Challenges for High Charge Operation of the APS Injection System

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Injector working group

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- RF group: T. Berenc, D. Horan, A. Goel, G. Waldschmidt
- Engineering, Software, Controls, & Operations Team: A. Brill, J. Carter, H. Bui, R. Flood, G. Fystro, A. Hillman, L. Morrison, S. Pasky, A. Pietryla, T. Puttkammer, H. Shang, R. Soliday, J. Wang, F. Westferro, S. Xiang, S. Xu

Outline

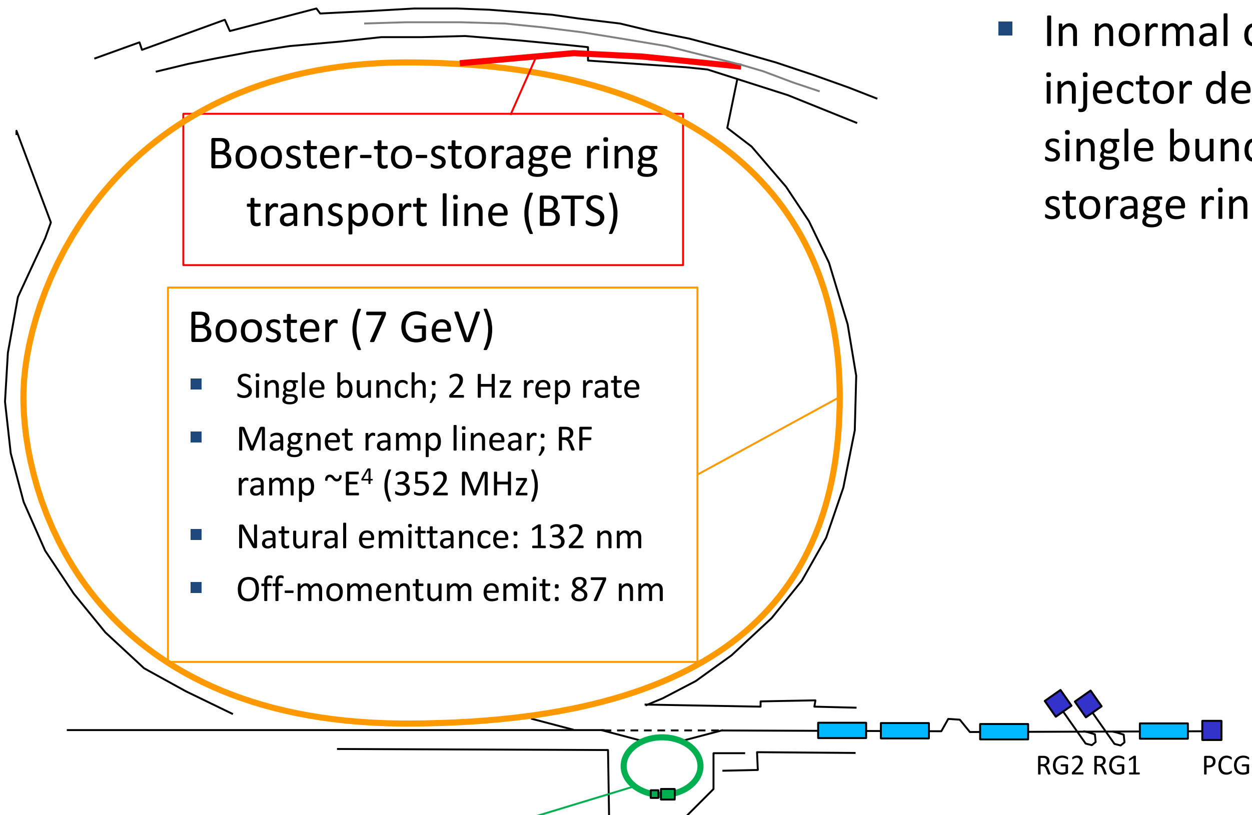
- Overview of APS injector complex
- High charge issues in the particle accumulator ring:
  - Bunch length blowup
  - Beam capture in 12th harmonic cavity
  - Longitudinal instability
  - Ion trapping
- High charge issues in the booster synchrotron:
  - Injection efficiency
  - Beam loading compensation
  - RF Frequency ramp

Introduction

- APS injectors were originally designed to deliver up to 6 nC.
  - Typical operation: 2-3 nC
- R&D is underway to study the high-charge performance. The charge and beam quality are limited primarily by longitudinal effects.
- So far we have achieved 16 nC in PAR, 12 nC in booster
- The present injectors are capable of supporting 200 mA in a total of 72 to 324 bunches (i.e., 2.5 nC to 11 nC).
- Improvements to support 200 mA in 48 bunches (16 nC) are being developed.

APS Injector Complex

- In normal operations, injector delivers 2-4 nC single bunch charge to the storage ring at 2-Hz rate.



Booster-to-storage ring transport line (BTS)

Booster (7 GeV)

- Single bunch; 2 Hz rep rate
- Magnet ramp linear; RF ramp ~E^4 (352 MHz)
- Natural emittance: 132 nm
- Off-momentum emit: 87 nm

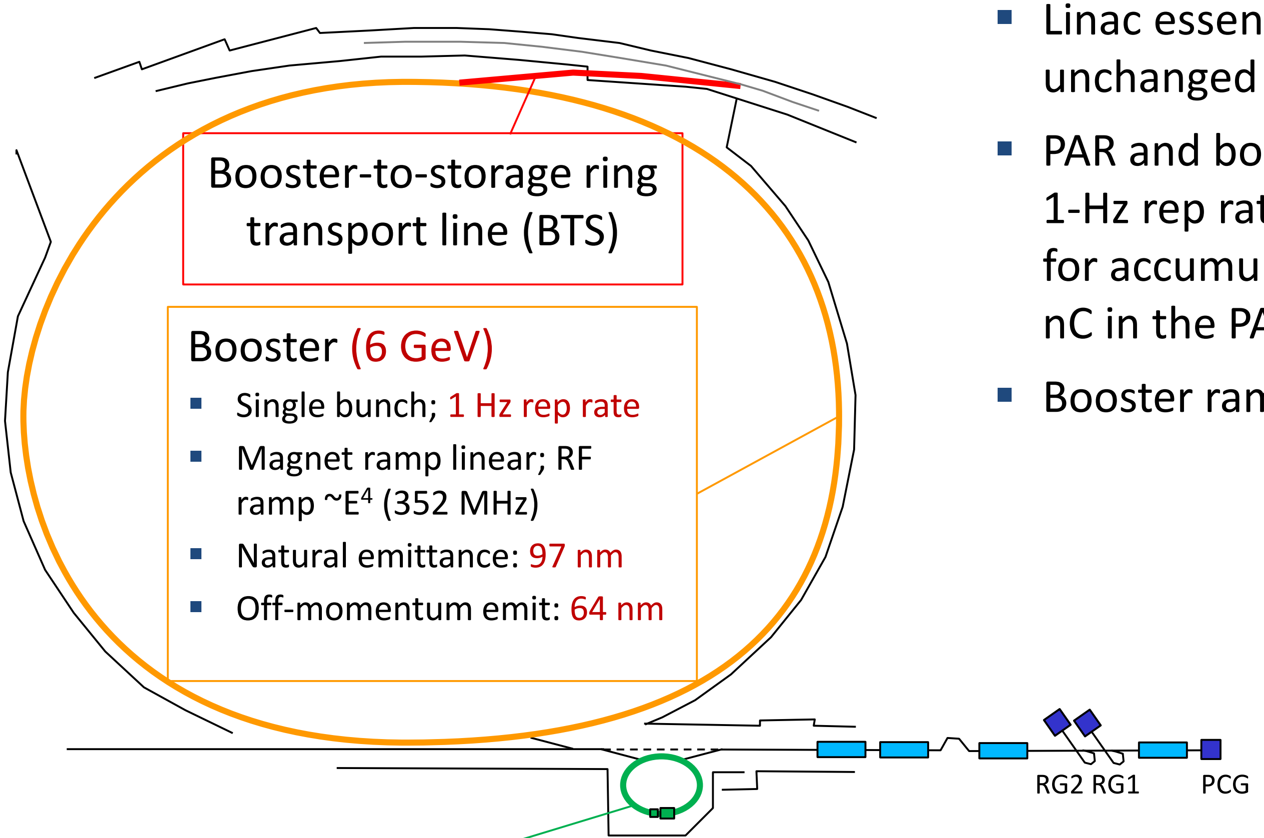
Particle accumulator ring (PAR) (375 MeV)

- Single bunch; 2-4 nC, 2-Hz rep rate
- Captures linac pulses in RF1 (9.8 MHz); compresses damped beam in RF12 (117 MHz); bunch cleaning system

Linac (375 MeV)

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

APS Injectors: High Charge



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

- Linac essentially unchanged
- PAR and booster run at 1-Hz rep rate, which allows for accumulation up to 20 nC in the PAR
- Booster ramps to 6 GeV

Particle accumulator ring (PAR) (375 MeV)

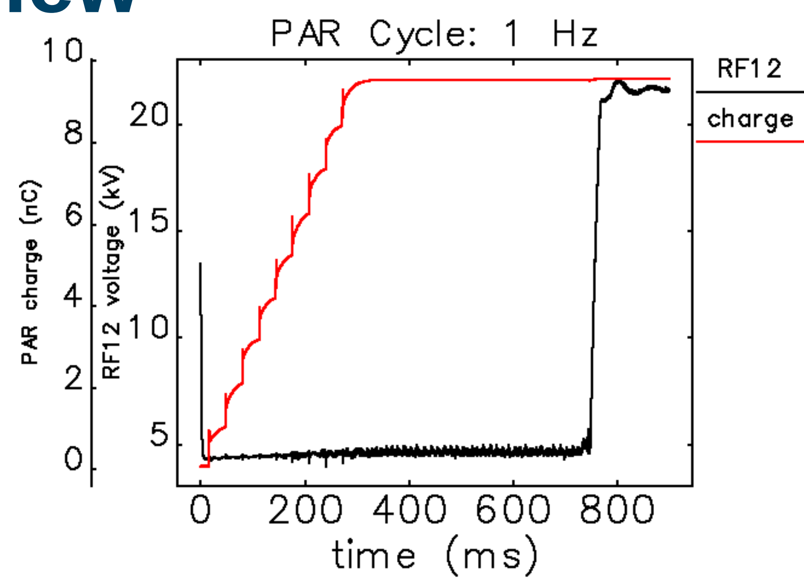
- Single bunch; up to 20 nC, 1-Hz rep rate
- Captures linac pulses in RF1; compresses damped beam in RF12 (117 MHz); bunch cleaning system

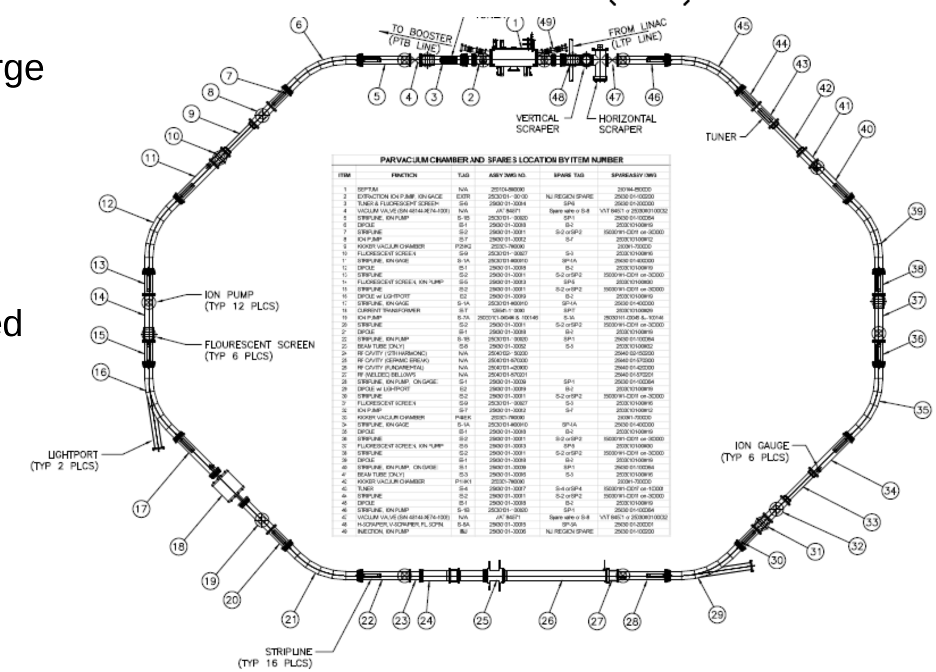
Linac (375 MeV)

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

PAR overview

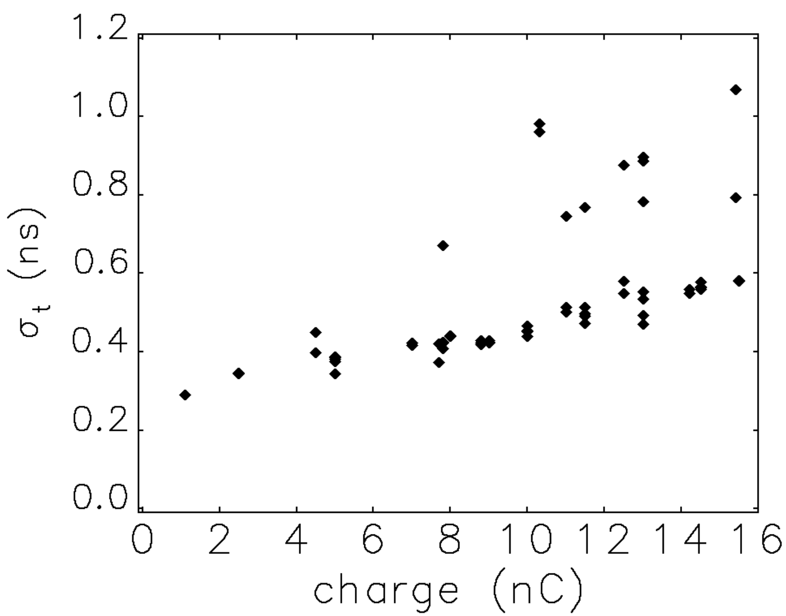
- Modeled after DESY's PIA ring
- 1 nC bunches from linac injected every 33 ms
- 1 Hz mode developed to allow accumulation for 750 ms
- At 750 ms, 12th harmonic cavity is turned on, shortening the bunch to ~350 ps (zero current)
- Highest charge achieved in PAR: ~16 nC
- Concerns for high charge operation:
  - Reduced injection efficiency at very high charge (> 16 nC injected)
  - Fundamental RF1 trips, believed caused by beam loading and HOMs presented to non-isolated amplifier
  - Significant bunch length blowup, accompanied by longitudinal instability.
  - Vertical beam size growth, likely due to ion trapping



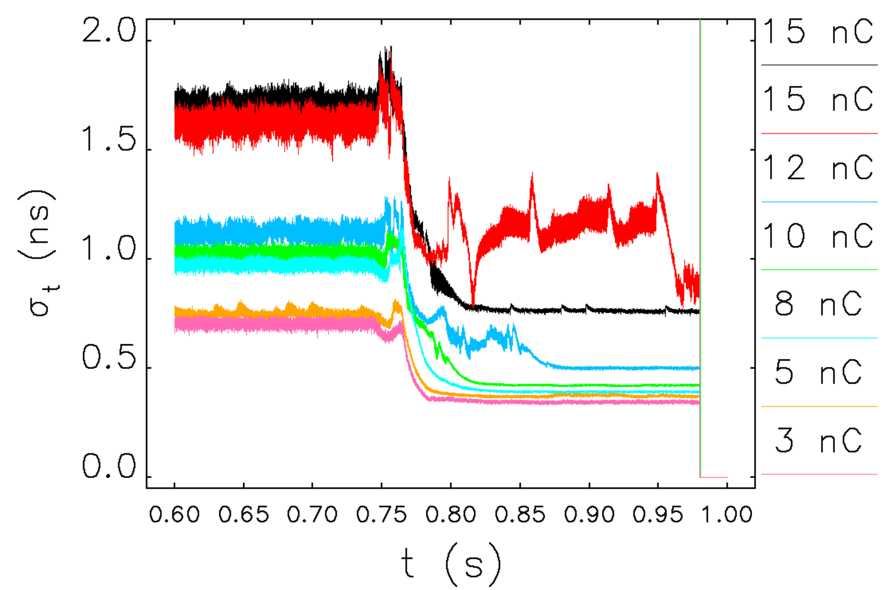


PAR bunch length blowup

- Data were acquired with a photodiode signal, calibrated using a laser and streak camera.
- Plot on left shows average bunch length over 10 turns at 900 ms in cycle. There is a linear trend towards twice the bunch length (potential well distortion), as well as instances of extreme bunch length blowup due to an instability (Robinson-type or microwave).
- Plot on right shows bunch length before and after RF 12 capture (750 ms). Sawtooth instability can be seen at 10, 12, 15 nC.



J. Dooling

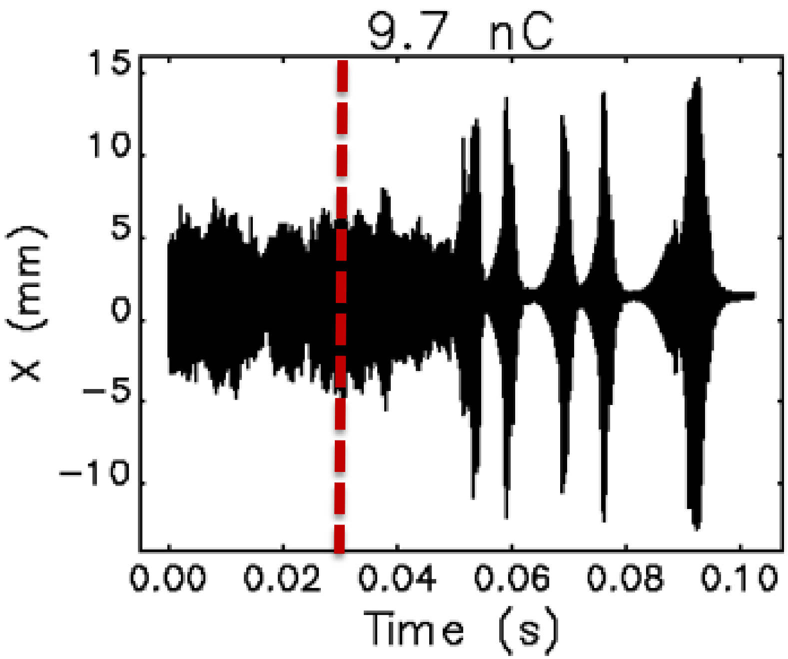


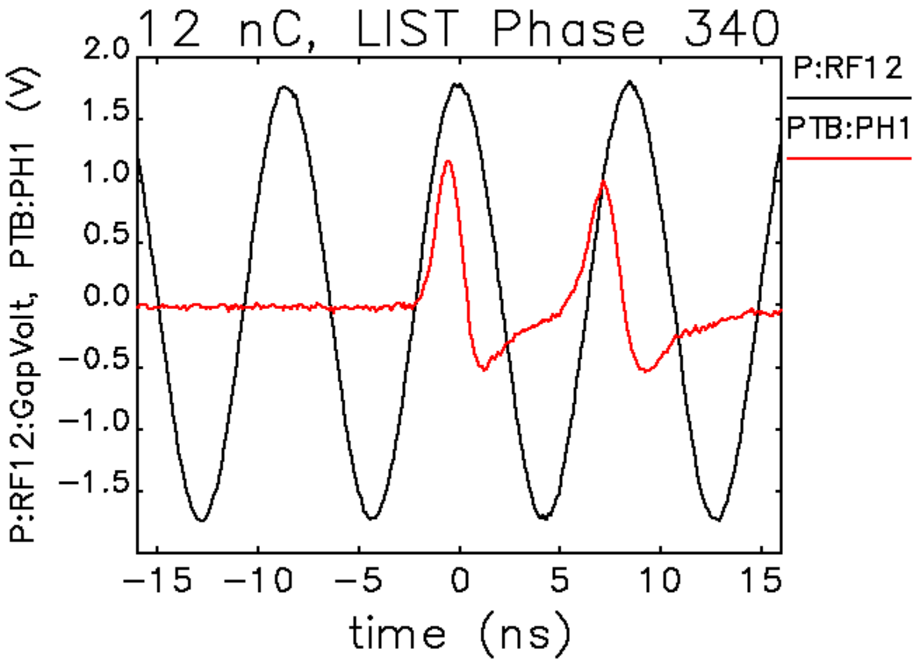
K. Harkay

PDR 4-3.13.2

PAR harmonic tuning

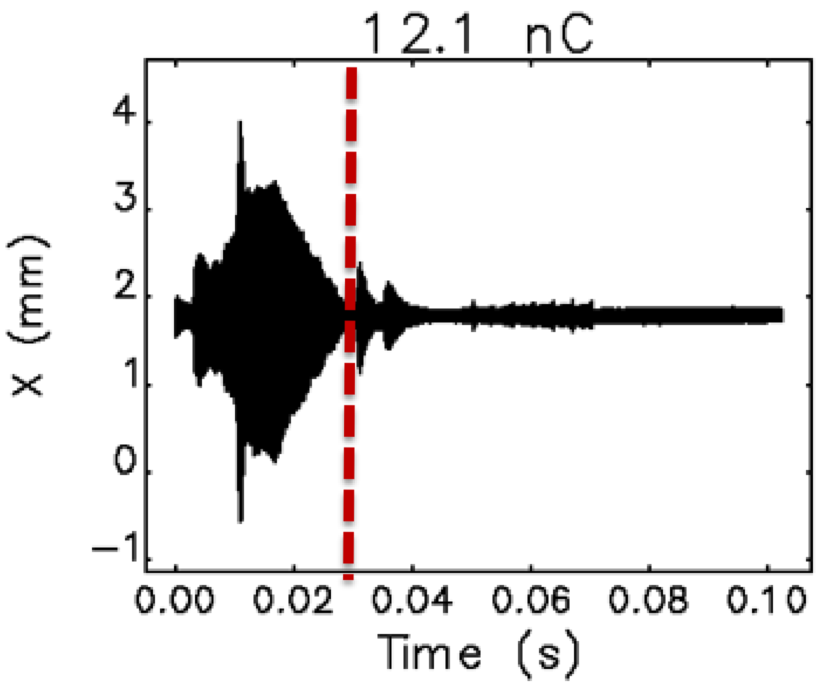
- 12th harmonic cavity detuning and phase must be carefully optimized for good capture at high charge
  - Bad choice of parameters leads to double bunching and/or instability
  - Left: sawtooth instability after RF12 turn-on (dashed line) measured by new turn-by-turn BPM (in a dispersive section)
  - Right: double-bunching in PAR-to-booster transfer line

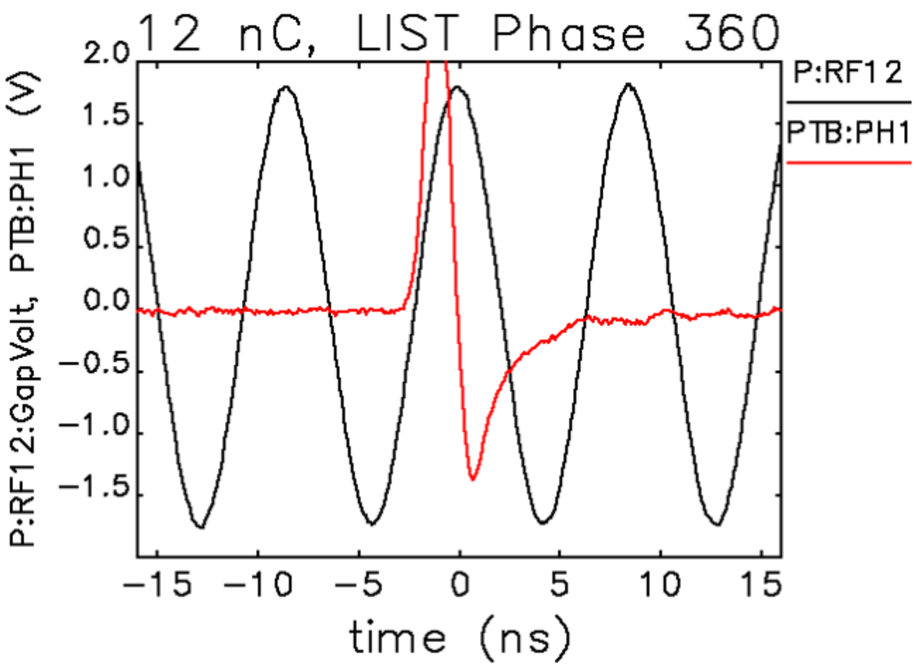




PAR harmonic tuning

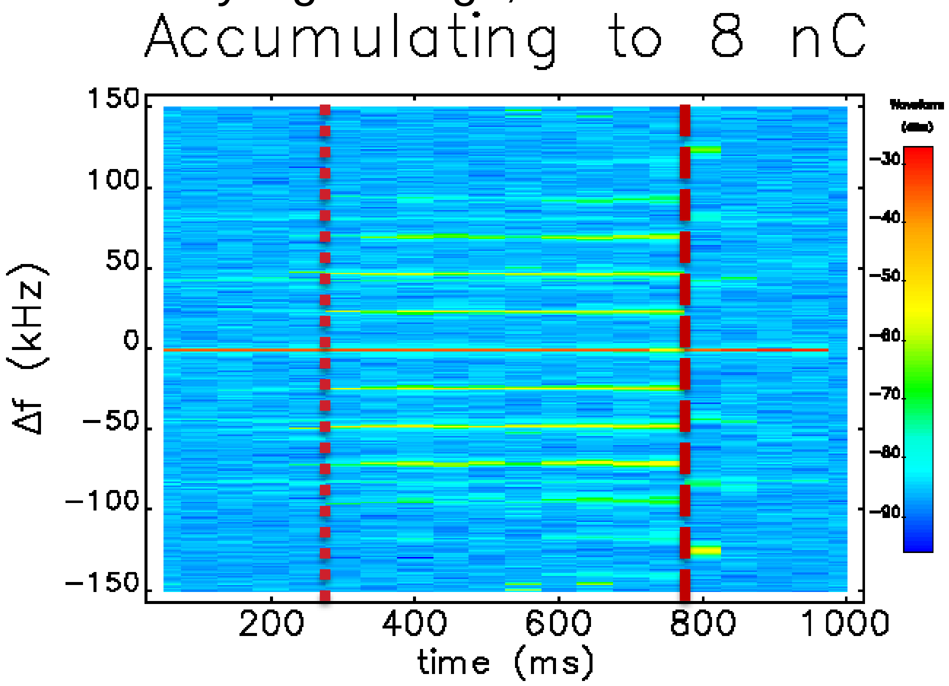
- 12th harmonic cavity detuning and phase must be carefully optimized for good capture at high charge
  - Both problems mitigated with good choice of tuning parameters

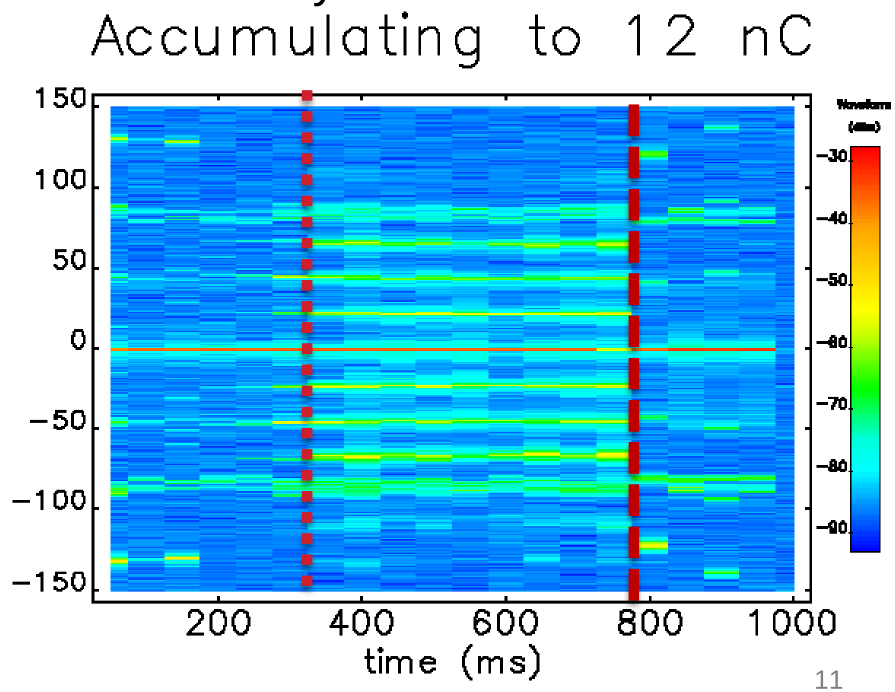




PAR longitudinal instability

- Beam is longitudinally unstable before 12th harmonic turn-on
  - Multiple synchrotron sidebands observed after accumulation (dotted line)
  - Bunch is long; instability is consistent with long-range, resonator impedance.
- With proper tuning of 12th harmonic detuning and phase, can stabilize beam after turn-on (dashed line)
- At higher charge, 12th harmonic synchrotron tune is visible after turn-on
  - Seems to persist until next turn, probably AGC loop is not fast enough
- At very high charge, beam remains unstable for entire cycle



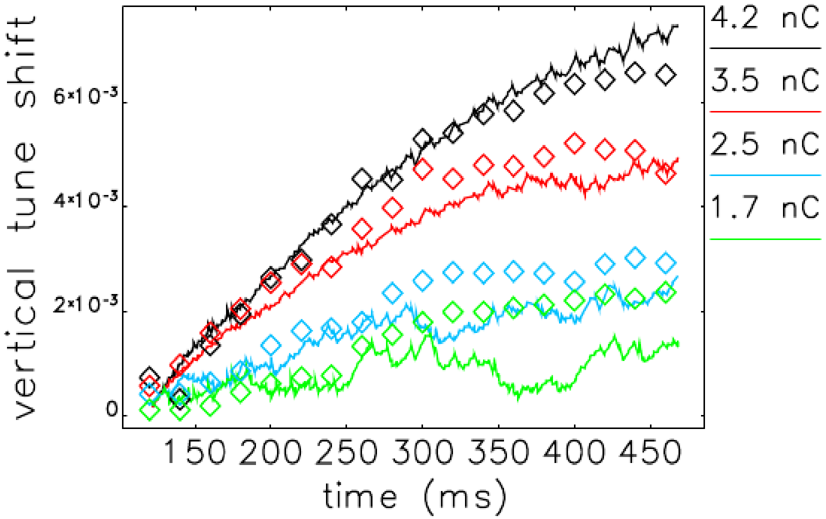


Modeling of PAR beam loading

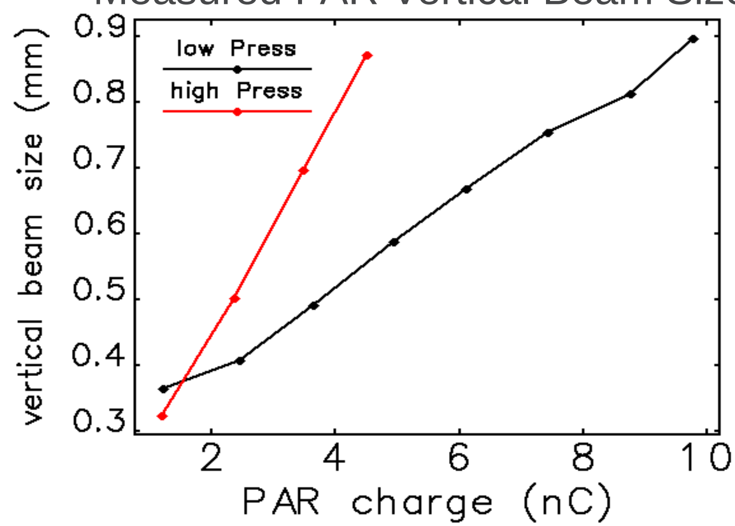
- Modeling of PAR beam loading is in early stages
- Beam loading in 12^{th} harmonic cavity is significant, even when it's detuned
  - Simple calculation gives ~14 kV at 20 nC and -140 kHz
  - (compared to ~22 kV cavity voltage when RF12 enabled)
  - Preliminary simulations suggest that the cavity could be used passively at very high charge
- Things to model:
  - Beam loading in both cavities
  - Harmonic capture in the presence of beam loading
  - Cavity HOMs (measurements are underway)
  - Efficacy of cavity feedback loops at high charge
  - Develop PAR impedance model

PAR ion effects

- Trapped ions cause a positive tune shift with charge, which increases along the PAR cycle. This effect has been reproduced with simulations [1,2]
- We haven't observed coherent ion instability, and don't anticipate it at high charge
- We believe ions are responsible for vertical beam size blowup with charge
  - Effect was stronger when pressure was high after a vacuum intervention
  - Plan to model this with IONEFFECTS element in ELEGANT



Measured PAR Vertical Beam Size



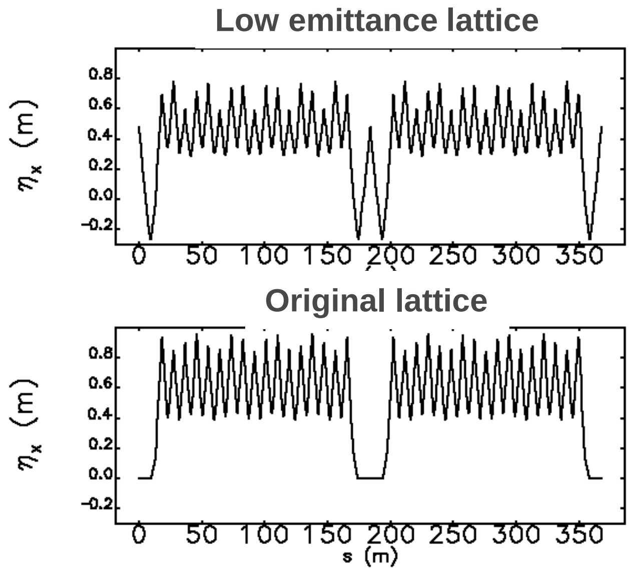
[1] L. Wang et al, PRST-AB 14, 084401 (2011).
[2] J. Calvey et al. *THPOA14, Proc. NAPAC16*.

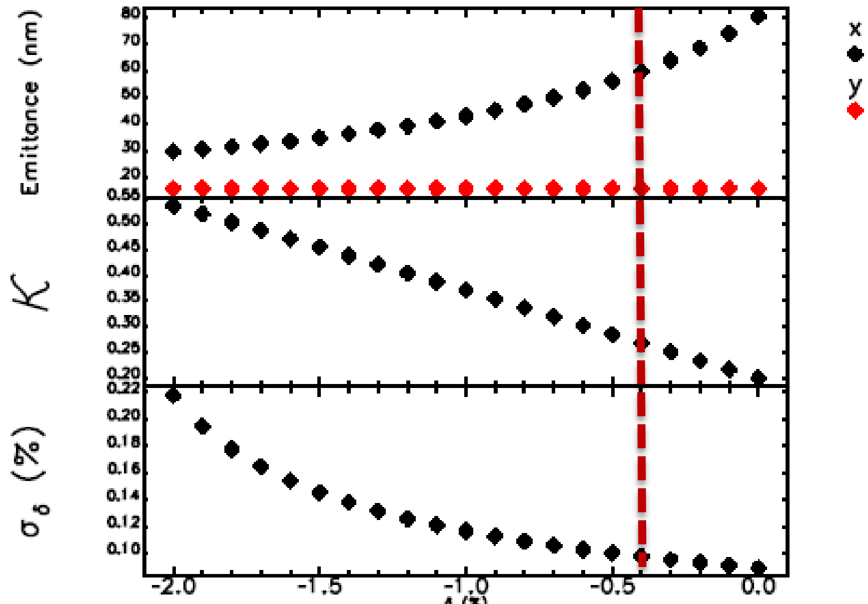
PAR plans

- Continue to study longitudinal blowup / instability with modeling, as well as improved diagnostics
  - Photodiode and streak camera
  - Detailed measurements of cavity HOMs
  - BPMs with turn-by-turn capability (2 so far)
  - Upgrade of RF diagnostics is underway
- Absorptive filter to cure fundamental RF trips (to be installed this fall)
- Mitigate vertical beam size blowup, if needed
  - Beyond vacuum conditioning, ion trapping could be mitigated further: e.g., NEG coating, adding more pumps, or clearing electrodes.
- Test alternate modes of operation:
  - Operate RF12 in passive mode
  - Operate at higher beam energy

Booster overview

- Ramp from 375 MeV to 7 GeV in 225 ms
- Two lattices studied:
  - Original (97 nm natural emittance at 6 GeV)
  - Low emittance (68 nm at 6 GeV)
  - Low emittance lattice has nonzero dispersion in the straight sections
- Run off-momentum
  - Reduces horizontal and vertical emittance
  - Original lattice meets storage ring injection requirements (ε_x=60 nm, ε_y=16 nm) if run far enough off-momentum
  - Increased energy spread may reduce collective instabilities at SR injection
- Recently upgraded BPM system to allow for orbit correction along the ramp

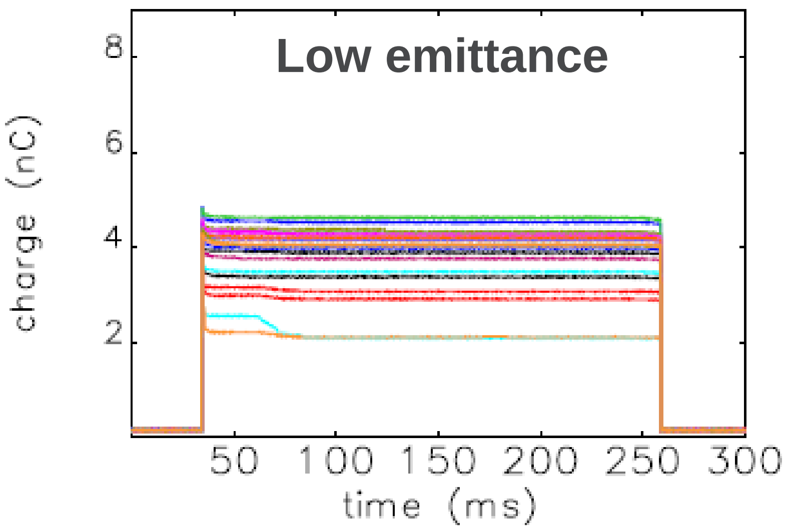


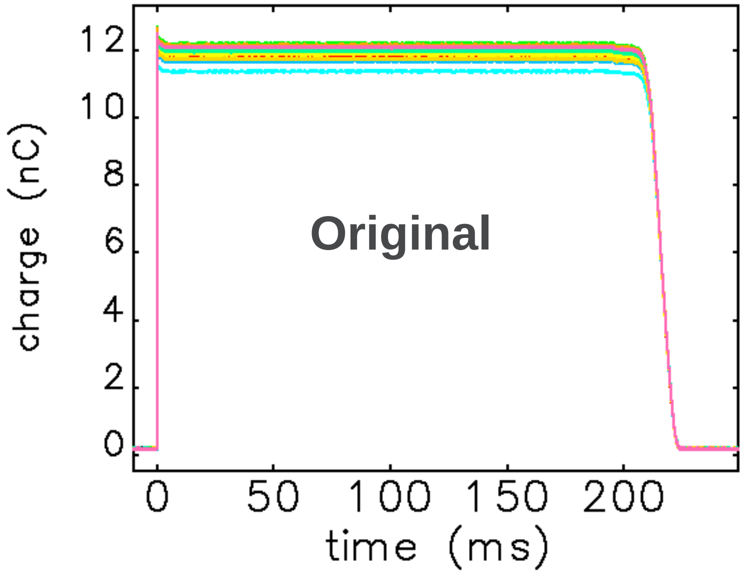


M. Borland

Booster injection efficiency

- Main limiting factor to achieving high charge operation is reduced injection efficiency in the booster.
- Goal is 17 nC (e.g. 85% efficiency for 20 nC injected charge)
- Originally planned to use low emittance booster lattice for high charge operation
  - Showed large losses in first few ms of ramp
  - Significant shot-to-shot variation
  - Maximum booster charge ~5 nC
- Switched back to original lattice
  - After optimization of injection voltage, cavity detuning, and ramp parameters, shows much better injection efficiency
  - Maximum charge in booster ~12 nC
  - Still observe early losses at high charge
- We have investigated this issue using particle tracking simulations





Booster simulations

- Particle tracking done with ELEGANT [1]
  - Track element-by-element
  - 50,000 macroparticles
  - Track 3000 turns (3.5 ms)
    - Where most losses occur
- Model includes:
  - Transverse and longitudinal impedance [2]
  - Beam loading in RF cavities
- Simulation parameters:
  - Transverse beam size measured on flag in PAR-to-booster transfer line
    - Vertical beam size blowup caused by ions in the PAR [3]
  - PAR bunch length measured photodiode detector (~350 ps at low charge)
  - RMS energy mismatch between booster and injected beam
    - Caused by variation in dipole ramp
    - Estimated to be ±0.5% based on amplitude of synchrotron oscillations
  - RMS transverse offsets

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

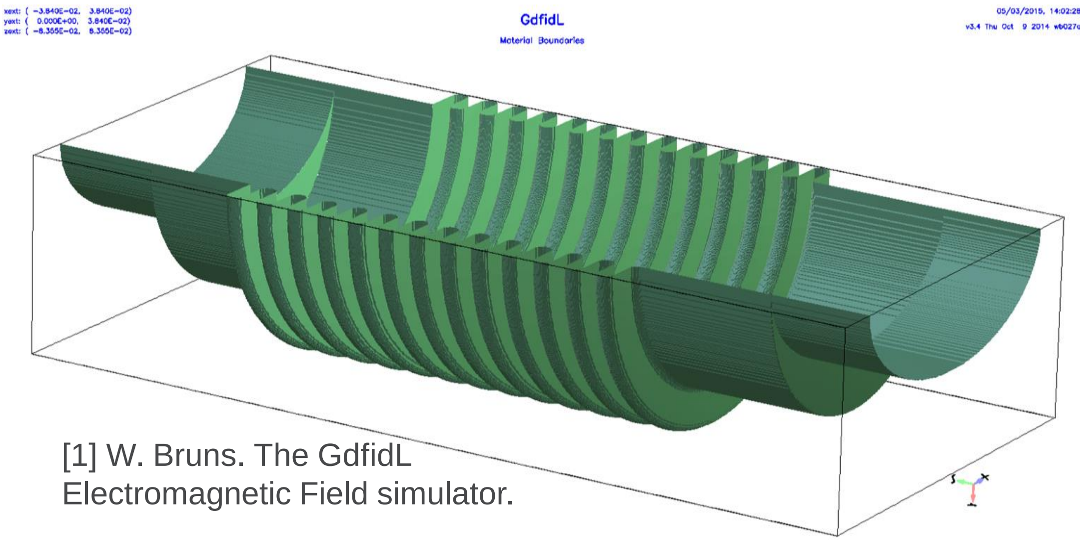
[2] R. R. Lindberg et al. *Proc. IPAC 2015*. TUPJE078.

[3] J. Calvey et al. *THPOA14, Proc. NAPAC16*.

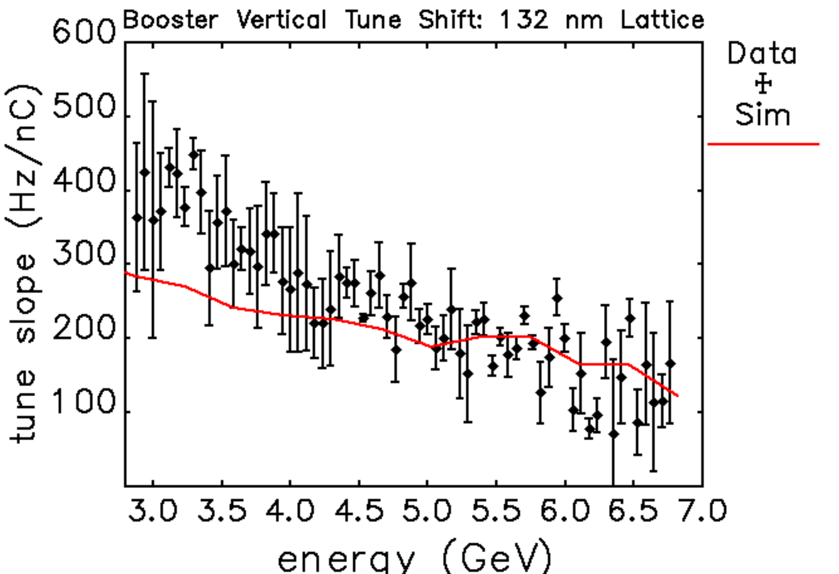
Booster impedance model

- Developed using same technique as storage ring model (by R. Lindberg)
- Elements included:
  - **RF cavities (4)**
  - **RF cavity bellows (10)**
  - **Booster bellows (40)**
  - T-vacuum port (37)
  - X-vacuum port (37)
  - 4-blade stripline (2)
  - Flange gaps (120)
- Compare simulated and measured tune shift with charge
  - Good agreement between model and measured data above 3 GeV
  - Data is very noisy earlier in the ramp

GdfidL[1] Model of Booster Bellows

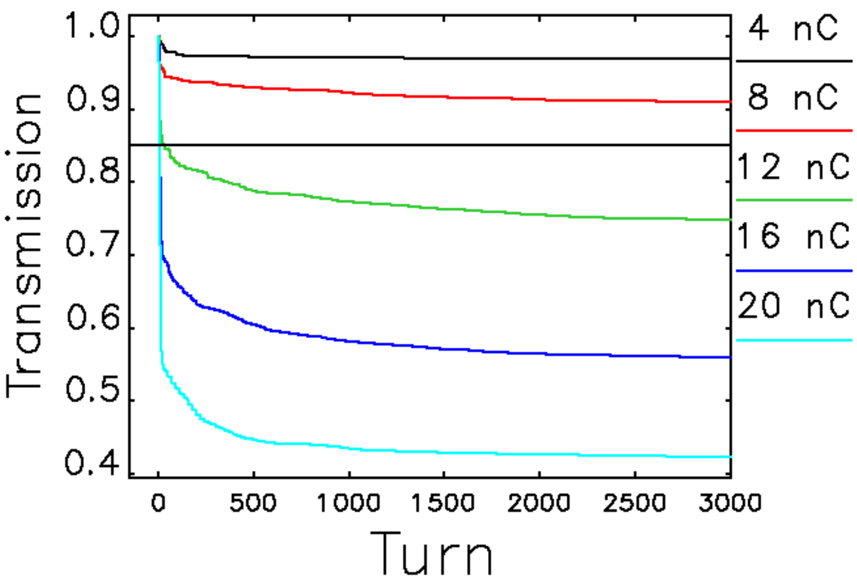


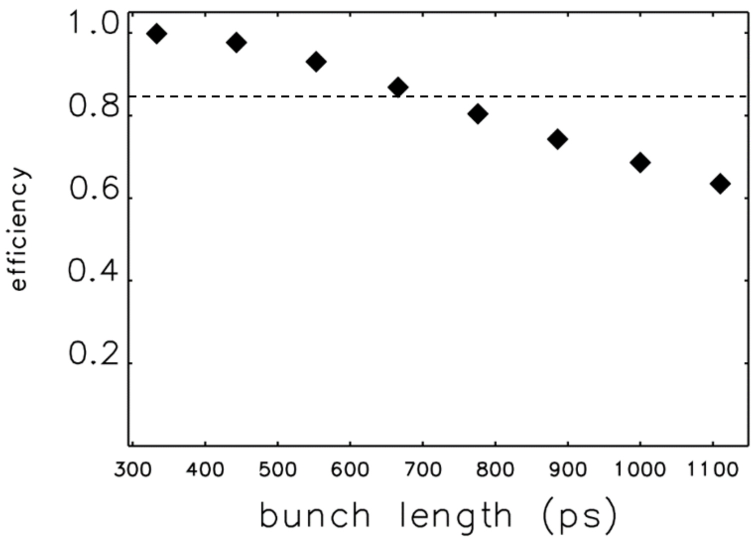
[1] W. Bruns. The GdfidL Electromagnetic Field simulator.



Simulation results

- Predicted efficiency is very good up to ~10 nC injected charge
- Predicted transmission begins to drop at higher charge
  - Most losses occur in first ~500 turns
  - Many particles lost on the horizontal aperture at high dispersion locations
- Beam loading is biggest contributor to simulated losses at high charge
- PAR bunch length blowup results in some particles not being captured in RF bucket
  - Left plot shows efficiency with blowup, but no other collective effects
- Small (~3-5%) losses due to vertical beam size blowup in PAR



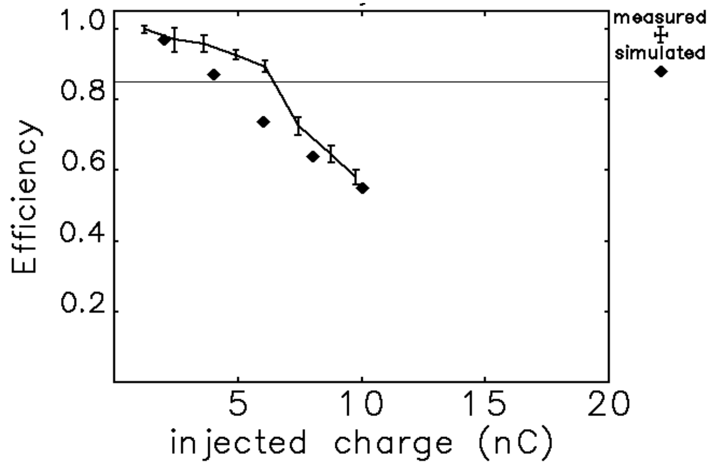


Simulated injection efficiency

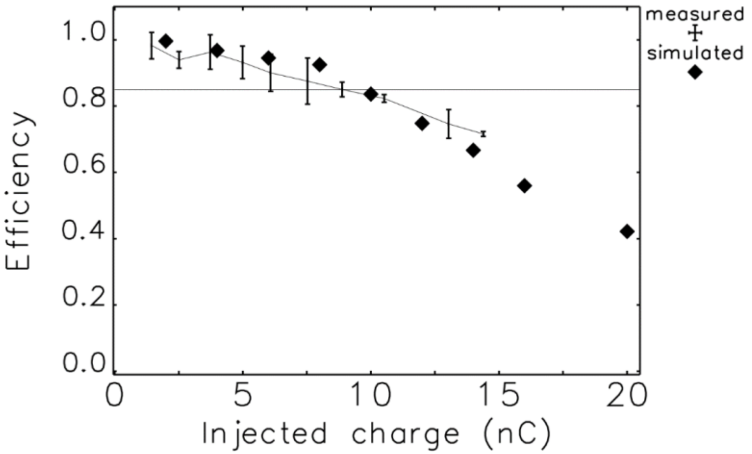
- Simulation matches measured injection efficiency for both lattices
- Maximum surviving charge in low emittance lattice is ~5 nC. This lattice has non-zero dispersion in the straight sections, which causes two problems [1]:
  - Closed orbit depends on energy offset (which varies shot-to-shot)
  - Synchro-betatron coupling (due to dispersion in RF cavities)
- Original lattice injection efficiency is > 85% up to 10 nC

[1] J. Calvey et al. WEA1CO03, *Proc. NAPAC16*.

Booster Efficiency: low emittance lattice



Booster Efficiency: original lattice



Beam loading

- The large shunt impedance of the booster cavities presents many challenges for beam-loading
- At 20 nC, beam loading voltage at resonance is 1.4 MV
  - Desired injection voltage is 600 kV.
- The beam-induced voltage builds up quickly since the cavity time constant is only 18 μsec (15 booster turns)

Booster has four 352-MHz, 5-cell LEP-style rf cavities.

Table 1: Nominal Booster cavity parameters

	Single Cavity	Total 4 Cav.
$(R/Q)_a$	1400 Ω	5600 Ω
Q_o	38,500	38,500
Present Q_L	~20,000	~20,000
Loaded $R_a{}^*$	28 MΩ	112 MΩ

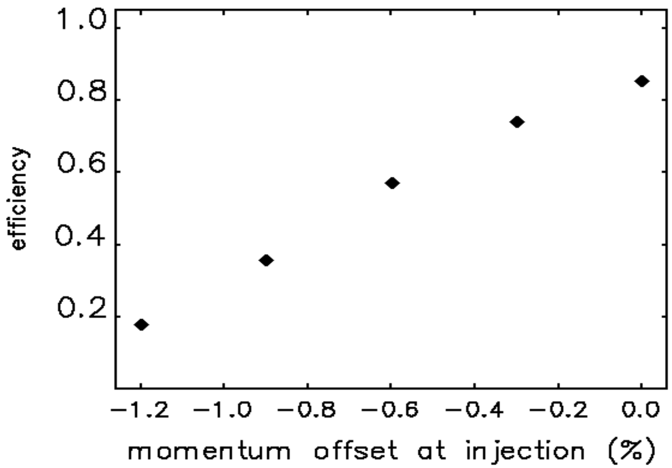
$^* \; R_a \equiv V^2/P$

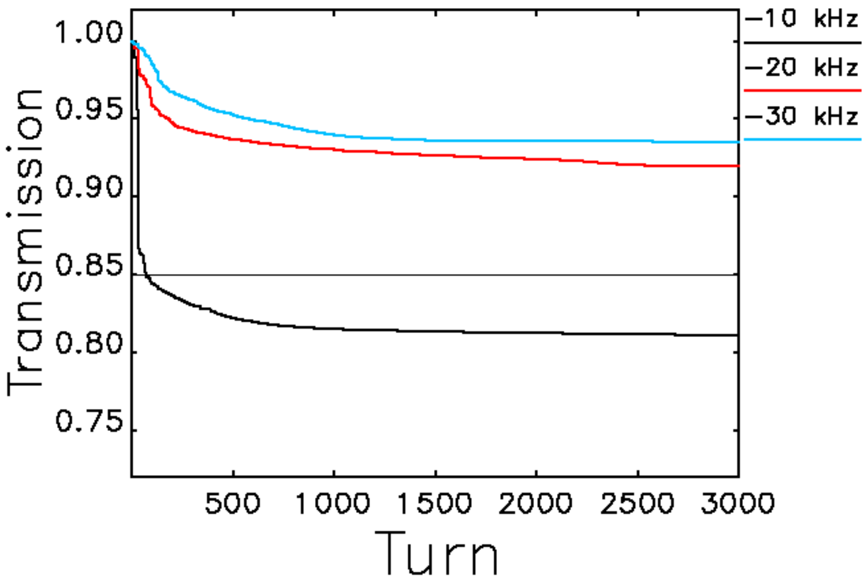
Injection vs extraction

- Rf requirements are very different at injection and extraction
- Injection:
  - Want to mitigate beam loading by detuning cavities
  - Optimal detuning: -27 kHz
  - Want to injection on-momentum to maximize injection efficiency
- Extraction:
  - Want to be near resonance to minimize power requirements
  - Optimal detuning: -2 kHz
  - Want to extract off-momentum (by at least -0.6%) to meet emittance requirements for injection into storage ring
- Plan to change momentum offset by changing frequency along ramp

Preferred solution: dynamic tuning

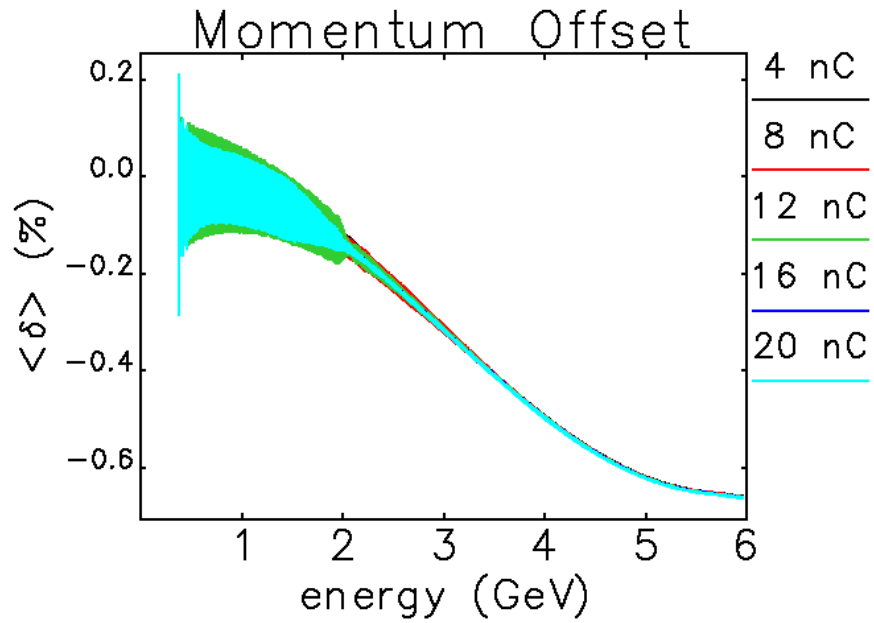
- Inject on-momentum
  - Moves beam away from horizontal aperture: improves transmission
- Detune cavities by 20 – 30 kHz at injection
  - Reduces beam loading: further improves transmission
- Achieve injection efficiency goal with -20 kHz (or more) detuning
  - Assumes PAR bunch length blowup is cured. If not, maximum efficiency is ~85%
- Sweep cavity frequency along ramp to bring cavities near resonance at extraction
  - Requires 50 kHz tuning range (20 kHz for frequency ramp + 30 kHz detuning)
  - Dynamic tuner design (ferrite) is under development

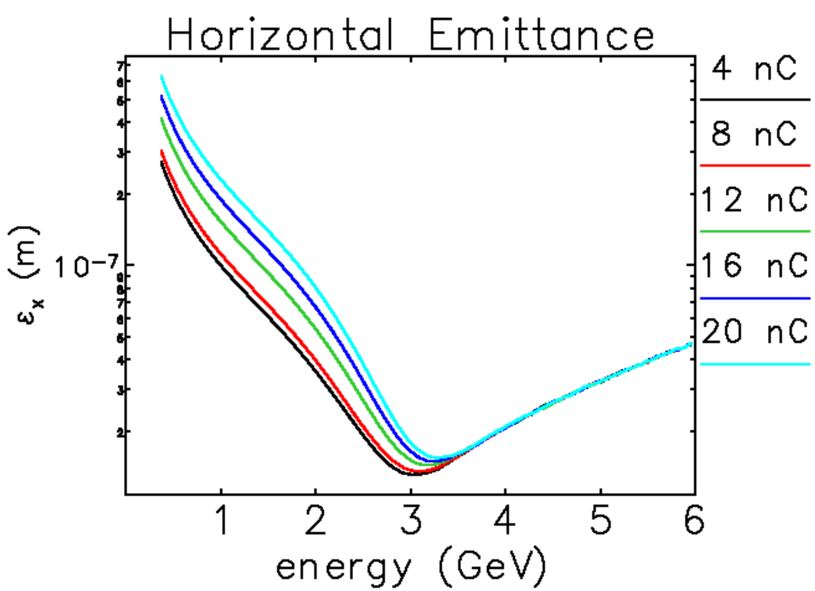


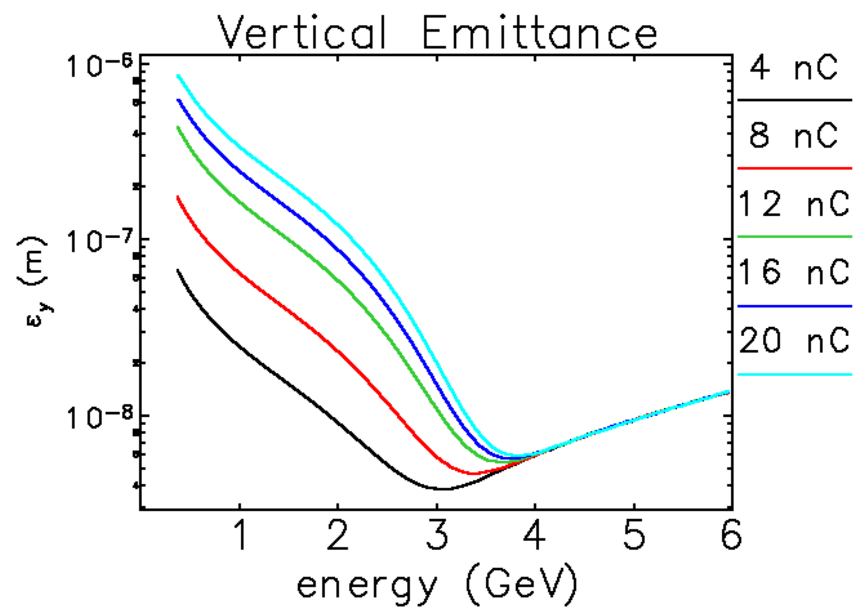


Full ramp simulations

- Simulations using ILMATRIX
  - Includes impedance, but not beam loading
  - Includes frequency ramp
- No transverse instability is expected up to 20 nC
- No growth in emittance or energy spread
- Meets emittance requirements for storage ring injection (ε_x=50nm, ε_y=16nm)







Summary

- High charge operation of the APS injectors has presented many interesting challenges
- PAR:
  - Biggest issue is bunch length blowup / instability
  - Plan to investigate this with a combination of modeling and improved diagnostics
  - Transverse blowup due to ions may have some effect on efficiency, mitigation options exist if necessary
- Booster:
  - Meet transverse emittance requirements by running off-momentum
  - Injection efficiency issue has been studied with simulations
  - Beam loading looks to be the most important factor at very high charge
  - Plan to mitigate this with dynamic tuning + frequency sweep, though other options are available

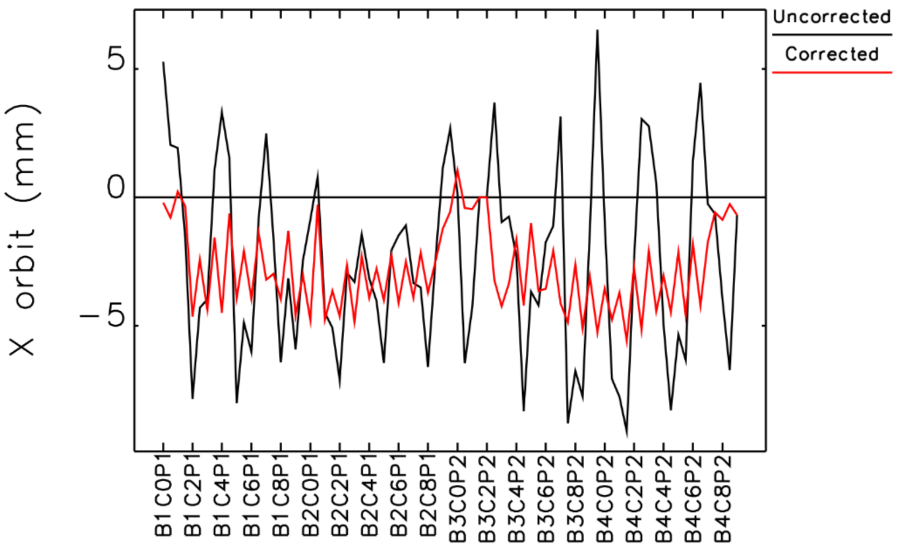
Thanks for your attention!

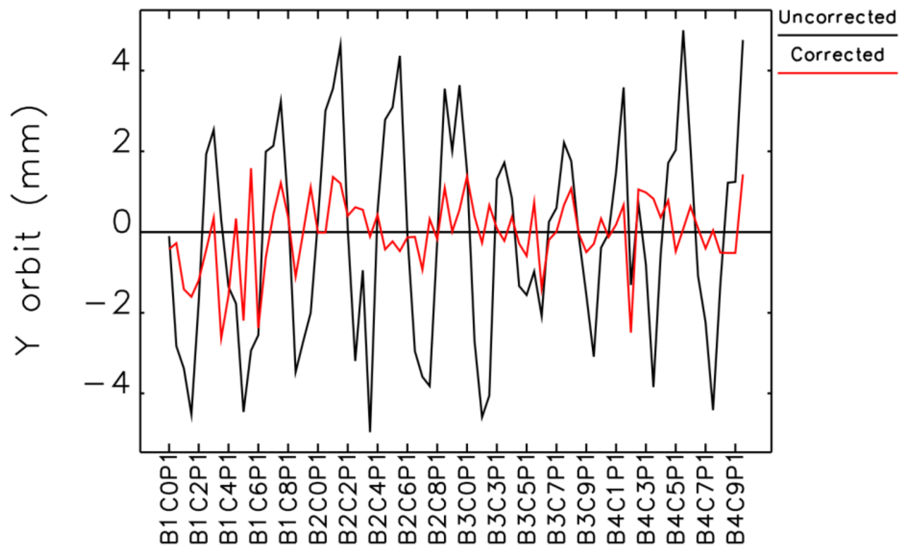
Backup slides

Booster orbit corrected over cycle using new BPMs

- Orbit corrected over the Booster cycle using new BPMs and corrector ramps. One (of ten) time slots shown.
- Rms orbit error is reduced significantly.
- Injection dynamics are improved with corrected orbit: 100% eff at low charge, and ~1 nC higher charge limit (including PAR rf tuning).
- LOCO measurements and analysis are ongoing. The need for lattice correction will be evaluated; implementation would require shunts or small power supplies.

Addresses #2908





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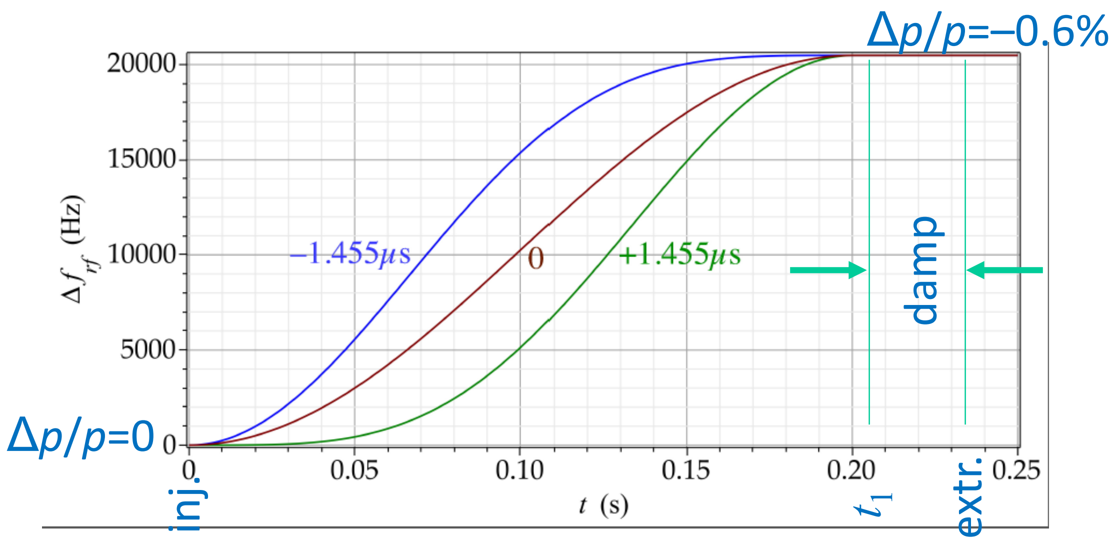
Booster-storage ring injection synchronization concept

- Beam transfer happens when the Booster bunch coincides in time with the storage-ring (SR) bucket to be filled and the energies match.
- The Booster rf follows a program that ensures this for a given SR bucket while moving the momentum of the beam in the desired way.

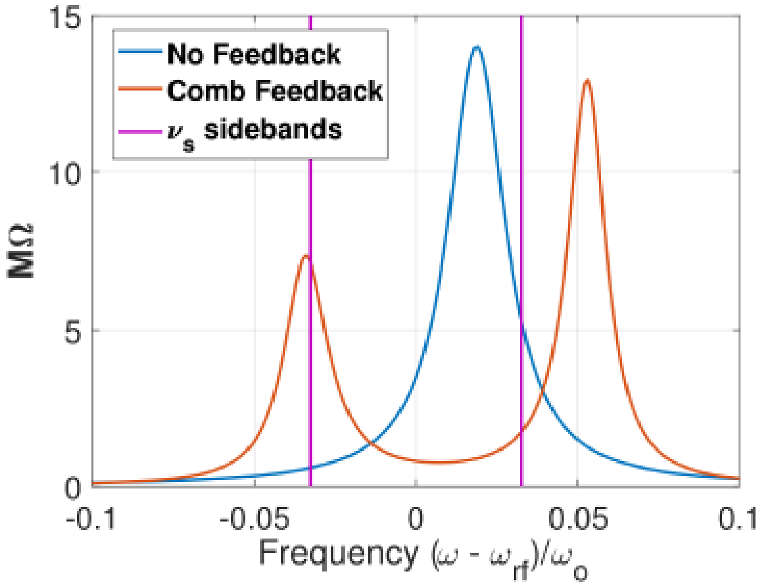
- A $(1\text{-}\cos(\pi t/t_1))$ component to change momentum
- A $(1\text{-}\cos(2\pi t/t_1))$ component to adjust path length (phase).
- Each SR bucket gets its own Booster rf program
- Graph shows the shortest and longest path through the Booster
- No. of turns in Booster varies.
- Tuning of RF cavities needs to follow

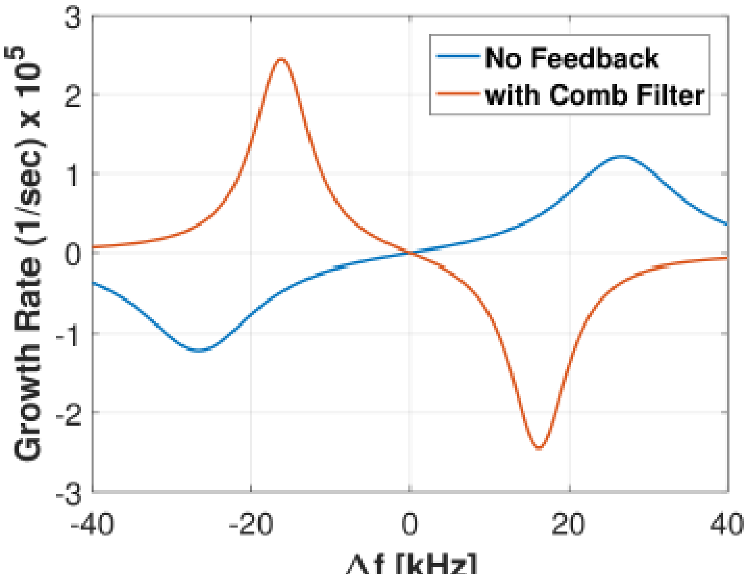


U. Wienands

Alternate scheme: comb filter

- Sweep booster frequency, keep tuners fixed
  - Detuning will go from ~+20 kHz to +2kHz
  - Robinson unstable
- Comb filter modifies the cavity impedance, provides damping when cavity is tuned to the “wrong” side for Robinson stability
- Other options, including direct RF feedback and feed-forward, are also under investigation
- So far, simulations point towards dynamic tuning as the best option





T. Berenc

Other beam loading compensation options

- Fixed frequency and fixed cavity detuning
  - Can improve transmission through detuning, but this requires excessive RF power at extraction (200+ kW/cavity)
  - Requires high power couplers: significant technical risk
- Direct RF feedback
  - Reduces effective impedance seen by beam
  - Also reduces Robinson damping
  - Implementation complicated by differential delay between the injection side and extraction side cavities (which are driven by a single klystron on the extraction side)
- RF feed-forward to counteract transient beam loading
- Preliminary simulations indicate these options are inferior to heavy detuning, but more work is needed