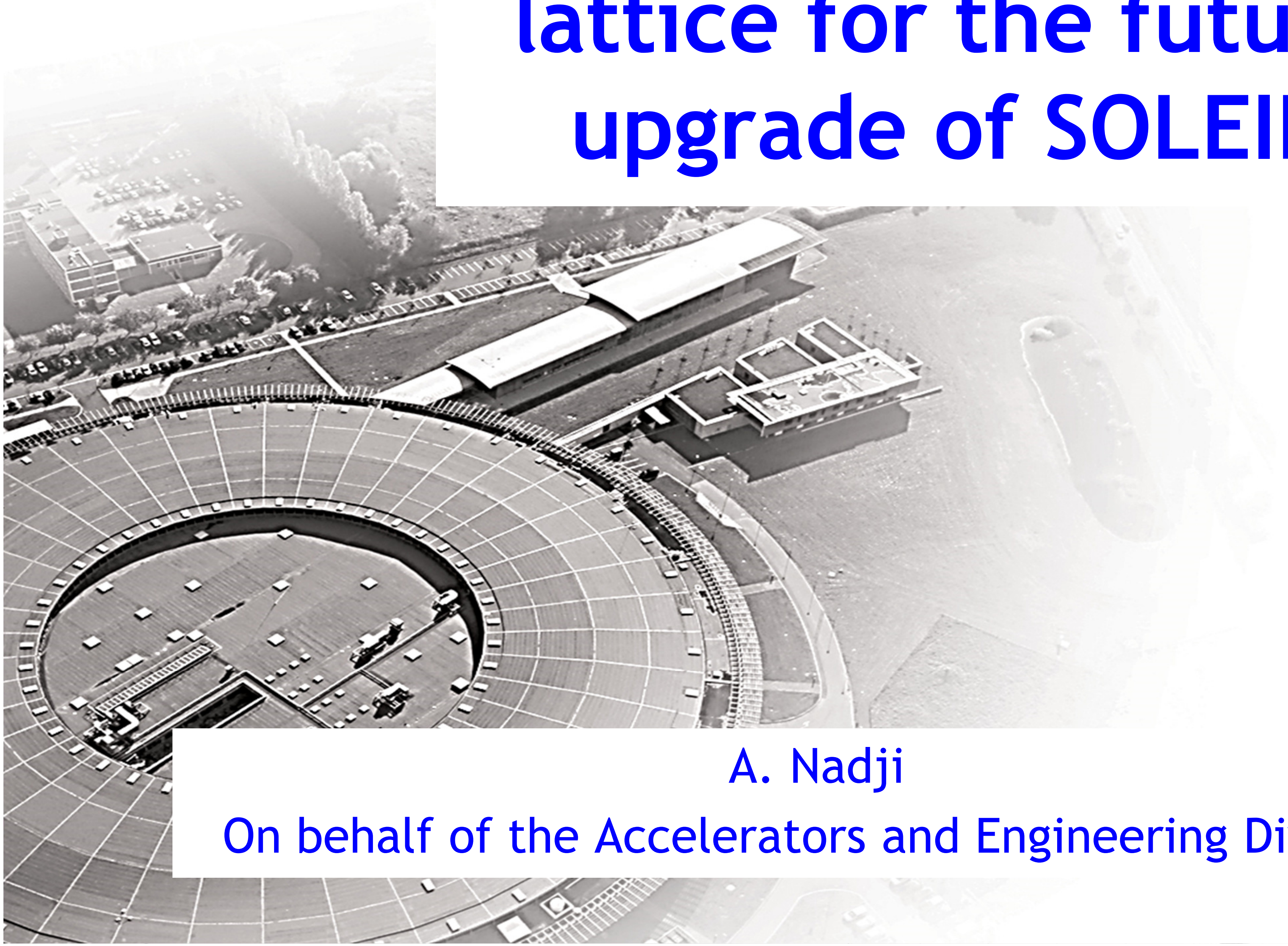
First propositions of a lattice for the future upgrade of SOLEIL



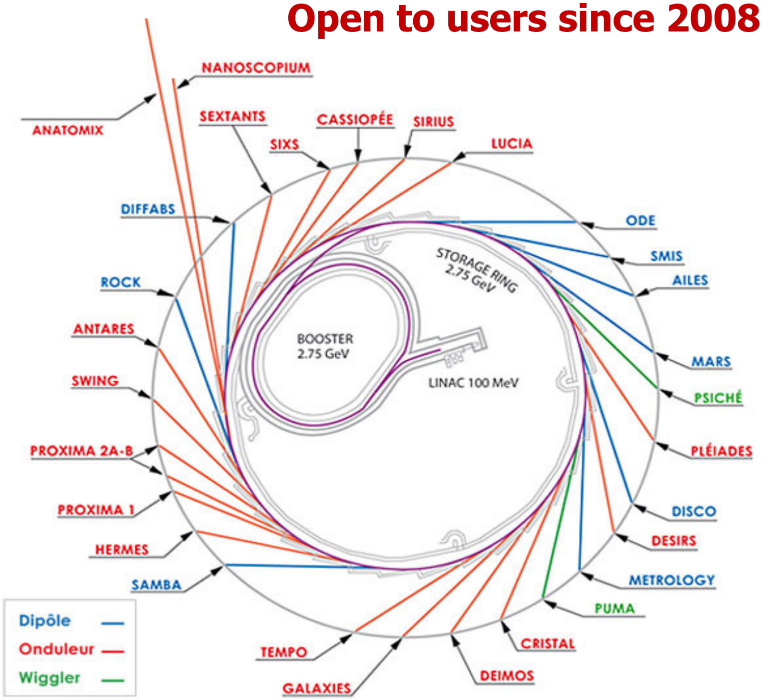
A. Nadji
On behalf of the Accelerators and Engineering Division

SOLEIL : A 3rd generation synchrotron light source

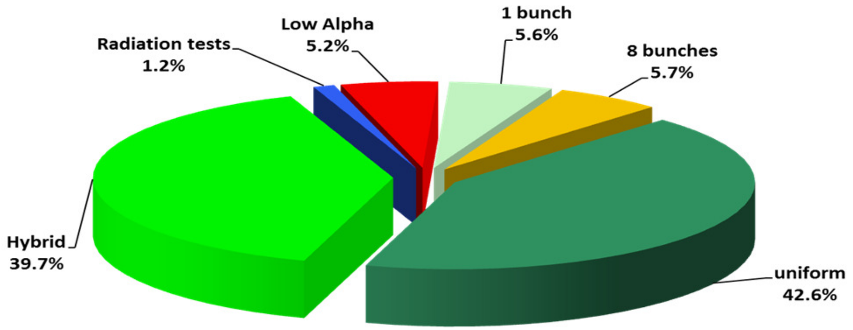
Open to users since 2008

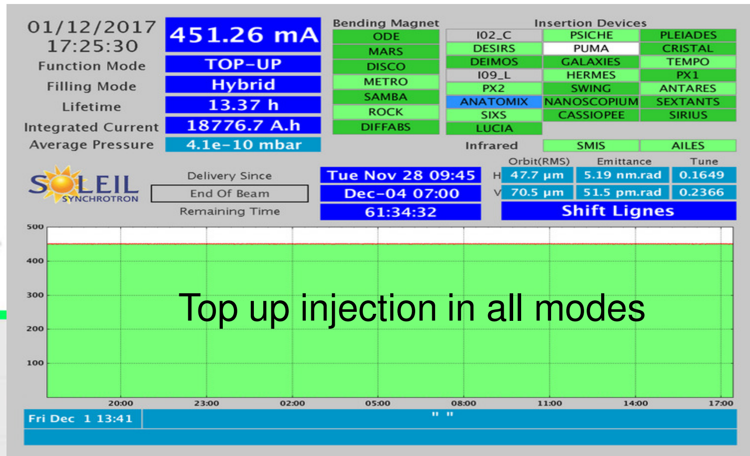
- 29 beamlines operational in 2018.
- ~ 37000 users visits since 2008.
- > 600 articles published yearly.
- Machine availability > 98% and MTBF > 90 hours.

Mode of operation Bunch fill. patterns	User Operation in 2017	Ultimate performance achieved
Multibunch (M2)	500 mA	500 mA
Hybrid/camshaft mode (M)	425 mA + 5 mA	425 mA + 10 mA
	+ Slicing on high intensity bunch	Slice length < 200 fs FWHM
8 bunches (8)	100 mA	110 mA
1 bunch (S)	16 mA	20 mA
Low-α: Hybrid mode (L)	4.7 ps RMS for 65 μA	< 3.2 ps RMS for 15 μA



Broadband spectrum:
9 orders of magnitude from far IR to hard X-rays.





Top up injection in all modes

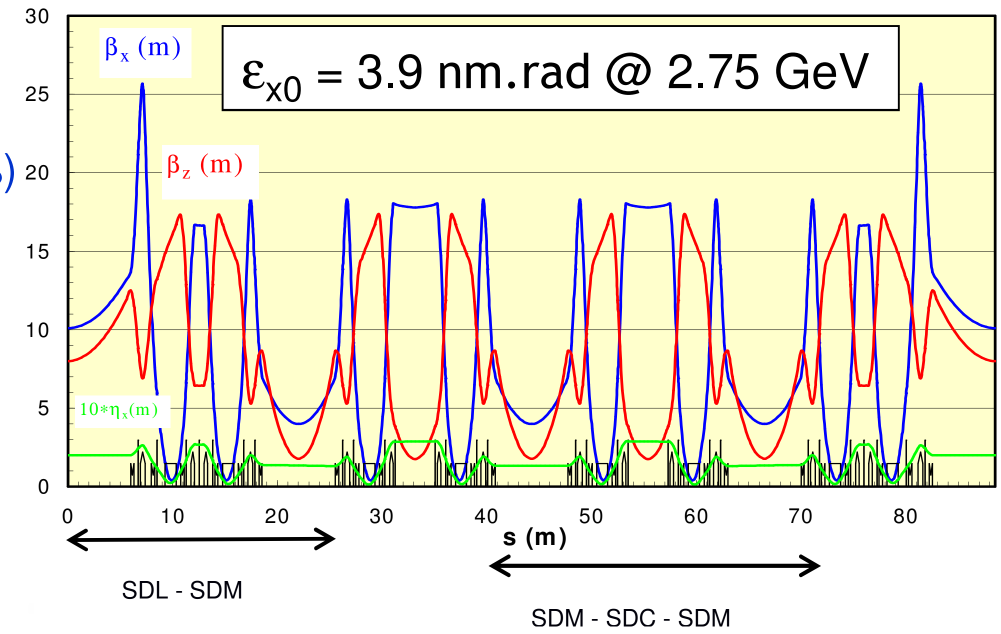
Today's SOLEIL Lattice and main Challenges

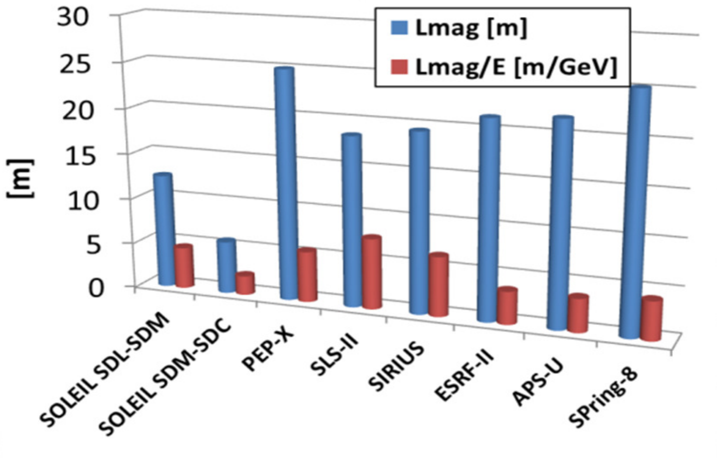
Rather small Circumference: **354 m**

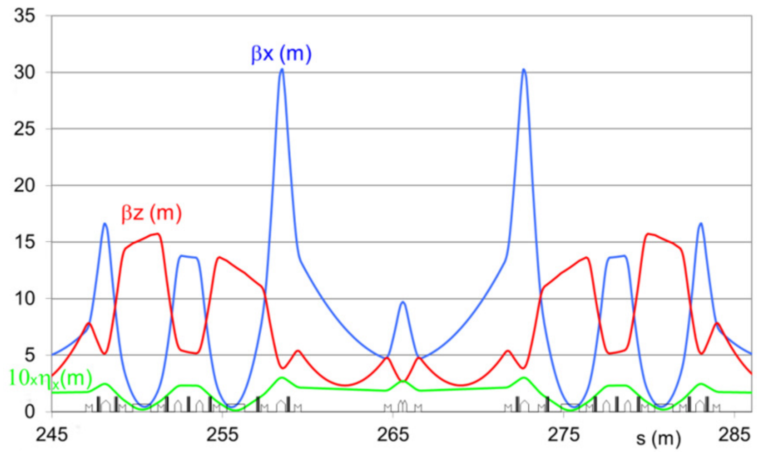
High ratio of free straight sections (~45%)

24 straight sections
4 x 12 m
12 x 7 m
8 x 3.6 m

Very compact magnetic structure







The lengths dedicated to magnets are relatively short; 12.5 m in SDL-SDM and 2 × 5.73 m in SDM-SDC-SDM.

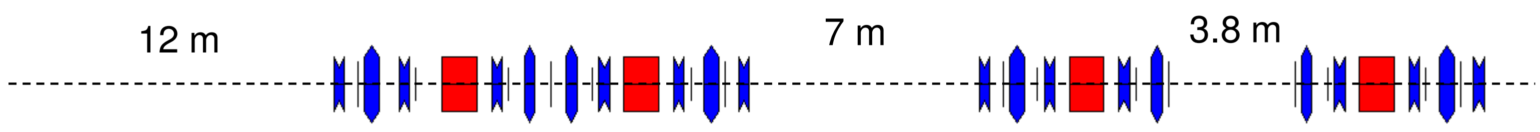
One long straight section (**SDL13**, accommodating 2 long beamlines) **has been modified.**

Upgrade lattice evolution

C = 354 m   2.75 GeV   16 cells – 24 straight sections

1/8 of the ring

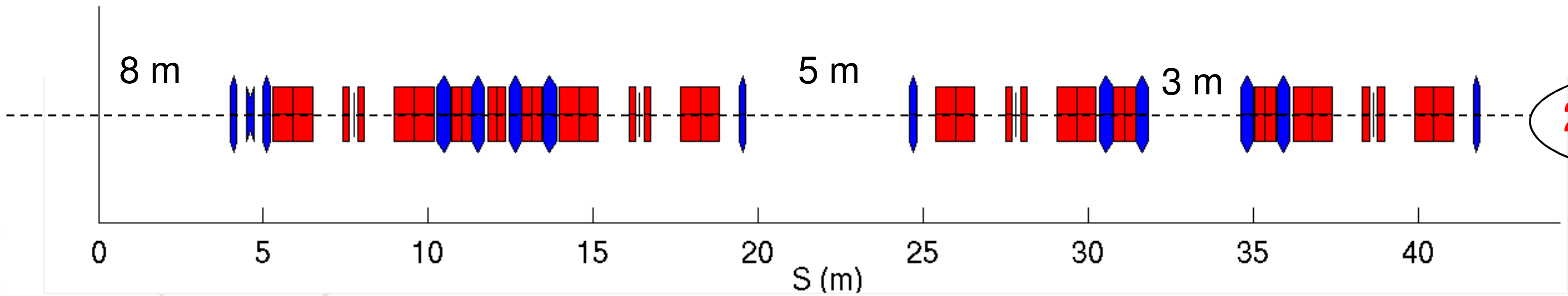
Present :



4 nm.rad

Upgrade November 2016 :

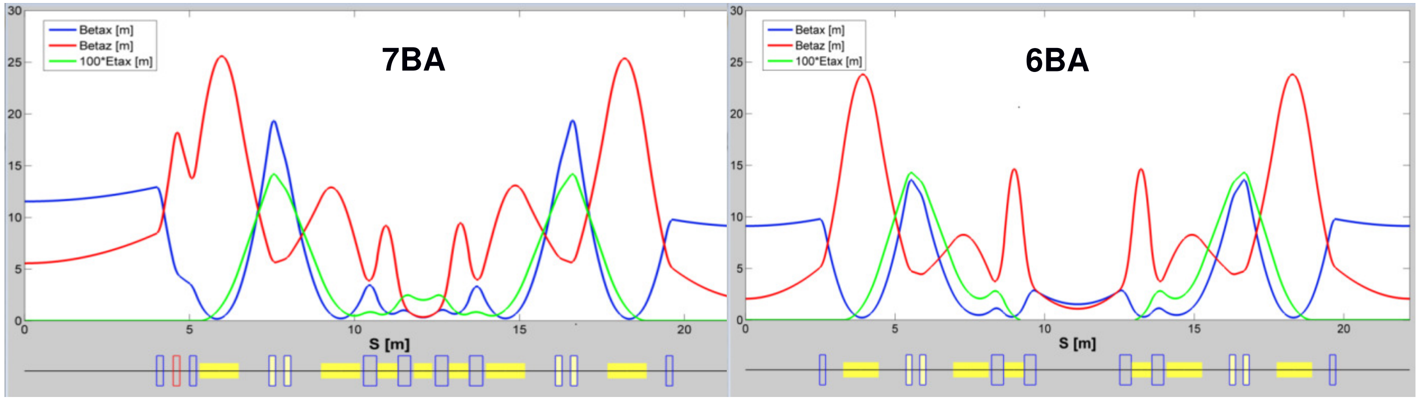
$$\varepsilon_x \approx \mathcal{F}(lattice)\frac{E^2}{N_D^3}$$



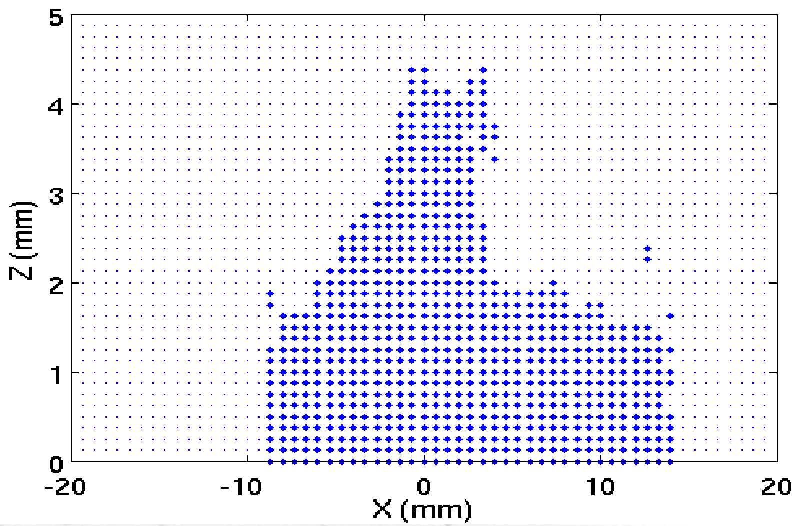
250 pm.rad

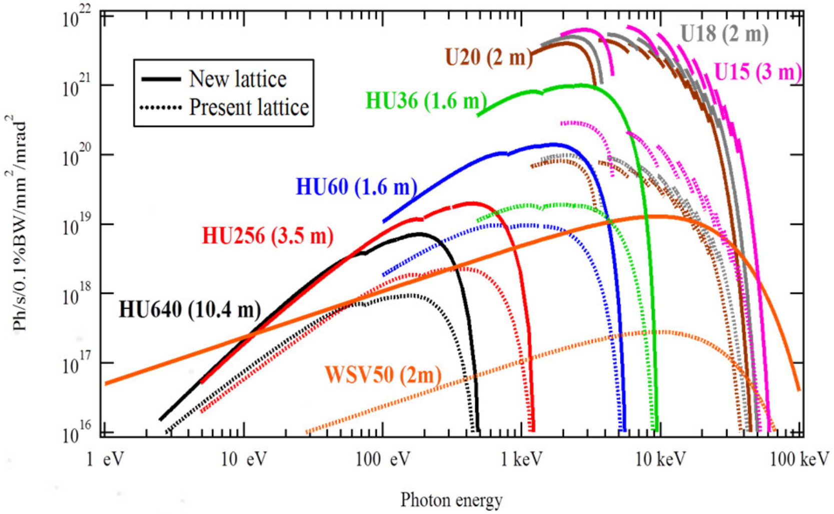
7BA   **6BA**

Upgrade November 2016



ε_x = 250 pm.rad ξ_{x0} = - 84 ξ_{z0} = - 77





- On-momentum dynamic aperture large enough to allow off-axis injection.
- The increase of **brilliance** and **transverse coherence fraction** expected using this lattice is more than one order of magnitude around 1 keV and almost two orders of magnitude at 10 keV.

Strategy and guideline for a new baseline lattice

- Push further the reduction of the emittance in order to **maximize** the intensity of **coherent** photon flux arriving at the beamlines especially in the soft to tender X-rays photon energy range up to 3 keV.

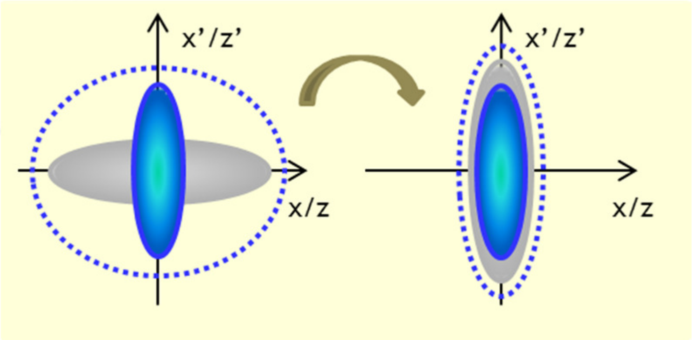
- To achieve this goal two objectives are the key guiding principle for the optimization of the new lattice.

  ✓ the electron beam emittances in both horizontal and vertical planes must be close to the single-electron photon beam emittance in this energy range.

$$B_n(\lambda) = \frac{F_n(\lambda)}{4\pi^2(\varepsilon_x \otimes \varepsilon_R(\lambda))(\varepsilon_z \otimes \varepsilon_R(\lambda))}$$

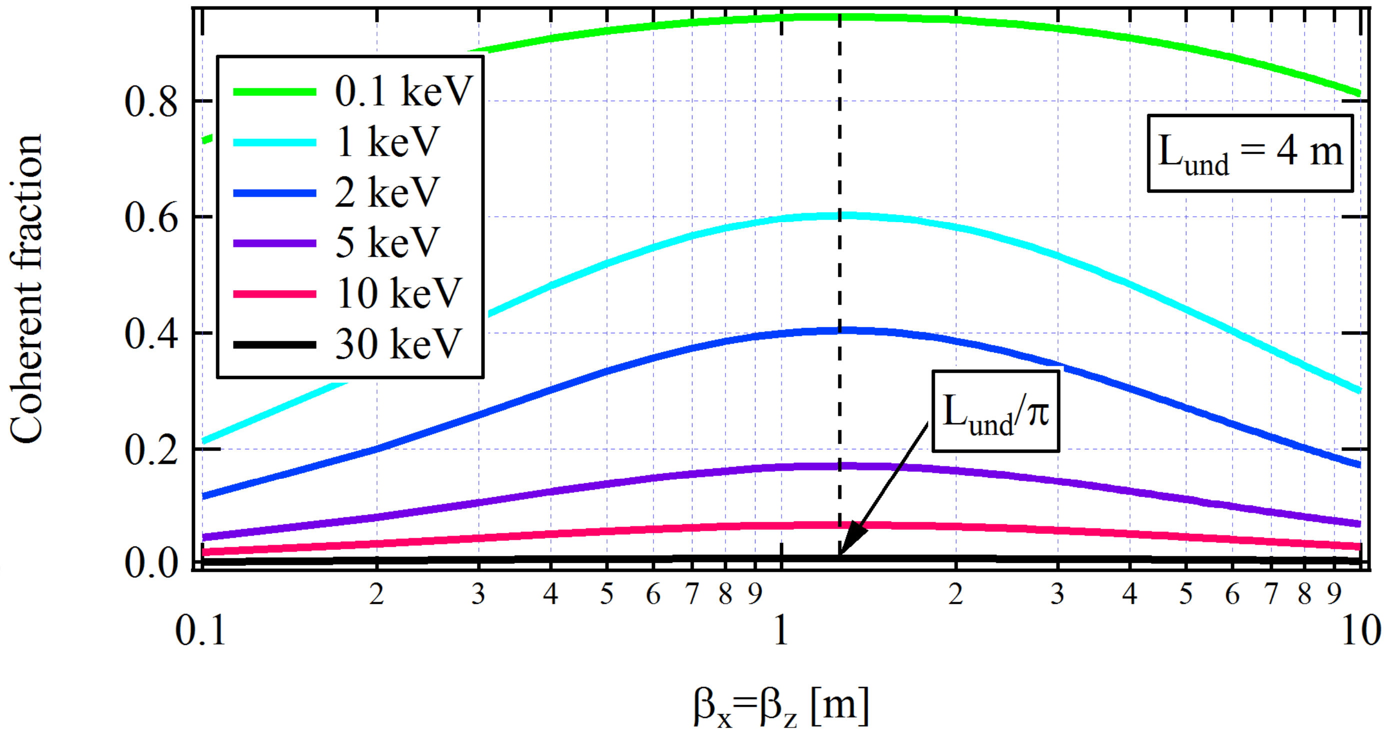
$$f_c(\lambda) = f_{cx}(\lambda)\, f_{cz}(\lambda) = \frac{\varepsilon_R(\lambda)}{\varepsilon_R(\lambda) \otimes \varepsilon_x(e^-)} \frac{\varepsilon_R(\lambda)}{\varepsilon_R(\lambda) \otimes \varepsilon_z(e^-)}$$

  ✓ the orientation of the phase space ellipse of the electron beam should match the one of the photon beam.



$\sigma'_R \approx \sqrt{\lambda/2L}$ $\sigma_R \approx \sqrt{2\lambda L}/2\pi$ $\varepsilon_R = \sigma_R \sigma'_R = \lambda/2\pi$ $\beta_R = \sigma_R/\sigma'_R = L/\pi$

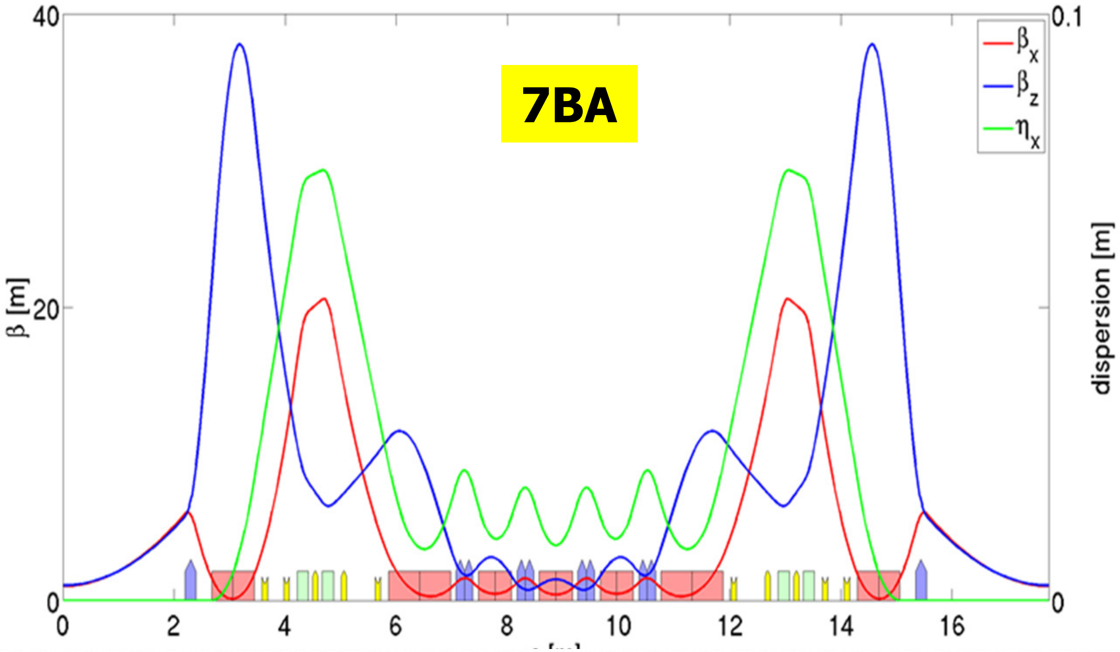
Phase space matching: Optimum β function



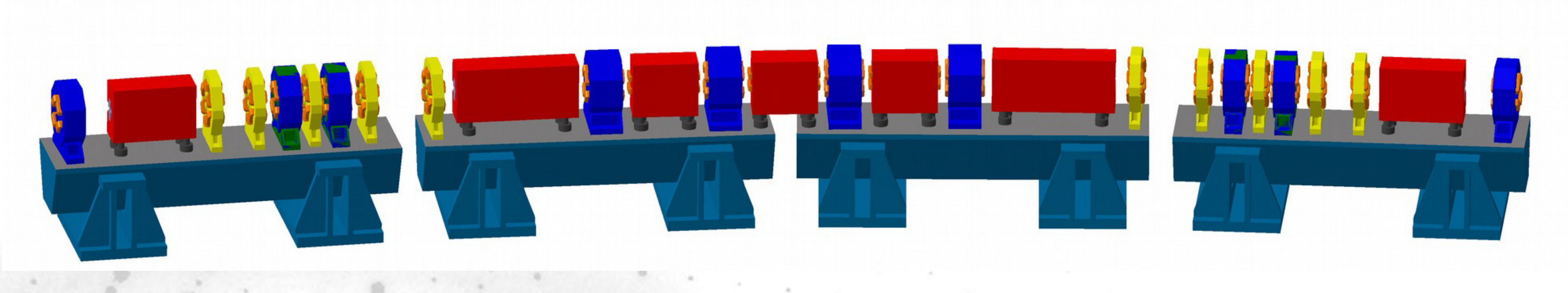
- Following the photon energy range of optimization (up to 3 keV), the target emittance should then be **less than 65 pm.rad in both planes** and for an undulator of **4 m** length, the ideal value of β_R at the center of the undulator should be around $\boldsymbol{\beta_R \approx 1.27\ \mathrm{m}}$.

New baseline Storage Ring Lattice – November 2017

ε_x = 72 pm.rad 20 identical cells – 20 straight sections L_{ss} = 4.4 m **$\beta_x = \beta_z$ = 1 m!**



Circumference	C (m)	354.7
Energy	E (GeV)	2.75
Working point	ν_x, ν_z	55.20 , 18.20
Natural Chromaticities	ζ_x, ζ_z	-134, -125
Momentum compaction	α_1	1.5 10^{-4}
Natural emittance	ε_0 (pm.rad)	72
Energy spread	$\sigma_{\Delta E}$	8.6 10^{-4}
Energy loss per turn	ΔE_{rad} [keV]	310
Damping times	$\tau_{x,z,s}$ [ms]	10, 21, 24



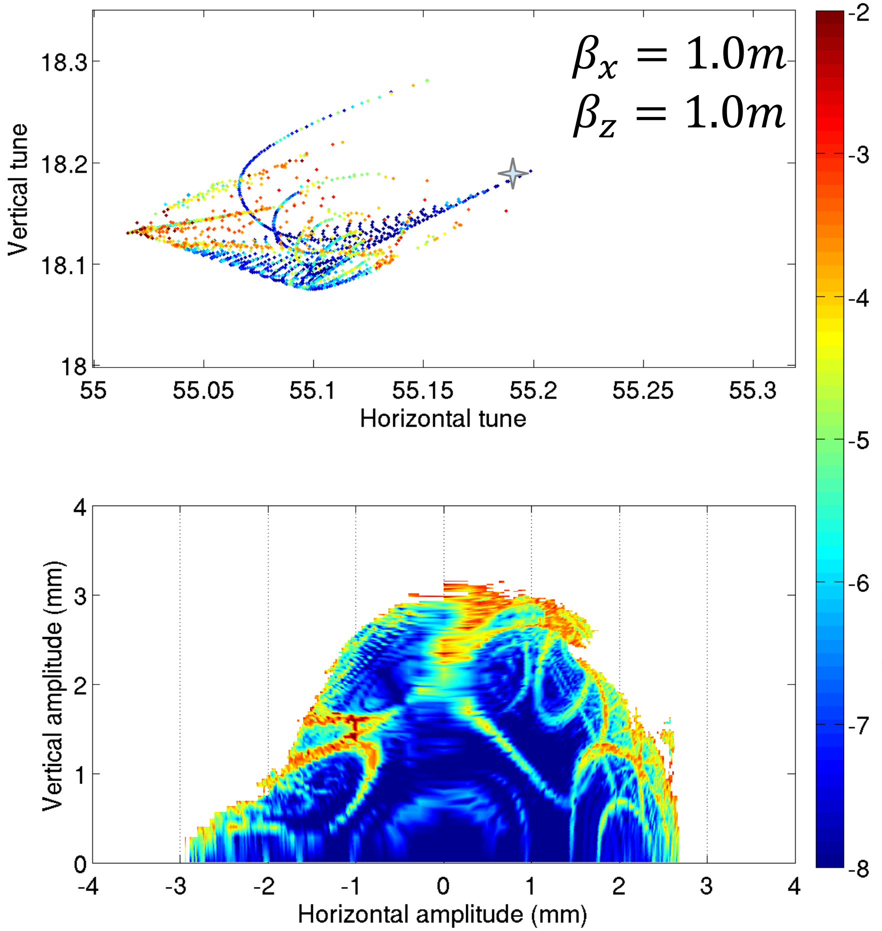
– Sextupole < 2000 T/m^2 – Quadrupole < **100 T/m** – Dipole ~ 0.6 T & **40 T/m**

– Without longitudinal gradient in bending magnets.

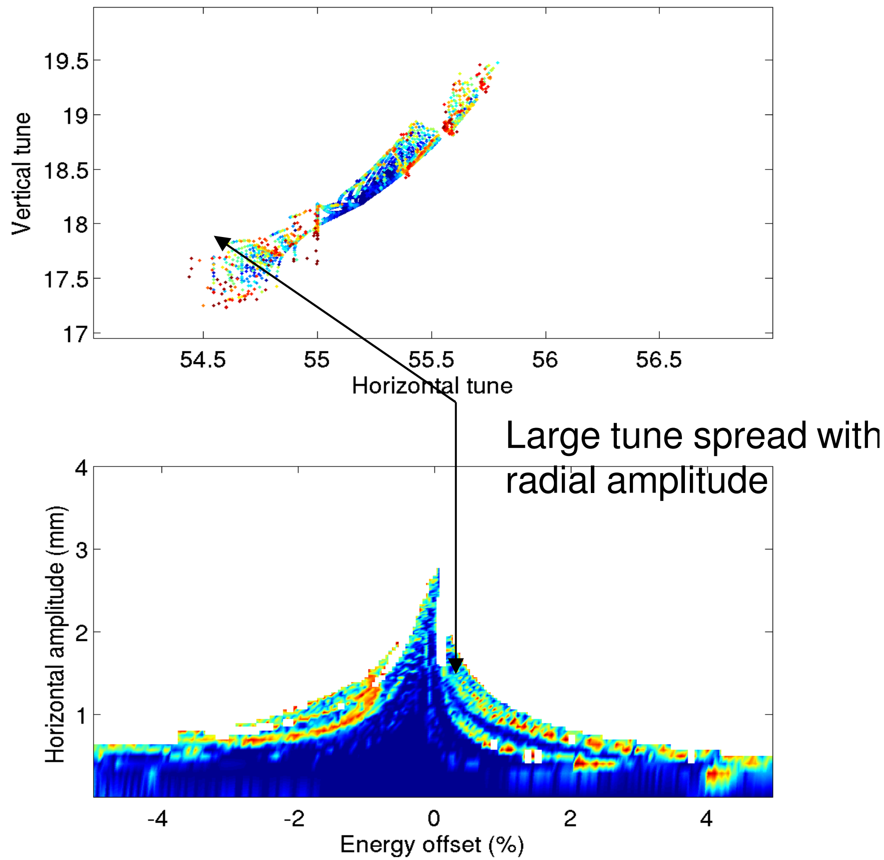
Dynamic Aperture

New baseline Storage Ring Lattice : 72 pm.rad.

Perfect lattice



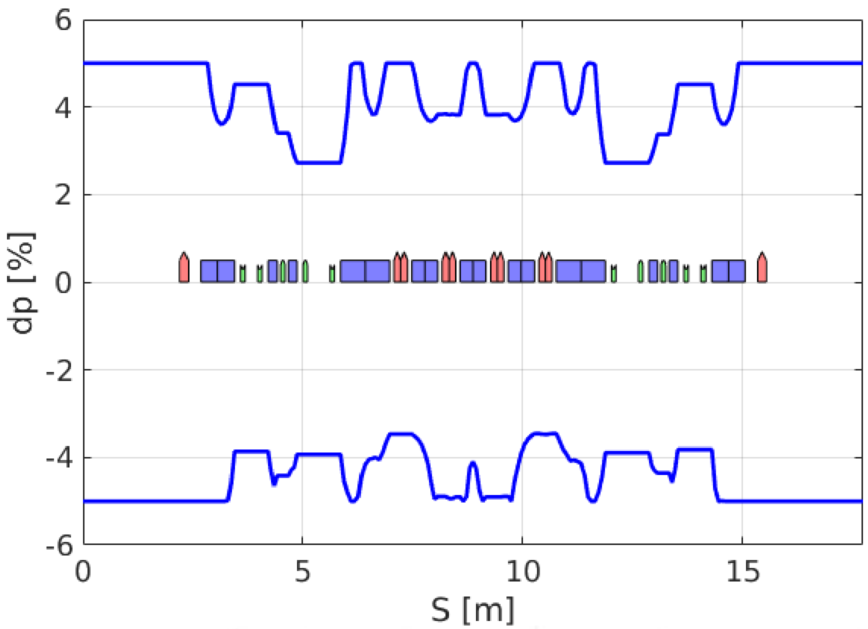
result.v9

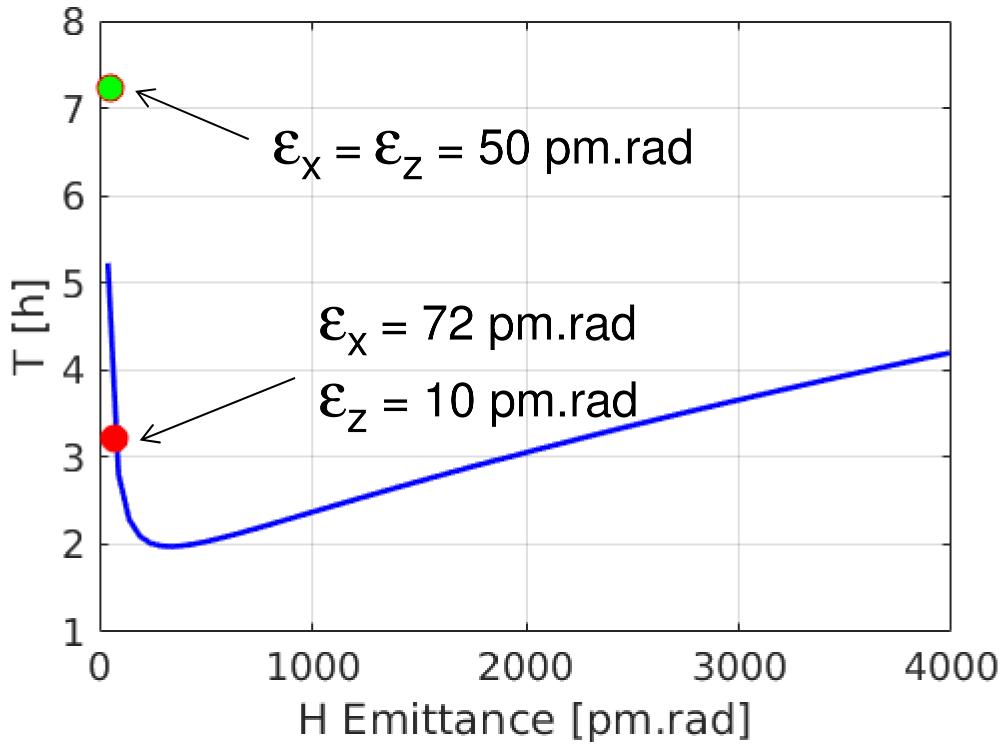


result.v9

$\xi_x = +1.5$
$\xi_z = +1.5$

Expected Touschek beam lifetime



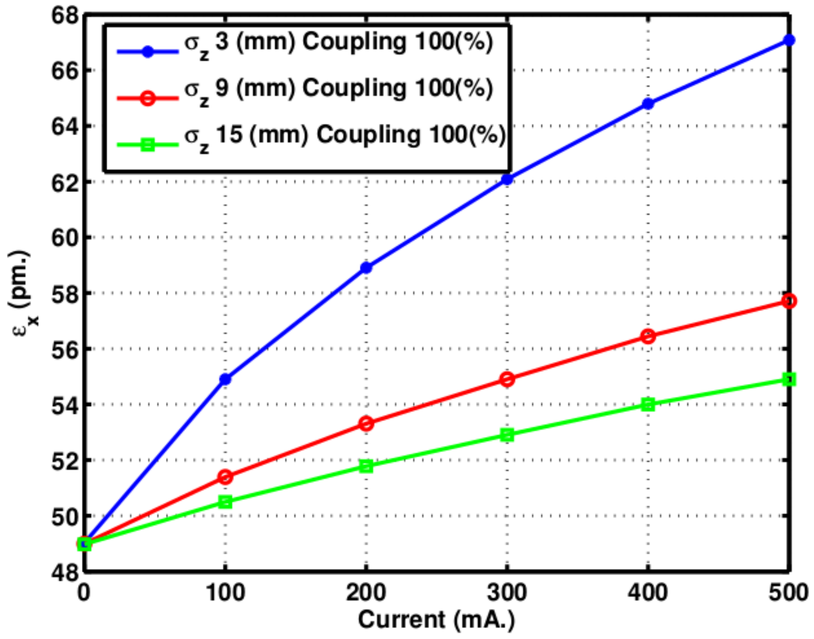


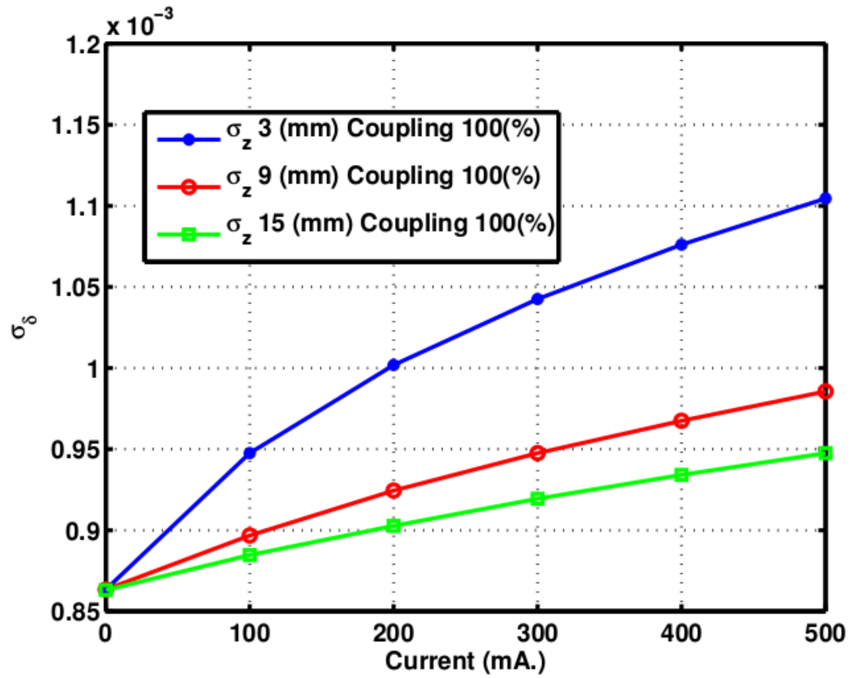
Simple horizontal emittance scan

Seems to be on the good side !

Beam pipe diameter of 16 mm, RF Voltage of 1.1 MV, **natural bunch length** of 3.7 mm rms and 500 mA.

IBS emittance increase



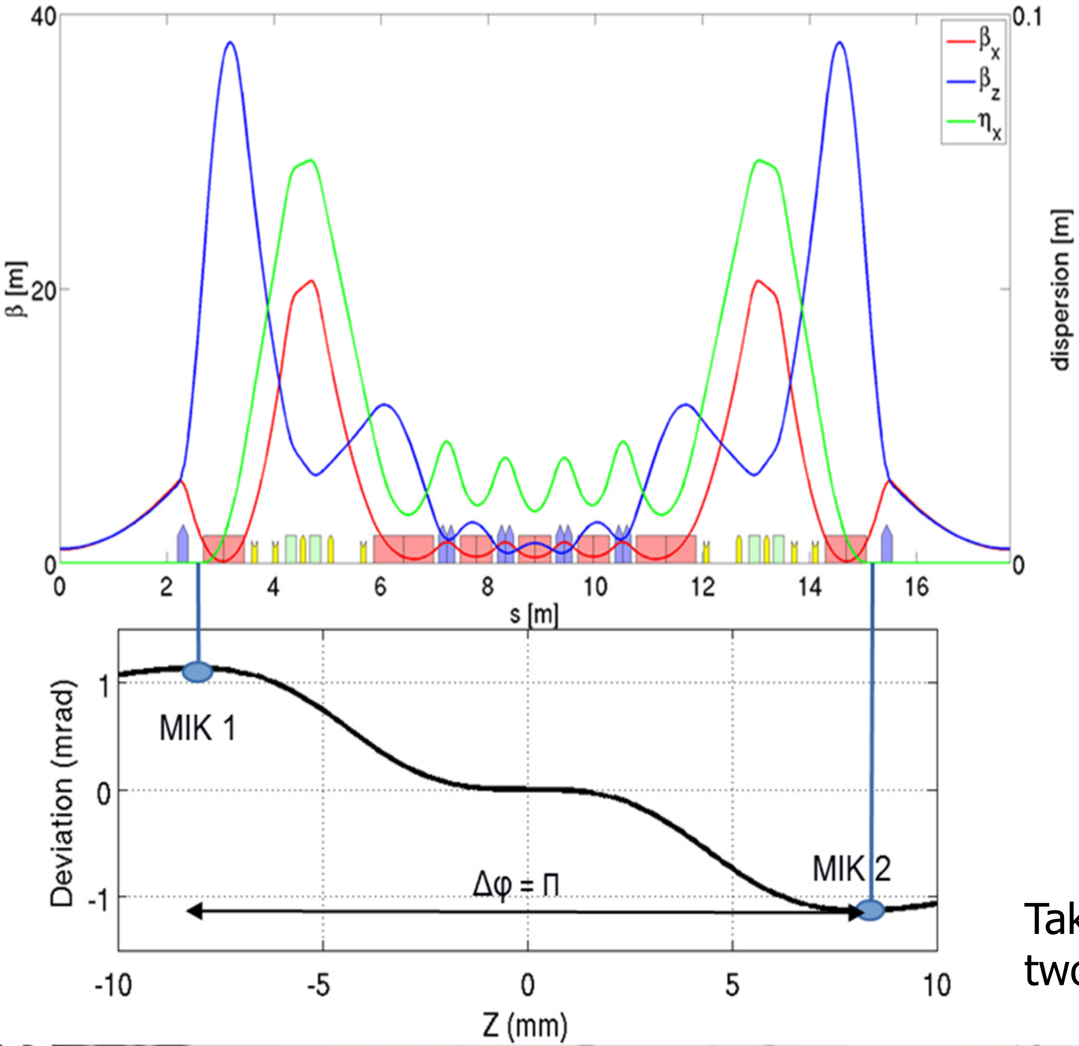


- Preliminary Intra Beam Scattering effect computed with Elegant code :
  Simple Gaussian distribution model (same result obtained with ZAP code).

- Emittance increase by 30 % with natural bunch length (0 mA)
  Limited to 10 % with RF harmonic bunch lengthening (x 5).

Injection scheme (1)

Try **vertical injection** with Multipole Injection Kicker (MIK) :



Off axis to accumulate.

Keep the lattice symmetry.

Take advantage of the large vertical beta function.

Take advantage of the natural small vertical emittance of the Booster.

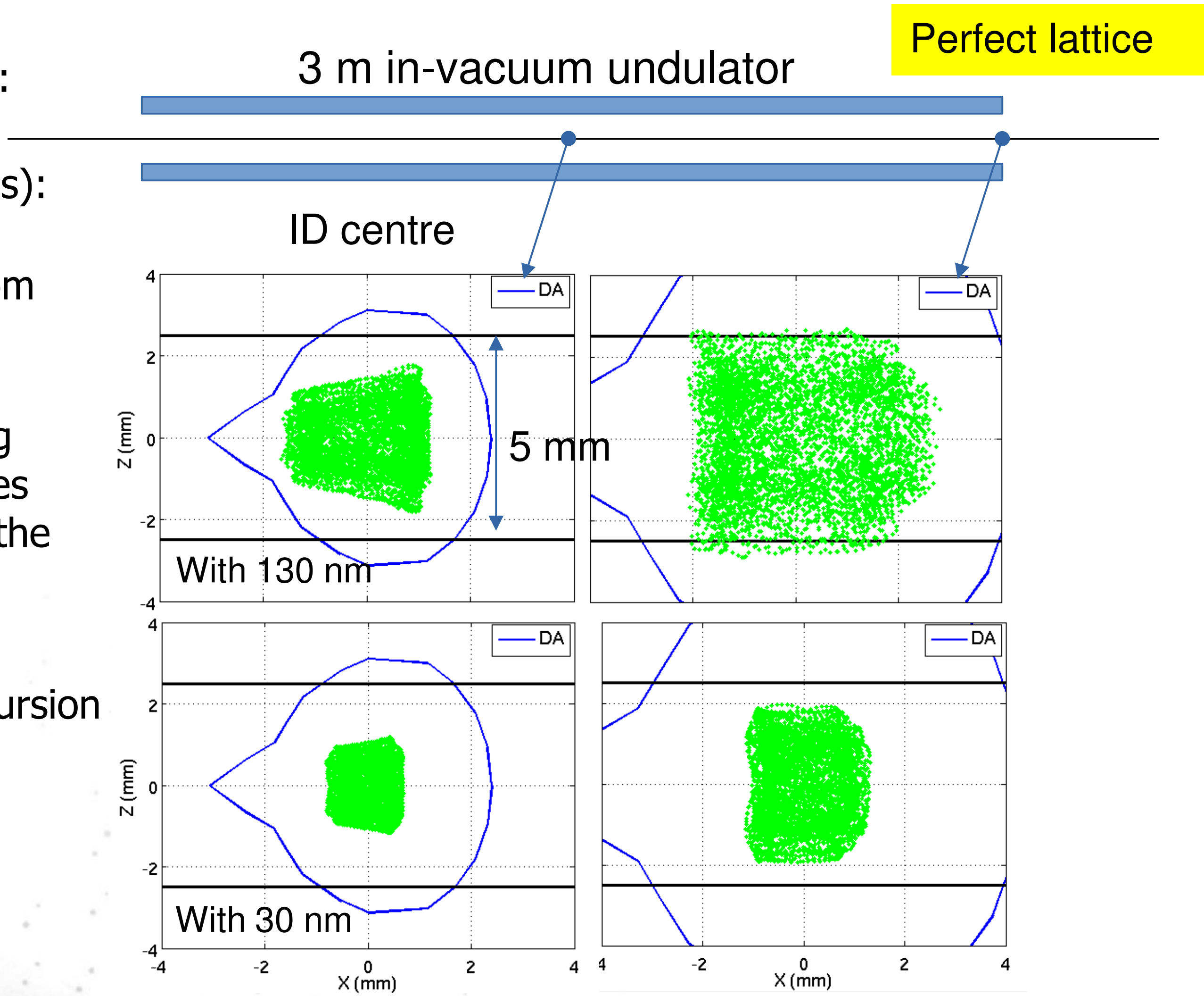
But : vertical betatron oscillation versus low gap ID …

Take advantage of the phase to use two small MIK.

Injection scheme (2)

Try **vertical injection** with
Multipole Injection Kicker (MIK) :

- Tracking with emittance (9 rms):
- With present **130 nm.rad** from the Booster.
- First cell large orbit and strong sextupoles enlarge the particles vertical excursions and reach the 5 mm gap.
- With **30 nm.rad**, vertical excursion are reduced.
- We envisage an upgrade of the Booster:



⇨ Doubling the cells (same circumference) gives **30 nm.rad**
Reuse of SR Quad. and Sext. ?

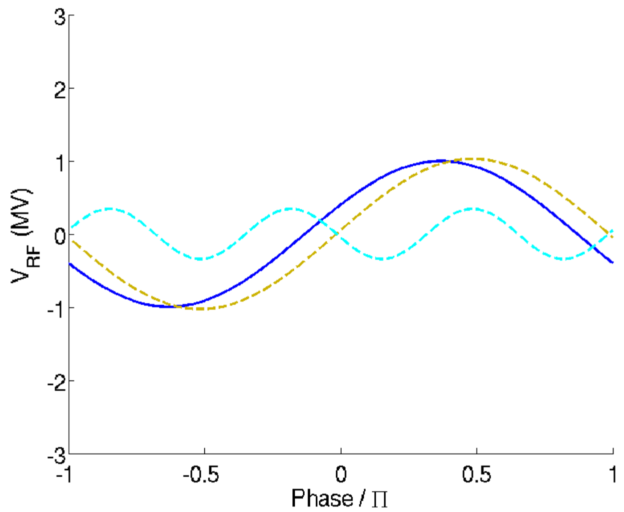
Longitudinal injection on chromatic orbit: a novel scheme under review at SOLEIL

- Use of the RF systems (nominal and harmonic) in a **original** manner, in association with the pulsed field of a multipole (MIK).

Main RF cavity 352 MHz

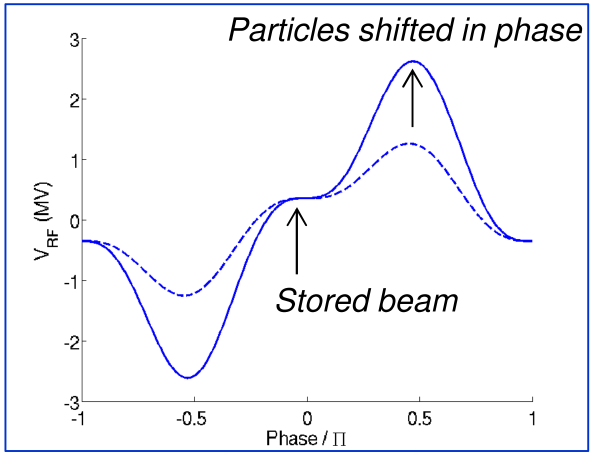
V_{RF} = 0.9 MV, U_0 = 310 keV/turn

\+ additional RF pulse of same frequency, shifted by φ_s, V_{add} ~ 1.4 MV



\+ correction by 3rd harmonic

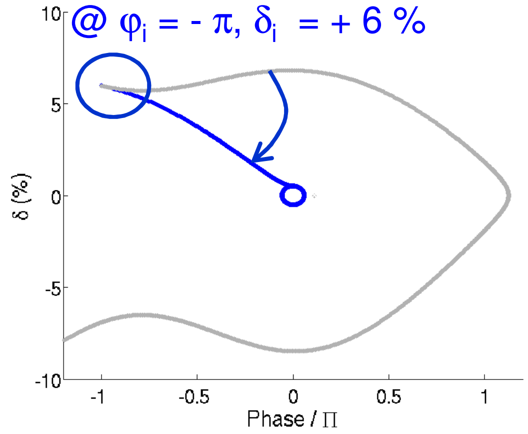
$V_{3rd} = V_{add} / 3$

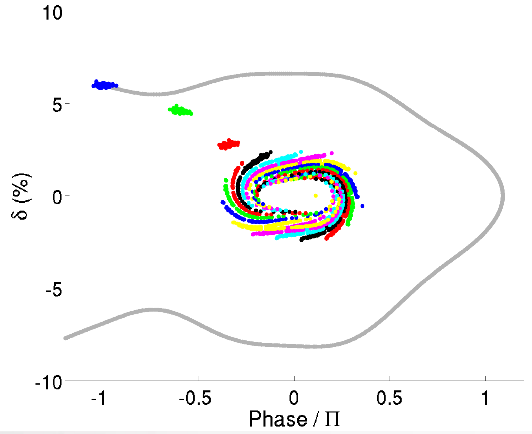


Total Voltage

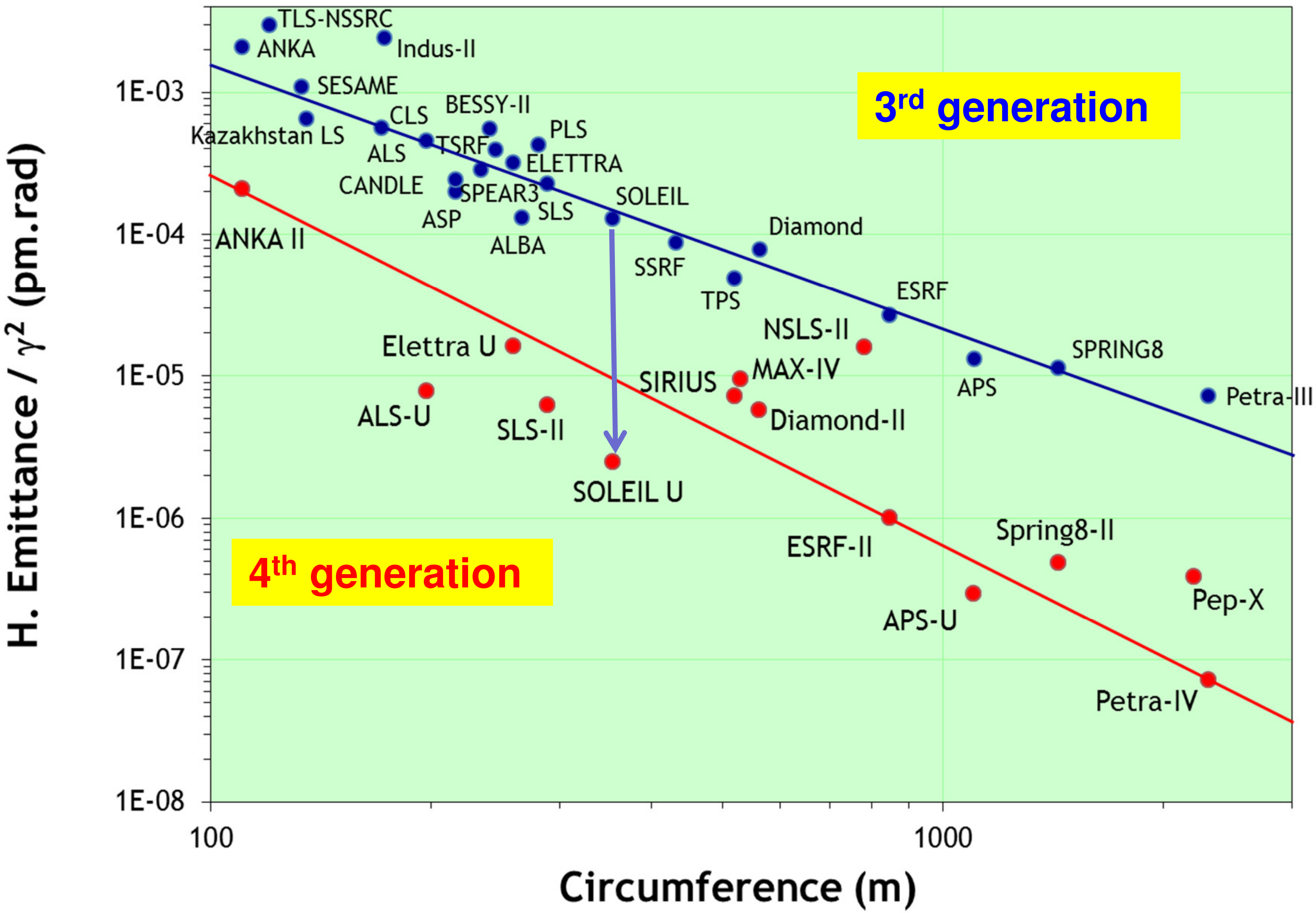
Injected beam

@ φ_i = - π, δ_i = + 6 %

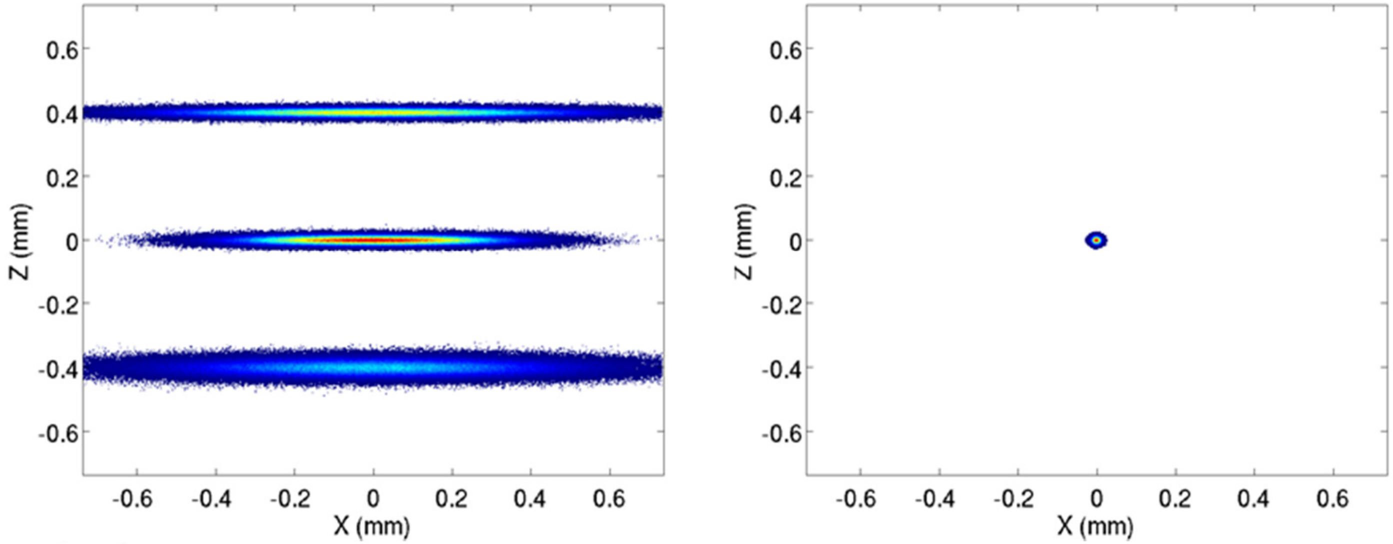




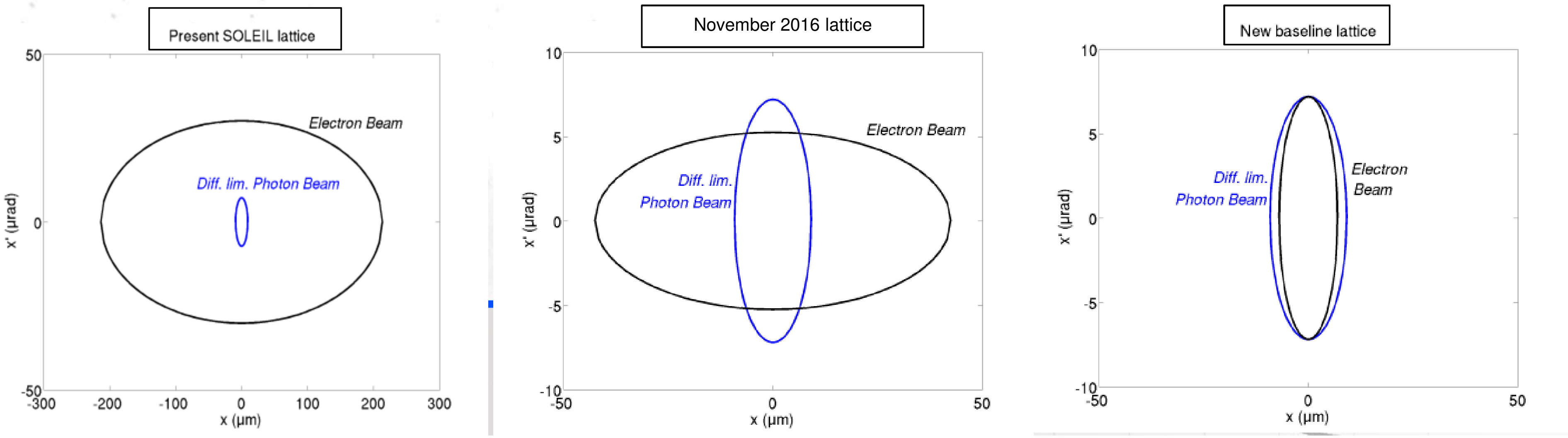
Horizontal emittance normalized to the square of the energy for 3rd generation lattices (blue) and for new lattice design studies (red).



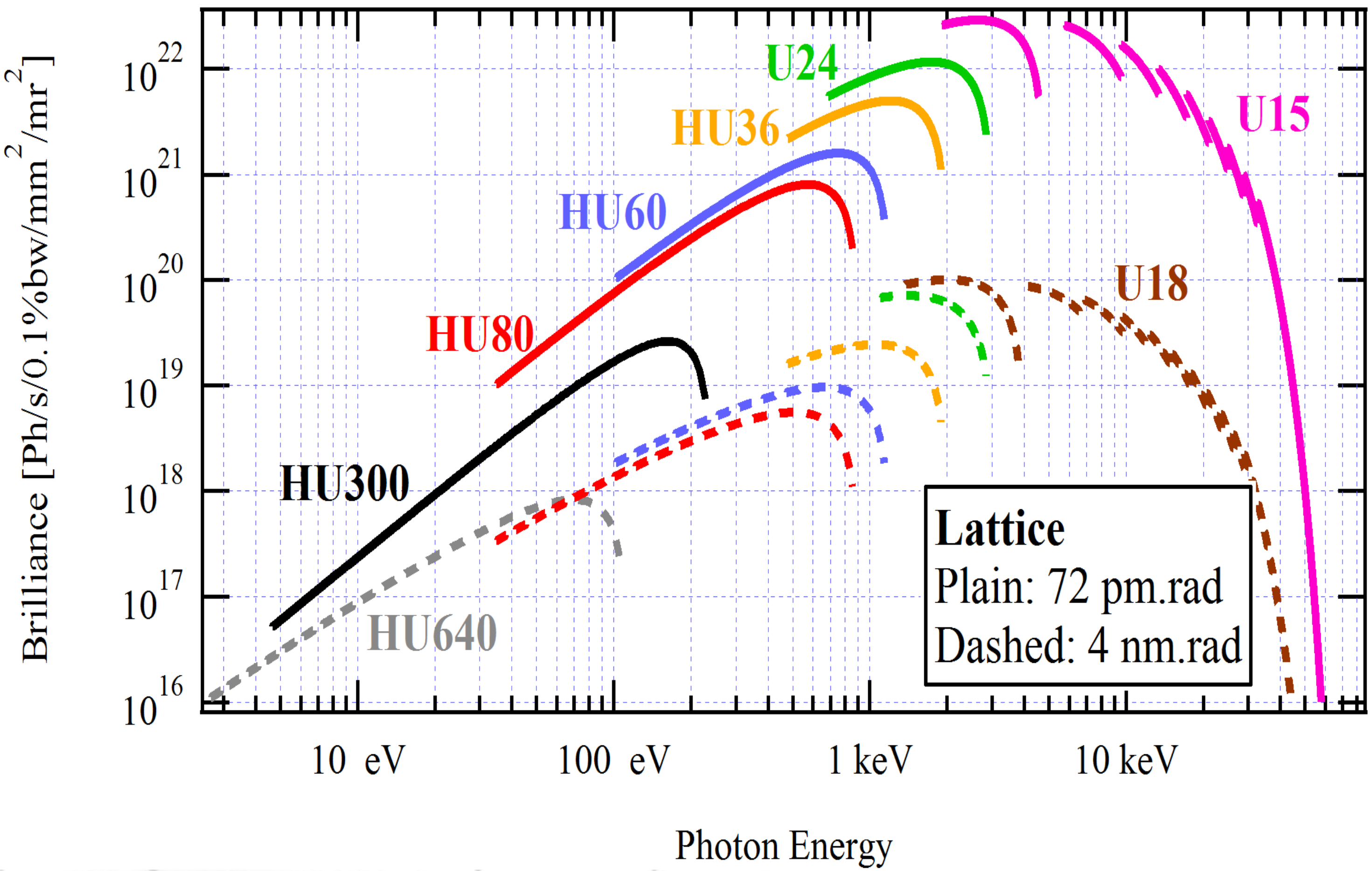
- Comparison of the transverse beam profiles of present SOLEIL (left) for the three straight sections (SDC, SDM and SDL) and SOLEIL Upgrade baseline (right) with 50 pm.rad emittance in each planes.



- Horizontal phase space of the electron beam (black) and diffraction limited photon beam at 3 keV (blue).



Photon Brilliance Comparison

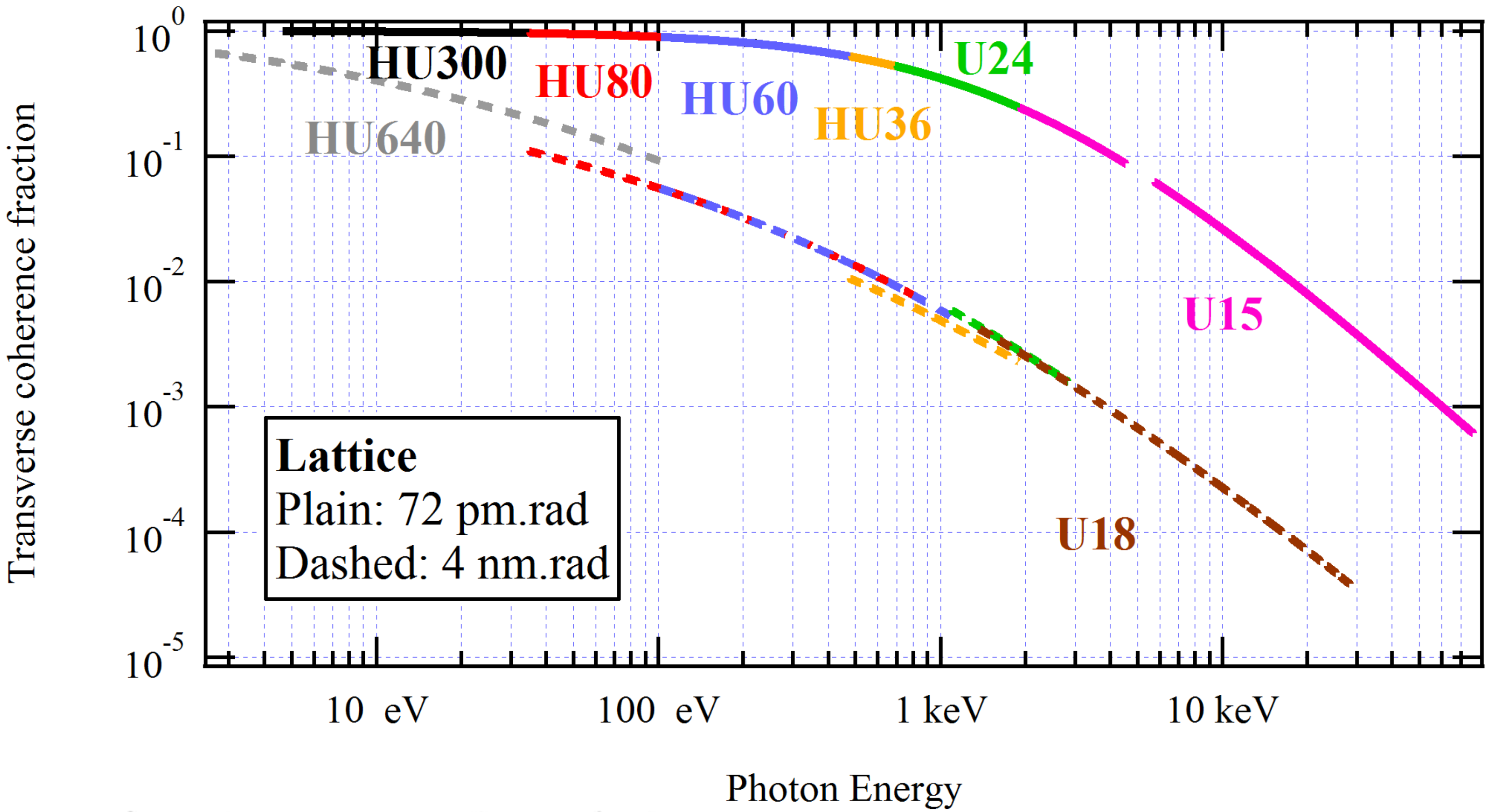


The brilliance increase reach **two orders** of magnitude in the region of interest :

between **1 to 3 keV**, exceeding a value of 10^{22} photons/s/mm²/mrad²/0.1%b.w

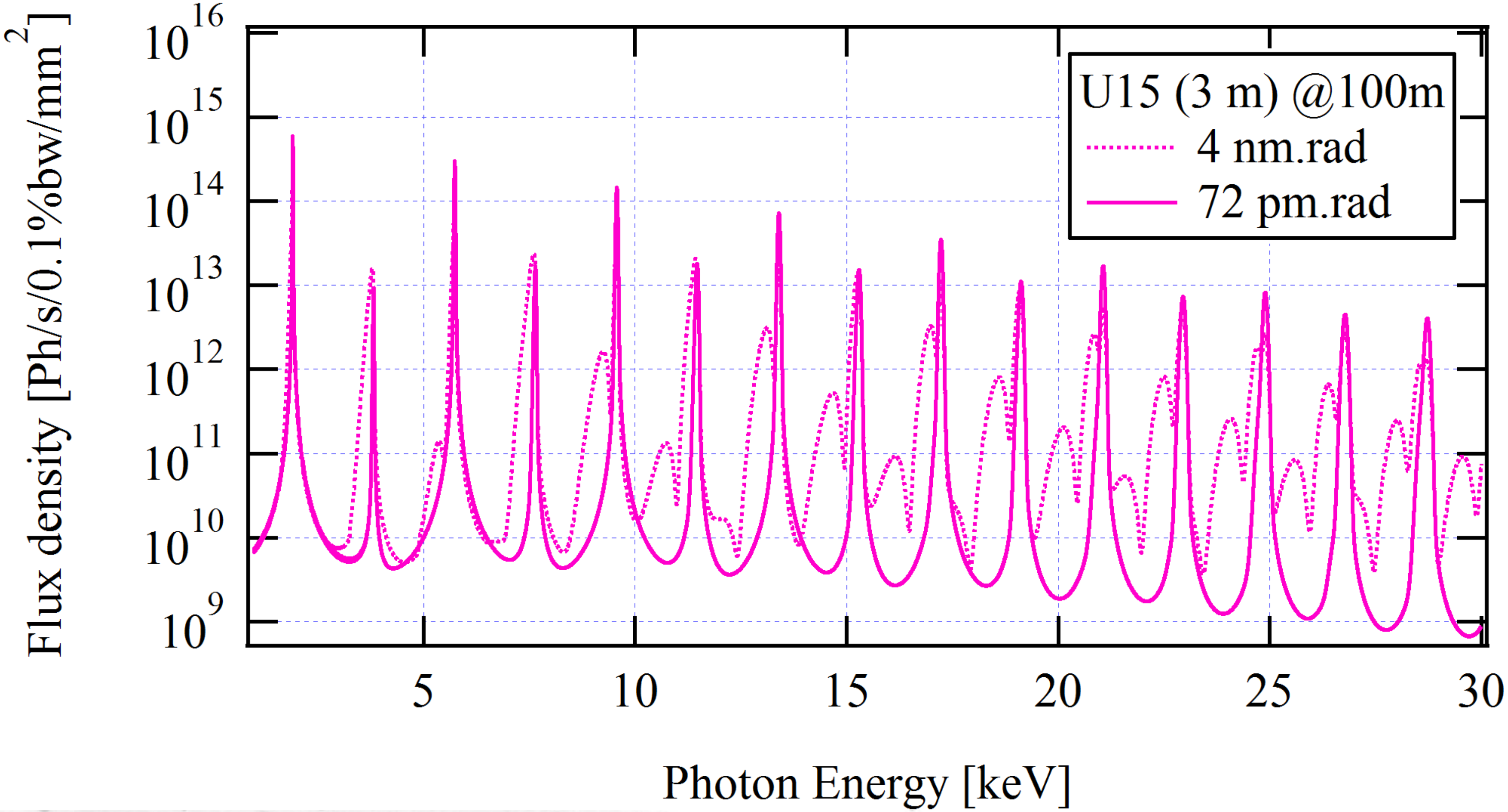
It can exceed 10^{20} photons/s/mm²/mrad²/0.1%b.w at 40 keV!

Transverse Coherence Fraction Comparison

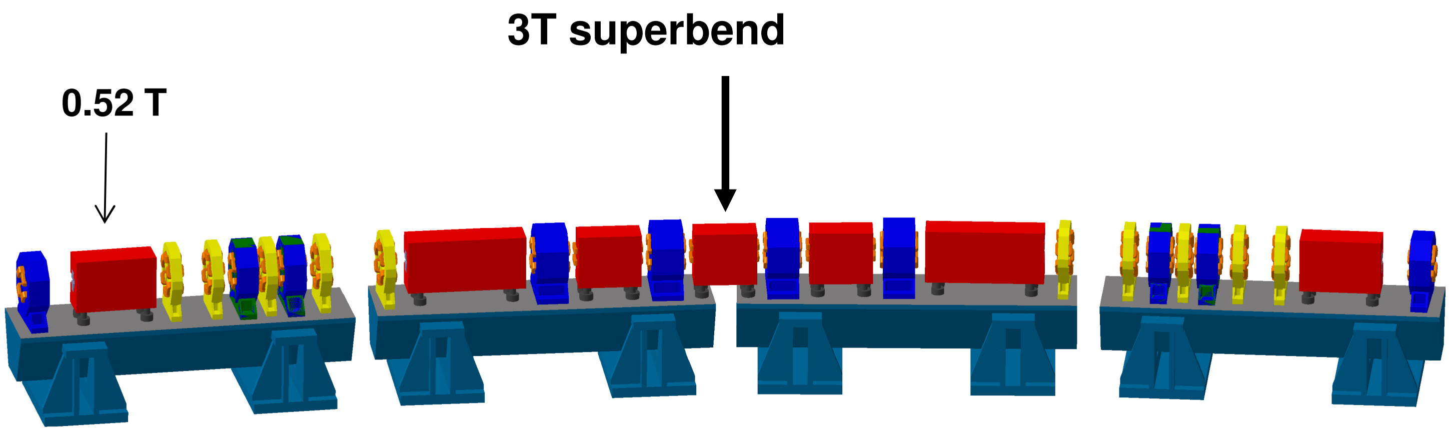


- The photon beam would be fully coherent up to almost 200 eV, exceeding 41% at 1 keV and reaching 14% at 3 keV.

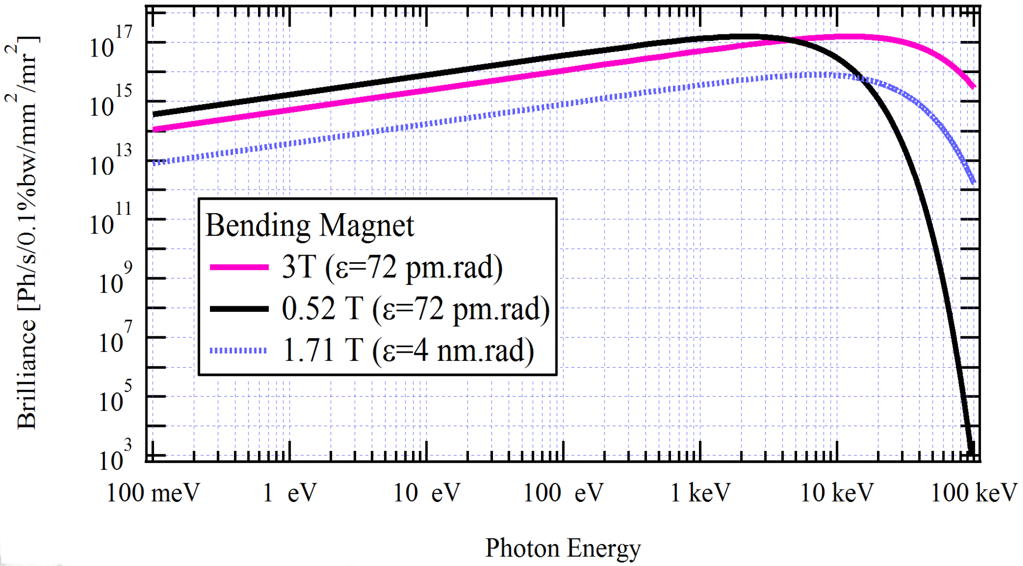
Undulator spectrum purity



Bending Magnet Sources



- Insertion of **3T** superbend in the central magnet of the cell
- The impact on the emittance depends on the number.
- Standard magnet (**0.52** T) could be used for IR and low photon energy.



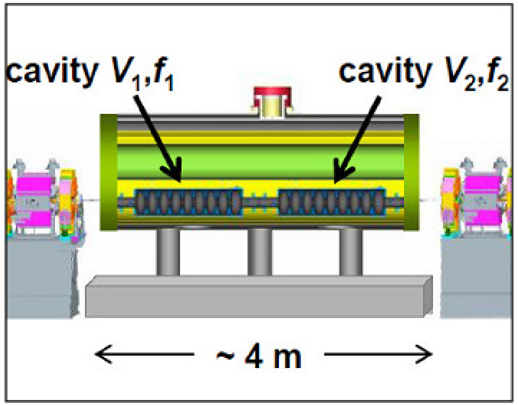
TEMPORAL STRUCTURE and SHORT PULSE

❑ Temporal structure:

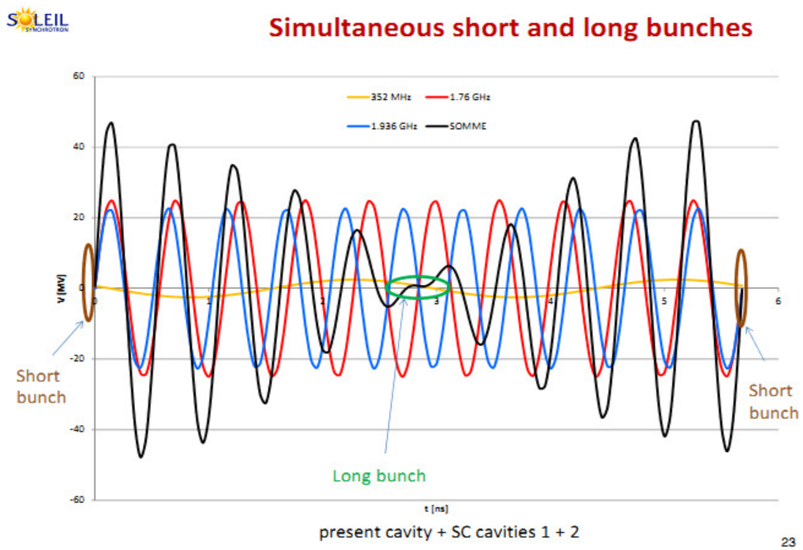
- Hybrid/camshaft mode, 1 bunch, 8/16 bunches.
- Possibility of Pseudo Single Bunch with the camshaft mode.
- *Bunch length ~ 24 ps - 120 ps FWHM.*

❑ Short pulse option:

- Use higher emittance ~ 600 pm.rad (compensate for IBS and reduced beam lifetime).
- Use of two harmonic cavities with two different frequencies "à la BESSY VSR", in order to shape the longitudinal phase space. Short and long bunch alternate.

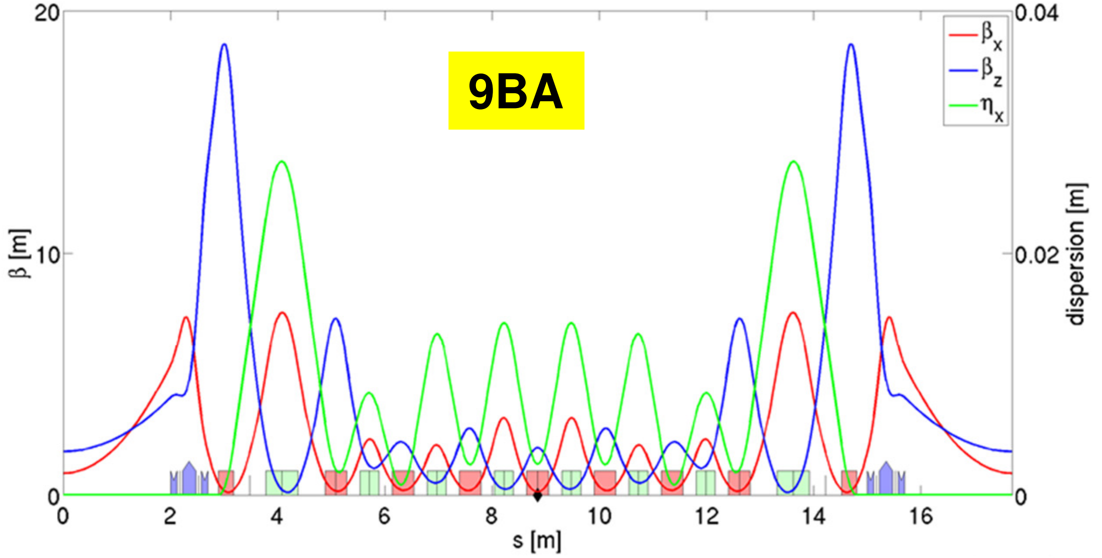


SOLEIL	f_{RF} (GHz)	V_{RF} (MV)	V'_{RF} (MV. GHz)
Nominal RF SC cavity	0.352	1	2π 0.35
First harmonic SC cavity (n=5)	1.760	10	2π 17.6
S[nd] harmonic SC cavity (n=5+1/2)	1.936	9.1	2π 17.6
Even fixed points			2π 35
Gain			35/0.35 = 100
Theoretical bunch length reduction			$\sqrt{100} = 10$

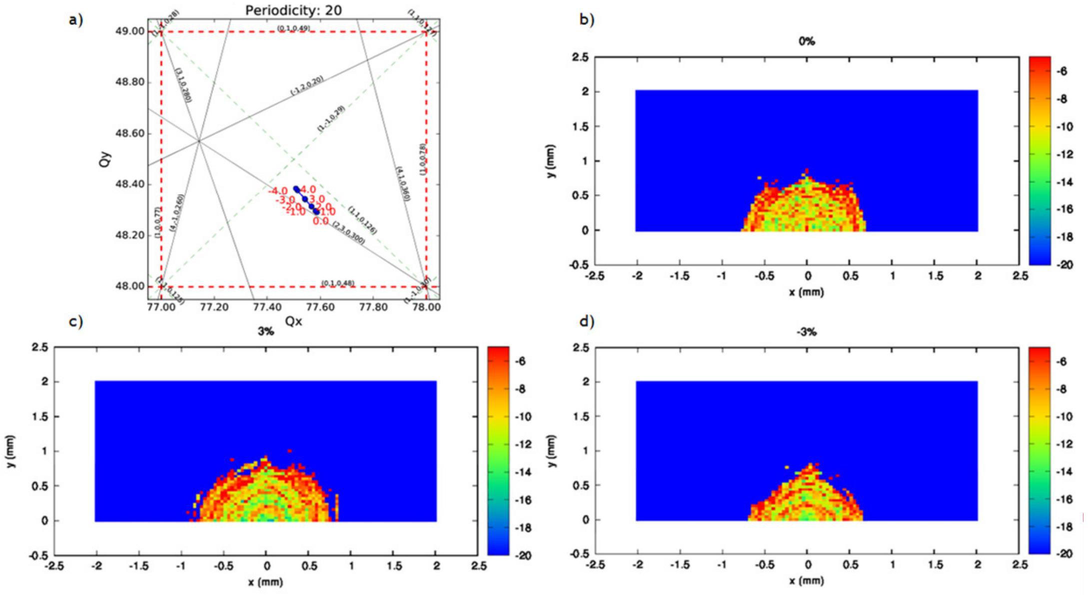


A potential candidate with even lower emittance

ε_x = 32 pm.rad 20 identical cells – 20 straight sections Lss = 4.4 m with **β_x = 0.9 m and β_z = 1.8 m.**



Nonlinear Optimisation (MOGA)



Timeline

Date	Phase
Dec. 2016	Council meeting, presentation of the first proposal for an upgrade.
2017 - 2019	Discussions regarding the definition of the project (beamlines and storage ring); definition of objectives. Baseline Lattice defined.
2018 - 2019	Continuation of discussions and prototyping to assess feasibility of key options.
2019	**Decision to launch a Conceptual Design Report (CDR).**
2019-2020	CDR based on preliminary studies and prototyping.
2020	**Decision to launch a Technical Design Report (TDR).**
2020-2022	Technical Design Report.
2022	**Decision to start the project.**
2022-2025	Reconstruction of storage ring and beamlines.
2026	Restart of user operation.

Conclusion

- The present SOLEIL upgrade lattice baseline achieve a low natural emittance of **72 pm.rad or 50 x 50 pm.rad** at full coupling.

- Including a third harmonic cavity should guarantee comfortable beam lifetime as well as a limited emittance increase from IBS.

- Low beta functions at ID straight sections for a good phase space matching enabling a very high brilliance, in particular in the desired region of 1 to 3 keV.

- Off axis injection is still under investigation while keeping the high lattice symmetry enabling a more comfortable beam dynamic aperture.

- Booster upgrade with much lower emittance is envisaged too.

Ongoing task :

- Needs much more qualification work to assess its robustness such as effects of errors, injection efficiency and beam lifetime.
- A lot of work and exchange between the different groups to meet engineering constraints.
- Magnet R&D feasibility just started.
- Commissioning strategy to be defined.

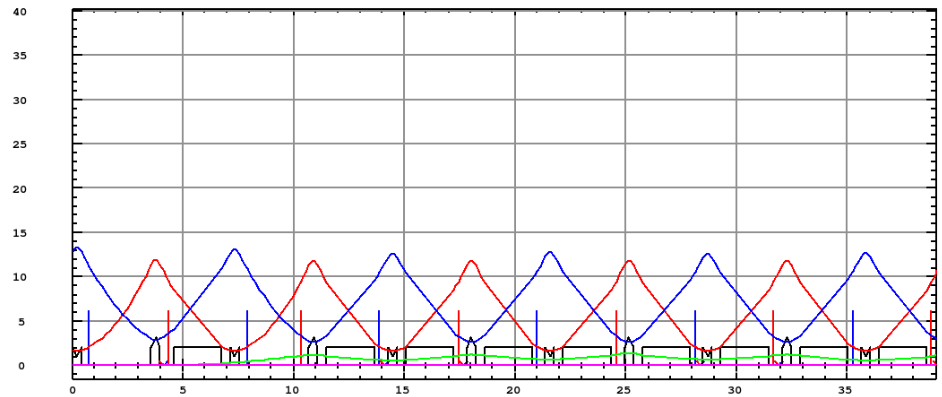
Backup

Increase the number of FODO-cell by 2 by splitting the long dipole

1/8 of the ring

Actual optics

Natural emittance : 140 nm.rad
110 nm.rad at minimum

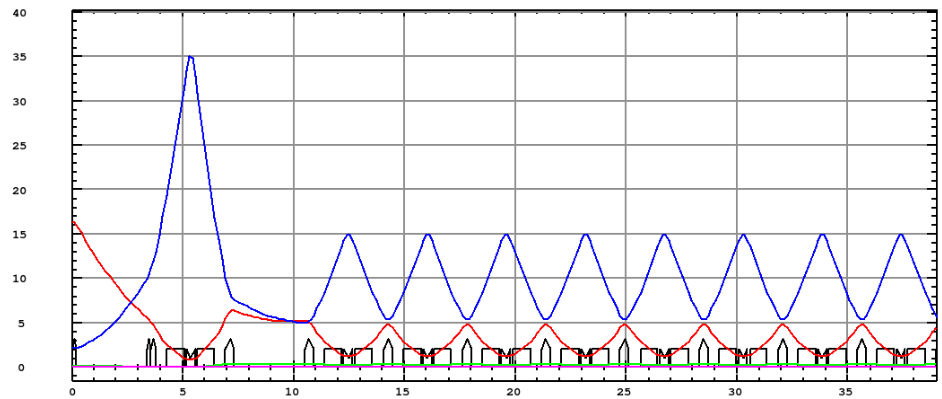


Possible upgrade :

Splitting the long 36 dipoles with
36 additional quadrupoles

Natural emittance is 30 nm.rad

Keep RF and injection/extraction
section as there are.



S(m)

Boundary Conditions and Constraints

- Reduce by more than a factor 30 or 40 the horizontal electron beam emittance (in the order of 100 pm.rad): this is 3 to 4 times more ambitious than in the first proposal .
- Reuse of the existing tunnel and its radiation shielding wall.
- Maintain the existing insertion device source point positions.
- Keep a storage ring energy commensurate with a very broad photon energy range.
- Preserve a current of 500 mA in multibunch operation.
- Preserve time structure and time resolved operations.
- Reuse of the injector complex: Linac and booster.
- Reuse much of the technical infrastructure.
- Limit downtime to a maximum of two years.
- Minimize operation costs, in particular the wall-plug-power.
- Preserve Infra-Red (IR) beamlines.
- Provide alternative radiation sources for the existing bending magnet based beamlines.