FCC

FULL-ENERGY BOOSTER

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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.

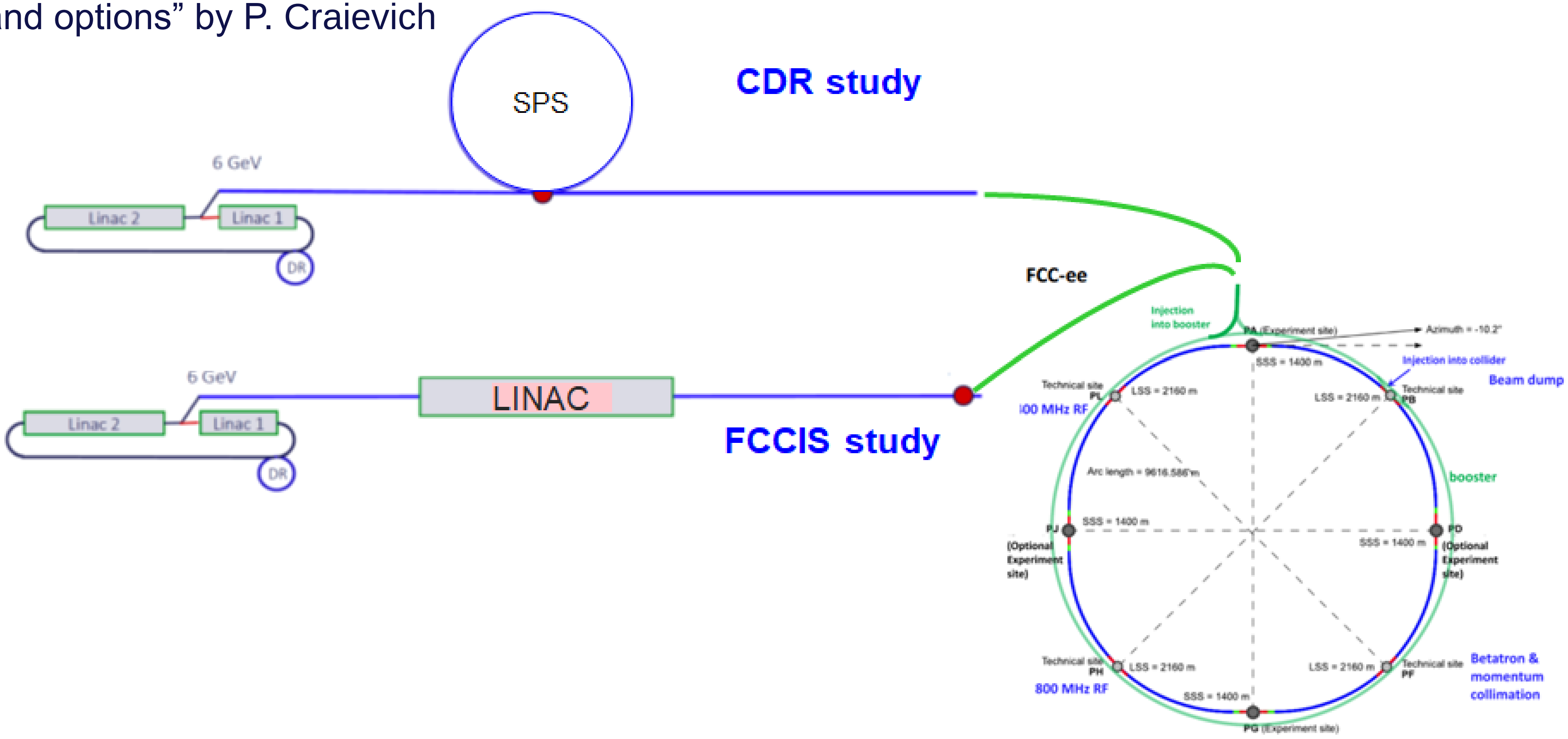
Injector complex

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

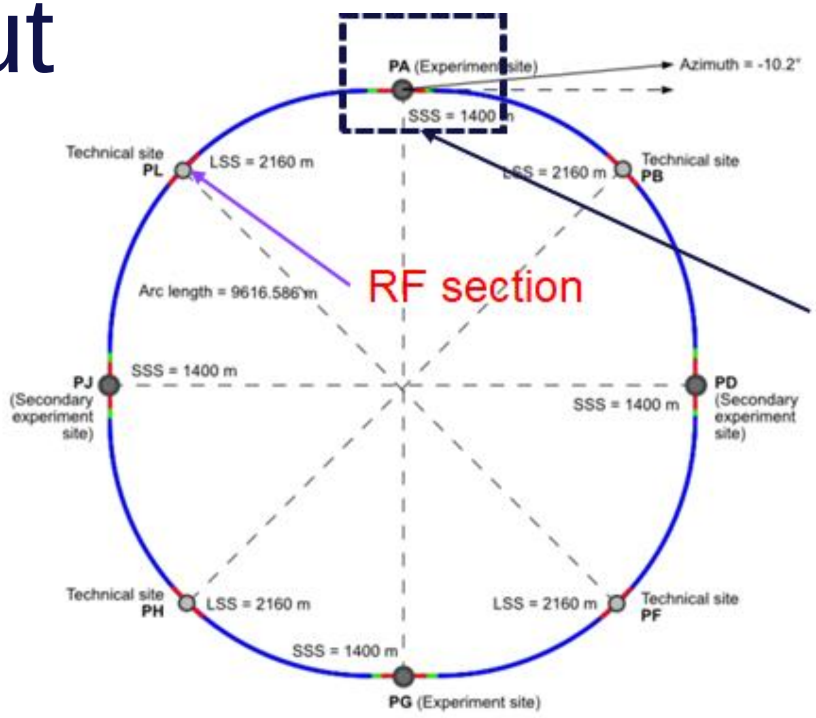
Ramping: 80-100 GeV / s (< 1 s)

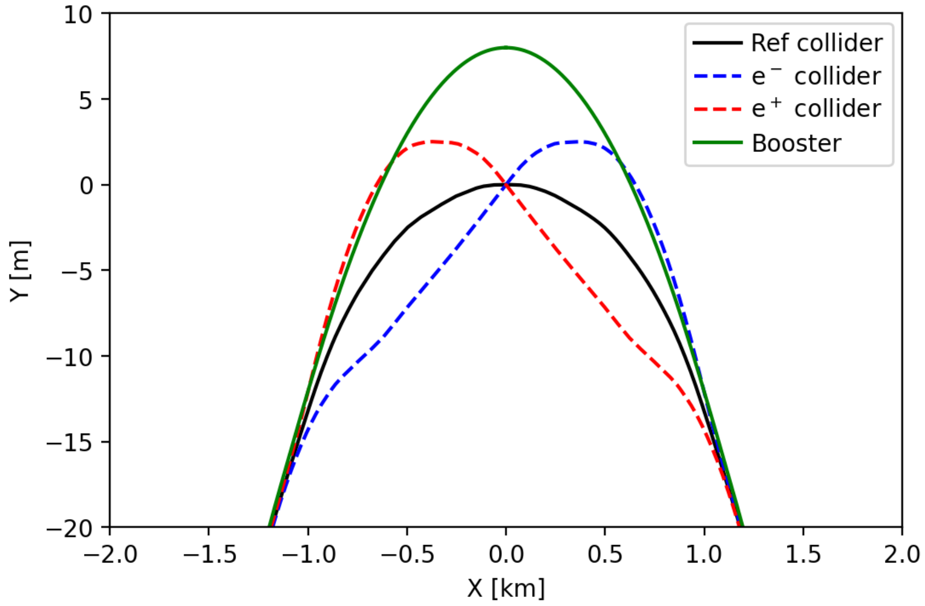
Alternatives: SPS as Pre Booster Ring (PRB) and a Linac

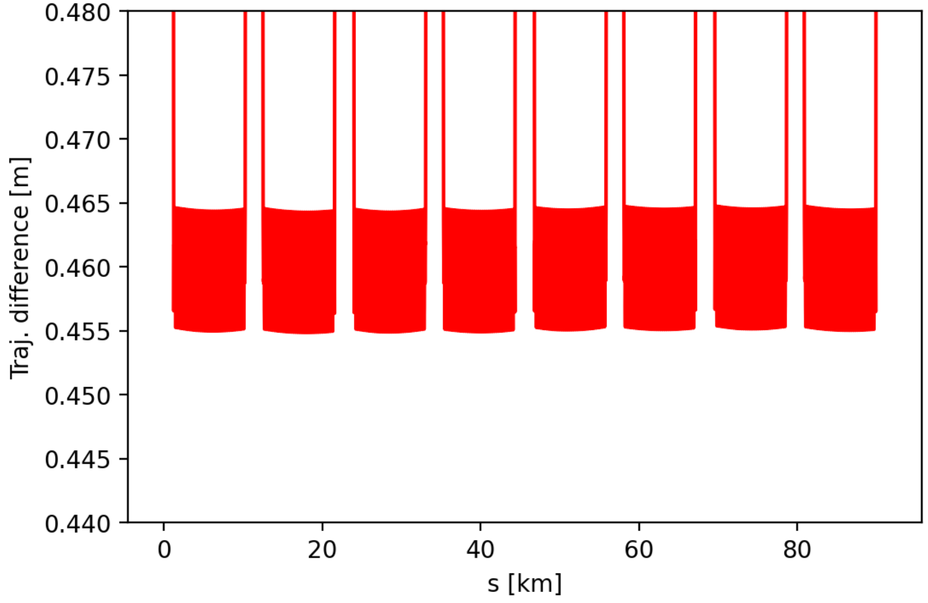
See “Pre-injector baseline and options” by P. Craievich



New layout







- In the baseline, 800 MHz cavities are now located in section L.
- The booster is now in the outer side of the collider with an offset with the IP of 8 m.
- Currently, the booster has a transverse shift of 0.46 m +/- 5 mm.
  - The circumference of the booster is 3.78 m longer than the collider.
  - The circumference of the booster can be adjusted to have a path length difference equal to a multiple of the RF wavelengths.
    - 2 possible knobs: offfset at the IPs or offset in the arcs.

Optics updates

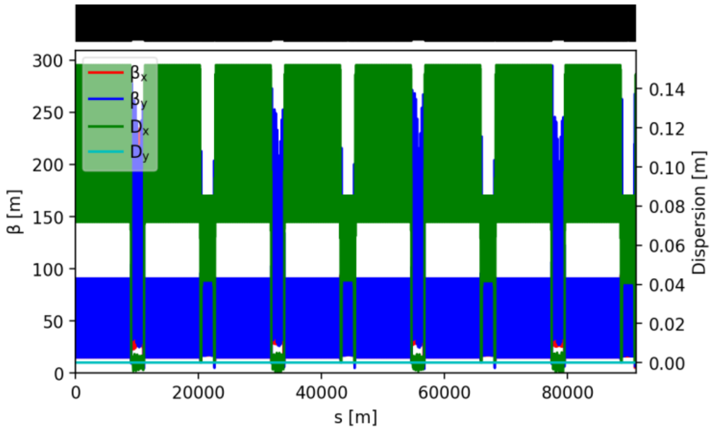
Magnet	Parameter	Unit	Value
Dipole	Field at injection (20 GeV)	G	64
	Field at ttbar energy (182.5 GeV)	G	593
	Length	m	11.1
Quadrupole	Gradient at injection (20 GeV)	T/m	2.5
	Gradient at ttbar energy (182.5 GeV)	T/m	23
	Length	m	1.5
Sextupole	Gradient at injection (20 GeV)	T/m^2	304
	Gradient at W energy (182.5 GeV)	T/m^2	2816
	Length	m	0.5

=> Very challenging low dipole field at injection

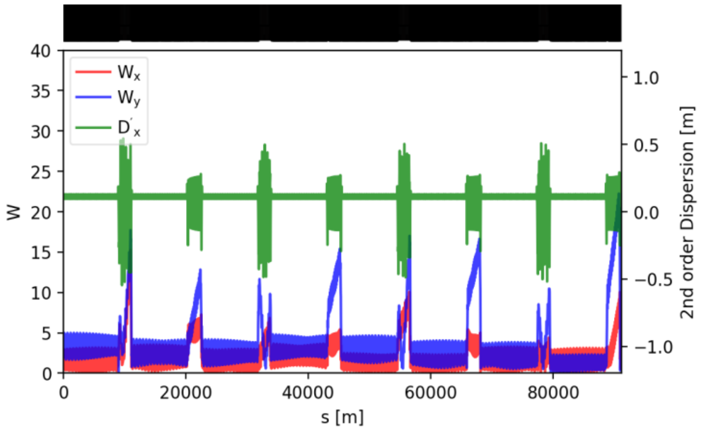
- Group of 5 FODO cells of ~52 m each.
- New tuning procedure to go into the direction of non-interleaved sextupoles:
  - Phase advance of π between 2 sextupoles of one pair.
  - Phase advance of $(2N + 1)\pi$ between the last sextupole of one arc and the first sextupole of the following one.
  - The tune of the arcs is adjusted to get the target tune.
  - The insertions are adjusted to match the Montague functions and second order dispersions.
- # dipoles = 2 x 2944
- # quadrupoles = 2944
- # sextupoles = 1120

- **Warning: The next results are for the optics shown at FCC week 2022.**

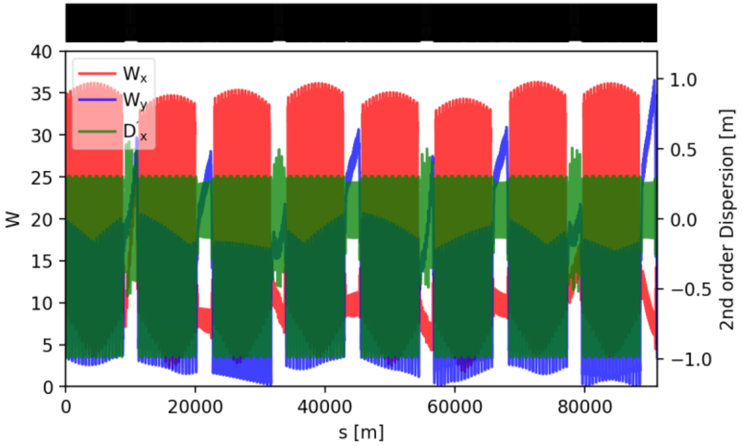
Full ring: betatron function and dispersion



Montague functions Sextupole OFF

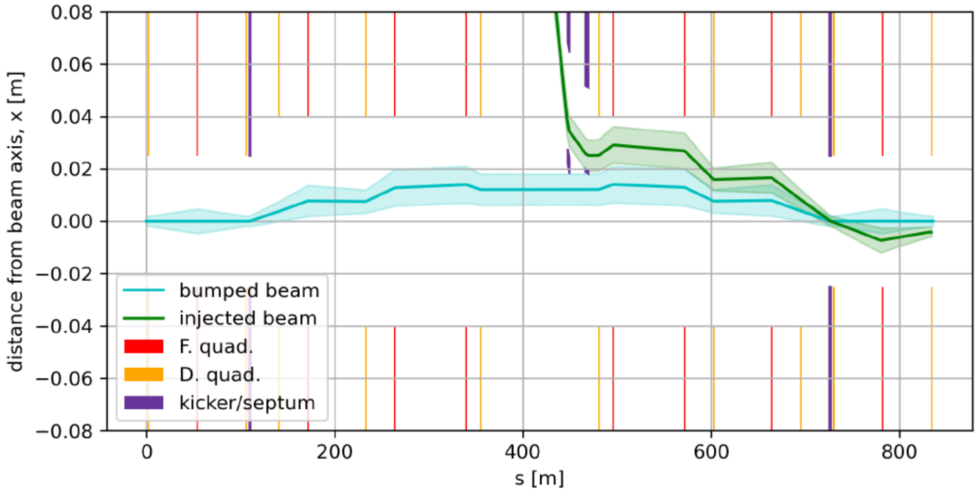


Montague functions Sextupole ON



Injection/ extraction in the High Energy Booster

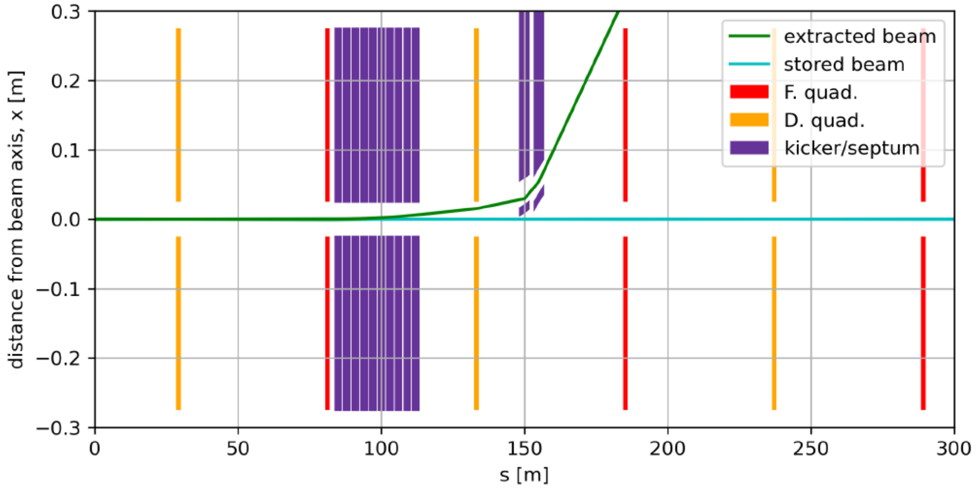
Injection scheme with orbit bump and thin electrostatic septum



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

RF budget

Modes	Injection 60°[a]/90°[b]	Z	W	H	$t\bar{t}$	[Units]
Energy	20	45.6	80	120	182.5	[GeV]
σ_z[c]	4	4.38	3.55	3.34	1.94	[mm]
δ_p[d]	3	4.38	3.55	3.34	1.94	[mm]
α_c[e]	14.9 / 7.34	14.9		7.34		[10^{-6}]
$V_{RF,400}$[f]	53.6 / 27.6	124.6	1023.2	2185.6	14205.4	[MV]
$V_{RF,800}$[g]	104.8 / 52.8	83.9	623.6	2038.3	11554.9	[MV]

[a] 60° phase advance lattice of the Z and W modes
[b] 90° phase advance lattice of the H and $t\bar{t}$ modes
[c] Bunch length
[d] Momentum acceptance
[e] Momentum compaction factor
[f] RF voltage for $\nu_{RF} = 400\ MHz$
[g] RF voltage for $\nu_{RF} = 800\ MHz$

Table. Update RF voltage budget for 800 MHz RF cavities.

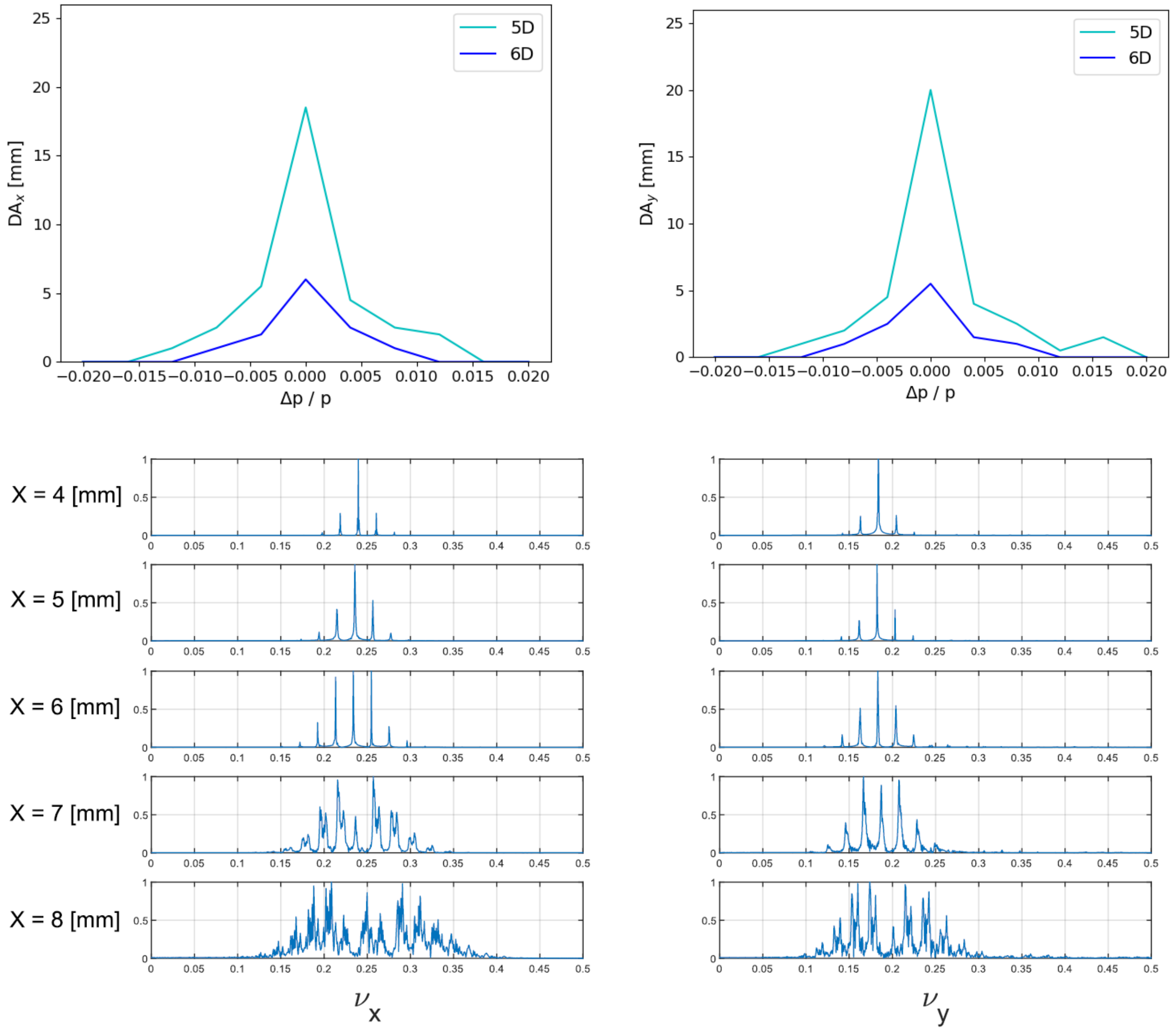
See [*Chance, Antoine, et al. "Optics design and correction challenges for the high energy booster of FCC-ee." arXiv preprint arXiv:2304.00135 (2023).*]

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

- Strong reduction of 6D DA on momentum due to syncro-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

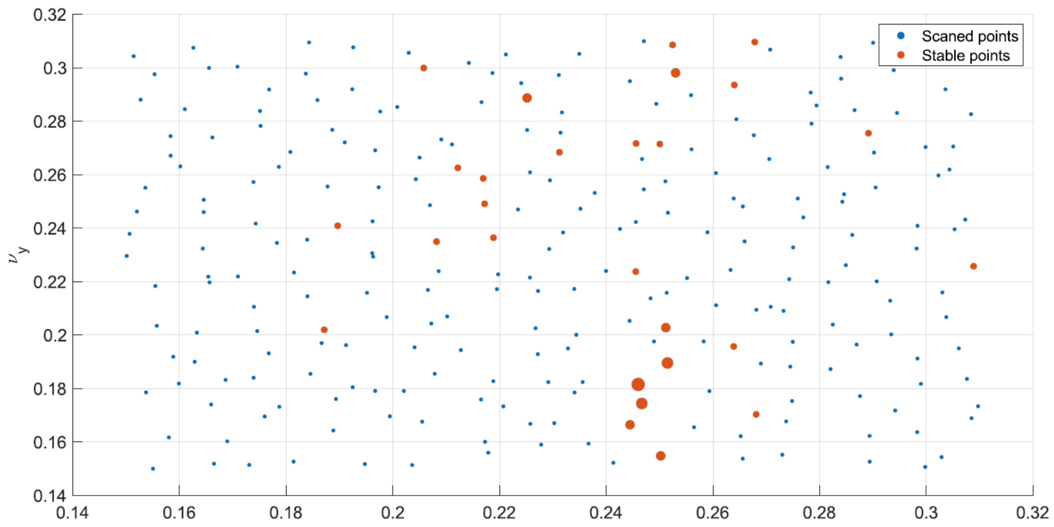


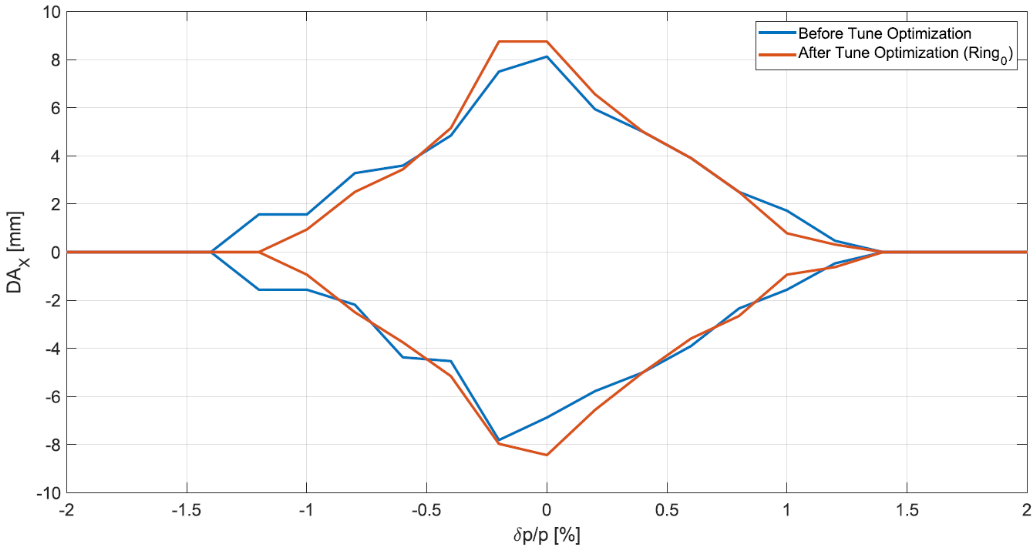
Dynamic aperture and momentum acceptance improvement

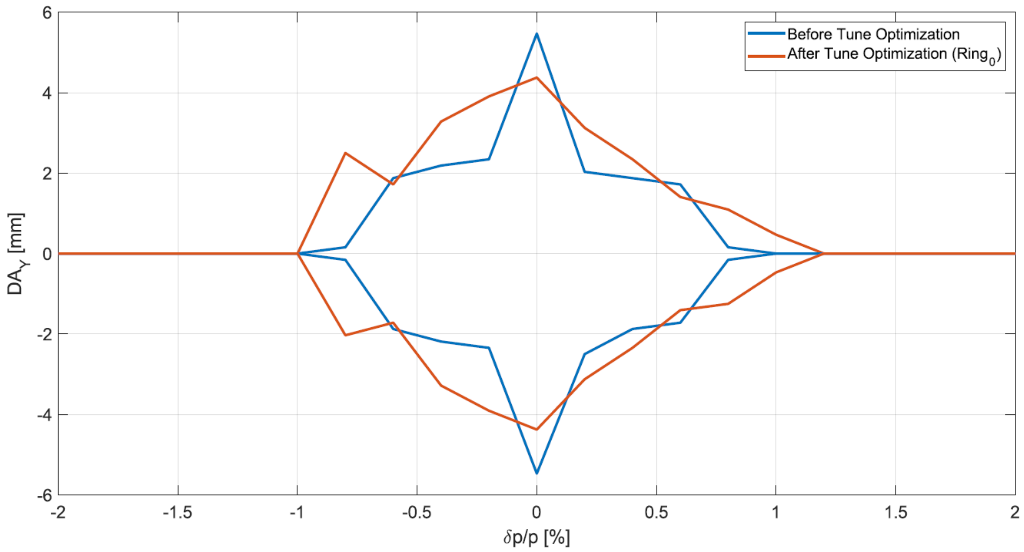
Courtesy: A. Mashal

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







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

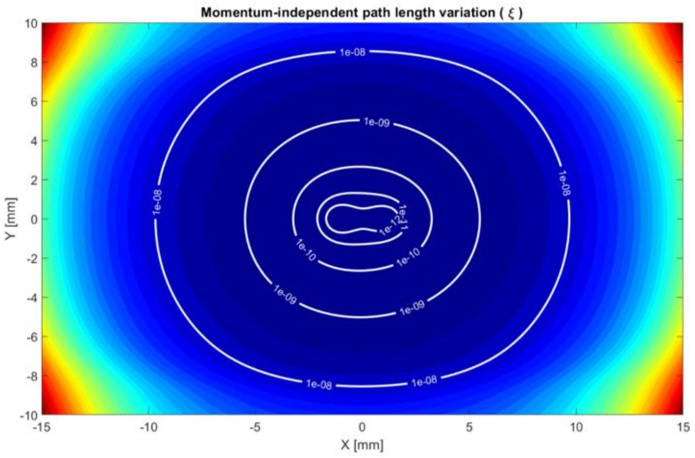
$$\xi = \frac{1}{4}\left(\epsilon_x \langle\gamma_x\rangle + \epsilon_y \langle\gamma_y\rangle + \epsilon_x \langle\kappa^2 \beta_x\rangle\right) \qquad (9.101)$$

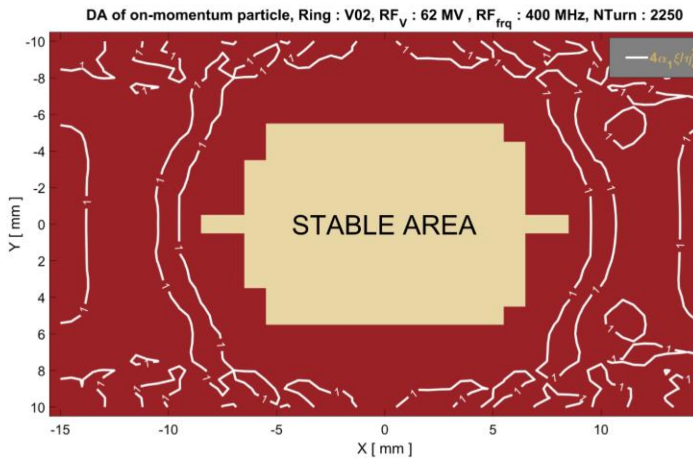
H. Widemann

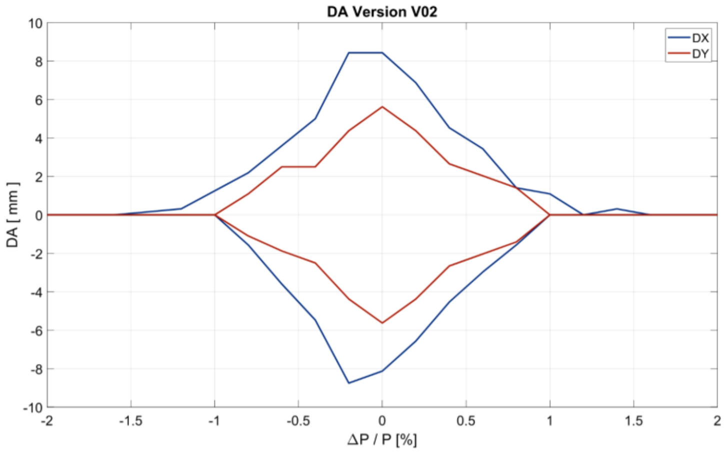
Stability criteria

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

Courtesy: A. Mashal







Static magnets imperfections

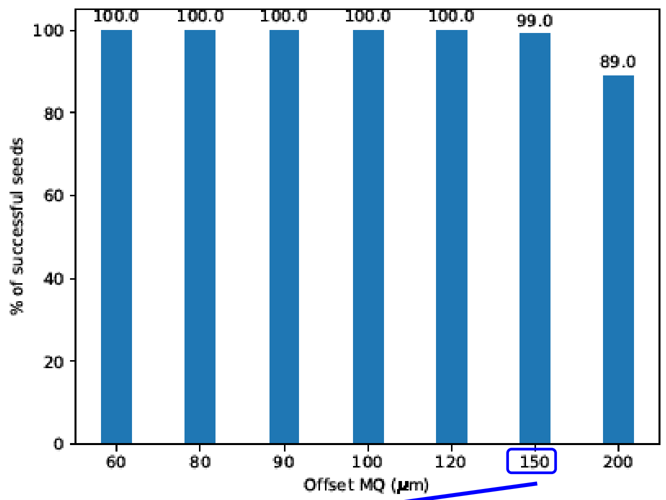
Courtesy: Tatiana Da Silva

Define pre-alignment tolerances of the elements and the orbit correctors specifications + establish a correction procedure for orbit correction for the FCC-ee high energy booster.

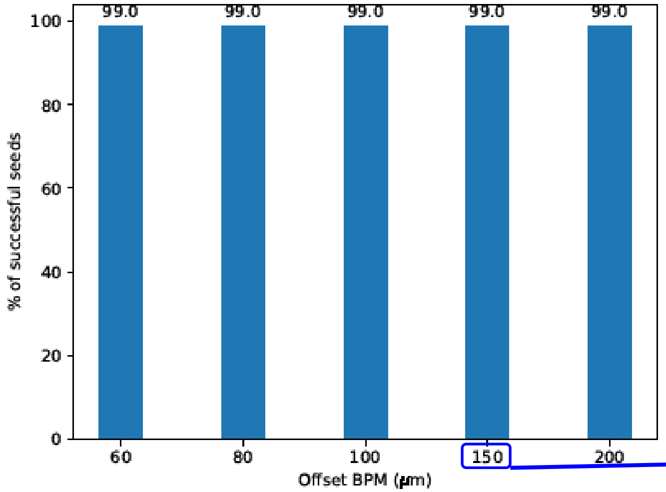
Orbit correction only   Statistics on 100 seeds

Error type	Value
Dipole relative field error	1e-4, 1e-3 10^{-3}
Main dipole roll error	300 mrad
Offset quadrupoles	60, 80, 90, 100, 120, 150 and 200 µm
Offset BPMs	60, 80, 100, 150 and 200 µm
Offset sextupoles	60, 80, 100, 120, 150 and 200 µm

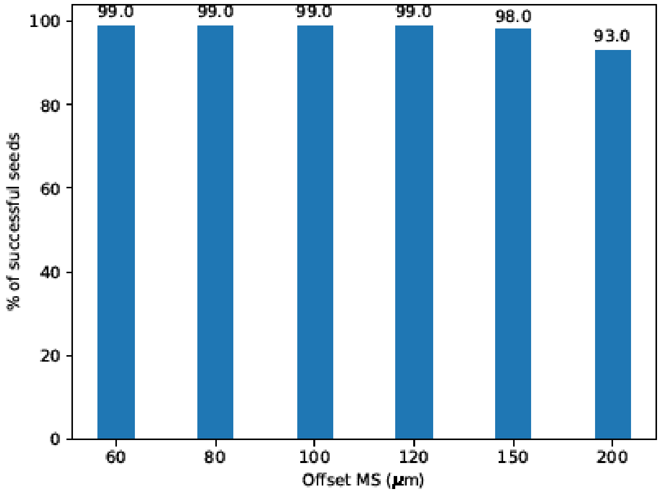
MQ offset, field err MB & MB roll



MQ offset, field err MB & MB roll, BPMs offset



MQ offset, field err MB & MB roll, BPMs offset, MS offset

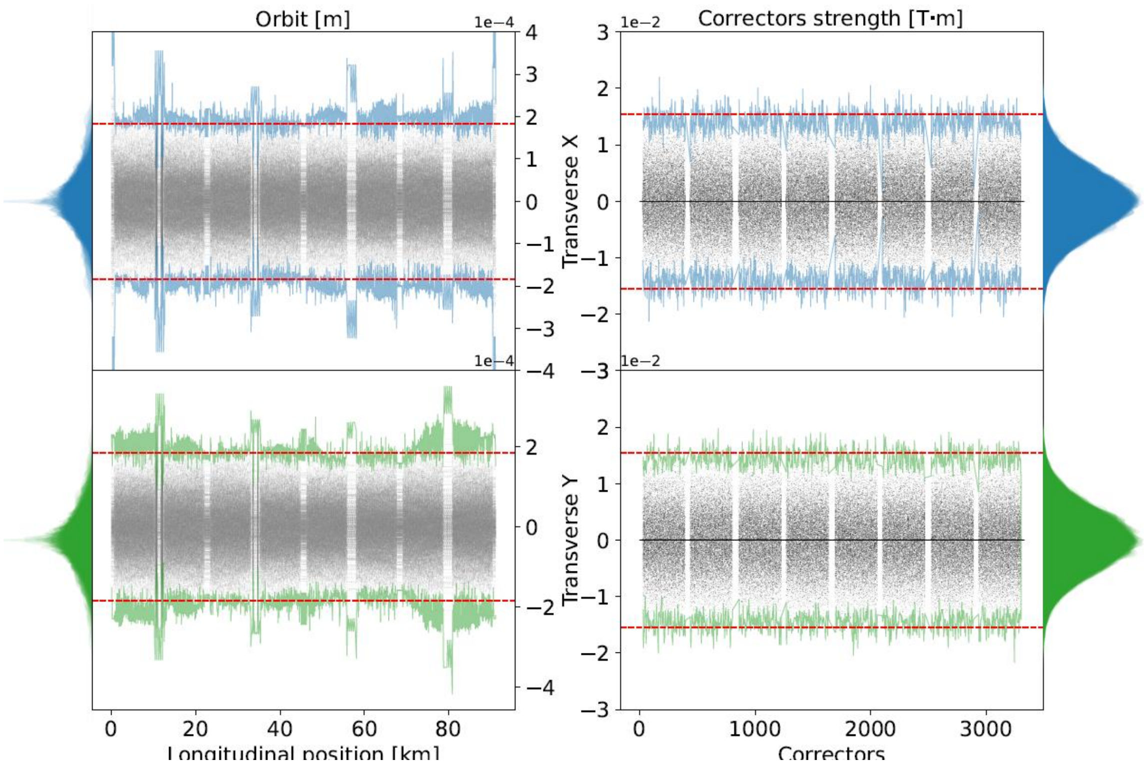


First pre-alignment and correctors specs

		Plane	3×RMS Analytic	3×RMS Seeds[a]
Residual orbit	[μm]	x	188	174
		y	192	180
Corrector strength	[mT·m]	x	16	12
		y	16	12

[a] Mean of RMS of all seeds.

Courtesy: Tatiana Da Silva



- First specifications of the main **magnets misalignment** of the High Energy Booster arcs cells **≃ 150 μm**
- **Relative dipole field error of 1e-3**
- First definition of the **orbit correctors** for the booster **≃ 20 mT**

- In order to preserve transverse emittances need to able to correct also beta-beating, dispersion and coupling (**emittance tuning**)

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:

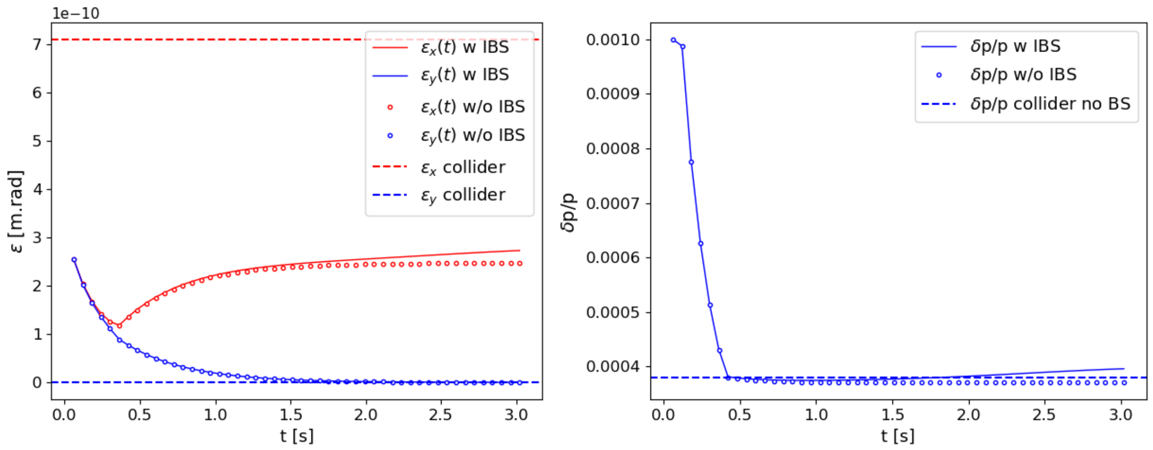
- Normalized emittance of **10 µm x 10 µm**.
- Energy spread of **0.1%**
- 2.53e+10 particles per bunch (**4 nC**)

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

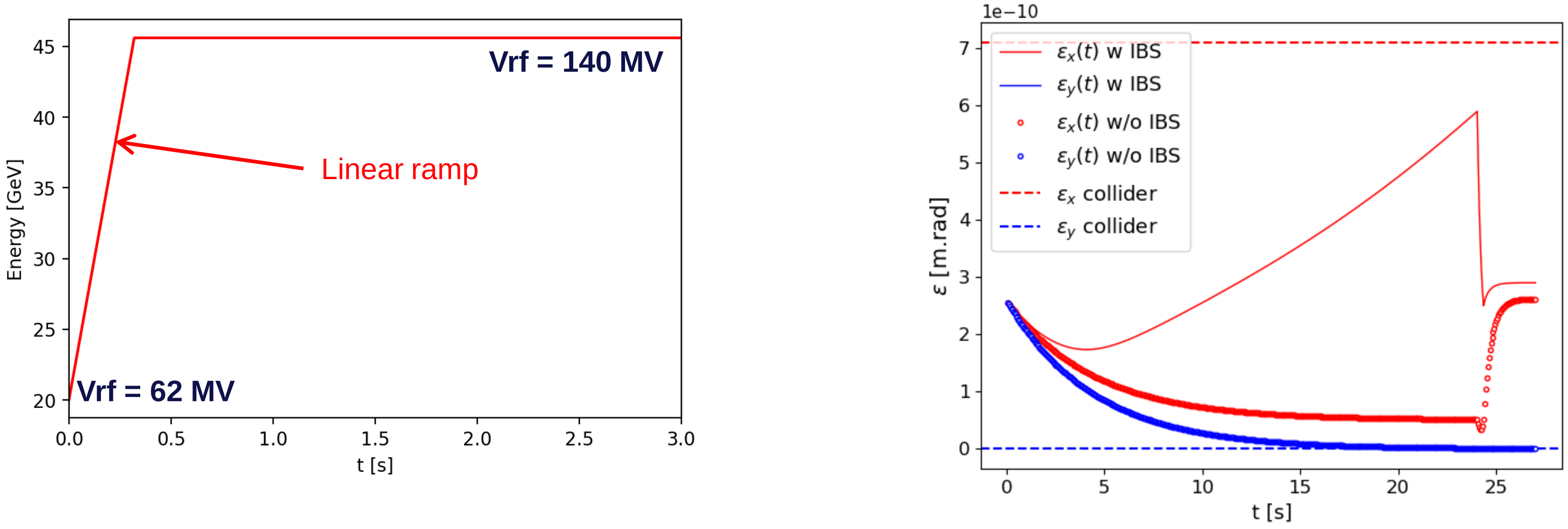
We assume a matched beam: the bunch length is deduced from the total voltage, energy spread and momentum compaction.

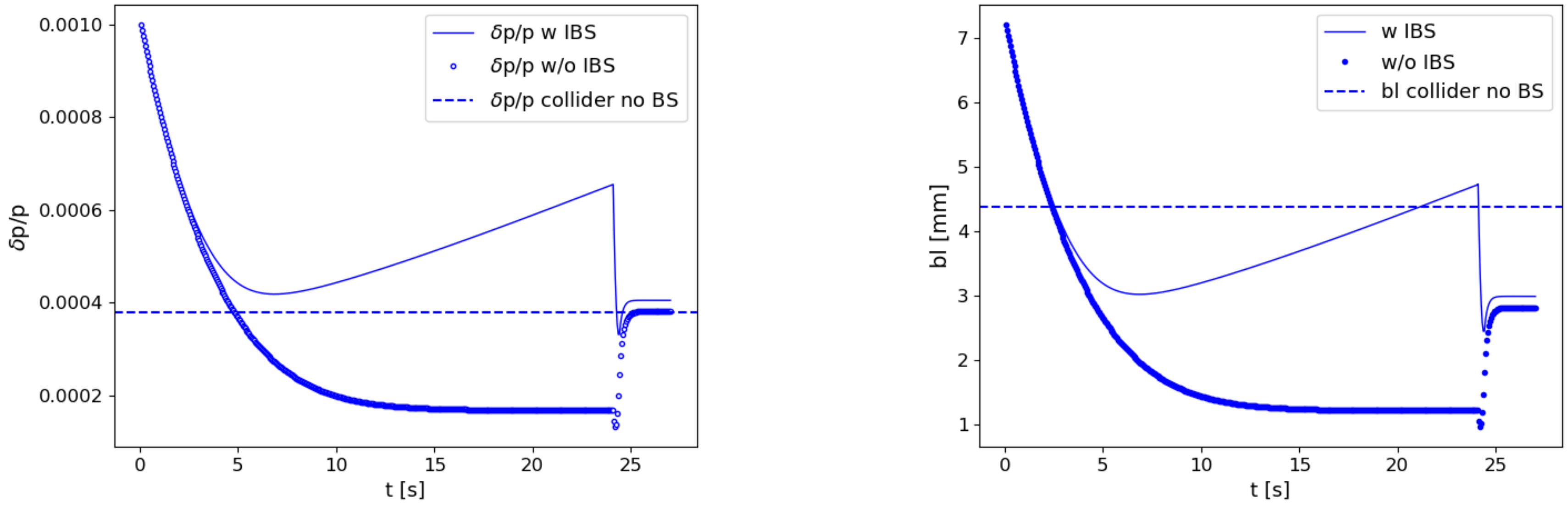
We consider the case with no IBS and with IBS, using MAD-X routines.

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%





Booster cycling for Z operation

Injector		LINAC	LINAC	LINAC	SPS
Injection energy	GeV	20	20	20	16
Extraction energy	GeV	45.6	45.6	45.6	45.6
Injection hor. emittance $\epsilon_{x,inj}$ (norm.)	µm	50	10	10	190
Injection vert. emittance $\epsilon_{y,inj}$ (norm.)	µm	50	10	1	4
Injection energy spread $\delta_{p,inj}$	%	0.1-0.15	0.1-0.15	0.1-0.15	0.4
Extraction hor emittance $\epsilon_{x,ext}$ (geom)	µm	<0.3	<0.3	<0.3	<0.3
Extraction vert emittance $\epsilon_{y\ ext}$ (geom)	pm	<1.42	<1.42	<1.42	<1.42
Extraction energy spread $\delta_{p,ext}$	%	0.04	0.04	0.04	0.04
Accumulation time	s	24	24	24	54
Ramp time	s	0.32	0.32	0.32	0.37
Flat top	s	2.6	1.9	1	1.9
Total cycling time	s	26.92	26.22	25.32	56.27

Collective effects at injection

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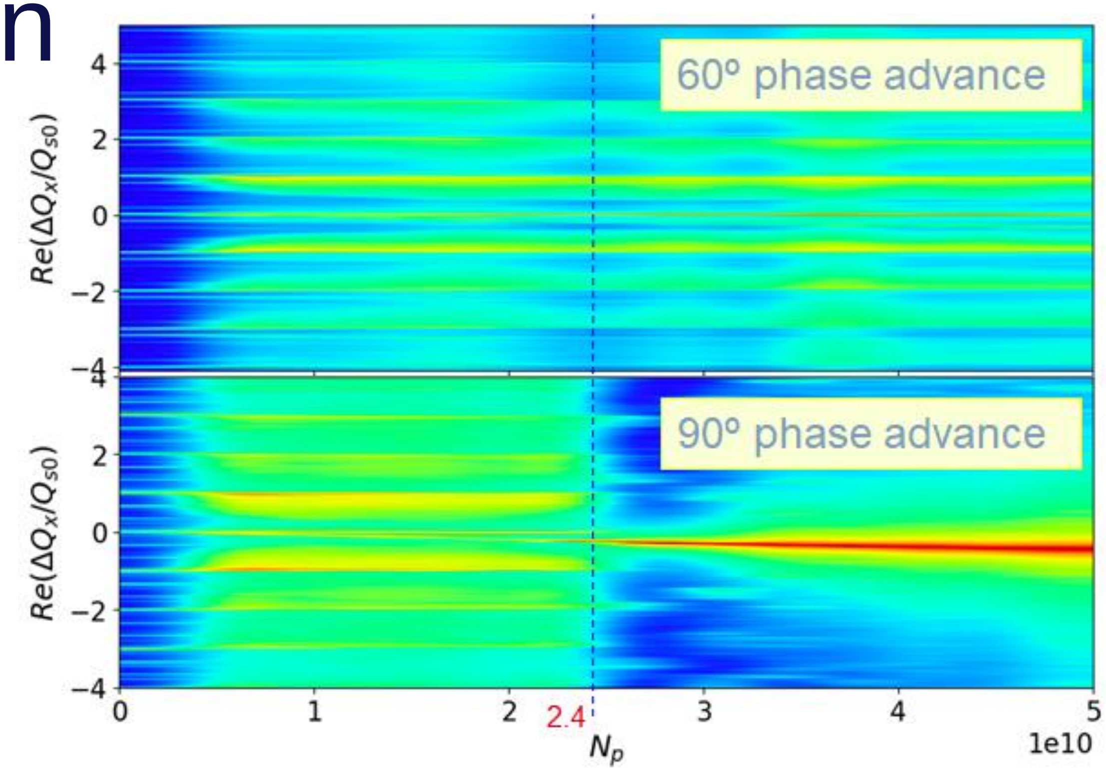
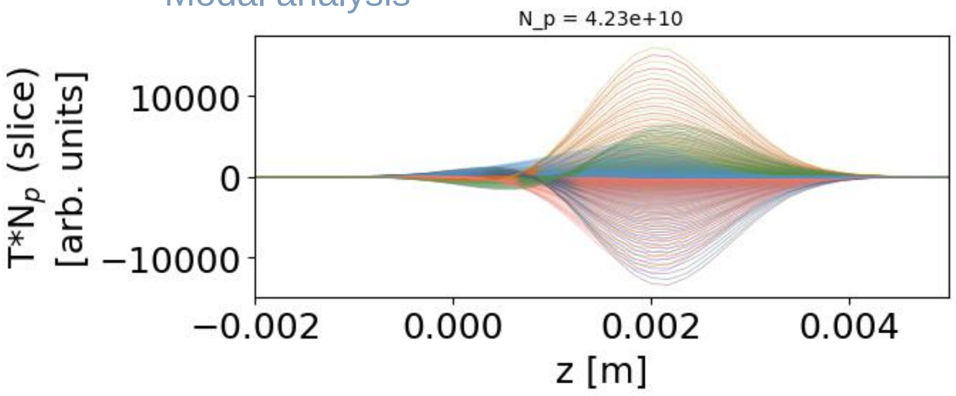
We consider the case with no IBS and with IBS, using MAD-X routines.

Courtesy: Adnan Ghribi

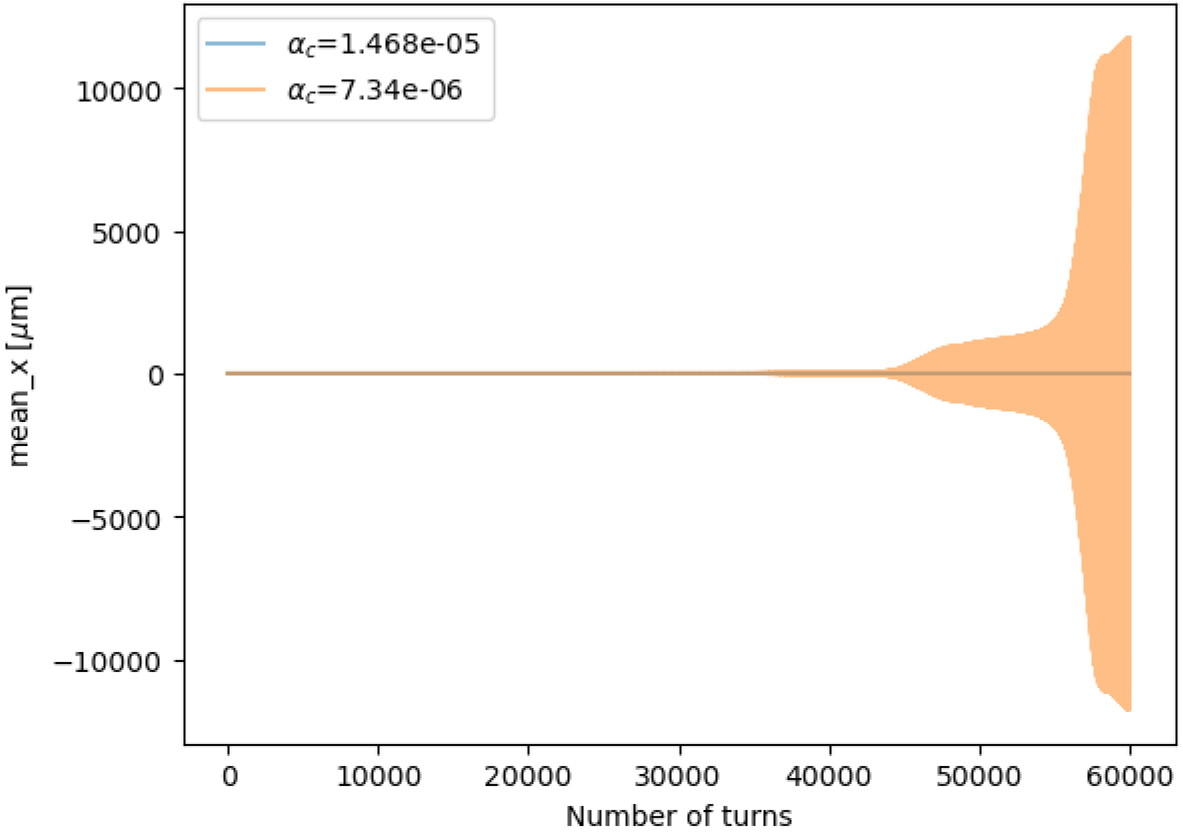


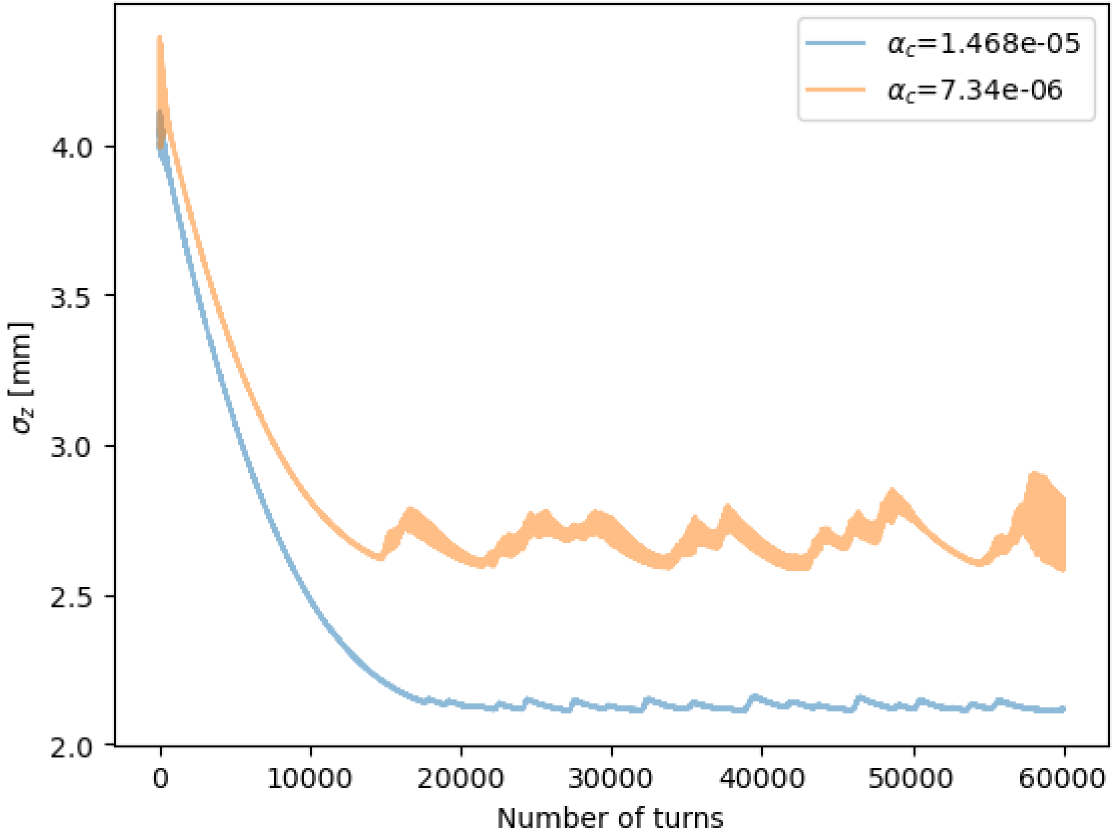
Modal analysis



Collective effects: momentum compaction effects

Courtesy: Adnan Ghribi





- Doubling the momentum compaction factor gets rid of TMCI at nominal current ;
- **TO DO** : Momentum compaction scan to investigate actual limits.

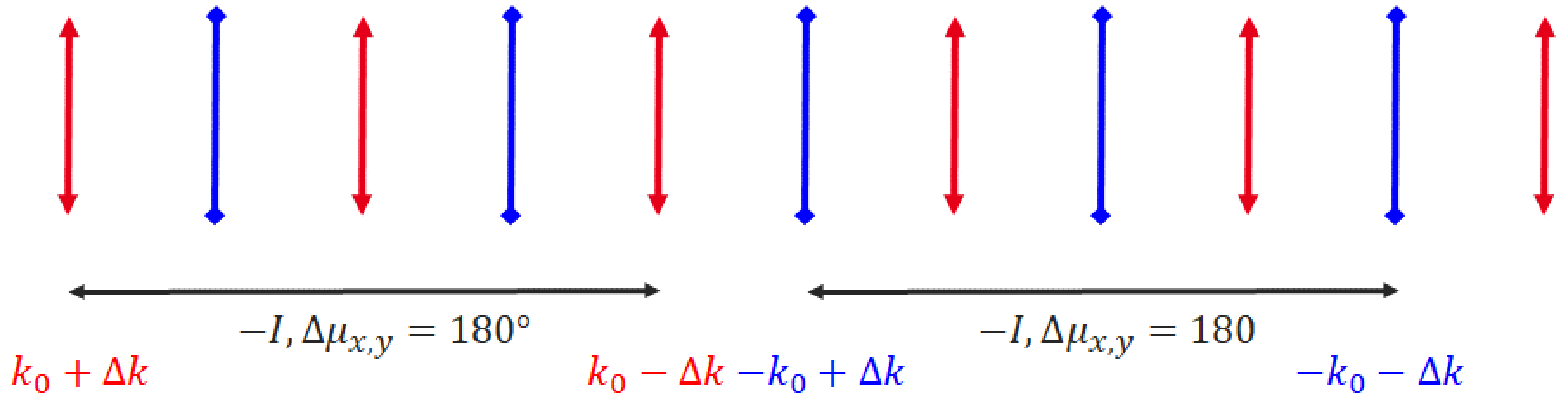
Momentum compaction tuning

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:

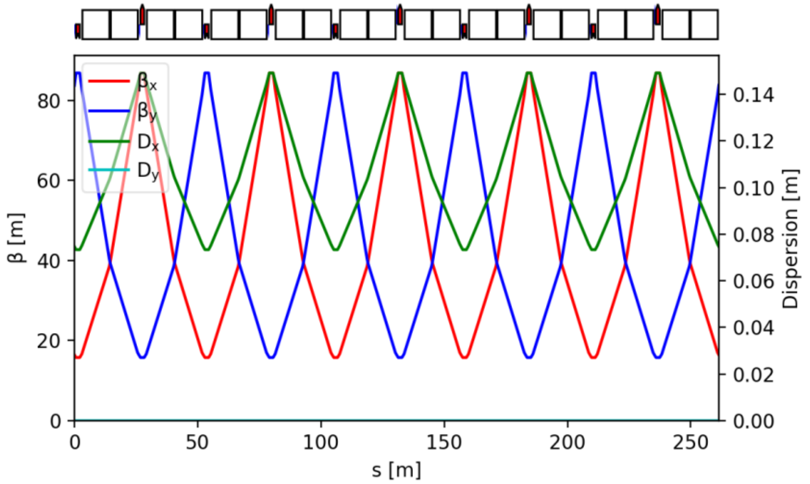
- We can have a larger momentum comapction at injection energy: better for collective effects.
- At higher energies, we can reduce the momentum compaction because collective effects are less critical at higher energy and we can get a smaller equilibrium emittance.



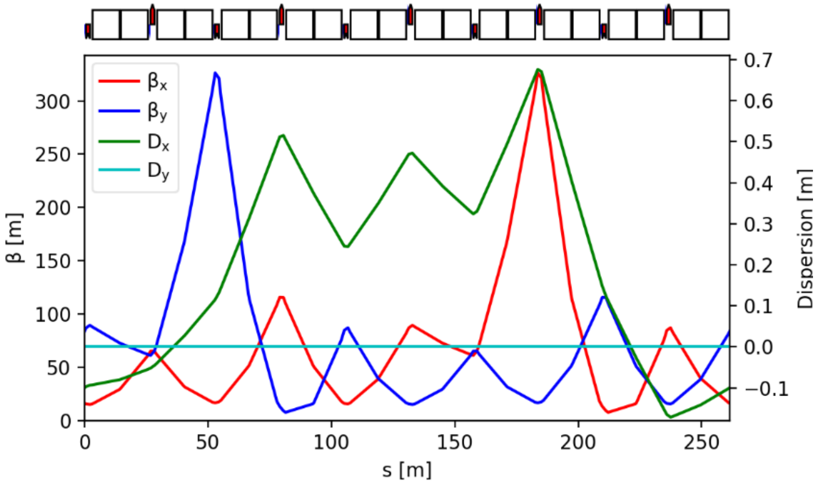
$\Delta k \approx \frac{\sqrt{x}}{2\sqrt{3}}$ with $x = \frac{\alpha}{\alpha_0} - 1$ where α is the momentum compaction and 0 when Δk=0

Alternative optics: comparison with the cell

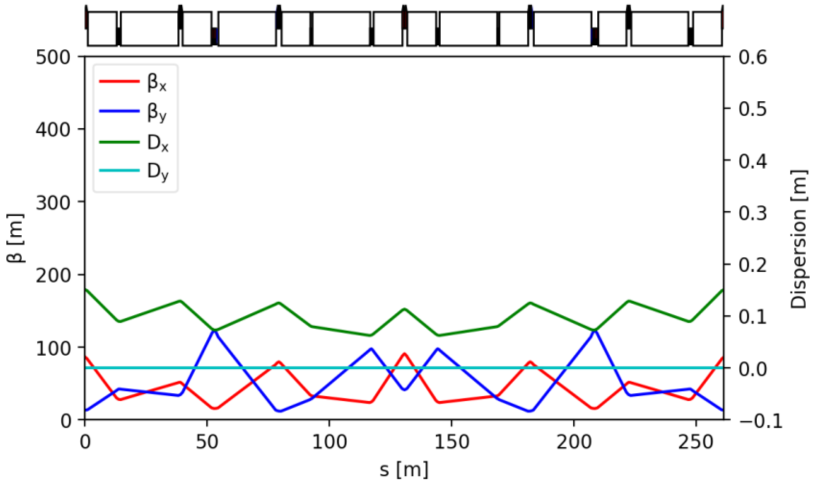
Arc FODO cell



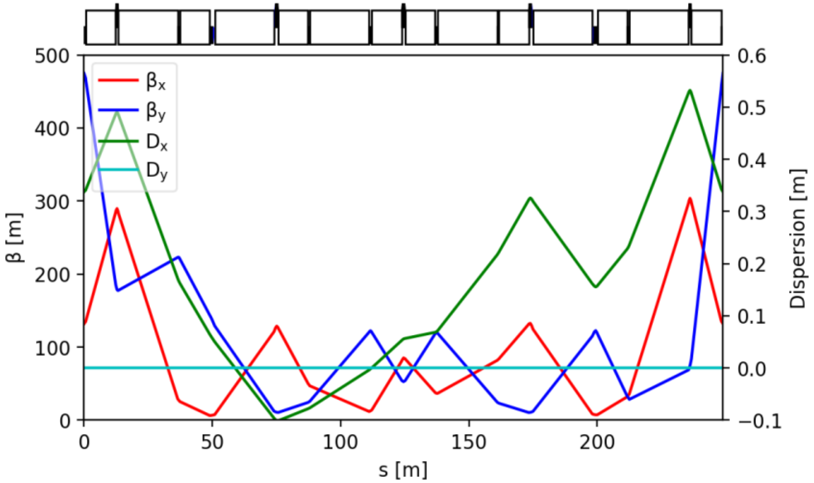
Arc FODO cell $\alpha \times 2$



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:

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

Conclusions

Optics:

- Procedures have been written to optimize the layout and booster positioning in the tunnel.
- Matching conditions have been updated to increase the transparency of the insertions.
- The dispersion suppressor needs to be improved to correct the 2nd order dispersion in the long insertions.

RF budget has been updated for 800 MHz cavities

Strong reduction of dynamic aperture and momentum acceptance due to synchro-betatron resonances

- Tune has been optimized
- Criteria stabilities under investigation to understand DA reduction

Orbit tuning

- First definition of the orbit correctors for the booster (≃ 20 mT) and orbit correction scheme.
- First specifications of elements misalignment (150 μm)
- Finalize the emittance tuning studies

HEB operation and emittance evolution

- Optimization of cycle time at Z
- IBS integrated in accumulation process
- Updates of the cycling in case of SPS as an injector

Collective effects

- Not real impact of injecting a mismatched beam.
- First Intensity scans at injection with PyHEADTAIL
- Confirmation of intensity above threshold for Z operation with 90 degrees FODO cells contrary to 60 degrees FODO cells.*
- Doubling the momentum compaction cures the TMCI.

An alternative optics to 60° FODO cells has been proposed.

- Momentum compaction of the HBD cell can also be tuned.

Perspectives

Optics and layout
- Provide a full list of the elements for the mid-term review.
- Provide an optics with the HBD cell.
- Apply the momentum compaction tuning to the optics and evaluate the impact on DA and MA.
- Evaluate the impact of the fringe field of the detectors on booster optics.

Dynamic aperture and momentum acceptance
- Improve DA and MA (increase the number of sextupole families for instance)
- Evaluate the dynamic aperture and momentum acceptance for the HBD optics and with a doubled momentum acceptance.

Machine tuning
- Finalize emittance tuning
  - Static and dynamic imperfections
  - Improve overall performances/cost with AI

Cycling optimization

Collective effects
- Perform a momentum compaction scan to find the threshold for TMCI
- Add the IBS
- Perform the calculations with X-Suite to include the optics

FCC

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.

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.

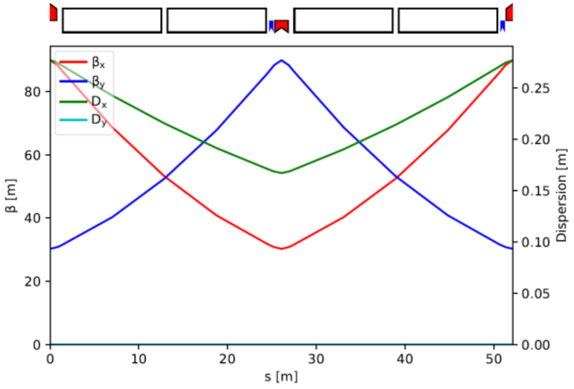
If we do not modify the I2 function (with different dipole families), we should have a flat top of at least 2 seconds to damp the beam with an initial round normalized emittance of 10 µm.
The duration of the flat top depends on the initial emittances 1-3 s for 1-50 µm.

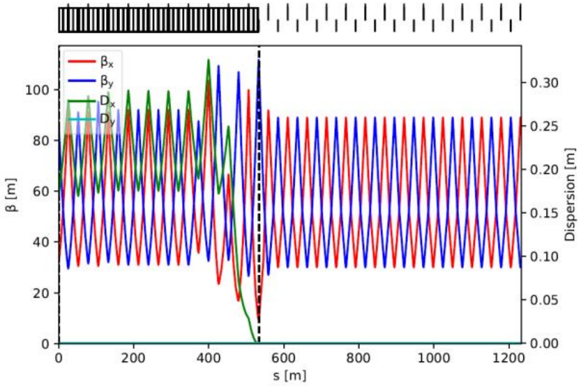
We have assumed that the beam is matched at the entrance. An initial energy spread of 0.1% gives a bunch length of 7.2 mm. We could reduce a bit the initial bunch length by increasing the initial RF voltage but we are quickly limited by the maximum total RF voltage.
If we do not match the longitudinal 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.

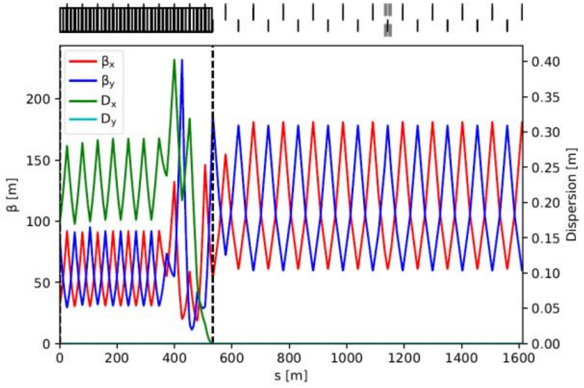
Optics updates

Magnet	Parameter	Unit	Value
Dipole	Field at injection (20 GeV)	G	71
	Field at W energy (80 GeV)	G	284
	Length	m	11.1
Quadrupole	Gradient at injection (20 GeV)	T/m	1.74
	Gradient at W energy (80 GeV)	T/m	6.9
	Length	m	1.5
Sextupole	Gradient at injection (20 GeV)	T/m^2	75
	Gradient at W energy (80 GeV)	T/m^2	300
	Length	m	0.5

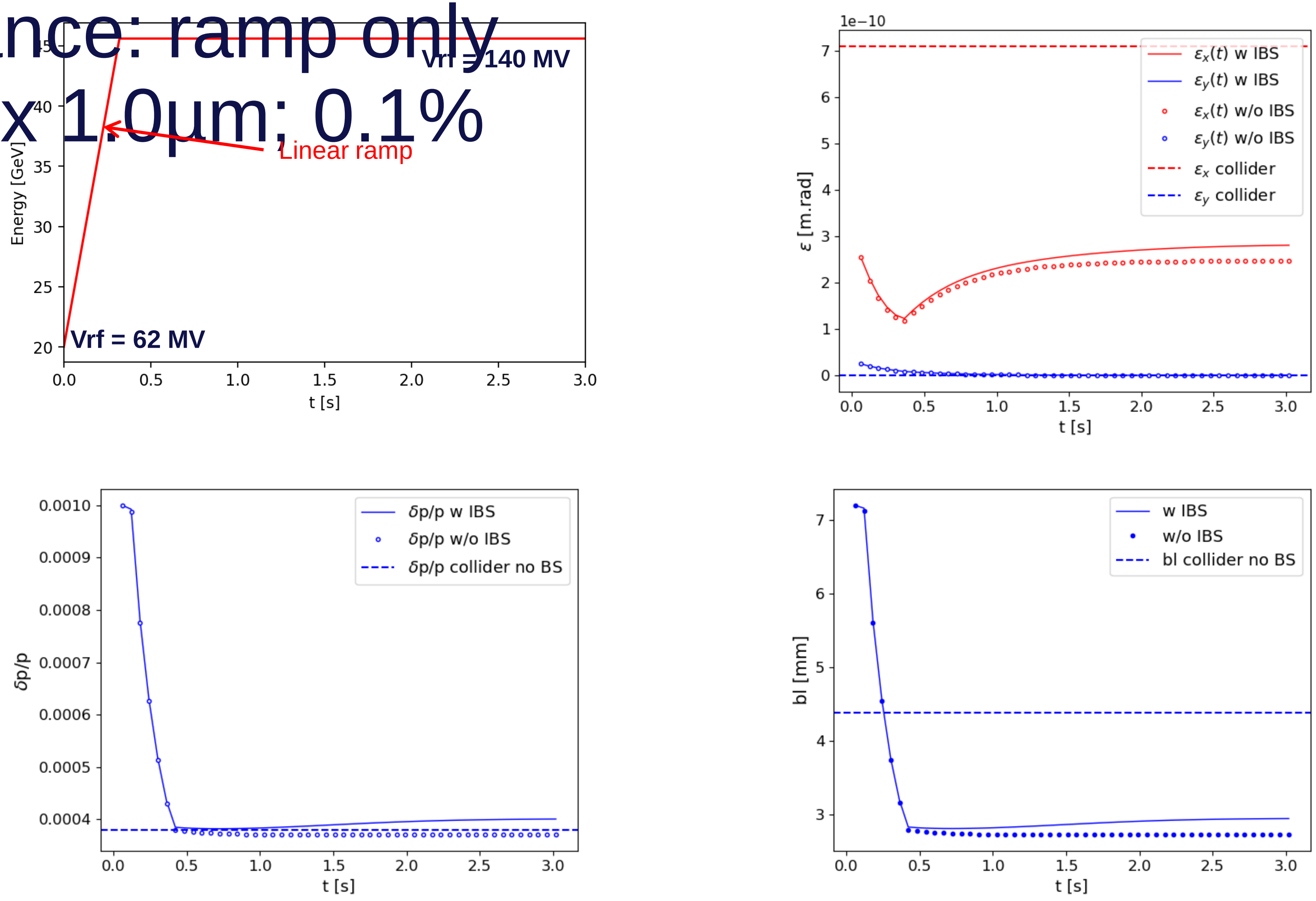
- FODO cells of ~52 m
- Made of 4 dipole, 2 quadrupoles and 2 sextupoles
- => Very challenging low dipole field at injection
- Distance between dipoles: 0.4 m
- Distance between quadrupole and sextupole: 0.165 m
- Distance between dipole and sextupole: 0. 504 m
- Distance between quadrupole and dipole: 0.869 m
- (it includes space for BPM and dipole correctors)
- # dipoles = 2 x 2944
- # quadrupoles = 2944
- # sextupoles = 2632/6







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



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.