Overview of future diffraction-limited light source storage rings:

Directions to follow in view of the physical and technological challenges we have today and how they are being overcome

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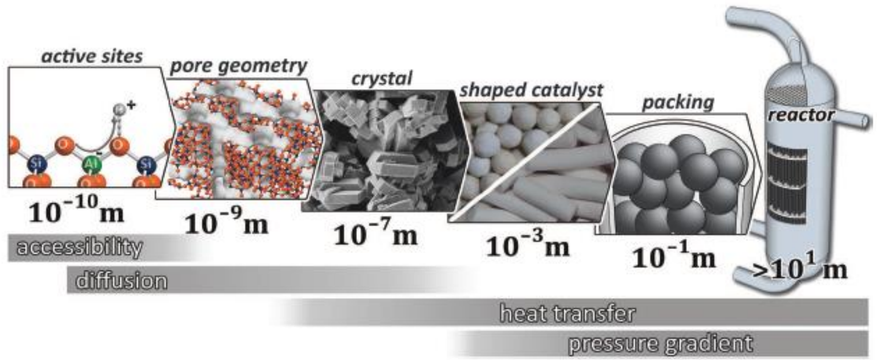
iFAST

Towards a New and Better SCIENCE

- In recent years, emergence of a whole new (**4th generation**) class of storage ring based light sources: **Diffraction Limited Storage Rings (DLSR).**
- Breakthroughs can be expected in **high-resolution imaging, microscopy and spectroscopy.** Allows science which is not possible or not even thinkable, today.

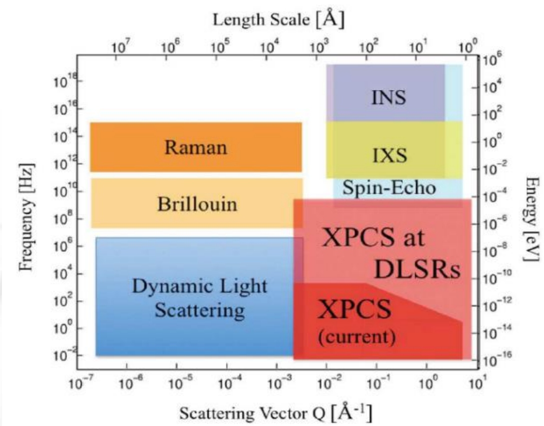
Bridging All Spatial Length Scales:
X-Ray Microscopy with Coherent Light.



In order to understand a catalytic reaction inside a chemical reactor, the chemical and physical processes involved need to be followed under working conditions and on a broad range of length scales, ***from atomic range to the dimension of the reactor***. (C. G. Schroer et al. JSR ISSN 1600-5775).

$$\text{Coherent flux} \propto \frac{Brilliance \times \lambda^2}{4}$$

Bridging Time Scales:
X-Ray Correlation Spectroscopies.



XPCS covers time scales down to the millisecond regime. At a diffraction limited storage ring (DLSR) source, the accessible ***time range is extended down to the nanosecond regime: 10000 faster in dynamics*** (C. G. Schroer et al. JSR ISSN 1600-5775).

$$\text{Fastest time scale} \propto \frac{1}{(Brilliance)^2}$$

Figure of merit for DLSR =

BRILLIANCE – SPATIAL RESOLUTION – TRANSVERSE COHERENCE

- **Brilliance** is usually defined as:

(Gaussian approximation)

In photons/s/mm²/mrad²/0.1%b.w

$$B_n(\lambda) = \frac{F_n(\lambda)}{(2\pi)^2 (\Sigma_x \Sigma_z)(\Sigma'_x \Sigma'_z)}$$

Brilliance is the metric of a source that determines the achievable spectral, spatial, and temporal resolution.

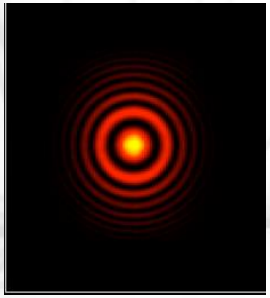
$F_n(\lambda)$ = total photon flux $\quad \Sigma_{x,z} = \sqrt{\sigma_r^2 + \sigma_{x,z}^2(e-)} \quad \Sigma'_{x,z} = \sqrt{\sigma'^2_r + \sigma'^2_{x,z}(e-)}$

Electron beam (simplest case): $\varepsilon_{x,z}(e-) = \sigma_{x,z}(e-)\sigma'_{x,z}(e-) \quad \sigma_{x,z} = \sqrt{\varepsilon_{x,z}\beta_{x,z}} \quad \sigma'_{x,z} = \sqrt{\frac{\varepsilon_{x,z}}{\beta_{x,z}}}$

- For an **undulator**, the photon beam emittance (single electron emission) depends strongly on detuning from on axis resonance, it is minimum close to resonance with a value approximately given by[1]:

$$\varepsilon_r = \sigma_r \sigma'_r = \lambda/2\pi$$

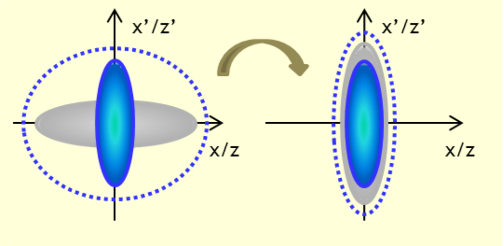
where $\quad \sigma_r \approx \sqrt{2\lambda L}/2\pi \qquad \sigma'_r \approx \sqrt{\lambda/2L}$



1 P. Elleaume, in Wigglers, Undulators, and Their Applications, 2003.

- **Brilliance** is maximum when: $\beta_x = \beta_z = \beta_r = \sigma_r/\sigma'_r = \mathbf{L}/\boldsymbol{\pi}$

  L is the length of the undulator



The orientation of the phase space ellipse of the electron beam (grey) match the one of the photon beam (blue)

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

- Corresponding **Transverse Coherence**:

$$f_c = \frac{\varepsilon_r^2}{(\varepsilon_x + \varepsilon_r)(\varepsilon_z + \varepsilon_r)}$$

Which = 1 for $\varepsilon_x << \varepsilon_r$ and $\varepsilon_z << \varepsilon_r$

'Ultimate case'

- The **Coherent Flux** $F_{coh}(\lambda)$ is defined by the product $f_c(\lambda)$ and $F_n(\lambda)$.

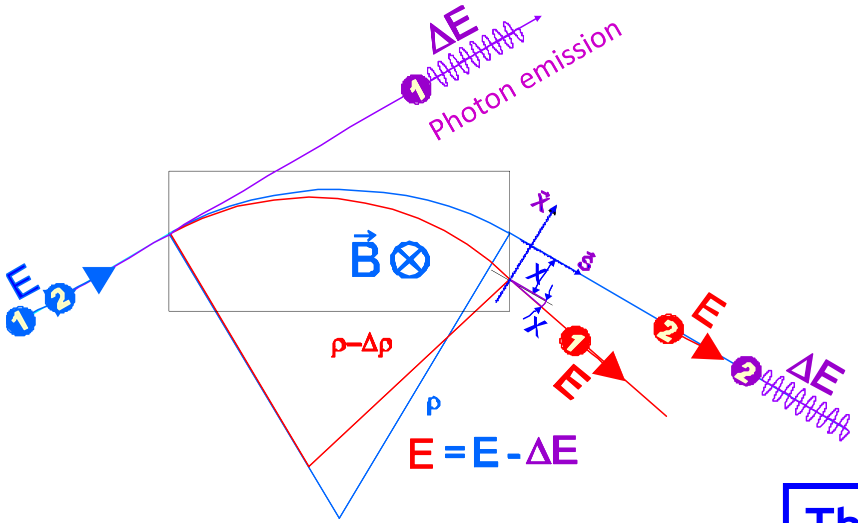
- It is customary to speak of being **'diffraction-limited'** when $\varepsilon_{x,z} < \left(\frac{1}{2}\right)\varepsilon_r = \frac{\lambda}{4\pi}$

In this case, the properties of the radiation are not dominated by the electron beam but by the intrinsic properties of the emitted photons.

~ 10 pm.rad for diffraction limit at ~1 Å (12.4 keV)
~ 100 pm.rad for diffraction limit at ~ 1 nm (1.24 keV)

Maximizing the x-ray Brilliance and Coherence requires minimizing the electron beam emittance!

Generation of emittance by radiation

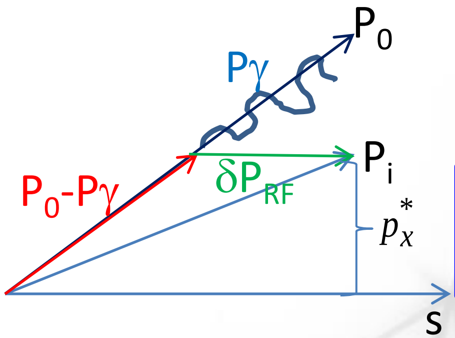


- ***Quantum Excitation*** = two e- with same E and same trajectory at the entrance of the Bending magnet (cannot be distinguished: no e- beam size). They both radiate ΔE and exit with E-ΔE.
  1 emits ΔE at the origin, smaller ρ
  2 emits ΔE but at the end.
  off-energy orbits, $dx(s) = \eta(s)\frac{\Delta E}{E}$ $dx'(s) = \eta'(s)\frac{\Delta E}{E}$
  where η (s) is the dispersion function

The beam is heated up by the radiation which introduces a sort of noise.

- ***Fortunately, there is a cooling effect: Radiation Damping***

The restoring of the lost energy by the RF cavity cool down the transverse oscillations in the horizontal plane.



$$x' = \frac{p_x^*}{p_s} = \frac{p_x^*}{p_s^* + \delta p} \approx x_0'\left(1 - \frac{\delta p}{p_s}\right)$$

Recirculation:
damping of transverse momenta

- Horizontal emittance in electron storage ring is determined by **radiation equilibrium.**
- Independent of initial conditions.

Horizontal Emittance

- The equilibrium horizontal emittance is approximately as follows:

$$\varepsilon_x \approx \frac{C_q \gamma^2 \langle H \rangle_{BM}}{J_x \, \rho}$$

$$\langle H(s) \rangle = \langle \gamma_x \eta_x^2 + 2\alpha_x \eta_x \eta_x' + \beta_x \eta_x'^2 \rangle$$

damping partition

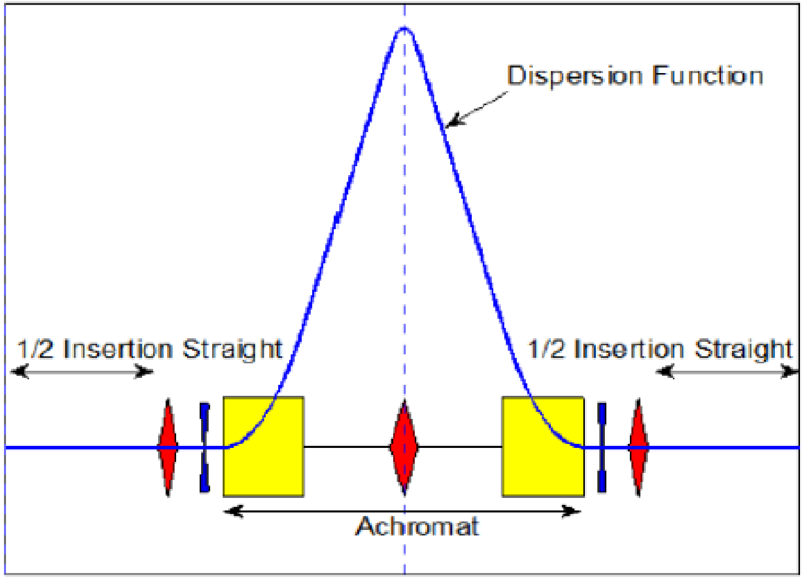
Minimize the dispersion and its derivative in the **BM**.
Keep *off-momentum* orbits close to nominal orbits.

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

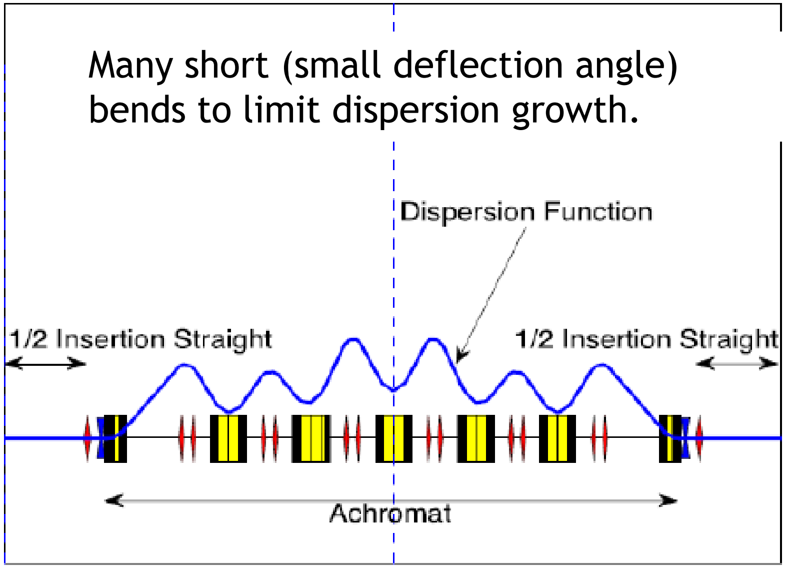
E= Electron Energy
M = Number of identical Bending Magnets

Exploit 1/M³ dependence

DOUBLE BEND ACHROMAT (DBA)



MULTI BEND ACHROMAT (MBA)



❑ Most 3rd generation storage rings use **DBA** or **TBA** lattice structures.

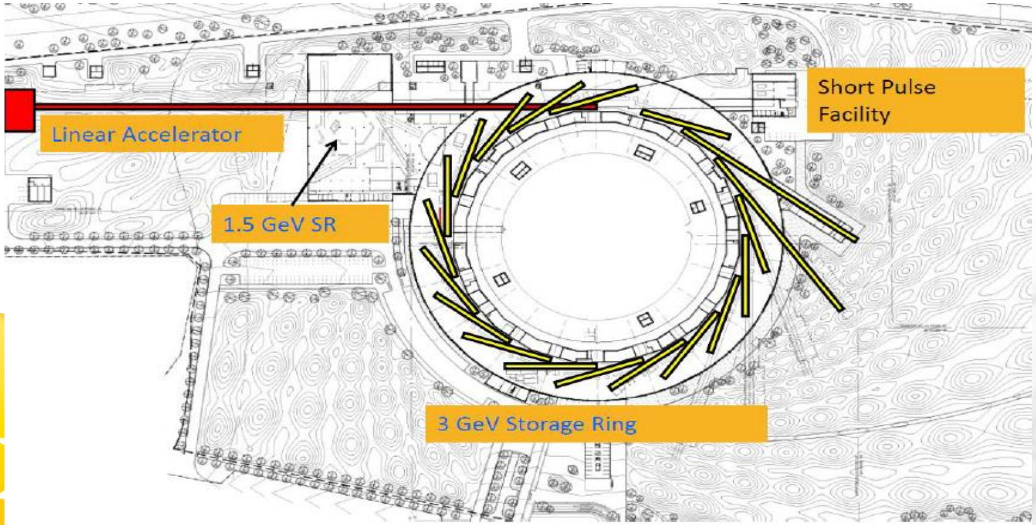
Typical emittance : **ε_x: [1000 , 5000] pm.rad and ε_z: [1 , 50] pm.rad**

❑ Several groups proposed **M > 3** lattices in 1990s[1] and many lattices have been studied.

❑ It took **20 years** from the first proposal (**1995**) to the first beam (**2015**)!!

➢ for the concept to be made technically and economically feasible through a number of advances in both accelerator physics and engineering of the various subsystems

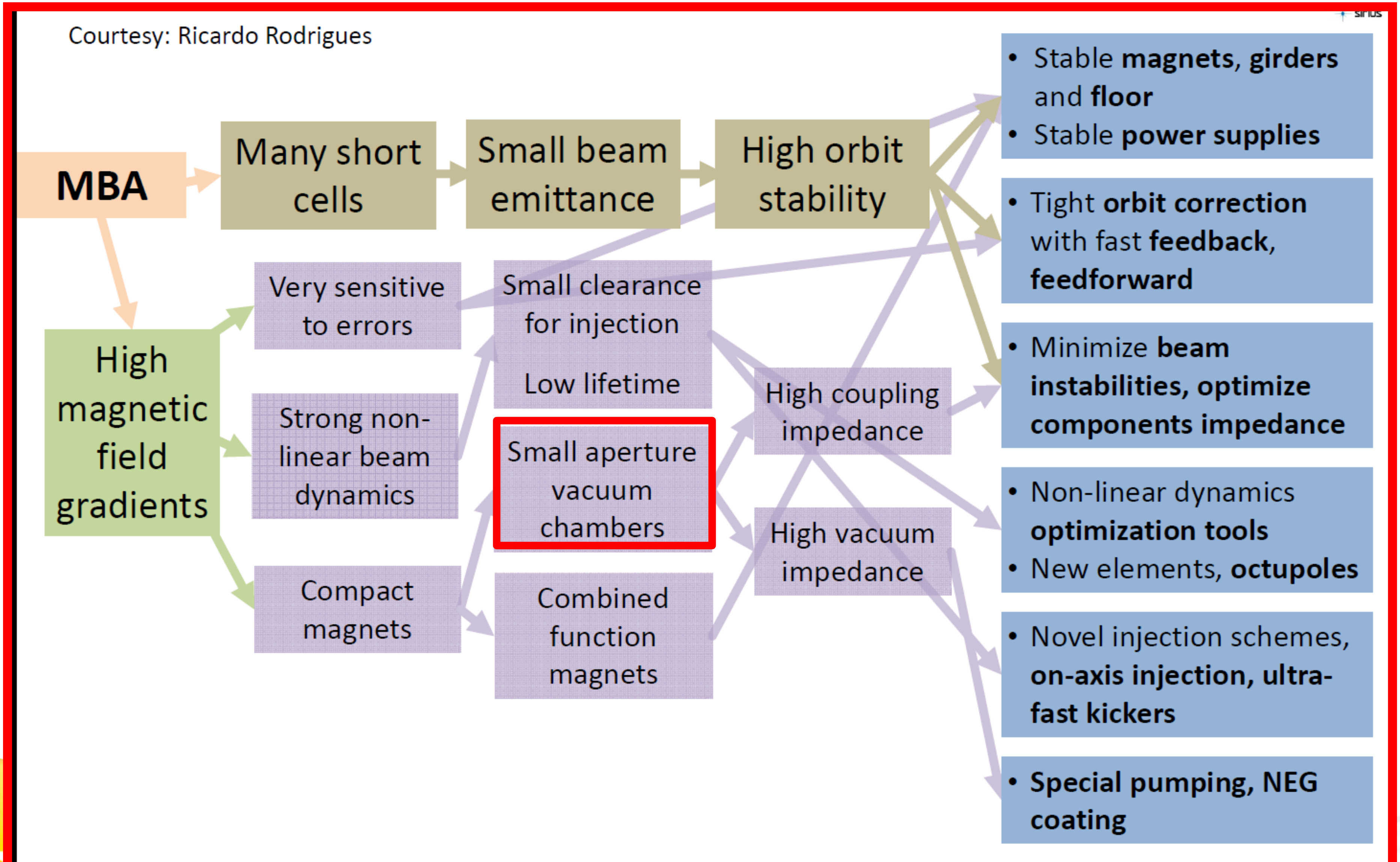
❑ Sweden's **MAX IV** facility is the first storage ring to employ a **Multi-Bend Achromat.**



First beam August 2015

[1]Einfeld et al., NIM A 335, 1993; Joho et al., EPAC94; Einfeld et al., PAC95; Kaltchev et al., PAC95

Why has it taken so long ?!...



Why it becomes possible now ?

- The development of better **accelerator physics** modelling and optimization methods, giving greater confidence in designs.

- A Paradigm Shift in **Engineering.**

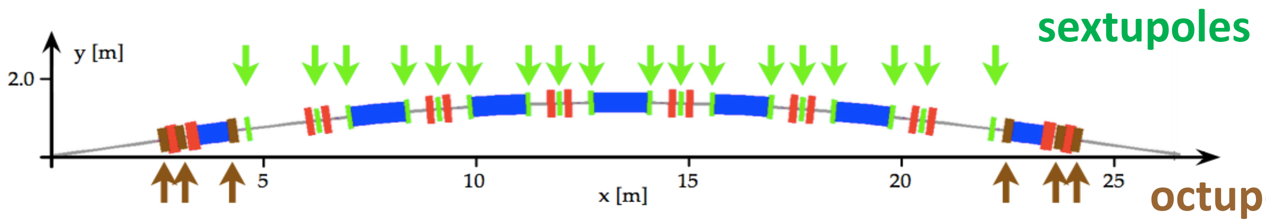
- The nerve of a man ?

- Confidence, good communication and very open accelerator community

Photographer: Madeleine Schoug, MAX IV

The technology step taken by MAX-lab has opened the door for other MBA lattice proposals and concepts.

How MAX IV spearheaded this revolution ?

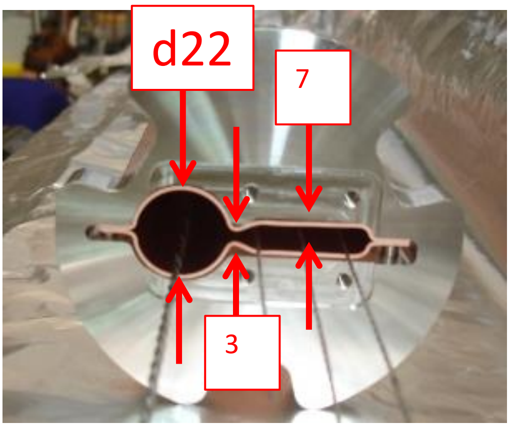


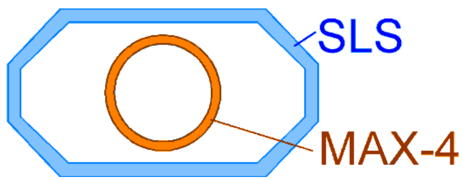
7BA

20 Cells

E = 3 GeV
C = 528 m
ε = **330 pm.rad**

– **NEG coating :** Non-Evaporable Getter (~1 μm Ti-Zr-V layer).
The entire circumference of the MAXIV ring is NEG coated.





Beam pipe cross section:
$65 \times 32\ mm^2 \rightarrow \varnothing\ 22\ mm$
3 × smaller beam pipe

Vacuum chambers with very small openings become possible.

– **Low frequency RF (100 MHz):**

– **Integrated magnets for compactness:**

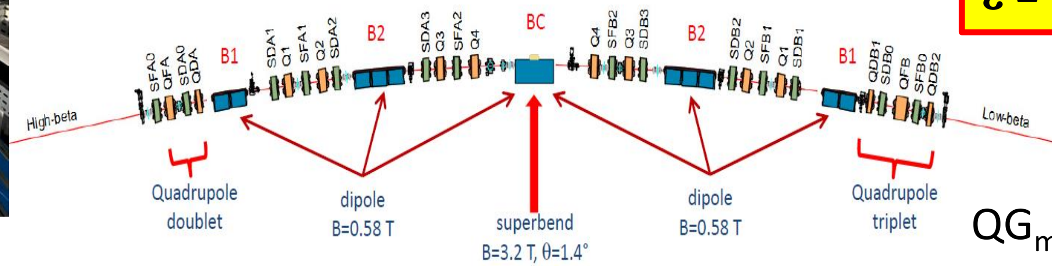
Machined out of solid iron block (~3.4 m)
Quadrupole :
ϕ = 25 mm
and G_{max} = **40 T/m.**

- Alignment based on mechanical tolerances (Reduced tolerances to 20 micron level).
- Good vibrational stability.

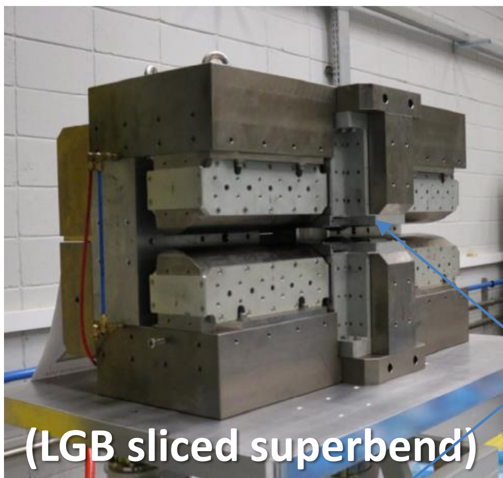
Sirius

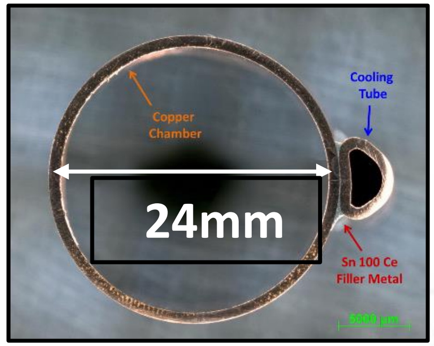
5BA – 20 cells

E = 3 GeV
C = 518 m
ε = 250 pm.rad

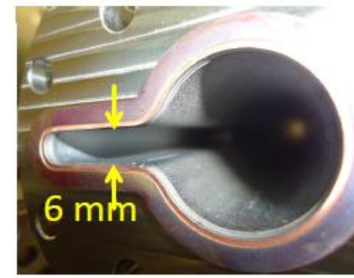


QG_{max} = 45 T/m.

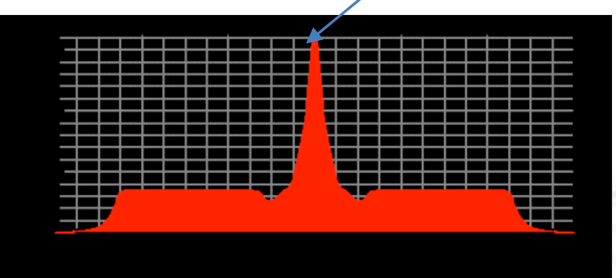


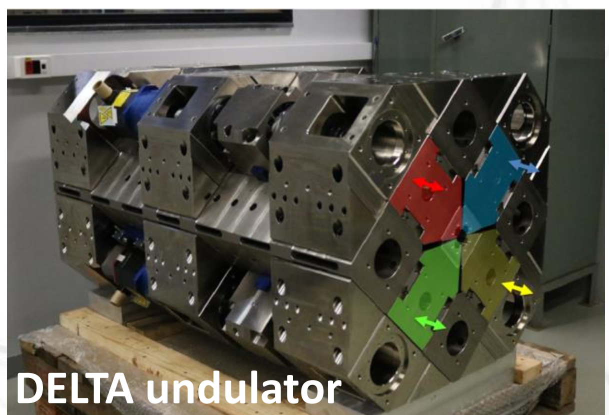


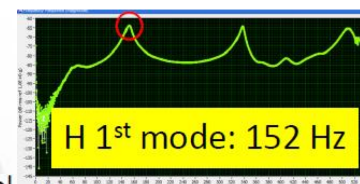
Dipole chamber w/ narrow gap for photon extraction

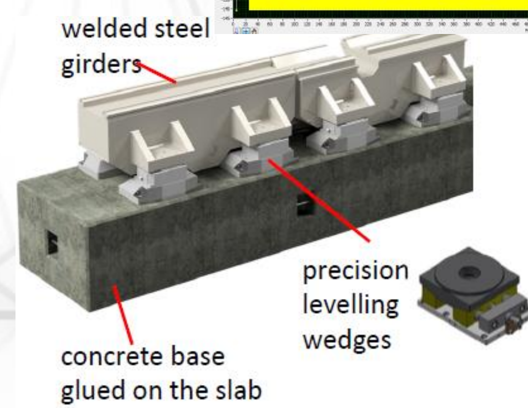


B = 3.2 T





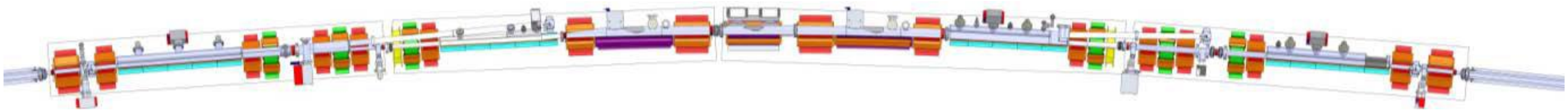




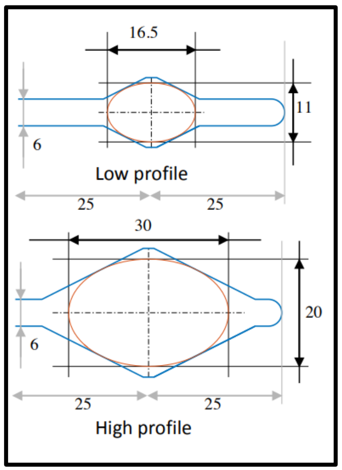
ESRF-EBS upgrade

7BA - 32 cells

E = 6 GeV
C = 844 m
ε = 140 pm.rad

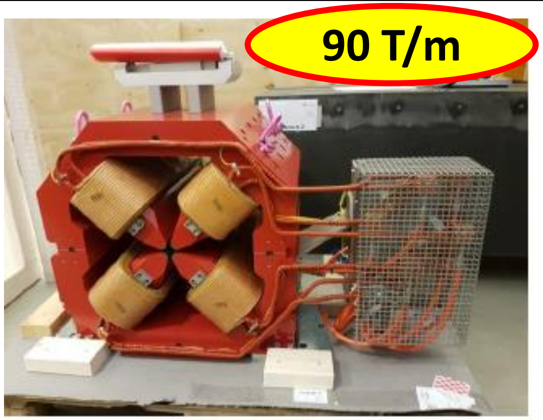


- High gradient magnets small aperture
- Strong gradient dipoles
- Longitudinal gradient dipoles



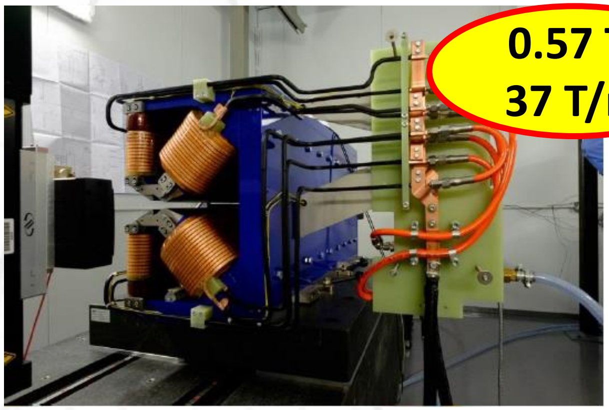
High gradient quadrupole

90 T/m

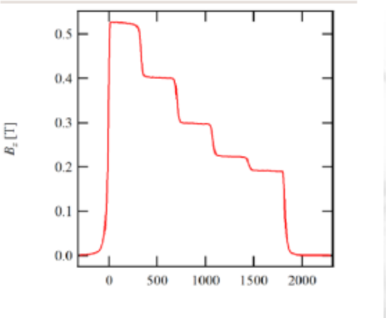


Dipole-quadrupole

0.57 T;
37 T/m



Longitudinal gradient permanent magnet dipoles



New projects based on MBA structure

Storage Ring	E (GeV)	C (m)	Emittance* (pm.rad)	Lattice	Status
MAX IV (Sweden)	3	528	330	7BA	operation
Sirius (Brazil)	3	518	250	5BA	operation
CANDLE (Armenia)	3	269	435	4BA	Study
CLS 2.0 (Canada)	3	590	40	9BA	Study
HALF (China)	2.2	480	85	6BA	Funded
HEPS (China)	6	1260	34	7BA	Construction
ILSF (Iran)	3	528	275	5BA	Study
KEK-LS (Japan)	3	571	130	8BA	Study
SLIT-J (Japan)	3	354	920	4BA	Construction
SPS-II (Thailand)	3	321	970	6BA	Study
TURKAY (Turkey)	3	477	510	4BA	Study
BESSY III	2.5	320	100	6BA	Study

*: natural emittance, no IBS included

Current <u>upgrade</u> based on MBA structure

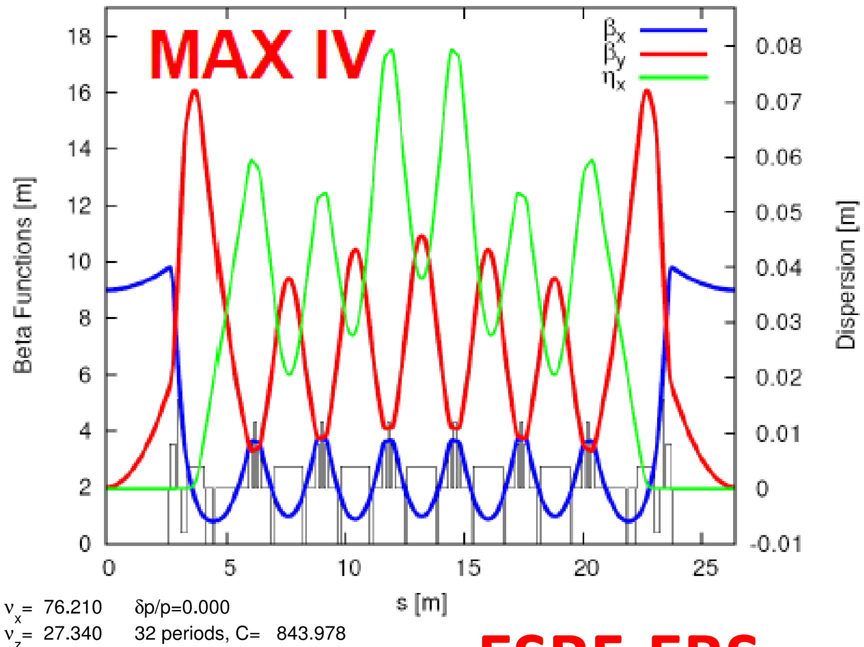
Storage Ring	E (GeV)	C (m)	Emittance* (pm.rad)	Lattice	Status
ALBA II (Spain)	3	269	140	6BA	CDR
ALS-U (USA)	2	197	109	9BA	Construction
APS-U (USA)	6	1104	42	7BA	Construction
Diamond-II (UK)	3.5	562	150	6BA	TDR
ELETTRA 2.0 (Italy)	2	259	250	6BA	Construction
ESRF-EBS (France)	6	844	140	7BA	Operation (2020)
PETRA-IV (Germany)	6	2304	40	6BA	TDR
SLS 2.0 (Switzerland)	2.7	290	158	7BA	Construction
SOLEIL II (France)	2.75	354	84	7BA-4BA	TDR
SPring-8-II (Japan)	6	1435	108	5BA	Study & RD
SSRF-U (China)	3	432	203	7BA	Study

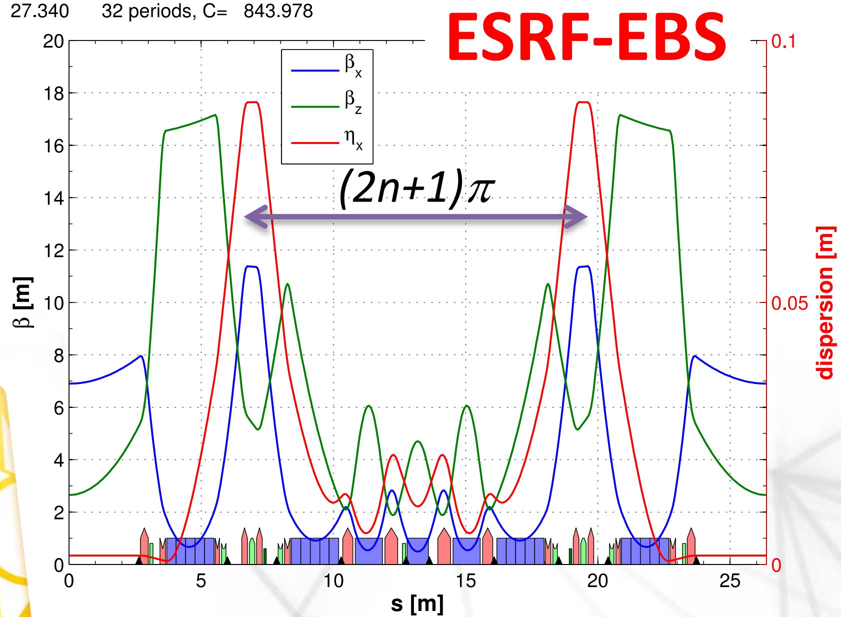
*: natural emittance, no IBS included, no DW

UPGRADE: A COMPLEX LOGISTIC

Courtsy of J. Susini

Lattice Design Philosophy (1)





Modified -TME (TME using gradient in the dipoles) unit cells in each **7BA**.

Higher-Order-Achromat ("Classic" MBA): a unit cell is repeated several times to generate a super period, which phase advance is adjusted to 2nπ in both planes.

(also SIRIUS, SLS2.0*, ELETTRA 2.0*, SOLEIL II*, ALBA II*, CLS-2*,...)

Hybrid-MBA (P. Raimondi): **7BA** consisting of 2 DBA-like cells with longitudinal gradient dipoles (LGBs) and 3 Modified-TME unit cells in the middle.

Dispersion bumps are created with chromatic sextupole located in the 2 DBA-like cells.

-I Transformer: *sextupole pairs separated by (2n+1)π phase advance in both planes.*

(also ALS-U*, APS-U*, Diamond II*, SPring-8-II*, HEPS*, PETRA-IV*,...)

'*': with some variation

Lattice Design Philosophy (2)

The novel LGB-RB unit cell

Systematic control of quantum excitation = source of emittance

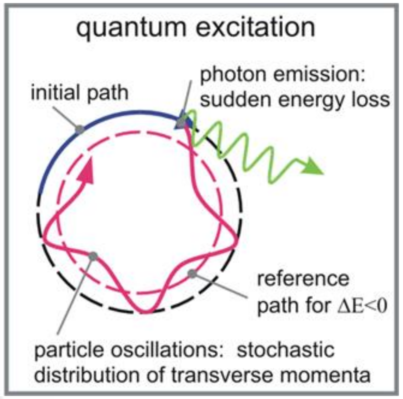
- function of magnet field strength (→ photon emission), and
- function of dispersion (→ translation of energy loss to transverse amplitude)

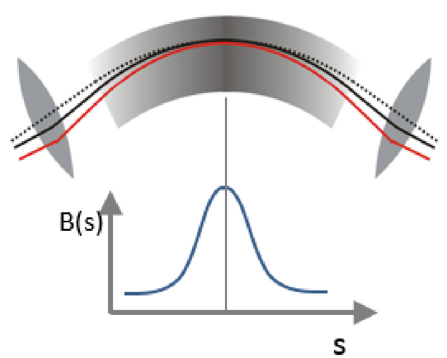
⇨ **LGB-RB lattice cell** = combination of

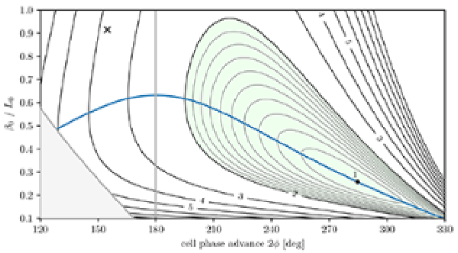
- **longitudinal gradient bend (LGB)**
  → high field (high emission) at location of low dispersion and v.v.
- and **reverse bending magnets (RB)** (= off-centered quadrupoles)
  → suppression of dispersion at LGB center
  not possible with quadrupoles only as in conventional lattice cells

⇨ ***factor 2-3 lower emittance !***

☝ developed for SLS 2.0, adopted by several other projects







EDITORS' SUGGESTION

→ link

Low emittance lattice design from first principles: Reverse bending and longitudinal gradient bends

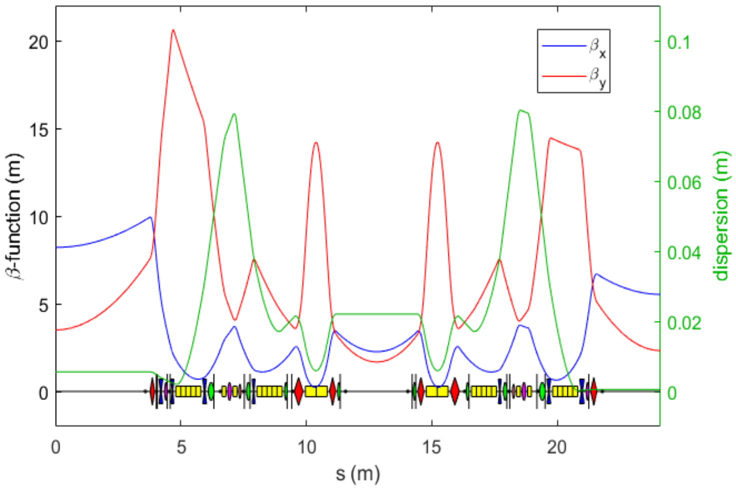
B. Riemann and A. Streun

Phys. Rev. Accel. Beams **22**, 021601 (2019)

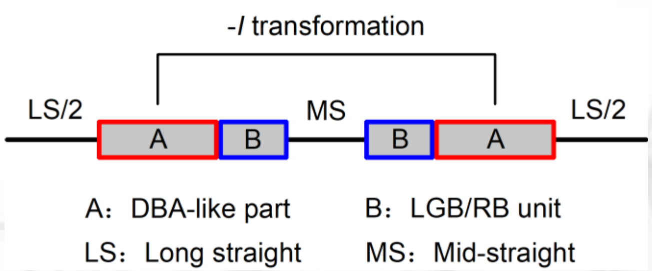
Combinations of standard and reverse bending magnets with distributed curvature can significantly reduce the horizontal emittance of future electron storage rings.

Modified-Hybrid MBA Lattices

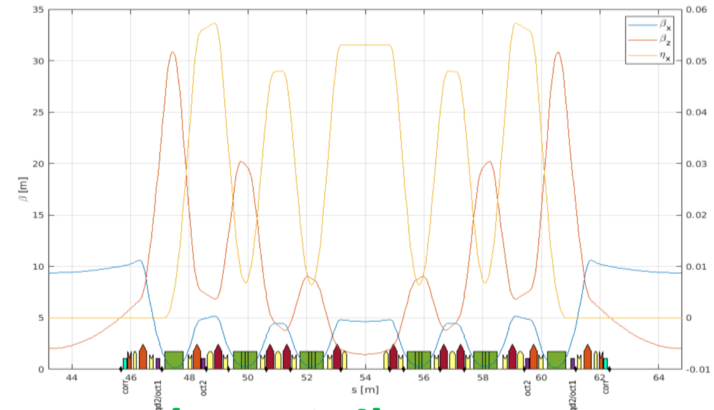
DIAMOND II



H6BA lattice: HMBA + LGB/RB unit + mid-straight. Off-axis injection (Low emittance new Booster).



ELETTRA 2.0

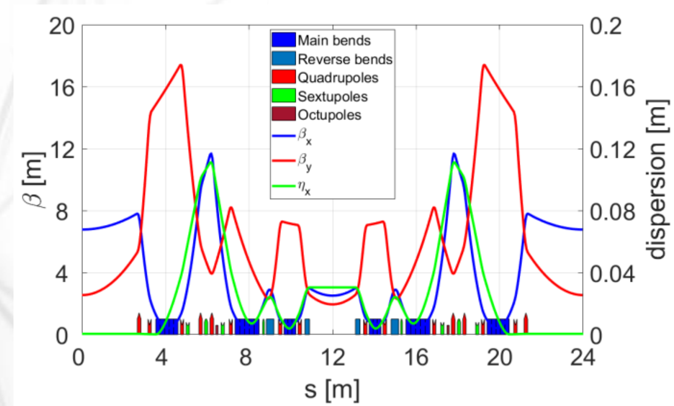


(Special) H6BA

LGB + RB

(emittance exchange in « old » Booster)

HALF



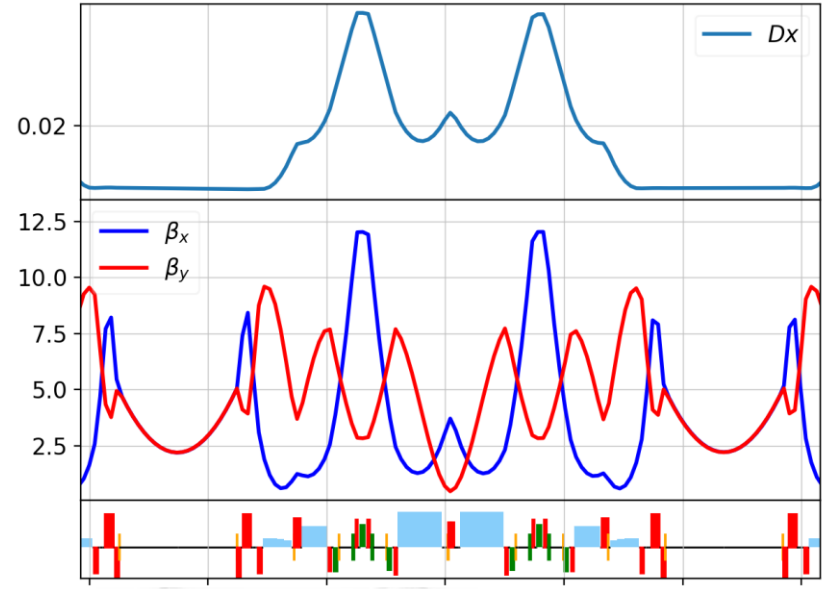
H6BA lattice: HMBA + LGB/RB unit + mid-straight. Off-axis injection (Linac).

Modified-Hybrid MBA Lattices
(high energy + very long straight sections)

- **LGB + TG dipoles.**
- **Use of extra-radiation damping by damping wigglers.**

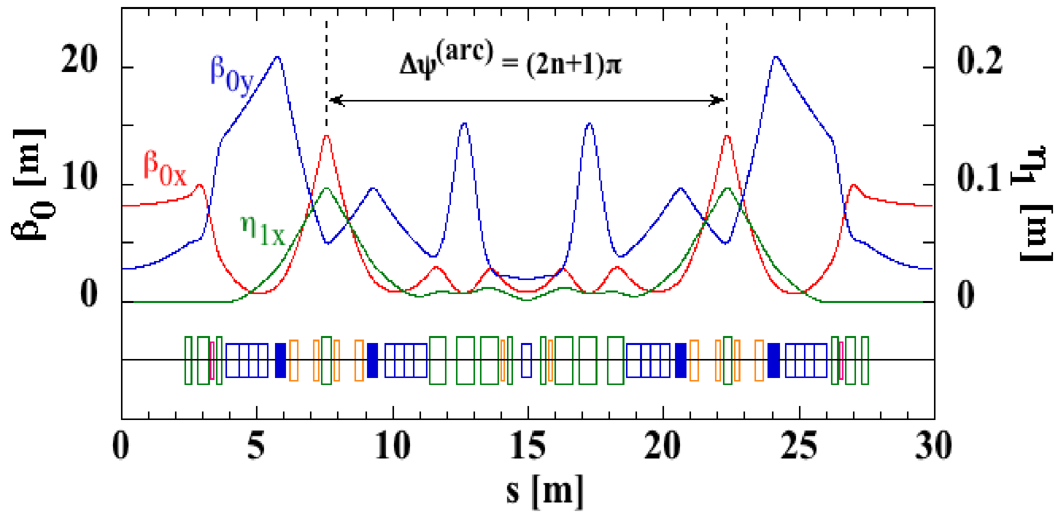
$$\frac{\varepsilon_W}{\varepsilon_0} \approx \frac{1}{1 + {}^{U_W}/_{U_0}}$$

PETRA IV
H6BA



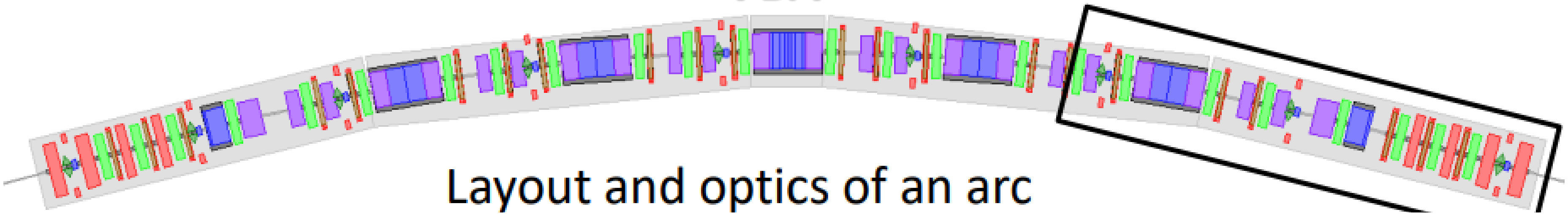
SPRING8-II
H5BA

- **LGB + TG dipoles.**
- **Use of extra-radiation damping by damping wigglers.**

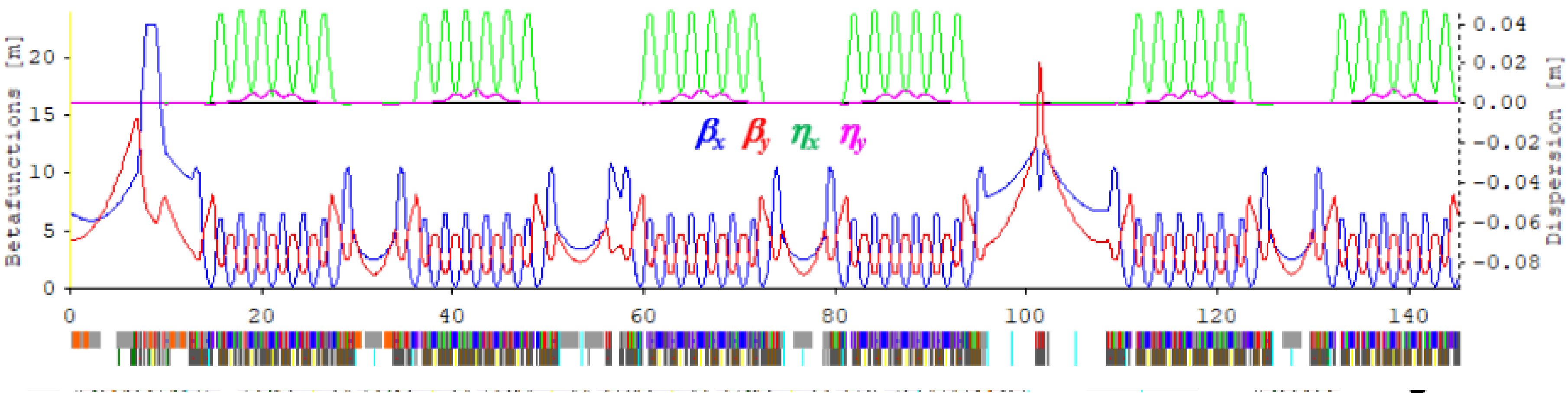


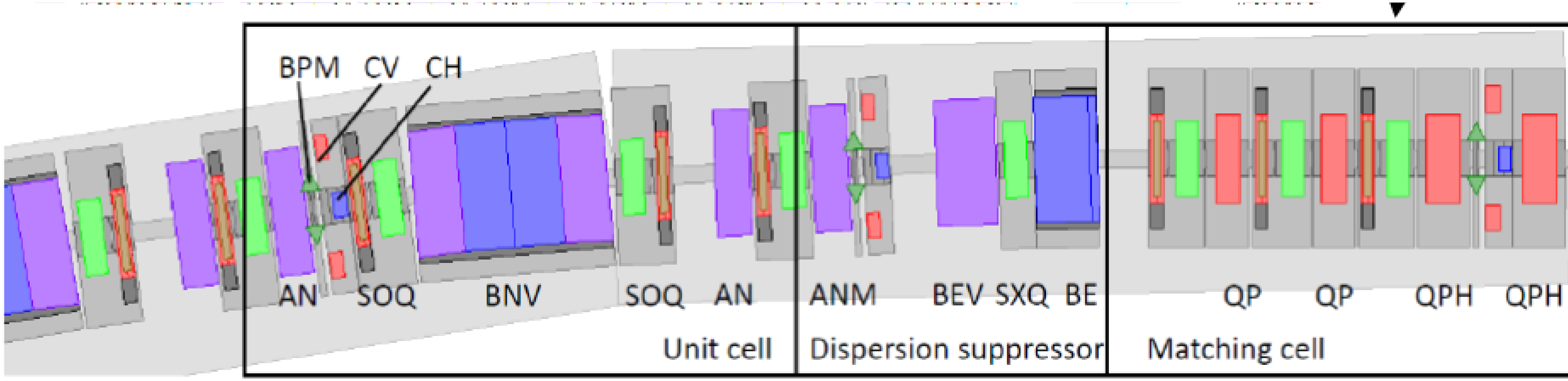
Compact Lattice: SLS2 example

7BA



Layout and optics of an arc



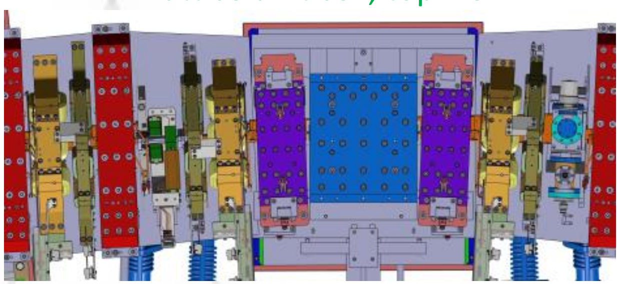


Magnet cross talk

(preliminary study for SLS2)

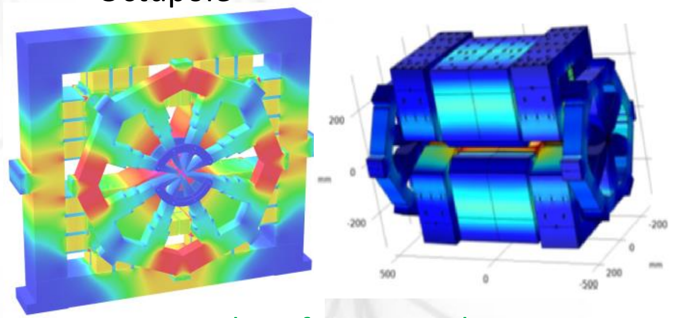
- Highly compact lattice, short distance between magnets
- Analysis of cross-talk effects
  - 3D FEM simulation: Opera, Comsol
  - Extracting multipole coefficients (see IPAC21, TUPAB238)
  - Tracking with multipoles up to 12-poles; Optics rematch, lifetime, DA
- Design changes
  - Shortening sextupoles by 10 mm and increasing the distance between Reverse bend and Octupole.
  - Magnetic shield attached to hor. corrector next to Reverse bend.

Lattice unit cell, top view



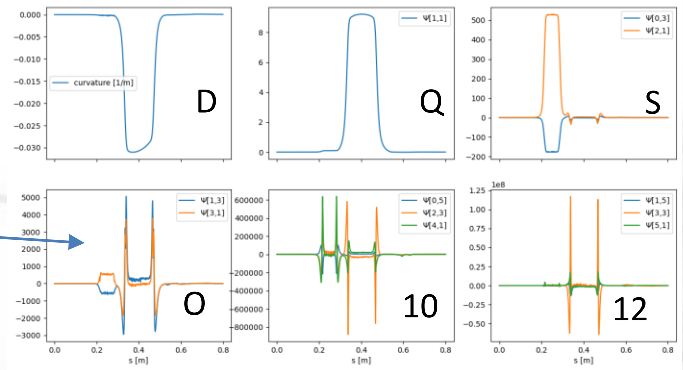
Reverse bend + Octupole

LGB + Sextupole



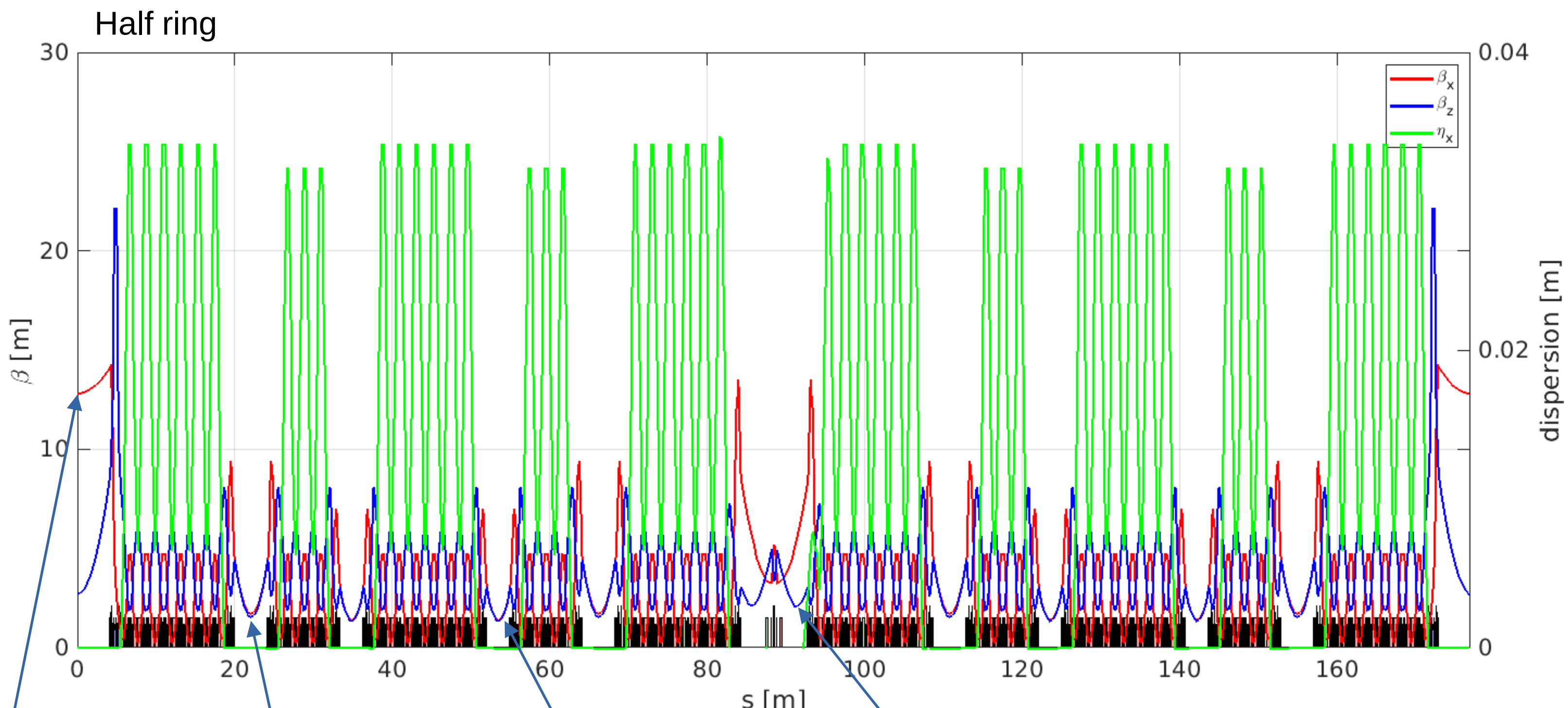
Examples of FEM simulation

Example of multipole coefficients Reverse bend +Sextupole



Octupole components in sextupole…

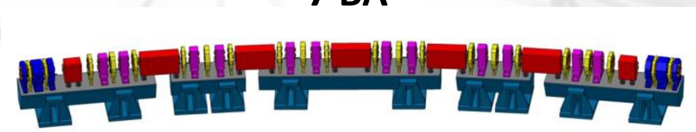
Alternated MBA (7BA - 4BA) and Compact Lattice: SOLEIL UPGRADE example



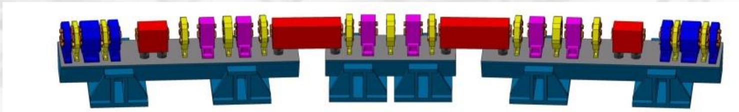
Injection	Medium section	Short section	Double low beta
$\beta_x \sim 12.7m$	$\beta \sim 1.6m$	$\beta \sim 1.4m$	$\beta_z \sim 2.1m$
$L = 8m$	$L = 4.20m$	$L = 3m$	$L = 3.23m$

Nom. Energy : 2.75 GeV
Ring circ. : 354 m
Nat. Horizontal emittance : 84.4 pm.rad
MCF : 1.04 10^{-4}

7 BA



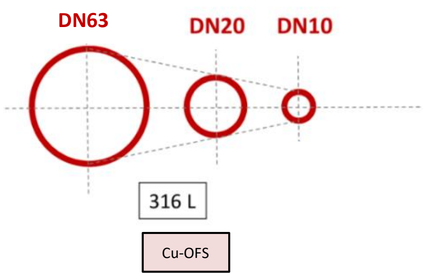
4 BA

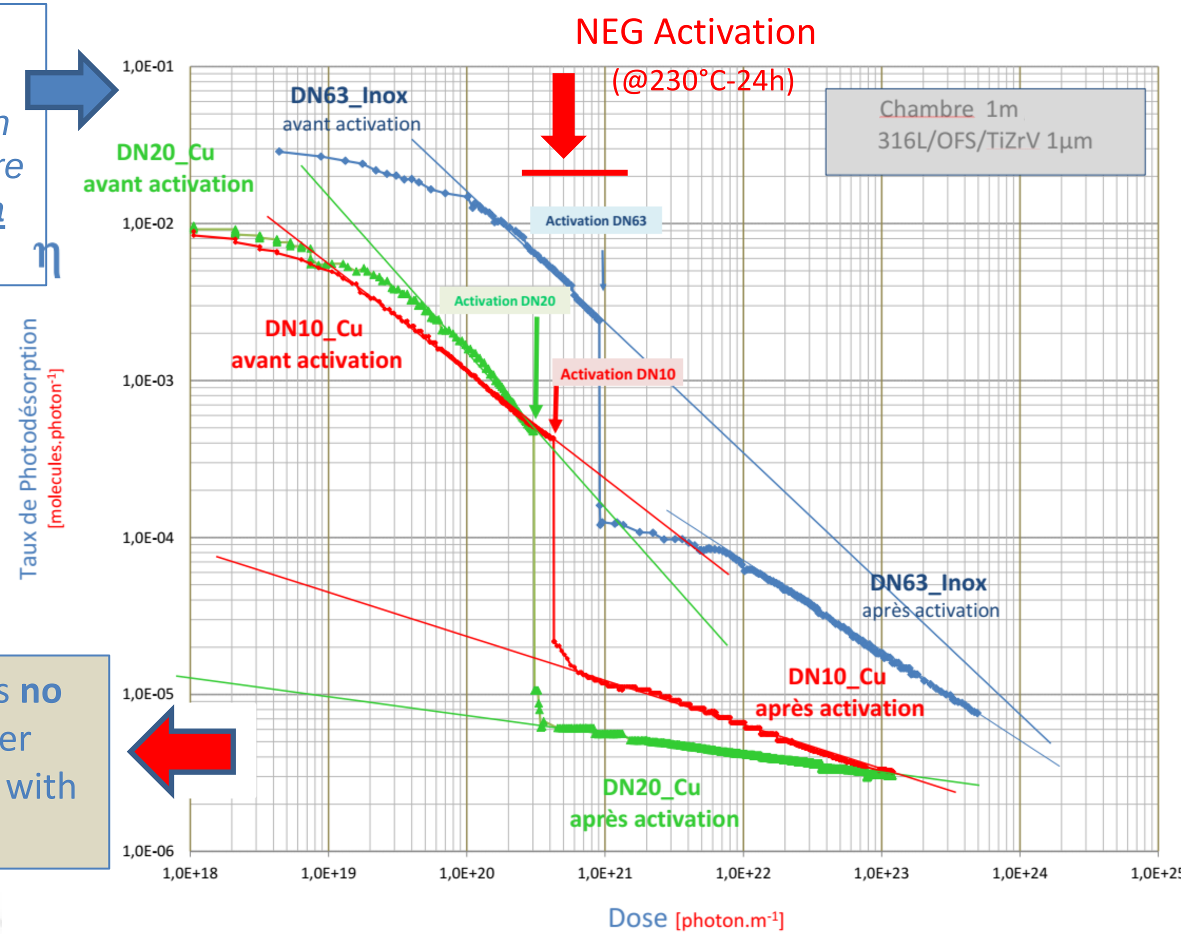


Pumping in small diameter chambers

TESTS on TiZrV 1µm NEG-coated pipes
Sorption capacity and Sticking factor

*In the framework of a collaboration with SAES Getter we have measured the PSD yields for 3 different 1m long-chambers with diameters **DN63 / DN20 / DN10** and compare the yields **before and after activation of a standard NEG** [1µm / TiZrV]*

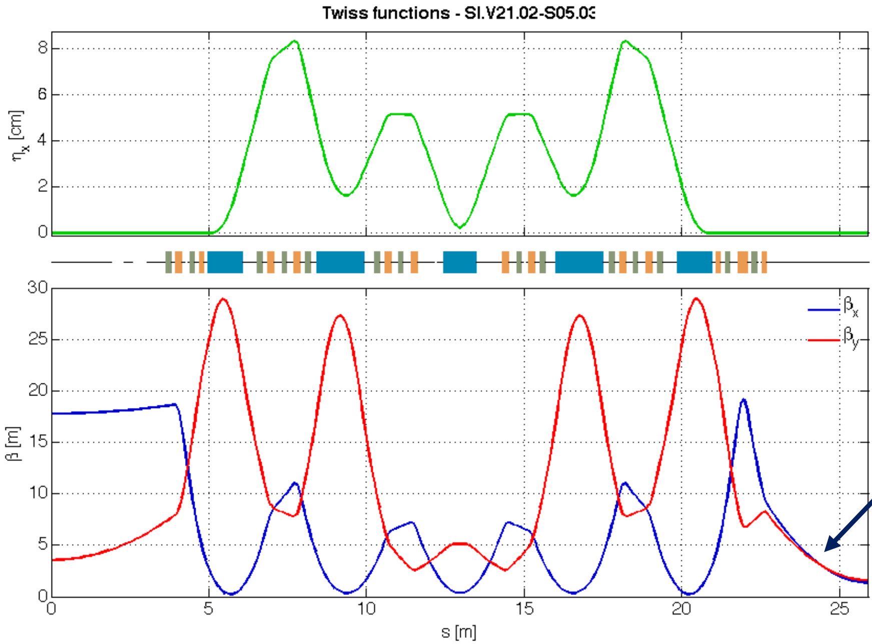




From a PSD point of view there is **no downscalling issues** for chamber size down to **10 mm** in diameter with standard 1µm TiZrV NEG coating

Phase space matching: Optimum β function

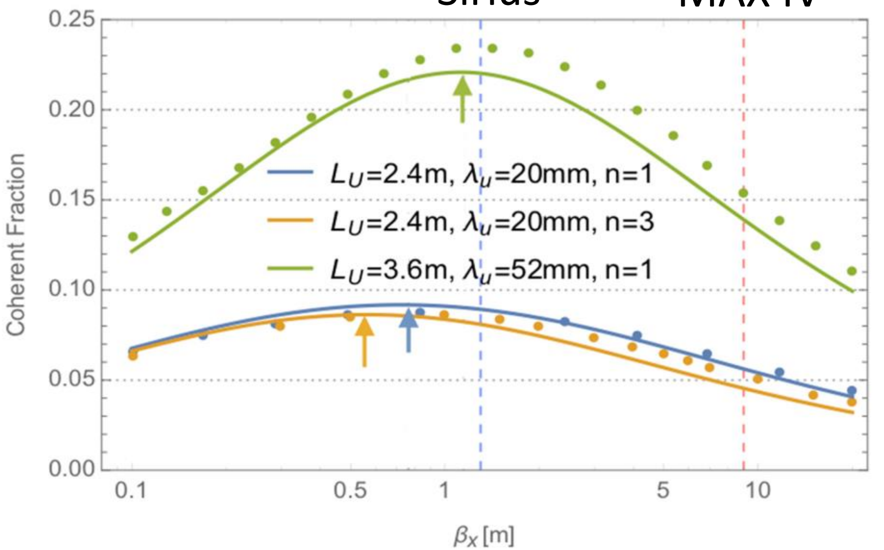
Sirius example



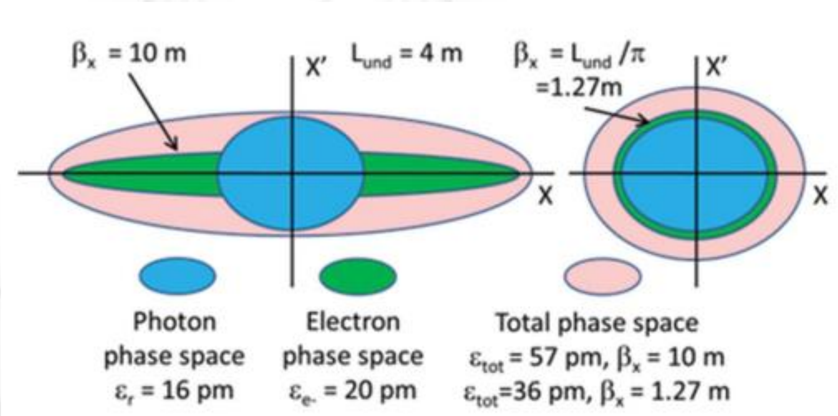
$\beta_x \approx \beta_y \approx$ **1.5 m**
– Optimized electron and photon beam phase-space matching for undulators.

Only few lattices push towards (very) small beta in both planes!

Sirius MAX IV



(Liu Lin IPAC 2020)



R. Hettel, JSR 1600-5775)

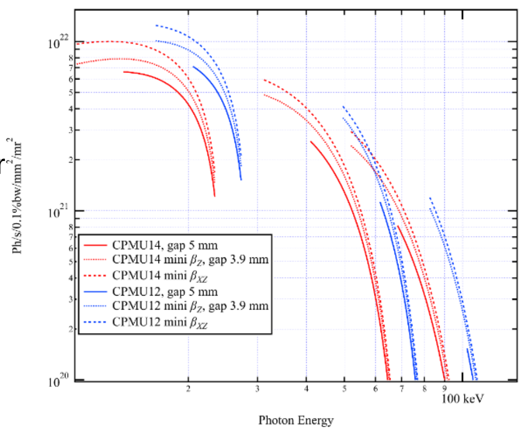
Mini-beta insertions at ESRF-EBS

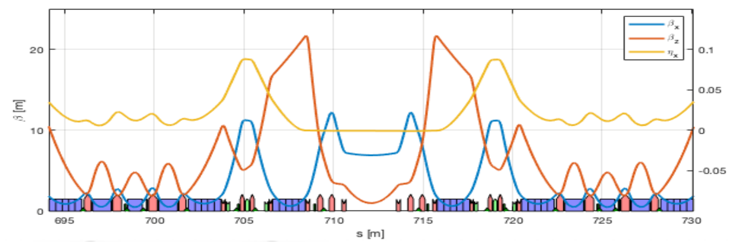
Provide optimum matching for IVU:

- Optimum beta ~ $L_{IVU}/2$ = 1m: **brilliance increase by a factor 2**
- Beta squeeze at the center of the straight section with 4 additional quadrupoles
- Low period undulator at the center of the straight section **could replace 2 undulators**

Test bench for ESRF:

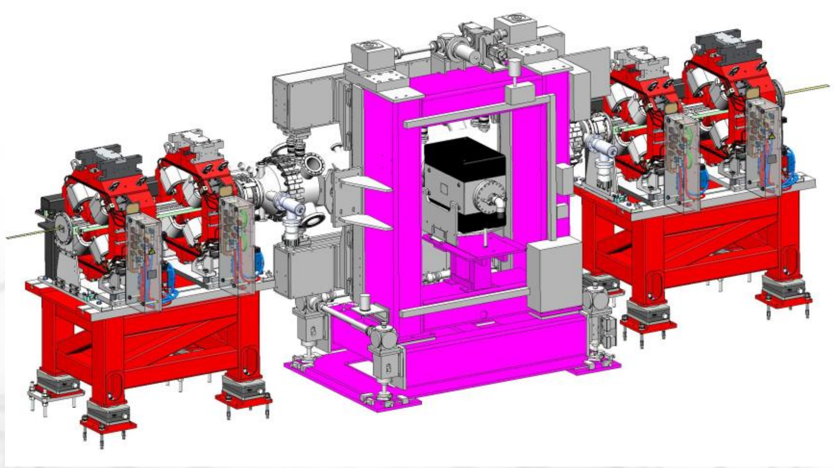
- ID31 already in the right configuration, support and chambers installed: **ready to install quadrupoles for commissioning**
- Flexible design to squeeze either plane or both at the same time
- **20% lifetime reduction without errors**, lattice with errors not optimized: factor 2 reduction
- Small reduction of DA and injection efficiency





Courtesy of B. Ogier

	Present lattice	Mini-beta
DA	-10.4 mm	-9.3 mm
TLT (7/8, 10pm)	43.0 h	34.4 h
DA errors	-9.1 mm	-8.8 mm
TLT errors	41.0 h	21.9 h
I.E. errors	96 %	89 %



HALO studies at ESRF-EBS

Hypothesis:

- Large vertical HALO observed at ESRF: **losses on IVUs, could prevent to reduce their gaps.**
- HALO is generated by off-energy particles with resonant tune conditions (Qh or Qv = 0.5, Qh + Qv =1, etc.)

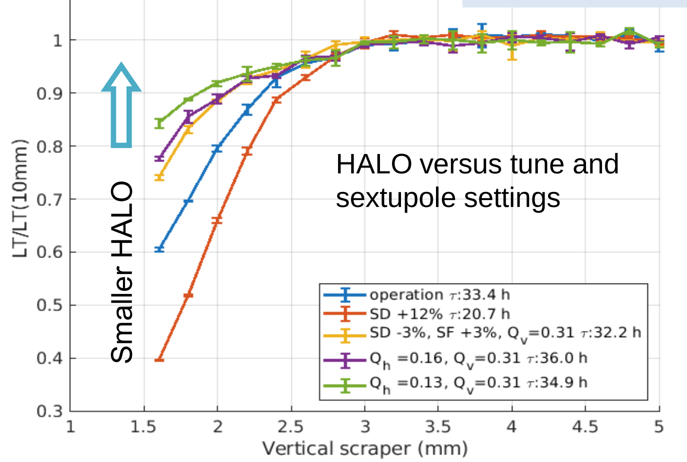
Possible Actions:

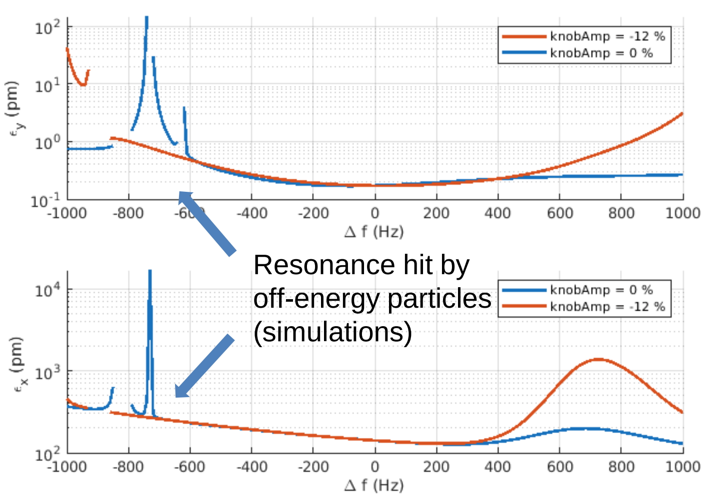
- Change sextupoles setting to adapt detuning with momentum.
- Change the tune working point

Measurement methods:

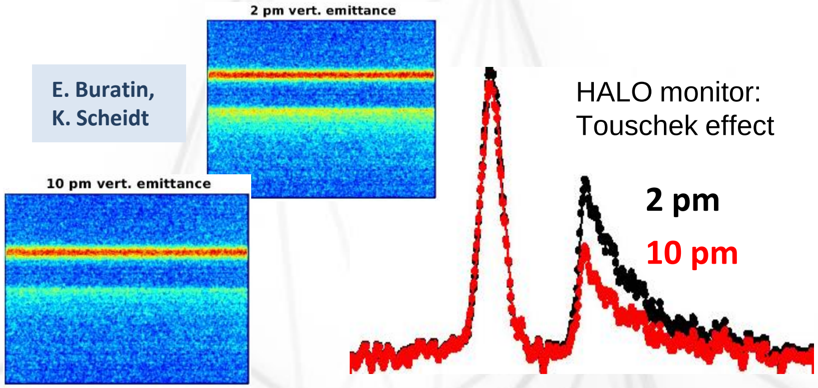
- Insert the vertical scraper until the lifetime is affected
- Halo monitor recently installed

P. Raimondi et al.





E. Buratin, K. Scheidt



Injection Schemes

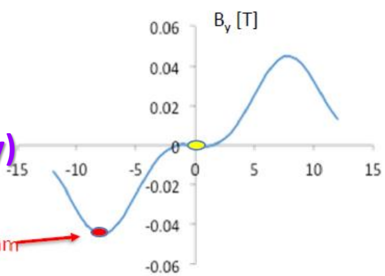
With the reduction of the emittance of these rings, the transverse acceptance shrinks and injecting and accumulating charge is becoming more and more challenging.

Small dynamic aperture can be partially overcome with advanced injection schemes.

Maintaining a constant stored current is an essential requirement for synchrotron radiation users, and a transparent beam injection scheme that does not perturb the stored beam is needed.

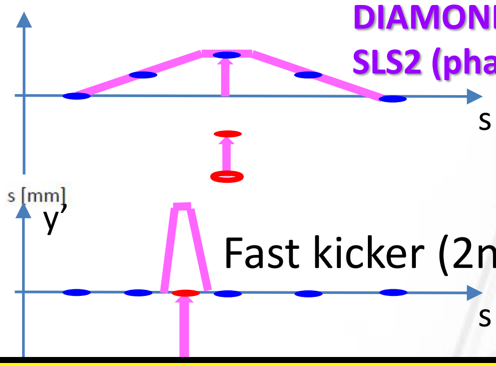
MAX IV
Sirius
SOLEIL II
SPRING-8 ?
ALBA-II
ESRF-EBS (study)
Used at BESSYII

Off-axis injection: Non Linear Kicker



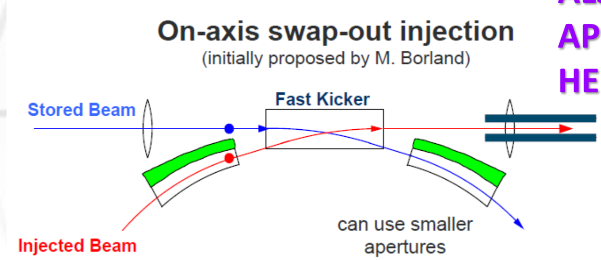
Single (few) -bunch aperture sharing

DIAMOND-II
SLS2 (phase 2)



On-axis swap-out injection

ALS-U
APS-U
HEPS



Either by damping the spent beam (APS-U) or by re-using the beam with the help of "accumulator" rings (ALS-U and HEPS)

Most upgrade programs involve changes in the injector :

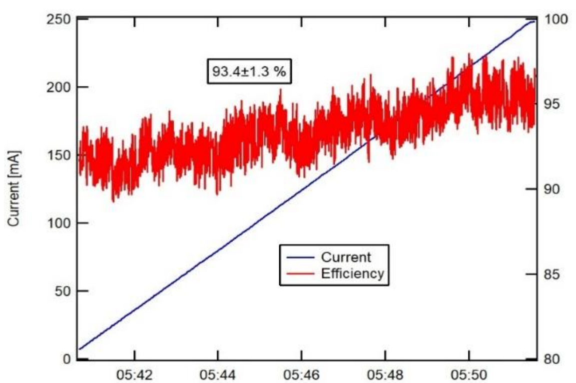
Low emittance Booster   Full Current   Accumulator

A certain flexibility of the injection system is very desirable in order to cope with future aperture challenges. The approach taken at SLS-2.0 and Diamond-II serves as a good example of this.

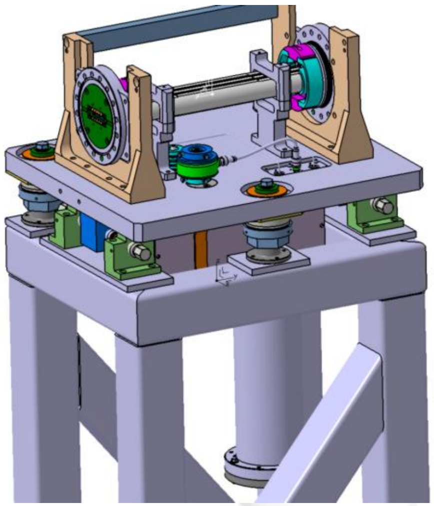
(Successful) operation of NLK for top-up injection at MAXIV, Sirius and SOLEIL

Injection efficiency

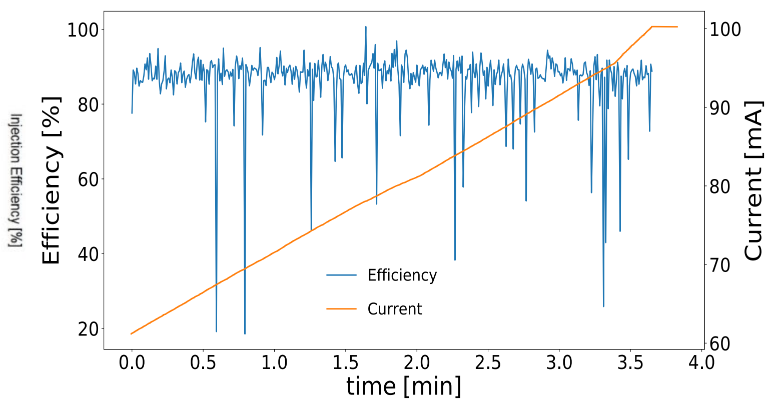
MAXIV



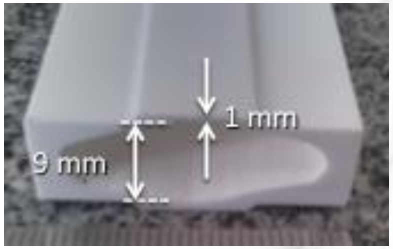
Operating since early 2018

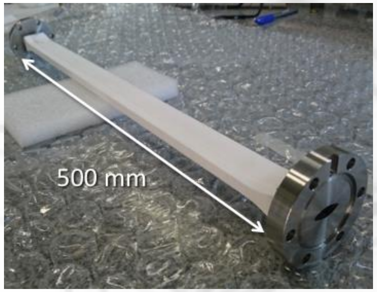


Sirius

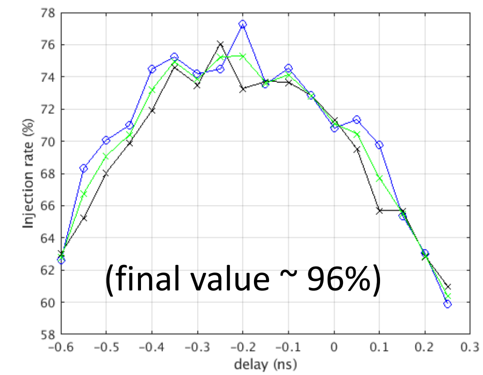


Operating since early 2020

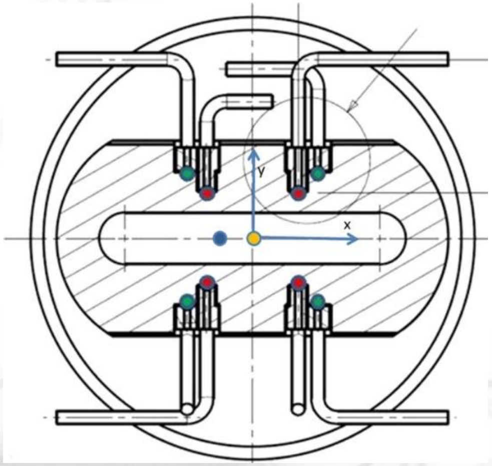




SOLEIL* (present Machine)



Operating since early 2021

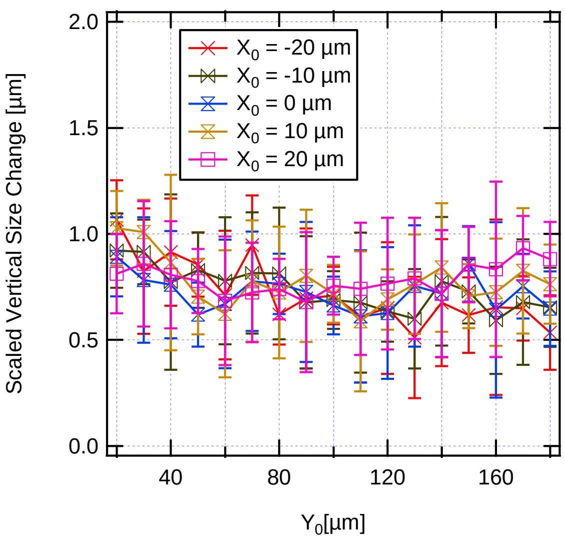


* Randy Ollier PhD thesis

(Successful) operation of NLK for top-up injection at MAXIV, Sirius and SOLEIL

Transparency

MAX IV 3 GeV



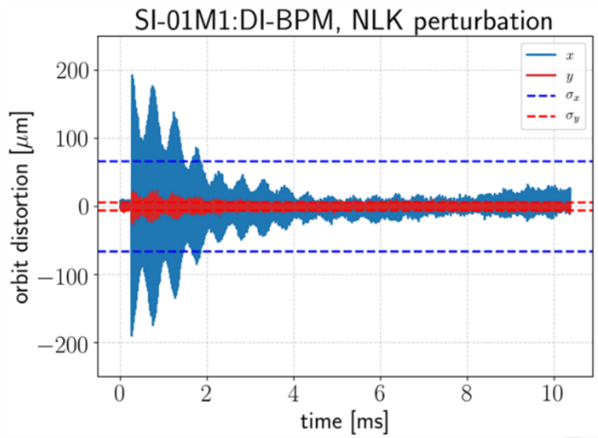
Minimum Vertical Size Change

$$\delta\sigma_x = 0.5 \pm 0.7\ \mu m$$

$$\delta\sigma_y = 0.6 \pm 0.1\ \mu m$$

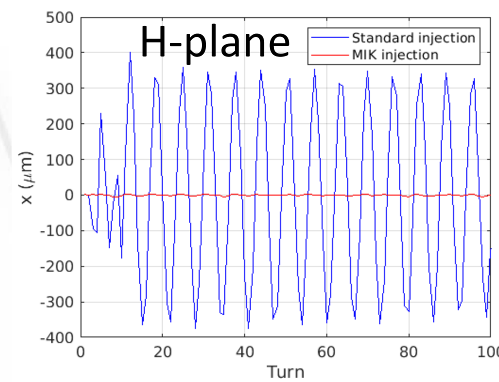
New Ideas:
SOLEIL II
ALBA II

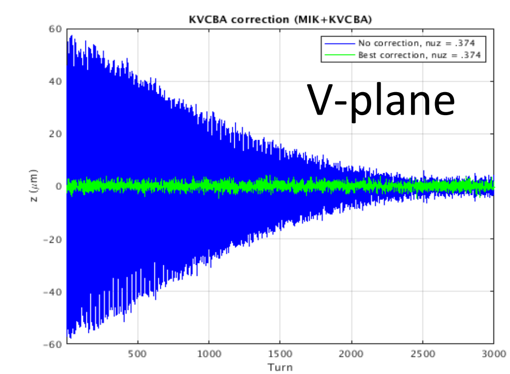
Sirius



- Transient perturbation in stored beam orbit at injection due to residual magnetic field at the center of the NLK is larger than required for transparent injection
- Variable inductors are being studied to be installed for fine tunning of the current pulse through each wire.

SOLEIL* (present Machine)





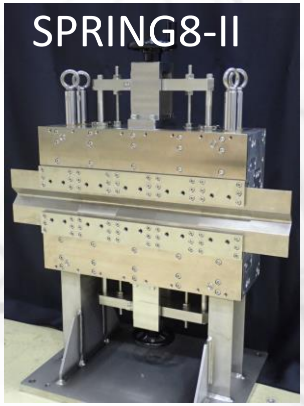
H-plane : quasi-transparent.
V-plane, some residual field, correction of the stored beam position using a pulsed pinger during injection with the NLK.

* Randy Ollier PhD thesis

Use of Permanent Magnets

Description	Pro	Cons
Permanent Magnets	No powering No cooling Compactness Reliability	Fixed field (unless trimmeable) Radiation damage Temperature stability

Project	TGB/LGB	Reverse Bend	QPOLE	Septum
ESRF-EBS	X			X
Sirius	central			
Diamond II	X			
PETRA IV	X			
SLS 2	X	X		
SOLEIL	X	X	X	X
SPRING8-II	X			X



T. Taniuchi et al., PRAB 23, 012401 (2020).

SOLEIL II: the use of permanent magnets for all bending magnets, reverse bends and quadrupoles enables a densely packed lattice and contributes most to a reduction of total power consumption of the facility by 50%.

PerMaLIC is a ***LEAPS Internal Collaboration***,

i.e. a collaboration between the institutes of the LEAPS Consortium (https://leaps-initiative.eu), about **development of Permanent Magnets for the future, ultralow emittance, light sources**.

Motivation

The **use of Permanent Magnets** in the new light sources has mainly two advantages: in the one hand, it allows a **more compact distribution of magnets**, since there is no need of coils and water cooling; in the other hand, it allows to **reduce the running costs and the carbon footprint** of the facility thanks to the removal of the power supplies associated to conventional electromagnets.

However, the use of Permanent Magnets also presents some **serious challenges**. These challenges include the **loss of flexibility** for the correction of errors, correction that it is needed to ensure the proper beam dynamics performance and stability, and the **long term stability** of the magnets themselves due to the risk of radiation-induced demagnetization.

Insertion Devices Developments

- **High photon energies: general tendency to reduce gap and period**

➢ **The "horses":** CPMUs, small gaps, mini β

Low gap CPMU: Example: CPMU 12-18 mm period, 3.0 to 4.0 mm gap (*SOLEIL Upgrade*).
Several labs: ESRF, Spring-8, Diamond, SLS, IHEP,
Automation of production
Robot for magnetic measurements
(*SOLEIL Upgrade, SLSII)*

CPMU12 Supermodule (SOLEIL)

Long CPMUs create thermal load issues.
Shorter devices at the middle of the straight section.
Smaller gaps.

➢ Superconducting undulators: **becoming mature devices**

APS-U: development: 8 mm magnet gap; 16.5 and 18.5 mm periods, 2 x 1.9 m SCU in 4.8 cryostat

APS-U

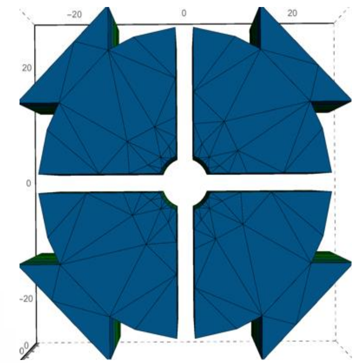
SLS2.0: Staggered arrangement
Tests done on short prototypes: 10 mm period, 4 mm gap, 1.29 T reached at 15K.
Project for 1m long prototype

Insertion Devices Developments

- **Variable polarizations.**

compact, variable-gap APPLE X (MAX IV).

  - ➢ DELTA and APPLE-X undulators.
    - ✓ Allows compact designs
    - ✓ Circular camber (4-fold symmetry)
  - ➢ Bi-periodic undulator



APPLE X ATHOS 5mm round 3 mm gap / slit (SLS2)

Sirius: DELTA-type 21 mm period and 7.0 mm gap
MAXIV: To be installed on a LINAC; 8 –28 mm gap (circular); 40 mm period Field ~ 1 T; 3 m long.

  - ➢ Cryo helical undulator

Developed at BESSY and SOLEIL

- APPLE-III / APPLE-X type
- Force compensation magnets
- Prototyping in progress

Several design challenges must be solved. Among them are a precise gap and phase drive on the micrometer level in the presence of strong tree-dimensional forces.

J. Bahrdt and S. Grimmer.
In-vacuum apple ii undulator with force compensation.
AIP Conference Proceedings, 2054(1):030031, 2019.

Other challenges of ultra low emittance

– Emittance growth due to Intra Beam Scattering (IBS).

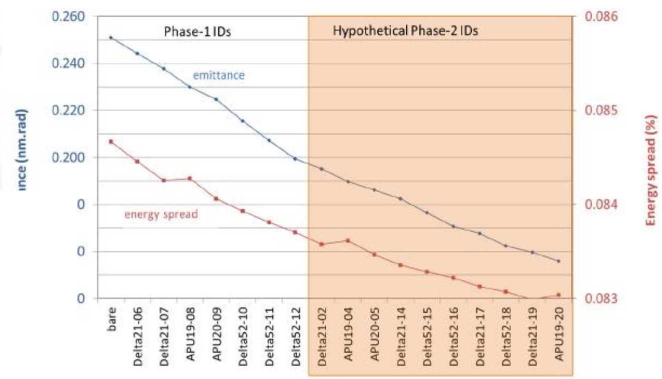
– Touschek effect: $$\frac{1}{\tau_{tous\_1/2}} = \frac{\sqrt{\pi}\, r_e^2 c\, N_b\, C(\zeta)}{\gamma^3 \sigma'_x V \varepsilon_{acc}^2} = \frac{\sqrt{\pi}\, r_e^2 c\, N_b}{\gamma\, \varepsilon_{acc}^4} \left(\frac{\sigma'_x}{V}\right) D(\zeta)$$

– To overcome IBS and Touschek effects
- ➢ Running with “round beams,” i.e., $\kappa=\varepsilon_z/\varepsilon_x \approx 1$
- ➢ Bunch-lengthening using a higher harmonic cavity.

– Lower thresholds for single and multi-bunch instabilities.

– **Very small vacuum chamber apertures : difficulty to extract IR & UV photons and difficulty to extract vertically/circularly polarized radiation at low photon energies.**

– Effects of Insertion Devices on emittance and energy spread.



(L. Lin (IPAC2017))

Potentiel solutions:
- ✓ Damping wiggler gap variation (PETRA IV)
- ✓ compensated in a passive way by leaking a small amount of dispersion to straight sections (SPRING8-II).

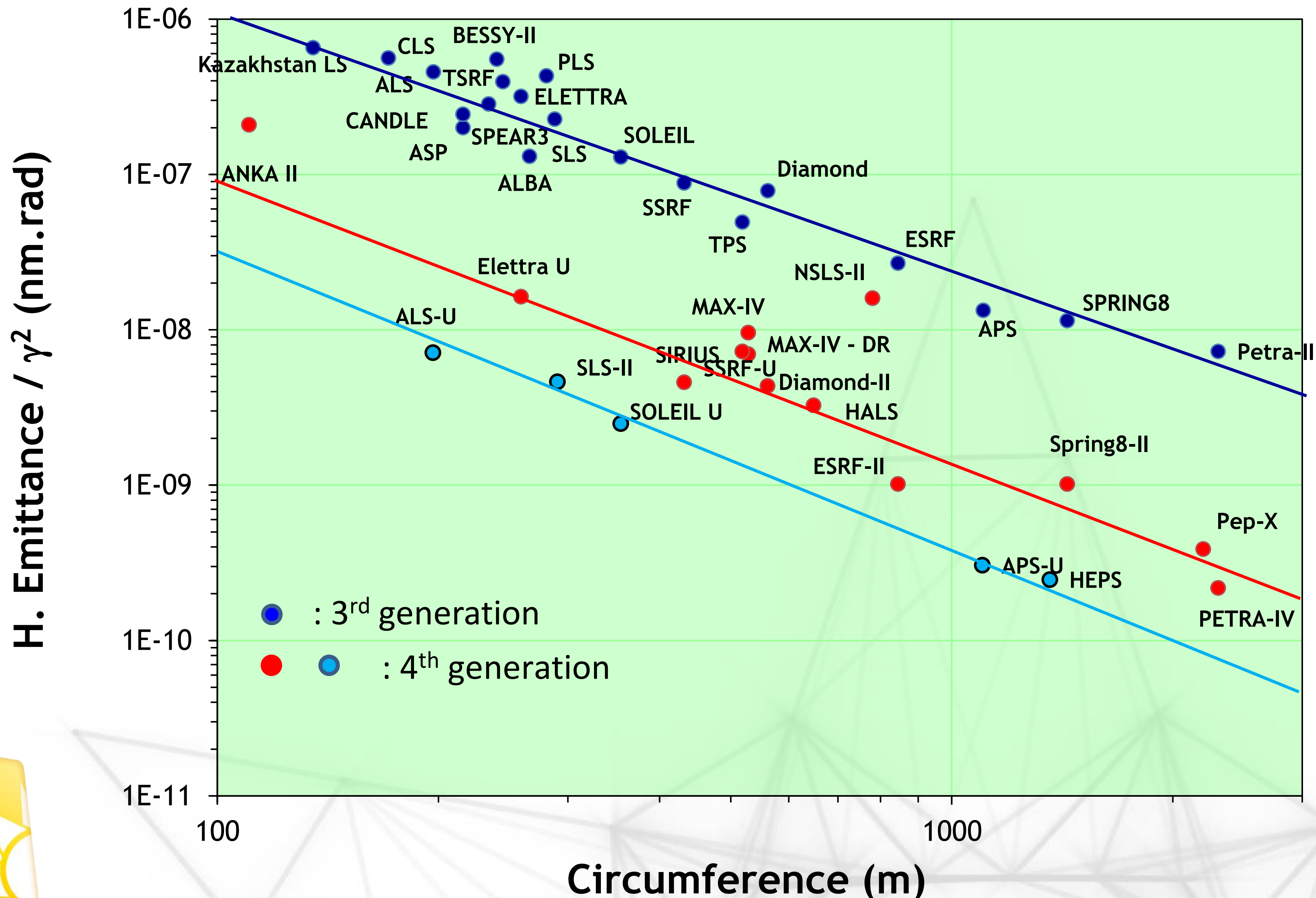
The full technology chain from source to detector must be developed.

- The optimization of the Accelerator and the Sources is not the end of the story!
- Detailed **commissioning simulations** have become an important part of MBA design.
- Electron and photon **Beam stability**: Integrated electron and X-ray feedback system?
- **Undulator gap scan** : follow a continuous photon energy variation versus time with the harmonic (becoming very thin!) of an undulator.
- **Coherent wavefront preservation :**
  Very significant work and creativity will be required to develop, fabricate and install brilliance and coherence-preserving optics up to wavelengths of the order of 1 A °.

To translate the progress in light source quality into new science requires similar progress in aspects such as optics, beamline technology, detectors and data analysis.

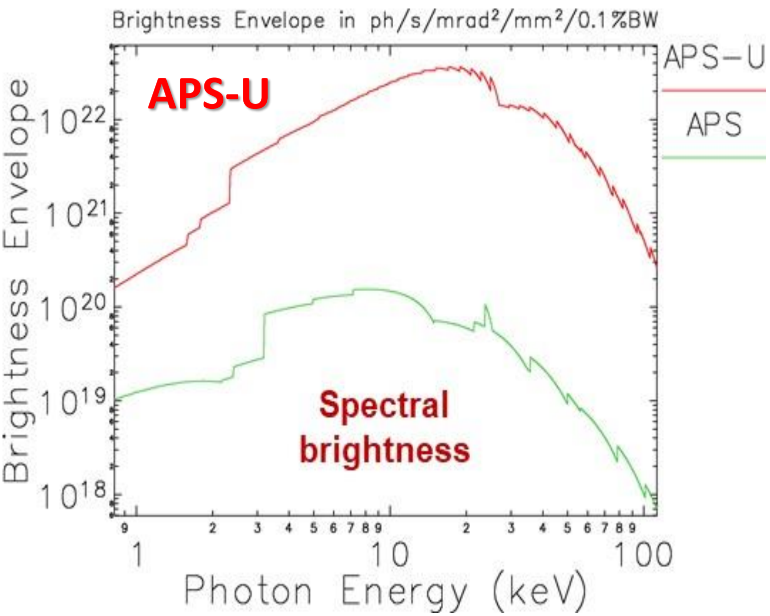
The quality of new science will be limited by the weakest component in this value chain.

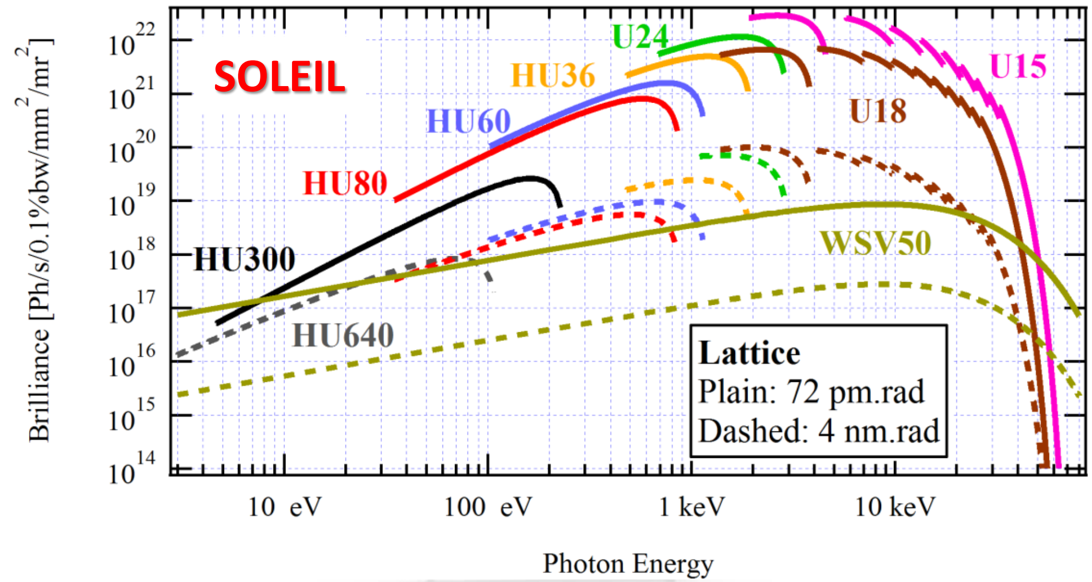
3rd and 4th Generation Storage Ring emittance

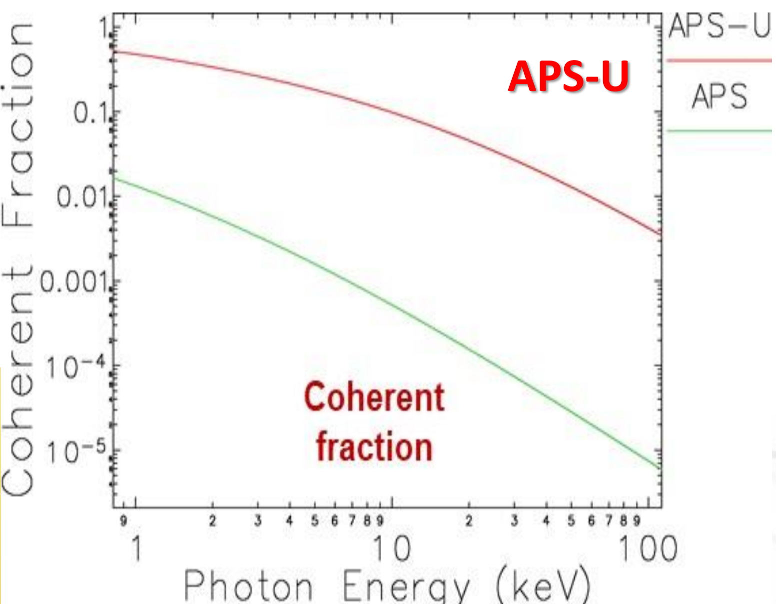


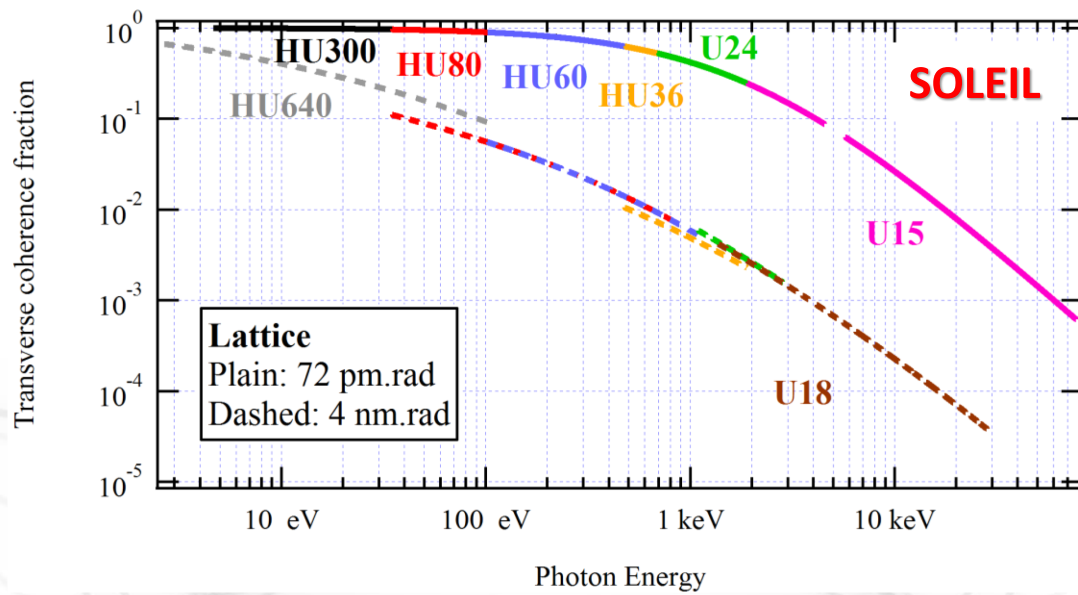
Adapted from R. Bartolini

Typical BRILLIANCE and TRANSVERSE COHERENCE EXPECTED

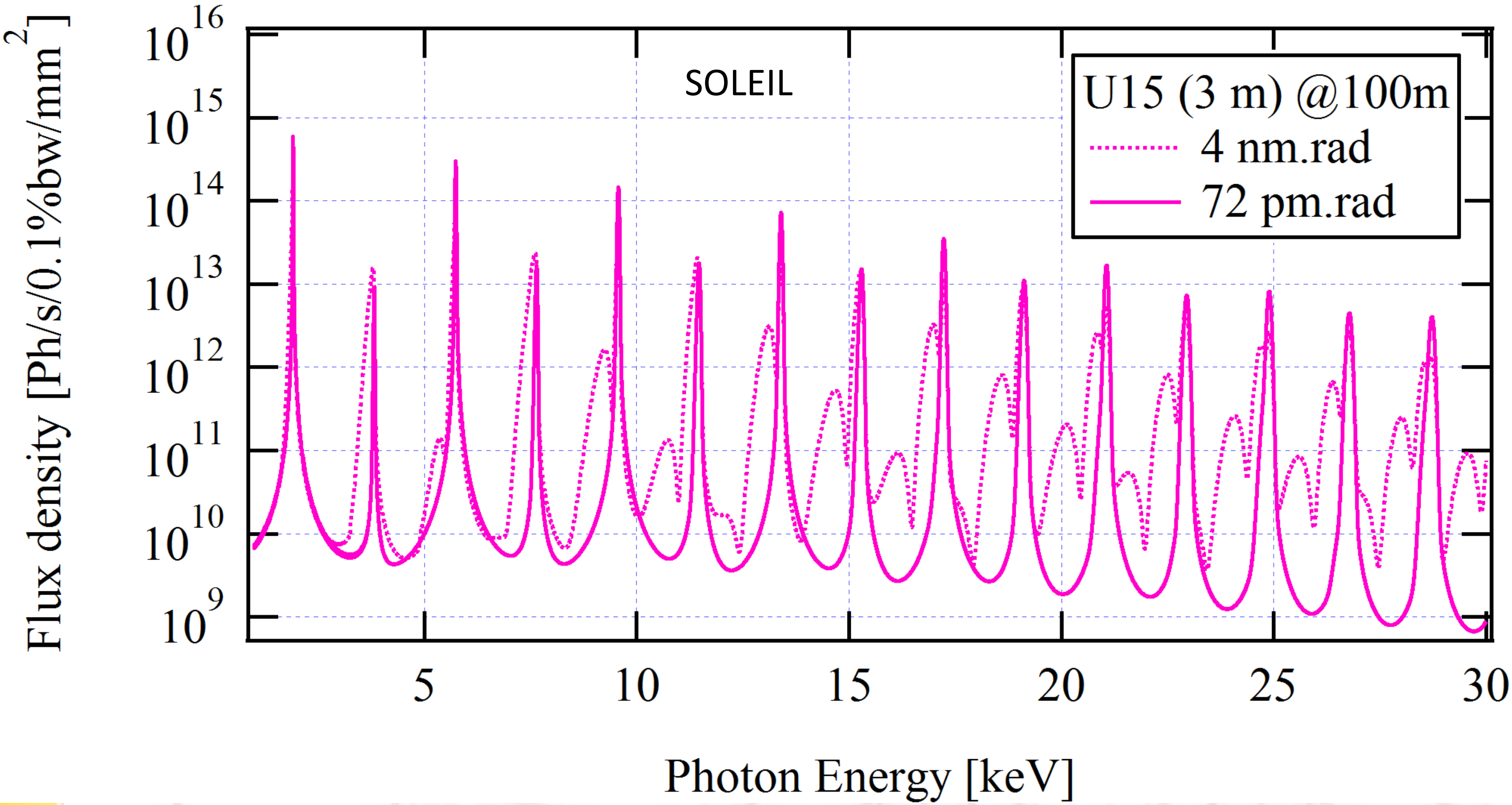




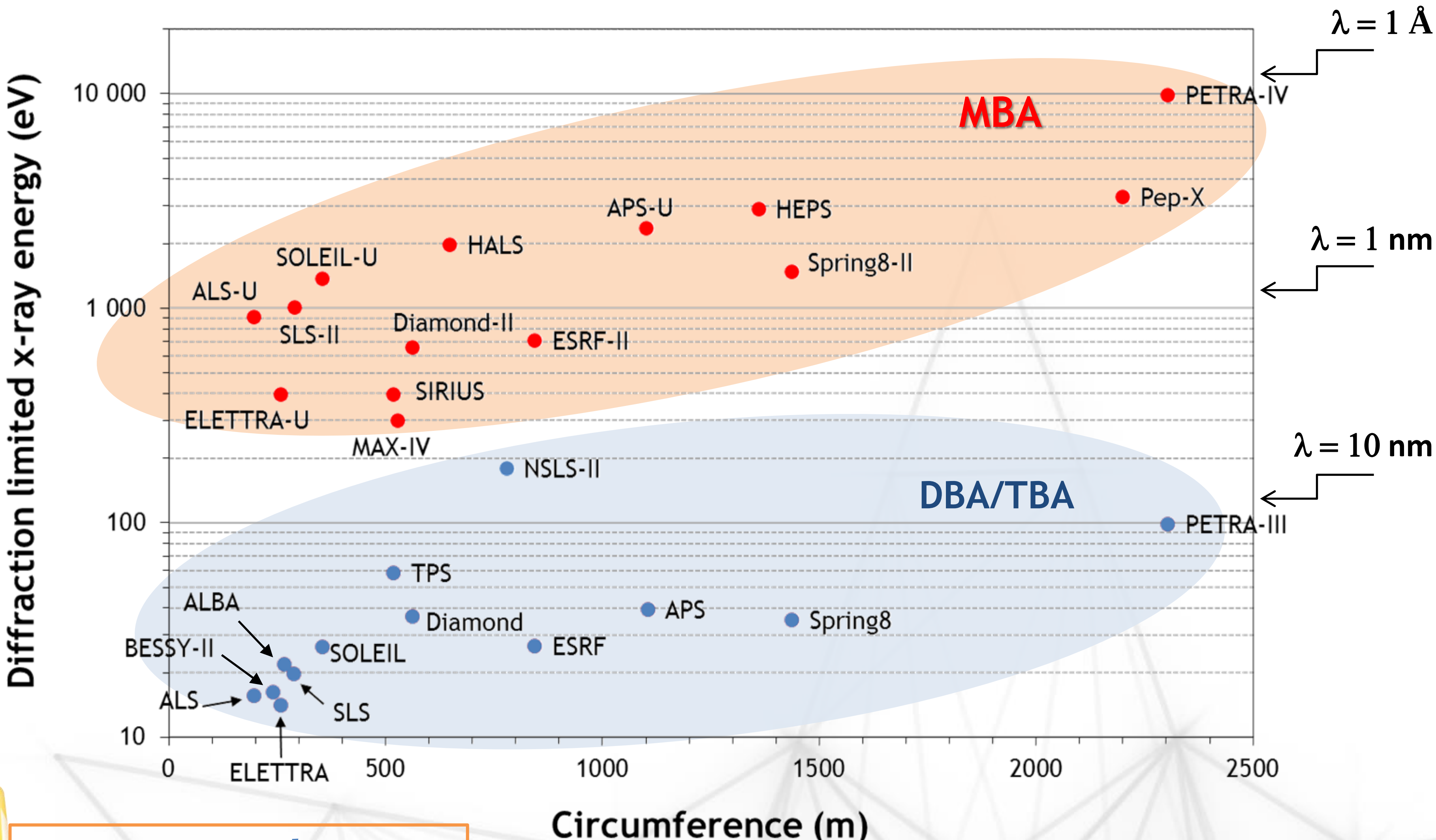




Undulator Spectral Purity



Diffraction limited photon energy



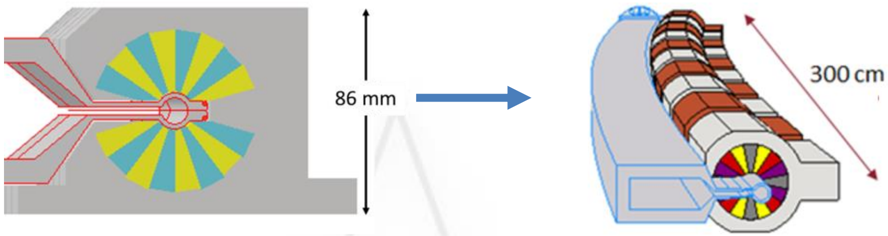
$$E\ (eV) = \frac{h \times c}{e \times 4\,\pi\ \times \epsilon_x\ (m)}$$

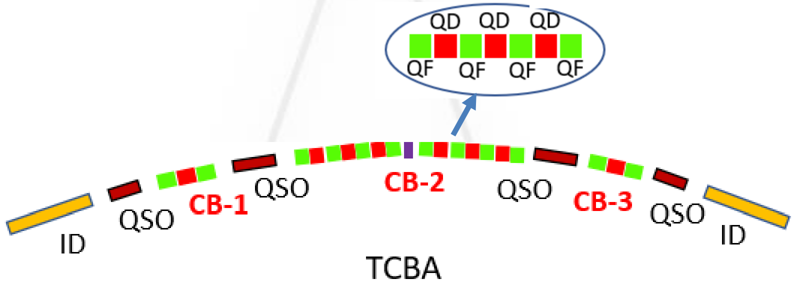
Adapted from C. G. Schroer

Potential Future Directions

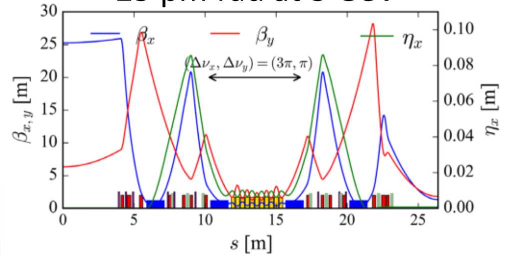
- Complex Bend concept (2018)
- Transition from individual dipoles to multiple dipole poles
  - APS DBA: 40x2=80 dipoles
  - APS-U MBA: 40x7=280 dipoles
  - NSLS-II upgrade with CBs: 30x2x20=1200 poles
- Potential of reaching horizontal emittance in the range of 10 pm·rad for **NSLS-II upgrade**
- Compact arrangement of ring elements, increasing lengths of ID sections
- Challenges (S. Sharma, IPAC-2022)
  - Gradients of 150 T/m are required
  - Small apertures / Heat load from Synchrotron Radiation
  - We are building full-scale CB element prototype
- Pursuing this as an option for NSLS-II upgrade
  - We are working on Triple Complex Bend Achromat (**TCBA**)
  - 30 cell lattices at 3 GeV with low emittance
- Successful example of integration of CBs into MBA lattice (HCBA, V. Smaluk 2021)
- Simultaneous correction of high order geometrical driving terms with octupoles for lattices with Complex Bends (F. Plassard, 2020-2021)

Complex Bends for Low-Emittance Ring Design

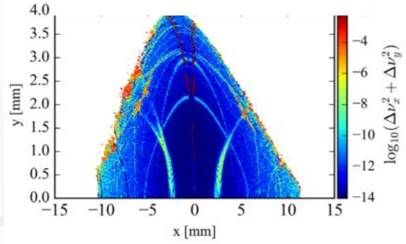




25 pm·rad at 3 GeV



On-momentum DA



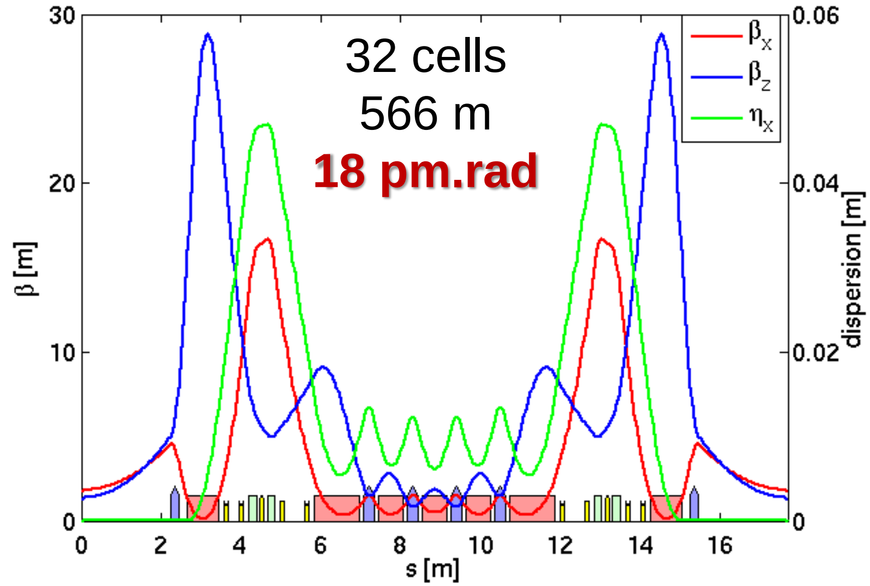
https://journals.aps.org/prab/pdf/10.1103/PhysRevAccelBeams.24.114801

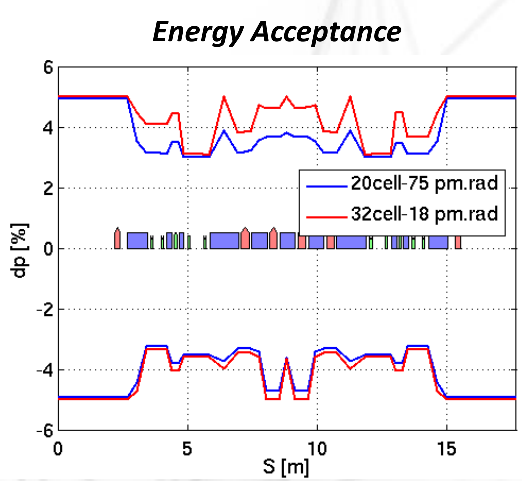
Potential Future Directions

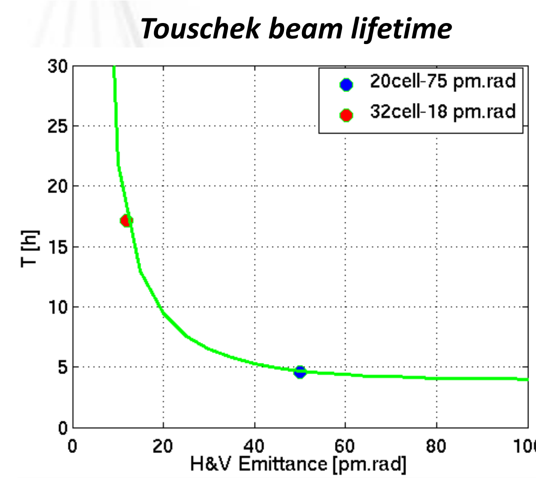
➢ **Reach the diffraction limited emittance at 1 Å (12.4 keV) in a reasonable circumference.**

➢ **We are not so far!** (example: scaling of one example of SOLEIL-U from 20 to 32 cells).

	Bare lattice
Circumference	**566 m**
Natural Emittance	**18 pm.rad**
Emittances @100 % coupling	**12 pm.rad**
Mon. Comp. Factor	$6\ 10^{-5}$
Energy spread	$6.9\ 10^{-4}$
Bunch Length	2.9 mm
Energy Loss per Turn	200 keV
Touschek Lifetime (500 mA)	**17 h**
Dipole Field	**0.32 T**
Quadrupole Gradient [T/m]	**95 T/m**
Sextupole Strength [T/m²]	**3200 T/m²**







Potential Future Directions

- If we refer to the history of permanent magnet undulators, the transition to in-vacuum undulators allowed us to get rid of the problem of the vacuum chamber in the quest for gap reduction, fairly profitable development for the community.

- It is interesting to note that this question could be considered today for the magnets : the vacuum chambers are getting narrower and more complex and the use of permanent magnets under vacuum could be a logical next step to explore.

- It is possible to build in-vacuum undulator assemblies of several meters in a chamber of about 30 cm inner diameter. Part of this technology could be applicable to permanent magnet multipoles because of their reduced size. Obviously this is only of interest if a certain number of consecutive magnets are in the same vacuum chamber. The NSLS complex bends concept could be a good candidate (version with dipolar field obtained by moving consecutive quadrupoles).

The topic of in-vacuum magnets in accelerators could most likely be part of a joint project for different synchrotron radiation facilities. LEAPS ?

Conclusions

- ❑ Ultra-low emittance light sources can open new frontiers in x-ray science.
- ❑ Multi-Bend Achromats can be the 4th generation low emittance storage rings.
- ❑ Along with great potential comes great challenges/opportunities in different areas.

The Quest for a DLSR @ 1 Å is now within the horizon

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