Overview of the APS-U Project

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Argonne National Laboratory

2018 Workshop on Future Light Sources

The APS Upgrade in brief

The APS Upgrade is designed to provide orders-of-magnitude improvements in brightness, coherent flux, and nano-focused flux

APS-U will serve an extensive set of existing beamlines

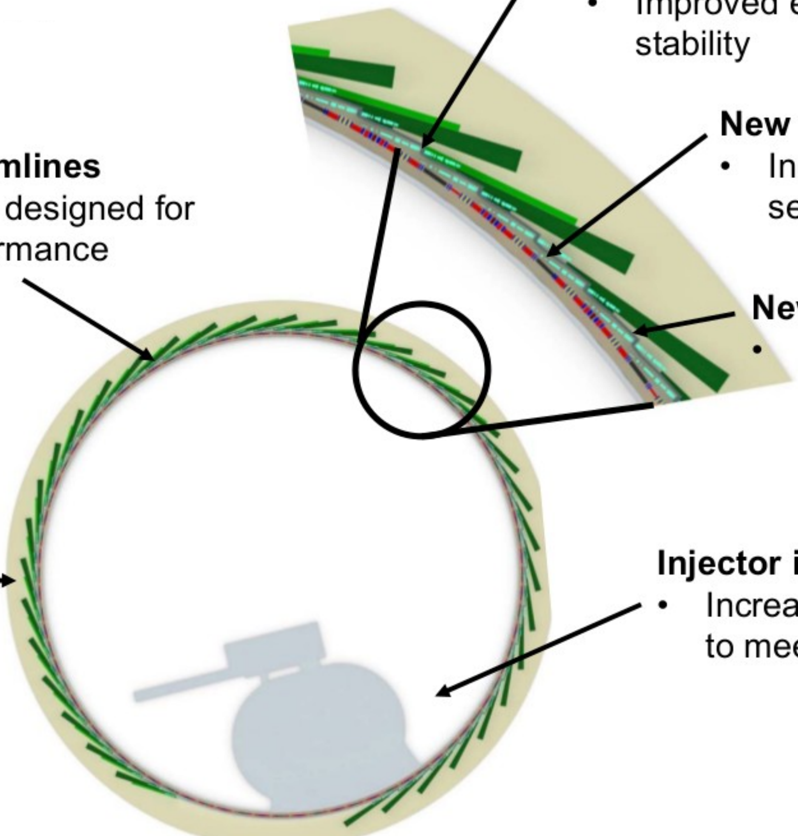
New Storage Ring
- 6 GeV MBA lattice
- 200 mA current
- Improved electron/photon stability

Eight feature beamlines
Suite of beamlines designed for best-in-class performance

New Insertion Devices
- Incorporate SCUs on selected beamlines

New/upgraded Front-ends
- Common design for maximum flexibility

Beamline Enhancements: improvements to make beamlines "Upgrade Ready"



Injector improvements
- Increase performance as needed to meet APS-U requirements

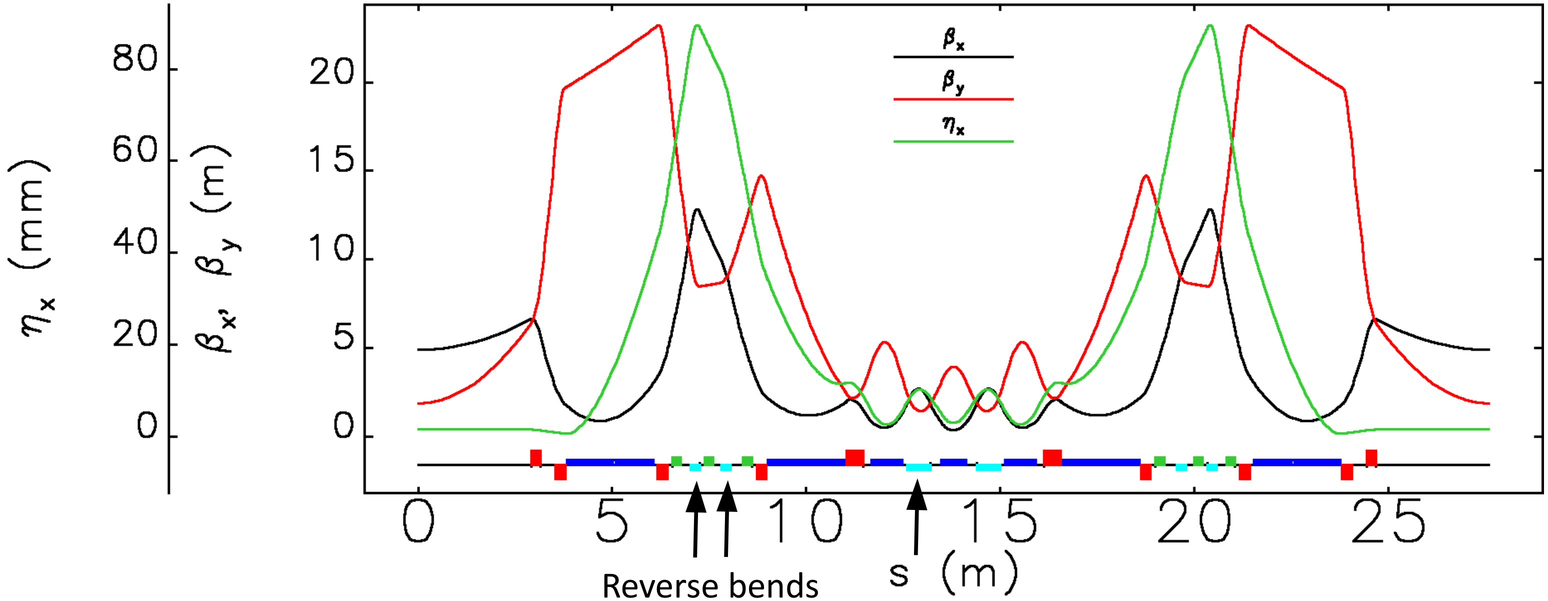
M. Ramanthan

Outline

- This presentation highlights some of the accelerator work
  - Lattice design and optimization
  - Mechanical layout
  - Magnet status
  - Injection systems status
  - Injector status
  - Tolerances and commissioning
  - Vibration and beam stabilization
  - Collective effects
  - Control of beam losses
- Several other talks in this workshop give a deeper dive
  - Superconducting undulators (J. Fuerst)
  - Ion effects (J. Calvey)
  - X-ray diagnostics (B. X. Yang)
  - Multi-bunch instabilities (R. Lindberg)

Lattice choice - hybrid 7-bend achromat

- After extensive study, chose hybrid 7-bend achromat[1] with 4 longitudinal-gradient dipoles and 3 transverse-gradient dipoles[2]
  - Provides two locations with larger dispersion, used for chromaticity correction
  - Phase separation between sextupole triplets is ≈3π in X and ≈π in Y
- Sextupoles have 20-fold symmetry to allow for more knobs
- Conversion of three quadrupole families to reverse bends[3,4] provided many benefits (see below)[5]



1: L. Farvacque et al., IPAC2013, 79.
2: Initial hybrid 7-bend lattice was provided by ESRF.
3: J. Delahaye et al., PAC89, 1611.
4: A. Streun, NIM-A 737 (2014)
5: M. Borland et al., NAPAC 2016, 877.

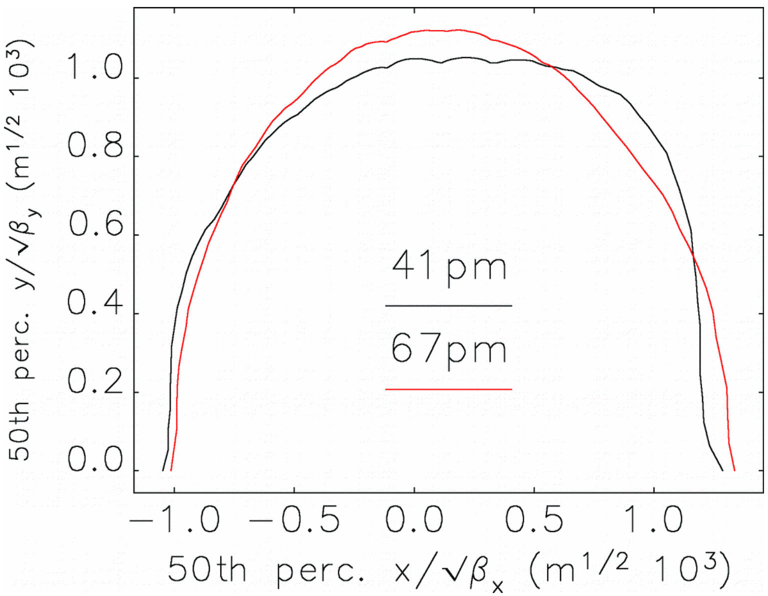
Lattice optimization[1]

- Linear lattice design iterated with magnet and vacuum systems designs
  - Magnet designers provide curves of integrated strength vs insertion length
  - Vacuum designers provide space requirements for bellows, absorbers, BPMs, etc.
- Tracking-based multi-objective genetic algorithm (MOGA) used for optimization
  - Includes various errors, vacuum chamber apertures, and effects of radiation damping and longitudinal motion
  - Directly optimizes quantities we care about
    - Touschek lifetime (from local momentum acceptance)
    - Dynamic acceptance (DA) area
    - DA smoothness
    - Momentum tune footprint
    - X-ray brightness at ~10 keV
- Went through several lattice versions, including
  - 90-pm – large enough dynamic aperture to allow for accumulation[2]
  - 67-pm – on-axis injection only, no accumulation[3]
  - 67-pm with high-beta insertion – targeting accumulation with lower emittance[4]
  - 42-pm – on-axis injection only, incorporates reverse bends[5]

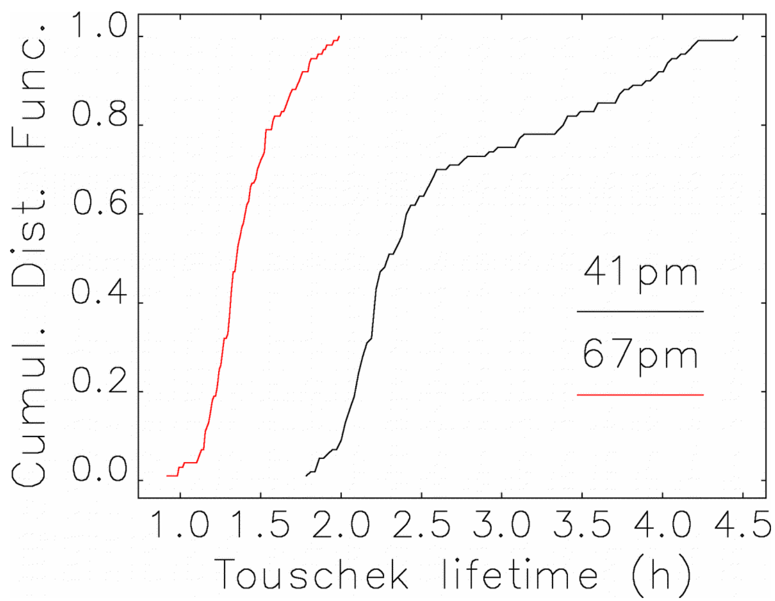
1: M. Borland et al., APS LS-319, 2010.
2. Y. Sun et al., NAPAC2016, 920.
3: M. Borland et al., IPAC2015, 1776.
4: Y. Sun et al., IPAC2015, 1803.
5: M. Borland et al., NAPAC2016, 877.

Reverse bends have numerous benefits

- Reverse bend design requires no additional magnets, but
  - Allowed increasing dispersion by ~20% → weaker sextupoles
  - Much better Touschek lifetime with the same dynamic acceptance
  - 60% higher x-ray brightness, partly from improved beta functions at IDs
  - Simulations show no increase in difficulty of commissioning
- Attempts to push emittance even lower gave poor nonlinear dynamics and difficult magnets



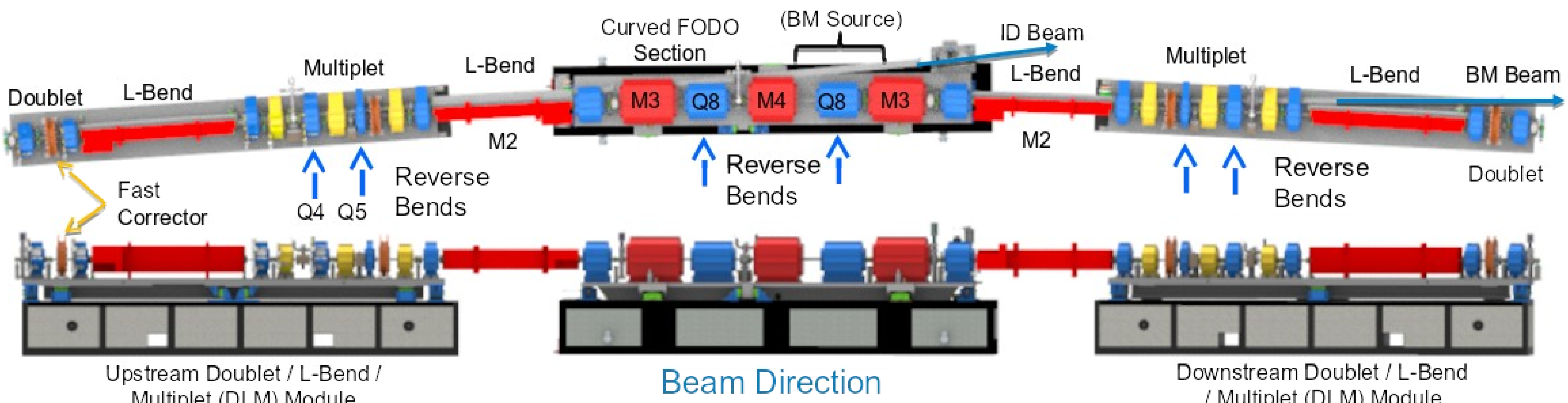
Comparison of median DA, scaled to beta functions, for 100 commissioning ensembles.



Approximate lifetime computation, valid for lattice comparison, for 48-bunch, 200-mA fill

The APS Upgrade parameters

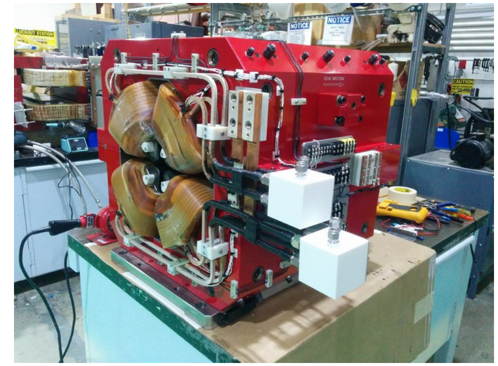
Quantity	APS Now	APS MBA Timing Mode	APS MBA Brightness Mode	Units
Beam Energy	7	6		GeV
Beam Current	100	200		mA
Number of bunches	24	48	324	
Bunch Duration (rms)	34	104	88	ps
Energy Spread (rms)	0.095	0.156	0.130	%
Bunch Spacing	153	77	11	ns
Horizontal Emittance	3100	32	42	pm·rad
Emittance Ratio	0.013	1	0.1	
Horizontal Beam Size (rms)	275	12.6	14.5	μrad
Vertical Beam Size (rms)	11	7.7	2.8	μrad
Betatron Tune	35.2, 19.27	95.1, 36.1		
Natural Chromaticity	-90, -43	-130, -122		

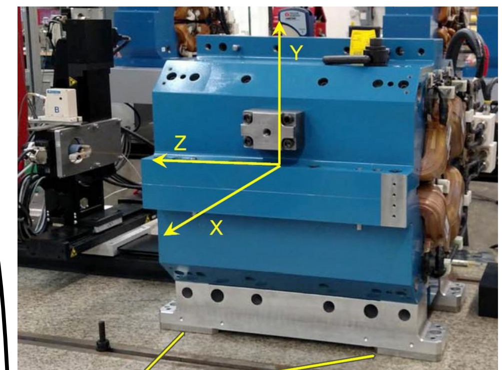


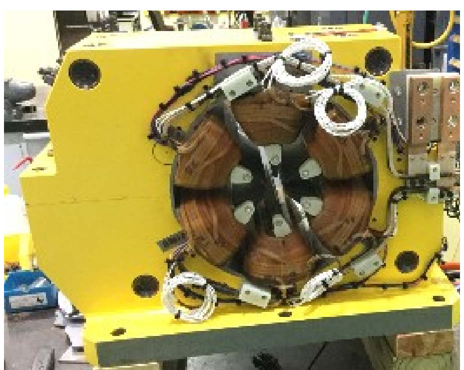
H. Cease, et al.

Every arc magnet type has been prototyped[1]

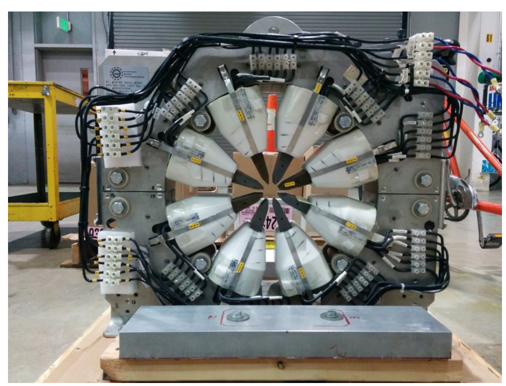
- There will be total of 1321 magnets
  - Longitudinal-gradient dipoles – 160
  - Transverse-gradient dipoles – 120
  - Reverse-bend quadrupoles – 240
  - Quadrupoles – 400
  - Sextupoles – 240
  - 8-pole fast correctors, skew quads – 161
- Measurements in good agreement with expectations
- About half of the magnets have vanadium permendur pole tips to achieve required strength
- Contract for purchase of first 160 quadrupoles already placed







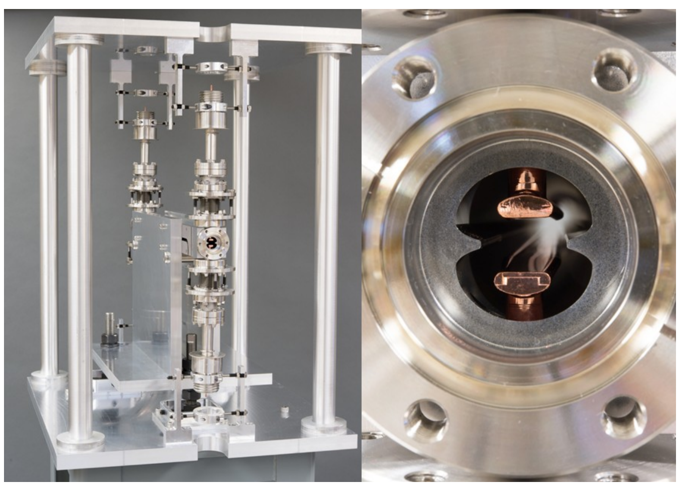
1: M. Jaski et al.

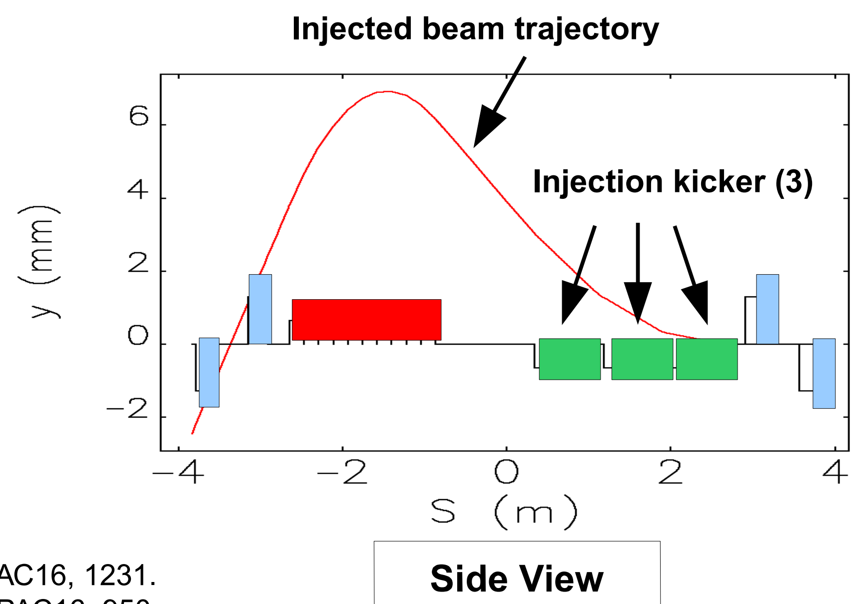


8-pole corrector (BNL)

Injection scheme[1]

- Swap-out injection[2,3] necessary to accommodate small DA:
  - one stored bunch is dumped, new bunch is put in its place in a single shot
  - use fast stripline kickers[4], slightly tilted Lambertson septum[5] for vertical-plane injection
- For 324-bunch mode, kickers need to be very fast (<20 ns)
  - Prototype stripline kicker, pulser tested to 30 kV (18 kV is required)
  - Meets timing requirements
- For 48-bunch mode, injector must provide high-charge bunches (16 nC)
  - Injector improvement program underway





1: A. Xiao et al., PAC13, 1076.
2: R. Abela et al., EPAC 92, 486.
3: L. Emery et al., PAC03, 256.
4: M. Abliz et al., NAPAC16, 1231.
5: C.-Y. Yao et al., NAPAC16, 950.

APS-U injector improvements

- Plan to meet APS-U injection requirements through upgrades of existing injector complex.
- Injectors need to deliver up to three times design charge level.
- Have achieved 100% of maximum required charge for PAR, and 70% of required charge for Booster.
- Booster improvements: lattice and injection tuning, new BPMs and orbit correction, rf tuning, beam loading compensation...
- PAR improvements: rf system and orbit tuning, higher energy...
- R&D ongoing, guided by modeling and experiment.

	Present APS	Achieved	Goal**
Rep rate	2 Hz	1 Hz	1 Hz
PAR charge	2-4 nC*	20nC	20nC
Booster charge	2-4 nC*	12nC	17nC
SR charge	Accumulated		16nC
Charge stability (rms)	10%	10%	5%
BTS x emit.	87nm		60nm
BTS y emit.	?		16nm
SR energy	7 GeV		6 GeV

* Design charge is 6 nC
** Timing mode

K. Harkay, CY. Yao, J. Calvey, and Injector Working Group.

Tolerances and stability[1]

- Tolerances are specified based on several requirements
  - Ease of commissioning
  - Ease of startup after shutdowns
  - Need to control beam motion during user operation with orbit correction
  - Need to have sufficiently quiet conditions for beam studies
- One major requirement is keeping orbit stable within 10% of beam size
- Tolerance calculations take into account many frequency-dependent effects
  - Electrical noise, ground vibration, attenuation due to vacuum chamber, lattice amplification, orbit correction
- The resulting requirements are tough, but feasible

Orbit stability requirements

Plane	**AC rms Motion (0.01-1000 Hz)**	
Horizontal	1.3 μm	0.25 μrad
Vertical	0.4 μm	0.17 μrad

Vibrational requirements

	X (rms) 1-100 Hz	Y (rms) 1-100 Hz
Girder vibration	20 nm	20 nm
Quadrupole vibration	10 nm	10 nm
Dipole roll vibration	—	0.2 μrad

Electrical requirements (rms)

Magnet type	Requirement	Based on
Correctors	$2 \cdot 10^{-4}$	Orbit stability
Dipoles M3-M4	$2 \cdot 10^{-5}$	Orbit stability
Dipoles M1-M2	$2.3 \cdot 10^{-5}$	Tune stability
Quadrupoles	$2.5 \cdot 10^{-5}$	Tune stability
Sextupoles	$2 \cdot 10^{-3}$	Tune stability

1: V. Sajaev, IPAC2015, 556.

Commissioning simulation[1]

- Commissioning simulation was developed to
  - Understand the likely performance of the machine after commissioning
  - Understand alignment and tolerances in relation to commissioning, performance
  - Assess the difficulty of commissioning within the 3-month commissioning window
- Commissioning simulation strives for high level of realism, including
  - Error generation
  - Trajectory correction
  - First orbit correction leading to stored beam
  - Final orbit correction and lattice correction
- Trajectory correction is complicated by weak correctors
  - Strength limit is 0.3 mrad (due to mechanical limitations), while 1 mm trajectory error in the strongest quad gives 2.3 mrad kick

Assumed rms error levels in commissioning simulations

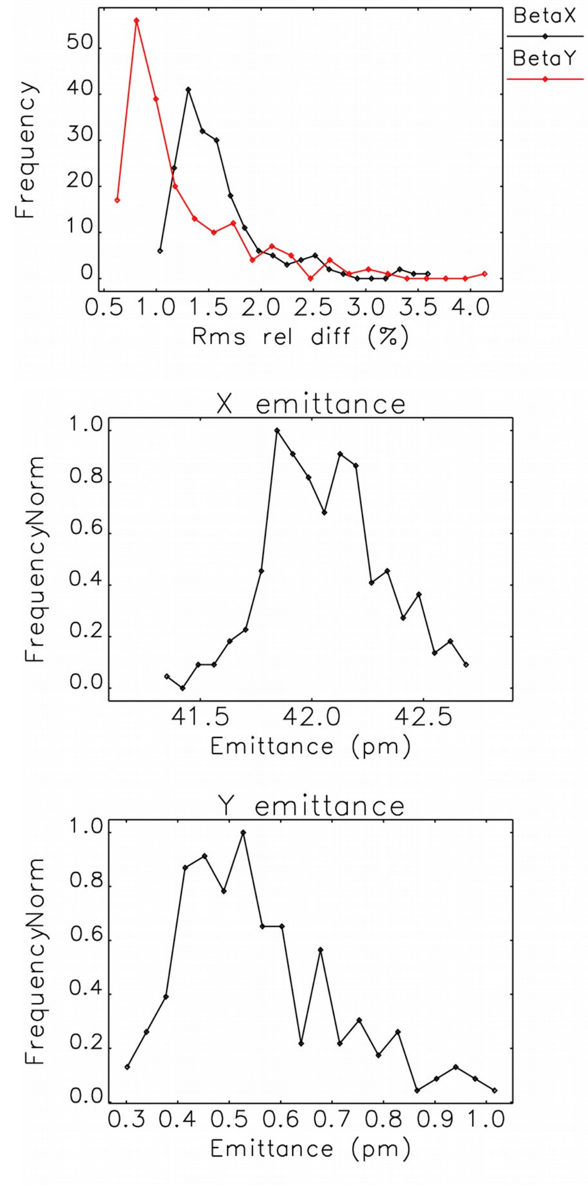
Girder misalignment	100 μm
Elements within girder	30 μm
Dipole fractional strength error	$1 \cdot 10^{-3}$
Quadrupole fractional strength error	$1 \cdot 10^{-3}$
Dipole tilt	0.4 mrad
Quadrupole tilt	0.4 mrad
Sextupole tilt	0.4 mrad
Corrector calibration error	5%
Initial BPM offset error	500 μm
BPM calibration error	5%
BPM single-shot measurement noise	30 μm
BPM orbit measurement noise	0.1 μm
BPM and corrector tilts	1 mrad

1: V. Sajaev et al, IPAC2015, 553.

Commissioning simulation (2)

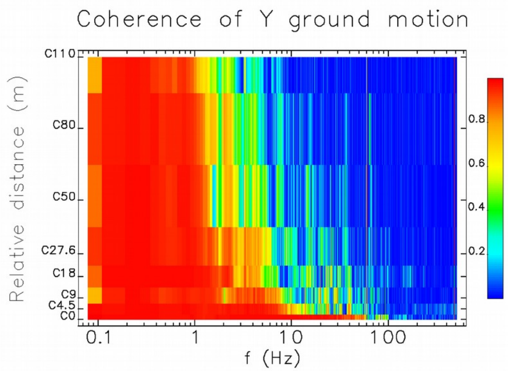
- Simulations are tracking-based, including
  - Physical apertures
  - Injection errors, static and variable
  - BPM shot-to-shot noise
- Simulations show
  - Zero chance of first turn without trajectory correction
  - Low chance of multi-turn capture after first-turn trajectory correction if sextupoles are on
  - Fast commissioning is possible with >95% success rate
- Simulations help establish alignment and magnet strength tolerances, corrector magnet strength limits, evaluate magnet support design
- Provides set of configurations for statistical assessment of post-commissioning performance
  - Emittance, lifetime, collective effects, injection efficiency, etc.

Distribution of parameters after commissioning

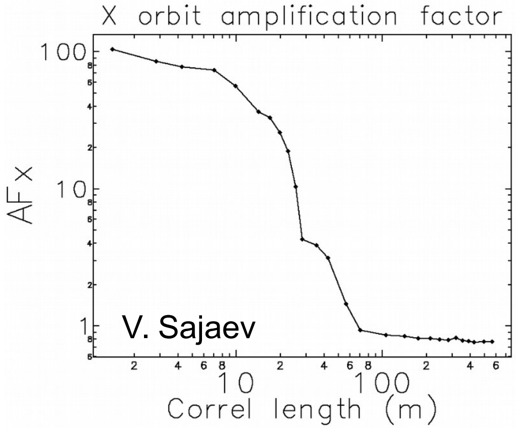


Ground and girder vibration study

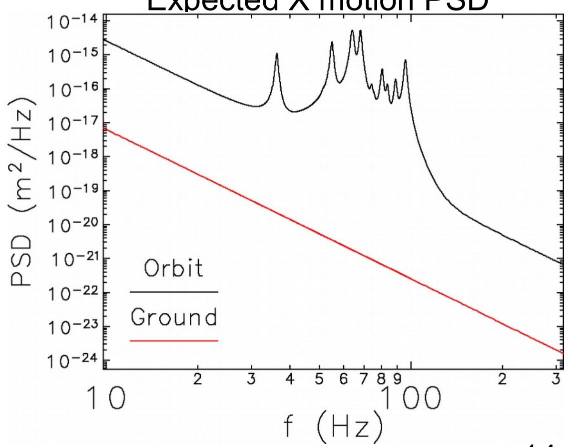
- Ground motion grows very fast toward slow frequencies (PSD ~ $1/f^4$) but becomes coherent at large distances
- Lattice amplification factors of magnet displacement become small as ground motion becomes coherent
  - Thus, low-frequency ground motion tends not to result in beam motion
- Girder vibration can amplify ground vibration
  - Girder resonant deformation modes were calculated
  - Orbit amplification factors for each mode were calculated
  - Measured ground motion was used as a driver to calculate beam motion due to girder resonances
- Total expected orbit motion due to girder resonances is 200 nm in X and 80 nm in Y (no orbit correction)

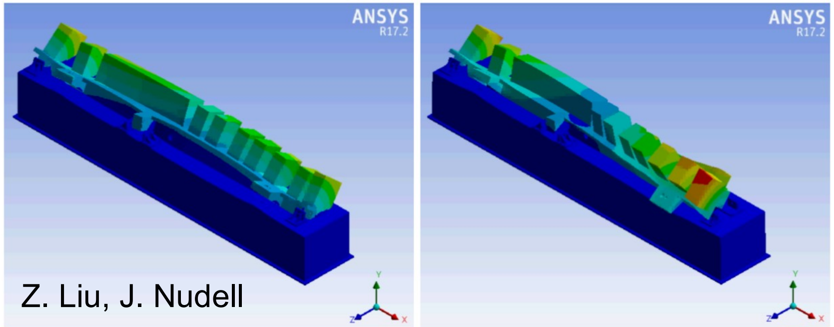


C. Preissner



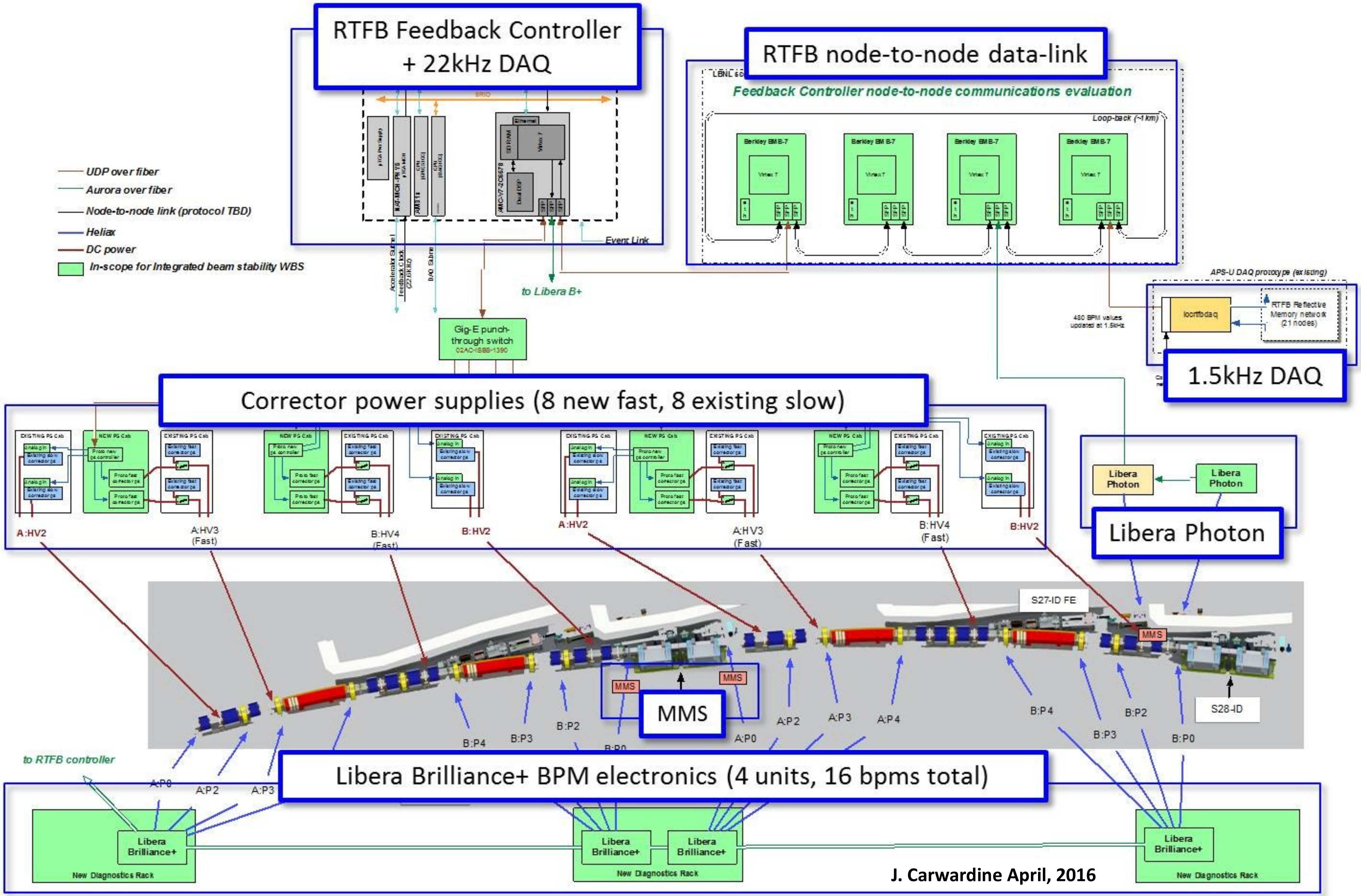
V. Sajaev





Z. Liu, J. Nudell

Integrated beam stability R&D in existing ring[1]



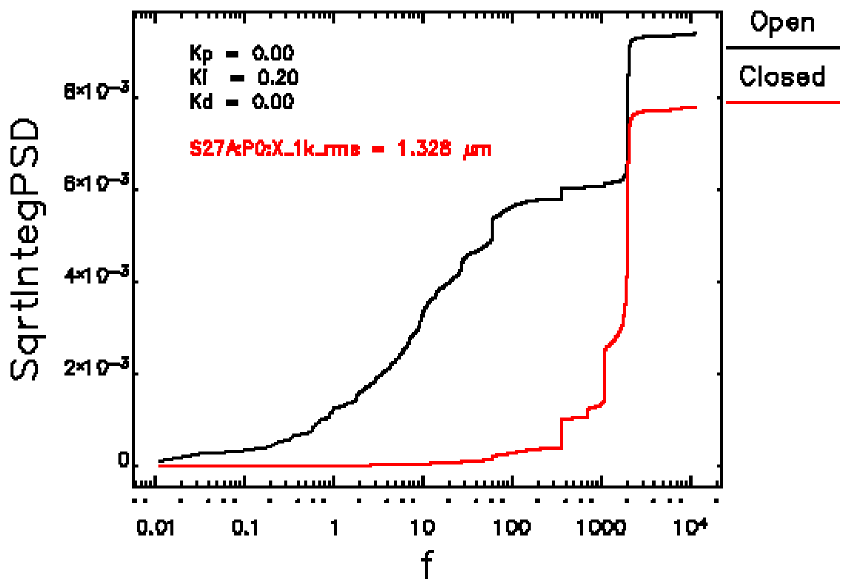
1: N. S. Sereno et al., IPAC15, 1167.

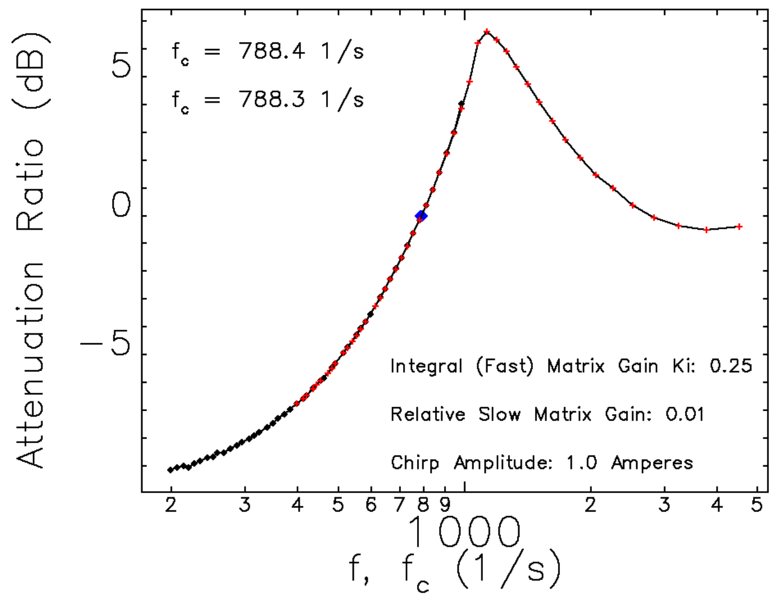
Beam stability

Orbit stability requirements

Plane	AC rms Motion (0.01-1000 Hz)	
Horizontal	1.3 μm	0.25 μrad
Vertical	0.4 μm	0.17 μrad

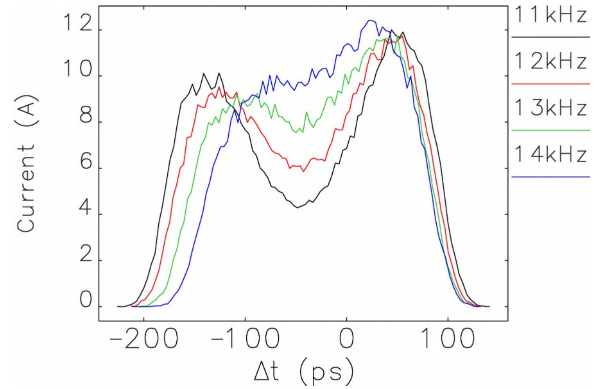
- Beam stability will rely in part on very fast orbit feedback
- Goal is to extend correction bandwidth to 1 kHz
- Prototype system with 22 kHz update rate tested in APS
  - 16 rf BPMs (Libera Brilliance+) and 2 photon BPMs (Libera Photon)
  - 8 correctors per plane, including 4/plane new fast power supplies
- Closed-loop bandwidth of 600-800 Hz, limited by existing corrector magnets
- RMS motion achieved in 0.01 – 1kHz band
  - Horizontal: 1.3-1.5 µm
  - Vertical: 0.4-0.5 µm

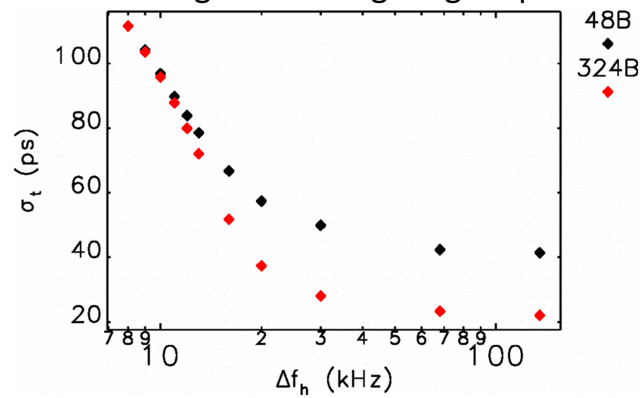




Bunch lengthening system

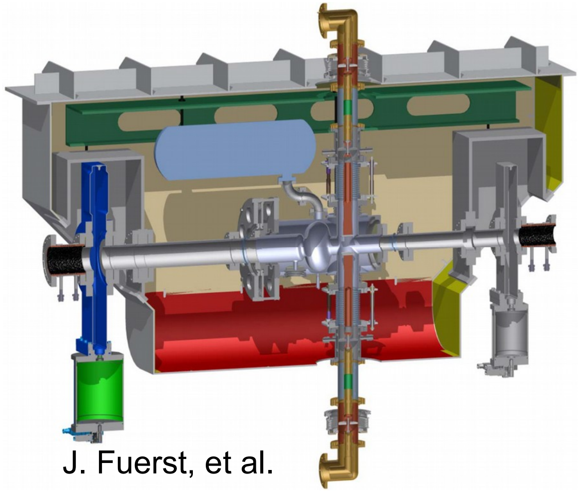
- Single-cell superconducting 1.4 GHz passively-driven cavity will be used to lengthen the bunch to achieve longer lifetime
- Lifetime improves by a factor of 3 for 324 bunch mode
  - Detuning of 11 kHz maximizes lifetime, but bunch is split; 14 kHz gives "normal" bunch w/15% lower lifetime
  - Lifetime improvement for 48 bunch mode is about 50% because the bunch is already lengthened by MWI
- R&D program demonstrated[1] 2 MV at 2 K
  - 1.25 MV is requried
- Cryovessel contract is placed



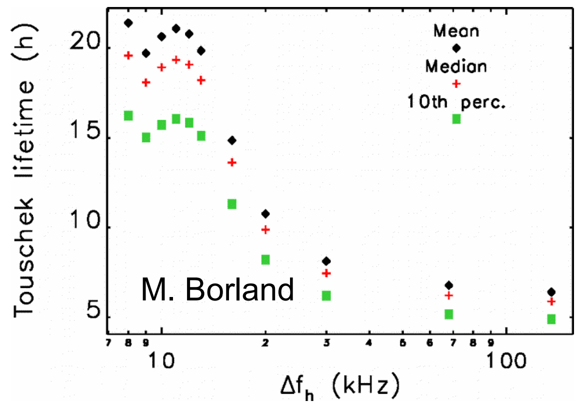


Bare cavity

1. M. Kelly, S. H. Kim, ANL-PHY



J. Fuerst, et al.



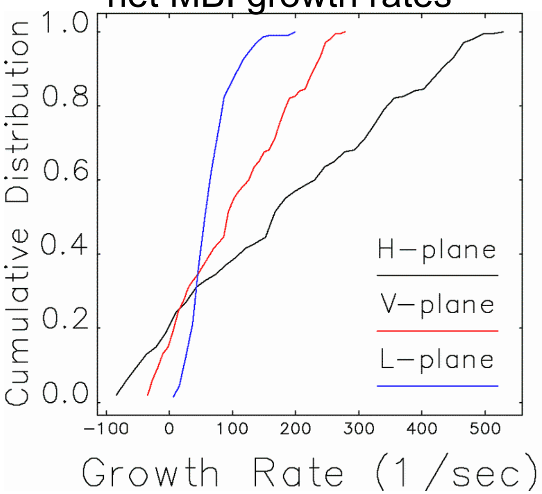
Multi-bunch instabilities

- Keeping 12 existing 352-MHz rf cavities, with their potentially troublesome HOMs
- Transverse planes are not a concern, because of strong coherent damping
- For longitudinal plane, get two-fold reduction in growth rates, ignoring higher-harmonic cavity (HHC) for the moment

Quantity	APS ring	42pm ring	Ratio in growth rate
Number of cavities	16	12	0.63
Total current (mA)	150	200	1.33
Energy (GeV)	7	6	1.17
Momentum compaction	2.83×10^{-4}	3.96×10^{-5}	0.14
Synchrotron frequency (kHz)	2.1	0.56	3.8

- Not enough, since radiation damping is four-fold less!
- Simulations with the program clinchor[1] and estimated HOMs confirm this[2]
- Does higher-harmonic cavity (HHC) help or hurt?
  - Lower synchrotron tune will increase growth rates
  - Spread in synchrotron tune will decrease growth rates

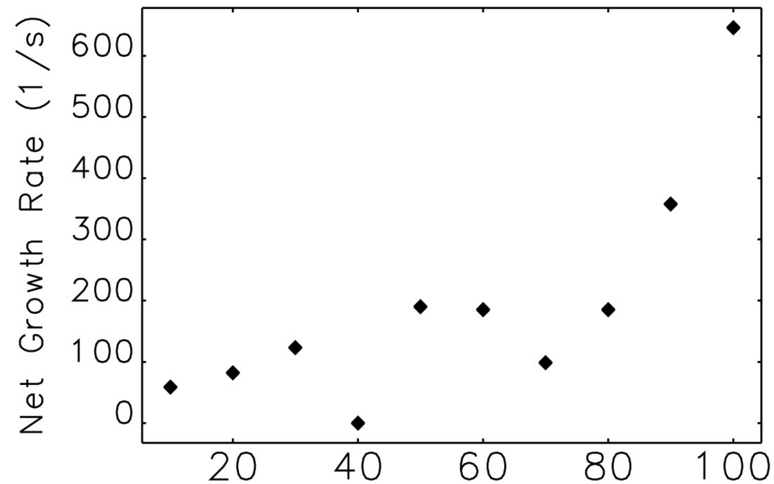
Distribution of expected net MBI growth rates



1: L. Emery, PAC93, 3360.
2: L. Emery et al., IPAC2015, 1784.

HHC and multi-bunch feedback

- Multi-bunch tracking was performed with elegant[1] to understand this issue[2,3]
  - Elegant and clinchor agree in absence of HHC
- Simulations include
  - 48 bunches, 10k particles per bunch
  - Beam-loading & main-cavity feedback[4]
  - Passive higher-harmonic cavity
  - Short-range longitudinal impedance[5]
  - Transverse and longitudinal feedback systems
- Conclusions:
  - Ordering of growth rates roughly agrees with expections from clinchor
  - Growth rates ~2-3x higher than clinchor estimates
    - HHC is not beneficial for MBI
  - 90% of cases were stabilized by LFB
  - 3-4 kV kick needed in transient conditions[3,6]
    - E.g., accidental kicking out of one bunch during swap-out
  - Because of high growth rates, very low synchrotron tune, direct detection of energy offset works best
    - Standard phase-detection feedback does not work well.

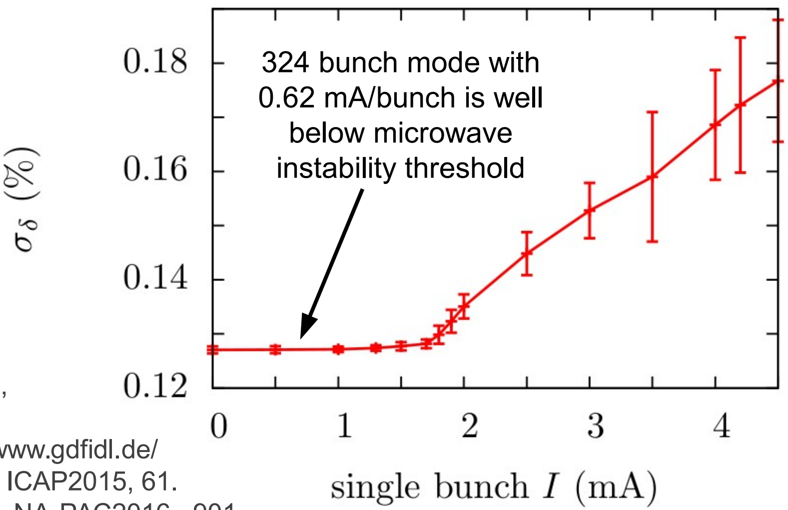


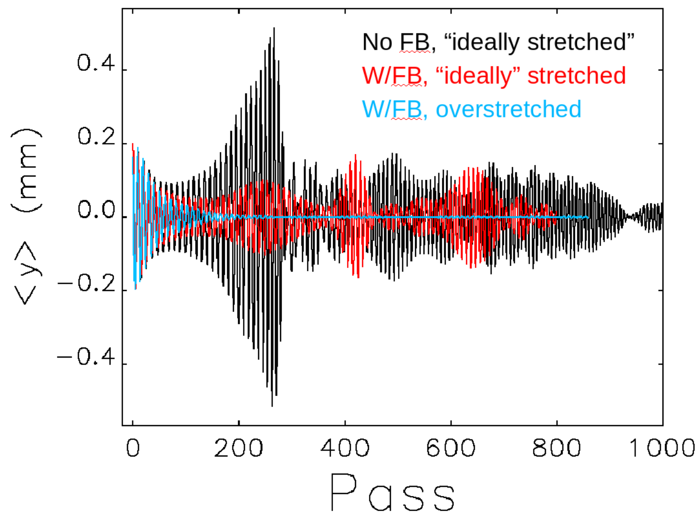
Percentile position of growth rate predicted by clinchor, ignoring HHC

1: M. Borland, APS LS-287, Sept. 2000.
2: L. Emery et al., IPAC2015, 1784.
3: M. Borland et al., ICAP2015, 61.
4: T. Berenc et al., IPAC2015, 540.
5: R. Lindberg et al., IPAC2015, 1825.
6: M. Borland et al., IPAC2015, 543.

Single bunch collective effects

- We have developed a detailed impedance model to predict collective effects[1]
  - Sums resistive wall impedance with the geometric contribution computed via GdfidL[2] simulations of vacuum components including BPMs, photon absorbers, tapered transitions, etc.
  - Impedance model is used to predict microwave instability, rf heating, and for many tracking studies including those of multi-bunch instabilities, beam loss, etc.
- Simulations with impedance predict that the APS-U is safely below the single-bunch instability limit, but that collective effects at injection must be controlled[3,4]
  - Longitudinal phase-space mismatch of injected and stored beam results in longitudinal oscillations/structure which can generate large transverse wakefields
  - Transient transverse wakefields can drive oscillations, emittance growth, and particle loss
  - Nonlinear resonances of large-emittance injected beam exacerbates these problems
- Single bunch feedback can cure any transient instability and prevent beam loss



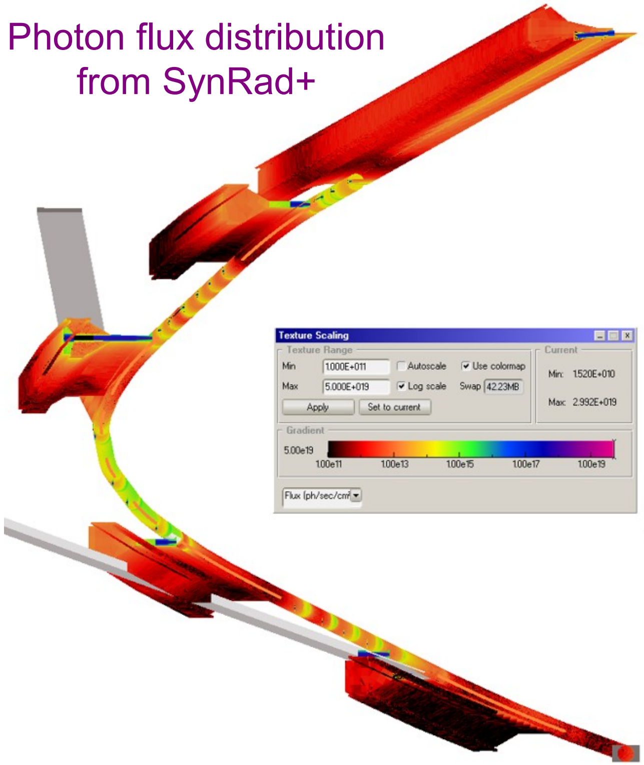


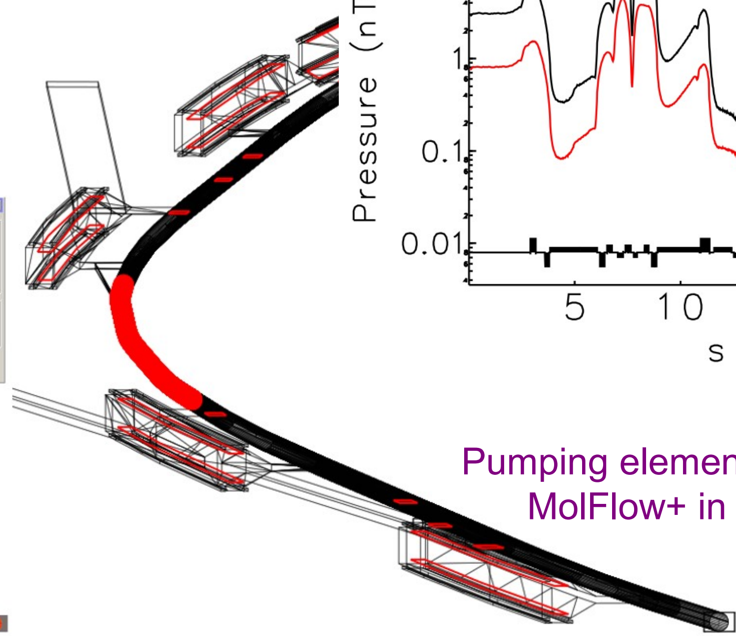
1. R. Lindberg et al., IPAC2015, 1822.
2. W. Bruns, http://www.gdfidl.de/
3. M. Borland et al, ICAP2015, 61.
4. R. Lindberg el al., NA-PAC2016, 901.

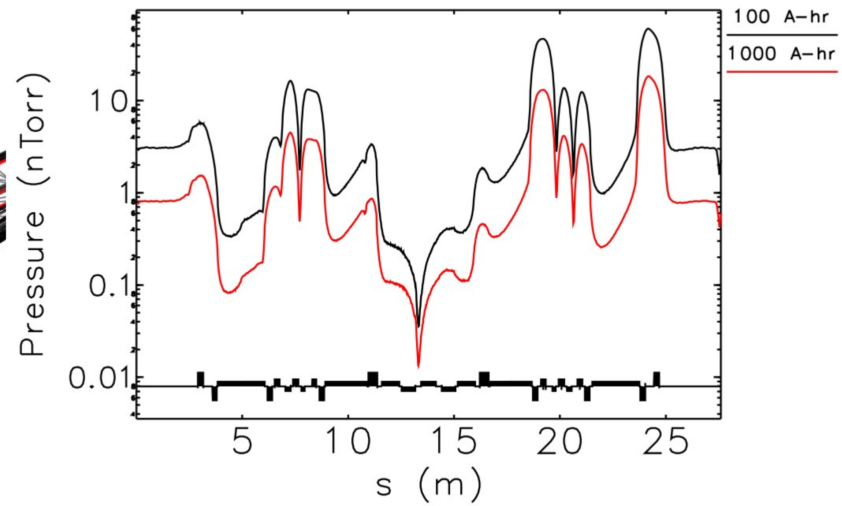
Pressure calculations and profiles

- CERN codes[1,2] SYNRAD+ and MOLFLOW+ used to compute pressure around the ring for various amounts of beam conditioning[3]
  - Includes generation and scattering of synchrotron radiation, photon stimulated desorption of gasses, vacuum conductance, and localized/distributed pumping
  - Data used for analysis of ion instabilities and gas scattering

Photon flux distribution from SynRad+





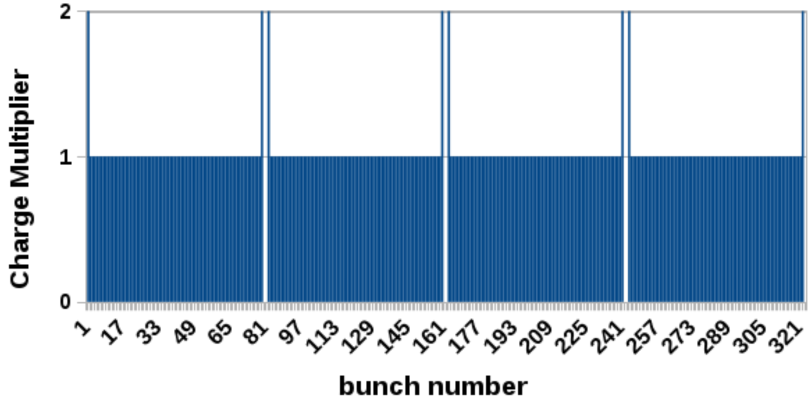


Pumping elements from MolFlow+ in red

1: R. Kersevan. Proc. PAC 1993, p. 3848.
2: M. Ady and R. Kersevan. Proc. IPAC 2014, p. 2348.
3: B. Stillwell, IPAC2017, 3590. Data courtesy J. Carter.

Ions and guard bunches

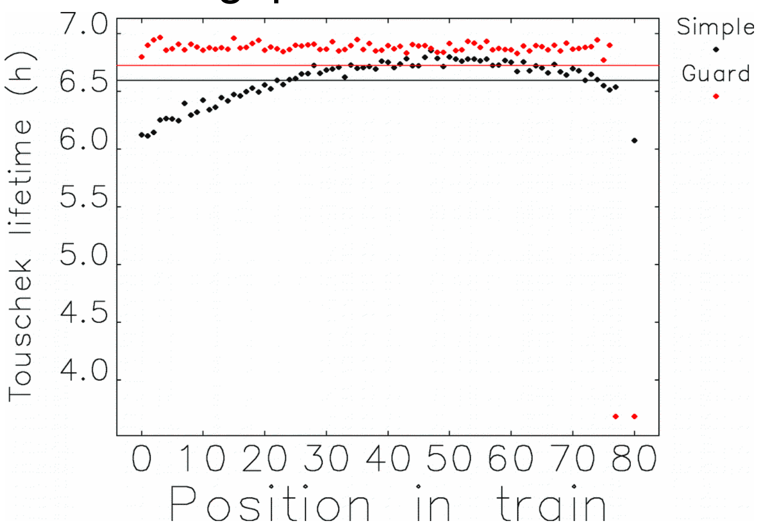
- For 324-bunch mode, will need at least 2 gaps in the bunch train to clear ions
- Developed idea of “guard bunches” to reduce rf transients
- More detail in J. Calvey's talk



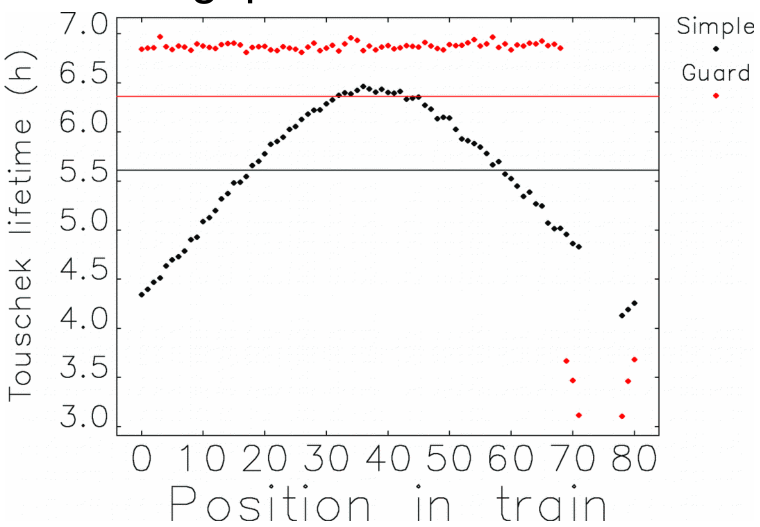
Example of 324-bunch fill with one double-charge guard bunch on either side of four two-bunch gaps.

Suppresses rf transients, reducing bunch-shape and lifetime variation.

4 gaps of 2 bunches

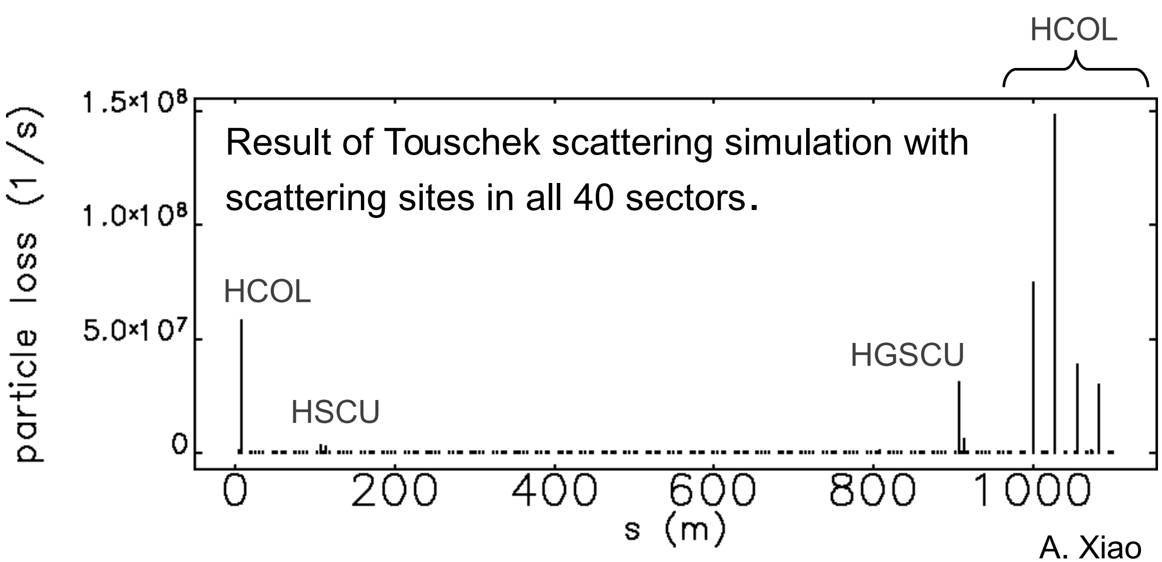


4 gaps of 6 bunches



Beam losses and collimation

- With shorter lifetime and higher beam energy density, understanding and control of beam losses becomes more important
- Beam dumps needed for swap-out and whole-beam abort
- Collimation must deal with Touschek scattering, gas scattering, and injection losses
  - Touschek is expected to dominate
- All of these processes have been simulated in detail for APS-U



Used Monte Carlo simulation of Touschek scattering[1,2] to determine loss locations.

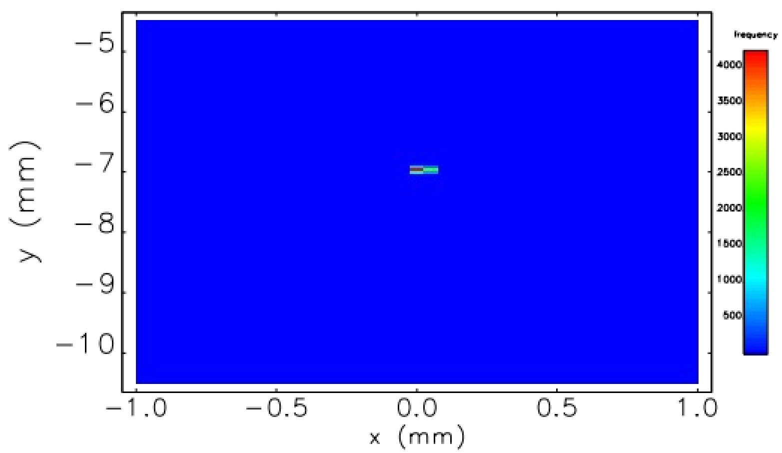
Based on sample of three cases, collimators intercept 75% or more of Touschek losses.

1: S. Khan, EPAC94 (1192).
2: A. Xiao et al., PRSTAB 13, 074201.

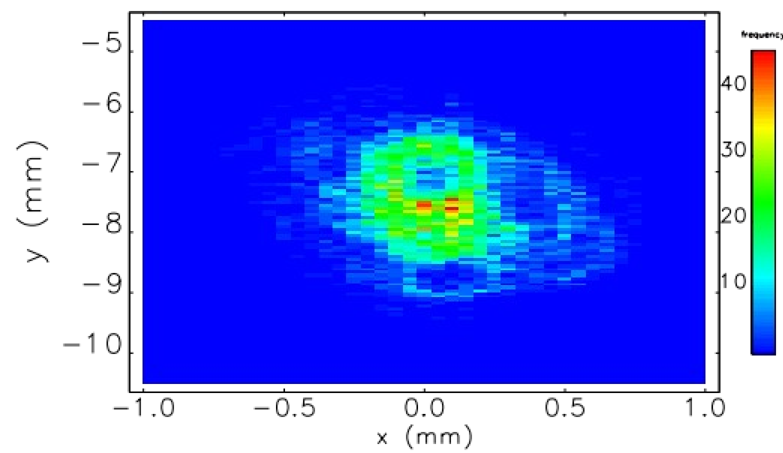
Swap-out and whole-beam dumps[1]

- Swap-out and whole-beam dumps can be damaged by a single bunch out of 48
  - Energy density is larger than for entire 100 mA APS beam
  - In APS, copper and tungsten dumps have been locally melted by beam impact
- For whole-beam aborts, need dumps in 5 consecutive sectors to protect IDs
  - Dumps will be damaged by beam, must have sacrificial surface
- For swap-out, fire a “decoherence prekicker” prior to swap out
  - Decreases energy density of dumped bunch ~100-fold
  - Simulations show only modest temperature increase (Pelegant+MARS)

Beam spot on swap-out dump
without decoherence prekicker



Beam spot on swap-out dump
with decoherence prekicker



1. J. Dooling et al., TWIIS Workshop, August 2017, Berlin.

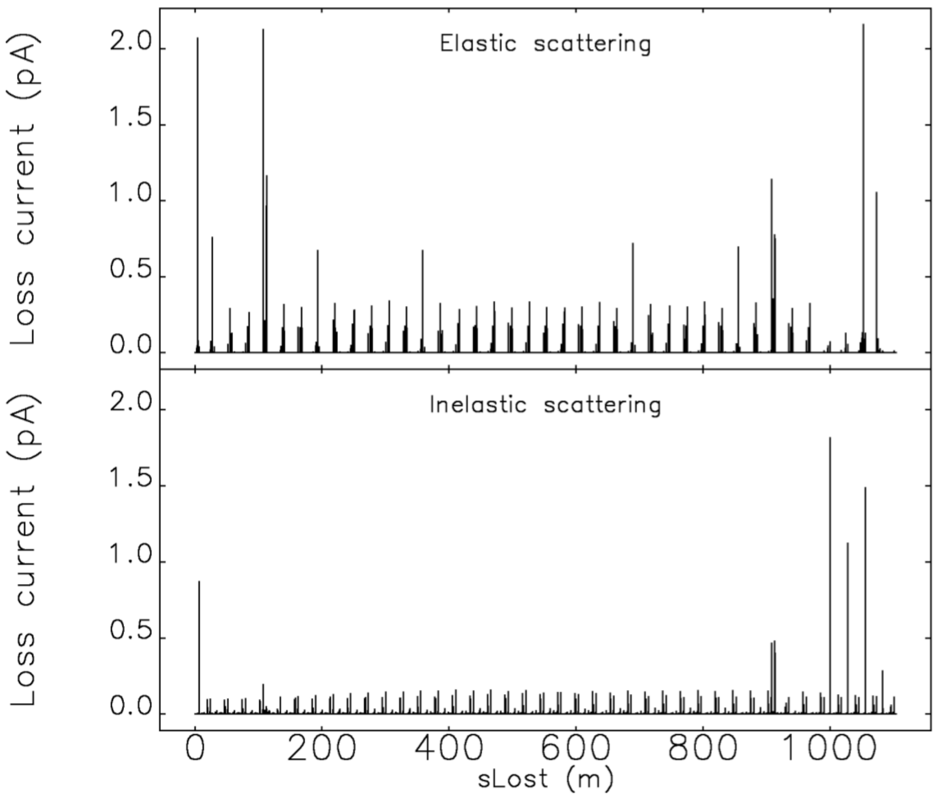
Summary

- Our overarching goal is a new machine that turns on easily with no surprises, which requires
  - Tight integration of physics, engineering, and planning
  - State-of-the-art simulations
- Engineering designs for many systems are well advanced, e.g.,
  - Several magnet orders already awarded
  - Harmonic cavity tested, meets voltage requirements
  - Swap-out kicker tested with beam
  - Full-sector mock-up of vacuum chamber
  - High-rate orbit feedback demonstrated
- Detailed design is documented in Preliminary Design Report
  - Available at https://www.aps.anl.gov/APS-Upgrade/Documents

Backup Slides

Beam losses - gas scattering[1,2]

- Simulations are tracking based
  - Tracking of many particles scattered at many locations
  - Combined with gas pressure distribution gives loss rates
  - Also provides loss particle distribution for radiation physics analysis
- Show reasonable agreement with previous results



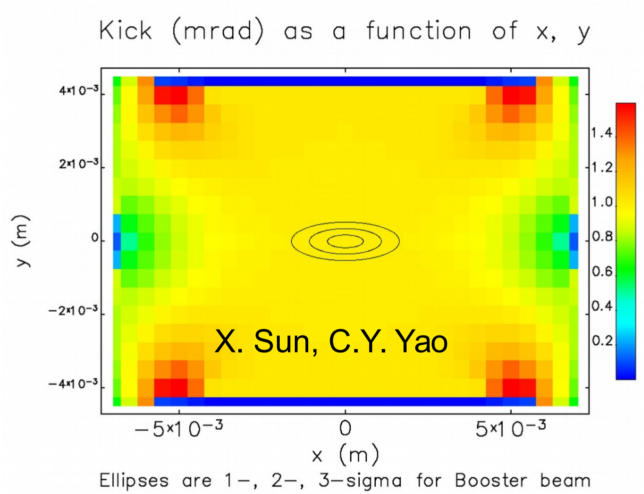
- Peak locations:
  - Vertical collimators
  - HSCU and HGSCU
  - Septum

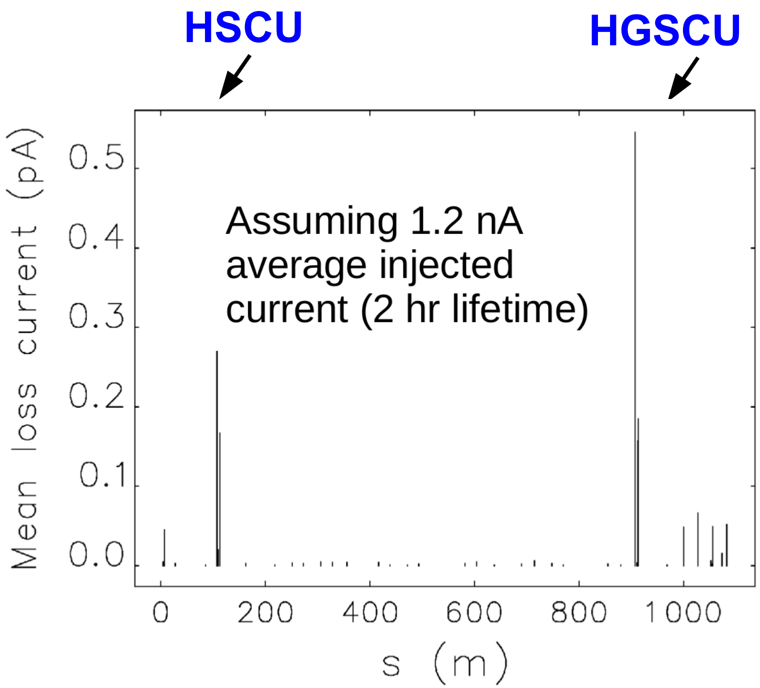
- Peak locations:
  - Horizontal collimators
  - HGSCU

1: M. Borland, AOP-TN-2017-040
2: M. Borland, AOP-TN-2017-043

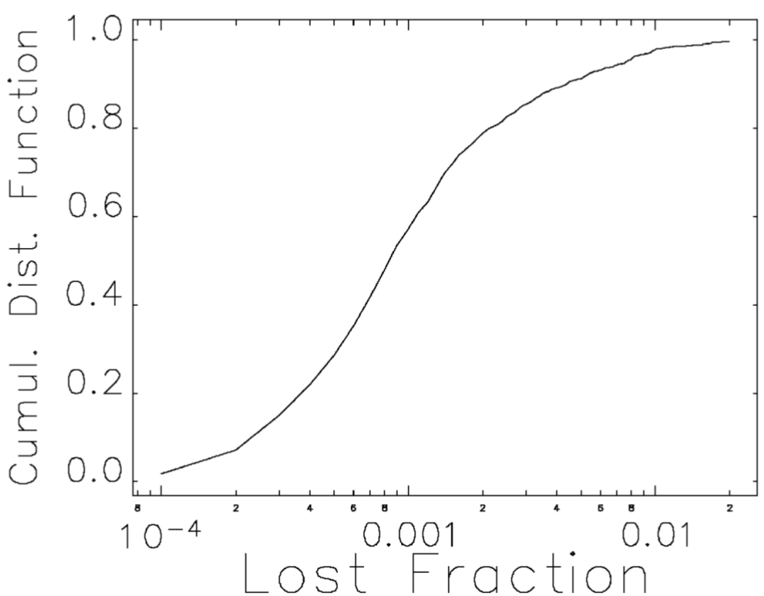
Beam losses - injection

- Injection simulations now include measured pulser waveforms, explicit timing and amplitude jitter of pulsed magnets, explicit phase jitter, computed stripline deflection map
- Helps set requirements on these quantities and on the incoming beam emittance
- 98% of cases have less than 1.1% loss



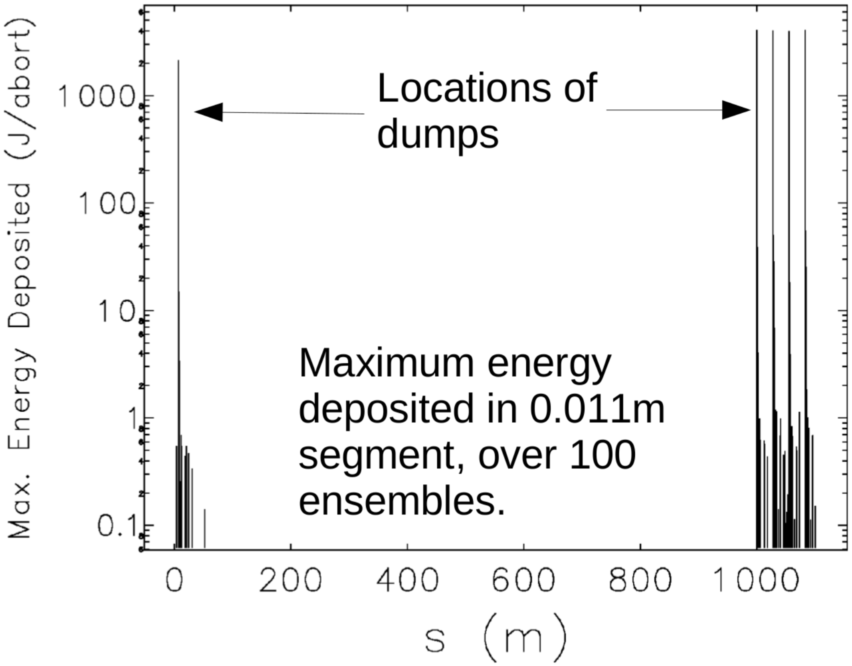


M. Borland



Beam losses - beam abort

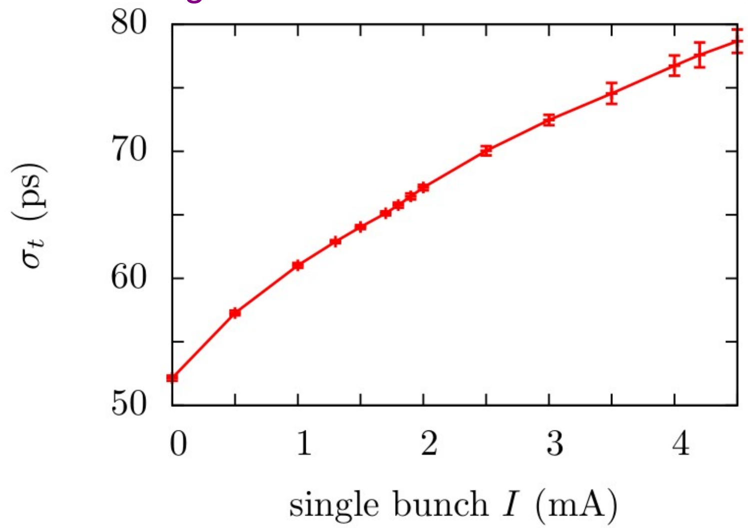
- Beam aborts may be commanded for equipment or personnel protection
  - Muting rf is the most reliable way to abort
- Whole-beam dump(s) will be damaged
  - Energy density ~20 times that for APS
  - Must move the dump surface after abort
- Conclusions of modeling[1] for 100 ensembles:
  - With only one dump, likely to hit ID unless dump aperture is sharply reduced
  - Planned five dumps provide certainty that the beam will be lost on the beam dump
  - These dumps double as Touschek and inelastic scattering collimators



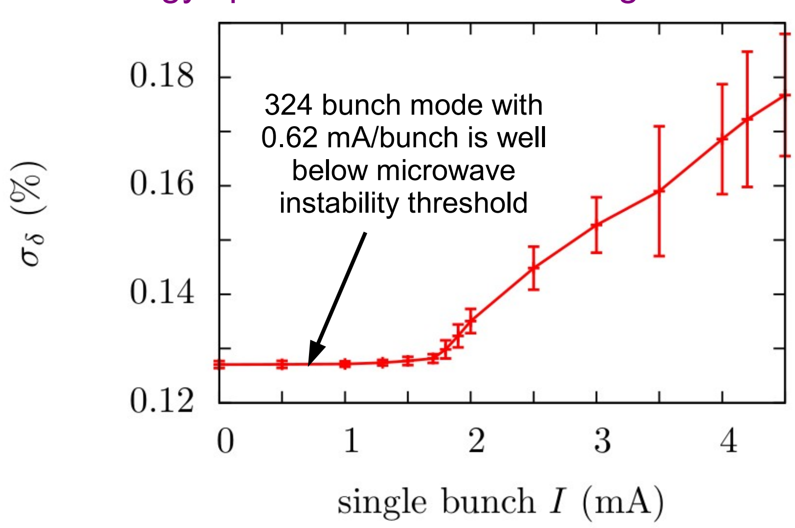
1: M. Borland, AOP-TN-2017-075.

Longitudinal collective effects: bunch lengthening and energy spread increase

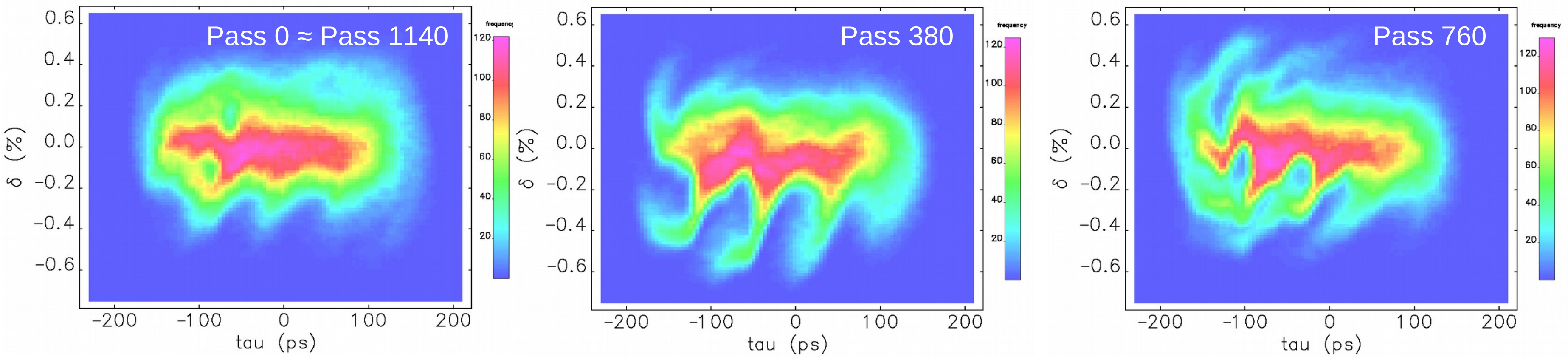
Bunch length increases → reduces rf heating



Energy spread increase is manageable

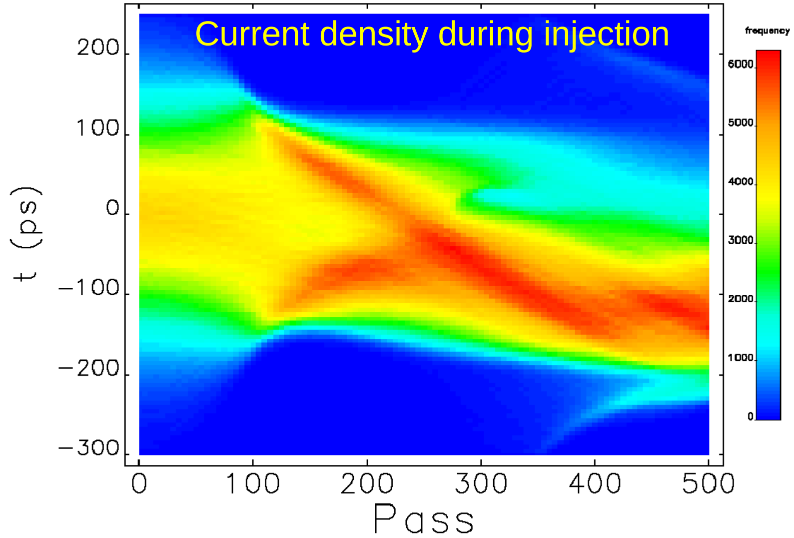


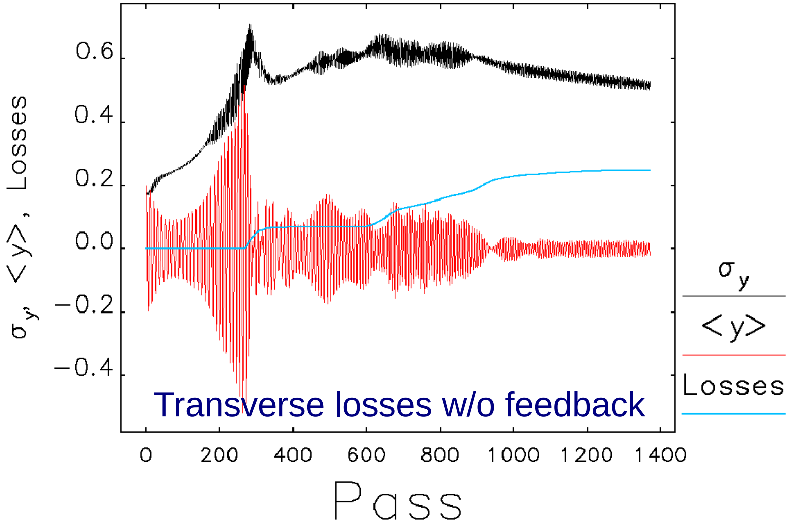
Longitudinal phase space at 4.2 mA/bunch is turbulent with fluctuations ~10% in energy spread and in the mean energy ~10^{-4}



Collective effects at injection

- Collective effects can reduce injection efficiency, even for on-axis injection†
  - Injection system errors will seed transverse instabilities by initial offsets up to 200 microns
  - Longitudinal phase-space mismatch of injected and stored beam results in longitudinal oscillations/structure which can generate large transverse wakefields
  - Transient transverse wakefields can drive oscillations, emittance growth, and particle loss





- Nonlinear resonances of the large-emittance injected beam exacerbates problem
- Improving the longitudinal phase-space mismatch can reduce the longitudinal tumbling and transient transverse instability
- Transverse feedback can cure the instability and prevent particle loss

† M. Borland, T. Berenc, L. Emery, R. Lindberg. Proc. ICAP,15, Shanghai, China, pp 61 (2015).

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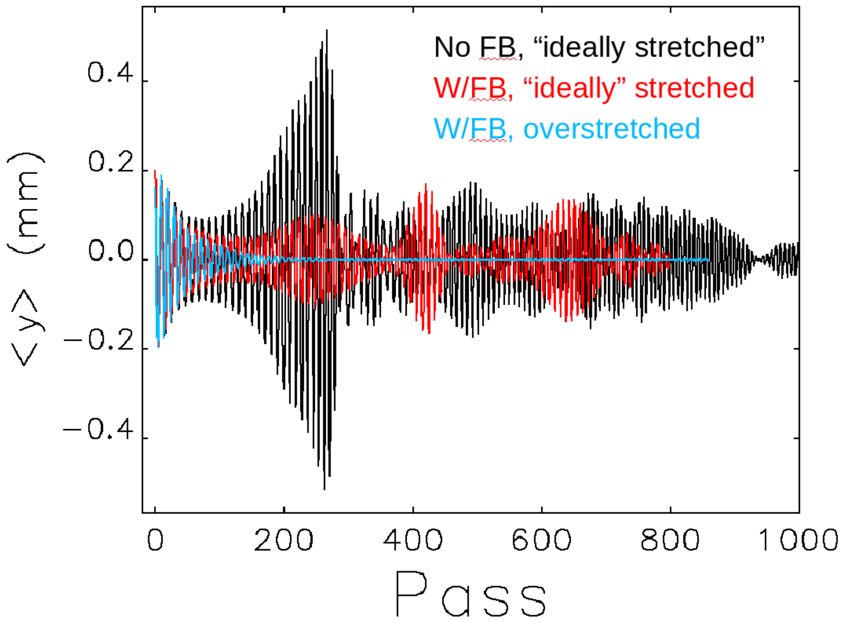
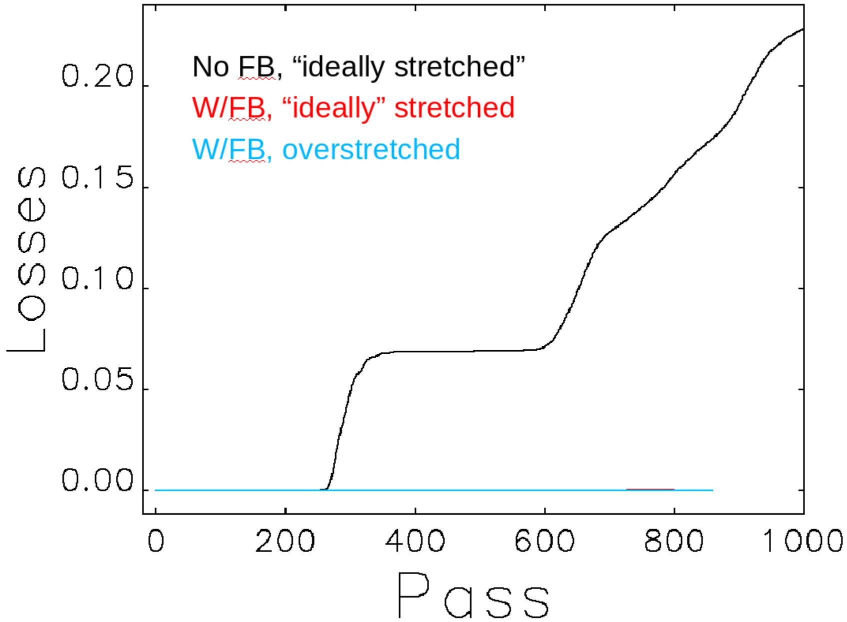
Better longitudinal matching can limit transient instability, and feedback can cure it

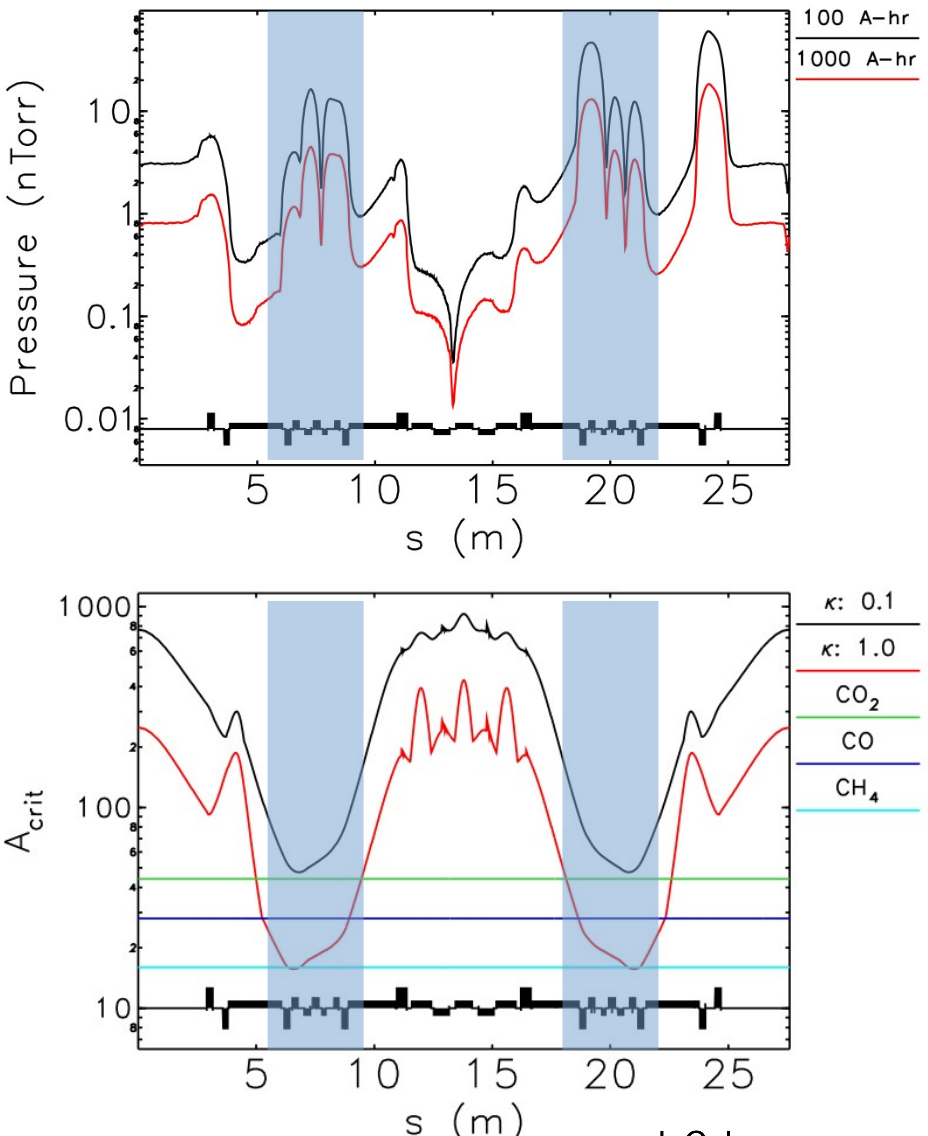




- Injected beam from booster has $\varepsilon_x \times \varepsilon_y = 60 \times 15$ nm, $\sigma_t = 100$ ps, $\sigma_\delta = 0.12\%$
- Simulations employ element-by-element tracking with HHC
  - "Ideally stretched" uses prescribed rf set to flatten potential ($\sigma_t = 51$ ps, $\sigma_\delta = 0.126\%$)
  - "Overstretched" has short-range wakefield and a passive HHC that is tuned to maximize lifetime ($\sigma_t = 100$ ps, $\sigma_\delta = 0.15\%$)
- Impedance is separated into 15 impedance elements per sector
- The transverse feedback is limited to 1 microradian maximum kick

Pressure profiles and ion trapping

- CERN codes[1,2] SYNRAD+ and MOLFLOW+ used to compute pressure around the ring for various amounts of beam conditioning[3]
  - Pressure is highest in the multiplets where there is no distributed pumping
  - Data used for analysis of ion instabilities and gas scattering
- An ion will be trapped at a given location in the lattice if its mass number is greater than A^{crit}
  - Unfortunately, this also happens in the multiplets due to large beam size



J. Calvey

1: R. Kersevan. Proc. PAC 1993, p. 3848.
2: M. Ady and R. Kersevan. Proc. IPAC 2014, p. 2348.
3: B. Stillwell, IPAC2017, 3590. Data courtesy J. Carter.

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