OFF-ENERGY OPERATION FOR HMBA LATTICES

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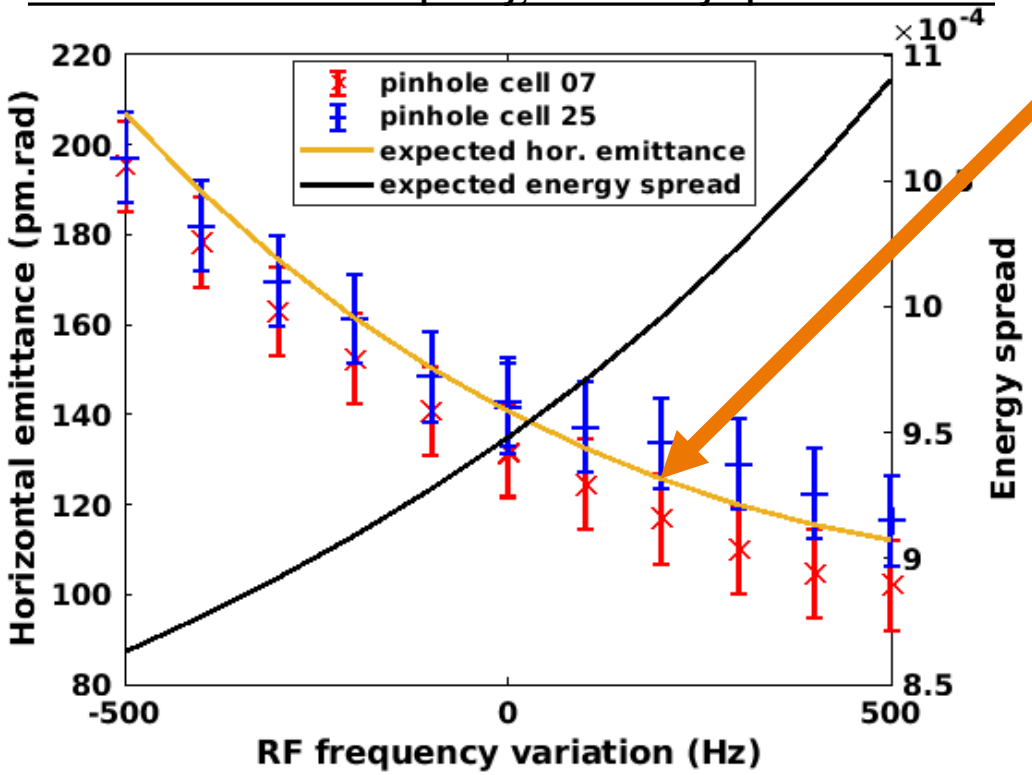
OFF-ENERGY OPERATION : PRINCIPLE

Objective: Obtain lower natural horizontal emittance keeping the existing Hybrid Multi-Bend Achromat (HMBA) layout.

Proposed solution: operate off-energy (present booster operation mode*).

Variation of the simulated (yellow line) and measured, horizontal emittance with the RF frequency, without any optics correction.



Expected 20 pm.rad reduction for a +300Hz shift in the RF frequency

Link between the energy deviation δ and the RF frequency shift Δf_{RF}

$$\delta = \frac{\Delta p}{p} = -\frac{1}{\alpha_C}\frac{\Delta f_{RF}}{f_0}$$

with p, the particle momentum, α_c the momentum compaction factor, and f_0 the nominal RF frequency following the synchronous principle.

Outline

- Optics proposal at -1% energy deviation
- Comparison of dynamic aperture and lifetime with errors and corrections
- Experiments in the storage ring :
  - DA measurement
  - Lifetime optimisation

*N. Carmignani et al., Proc. 12th IPAC'21, Campinas, SP, Brazil, 2021, paper MOPAB051
or N. Carmignani et al., Proc. 9th IPAC'18, Vancouver, BC, Canada, April 29-May 4, 2018

OFF-ENERGY HYBRID MULTI-BEND ACHROMAT STANDARD CELL

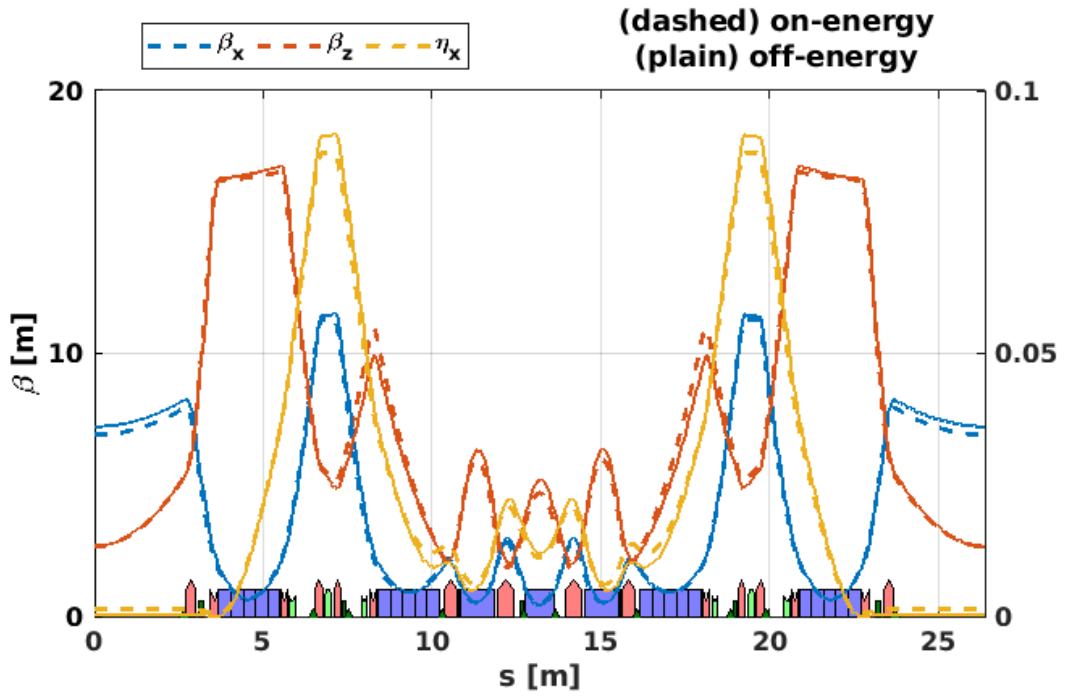
The optics off-energy were rematched to recover the on-energy optics: tunes, -I transformation, dispersion bumps, canted cells, SB, 2PW/3PW, etc.

- **Slightly lower dispersion in the straight section**
- **Higher horizontal beta function in the straight section**

Magnet strength variations

-0.48% Dipole Quadrupoles (DQs) of the nominal lattice, within +/- 5 % for quadrupoles and sextupoles.

Comparison of the standard cells of the on-energy and the off-energy lattices



Comparison of the nominal and the off-energy optics for ESRF-EBS

Energy deviation	0%	-1 %
Betatron tune (Q_x, Q_y)	(76.180, 27.340)	(76.184, 27.341)
Nat. hor. em. ϵ_H	**140 pm.rad**	**121 pm.rad**
Energy spread	**9.5 E-4**	**1.0 E-3**
Mom. comp. factor	**8.6 E-5**	**7.65 E-5**
Energy loss	2.6 MeV	2.5 MeV
Chromaticity	(8.3, 5.5)	(6.6, 6.2)*

*chromaticity was matched during the standard cell optics matching, for a reference theoretical chromaticity of (7,6).

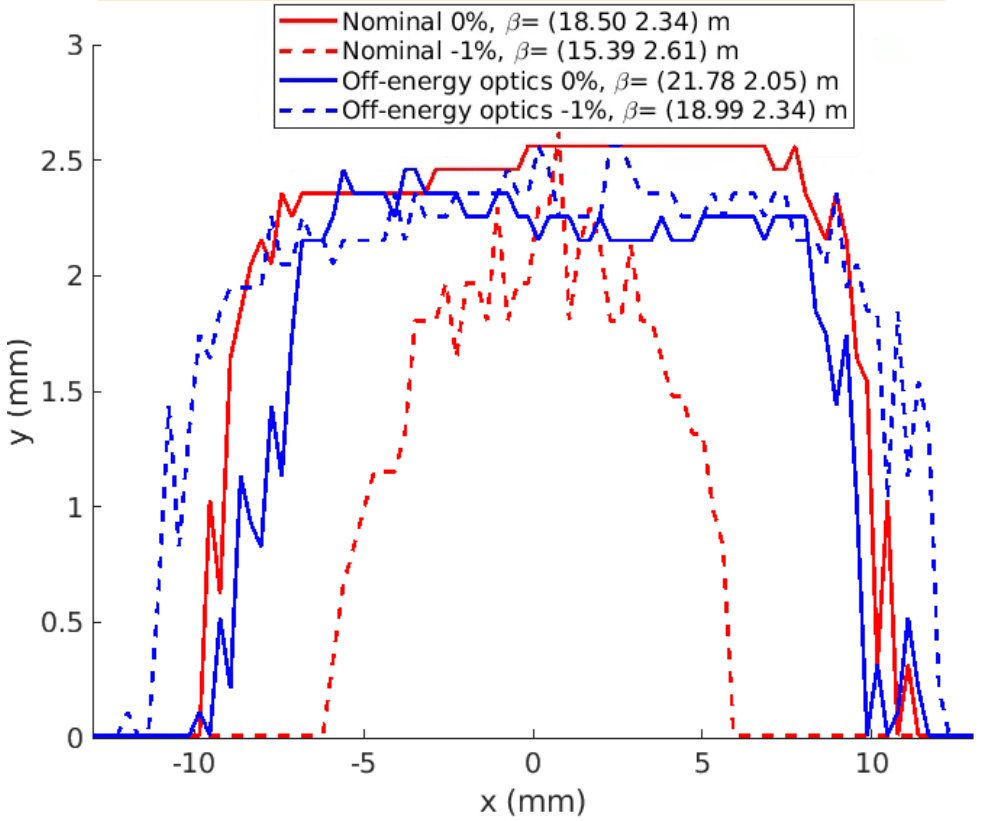
DYNAMIC APERTURE AND TOUSCHEK LIFETIME – COMPARISON

The off-energy optics restore the DA at the injection point of the on-energy lattice.

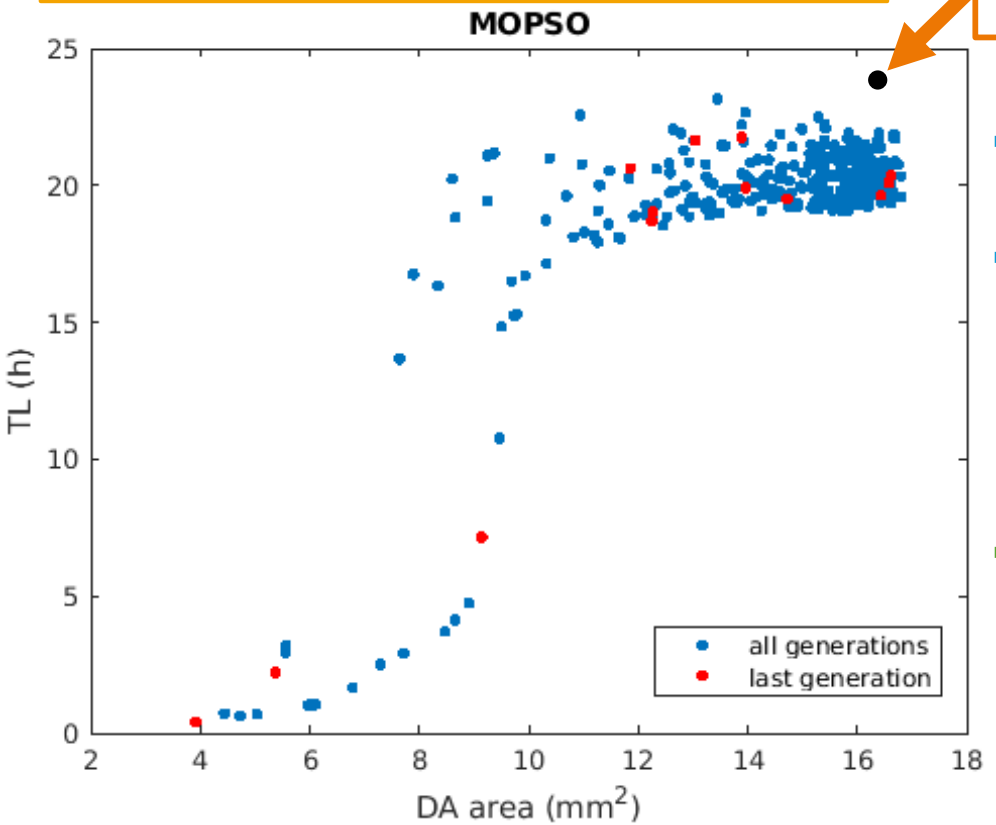
About 30% reduction of lifetime → the injection sextupoles will be used to optimize the Touschek lifetime.

Filling mode	Off-energy lattice	Nominal lattice
7/8	24.4 h	35.5 h
16 bunches	2.36 h	3.38 h
4 bunches	1.62 h	2.31 h

DA at injection tracked over 5000 turns



Lifetime and DA optimization using MOPSO*



Current off-energy option

- Knobs: injection sextupoles
- Chromaticity and tune correction using a 4x4 response matrix with QF1/QD2 and SF2/SD1(BD)
- Betabeating constraint

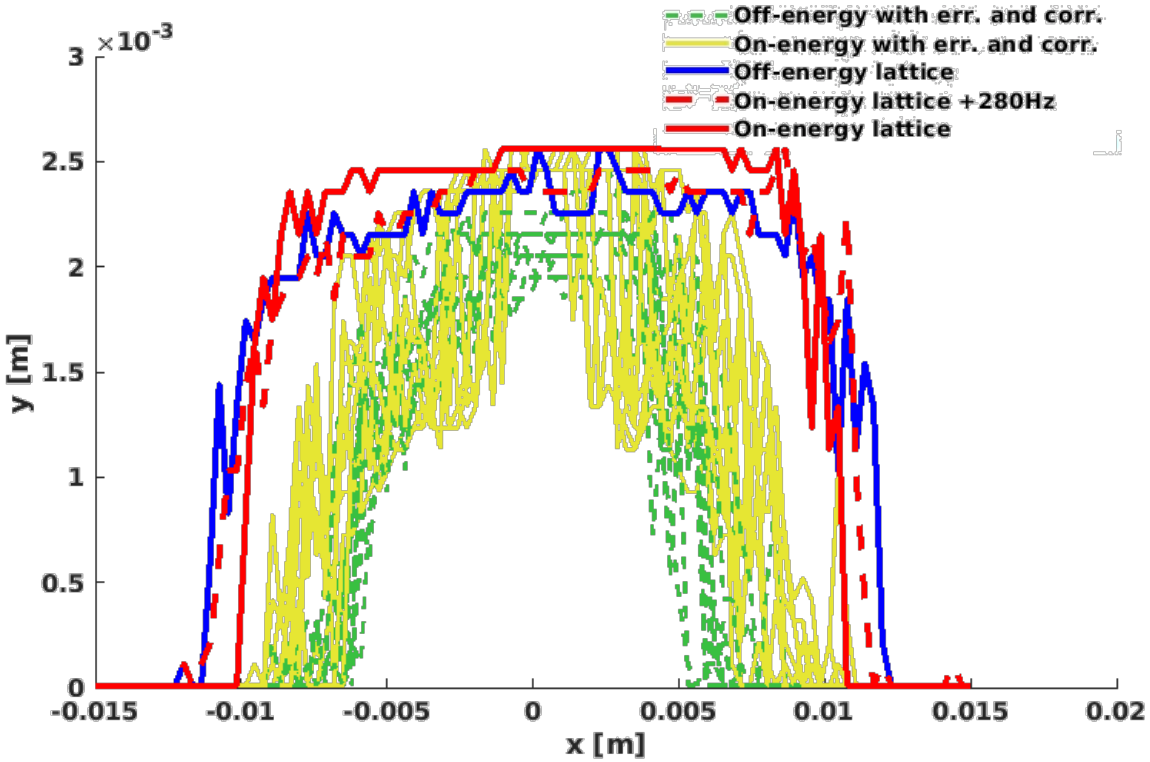
*X. Huang and J. Safranek, NIM A, 2014, v. 757, p. 48-53, doi = 10.1016/j.nima.2014.04.078

DYNAMIC APERTURE AND TOUSCHEK LIFETIME IN THE PRESENCE OF ERRORS

Off-energy quadrupoles settings were applied to the on-energy lattices with errors and corrections. No further optics correction was conducted in simulations, even when required.

Eventually, the final horizontal dynamic aperture is on average 0.4 mm smaller and lifetime reduced by 30% compared to the on-energy case. The matched off-energy optics have the potential to give similar operation parameters as the on-energy optics.

DA at injection in the presence of errors



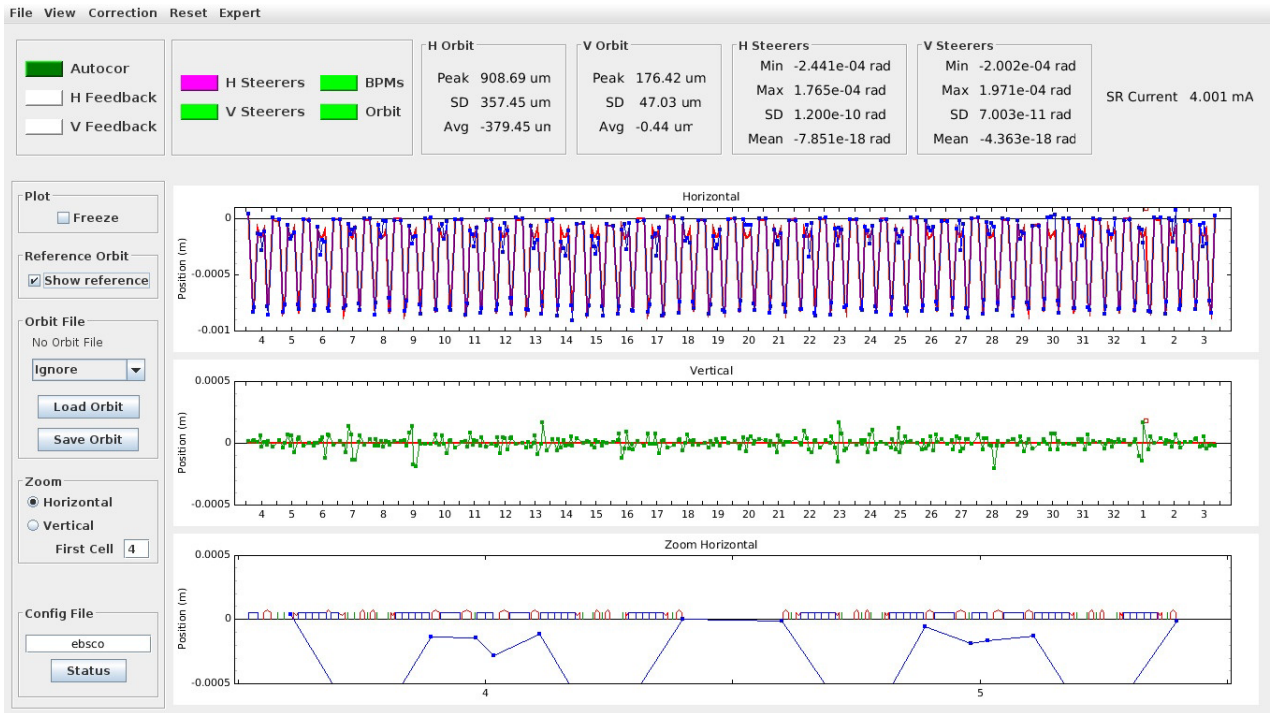
Touschek lifetime in the presence of errors

Filling mode	On-energy lattice Errors+correction	Off-energy lattice Errors+correction
7/8	37.9 ± 1.3 h	26.8 ± 2.2h
16 bunches	2.86 ± 0.09 h	2.59 ± 0.21 h
4 bunches	1.93 ± 0.06 h	1.78 ± 0.15 h

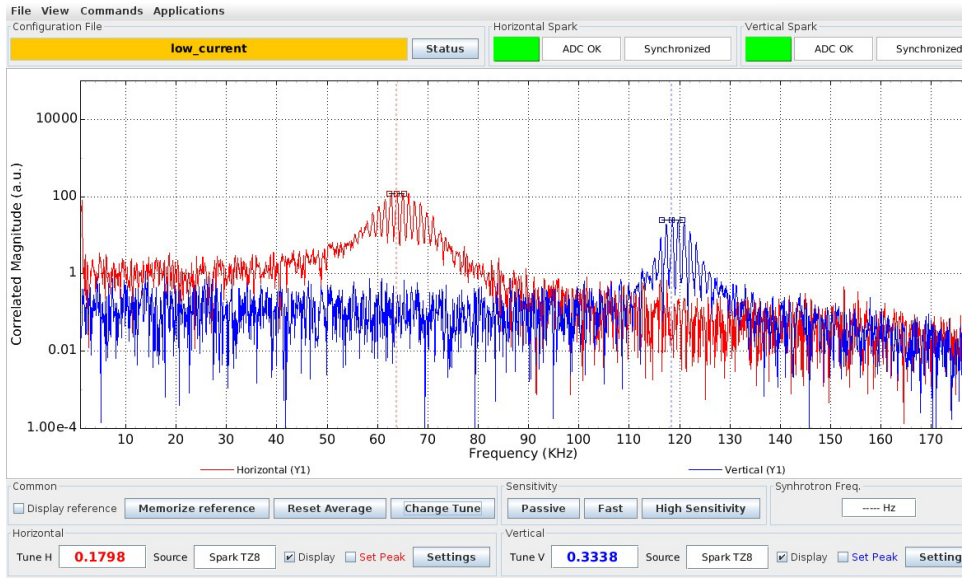
EXPERIMENTS IN THE ESRF-EBS STORAGE RING

CLOSED ORBIT AND TUNES A +280 HZ

Off-energy dispersive reference orbit, at the limit of the BPIs



Same tunes as operation (at the time of the MDT)



Tune and orbit corrections could be conducted with the nominal response matrices

- **High dispersive orbit at the location of the BM sources (about -180 urad horizontal angle)**
- **Effect on the FE and beamline under study, about 10 mm expected shift at the sample for the BMs**

Chromaticity measurement

Chromaticity	Model lattice	Off-energy optics
Model	(7.5, 7.6)	(7,6)* + (-0.4,0.2)
Measured	(9.9, 9.9) ± (1,1)	(8.4, 10) ± (1,1)

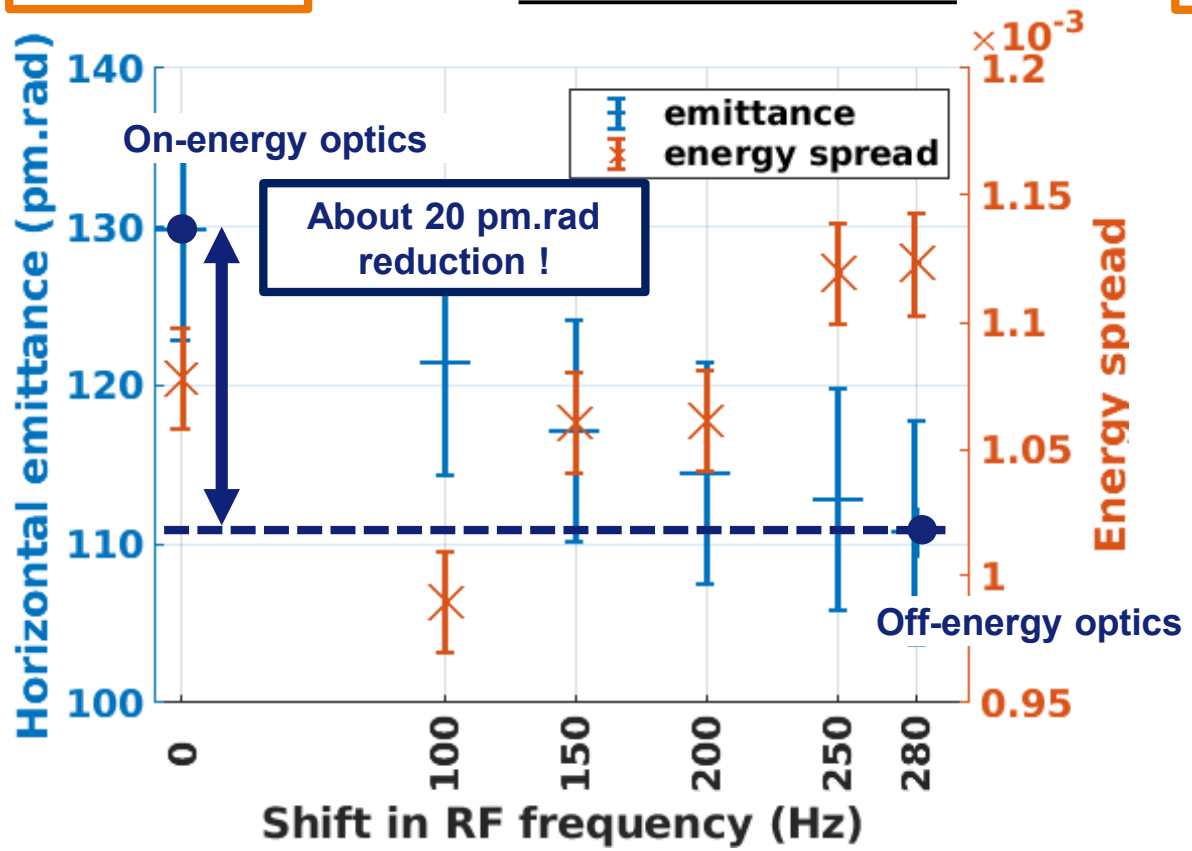
*chromaticity was matched during the standard cell optics matching, for a reference theoretical chromaticity of (7,6).

EXPERIMENTAL RESULTS

- Smooth transition from on- to off-energy settings.
- Injection possible directly on the off-energy settings: optimisation to 70%, close to operation.

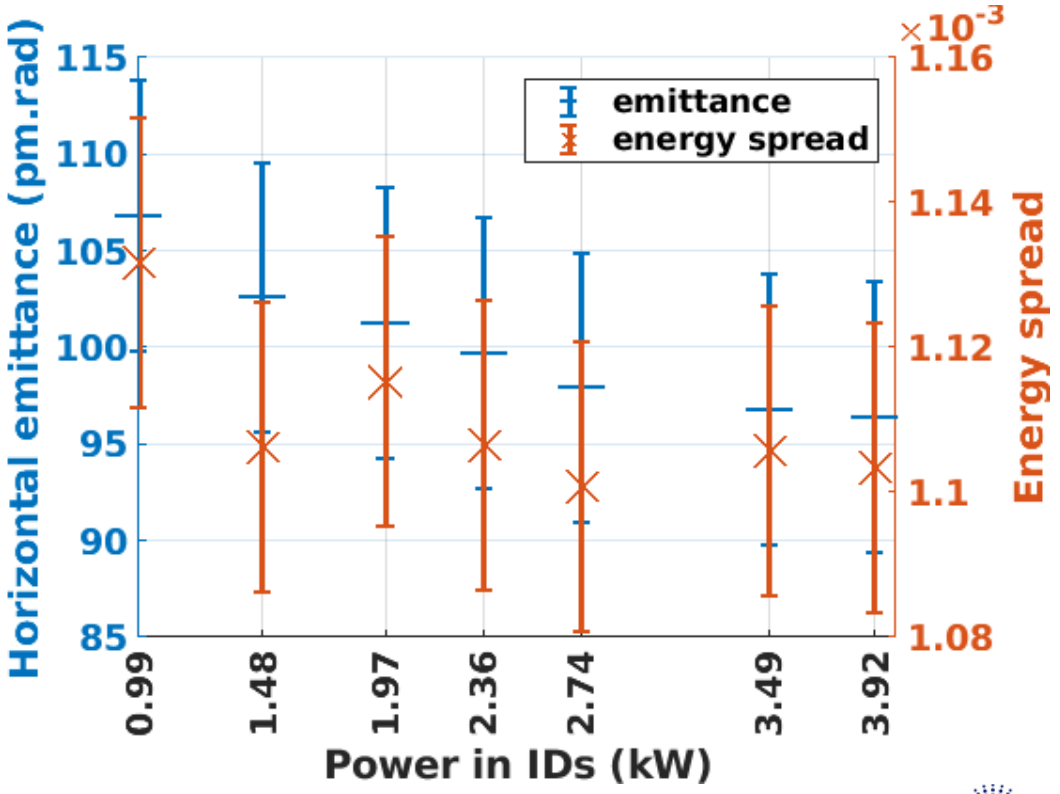
Gaps opened

Measured emittance with the RF shift, optics, tune and orbit correction

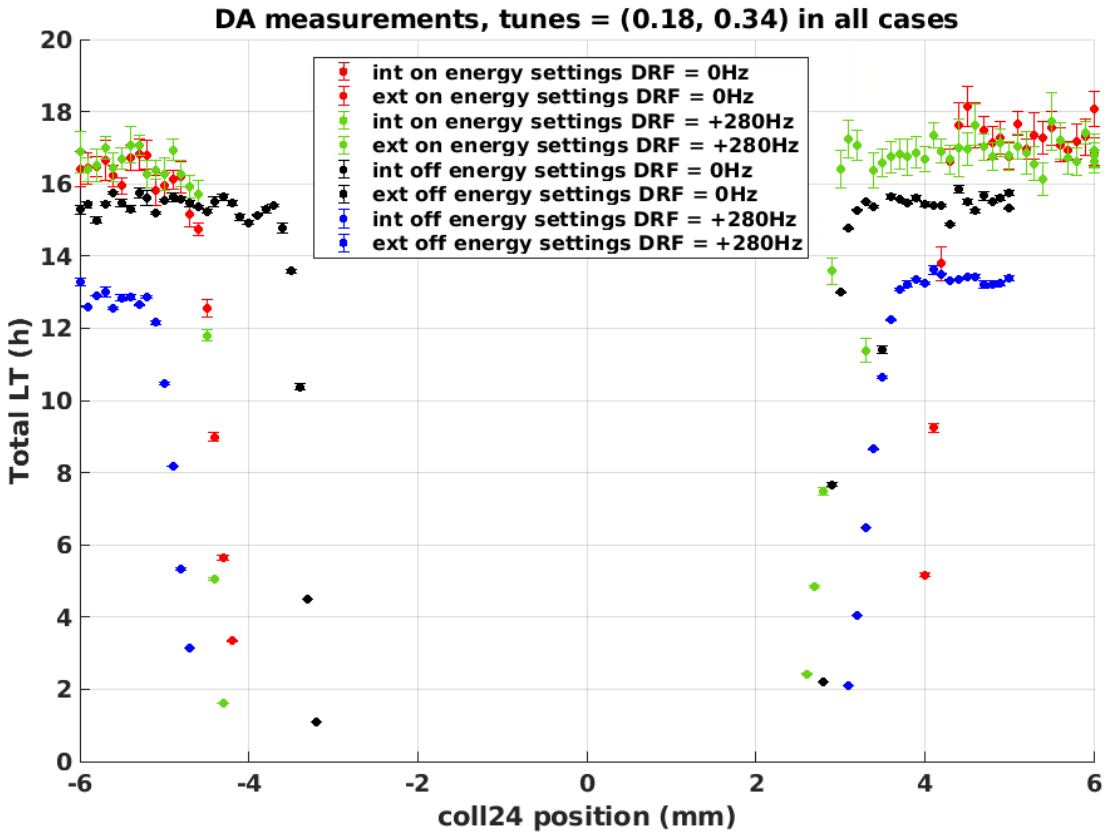


Closing ID gaps…

Measured emittance with ID radiated power (expressed at low current (about 5 mA))



DYNAMIC APERTURE MEASUREMENT



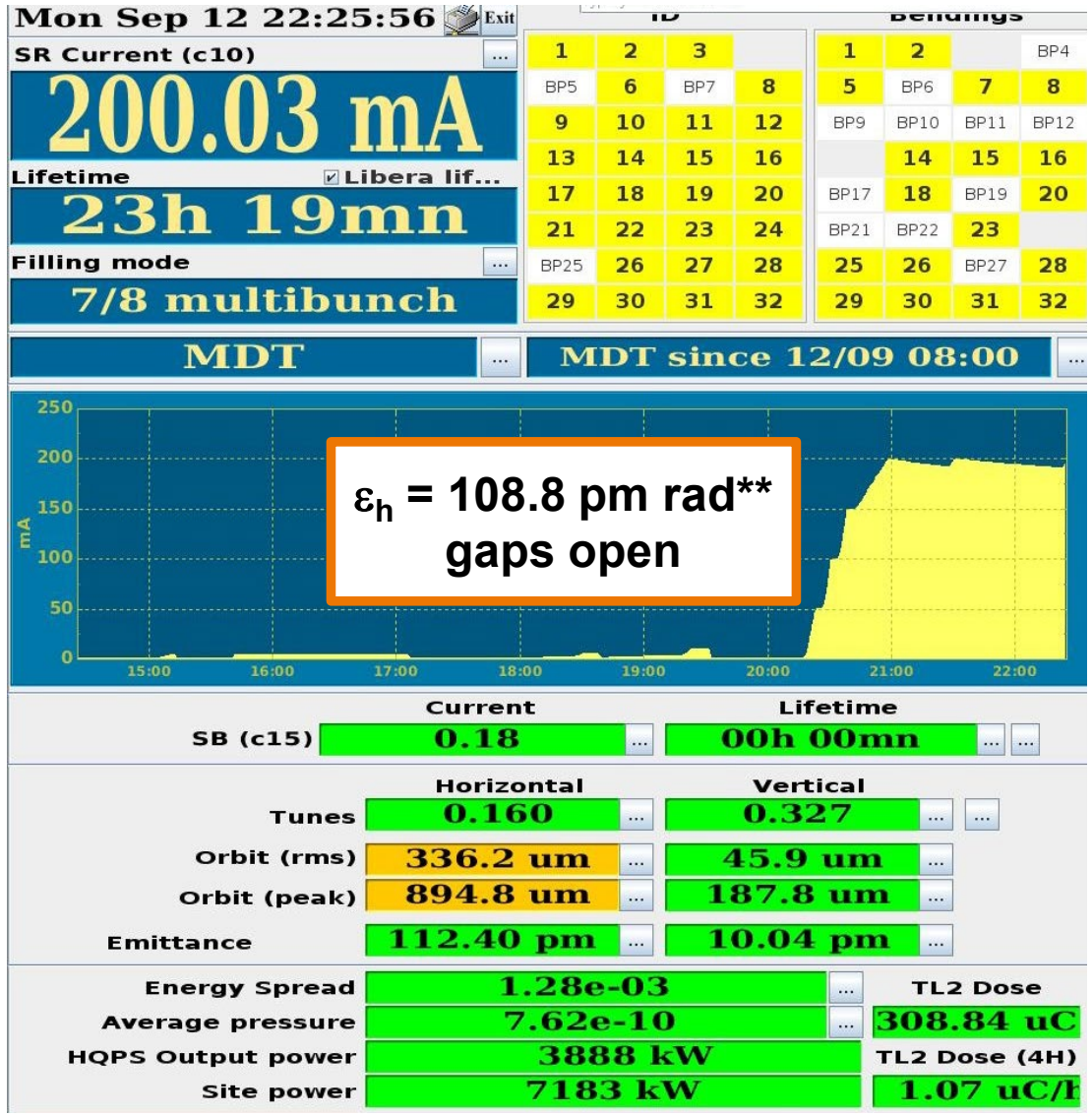
Dynamic aperture measurement on the ESRF-EBS storage ring (scaled at the injection point)

Optics	RF shift	Horizontal DA
On-energy*	0 Hz	$[-6.5; 6.0] \pm [0.2; 0.2]$ mm
	+280 Hz	$[-5.4; 4.9] \pm [0.2; 0.3]$ mm
Off-energy	0 Hz	$[-5.0; 4.3] \pm [0.2; 0.2]$ mm
	+280 Hz	$[-6.3; 6.0] \pm [0.2; 0.4]$ mm

* The on-energy optics used for comparison are the operation settings with removed nonlinear corrections.

Confirmed restoration of the on-energy DA with the off-energy optics.

LIFETIME OPTIMISATION



Quick lifetime optimization using 10 sextupole and 4 octupole knobs*.

Increase of the total beam lifetime

From 11h to 23h

Lifetime [h]	On-energy	-1%	-1% optim.
Vacuum	85 +/- 24	65 +/- 6	126 +/- 26
Touschek	30 +/- 8	13 +/- 1	28 +/- 6

Lifetime versus vertical emittance measurements

Emittance measurements with beam horizontally displaced by 108.8 pm.rad at pinhole ID07 with a vertical emittance of 11.2 pm.rad**.**

To be verified and corrected with the help of diagnostic colleagues at the next MDT.

**rescaled the value with the off-energy optics

* N. Carmignani et al., Proc. 13th IPAC'22, Bangkok, Thailand, 2022, paper THPOPT001

OFF-ENERGY SETTINGS : PERSPECTIVES

- **Limited gains in the ESRF-EBS due to built-in constraints**
  - Ongoing studies to limit the effect of the Short Bending magnets and 2/3-Pole wigglers on the natural horizontal emittance.
- **Impact of the off-energy optics on the brilliance of each type of photon sources under study.**
  - Expected 10-15% brightness increase with the reduction of emittance alone
  - Higher energy spread limits the gain in brilliance in higher harmonics in undulators
  - Reduction of the photon flux with the electron beam energy plus the opened gaps, further limiting the gain in brilliance.

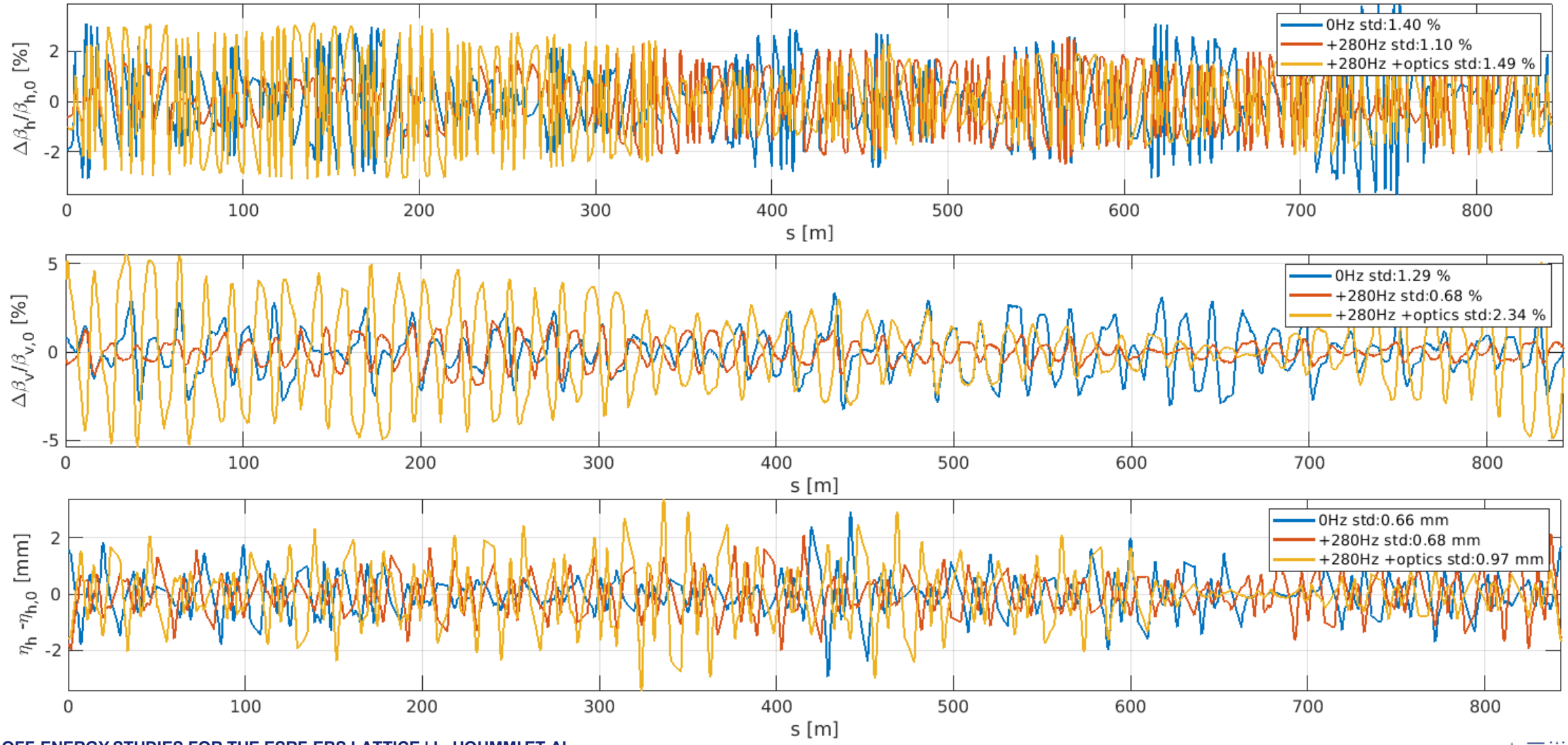
- **Strong interest in green field lattices, where the HMBA optics could be recovered more easily with no power supply constraints, and increase the RF frequency shift by a stronger value.**
- **Reduction of emittance while preserving DA and lifetime, and tunable option. Could be an alternative to reverse bends in HMBA lattices.**

THANK YOU

APPENDICES

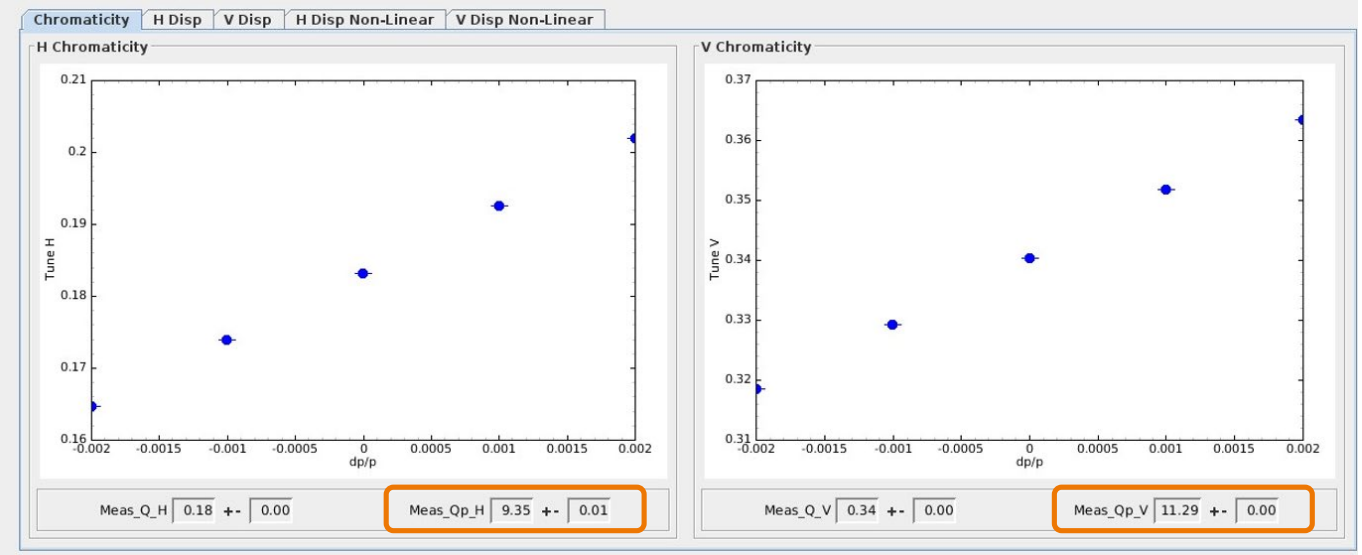
BETA BEATING

Comparison of the beta-beating for the reference on-energy lattice, the reference lattice with +280 Hz RF frequency and the off-energy optics, compared to their corresponding theoretical optics.



CHROMATICITY MEASUREMENT

Off-energy optics implemented on top of the high-chromaticity operation lattice.



Chromaticity	Model lattice	Off-energy optics
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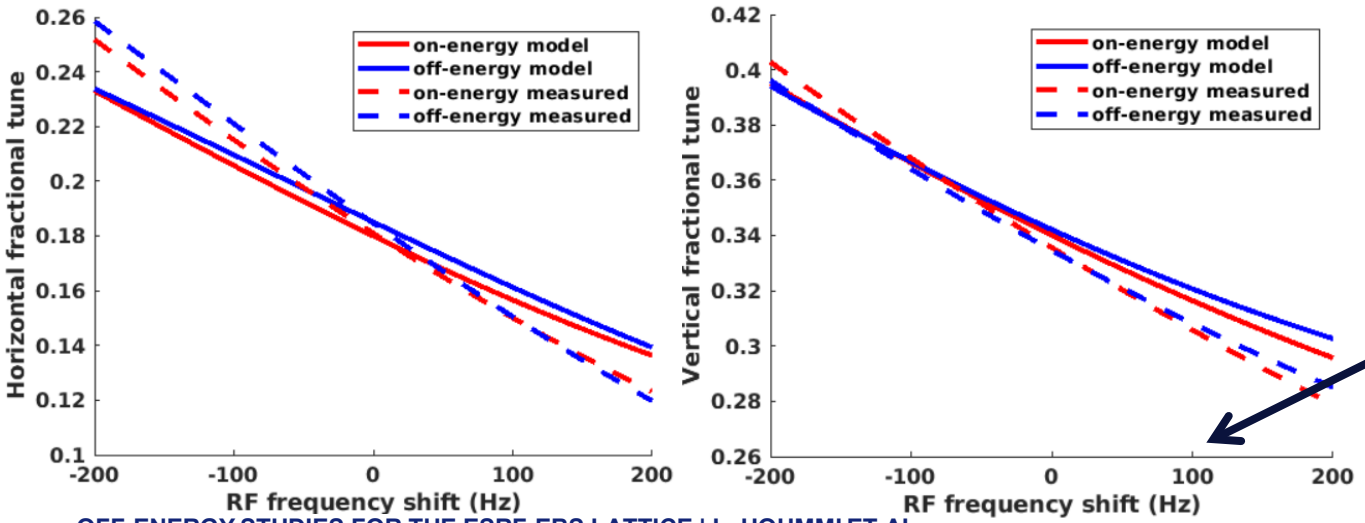
Measured	(9.9, 9.9) ± (1,1)	(8.4, 10) ± (1,1)

*chromaticity was matched during the standard cell optics matching, for a reference theoretical chromaticity of (7,6).

Comparison of theoretical and measured detuning with the RF frequency shift

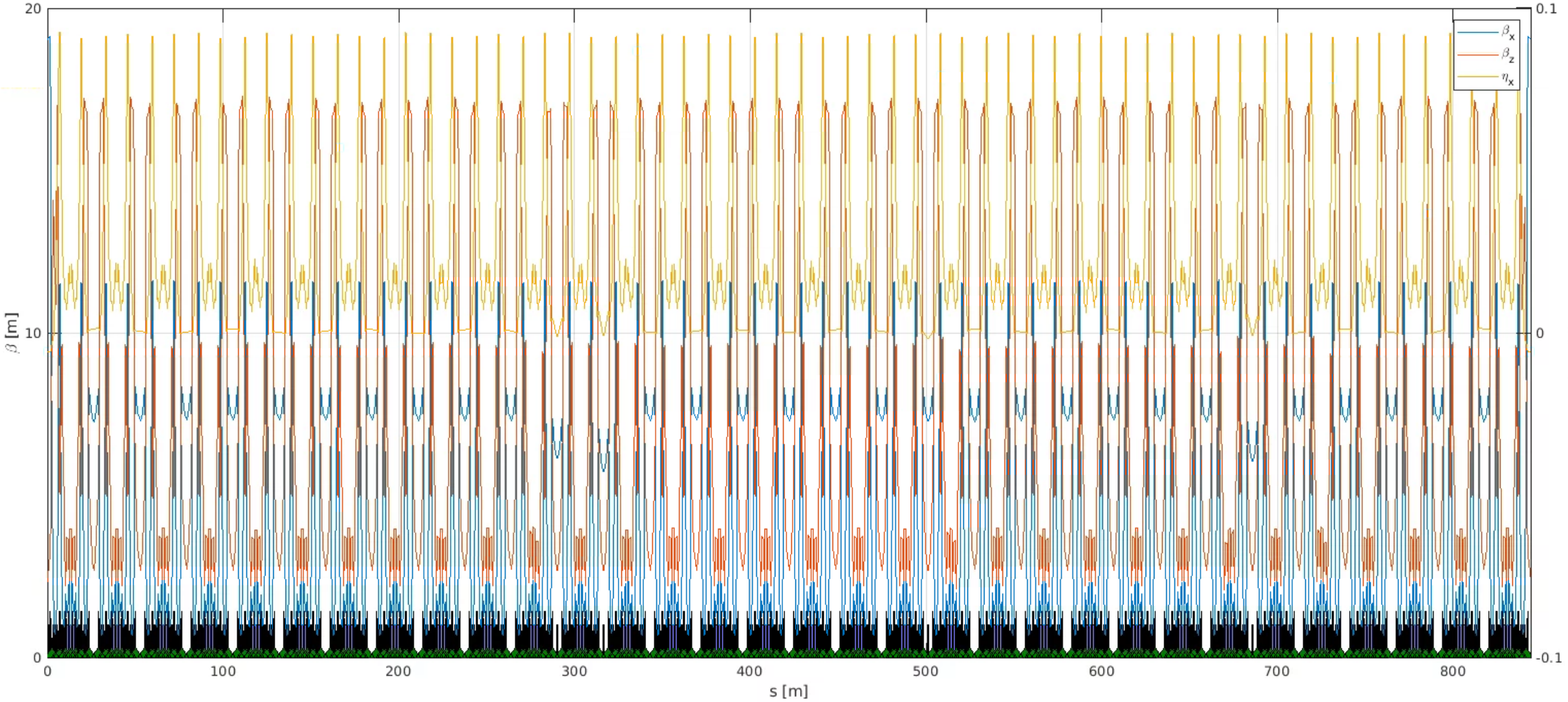


Rescaling the energy deviation to the off-energy momentum compaction factor (=7.65E-5) :

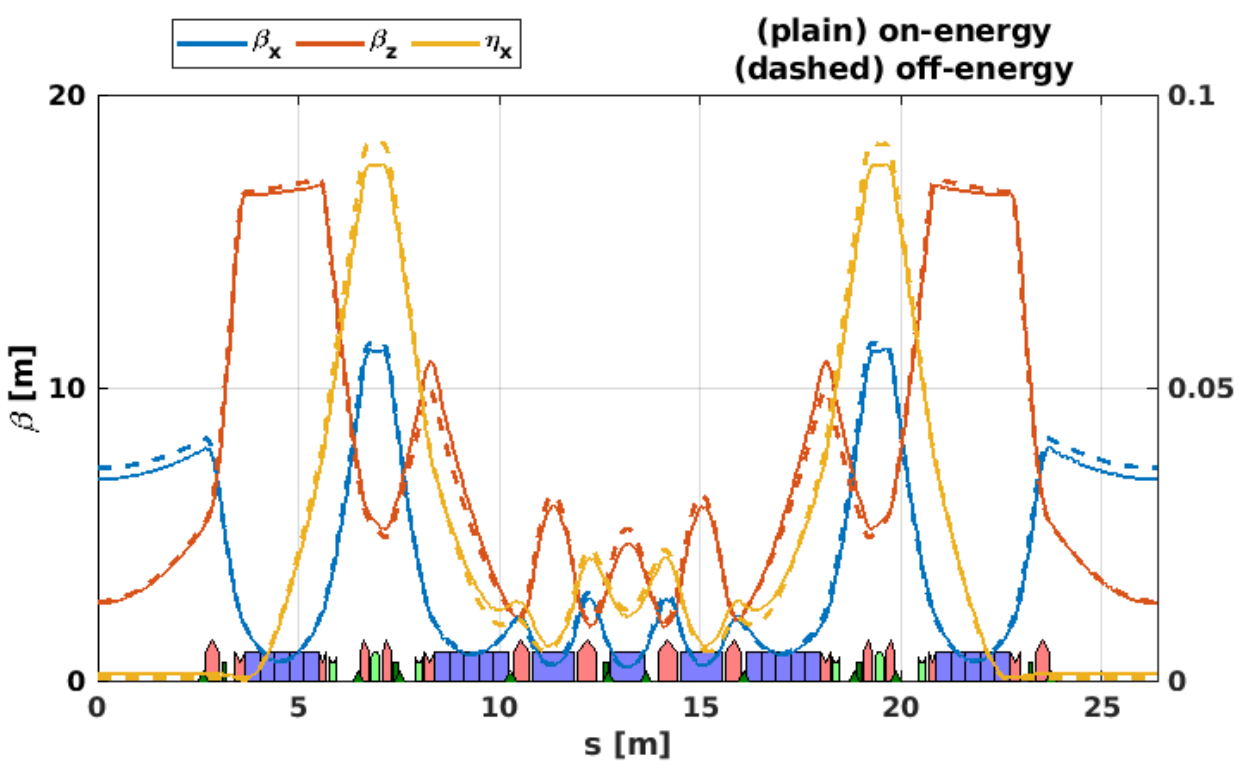
$$(\xi_x, \xi_y) = (8.4, 10)$$

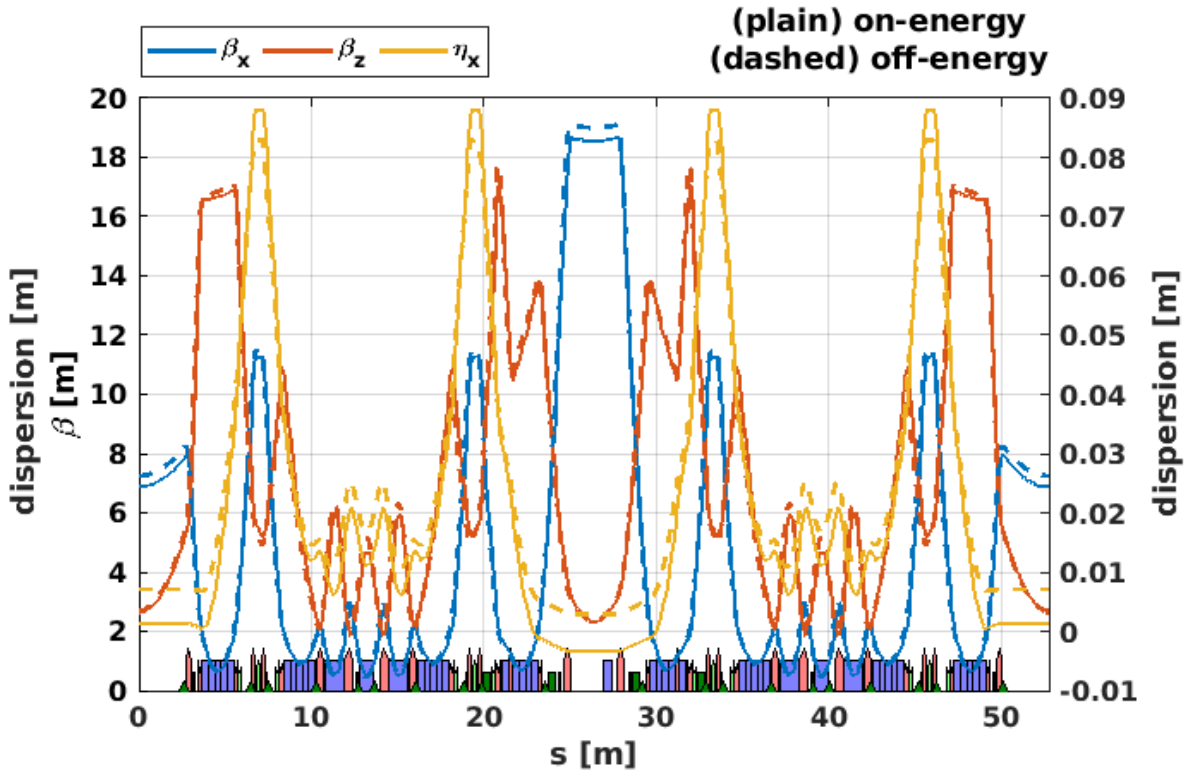
Relative variation of the RF frequency for both lattices.

ν_x= 76.185
ν_z= 27.342 1 period, C= 843.977



CELL COMPARISON BETWEEN ON- AND OFF-ENERGY LATTICES

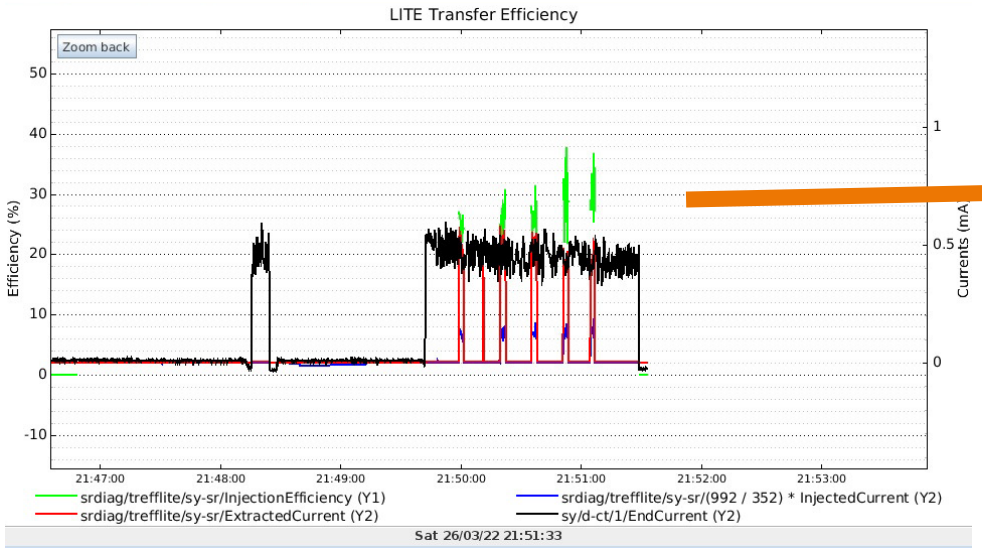




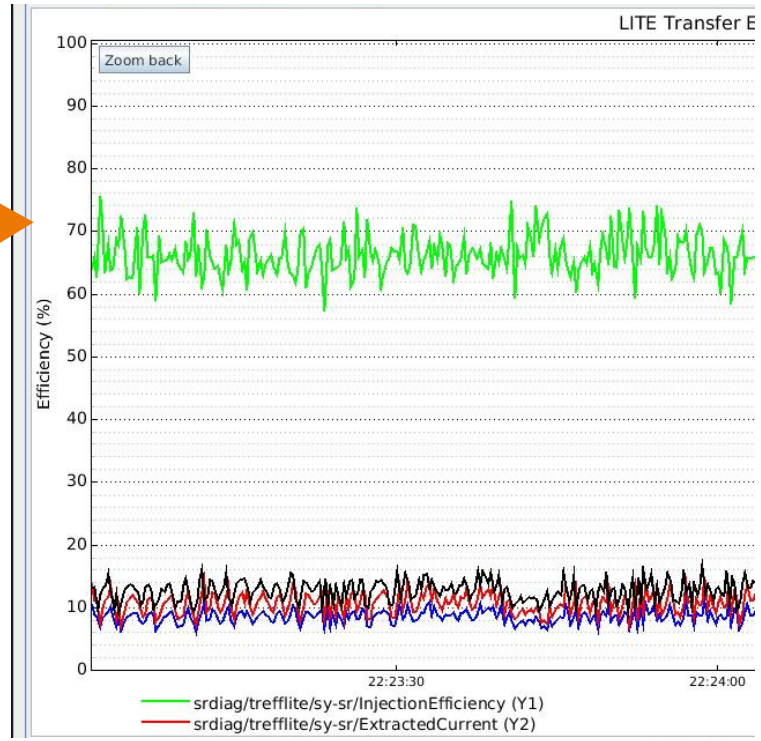
INJECTION EFFICIENCY TUNING WITH SR OFF-ENERGY

Increased injection efficiency from 20-30% to 65%

March 2022



September 2022



Yet, the expected TL2 and injection elements scaling was far from the optimum for I.E (I.E.~10% at half the expected scaling factor).

PARAMETERS FOR LIFETIME CALCULATIONS

Parameters	Off-energy lattice	Nominal lattice
Number of turns	1000	1000
Energy deviation	-1%	0%
Horizontal emittance	121.2 pm.rad	141 pm.rad
Vertical emittance	10 pm.rad	10 pm.rad
Energy spread	1.0E-3	9.5E-4
Bunch length	(4.4, 10.6, 12.6) mm	() mm
Current per bunch	(0.23, 5.8, 10) mA	(0.23, 5.8, 10) mA