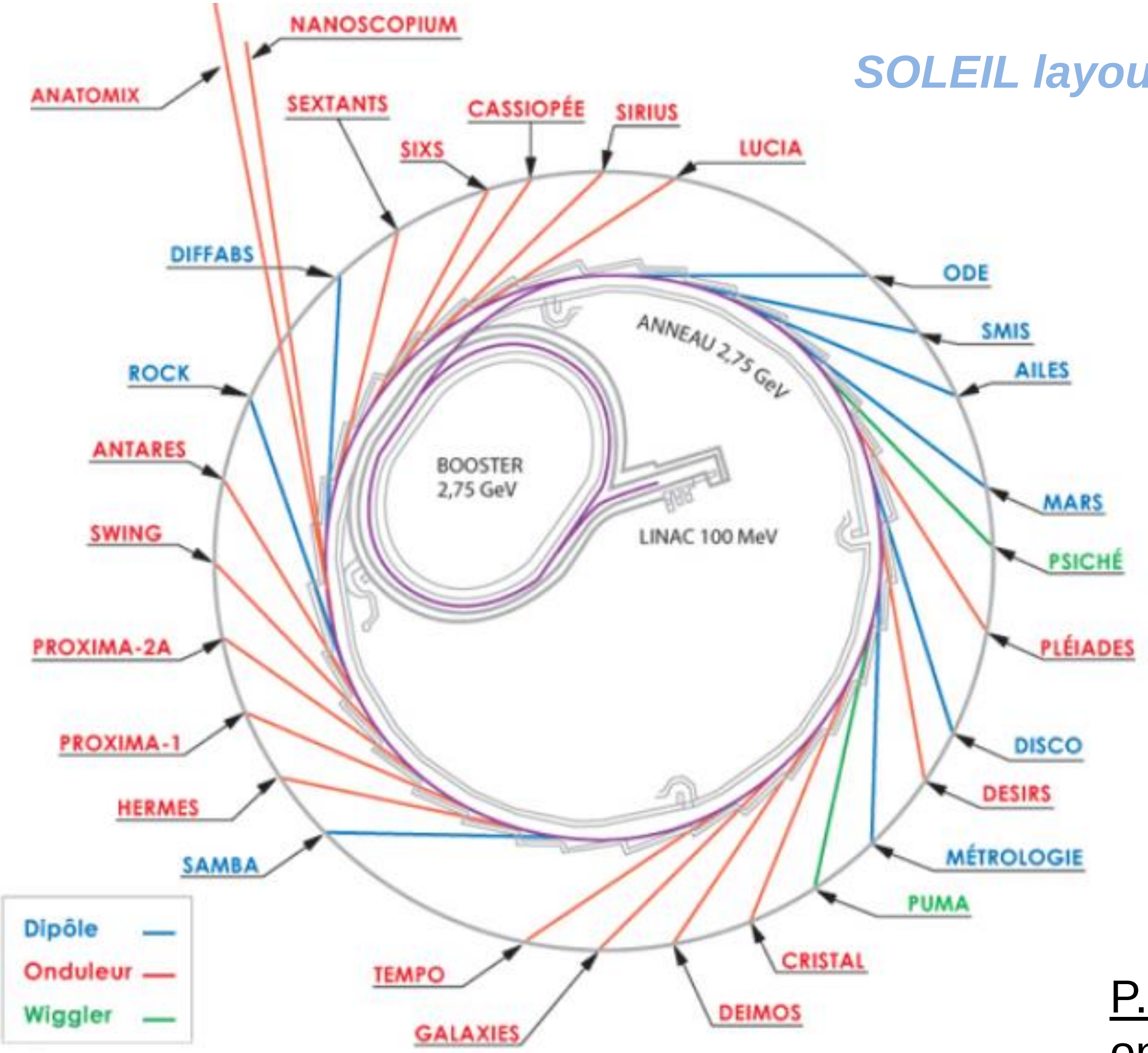


SOLEIL layout

A new injector for SOLEIL II project

P. Schreiber, M.-A. Tordeux, P. Alexandre,
on behalf of SOLEIL UPGRADE Project Team

Outlook

- ❑ Motivation for a new booster for SOLEIL II

- ❑ Constraints for the new booster and proposed solution

- ❑ Injector upgrade general performance

- ❑ New issues:
  - ➢ Coming with low-emittance boosters:
    - Low momentum compaction factor and sensitivity to RF frequency and circumference errors
    - High-focusing optics and sensitivity to power supply tracking errors
    - Small dynamic aperture and sensitivity to LINAC beam emittance and errors
  - ➢ Coming with the presence of a harmonic cavity in storage ring:
    - Achieving filling pattern homogeneity in the storage ring

- ❑ Emittance exchange in the new booster in presence of realistic errors

- ❑ Conclusions

Motivation for a new booster for SOLEIL II

Injection performance into the new SOLEIL II storage ring (SR) has been simulated, taking into account realistic SR errors, physical apertures, presence of 4th harmonic cavity. It uses the non-linear multipole kicker (MIK) for an off-axis injection.

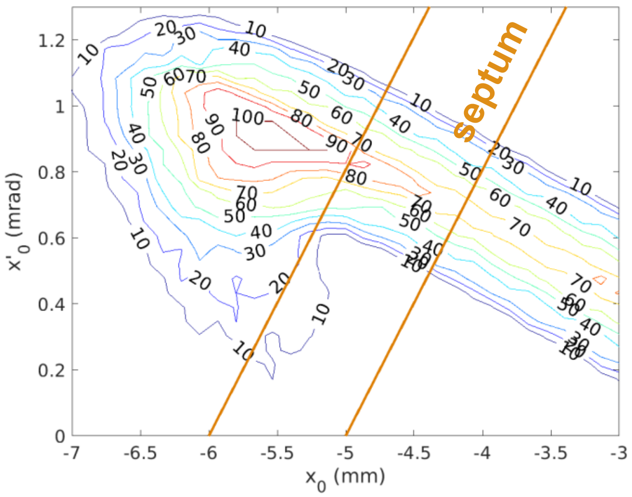
- As far as possible, a 100% injection rate into SR is required in order to:
  - Prevent demagnetization of permanent magnets which are the heavily used in SR SOLEIL II
  - Allow the closure of in-vacuum undulator horizontal and vertical gaps, without losses at these locations
  - Provide sufficient margin to anticipate possible deterioration of dynamic aperture in the long term
- The present booster emittance of 140 nm.rad does not match anymore the beam requirements for injection into the SR.

⇒ A drastic reduction of this natural emittance to less than 10 nm.rad is required.

⇒ An exchange of H and V emittances of the injected beam into the SR could be favorable.

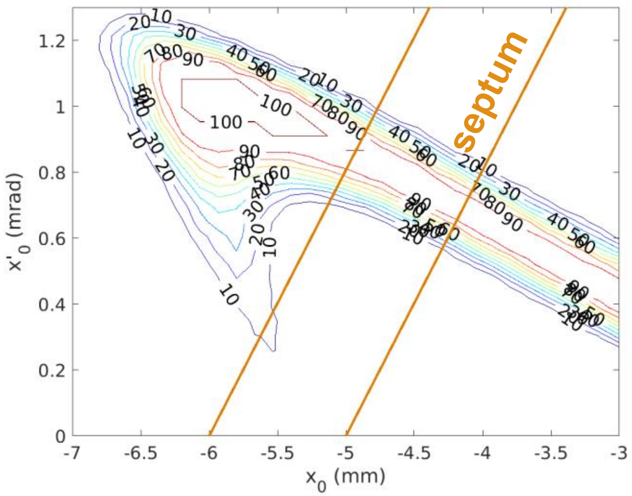
‘Weather map’ of injection:
Injection rate versus horizontal steering errors at SR injection point

- Example of SR lattice version V2366 w/ errors corrected – no multipoles, and 4th harmonic cavity (Dec 2023)
- Injected beam = hypercontour 6D 3 RMS, 512 particles / 2000 turns, σ_S =25 ps, $\sigma_{E/E}=10^{-3}$



Booster emittances: ε_x = 5.0 nm.rad, ε_z = 0.5 nm.rad

Emittance exchange

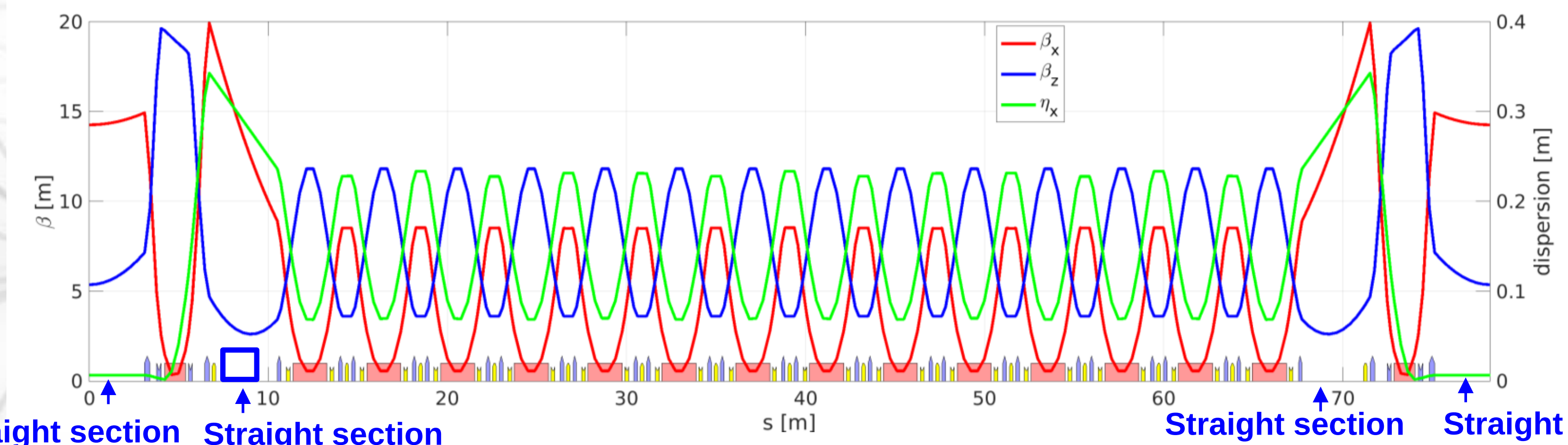


ε_x = 0.5 nm.rad, ε_z = 5 nm.rad

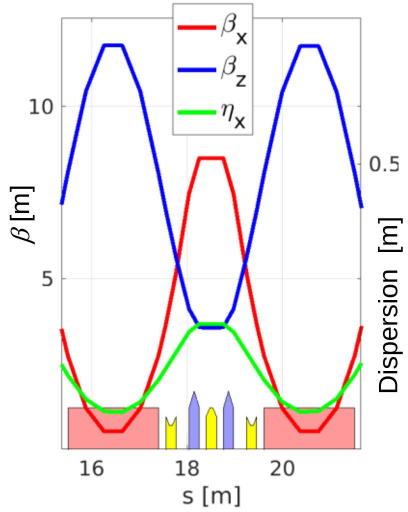
Constraints on new booster and proposed solution

- Technical constraints:
  - Keep the same Booster tunnel, respecting the current race-track lattice configuration
  - Reuse the 2 current RF systems (2 copper units, each comprising 5 cells @ 352 MHz, LEP type)
  - Reuse the LINAC and transfer lines with marginal changes
  - Long-term reliability of the injector

- New Booster: multi-bend achromat with the higher-order-achromat (HOA) concept
  - Design in the frame of a collaboration between SOLEIL and NSRL (Z. Bai).
  - 2 super-periods 16BA lattice based on a combination of three HOA type 5BA cells
  - 2 matching cells, a 6.2 m long straight section for injection and extraction and two 3.44 m short straight sections for existing RF systems and diagnostics.
  - Combined function in dipoles (defocusing dipoles) except in the matching sections, separate function for sextupoles and focusing quadrupoles.



Optics of the booster upgrade (one super-period)



HOA cell

Injector upgrade: general performance

Booster parameters @ 2.75 GeV

Parameter	Unit	Present booster	Upgrade booster
Energy range	GeV	0.11 – 2.75	**0.15** – 2.75
Circumference	m	156.6	156.46*
Natural emittance	nm.rad	140	**5.2**
Betatron tunes	-	6.65, 4.58	13.19, 4.19
Natural chromaticities	-	-7.3,-5.8	-27, -12
Mom. comp. factor	-	$2.8 \cdot 10^{-2}$	**$3.3 \cdot 10^{-3}$**
Damping partitions	-	1, 1, 2	1.58, 1.0, 1.42
Natural damping times	ms	6.3/5.7/2.7	3.3/5.2/3.7
Energy loss per turn	keV	409	554
Natural energy spread	-	$0.66 \cdot 10^{-3}$	$0.93 \cdot 10^{-3}$
RMS bunch length	ps	95 @ 1 MV	**25 @ 3 MV**

* Circumference not yet updated, waiting for SR final circumference

- New booster: low-emittance and short bunch
  - **Natural emittance of 5.2 nm.rad**
  - Momentum compaction factor decreased by a factor 10 compared to the present booster
  - Use of the 2 current RF systems (each comprising 5 room-temperature Cu cells @ 352 MHz, LEP type)
  - to allow 3 MV RF voltage and 25 ps RMS bunch length @ 2.75 GeV

- LINAC upgrade
  - Increase of the **final energy from 110 MeV presently, to 150 MeV** in order to reduce issues at booster injection: eddy currents, remanent field impact and geometric injected emittance, collective effects, as well as to increase the gas lifetime of first injected beam.

- New booster installation and commissioning scheduled for 2029
- LINAC/L2B transfer line upgrades starting from now, completion scheduled for 2026.

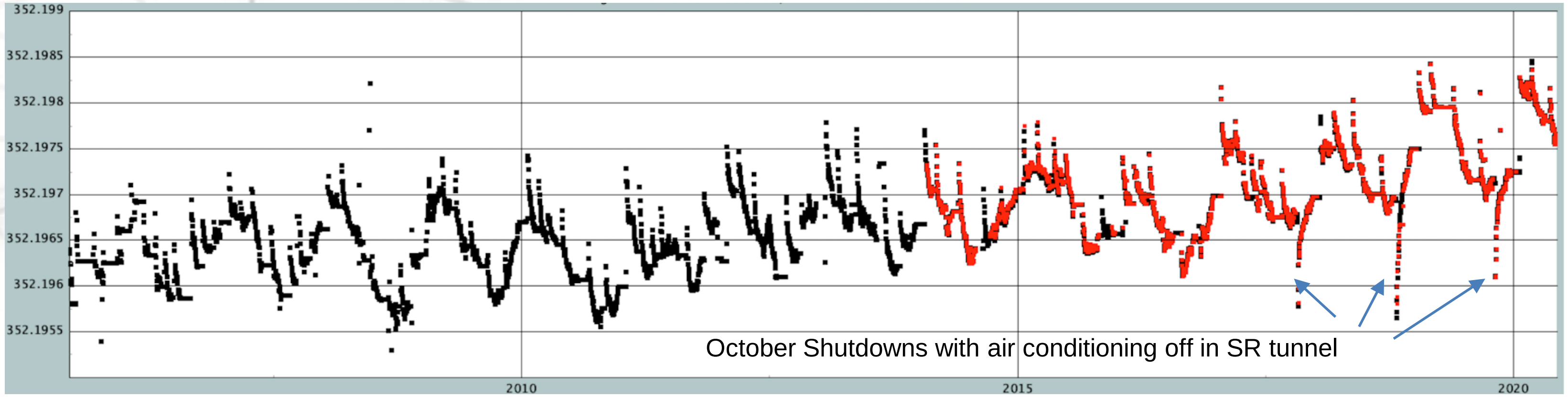
New issues coming with low-emittance boosters

❑ Low value of momentum compaction factor

It makes the impact of a circumference error more substantial, as a unique master clock for RF system is still foreseen for SOLEIL II. Many sources of circumference errors:

- Mismatch of time of flight in the booster, between low and high energy electron (**ΔC = 0.9 mm!** remark raised by Liu Lin/SIRIUS)
- Error in the SR and booster circumference ratio at construction (foreseen absolute circumference error set as **ΔC = 1 mm rms** for each machine)
- Mismatch of this ratio afterwards due to thermal drifts (both machines are located on different slabs), and SR path length variation with insertion device gaps/phase.

Typical SOLEIL RF frequency variation since 2006



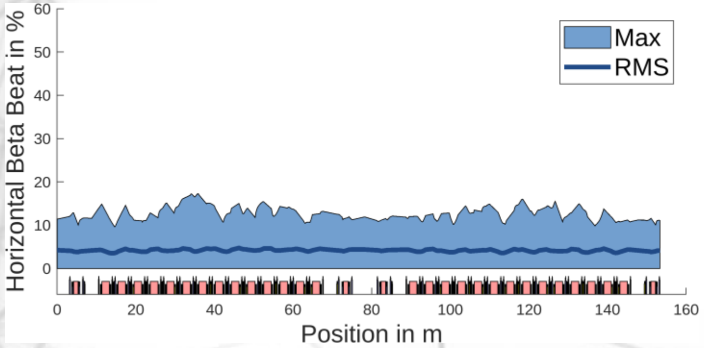
$\Delta fRF_{2006 \rightarrow 2022}$ = 3 kHz

New issues coming with low-emittance boosters

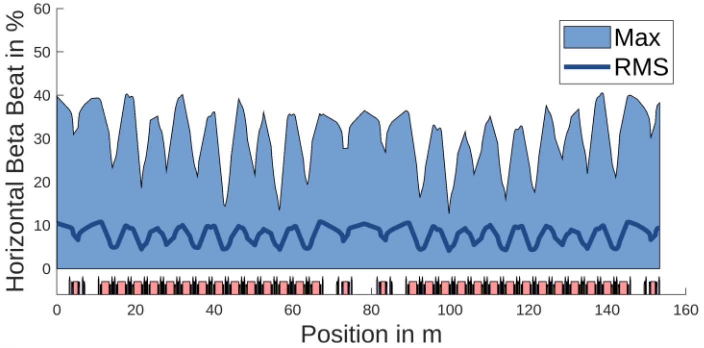
❑ Low value of momentum compaction factor

⇒ As a consequence, an increase of the beta beat is observed while taking into account circumference and f_{RF} errors.

No RF or Circumference Errors



With RF and Circumference Errors



Considered Errors:

Offset Magnets X/Y	100 µm
Offset Girders X/Y	100 µm
Roll Magnets	400 µrad
Roll Girders	400 µrad
Magnet Calibration	0.001
BPM Offset	500 µm
BPM Roll	400 µrad
Circumference	1 mm
RF Frequency	2.5 kHz

+ Fixed circumference offset of –0.9 mm at high energy

⇒ A countermeasure in terms of adapting the energy of the LINAC and booster beams can be found during the top-up process, by shifting the arrival time of the LINAC beam in the booster, depending on the actual f_{RF}.

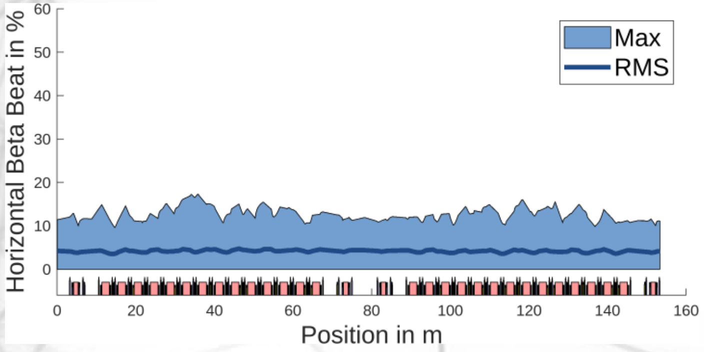
⇒ It is under consideration to whether the future air conditioning system of the booster could somehow smoothly anticipate and correct for the f_{RF} mismatch.

New issues coming with low-emittance boosters

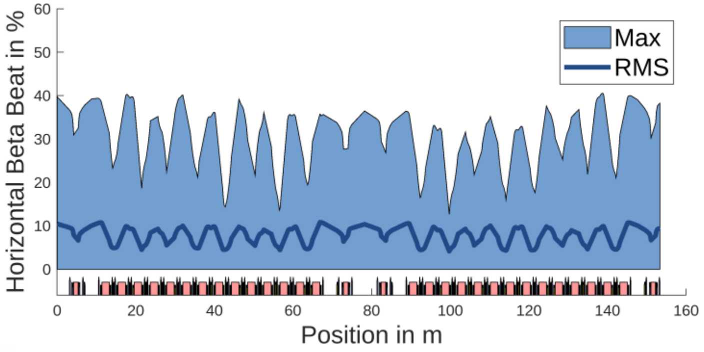
- High-focusing optics

Increased sensitivity of the beta beat and of the transverse tunes at beam extraction time to the power supply tracking errors.

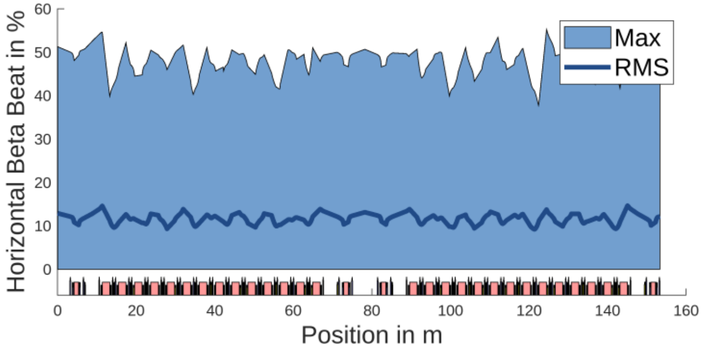
No RF or Circumference Errors



With RF and Circumference Errors



With RF and Circumference Errors
With PS tracking Error $\sigma = 0.3\ 10^{-3}$

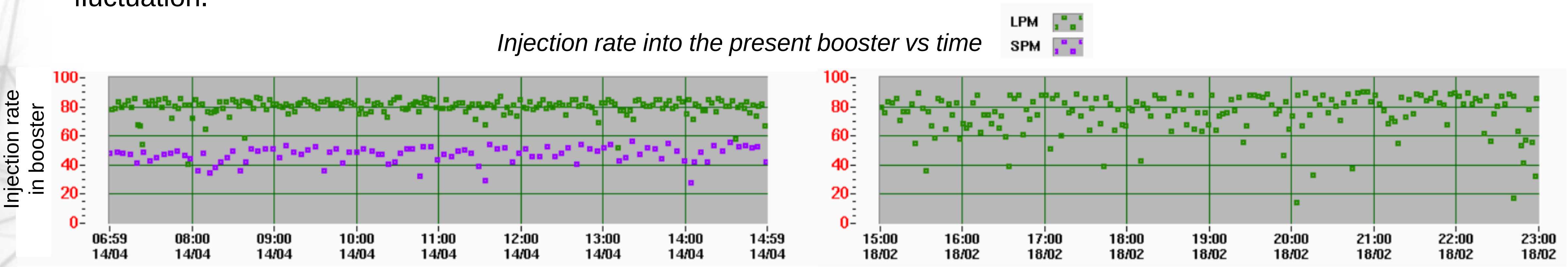


New issues coming with low-emittance boosters

- On and off momentum dynamic aperture

In fact, the **present injection rate into the booster** is not completely under control. Despite a rather large transverse acceptance of the present booster FODO lattice, we observe frequent injection performance fluctuation.

Injection rate into the present booster vs time



Stable → *Fluctuating Long Pulse Mode injection rate*

⇒ A comprehensive list of relevant parameters (machine, infrastructure, ..) has been made: *LINAC RF phase comparator, temperature sensors in LINAC & booster tunnel and power supplies cabinets, charge monitors, beam loss monitors, synchronization, etc.*

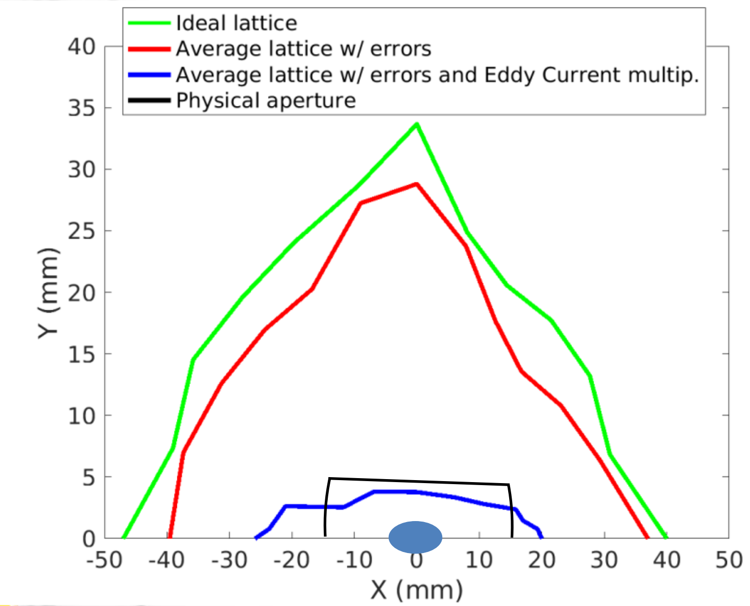
⇒ A **machine learning study** should start from Spring 2024

New issues coming with low-emittance boosters

- On and off momentum dynamic aperture

With the new booster lattice, an increased sensitivity is expected for the booster injection efficiency, to the LINAC beam emittance and energy error, and to the mismatch of the LINAC to booster transfer line.

On-momentum Dynamic Aperture



$3\ \sigma_x$ x $3\ \sigma_y$ injected beam

Injection rate of the LINAC macro-bunch in presence of vacuum chamber, w/ all parameters conservative. Multipoles in progress

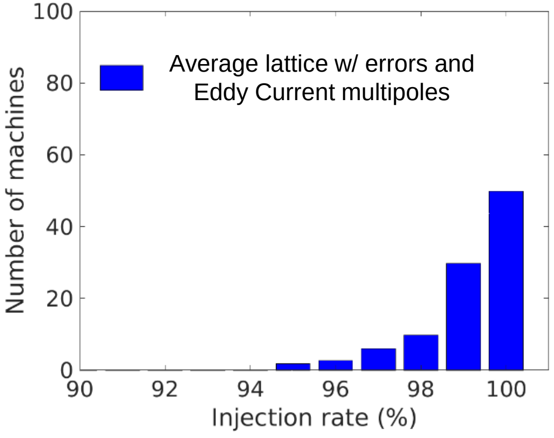


Table for injected beam values and errors: (all conservative values)

	Parameters	Unit	Values
LINAC beam @ 150 MeV	Energy offset (RMS)	-	0.25 10^{-2}
	Energy spread (RMS)	-	0.35 10^{-2}
	Normalized emittance (90% part., 4 $\sigma\sigma'$ β γ) in H & V planes	π m.rad	200 10^{-6}
	Emittance ampli. factor due to TL1 mismatch		1.2
	Systematic error of steering at injection	Supposed to be injected on the mean booster orbit	
	Phase error relatively to booster synchronous phase	π	-0.6 $\rightarrow$ +0.6
Injection pulsed elements	Pulse to pulse repeatability (RMS)	-	2 10^{-4}
	Roll error (RMS)	mrad	0.4

New issue coming with the new harmonic cavity in SR

❑ Filling pattern homogeneity in the storage ring

The **filling patterns** in the storage ring are expected to be crucial in terms of beam lifetime, due to beam loading in the Harmonic Cavity. Its improvement at the LINAC stage and throughout the whole injection process is a mandatory step.

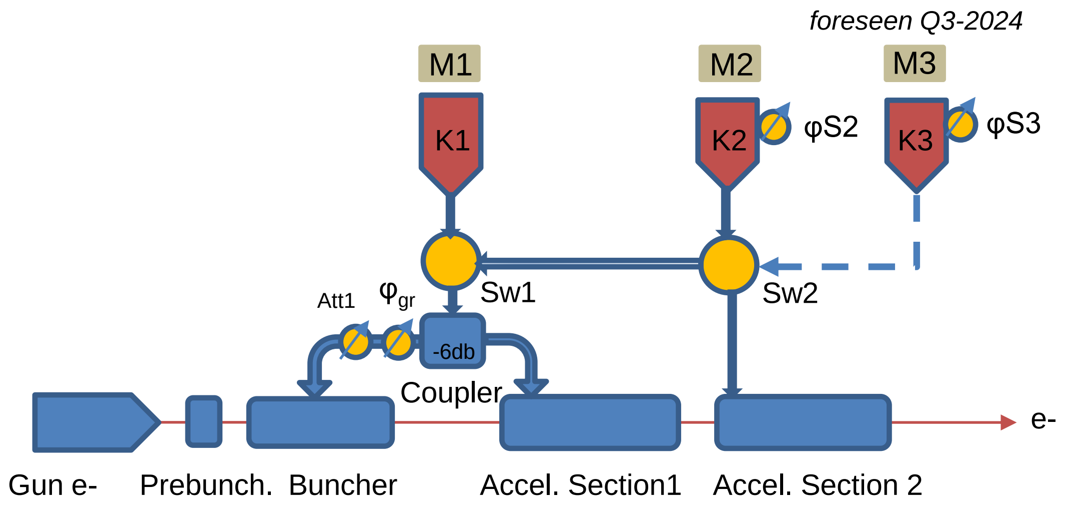
In progress:

- New LINAC event synchronization system
- New LINAC gun triode PCB card
- Additional solid-state modulator #3

⬇

- Fine-tuning of the duration of the Long Pulse Mode (LPM)
- Reduction of the phase error between the HF and the beam
- Better control of the LPM rise time and overshoot
- Foreseen automatic adjustment of the Short Pulse Mode (SPM) charge in top-up mode
- Better control of the modulator output voltage

SOLEIL LINAC @ 3 GHz & RF network



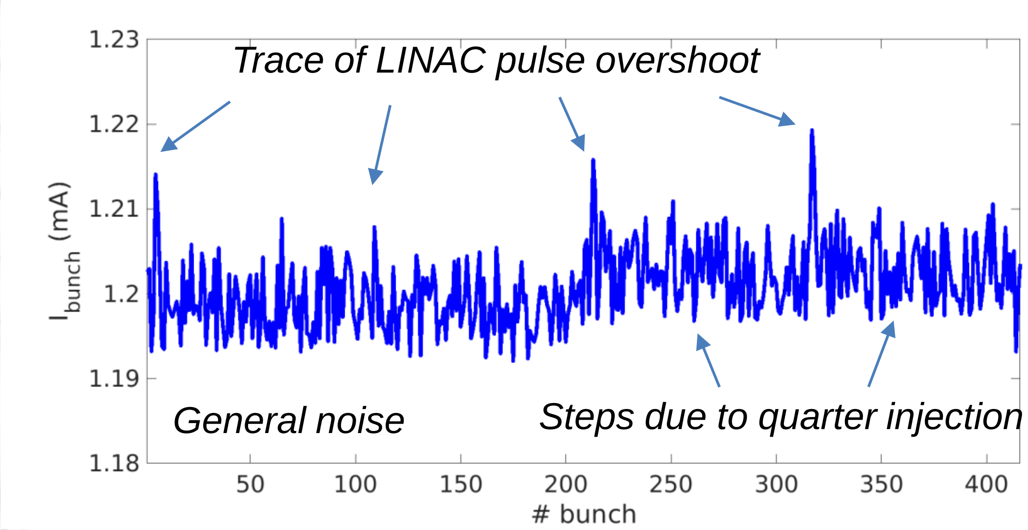
New issue coming with the new harmonic cavity in SR

❑ Filling pattern homogeneity in the storage ring

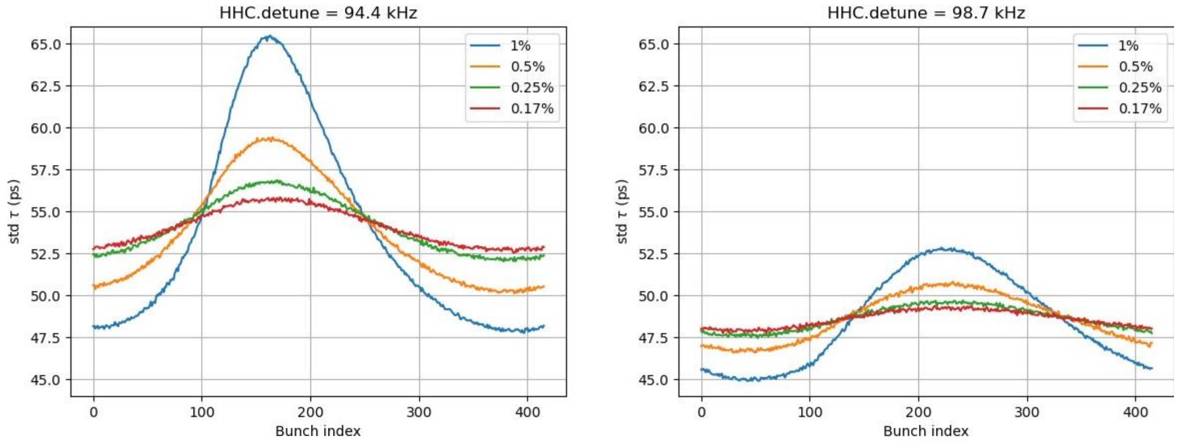
The **filling patterns** in the storage ring are expected to be crucial in terms of beam lifetime, due to beam loading in the Harmonic Cavity. Its improvement at the LINAC stage and throughout the whole injection process is a mandatory step.

⇒ Top-up injection is simulated in terms of SR beam lifetime, LINAC charges (Long and Short Pulses) and injector frequency.

*Example of a 500 mA - 416 bunches storage ring filling pattern with a typical **unfavorable LINAC long pulse shape** (see hypothesis in appendix)*



Induced bunch-to-bunch bunch length variation in the storage ring, by typical current steps of the top-up.



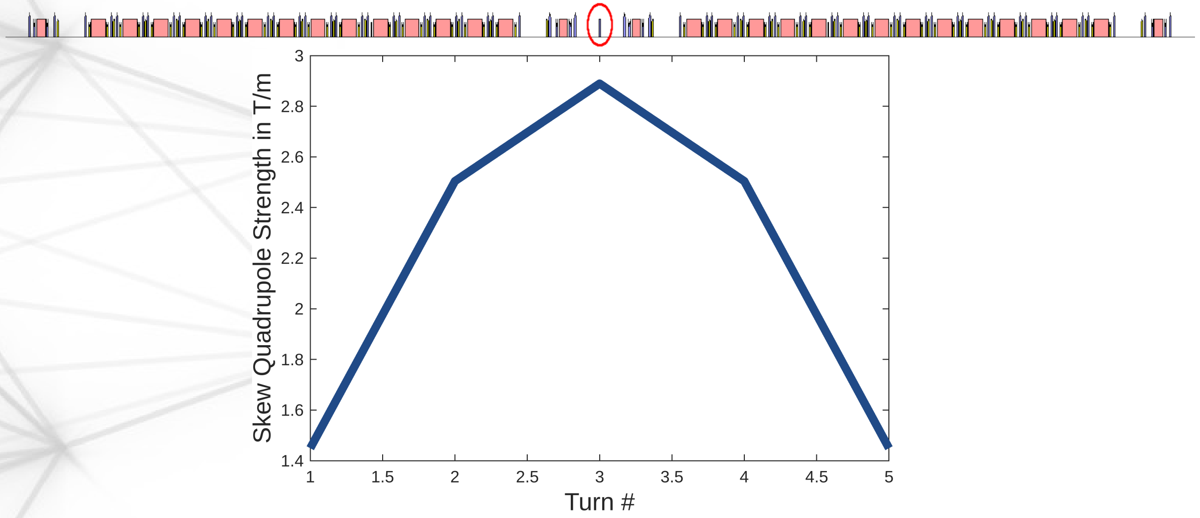
Courtesy A. Gamelin

Two possible methods considered: **Pulsed Skew Quadrupole** & **Resonance Crossing**

Ref. P. Kuske et al., J. Kallestrup, M. Aiba et al.

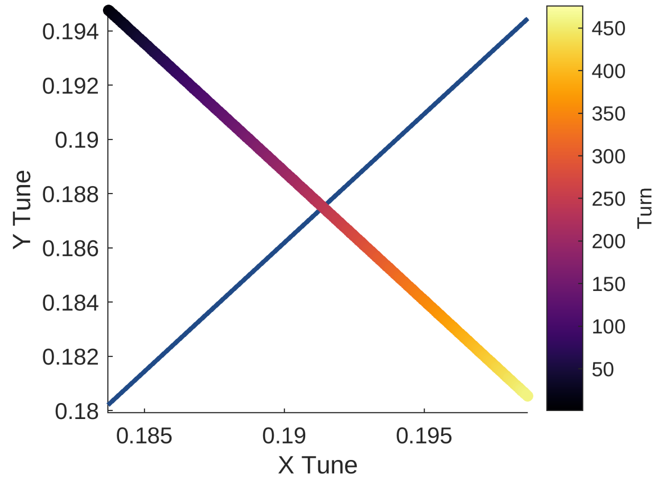
Pulsed Skew Quadrupole

- Skew quadrupole at center of long straight section
  $\Rightarrow$ No dispersion
- One pulse optimised for all machines with errors
  - Pulse length: 5 turns
  - Pulse shape: Sinusoidal
  - Pulse strength: $2.89\,\mathrm{T/m}$ (@ $30\,\mathrm{cm} \mathrel{\widehat{=}} 0.87\,\mathrm{T}$)



Resonance Crossing

- Crossing the coupling resonance
- Quadrupole families Q2 (straight sections) and Q6 (arcs)
- Longer process (multiple 100 turns)
- Optimisations necessary for each machine with errors
  - Crossing speed
  - Initial coupling



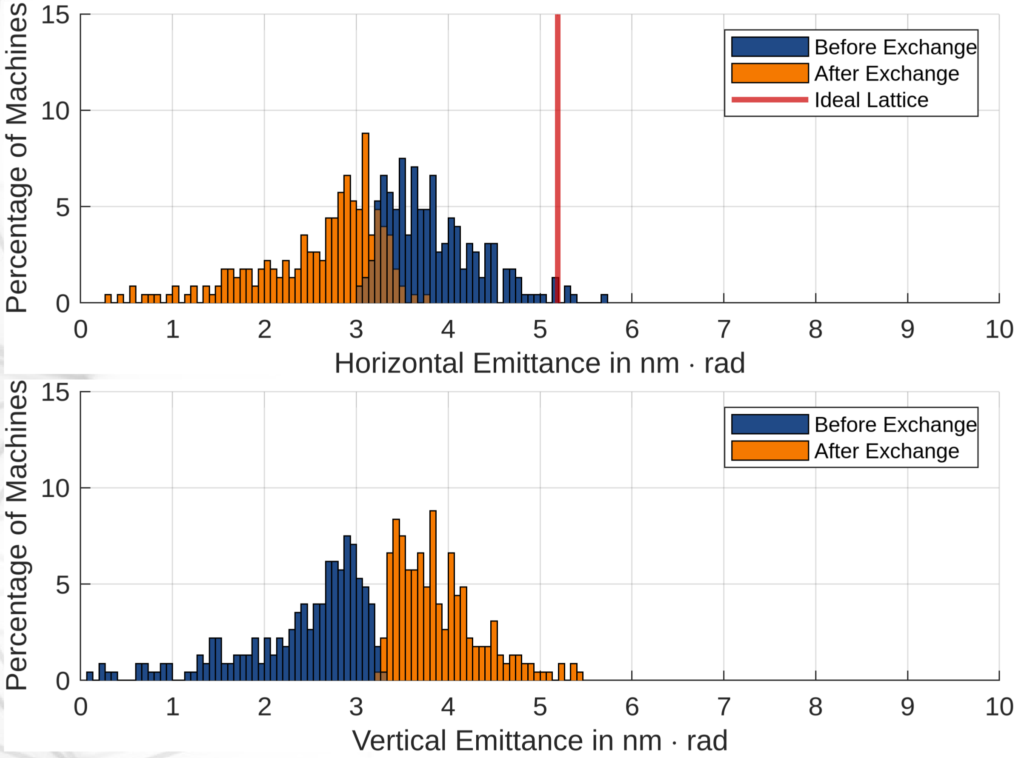
Both studied in presence of general errors and tracking errors

Tracking Errors: Random shot-to-shot variation of powersupply output in amplitude and phase during the ramp

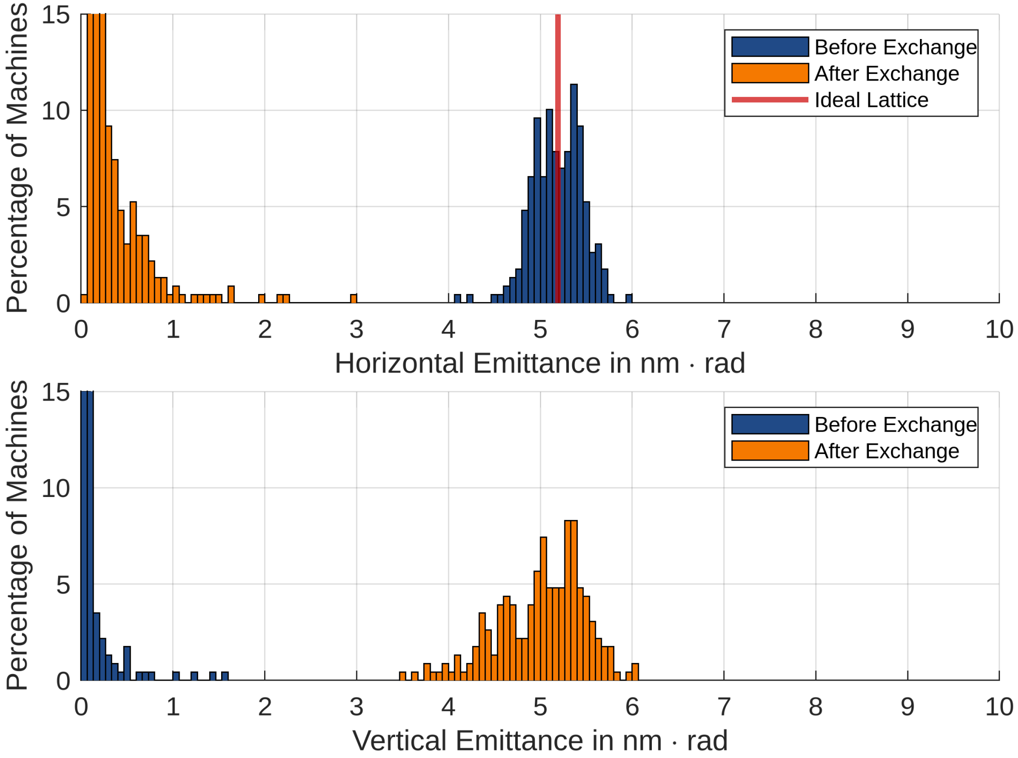
Pulsed Skew Quadrupole

No Tracking Errors

Lattice ON Resonance $\nu_{x,y} = [0.19, 0.19]$



Lattice OFF Resonance $\nu_{x,y} = [0.18, 0.195]$



Error induced coupling + Tune close to resonance

$\Rightarrow$ Preexisting emittance sharing

$\Rightarrow$ Emittance exchange limited

Error induced coupling but tune away from resonance

$\Rightarrow$ Limited emittance sharing

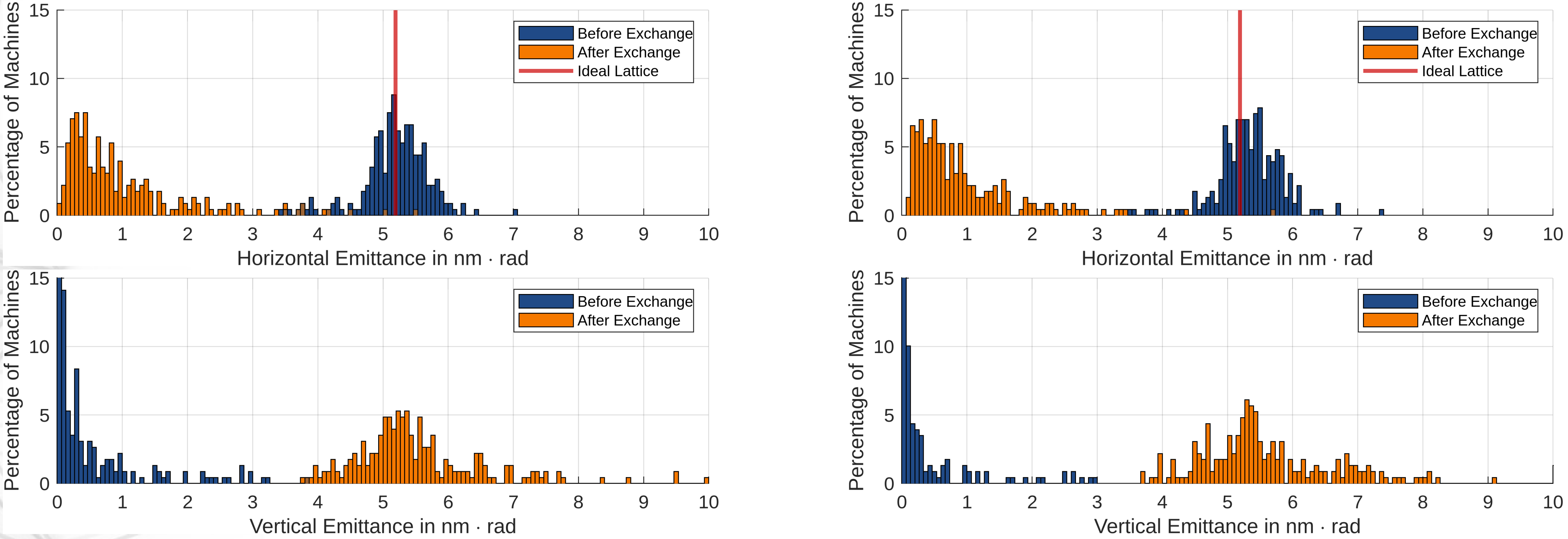
$\Rightarrow$ Higher efficiency of emittance exchange

Pulsed Skew Quadrupole

Tracking Errors: $\sigma = 0.3 \times 10^{-3}$

Lattice ON Resonance $\nu_{x,y} = [0.19, 0.19]$

Lattice OFF Resonance $\nu_{x,y} = [0.18, 0.195]$

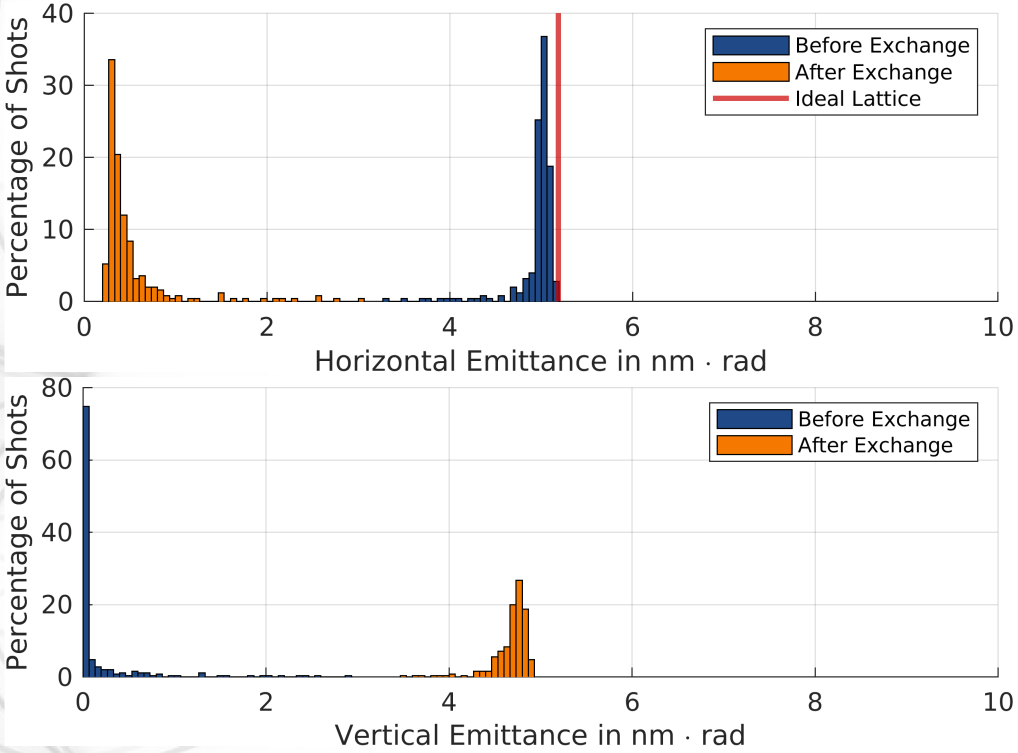


- Similar behaviour for ON and OFF resonance
- Due to tracking errors: lattice OFF resonance in both cases
- Emittance exchange successful - with limitations

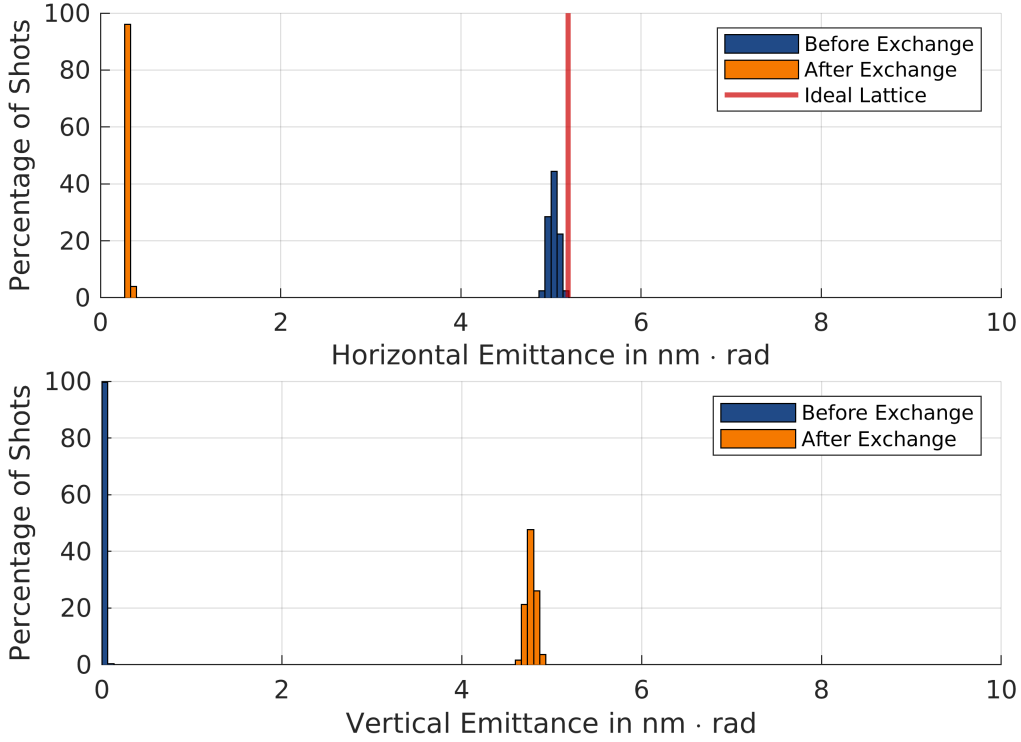
Pulsed Skew Quadrupole

Machine with median orbit after correction (OFF resonance) - shot-to-shot variation

Tracking error level: 0.3×10^{-3}



Tracking error level: 0.05×10^{-3}

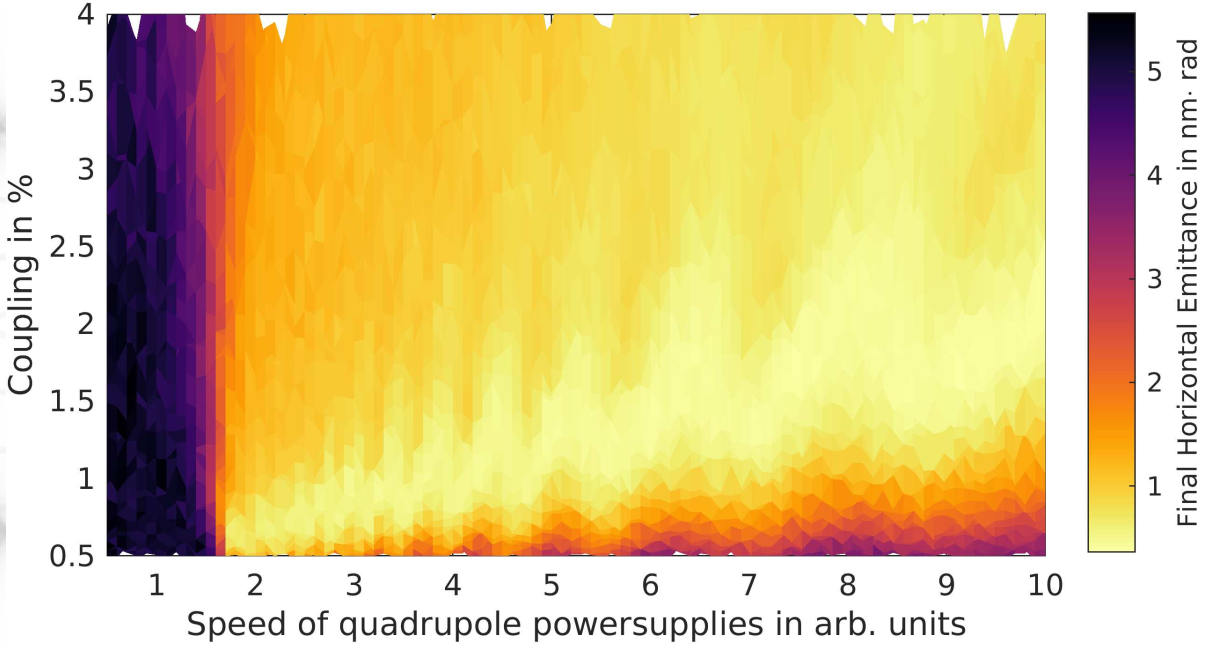


- Reduced spread for lower tracking errors
- Good performance for this example
- With 0.05×10^{-3} the results are better than the requirements

Resonance Crossing

Optimisation of resonance crossing for an example machine with median orbit after correction

- Crossing the coupling resonance using quadrupole families Q2 (in straight sections) and Q6 (in arcs)
- Optimised for corrected average performance lattice
- Optimisation in terms of crossing speed and coupling
- "Extraction" at optimal (minimal horizontal) emittance



Clear dependency of final emittance on crossing speed as well as coupling

Optimisation of resonance crossing for an example machine with median orbit after correction

- Crossing the coupling resonance using quadrupole families Q2 (in straight sections) and Q6 (in arcs)
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- Optimisation in terms of crossing speed and coupling
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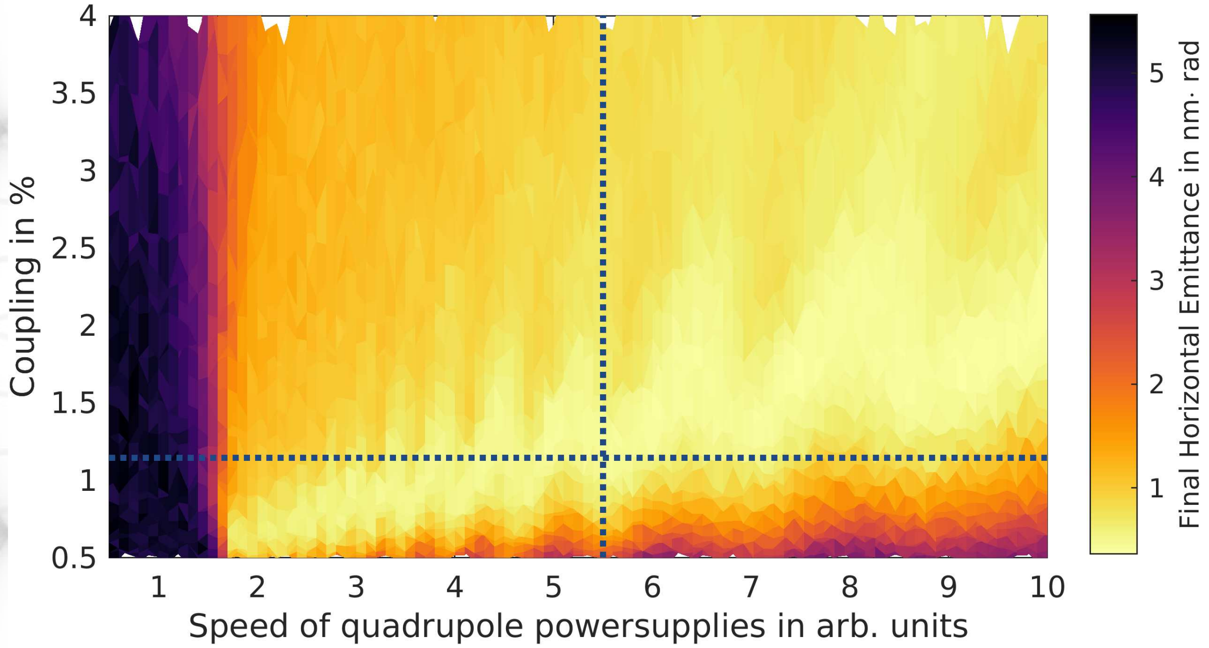
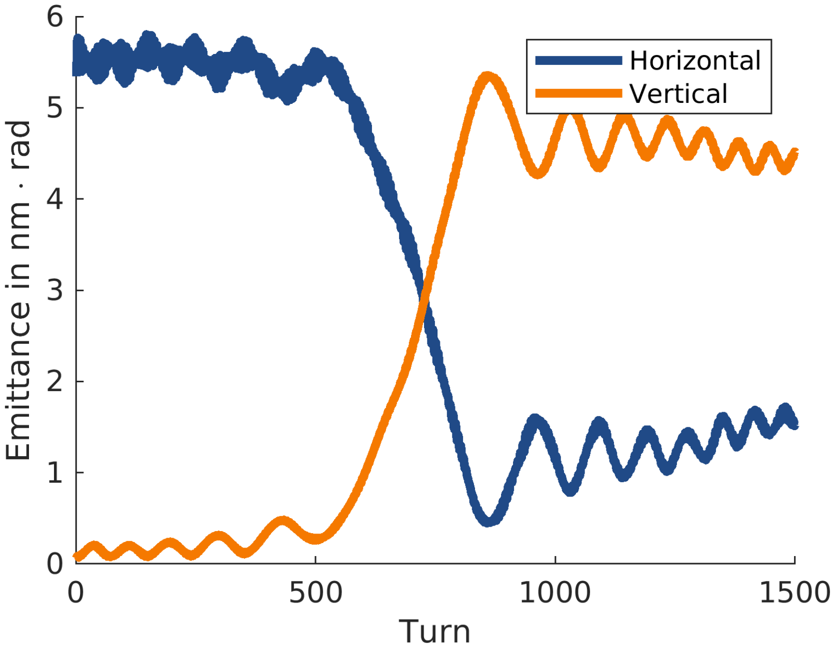
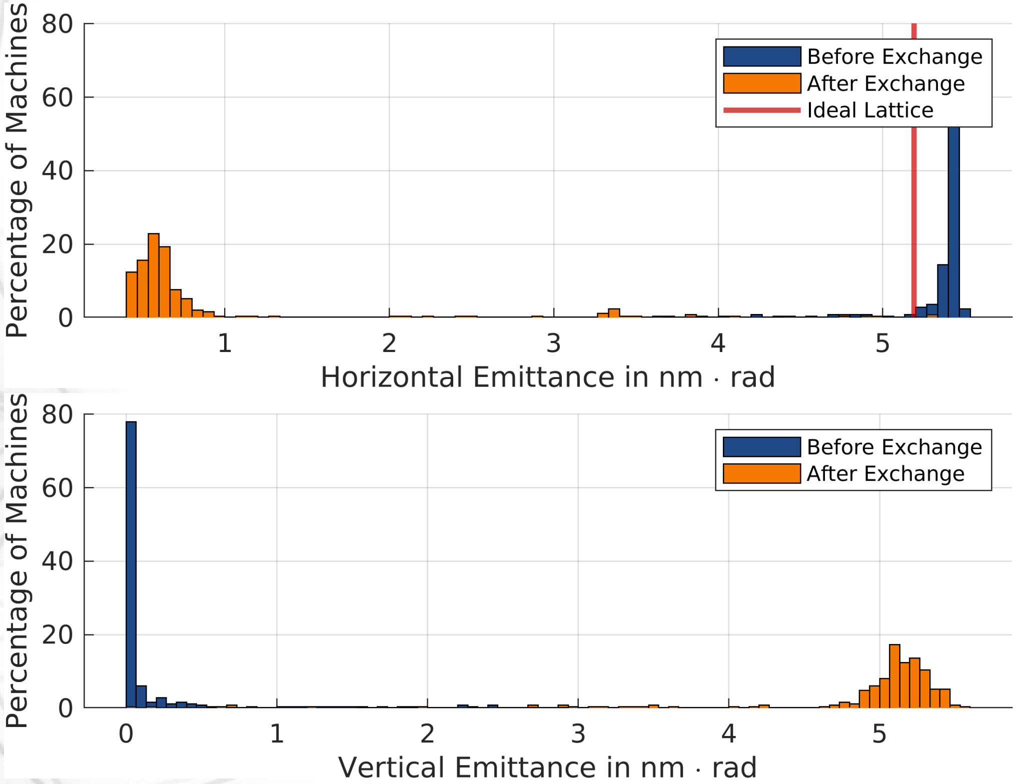


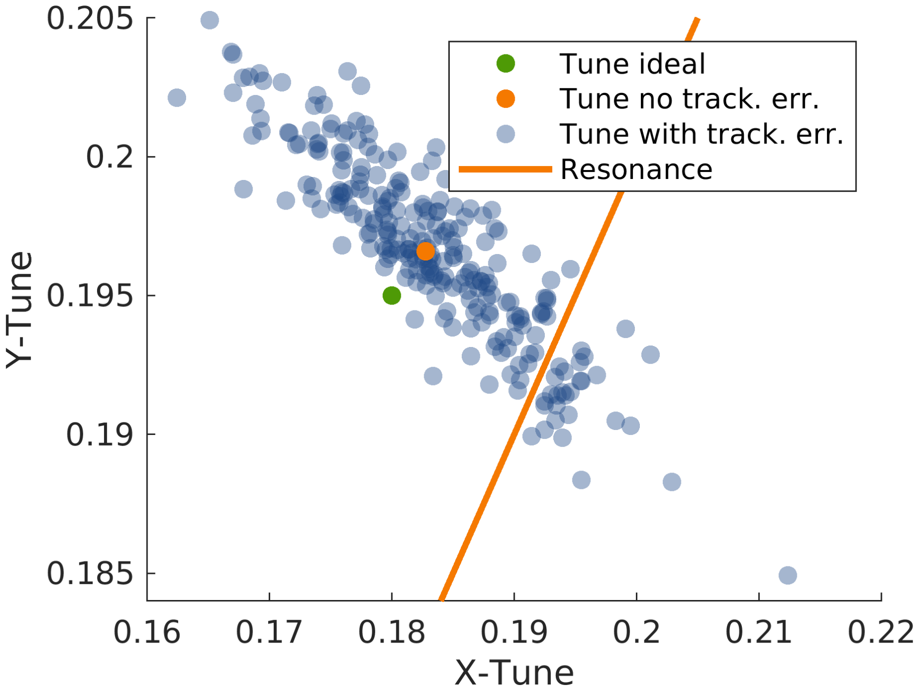


Clear dependency of final emittance on crossing speed as well as coupling

Resonance Crossing

Shot-to-Shot variation. Tracking error level: 0.3×10^{-3}

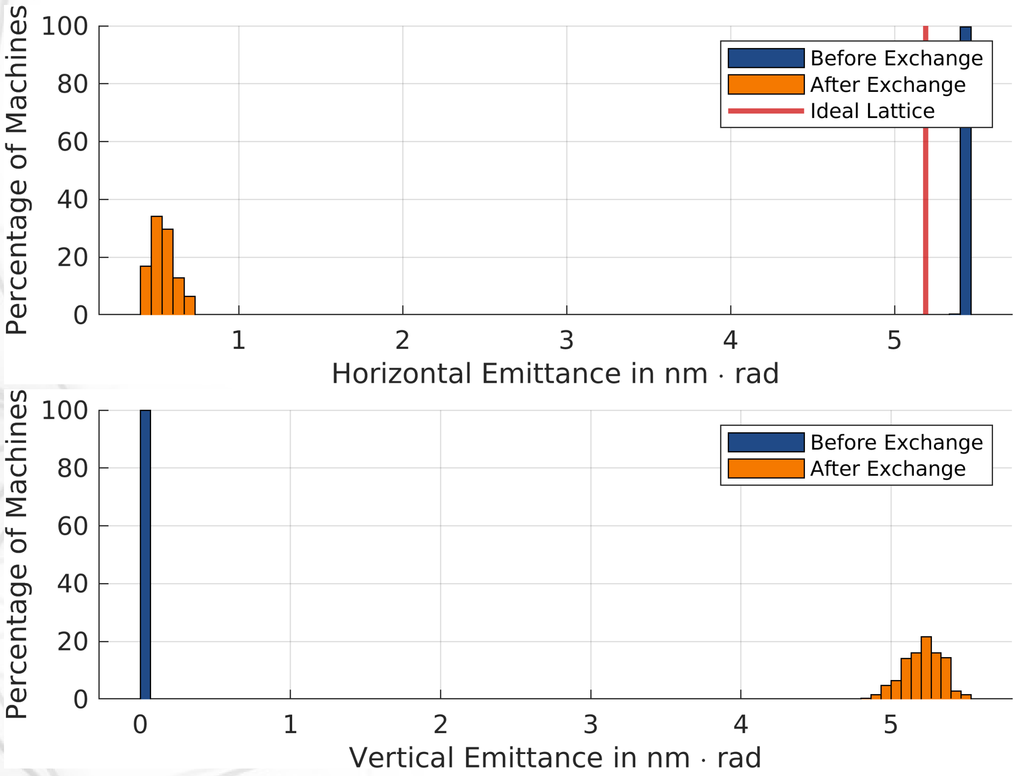


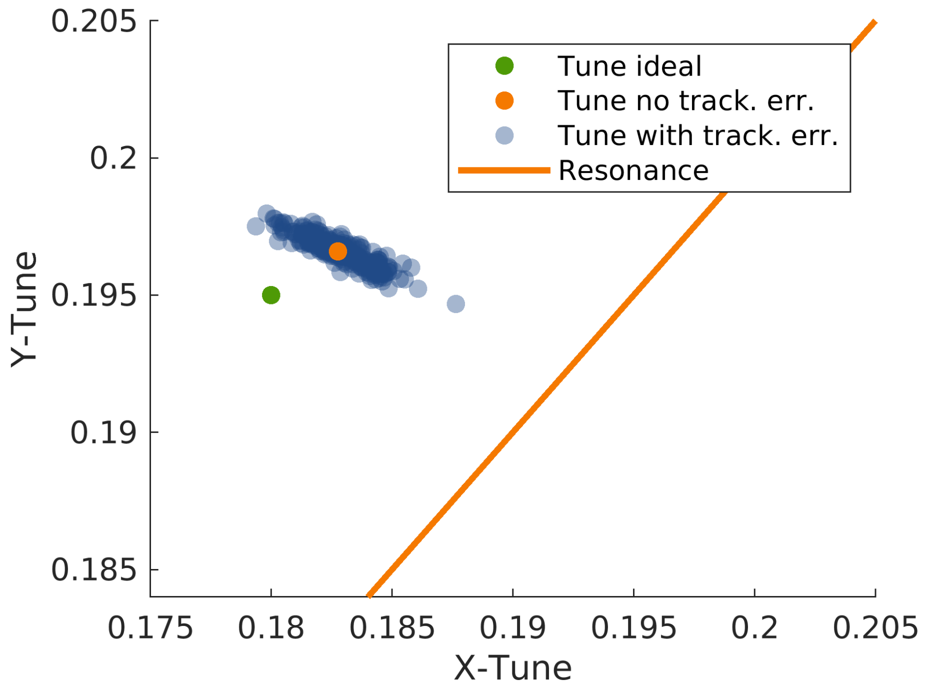


- Emittance exchange working mostly
- Sometimes the tune is already on the other side of the resonance and no emittance exchange possible

Resonance Crossing

Shot-to-Shot variation. Tracking error level: 0.05×10^{-3}

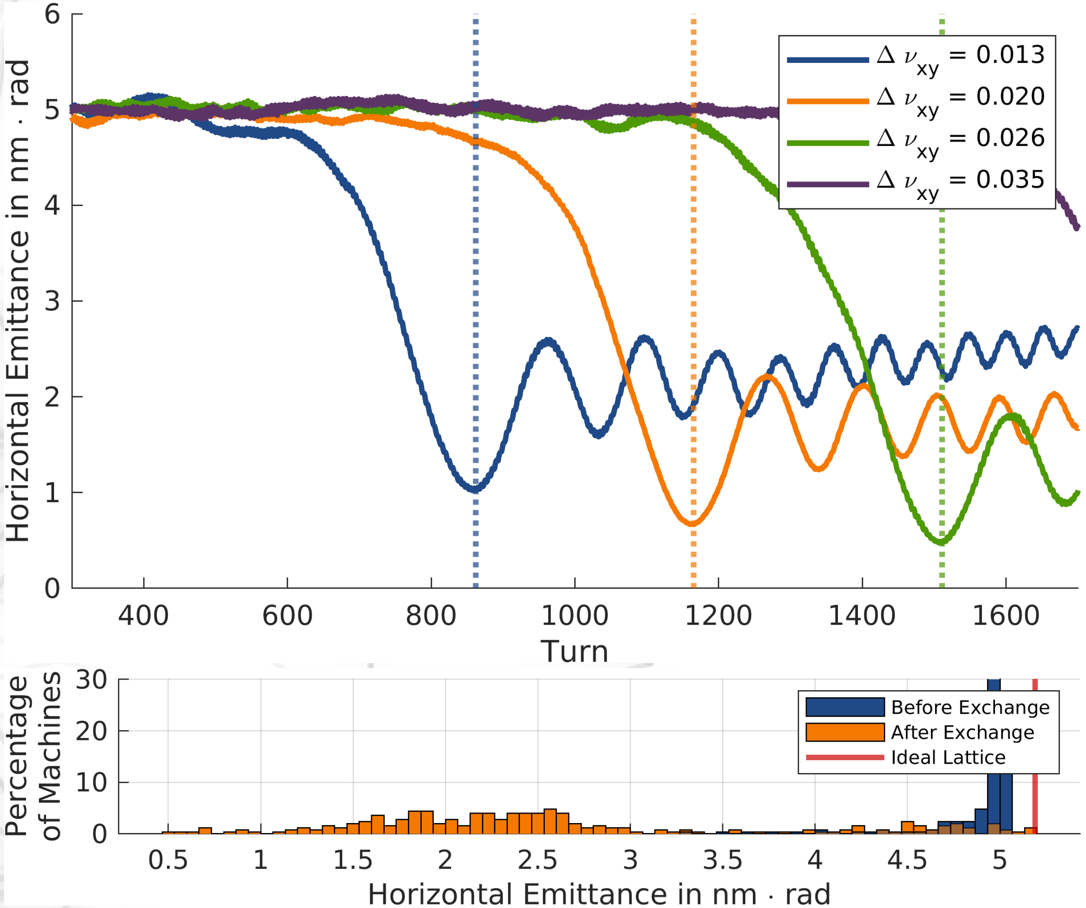




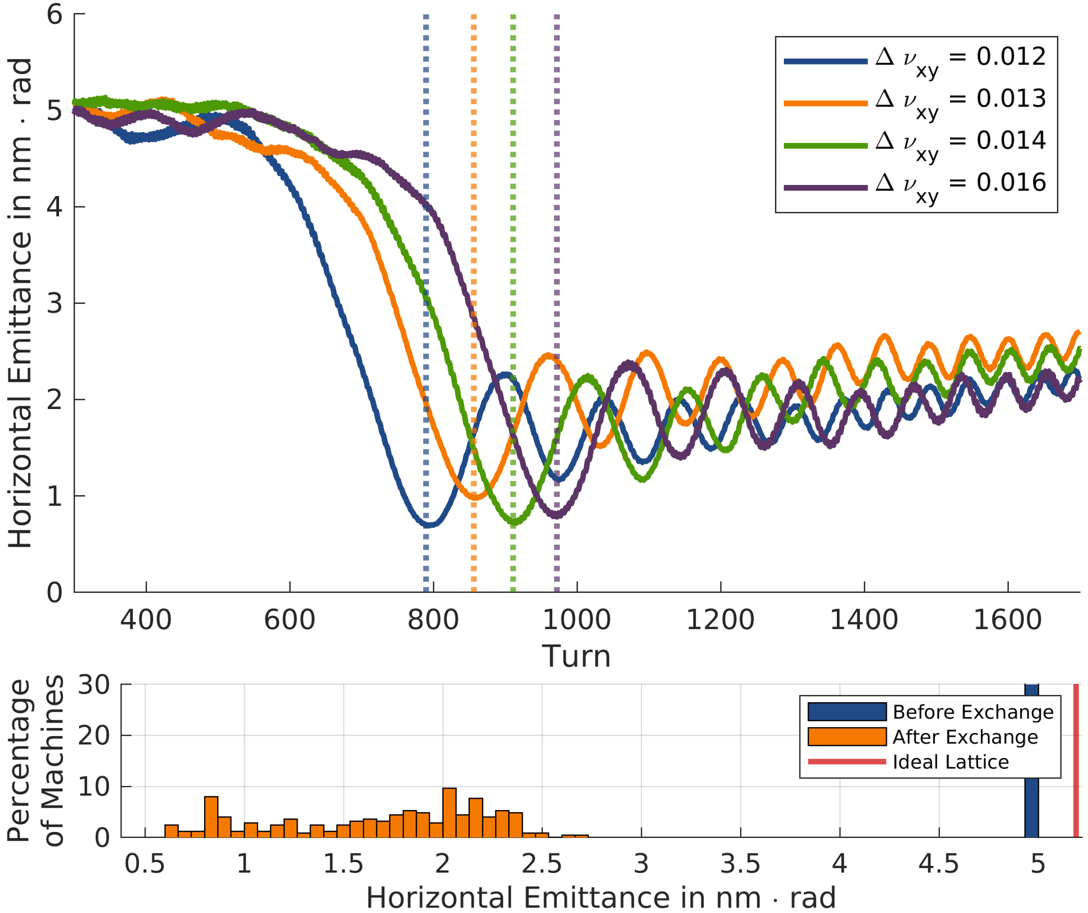
- Emittance exchange working nicely
- Tune is now always close to design value and emittance exchange possible

Resonance Crossing

Tracking error level: 0.3×10^{-3}



Tracking error level: 0.05×10^{-3}



- Optimal extraction point varies significantly with distance of initial tune to resonance
- Fixed extraction turn not efficient

Conclusions

- A new booster has successfully been designed in the frame of the SOLEIL II project, providing an emittance as low as 5.2 nm.rad by keeping it in the same existing tunnel.

- It raises issues in terms of error sensitivity
  - *Lattice correction by LOCO has still to be confirmed in terms of realistic response matrix measurement (with the ramping power supplies and in presence of power supply tracking error)*
  - *BBA is a priori not feasible.*

- The need for a transverse feedback system in the booster is currently being discussed:
  - Shaping trains to achieve good filling pattern homogeneity or even gaps
  - Allowing more control in case instabilities are stronger than assumed.

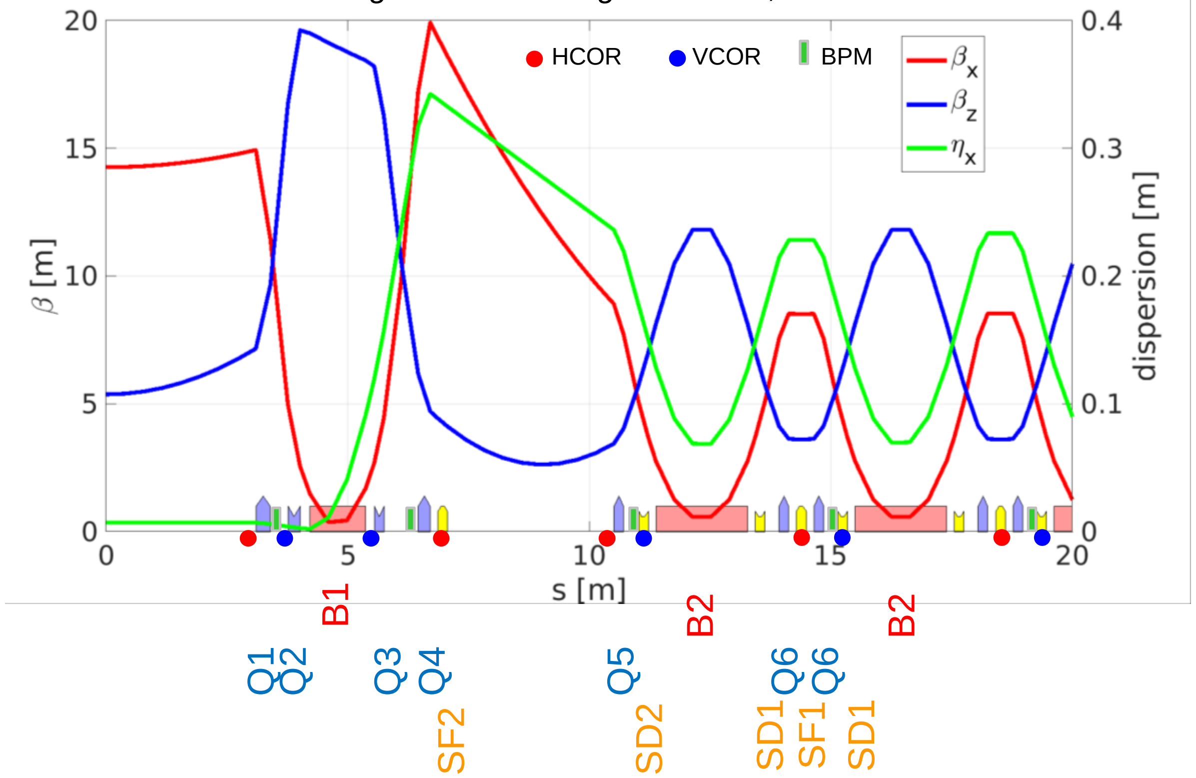
- Emittance exchange seems feasible with a pulsed quadrupole, but might result in higher sum of H and V emittances
- Emittance exchange with resonance crossing in theory possible with no tracking errors but with tracking errors the efficiency drops slightly, and the extraction time varies strongly.

Appendix

Magnet specification @ 2.75 GeV for Booster upgrade

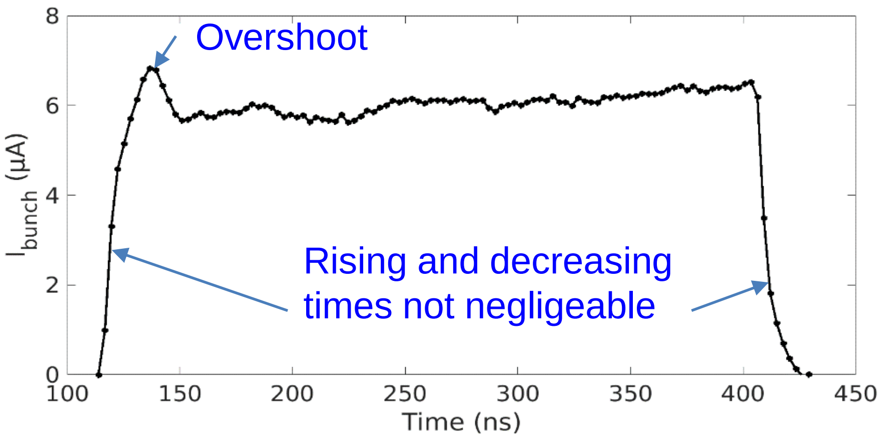
Magnet (all ramped)	Parameter	Unit	Value
Normal dipole 'B1'	Number	-	4
	Field	T	1.29
	Length	m	1.15
Defocusing dipole 'B2'	Number	-	28
	Field	T	0.97
	Gradient	T/m	-3.79
	Length	m	1.90
Quadrupole type 1 Q1, Q2, Q4	Number	-	12
	Max.gradient	T/m	35
	Length	m	0.250
Quadrupole type 2 Q3, Q5, Q6	Number	-	60
	Max.gradient	T/m	30
	Length	m	0.200
Sextupole	Number	-	86
	Max strength	T/m^2	300
	Length	m	0.200
Dipolar corrector mostly in sextupoles, except 16 independent	Number	-	2 x 38
	Max. deviation	mrad	0.3
Skew quadrupolar corrector in sextupoles	Max strength	T/m	0.25

Long and short straight sections, HOA cells



List of parameters used in the top-up simulation:

- Storage ring beam lifetime τ_{SR} = 6 hours
- Top-Up conditions in the simulation:
  - $f_{injector}$ = 3 Hz, $R_{injection}$ = 70% with +/- 10% RMS random error
  - Small injected currents :
    Q_{LPM} = 1.5 nC (*present 3 nC*),
    Q_{SPM} = 0.03 nC (*present 0.5 nC*)
  - **Pessimistic** LINAC pulse shape, with deleterious superposition of pulses in storage ring.



Exemple of present LINAC pulse (Long Pulse Mode)