The Upgrade of the Advanced Photon Source

Aimin Xiao on behalf of the APS-U team

Argonne National Laboratory

9th International Particle Accelerator Conference

April 29–May 4, 2018
JW Marriott parq | Vancouver, Canada

IPAC18

Hosted by TRIUMF

Acknowledgment

- This talk draws summary talks given by

  Robert Hettel, Glenn Decker, Michael Borland, Katherine Harkay, Ulrich Wienands, Herman Cease, John Carwardine and John Byrd, with support from the entire APS-U team

- Simulations used ANL's Blues and Bebop clusters, ASD's Weed cluster

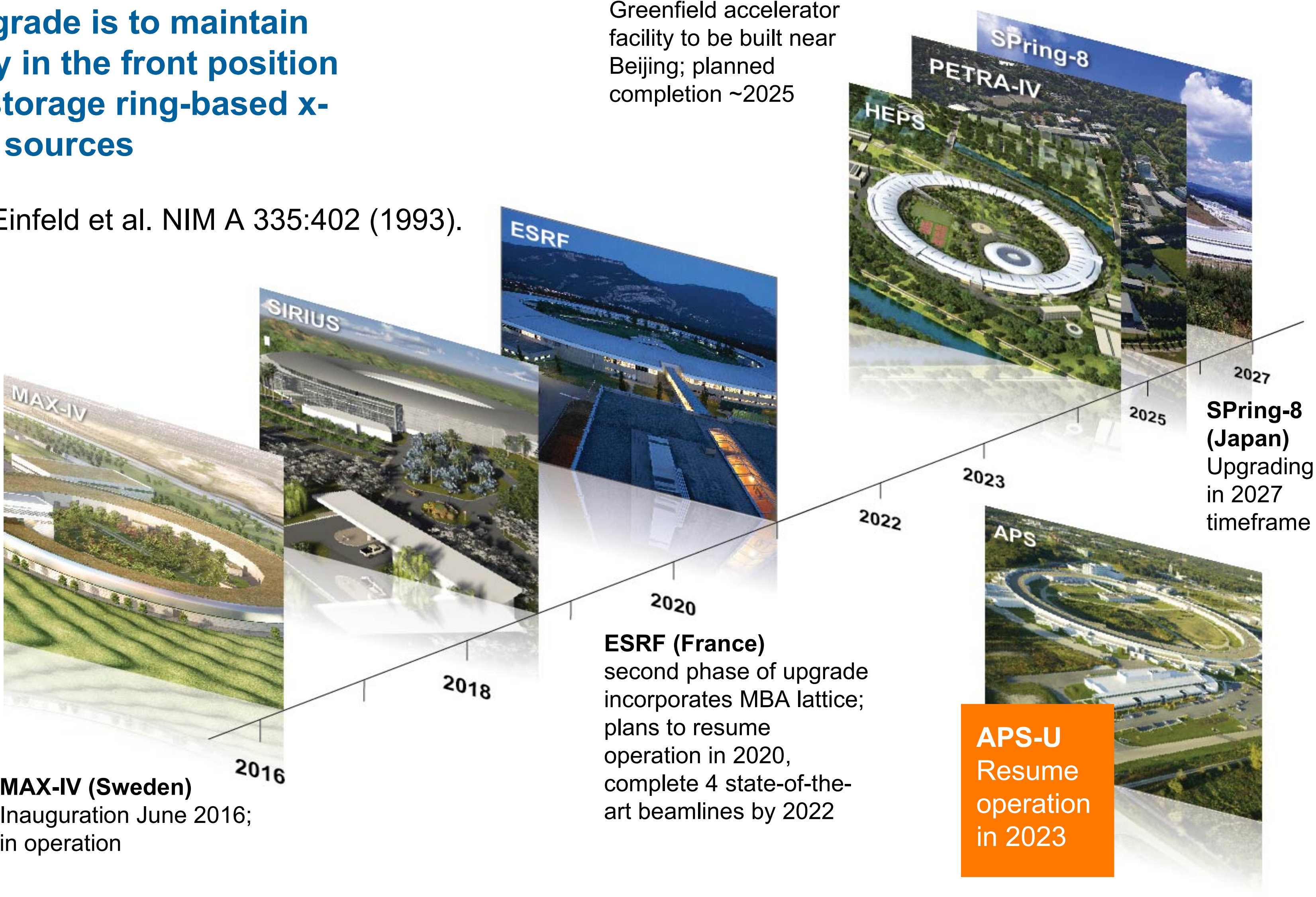
- ESRF generously shared an early version of their H7BA lattice

To stand still is to lose ground

Our plans for the APS Upgrade is to maintain stay in the front position in storage ring-based x-ray sources

1: D. Einfeld et al. NIM A 335:402 (1993).

and more...



HEPS (China)
Greenfield accelerator facility to be built near Beijing; planned completion ~2025

SPring-8 (Japan)
Upgrading in 2027 timeframe

ESRF (France)
second phase of upgrade incorporates MBA lattice; plans to resume operation in 2020, complete 4 state-of-the-art beamlines by 2022

MAX-IV (Sweden)
Inauguration June 2016; in operation

APS-U
Resume operation in 2023

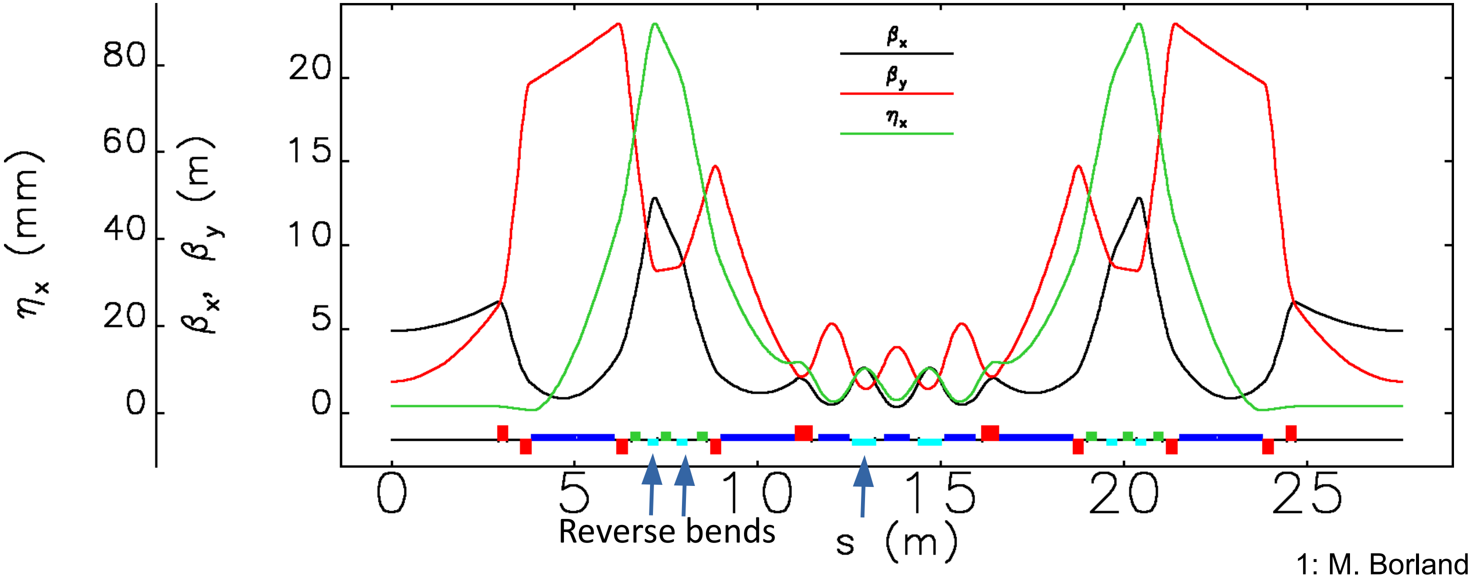
Goal, Challenges, Strategy & Development (1)

- Goal:
  - 6 GeV, 42-pm
  - ~100-fold increase of brightness at 10 keV
- Beam physics design: small emittance → strong focusing
  - Strong nonlinear effects
    - Fringe field included
    - Thorough commissioning simulation
  - Small vacuum chamber size
    - Collective effects need be carefully addressed
  - Shorter beam lifetime
    - Study of beam loss and collimation
  - Small dynamic aperture
    - On-axis swap-out injection scheme

Goal, Challenges, Strategy & Development (2)

- Engineering system
  - Risks and challenges identified
  - Intensive R&D made to understand critical issues
    - Prototype almost all magnet types
    - Validate alignment methodology
    - Prototyping of vacuum system components w/full-sector mockup
    - Higher harmonic cavity (HHC) R&D
    - Prototype power supplies, develop calibration techniques
    - Development of FOFB with modern BPM electronics and control algorithms, tested with beam
    - Prototype fast stripline kicker, tested kicker+pulser with beam

Lattice choice – H7BA + reverse bend[1,2,3,4,5]

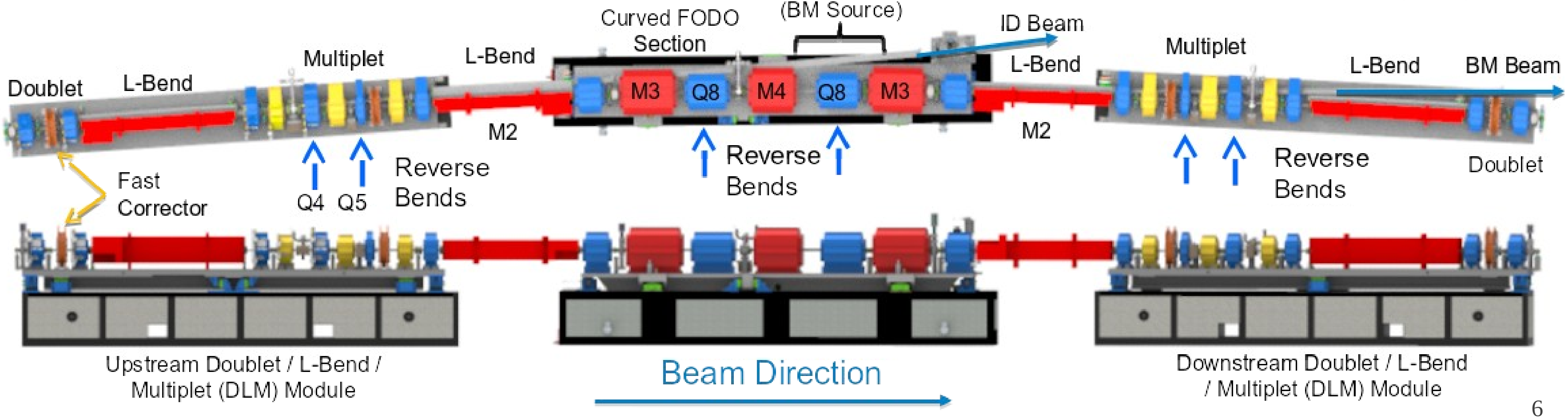


M. Borland
Y. Sun

TUPMF013

1: M. Borland et al., NAPAC16, 877.
2: L. Farvacque et al., IPAC2013, 79.
3: Initial H7BA was provided by ESRF.
4: J. Delahaye et al., PAC89, 1611.
5: A. Streun, NIM-A 737 (2014)

H. Cease, et al.



The APS Upgrade Parameters

M. Borland
Y. Sun

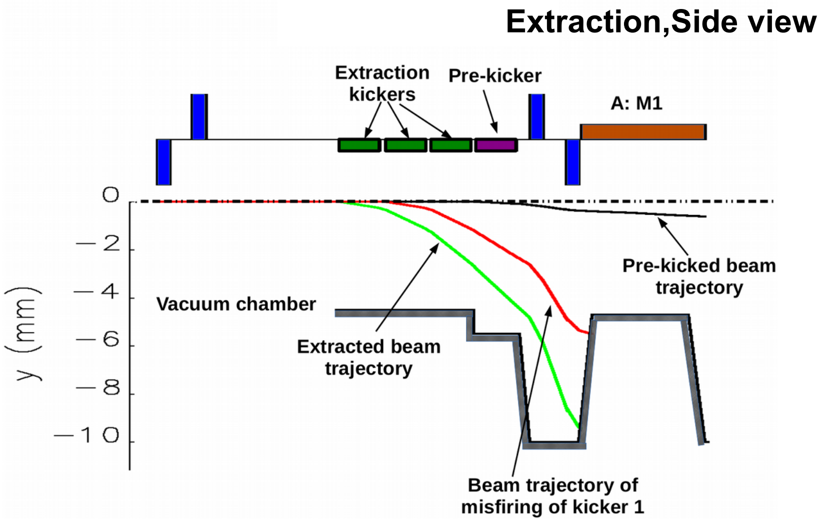
Quantity	**APS Now**	**APS MBA Timing Mode**	**APS MBA Brightness Mode**	**Units**
Beam Energy	7	6		GeV
Beam Current	100	200		mA
Number of bunches	24	48	324	
Bunch Duration (rms)	34	104	88	ps
Energy Spread (rms)	0.095	0.156	0.130	%
Bunch Spacing	153	77	11	ns
Horizontal Emittance	3100	32	42	pm·rad
Emittance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

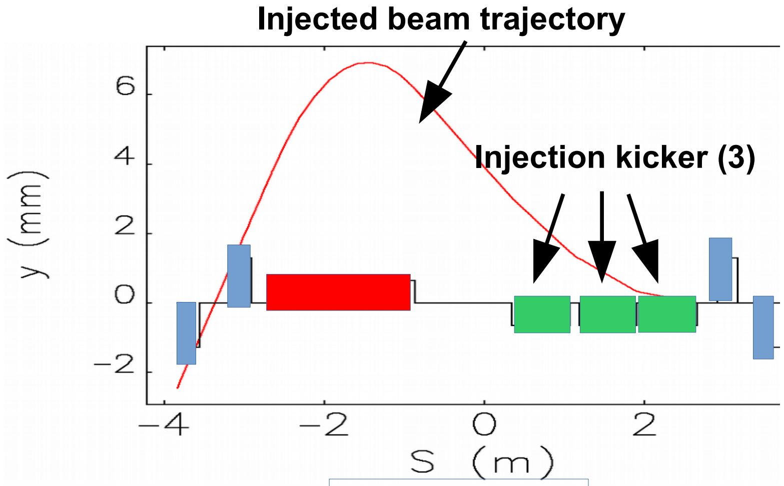
TUPMF017

On-axis swap-out injection

A. Xiao

- On-axis swap-out injection[1,2,3] is a necessary for small DA
  - Fast stripline kickers[4] + Slightly tilted Lambertson septum[5]
- 324-bunch mode → stringent demands on pulser
  - Total pulser waveform length <16ns; rise/fall time < 4.5 ns
- High energy density → decoherence pre-kicker





Side View

1: R. Abela et al., EPAC 92, 486.
2: L. Emery et al., PAC03, 256.
3: A. Xiao et al., PAC13, 1076.
4: C.-Y. Yao et al., NAPAC16, 950.
5: M. Abliz et al., NIMA-2017-11-090.

Tolerance and Stability[1]

V. Sajaev

- Tolerance specifications based on requirements of
  - Orbit stability within 10% of beam size
  - Ease of commissioning and startup after shutdowns
  - Low noise level for accurate beam measurement
- Many effects have been taken into account
  - Static systematic and random errors: magnet, PS calibration, alignment
  - Time-varying errors: electrical noise, ground motion
  - Other effects: attenuation of magnet core and vacuum chamber, lattice amplification, orbit correction
- 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

10ppm class PS commercially available!

Vibrational requirements

	X (rms) 1-100 Hz	Y (rms)
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]

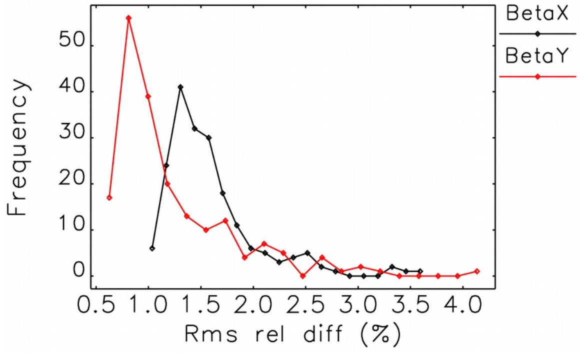
V. Sajaev

- Explores commissioning feasibility and likely performance of the machine after commissioning
- Simulation includes:
  - Realistic error generation
  - Physical apertures
  - Strategy/tools used for real machine operation: orbit and lattice correction
- Results (machine errors after correction) are used for realistic simulations of likely performance

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

Distribution of parameters after commissioning



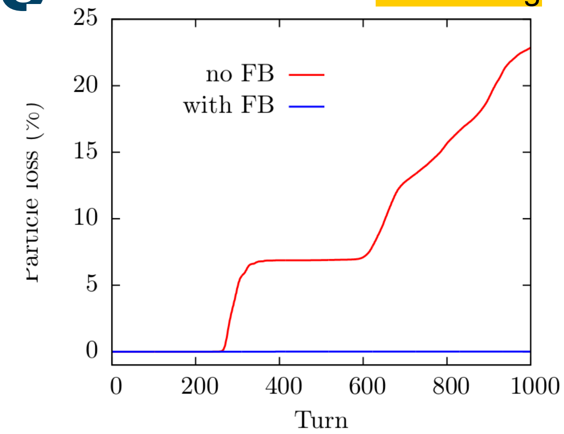
1: V. Sajaev et al, IPAC2015, 553.

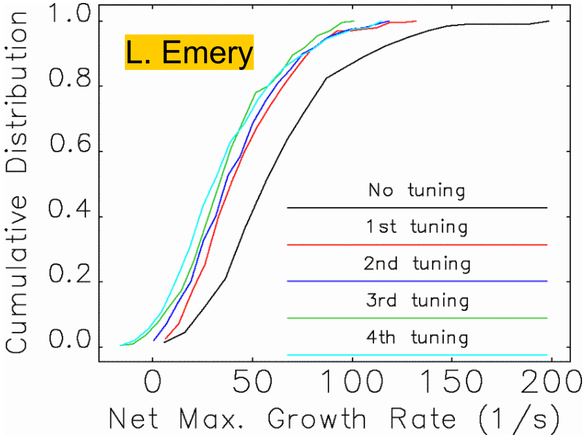
TUPAK005

Collective Effects

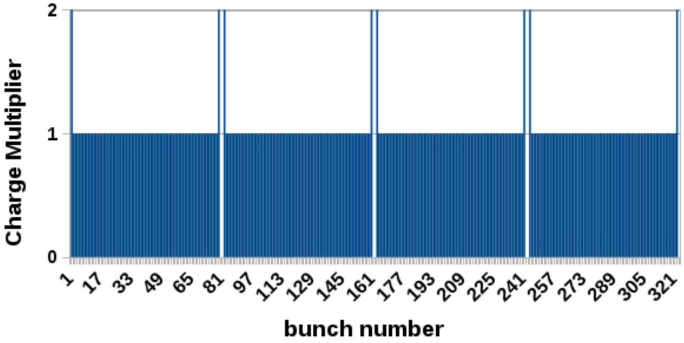
- Single bunch instability
  - Detailed impedance model evolving with and guiding engineering designs
  - Injected bunch can be stabilized with modest feedback
- Multi-bunch instability studied with HHC
  - Longitudinal multi-bunch instability predicted
  - Can be cured with feedback and cavity temperature tuning
- Ion effects
  - Ion instability predicted for 324-bunch mode unless beams are flat (k≤0.1)
  - Can be cured with small cleaning gaps
  - Beam loading variation effects was simulated and can be mitigated by adding missing charge to nearby buckets

R. Lindberg




L. Emery

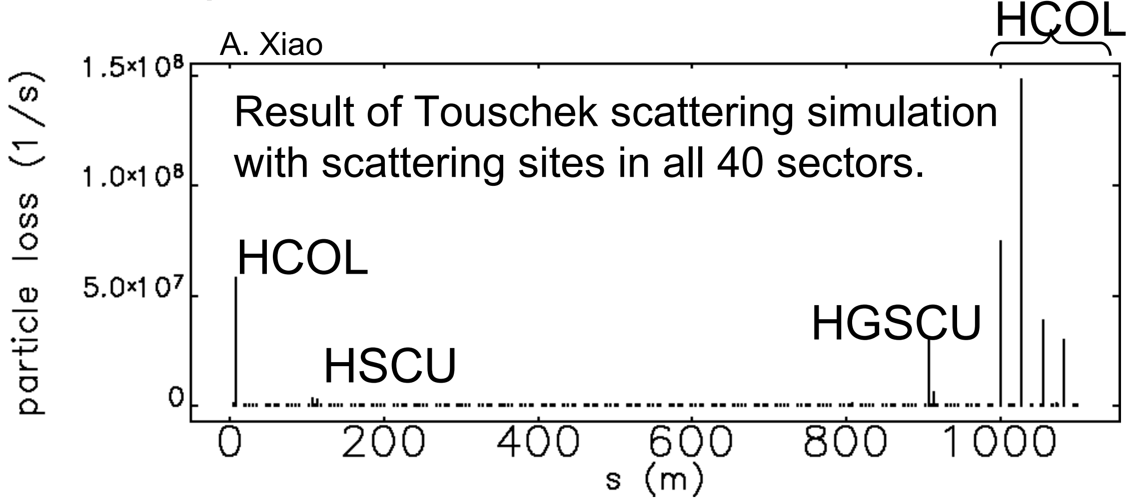
J. Calvey



Beam loss and collimations

A. Xiao
M. Borland

- APS-U SR will use existing APS tunnel
- Loss location need to be localized → easier supplemental shielding
- Loss distributions simulated for Touschek scattering, gas scattering and injection
- Two types of collimators
  - Horizontal collimators (5) for beam loss due to energy error and also whole beam dump (multiple instances cover phase space at different angles)
  - Vertical collimators (2) for beam loss due to large betatron oscillation and swap-out dump


A. Xiao

Result of Touschek scattering simulation with scattering sites in all 40 sectors.

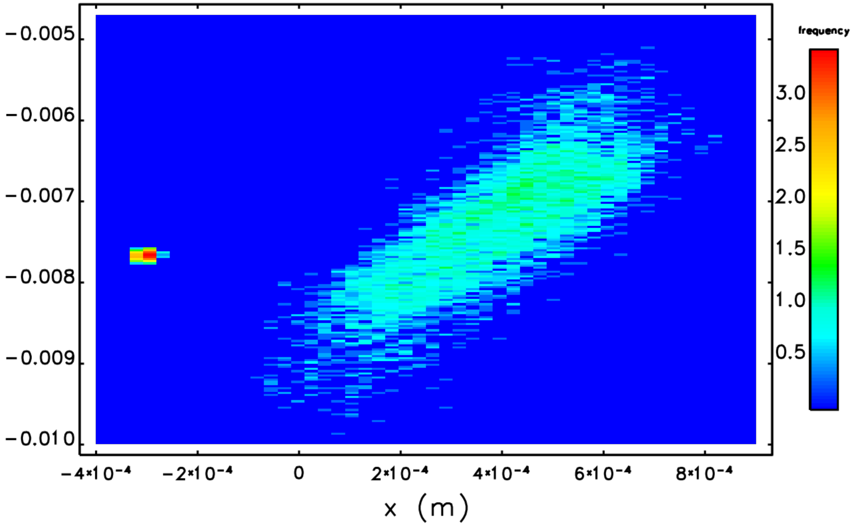
TUPMK004

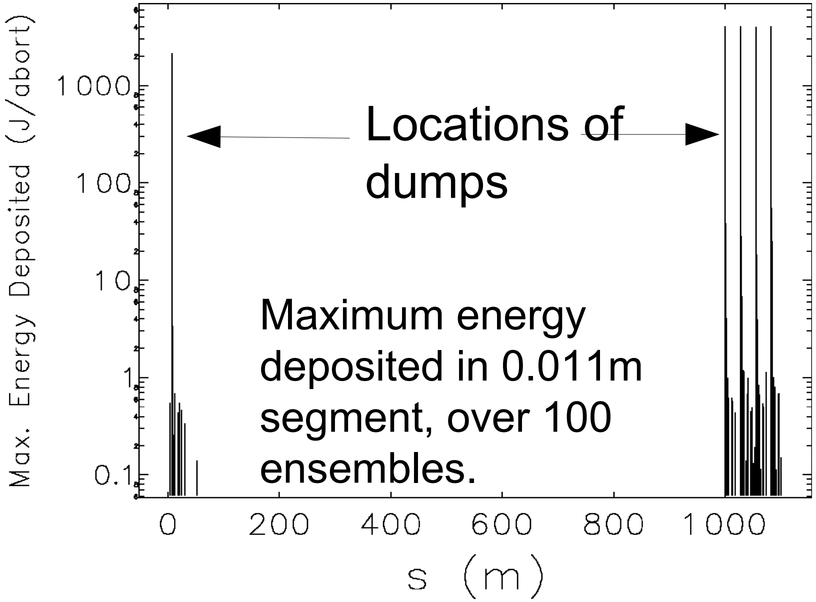
Beam Dumps

M. Borland
J. Dooling

- Two dump types: swap-out beam dump for injection; whole-beam dump for machine protection
- Energy density from a single bunch out of 48 is larger than current APS whole beam abort
  - Damage to copper and tungsten collimators observed in APS operation
  - All materials expected to melt locally
  - Use a “decoherence prekicker” prior to swap-out to inflate beam size
- Whole-beam dump damage is unavoidable
  - Too fast, decoherence not an option
  - Must move the dump surface post-abort
  - Investigation is underway

Beam distribution with and without decoherence delay





Locations of dumps

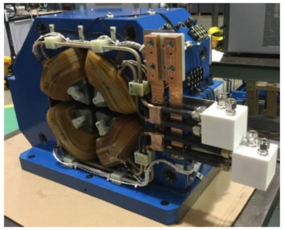
Maximum energy deposited in 0.011m segment, over 100 ensembles.

Accelerator Mechanical System

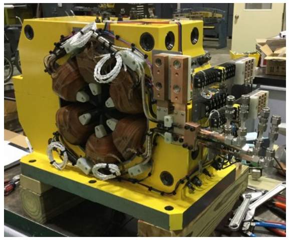
Key requirement drivers

- Magnets M. Jaski, et al.
  - Combined function magnets
  - Challenging field strength
- Vacuum J. Carter, et al.
  - 22-mm inside diameter,
  - Gas scattering lifetime 30 hr,
  - Challenging synchrotron radiation masking and power handling
- Supports A. Jain / J. Nudell, et al.
  - Girder-girder: 100 µm rms
  - Magnet-magnet: 30 µm rms
  - Stability of magnets: 10 nm rms, 1-100 Hz

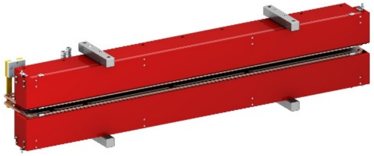
All magnet types prototyped in R&D
8-piece design for all quadrupoles



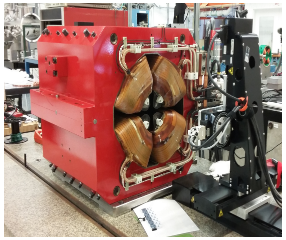
Q1- Q6 Quadrupole Magnets
Photo: DMM Quadrupole



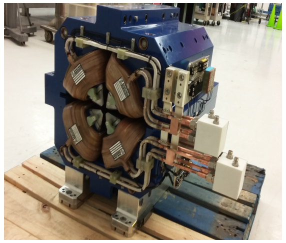
S1-S3 Sextupole Magnets
Photo: DMM Sextupole



L-Bend Magnets M1, M2
R&D collaboration with FNAL



Q-Bend Magnets
M3, M4

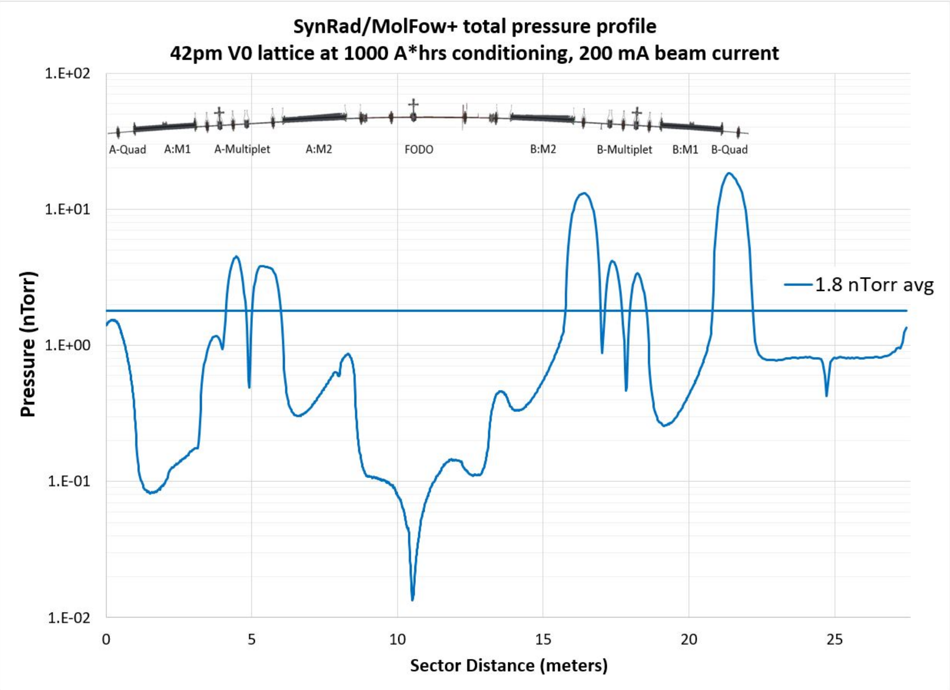


Quadrupole Magnets
Q7, Q8

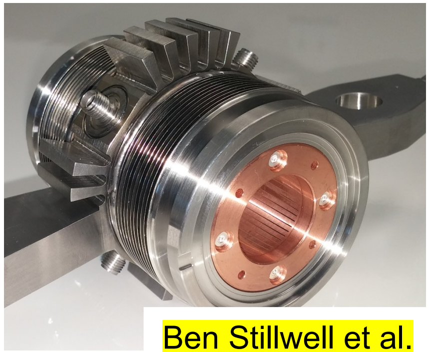
Fast Corrector
Photo: R&D Corrector
Collaboration with BNL

Vacuum System Design

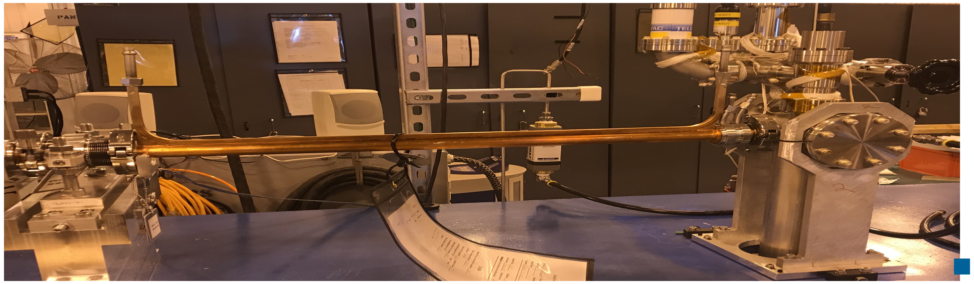
(B. Stillwell)
J. Carter et al.


SynRad/MolFow+ total pressure profile
42pm V0 lattice at 1000 A*hrs conditioning, 200 mA beam current

BPM Prototype


Ben Stillwell et al.

- CERN code[1,2] SYNRAD+ and MOLFLOW+ used to compute pressure[3]
- Sector Mockup assembly complete
  - Includes all chambers
  - Testing is starting in FY18,
    - Compare with simulations
    - Develop process for in-situ bake, maintenance activities
- In-ring test planned for BPM


NEG-coated Prototype FODO Chamber
Bran Brajuskovic

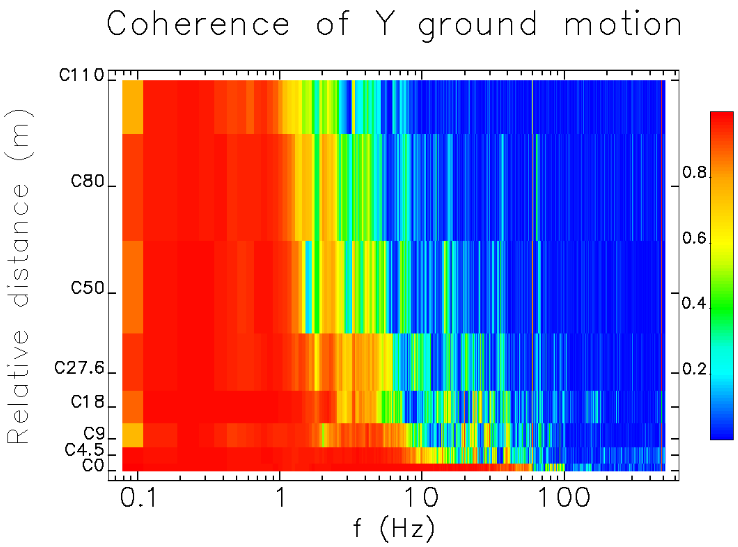
1: R. Kersevan. Proc. PAC 1993, p. 3848.
2: M. Ady and R. Kersevan. Proc. IPAC 2014, p. 2348.
3: B. Stillwell, IPAC2017, 3590. Data courtesy J. Carter.

Ground and Girder Vibration Study

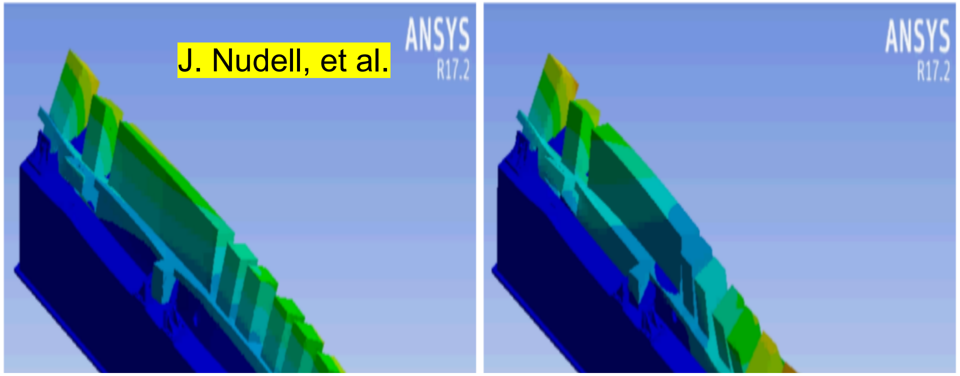
V. Sajaev, et al

TUPMF011
TUPMF012

- Ground motion was measured in both frequency and coherence length, PSD ~ $1/f^4$
- Girder resonant deformation modes 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 (without orbit correction)



C. Preissner



J. Nudell, et al.

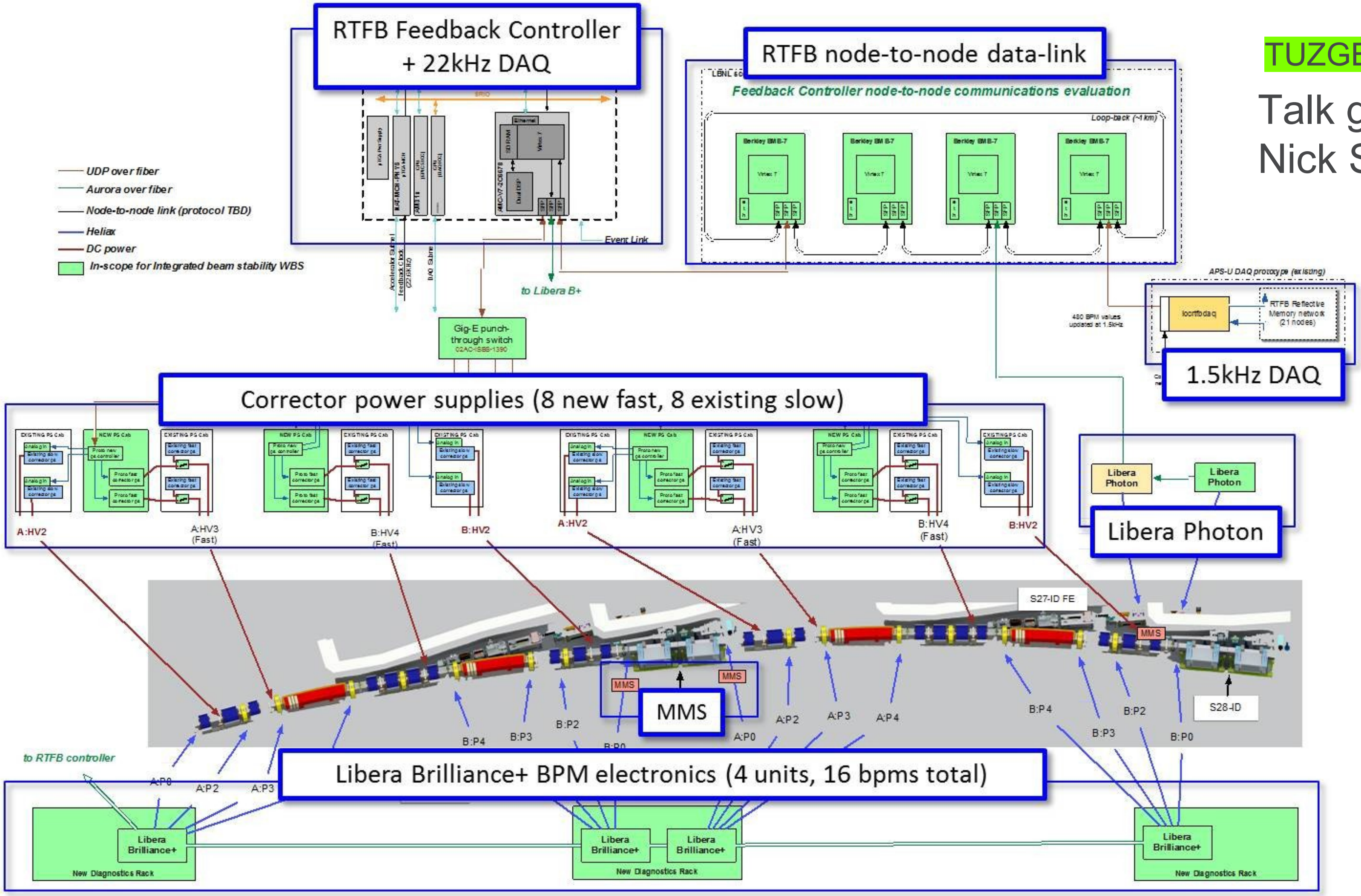
APS-U Orbit feedback Integrated R&D

J. Carwardine
N. Sereno
N. Arnold, et al.

- Goal: extend correction bandwidth to 1 kHz
- Prototype system under test in a double sector 27/28
  - 22 kHz update rate; 16 rf BPMs + 2 photon BPMs; 8H + 8V corr.

TUZGBD3

Talk given by Nick Sereno



RTFB Feedback Controller + 22kHz DAQ

RTFB node-to-node data-link

1.5kHz DAQ

Corrector power supplies (8 new fast, 8 existing slow)

Libera Photon

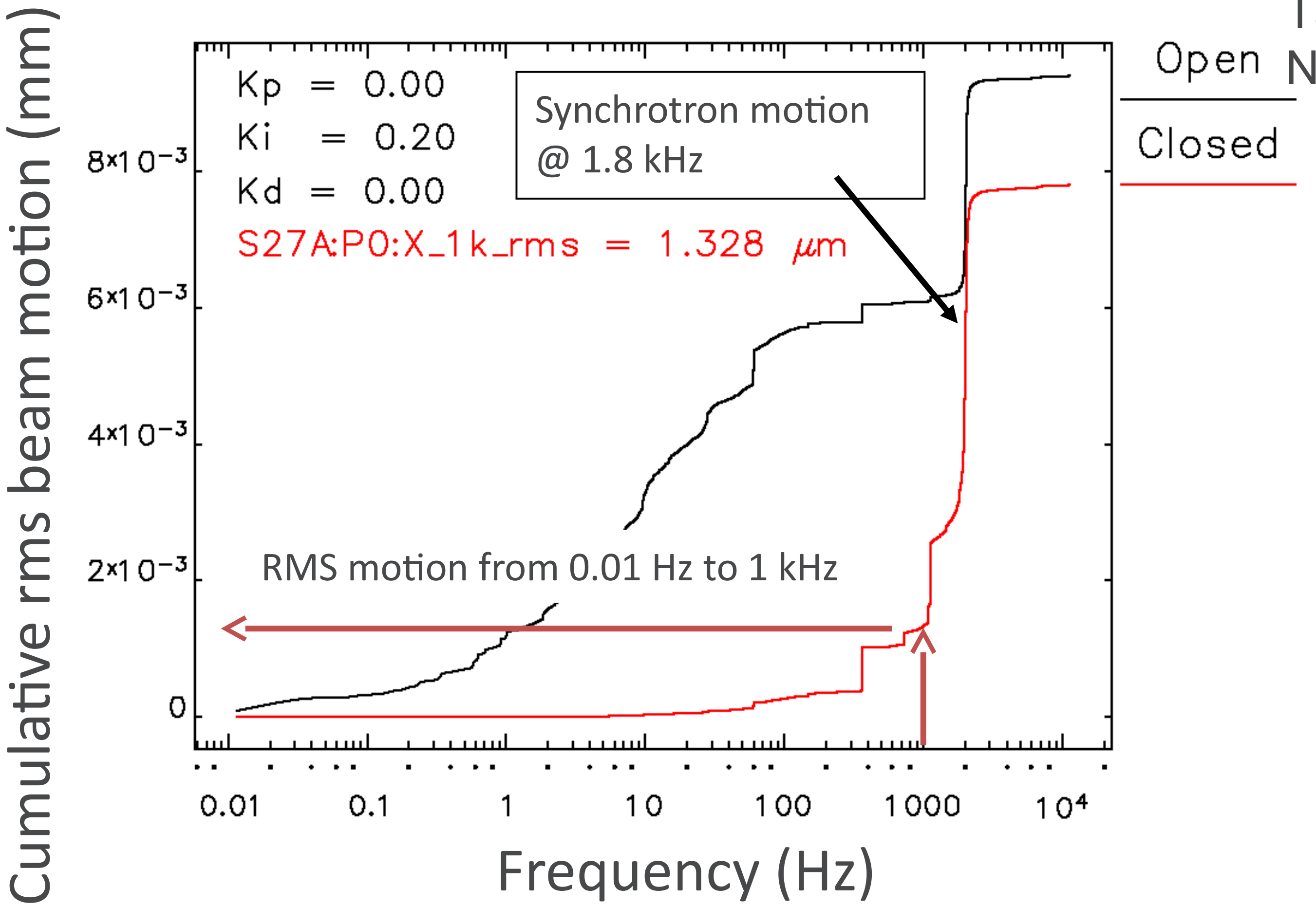
MMS

Libera Brilliance+ BPM electronics (4 units, 16 bpms total)

RMS beam stability test at S27 with 22.6 kHz sampling rate and unified feedback (rms beam motion)

TUZGBD3

Talk given by Nick Sereno



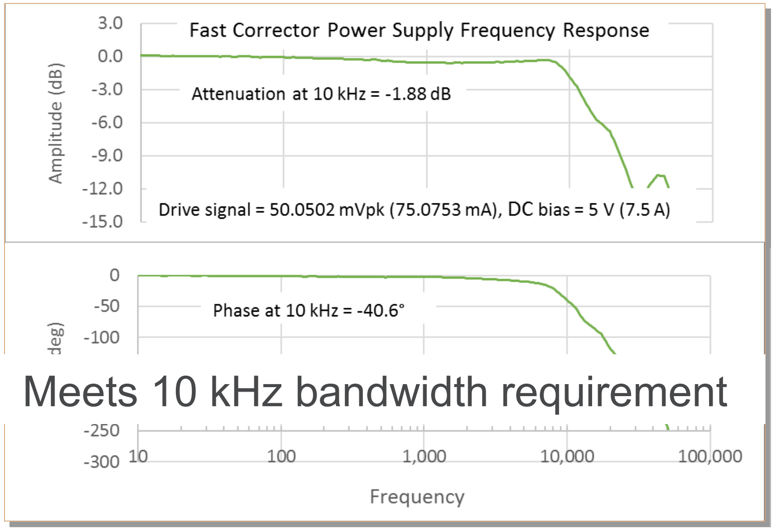
We are near spec for AC stability (400 nm vertical and 1300 nm horizontal)
Achieved > 700 Hz closed loop bandwidth

WEPMF008

Power Supplies R&D

J. Wang, et al.

- Fabricated, field-tested fast bipolar power supplies with response > 10 kHz
- Unipolar PS external measurement will allow calibrating installed PS with common reference

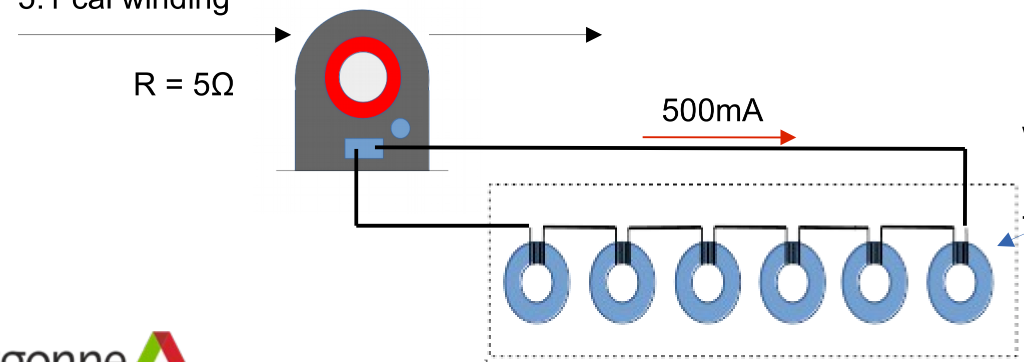


Meets 10 kHz bandwidth requirement

In-house design and Built-to-print bipolar PS

Ratio DCCT: Calibration (primary) winding to secondary winding ratio **1000:200 = 5:1**
100mA calibration current => **500mA secondary current for use as calibration current**

New measurement DCCT: 600 calibration windings x 500mA = **300A** calibration range.



100mA into
5:1 cal winding

Ratio
DCCT

R = 5Ω

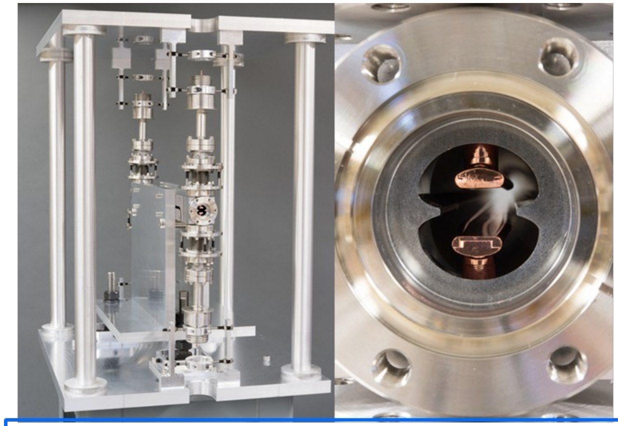
500mA

Resistance of each DCCT 600x calibration winding is 3 ohms nominal. 6 x 3 =18 ohms.

This requires only (0.5 x 18) = 9V.

Injection / Extraction System

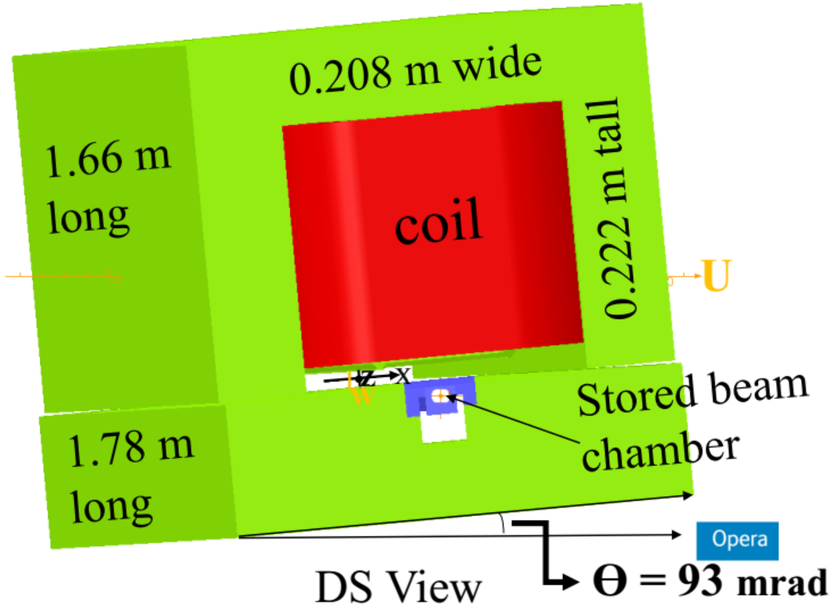
J. Carwardine
U. Wienands
H. Cease, et al.



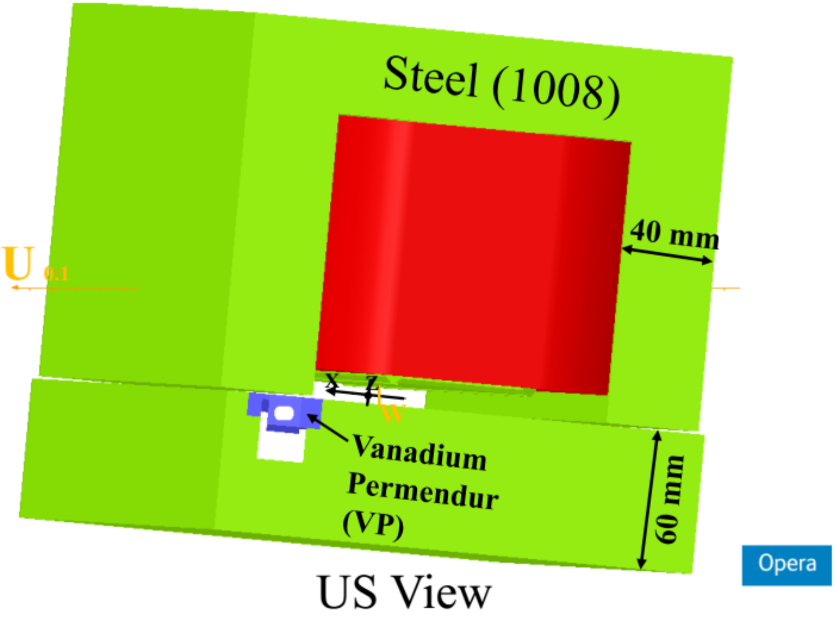
Prototype Stripline Kicker used for successful BTX Beam Tests

Operation demonstrated with beam to 30 kV; Required 18 kV

1: C.-Y. Yao et al., NAPAC16, 950.
2: M. Abliz et al., NIMA-2017-11-090.



(a)

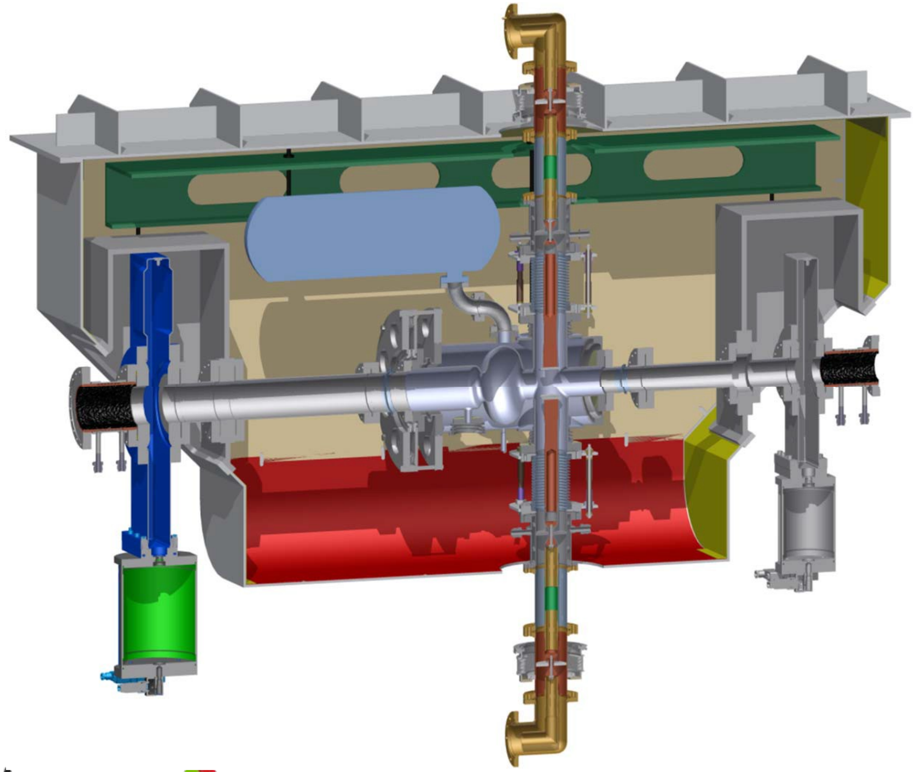


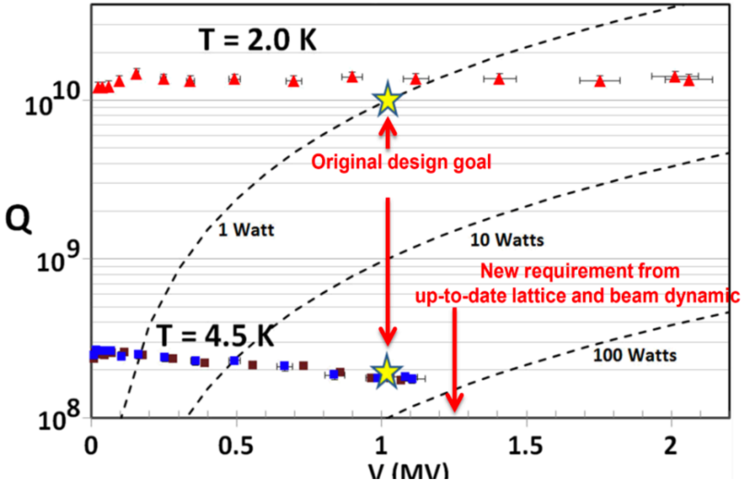
(b)

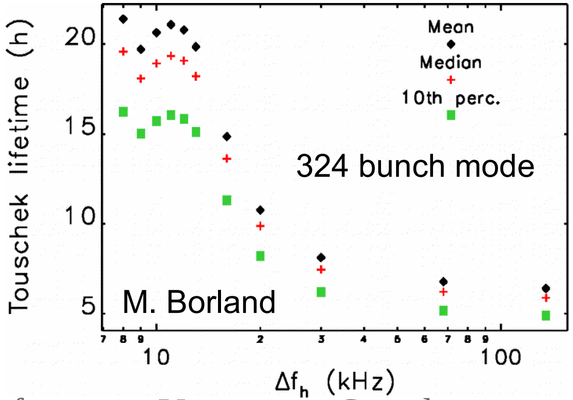
Bunch-Lengthening System

M. Kelly, et al.

- Used to improve beam lifetime, ~ factor of 3 for 324 bunch mode
- Single cell 1.4 GHz superconducting cavity (HHC), passively driven, required 1.25MV, achieved 2MV@2k
- R&D is completed with cavity cold tests, HOM dumper tests, High-power coupler tests and Tuner test







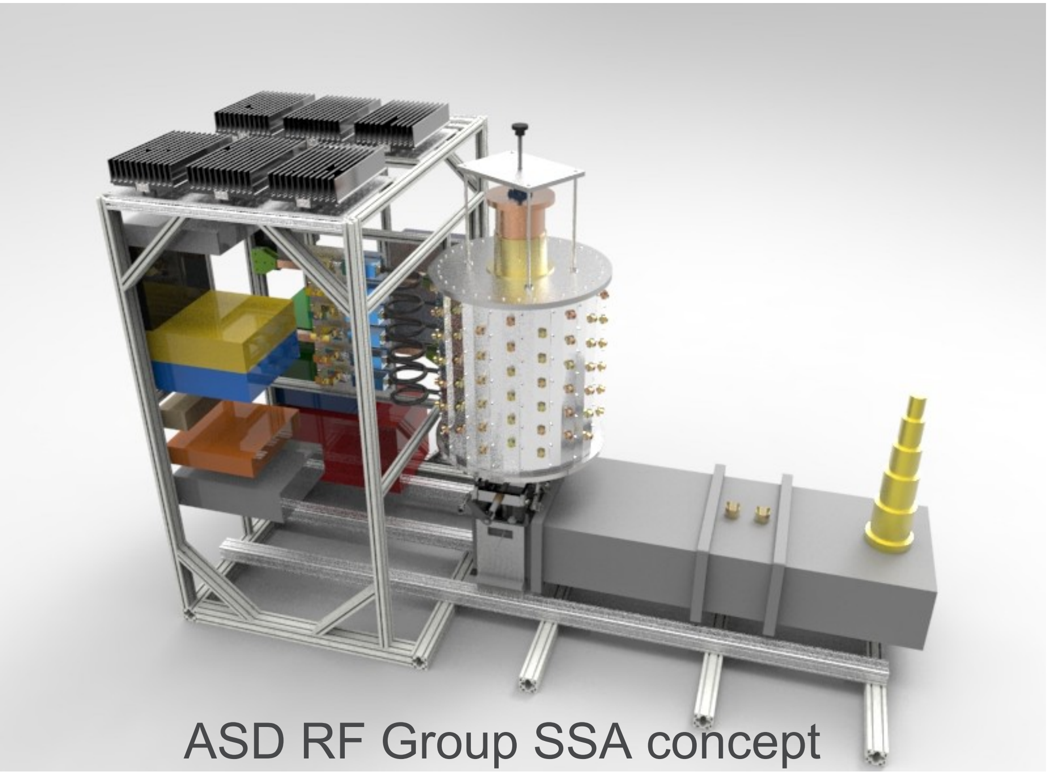
M. Borland

WEPMF005

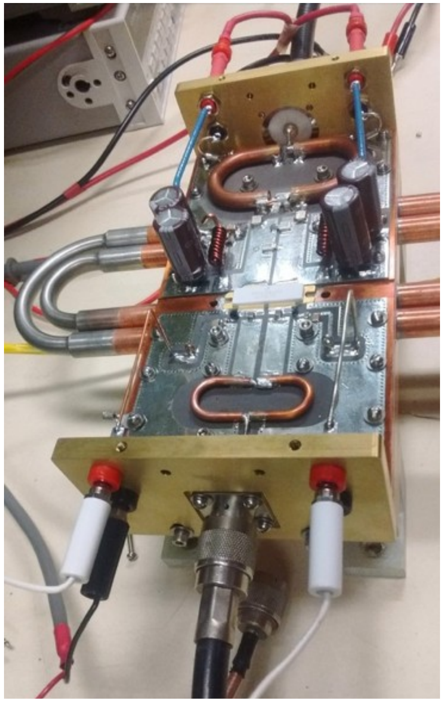
RF systems

D. Horan, et al.

- After extensive study of costs and benefits, decided to keep existing 352-MHz rf cavities
- Klystrons increasingly hard to get, so phase in solid state systems
- Upgrade all ring and injector LLRF systems to improve stability



ASD RF Group SSA concept



Single 2-kW module

Longitudinal Feedback System (1)

U. Wienands, et al.

- APS-U: 200 mA, radiation damping rate 50 s^{-1}
- APS: 100 mA, radiation damping rate 200 s^{-1}

APS-U is likely multi-bunch unstable in longitudinal plane

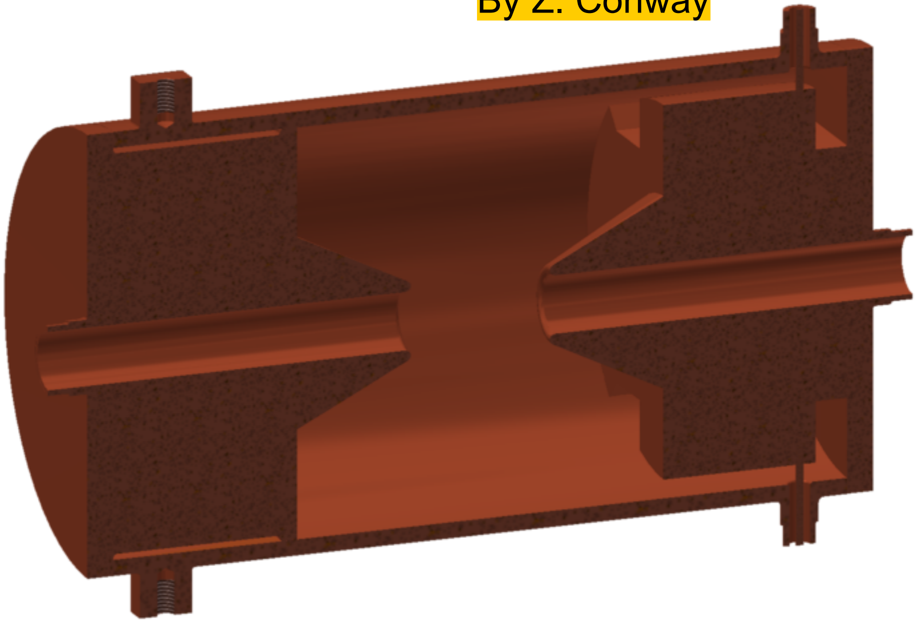
- Operation with HHC - ν_s is not constant, put novel requirement on longitudinal feedback system
  - Filtering would need to be different from conventional
  - Probably need to use yet-to-be developed “direct energy sensing” as a new pick-up mode

Longitudinal Feedback System (2)

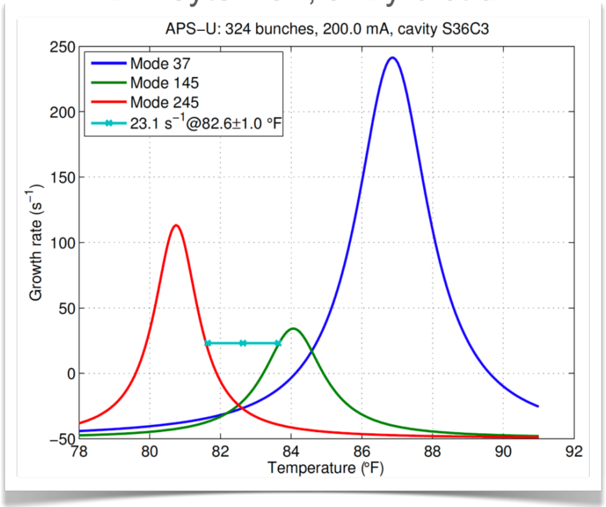
U. Wienands, et al.

- Mitigation methods
  - Temperature tuning of cavities to move HOM peaks from beam resonances
  - Designing a longitudinal feedback system
    - Design system for highest practical kick (6 kV)
    - Up to 600 ms^{-1} damping rate
- Study at APS identified design choices and demonstrated cavity characterization

By Z. Conway



D. Teytelman, J. Byrd *et al.*

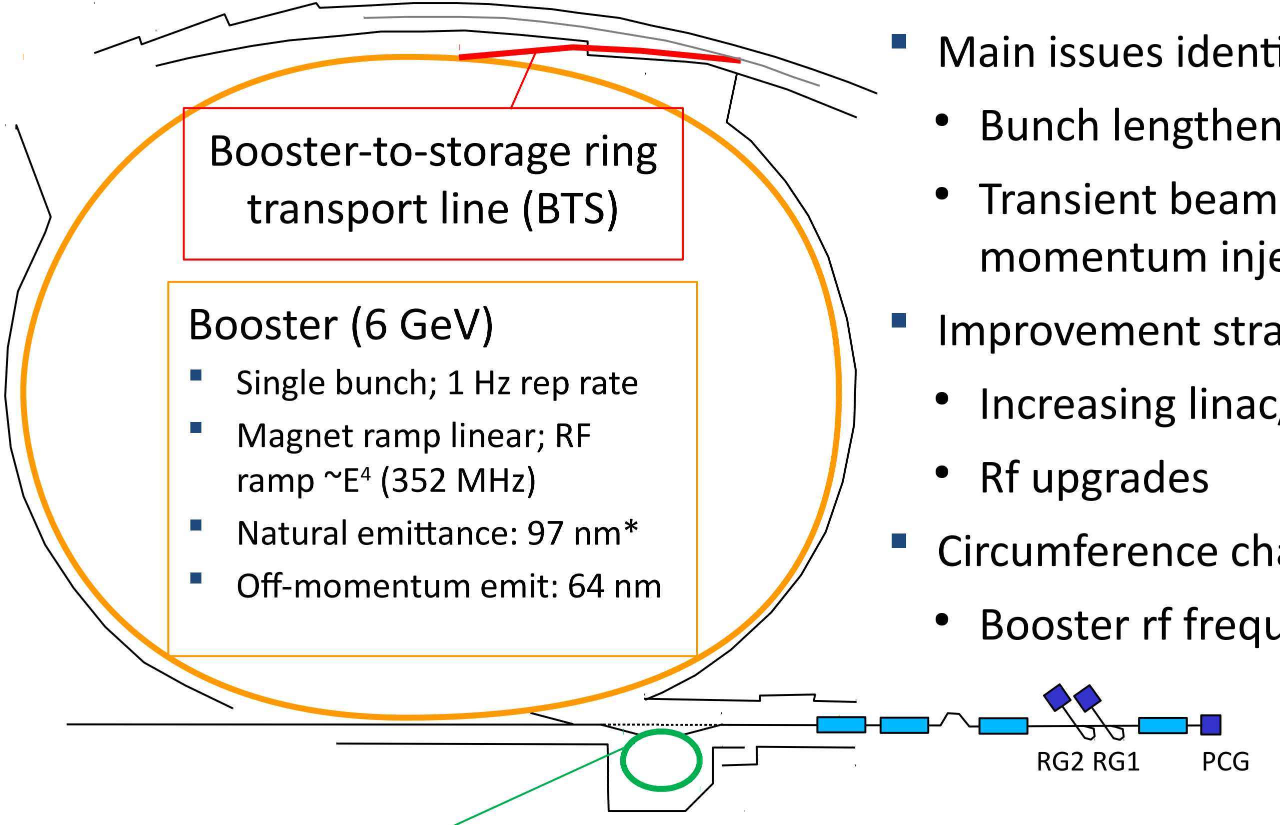


TUPMF003
WEPAF005
WEPAF006
WEPAF007

APS Injector Complex

K. Harkay, et al.

- Max charge 16 nC for APS-U; 2-3 nC for APS; Reached 12 nC (~70% of goal).
- Main issues identified:
  - Bunch lengthening in PAR
  - Transient beam loading and off-momentum injection cause limitations.
- Improvement strategies
  - Increasing linac/PAR energy
  - Rf upgrades
- Circumference change of new SR
  - Booster rf frequency ramping



Booster-to-storage ring transport line (BTS)

Booster (6 GeV)
- Single bunch; 1 Hz rep rate
- Magnet ramp linear; RF ramp ~E^4 (352 MHz)
- Natural emittance: 97 nm*
- Off-momentum emit: 64 nm

Particle accumulator ring (PAR) (425 MeV)
- Single bunch; 1-Hz rep rate
- Captures linac pulses in RF1; compresses damped beam in RF12 (117 MHz); bunch cleaning system

Linac (425 MeV)
- 1 nC/pulse; 30 Hz rep rate
- Thermionic RF guns: RG1, RG2 (1 hot spare)

Summary

- The APS-U physics design is nearly complete
- Accelerator R&D programs have been successful
  - Prototyped all magnet types except longitudinal-gradient dipole and injection septum
  - Demonstrated magnetic measurement and alignment techniques for all magnet types
  - Constructed full-sector vacuum system mockup
  - Completed warm and cold tests of HHC
  - Developing diagnostic systems, control system, rf systems, injector tuning, and more...
- Detailed design documented in Preliminary Design Report
  - Available at https://www.aps.anl.gov/APS-Upgrade/Documents
- The APS-U project is well underway

Thank you for your attention!