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A Novel Beam Injection Scheme in the Fermilab Booster

for Intensity Upgrade

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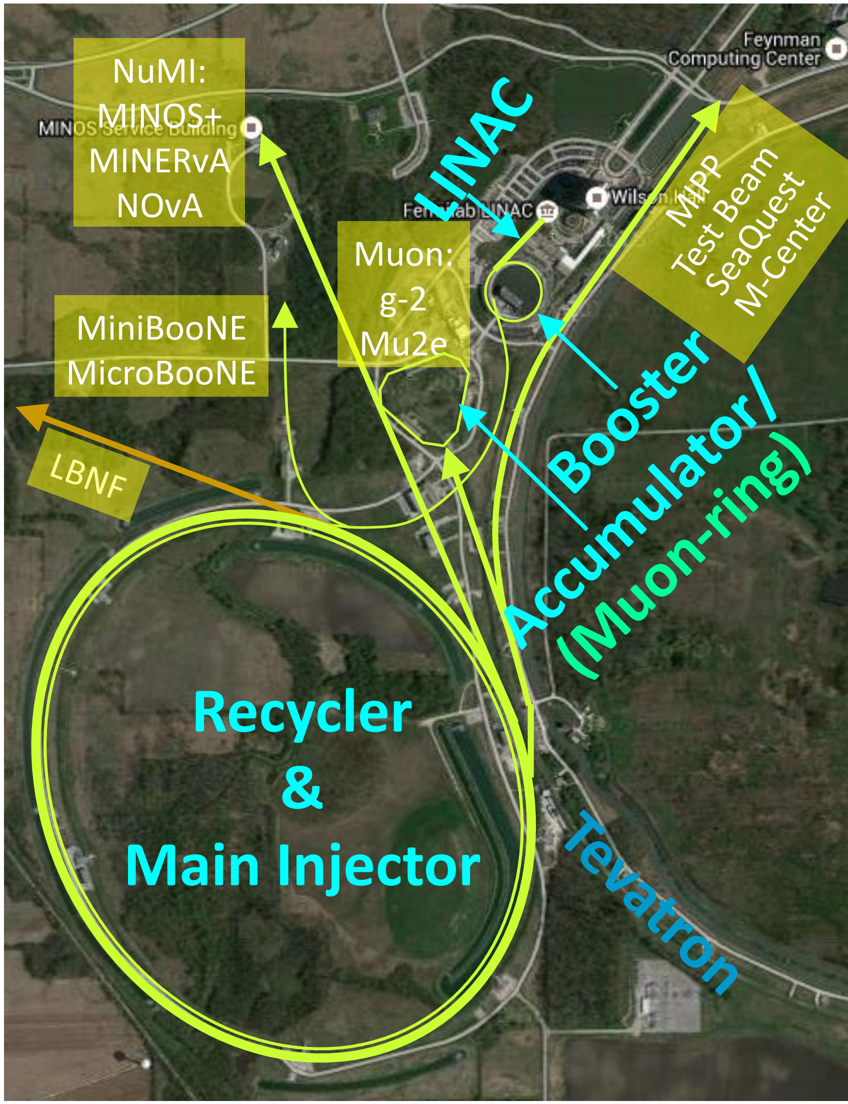
September 15, 2015

Fermilab, US Premier Particle Physics Laboratory

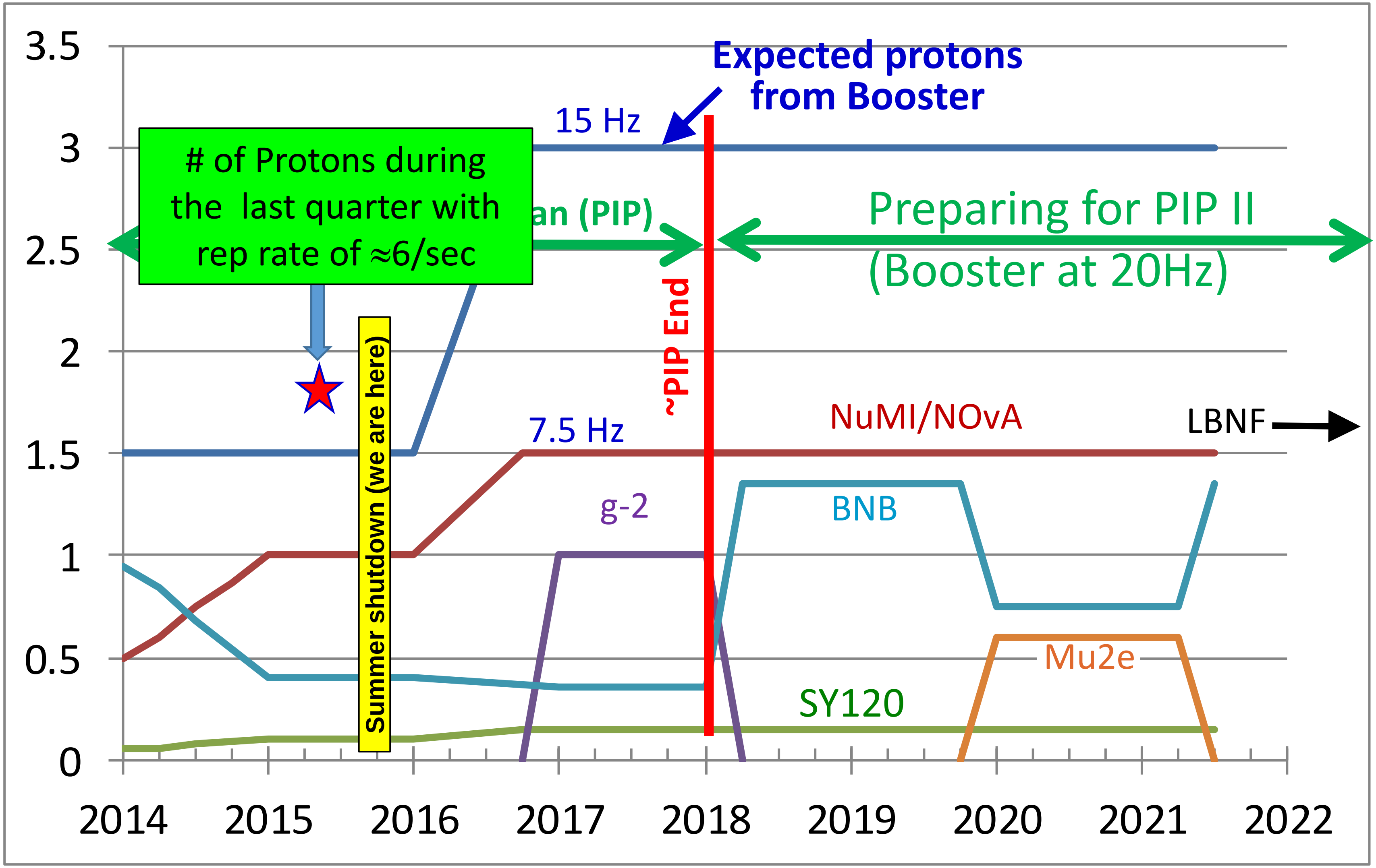


Booster:
0.4-8 GeV
Accelerator

Recycler:
8 GeV
Permanent
Magnet Storage
Ring

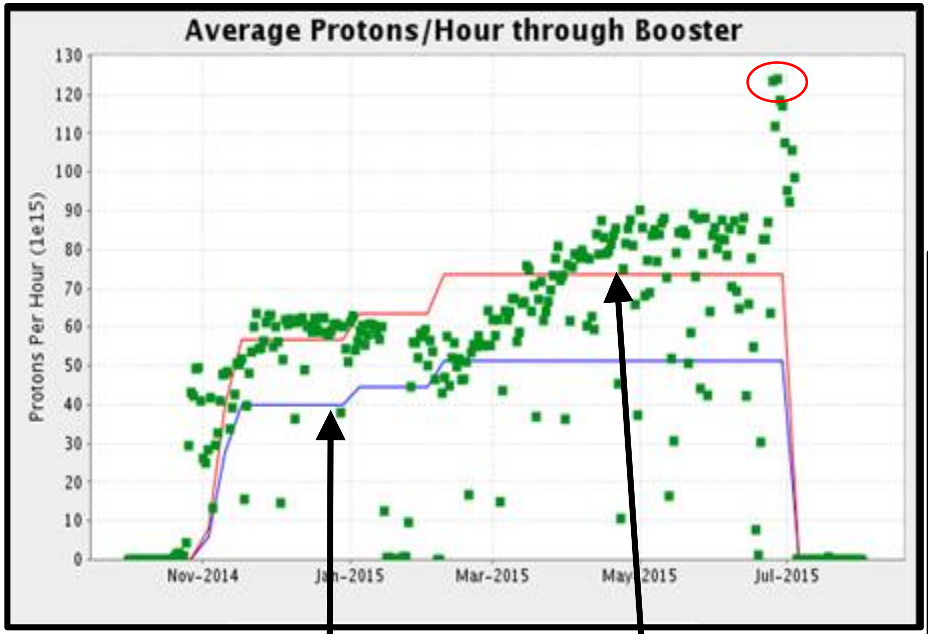
Main Injector:
8 -120 GeV
Accelerator

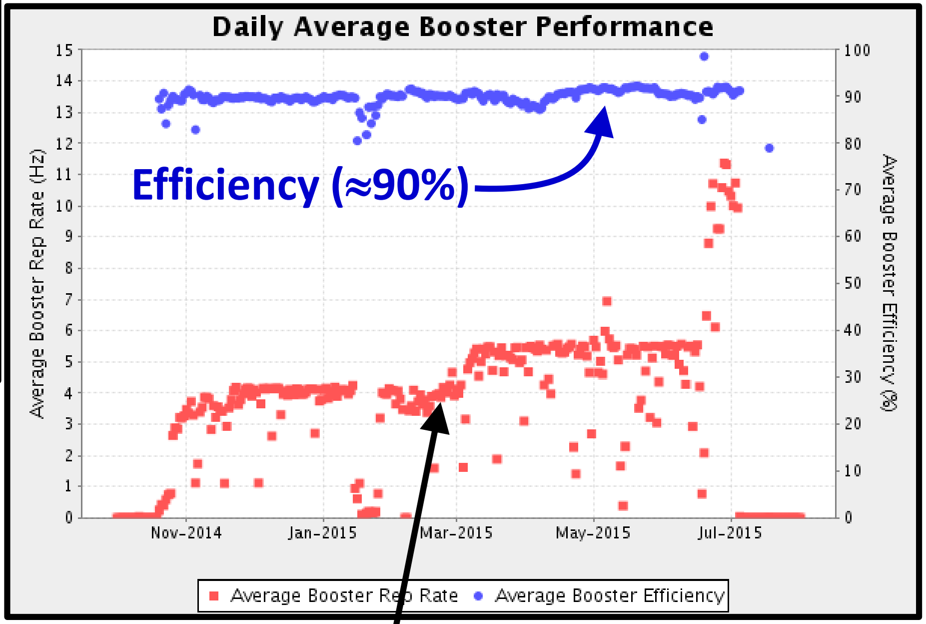
Proton Delivery Scenario from the Booster
(approximate)



From Bill Pellico

Record 1.25x10^{17} protons/hour on July 24, 2015
(previous record 1.1x10^{17} protons/hour)





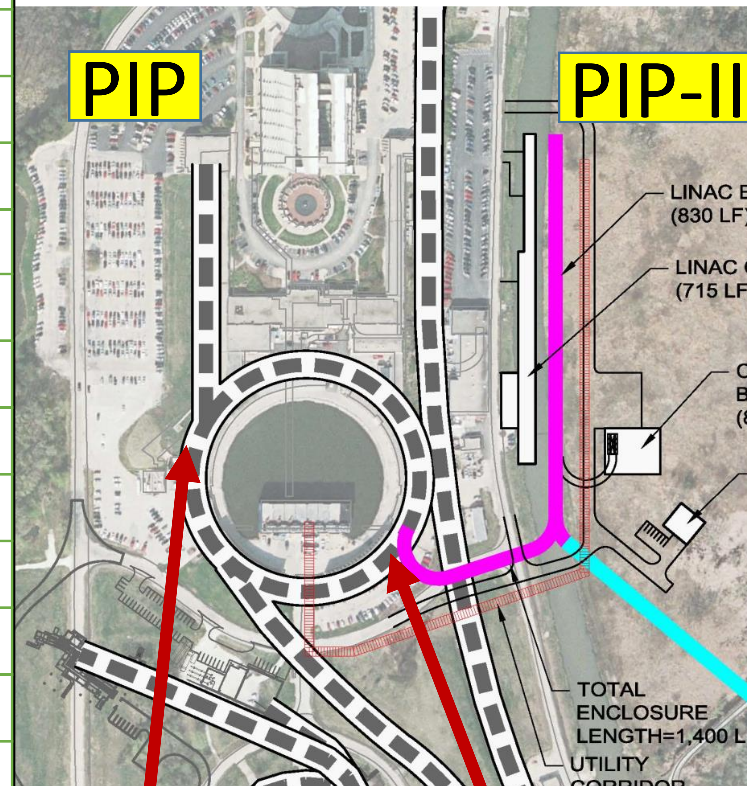
Base

Design

Average rep. Rate

Upgrade Path for Power on Target

Parameter	PIP Completed	PIP-II
Injection Energy (KE) (GeV)	0.4	0.8
Extraction Energy KE (GeV)	8	8
Injection Intensity (p/pulse)	4.52E12	6.63E12
Extraction Intensity (p/pulse)	4.3E12	6.44E12
Bunch Removed	3	3
Efficiency (%)	95	97
Booster repetition rate (Hz)	15	20
Booster Beam Power at Exit (kW)	94	184
MI batches	12 per1.33 sec	12 per 1.2 sec
NOvA beam power (kW)	700	1200
Rate availability for other users (Hz)	5	8
Booster flux capability (protons/hr)	~ 2.3E17	~ 3.5E17
Laslett Tune shift at Injection	≈- 0.227	≈ -0.263
Longitudinal energy spread	< 6 MeV	< 6 MeV
Transverse emittances (p-mm-mrad)	< 14	18
Booster uptime	> 85%	> 85%



Present inj. point at L1

New inj. point at L11

Are there innovative ways to increase the Booster beam before the PIP-II era?

- ❑ Introduction
- ❑ Beam Simulations
- ❑ Experimental Demonstrations
  - ➢ Beam studies and Findings
- ❑ Summary and Future Plans

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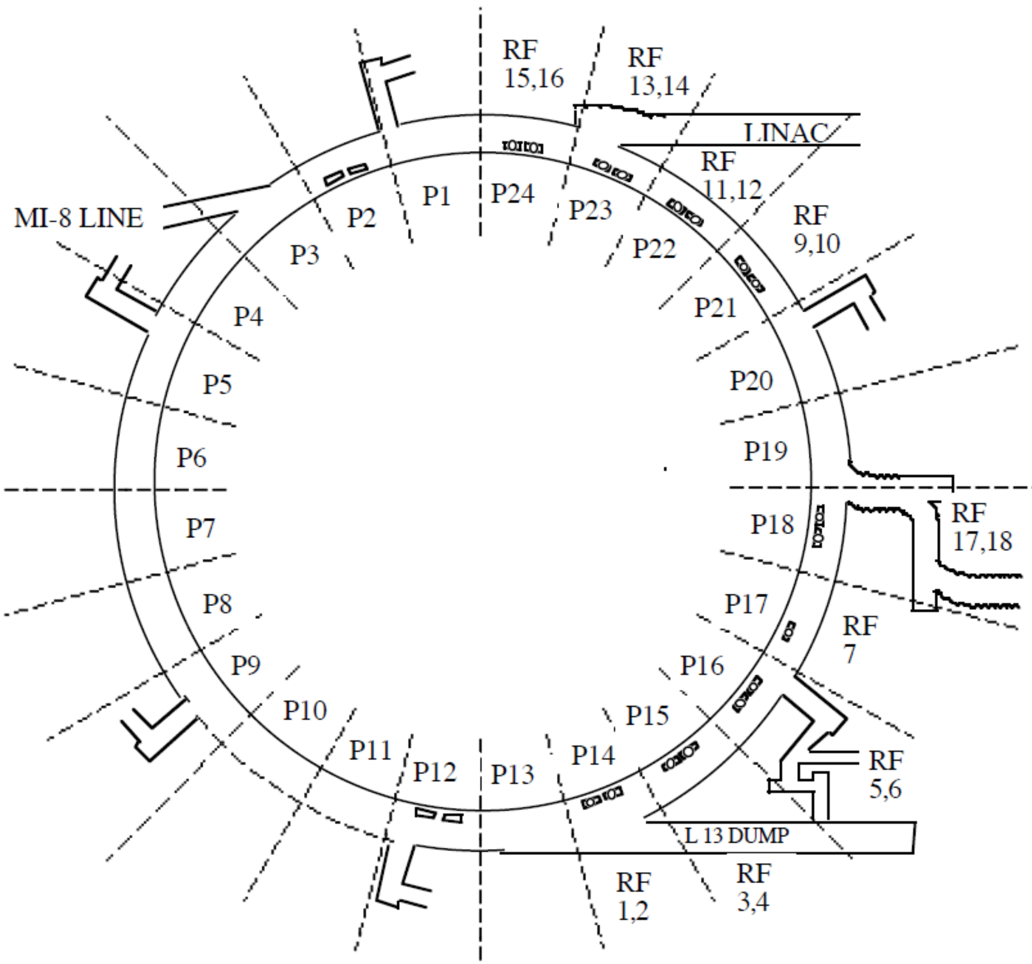
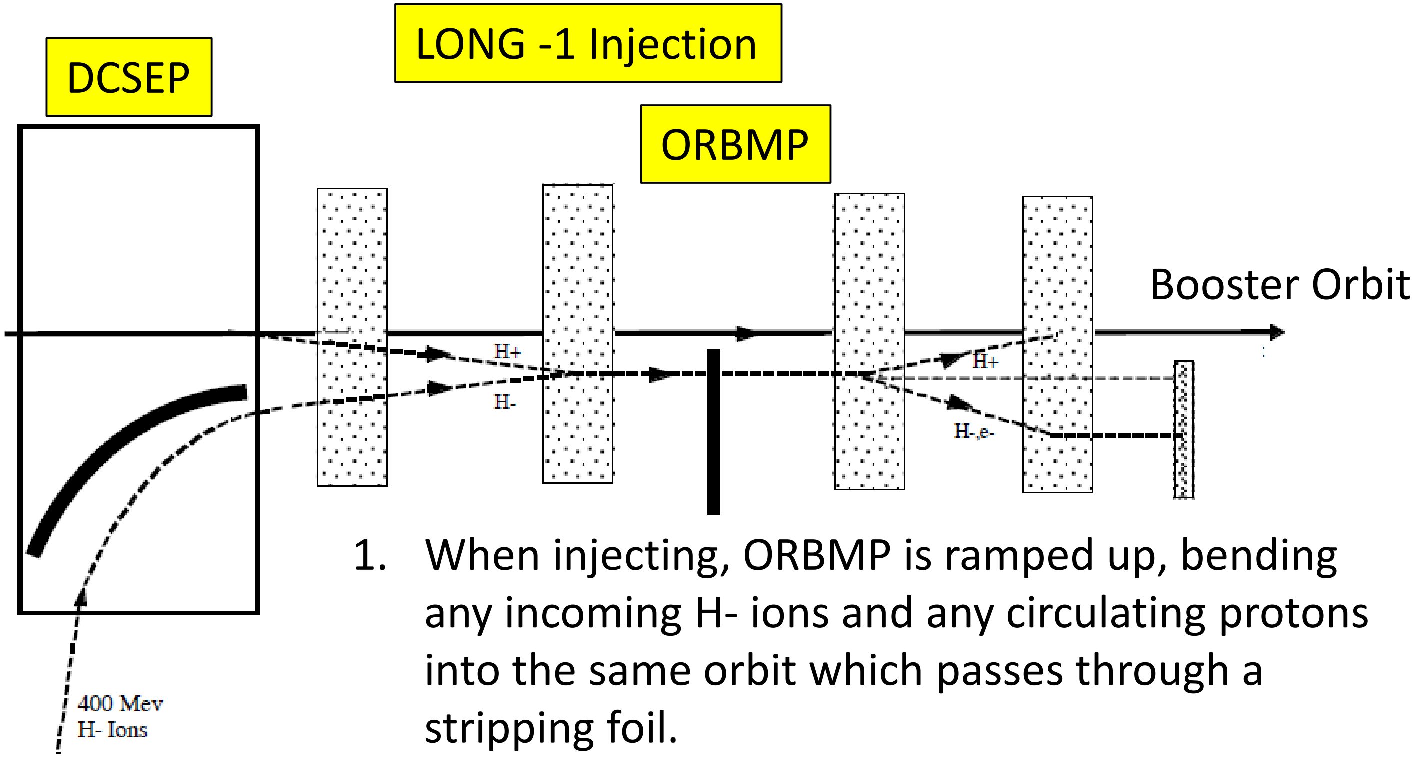
Layout of the Fermilab Booster



Booster Lattice Parameter

Circumference..............................2π x 74.47 meters
Injection energy.............................400 Mev (kinetic)
Extraction energy...........................8 Gev (kinetic)
Cycle time...................................1/15 sec
Harmonic number, h.......................84
Transition gamma..........................5.45
Injection Frequency........................37.77 Mhz
Extraction Frequency......................52.81 Mhz
Maximaum RF voltage....................0.86 MV
Longitudinal emittance...................0.25 eV sec
Horizontal β max..........................33.7 meters
Vertical β max..............................20.5 meters
Maximum dispersion......................3.2 meters
Tune $\upsilon_x = \upsilon_y$..................................6.7
Transverse emittance(normailized).....12π mm rad
Bend magnet length........................2.9 meters
Standard cell length........................19.76 meters
Bend magnets per cell 4
Bend magnets total.........................96
Typical bunch intensity...................3 x 10e10
Phase advance per cell....................96 degs
Cell type.......................FOFDOOD (DOODFOF)

Beam Injection into the Booster

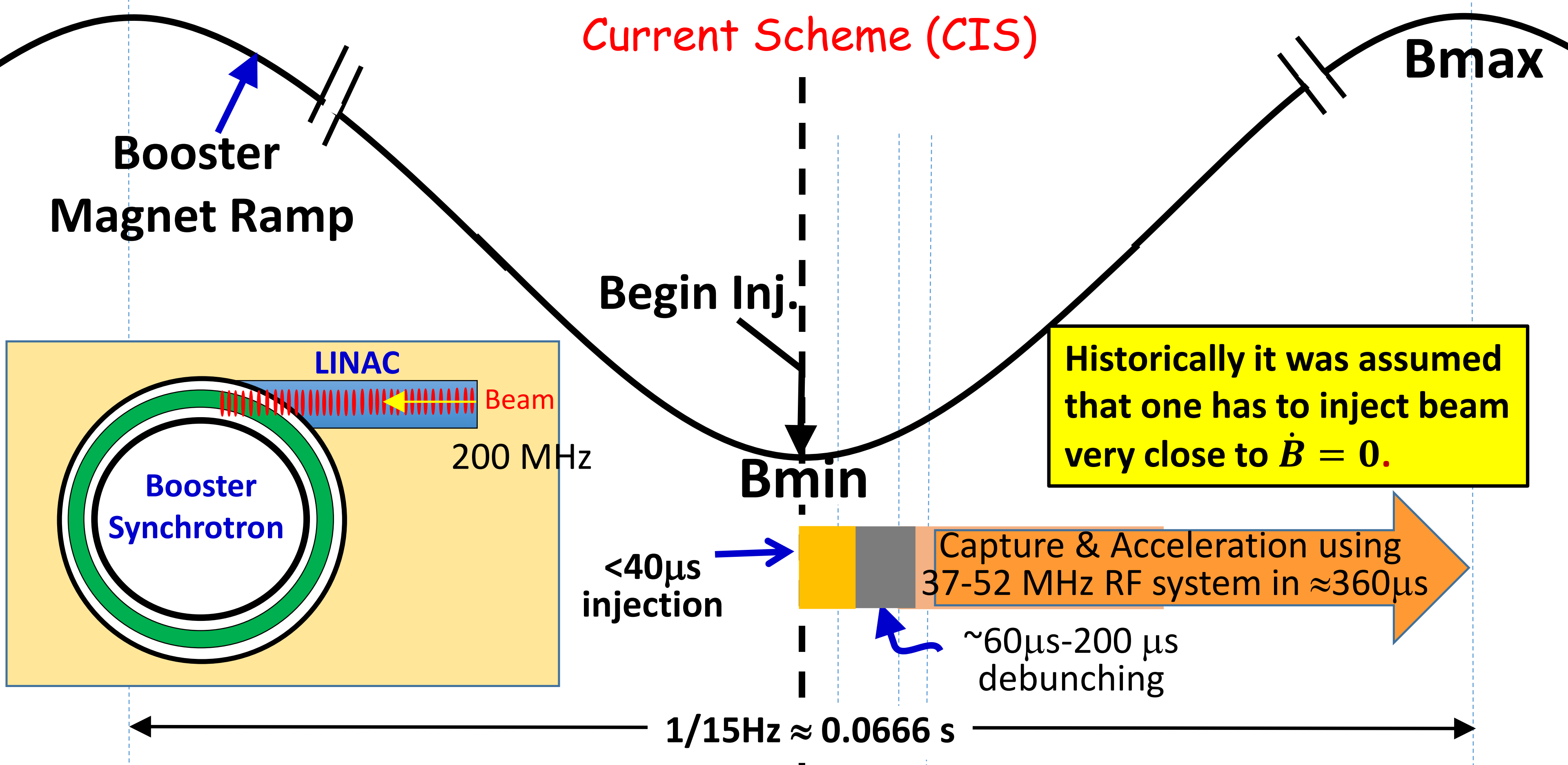


1. When injecting, ORBMP is ramped up, bending any incoming H- ions and any circulating protons into the same orbit which passes through a stripping foil.
2. Once beam injected, ORBMP is ramped back so that the circulating beam is sufficiently away from the stripping foil.

Schematic of the

Beam Injection in the Booster

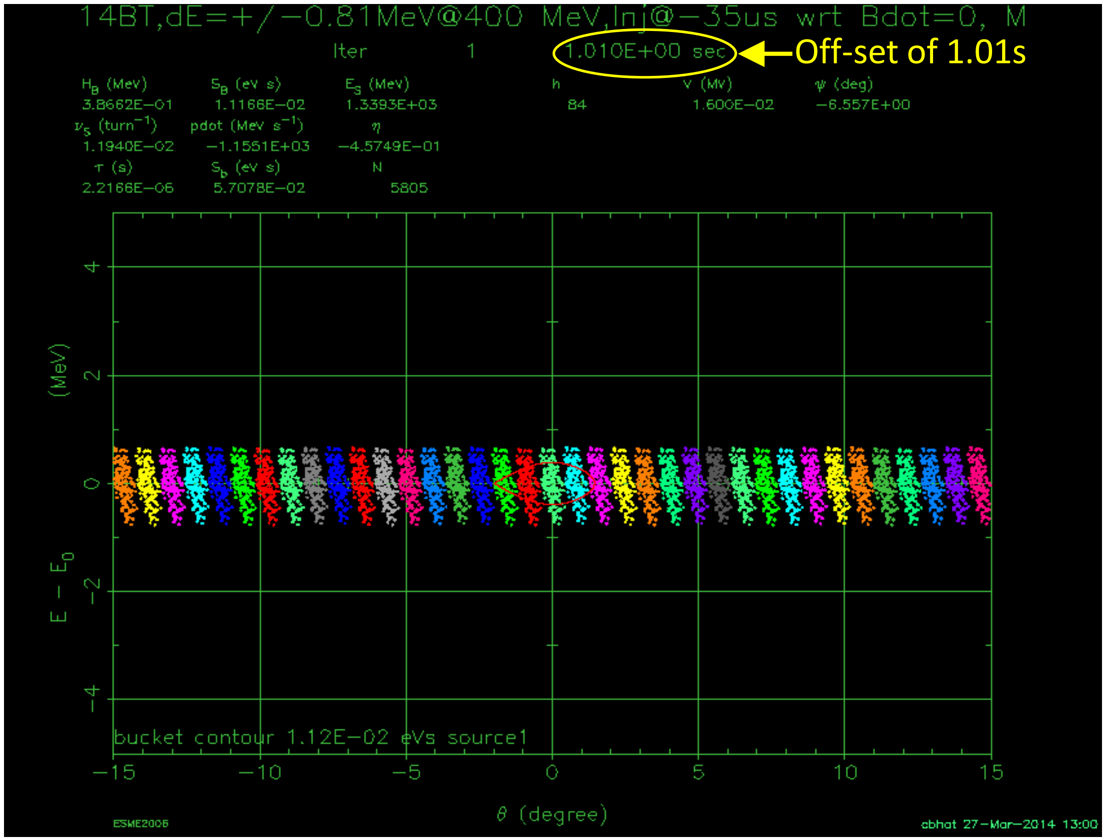
Fermilab Booster is the 2nd oldest RCS in the world & its magnets ramp at the rate of 15 Hz.

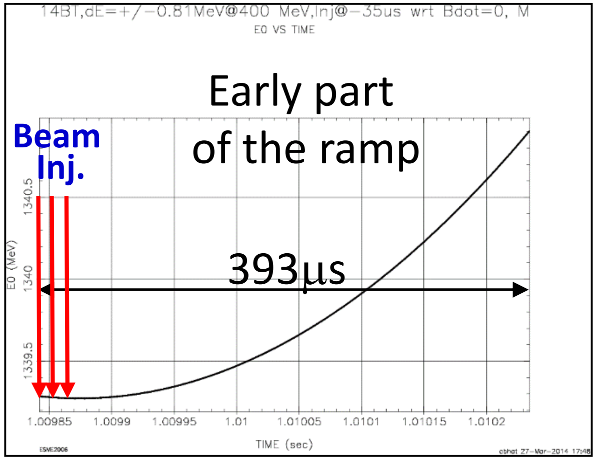


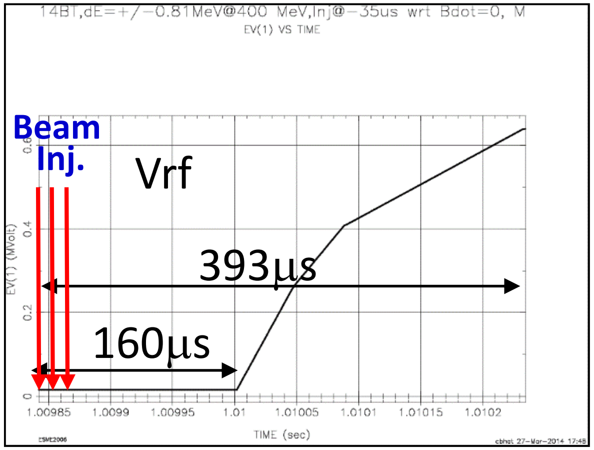
Simulations for CIS

Mimic **Operational** Beam: injection at ~35us before BDOT=0

VIDEO



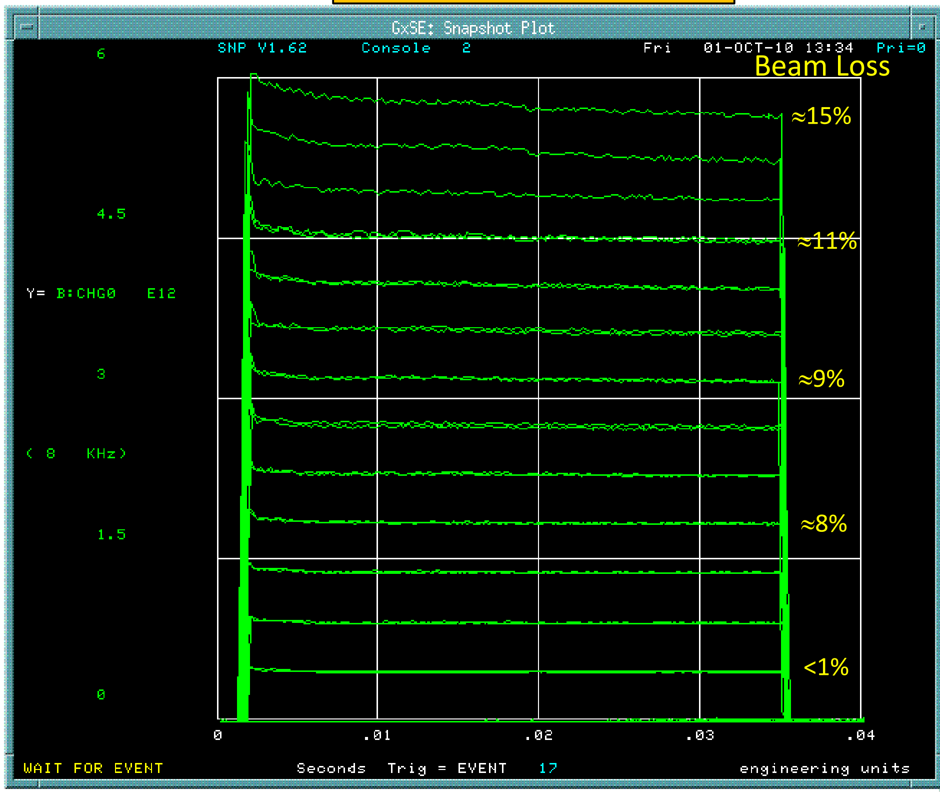




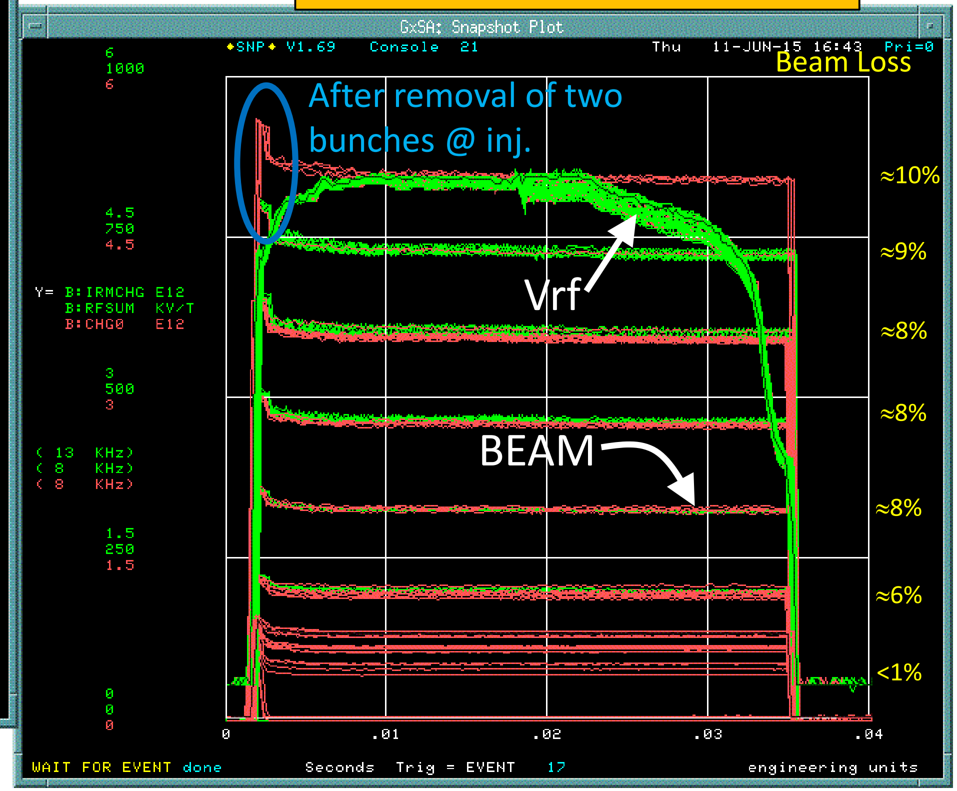
<u>Issues:</u> A limited time for Beam Capture. RF manipulations are non-adiabatic at capture← ~50% emittance dilution, ≈10% beam loss

Beam Transmission in the Current Booster and Intensity Limit

Beam in 2010



Beam in 2015 (now)



Observations:

1. **Beam loss as a function of beam intensity**
2. **<50% emittance dilution at injection**
3. **Large Vrf power**

I believe that the longitudinal beam dynamics at injection is the problem.

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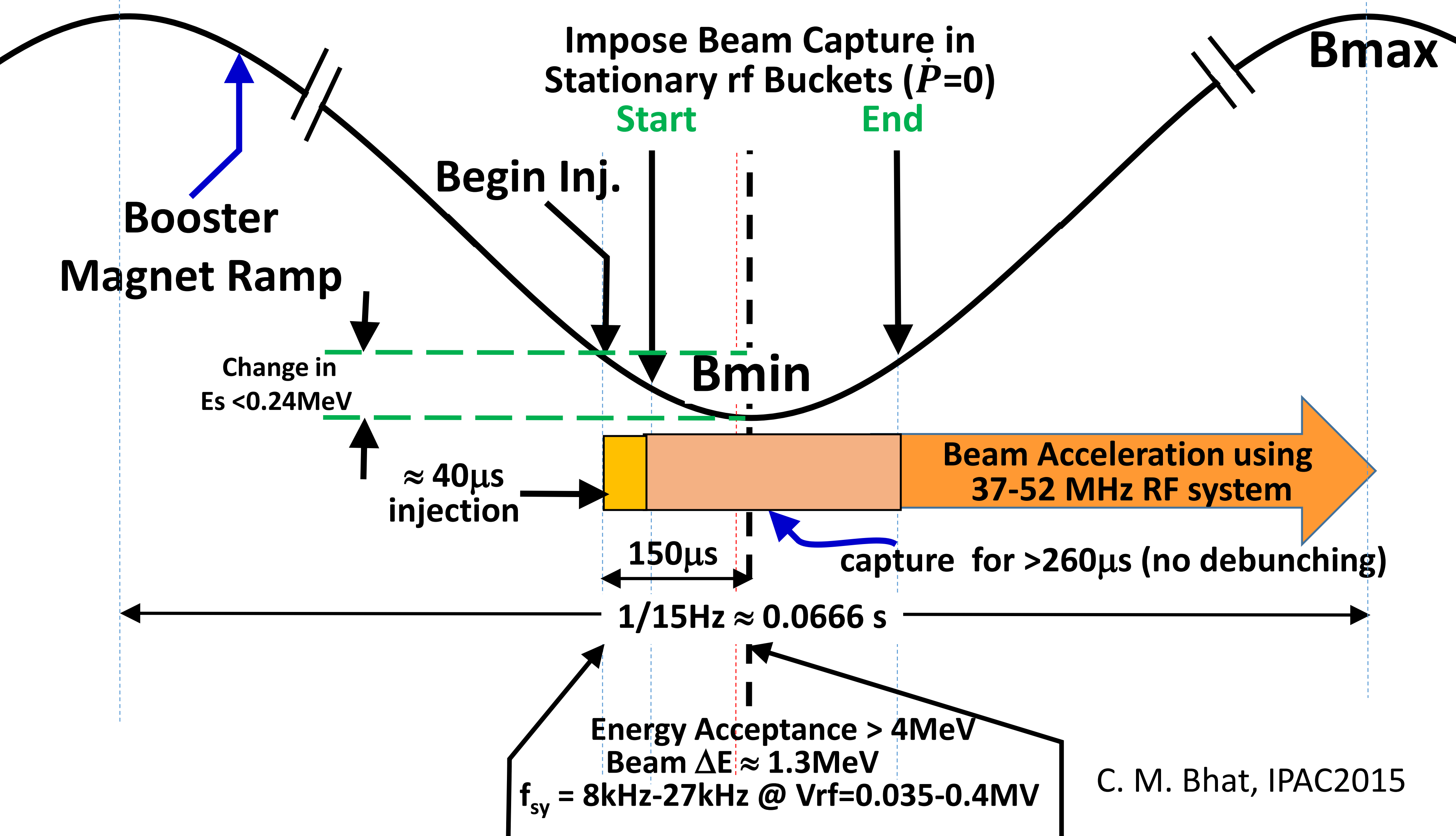
Schematic of the Early Injection Scheme for the Booster (EIS)



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Early Injection Scheme

- What is spooky about this method
  - The beam is injected on the deceleration part of the magnetic ramp.
  - Beam capture takes place while magnetic field is changing.

  Historically, it was believed that the capture and acceleration efficiencies in the Booster will be optimal if beam is injected close to $\dot{B}$ = 0.

- What is Innovative about this Method?
  - Beam capture should be carried out by imposing $\dot{P}$ = 0 even though $\dot{B} \neq 0$.
  - Since the fs $\approx$ 8-27kHz for Vrf=0.034-0.34MV, nearly adiabatic capture of the beam needs only $\approx$ 260μs.
  - Preserving the longitudinal emittance at capture means less rf voltage through the acceleration cycle ← Lesser RF power
  - Better beam for slip-stacking. ← Main Injector/RR demand smaller dp/p beam for improving slip-stacking

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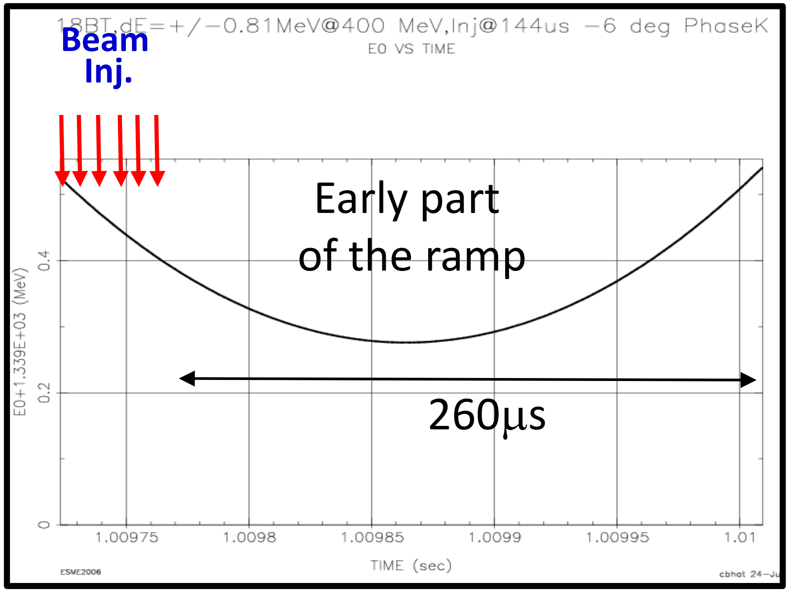
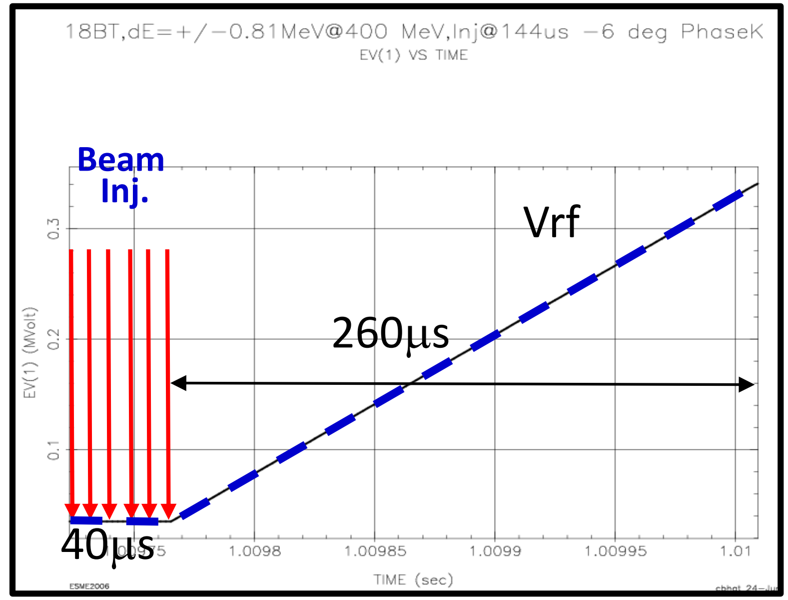
Beam Simulations with ESME

Inj. @ at ≈ -150μs w.r.t. $\dot{B} = 0$ for 40μs. Start beam capture immediately after 10 μs for next 250 μs.





Since we impose $\dot{P}=0$, one demands $\Delta B/B = \gamma_T^2 \Delta f/f$ during beam capture.

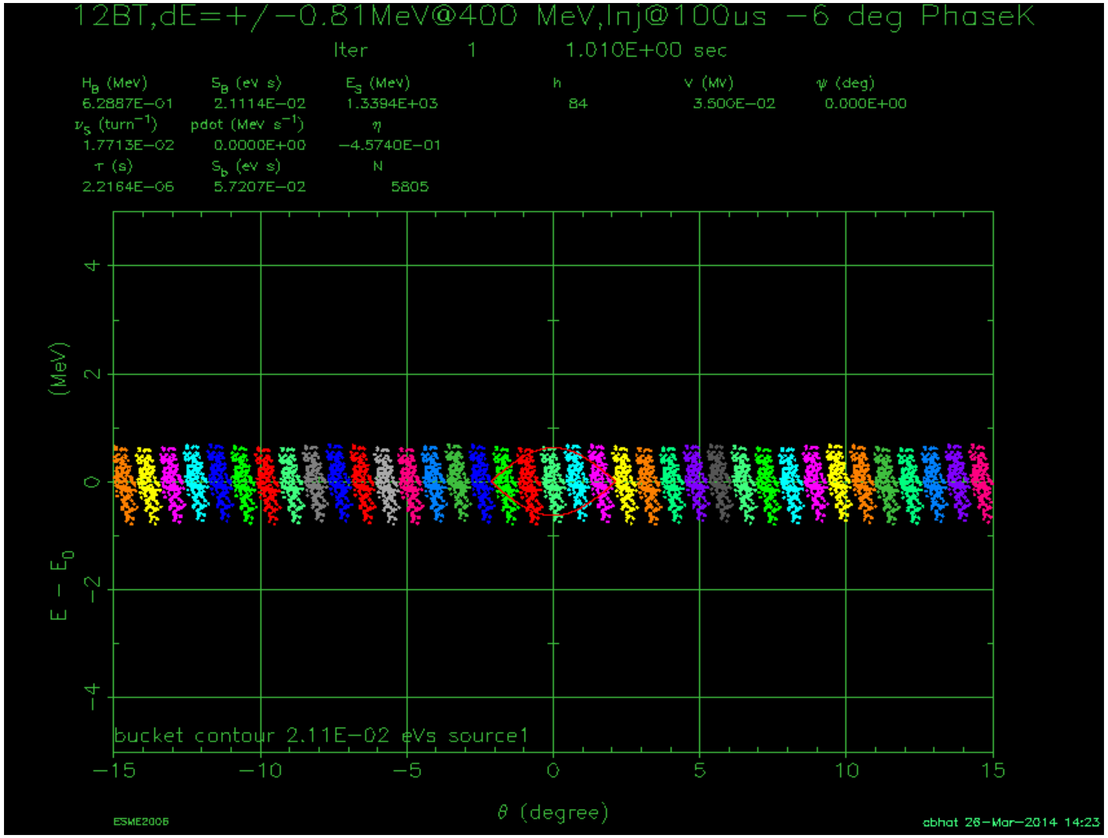
RF manipulations are more adiabatic at capture← ~0% emittance dilution and no beam particle losses

Beam Simulations from Injection → Extraction

(Evolution of Phase space Distribution)

Inj. @ at -100μs w.r.t. $\dot{B} = 0$, Capture from -64 μs to 135μs, with a phase kick of ~ 6 deg after transition crossing.

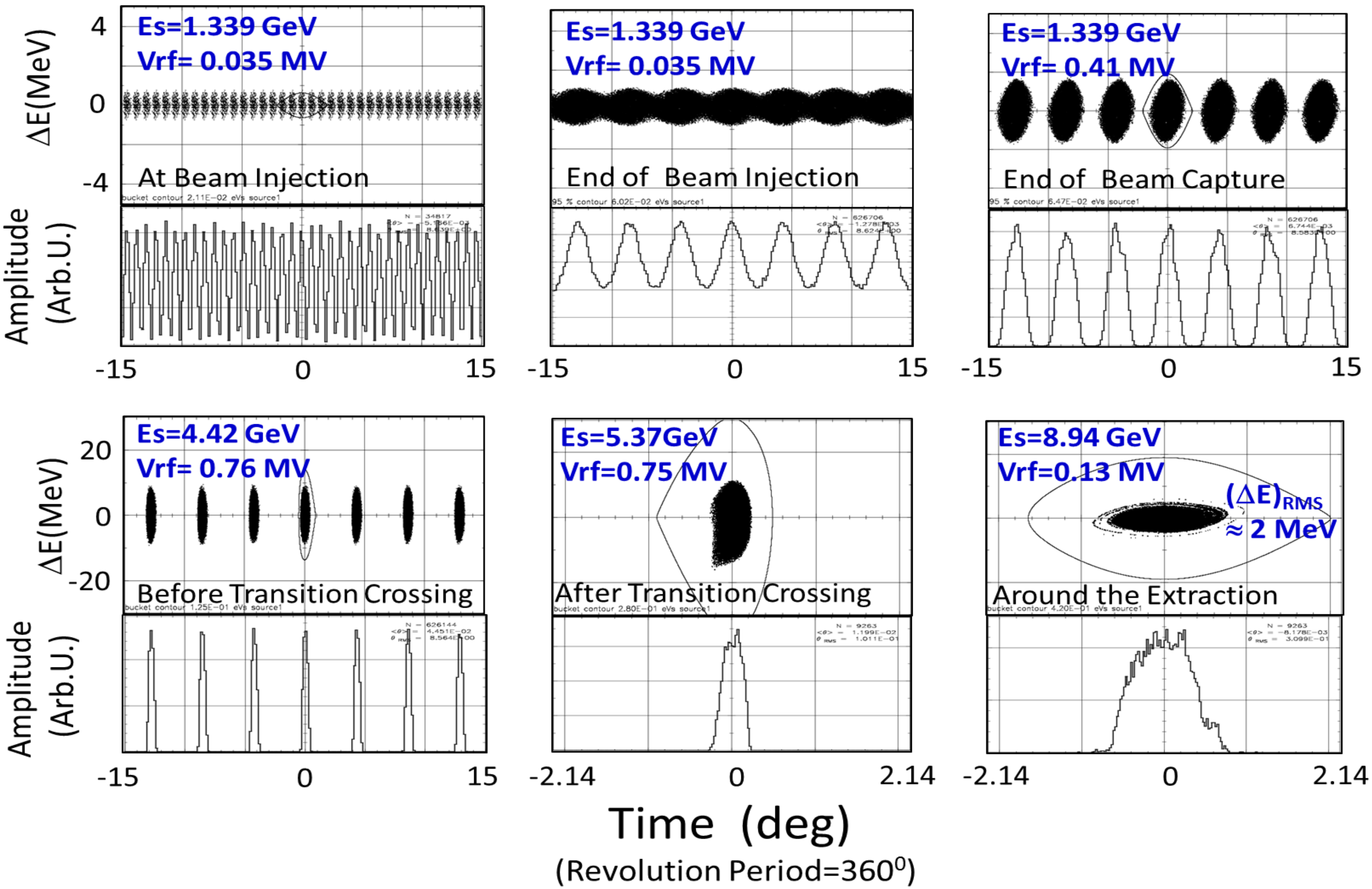
VIDEO



Because of small emittance at capture acceleration needs less rf voltage

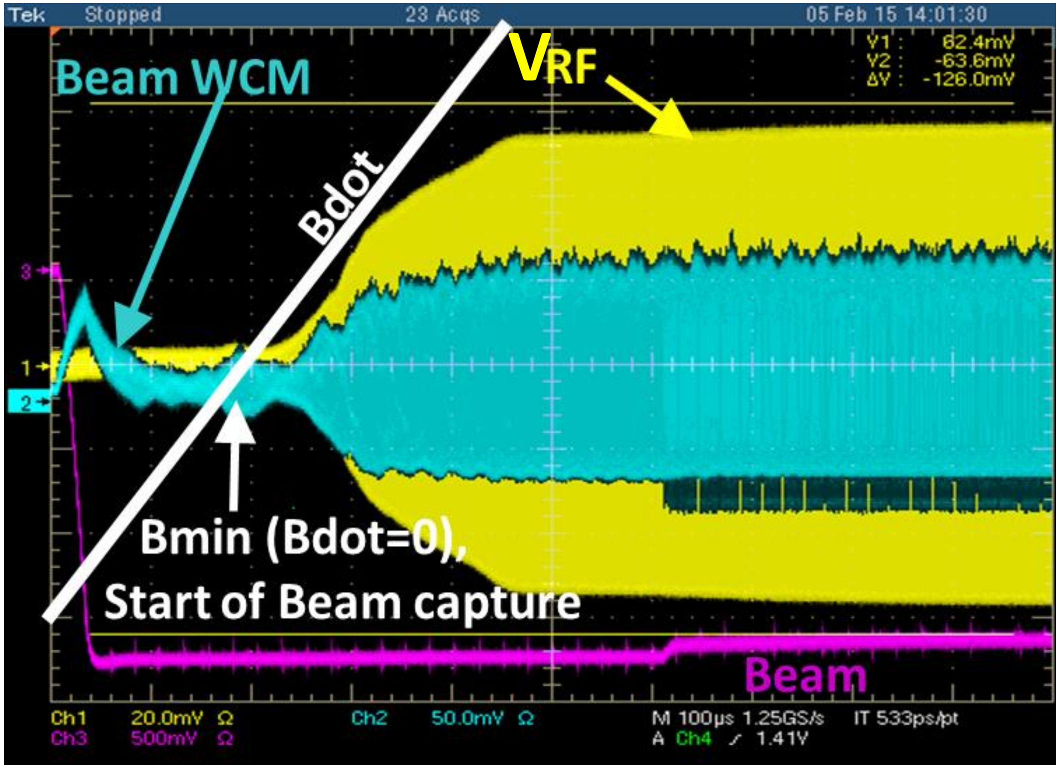
Beam Simulations from Injection → Extraction

with 2E10-12E10p/bunch



"Proof of Principle" Experiment

- Beam injection at 144 μs earlier than $\dot{B} = 0$.

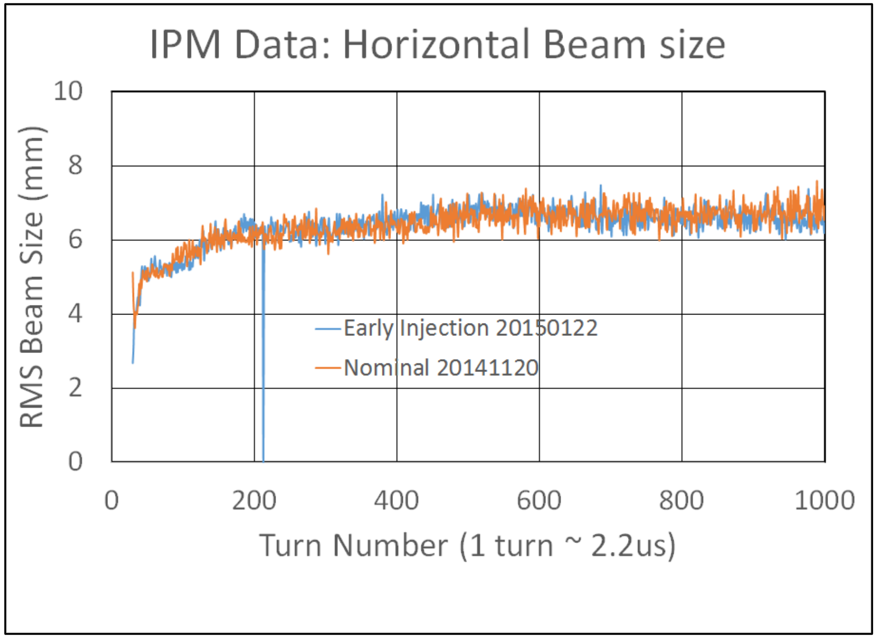


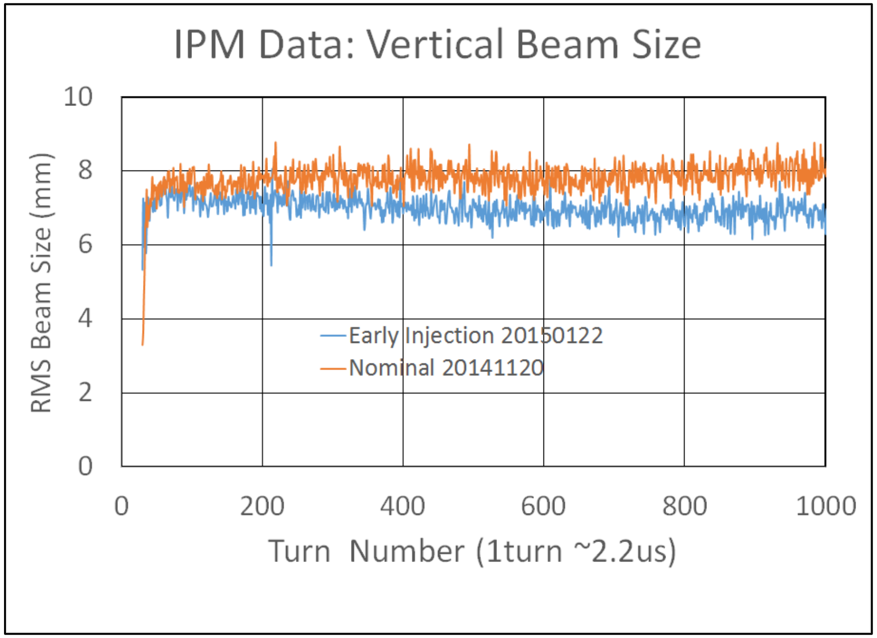
- Simulated Vrf curve is used
- Transition crossing needed additional tuning

Samples of Transverse Beam Sizes for the First 2 ms

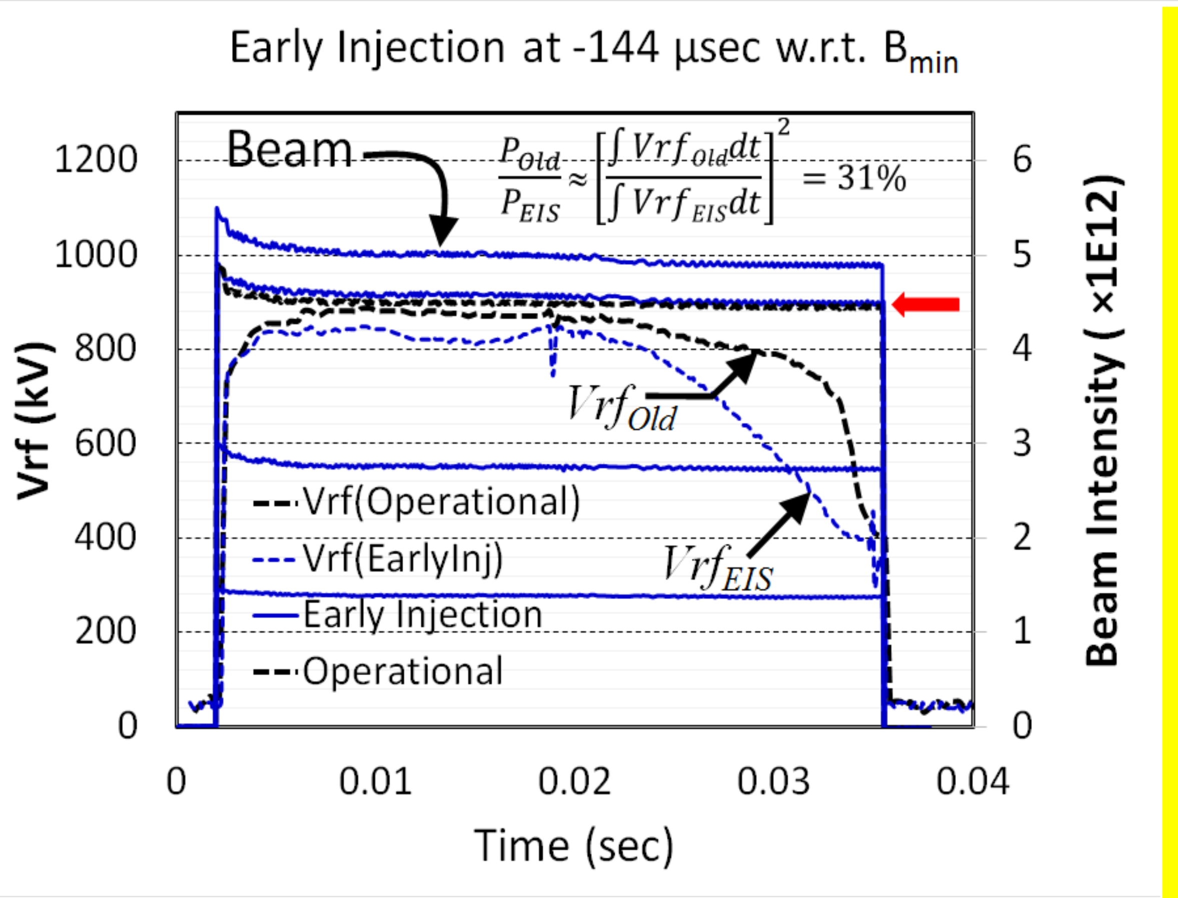
(Nothing Unusual)

5E12 p/ Booster Batch





"Proof of Principle" Experiment



These experiments proved that

1) One can inject the beam much earlier than $\dot{B} = 0$.
2) Can achieve beam transmission efficiency comparable to the current operation.
3) There is ample of room to increase beam intensity in the Booster by a factor more than 1.5.

But we did not have all beam controls during these beam experiments established by simulations.

Tasks under Development

- Beam capture soon after the completion of the beam injection,
- A frequency synchronization between the LLRF and changing magnetic field on the down ramp.
- Implement phase corrections/jump at transition crossing.
- Fast bunch rotation← Gives lower beam energy spread at extraction. Hence, is better for slip-stacking in RR.
- Beam loading compensation

Implications of EIS

- One can increase the Booster beam power at extraction, because more number of Booster turns can be accommodated
- Higher brightness beam to the downstream machines
- Booster can be run with nearly 30% less RF power per cycle ← This is a great bonus.

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Acknowledgements

W. Pellico, C. Drennan,
K. Triplett, S. Chaurize,
B. Hendrick, T. Sullivan
and A. Waller

Summary

Expected by adopting Early Injection Scheme

Parameter	PIP	PIP-II (After 2022)
Injection Energy (KE) (GeV)	0.4	0.8
Extraction Energy KE (GeV)	8	8
Injection Intensity (p/pulse)	4.52E12 **(x ~1.4)**	6.63E12
Extraction Intensity (p/pulse)	4.3E12 **(~6E12)**	6.44E12
Number of Booster Turns	13 **(18)**	300
Efficiency (%)	95 **(≥97)**	97
Booster repetition rate (Hz)	15	20
Booster Beam Power at Extraction (kW)	94 **(~130)**	184
MI batches	12 every 1.33 sec	12 every 1.2 sec
NOvA beam power (kW)	700 **(~950)**	1200
Rate availability for other users (Hz)	5	8
Booster flux capability (protons/hr)	~ 2.3E17 **(3.2E17)**	~ 3.5E17

Backup

Beam Simulations from Injection → Extraction

Parameters	
Booster circumference (2πR) [m]	473.8
Injection KE [MeV]	400
Extraction KE [MeV]	8000
Cycle Time[sec]	1/15
Beam injection w.r.t. $\dot{B} = 0$ [μsec]	0, -90, -144
Harmonic Number	84
Transition Gamma γ_T	5.478
ΔE at Injection [MeV] Longitudinal Emittance [eV sec]	1.6 0.04
Beam Structure at Injection	201MHz
Number of BT	1-17
Bunch Intensity [protons/bunch]	2E10-12E10
Beam transverse radius [cm]	1.2*
Beam pipe (RF) radius [cm]	2.86*

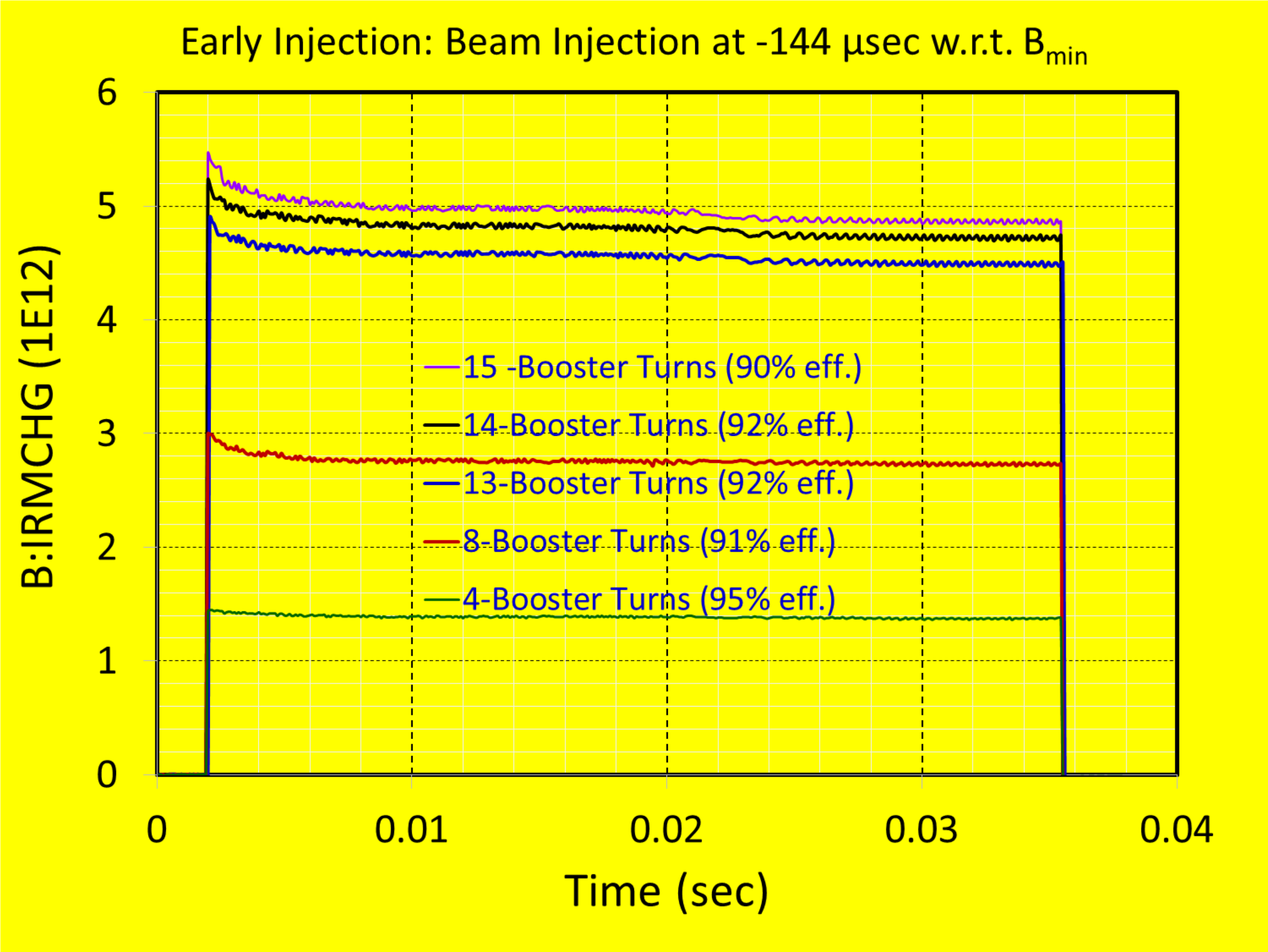
*Used in simulations with space charge effects

Laslett SC tune shift

$$\Delta\nu_{SC} = -\frac{N_{tot} r_c B_f}{4\pi\varepsilon_n \beta_p \gamma_p^2},$$

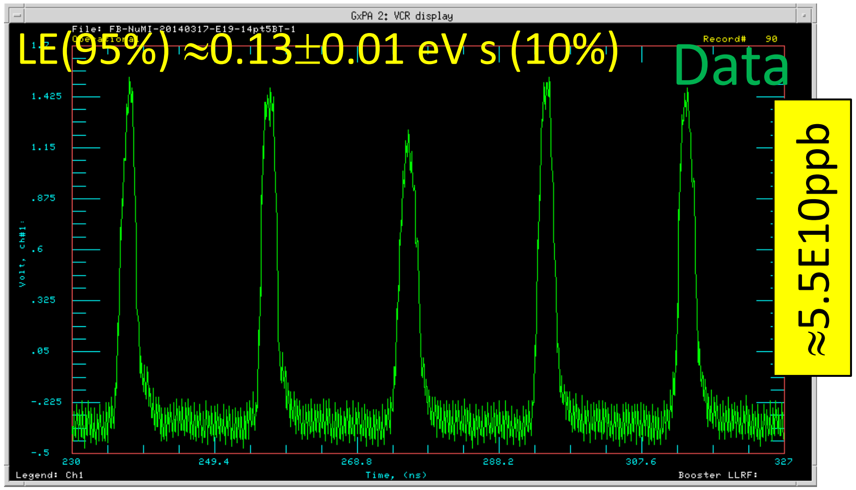
where N_{tot} is total number of particles in the ring, $r_c = 1.53 \cdot 10^{-18}$m for protons, ε_n is rms normalized emittance, $\beta_p = v_p/c$ and γ_p are usual relativistic parameters, and $B_f \geq 1$ is a peak to average current ratio. Normally, for proton low-energy synchrotrons the tune shift lays in range of -0.1...-0.5 (see, e.g.,[4]). Above the threshold, the beam emittance dilute and particles are lost. Due to the acceleration, the short time at low energy is enough for developing only the lowest order resonances.

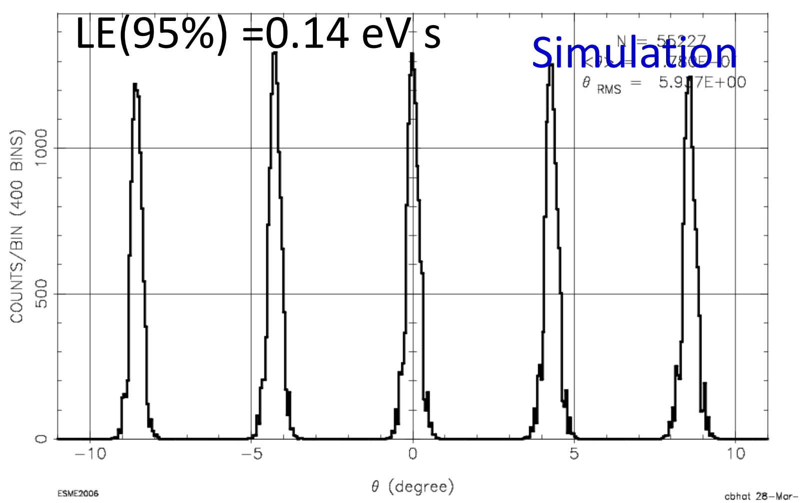
Studies with Different Intensities



Beam Emittance

Near Extraction





14BT,dE=+/−0.81MeV@400 MeV,Inj@−35us wrt Bdot=0, M
EV(1) VS TIME

RF Voltage