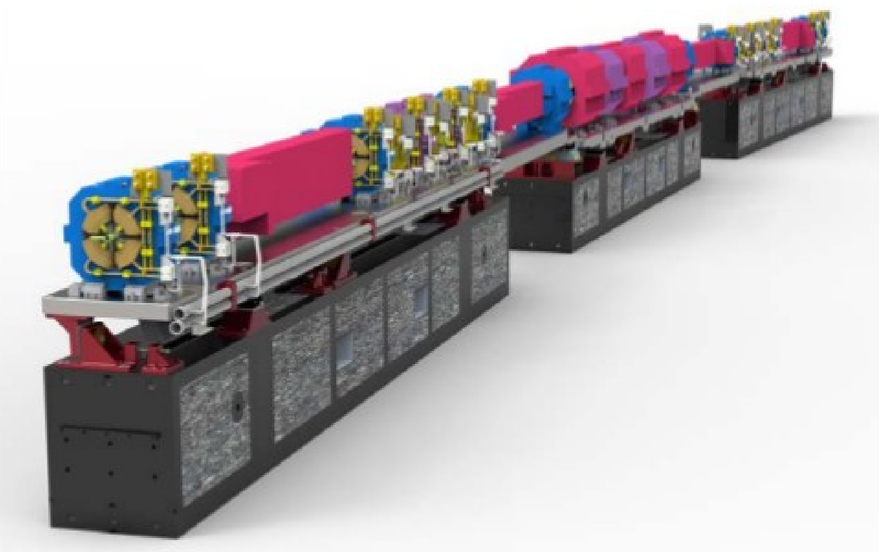
Argonne NATIONAL LABORATORY

Argonne Accelerator Capabilities and Potential Contributions to the EIC



Michael Borland
Jason Carter, John Carwardine, Manoel Conde, Mark Jaski, Michael Kelly, Brahim Mustapha, Joseph Xu

10 October 2019

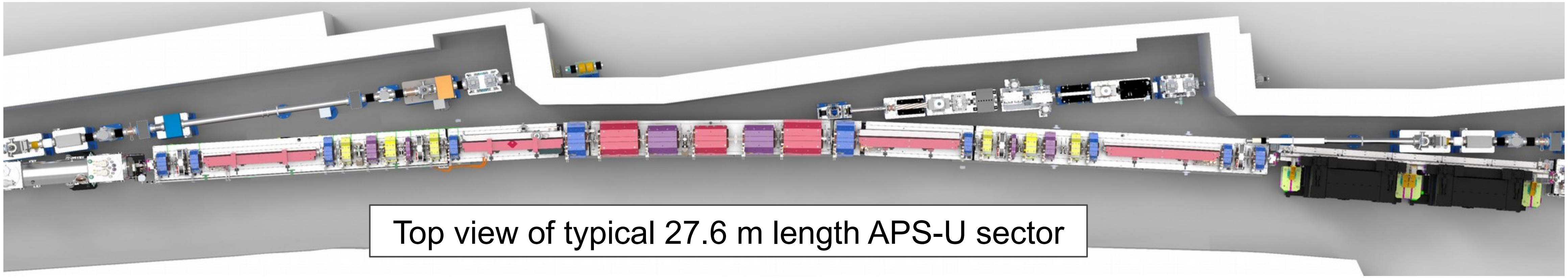
Argonne has a significant presence in accelerators

- Argonne operates four national accelerator-based facilities
  - APS: 7-GeV electron storage ring for x-ray production
  - ATLAS: world's first heavy ion superconducting accelerator
  - AWA: facility for characterization of wakefields, advanced beam acceleration and manipulation techniques
  - LEAF: 25-kW electron beam facility for radioisotope production
- We support facilities under construction elsewhere, e.g.,
  - LCLS-II (SLAC)
  - FRIB (MSU)
  - PIP-II (FNAL)
  - Support has included simulation, vacuum systems, conventional magnets, insertion devices, SC rf cavities, and diagnostics
- On-going ANL projects include APS-U, a world-leading ultra-low-emittance ring for APS

APS Upgrade project showcases ANL expertise

- Entirely new 6-GeV, 200-mA ring, including
  - Advanced multi-bend-achromat lattice
  - 1104 m of vacuum systems
  - 1320+ high-strength conventional magnets
  - Superconducting insertion devices
  - Orbit correction system with 1 kHz bandwidth
  - New and upgraded x-ray beamlines
- Will exceed capabilities of today's storage ring light sources by 2 to 3 orders of magnitude

Advanced Photon Source (APS)

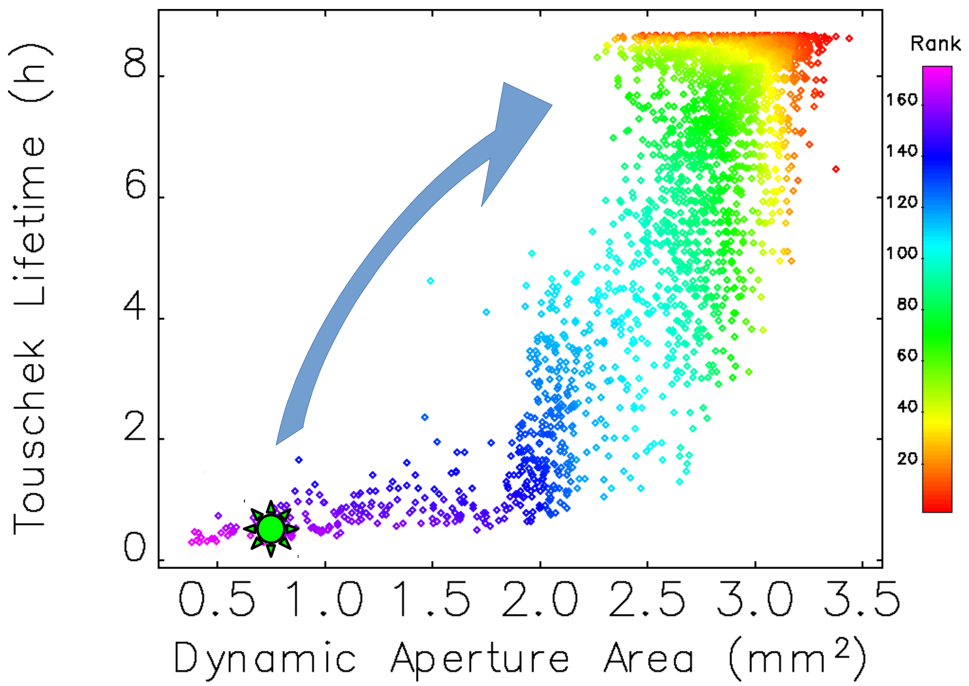


Top view of typical 27.6 m length APS-U sector

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 to new solutions to find best
  - Dynamic acceptance
  - Touschek lifetime from local momentum acceptance
  - Momentum tune footprint
  - X-ray brightness
- Applications to present-day APS found to provide unexpected solutions

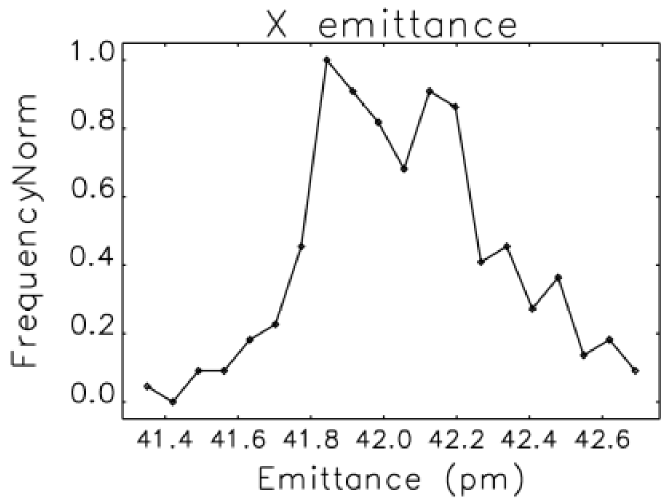


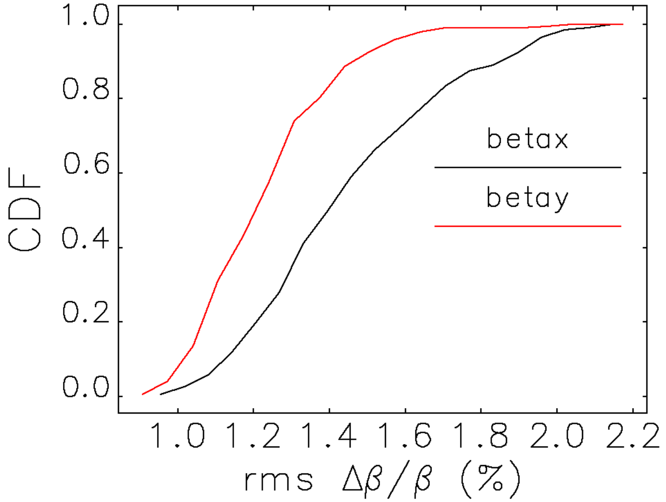
Example of DA and Touschek lifetime optimization for an early APS-U design

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).

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
- Tests on existing APS ring have demonstrated ability to achieve stored beam



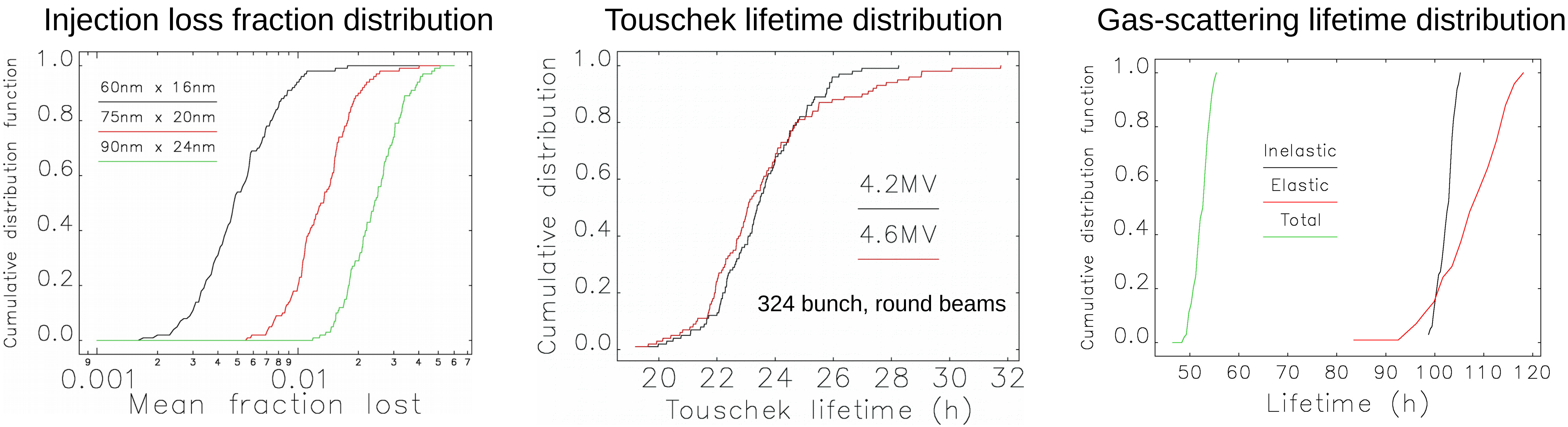


V. Sajaev

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

Large-scale simulations confirm robustness of lattice

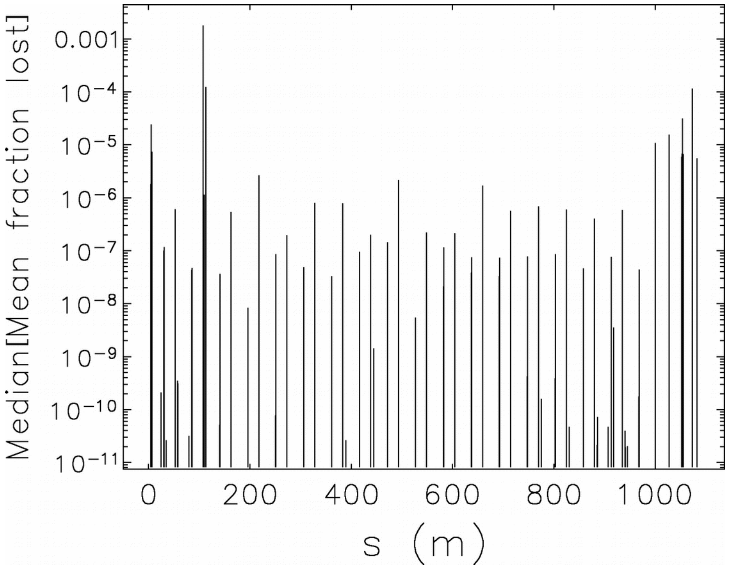
- Commissioning simulation gives 100+ ensembles of errors and corrections
  - More representative of possible machines than alternative methods
- Evaluate using tracking-based simulations to give distributions of possible performance



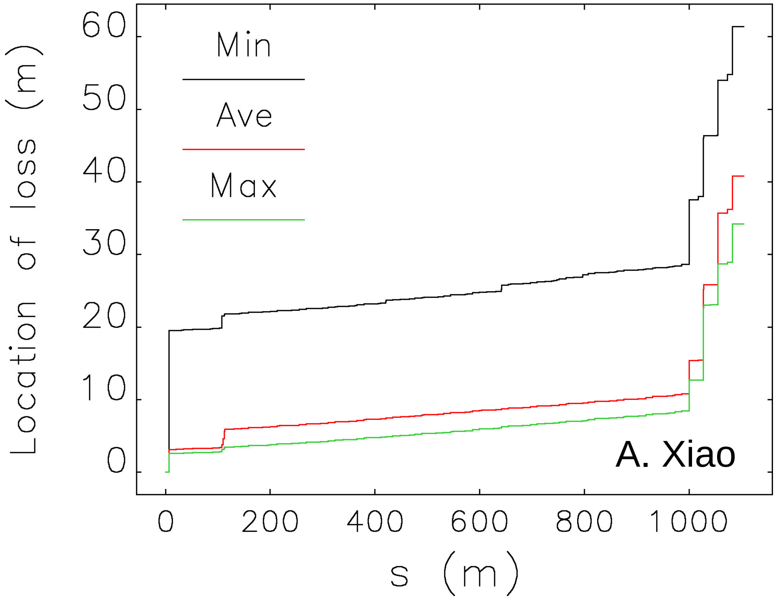
- Use of parallel code (***elegant*** in our case) is essential

Direct simulation of loss mechanisms has many benefits

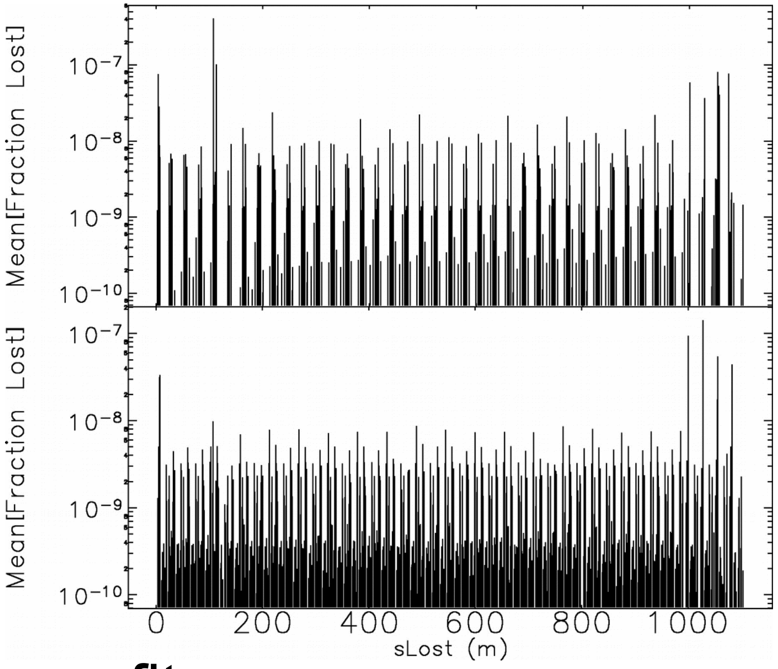
Injection loss distribution



Touschek scattering loss distribution[1]



Gas-scattering loss distribution[2]

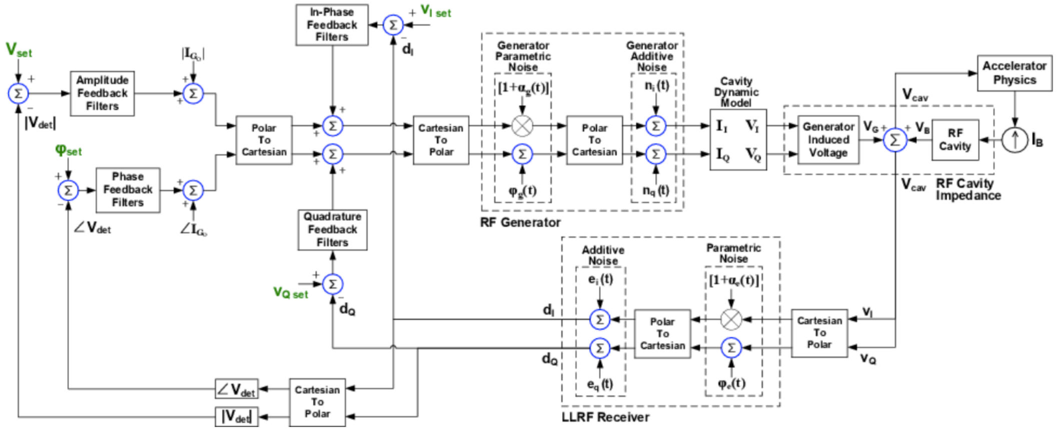


- Direct simulation of loss mechanisms provides several benefits
  - Assessment and tuning of collimation strategy
  - Prediction of loss distribution for use in shielding analysis[3] with MCNP[4]
  - Confirmation of lifetime and injection efficiency expectations

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).

Combined single- and multi-bunch modeling supported

- ***elegant*** supports various collective effects[1,2]
  - Short and long-range wakes
  - Resonant cavity modes
  - Accelerating cavities with feedback, noise/modulation injection[3]
  - Bunch-by-bunch feedback incl. feedback cavity[4]
  - Slice-based Touschek lifetime and intrabeam scattering[5]
  - Supports energy-ramped rings



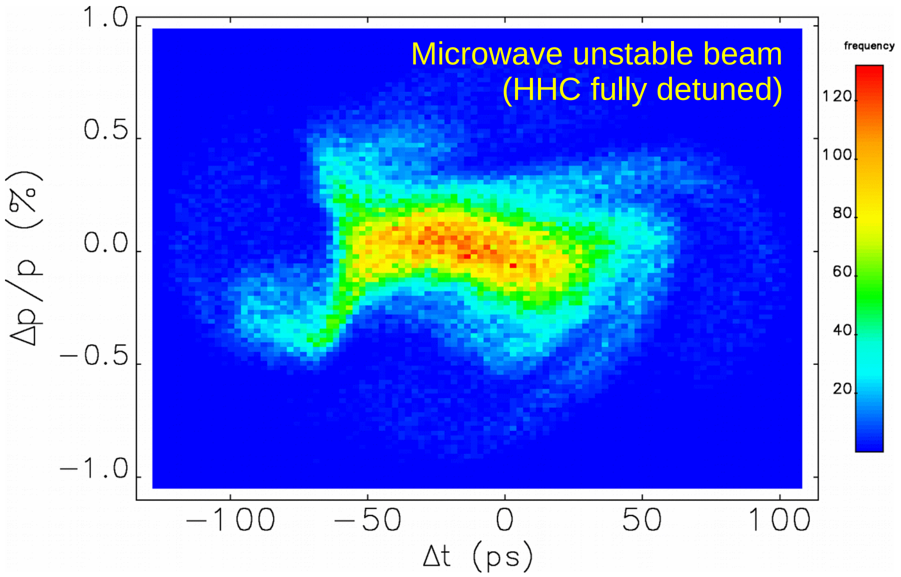
Rf feedback model (T. Berenc).

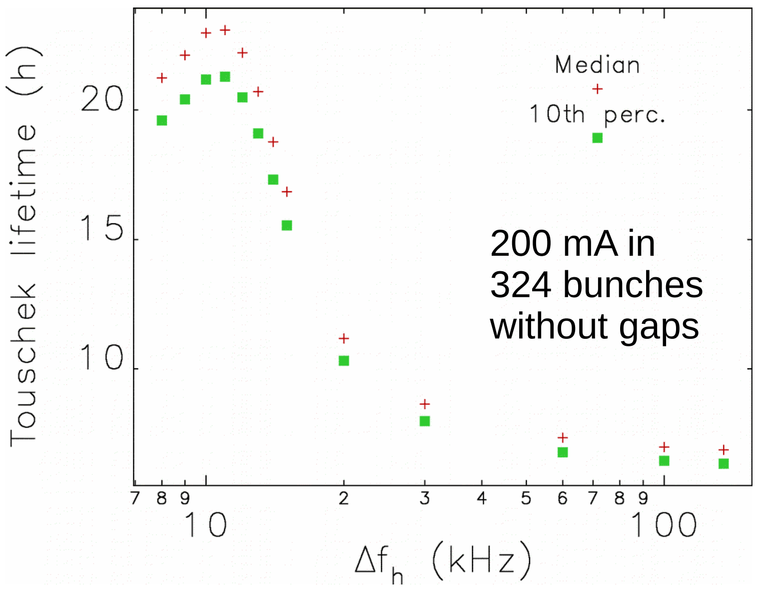
- ***clinchor***[6] is a complementary tool for fast coupled-bunch analysis
  - Performs normal-mode analysis[7] for arbitrary fill patterns
  - Sweeping, staggering, and randomization of HOM frequencies
  - Initialized by data from ***elegant***
  - Shares mode data files with ***elegant***

1: M. Borland et al., IPAC15, 549.
2: M. Borland et al., ICAP15, 61.
3: T. Berenc et al., IPAC15, 540.
4: L.. Emery et al., IPAC15, 1784.
5: A. Xiao et al., PAC09, 3281.
6: L. Emery, PAC93, 3360.
7: K. Thompson et al., PAC89, 792.

Comprehensive simulations yield crucial information

- 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]
  - Overstretching helps, up to a point
- Touschek lifetime with compensated train gaps[4]
- Injection transients when filling from zero[5,6]
  - Fill in stages to avoid beam losses
  - Ensure that tune shift with amplitude not too low

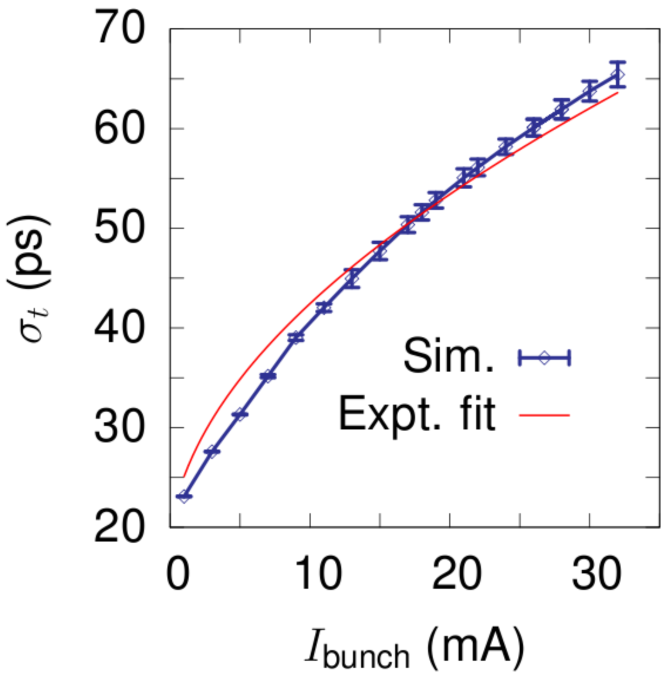




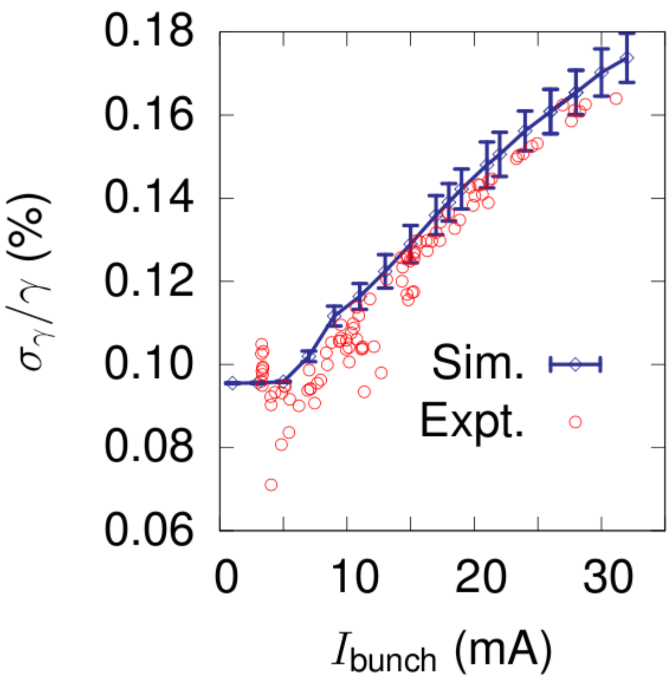
1: R. Lindberg et al., IPAC15, 1822.
2: L. Emery et al.,
3: A. Xiao et al., PAC09, 3281
4: J. Calvey et al., submitted to PRAB.
5: M. Borland et al., ICAP15, 61.
6: R. Lindberg et al., NAPAC16, 901.

Tracking-based predictions of collective effects for the present APS agree with measurements[1,2,3]

Longitudinal collective effects

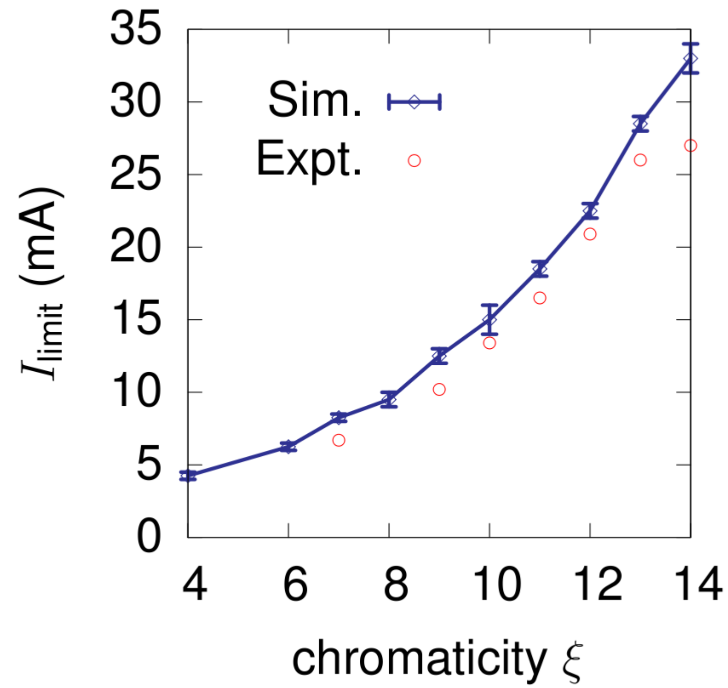


Bunch lengthening is well captured by simulation



Microwave instability onset and energy spread growth is closely predicted

Instability threshold current



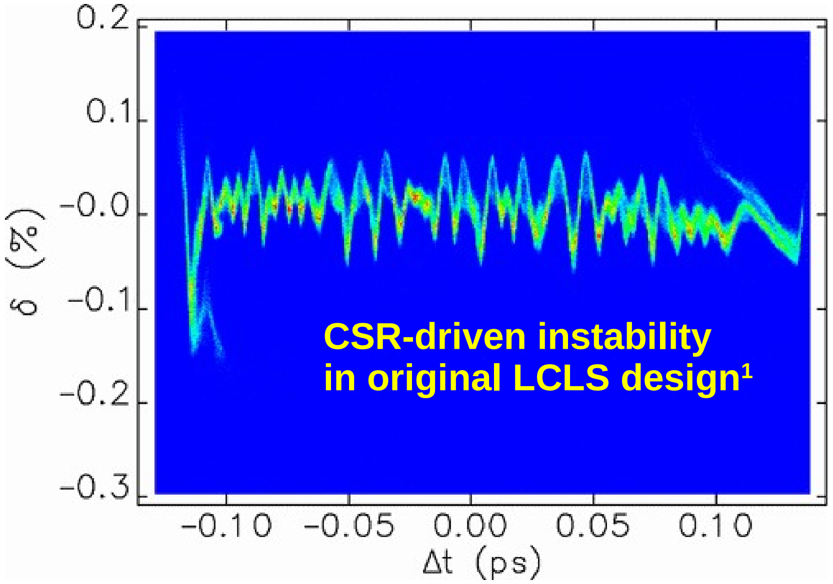
Simulations predict transverse collective instability threshold to within 15% over wide range of chromaticity

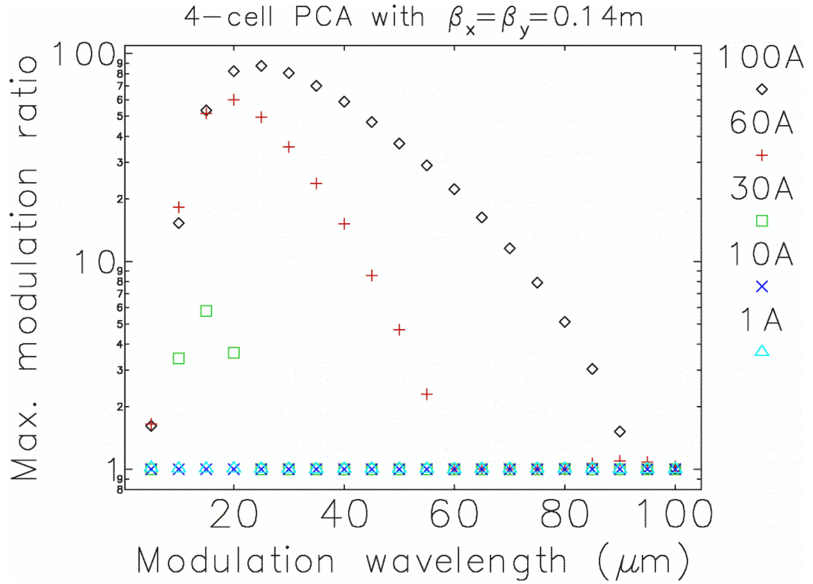
1: V. Sajaev et al., PAC13, 405 (2013).
2: R. Lindberg et al., IPAC15, 1822 (2015).
3: S. Shin et al., PRAB 22, 032802 (2019).

R. Lindberg

Capabilities extend beyond storage ring modeling

- ***elegant*** is used for many FEL designs, e.g., DESY, SLAC, MAX-IV, PSI, PAL, ...
  - Fast parallel CSR[2], LSC[3], wakes
  - Component of start-to-end simulations[4,5]
- Recently used to compute microbunching gain curves for 4-cell Plasma Cascade Amplifier[6] as a function of modulation wavelength and peak current
  - A single job, using 100M macroparticles, takes ~2 hours on 48 cores

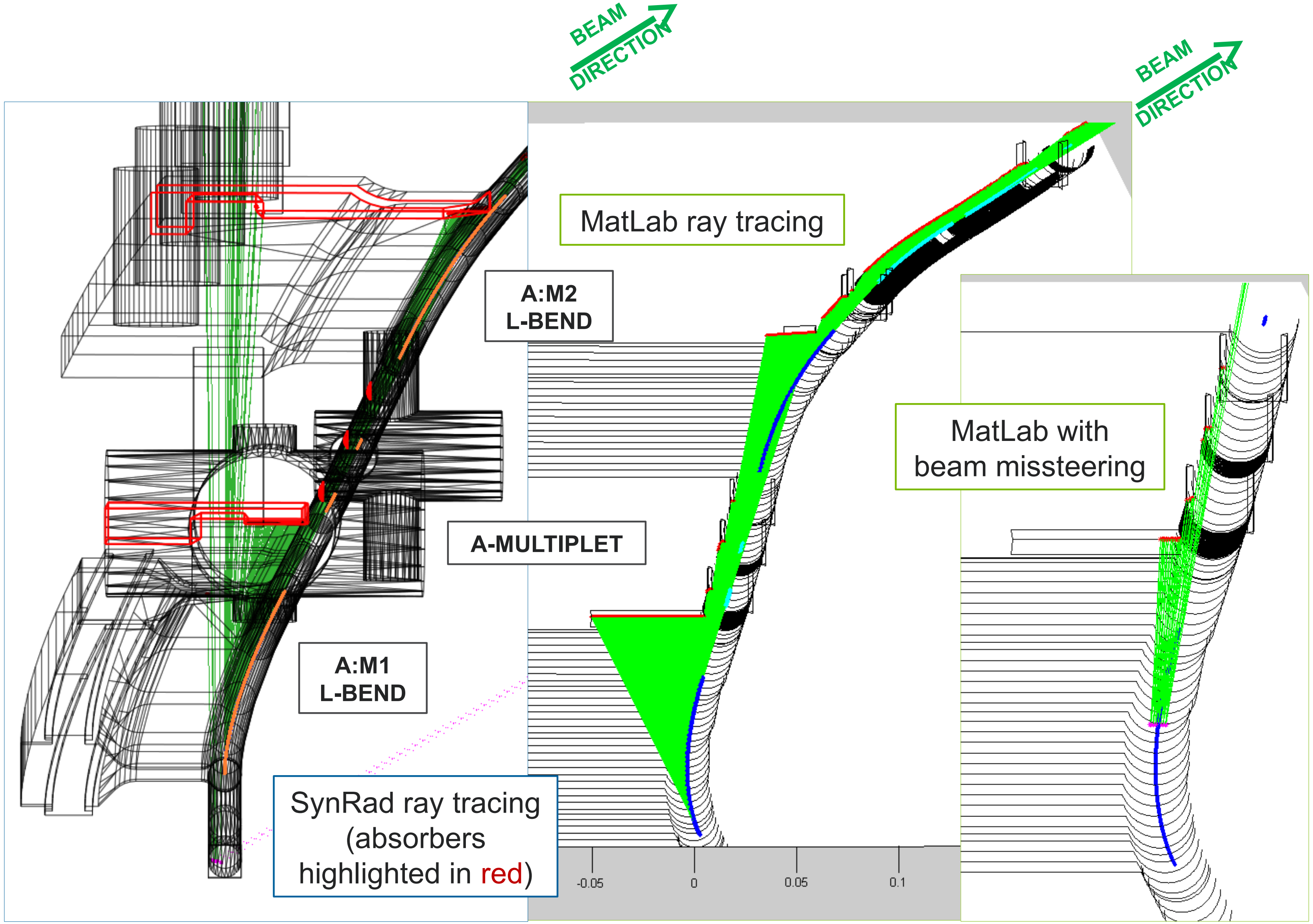




1: M. Borland et al., PAC2001, 2707.
2: M. Borland, PRSTAB 4, 070701.
3: Z. Huang et al., PRSTAB 7, 074401
4: C. G. Parazzoli et al, NIM A 449, 1.
5: M. Borland et al., NIM A 483, 268.
6: V.Litvinenko et al., arXiv:1802.08677.

SR masking is critical for high-current electron rings

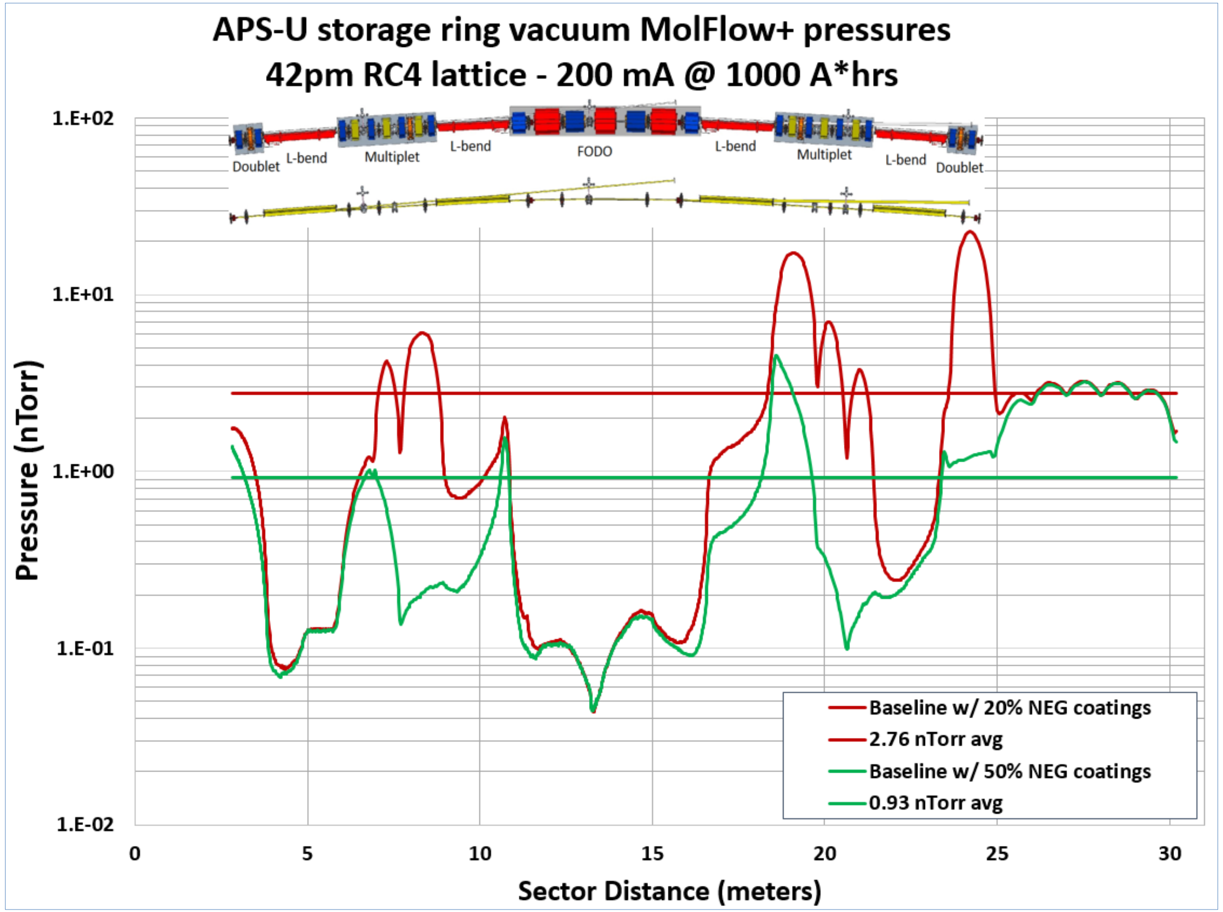
- Strong bends, narrow apertures, and high beam current imply high power density on APS-U chambers[1]
- 3D ray tracing performed using several methods
  - SynRad[2] from CERN
  - 3D MATLAB: explore missteering, verify ‘perfect steering’ case from SynRad
- Masking strategy also evaluated for beam impedance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



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
  - Gas scattering lifetime and loss distribution
  - Ion instabilities
  - Conditioning schedule
- Coupled analysis led to conclusion that more wide-spread NEG coating was needed to suppress PSD in regions with large lattice functions



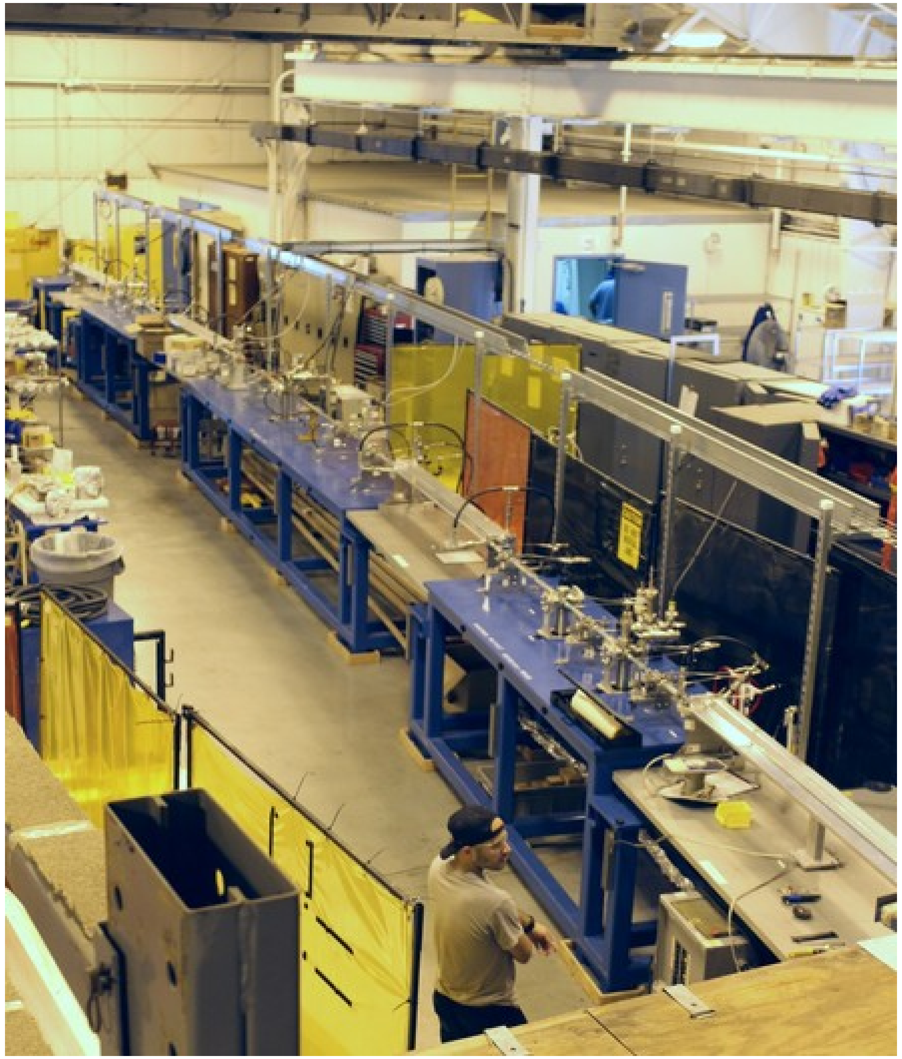
Configuration with wider application of NEG provides >2-fold increase in gas scattering lifetime

1: M. Ady et al., IPAC14, 2344.
2: J. A. Carter et al., MEDSI 18, 30.

Vacuum R&D and fabrication capabilities are well developed

- APS aluminum chamber welding system used for APS, BESSY, DESY FEL, SLS, ESRF, CLS, KEK, NSLS-II, LCLS, APS-U
- APS-U full-sector mockup of conceptual design components tests vacuum, bakeouts, NEG-activations, water cooling, ...

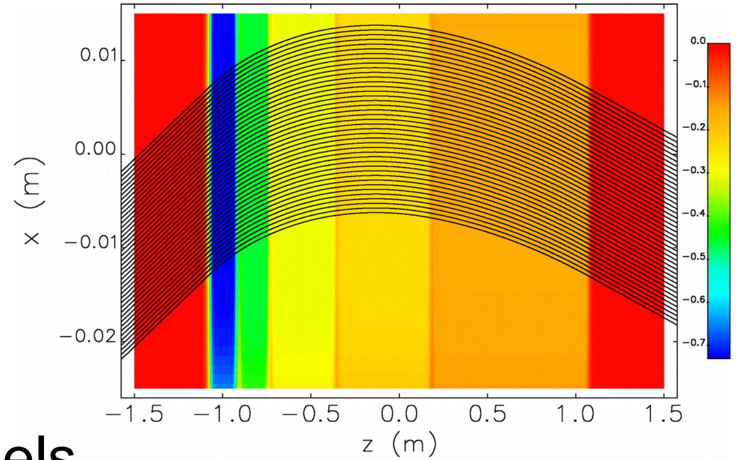
Aluminum L-bend A-Joint Welding at ANL with 5-axis welder



Storage Ring Vacuum System Sector Mockup

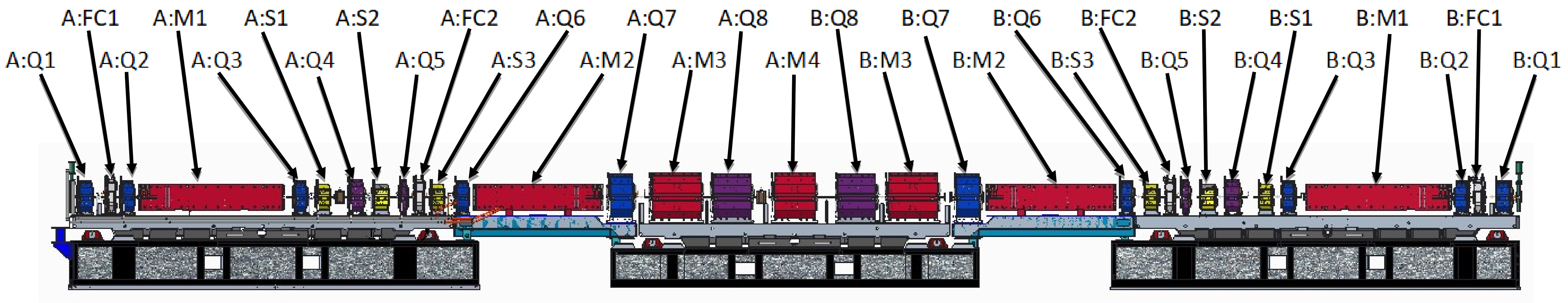
APS-U requires 15 magnet types, 33 magnets/sector

- 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

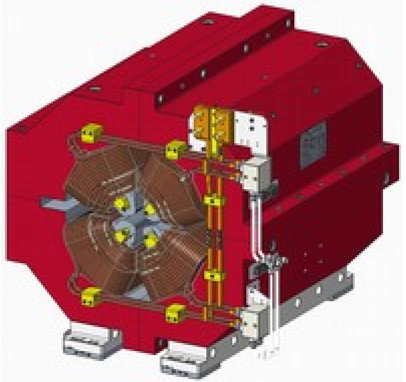


Rays tracked through 5−segment dipole field map

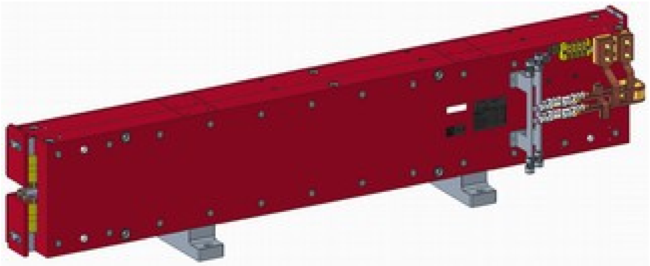
1: operafea.com
2: M. Venturini et al., NIM A 427, 387.
3: M. Borland et al., NAPAC16, 1119.



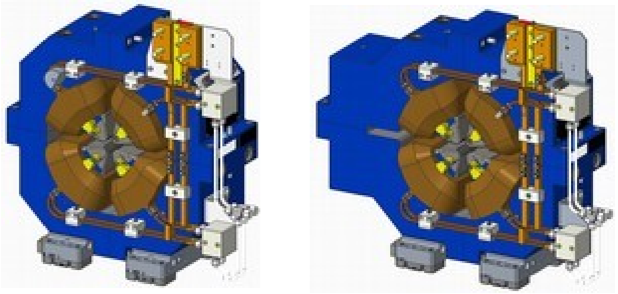
APSU magnet production is well underway



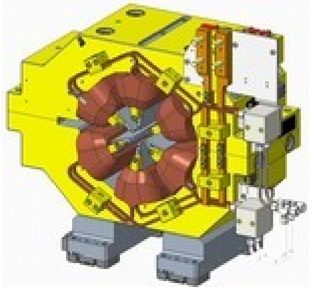
Q-Bend Magnets
M3,M4



L-Bend Magnets (M1, M2)

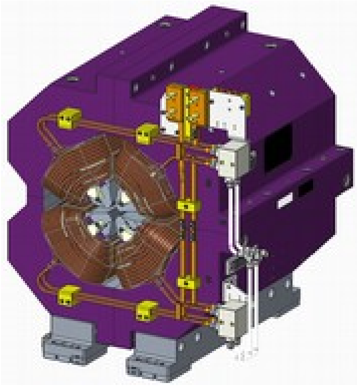


Q1, Q2, Q3, Q6 and Q7
Quadrupole Magnets

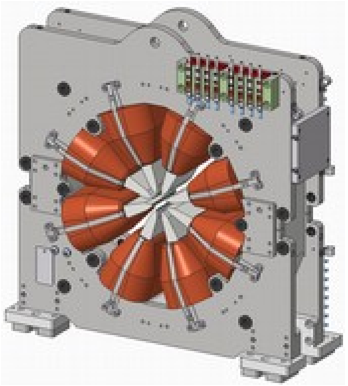


Sextupole Magnets
S1- S3

- All magnets have been prototyped
- Precision measurement and alignment methods developed and validated[1]
- Strength and field quality in good agreement with expectations
- Measurements from several first-article magnets and series (Q1, Q2) production validated by tracking



Reverse Bend
Quadrupole Magnets
Q4, Q5, and Q8



8-Pole Corrector[2]
(FC1 and FC2, BNL design)

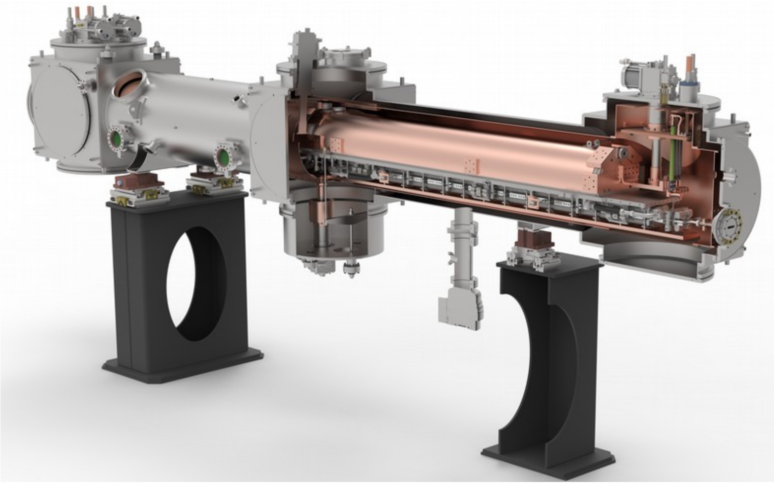
1: C. Doose et al., NAPAC16, 884.
2: F. DePaola, MEDSI 18, 50.

Unique insertion devices provided for many applications

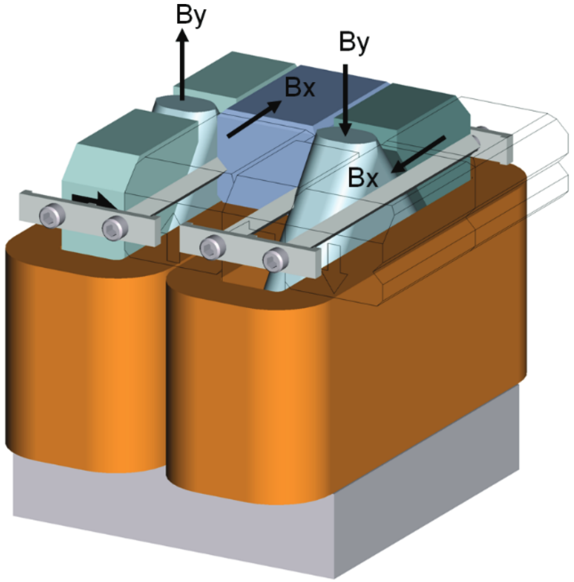
- Electron storage rings use IDs (wigglers, undulators) for radiation production and damping
- We design, build, measure, tune, and operate permanent-magnet, electro-magnetic, and superconducting IDs

XLEAP Wiggler for LCLS,
J. P. MacArthur et al., IPAC17, 2848.

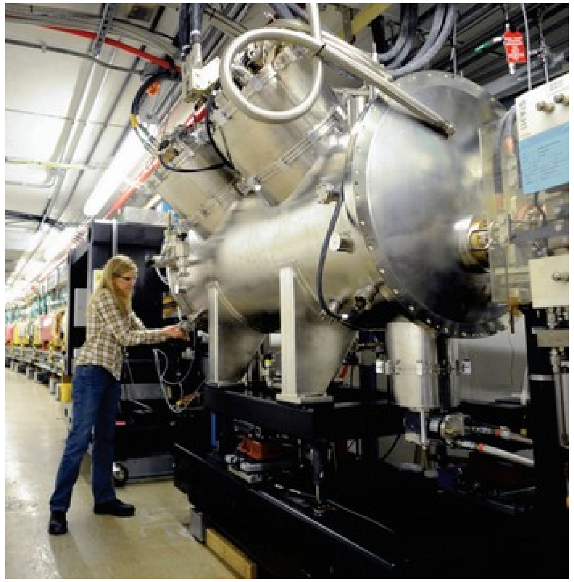
LCLS-I undulators after installation.
J. C. Bailey et al., FEL08, 460.



Cut-away view of APS-U superconducting undulator (M. Kasa *et al.*, IPAC19, 1885)



Quasi-periodic wiggler for arbitrary radiation polarization (M. Jaski et al., PAC09, 318.)

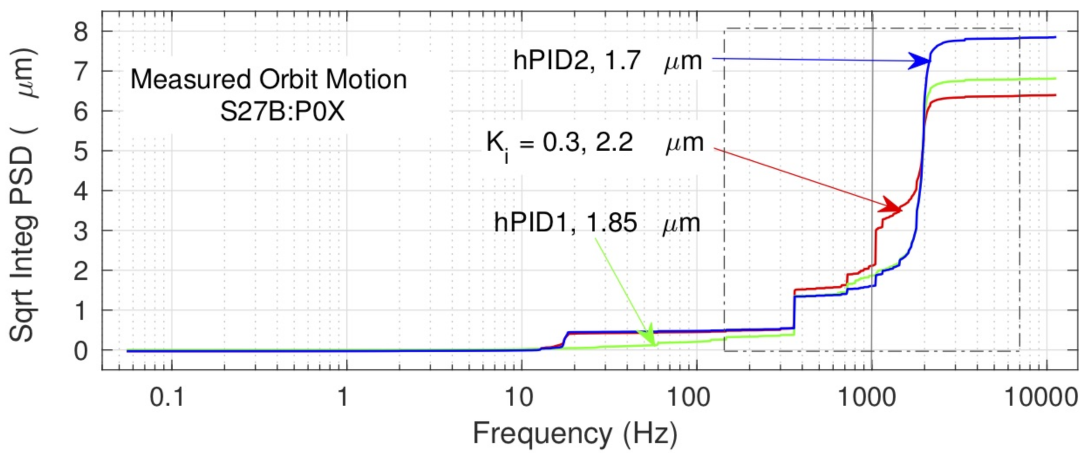


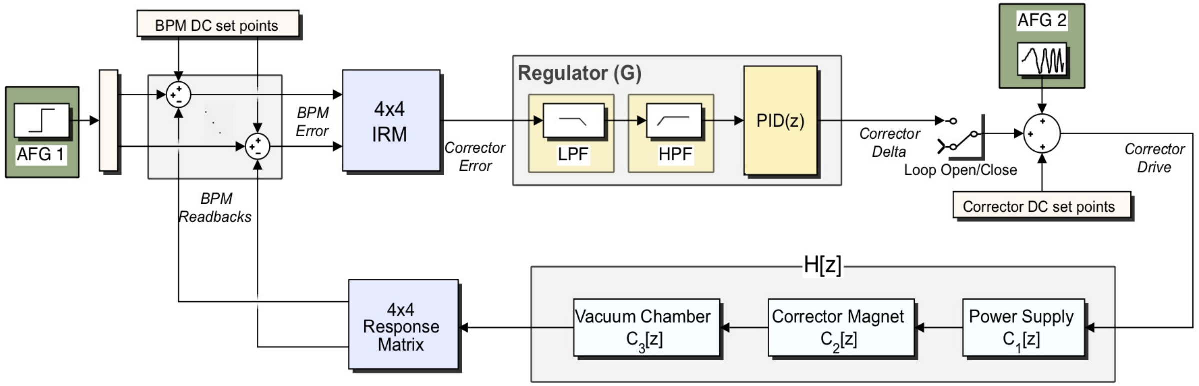
First SCU in a 3GSR light source
(Y. Ivanyushenkov et al. PRSTAB 18, 040703.)

APS-U building the world's fastest orbit feedback system[1]

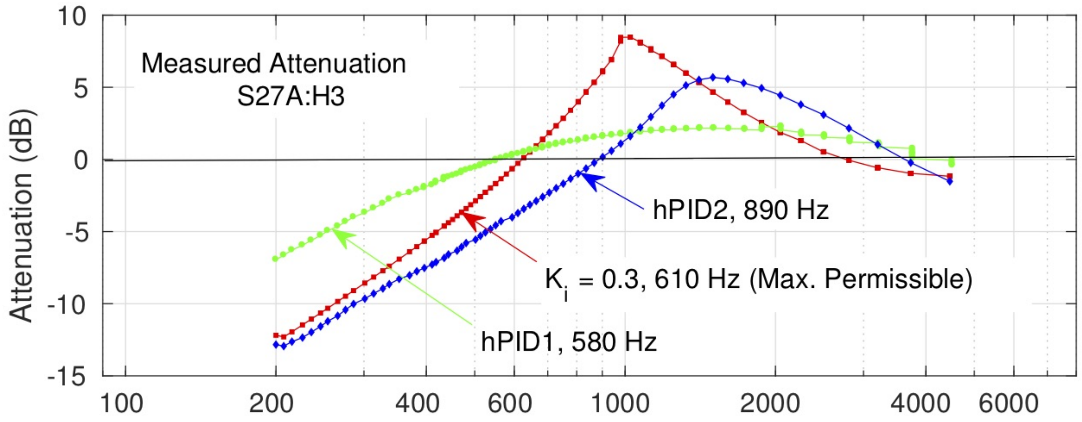
- APS-U beam stability needs to be 1.3μm (x) and 0.4μm (y) over 0.01-1000 Hz band
  - To achieve this, orbit feedback will have 22-kHz update rate
- Created dynamical system model that includes effects of eddy currents and latency
- Tests in APS double-sector show world-leading 890 Hz closed-loop bandwidth

Testing candidate PID regulator settings:
Measured residual orbit motion spectrum



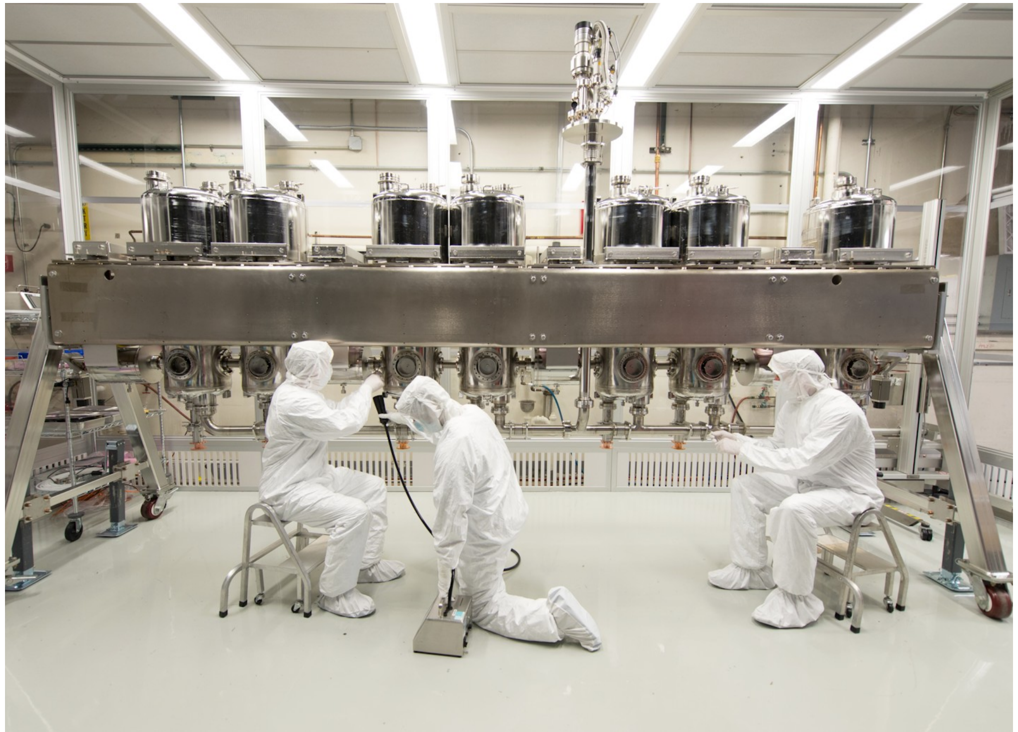


Corresponding closed-loop attenuation responses

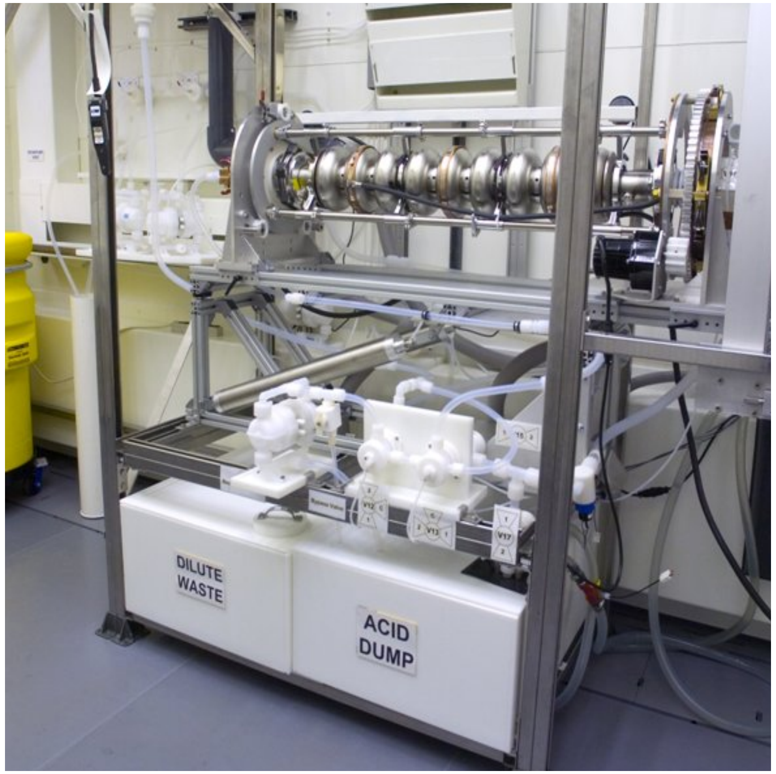


1: J. Carwardine et al., IBIC18, tuoc02_talk

SC rf capabilities encompass design through testing and operation



Assembly of ANL-designed ATLAS Intensity Upgrade 72 MHz Quarter-Wave Resonator Cryomodule (2014)[1]



Superconducting cavity processing at the ANL facility jointly funded and staffed by Argonne/Fermilab[2]

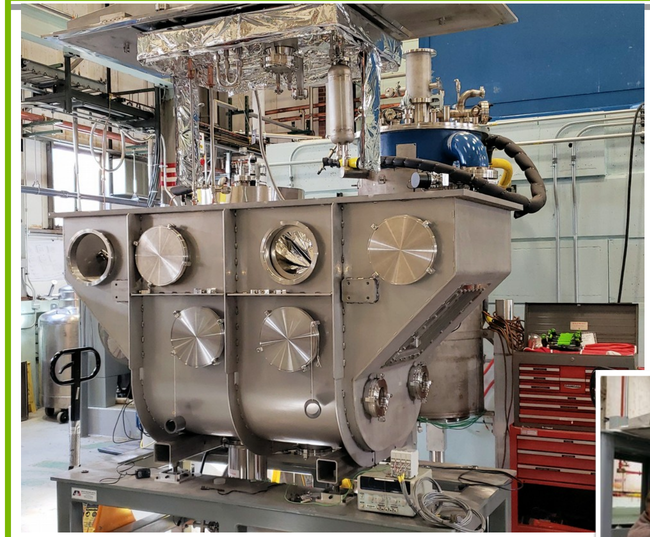
Cavity and accelerator systems testing

1: M. Kelly et al., LINAC2014, 440.
2: M. Kelly et al., LINAC2014, 839.

Compact, high-voltage bunch lengthening system created for APS-U

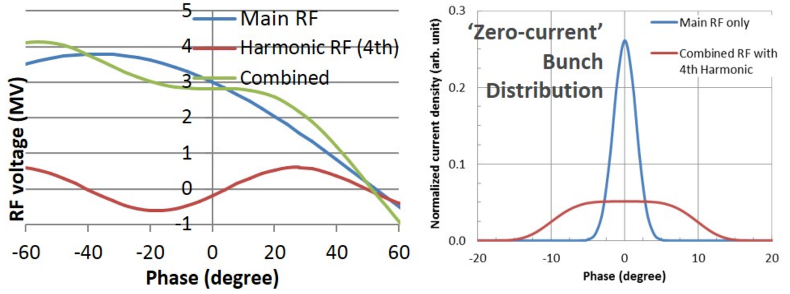
- Touschek lifetime, instability concerns for APS-U
  - Higher harmonic cavity (HHC) required to lengthen bunch
- ANL-conceived solution using a single 4th harmonic (1.4 GHz) superconducting cavity provides sufficient voltage (1.25 MV) in a 2-meter footprint
  - New cavity design[1]
  - New high-power 20 kW CW RF couplers[2]
  - Robust HOM-damping scheme uses room temperature silicon carbide absorbers[3]

1.4 GHz superconducting cavity



Bunch lengthening system cryomodule

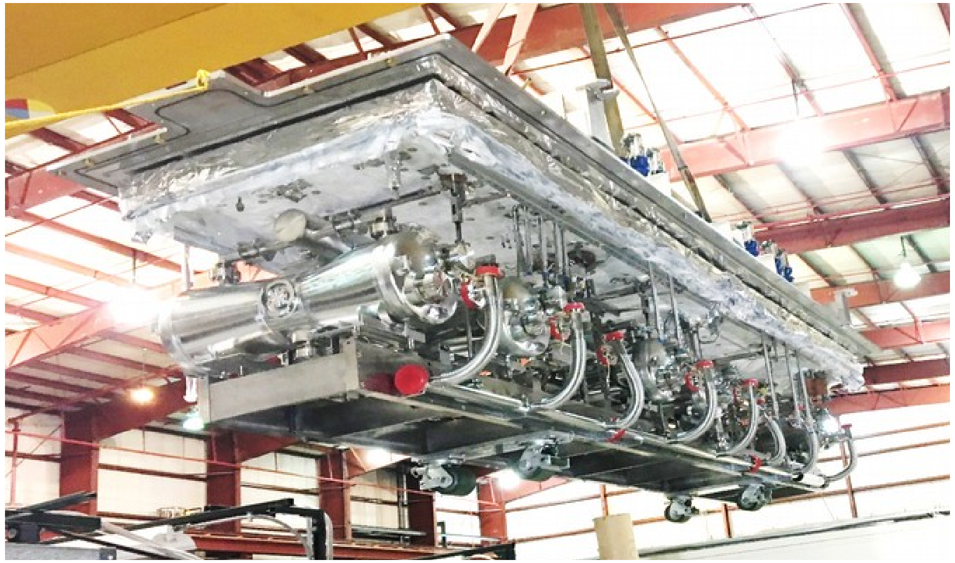
Analytical calculation of bunch lengthening[4]



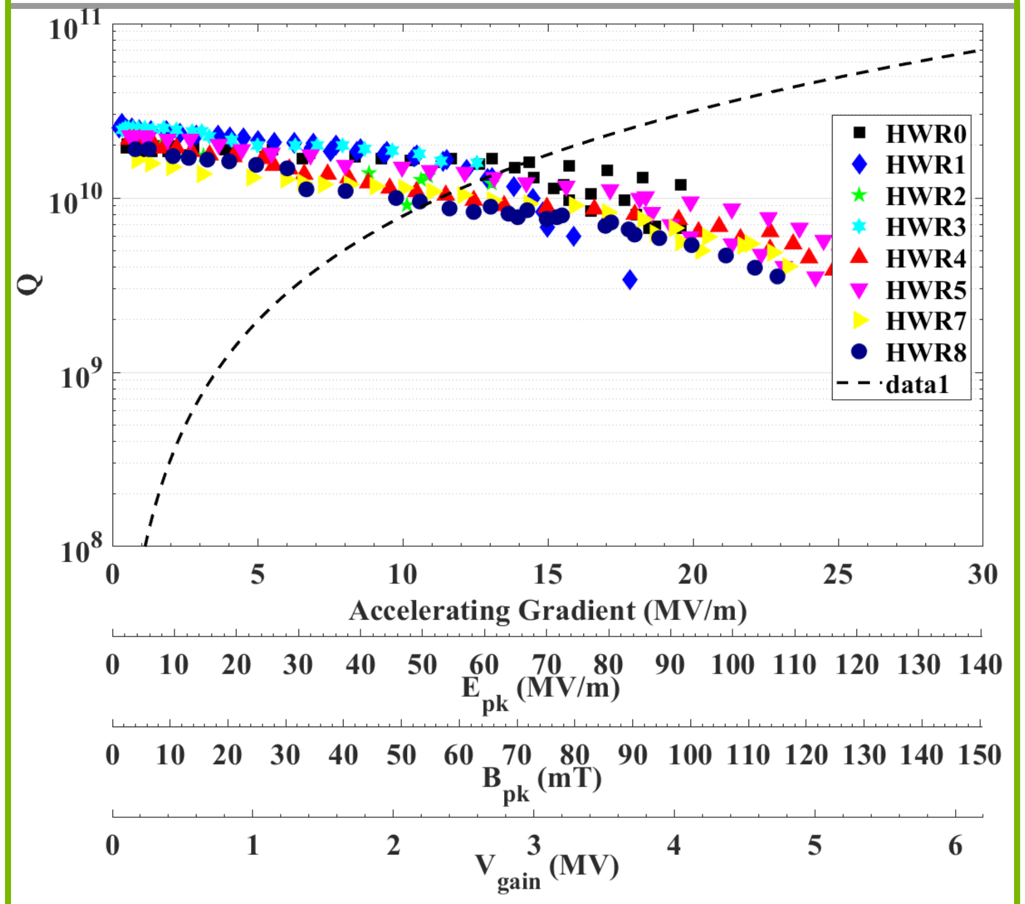
1: M. Kelly et al., IPAC15, 3267.
2: M. Kelly et al., SRF15, 1346.
3: S. H. Kim et al., SRF15, 1293.
4: S. H. Kim et al., IPAC15, 1810.

Half-wave resonator module supports PIP-II[1] at FNAL

- ANL-conceived 6-m HWR cryomodule for 2 mA CW proton beams[2]
- Delivered in 2019, includes 8 SC cavity and 8 solenoids
- Highest performance to date for this class of cavities



Half-wave cryomodule

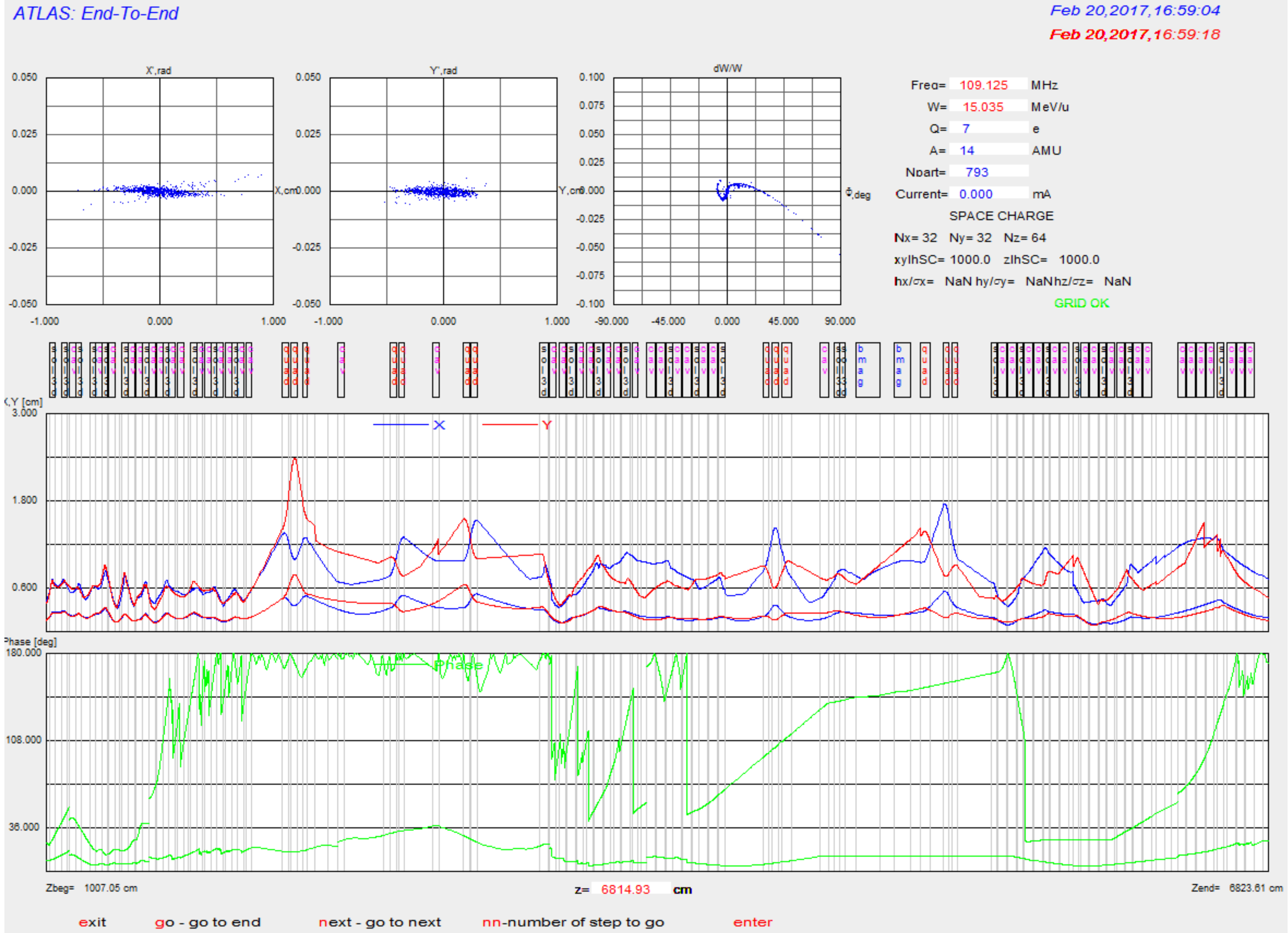


Cavity performance curves

1: S. Holmes et al., IPAC15, 3982.
2: Z. A. Conway et al., SRF17, 692.

Ion linac design, modeling possible with ANL's TRACK3D[1] code

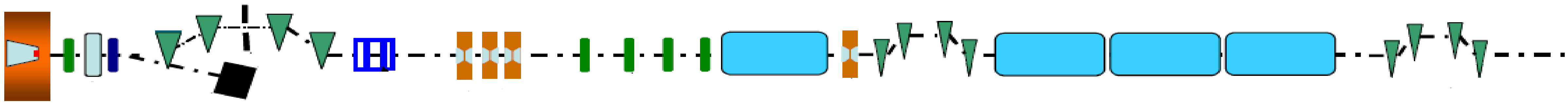
- ✓ Integrates equations of motion with external and self fields
- ✓ Full 3D maps, design optimization and beam dynamics simulations
- ✓ Supports most EM elements, start-to-end simulations
- ✓ Includes ion beam stripping on foils and targets & Multi-beam tracking
- ✓ H-minus beam stripping due to different effects: IBS, …
- ✓ Spin tracking under development



1: V. N. Aseev et al., PAC05, 2053.

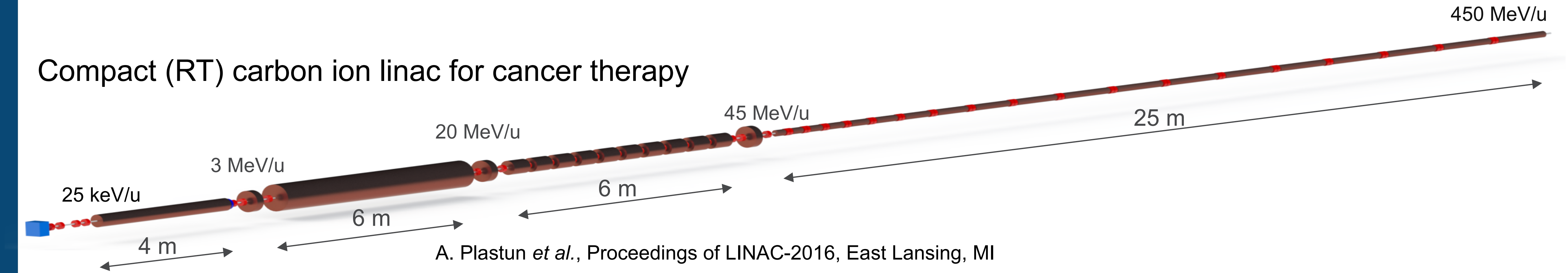
TRACK3D applied to linac designs for diverse applications

Ultra low-emittance injector for an X-FEL Oscillator

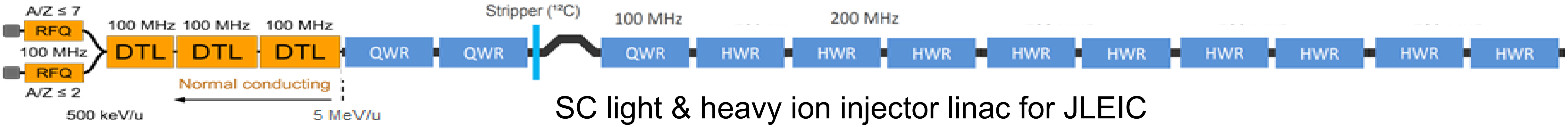


P. Ostroumov *et al.*, Proceedings of PAC-2009, Vancouver, Canada

Compact (RT) carbon ion linac for cancer therapy



A. Plastun *et al.*, Proceedings of LINAC-2016, East Lansing, MI



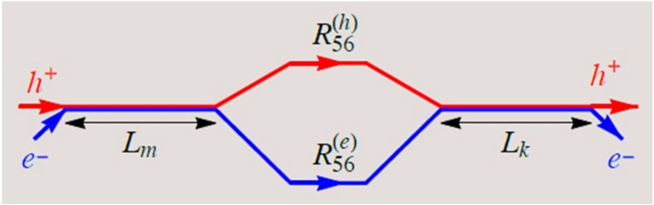
SC light & heavy ion injector linac for JLEIC

B. Mustapha *et al.*, Proceedings of HIAT-2018, Lanzhou, China

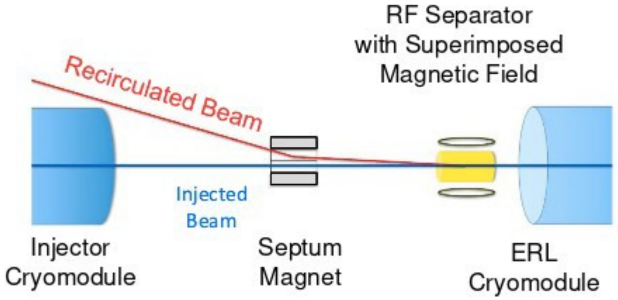
POSSIBLE EIC-RELATED EXPERIMENTAL STUDIES AT ARGONNE WAKEFIELD ACCELERATOR FACILITY (AWA)

(See presentation by Gwanghui Ha for more details.)

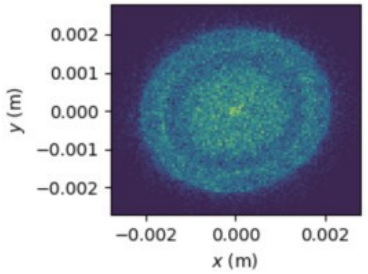
Wiggler impact on the electron beam self energy modulation in view of electron-ion collider R&D. Microbunched electron cooling (MBEC) (G. Stupakov and P. Baxevanis). Experiment proposed at AWA by A. Zholents.



Straight Merger (proposed by A. Hutton; preliminary tests by K. Deitrick), further demonstration proposed at AWA by P. Piot, using magnetized beam.



Halo Distribution Measurement: understanding of origin of large-orbit particles, in context of EIC e-cooler. Experiments proposed at AWA by P. Piot.



Summary and points of contact

- Accelerator simulation:
  - General: Michael Borland
  - Ion effects: Joseph Calvey
  - Collective effects: Ryan Lindberg
  - Ion linacs: Brahim Mustapha
  - Commissioning simulation: Vadim Sajaev
- Vacuum systems: Jason Carter
- Conventional magnets:
  - Design and production: Mark Jaski
  - Measurement: Animesh Jain
- Conventional insertion devices: Joseph Xu
- Superconducting insertion devices: Yury Ivanyushenkov
- Fast orbit feedback: John Carwardine
- Superconducting rf cavities: Mike Kelly
- Experiments and measurements at AWA: Manoel Conde
- Use of LEAF: Sergey Chemerisov