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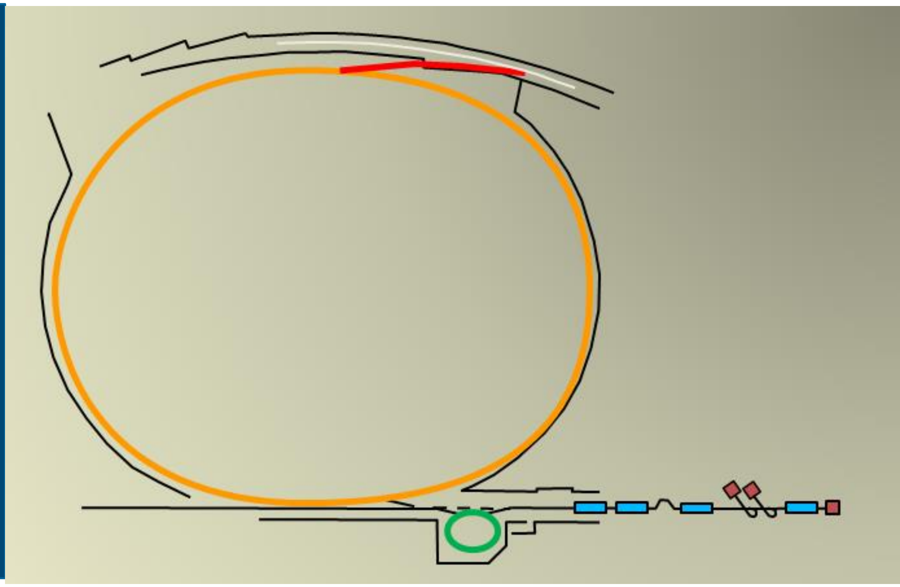
Upgrade of the APS-U Booster for High-charge Bunches and Frequency Sweep



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I.FAST Workshop 2024 on Injectors for Storage Ring Based Light Sources

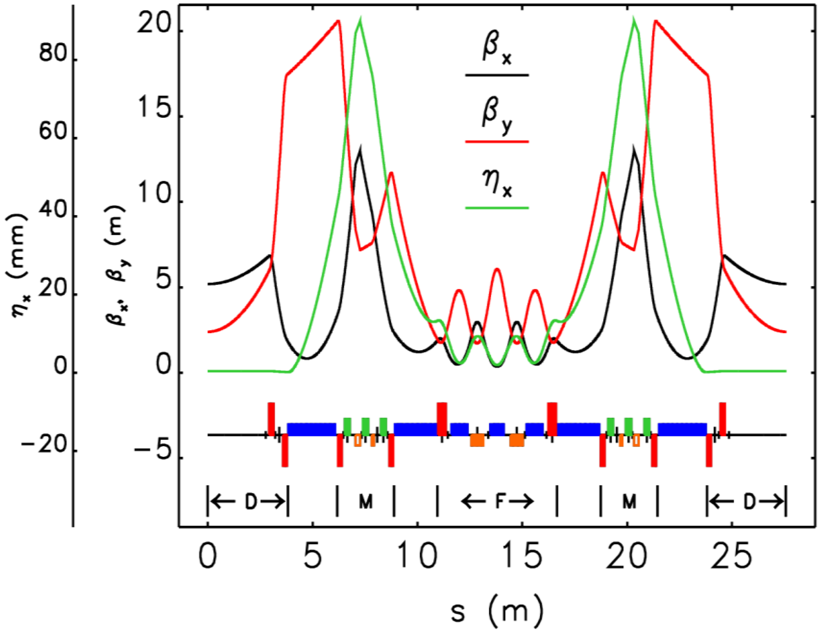
March 7, 2024

Outline

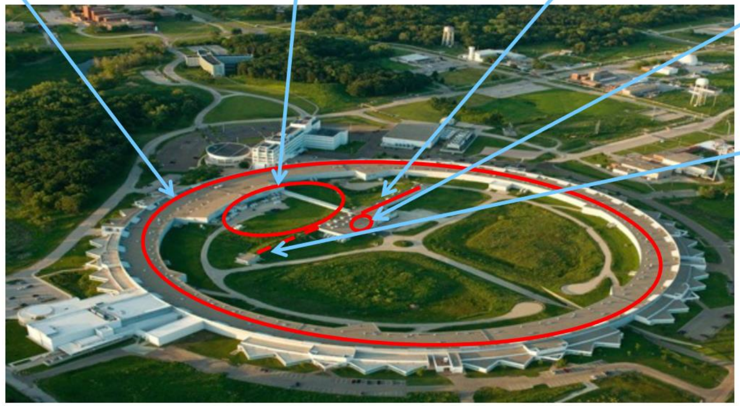
- APS-Upgrade introduction
- Particle accumulator ring (PAR) and Booster status
- High charge issues:
  - Booster injection efficiency
  - PAR longitudinal instability
- Injector charge stability
- Injection / extraction timing and synchronization system
- Plan for achieving higher charge
- Injector commissioning status

Advanced Photon Source Upgrade[1] (APS-U)

- New storage ring: 42-pm emittance @ 6 GeV, 200 mA
- Seven-bend hybrid multibend achromat[2] (MBA) with reverse bending magnets
- New and updated insertion devices, including superconducting undulators (SCUs)
- Combined result in brightness increases of up to 500x
- Two operational modes: 48 and 324 bunches
- **Uses swap-out injection: full bunch replacement**



APS ACCELERATOR COMPLEX

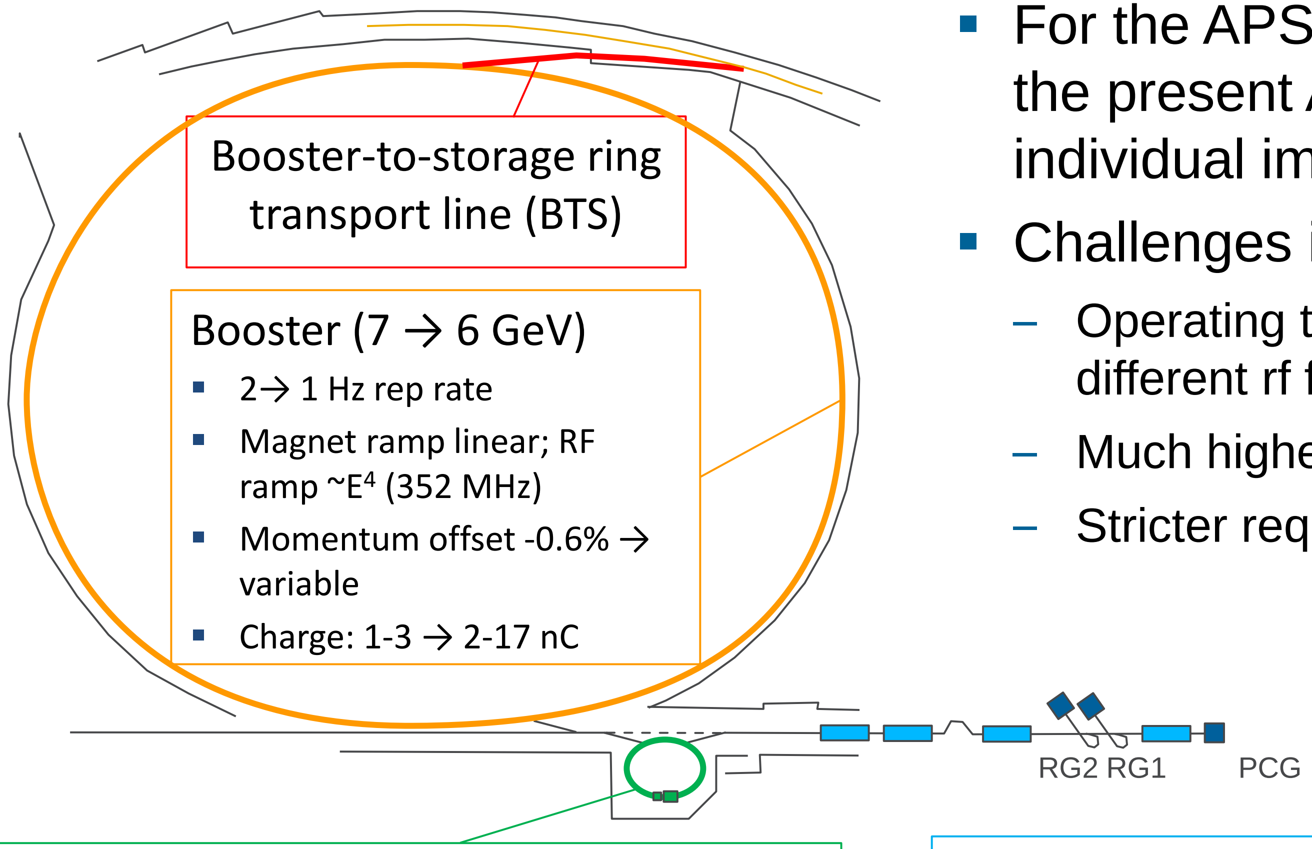


[1] https://aps.anl.gov/APS-Upgrade/Documents
[2] L. Farvacque et al., PAC-2013, pp. 79–81.

Quantity	Value
Beam energy	6 GeV
Natural emittance	42 pm
Circumference	1104 m
Revolution time	3.68 μs
Beam current	200 mA

Quantity	Timing	Brightness
Bunches	48	324
Bunch spacing	77 ns	11 ns
Bunch charge	15.4 nC	2.2 nC

APS → APS-U injector chain



Booster-to-storage ring transport line (BTS)

Booster (7 → 6 GeV)

- 2→ 1 Hz rep rate
- Magnet ramp linear; RF ramp ~E^4 (352 MHz)
- Momentum offset -0.6% → variable
- Charge: 1-3 → 2-17 nC

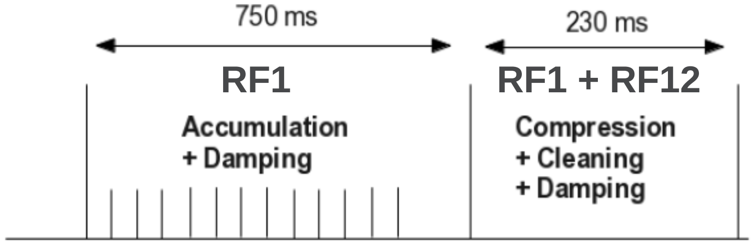
Particle accumulator ring (PAR) (425 → 450+ MeV)

- Single bunch; 2 → 1-Hz rep rate
- Captures linac pulses in RF1 (9.8 MHz); compresses damped beam in RF12 (117 MHz)

Linac (425 → 450+ MeV)

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

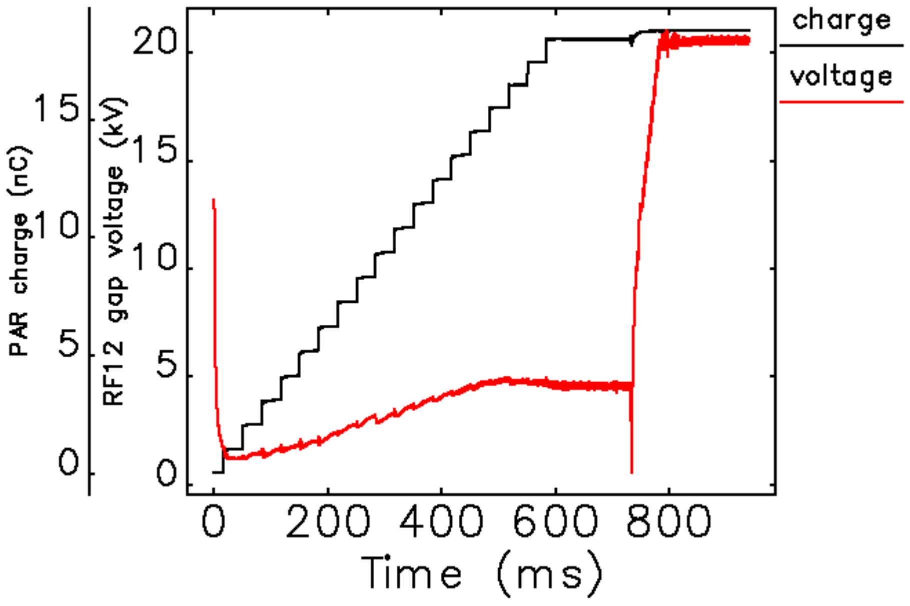
- For the APS-Upgrade, it was decided to leave the present APS injector chain in place and make individual improvements where needed.
- Challenges include:
  - Operating the booster synchrotron and storage ring at different rf frequencies
  - Much higher charge per bunch (up to 17 nC)
  - Stricter requirement for charge stability (±5% rms)

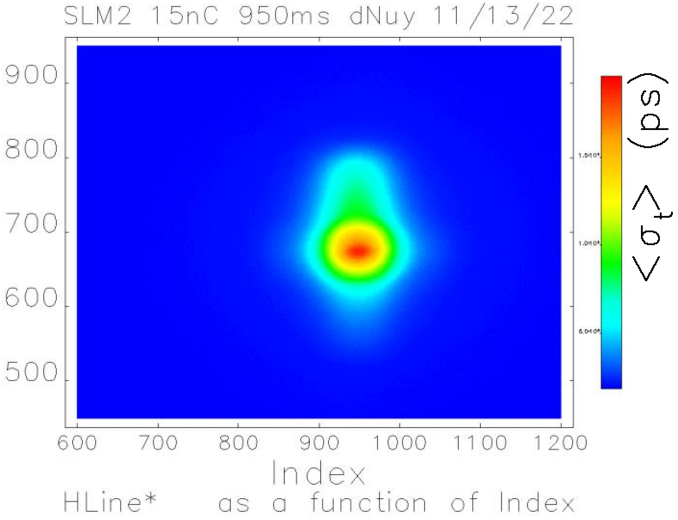


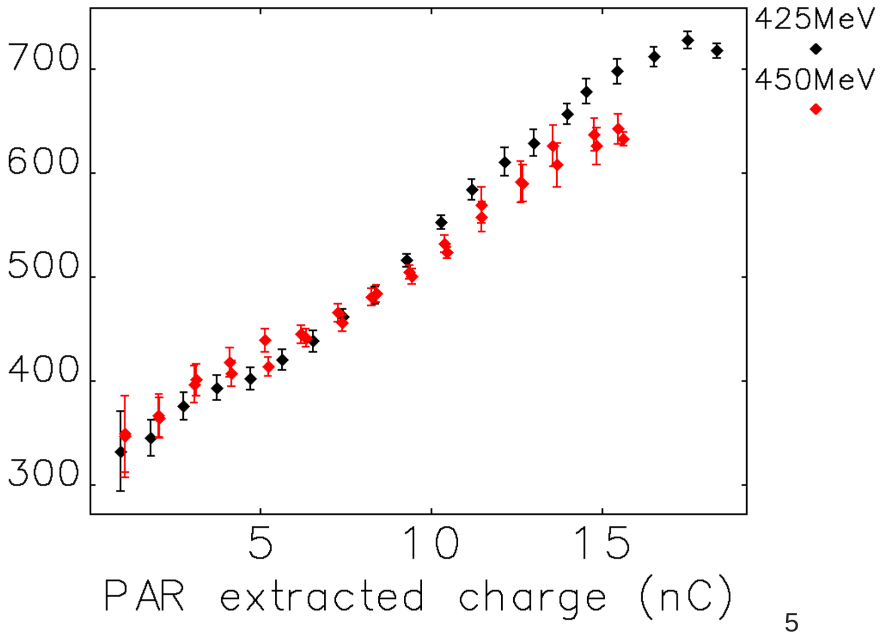
PAR cycle

PAR status[1,2]

- Achieved high-charge goal of 20 nC extraction in 1-Hz operations.
- PAR bunch length more than doubles from 1 – 20 nC.
  - Large reduction in booster injection efficiency.
- Plan to mitigate:
  - High power 12th harmonic amplifier (compress bunch)
  - Higher energy from linac (stabilize bunch)
- Also observe ion-induced vertical beam size blowup[3]

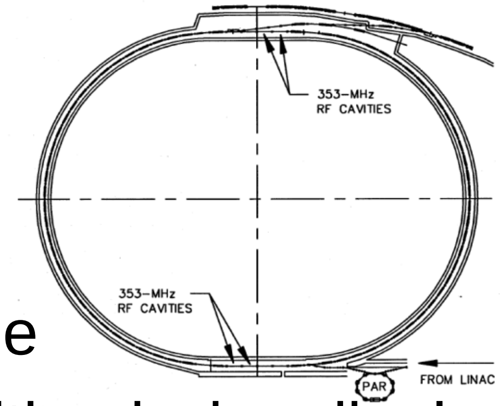






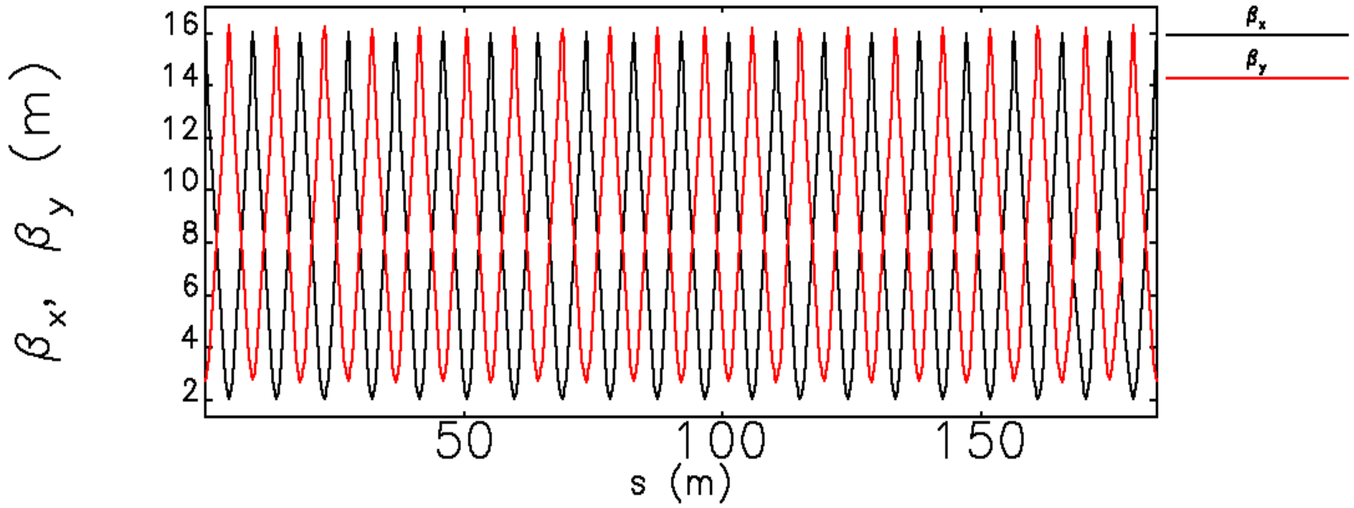
[1] K. Harkay et al., MOPLM21, NAPAC19
[2] K. Harkay et al., THYYPLM3, IPAC19
[3] J. Calvey et al., THPOA14, NAPAC16.

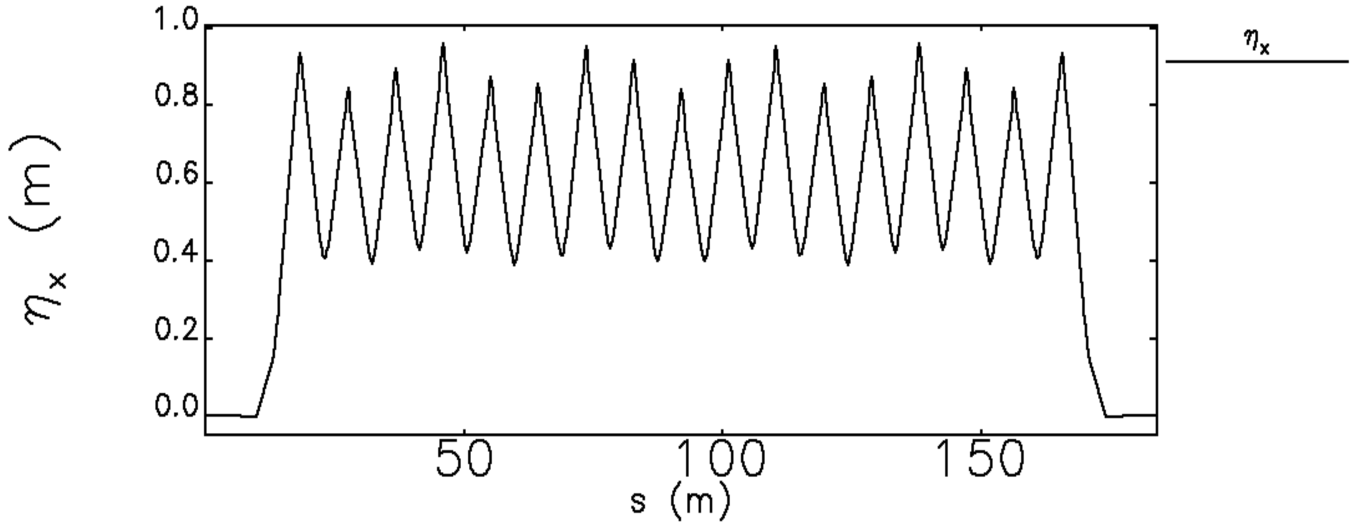
Booster parameters



- Racetrack shape
- FODO lattice with missing dipoles in straight section
- Lattice functions for one half of booster shown
- Operated off-momentum

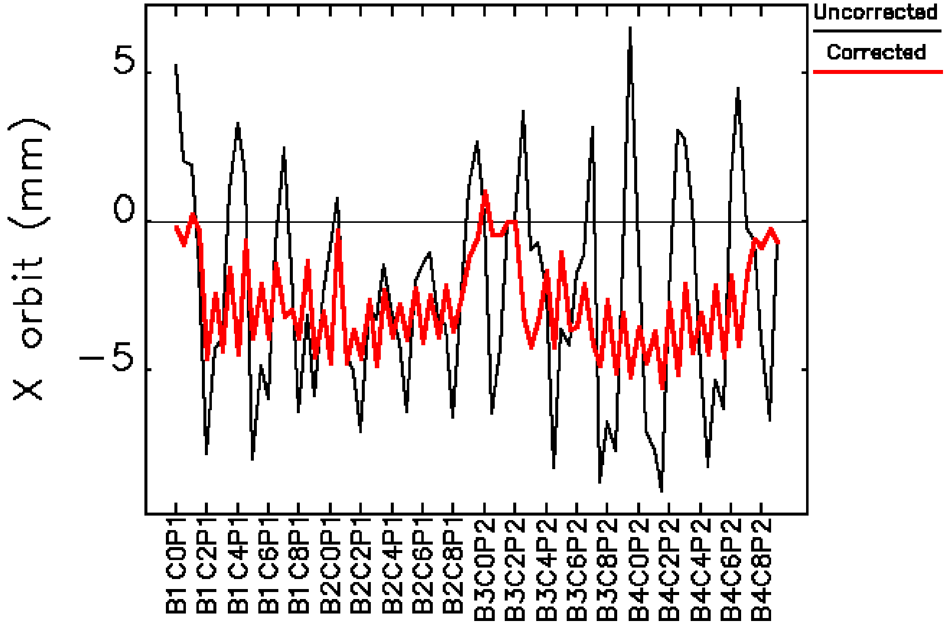
Parameter	Value
Beam energy	0.5 - 6.0 GeV
Bunch charge	2 - 17 nC
Circumference	368 m
Revolution frequency	815 kHz
RF frequency	352 MHz
Ramp time	225 ms
Momentum offset	-0.6%
Horizontal tune	11.75
Vertical tune	9.8
Momentum compaction	9.71×10^{-3}

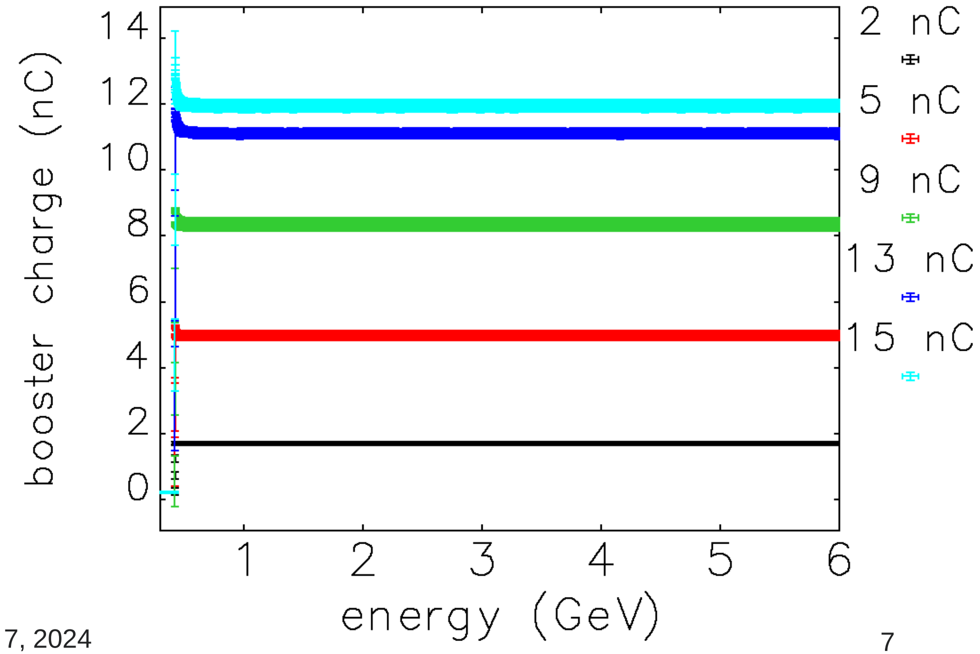




Booster status

- Achieved 12 nC booster charge (70% of goal)
- Progress and improvements:
  - Switching from a “low emittance” lattice to one with zero dispersion in the straight sections[1]
  - Orbit correction over the booster ramp.
  - Current-controlled sextupole power supplies
  - New and re-commissioned diagnostics: synchrotron light monitors (SLMs)[2], photodiode bunch duration monitor (BDM)[3] and turn-by-turn BPMs.
  - Improvements to control of injection trajectory[4]
  - Optimizing RF cavity voltage at injection vs charge
- Efficiency drops above 10 nC injected charge[5].
- Good short-term charge stability (<5% rms)

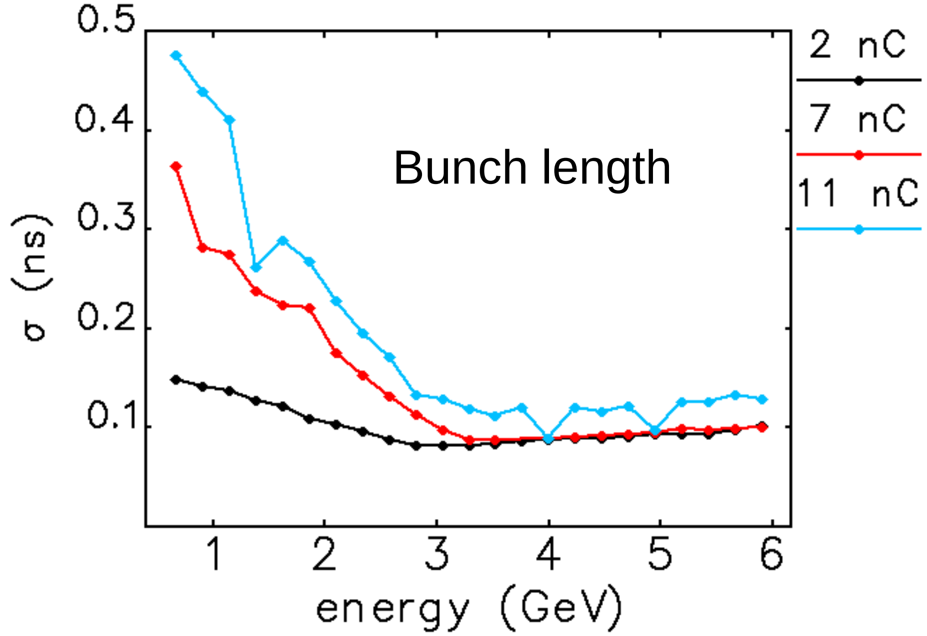


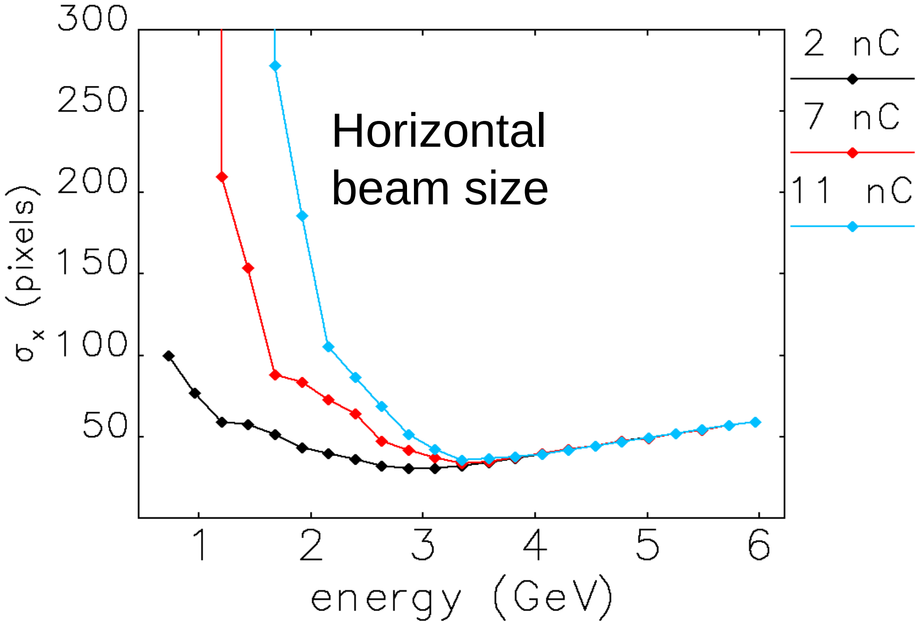


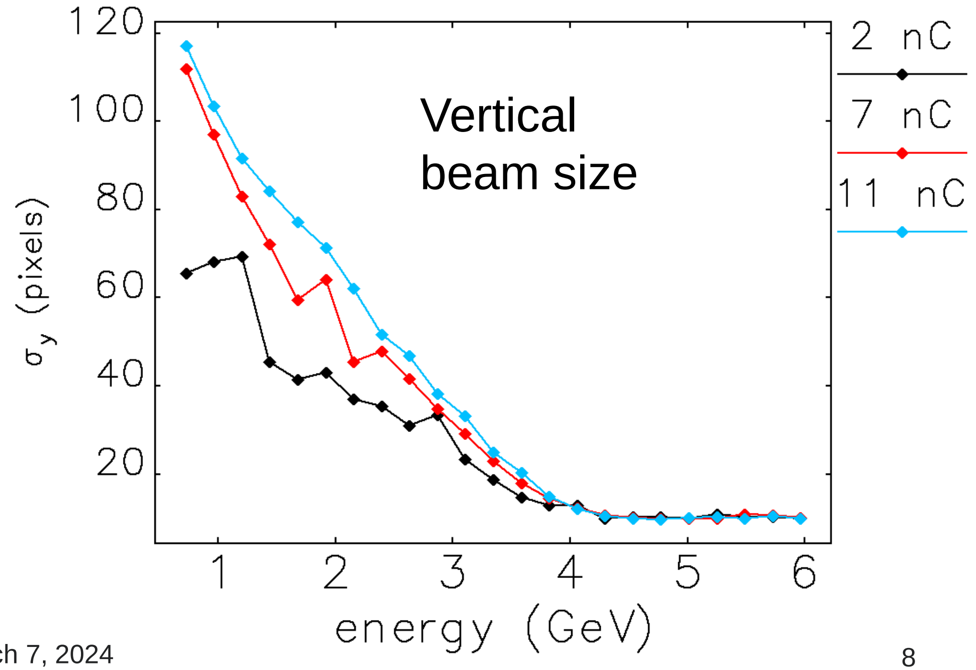
[1] J. Calvey et al., NAPAC16, pp. 647-650.
[2] K. Wootton et al., proc. IBIC23.
[3] J. Dooling et al., IPAC18, pp. 1819-1822.
[4] C-Y. Yao et al., IPAC21, pp. 419-421.
[5] J. Calvey et al., IPAC21, pp. 197-199.

Measurements along the ramp

- Beam size measurements from synchrotron light monitors (SLMs), bunch length from fast photodiode
- Initial beam size blowup damps away by end of ramp
- Suggestion of bunch length blowup at 11 nC
- Observed thermal drift in photon diagnostics due to mirror heating, more stable mirrors are being installed







Available charge for swap-out

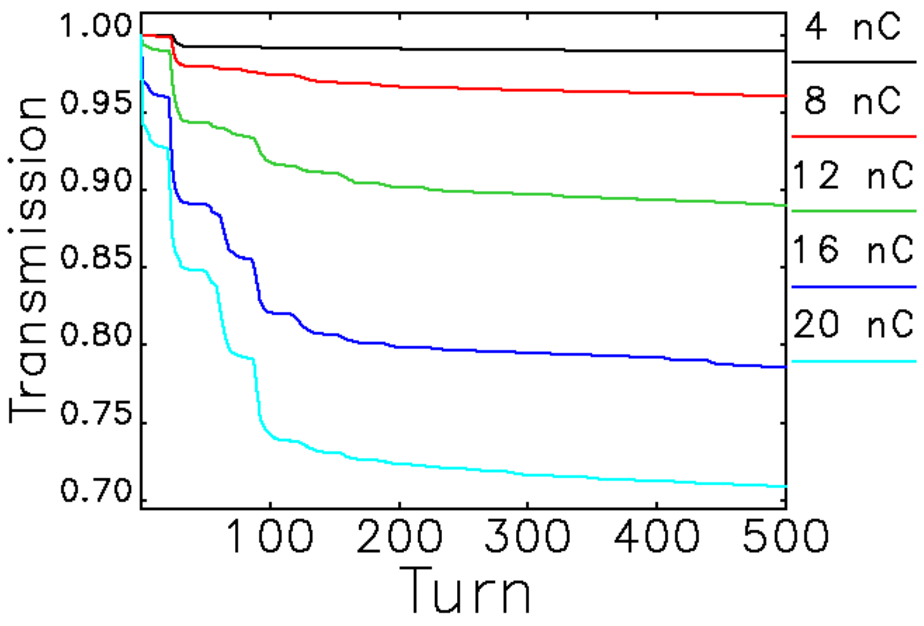
- Reliable injector charge limit is ~10 nC. More than sufficient for APS-U commissioning & KPPs.
- Higher charge was de-emphasized by APS-U project. Achieved ≥ 12nC in studies but more work is needed after APS-U commissioning to achieve sufficient reliability.
- Possible APS-U bunch patterns are highlighted in green.
  - Table assumes 5% swap-out overfill and 95% injection efficiency.
  - E.g., 48 bunches require 15.3 nC stored per bunch. Swap-out bunch charge is (15.3 x 1.05) / 0.95 = 17 nC.

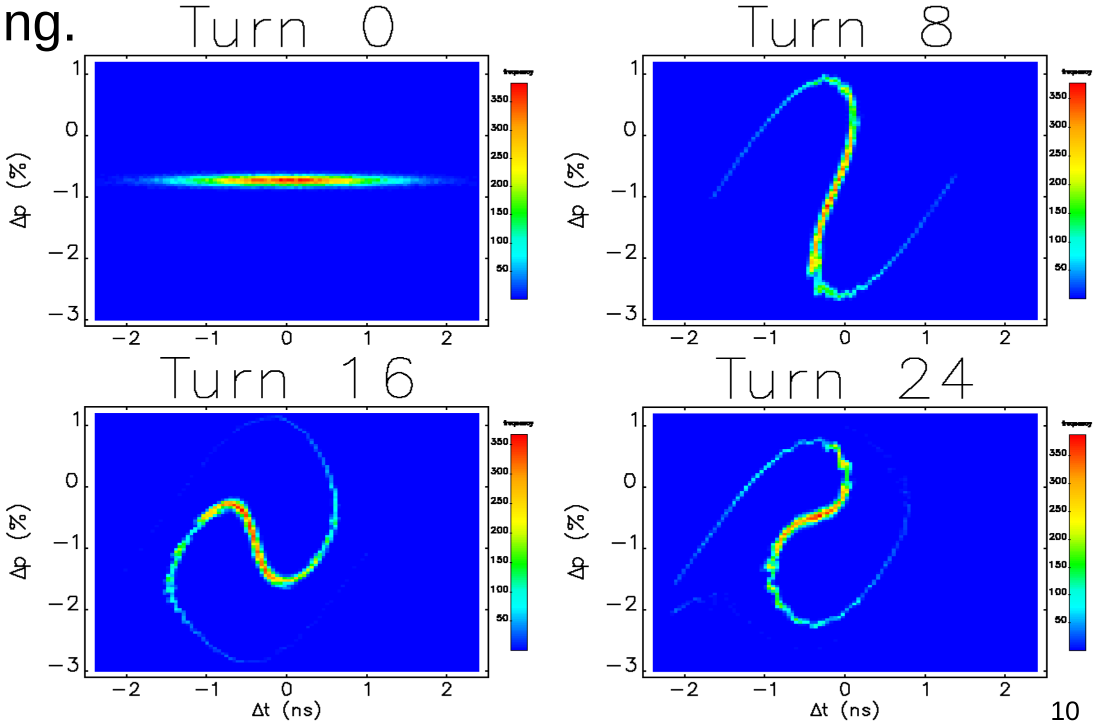
# bunches/ total current	48	54	72	81	108	144	162	324
200 mA	17.0	15.1	11.3	10.0	7.5	5.7	5.0	2.5
175 mA	14.8	13.2	9.9	8.8	6.6			
160 mA	13.6	12.1	9.0	8.0	6.0			
130 mA	11.0	9.8	7.3	6.5				
120 mA	10.2	9.0	6.8	6.0				

nC bunch charge

Comprehensive injection model

- Using elegant [1], tracked 3000 booster turns (3.5 ms), where most losses occur.
- Model includes momentum offset (-0.6%), transverse and longitudinal impedance [2], beam loading in rf cavities, and incoming beam parameters (e.g., beam size and bunch length vs charge) derived from measurements.
- Good agreement with measured efficiency.
- Main source of losses: PAR bunch length, beam loading.
- Efficiency can be improved with shorter bunch length (PAR improvements) and detuning cavities[3].

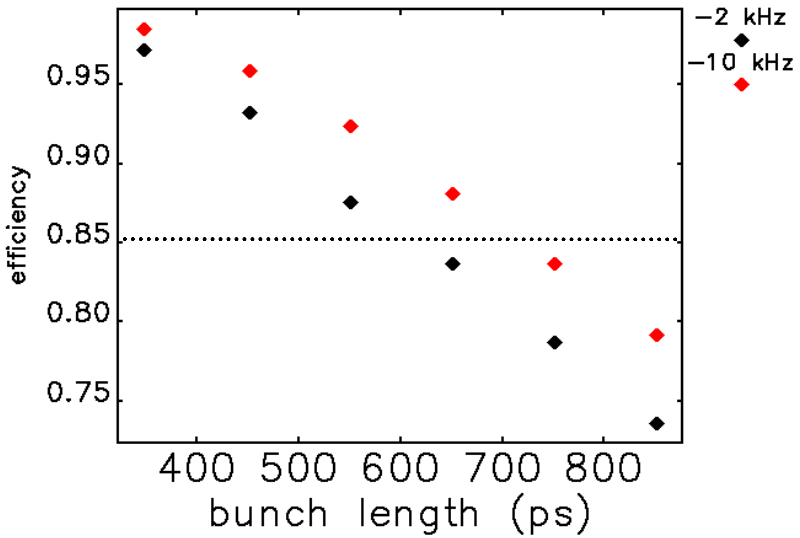




[1] M. Borland. ANL/APS LS-287, (2000). Y. Wang et al. *Proc. of PAC 2007*, 3444–3446 (2007).

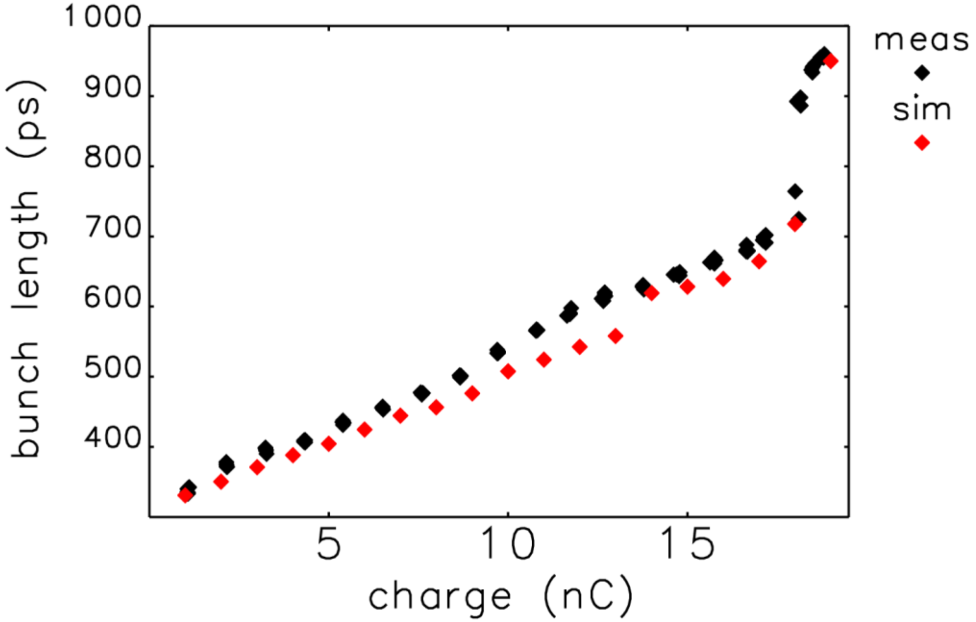
[2] R. R. Lindberg et al. *Proc. IPAC 2015*. TUPJE078.

[3]] J. Calvey et al., *Proc. IPAC21*, pp. 197-199

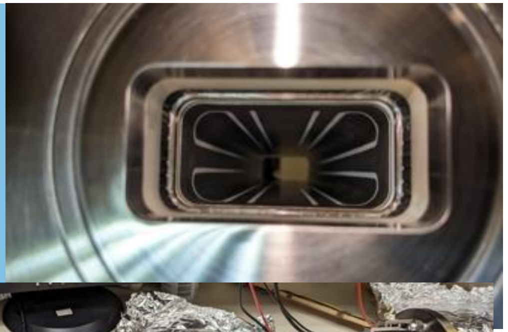


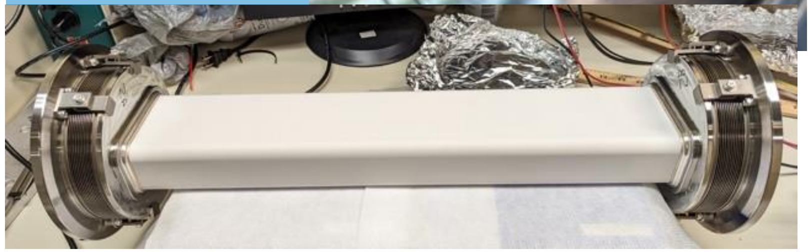
PAR longitudinal instability

- Large bunch length blowup vs charge, caused by potential well distortion and microwave instability[1]
- Limiting factor for high charge booster injection[2]
- Simulate with elegant[3,4]. Model includes longitudinal impedance[5] and beam loading in the rf cavities
- Simulated bunch length agrees well with measurement (but a bit lower)[6]
- Installed new kicker chambers with patterned Ti coating for reduced impedance



PAR kicker chamber with innovative Ti coating

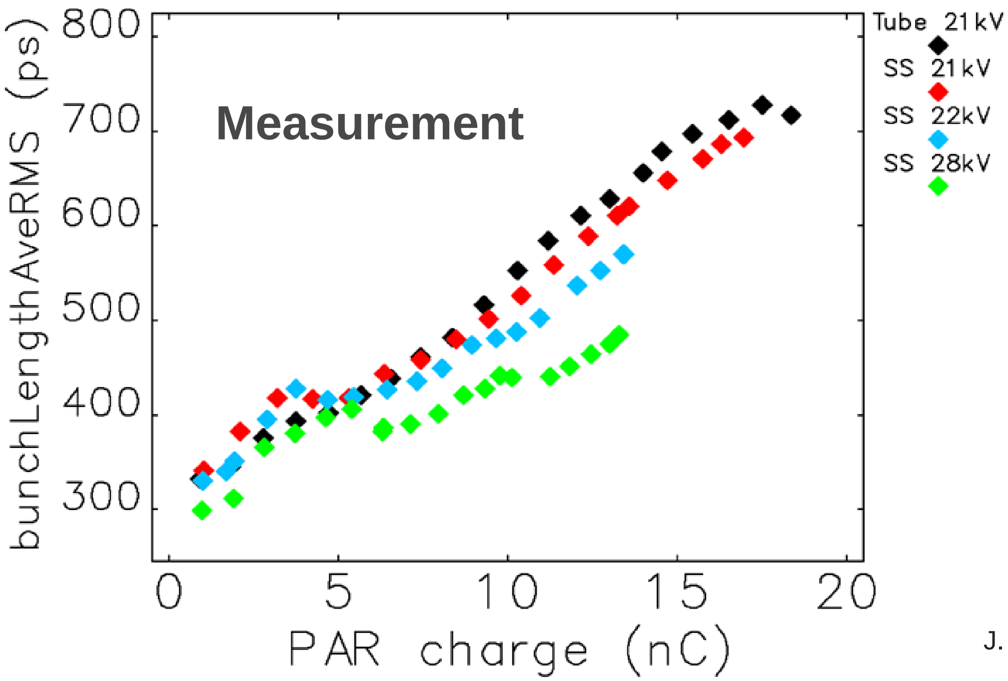


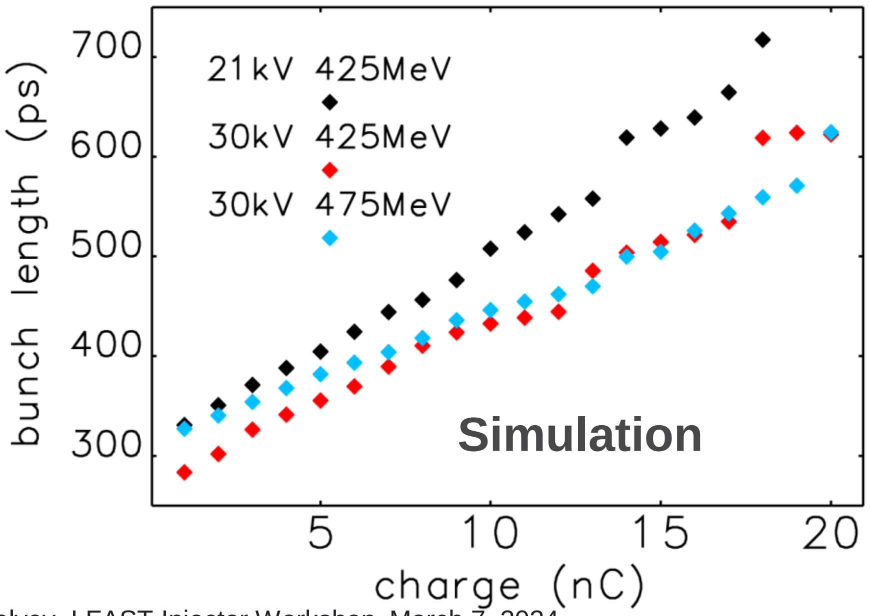


[1] K. C. Harkay et al., Proc. NAPAC'19, pp. 151–154.
[2] J. Calvey et al., Proc. IPAC'21, pp. 197–200.
[3] M. Borland, Rep. LS-287, APS, Sep. 2000.
[4] Y. Wang and M. Borland, Proc. AAC 877, p. 241, 2006.
[5] C. Yao et al., Proc. NAPAC'19, pp. 140--143.
[6] J. Calvey, Proc. NAPAC'22, pp. 859 – 862.

Shorter bunch length with new RF12 amplifier

- 10-kW harmonic rf solid-state amplifier (SSA) installed and operating reliably
- Shorter bunch length even above microwave instability at ~10 nC.
- Further optimization is planned to achieve higher bunch charge.
- Further studies with >425 MeV and injecting into booster also planned.
- Simulations predict bunch length can be kept below 600ps up to 19 nC with high voltage and higher energy

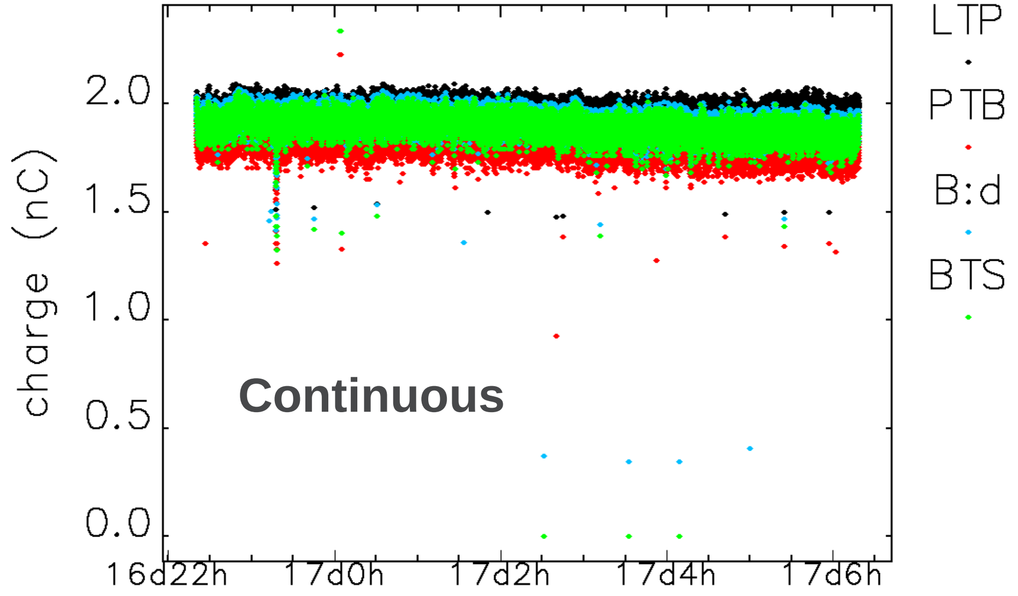


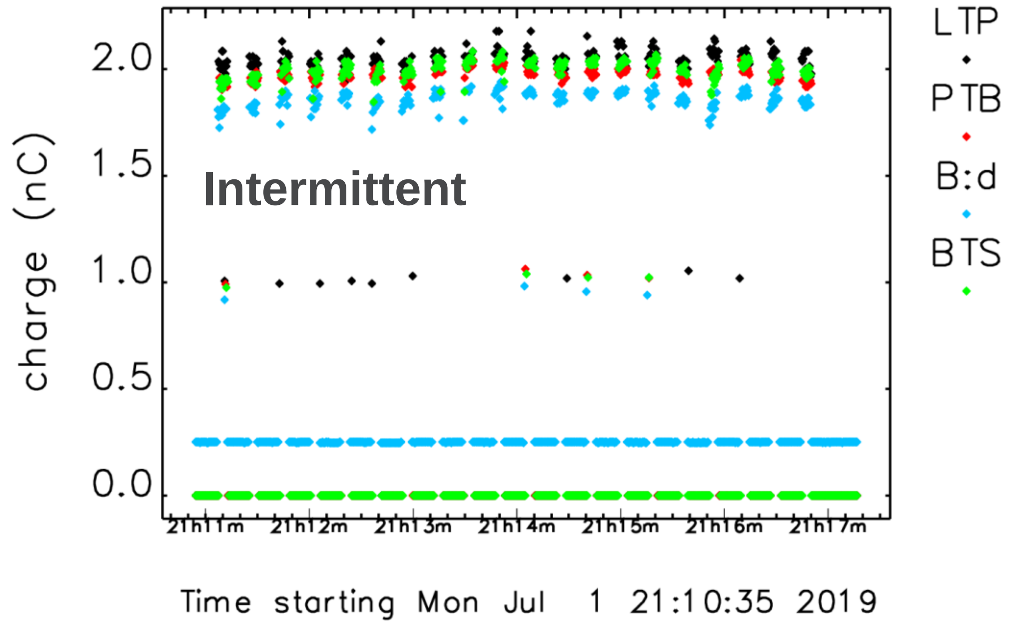


K. Harkay et al., Proc. NAPAC'22, TUPA23.

Injector charge stability

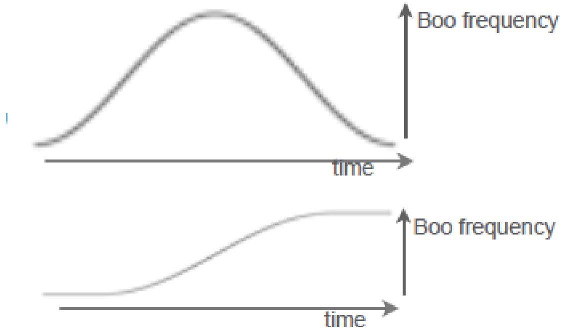
- APS-U requires 5% rms charge stability from the injectors
- APS-U will require frequent injection: 9 – 30 sec
- Injector charge stability over several hours studied with 2 – 10 nC
- Continuous and intermittent injection
- Most cases have ≥ 90% efficiency, < 5% rms charge stability
- Diagnose cases with low stability/efficiency by monitoring relevant process variables, looking for correlations with booster charge





Injection/extraction timing & synchronization (IETS)

- APS-U storage ring (SR) will have higher frequency than old one
- SR, booster, and PAR rf frequencies will be decoupled
- Booster frequency can be adjusted along the energy ramp
  - Bucket targeting with frequency bump- changes time beam spends in the booster
  - Overall frequency ramp - optimize both injection efficiency and extracted emittance



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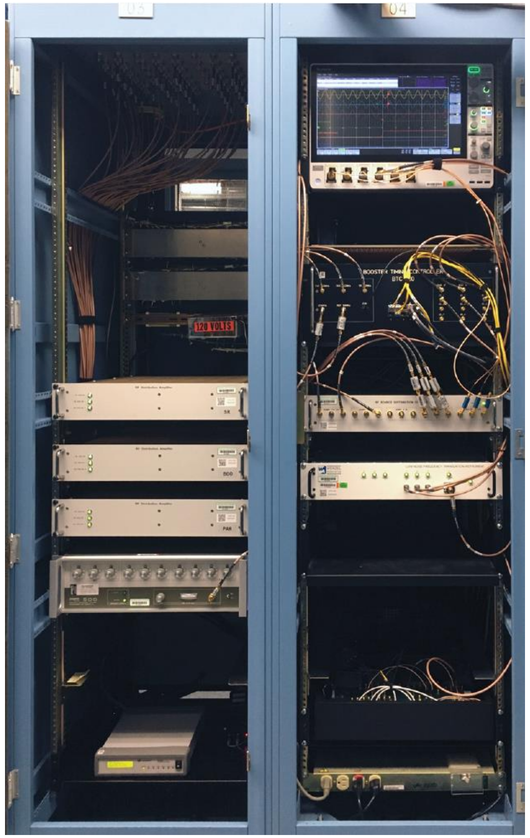
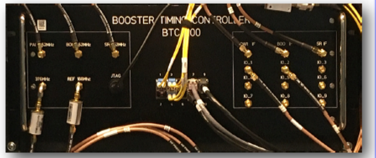
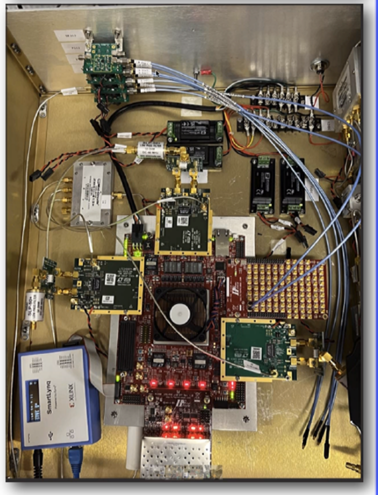
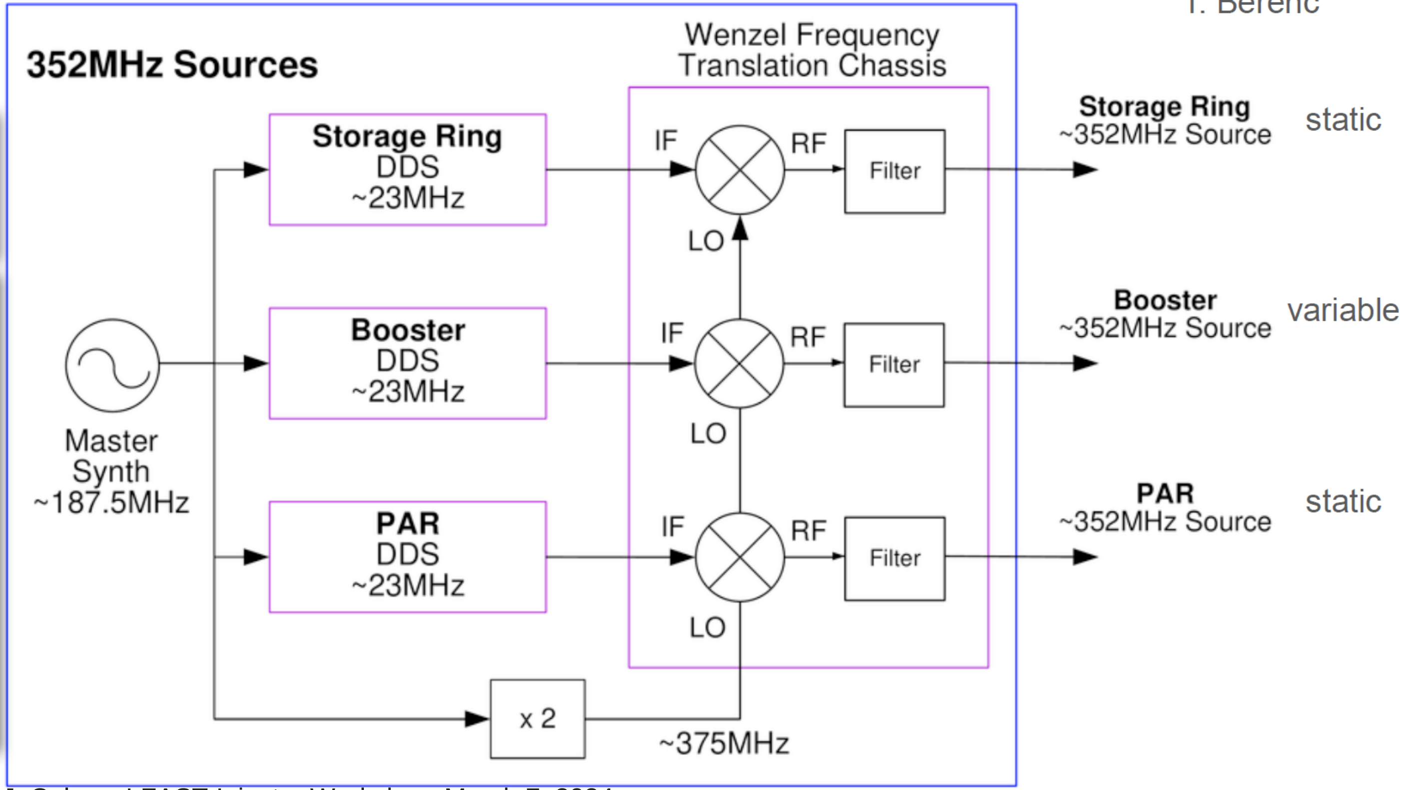




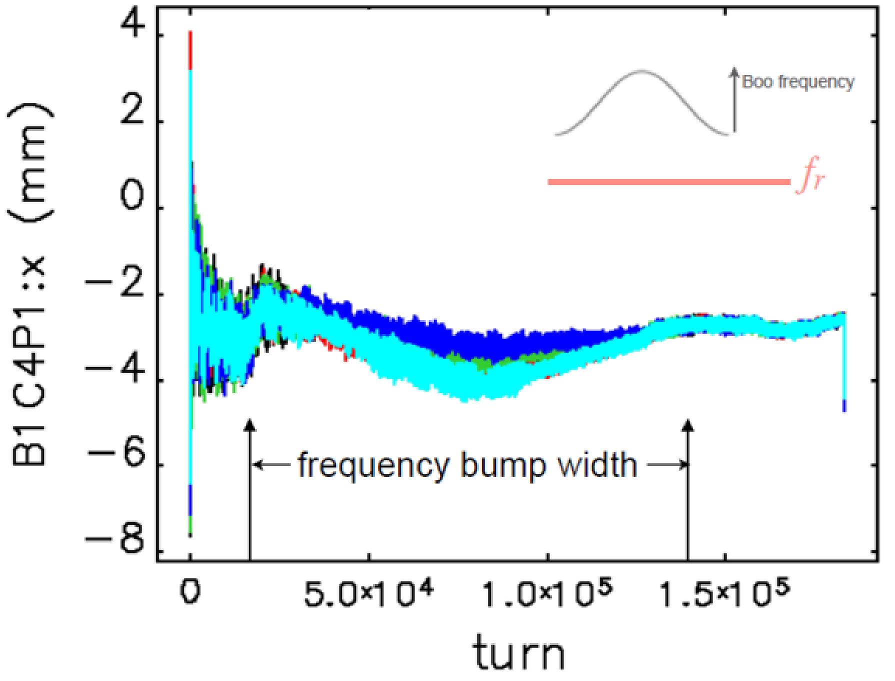


U. Wienands

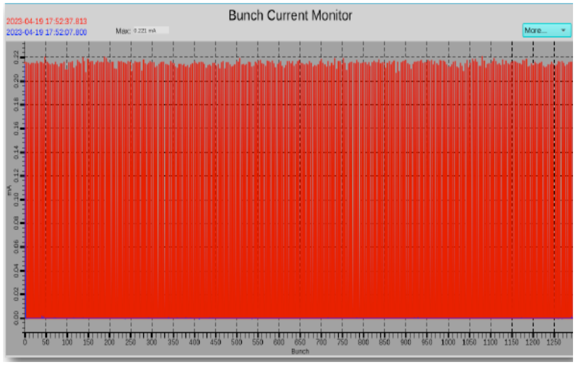


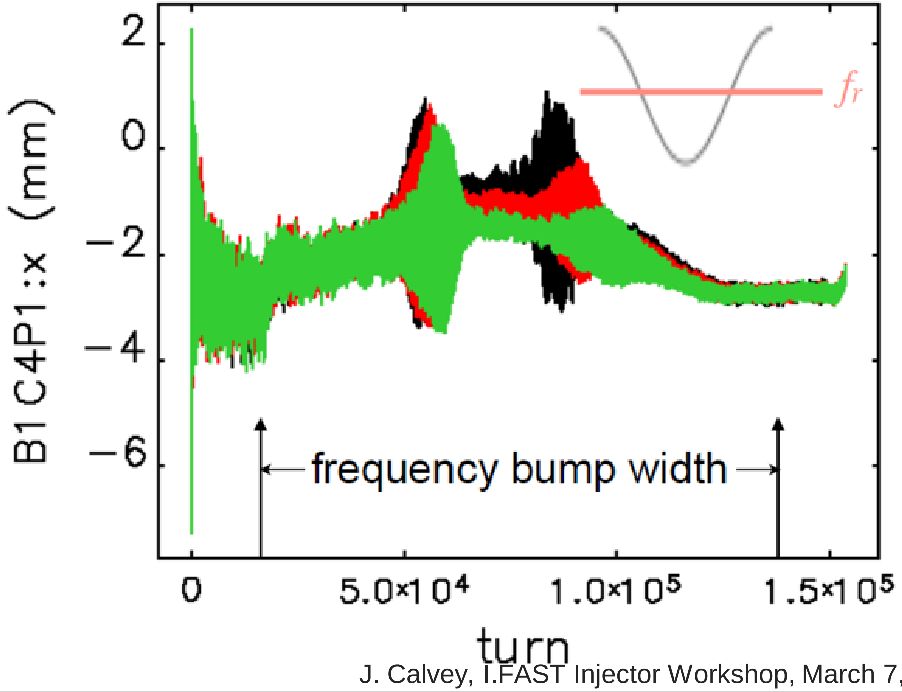
Targeting bumps

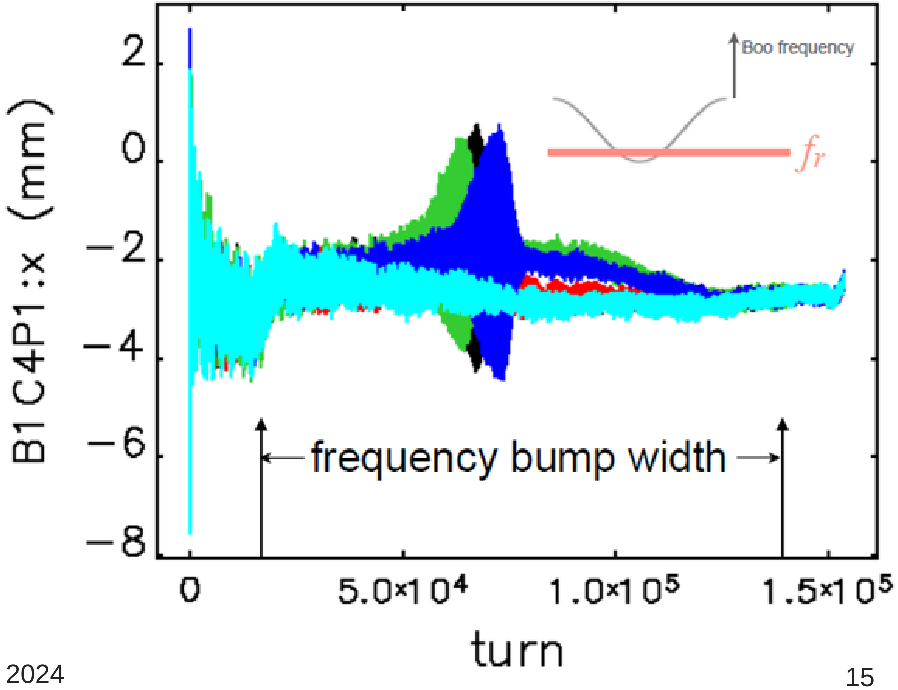
- X position in dispersive BPM
- Positive frequency bump -> negative X bump
- Bump height different for each shot
- Instability seen for negative frequency bump from crossing cavity resonance
- Confirmed that bumps put the beam in the right SR bucket



Ring filled with IETS system

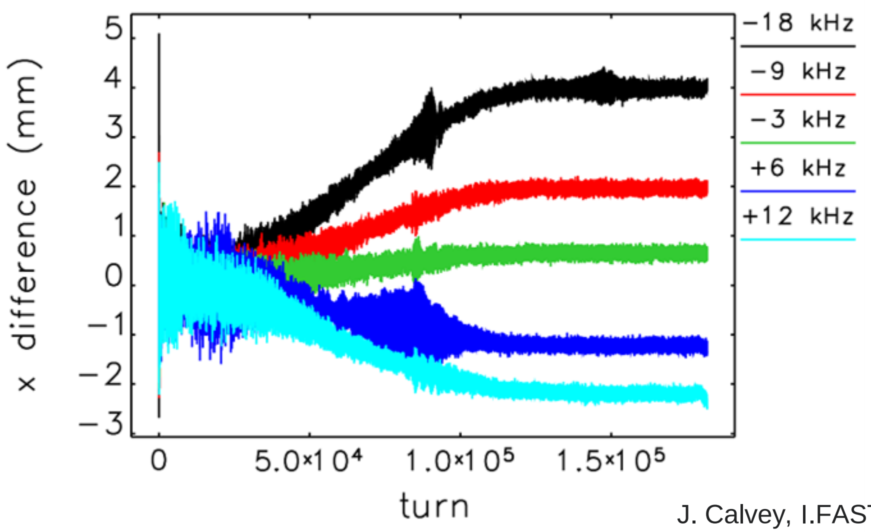


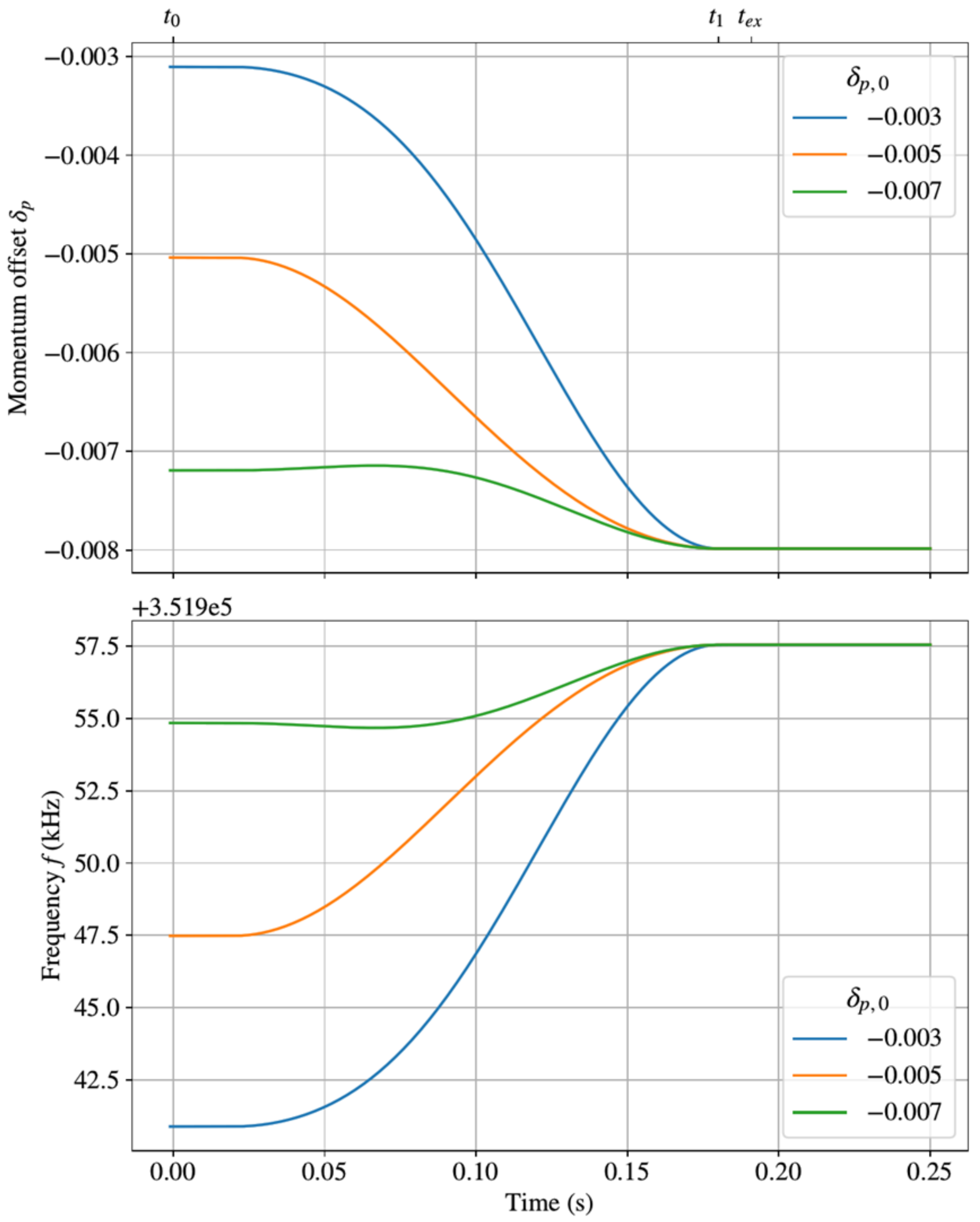




Frequency ramp

- Want good booster injection efficiency (85+%) up to 20 nC
  - Favors on-momentum injection.
- Small emittance (preferably < 60 nm) at extraction
  - Favors off-momentum extraction.
- Achieve both with a frequency ramp
- Each ramp shown has a different initial momentum offset, but a final offset of -0.8%.
- Negative momentum sweep → positive frequency sweep
- Results in large detuning at extraction

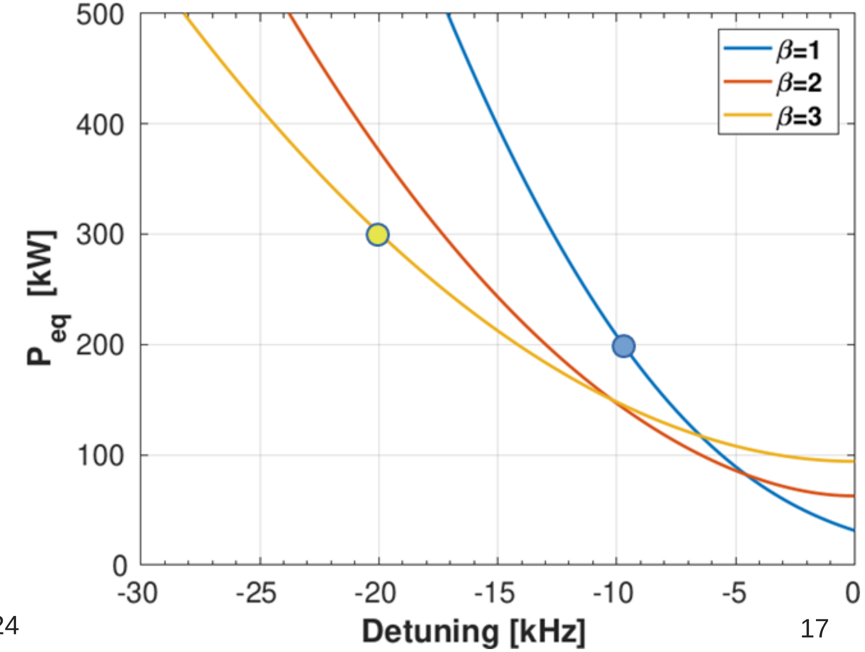




Achieving higher charge

- High power couplers (HPCs) needed in the booster cavities to needed to handle high equivalent power at extraction
- Total detuning = (detuning at injection) + (frequency ramp)
- Over-couple the cavities to reduce beam loading and P_{eq}
- Simulations showed good injection efficiency up to 20 nC with this scheme
- HPC prototype was designed, installed and tested in the booster
  - Rated for 500 kW, planned to run at 300 kW.
  - No operational issues.
  - Design had undesirable water-vacuum joints, had to be modified.
  - HPC project was descoped by APS-U project.
  - Renewed interest recently, working with CERN on a new 500 kW design.

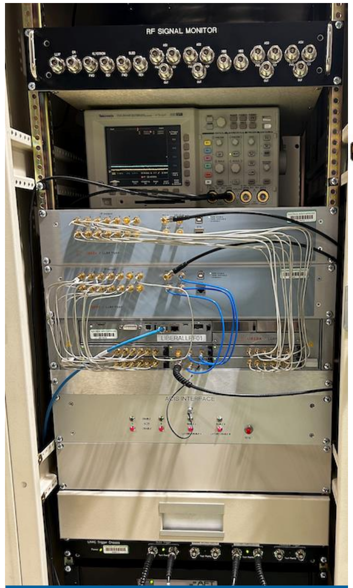
$$P_{eq} = P_{fwd}\left(1+\sqrt{\frac{P_{rev}}{P_{fwd}}}\right)^2$$



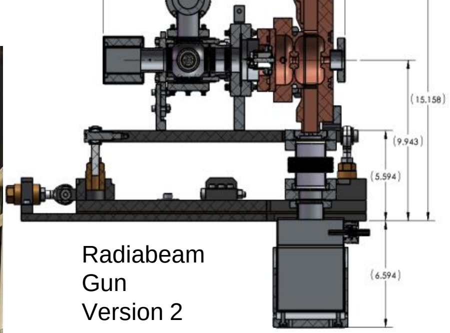
Injector re-commissioning: linac and PAR

- Linac and PAR restarted last fall
- Linac upgrades
  - New timing system
  - Higher power (50 MW) klystron in 1/3 stations
  - New thermionic RF guns
  - Faster corrector power supplies
  - Recovered 1 nC/pulse, good PAR injection efficiency
- New kicker chambers in PAR
- PAR vacuum initially very poor, limited fundamental RF gap voltage
  - Slowly improving with beam scrubbing

Production gun installed at RG2

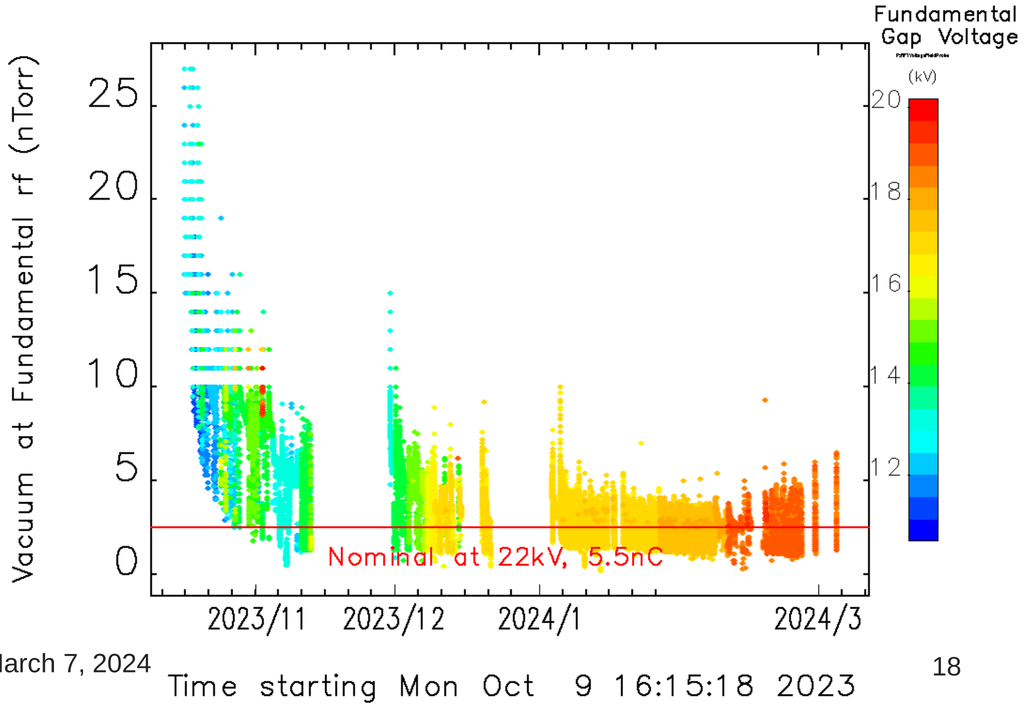


Libera DLLRF at K2



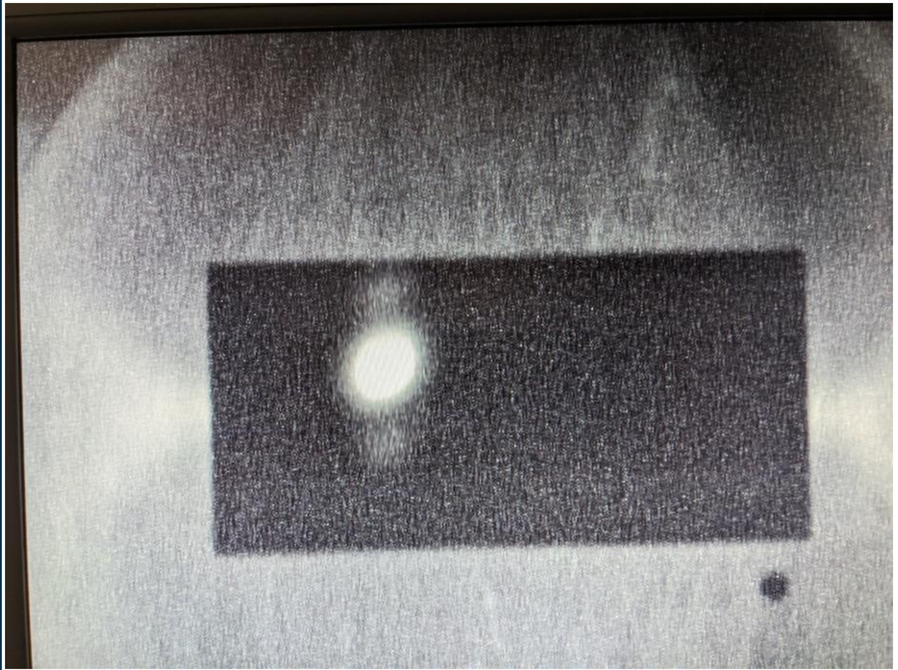
Radiabeam Gun Version 2

50-MW K2 klystron and modulator

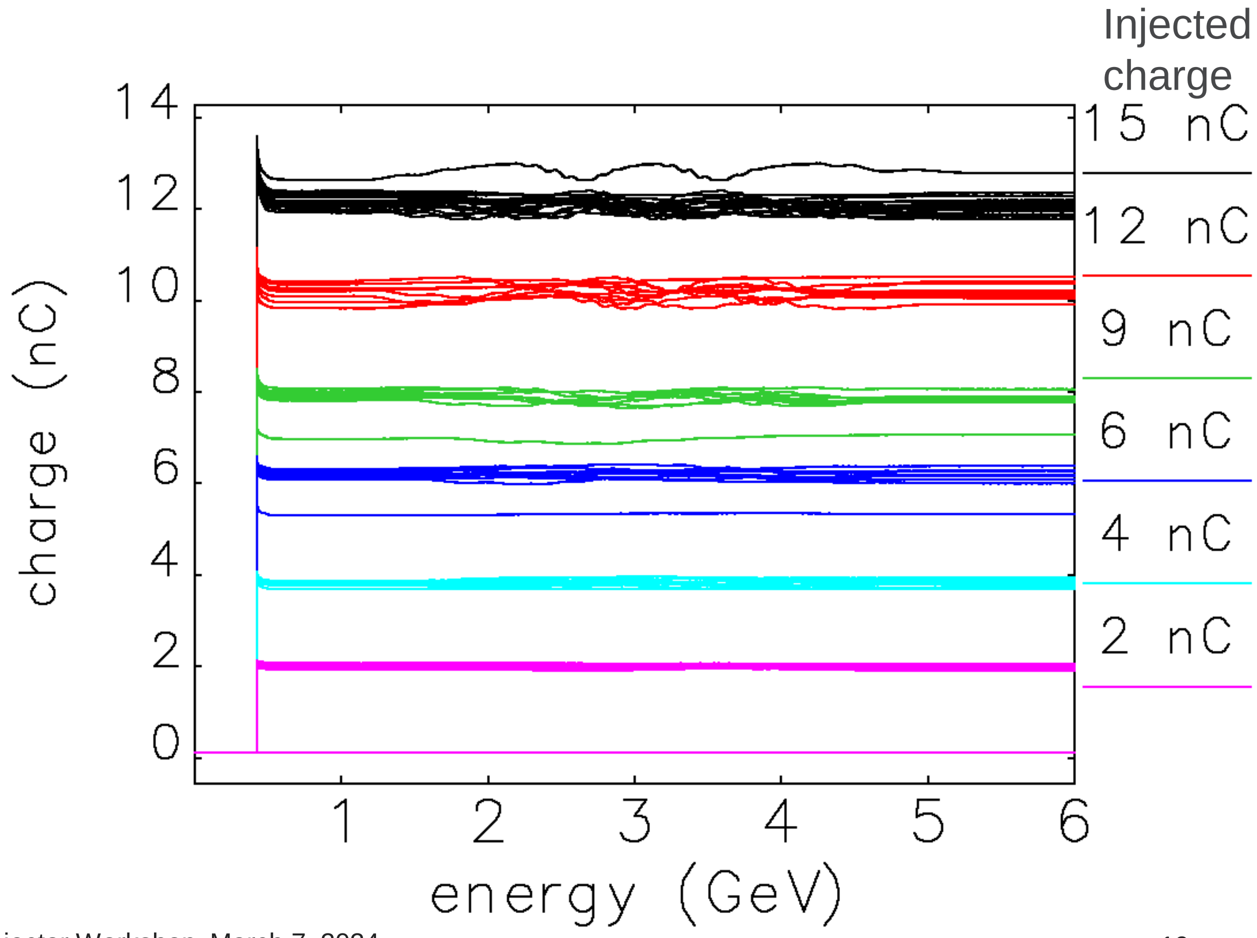


Injector re-commissioning: booster

- Booster re-started in February
- Demonstrated injection and acceleration to 6 GeV
  - Tuned for good injection efficiency, charge stability
  - Ran with IETS frequency bumps and ramps
  - High charge: 9 nC with frequency ramps, 12 nC without
- Demonstrated booster extraction to BTS dump



Beam image on BTS dump flag



Conclusions

- Upgrades and intensive studies have raised the APS injector charge limit from ~4nC to 12 nC
- Injector charge stability has been characterized up to 10 nC
- Booster is run with separate, variable rf source
  - Frequency bumps for bucket targeting
  - Overall frequency ramp for optimizing injection/extraction
- To achieve higher charge:
  - Finish commissioning new RF12 amplifier, for shorter PAR bunch length
  - Raise linac energy, for more stable PAR beam
  - Install high power couplers in the booster cavities, to allow for large detuning and over-coupling
- Injector re-commissioning is essentially complete
- APS-U storage ring commissioning starting soon!

Acknowledgements: Injector Working Group

K. Harkay – PAR Machine Manager

G. Fystro – Injector Chief of Operations

M. Borland[1], J. Dooling, L. Emery, D. Hui, N. Kuklev, R. Lindberg, I. Lobach, A. Lumpkin[2], B. Micklich[4], A. Nassiri[3], V. Sajaev[1], N. Sereno[3], Yine Sun[3], Yipeng Sun, A. Xiao[6], U. Wienands[4], K. Wootton, B-x. Yang, C-Y. Yao[2]; A. Blednykh[5]; J. Steinmann[6]

I. Abid, R. Agner, N. Arnold[2], K. Belcher, T. Berenc, D. Bromberek, A. Brill, G. Bruno, H. Bui, J. Carter, C. Doose, S. Farrell, R. Flood, T. Fors, A. Goel, M. Henry, E. Heyeck, A. Hillman, R. Hong, D. Horan, R. Keane, R. Laird, F. Lenkszus[2], T. Madden, L. Morrison[3], S. Pasky, A. Pietryla, T. Puttkammer, F. Rafael[4], P. Rossi, H. Shang, S. Shoaf, T. Smith, R. Soliday, J. Stevens, J. Vacca, G. Waldschmidt, J. Wang[3], F. Westferro, S. Xiang, S. Xu, Y. Yang, W. Yoder, B. Berg

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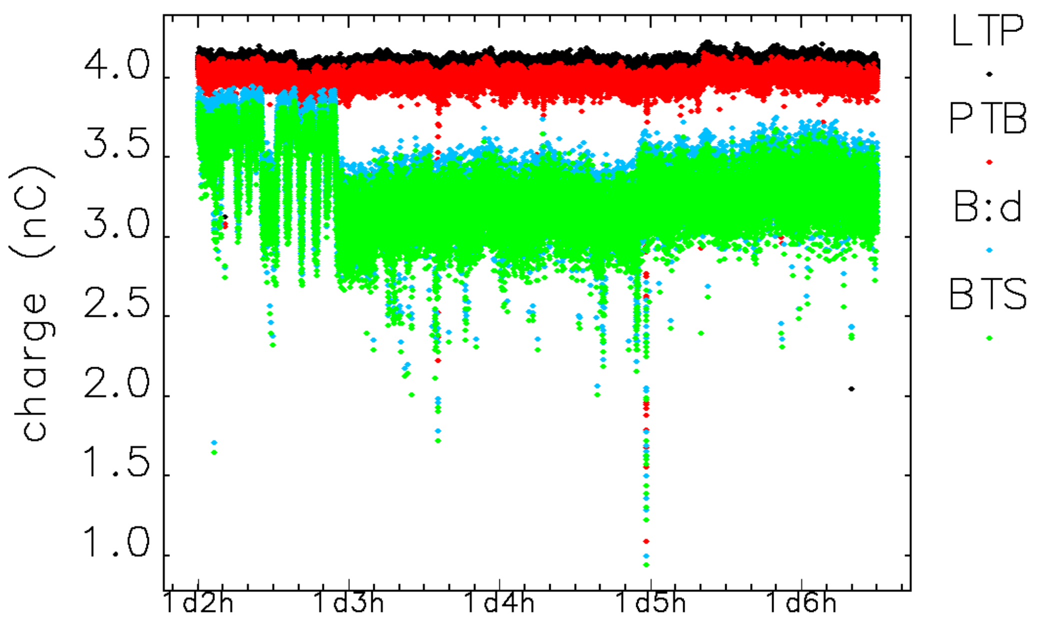
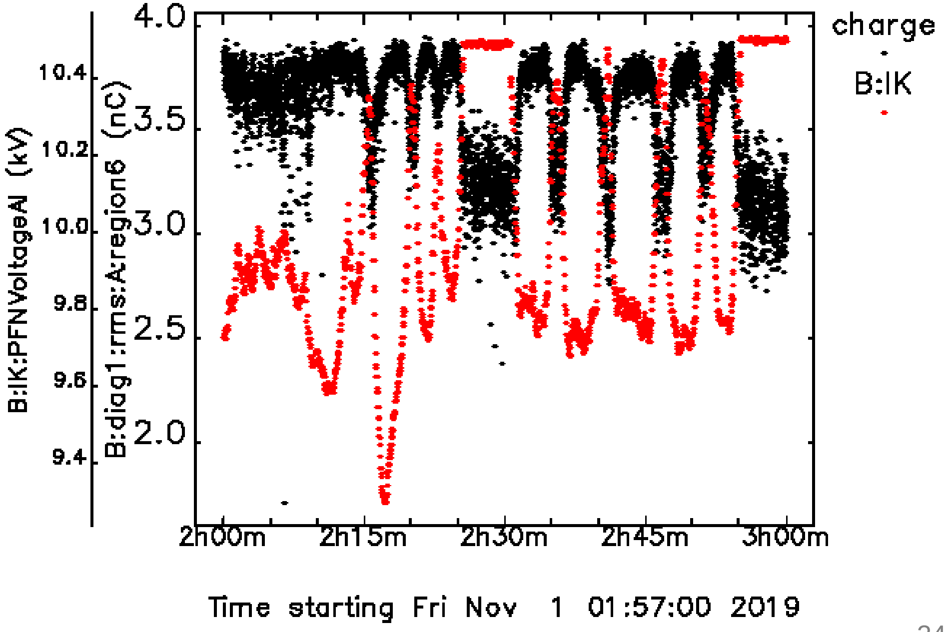
Thanks for your attention!

Backup slides

Identifying source of bad efficiency / stability

- Ex: 4 nC, 80% efficiency, 7.5% rms
- Monitor relevant process variables (PVs) at a 2 Hz rate
- Look for correlation between booster charge and each PV
- Clearly related to injection kicker voltage
  - Process for correcting booster injection trajectory was misbehaving
  - Has since been improved, works well consistently

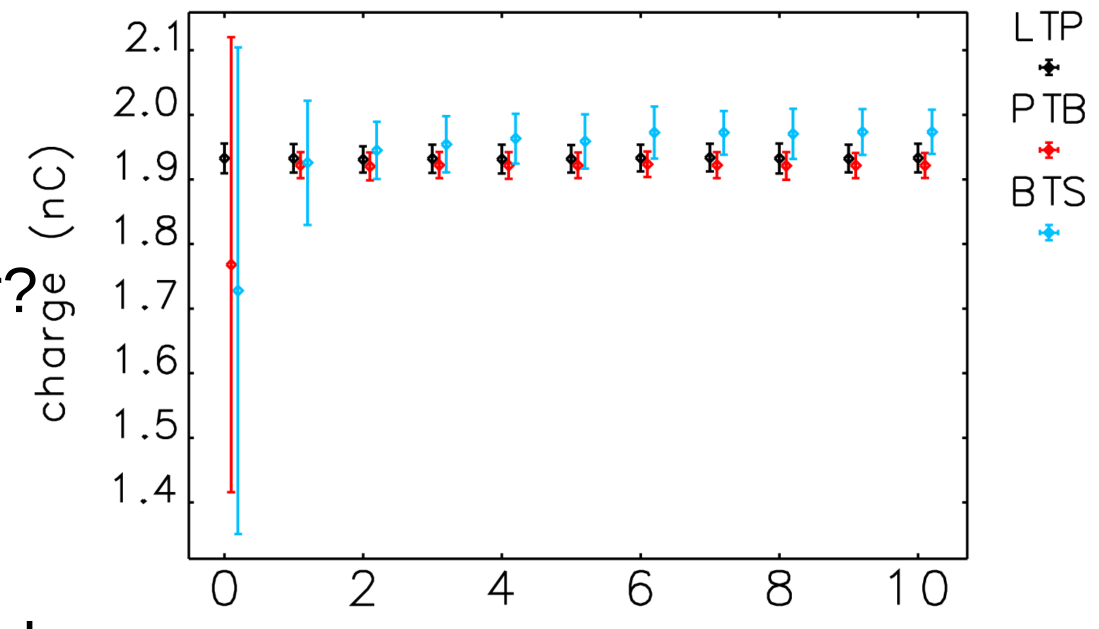


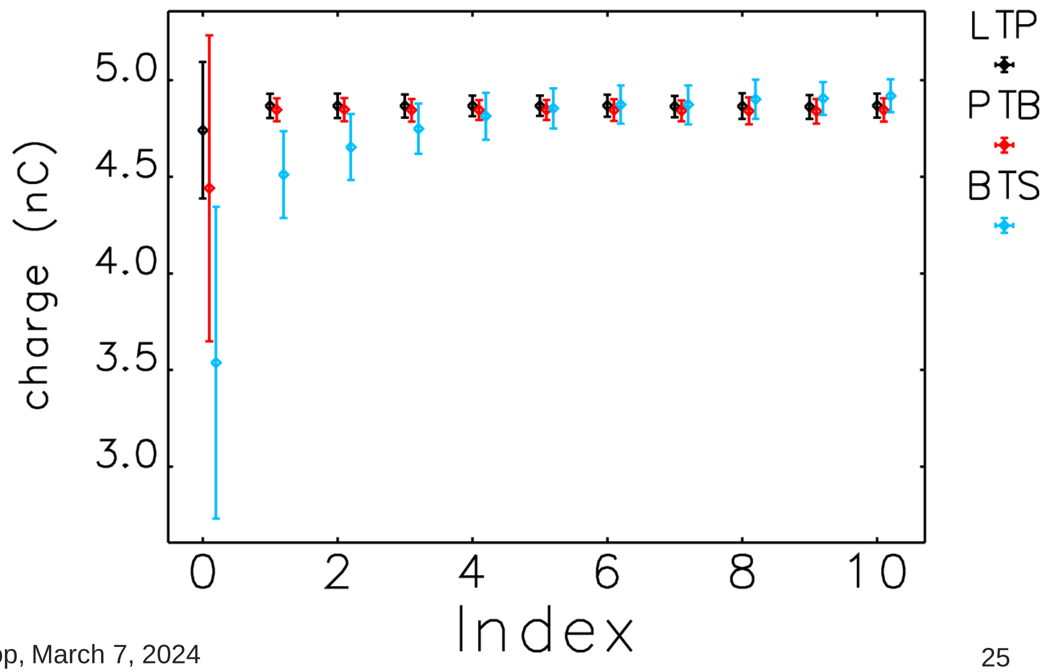


[1] C. Yao et al., Proc. IPAC'21, pp. 449–450.

Time to stabilize

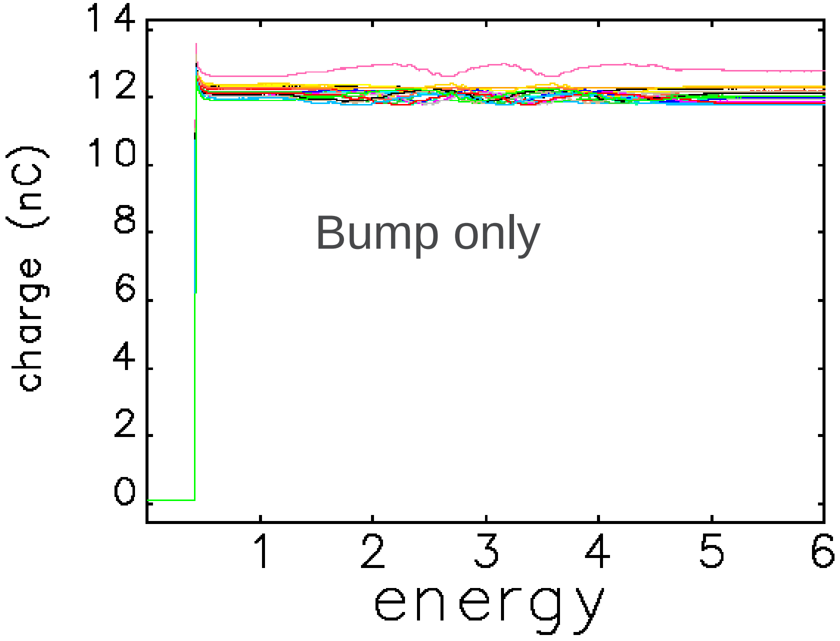
- After beam is enabled, how many shots does it take to get stable beam through the injector?
- Special PVs developed to track a bunch through the injector chain
- Study injector issues on a shot-by-shot basis
- Look at many (~100) cycles, take average and standard deviation
- Time to stabilize
  - 2 nC: 1 shot (0.5 sec) for PTB, 4 for BTS
  - 5 nC: 1 shot for PTB, 6-8 for BTS (3-4 sec)
  - High charge: 9+ seconds
- Fix by locking booster cavity tuners in place. After this, 3-4 sec for stable high charge beam

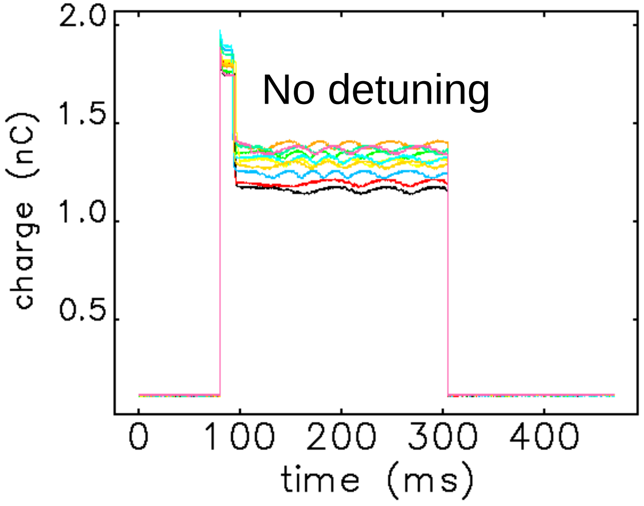


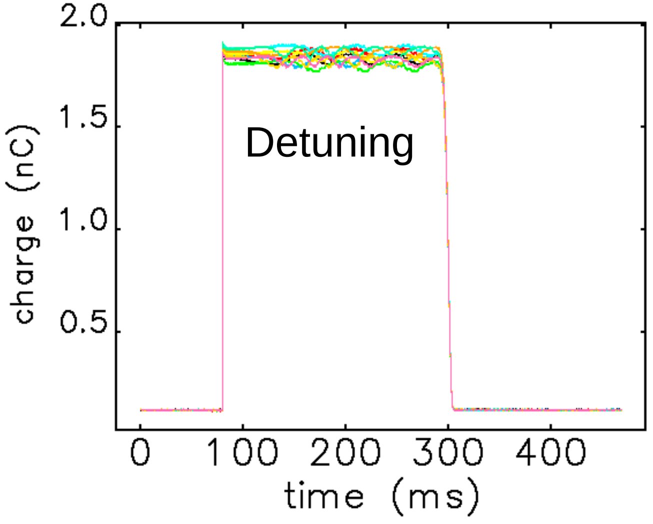


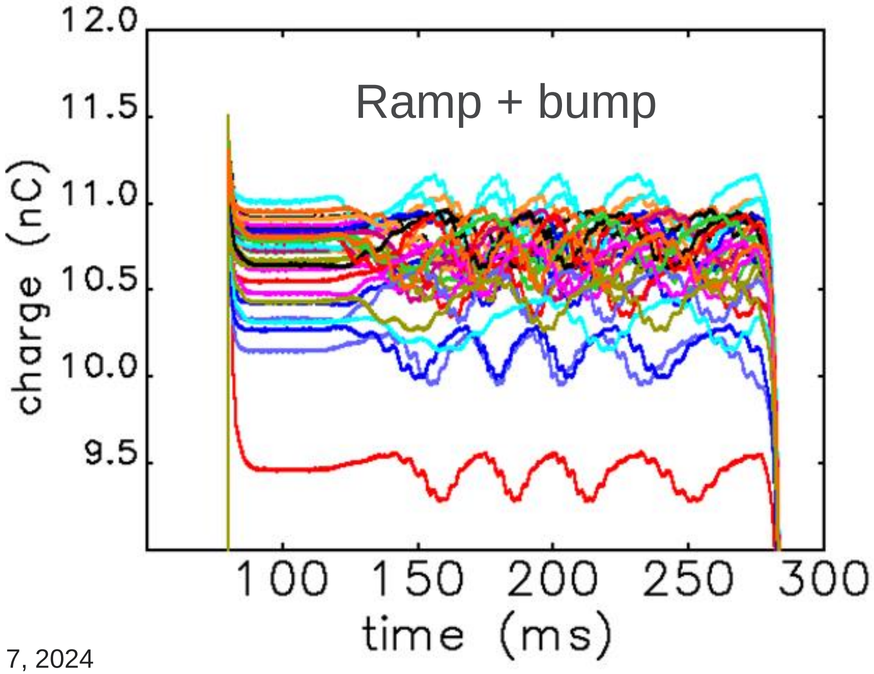
High charge with IETS

- Achieved 12nC with frequency bumps only, 10.5nC with bumps+ramp
- With frequency ramp, need to detune cavities to prevent charge loss
- Current monitor wavy because it is not (yet) synchronized to new booster rf



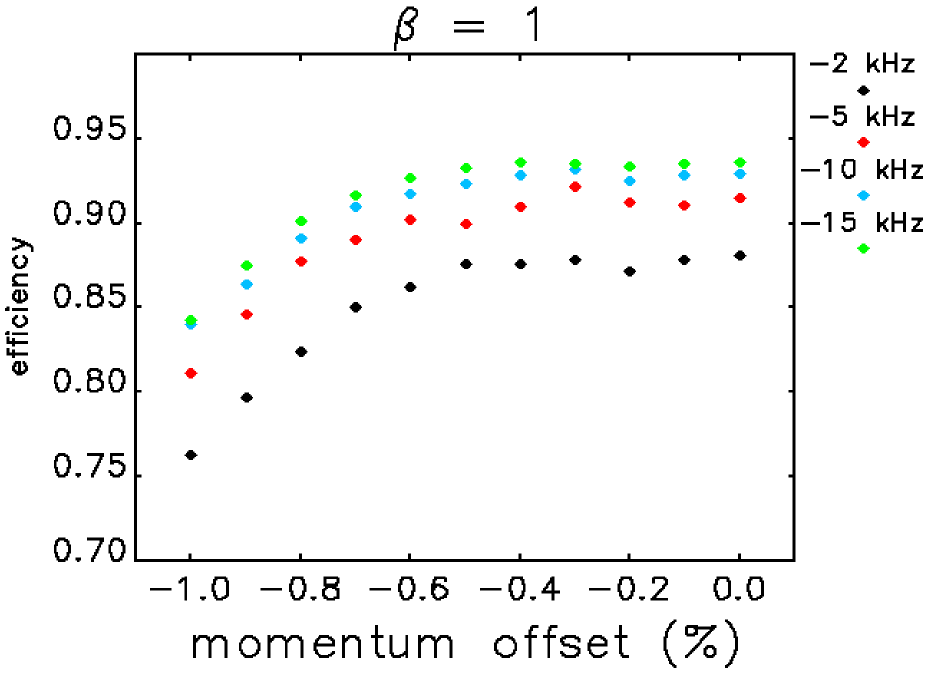


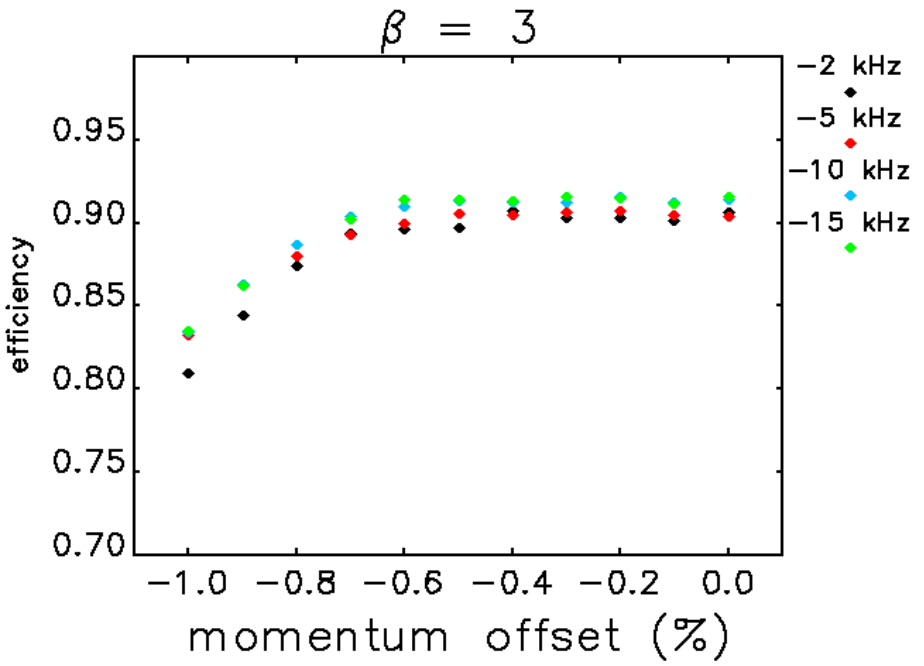




Booster injection efficiency vs rf parameters

- Simulations with 20 nC, 600 ps bunch length
- Injecting off momentum reduces injection efficiency
- Detuning the cavity reduces beam loading, increases efficiency
- Over-coupling reduces sensitivity to detuning
- Scheme is flexible, provides range of possible options





For -0.8% extraction offset

P_{eq} = 300 kW: total detuning = -20 kHz

Injection detuning (kHz)	Frequency sweep (kHz)	Injection offset (%)	Injection efficiency (%)
-2	-18	-0.27	90
-5	-15	-0.36	91
-10	-10	-0.51	91
-15	**-5**	**-0.65**	**91**

Development plans for post-commissioning APS-U needs

- **Booster digital LLRF system (started, but deferred)**
  - **Needed to measure/maintain constant detuning**
  - Option for direct feedback and/or feedforward
- **More synchronized PVs**
- Booster photon diagnostics: glidcop mirrors for other photon ports
- Injector current monitor upgrades, using BTS BESOCM electronics
- **High power couplers for high charge operation**
- Re-deploying old SR DCCT in the booster
- Long term:
  - Upgraded ramping power supplies for the booster
  - Comb filter LLRF feedback could allow for positive detuning