Booster Space Charge Simulation For proton Beams

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RHIC Retreat

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Tracking with space charge in synchrotrons

Particle In Cell (PIC) model:

- Update space charge potential every time step.
- PyOrbit, PTC-Orbit, Synergia, Micromap, Simpsons-PIC, …

Frozen space charge model:

- Fix the charge distribution and space charge potential at the beginning.
- Keep using the same potential even after the charge distribution evolves, till the next distribution update.
- MAD-X-frozen, Simpsons-frozen, …

	PIC	Frozen
Pros	Follow the change of potential self-consistently.	1. fast 2. Can trace single particle motion
Cons	It is slow. Need many macro particles, e.g. > 1 M	Not accurate when charge distribution changes a lot
comments	Noise due to grids and numerical IBS (Intra Beam Scattering) are issue.	Update of emittance, but not distribution, can be included if reasonable number of macro particles are tracked.
examples	CERN-PSB, SNS, J-Parc RCS, …	CERN-PS, SPS, …

Hybrid Model in Simpsons

1. Track the reasonable number of macro particle (5k to 20k) to reconstruct (only) longitudinal beam profile.
   - First do binning into ~50 longitudinal slices.
   - Fourier decompose each slice.
   - Reconstruct longitudinal profile by taking low frequency contributions (to cut high frequency noise).

2. In Transverse, calculate rms emittance of the entire beam every turn to update the frozen space charge potential. The charge distribution is kept the same, e.g. Gaussian or Waterbag. Then apply space charge kick on macro-particles.

3. Transient behavior of bunch shape can be modelled.

4. No need of many (> 1M) macro particles and keep reasonable CPU time.

Code Features required to Simulate Beams in Booster

1. Coasting beam at injection;
2. Capture by RF before acceleration;
3. Longitudinal charge distribution (therefore peak line density) changes very much. So, need a good 3D code.
4. RF voltage changes throughout the cycle of costing beam, RF capture and energy ramping. So, need to take 1st and 2nd RF voltage profile and relative phase as tables with fine time step.
5. Set tunes (H & V) change throughout a cycle. So, needs to specifying Quad current as a function of time.
6. Need to have different physical aperture at different elements (Bend, Quad and Sext) for accurate beam loss estimate.

All above features, Simpsons either already have, or now added as new features for AGS Booster simulations. Thanks to Shinji Machida!

Simpsons have also been benchmarked very well at J-Parc RCS.

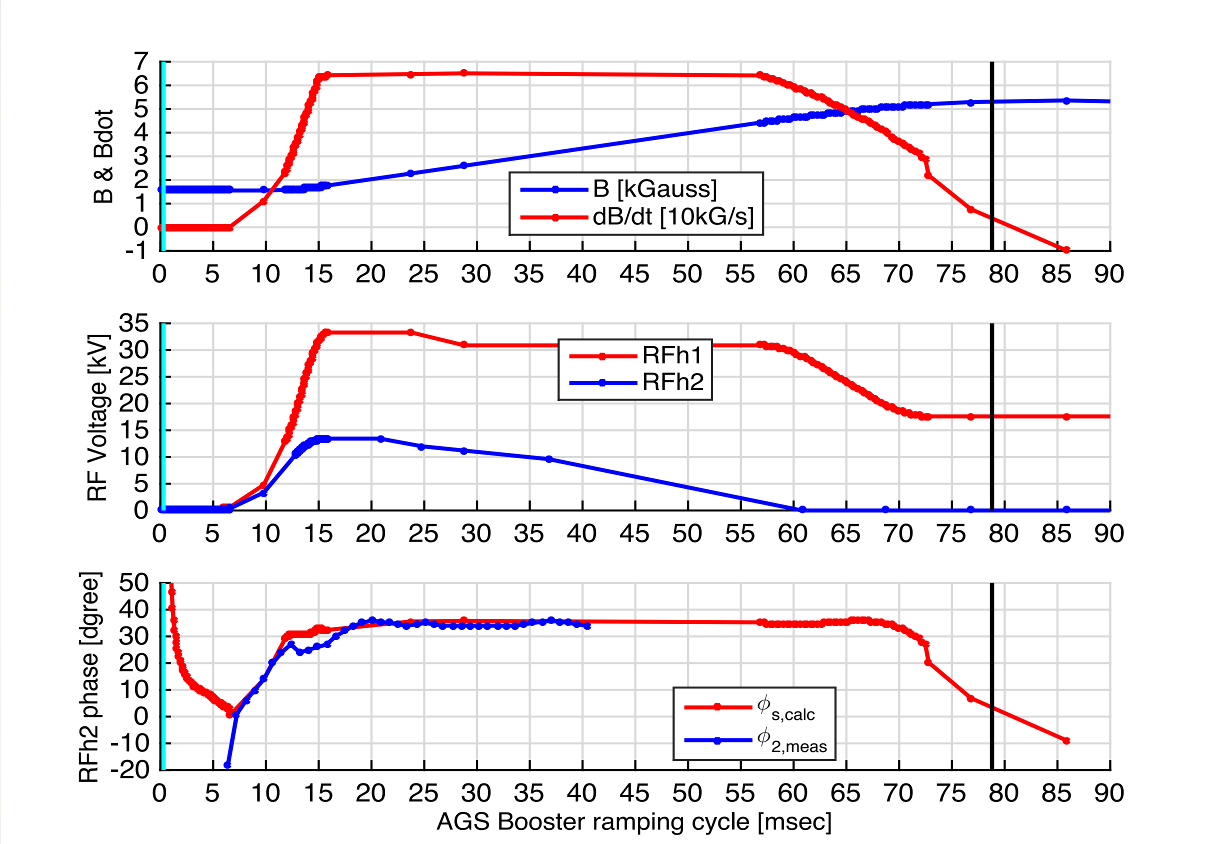
Physical Parameters used in proton Simulations

Table 1: Polarized Protons in Booster

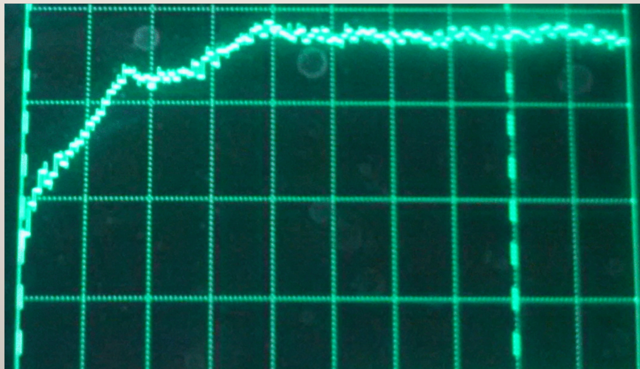
Parameter	Injection	Extraction	Unit
$G\gamma$	2.17500674495	4.5	
W	200.000	1416.76626314	MeV
cp	644.444581326	2160.05810228	MeV
E	1.13827204600	2.35503830914	GeV
$B\rho$	2.14963573675	7.20517826462	Tm
β	0.566160421483	0.917207203761	
γ	1.21315779454	2.50997386012	
η	-0.6362	-0.1159	
h	1	1	
hf	841.166737926	1362.77884657	kHz
R	$201.780/(2\pi)$	$128.4526/4$	m

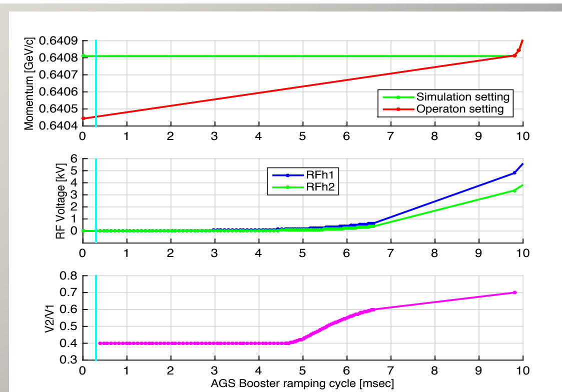
Table 2: Polarized Protons in Booster

Parameter	$G\gamma = 3$	$G\gamma = 4$	Unit
$G\gamma$	3.0	4.0	
W	631.753493427	1155.09533990	MeV
cp	1.25881919359	1.87131840691	GeV
E	1.57002553943	2.09336738590	GeV
$B\rho$	4.19896885328	6.24204631230	Tm
$(B\rho)/\rho$	0.302833548731	0.450182199999	T
β	0.801782621988	0.893927372480	
γ	1.67331590675	2.23108787566	
η	-0.3143	-0.1581	
h	1	1	
hf	1.19123988020	1.32814294910	MHz
R	$201.780/(2\pi)$	$201.780/(2\pi)$	m



All physical parameters as functions of time are taken either from operational settings or from run-time read-backs.

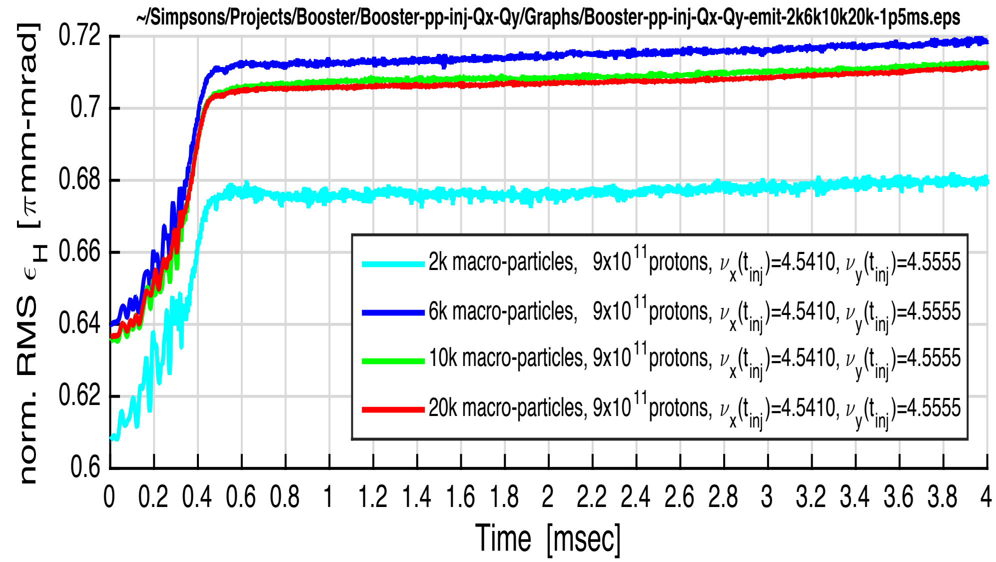


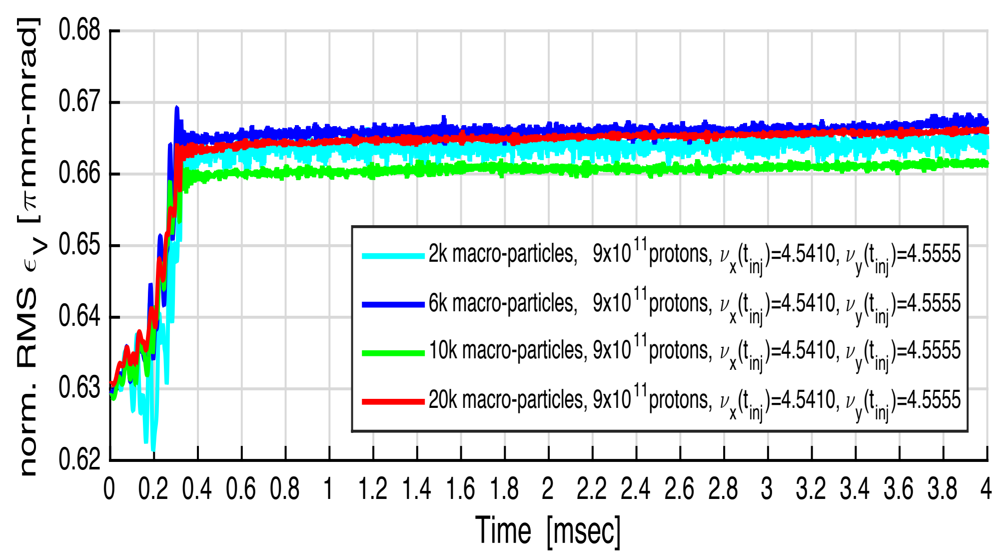


Other Parameters used in proton Simulations

Parameter	Value
H Inj. Emit (95%, norm.)	3.5 πmm-mrad
V Inj. Emit (95%, norm.)	5.5 πmm-mrad
Δp/p (RMS)	6×10^{-4}
Injection Beam Intensity	9×10^{11}
Injection Beam pulse	0.3 msec
Transverse Distribution	4D Gaussian
Stripping Foil Thickness	100μg/cm^2
# of Macro-particles	5,000-20,000

All numerical parameters are validated through test runs.

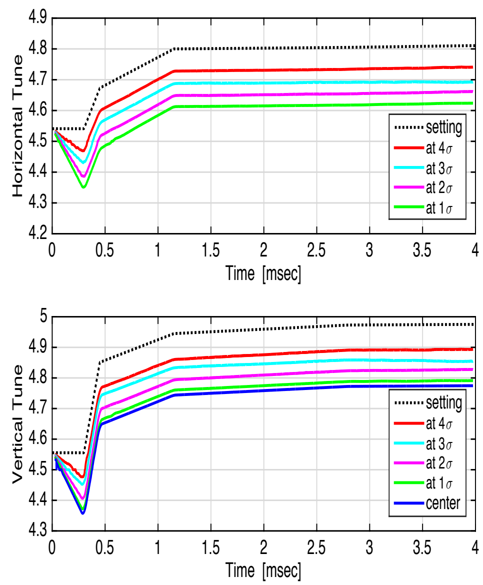




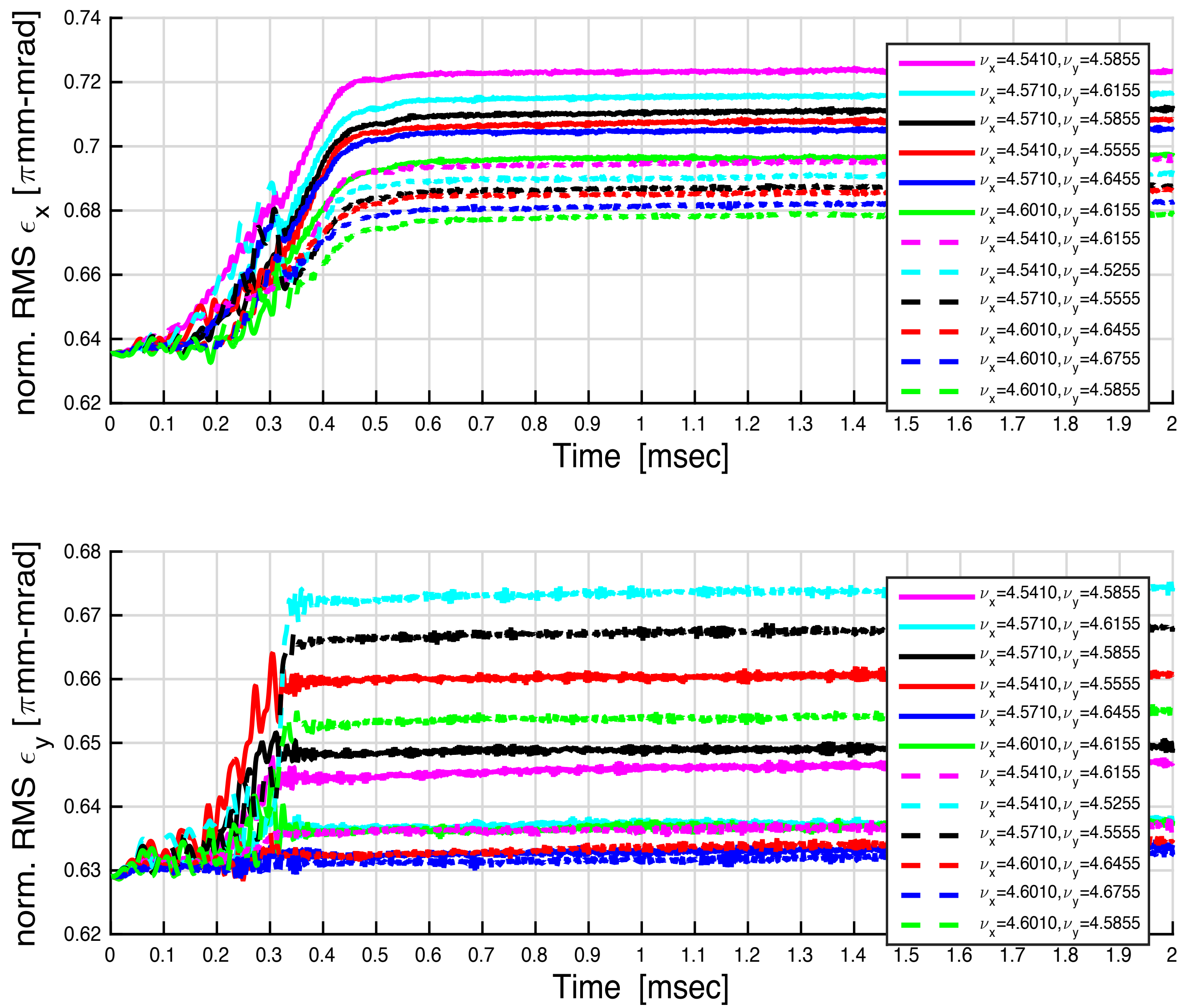
Tune Scan with Space Charge at Injection

Tune scan (Δν =0.03) for Multi-turn injection (the first 0.3 msec)

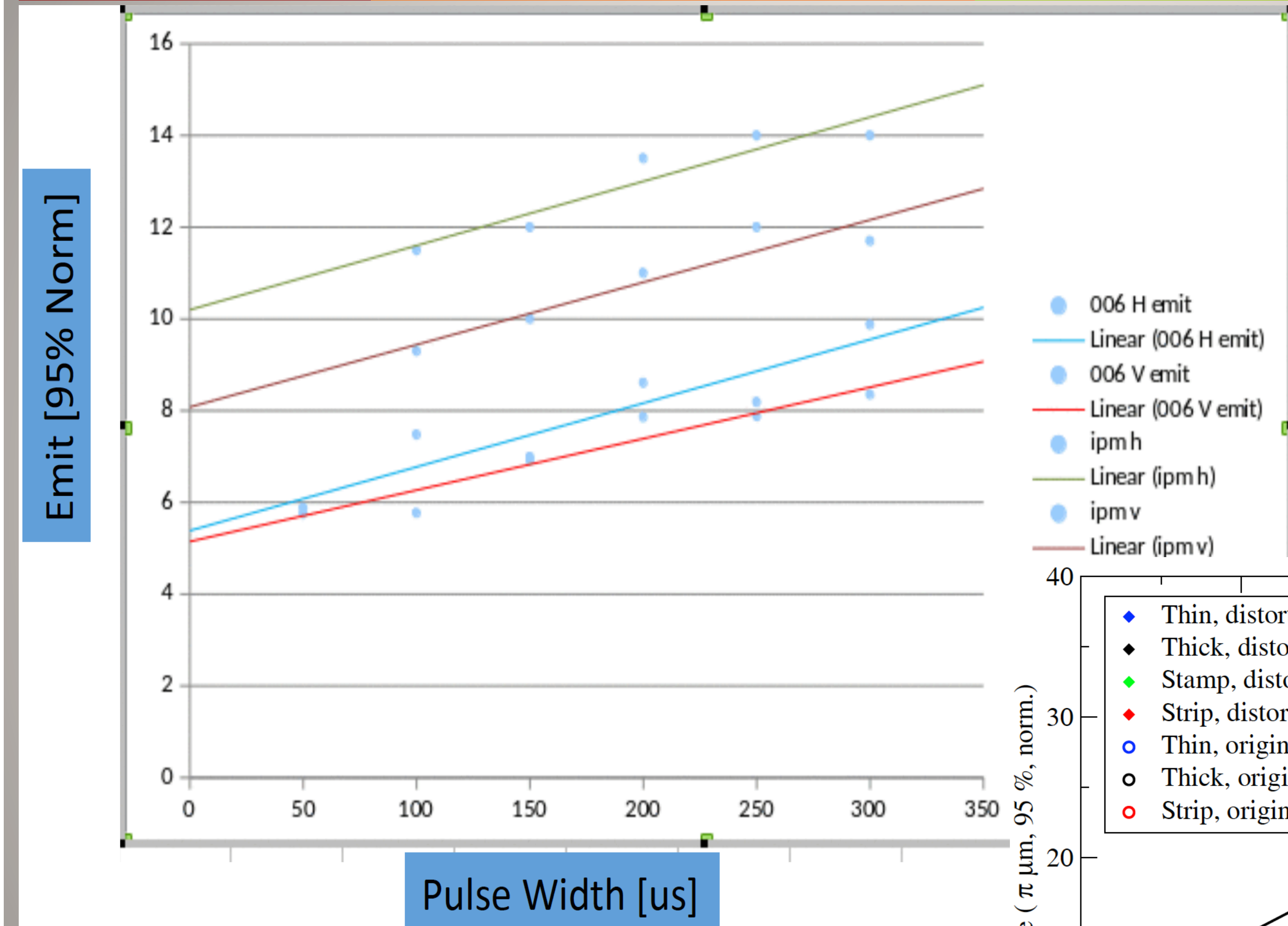
- Coasting beam
- No set tune changes
- No energy ramping
- No RF
- Observe transverse Emittance increase



Optimum:
Qx=4.6010
Qy=4.5855

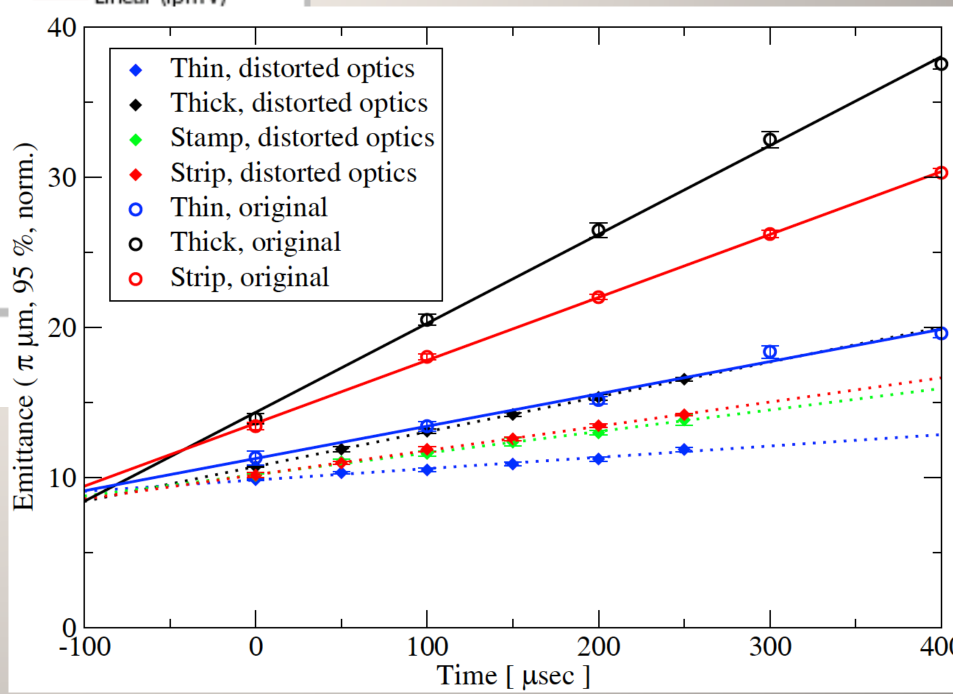


Effects of Charge Exchange Foil



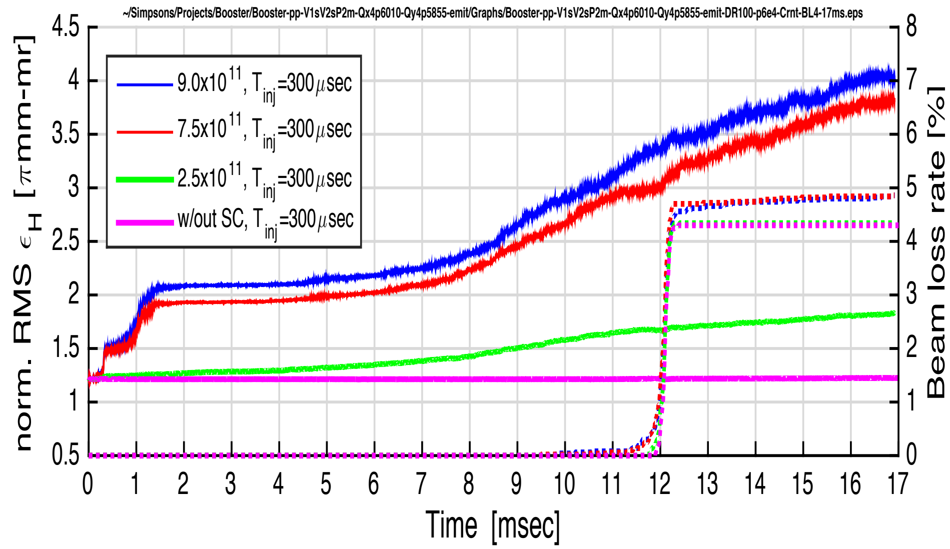
Simpsons is capable of simulating with charge exchange foil and injection bump. But, since we have 2 sets of measurement data that are Booster specific and they agree with each other. So, Effects of foil is accounted using Booster measurement data instead of simulation.

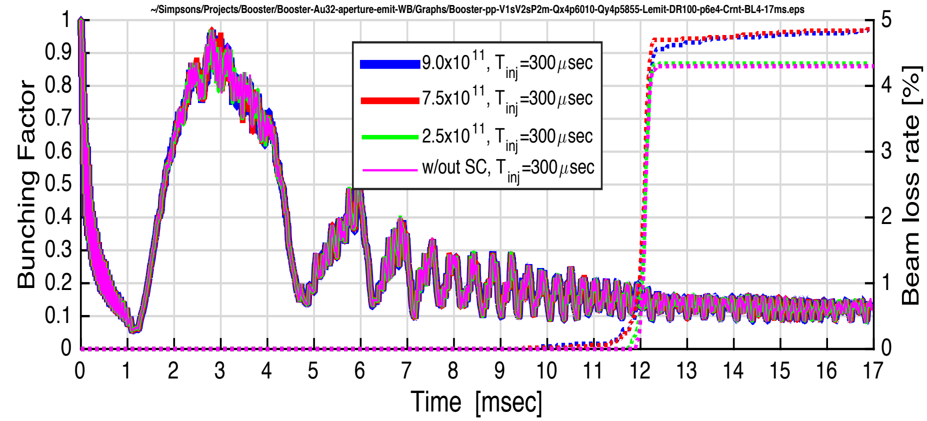
K. Zeno Measurement 2016

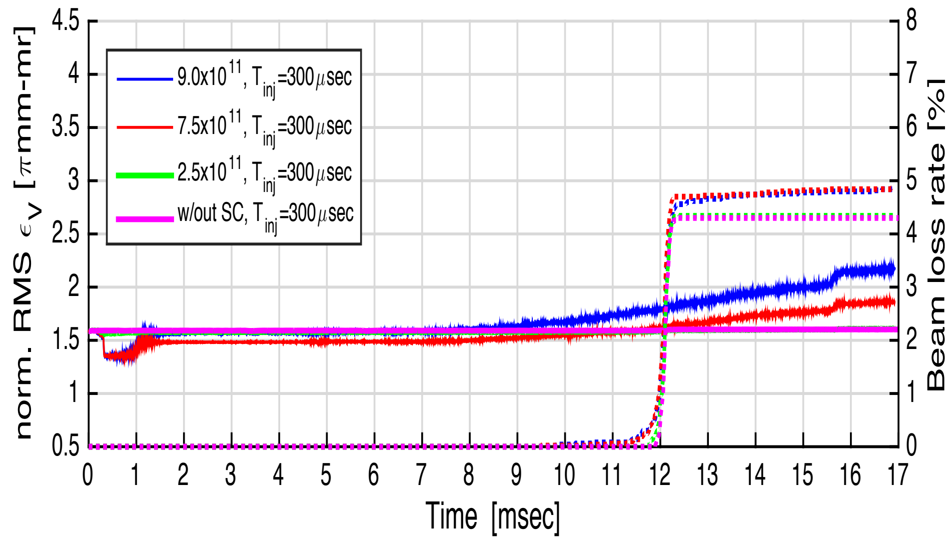


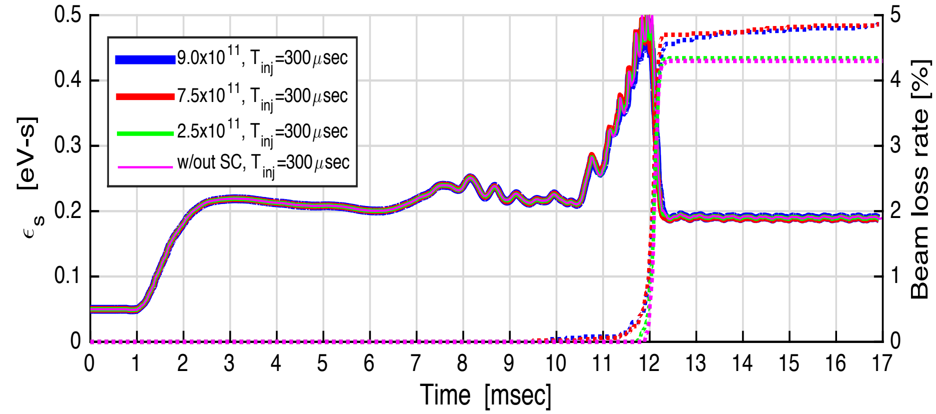
K. Brown measurement 2009

Emittance & Beam Loss vs Beam Intensity









Observation:

1. Transverse emittance growth is largely dependent to beam intensity.
2. Part of the beam are not bunched during RF capture. They are lost longitudinally

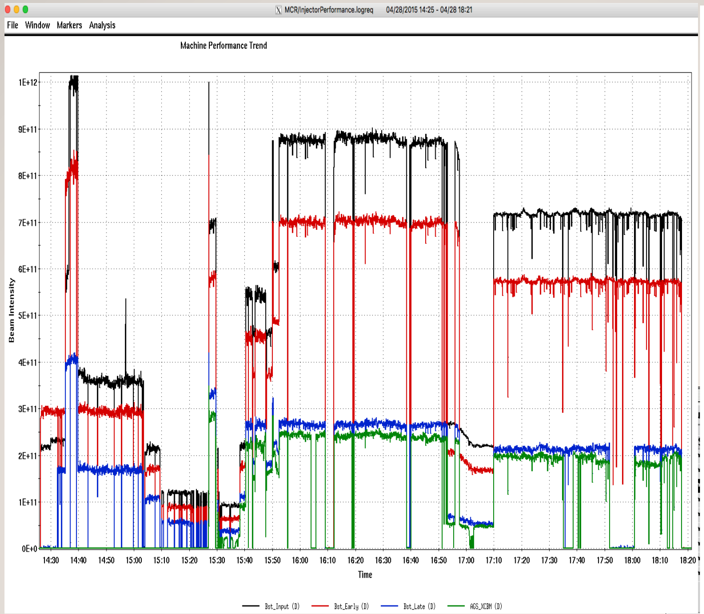
When and Where Beam Gets Lost

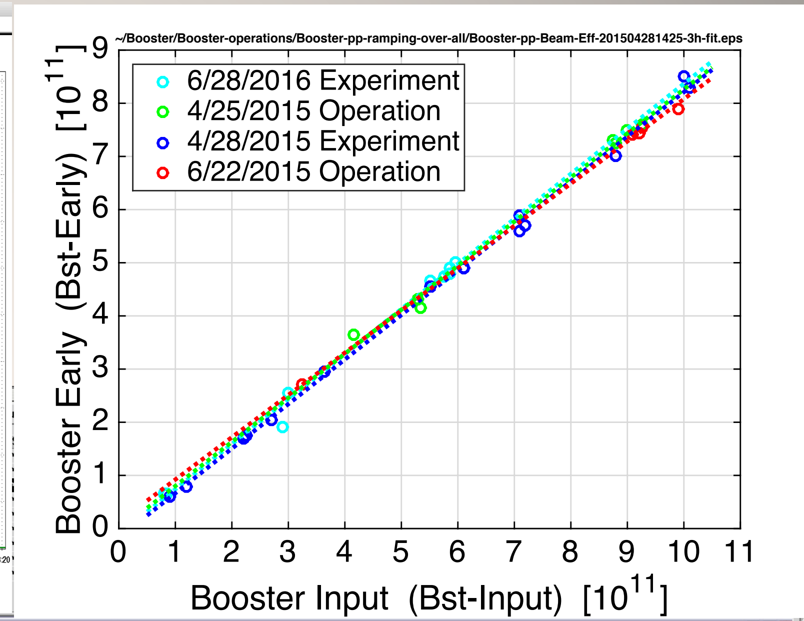
Black: Booster _Input
(in Linac Line, before LTB)

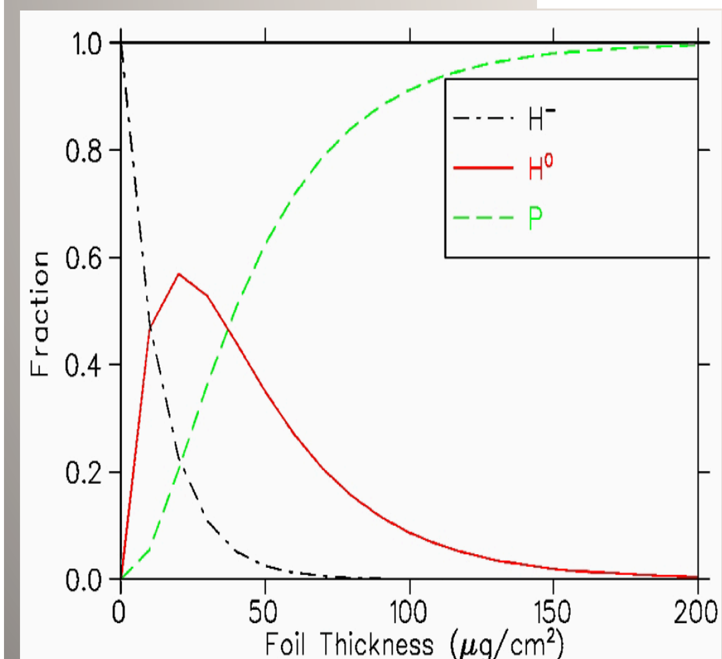
Red: Booster_Early
(at Booster time = 73ms;
1.8ms after 1st turn Injection)

Blue: Booster_Late
(at Booster time = 120ms;
48.8 ms after 1st turn Injection)

Green: AGS_Late
(Late in AGS)





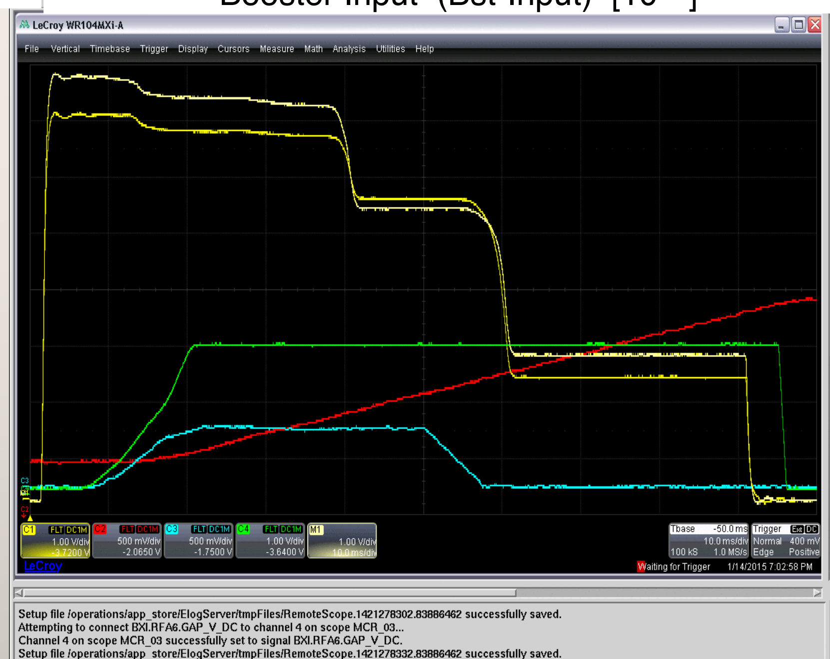


The beam loss from "Booster_Input" to "Booster Early" has a hard minimum:

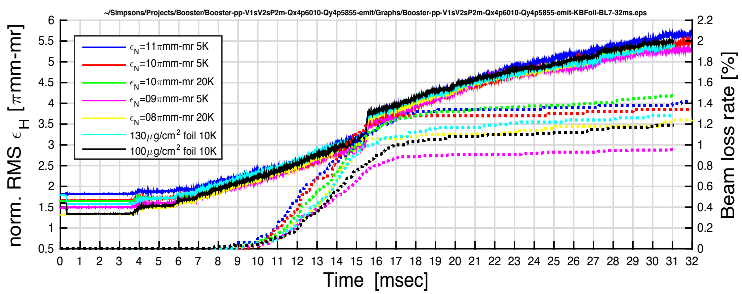
17%

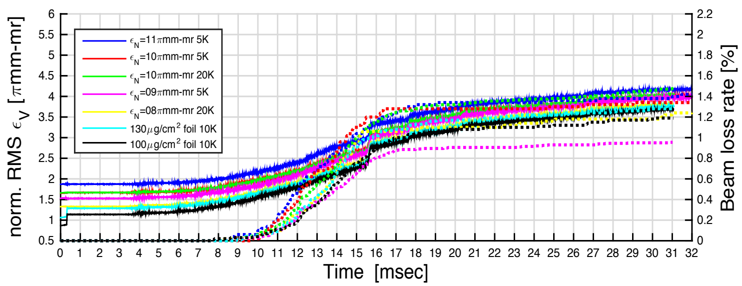
1). 9% loss to H0 on Foil (thickness = 100mg/cm^2)
2). 5+-5% loss in LTB line 3). A few % loss due to injection mismatch

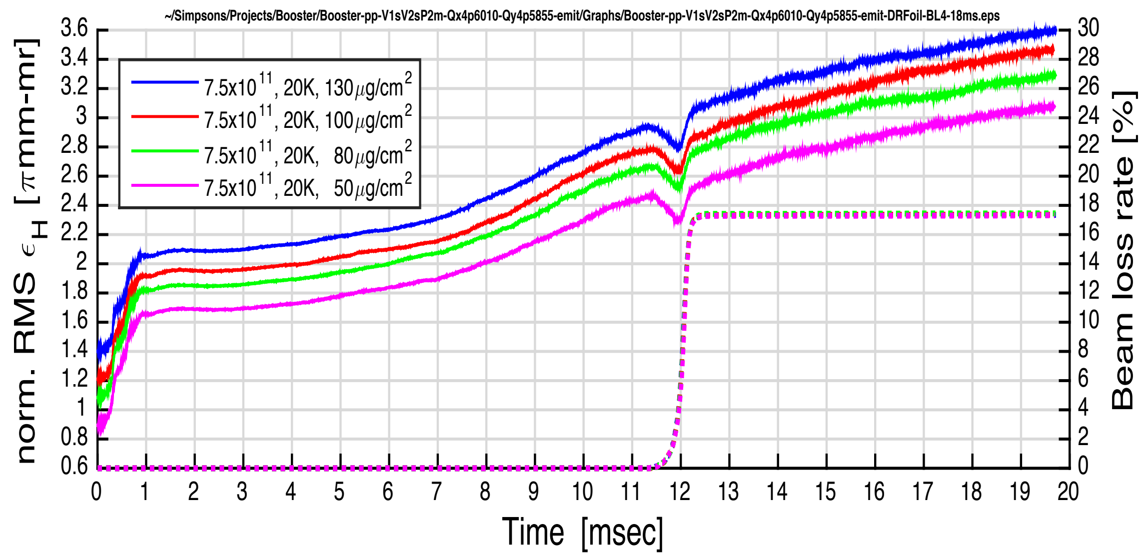
Conclusion:
Booster beam loss is a few %, most likely at 12ms after the 1st turn of injection

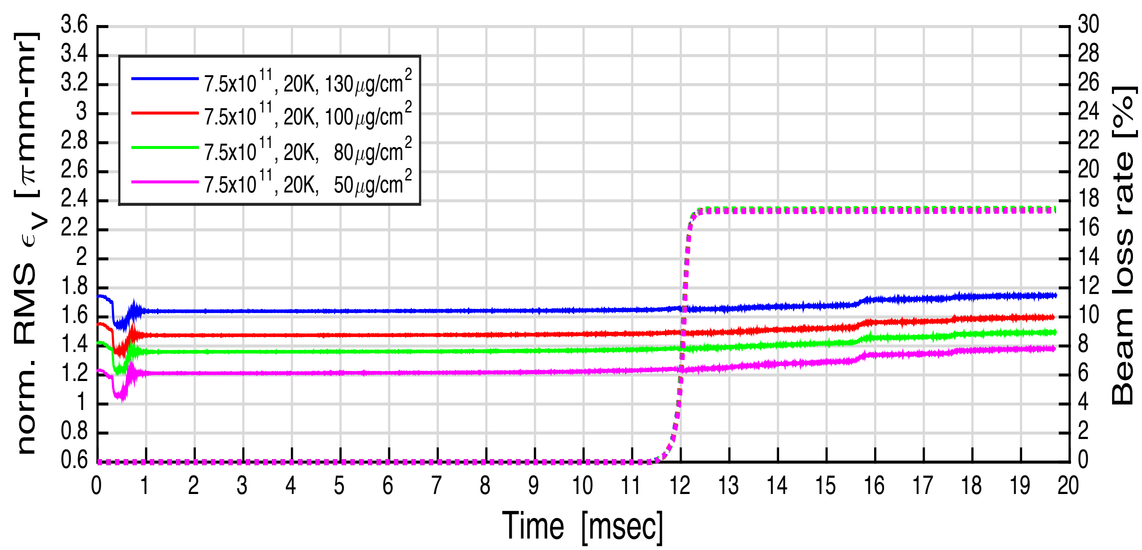


Effect of Initial Emittance (after Traverse Foil)

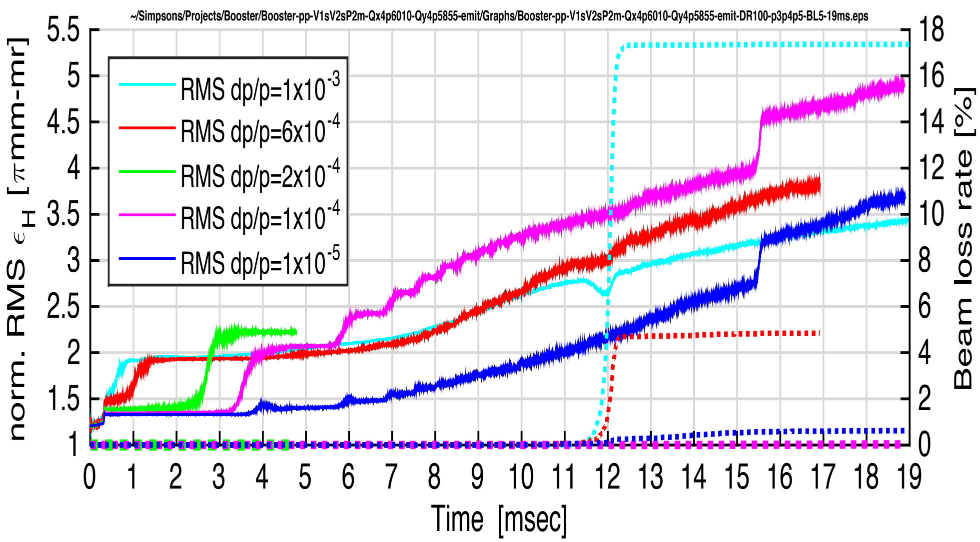


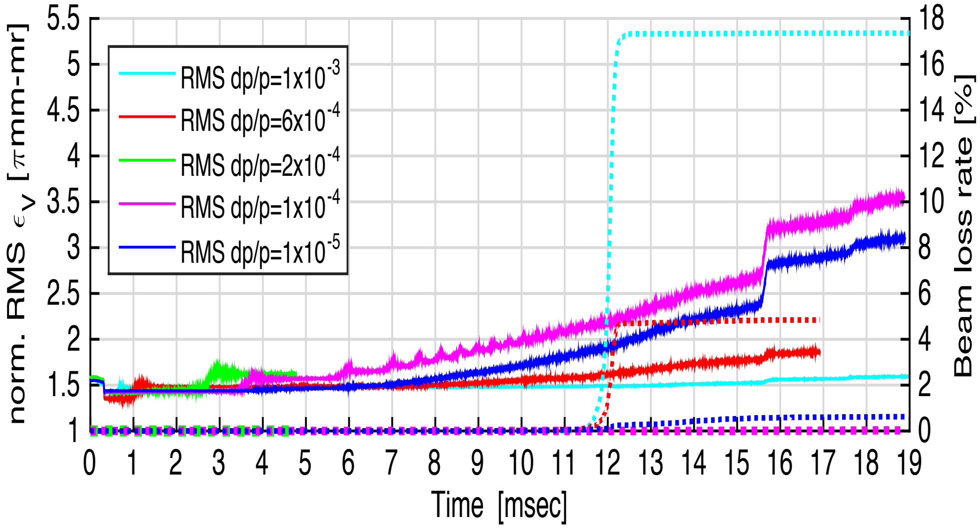


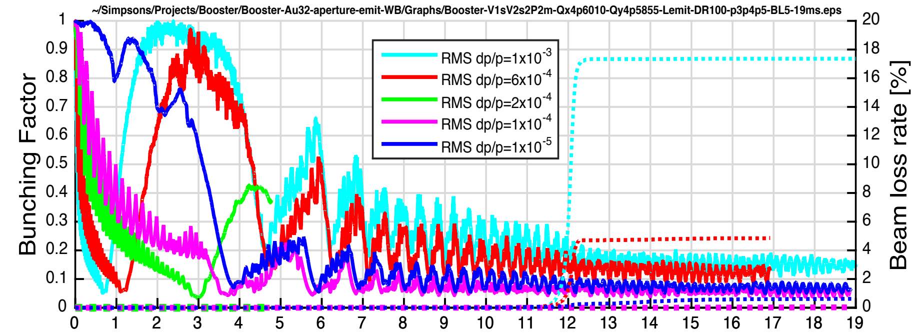


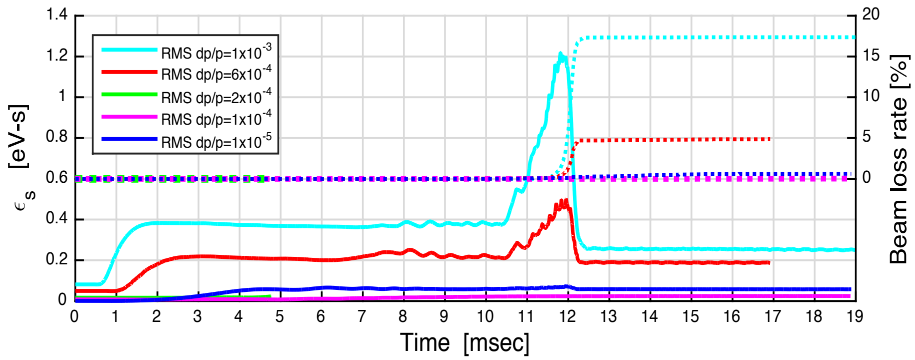


Effect of dp/p and Possible Improvement









Conclusion:

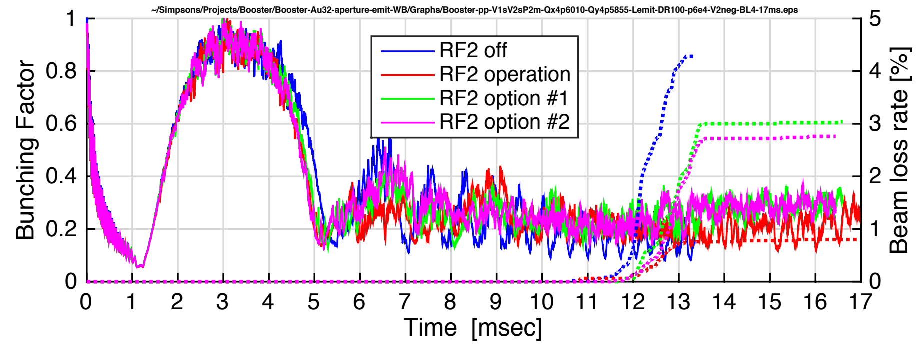
1. Reducing dp/p can largely reduce beam loss due to Longitudinal emittance at the start of energy ramping.
2. However, small longitudinal emittance causes larger emittance growth in transverse.

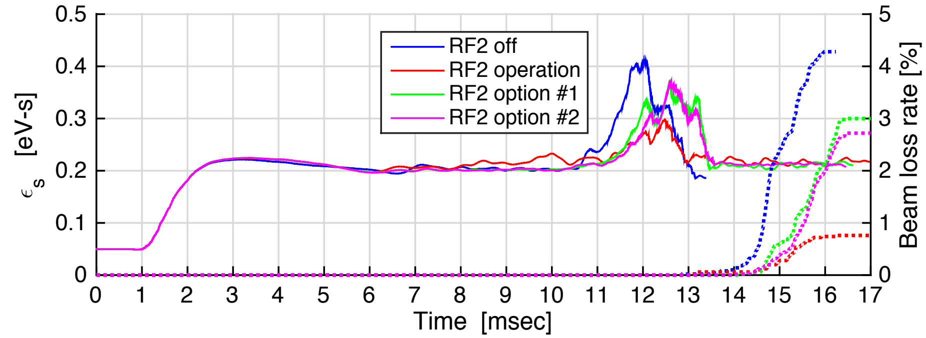
Effect of Second harmonic of RF

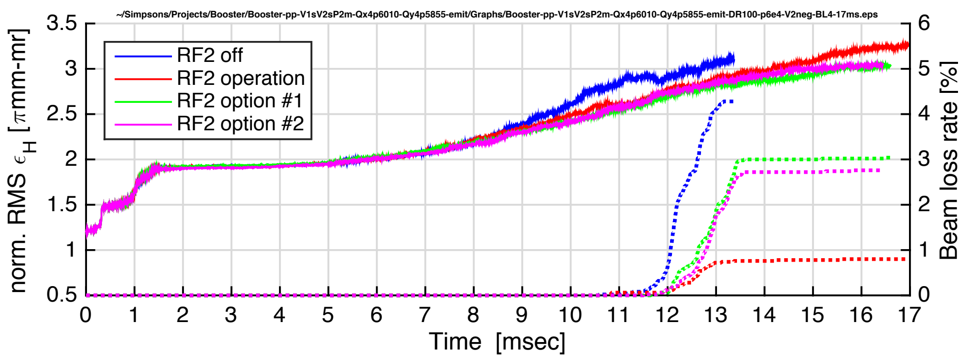
Option #1 and Option #2 are the implementations of 2 options in Kip Gardner's Tech Note CA/AP/535

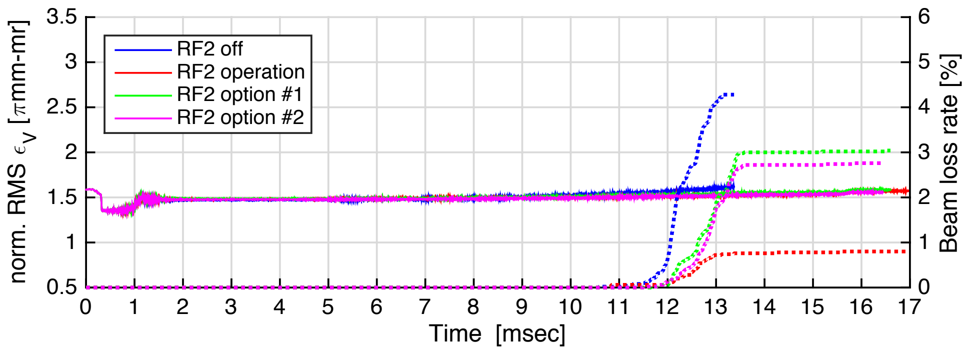
Observations:

1. There are only 6 synchrotron oscillations before acceleration starts. So, the beam does not have a chance to fill up flattened bucket before acceleration.
2. The benefit of RF2 is significant after acceleration.
3. Keith's tuning RF2 by looking into "mountain ranges" are very effective.



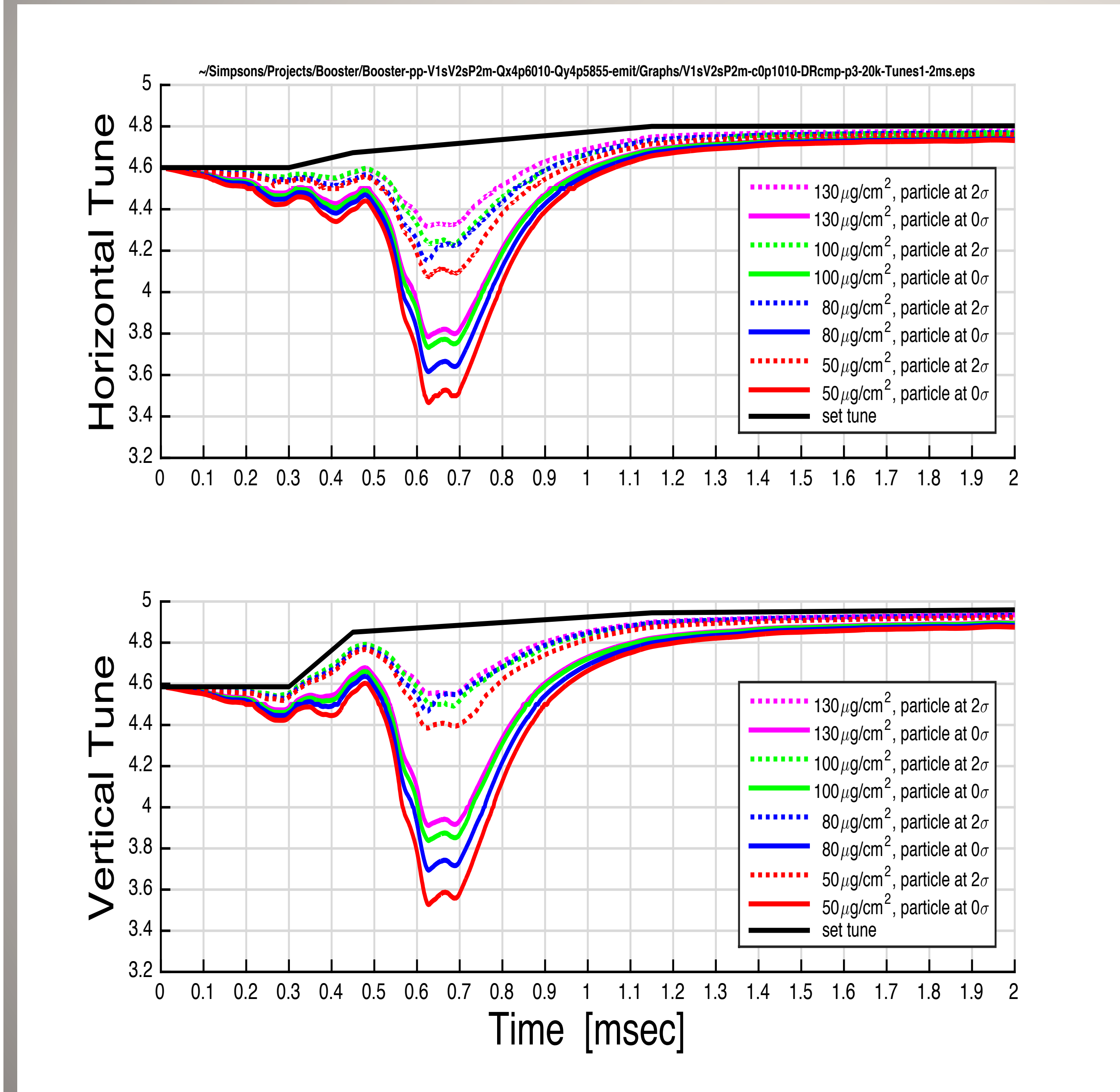


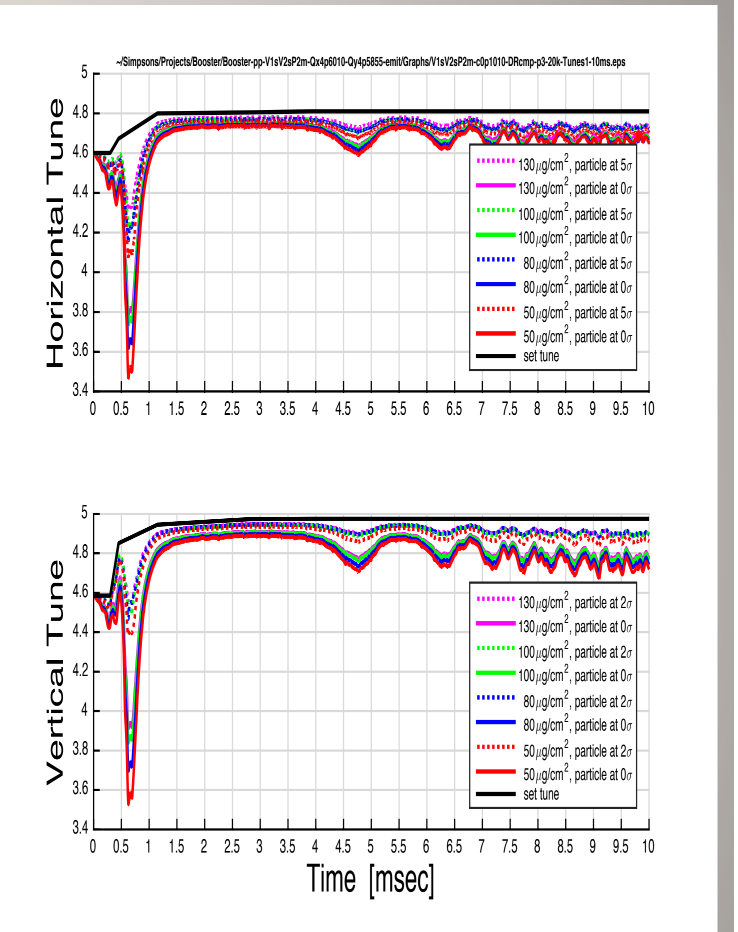




Conclusion:
The benefit of RF2 is not significant before acceleration while bunching process is happening. This is the time when the beam suffers from space charge most and transverse emittance growth is obvious. The further optimization of RF1 and RF2 as functions of time could suppress the transverse emittance degradation before the acceleration starts.

Tune shifts vs Initial Transverse Emittance

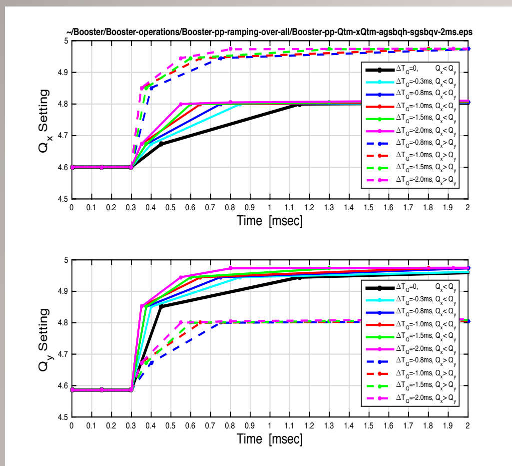


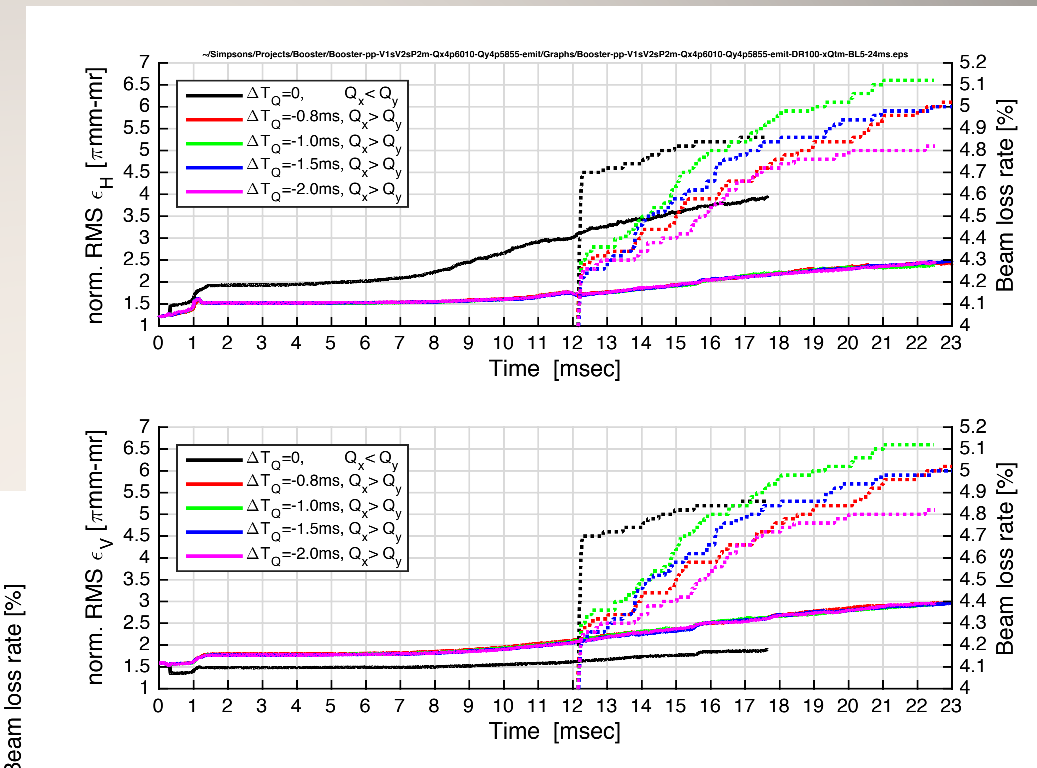


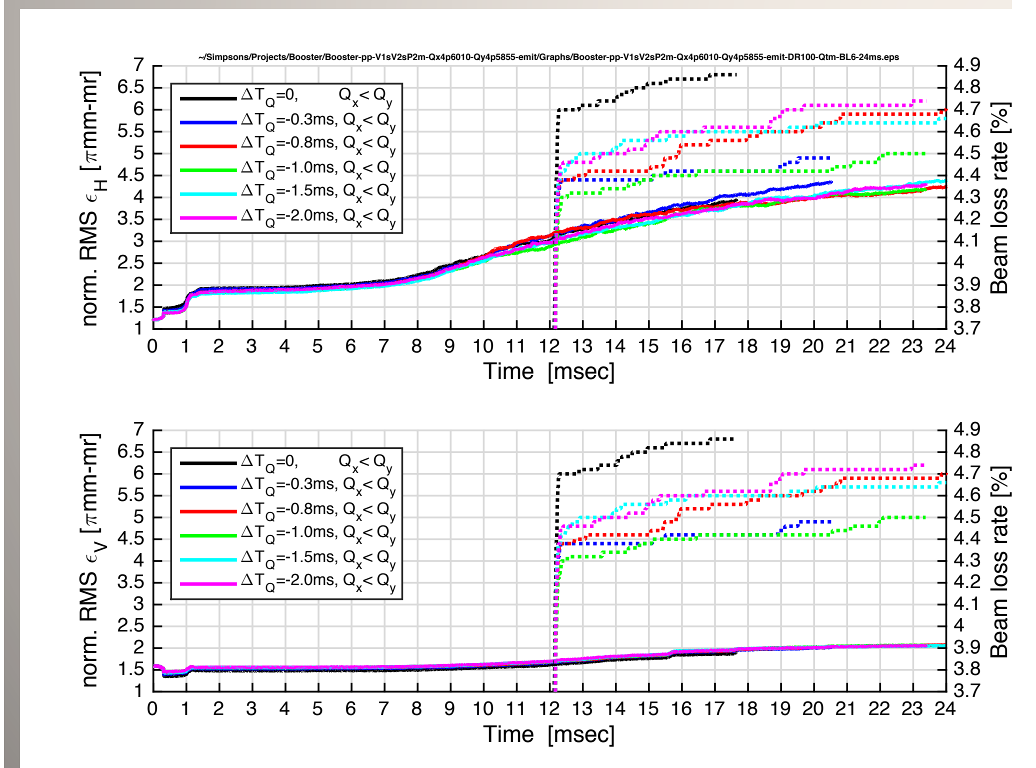
Possible Improvement:

1. Move the tunes upward faster;
2. If the power supplies can't move faster, then ramp up RF later;
3. Reverse final tunes, so Qx>Qy

Tune shifts and Possible Improvement







Conclusion:

1. Moving the tunes upward faster can reduce beam loss;
2. Reverse final tunes to Qx>Qy can largely reduce horizontal emittance. However, it has a small increase in vertical emittance and beam loss.

Summary

1. Simulations with space charge and element-by-element physical aperture verifies that the particle loss in the circulating beam in Booster is on the level of a few percent.
2. The beam loss from "Booster_Input" to "Booster Early" has a hard minimum of 17%. It is caused by foil efficiency (9% for foil thickness of 100mg/cm^2); small loss in LTB line and/or injection mismatch.
3. The beam loss starting at around 10ms and sometimes appearing as the sudden increase at 12ms is, most likely, due to longitudinal momentum acceptance.
4. The momentum spread of the uncaptured particles depends on the initial momentum spread and the beam intensity.
5. The Simulation shows that transverse emittance growth can be very large. It is largely dependent to beam intensity. However, transverse acceptance is large enough to keep most of the beam.
6. The benefit of RF2 is significant after acceleration, but not during RF capture which is the time when the beam suffers from space charge most. Further optimization of RF1 and RF2 could suppress the transverse emittance degradation before the acceleration starts.
7. Transverse emittance is depended of initial emittance, which can be reduced by (a) using thinner foil; (b) shorter injection pulse. Both require higher Linac beam intensity.
8. Moving the tunes upward faster can reduce beam loss. If the power supplies can't move faster, may consider delay RF ramping till tunes finishing up to the higher settings.
9. Reverse final tunes to Qx>Qy can largely reduce horizontal emittance. However, it has a small increase in vertical emittance and beam loss.