Accelerator Physics Challenges in the Design of Multi-Bend-Achromat-Based Storage Rings

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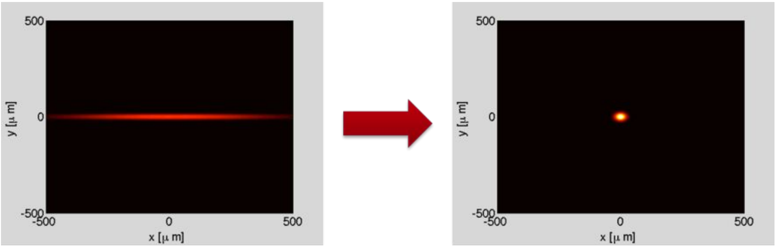
Outline

- Introduction and motivation
- Lessons from MAX IV
- Physics issues and challenges
- Engineering issues and challenges
- Conclusions

Why lower emittance matters



courtesy C. Steier

- <u>Brightness and coherence increase, beam dimensions decrease</u>
- New science capabilities, including

  Coherent wavefronts: coherent imaging, holography, speckle, ptychography, etc.

  Small focused spot size: nano-probes

  High flux density: ~10^{14}-10^{15} photons/sec/mm^2; slits may not be required, etc.

  Round beams: H-V symmetric optics, circular zone plates, flexibility in optics geometry

- The intrinsic x-ray emittance is given by

$$\varepsilon_r(\lambda) = \sim\frac{\lambda}{4\pi} - \frac{\lambda}{2\pi}$$

- A storage ring is called **diffraction limited** for X-ray wavelength λ when the electron beam emittance approaches this value

How close are we now?

- In practical units

$$\epsilon_q[pm] \lesssim \frac{100}{E_p[keV]}$$
$$\epsilon_q[pm] \lesssim 8\lambda[\mathring{A}]$$
$$\Rightarrow \begin{array}{lcl} 1 \text{ keV} & \rightarrow & \epsilon_q \lesssim 100 \text{ pm} \\ 10 \text{ keV} & \rightarrow & \epsilon_q \lesssim 10 \text{ pm} \\ 100 \text{ keV} & \rightarrow & \epsilon_q \lesssim 1 \text{ pm} \end{array}$$

- Typical present-day storage rings provide

$$\epsilon_x : [1, 5]\text{nm} \qquad \epsilon_y : [1, 40]\text{pm}$$

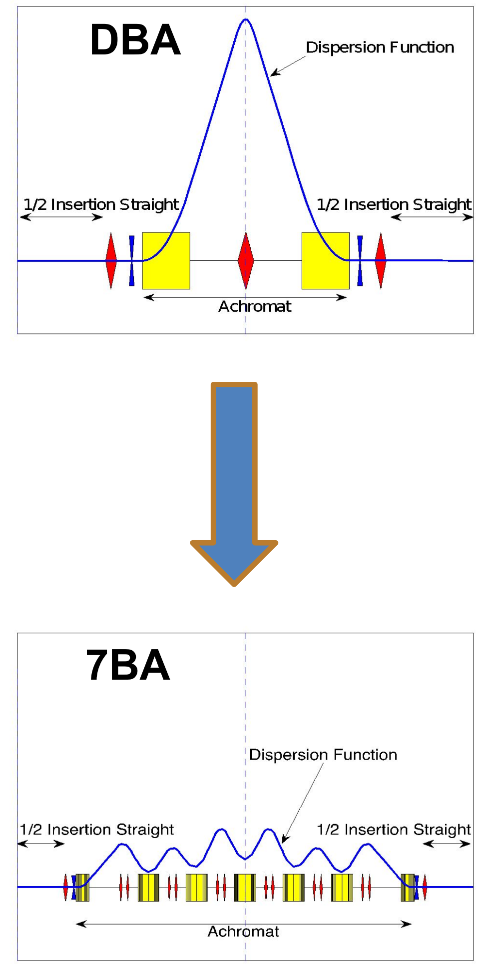
- We are at least an order of magnitude too high in the horizontal

The path to lower emittance rings: MBA lattices

- Emittance is governed by[1]

$$\varepsilon_0 = F(\nu, cell)\frac{E^2}{(N_s N_d)^3}$$

  where N_s=#sectors and N_d=#dipoles/sector
- MBA early history (partial): 1993 - DLS 7BA design, D. Einfled et al., SPIE 2013; QDA by D. Einfeld et al. NIMA 335(3); 1994 - SLS early design with 7BA (W. Joho, P. Marchand, L. Rivkin, A. Streun, EPAC'94); 1995 - 7BA by Einfeld et al. (0.5 nm-rad, 3 GeV, 400m, PAC 95); 2002: MAX IV 7BA concept (M. Eriksson et al., EPAC 2002)
- Other important "knobs"
  - Damping wigglers
  - Reverse bends [PAC89, p.1611; NIM A 737, 148]



courtesy C. Steier

1: J. Murphy, NSLS Light Source Data Booklet

The world is moving to MBA ring sources

3 GeV, 500 mA rings

NSLS-II: operational since 2014
1000 pm x 8 pm

MAX IV: operational since 2016
320 pm x 8 pm

SIRIUS: planned 2016/2017
280 pm x 8 pm

MBA ring upgrades

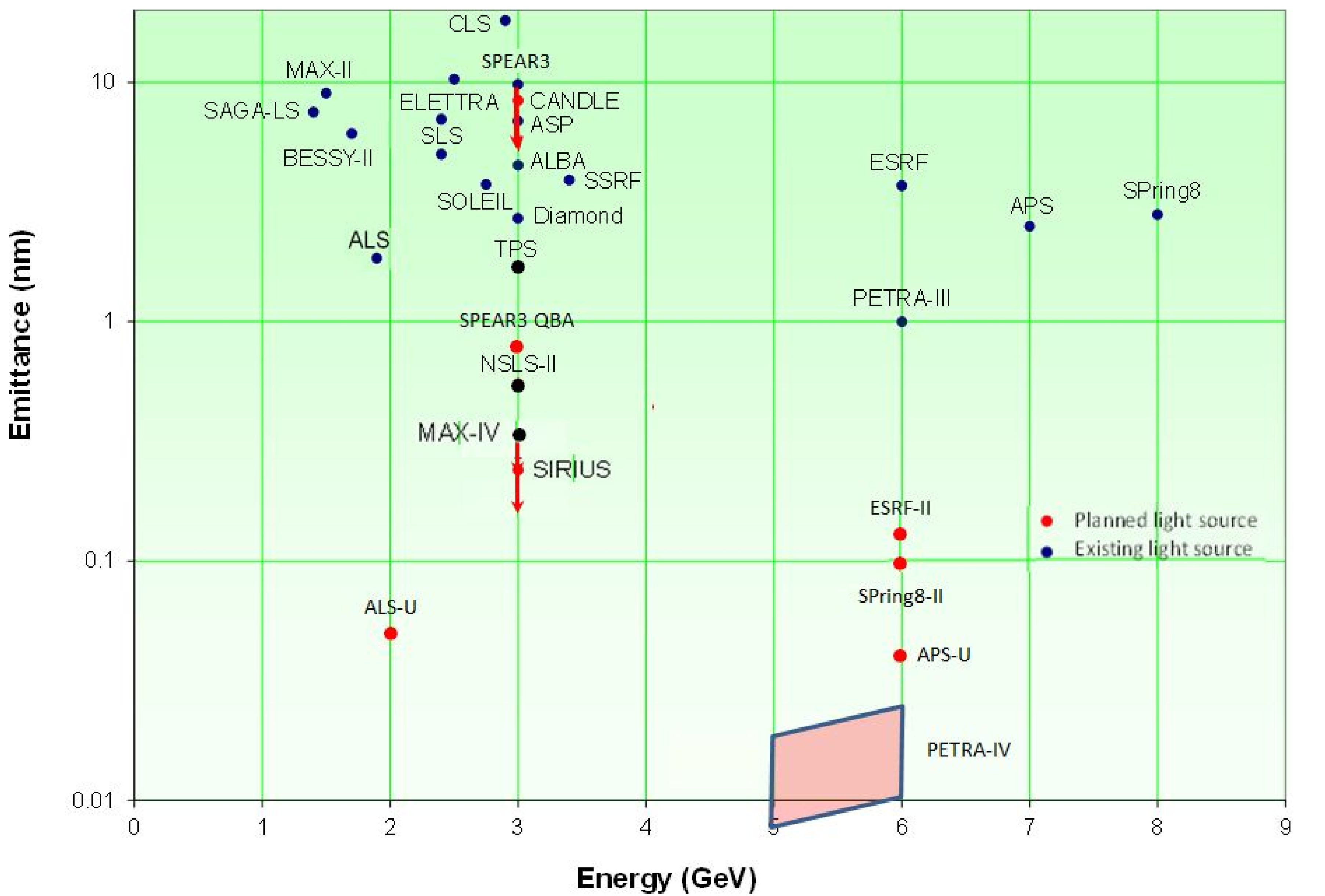
Planned 2020, 6 GeV
160 pm x 3 pm, 200 mA

Planned ~2022, 6 GeV
40 pm x 4 pm, 200 mA

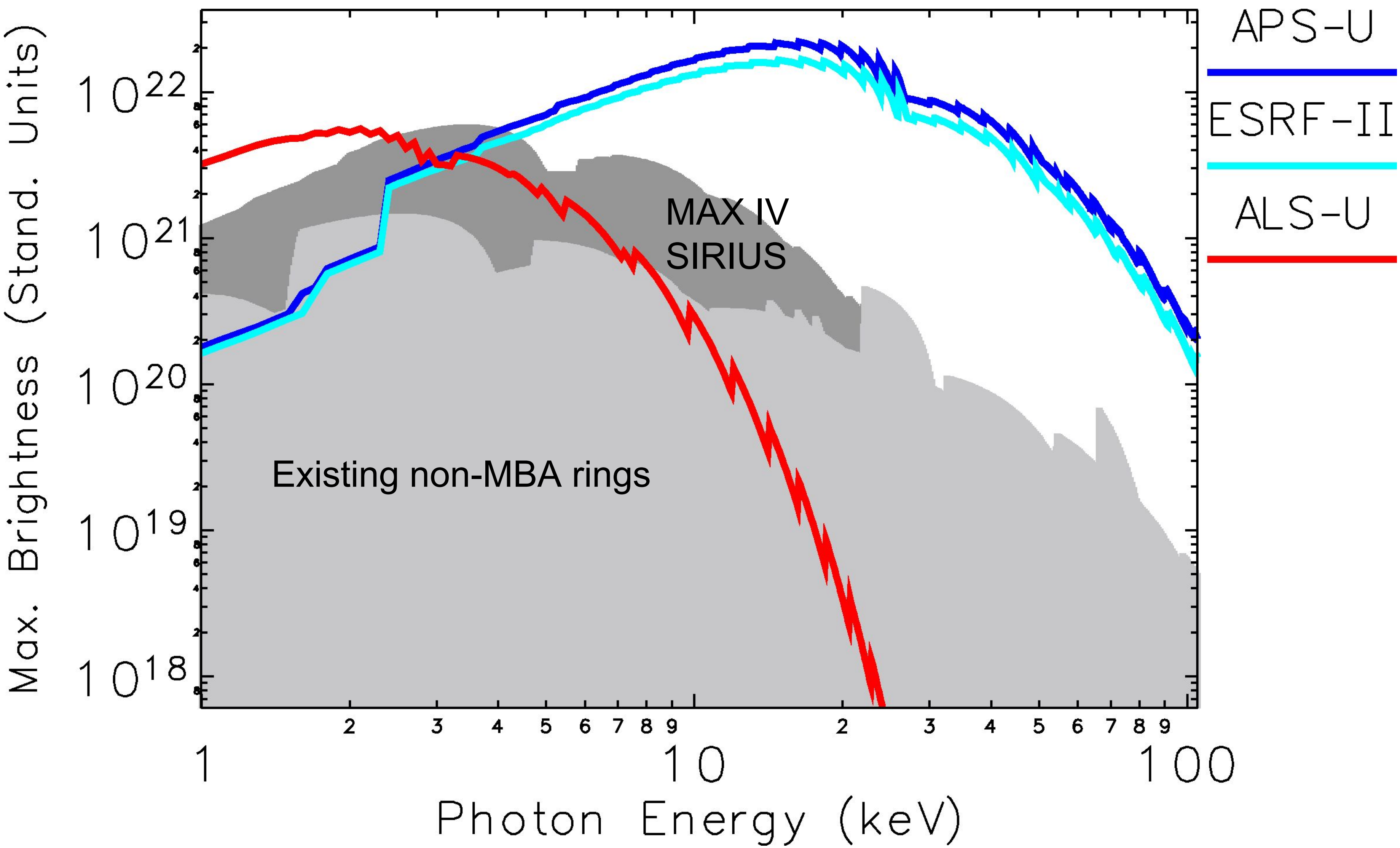
Proposed, 2 GeV
50 pm x 50 pm, 500 mA

Other international implementations: *Japan (SPring8-2, 6 GeV), China (HEPS, 5-6 GeV), Germany (PETRA-IV), France (SOLEIL), Switzerland (SLS, 2.4 GeV), Italy (ELETTRA) and others are developing plans*

SR light source emittance landscape



An incomplete snapshot of the SR light source brightness landscape



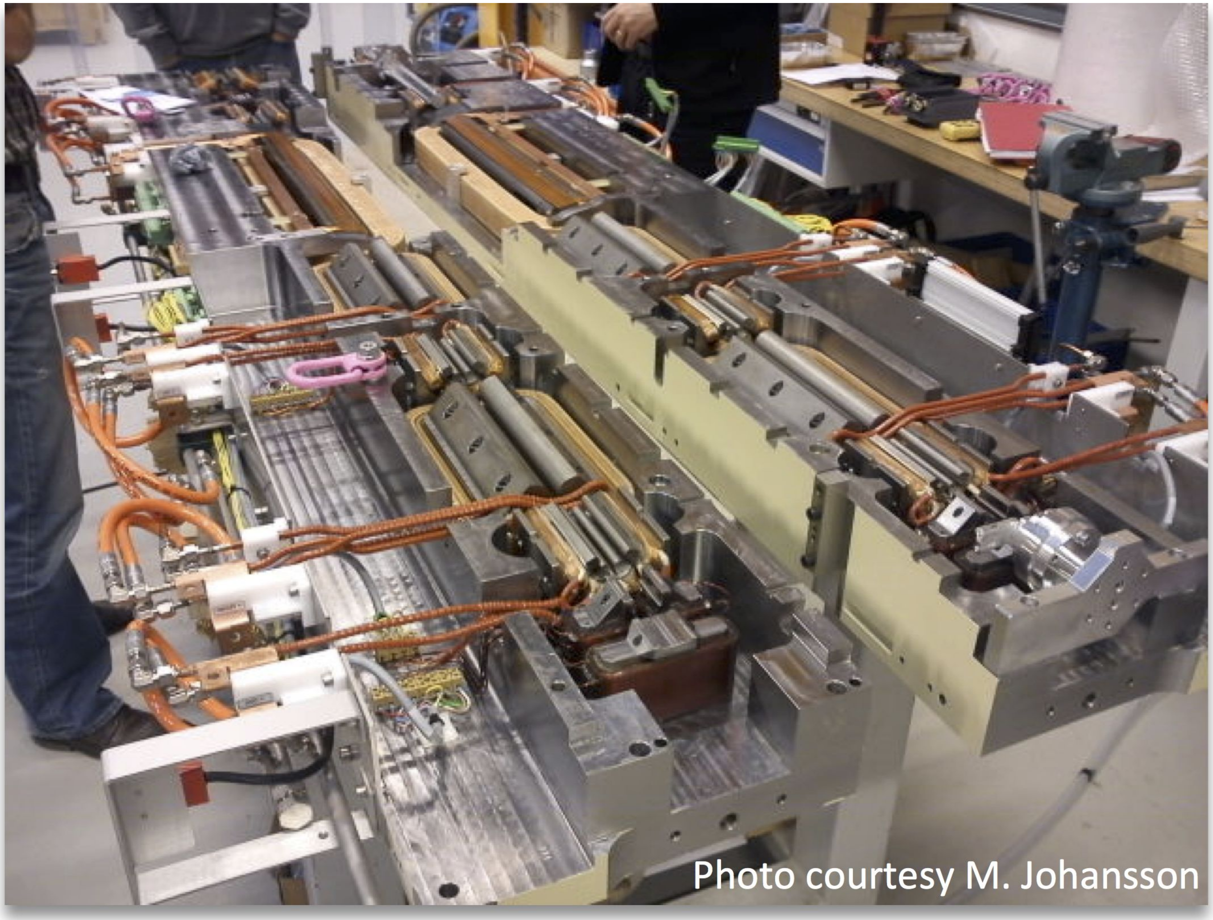
Based on data supplied by O. Chubar (BNL), R. Hettel (SLAC), A. Kling (DESY), S. Krinsky (BNL), S. Leemann (MAX IV), T. Rabedeau (SLAC), P. Raimondi (ESRF), C. Steier (ALS), T. Watanabe (SPRing-8)

Lessons from MAX IV: Magnets

TUB3IO01
THPOA64

- Magnets built in blocks instead of traditional discrete units
- Magnet blocks showed excellent internal alignment
- Alignment of magnet blocks (laser tracker) is very accurate

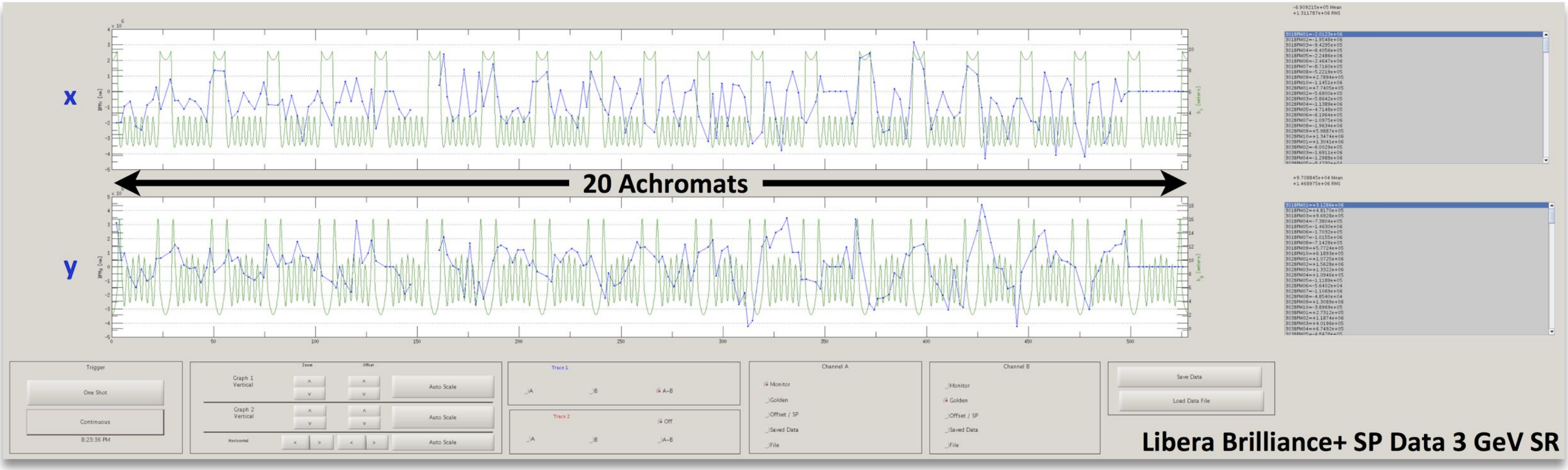
JSR **21**, 884-903 (2014)
IPAC'**15**, MOAD3, p.57



Reproduced from Johansson, Anderberg & Lindgren (2014), J. Synchrotron Rad. 21, 884-903.

Lessons from MAX IV: Magnets (cont.)

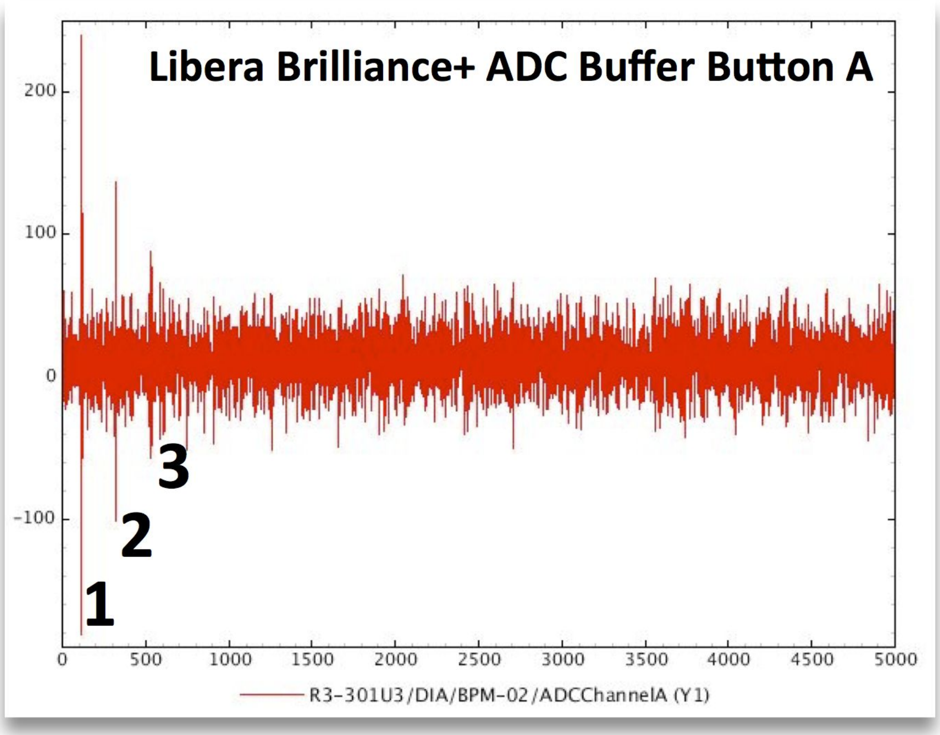
- Achieved first turn without excitation of a single corrector and with all magnets at nominal settings, i.e. currents set according to magnetic measurement data
  - High-quality field mapping (especially in gradient dipoles) is crucial
  - Careful modeling of magnets with (longitudinal) gradients is very important
- Particularly remarkable given
  - 22 mm beam pipe diameter throughout
  - Strong sextupoles and octupoles



First turn in MAX IV 3 GeV ring. All magnets are at nominal settings and no correctors are powered.

Lessons from MAX IV: Instrumentation

- High-resolution BPMs are a requirement in modern rings
  - single-pass capability especially needed during early commissioning
  - sum signal used as loss monitor
  - raw ADC buffers used to determine loss locations even on n-th turn
  - button sum also fed to oscilloscope → fill pattern monitor
  - button signal fed to spectrum analyzer → simple f_s measurement (→ cavity phasing)
- However, reliability of BPM units should be thoroughly tested & confirmed well before beam commissioning

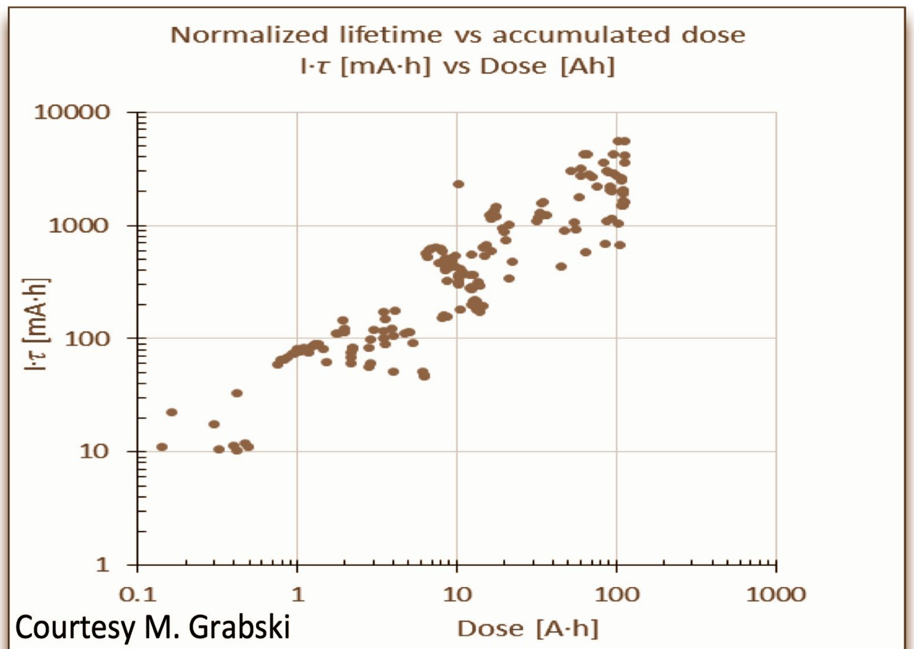


Lessons from MAX IV: Vacuum

- 22 mm chamber diameter presents vacuum challenge
- NEG-coated Cu vacuum system meets the challenge
  - reached good pressure already after ~10 Ah
  - pressure still showed significant reduction with accumulated dose towards 100 Ah
  - see signs of ion-driven instabilities

JSR **21**, 878-883 (2014)

WEA3CO04

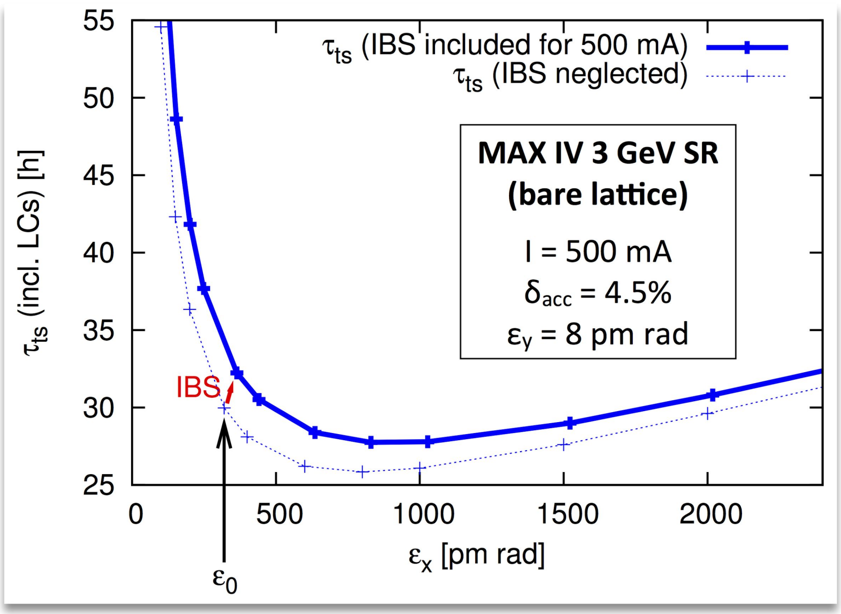


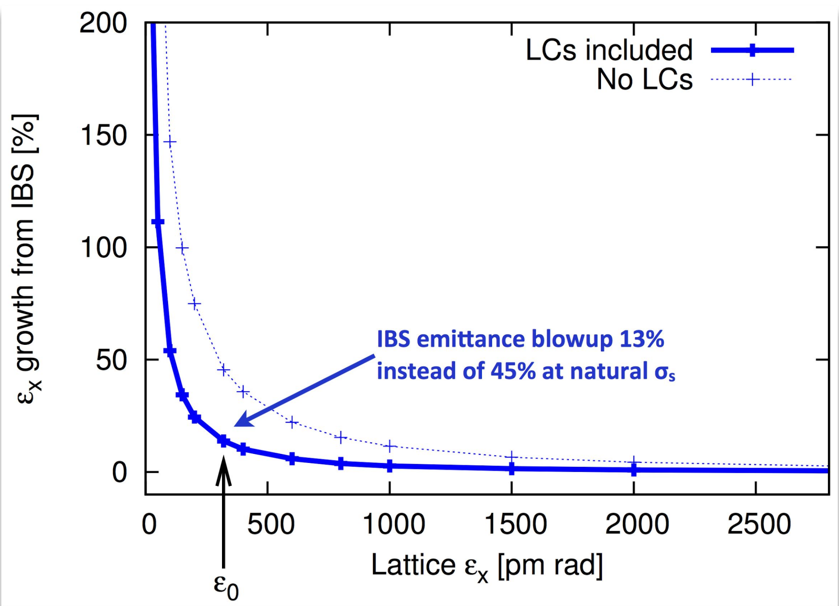
Approaching design lifetime of 10 h at 500 mA after only 100 A*h of integrated current

Lifetime still improving as conditioning continues

Lessons from MAX IV: Long bunches

- 100-MHz rf plus 300 MHz bunch-lengthening cavity gives long bunches
- Reduced collective instabilities
- Reduced rf heating
- Increase Touschek lifetime
- Decrease emittance blowup caused by IBS
- Timing modes present an unsolved challenge





PRST-AB **17**, 050705 (2014)

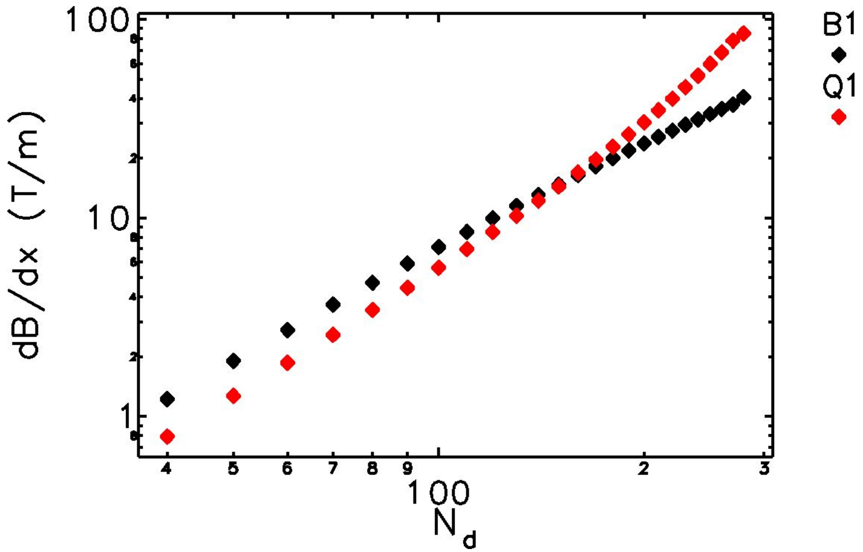
Physics issues and challenges for future machines

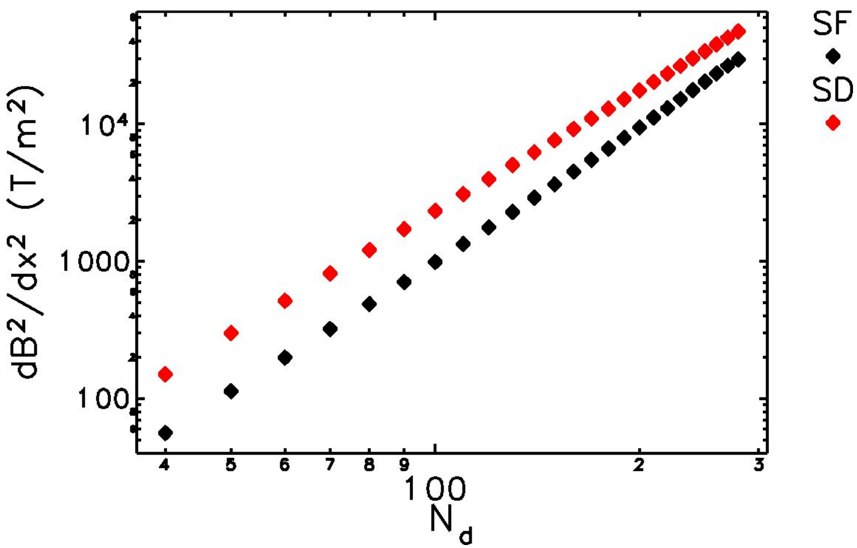
- MAX IV has demonstrated that MBA lattices work
  - More about MAX IV later today: TUB3IO01
  - Future machines will be even more challenging
- We'll cover just two items
  - Nonlinear dynamics
  - Collective instabilities
- Many others not covered here, e.g.,
  - Collimation and insertion device protection
  - Intrabeam scattering
  - Trading off between lifetime, injection aperture
  - Bunch lengthening and stability
  - Ion instabilities
  - Round vs flat beams
  - High-fidelity magnet modeling and beam dynamics
  - Optimization of beam energy

Nonlinear dynamics

- Reduction of the emittance requires stronger, more frequent focusing
  - Quadrupole gradients scale like N_d^2
- This increases the natural chromaticity and reduces dispersion
  - Integrated sextupole strengths scale like N_d^3
- This leads to strong higher-order aberrations
  - Reduced dynamic acceptance, leading to more difficult injection
  - Reduced local momentum acceptance, leading to shorter Touschek lifetime
  - Both lead to shorter gas-scattering lifetime

Scaling of quadrupole (left) and sextupole (right) strength for a model ring composed of TME cells, vs the total number of dipoles N_d [JSR 21, p. 912]



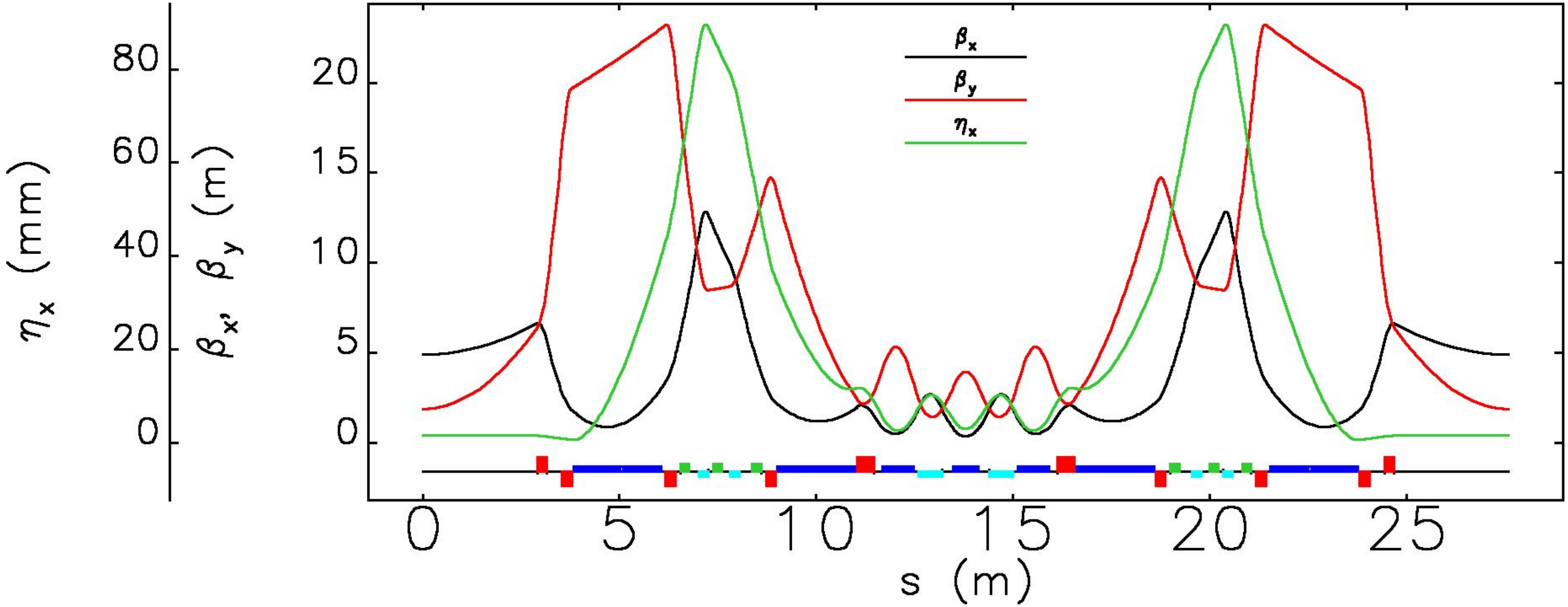


Optimization methods

- Choice of lattice
  - MAX IV lattice [PRAB 12:120701]:
    - Central TME-like cells with many sextupoles distributed throughout entire arc
    - No “automatic” cancellation of aberrations
  - ESRF-upgrade lattice [IPAC13, p.79]:
    - Hybrid configuration with sextupoles only in dispersion bumps
    - Partial cancellation of geometric aberrations
  - PEP-X lattice [PRAB 15:054002]:
    - Specially-chosen phase advance provides cancellation of high-order aberrations
- Inclusion of many nonlinear knobs (sextupoles, octupoles) is essential
- Various approaches to optimizing these knobs
  - “Traditional” approach based on resonant driving terms [SLS-TME-TA-1997-0009]
  - Multi-objective, tracking-based approaches, e.g., [PRAB 8:034202]
    - Direct optimization of DA and Touschek lifetime [ANL/APS/LS-319]
    - Optimization of on- and off-momentum DA [PRAB 14:054001; PRAB 19:044001]
  - Flattening one-period CS invariant [TUPOB54]
    - Appears comparable to tracking-based approaches [WEPOB15]

APS Upgrade Lattice (6 GeV)

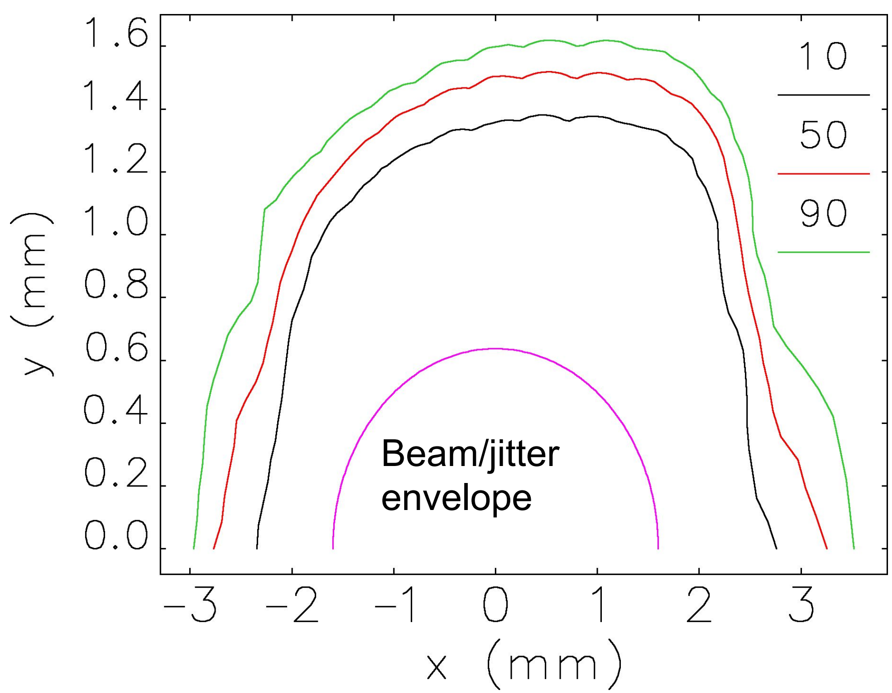
- APS-U exploring variants of ESRF’s hybrid multi-bend achromat [IPAC13, p.79]
  - Dispersion bump very helpful to reduce sextupole strength in high-energy rings
  - Phase advance between sextupoles gives near-cancellation of geometric aberrations
  - Seven normal-direction dipoles per sector gives 67-pm emittance [IPAC15, p. 1776]
- To further reduce emittance, considering six reverse bends per sector [PAC89, p.1611; NIM A 737, 148]
  - Increase damping rates and change damping partition giving 41-pm emittance
  - Manipulate dispersion somewhat independently of beta functions
  - More details WEPOB01



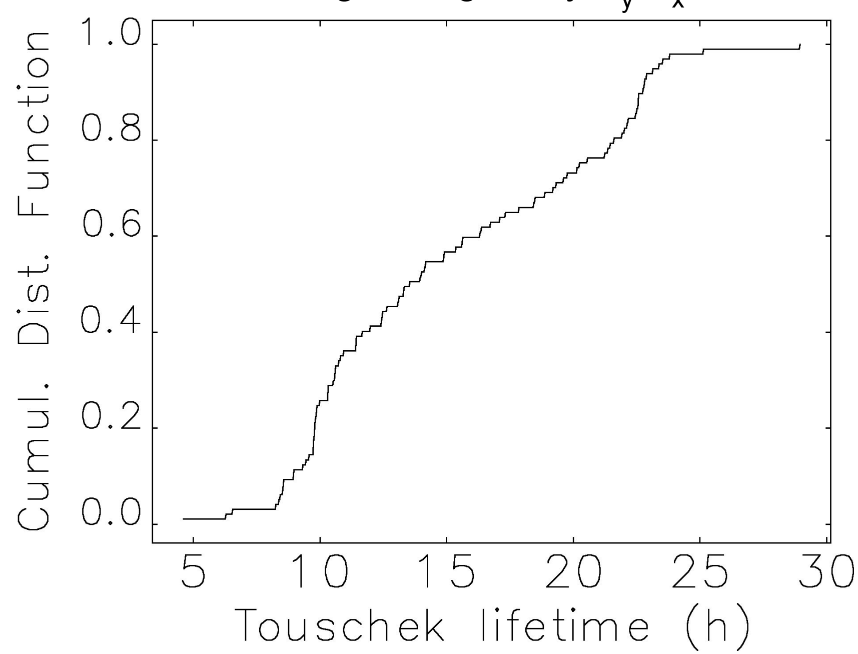
Robustness evaluation

- Regardless of optimization method, robustness testing is essential
- APS-U approach uses commissioning simulation with ~100 error seeds [IPAC15, p.553]
  - Injection tuning
  - Establishing closed orbit
  - Establishing stored beam with workable lifetime
  - Measurement and correction of optics
  - Perform tracking to determine DA, LMA for each case

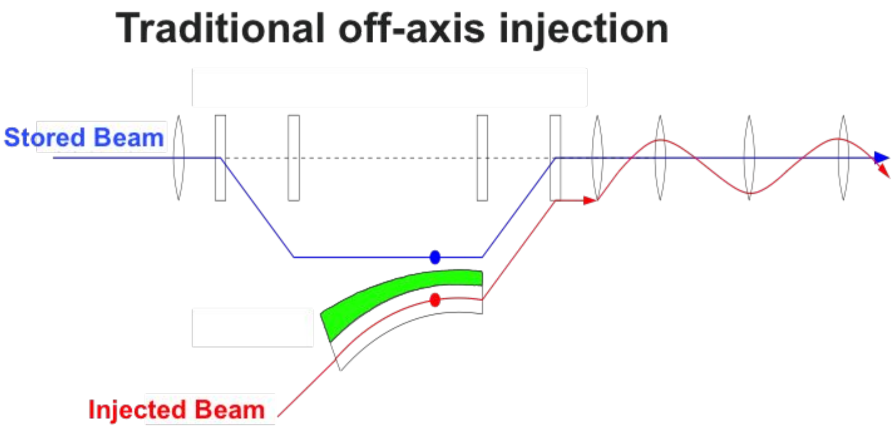
10th, 50th, and 90th-percentile DA contours

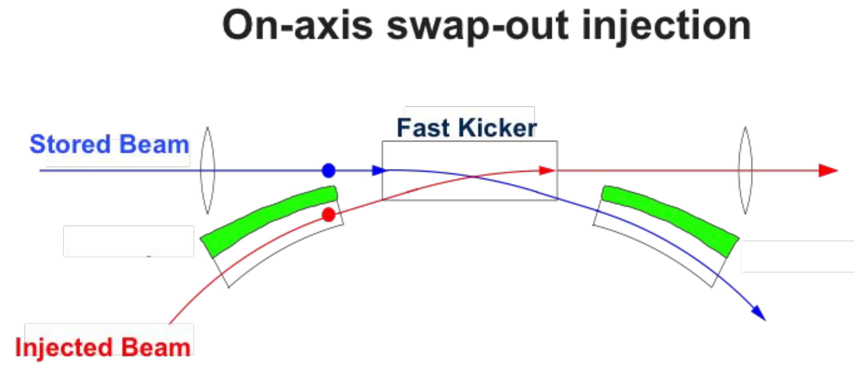


Touschek lifetime for 324 bunches, bunch-lengthening cavity, $\epsilon_y=\epsilon_x$

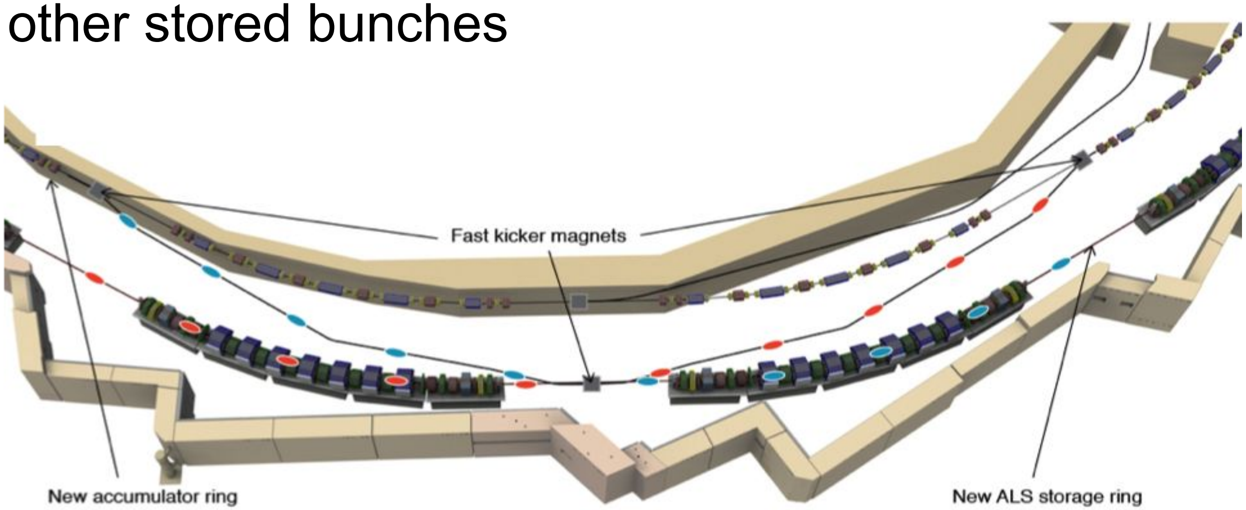


On-axis injection





On-axis injection requires fast pulsers/kickers that have sufficiently fast rise and fall times, kick strengths, and flat tops to extract and replace selected bunches/bunch trains without perturbing the other stored bunches



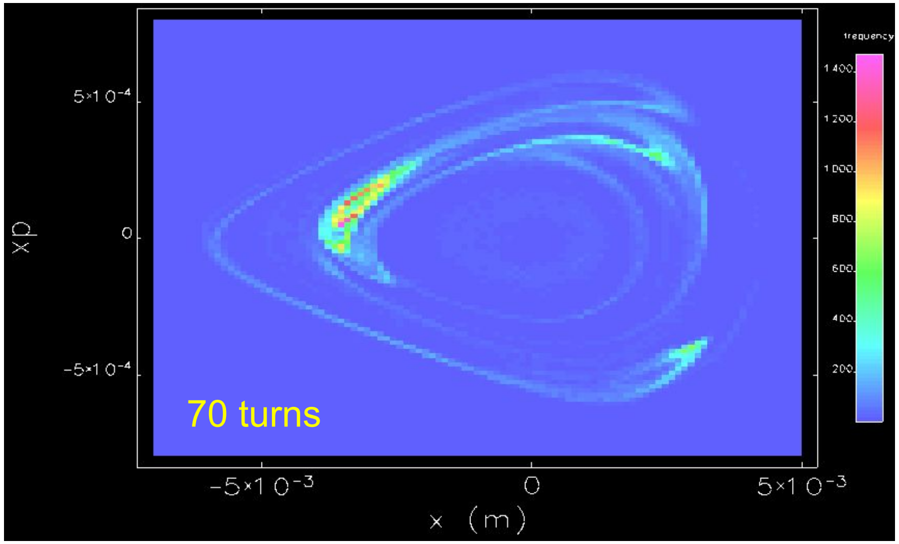
Example: Swap-out of bunch trains in ALS-U

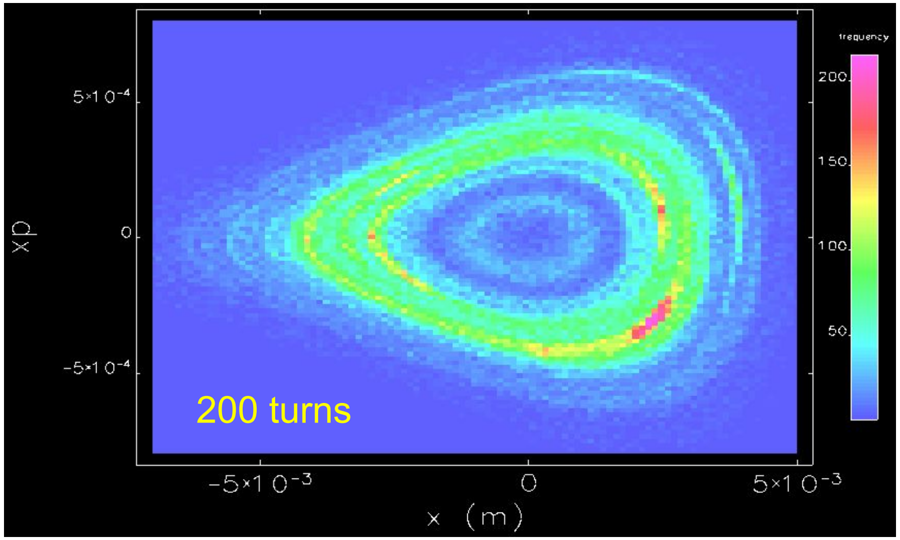
TUB1CO03

Collective effects for APS-U

- Modeling of collective effects for APS-U is quite advanced [IPAC15, p1822]
- Use ECHO [PRAB 8:042001] and GdfidL [W. Bruns] to determine impedance
- Track with parallel ELEGANT using various methods, e.g.,
  - Single-turn transport and single lumped impedance
  - Element-by-element transport with many impedance locations, lattice errors
- Most surprising result: high-charge accumulation not workable WEPOB08
  - Beam will be lost on small (±4mm) horizontal ID apertures
  - APS-U has abandoned use of accumulation in favor of on-axis, swap-out [EPAC92, p. 486; PAC03, p. 256]

Horizontal phase space during attempted accumulation of 4.2-mA bunch in 90-pm APS-U lattice [WEPOB14]
Figures courtesy R. Lindberg (ANL).





Engineering challenges associated with MBA storage rings

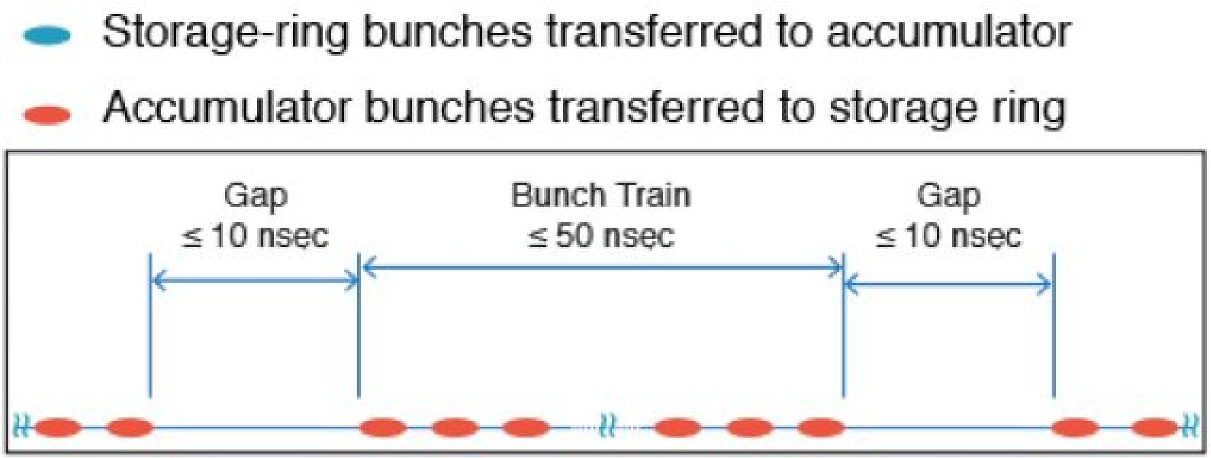
Many challenges associated with aggressive MBA storage rings

- Fast injection elements for swap-out injection
- Vacuum Systems
- Magnet Strength
- Alignment
- Beam Stability

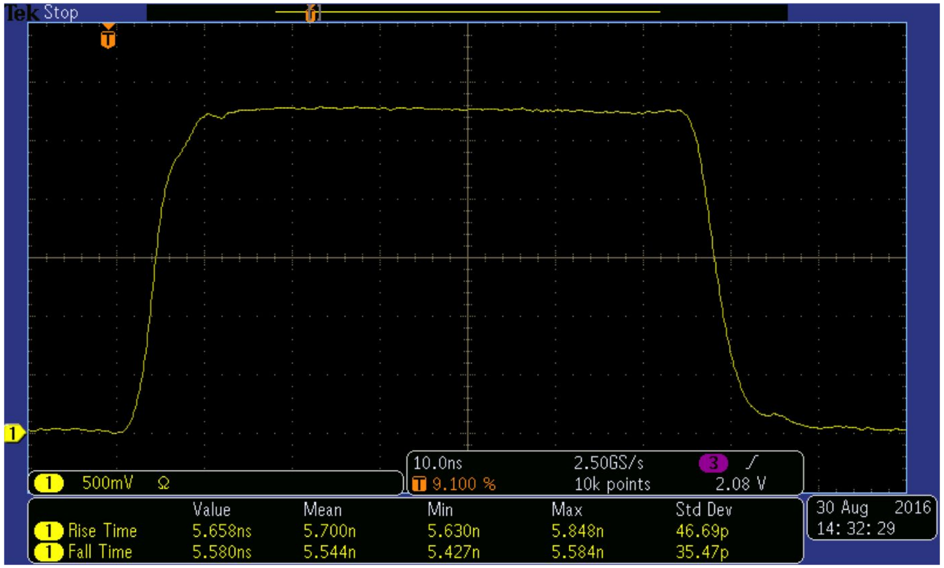
Next few pages show two examples of engineering challenges

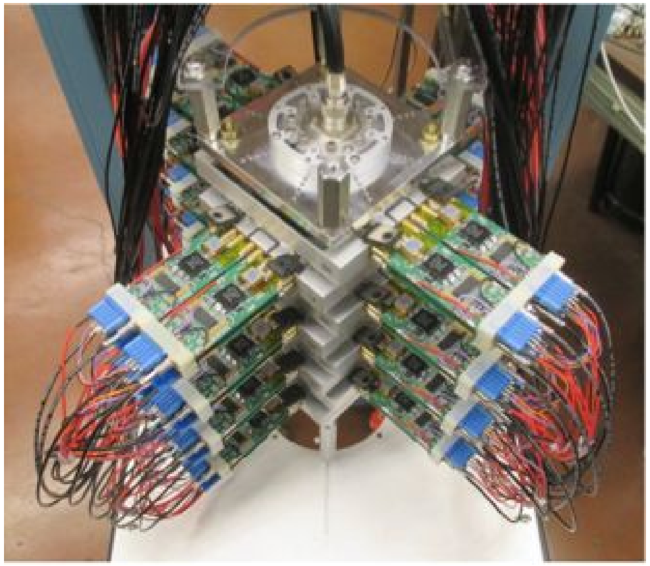
- Fast pulsers and striplines for on-axis injection
- Vacuum systems

Kicker challenges for swap-out: ALS-U



Fill pattern





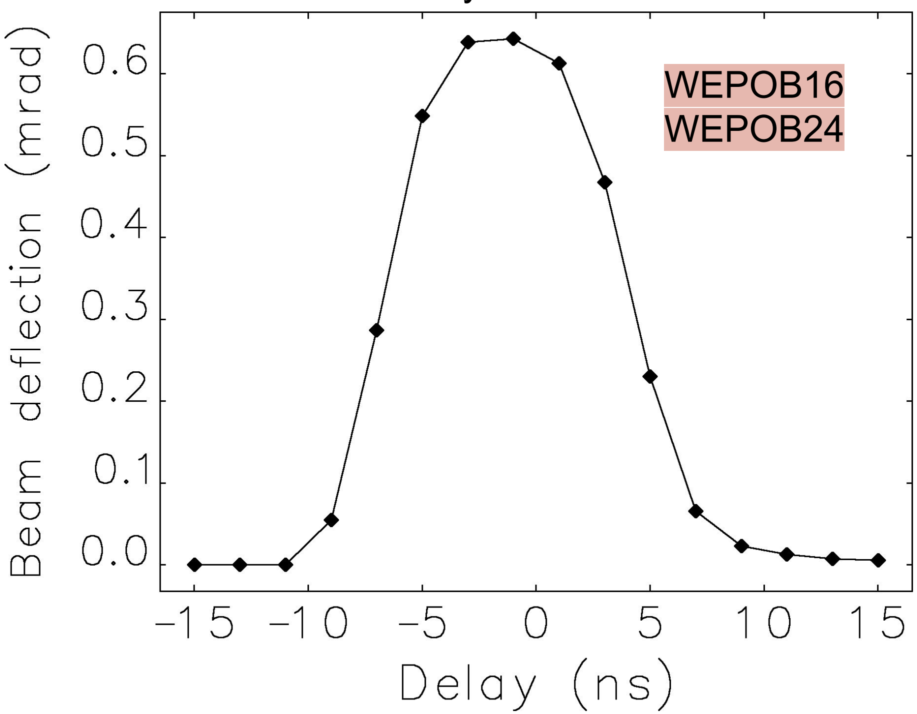
Goals for pulser and kicker:
~5kV, ~50 ns flat top, <7ns rise and fall time

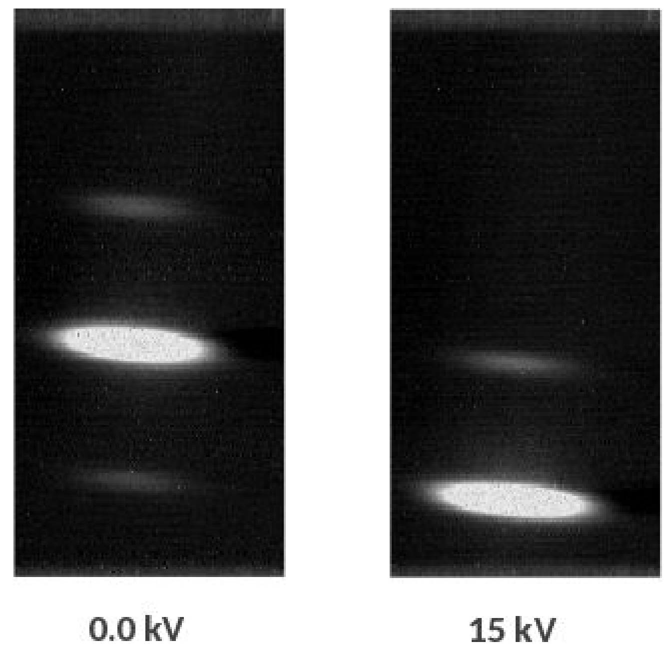
Inductive adder pulser

Kicker challenges for swap-out: APS-U

- APS-U will use single-bunch injection with fast stripline kickers [IPAC15, p. 1797; IPAC15, p. 3286]
  - ±15 kV voltage requirement
  - 4.5 ns rise and fall times
  - 5.9 ns flat top (90%-90%)
- Kicker and pulser recently tested at 7 GeV, appears to meet specs.
  - Pulser built by FID GmbH

Courtesy C. Y. Yao et al.





Images courtesy C.Y. Yao

Engineering challenges for vacuum systems

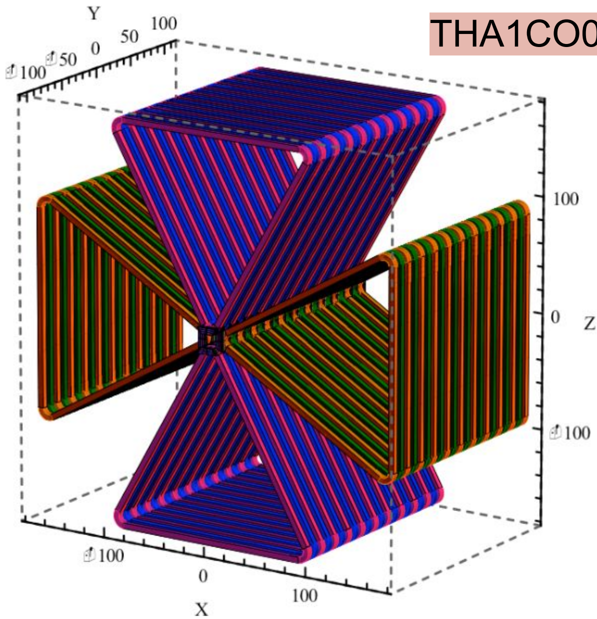
NEG-coated vacuum chambers pioneered at CERN and used extensively at SOLEIL and MAX IV

- NEG coating of long round arc chambers with ~20mm apertures exists at MAX IV and other laboratories

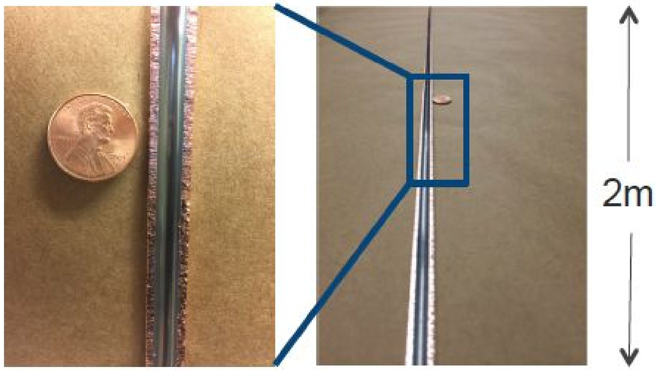
Challenges for coming rings:

- Small <10mm round ID chambers,
- Complicated geometry extraction chambers
- Handling of synchrotron radiation power MOPOB11
- In situ activation

THA1CO06



APS-U SCAPE insertion device will require an 8-mm-diameter chamber (Y. Ivanyushenkov)



Coating of a 6mm-diameter chamber at LBNL (A. Anders)

Conclusions

- Storage ring light sources are arguably the most productive large-scale research facilities in existence
- Low emittance electron rings open up new avenues for x-ray research, e.g.,
  - Enhanced use of coherence
  - Nano probes
- Multi-bend achromat lattices are the key to the next generation
  - Deliver >100-fold brightness increase
- World-wide effort now to upgrade to MBA lattices, or build new facilities
  - Success of MAX IV shows that MBA lattices are very feasible
  - Many physics and engineering challenges, but no show-stoppers
- The first MBA concepts were developed in the early 1990s
  - Time to start developing ideas for 25 years from now!