Overview of Diffraction Limited Storage Rings

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Diamond Light Source
and
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PHANGS Workshop
Trieste, 4 December 2017

- ***Introduction to DLSR***
- ***Lattice developments***
- ***Technical challenges***

Brilliance and transverse coherence

Photon flux and brilliance and coherent fraction

$$\text{flux} = \frac{N_{ph}}{\Delta T \cdot \Delta\omega/\omega} \qquad \text{brilliance} = \frac{\text{flux}}{4\pi^2 \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}} \qquad F = \frac{\lambda^2/(4\pi)^2}{\Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}}$$

Σ's are the convolution of electron and photon beam size and divergence

$$\Sigma_x = \sqrt{\sigma_{x,e}^2 + \sigma_{ph}^2} \qquad \Sigma_{x'} = \sqrt{\sigma_{x',e}^2 + \sigma'^2_{ph}}$$

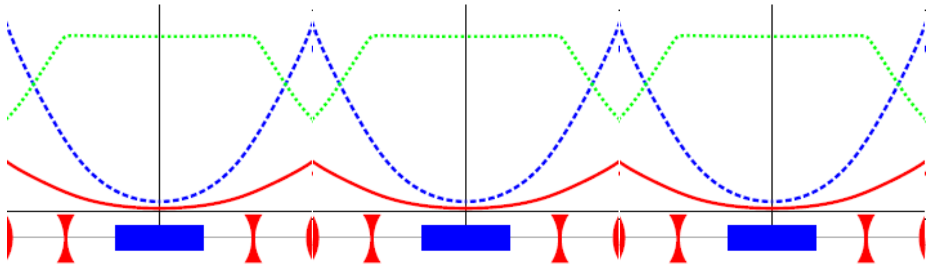
Brilliance and coherent fraction are maximised for smaller electron beam emittances until the diffraction limit is reached

$$\varepsilon_{e^-} \le \varepsilon_{ph} = \frac{\lambda}{4\pi}$$

~10 pm for diffraction limit at ~1 Angstron (12.4 keV)
~100 pm for diffraction limit at ~ 1nm (1.24 keV)

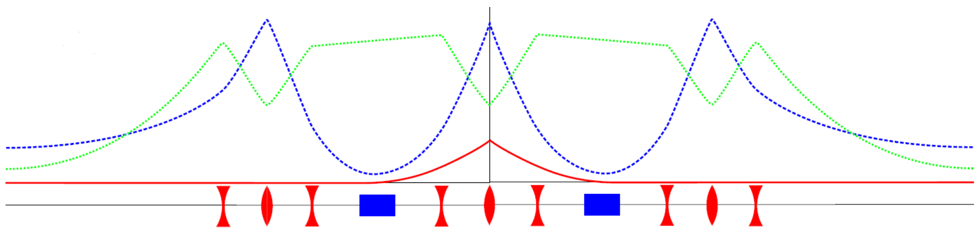
Low emittance lattices: from TME to MBA cells

TME



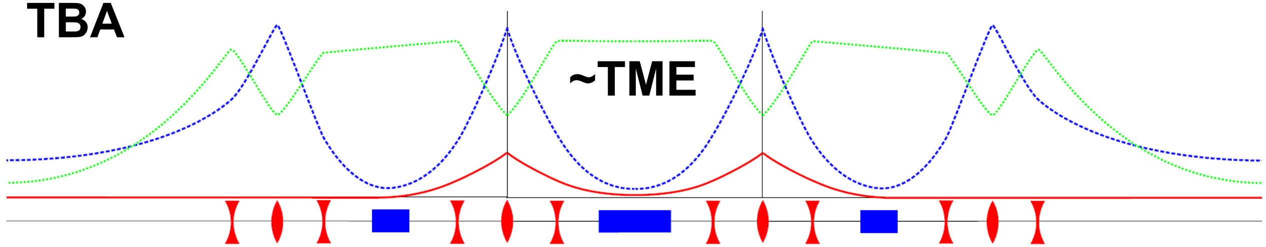
$$\varepsilon_{TME} = \frac{C_q}{12\sqrt{15}}\gamma^2\theta^3$$

DBA



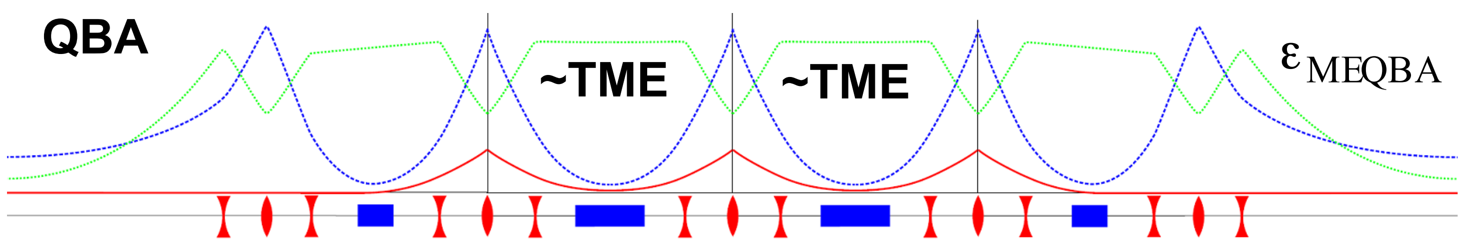
$$\varepsilon_{MEDBA} = \frac{C_q}{4\sqrt{15}}\gamma^2\theta^3$$

TBA



$$\varepsilon_{METBA} \approx 0.66\,\varepsilon_{MEDBA}$$

QBA

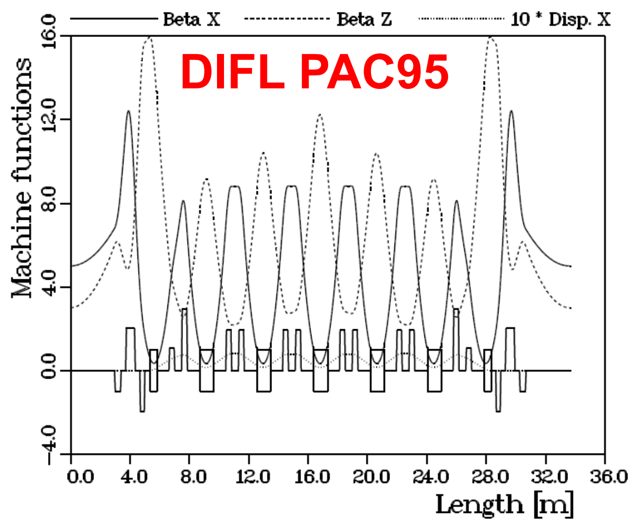


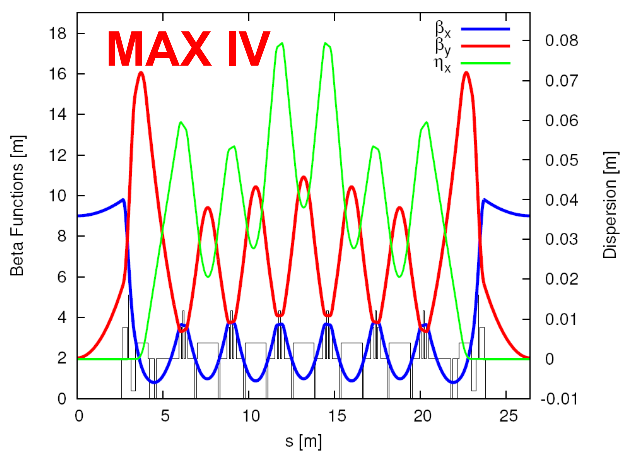
$$\varepsilon_{MEQBA} \approx 0.55\,\varepsilon_{MEDBA}$$

$$\varepsilon_{MEMBA} = C_q F \gamma^2\theta^3$$

S.Y. Lee, PRE 54, 1940, (1996)
S.Y. Lee, Accelerator Physics, World Scientific
A. Streun, CAS, (2003)

DIFfraction Limited light source (DIFL)





~20 years from the first proposal

- **D. Einfeld et al. NIMA 1993, PAC1995**

to the first beam

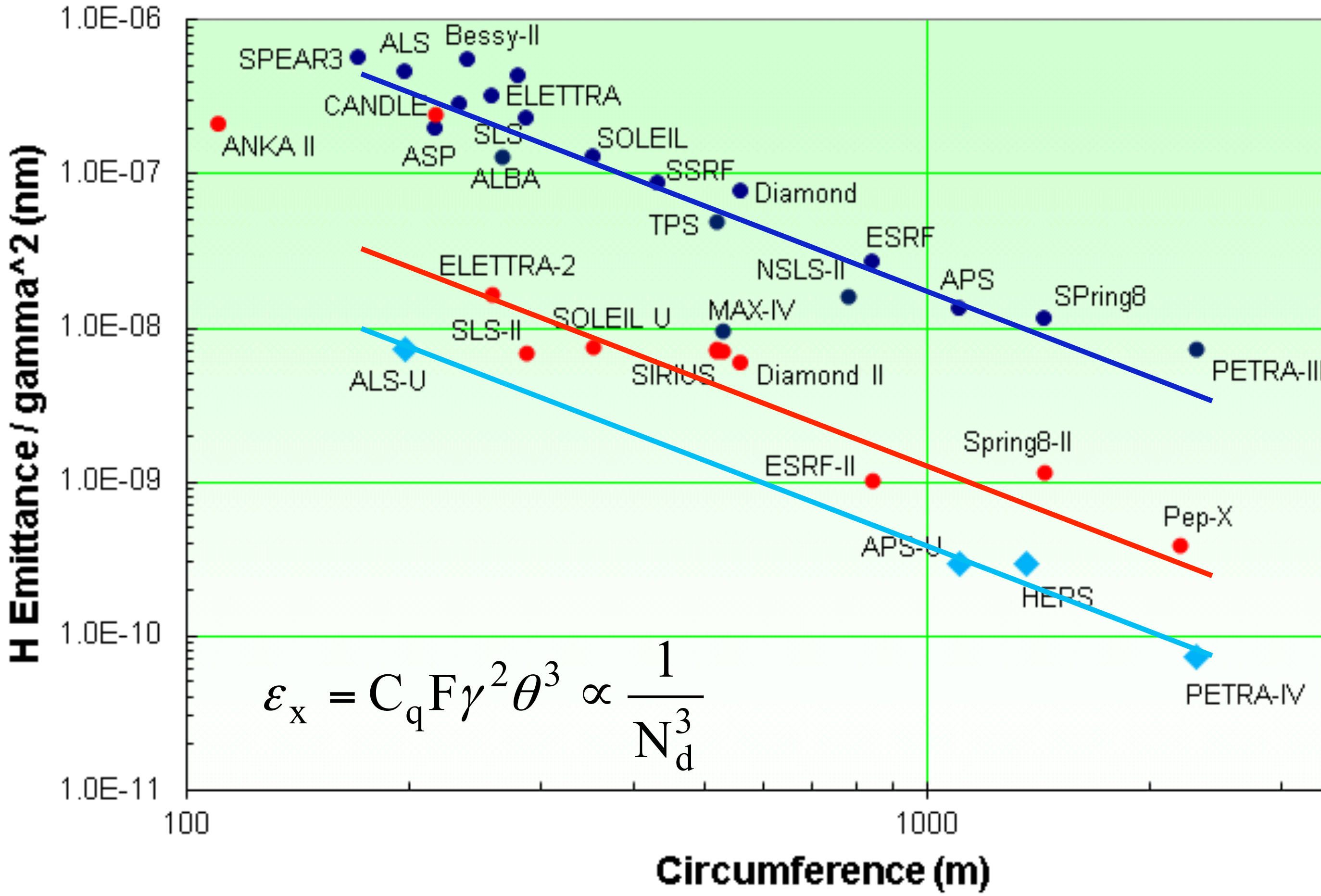
- **M. Eriksson et al. IPAC 2016**

Presently 2 new machines under constructions

SIRIUS, ESRF-EBS

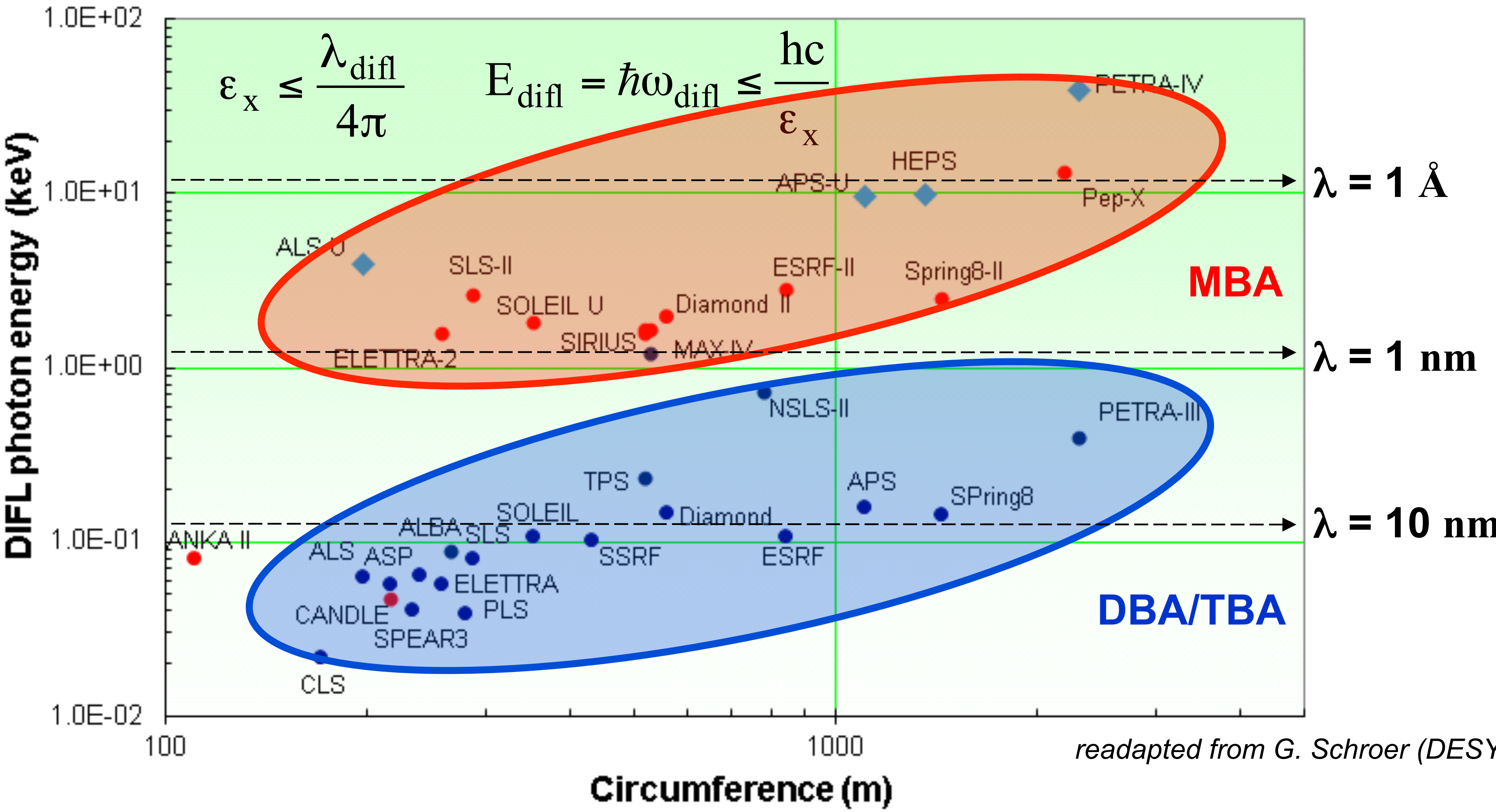
about 15 new / upgrade R&D projects

Survey of low emittance lattices for light sources



$$\varepsilon_x = C_q F \gamma^2 \theta^3 \propto \frac{1}{N_d^3}$$

(quasi-) diffraction limited light sources



readapted from G. Schroer (DESY)

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John Adams Institute for Accelerator Science

diamond

$\varepsilon_x \leq \varepsilon_{ph} = \lambda/2\pi$ or $\varepsilon_x \leq \varepsilon_{ph} = \lambda/4\pi$?

Many authors have tried to shoehorn the single electron undulator emission into a Gaussian beam …see e.g.

Elleaume (2003), Borland (2013), Hettel (2014)

$$\sigma_{ph} = \sqrt{2\lambda L}/2\pi \qquad \sigma'_{ph} = \sqrt{\lambda/2L} \quad \rightarrow \quad \varepsilon_{ph} = \sigma_{ph}\sigma'_{ph} = \lambda/2\pi$$

Lindberg & Kim (2015)

$$\sigma_{ph} = \sqrt{\lambda L}/2\pi \qquad \sigma'_{ph} = \sqrt{\lambda/4L} \quad \rightarrow \quad \varepsilon_{ph} = \sigma_{ph}\sigma'_{ph} = \lambda/4\pi$$

Huang (2013)

$$\sigma_{ph} = \sqrt{2\lambda L}/4\pi \qquad \sigma'_{ph} = \sqrt{\lambda/2L} \quad \rightarrow \quad \varepsilon_{ph} = \sigma_{ph}\sigma'_{ph} = \lambda/4\pi$$

If the emission for an undulator has

$\varepsilon_{ph} = \lambda/2\pi$ **then** $$F = \frac{\lambda^2/(4\pi)^2}{\Sigma_x\Sigma_{x'}\Sigma_y\Sigma_{y'}} = \frac{1}{4}$$

the coherent fraction will never reach the one of the fundamental Gaussian mode, not even from a single electron (let alone for an electron beam with finite emittance and energy spread)

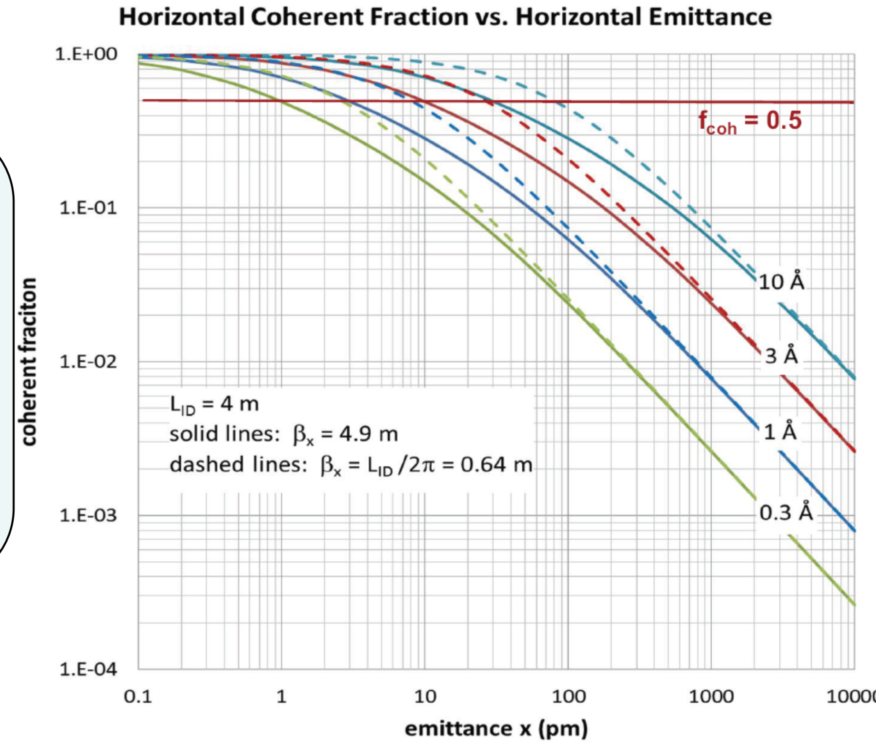
Matching in phase space

The electron phase space should be matched to the photon phase, i.e.

$$\frac{d}{d\beta_x}\frac{1}{\Sigma_x\Sigma_{x'}\Sigma_y\Sigma_{y'}} = 0 \longrightarrow \beta_{x,max} = \frac{\sigma_{ph}}{\sigma'_{ph}}$$

ditto for y

otherwise the brilliance and coherent fraction are smaller



Elleaume (2003), Borland (2013), Hettel (2014)

$$\beta_{x,max} = \sigma_{ph}/\sigma'_{ph} = L/\pi$$

Lindberg & Kim, PRSTAB (2015)

$$\beta_{x,max} = \sigma_{ph}/\sigma'_{ph} = L/\pi$$

Huang (2013)

$$\beta_{x,max} = \sigma_{ph}/\sigma'_{ph} = L/2\pi$$

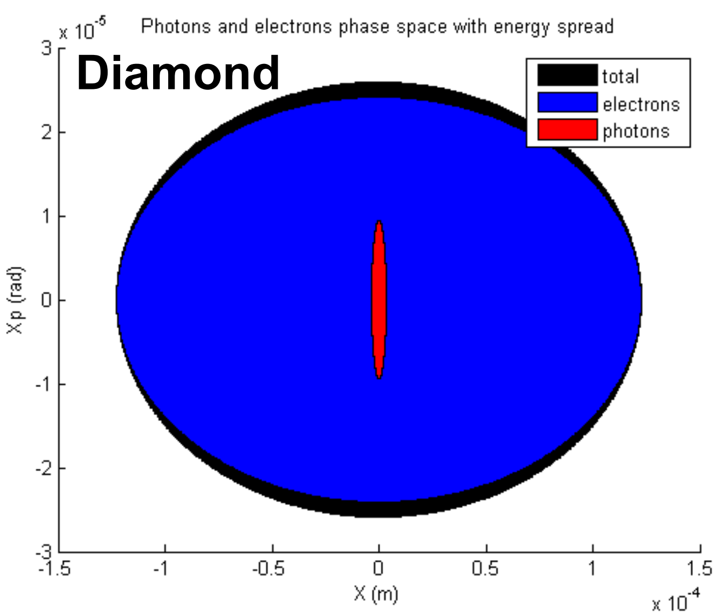
In any case $\varepsilon_{ph} \le \lambda/4\pi$ means equal contributions of photons and electrons

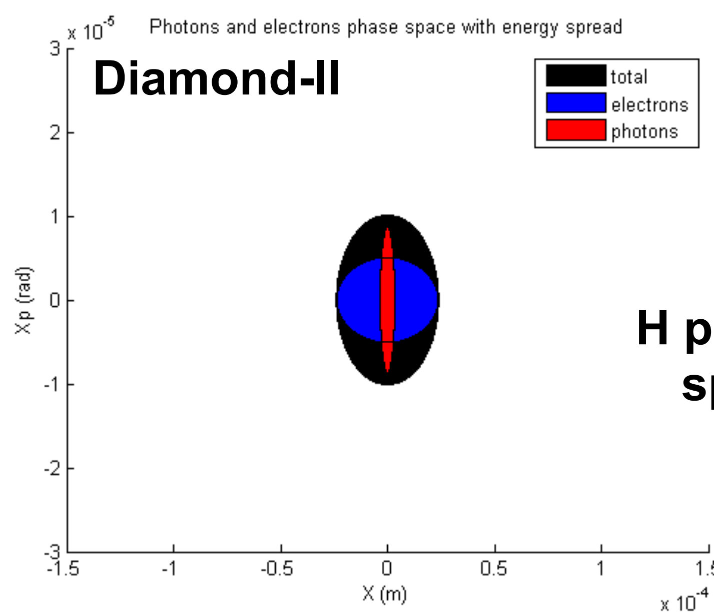
electron and photon phase space: Diamond (2700 pm) and Diamond II (120 pm)

e^- parameter (rms values)	Diamond	Diamond-II
Horizontal size, σ_x [mm]	123.5	23.6
Vertical size, σ_y [mm]	3.5	3.5
Horizontal divergence, $\sigma_{x'}$ [mrad]	24.1	5.1
Vertical divergence, $\sigma_{y'}$ [mrad]	2.3	2.3
Product	$2.38\ 10^4$	$9.60\ 10^2$
Electron beam brightness ratio	1	~25

photon parameters at 12.4 keV (i=7 U21)	
Diamond	Diamond-II
123.6	23.8
4.7	4.7
25.8	10.5
9.5	9.5
$1.44\ 10^5$	$1.13\ 10^4$
1	~13

The electron beam brightness is improved by nearly a factor of 25 [only in H; no gain in V (ε_y = 8 pm)]

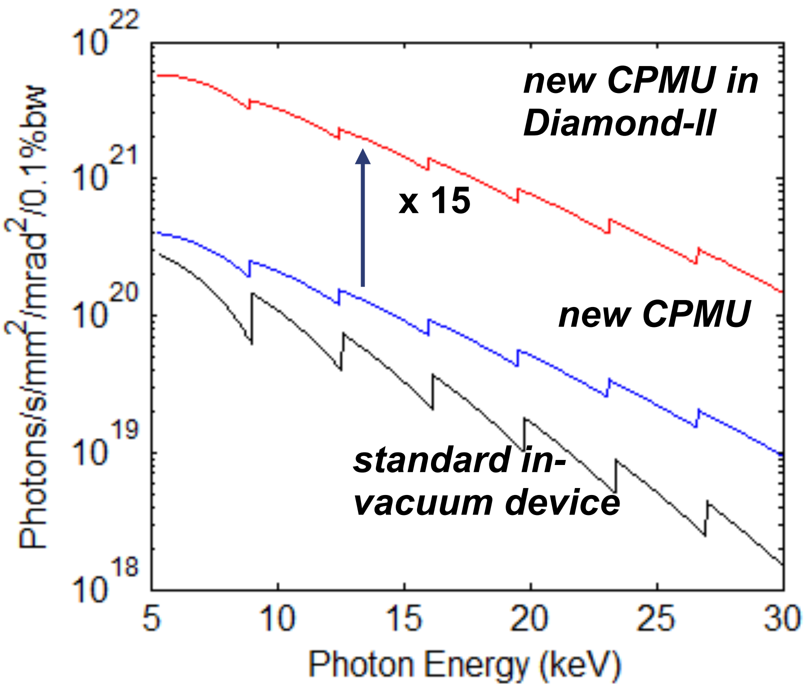




H photon phase space @ 1Å

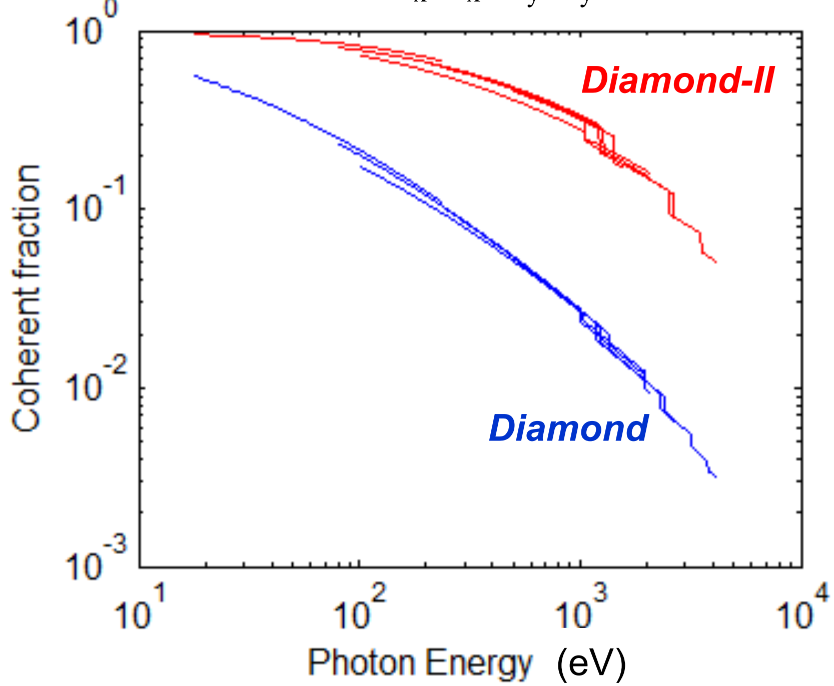
Brightness and coherent fraction improvement e.g. Diamond (2700 pm) vs Diamond-II (120pm):

Brightness for hard X-rays undulator CPMU 300 mA 1%K
116 periods 2 m long with K_{max} = 1.86



Transverse coherence fraction

$$F = \frac{\lambda^2/(4\pi)^2}{\Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}}$$

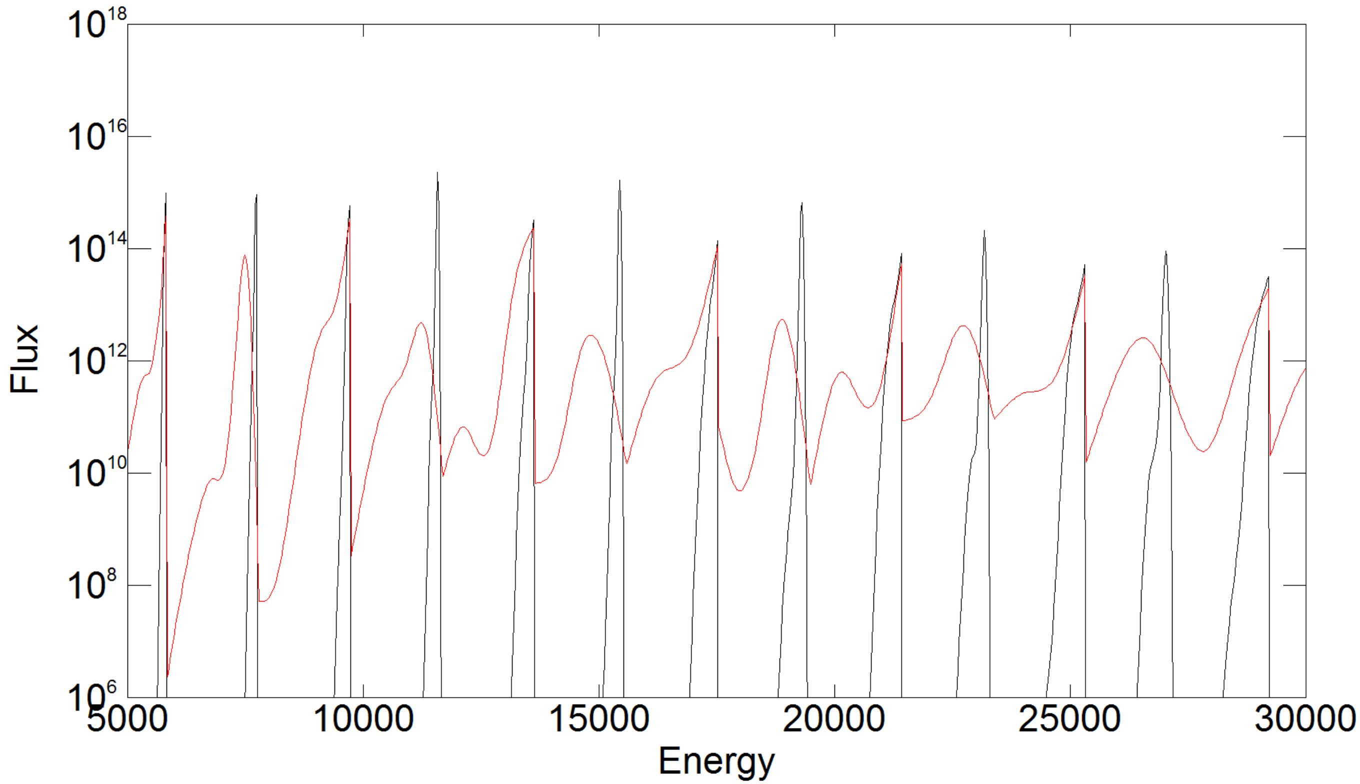


The improvement in brightness/coherence is approximately a factor of x3 at 100 eV and x10 at 1 keV, the main benefit coming from the reduction in horizontal source size

Pinhole Flux

Much cleaner spectral flux

- **smaller pinhole needed to collect the same fraction of flux**
- **smaller mirror sizes, higher quality**
- **reduced power loading, better thermal stability**



Flux through a 40 μrad * 40 μrad aperture for the CPMU in the existing ring (red) and in Diamond-II (black).

Present status

- MAX IV in operation (200 mA – IPAC17)

- ESRF contracts and large scale proc. ongoing; back in op. 2020
- Sirius (Brazil) under construction; commissioning in 2018

- APS-U (US) has passed CD1

- ALS-U (US), HEPS (China) got money for R&D programmes

- ELETTRA II and SLS-II completed CDR by 2017

- many labs are investigating options (Diamond, SOLEIL, ...) in more or less advanced consultations with users in view of CDR

Lattices for DLSR

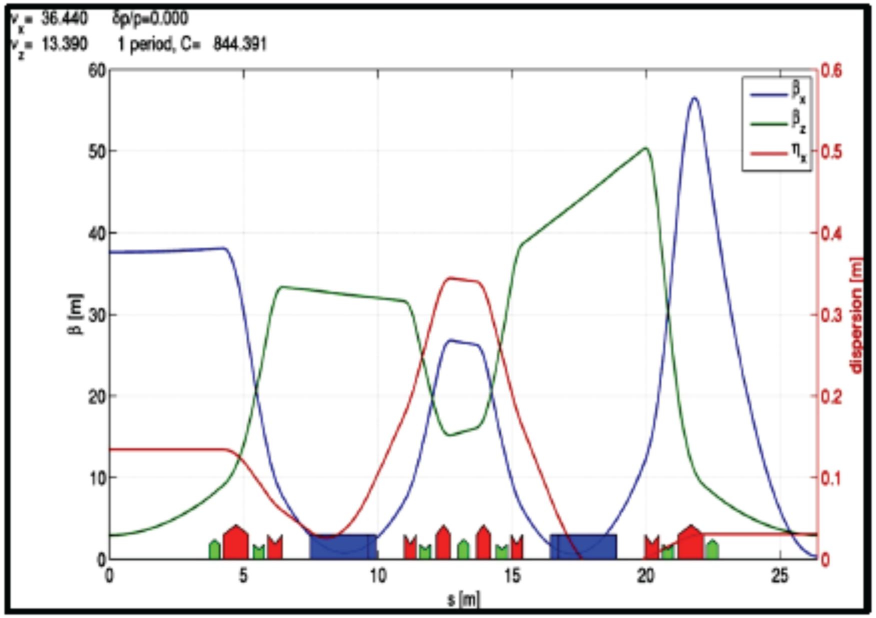
- **MBA**
  detuned TME cells with small Dx
  TME: MAX IV see P. Tavares' talk, SIRIUS, ALS U
  TME + Reverse Bends + LGBs: SLS II see A. Streun's talk

- **HMBA**
  LGBs + D_x bump + paired sexts.
  HMBA: ESRF-EBS
  HMBA + Reverse Bends: APS-U, HEPS

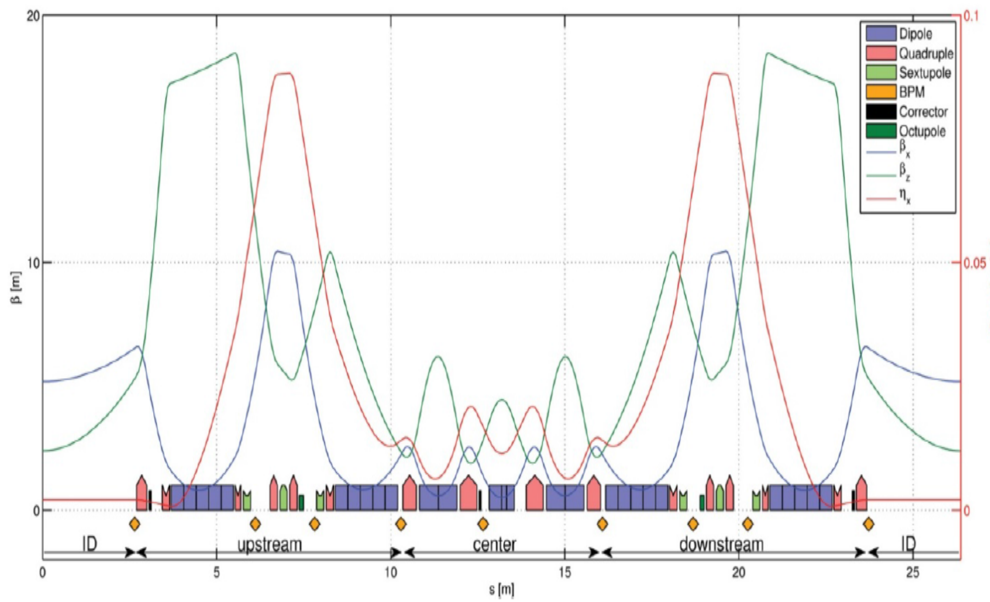
- **Modified MBA**
  with mid-straigth sections in the arcs with M = even
  Diamond II, Elettra II, SLiT-J, KEK-LS
  see also E. Karantzoulis' talk
  see also A. Nadji's talk

ESRF-EBS

Original DBA cell: 3800 pm



Hybrid 7BA cell: 130 pm

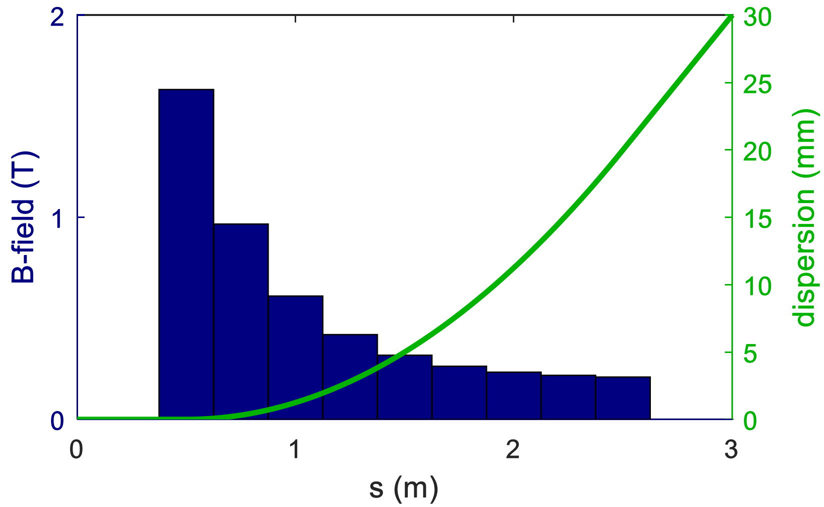


Hybrid 7BA cell features:

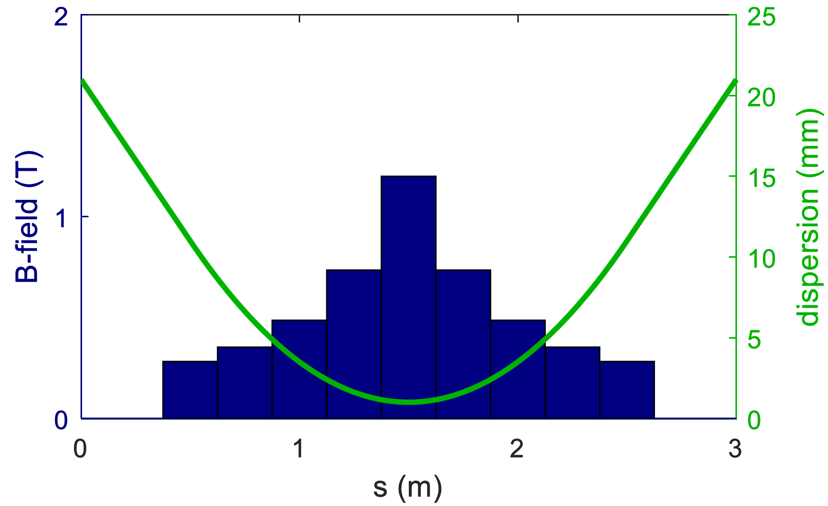
- Dispersion bump for chromatic sextupoles;
- 3π / π phase advance for cancellation of sextupole driving terms;
- Longitudinal gradient bend for emittance minimisation;

Longitudinal gradient bends

ESRF-EBS longitudinal bends in matching cells



SLS II longitudinal bends in TME cells

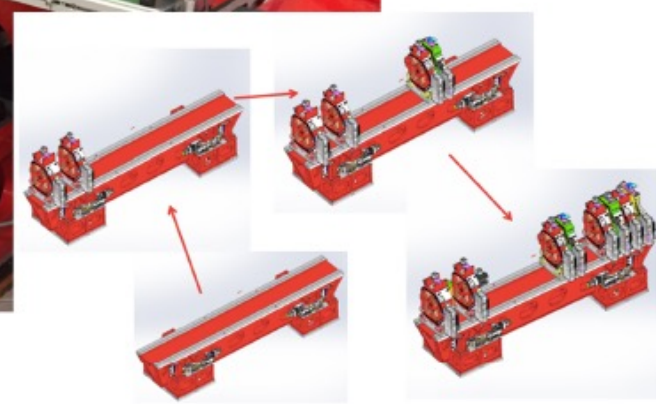


- **Emittance lowered by minimising I_5**

$$\epsilon_x = C_q \gamma^2 \frac{I_5}{J_x I_2} \qquad I_5 = \oint \frac{\mathcal{H}(s)}{\rho^3(s)} ds \qquad \mathcal{H}(s) = \gamma_x \eta_x^2 + 2\alpha_x \eta_x \eta_{x'} + \beta_x \eta_{x'}^2$$

- **Make the dipole field strongest where the dispersion is at a minimum**
- **Total bend angle is kept constant**
- **Can get below TME of uniform dipole**
- **Have the benefit of producing hard x-rays where B-field is large**

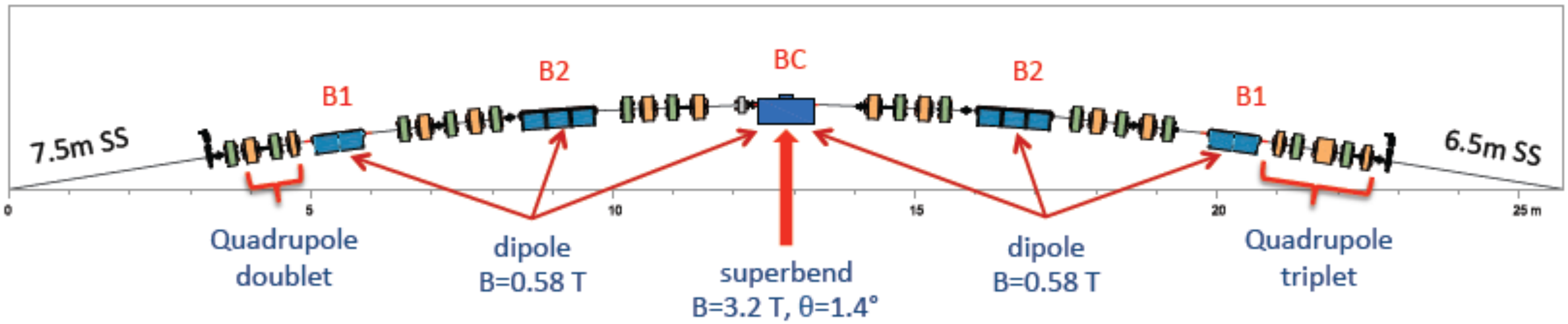
Status of ESRF-EBS

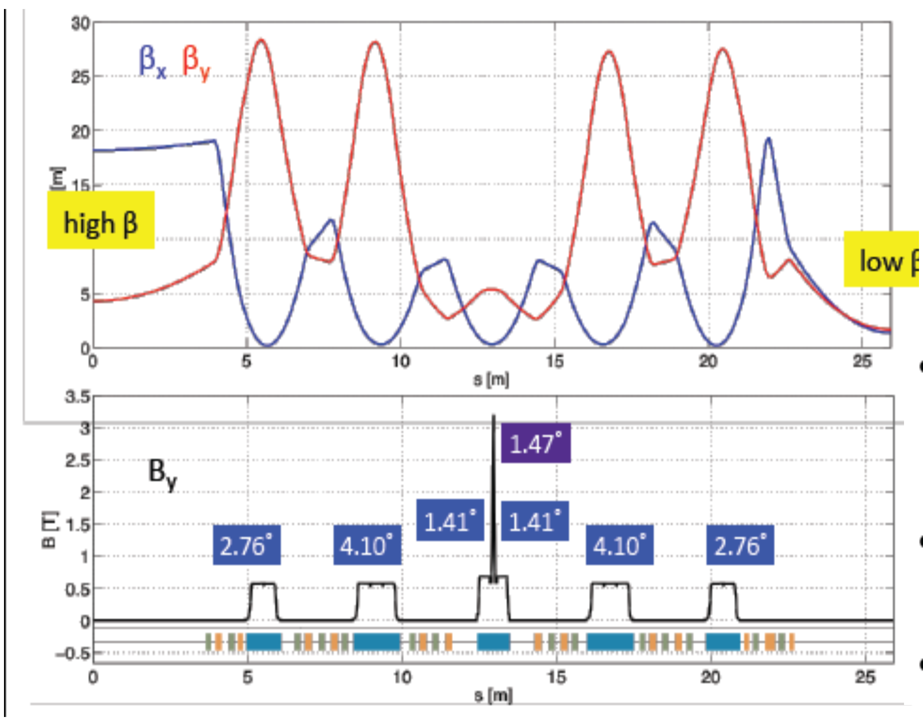


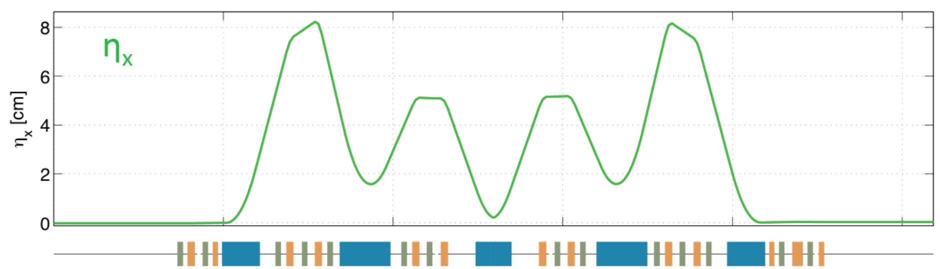
magnets and vacuum assembly on girders in full swing

SR commissioning starts 02/12/2018 (Raimondi IPAC17)

SIRIUS (5BA lattice)







- 20 5BA arcs and 2 types of straight sections for insertion devices:
  - 10 **high β_x** straight sections of **7.5 m** – matching with quad **doublets**.
  - 10 **low β_x** straight sections of **6.5 m** – matching with quad **triplets**.
- 20 PM superbends (short slice sandwiched in the center dipole)
  - peak field of B_p= 3.2 T → critical photon energy of e_c = 19.2 keV
- Low field (0.58 T) EM and PM dipoles with transverse field gradient (7.8 T/m)

Courtesy L. Lin

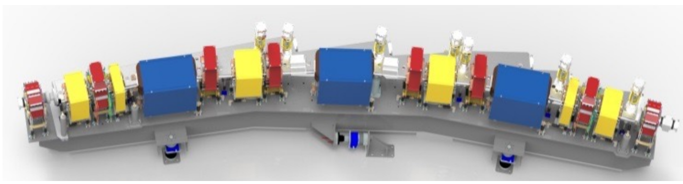
Status of SIRIUS

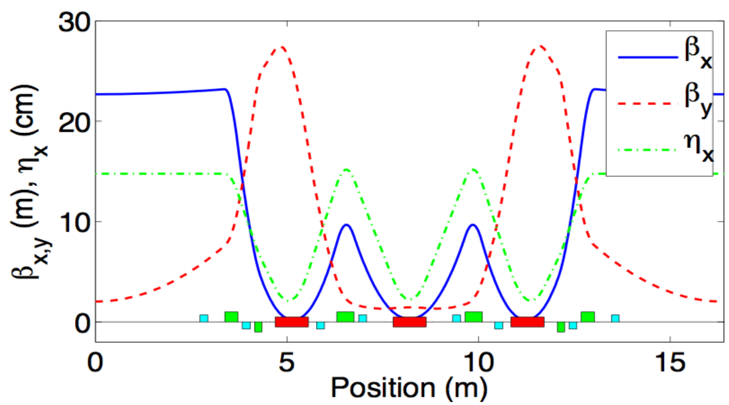
(March 2016)

(March 2017)

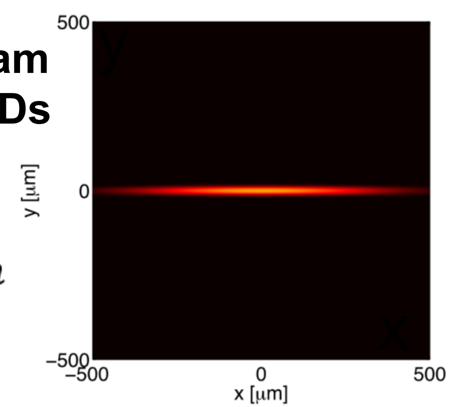
ALS-U: diffraction limited light source

ALS today: 3BA @1.9 GeV





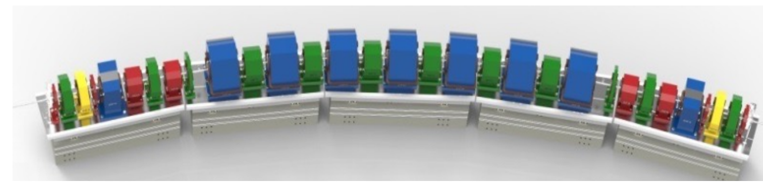
Electron beam at the IDs

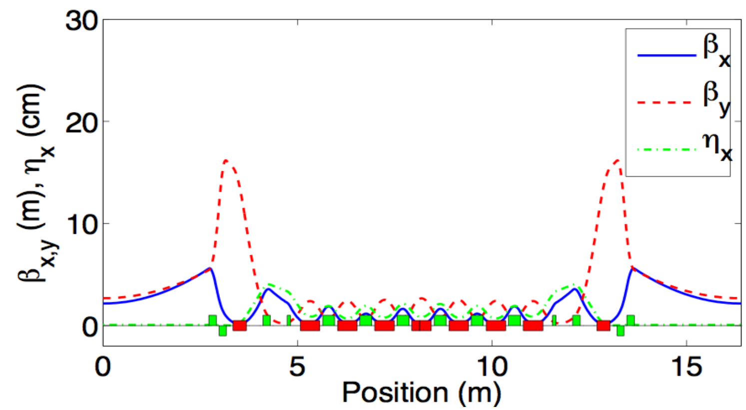


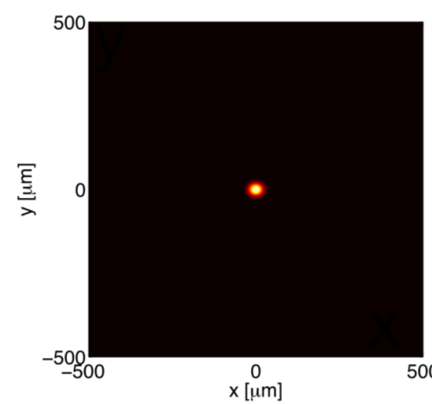
$\varepsilon_x \simeq 2000\ pm$

$\varepsilon_y \simeq 30\ pm$

ALS-U: 9BA @2 GeV







With full coupling:

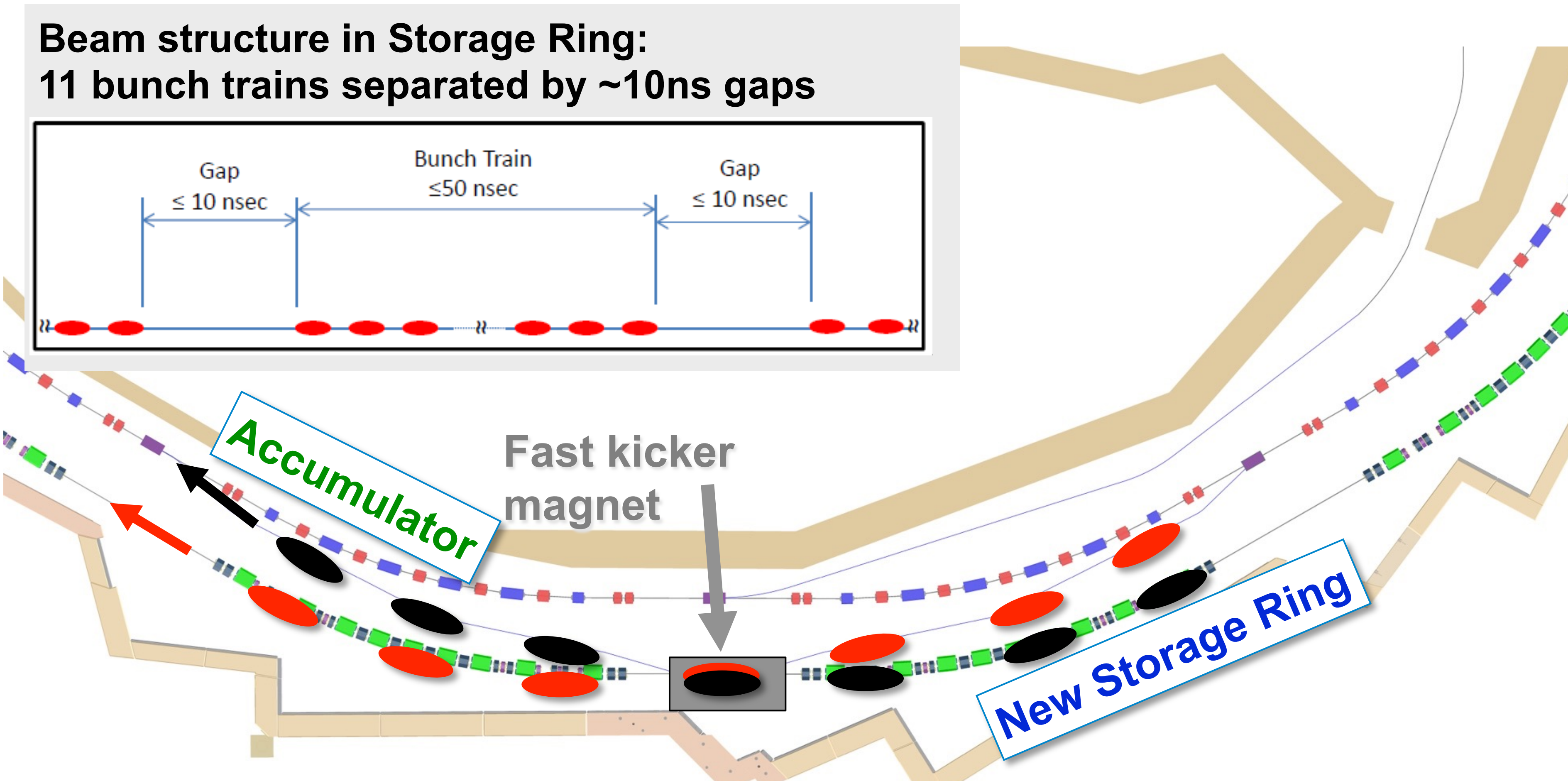
$\varepsilon_x \simeq 50\ pm$

$\varepsilon_y \simeq 50\ pm$

Courtesy C. Steier, M. Venturini

ALS-U: swap out injection

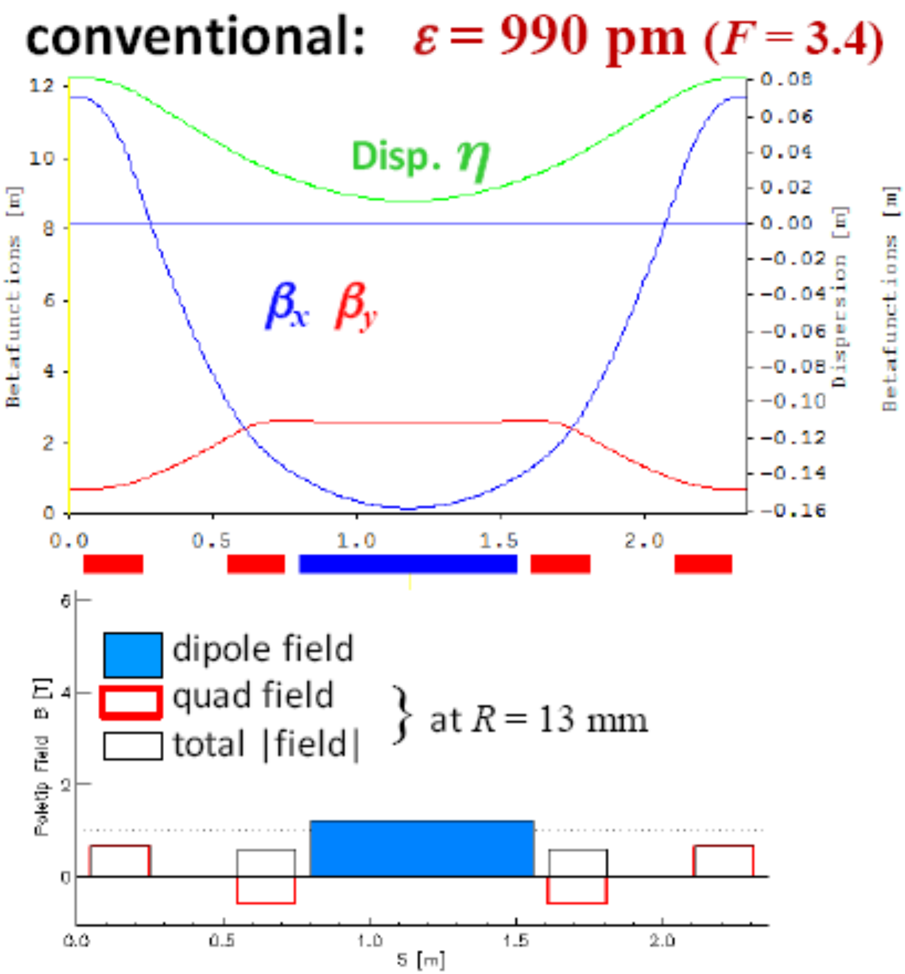
Very aggressive design, but **small DA (few mm)** not allowing off-axis injection
Accumulator will enable on-axis injection with bunch-train swap-out

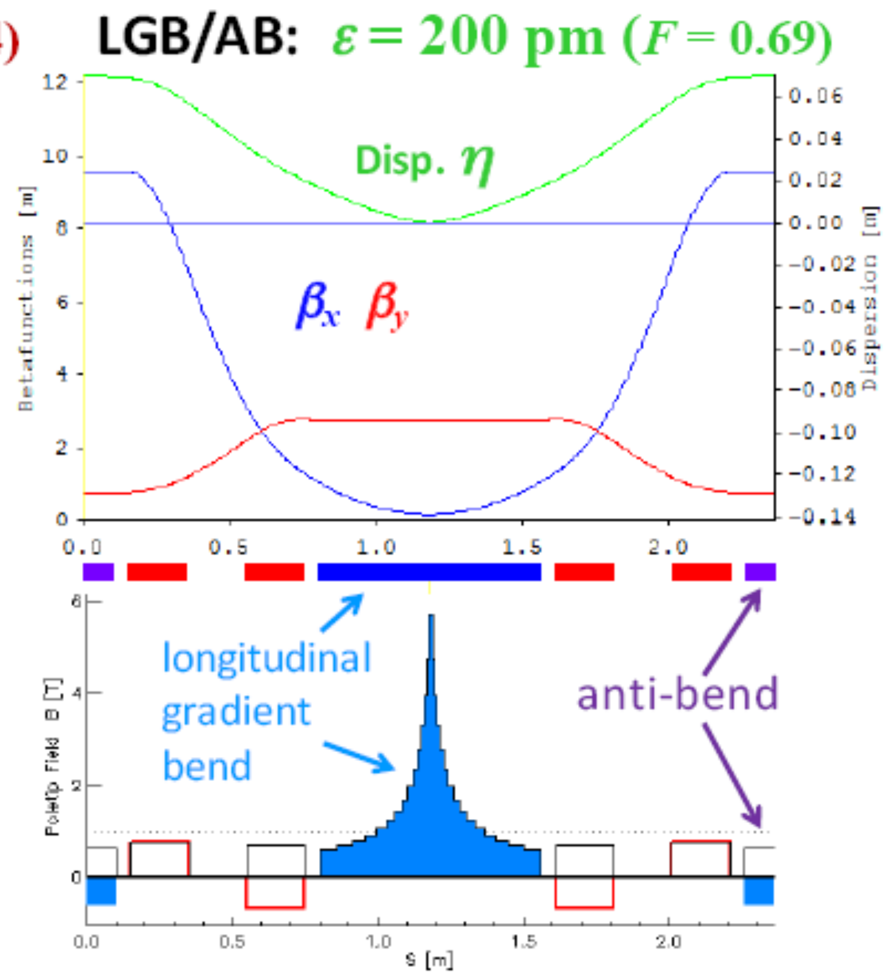


- Pulser prototype being developed at LBNL has demonstrated ~5ns rise/fall time
- Preliminary Accumulator design achieves $\varepsilon_x < 2nm$ with 5BA lattice.

SLS II – reverse bends

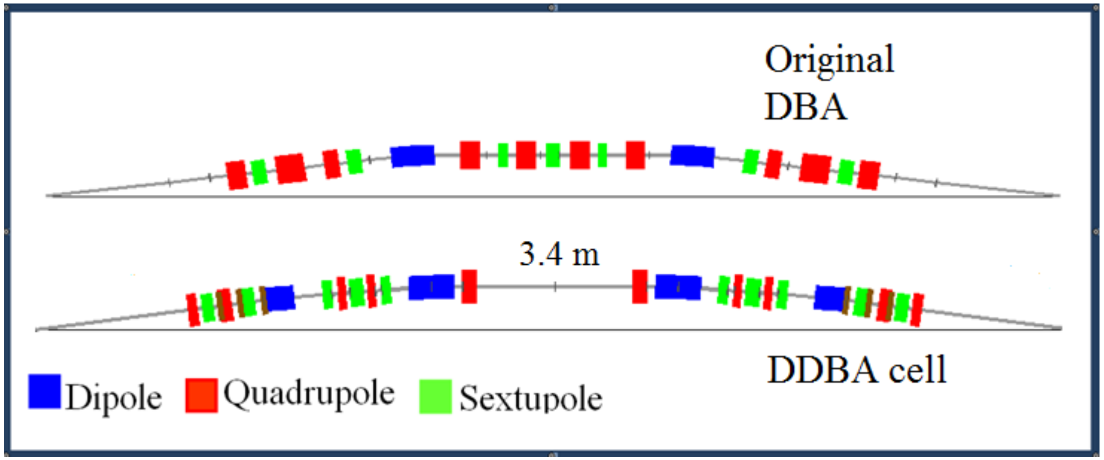
Combining longitudinal gradient bends and reverse bends to reduce the emittance

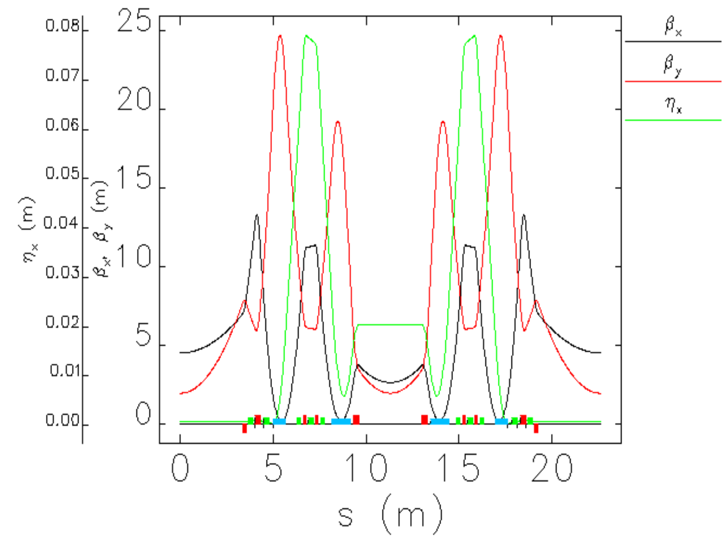




Courtesy A. Streun

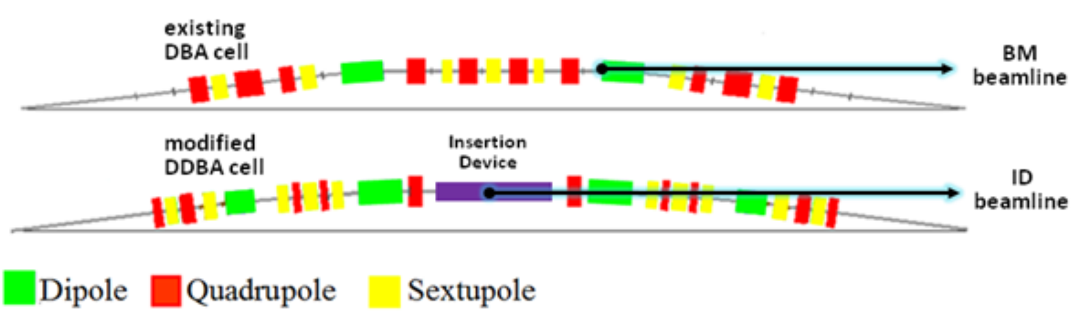
Diamond II: modified 4BA – 270 pm

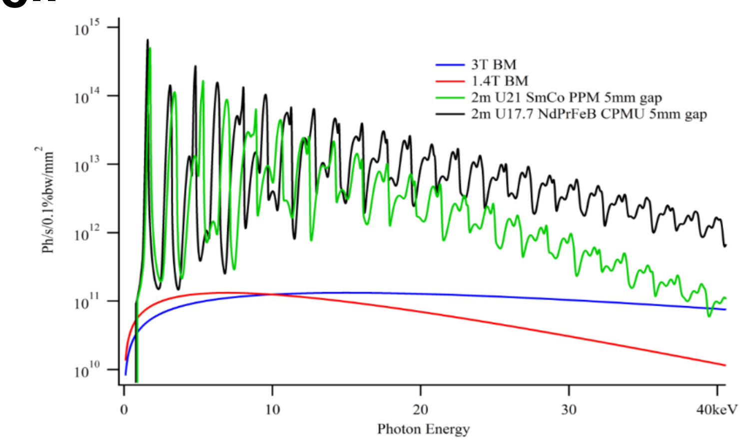




This lattice combines the idea of doubling the capacity of the ring with the low emittance

The Diamond Board approved the project to replace the existing cell2 with a DDBA cell

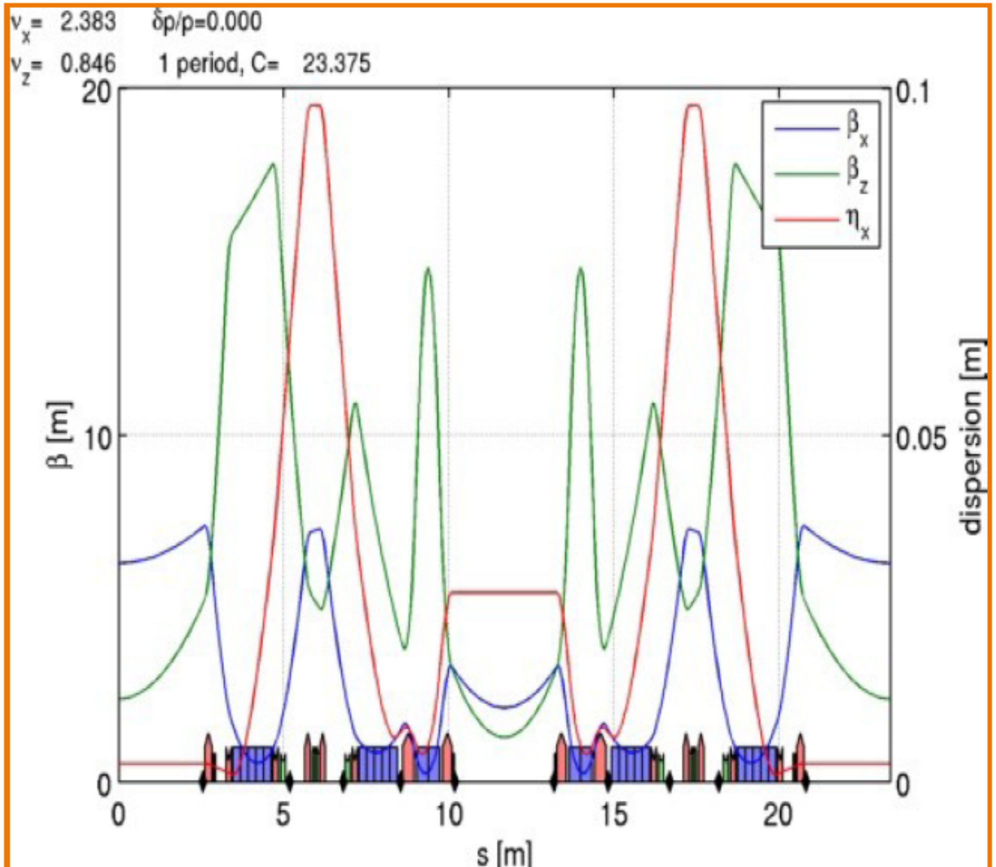




Diamond II: DTBA cell – 120 pm

A more aggressive design has been proposed that merges the ESRF HMBA concept with the Diamond DDBA mid straight section taking the best of both

Use the ESRF cell (7BA with longitudinal gradient dipoles) – removing the mid dipole to make it a 6BA with a straight at the centre



Promising design:

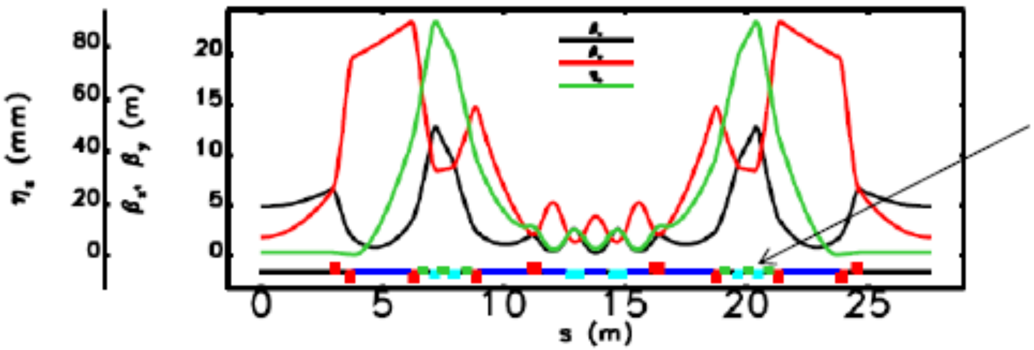
Emittance 120 pm
~ 10mm DA
~ 3 h lifetime

short straight sections ~5m
long straight sections ~8 m
mid-straight section ~3 m

Large beta x for injection under investigation

and many other variants

APS-U incorporating reverse bends in the HMBA
42 pm @ 6 GeV – on-axis injection

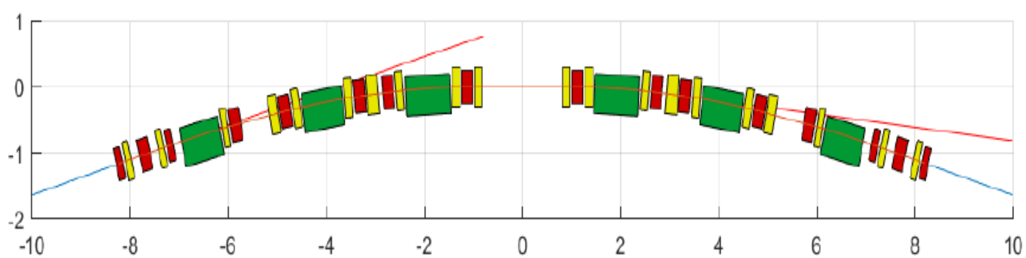


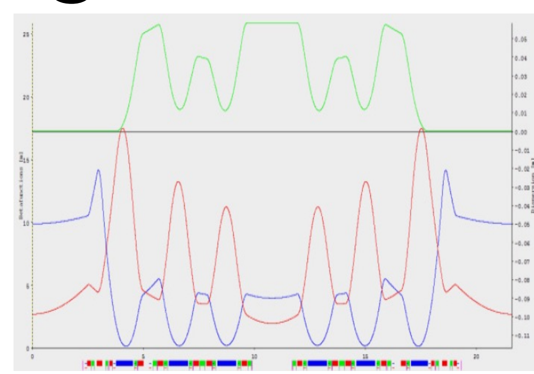
reverse bends (cyan),
(actually offset quadrupoles)
reduces ex 67 to 42 pm

M. Borland et al., NAPAC 2016

very similar design followed by HEPS

Elettra – II: modified 6BA – 250 pm @ 2 GeV

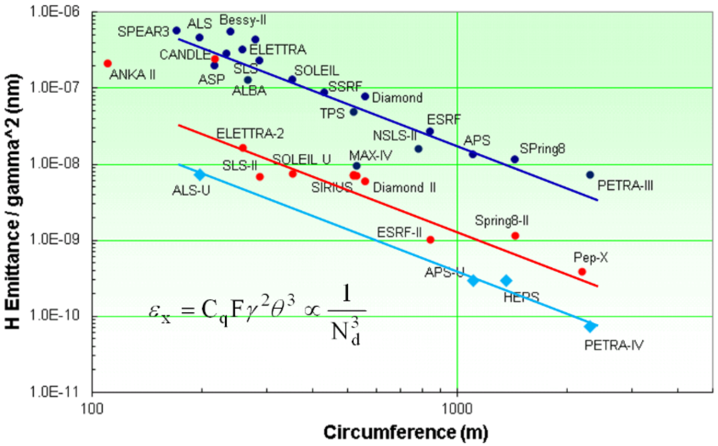




Why this renaissance of the rings?

Enabling a stronger(?) science case based on

- higher brightness
- higher transverse coherence
- small photon beam size
- small photon beam divergence
- cleaner spectral flux



Growing confidence in design and optimisation tools

Acc. Physics:

- DBA/TBA → MBA
- off-axis injection → on-axis injection

Growing confidence and first experience with technological subsystems

Acc. Technology:

- high gradient magnets small apertures (100 T/m 12.5 mm)
- longitudinal gradient dipoles – strong gradient dipoles
- NEG pumping - not in all projects
- fast pulsed kickers – feasibility of on-axis injection
- (feedbacks, HHC, …)

Optimisation of lattices for DLRS

Analysis tools based on perturbative theory of betatron motion

- resonance driving terms (and detuning terms)
- cancellation rules – symmetries (pairing sextupoles and cells)

Analysis tools based on numerical tracking

- accurate and direct evaluation of detuning, DA, MA, injection efficiency, RDTs, FMA

verified experimentally: Diamond, SOLEIL, ESRF, SPEARIII, NSLS-II, ...

Optimisation based on numerical search of paraemters space

- GLASS (GLobal Search of All Stable Solutions)
- gradient search, simplex, least squares, ...
- genetic algorithms, MOGA, particle swarms (or just randomg search!)

Use of large computer clusters

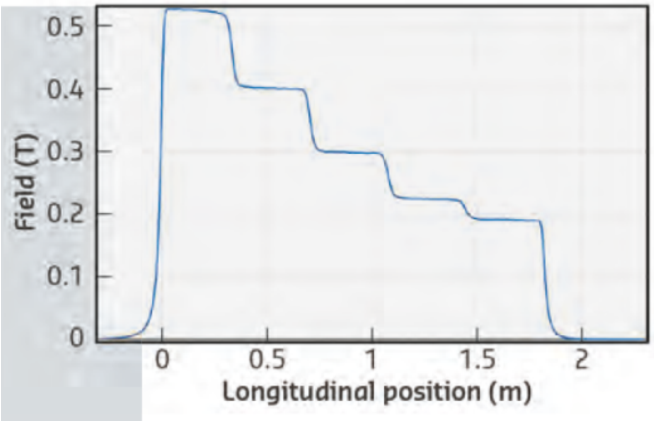
Realistic models can be used *directly in the optmisation stage*

- engineering apertures, IDs, full 6D motion with RF, radiation damping
- effects of errors in magnets, fringe fields, systematic and random
- misalingments: of girders, individual magnets, BPMs

ESRF-EBS (magnets)

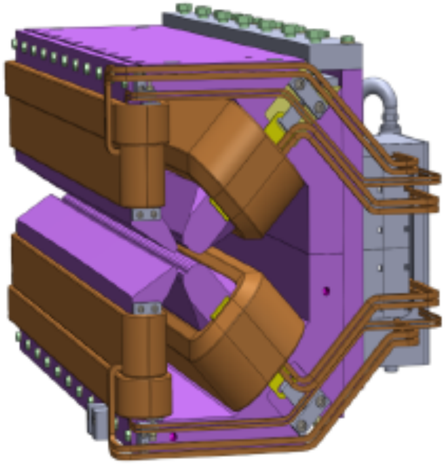
Longitudinal gradient dipole

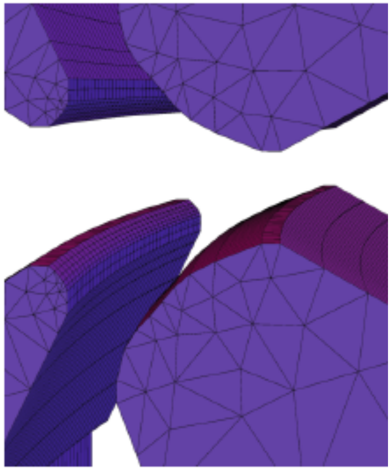
0.17- 0.67 T field (PM)
5 modules of 357 mm each

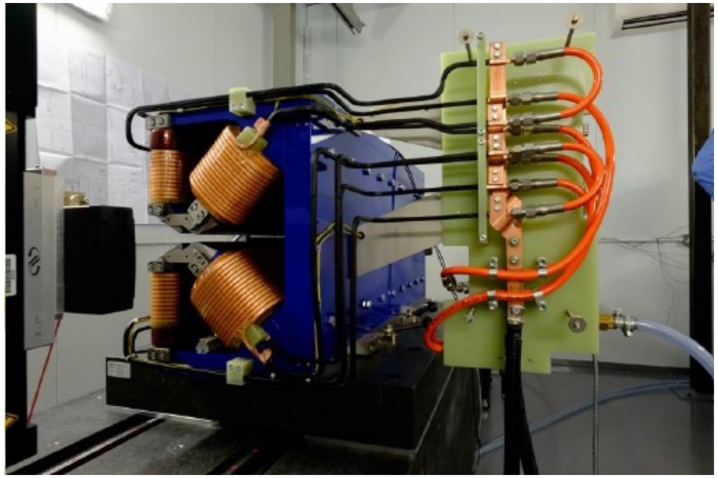


Transverse gradient dipole

0.57 T/, 37.1 T/m
machined from solid iron

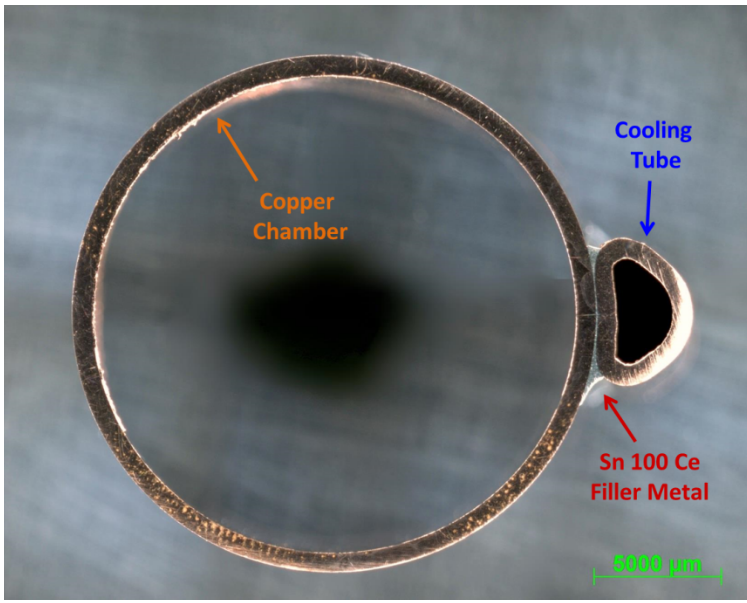






SIRIUS (NEG coated chambers)

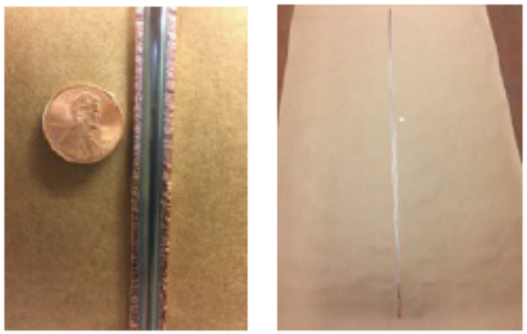
Small diameter vacuum vessel 24 mm internal radius pumped with NEG coating - collaboration with CERN



Courtesy L. Lin

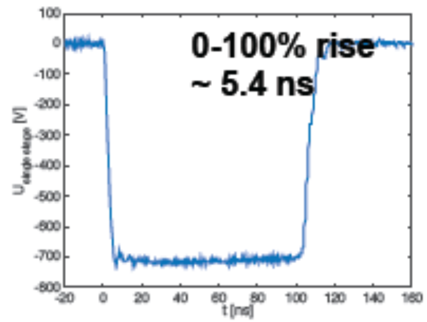
ALS-U: R&D programme

Very small NEG coated vacuum chambers



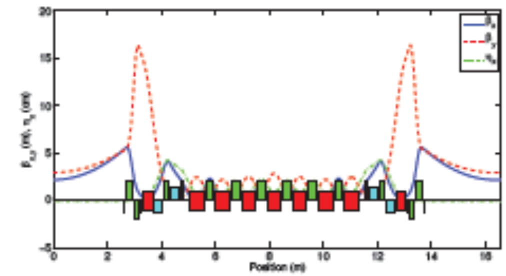
Coated 6 mm chamber (world record)

On-axis Injection – Fast pulsed magnets



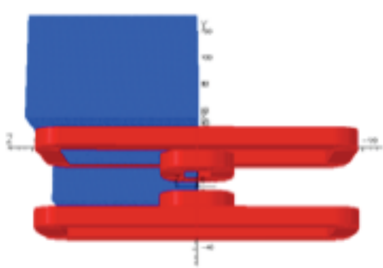
Adder achieves 5 ns rise (7 ns needed)

Optimization of Physics Design



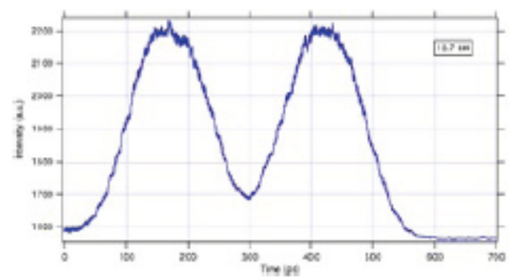
Released Baseline Lattice

Magnets – SR Production



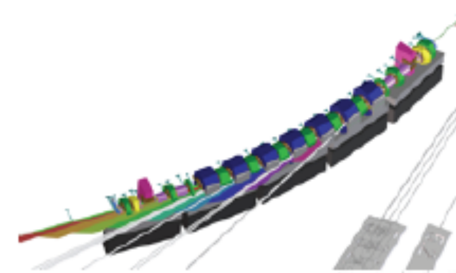
Evaluated Superbend options

Harmonic Cavities - Transients



Achieved needed bunch lengthening with ALS-U bunch trains in ALS (3HC)

Engineering



Automated iteration between physics and CAD model

On-axis injection route

Lattices with small DA require careful study of the injection process. The minimum required DA is in the order of 5-10 mm

- **artifical enhancement of beta x at the injection point**
- **small emittance injected beam**
- **reduced septum thickness (e.g. electrostatic septa)**
- **nonlinear kickers**

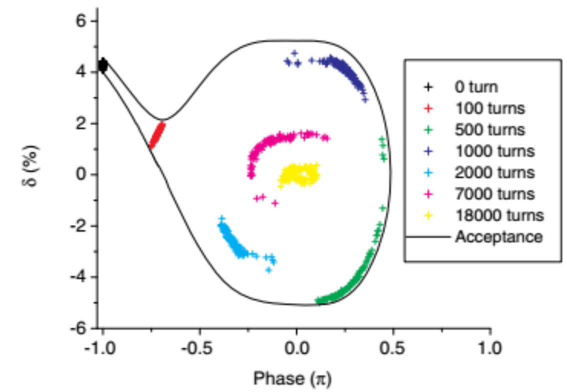
If DA is too small, the only option is to give up off axis injection

- **On-axis injection**

Many variants proposed for either swap-out or accumulation, see e.g.
Topical Workshop on Injection and Injection Systems, Bessy, Aug 2017
https://indico.cern.ch/events/635514

Longitudinal (on-axis) injection

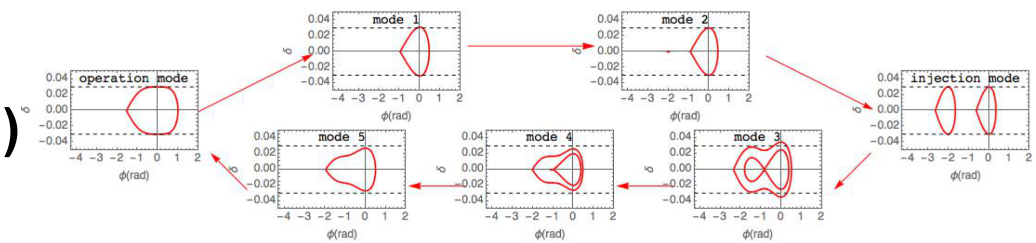
Longitudinal injection, i.e. in between circulating bunches using a fast kicker and



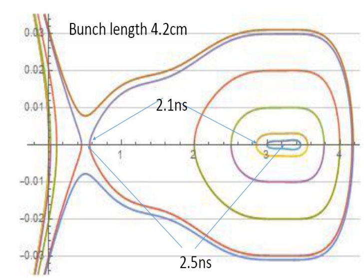
Beam dynamic in the RF golf club (M. Aiba, SLS)

Deformation of the RF potential to create intra bunch fixed points

Time varying RF gymnastic (double RF ramp, Z. Duhan, HEPS)



Static (triple RF system, G. Xu, HEPS)

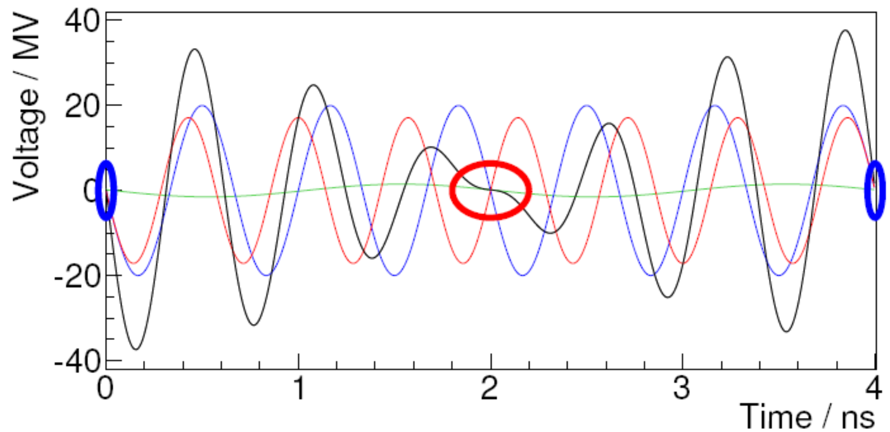


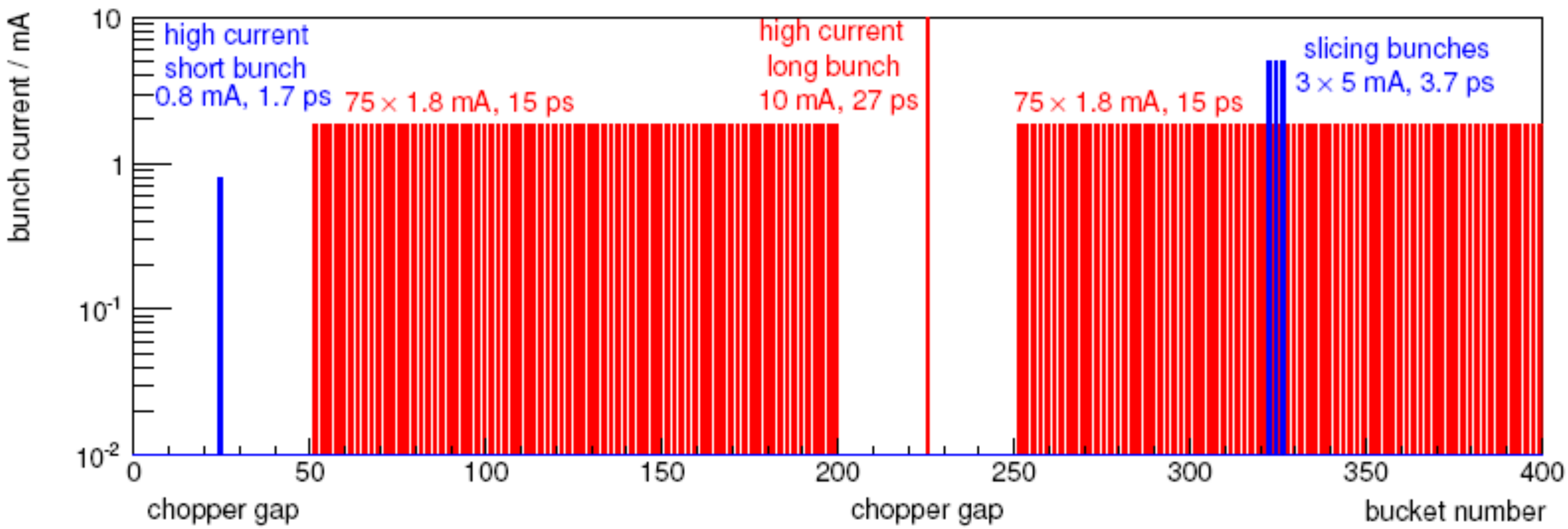
Unlike swap out, it allows accumulation!

Many schemes some are very new (e.g. SOLEIL longitudinal NL kicks)

Time resolved science via Variable pulse length SR - VSR

Combining harmonic cavities at 1.5 GHz and 1.75 GHz to store simultaneously long and short pulses – SC RF





From Bessy VSR CDR and A. Jankowiak private communications

Round beams

Round beams are proposed for a number of upgrades

- ALS-U 50pm in both planes
- APS-U in timing mode 32 pm in both planes
- PETRA IV 10-30 pm in both planes

by means of
- Emittance exchange Petra IV
- Horizontal wiggler field (Bogomakov, LER14)
- Coupling resonance with on axis injection
- Coupling resonance with time varying skew quadrupoles
  (**see P. Kuske's talk**)

Workshop on round beams at SOLEIL, June 2017
https://www.synchrotorn-soleil.fr/fr/evenements/mini-workshop-round-beams

Conclusions

Ultra low emittance rings are becoming reality

MAX IV in operation
SIRIUS in operation by 2018
ESRF EBS in operation by 2020

Many light sources are studying upgrades based on MBA with many variants

R&D still required: magnets, vacuum, diagnostics for stability, fast kickers, harmonic cavities, but the **technological challenges appear solvable**

The development of ultra low emittance rings is now seriously tackled by a large community, in EU, US and Asia. The next push it to get to true diffraction limited ring (tens pm emittance)

LER18 - 15-17 January 2018 - CERN

Accelerator Research and Innovation for European Science and Society

The Lowεring network will continue to be supported as work package in ARIES called RULE

Ring with Ultra Low Emittance

7th Low Emittance Rings Workshop

15-17 January 2018
CERN
Europe/Zurich timezone

Search...

- Overview
- Timetable
- Contribution List
- Registration
- Participant List
- Accommodation
- Coming to CERN
- Free shuttle Airport-CERN-Airport
- How to upload your presentation

The goal of the workshop is to bring together experts from the scientific communities working on low emittance e+/e- rings. The workshop is sponsored by the RULE network under the ARIES European project and includes light source storage rings, linear collider damping rings and future e+/e- circular colliders.

The workshop will treat beam dynamics and technology challenges for producing and controlling ultra-low emittance beams. Participants will benefit from the experience of colleagues who have designed, commissioned and operated such rings.

Workshop sessions will include:

- Low Emittance Optics Design and Tuning

- Collective Effects and Beam Instabilities

- Low Emittance Ring Technology

Students are encouraged to participate and present posters.

A prize will be awarded to the best student poster to allow for participating in a major conference presenting works related to Low Emittance Rings.

Relevant information about the workshop organisation and scientific timetable will be communicated shortly in a workshop web site.

Proposals for contributions to the workshop should be addressed to any member of the program committee: