TOWARDS A TRUE DIFFRACTION-LIMITED STORAGE RING LIGHT SOURCE

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May 10th 2023, IPAC23, Venice, Italy

Acknowledgements:
ESRF-EBS Beam dynamics group: N. Carmignani, L.R. Carver, S.M. Liuzzo, T. Perron, S.M. White,
ESRF-EBS Accelerator and Science Division colleagues,
SOLEIL colleagues: P. Alexandre, P. Brunelle, A. Gamelin, R. Nagaoka, M.-A. Tordeux,
M. Apollonio, A. Brainbridge, R. Ollier, A. Poyet, R. Sirvinskaite, P. Tavares, T. Shaftan, for their help and fruitful discussions.

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OUTLINE

- **Diffraction limit**: definition, impact on brilliance and electron beam conditions

- **Ultra-low emittance storage ring lattices**
  - High-Order Achromat and Hybrid Multi-Bend Achromat (MBA)
  - Reverse Bend and Longitudinal Gradient Bend unitcell
  - Examples of MBA lattices with an ultra-low natural emittance
  - Complex Bend II

- **Challenges**
  - Magnet technology: high-gradient, permanent magnets, cross-talks
  - Bunch lengthening with Harmonic Cavities (HC)
  - Injection schemes and transparent top-up injection

- **The challenge of the century**: Climate change and energy/resources crisis to come

Provide a high quality photon beam for the synchrotron user community, and enable breakthroughs in spectroscopy, high-resolution imaging, microscopy, etc.

Photon beam parameters:

- → Wavelength λ
- → Spectral flux $F(\lambda)$: number of photons per solid angle $d\Omega$ and per bandwidth $d\lambda/\lambda$
- → Brilliance $B(\lambda)$: the number of photons per second emitted in a given spatial section $d\Omega dS$ and in a given bandwidth $d\lambda/\lambda$
- → Temporal and spatial coherence
- → Required time for characterization of a sample

$$F(\lambda) \geq \frac{B(\lambda)\lambda^2}{4}$$

$$l_{temp} = \frac{\lambda^2}{\Delta\lambda}, f_{coh}$$

$$\tau \propto \frac{1}{B(\lambda)^2}$$

Fourth generation storage ring (SR) light sources and projects are under development, and start a new era, towards the:

Diffraction-Limited Storage Ring (DLSR)

at a given λ

Maximum brilliance of a Gaussian photon beam from an undulator of *N* periods, length L, for an odd harmonic *n*:

Photon flux → ← Wavelength

$$B_n^{max} \simeq \frac{NF_n(\lambda)}{(2\pi)^2(\Sigma_x\Sigma_{x'})(\Sigma_y\Sigma_{y'})}$$

Photon beam sizes

$$\Sigma_{x,y} = \sqrt{\sigma_r^2 + \sigma_{x,y}^2}$$

$$\Sigma'_{x,y} = \sqrt{\sigma'^2_r + \sigma'^2_{x,y}}$$

Photon beam emitted by a single electron

$$\sigma_r\sigma'_r \geq \frac{\lambda}{4\pi}$$

Equality with $\sigma_r = \sqrt{\frac{\lambda L}{8\pi^2}}$, $\sigma'_r = \sqrt{\frac{\lambda}{2L}}$

Electron beam

$$\sigma = \sqrt{\epsilon\beta + (D\sigma_E)^2}$$

$$\sigma' = \sqrt{\epsilon\gamma + (D'\sigma_E)^2}$$

with (β, α, γ) the Twiss functions, D the dispersion and σ_E the energy spread

Diffraction limit condition on the electron beam

$$\Longrightarrow \quad \sigma_{x,y} \ll \sigma_r \qquad \sigma'_{x,y} \ll \sigma'_r \quad \Longrightarrow$$

Total photon beam size does NOT depend on the source characteristics

Spatial coherence

$$f_{coh} = \frac{(\sigma_r\sigma'_r)^2}{(\Sigma_x\Sigma_x{}')(\Sigma_y\Sigma_y{}')} \leq 1$$

Electron emittances

$\epsilon \ll \frac{\lambda}{4\pi}$ → 99 pm.rad for 1 keV; 9.9 pm.rad for 10 keV

$\beta \leq \frac{L}{\pi}$ → 0.6 m for L = 2 m; 1.2 m for L = 4 m

Matching condition for optimum brilliance

P. Elleaume, *Undulators, Wigglers and their applications*, Chapter 2, Taylor and Francis, 2003

Y. Cai, et al. PRAB2012, https://doi.org/10.1103/PhysRevSTAB.15.054002

ULTRA-LOW EMITTANCE LATTICES

ORIGIN OF THE NATURAL HORIZONTAL ELECTRON EMITTANCE

$$\epsilon_x = C_q \gamma^2 \frac{< \mathcal{H} h^2 >}{J_x h^3}$$

$\mathcal{H} = \beta_x D_x'^2 + 2\alpha_x D_x D_x' + \gamma_x D_x^2$, the $\mathcal{H}$-function

Compton constant

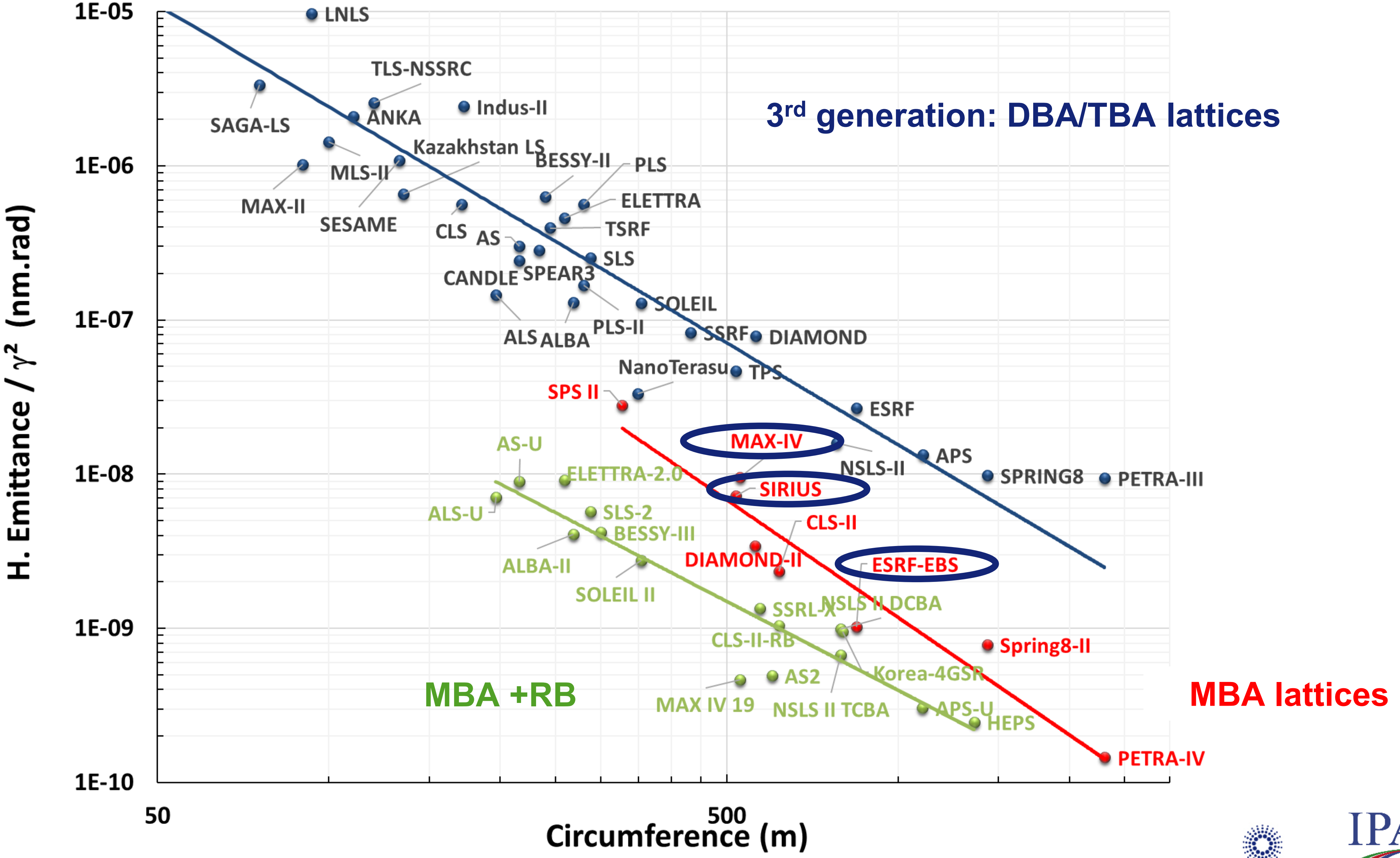
Lorentz factor

Damping partition number

Bending curvature $h = 1/\rho$

Reduction of the natural horizontal emittance by:

- Reduction of the electron energy E → Shifts the photon beam wavelengths and reduces its flux ($\propto E^2$); → More sensitive to collective effects
- Increase J_x → Increase electron oscillations and radiation damping → Combined-Function dipoles, Reverse Bends, Damping Wigglers
- Reduce $< \mathcal{H} h^2 >$ → Control of dispersion and Twiss functions in bending magnets → Longitudinal-Gradient Bends, Split bends
- Increase ρ → Lower angle per bend → Increase number of cells; → Increase N_{bends} per cell → Multi-Bend Achromat lattices (MBA)


1E-05
1E-06
1E-07
1E-08
1E-09
1E-10
H. Emittance / γ² (nm.rad)
50
500
Circumference (m)
3rd generation: DBA/TBA lattices
MBA +RB
MBA lattices
LNLS
TLS-NSSRC
SAGA-LS
ANKA
Indus-II
Kazakhstan LS
MLS-II
MAX-II
SESAME
BESSY-II
PLS
ELETTRA
TSRF
CLS
AS
SLS
CANDLE
SPEAR3
SOLEIL
ALS
ALBA
PLS-II
SSRF
DIAMOND
NanoTerasu
TPS
SPS II
ESRF
MAX-IV
NSLS-II
APS
SPRING8
PETRA-III
SIRIUS
CLS-II
DIAMOND-II
ESRF-EBS
AS-U
ELETTRA-2.0
ALS-U
SLS-2
BESSY-III
ALBA-II
SOLEIL II
SSRL-X
NSLS II DCBA
CLS-II-RB
Spring8-II
AS2
Korea-4GSR
MAX IV 19
NSLS II TCBA
APS-U
HEPS
PETRA-IV

To increase **both DA and lifetime**, linear optics include nonlinear compensation into their designs:

High-Order Achromat (HOA)

MAX IV, SOLEIL II, SLS 2.0, …

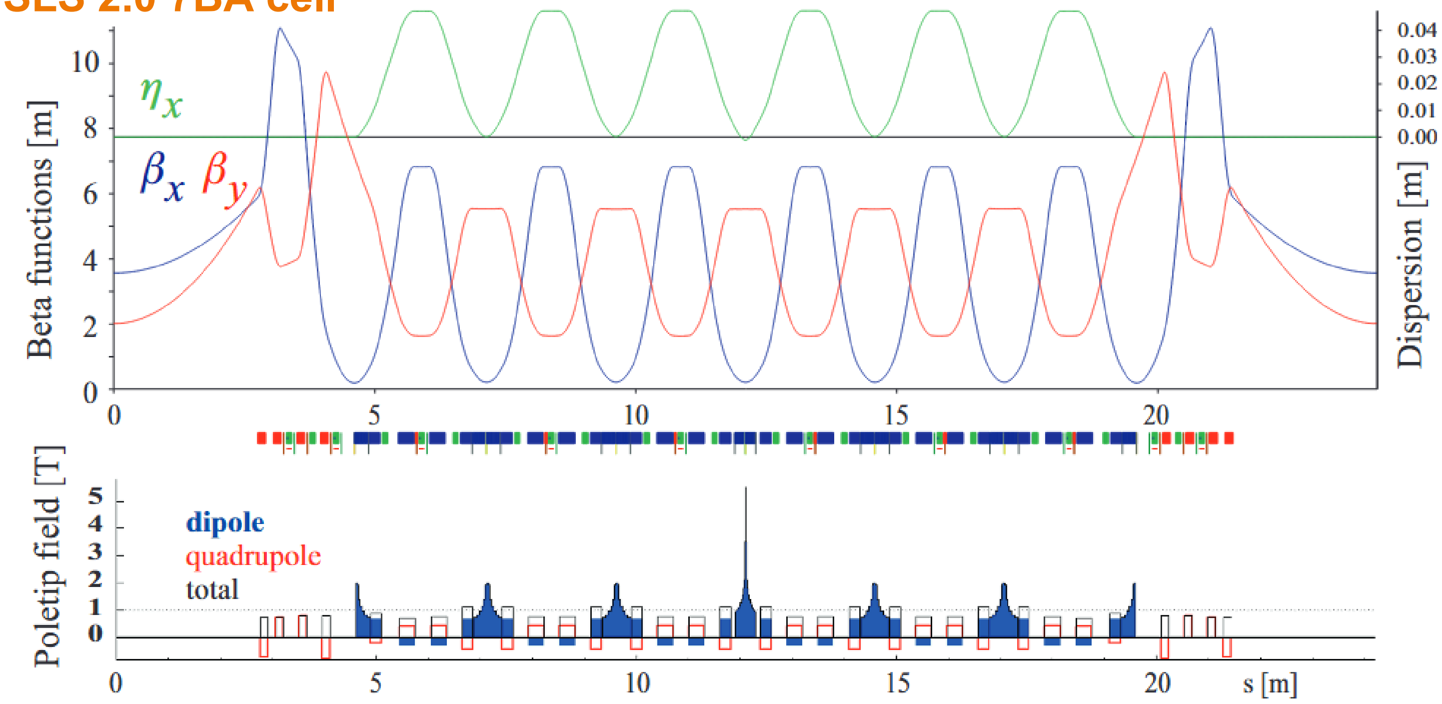
Cancellation of lowest RDT orders over a cell with tight control of the phase advance of each unitcell

$$\left(\nu_x^c, \nu_y^c\right) = \left(\frac{p}{M}, \frac{q}{M}\right),\ p \wedge q = 1$$

for a MBA lattice

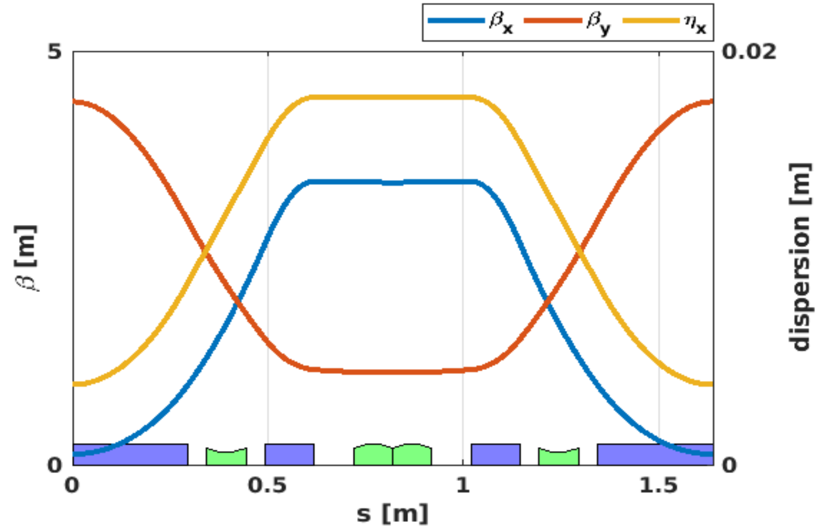
Local correction of the chromaticity.

SLS 2.0 7BA cell



From doi:10.18429/JACoW-FLS2018-WEP2PT038

Example of a HOA unitcell



Optimal reduction of the beam size in the LGB thanks to RBs (SLS-2)

B. Riemann, A. Streun, arXiv:1810.11286v1, 2018

Hybrid Multi-Bend Achromat (HMBA)

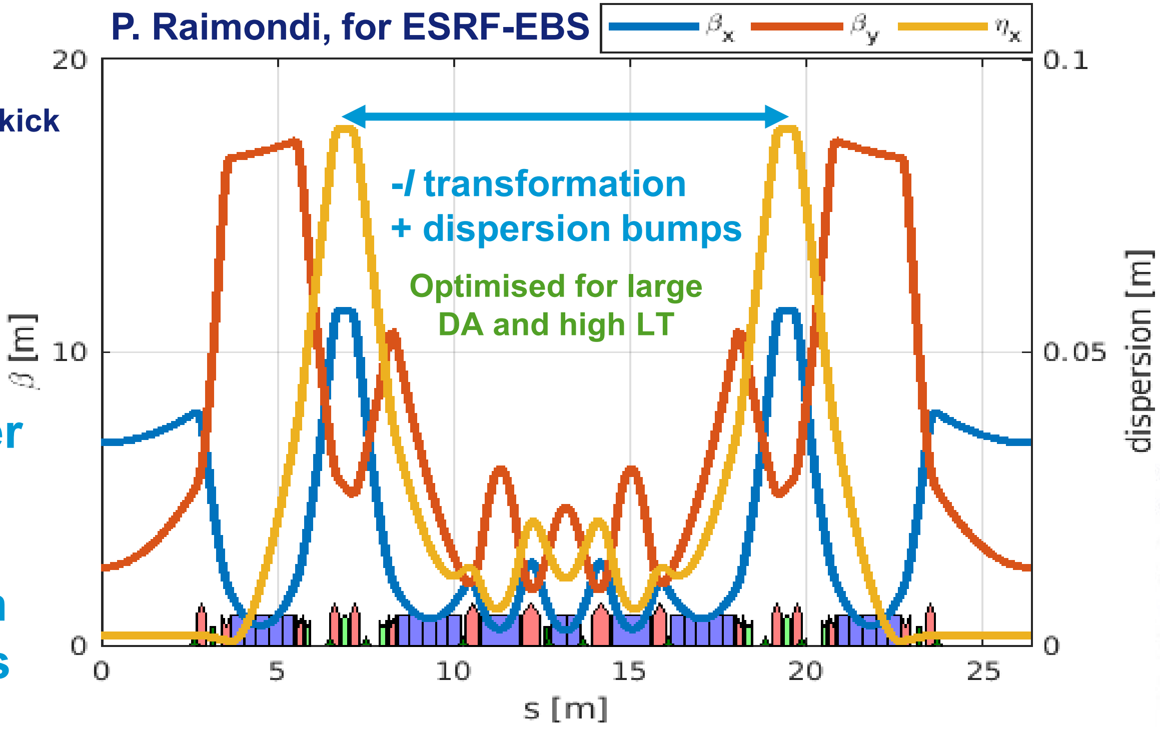
-*I* transformation

The phase advance between two symmetric sextupoles is set to $(\Delta\phi_x, \Delta\phi_y) = (\pi + 2k\pi, n\pi)$*, for kick cancellation$(k, n, \in \mathbb{Z})$.

Dispersion bumps

LGB and Dipole-Quadrupole for further emittance reduction

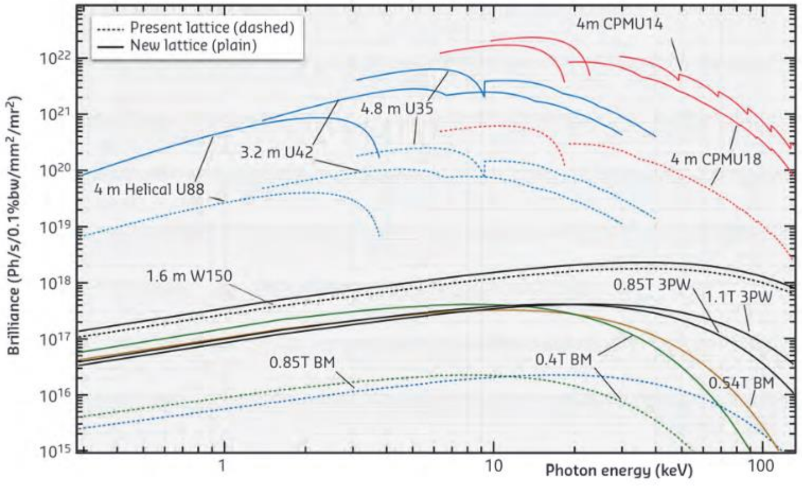
Off-axis injection with high-β_x injection cells



In user operation since August 2020

FROM ESRF TO EBS

ϵ_x^{nat}: 3985 → 133 pm.rad
Number of dipoles per cell: 2 →7
≈ 20% reduction in electricity costs
Off-energy operation of its booster
10^{20-22} brilliance in IDs
Factor 10 gain in coherence



Raimondi, P., *et al. Commun Phys* 6, 82 (2023). https://doi.org/10.1038/s42005-023-01195-z

Scheme widely adapted to different light sources: APS-U (H7BA+RB), PETRA IV (H6BA), HEPS (H7BA+RB), …

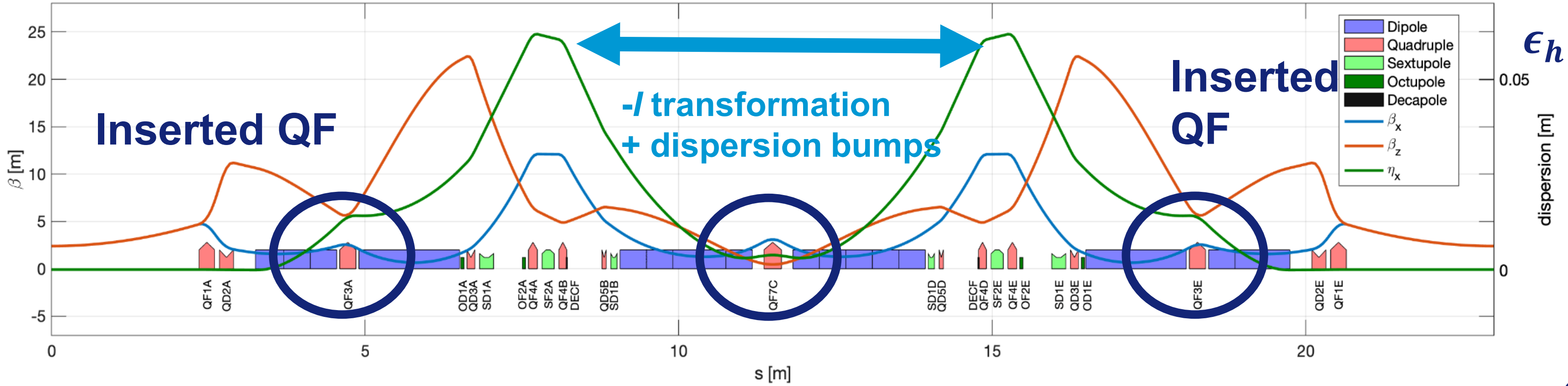
Further reduction of emittance with RB at the cost of LT and DA

P. Raimondi, S. Liuzzo, *Towards a diffraction limited light source*, PRAB, 2023

A close to "diffraction-limit" hard X-ray lattice proposal : $\epsilon_x = 10$ pm.rad for a 6 GeV, 1656.5 m circumference, optimized for large DA and large beam lifetime

Standard cells: H6BA lattice with:

- Longitudinal gradient Dipole Quadrupole + split bend
- Ultra-low emittance (< 40 pm.rad) thanks to a large SR
- Beam matching ($\beta_x = \beta_y = 2.5$ m)



$\epsilon_h = 38.4$ pm.rad

HMBA lattice
- *-I* transformation
- Dispersion bumps
- Large number of cells

$\epsilon_h = 20.1$ pm.rad

Radiation damping
- H emittance stabilization
- Less space for IDs
- Less beamlines
- Increased losses and operation costs

$\epsilon_h \geq 10$ pm.rad

Coupling resonance
- Reduced horizontal beam size
- Reduced horizontal particle density

+ Damping wigglers

PETRA III, NSLS II, PETRA IV, SSRL-X, SPring-8-II, …

+ Coupled round beam

$$\epsilon_{x=y} = \frac{J_x}{J_x + J_y}\epsilon_0$$

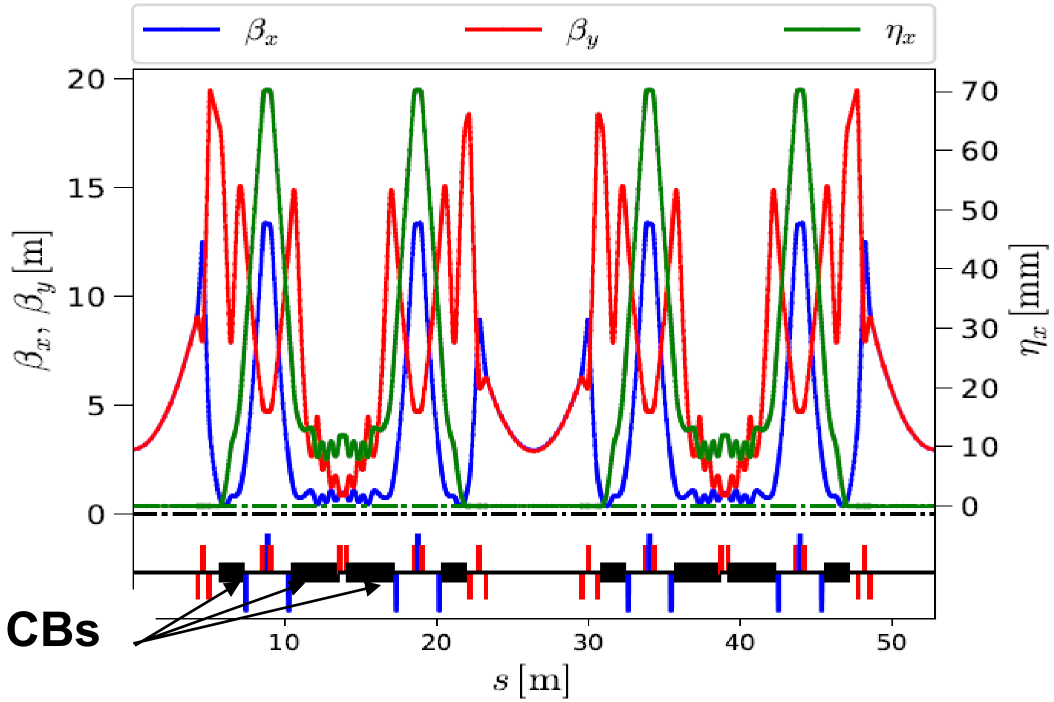
Scaling of the H6BA cell for different circumferences **S.M. Liuzzo, MOPA144**

 Courtesy of T. Shaftan

From bi-pole bending magnets to multipole bending magnets: the Complex Bend (CB)

Option for NSLS II upgrade:

Triple Complex Bend Achromat (TCBA), 3 GeV, 792 m, 30 cells, reaching 23 pm.rad natural emittance → M. Song *et al.*, 2023?



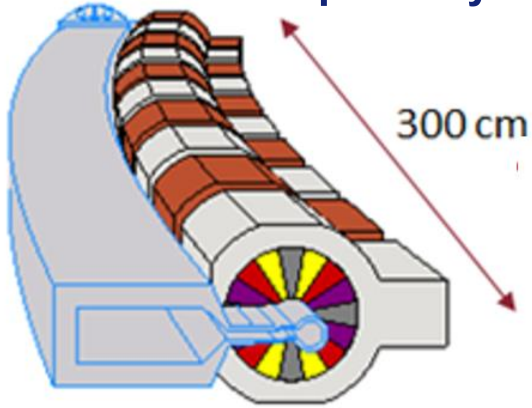
Correction of RDTs and ADTS with octupoles for CB lattices → F. Plassard *et al.*, 2021

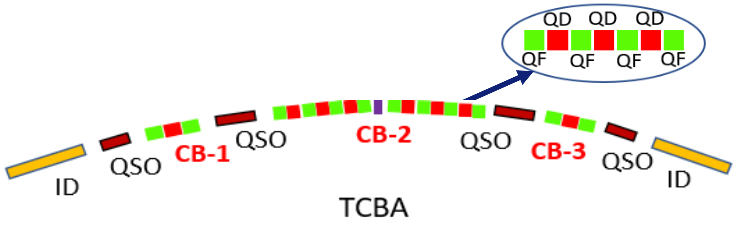
https://journals.aps.org/prab/cited-by/10.1103/PhysRevAccelBeams.22.110703

$$\epsilon_x \propto \frac{E^2}{(N_{CB}N_p)^3}$$

E the beam energy, N_d number of CB and N_p number of poles per CB.

Conceptual layout





NSLS-II upgrade with CBs: 30 cells x 4 dipoles x ~10 poles ≈ 1200 poles

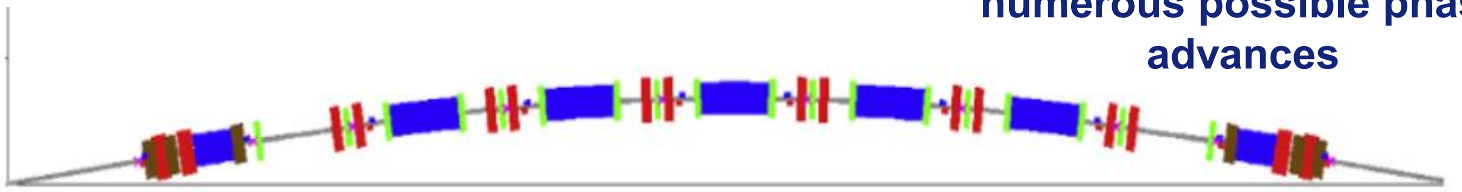
- Gradients of 130 T/m are required (PM Bend/Quad)
- Small apertures and heat load from synchrotron radiation are being assessed
- Full-scale CB element prototype (S. Sharma, IPAC22)

https://www.osti.gov/servlets/purl/1504393

P. Tavares, J. Bengtsson, Å. Andersson, Journal of Electron Spectroscopy and Related Phenomena 224 (2018)

A close to diffraction limited hard X-ray lattice proposal : $\epsilon_x = 16$ pm.rad – with IBS, for a 3 GeV, 528 m circumference, pushing the limits of the MBA lattice.

MAX IV 7BA cell



Large number of unitcells = numerous possible phase advances

5m-long straight sections

19BA cell proposal

$(\nu_x^c, \nu_y^c) = \left(\frac{2}{16}, \frac{1}{16}\right)$

19BA cell for MAX IV

E	3 GeV
C	528 m (20 periods)
(Q_x, Q_y)	(101.2, 27.28)
ϵ_x^{nat}	16 pm.rad
α_C	5.3×10^{-5}
$(\beta_x, \beta_y)_{ID}$	$(3.3, 3)$ m
σ_E	9×10^{-4}

High-gradient magnets ($\simeq 200$ T/m, $\simeq 34$ kT/m^2) → PM, small gap, cross-talks, small vacuum chambers → pumping, coating, Low DA, low lifetime, on-axis transparent injection scheme, Low momentum compaction factor, IBS, Harmonic Cavity, …

MBA challenges pushed to the limits !

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CHALLENGES

P. JAYET/ESRF

Extensive use of MBA lattices → Robustness and error tolerances → Alignment, field quality, corrections, girders

- Strong focusing → Higher chromaticity → Strong nonlinearities → Small DA → Injection scheme and efficiency
- Low dispersion → Strong sextupoles → Strong nonlinearities
  - Strong sextupoles → High gradients → Small magnetic gaps
    - High gradients → Permanent magnets → Tunability, temperature control, commissioning, first turns, homogeneity, …
    - Small magnetic gaps → Small chamber apertures
      - → Pumping, NEG coating, impedance, …
      - → Miniaturisation of magnets, chambers, correctors
  - Low α_C → Longitudinal stability (α_2, α_3); Negative α_C
- Compactness → Reduced distance between magnets
  - → Less space for corrections, pumps, etc.
  - → Crosstalk
- Small electron beam size → Stability constraints
  - → Online control tools (ML, faster feedback, …)
  - → Emittance control
  - → Increased number of controls, BPMs, detectors, …
  - BPM too close to the beam
    - → “Accordion” vacuum chambers
    - → Large impedance → Machine protection
      - → Machine interlocks, collimation, …
      - → Beam power density
        - → IDs, beamline optics
        - → Other operation challenges
- Stronger collective effects → Lower instability thresholds
  - → Increased probability of particle interactions
    - → High IBS grow rate
    - → Reduced Touschek lifetime
    - → Harmonic cavities to lengthen the bunch

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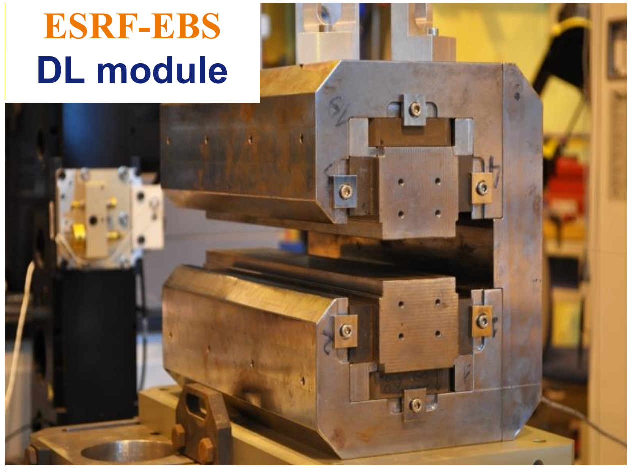
Motivation: Achieve high-gradient and Combined-Function magnets (dipoles-quadrupoles) in compact lattices while maintaining a minimum gap for vacuum specifications (coating, pumping, lifetime).

ESRF-EBS
DL module



7.7 GWh yearly savings in electricity with EBS magnets

Advantages	Challenges
High-gradients Compactness (no coils, no yoke) Reliability Less control systems Low operational costs (no cooling, no current) Low operational environmental impact	Fixed field (correctors), tunability (motorized poles) Temperature stability (shunts, control), Field homogeneity, Commissioning (first turns) Demagnetization

ZEro Power Tunable Optics (ZEPTO):
quadrupole in place in DIAMOND II booster to SR transfer line

$g_2^{max} = 60$ T/m

A. Brainbridge, IPAC22 talk, Bangkok, 2022

G.W. Foster et al., EPAC98, Stockholm, Sweden, 1998

C. Benabderrahmane, IPAC17, talk

Environmental impact
PM vs EM ?
Production costs and impact, operational costs, performances, lifetime, CO_2 emissions, etc.

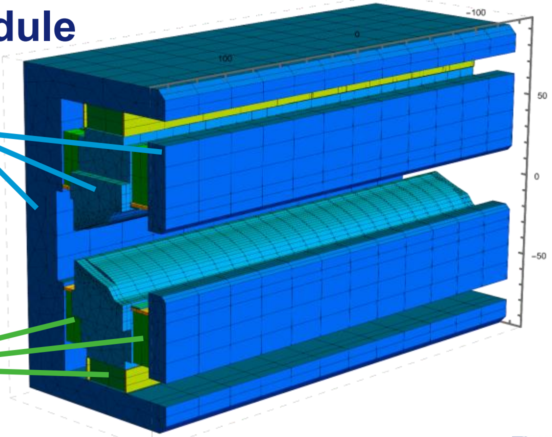
J. Dreikorn, WEPM133

PETRA IV
Longitudinal gradient DQ module

M. Gehlot, WEPM100

DLQ1 module
g_2 =–11.3/-8.6 T/m
for 0.22 to 0.29 T

Soft iron parts



Permanent magnet arrays

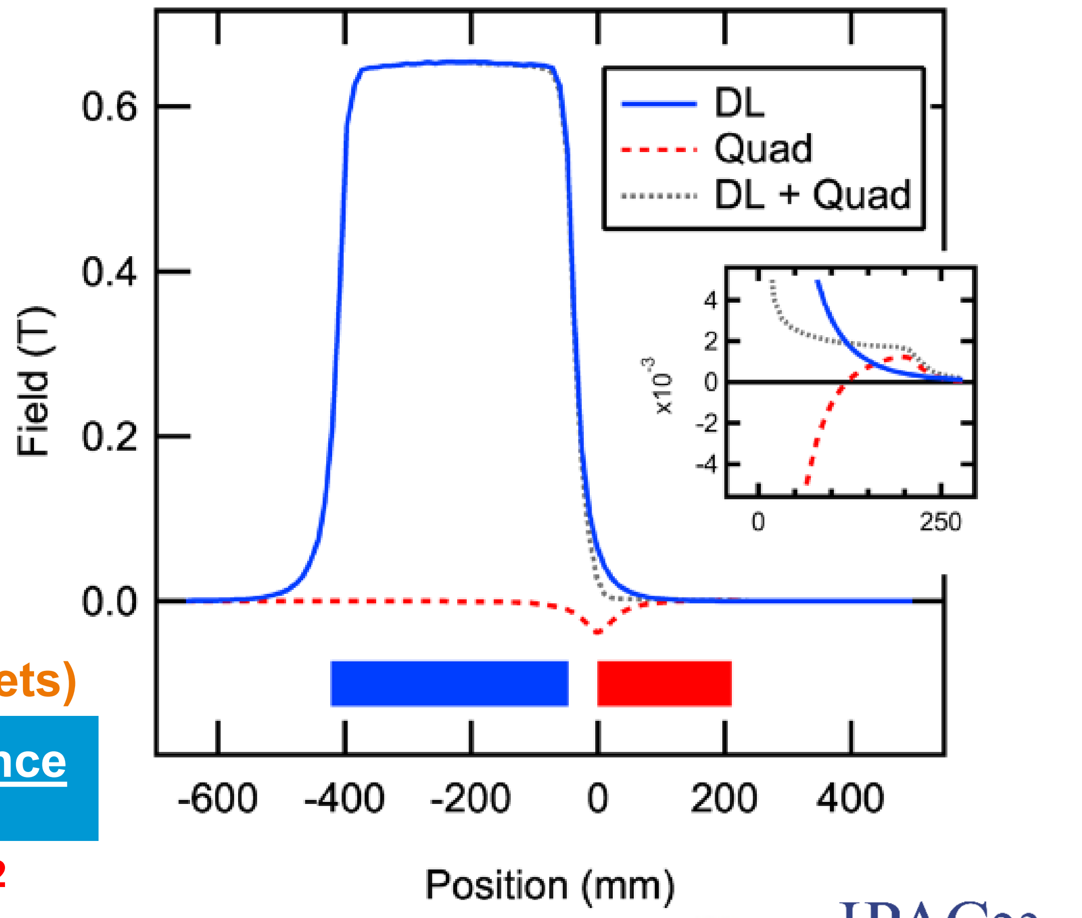
Problematic: neighboring magnets are influenced by each other’s magnetic field

Case of the ESRF-EBS

- Discovered during commissioning
- Strong impact (max. 1.8%) in quadrupole strengths
- Cross-talk model implemented in the theoretical ring for optics correction
- Good agreement between measurements and simulations

G. Le Bec, et al., PRAB 24, 072401, 2021, doi= 10.1103/PhysRevAccelBeams.24.072401

Example of the DL-Quadrupole crosstalk at the ESRF-EBS



Cross-talk considered for all upgrade projects

- Evaluation of magnet strengths variations
- Subsequent lattice design (distance between coils/magnets)
- Design of magnets
- PM magnets: corrections?

Simulations? Redesign?

Cross-talks in this conference

Dedicated posters:

on PETRA IV J. Keil, WEPM032

on SPS II P. Sunwong, WEPM047

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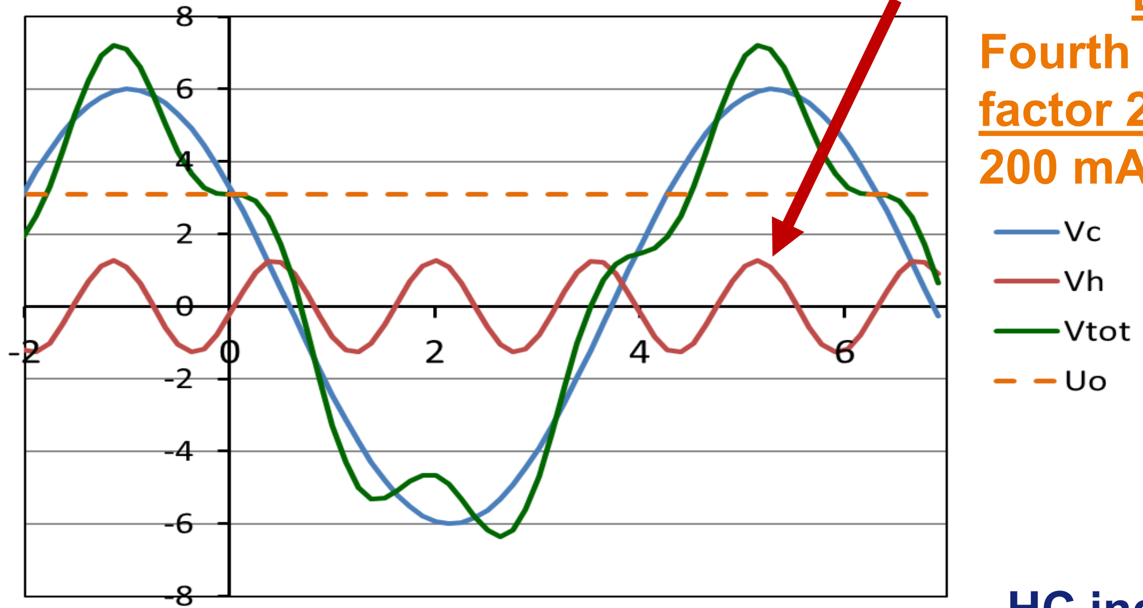
Multiple motivations: Reduce the particle density per bunch for **higher TL**, **reduced IBS growth rate**, $\propto \frac{1}{E^4}$, reduce the **beam-induced heating** in high current per bunch operation modes, transverse stabilizing effect.

Principle: Use a Harmonic Cavity (or Landau cavity)

$$V_{tot}(t) = V_c \cos(\omega_{RF} t + \phi_c) + V_h \cos(m\omega_{RF} t + \phi_h)$$

Main RF Cavity

m-order HC



J. Jacob, HArmonLIP'2022

ESRF-EBS HC

Fourth harmonic, about a factor 2,5-3 lengthening at 200 mA.

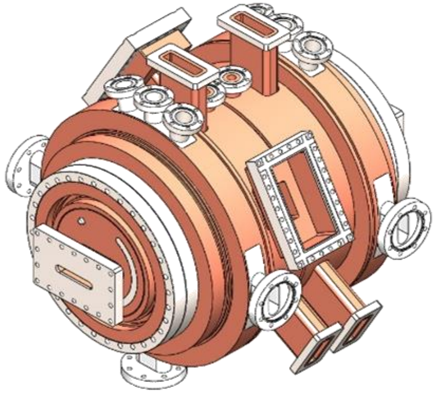
Factor depends on the uniformity of the filling pattern,and beam stability

Different types of HC cavities:

- Passive
  - Electric field generated by the electron beam
- Active
  - Power supplied
- Normal conducting /Superconducting

ESRF-EBS
2-cell HC

Total Length = 710 mm



V. Serrière, HArmonLIP'2022

HC induced instabilities: dependent on the lattice, parameters, to be assessed.

Challenges:

- Small DA, low beam lifetime (even with HC),
- Different operation modes, bunch currents
- Top-up, frequent injections, stored beam perturbations

→

Targets:

- Inject in a small DA and low lifetime lattice
- Compatible with different operation modes
- No perceived perturbation to the stored beam
- Towards 100% injection efficiency

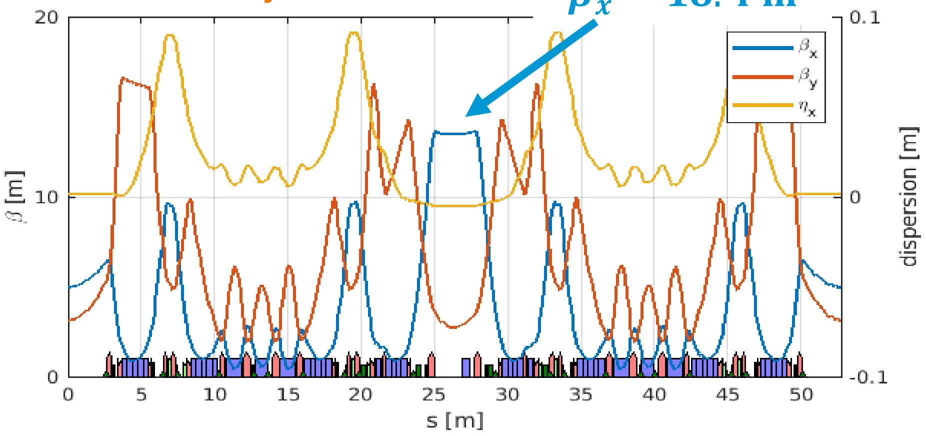
Standard off-axis injection ESRF-EBS, PETRA IV, …

Requires large horizontal DA (≥ 5 mm) at the injection point → High β_x injection cells

- Disruption of the lattice periodicity
- Stored beam perturbations
- Inevitable betatron oscillations

ESRF-EBS injection cells

$\beta_x = 18.4$ m



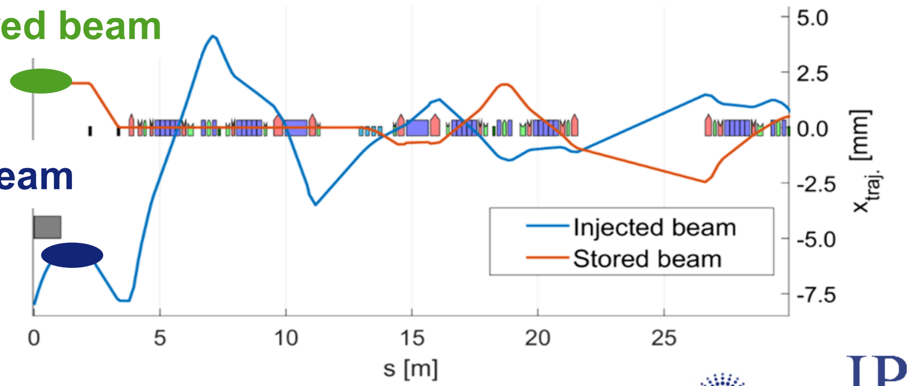
Aperture sharing injection SLS 2.0, DIAMOND II

Relaxed DA condition ($\approx 2-3$ mm) at the injection point

- Kick the stored and injected beam
- Betatron oscillations
- Perturbations limited only to a couple of bunches

Stored beam

Injected beam



A. Streun, IPAC22, TUPOST032

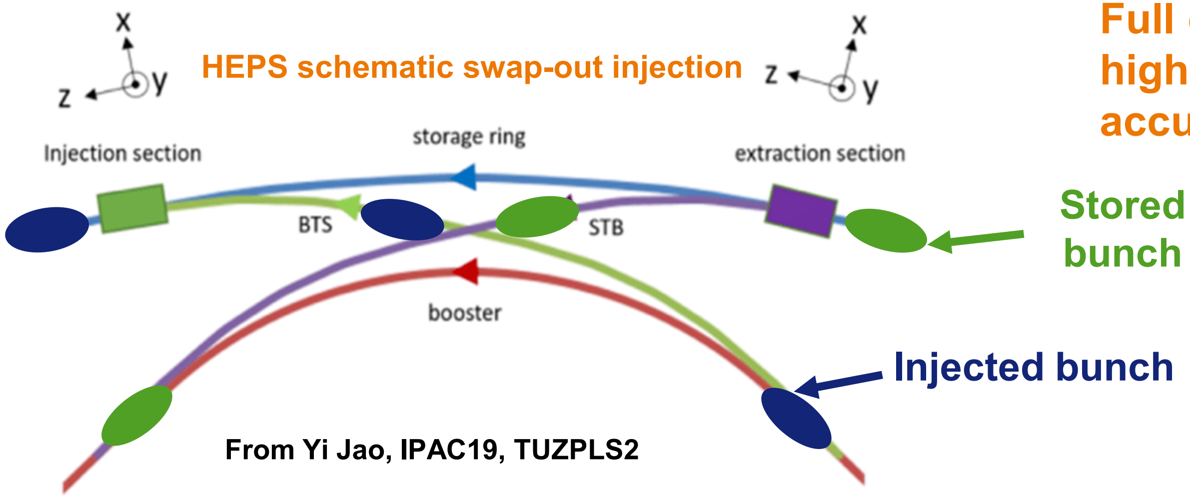
From J. Kallestrup, IPAC22, THPOPT018

Swap-out injection

APS-U, ALS-U, HEPS

+ flat-top kicker for bunch train
+ short-pulse kicker for bunch by bunch (a few ns)

HEPS schematic swap-out injection



From Yi Jao, IPAC19, TUZPLS2

Full charge injector required esp. for high-current per bunch modes – no accumulation in the SR possible

→ Additional accumulator ring for fully charged bunches (ALS-U)

→ Full charge booster with low emittance (HEPS)

Longitudinal injection

SLS 2.0, …

Beam injected longitudinally at $\phi = \pm\pi$

→ Momentum acceptance

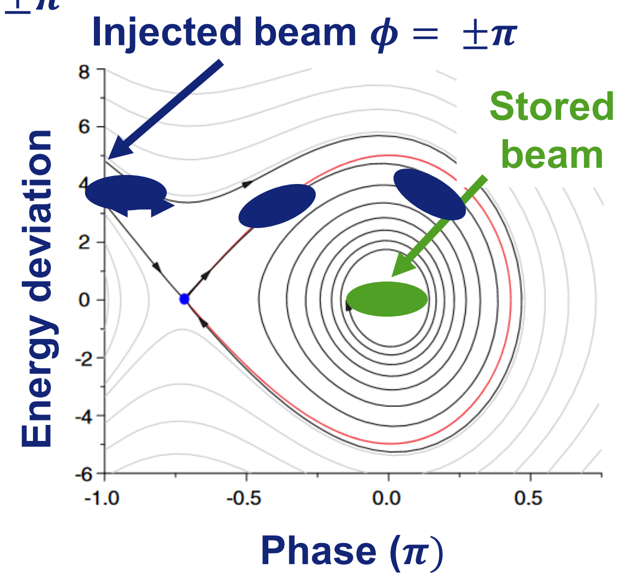
→ Golf club thickness measurement at BESSY II

P. Kuske, J. Li, PRAB, 2020

SLS 2,0 + < 2ns kicker + 1ns delay between injected and stored bunches

A. Streun, IPAC22, TUPOST032

From M. Aiba, PRAB, 18, 020701 (2015)

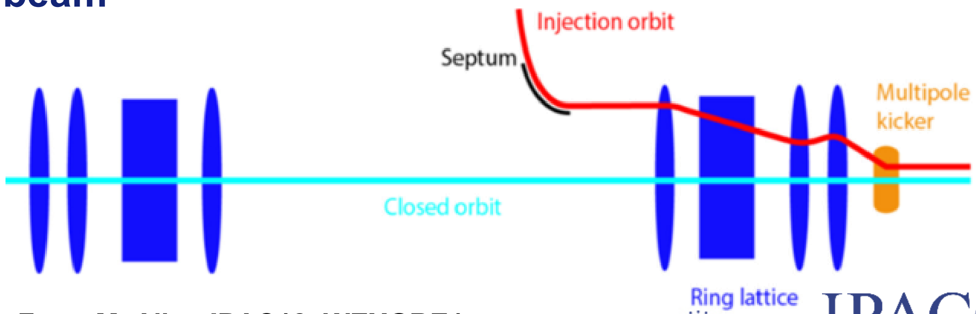


MAX IV, SOLEIL II, …

Non-Linear Kicker (NLK) injection principle

Replace the 4-kicker bump with a single NLK with septum.

Multipolar field profile, with flat potential for the stored beam

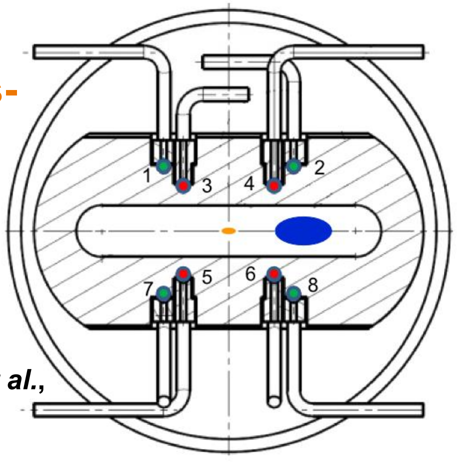


From M. Aiba, IPAC18, WEXGBE1

Multipole Injection Kicker (SOLEIL-MAX IV collaboration)

In operation at MAX IV since 2019

MIK cross-section



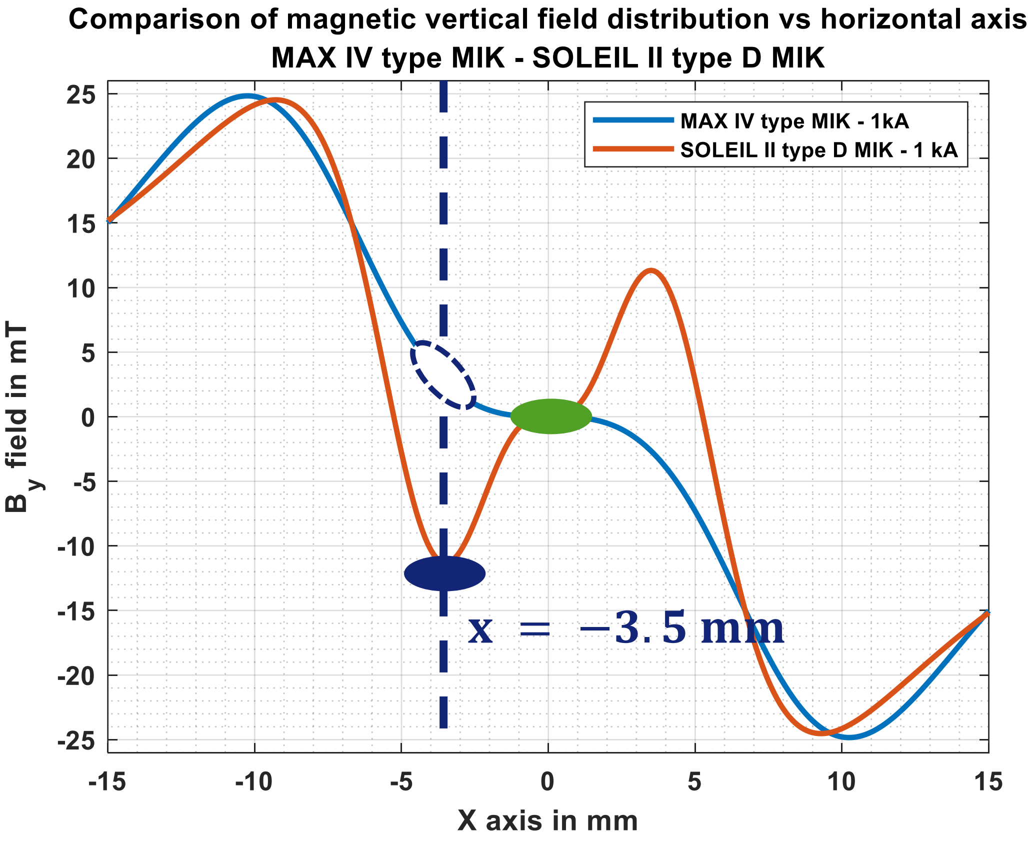
From R. Ollier *et al.*, PRAB, 2023

Test of MIK in SOLEIL

Off-axis injection with the MIK

Reduction of stored beam residual betatron oscillations compared to the standard four kicker bump

New MIK in development for SOLEIL II



Courtesy of P. Alexandre

SOLEIL II off-axis injection requirement:

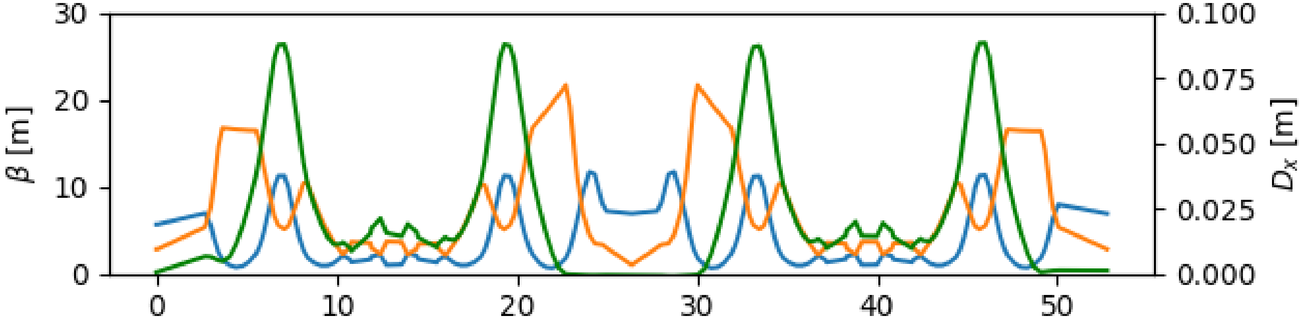
- MIK (type D) in-vacuum, 5 modules for off-axis injection
- Magnetic peak field at $\mathrm{x} = -3.5\ \mathrm{mm}$ (instead of -10 mm for the MAX IV-SOLEIL collaboration)
- Two mobile conductors for fine tuning of the flat potential at $x = 0\ \mathrm{mm}$

R. Ben El Fekih, THPA175

Mini-β optics for the ESRF-EBS

S.White, WEPL029

Local reduction of $\beta_y: 2.7 \rightarrow 1$ m for an expected 40% increase in brilliance. Optics tests to be conducted during 2023



Off-energy operation mode

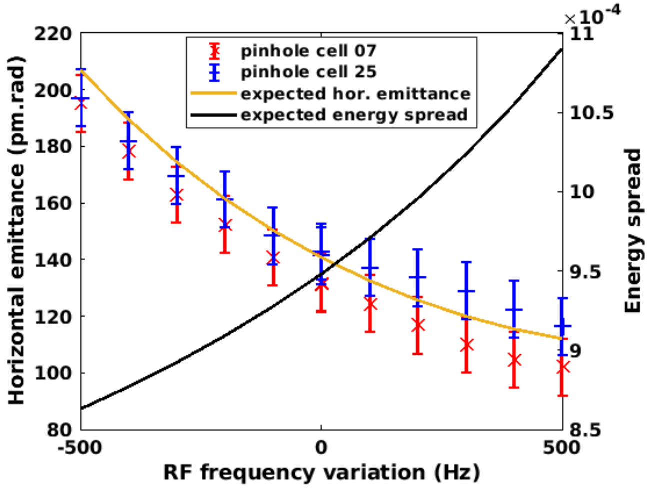
L. Hoummi, MOPA143

Beam on a dispersive orbit: HG quadrupoles provide extra damping:

$\epsilon_x^{nat}: 140 \rightarrow 121$ pm.rad

$\Delta f_{RF} = +280$ Hz

Successful tests on the ESRF-EBS SR

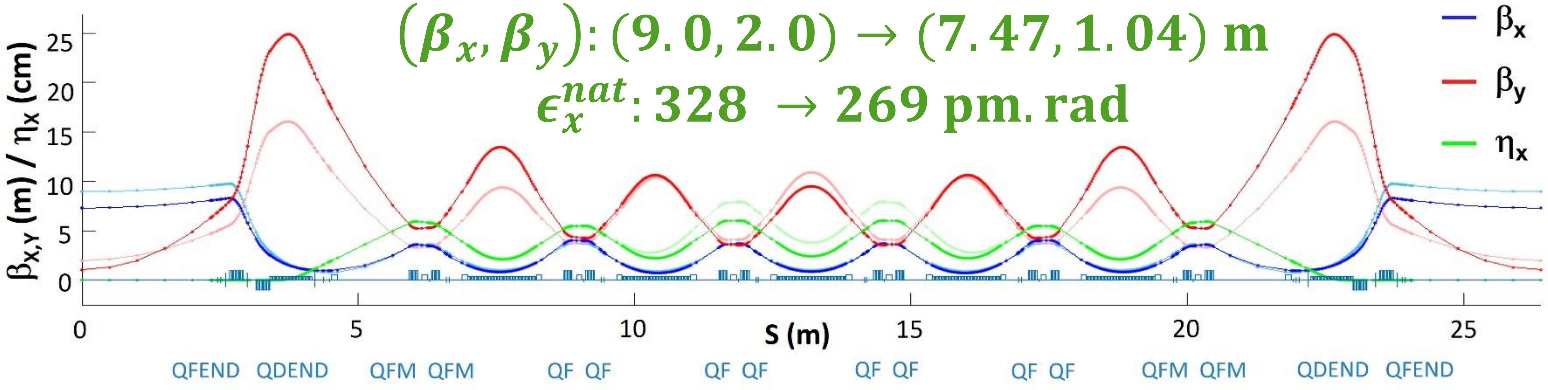


Low emittance optics for MAX IV

M.Apollonio, MOPM012

$(\beta_x, \beta_y): (9.0, 2.0) \rightarrow (7.47, 1.04)$ m

$\epsilon_x^{nat}: 328 \rightarrow 269$ pm.rad



Injection in such optics difficult

- **1st turn threading needed to achieve initial capture (with Dipole Kicker (DK))**
- **Optics characterization at low current**
- **Accumulation demonstrated (> 5 mA) with the combined use of DK and MIK**

Fourth generation storage ring light sources are increasing their diffraction-limited photon energy, with upgrades approaching the:

Diffraction-limit condition for a 1 keV photon beam: $\epsilon_x \ll 80$ pm.rad

Several challenges to be overcome and mastered: DLSR at 10 keV one step closer !

Large storage ring light sources

- Larger storage ring to reduce the bending angle
- Relaxed optics, gradients, high DA, LT
- High-number of magnets, operational costs, environmental impact of such accelerators

Miniaturized SR elements

- Compact permanent and tunable magnets with high-gradient, multiple-function magnets, in-vacuum and coated?
- In-vacuums IDs for high-brilliance photon beams
- Towards in-vacuum SR?

Yet, global challenges are to be added on top!

ENERGY, ENVIRONMENTAL AND CLIMATE CRISIS

Increased electricity costs

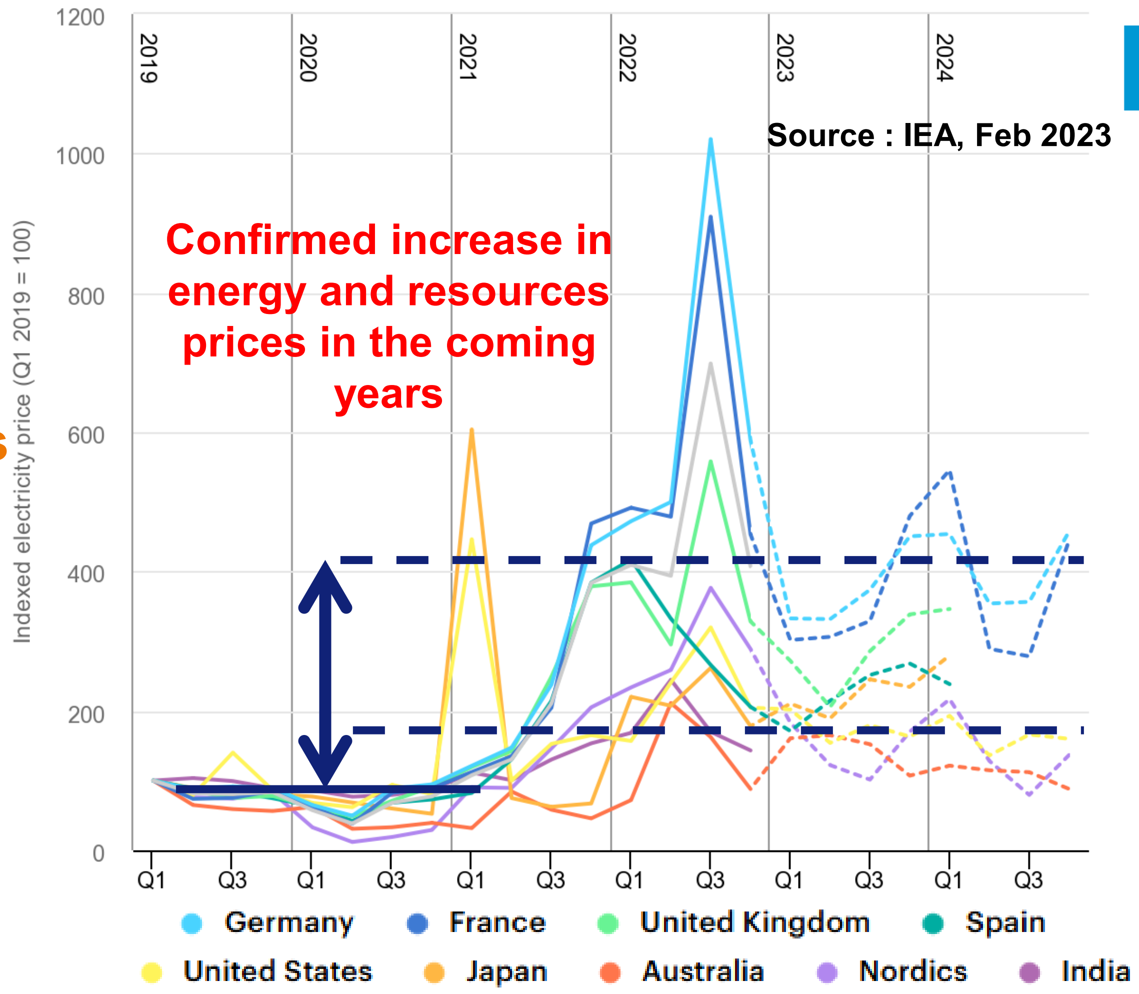
Increased resources costs: helium, computing goods, raw materials, …

Increased prices   Shortages   Accidents   Geopolitics

Socio-economic crisis   Climate change

Several facilities had to adapt their user mode schedule to cope with the increase of costs in different energy sources:

Extended shutdown, cancelled runs over the cold season



Sustainability and environmental impact should be at the heart of any development in our research institutes

Sustainability
Optimisation
Sobriety

Sustainability session tomorrow morning
J.-L. Revol @ 12:10

Time for questions !

Sustainability and environmental impact should be at the heart of any development in our research institutes → **Sustainability session tomorrow morning**

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Sustainability
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