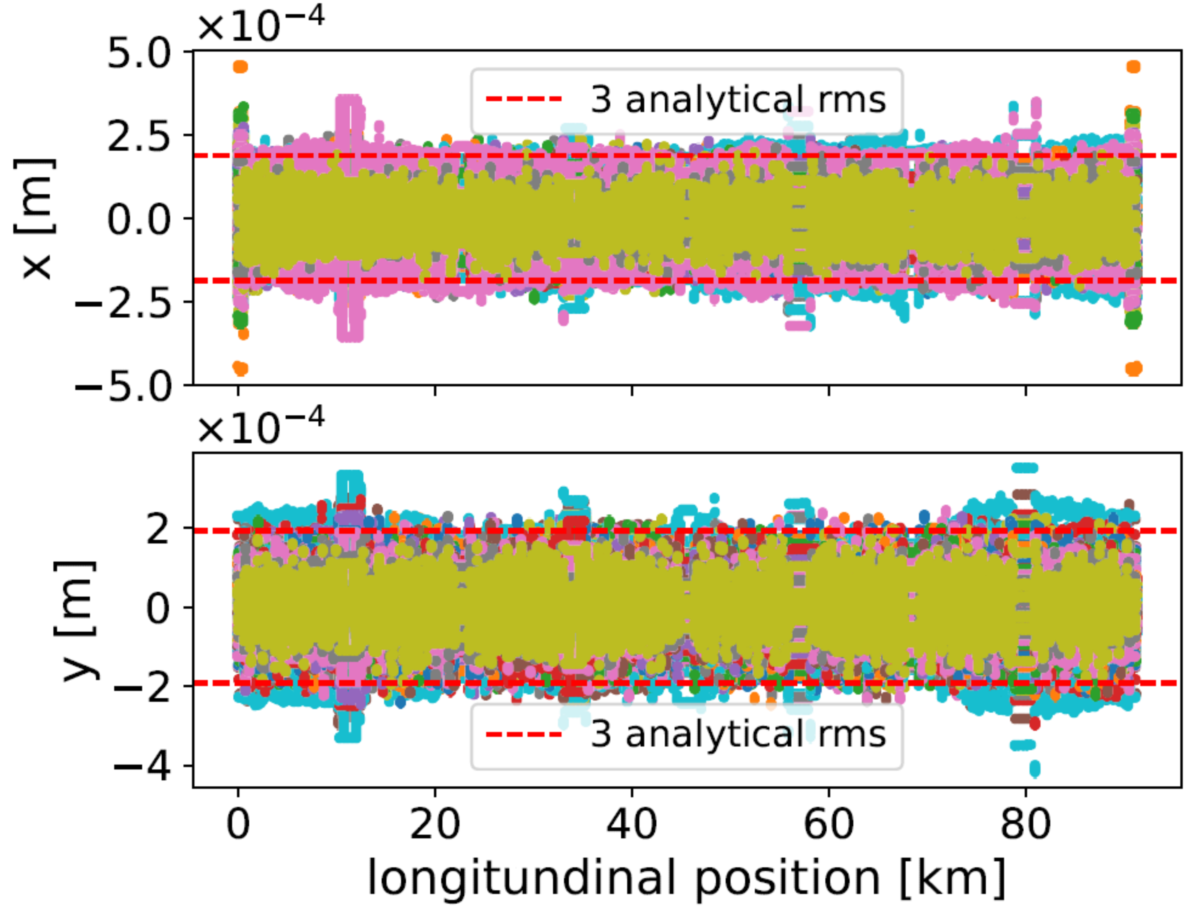




Orbit (FODO 90deg lattice)

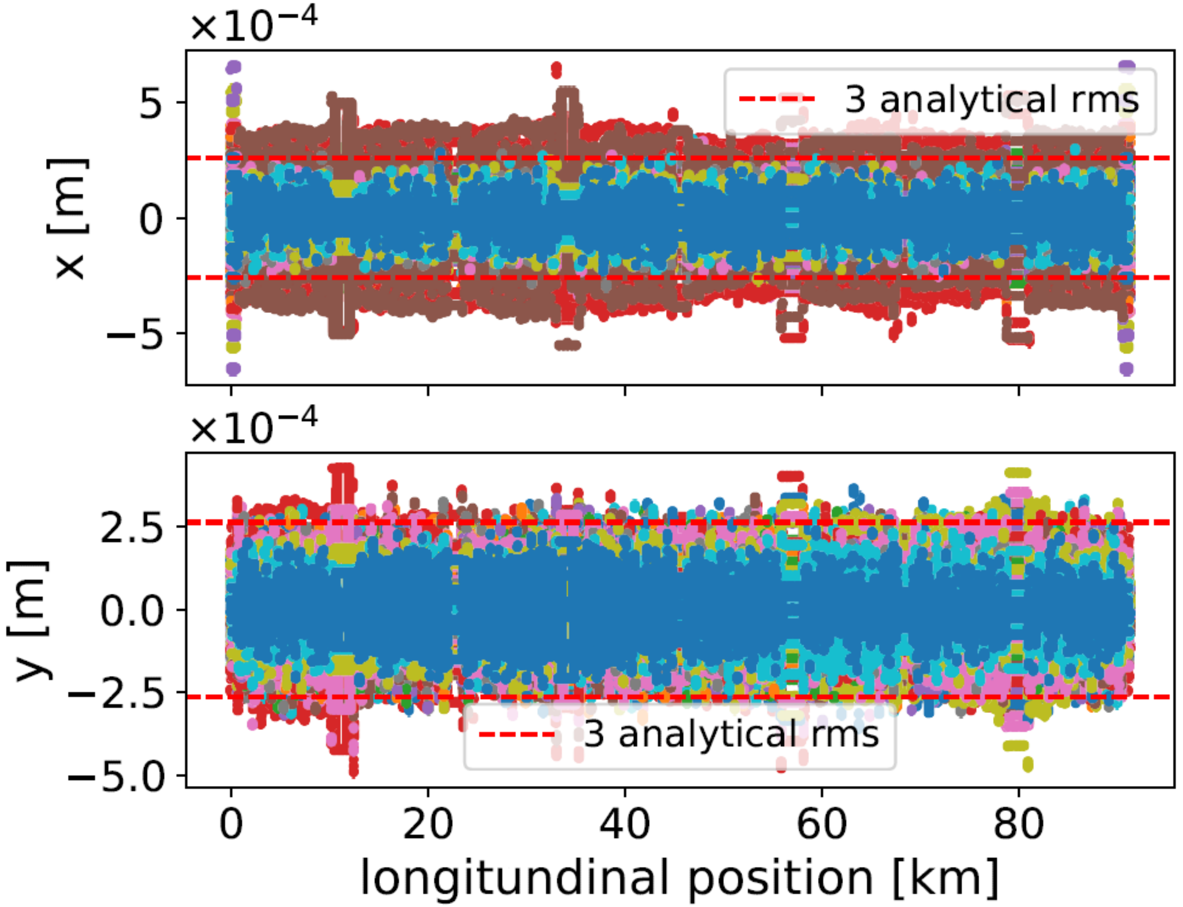
Courtesy: B. Dalena

old w/o girders



99 successful seeds

new w girders

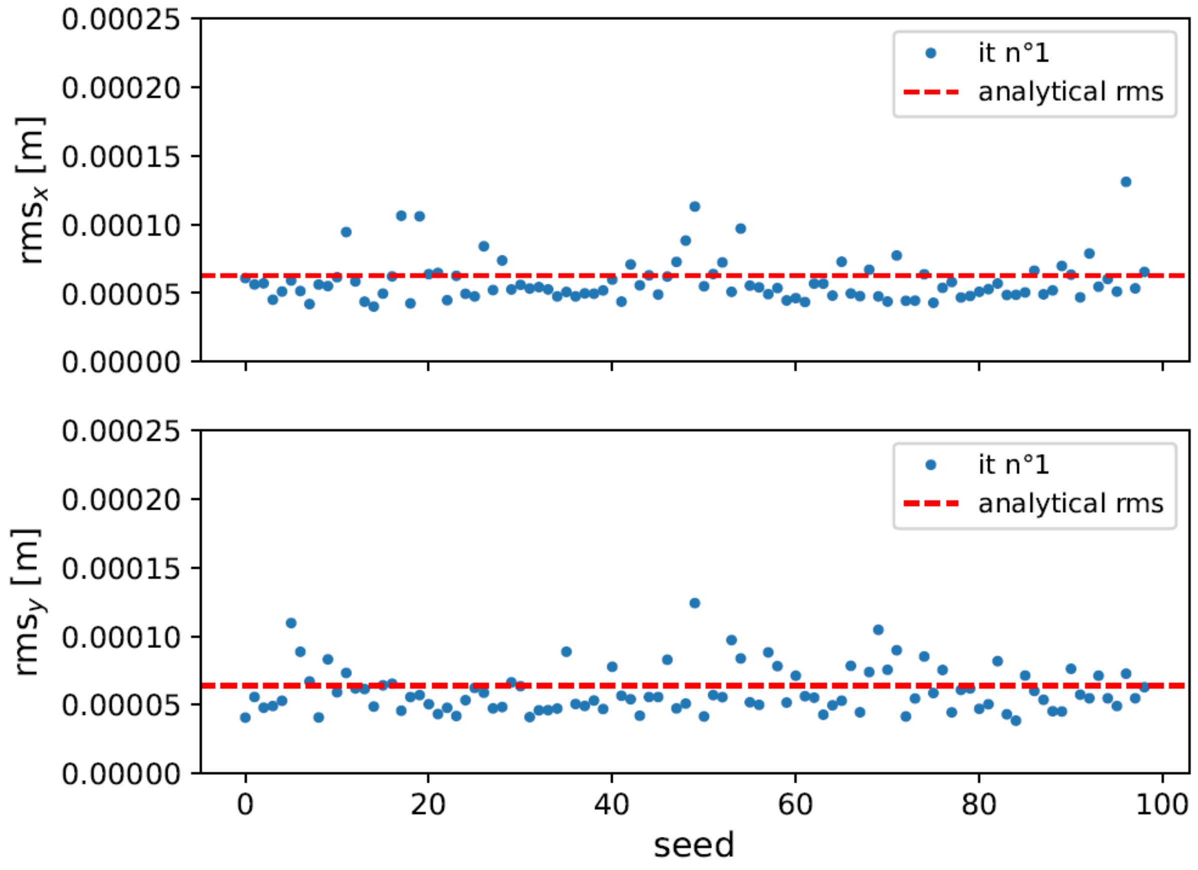


81 successful seeds

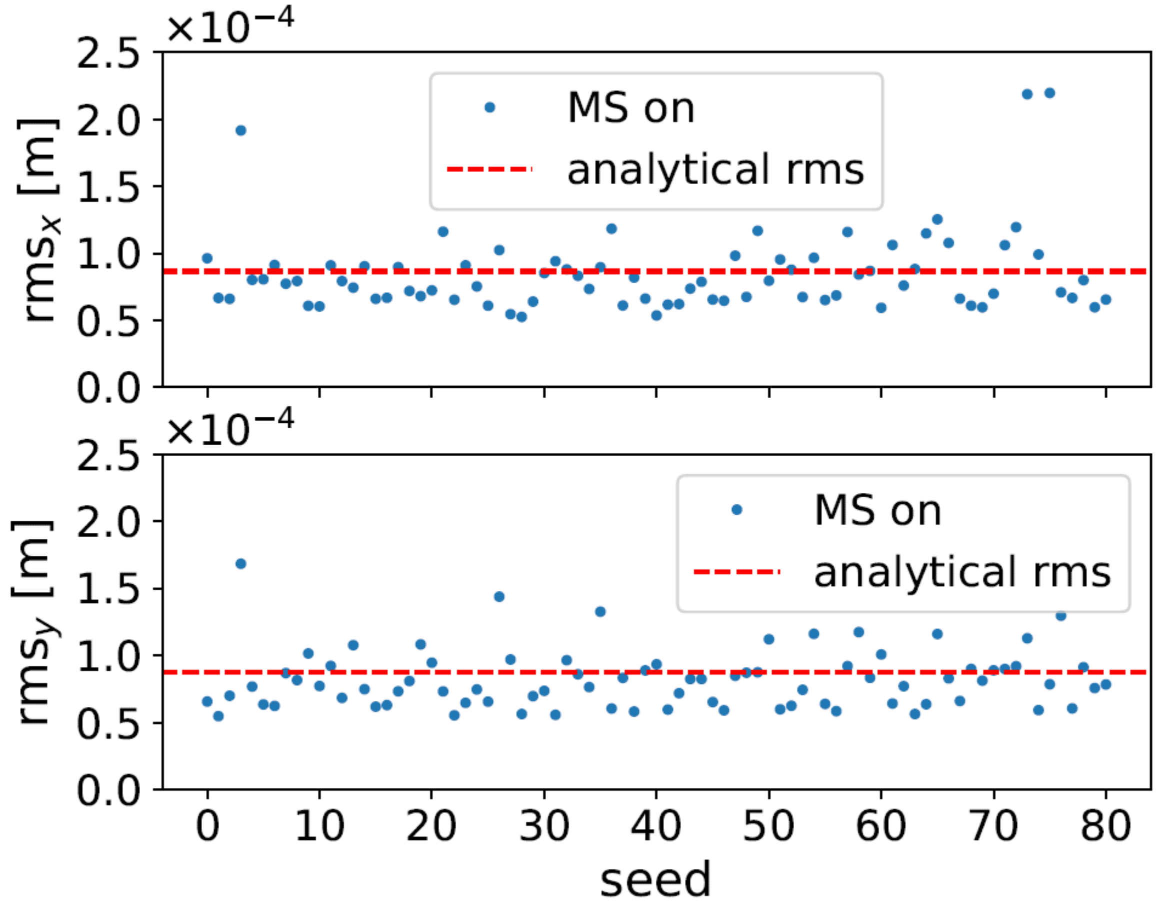
Orbit (RMS)

Courtesy: B. Dalena

old w/o girders



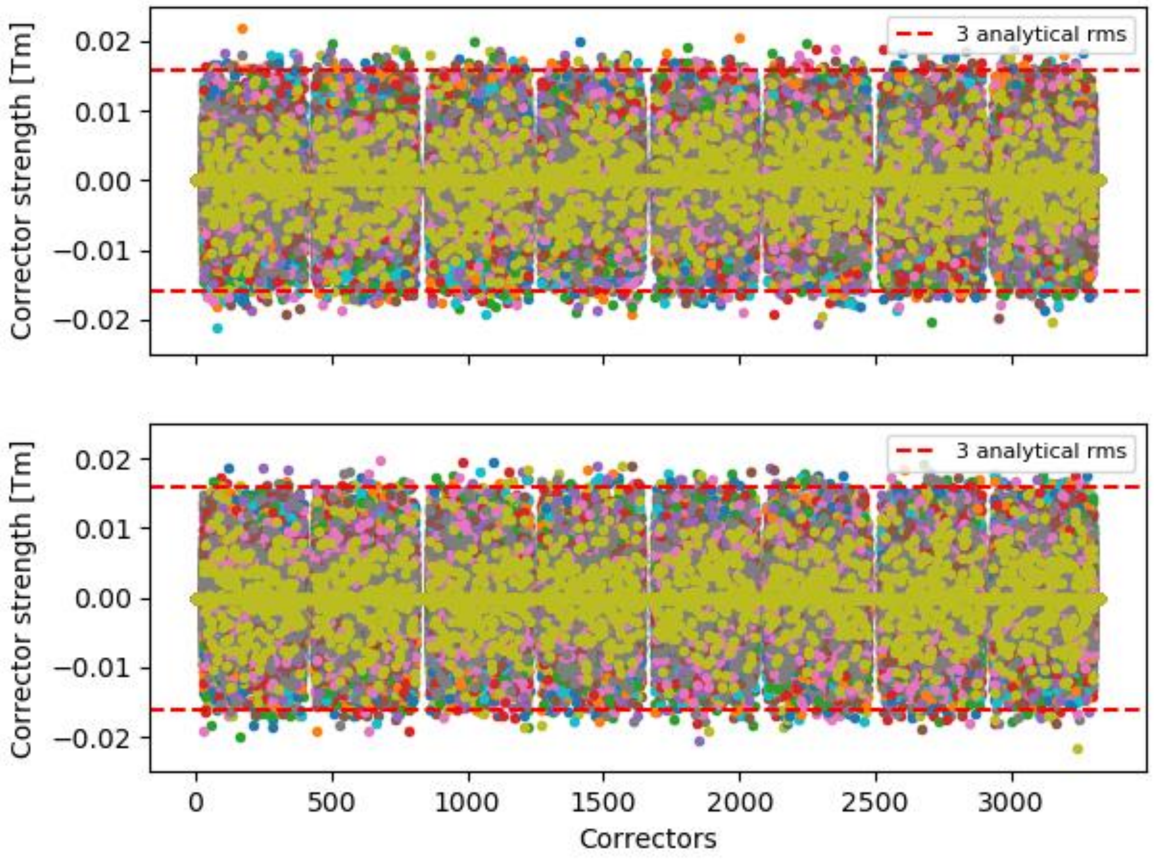
new w girders



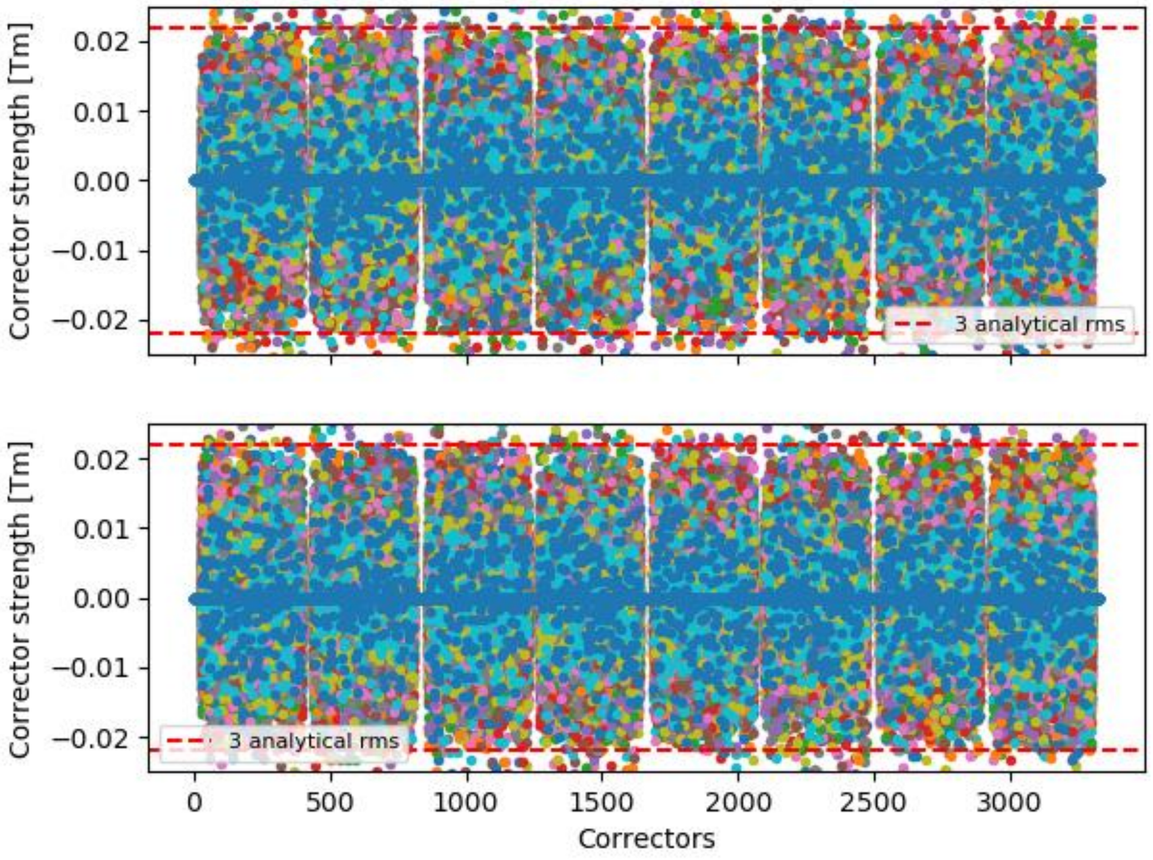
Correctors strength

Courtesy: B. Dalena

old w/o girders



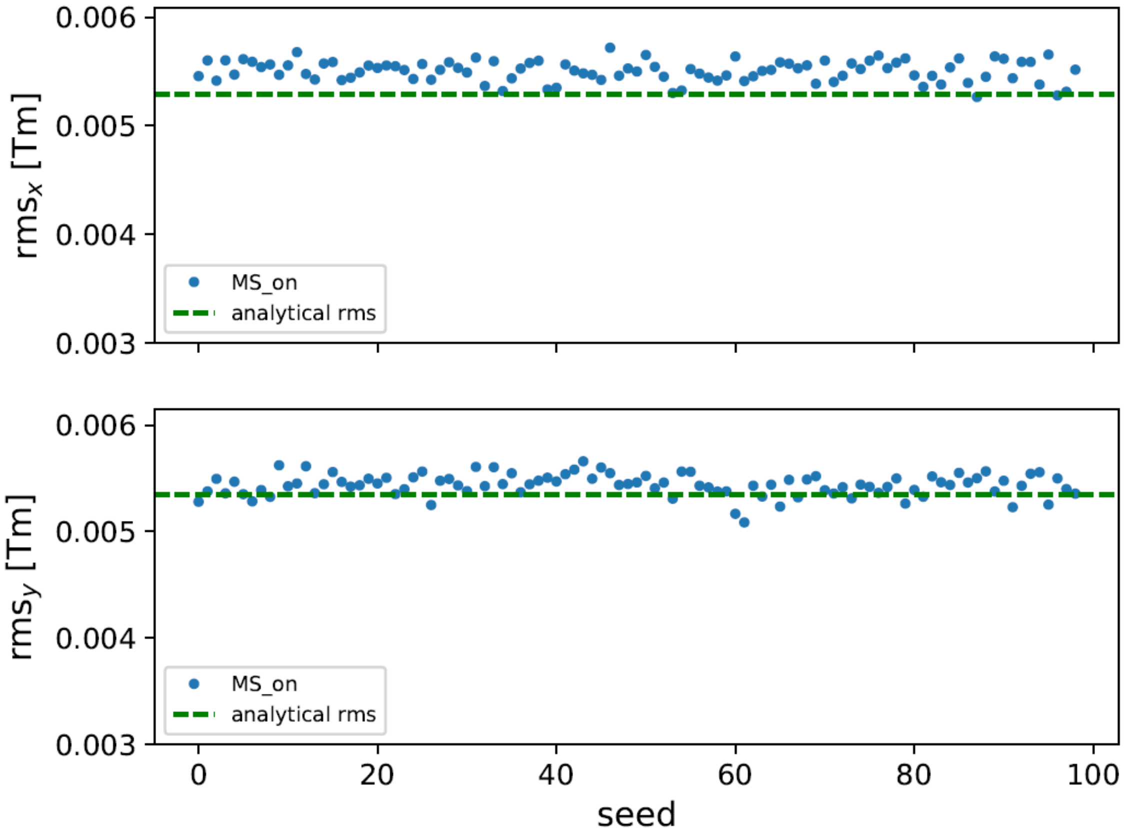
new w girders



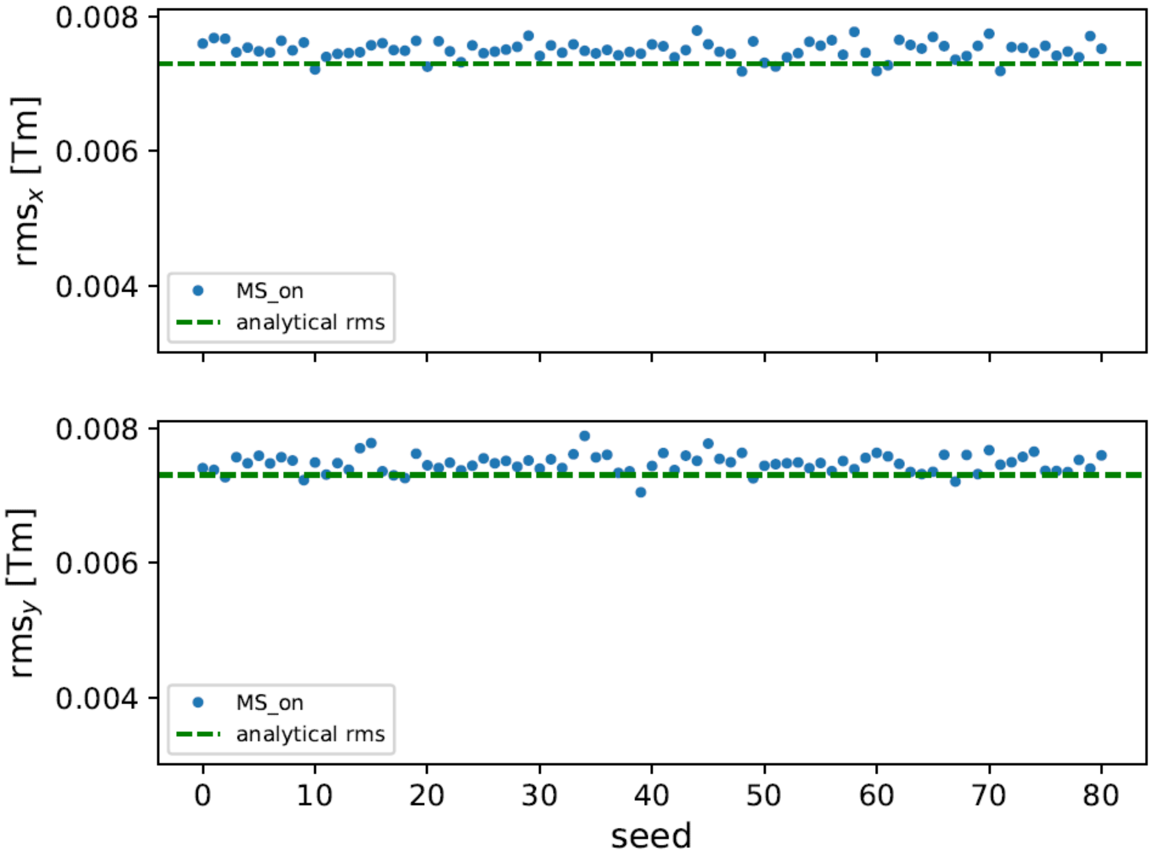
Correctors strength (RMS)

Courtesy: B. Dalena

old w/o girders



new w girders



Conclusion and perspectives

200 μm of girder mis-alignment and 50 μm mis-alignement of the MQ, MS and BPM on top of each girder

- Reduction of the successful seeds 99→ 81 ⇒ need to change strategy
  - More iteration of SVD with sextupole ON with increasing strength
  - Change strategy (BBA, …)

- Orbit correctors strength > 20 mTm

Problems:
- Tune match does not work for all the seeds (63/99 successful)
- Convergence of SVD ⇒ alternative ?
- Quentin Bruant: new PhD Emittance tuning

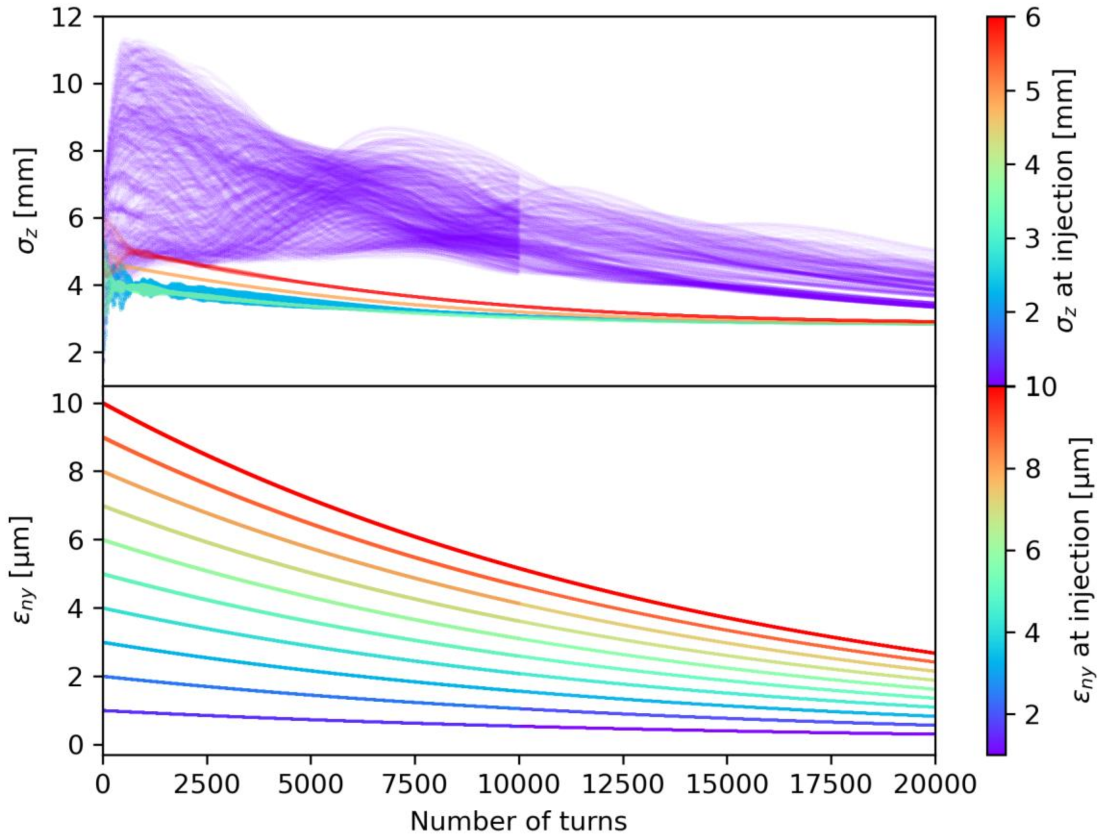
To do:
- Same exercice for the HFD optics
- Correct β-beating, dispersion and coupling (emittance tuning)
- Impact of booster support vibrations on emittance
- Include the impact of energy ramp during the booster cycle
- Tapering

- See "Collective effects in the booster" (A. Ghribi)

Collective effects

- Booster design seems robust to mismatched beams at the injection ;
- TMCI is present at nominal current ;
- Momentum compaction seems to mitigate it if we stay with copper ;
- However moving from copper to stainless steel would require to increase the beam pipe diameter from 50mm to at least 84mm.

Courtesy: A. Ghribi



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Courtesy: A. Ghribi

Collective effects (baseline FODO lattice)

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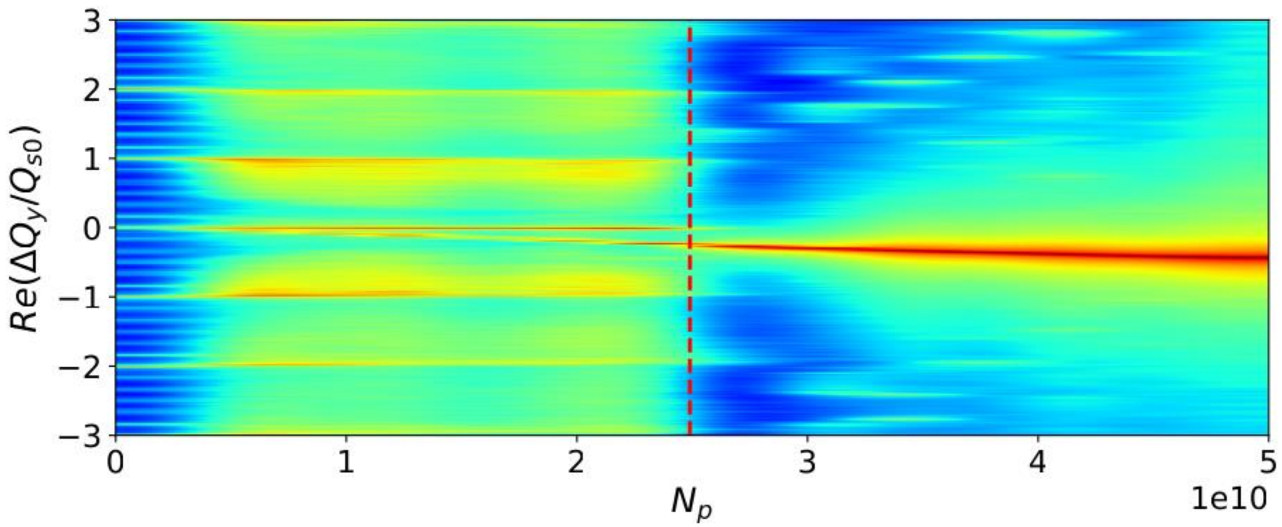

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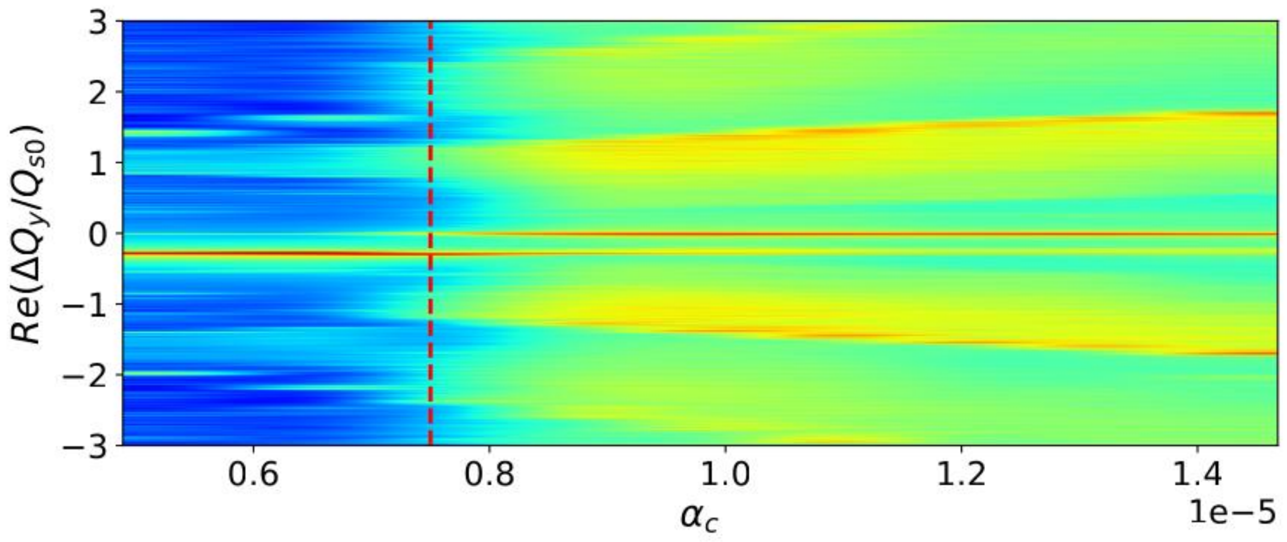

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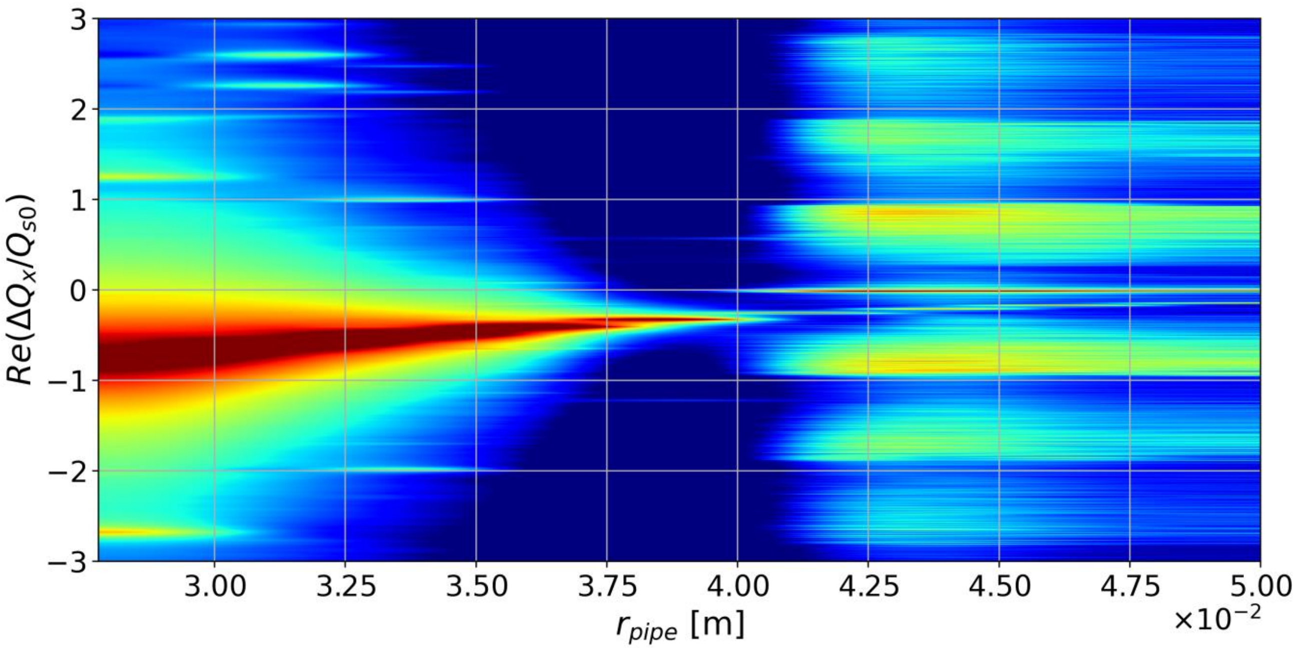


- The change of the beam pipe radius has a big impact.
  - See “Vacuum systems and photoelectron distributions in the booster” (R. Kersevan)
  - See “Which vacuum pressure is acceptable in the booster ?” (L. Mether)
  - See “Booster coupled bunch instabilities and ramp optimisation” (A. L. Vanel)

Impact of external field

- The impact of the detector solenoid on the booster still needs to be evaluated. Not a simple case because:
  - We need to include the fringe field field map from the detector solenoid (the multipole components of the fringe field are different from pure multipole magnets).
  - The booster trajectory is not parallel to the solenoid axis. We need to apply a rotation matrix.
- The Earth magnetic field is not yet studied. However, if we assume a continuous focusing channel and a circular booster. The orbit perturbation can be modelled:
  - $x'' + k^2 x = \frac{B_{earth}}{B\rho} \cos\frac{s}{\rho} \Rightarrow \Delta x = \frac{B_{earth}}{B\rho} \frac{\rho^2}{Q_x^2 - 1} \cos(\frac{s}{\rho} + \phi)$
  - The systematic vertical part of the magnetic field can be corrected by dipole correctors.
  - The perturbation is a few millimeters: not small but should be manageable.
- More investigation is needed to check this assumption.

Conclusions and perspectives (1)

Optics

- The layout and booster positioning in the tunnel has been updated with the new survey.
- Matching conditions have been updated to increase the transparency of the insertions.
- Genetic algorithm has been developed to optimize the arc cell.
- Dynamic aperture and momentum acceptance have been evaluated for FODO, HFD, and HFD cell with 3 times larger momentum compaction.
- The momentum acceptance has been improved but the dynamic aperture still needs to be improved.
- Next steps:
    - Include RF cavities to evaluate the 6D DA.
    - Improve the insertion and transparency conditions.
    - Optimize the magnet lengths according to the maximum allowed field.
    - ¨Integrate the injection/extraction sections.

    See “Injection/extraction kicker updates; update or perspective on booster injection/extraction optics” (Y. Dutheil)

Conclusions and perspectives (2)

Orbit tuning

- The orbit tuning has been updated with the new girder tolerance table.
- Reduction of the successful seeds: need to change tuning strategy strategy
- Next steps:
  - Do the exercise for HFD optics
  - Go further in emittance tuning and refine algorithms.

Collective effects

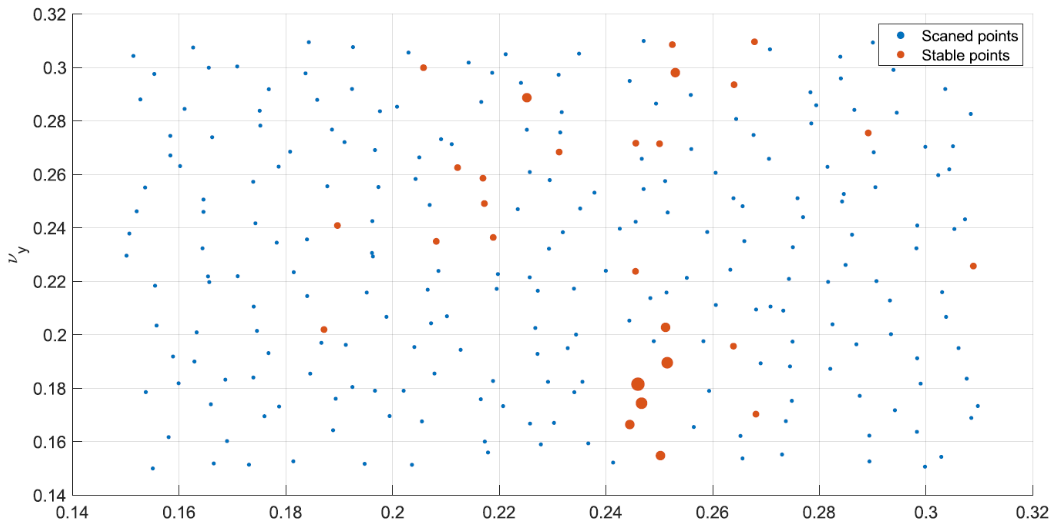
- TMCI is present at nominal current.
  - The collider bunch charge is smaller at ttbar/ZH mode and up to 3% (against 5% at Z) is to be replaced. Moreover, the filling is mush faster at ttbar/ZH compared to Z.
  - A smaller maximum bunch charge at ttbar/ZH in the booster relaxes the constraints.
  - **Do we need the same maximum bunch charge at all modes?**

Thank you for your attention

FCCIS – The Future Circular Collider Innovation Study. This INFRADEV Research and Innovation Action project receives funding from the European Union's H2020 Framework Programme under grant agreement no. 951754.

Dynamic aperture and momentum acceptance improvement

Courtesy: A. Mashal



Improvement in the matching of insertions

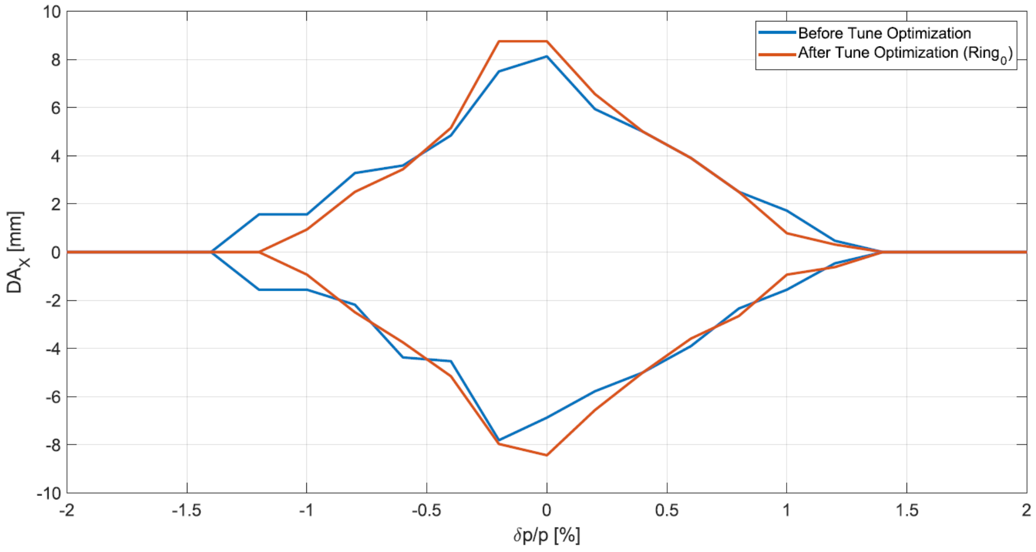
Tune scans (0.2515, 0.1896)

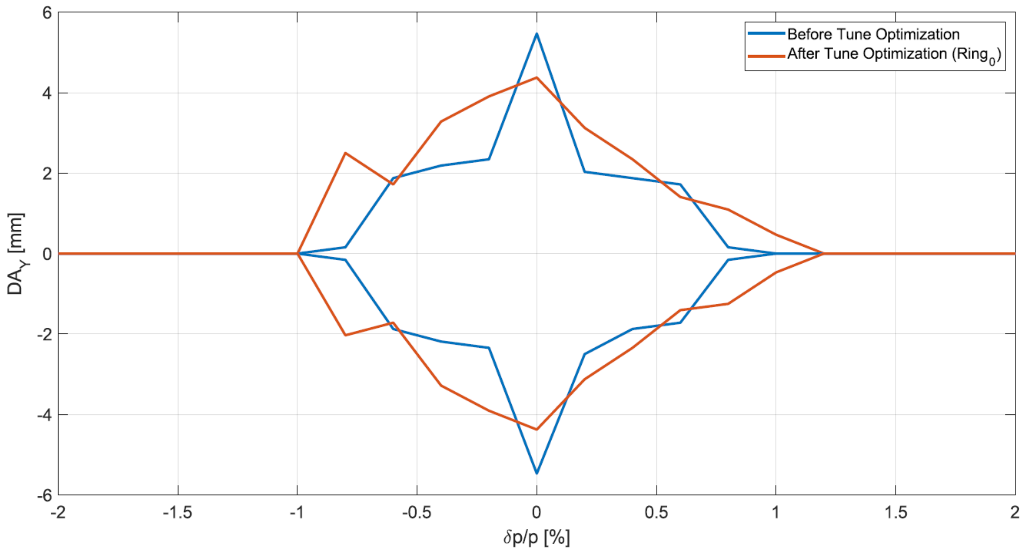
2 sextupole families per plane

Baseline optics.

FODO cells of 90 degrees.

Optics as presented at FCC week 2022





Parameter variation during the cycling

During the accumulation process,

- IBS processes drive the emittance evolution.
- The bunch parameters (length, emittance, size) vary from a bunch to another bunch. Energy spread doesn't reach equilibrium emittance at injection.

If we do not modify the I2 function (with different dipole families), we should have a flat top of at least 2 seconds to damp the beam with an initial round normalized emittance of 10 µm.
The duration of the flat top depends on the initial emittances 1-3 s for 1-50 µm.

We have assumed that the beam is matched at the entrance. An initial energy spread of 0.1% gives a bunch length of 7.2 mm. We could reduce a bit the initial bunch length by increasing the initial RF voltage but we are quickly limited by the maximum total RF voltage.
If we do not match the longitudinal parameters, we will have some bunch length and momentum spread breathing. We need to do tracking simulations to check that is not an issue.
We can lengthen the final bunch length by adjusting the final total voltage, to be studied.

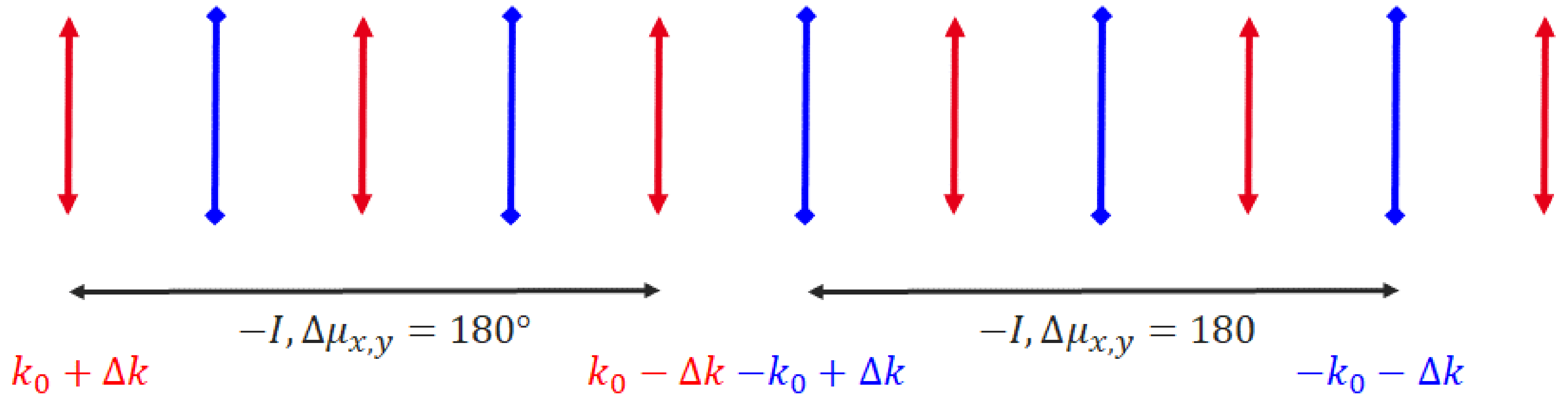
Momentum compaction tuning

Due to collective effects, we have to maintain 2 arc optics

- Z/W operations (with a momentum compaction of $\mathbf{1.49 \times 10^{-5}}$ corresponding to a FODO cell of 60 degrees and an I5 of $\mathbf{5.21 \times 10^{-11}}$).
- H/ttbar operations (with a momentum compaction of $\mathbf{0.73 \times 10^{-5}}$ corresponding to a FODO cell of 90 degrees and an I5 of $\mathbf{1.79 \times 10^{-11}}$).

The motivation is to have an additional knob to tune the momentum compaction during the ramp:

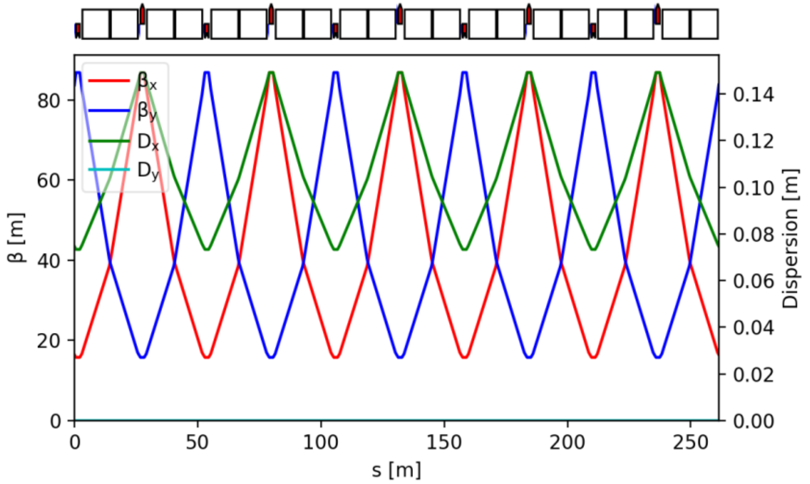
- We can have a larger momentum comapction at injection energy: better for collective effects.
- At higher energies, we can reduce the momentum compaction because collective effects are less critical at higher energy and we can get a smaller equilibrium emittance.



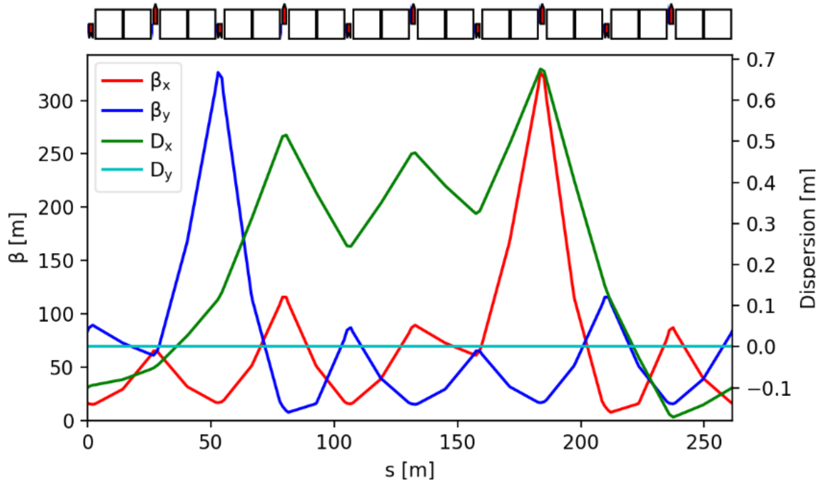
$$\Delta k \approx \frac{\sqrt{x}}{2\sqrt{3}} \text{ with } x = \frac{\alpha}{\alpha_0} - 1 \text{ where } \alpha \text{ is the momentum compaction and 0 when } \Delta k = 0$$

Alternative optics: comparison with the cell

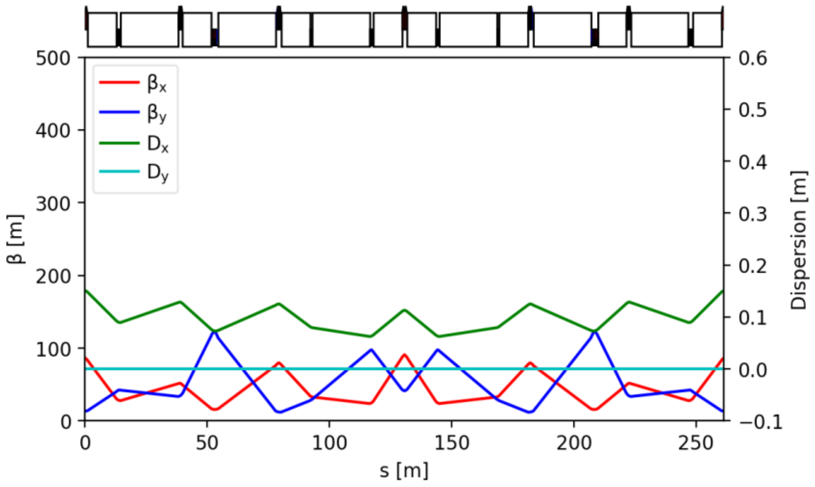
Arc FODO cell



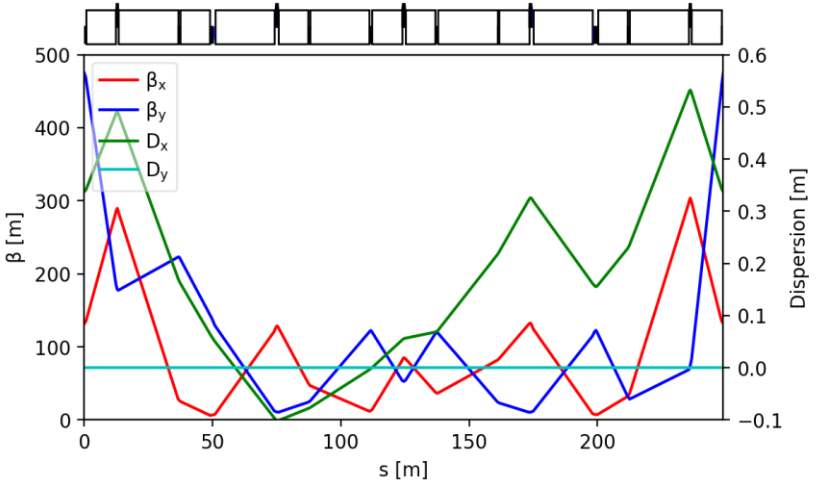
Arc FODO cell $\alpha \times 2$



HBD cell



HBD cell $\alpha \times 2$



Ratio FODO cells:

$$\frac{\alpha_{c,2}}{\alpha_{c,1}} = 2; \frac{I_{5,2}}{I_{5,1}} = 6.25$$

Ratio HBD cells:

$$\frac{\alpha_{c,2}}{\alpha_{c,1}} = 1.8; \frac{I_{5,2}}{I_{5,1}} = 5.6$$

60 degrees cells:

$$\frac{\alpha_{c,2}}{\alpha_{c,1}} \approx 2; \frac{I_{5,2}}{I_{5,1}} \approx 3$$

90 degrees twice longer cells:

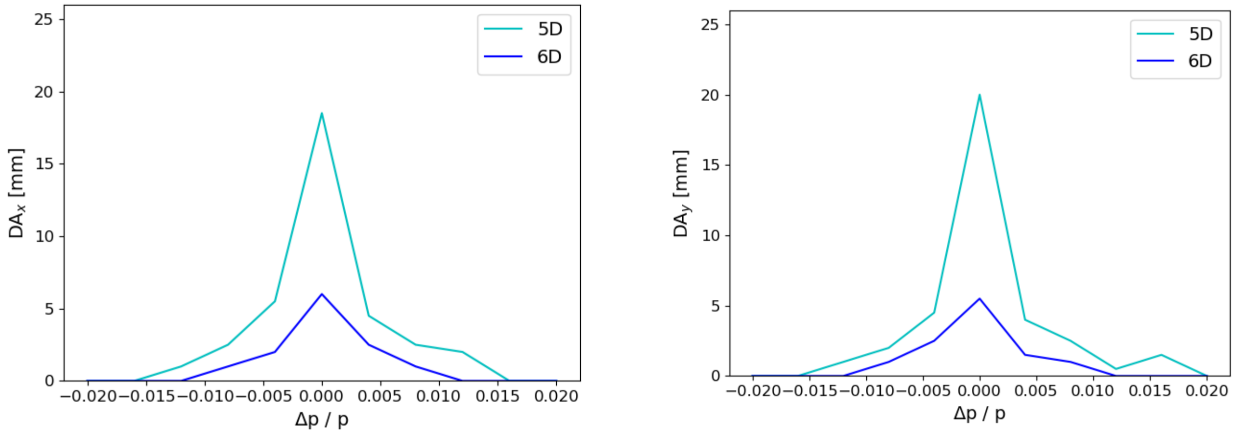
$$\frac{\alpha_{c,2}}{\alpha_{c,1}} \approx 4; \frac{I_{5,2}}{I_{5,1}} \approx 8$$

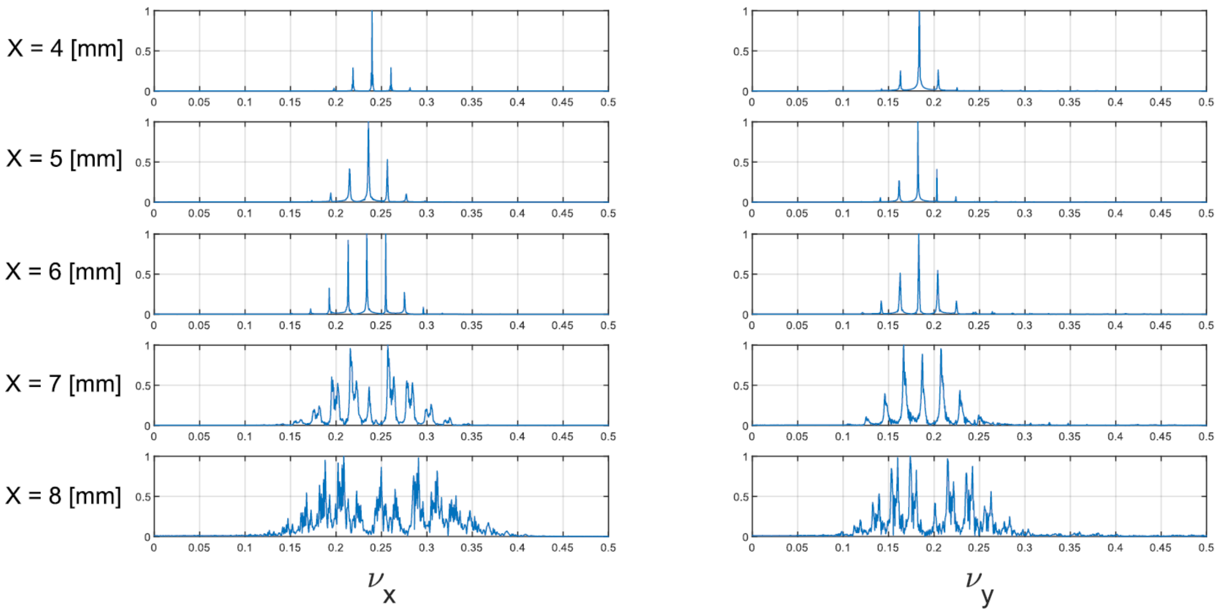
5D vs 6D DA at injection (20 GeV)

- Strong reduction of 6D DA on momentum due to synchro-betratron resonances.
- Momentum DA also to be optimized

Courtesy: A. Mashal , B. Dalena

Baseline optics.
FODO cells of 90 degrees.
Optics as presented at FCC week 2022





Amplitude variation

conditions for the loss of phase stability, we evaluate the path length variation (9.99) with momentum in higher order

$$\frac{\Delta L}{L_0} = \alpha_c \delta + \alpha_1 \delta^2 + \xi + \mathcal{O}(3), \qquad (9.100)$$

where ξ represents the momentum independent term

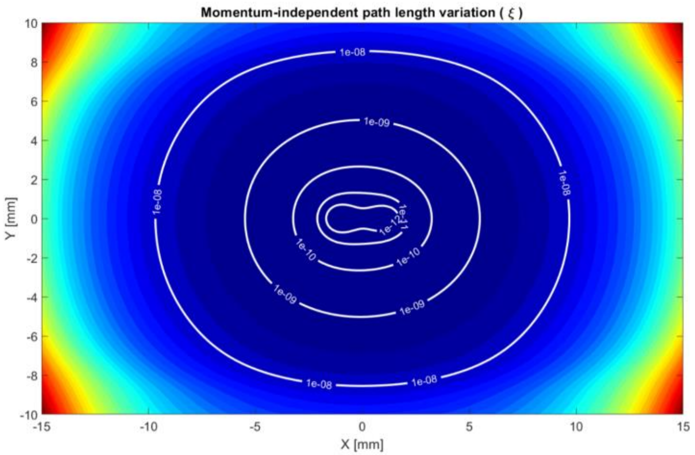
$$\xi = \tfrac{1}{4}\left(\epsilon_x \langle \gamma_x \rangle + \epsilon_y \langle \gamma_y \rangle + \epsilon_x \langle \kappa^2 \beta_x \rangle\right) \qquad (9.101)$$

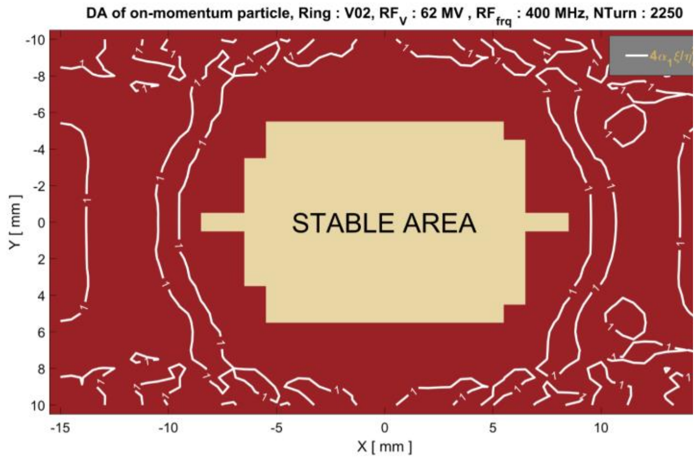
H. Widemann

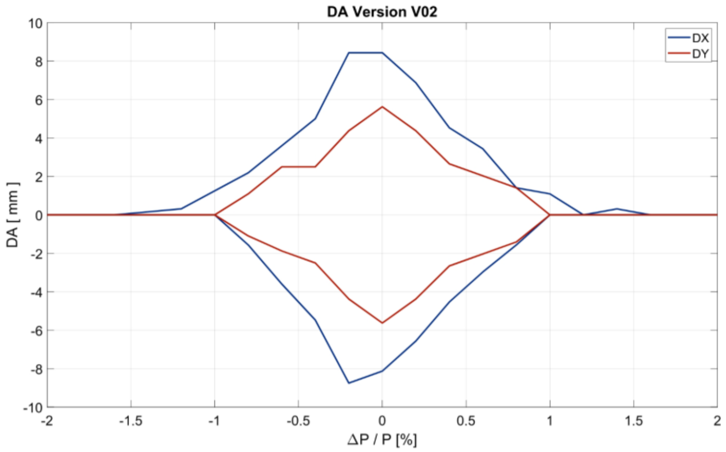
Stability criteria

$$\frac{4\xi\alpha_1}{\eta_c^2} < 1$$

Courtesy: A. Mashal

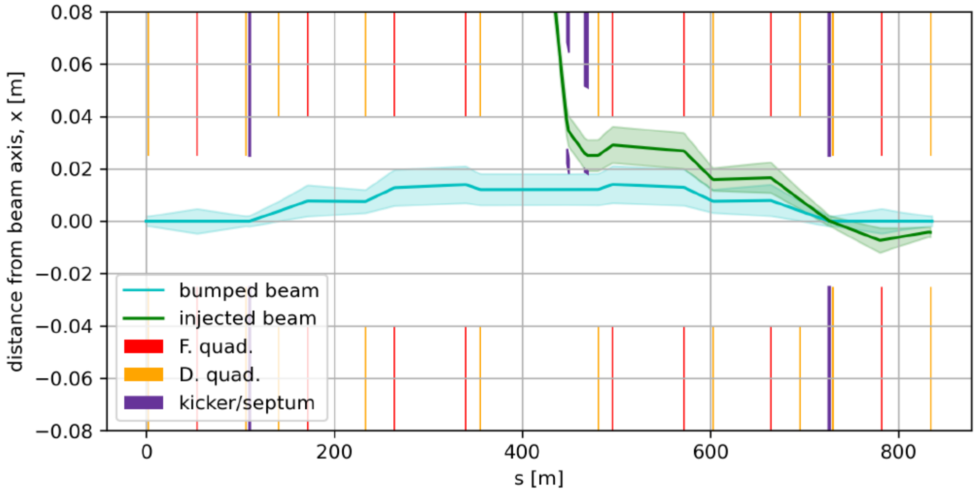






Injection/ extraction in the High Energy Booster

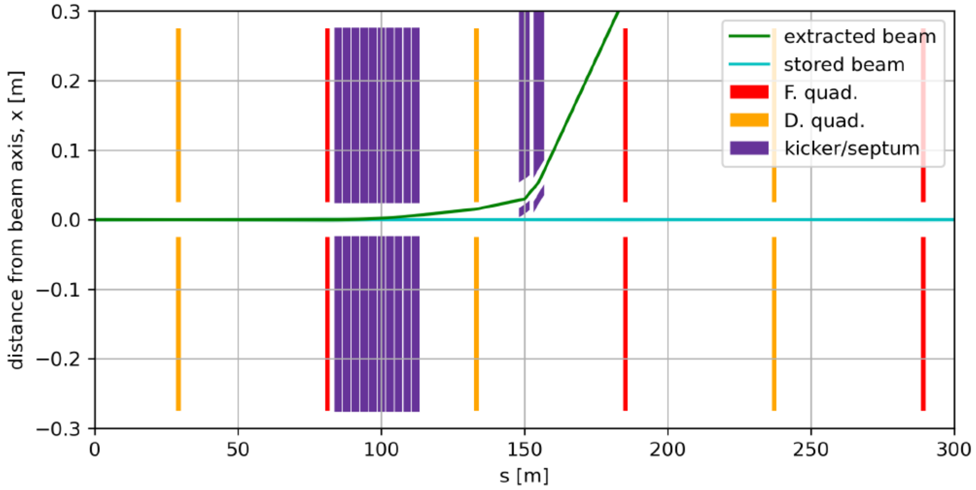
Injection scheme with orbit bump and thin electrostatic septum



Possibility to have vertical injection to be studied

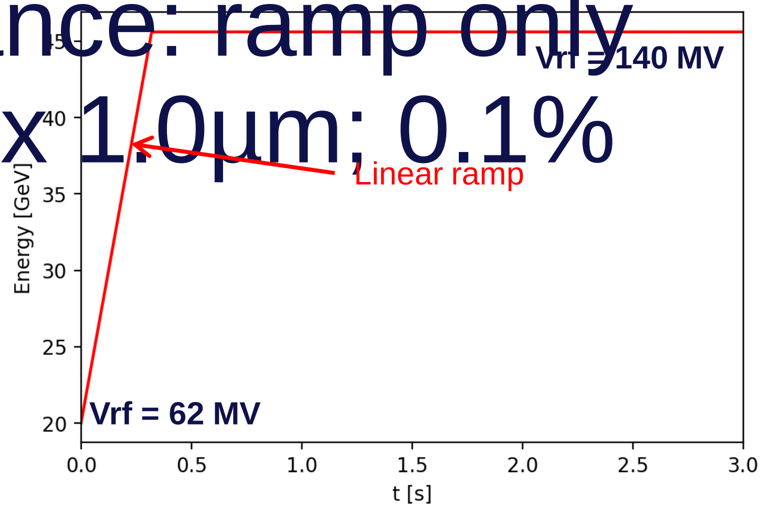
Courtesy: R. L. Ramjiawan & E. Howling

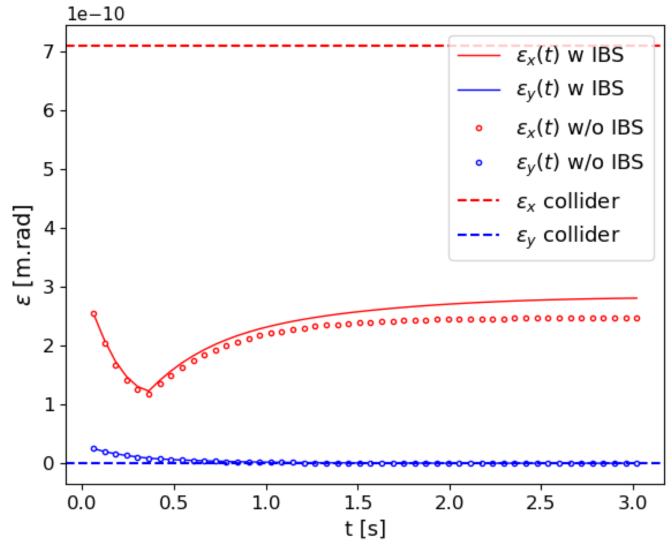
Extraction scheme with 10 kickers

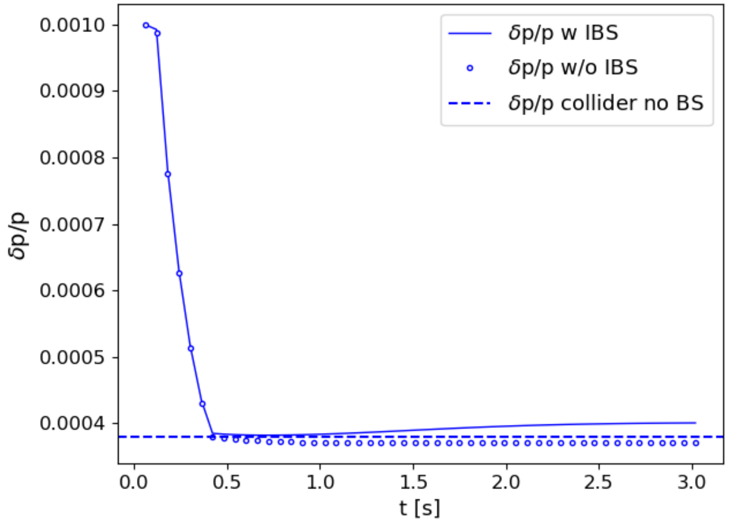


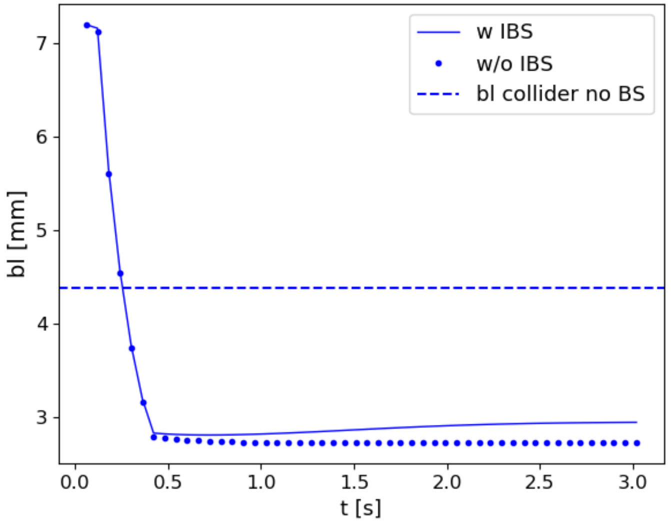
Room for optics optimization of both injection and extraction

Emittance: ramp only
10µm x 1.0µm; 0.1%









Emittances evolution

We consider the Z mode:

- We accumulate in the booster for 24 s: for the emittance evolution we consider 2 cases:
  - 1 fresh beam (the ramp begins directly after injection).
  - 1 accumulation time of 24 s before the ramp.
- We ramp from 20 GeV to 45.6 GeV for 0.32 s.
- We consider also a flat-top of 2.7 s (to get a total cycling time of 27 s) to evaluate the gain of damping at top energy.

LINAC parameters: **S. Bettoni, A. Latina, A. Grudiev, P. Craievich**

The injection is from the LINAC at 20 GeV:

- Normalized emittance of **10 µm x 10 µm**.
- Energy spread of **0.1%**
- 2.53e+10 particles per bunch (**4 nC**)

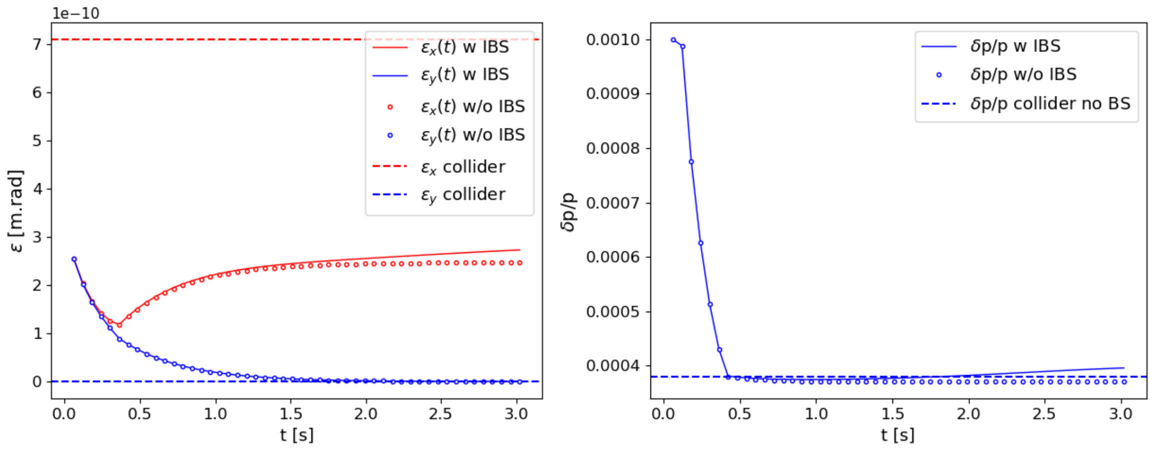
Thanks to M. Zampetakis, F. Antoniou, O. Etisken for IBS

We assume a matched beam: the bunch length is deduced from the total voltage, energy spread and momentum compaction.

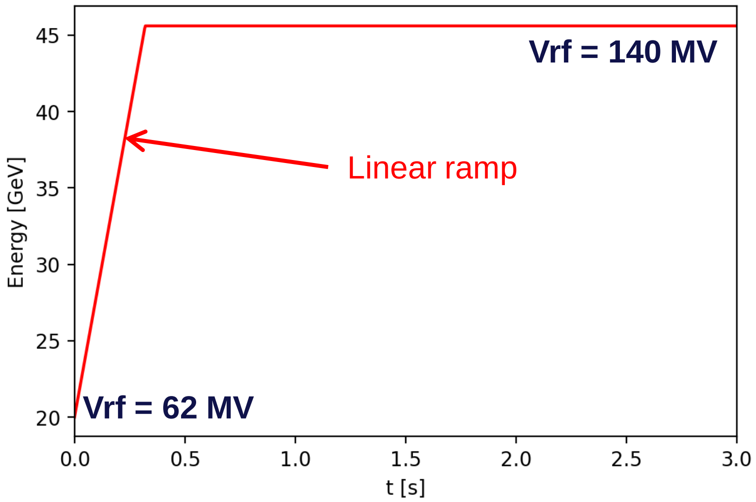
We consider the case with no IBS and with IBS, using MAD-X routines.

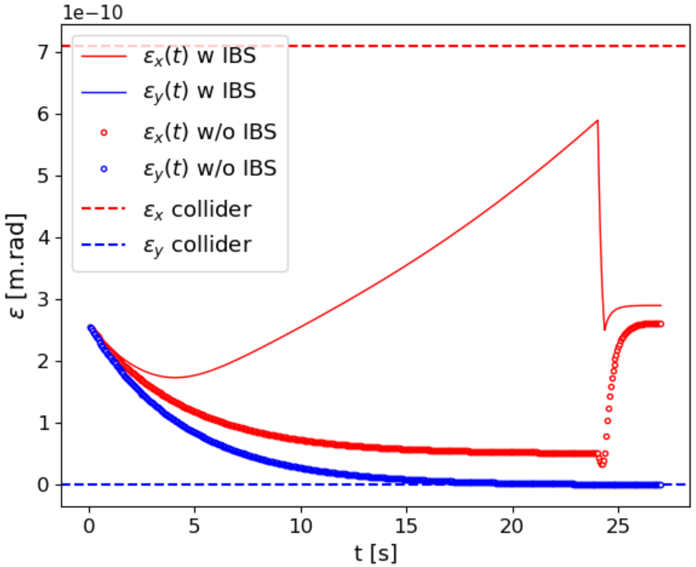
EN BACK-UP

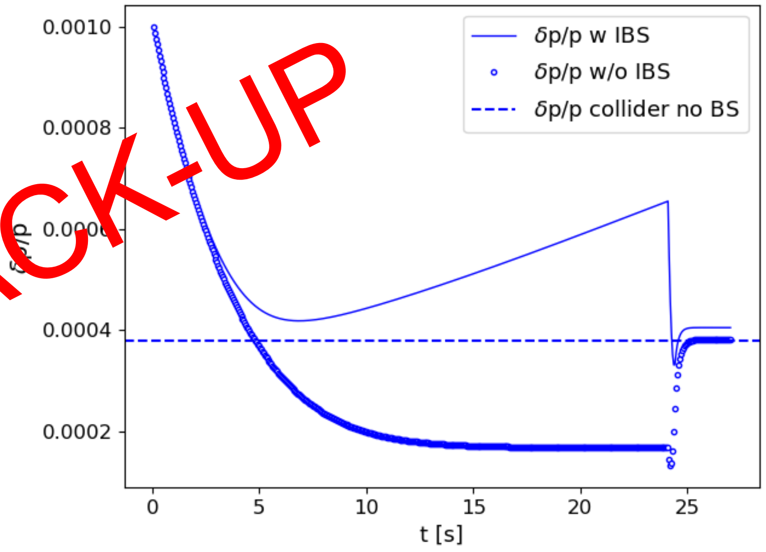
Normalized transverse emittance of **10 µm x 10 µm**
Energy spread of **0.1%**
With flat-top
Ramp Only

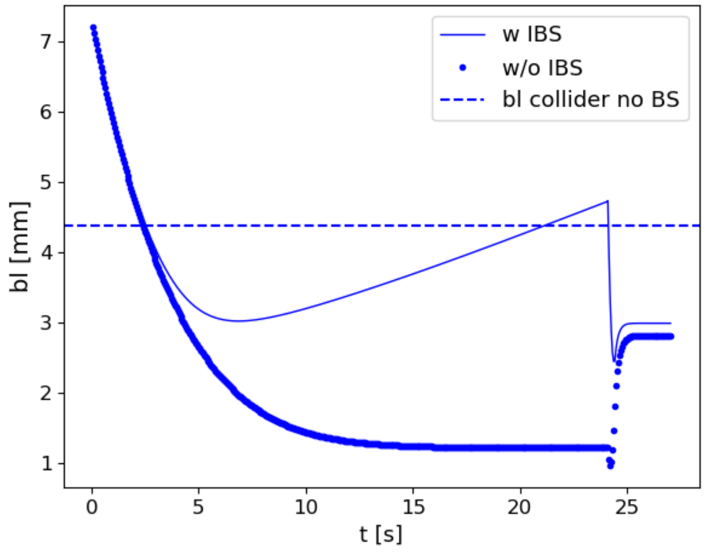


Emittance: accumulation + ramp 10µm x 10µm; 0.1%









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Alternative optics: discussion

The advantages of this alternative optics are:

- **Possibility to tune the momentum compaction** during the ramp.
  - Different I5 at injection and extraction.
  - Needs to know the limitation of collective effects at injection but also at extraction to evaluate the optimum momentum comapction during the ramp.
- **We keep the same sextupole correction scheme for all modes.**
  - We could add an additional sextupole at the dispersion peak to correct the extra chromaticity due to the betatron wave (the chromaticity increase is about 50% more in comparison with the reference case). The extra sextupoles are 10 times weaker to double the momentum compaction.

The drawbacks are:

- A larger equilibrium emittance in comparison with FODO cells.
  - We are still below the equilibrium emittance of the long 90 degrees cells.
  - We can reduce the imapct by decreasing the momentum compaction during the ramp.
- We need to increase the number of quadrupole families and thus power supplies.
  - 6 families against 2 families.
- Larger maximum peak betatron functions in the arcs.
  - Need for more work to improve the matching sections.

We have to evaluate the impact on the dynamic aperture and momentum acceptance.