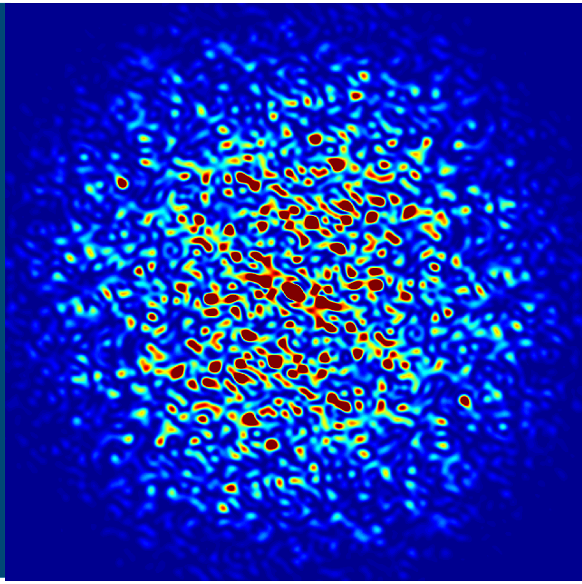
Progress on the APS-U Injector Upgrade



J. Calvey, T. Fors, K. Harkay, U. Wienands

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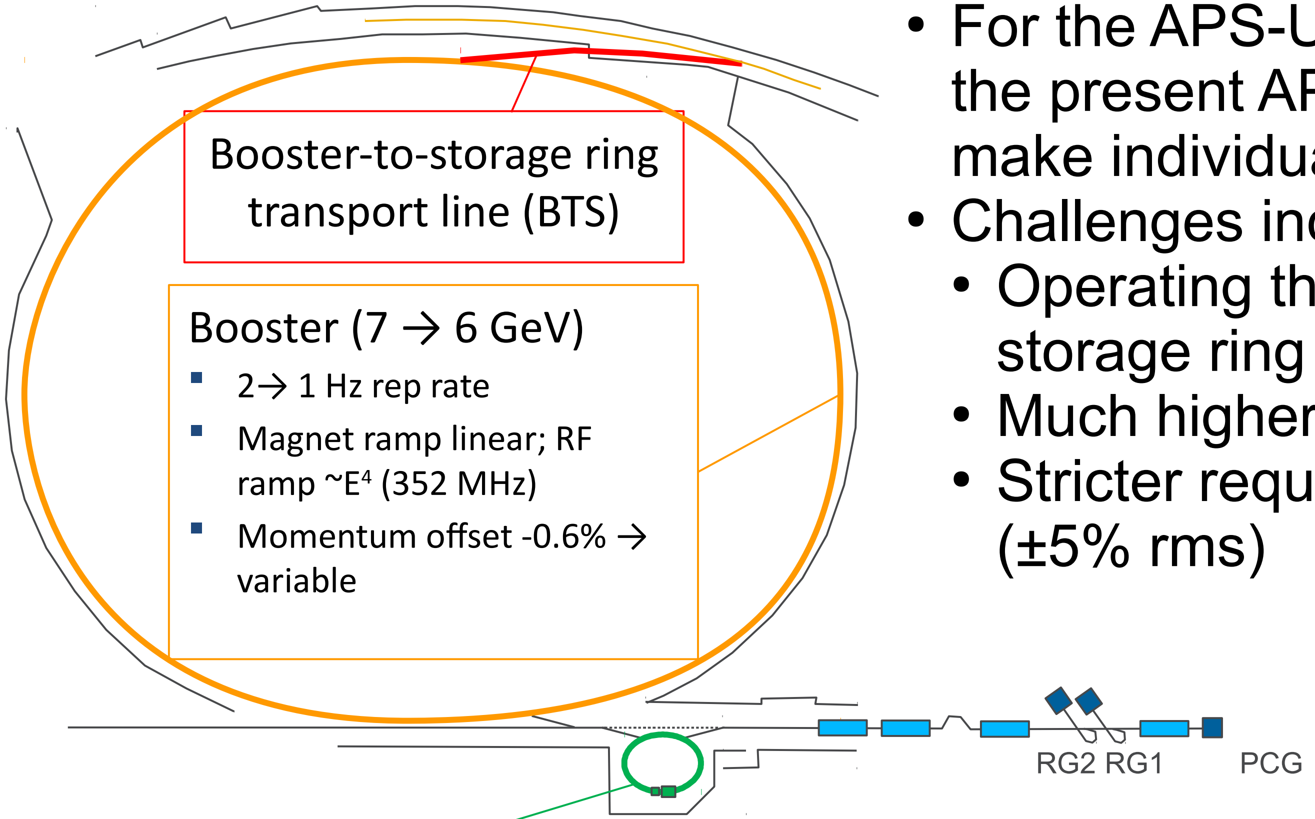
APS → APS-U injector chain

- 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 16 nC)
  - Stricter requirement for charge stability (±5% rms)

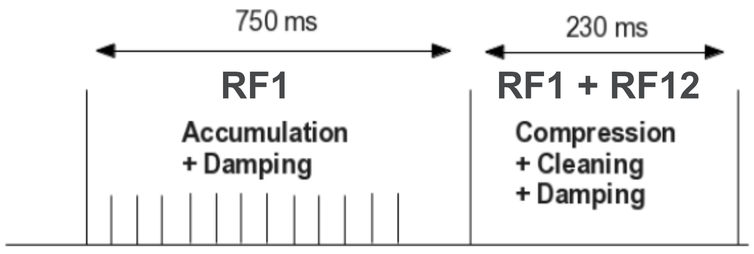


Booster-to-storage ring transport line (BTS)

Booster (7 → 6 GeV)
- 2→ 1 Hz rep rate
- Magnet ramp linear; RF ramp ~E^4 (352 MHz)
- Momentum offset -0.6% → variable

Particle accumulator ring (PAR) (425 → 475 MeV)
- Single bunch; 2 → 1-Hz rep rate
- Captures linac pulses in RF1 (9.8 MHz); compresses damped beam in RF12 (117 MHz)

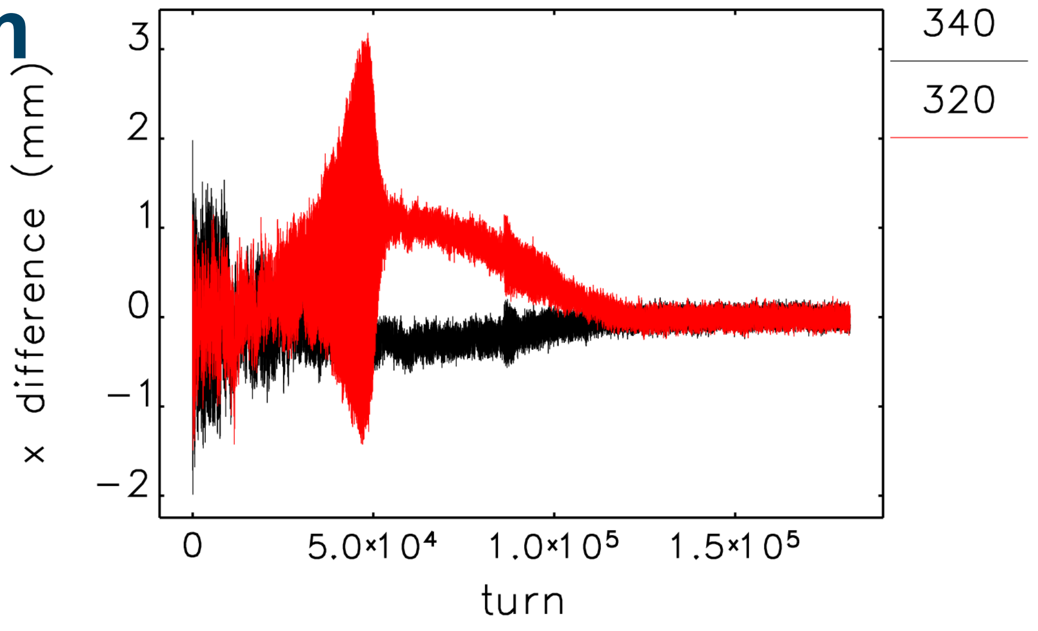
Linac (425 → 475 MeV)
- 1 nC/pulse; 30 Hz rep rate
- Thermionic RF guns: RG1, RG2 (1 hot spare)

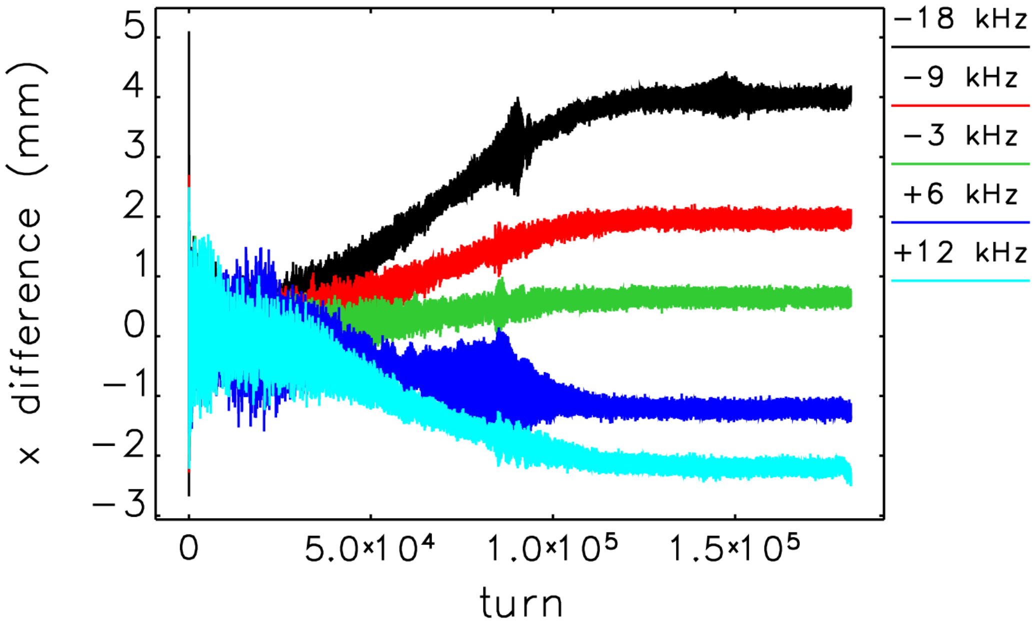


PAR cycle

Injection/extraction timing system

- APS-U storage ring (SR) will have higher frequency than present
- SR and booster rf frequencies will be decoupled
- Booster frequency can be adjusted along the energy ramp[1]
  - Bucket targeting with frequency bump- changes time beam spends in the booster
  - Overall frequency ramp - optimize both injection efficiency and extracted emittance
- Measurements from a dispersive BPM
  - Top: different frequency bumps
  - With large negative bump, cross cavity resonance -> Robinson instability
  - Bottom: different frequency ramps





[1] J. Calvey et al., Proc. IPAC’21, pp. 201–204.

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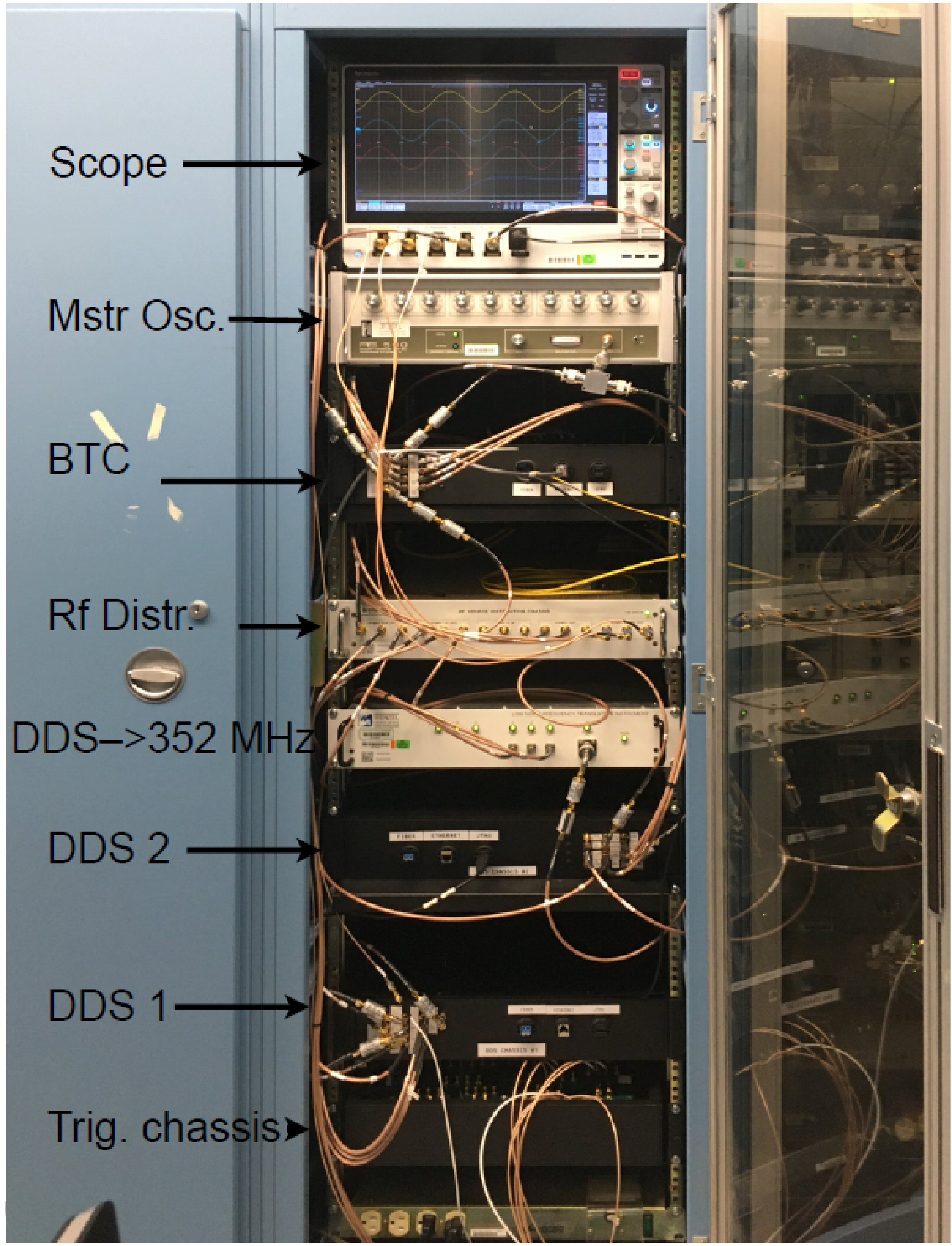
Machine studies with prototype system

- Verified we can control the three rf sources (PAR, booster, SR) separately.
- Demonstrated bucket targeting in the Booster (bump).
- Tested transfer from the Booster to Storage Ring at different rf frequencies of both rings at extraction (ramp).
- Verified that we can inject into Booster and transfer to SR, with different rf frequencies at injection. Observe larger than expected rf jitter.



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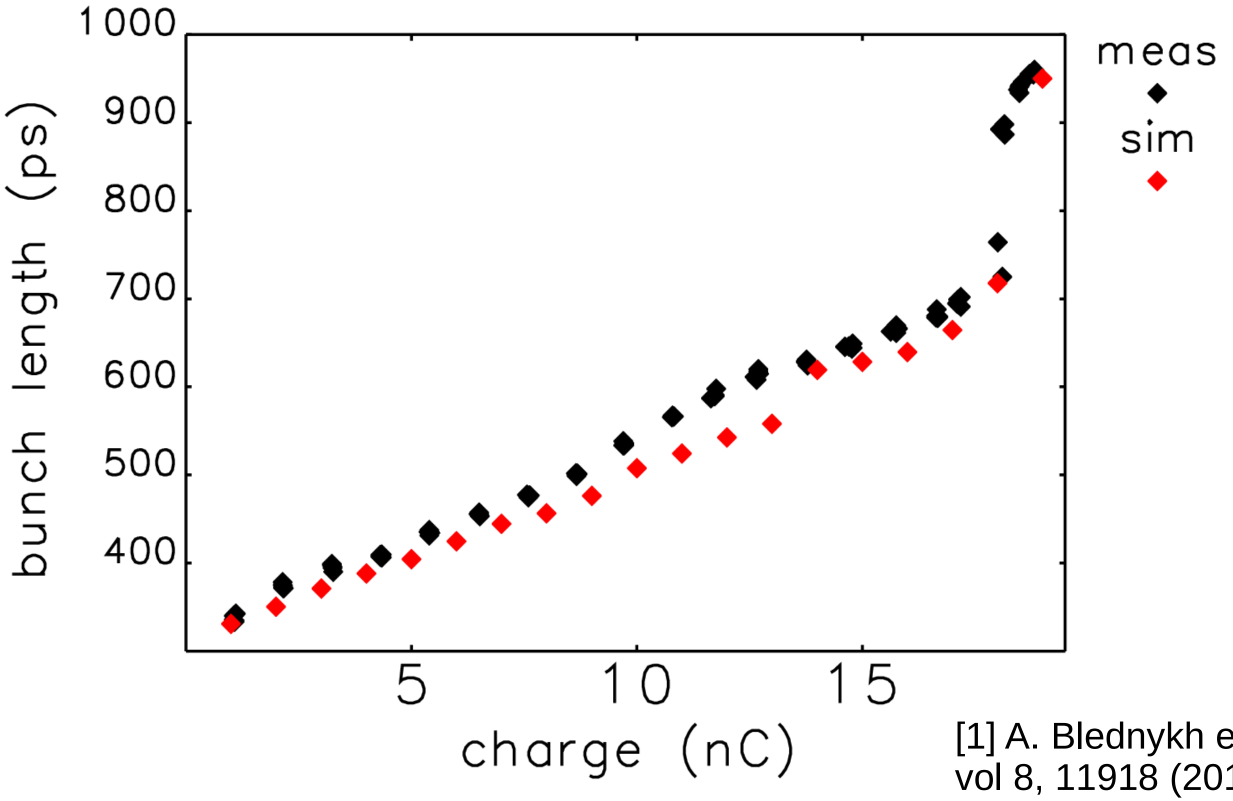
PAR longitudinal instability

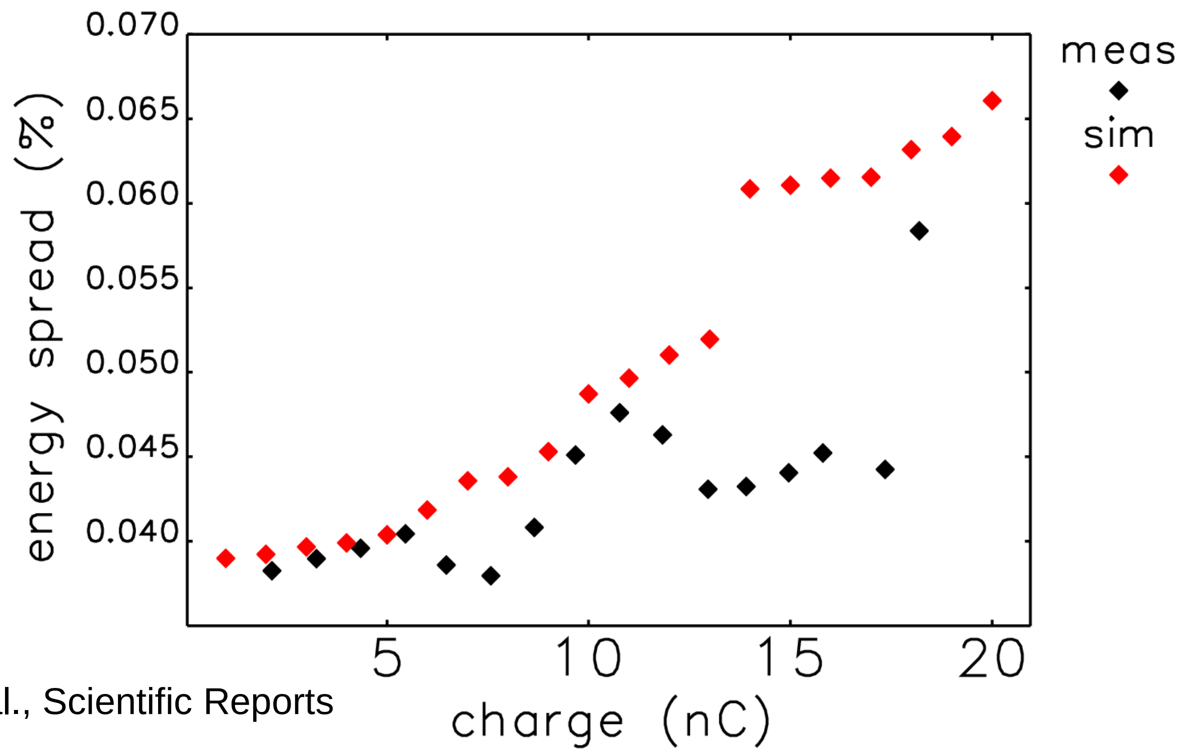
- Large bunch length blowup vs charge
- Caused by potential well distortion and microwave instability[1]
- Limiting factor for high charge booster injection[2]
- Simulate with elegant[3,4]. Model includes longitudinal impedance and beam loading in the rf cavities
- Impedance model developed using CST Microwave Studio[5]

[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.

Simulation results

- Simulated bunch length agrees well with measurement (but a bit lower)
- Energy spread blowup of the same order, but different in detail
  - Measurement shows dips in energy spread vs charge[1]
- May be missing high frequency part of impedance

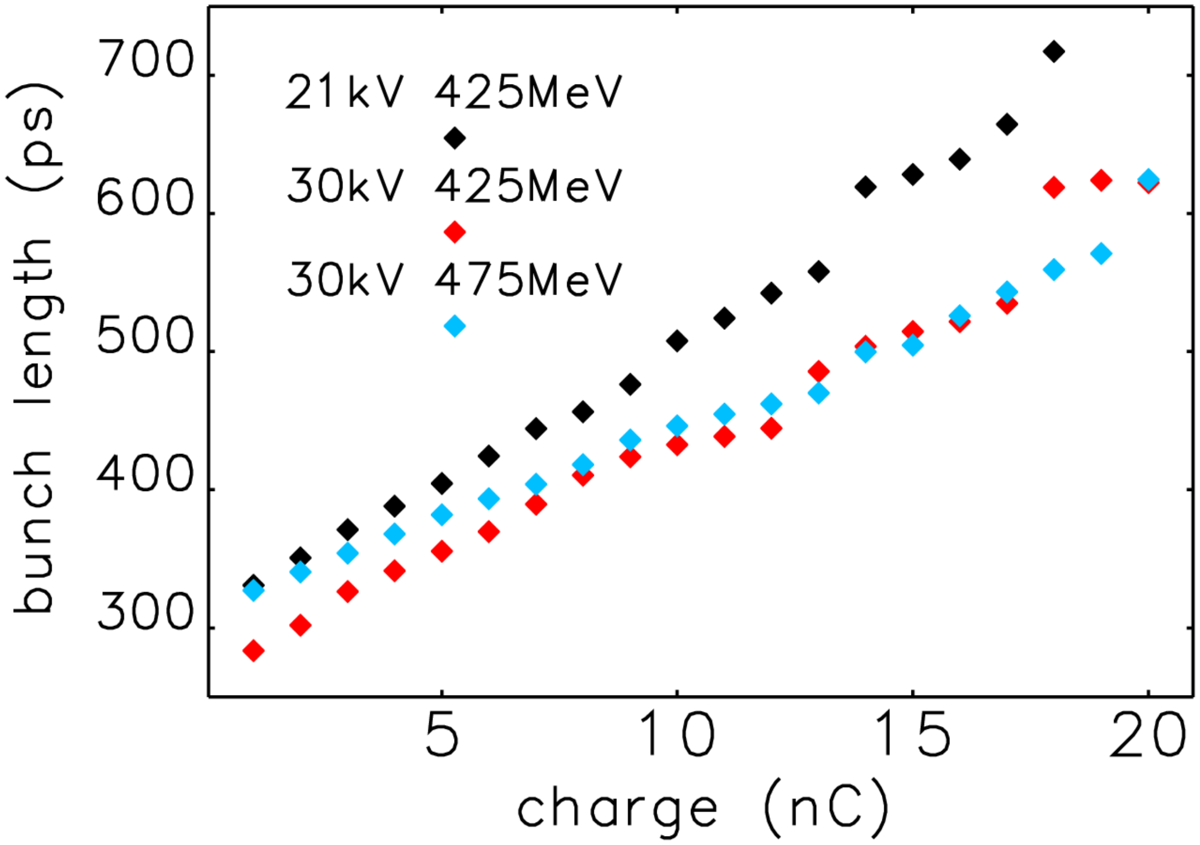




[1] A. Blednykh et al., Scientific Reports vol 8, 11918 (2018)

Reducing bunch length blowup

- Plan to increase RF12 voltage with high power amplifier[1], and raise PAR/linac energy
- 30 kV greatly reduces bunch length up to a threshold at 17 nC
- 475 MeV pushes the threshold to 19 nC
- Bunch length below 600 ps goal up to 19 nC



[1] K. Harkay, these proc., TUPA23

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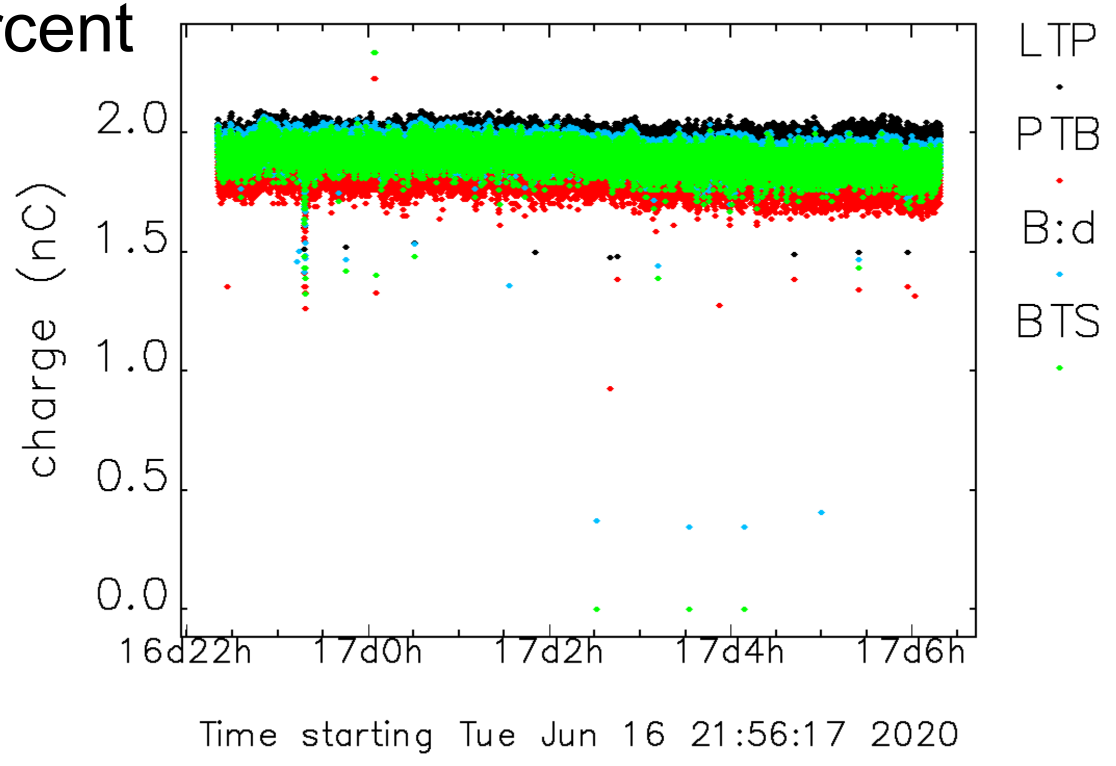
Charge stability

- Not really a concern at the present APS
- APS-U requires ±5% rms charge stability from the injectors
- Also, frequent injection: 9 – 30 sec
- Studied charge stability in two modes:
  - Continuous injection (beam run continuously through the injector)
  - Intermittent injection (beam is enabled and disabled in set intervals)
- Monitor charge in transfer lines:
  - Linac-to-PAR (LTP)
  - PAR-to-booster (PTB)
  - Booster-to-storage ring (BTS)

Continuous injection studies

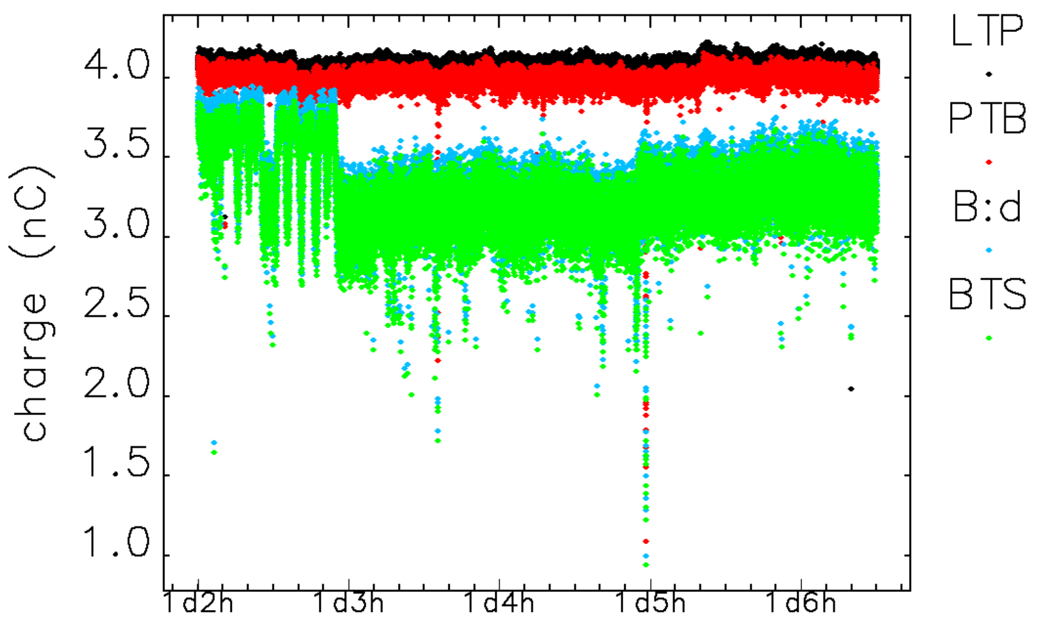
- Studies done from 2 – 4 nC, 5 - 8 hours
- Studies up to 8 nC had good stability for ~1 hour
- Most studies had < 5% rms variation and > 90% efficiency, with a few outliers
- Current monitors accurate to a few percent

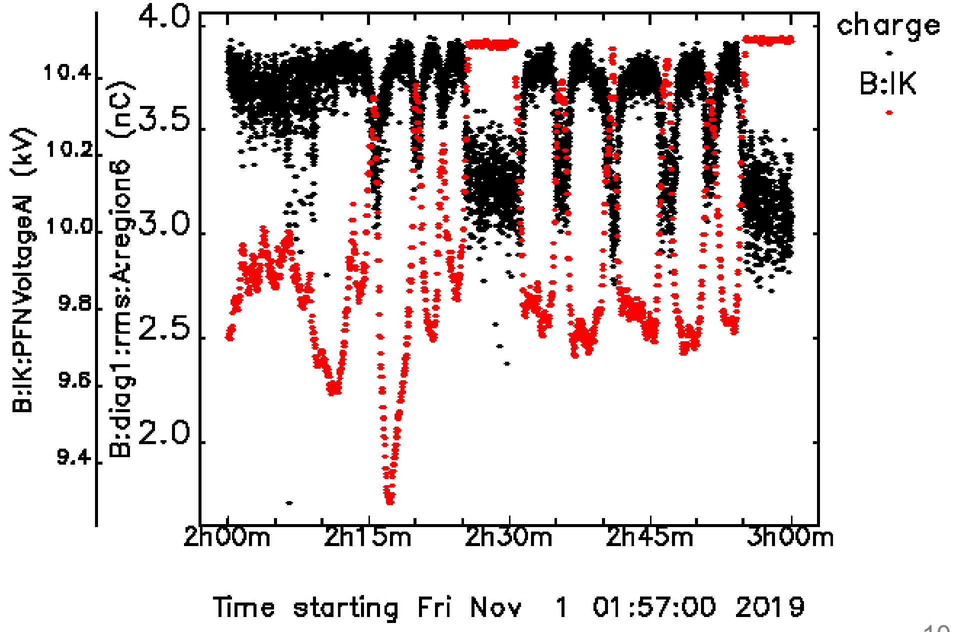
Index	LTP (nC)	PTB (nC)	BTS (nC)	eff (%)	RMS (%)
1	1.99	1.80	1.90 ± 0.05	95	2.6
2	2.02	1.96	2.00 ± 0.15	99	7.5
3	1.99	1.96	1.81 ± 0.08	91	4.4
4	3.07	3.01	3.10 ± 0.08	101	2.6
5	4.17	3.85	4.12 ± 0.15	99	3.6
6	4.08	4.01	3.26 ± 0.23	80	7.1



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]
- Could be automated with AI/ML

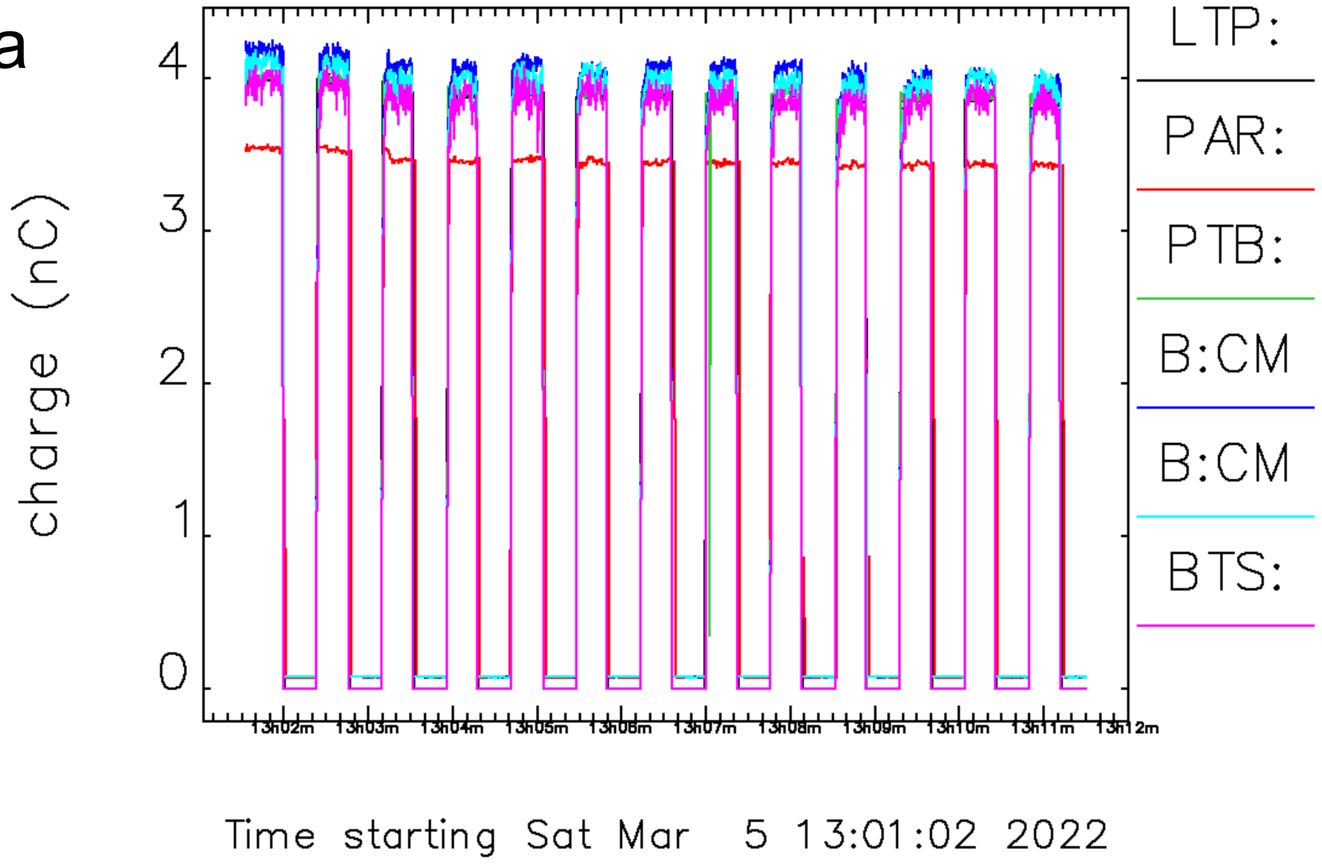




[1] C. Yao et al., Proc. IPAC'21, pp. 449–450.

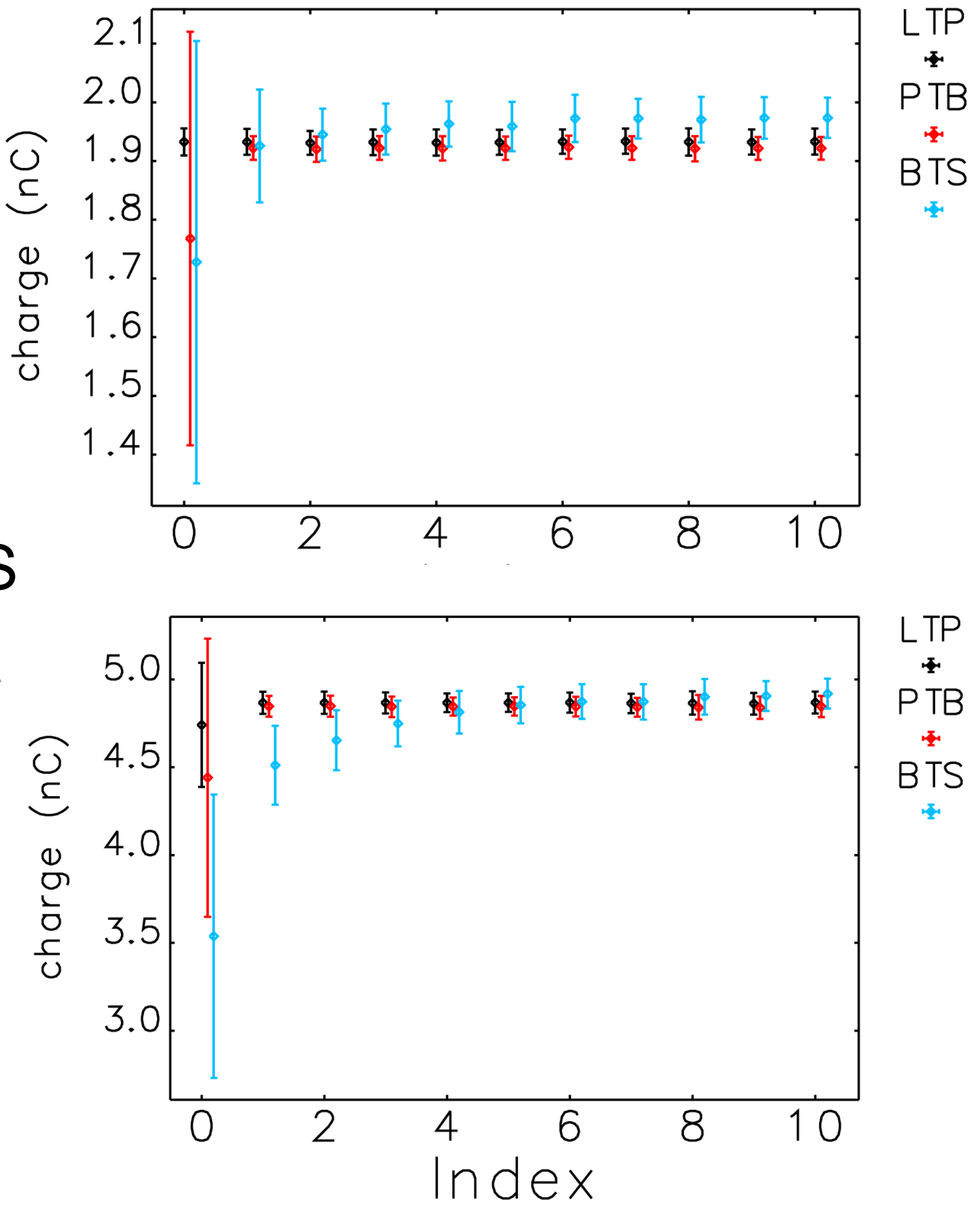
Intermittent injection

- Enable beam for 20 seconds, disable for 20 seconds
- Closer to APS-U condition
- Measure charge stability and identify causes of slow stabilization
- Special PVs developed to track a bunch through the injector chain
- Allows us to study injector issues on a shot-by-shot basis



Time to stabilize

- After beam is enabled, how many shots does it take to get stable beam through the injector?
- Look at many (~100) cycles, take average and standard deviation
- 2 nC: 1 shot (0.5 sec) for PTB, 4 for BTS
- 5 nC: 1 shot for PTB, 6-8 for BTS. Most likely culprit is booster cavity tuning loops



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Conclusions

- Work on the APS-U injector complex is ongoing
- Studies with a separate booster rf source have demonstrated bucket targeting and frequency ramps.
- PAR instability simulations agree reasonably well with measurements.
- Simulations with 30 kV RF12 voltage and 475 MeV beam energy predict the bunch length can be kept below 600 ps up to 19 nC.
- Injector charge stability has been studied, using both continuous and intermittent injection. Charge stability is generally good up to 5 nC, and causes of poor efficiency can usually be identified.