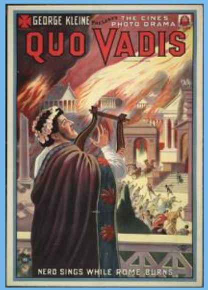
Survey, Outlook and Perspectives

Storage Ring based Light Sources

Andreas Jankowiak
Institute for Accelerator Physics
Helmholtz-Zentrum Berlin / BESSY II

Quo vadis?



1913, Enrico Guazzoni, Italy
First blockbuster in history of cinema!

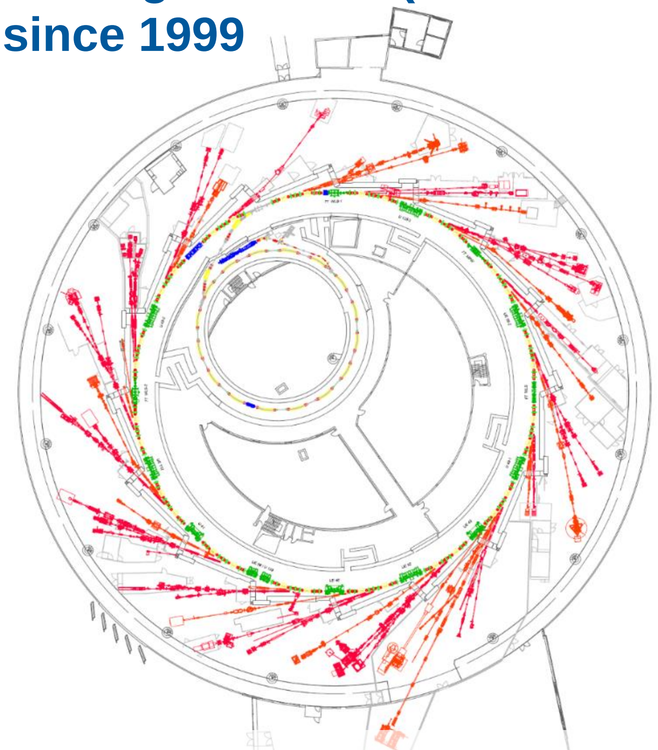
KOMITEE FÜR BESCHLEUNIGER-PHYSIK KfB

KfB-Perspektiven-Workshop
Strahlungsquellen
26. – 27.04.2018, Karlsruhe

3^{rd} generation storage ring light source – e.g. BESSY II

Successor of BESSY I, Germanys first dedicated light source (1981 – 1999)
Construction 1992 – 1998, in user operation since 1999

Energy/current	1.7GeV / 300mA
Emittance	4/6 nm rad
Pulse length	15 ps (rms)
Circumference	240 m
Straight sections	16
Undulators / MPW+WLS	12 / 1+2
Beamlines	36
end stations (fixed+var)	52



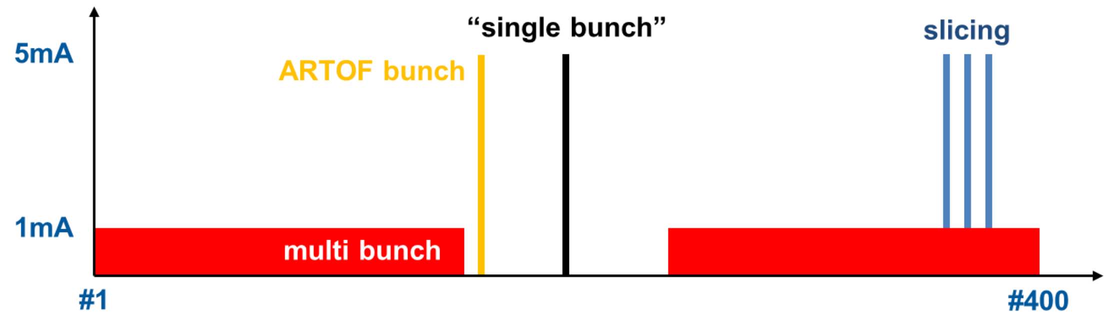
5000 h user operation, 3000 user visits / a

specialties

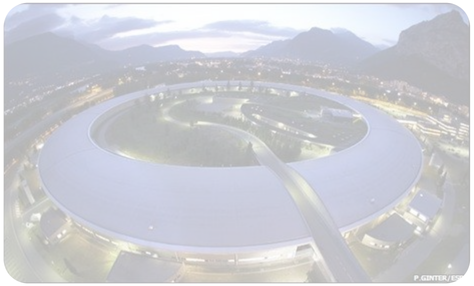
low-α operation
ps beams, CSR, THz

femto slicing
100 fs, polarised x-rays
6 kHz and variable
pump probe laser

standard mode = 4 in 1
excellent support of timing experiments



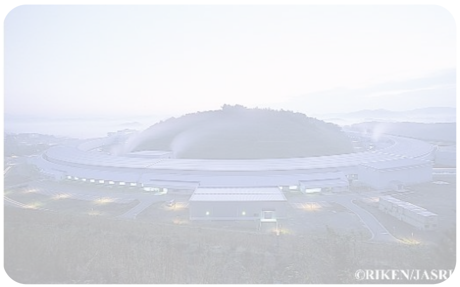
3rd generation storage ring light sources – the 90ies ++


ESRF / France, 1993


ALS / USA, 1993


ELETTRA / Italy, 1994


DELTA / D, 1996



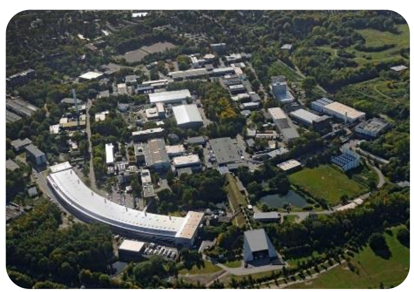
SPring-8 / Japan, 1997


BESSY II / D, 1998

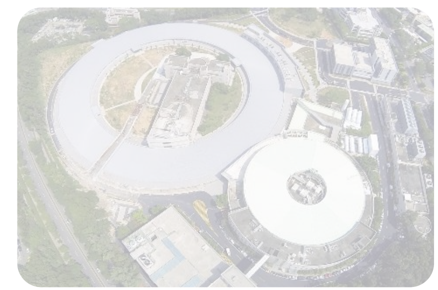

SLS / Switzerland, 2001


KARA/ANKA / D, 2003


DIAMOND / UK, 2007


PETRA III / D, 2010


ALBA / Spain, 2010


TPS / Taiwan, 2014

Energy:	**1.7 GeV – 8 GeV**
Beam Current:	**100 mA – 500 mA**
Natural Emittance:	**1 nm rad – 20 nm rad (coupling down to << 0.1% = 5 pm rad vertical)**
Pulse Length:	**~ 30 ps (~ ps in low-α and 100 fs slicing @ strongly reduced current)**

The phase space of parameters

Brilliance

$$B_{average}(\lambda) \sim \frac{N_{photon}(\lambda)}{\varepsilon_x \cdot \varepsilon_y}$$

Photons on Sample

Advanced IDs,
tailored beam optics,
efficient photon optics

Diffraction limit, coherence

$$\varepsilon_{x,y} \sim \frac{\lambda}{4\pi}$$

Light Source

Repetition Rate & Pulse Structure

pulses, pulse trains, cw

Timing Resolution

electron / photon pulse length

Longitudinal Coherence

SASE, seeded radiation, stability,
“monochromatic” photons

Peak Brilliance

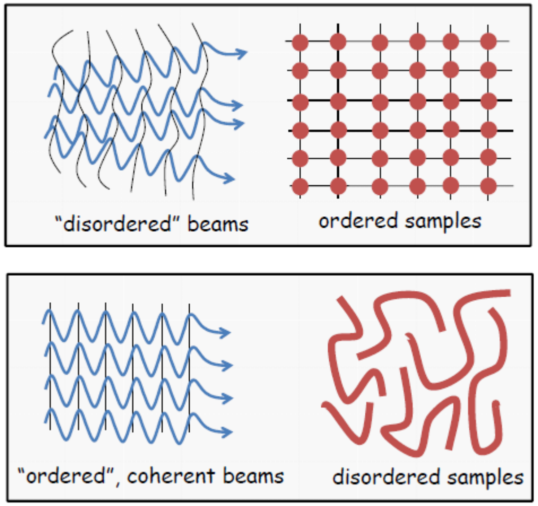
$$B_{peak} \sim \frac{N_e}{\sigma_t} \quad \text{incoh.} \qquad B_{peak} \sim \frac{N_e^{\,2}}{\sigma_t} \quad \text{coh.}$$

The coherence challenge in pictures

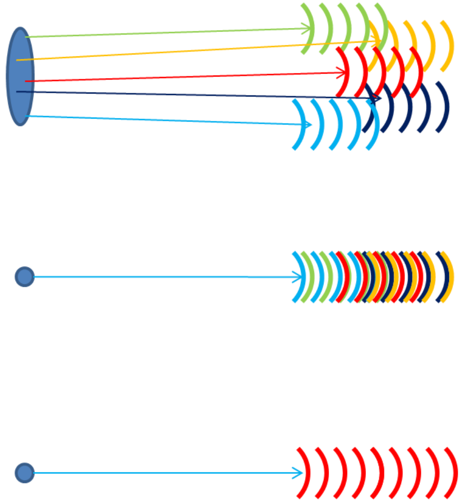
Incoherent vs. coherent X-ray beams

PAST & PRESENT:

FUTURE:



source



Case1: Currently …
e.g. **3rd gen. synchrotron sources**

Case2: Near Future …
Diffraction-limit light source

Case3: Ultimately …
Fourier transform-limit light source

http://erl.chess.cornell.edu/gatherings/2011_Workshops/talks/WS1Shpyrko.pdf

Brilliance

$$B_{average}(\lambda) = \frac{N_{photon}(\lambda)}{4\pi^2 \cdot \left(\varepsilon_x \oplus \varepsilon_{photon}(\lambda)\right) \cdot \left(\varepsilon_y \oplus \varepsilon_{photon}(\lambda)\right)\left(s \cdot 0.1\%BW \cdot A\right)}$$

defined by lattice="beam optics", beam energy

$$\varepsilon_{photon}(\lambda) = \frac{\lambda}{4\pi}\ \text{(Gaussian)},\ \frac{\lambda}{2\pi}\ \text{(undulator)}\quad : \text{photon beam emittance}$$

Electron beam emittance for diffraction limited radiation:

$$\boxed{\varepsilon_{x,y}(\lambda) = \frac{\lambda}{4\pi}} \qquad f_{coh}(\lambda) = \frac{\varepsilon_{photon}(\lambda)}{\varepsilon_x \oplus \varepsilon_{photon}(\lambda)} \cdot \frac{\varepsilon_{photon}(\lambda)}{\varepsilon_y \oplus \varepsilon_{photon}(\lambda)} \quad \sim 44\%$$

ε = 1 nm rad → λ = 13 nm (95 eV)

λ = 10 nm (124 eV) → ε = 800 pm rad

λ = 1 nm (1.240 keV) → ε = 80 pm rad

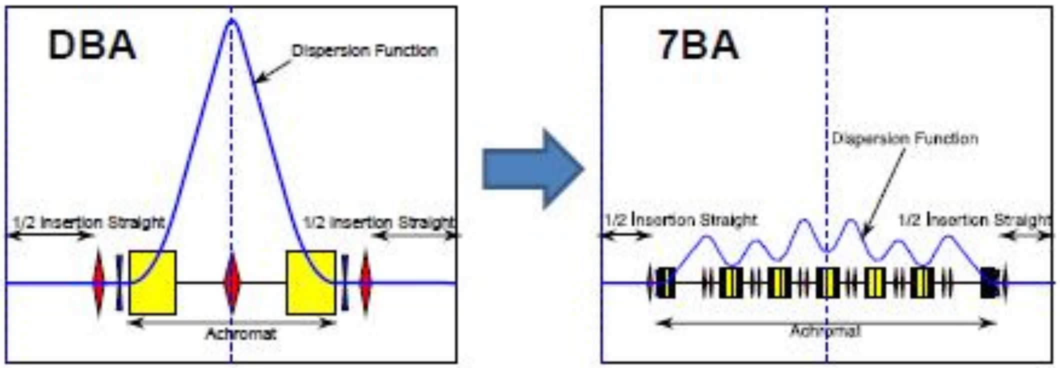
λ = 1 A (12.4 keV) → ε = 8 pm rad

Quo vadis storage rings? – The diffraction limit challenge

Lattice design evolution from double- and triple-bend achromats (DBA, TBA) to multi-bend achromats: increase N_D.

$$\varepsilon_x = C_L \frac{E^2}{N_D^3}, \quad \varepsilon_x \underbrace{\propto}_{\text{Fixed E}} \frac{1}{C^3}$$

C_L = lattice constant
N_D = # dipoles
C = Circumference



Strong Focusing and Low Dispersion

First used for MAX-IV.

D. Einfeld *et al.*, Proc. PAC 95, Dallas TX

Multi-bend lattices are becoming a reality:

- MAX IV (Sweden) is in operation (~ 300 pm rad)
- Sirius (Brazil) just started construction
- ESRF MBA upgrade on the way (France)
- APS-U (US), ALS-U (US), SPRING-8 (Japan), PETRA IV (D), SLS2 (Switzerland), DIAMOND2 (UK), SOLEIL2 (F), BESSY III (D), … planning

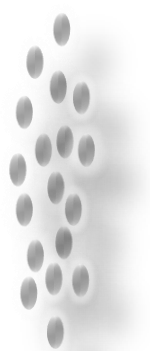
Full energy, low emittance injector
usefull as “short pulse” or even “FEL” source

DLSR compared to 3G SR:

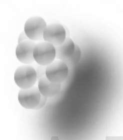
Emittance reduction < 1/10 (~ 100 pm), maybe down to < 1/100 (~ 10pm)

but:

- lattices with very strong quadrupoles (and multipoles)
- reduced dynamic aperture makes injection complicated
  “If you can inject in your lattice, your emittance is still too large”
  → new concepts for injection, e.g. “swap-out injection”
- careful control of Intra Beam Scattering and Touschek lifetime

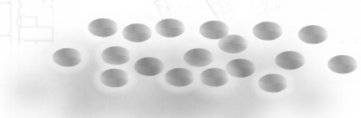


3G, 20ps



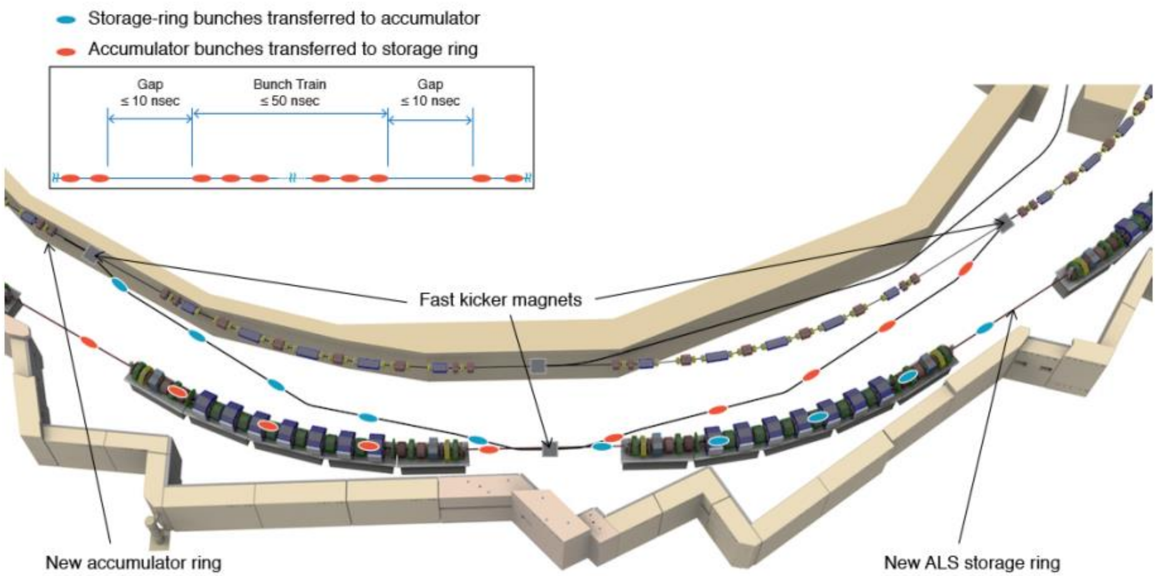
DLSR, 20ps
- high phase space density
- many scattering processes
- low lifetime, emit. increase

MAX IV
3 GeV, 500mA, 528m, 320 pm (200 pm with IDs)

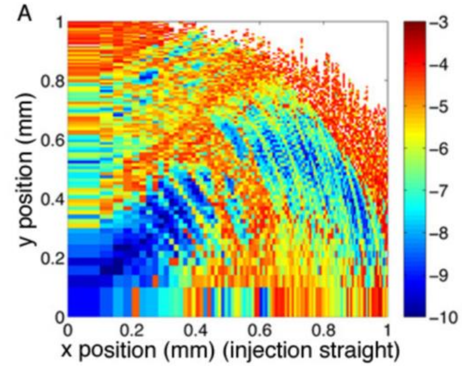


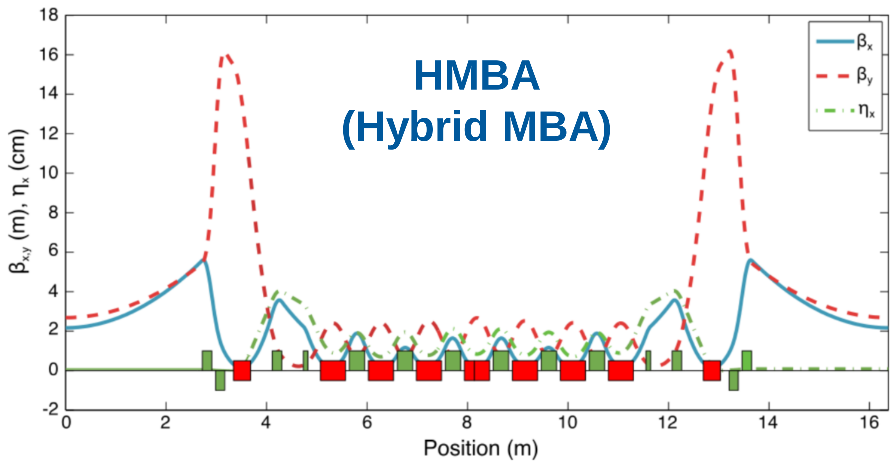
work around
- increase bunch length, 75 – 200 ps
- transfer hor. emittance to vert. “round beams”

ALS-U: 2 GeV, C = 200 m, 50 pm rad (round beam), 500 mA, ~ 200 ps

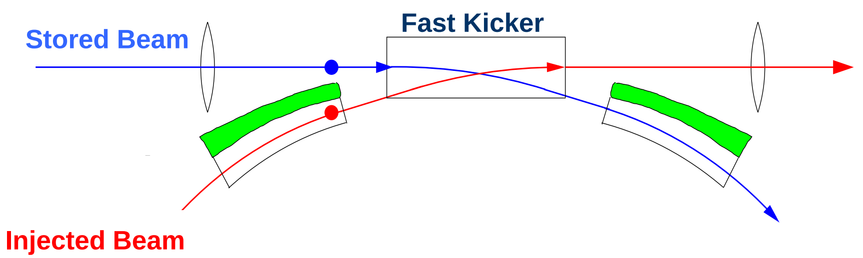


very low dynamic apperture





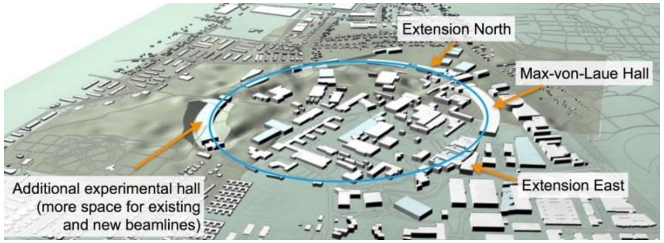
On-axis swap-out injection
(initially proposed by M. Borland)



(need additional accumulator ring)

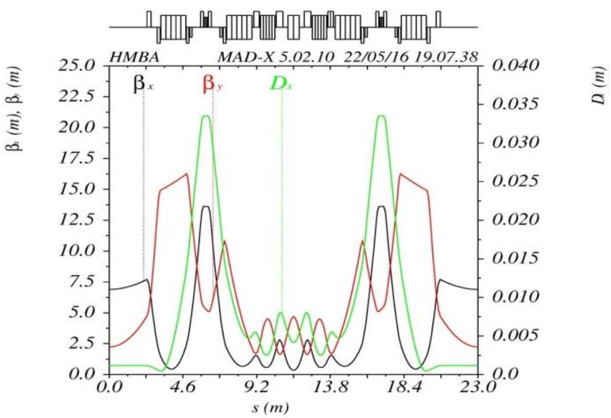
ALS-U proposal, April 2016

PETRA IV: 6 GeV, C = 2300 m, ~ 10 - 15 pm rad, 100 mA, 100 ps



1. Lattice based on HMBA Cells

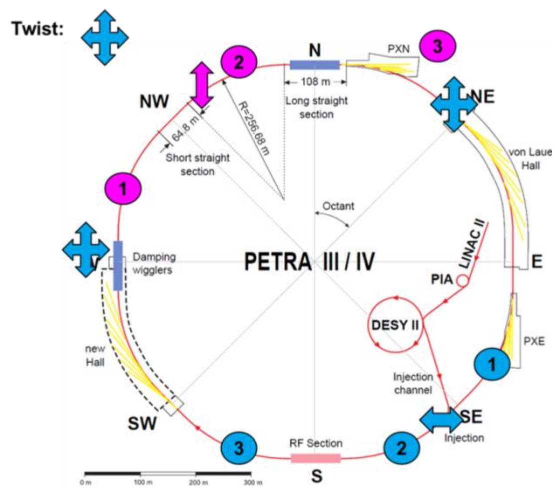
- Arcs: 8 HMBAs cells to build a 45° arc
- 8 identical arcs
- Straight sections: FODO cells

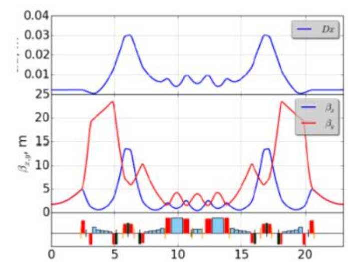


- horz. emittance of HMBA-based ring is 15 pm·rad at 6 GeV
- on axis injection most likely needed

2. 4D-phase space exchange and MBAs

- arc cells with non interleaved sextupoles
- Undulator section, preliminary version with HMBA

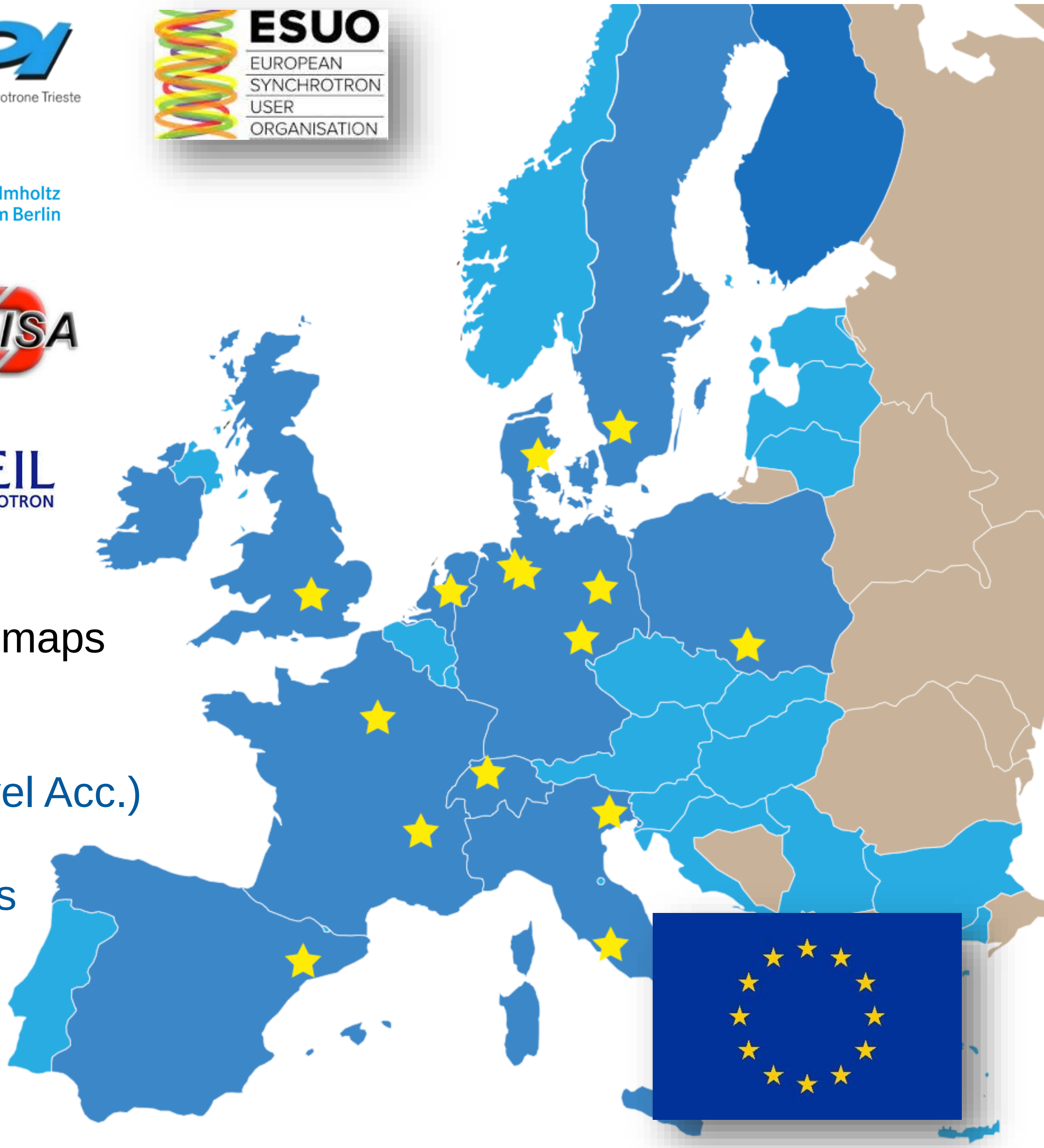




- Emittance ~ 30 pm
- off axis injection seems to be possible
- no satisfactory solution for ARC cells w/o ID

R. Wanzenberg,
R. Brinkmann, et al.

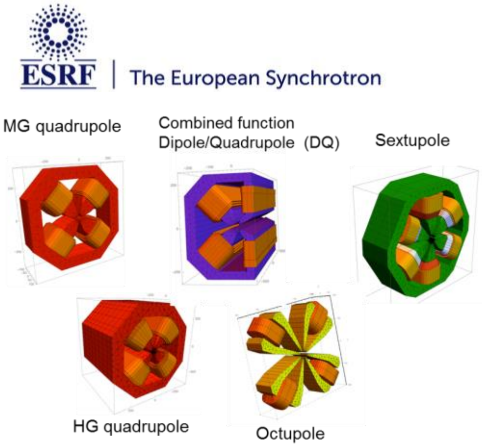
League of European Accelerator Based Photon Sources

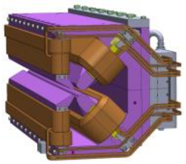


Development of Technology Roadmaps (financed within FP9) for

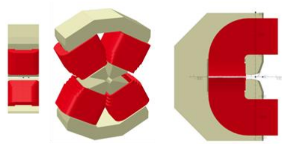
- Photon Sources (FEL+SR+novel Acc.)
- Beamlines/Detectors
- Data Management and Analysis

Magnets





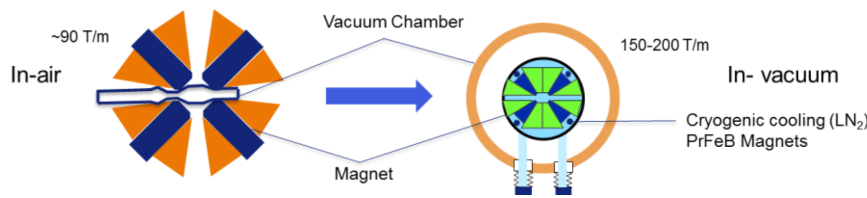
Elettra Sincrotrone Trieste



resistive magnets of many different kinds

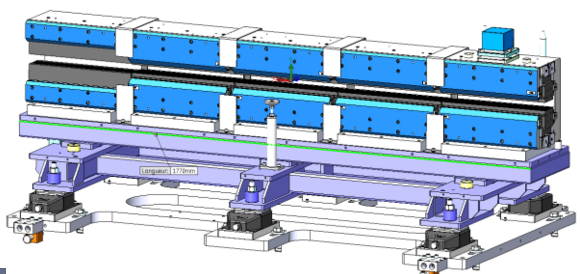
- **high gradient, “combined function”, …**
- **relying on highest manufacturing precision**
- **precise magnetic field measurement for development work and quality control**

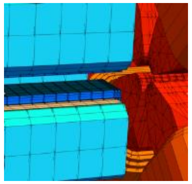
- **are we at the limit? What next?**



permanent magnets

- **large scale installation**
- **stability, field quality**
- **longterm rad. hard.**

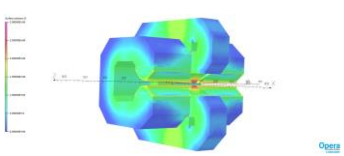


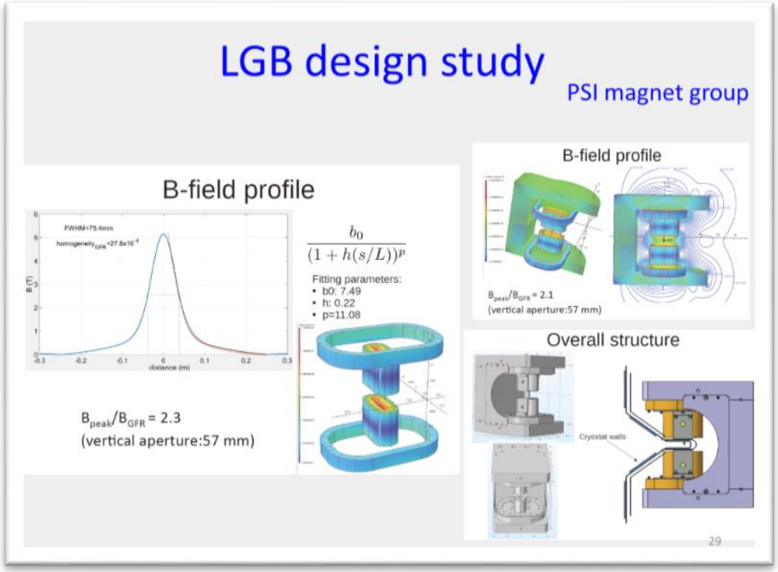


SR

FEL

Compact



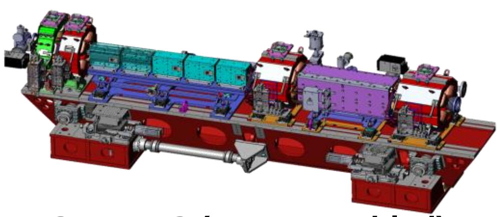


superconducting magnets

- e.g. longitudinal gradient dipole with up to 6T

new girder concepts

- stability, damping, alignment, costs



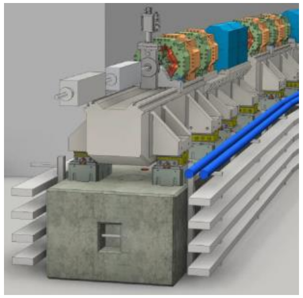
ESRF-EBS (pre-assembled)

SR

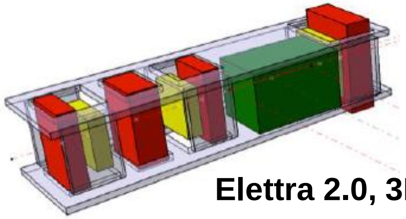
FEL

Compact

MAX IV



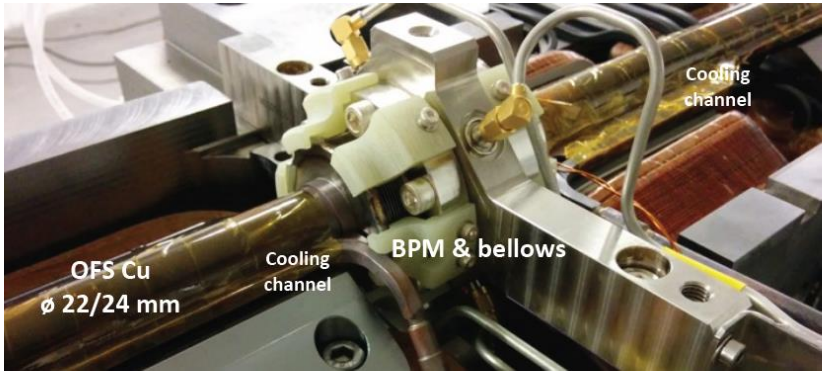
SIRIUS



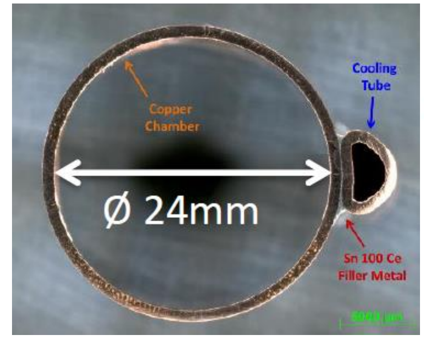
Elettra 2.0, 3D girder

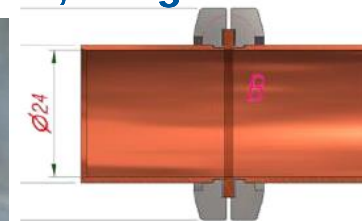
Vacuum systems and "other" vacuum installations

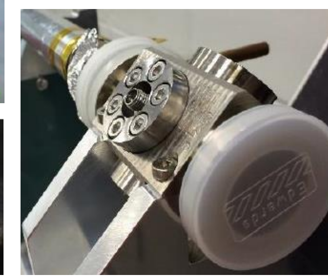
MAX IV chamber + BPM, 22mm



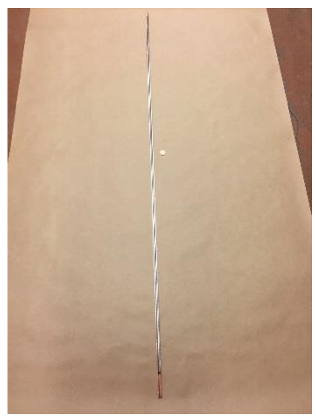
SIRIUS chamber, BPM, flanges



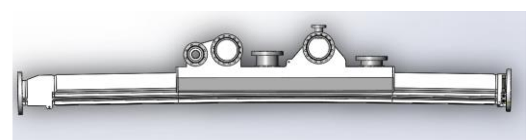


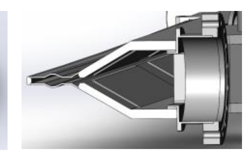


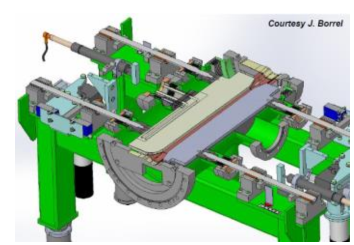
ALS-U, coated 6 mm (!) chamber



ESRF chamber, collimators







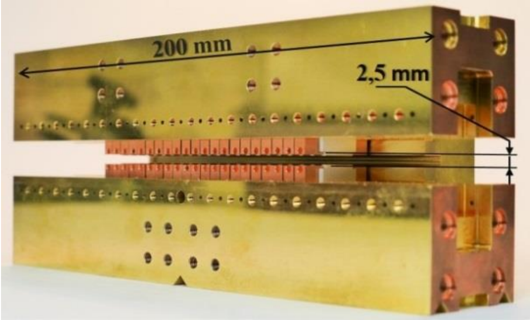
SR

FEL

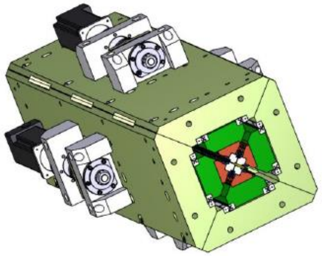
Compact

- advanced in-vacuum CPMU
  - polarized photons (APPLE II/III type)
  - shorter period length
- in-vacuum SC Undulators, polarized (?)
- special “dipole” / WLS like devices for “*hard* bending radiation” from DLSRs
  - with traceable field quality, e.g. for metrology applications

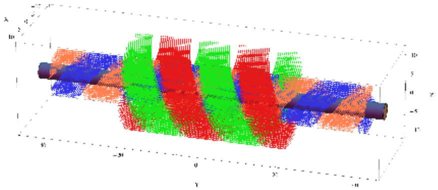
HZB 9mm-Prototyp 2 with hybrid poles (FeCo & PrFeB)



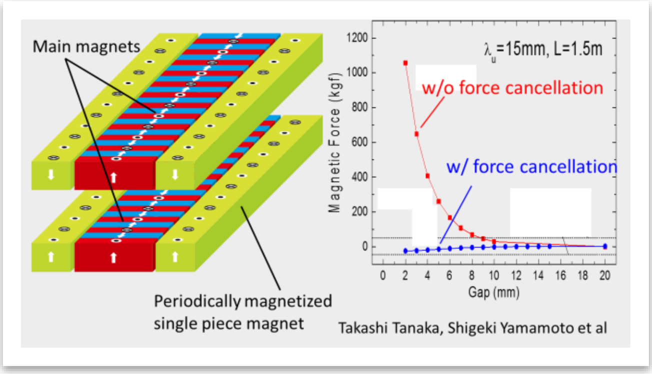
DELTA Undulator



sc Helical



force free P.M. IDs, fixed gap IDs

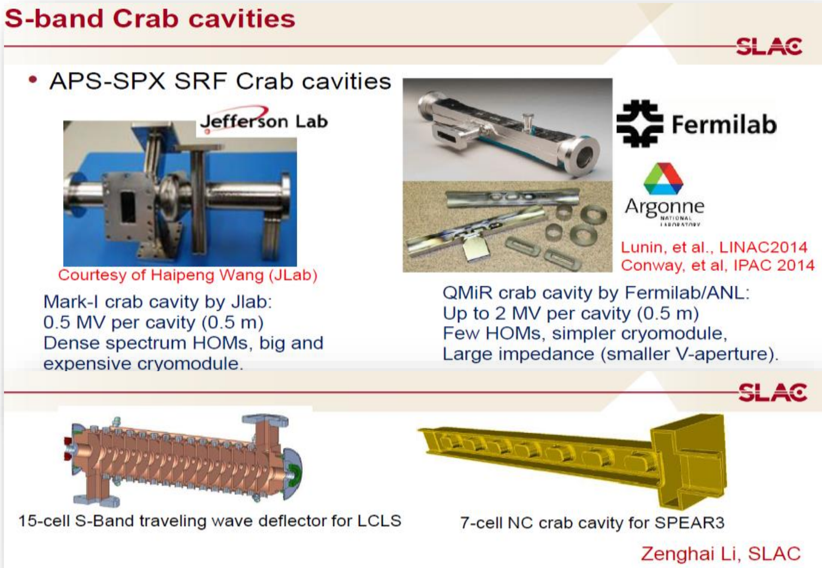


SR

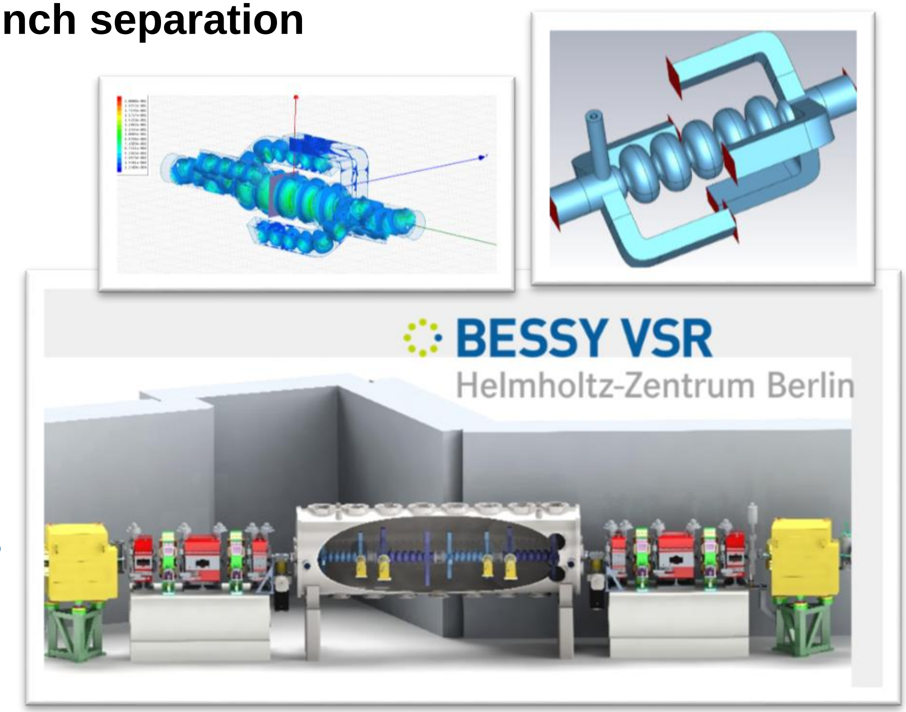
FEL

Compact

SC/NC Cavities – harmonic cavities and others



sc / nc. crab cavities
- short photon pulses
- bunch separation



sc cw multi cell, high gradient cavities
- short electron pulses
- beating schemes for variable pulses
- usage in DLSR ?

SR

FEL

Compact

nc/sc cavities with a variety of frequencies from some 10 MHz up to 2 GHz for ultimate control of the longitudinal phase space !

Solid state amplifier technology

solid state amplifier

352 MHz, > 100 kW, available
500 MHz, 70 kW, available
1.3 GHz, 20 kW, available
1.5 GHz, 1.75 GHz to come
and others

reliability, stability, scalability

push the limits in terms of frequency and power



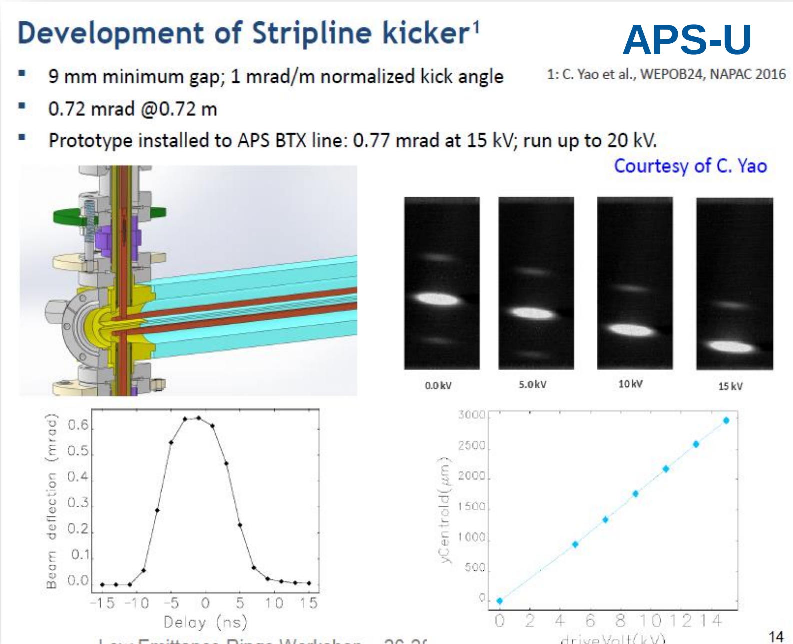


SR

FEL

Compact

Injection / kicker technology

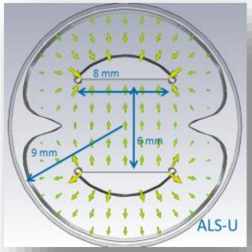


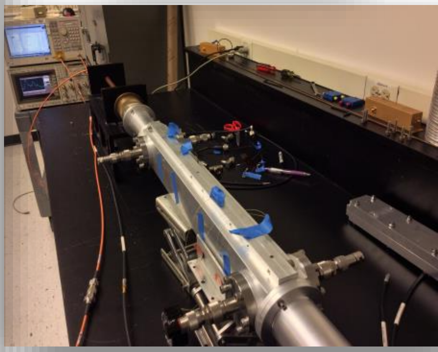
Fast (ns) strip line kickers and pulser for swap-out injection, spreader, diagnostic, beam separation

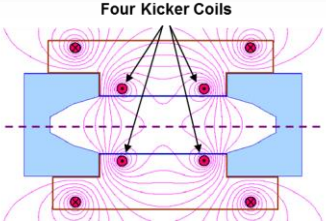
- stability, reliability, …

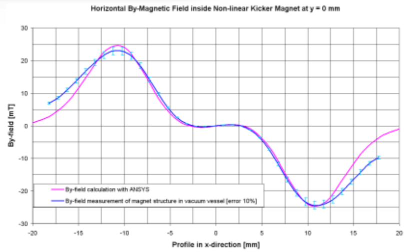
- beam tests started/ongoing

ALS-U







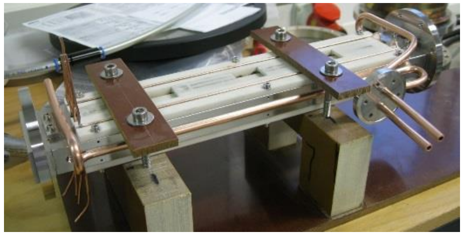


SR

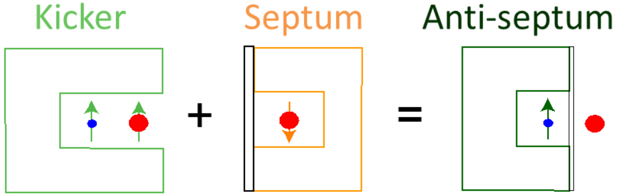
FEL

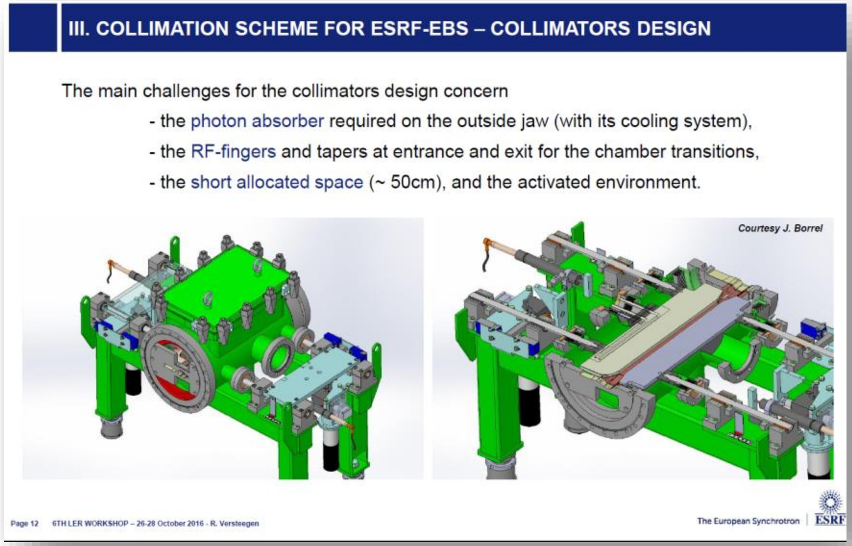
Compact

Non-linear injection kicker



injection with anti-septum



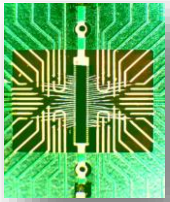


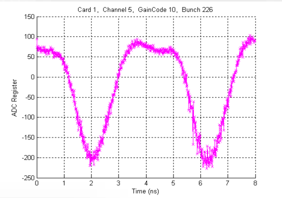
collimators

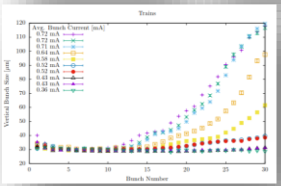
- to cope with radiation issues due to beam lifetime in existing enclosures
- reliable, compact design needed
- shielding and activation issues

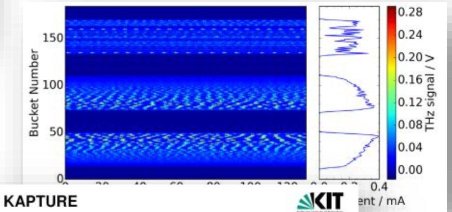
diagnostics

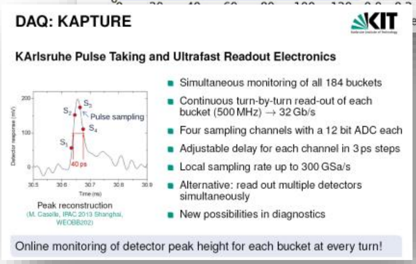
- Bunch By Bunch (BBB) and Turn By Turn (TBT) data
  position, beam size, length, current, CSR, …







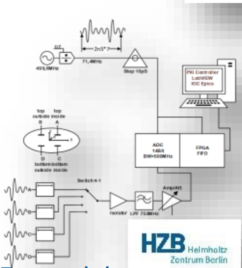


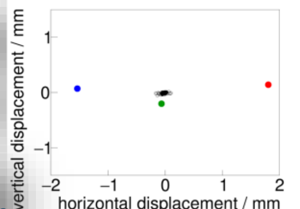


SR

FEL

Compact





Technology Developments – Storage Ring (i)

1. High gradient / field magnets with low aperture (lattice magnets)

SR FEL Compact

em/pm/sc small aperture (<10mm) magnets, compact, high gradient
mock up girder
advanced meas. systems for qualification

2. Very small aperture vacuum systems

SR FEL

NEG coating tests
surface roughness / impedance optimization
comparison of different materials

3. Injection systems for low dynamic aperture rings (kicker & pulser)

SR FEL

non-linear kicker module (higher field, peak field near to axis)
ns stripline kicker
pulser
anti-septa

4. Small period, low gap, high K undulators with polarisation control

SR FEL Compact

short period (< 10mm) planar CPMU, SCMU
in vacuum, short period, polarised CPMU
undulators for round beams (circular aperture)
revolver undulator, switchable period length SCU
advanced magnet meas. devices for qualification

Technology Developments – Storage Ring (ii)

5. sc/nc cavities for bunch length control + RF systems

SR FEL

module with advanced sc cw HOM multi-cell cavities
nc cavities for multi harmonic operation
scalable power sources (SSA)

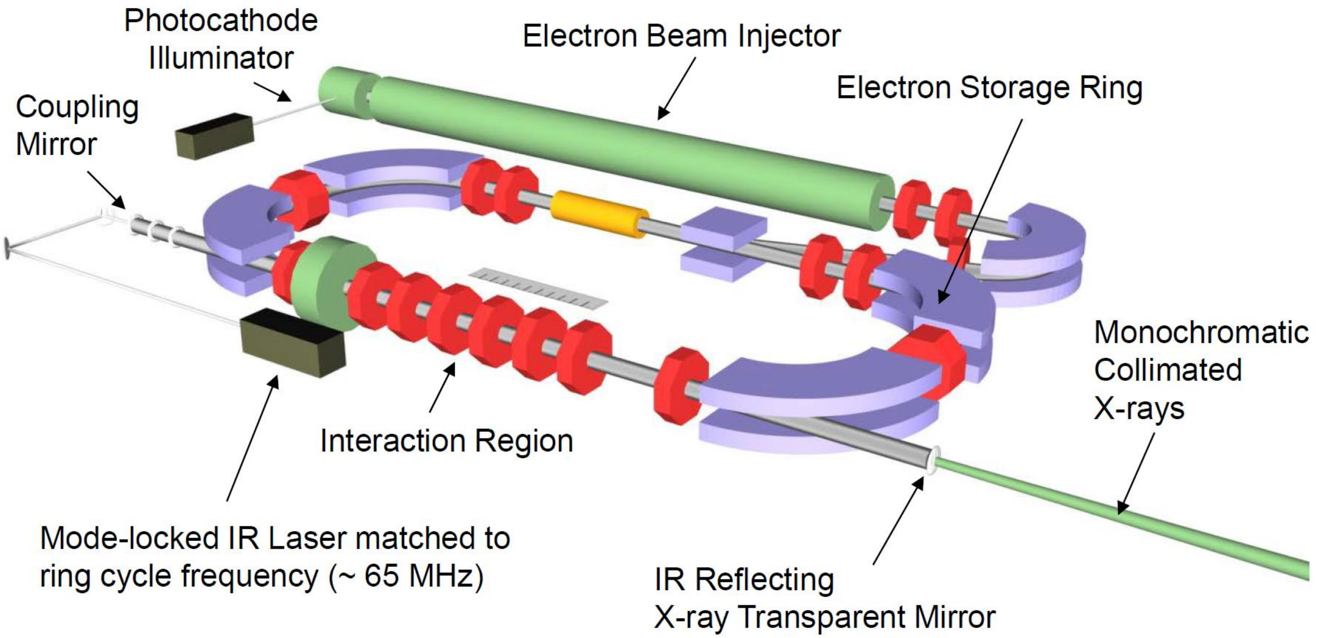
6. Diagnostics and feedback for advanced photon beam stability

SR FEL

photon beam bpm for EPUs
closed loop local “beamline / beam on sample” FB (e- and photon based)
6D bunch profile feedback based on 3D bbb DAQ

A Mini-synchrotron

- A miniature synchrotron x-ray source
  - Electron bunch stored in a miniature electron storage ring
  - Picosecond laser pulse stored in high-finesse optical cavity providing electron “undulation” to produce x-rays in interaction region



CLS Technology & Applications

lyncean TECHNOLOGIES, INC.

Zusammenfassung

Dramatische Entwicklungen in Bezug auf erreichbare Emittanz (Brillanz, Kohärenz) in Elektronenspeicherringen

→ höchste transversale Kohärenz möglich bis herunter zu 0.1 nm ….

Weiterentwicklung der Technologie und Methoden notwendig

→ Dipole mit transversalen/longitudinalen Gradienten
→ Quadrupole / Sextupole / Multipole hoher Gradienten
(normalleitend, supraleitend, Permanent Magnete, Hybride, mit kleinstem Gap und höchster Präzision)

→ Vakuumkammern für kleinste Aperturen

→ Undulatoren mit kurzer Periodenlänge und hohen Feldern (CPMU, SC, …), auch für runde Strahlen, für höhere Photonenenergien bei gleicher Elektronenenergie (im Zusammenhang mit „miniaturisierten“ MBA Systemen höchste Kohärenz für kurze Wellenlängen auch in „kompakten“ Speicherringen)

→ Diagnose, Feedback, Automatisierung, Anwendung von KI, Machine learning, …

→ Simulations- und Optimierungsmethoden

Innovative Methoden zur Manipulation des longitudinalen Phasenraums

→ sehr lange Elektronenpakte zur Erzeugung von Strahlen höchster transversaler Dichte
→ Elektronenpakte alternierende Länge zum Erhalt von zeitaufgelösten Methoden an DLSR
→ Anwendung von Konzepten von SSMB (stabiles Mikrobunching) oder EEHG, CHG zur Erzeugung intensiver, kohärenter Strahlung im nm Bereich

Dies alles im Hinblick auf die Weiterentwicklung der deutschen Synchrotronstrahlungsquellen und auch um starker Partner in der LEAPS Technology Roadmap Initiative sein zu können.

Stärken Deutschlands:

- Deutschland verfügt über weltweit führende SR Quellen in allen Energiebereichen (SR, FEL) + “Testanlagen” wie KARA & DELTA
- es gibt eine große Zahl an Universitätsgruppen, die breit aufgestellt auf diesen Feldern forschen

Light matters!

THANK YOU FOR YOUR ATTENTION

Many thanks to all colleagues for providing material:

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