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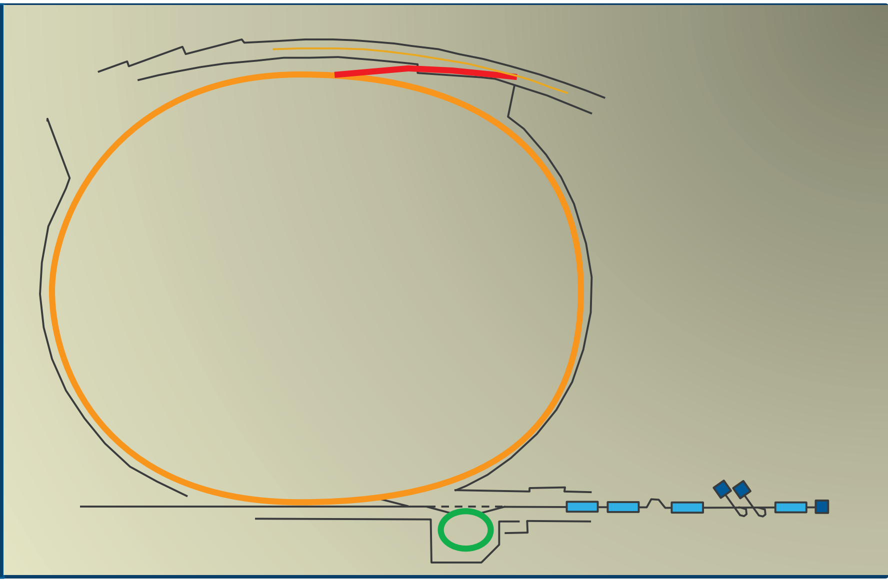
Simulations of Booster Injection Efficiency for the APS-Upgrade



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Outline

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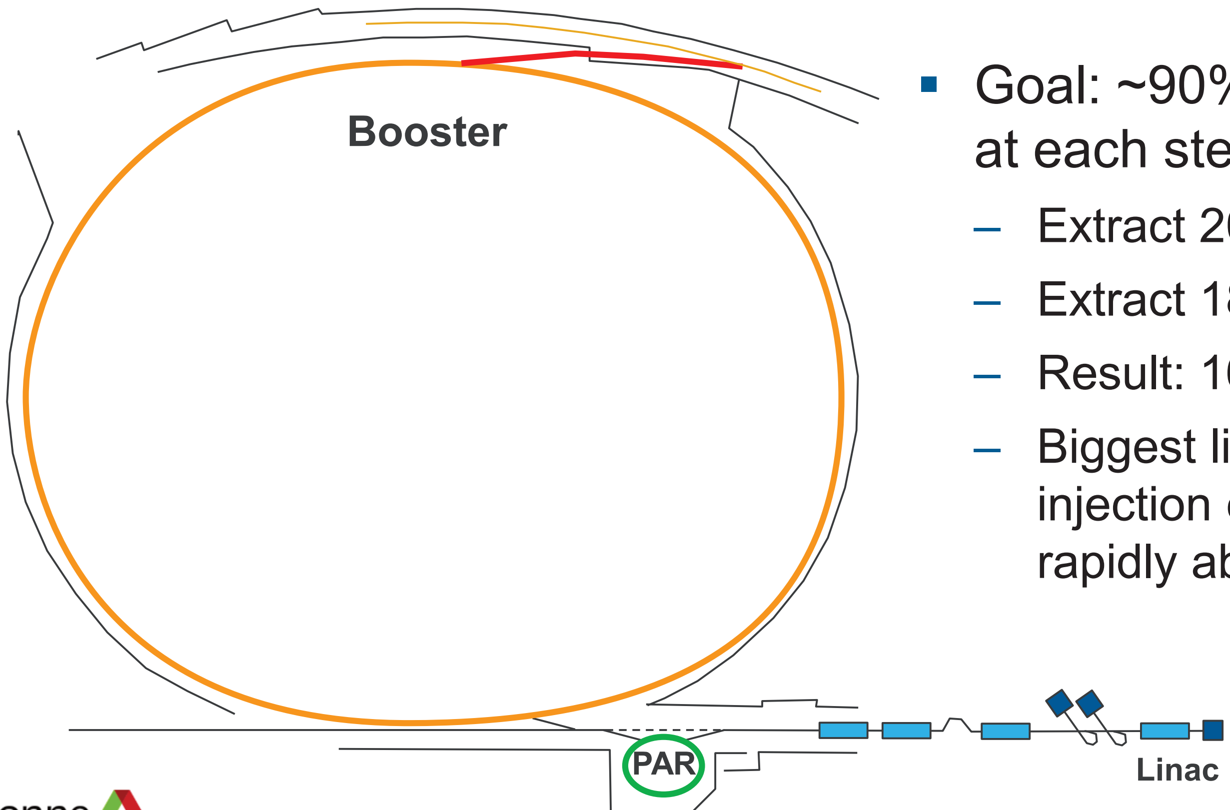
Introduction

- The Advanced Photon Source upgrade will improve the brightness of the APS by 2-3 orders of magnitude
- From APS to APS-U:
  - Horizontal emittance: 3100 pm-rad → 40 – 70 pm-rad
  - Energy: 7 GeV → 6 GeV
  - Beam current: 100 mA → 200 mA
  - Injection: top-up → swap-out
- Two modes of operation:
  - Brightness mode: 324 bunches, 2.5 nC/bunch
  - Timing mode: 48 bunches, 16 nC/bunch
- The injector chain will need to deliver up to 16 nC single-bunch charge for swap-out injection in timing mode
  - Present operation: 2-3 nC
  - Plan to meet APS-U injection requirements through upgrades of injector complex, while keeping basic structure
- An R&D program was recently started to identify limitations to achieving reliable high-charge injection into the storage ring

APS Injector Chain

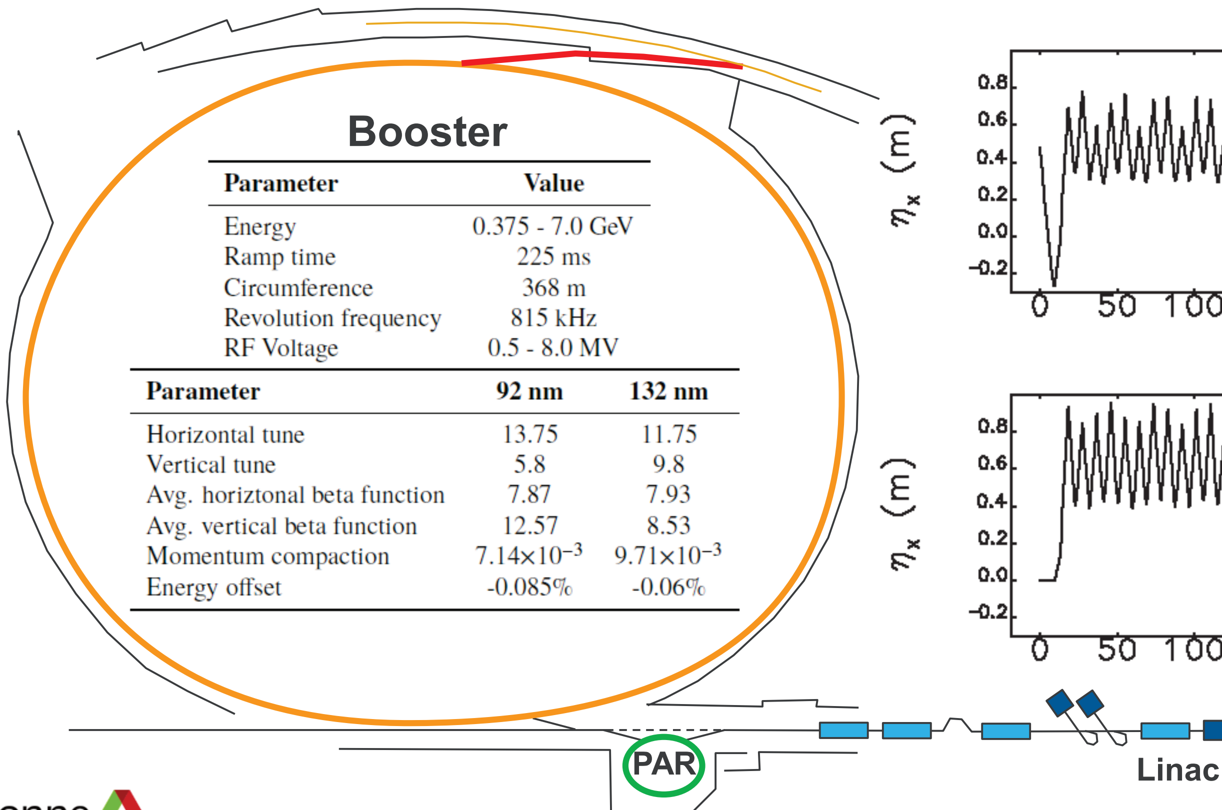
- Linac: accelerate ~1 nC bunches to 375 MeV
  - Rep rate: 30 Hz
- Particle accumulator ring (PAR): accumulate up to 20 linac bunches
  - Rep rate: 2 Hz (1 Hz for upgrade)
- Booster: accelerate bunch to 7 GeV (6 GeV in upgrade)



- Goal: ~90% injection efficiency at each step
  - Extract 20 nC from PAR
  - Extract 18 nC from booster
  - Result: 16 nC in storage ring
  - Biggest limitation: booster injection efficiency dropped rapidly above ~4 nC

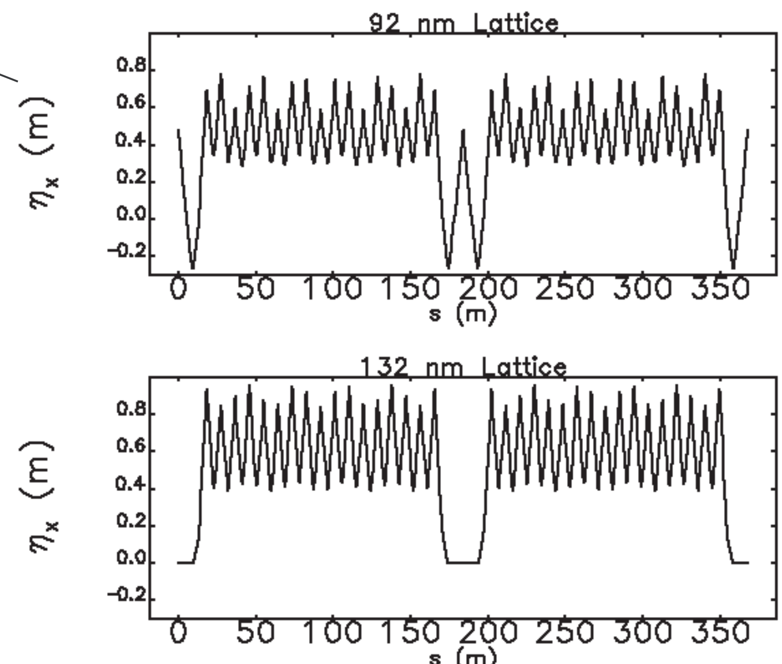
Booster Parameters

- Basic parameters given in table below
- Two lattices: 92 nm (current operation) and 132 nm (original design)
  - 132 nm lattice has zero dispersion through straight sections, lower vertical beta function
- Operated off-momentum (RF frequency does not match circumference)
  - Results in lower transverse emittance, better injection efficiency into storage ring



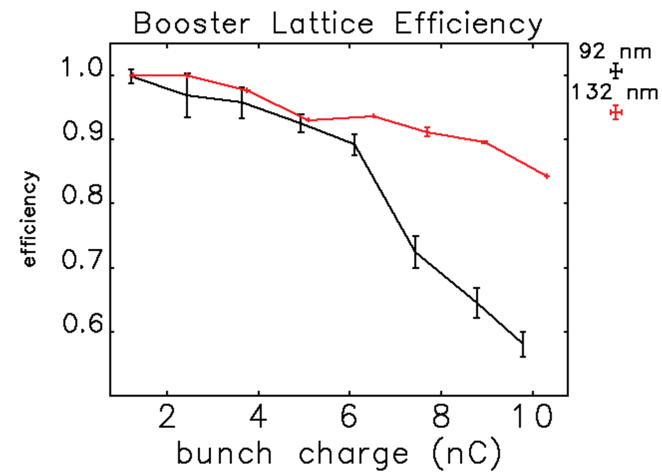
Parameter	Value
Energy	0.375 - 7.0 GeV
Ramp time	225 ms
Circumference	368 m
Revolution frequency	815 kHz
RF Voltage	0.5 - 8.0 MV

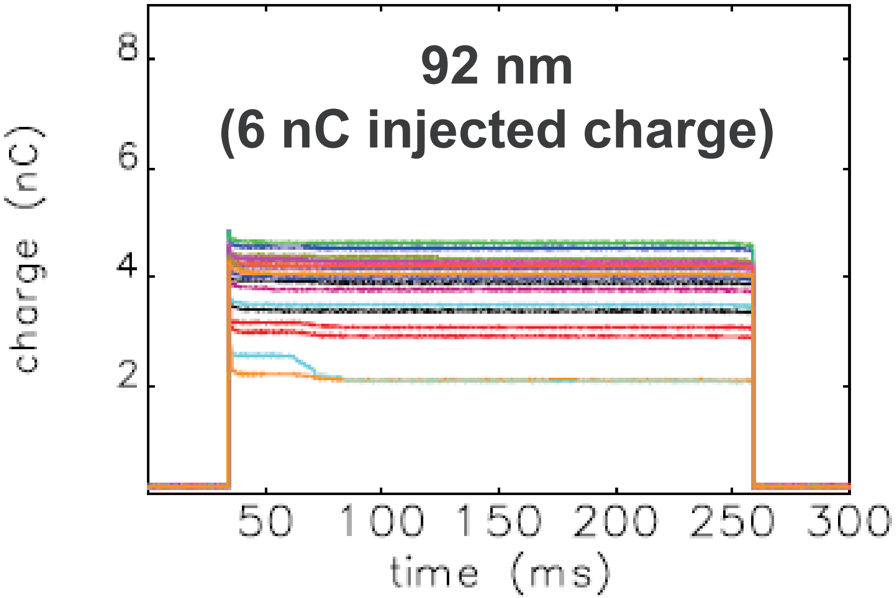
Parameter	92 nm	132 nm
Horizontal tune	13.75	11.75
Vertical tune	5.8	9.8
Avg. horiztonal beta function	7.87	7.93
Avg. vertical beta function	12.57	8.53
Momentum compaction	7.14×10^{-3}	9.71×10^{-3}
Energy offset	-0.085%	-0.06%



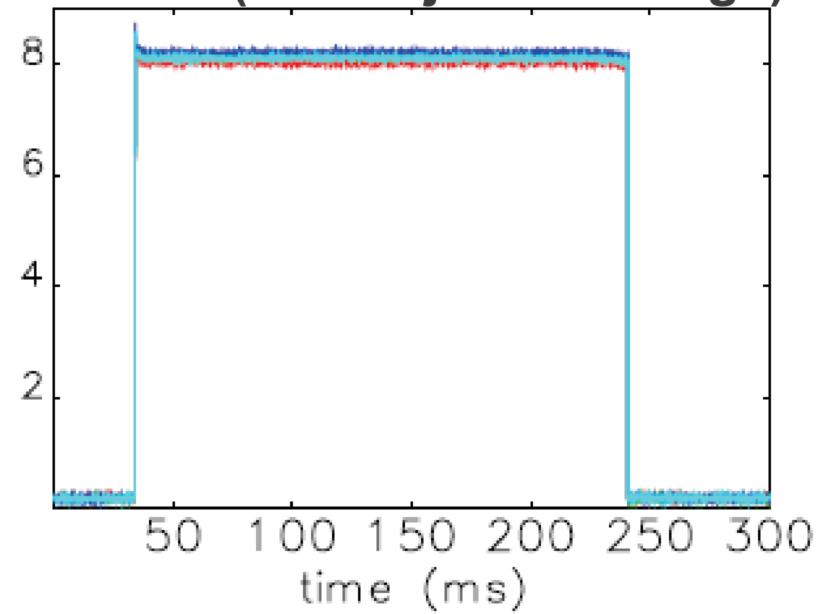
Efficiency Measurements

- 92-nm lattice proved very difficult to work with
  - Significant losses in first few ms of ramp
  - Magnitude of loss varies shot-to-shot
  - Increasing RF voltage at injection made losses worse
  - Maximum extracted charge ~4 – 5 nC
- 132 nm lattice much better behaved
  - 90% efficiency up to 10 nC
  - Very little shot-to-shot variation





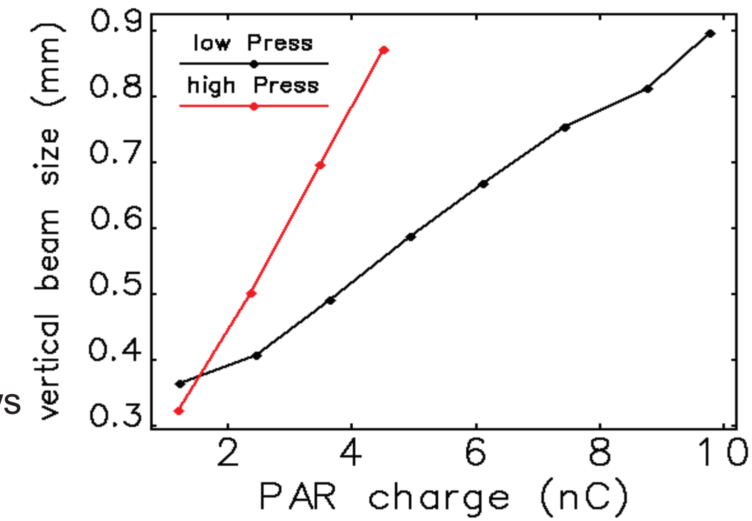
132 nm (9 nC injected charge)



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]
    - Biggest sources: RF cavities, unshielded bellows
  - Beam loading in RF cavities
- Simulation parameters:
  - Transverse beam size measured by flag in PAR-to-booster transfer line
    - Vertical beam size blowup caused by ion in the PAR [3]
  - Bunch length measured by PAR streak camera (~350 ps)
  - 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
    - Based on amplitude of oscillations at horizontal and vertical tune

Measured PAR Vertical Beam Size



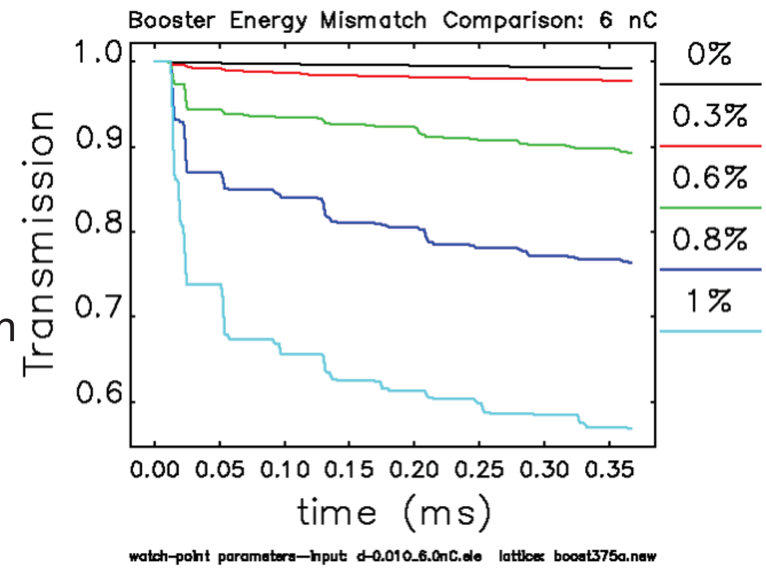
[1] M. Borland. ANL/APS LS-287, (2000).
Y. Wang et al. *Proc. of PAC 2007*, 3444–3446 (2007).

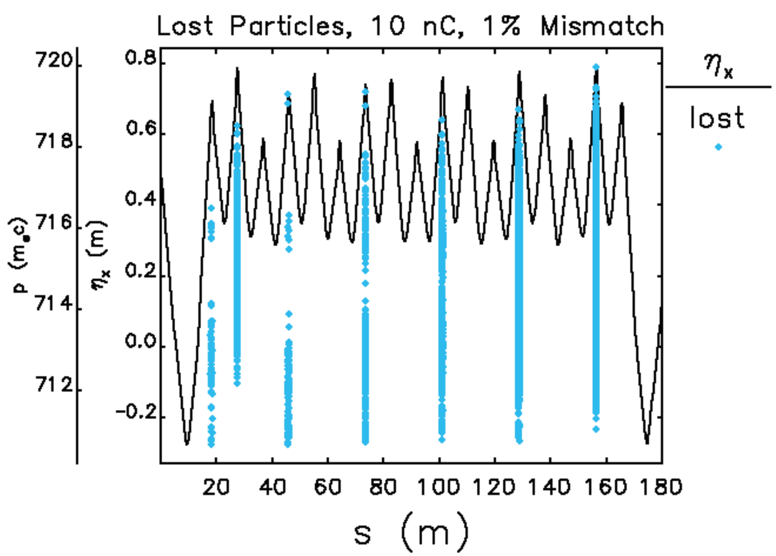
[2] R. R. Lindberg et al. *Proc. IPAC 2015*. TUPJE078.

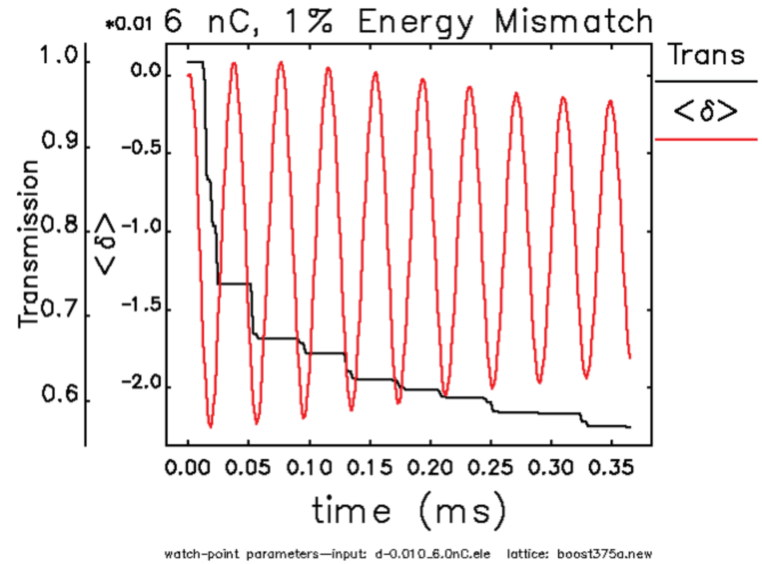
[3] J. Calvey et al. *THPOA14, these proceedings*.

Effect of Energy Mismatch (92 nm lattice)

- Booster efficiency depends strongly on energy mismatch
  - Losses correspond to large negative energy deviation
  - Particles lost at locations with large dispersion, on inboard side of horizontal aperture
  - Increasing RF voltage reduces efficiency, since it increases the amplitude of particles' energy oscillations

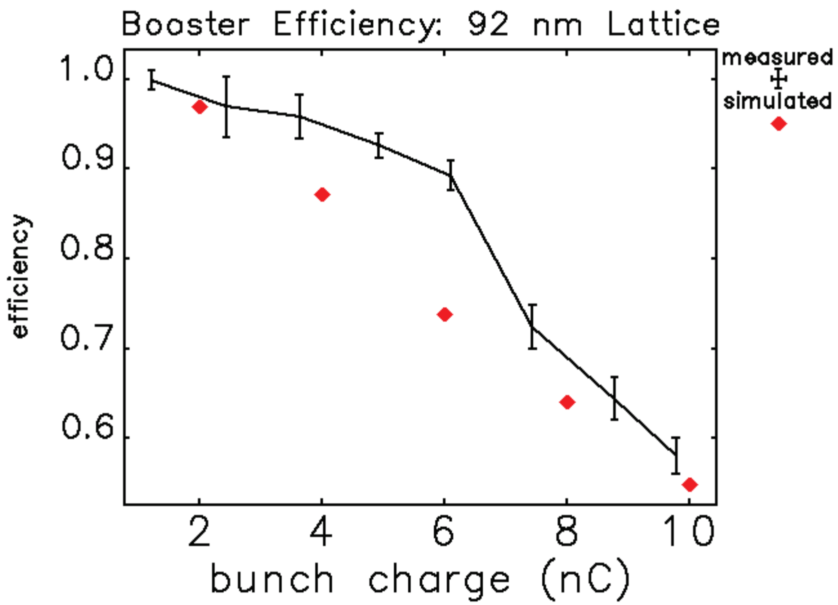


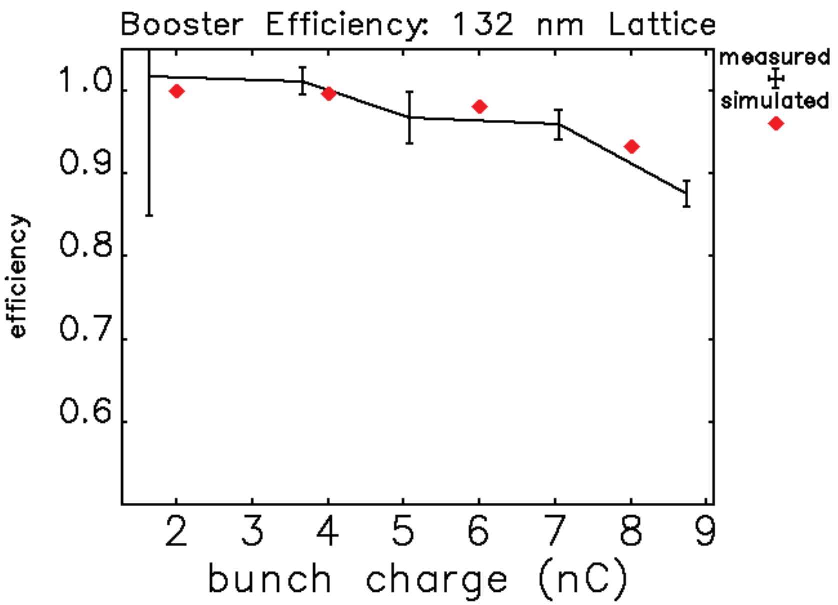




Lattice Comparison

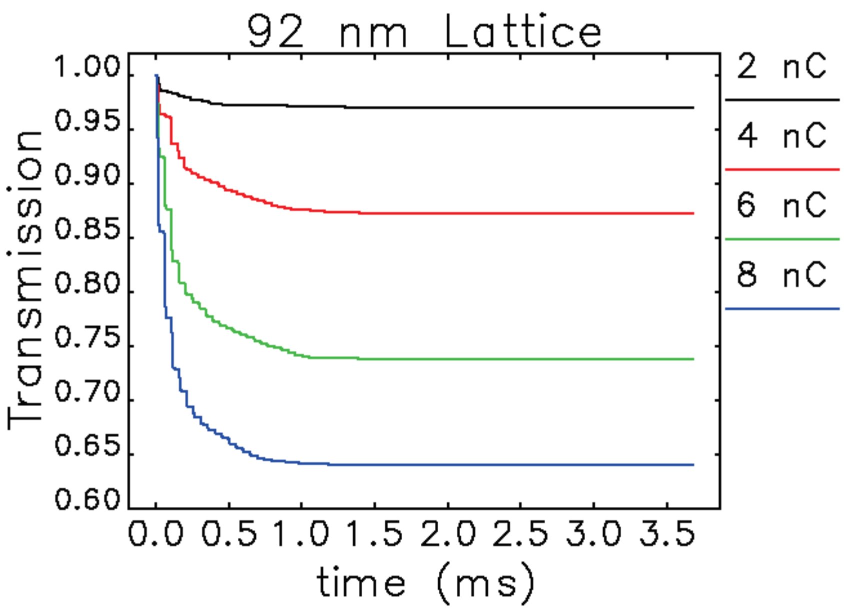
- Simulation is consistent with measured data
  - 92 nm lattice shows charge dependent loss
    - Maximum surviving charge ~5 nC
  - 132 nm lattice efficiency is > 90% up to 9 nC

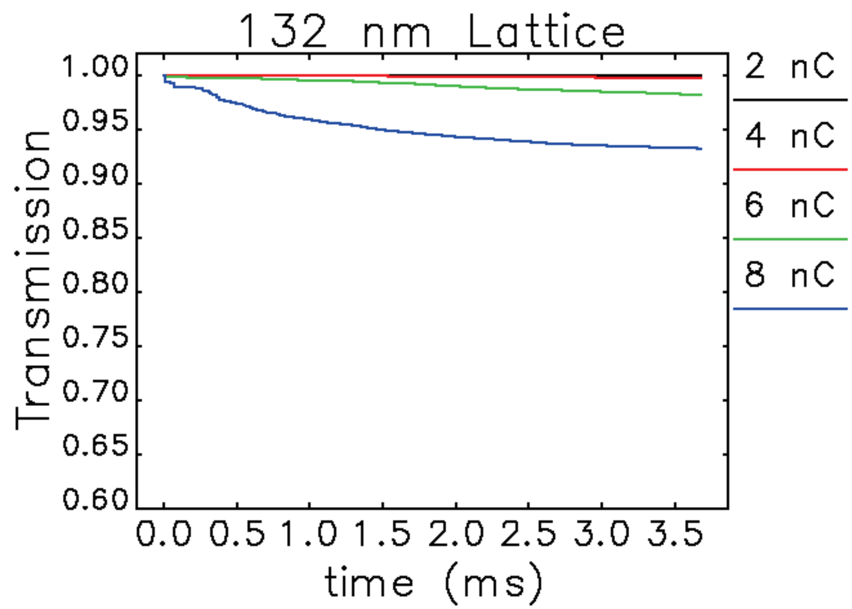




Lattice Comparison

- Simulation is consistent with measured data
  - 92 nm lattice shows charge dependent loss
    - Maximum surviving charge ~5 nC
  - 132 nm lattice efficiency is > 90% up to 9 nC
- Most losses in 92 nm lattice occur in first ms

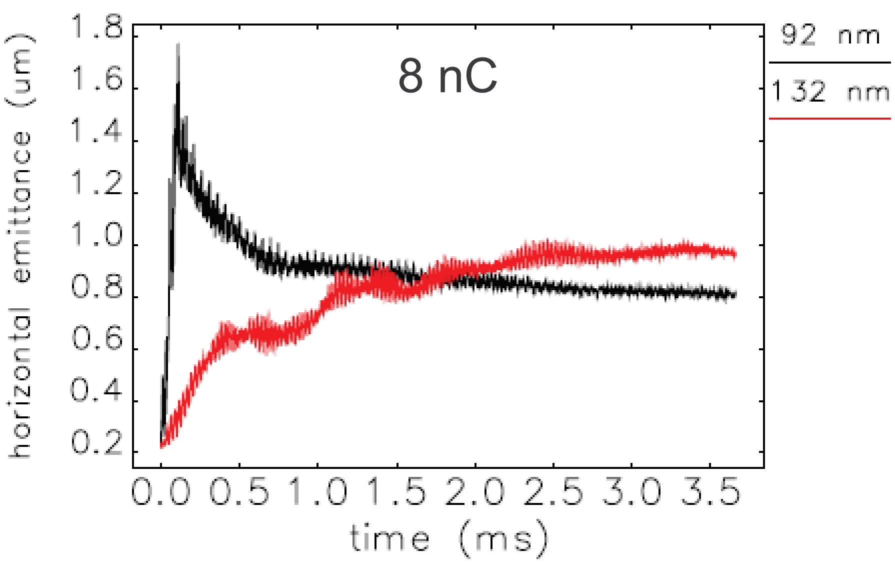


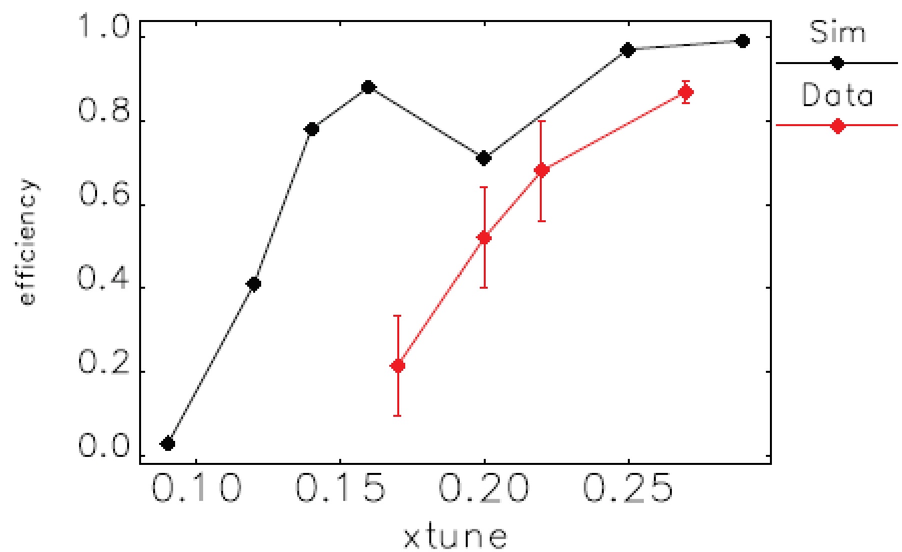


Synchro-betatron Coupling

- 92-nm lattice has nonzero dispersion through the RF cavities
  - This can lead to synchro-betatron coupling [1]
  - In the presence of collective effects, this can cause a charge (and tune) dependent emittance blowup [2,3]
  - Simulation shows fast horizontal emittance blowup in the 92 nm lattice
- 92 nm lattice also much more sensitive to tunes
  - Efficiency drops as horizontal tune moves toward synchrotron tune (0.025)
  - Observed in both data and simulation (more severe in data)
  - Not seen in 132 nm lattice

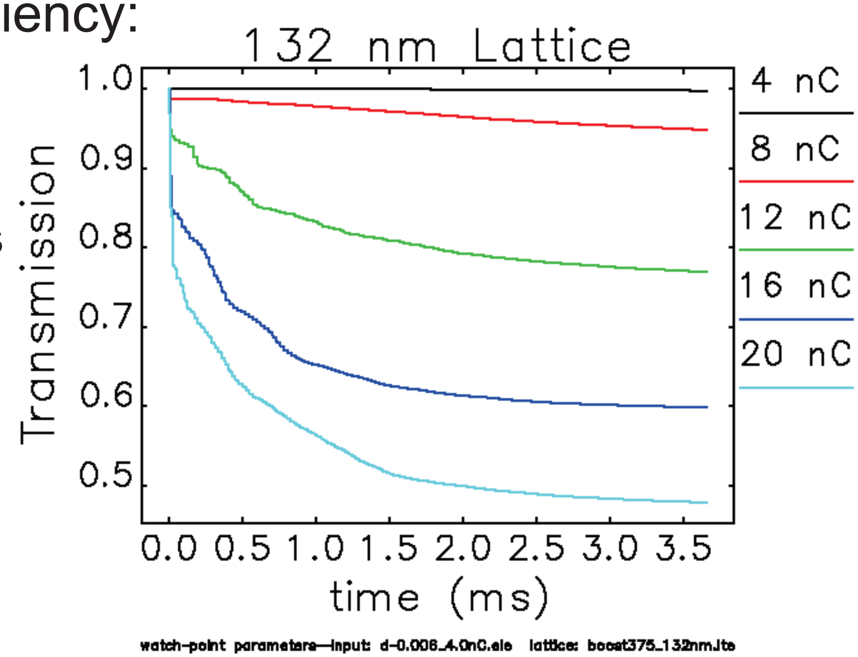
[1] A. Piwinski. DESY 93-189, DESY (1993).
[2] J. Hagel et al. CERN/LEP-TH/88-57, CERN (1988).
[3] K. Nakajima et al. *Part Accel*, 27:77 (1990).





High Charge Simulations

- Simulate high charge bunches in 132 nm lattice
  - Increase RF voltage to compensate beam loading
  - Extrapolate injected beam size from measurements
- Simulation predicts 132-nm efficiency will begin to drop after ~10 nC
  - Some vertical losses due to vertical beam size blowup
  - Transient beam loading is significant
- Options for improving high charge efficiency:
  - Mitigate beam loading through RF feedback or dynamic tuning
  - Reduce impedance by shielding bellows
  - Run booster on-energy at injection
  - Improve dipole ramp stability
  - Mitigate PAR ion effect through improved pumping or clearing electrodes



Summary

- Charge loss shortly after booster injection has been studied with ELEGANT simulations
- Simulations indicate losses are mainly on the horizontal aperture at high dispersion locations, due to energy oscillations (caused by an RMS mismatch between the injected beam and booster)
- This effect may be worse in the 92-nm lattice due to synchro-betatron coupling caused by nonzero dispersion in the RF cavities
- 132-nm lattice performs well (in measurements and simulations) up to 10 nC
- We are working on anticipating and mitigating potential issues at higher charge (up to 20 nC)