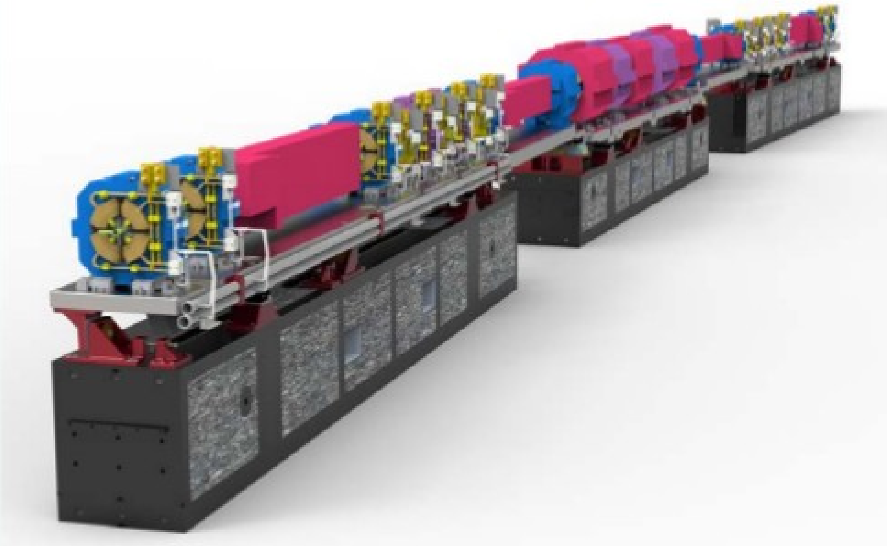
Synergies with ring-based light sources



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Ring light source challenges are fairly general at root

- Want much lower beam emittance, entailing
  - Shorter, stronger quadrupoles and sextupoles
  - Dipoles with longitudinal or strong transverse gradients
  - Small physical and dynamic acceptance
  - New methods of filling
  - Improved beam stabilization
- Want high average current and few-bunch modes, raising several concerns
  - Interplay of single-particle and collective dynamics
  - Single- and multi-bunch instabilities
  - Rf heating and synchrotron radiation masking
  - Machine protection
- Both lead to shorter lifetime and more frequent injection, motivating
  - More precision in lifetime and injection efficiency predictions
  - Bunch lengthening and emittance sharing
  - Detail in loss prediction and localization

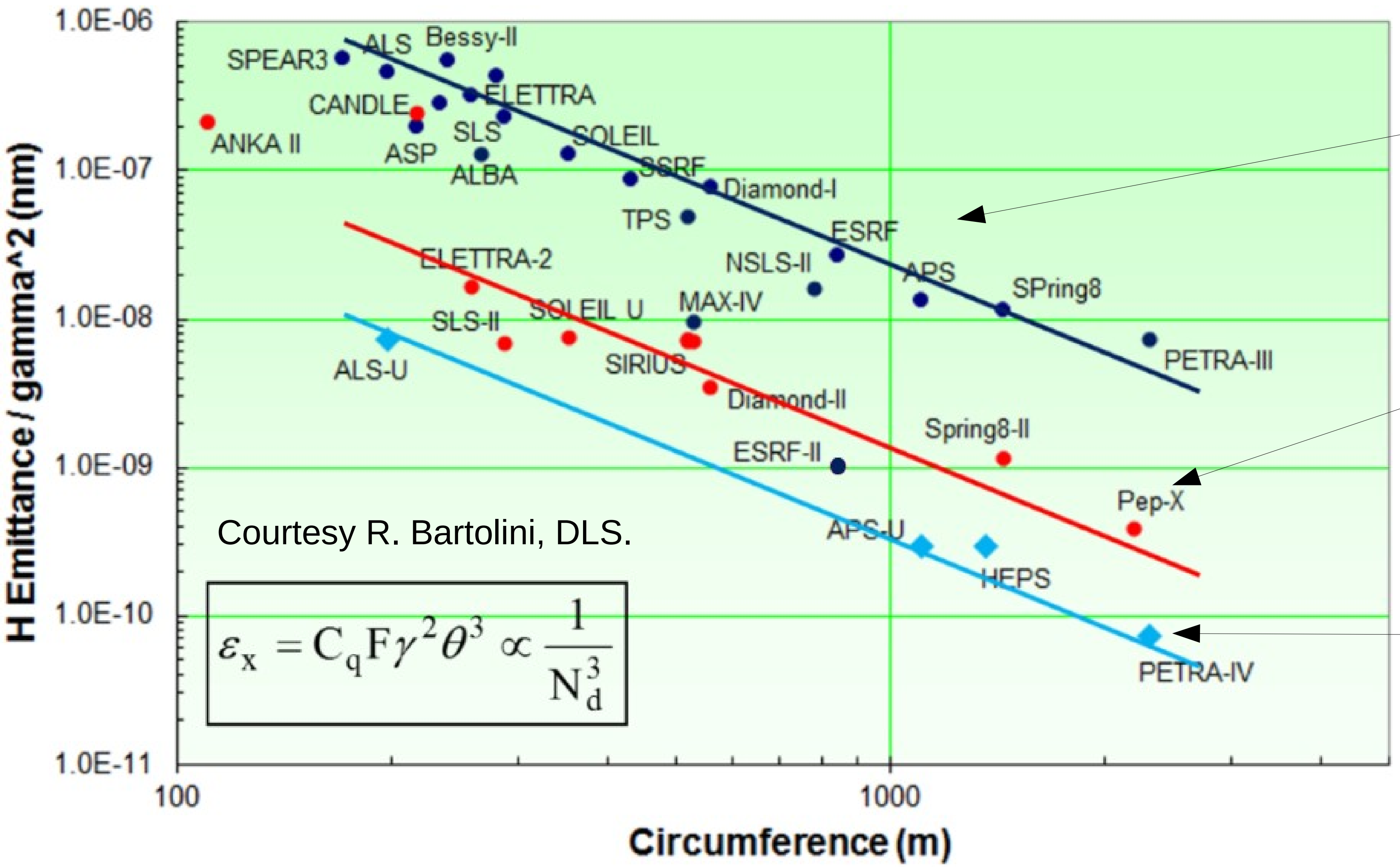
Many factors contributed to success of 3GSRs

- Maturity of design tools and reliability of accelerator hardware
- Lattice correction [1] reduced lattice errors to ~1% rms, improving lifetime and injection efficiency
- Top-up operation [2] increased tolerance for short lifetime from lower emittance, few-bunch modes
- Tracking-based optimization increased lifetime up to 25% [3], nearly eliminates impact of symmetry breaking, high chromaticity [4]
- In-vacuum [5], cryogenic [6], and superconducting [7,8] undulators gave strong fields with shorter periods, hence higher brightness
- Improvements in fast orbit correction, gave ~100 Hz closed-loop BW [9]

1: J. Safranek, NIM A 388, 27-36 (1997).
2: L. Emery et al., PAC99, 200; L,. Emery et al, EPAC02, 218.
3: M. Borland et al., ICAP09, 256.
4: Y-P Sun (APS), private communication.

5: T. Hara et al., J. Sync. Rad. 5, 403 (1998).
6: T. Hara et al., PRSTAB 7 (2004), 050702.
7: S. Casalbuoni et al., AIP Conf. Proc. 1741 (2016), 020002.
8: E. Gluskin et al., SRN 28 (3), 4 (2015).
9: J. Carwardine et al., PAC97, 2281.

Three groups apparent in 3rd and 4th generation rings



Courtesy R. Bartolini, DLS.

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

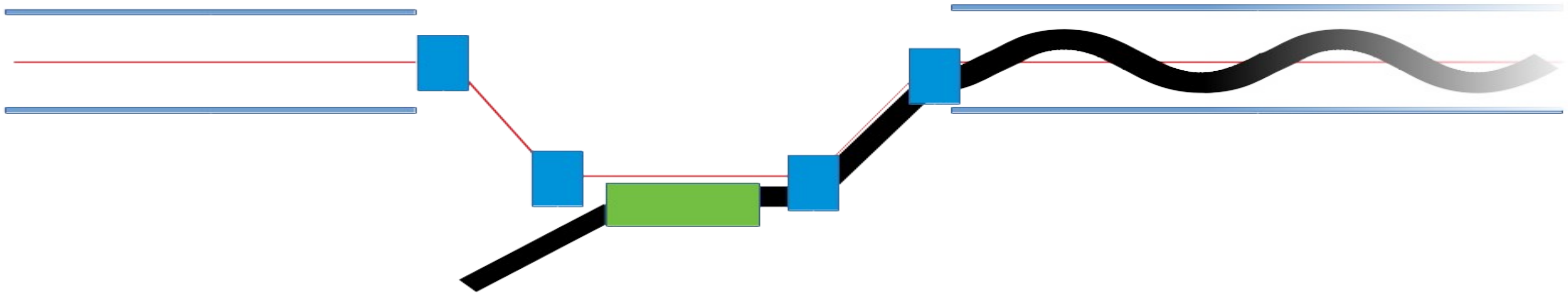
Rings using double- and triple-bend cells, accumulation-based injection, usually top-up

Rings using multi-bend cells (M>3) with accumulation-based top-up operation

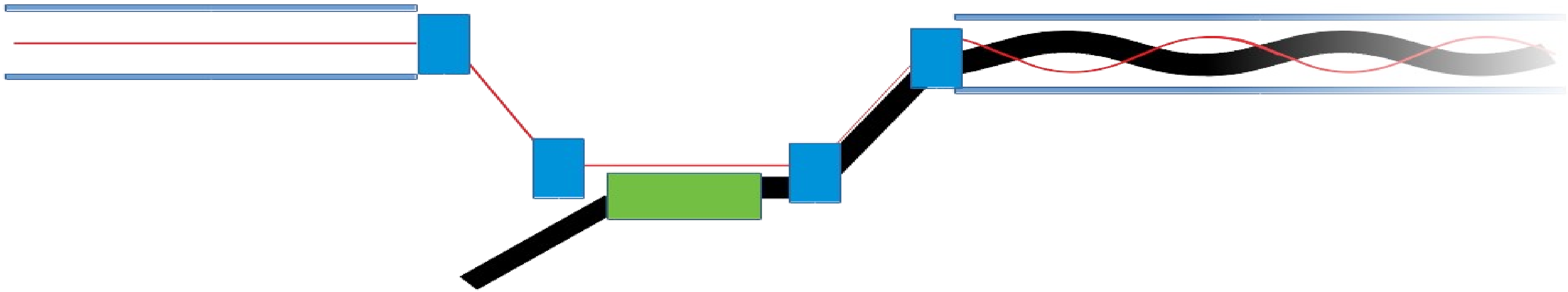
Rings using multi-bend cells (M>3), with on-axis swap-out operation

Legend: blue circles are in operation, red circles and blue diamonds are under study or construction.

Two popular approaches to injection in 3GSRs



Closed-bump accumulation, giving no residual stored-beam oscillation. Aperture must accommodate large oscillation and emittance of injected beam.



Shared-disturbance accumulation, reduces required aperture ~2-fold, may worsen charge-dependence of injection efficiency.

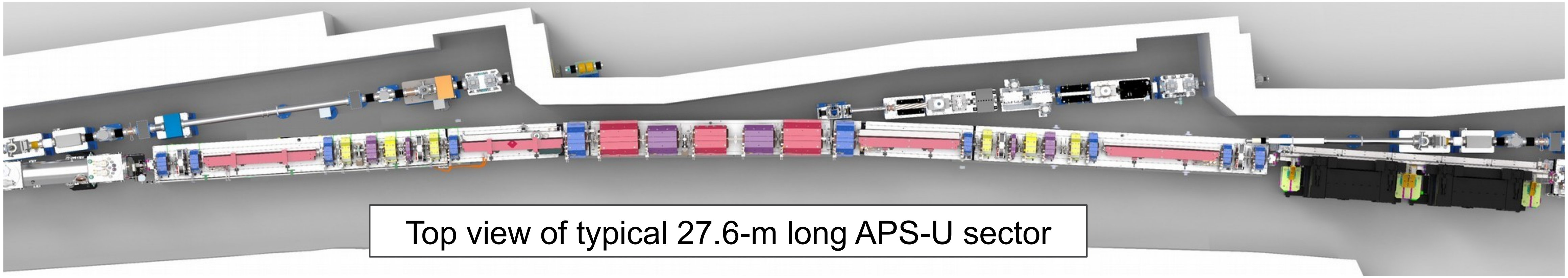
Swap-out injection[1,2] uses fast kickers to replace depleted bunches or bunch trains. Aperture requirements set by incoming emittance only.

1: R. Abela et al, EPAC 92, 486.
2: L. Emery et al., PAC03, 256.

APS Upgrade project building 4GSR at Argonne

- Entirely new 6-GeV, 200-mA ring, including
  - Reduction of emittance from 3200 to 41 pm
  - 1104 m of vacuum systems
  - 1320+ high-strength conventional magnets
  - 2243 power supplies, many with 10 ppm regulation
  - Superconducting insertion devices
  - Orbit correction system with 1 kHz bandwidth
  - Injector upgrades for high-charge swap-out
- Will exceed capabilities of 3GSRs by 2 to 3 orders of magnitude

Advanced Photon Source (APS)

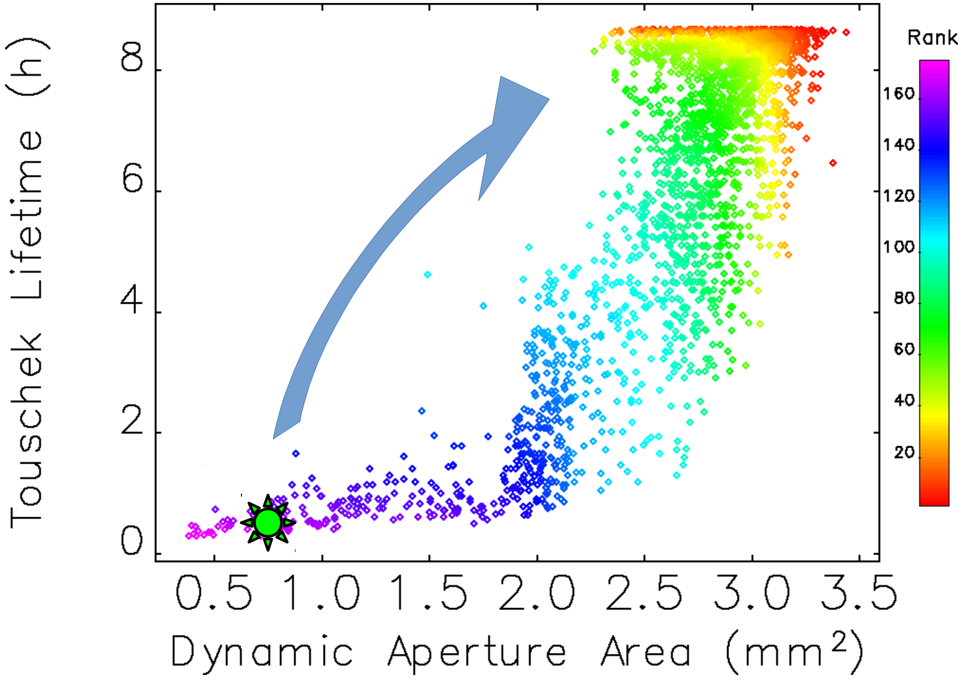


Top view of typical 27.6-m long APS-U sector

APS-U optimization directly targets key performance metrics[1,2]

Parallel, multi-objective genetic algorithms[3,4] for linear and nonlinear dynamics optimization

- Uses parallel version of ***elegant***[5,6]
- Breeds new solutions to find best
  - Dynamic acceptance
  - Touschek lifetime from local momentum acceptance
  - Momentum tune footprint
  - X-ray brightness
- Validated with present-day APS, other rings
- 5GSR challenges:
  - Based on lumped-element models, which may be inadequate or inappropriate
  - Methods based on field maps, generalized gradients[7], etc., difficult to apply with confidence even to 4GSRs

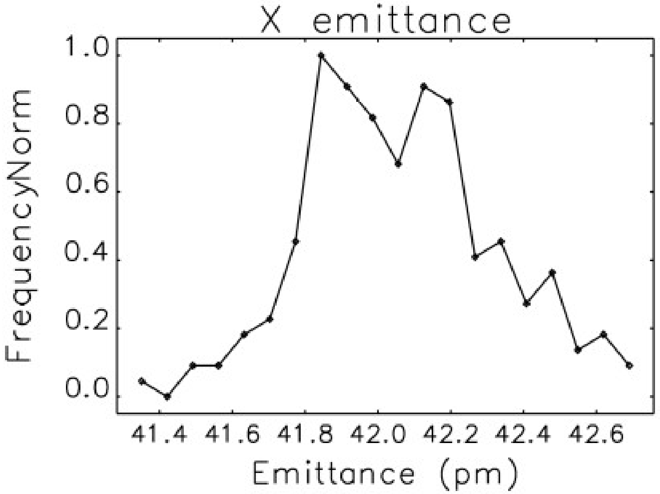


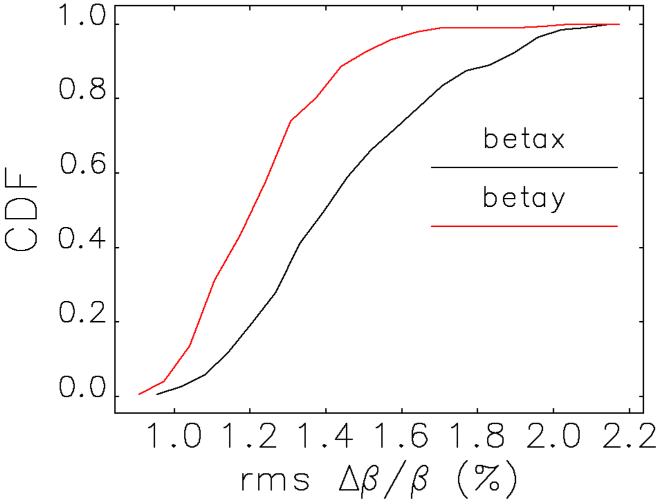
Example of DA and Touschek lifetime optimization for an early APS-U design

1: M. Borland et al., ANL/APS/LS-319 (2010).
2: M. Borland et al., ICAP09. THPsc009 (2009).
3: N. Srinivas et al., Evol. Computing 2, 221-248 (1995).
4: I. Bazarov et al., PRSTAB 8, 034202 (2005).
5: M. Borland, ANL/APS/LS-287 (2000).
6: Y. Wang et al., AIP Conf. Prooc. 877, 241 (2006).
7: M. Venturini et al., NIM A 427, 387.

Automated commissioning simulation has many benefits[1,2]

- Procedure made as realistic as reasonably possible by including
  - Alignment strategy (supports, survey, magnet groups)
  - Error generation, field-quality errors
  - Trajectory threading transitioning to orbit correction
  - Beta function and coupling correction
- Provides statistical distributions of basic quantities and “ensembles” of errors and corrections
- Defines many requirements for magnet measurement, power supplies, diagnostics, correctors, alignment
- 5GSR challenges:
  - Diagnostics must get progressively better, e.g., small BPM offsets, increased BPM sensitivity, reliable loss localization





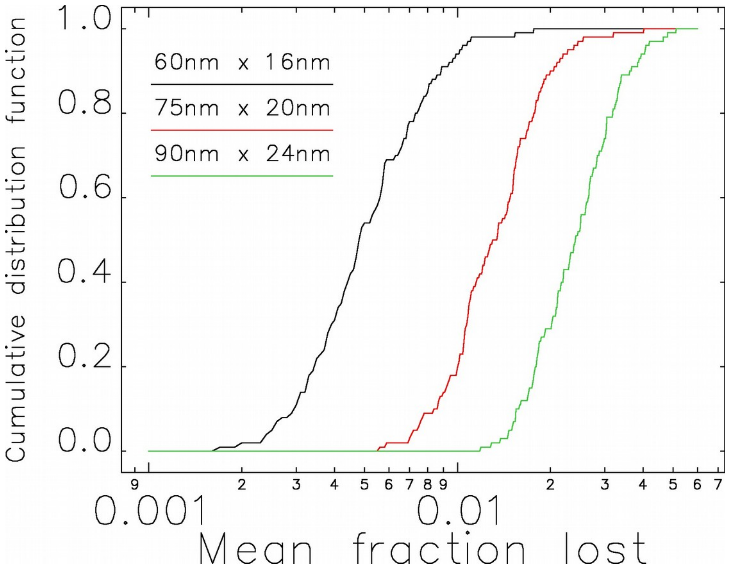
V. Sajaev

[1] V. Sajaev et al., IPAC15, 553.
[2] V. Sajaev PRAB 22, 040102 (2019).

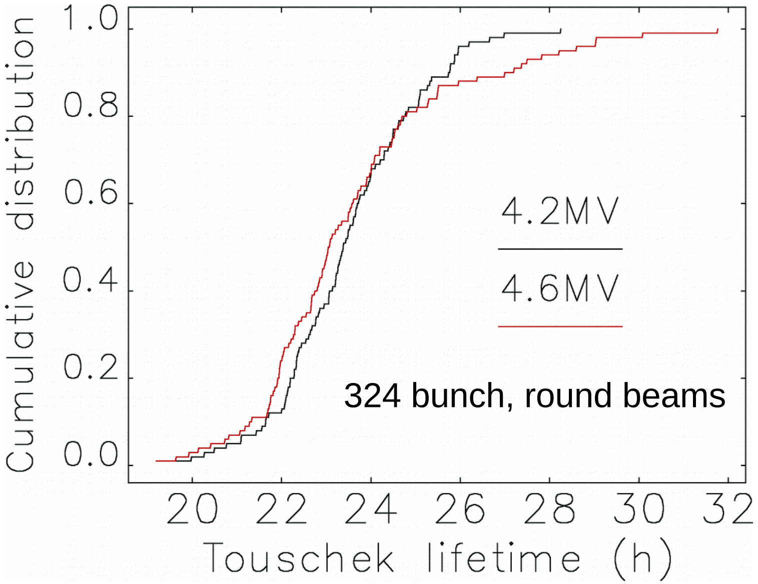
Large-scale simulations confirm robustness of lattice

- Commissioning simulation gives 100+ ensembles of errors and corrections
  - More representative of possible machines than alternative methods
- Use with tracking-based simulations to give distributions of possible performance

Injection loss fraction distribution

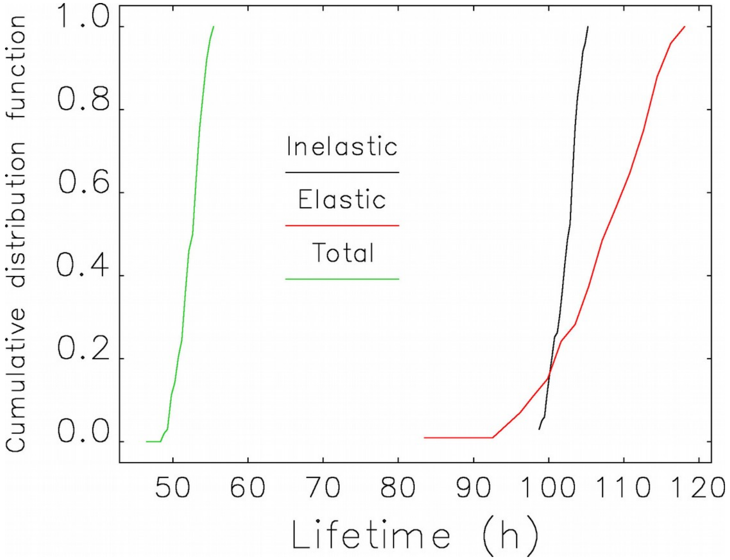


Touschek lifetime distribution



324 bunch, round beams

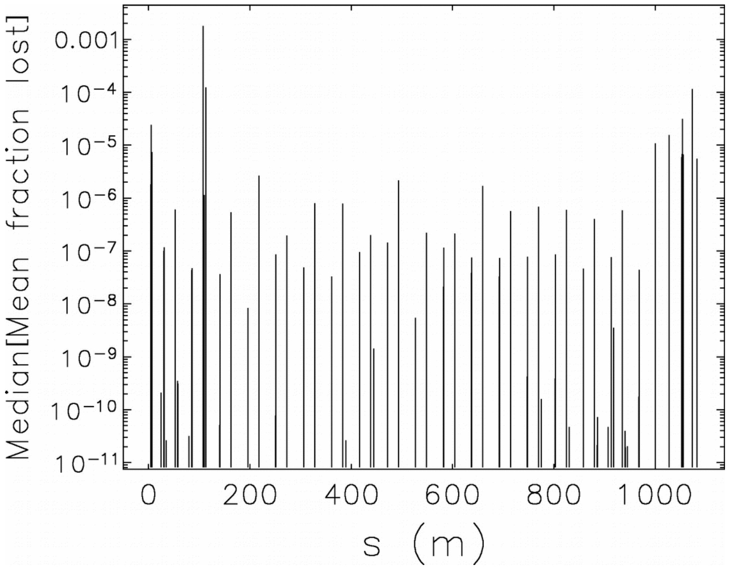
Gas-scattering lifetime distribution



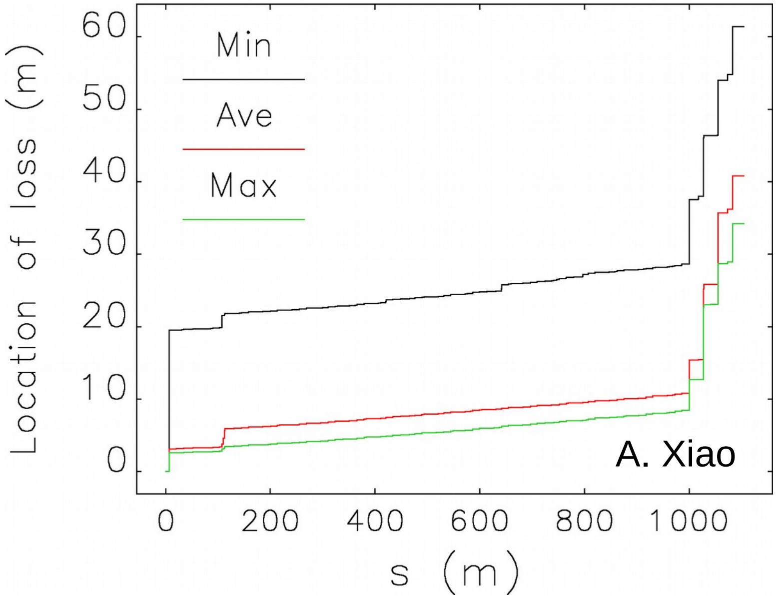
- Use of parallel code (***elegant*** in our case) is essential
- 5GSR challenge again is the underlying simulation method

Direct simulation of loss mechanisms has many benefits

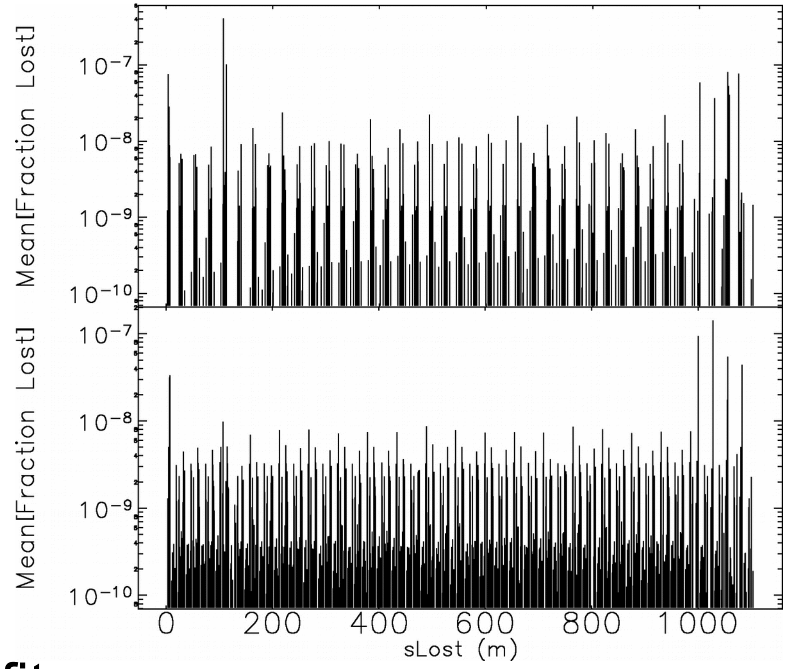
Injection loss distribution



Touschek scattering loss distribution[1]



Gas-scattering loss distribution[2]

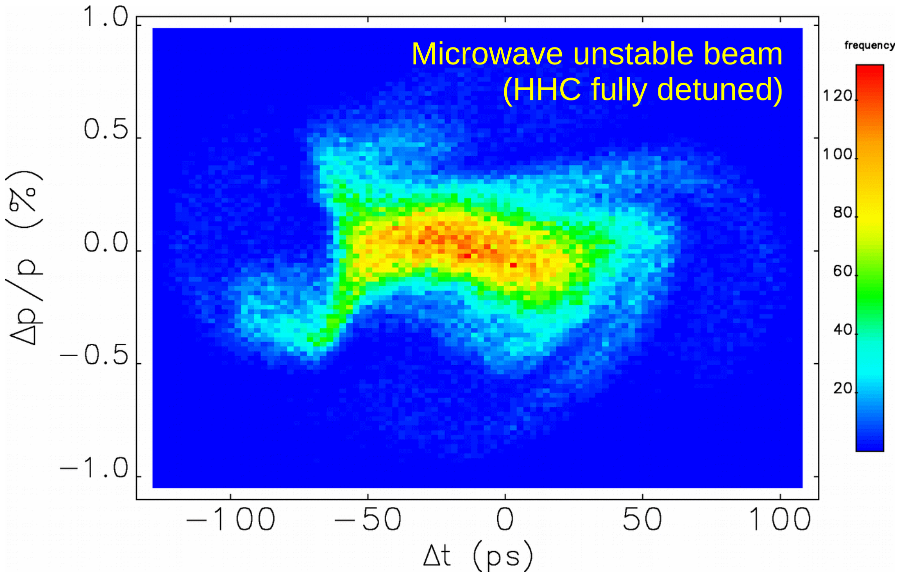


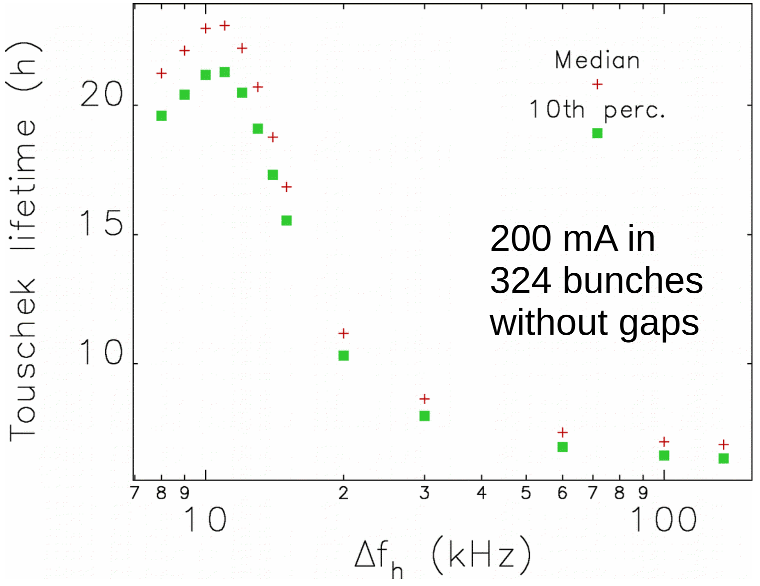
- Direct simulation of loss mechanisms provides several benefits
  - Assessment and tuning of collimation strategy
  - Prediction of loss distribution for use in shielding analysis[3] with MCNP[4]
  - Confirmation of lifetime and injection efficiency expectations
- 5GSR challenge again is the underlying simulation method

1: A. Xiao et al., PRSTAB 13, 074201 (2010).
2: M. Borland, NAPAC19, WEPLE08 (2019).
3: B. Micklich et al., AccApp 2017,52.
4: C. J. Werner et al., LANL LA-UR-18-20808 (2018).

Combining single- and multi-bunch effects yields insights

- Microwave and transverse instability thresholds[1]
- Determination of bunch-by-bunch feedback requirements including Higher Harmonic Cavity[2]
  - Synchrotron tune suppression overwhelms benefit of Landau damping
  - Energy-sensing pickup highly favored
- Touschek lifetime vs passive HHC detuning[3], with gaps[4]
  - Overstretching helps, up to a point
- Injection transients when filling from zero[5,6]
  - Fill in stages to avoid beam losses
  - Ensure that tune shift with amplitude not too low
  - Use on-axis injection to minimize centroid motion
- Challenges
  - Sufficient spatial resolution to get high-frequency impedance for long structures
  - Strict correspondence between what's designed and what's built
  - Including real-world noise and spurious signals in feedback simulations



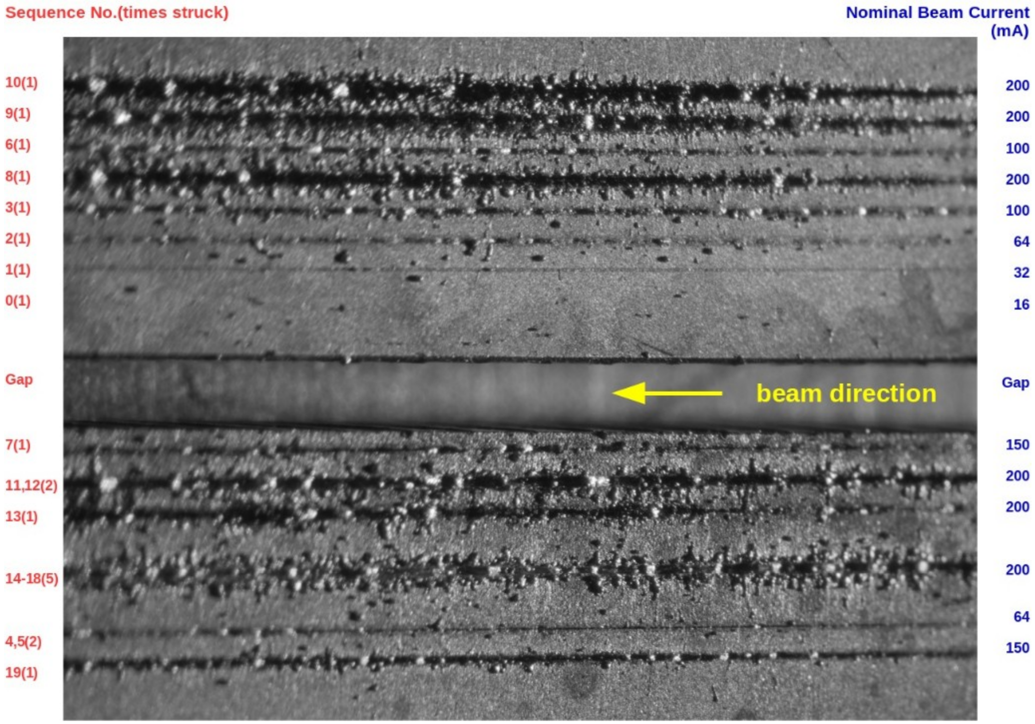


1: R. Lindberg et al., IPAC15, 1822.
2: L. Emery et al.,
3: A. Xiao et al., PAC09, 3281

4: J. Calvey et al., PRAB 22, 114403.
5: M. Borland et al., ICAP15, 61.
6: R. Lindberg et al., NAPAC16, 901.

4GSR beams are destructive

- Even in APS today, beam dumps are damaged by beam strikes[1]
- In APS-U, problem for swap-out and whole-beam dumps
- Several approaches to solving this
  - Decoherence kicker[2], if time permits
  - Sacrificial surfaces for unplanned aborts
  - Unpopular materials (graphite, beryllium)
  - Solid xenon dump[3]
- Challenges
  - Control of rf heating in a complex dump geometry or cryogenic materials
  - Need a code suite that couples beam dynamics, beam-matter interaction, and material evolution
    - ANL is working on this with elegant, MARS[4], and FLASH[5], but underfunded

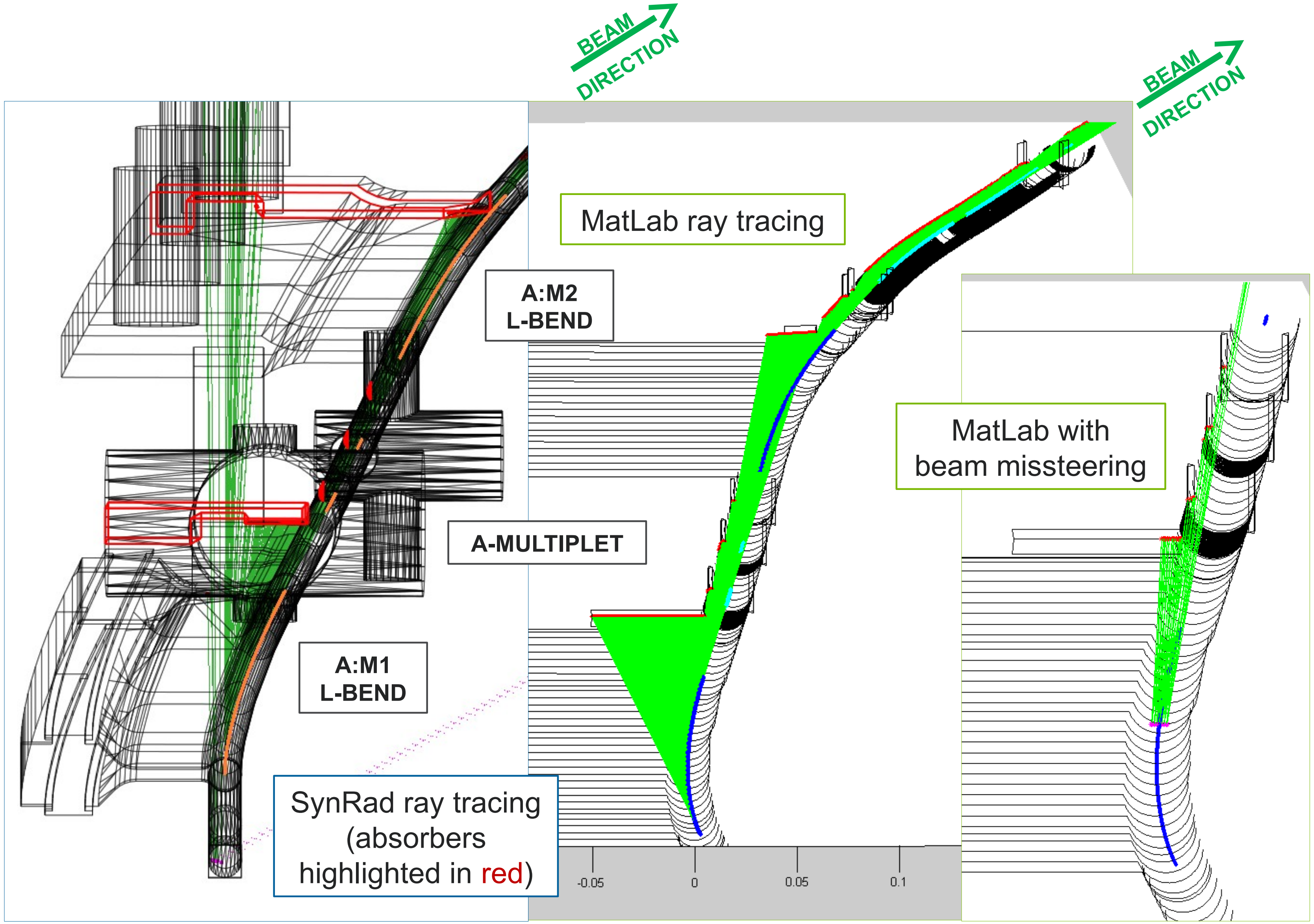


Experiment in APS, Feb. 2020 at approximate APS-U conditions, Al-6061 target.

1: J. C. Dooling et al., PAC13, 1361.
2: M. Borland et al., IPAC18, 1494.
3: M. Borland et al., NAPAC19,
4: N. Mokhov et al. Fermilab-Conf-07/008-AD (2007).
5: http://flash.uchicago.edu

SR masking is critical for high-current electron rings

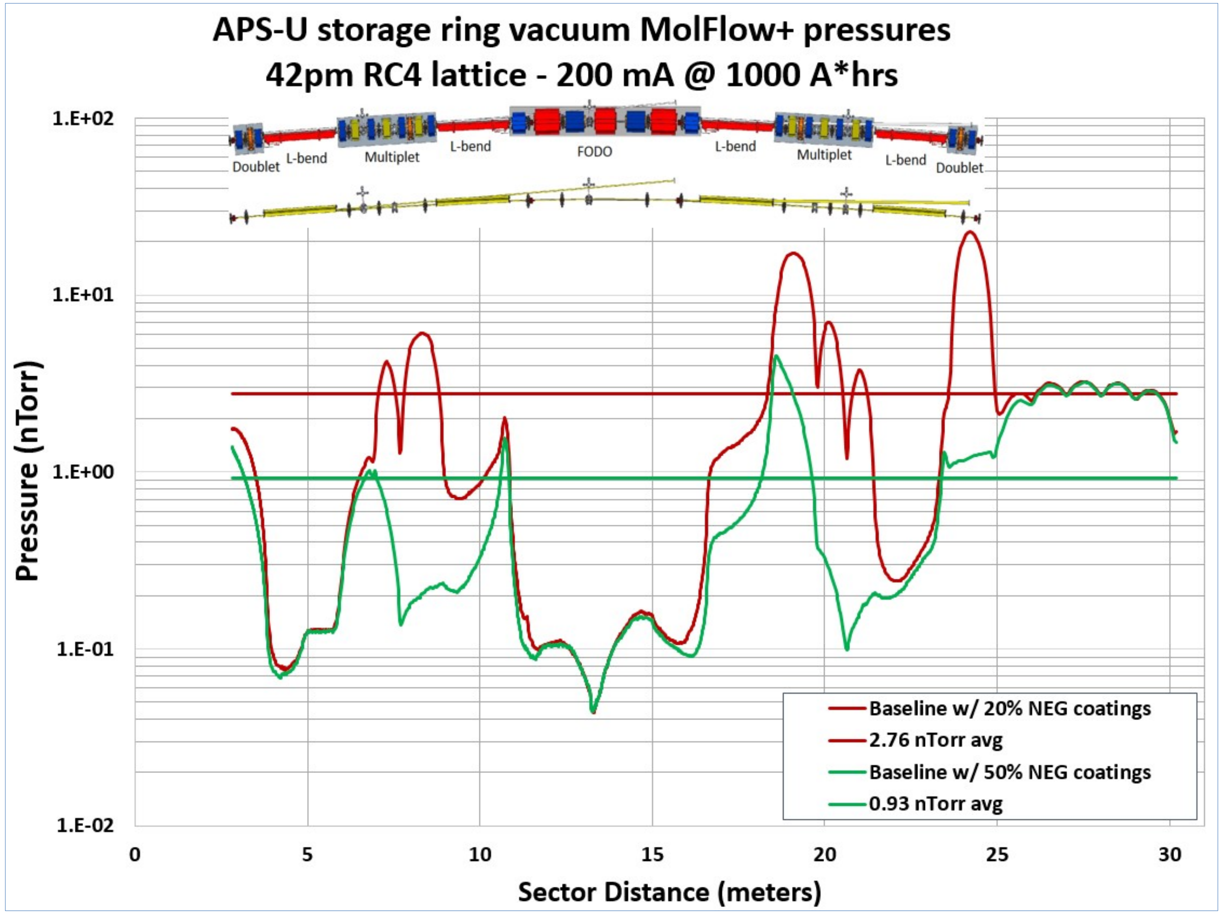
- Strong bends, narrow apertures, and high beam current imply high power density on APS-U chambers[1]
- 3D ray tracing performed using several methods
  - SynRad[2] from CERN
  - 3D MATLAB: explore missteering, verify 'perfect steering' case from SynRad
- Masking strategy also evaluated for beam impedance effects
- 5GSR challenge: even smaller apertures, brighter beams



1: J. A. Carter et al., MEDSI 18, 312.
2: R. B. Kersevan et al., PAC93, 3848.

Coupling vacuum and physics modeling is important

- Vacuum pressure analysis with MolFlow[1] provides species-specific pressure profiles
    - Based on measured photon-stimulated desorption data coupled with SR distribution from SynRad
- Pressure profiles[2] shared with physics team, allowing computation of
    - Gas scattering lifetime and loss distribution
    - Ion instabilities[3]
    - Conditioning schedule
- Coupled analysis led to conclusion that more wide-spread NEG coating was needed to suppress PSD in regions with large lattice functions
- 5GSR challenge: need much lower pressure


APS-U storage ring vacuum MolFlow+ pressures
42pm RC4 lattice - 200 mA @ 1000 A*hrs

Configuration with wider application of NEG provides >2-fold increase in gas scattering lifetime

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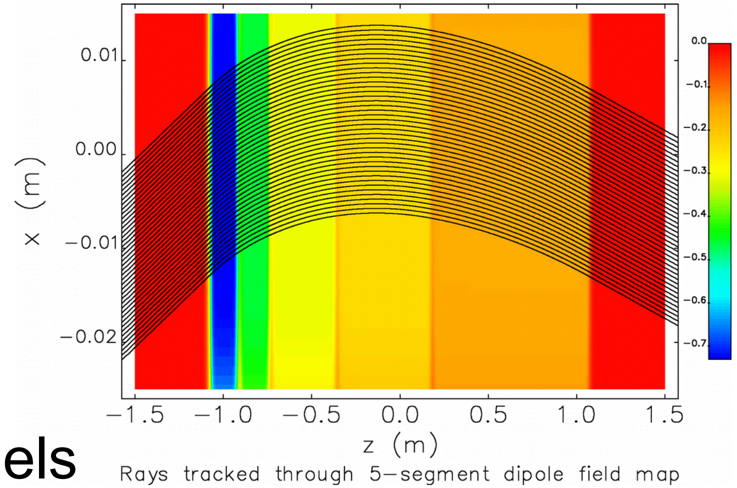
1: M. Ady et al., IPAC14, 2344.
2: J. A. Carter et al., MEDSI 18, 30.
3: J. Calvey et al, PRAB **22**, 114403.

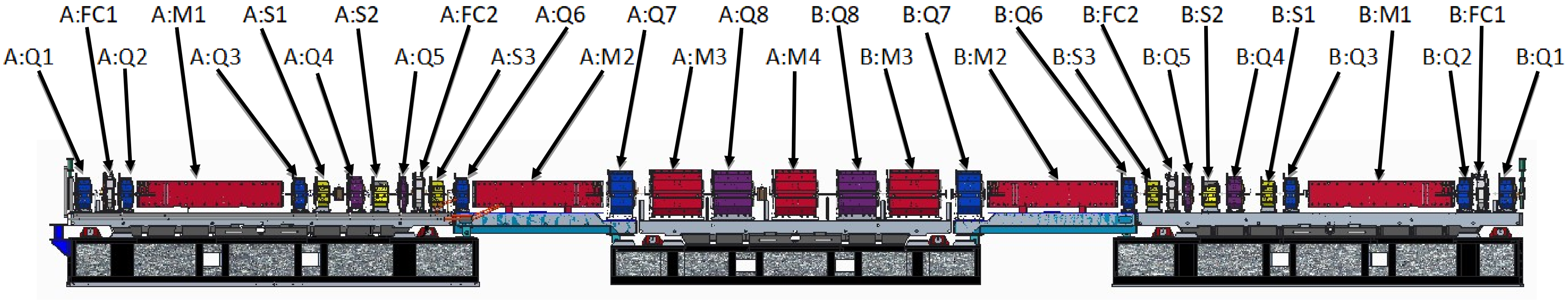
APS-U requires 15 magnet types, 33 magnets/sector

- Variety and strength of magnet designs is remarkable, e.g.,
  - Dipoles with 5-segment longitudinal field variation
  - Gradients up to 97 T/m
  - Sextupole strength up to 6000 T/m^2
- 3D magnet designs developed with OPERA[1]
  - Iterative process with lattice design using parametric models
  - 3D field maps, generalized gradient expansions[2] imported into ***elegant*** to validate designs[3]
  - OPERA used to assess cross-talk of closely-spaced magnets



Rays tracked through 5−segment dipole field map

[1] operafea.com
[2] M. Venturini et al., NIM A 427, 387.
[3] M. Borland et al., NAPAC16, 1119.



Now is the time to plan for 5th generation rings

- First 4th-generation design was published in 1996 [1]
- "Ultimate" ring would have <1-pm emittance, diffraction-limited at ~100 keV
- Conceivable with, e.g., 21 dipoles per cell instead of the 7 in APS-U
- What's needed for M=7 → M=21 (see [2] for scaling behavior)
    - Higher focusing gradients ~600 T/m with ~1.5mm bore radius
    - Higher sextupole strength ~160 kT/m^2, with ~2.5mm bore radius
    - Alignment precision of ~2 μm, or individual movers for all magnets
    - Low-emittance recycler ring to prepare and reclaim bunches for ring
    - Accumulator ring to prepare beams from injector for the recycler ring
    - Superconducting vacuum chamber to reduce resistive wall impedance
    - ~100-fold reduction in vacuum pressure to improve lifetime with small acceptance
    - New ideas for optimizing nonlinear dynamics
    - 3D magnet code with higher resolution, faster execution, perhaps coupled directly to tracking code
    - Confident prediction of nonlinear dynamics, lifetime, collective effects, etc.
- The necessary knowledge might not be gained incrementally from 4GSRs

} From naive scaling of present conventional magnets

1: D. Einfeld et al., EPAC96, WEP038G.
2: M. Borland et al., J. Synch. Rad **21**, 912-936 (2014).