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Early Beam Injection Scheme for the Fermilab Booster: A Path for Intensity Upgrade

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Abstract: Over the past six years Fermilab has put a lots of effort on intensity frontier and is committed to increase the average beam power to the neutrino and muon programs substantially . Many upgrades to the existing injector accelerators are in progress under the Proton Improvement Plan (PIP). Proton Improvement Plan –II proposes to build an 800 MeV LINAC (that adopts super conducting RF technology) adding to the existing facility in the complex. In any case, the Fermilab Booster, an 8 GeV injector to 120 GeV Main Injector, is going to play very significant role for nearly next two decades. In this context, very recently we have proposed a new beam injection scheme called "early injection scheme" for the Fermilab Booster that has a high potential to increase the beam intensity output from the Booster, resulting in increased beam power to the HEP experiments. The scheme, if implemented, could also help improve the slip-stacking efficiency in the MI/RR with further gains in beam power. Here we present results from recent beam studies, current status of operational implementation and future plans for the early beam injection scheme.

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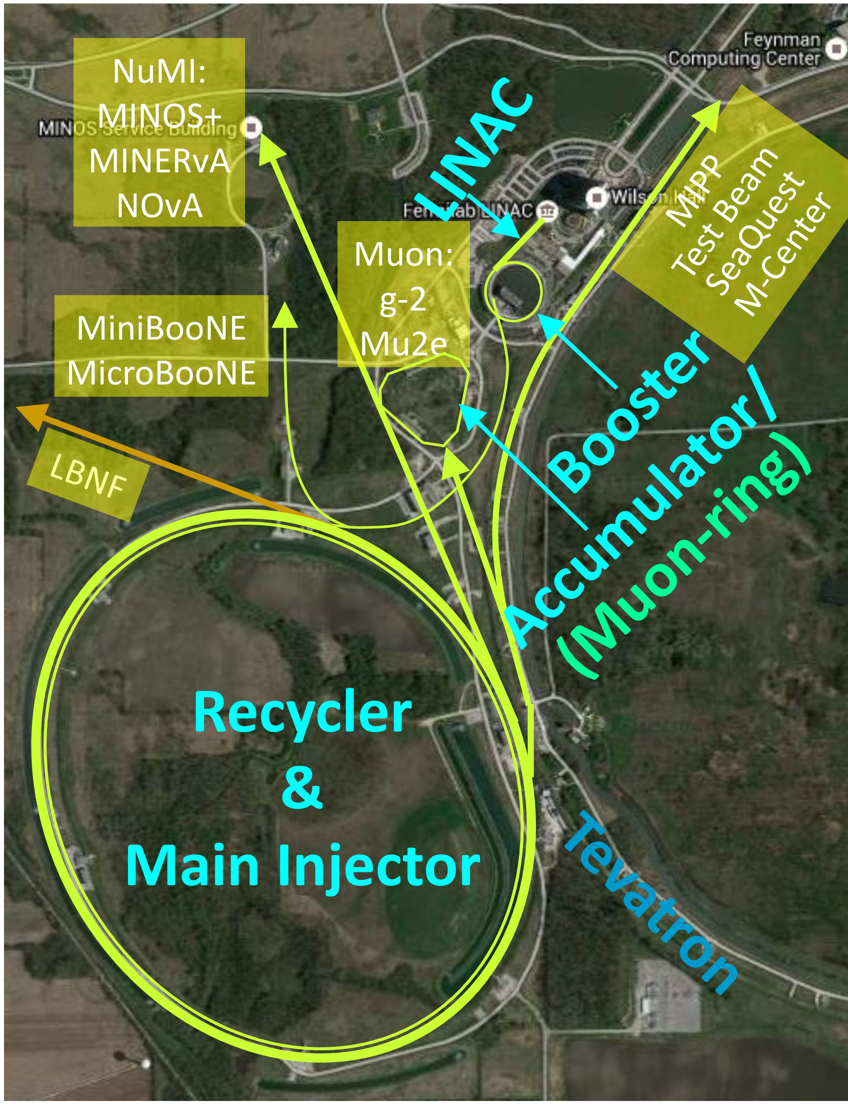
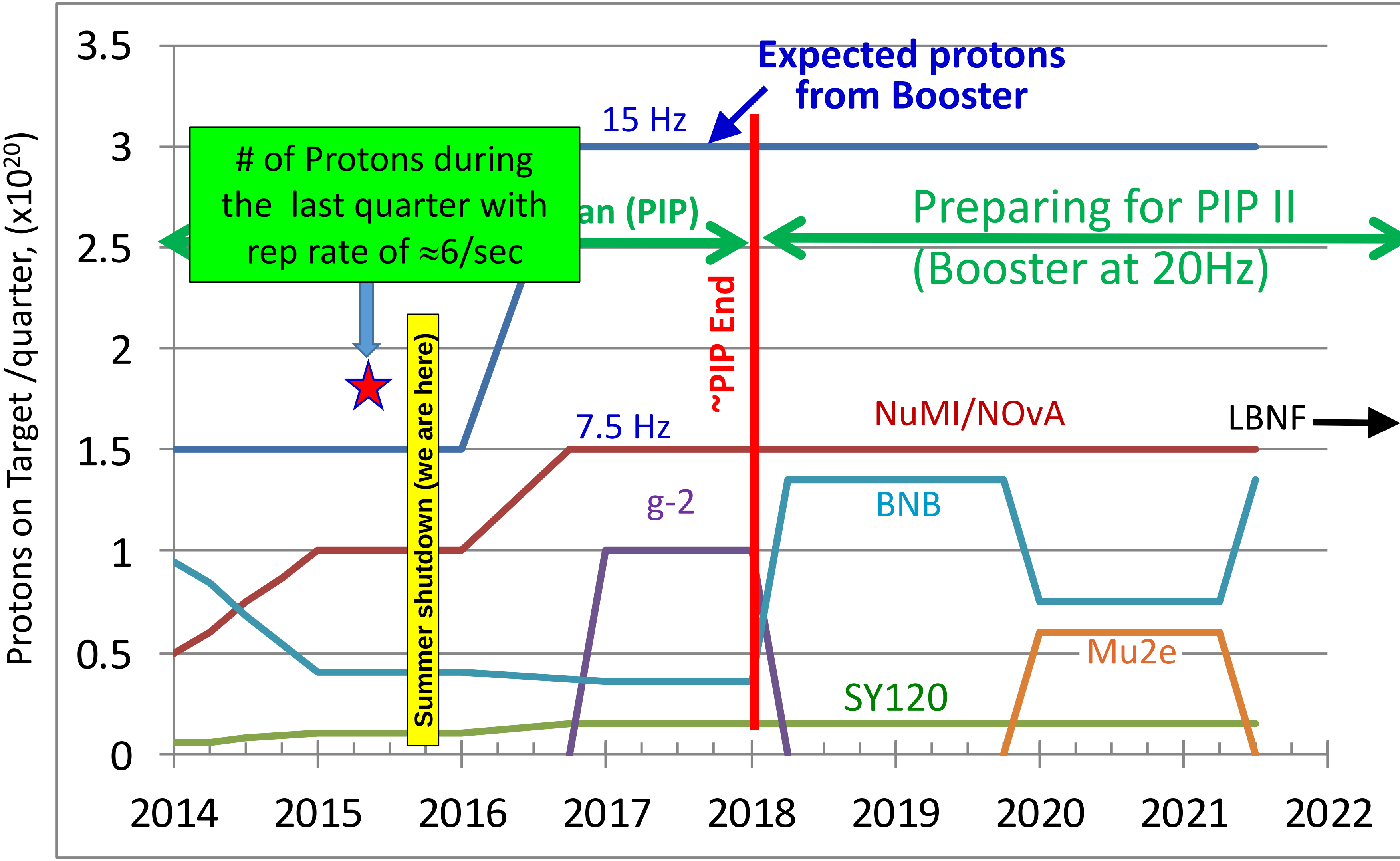


Booster:
0.4-8 GeV
Accelerator

Recycler:
8 GeV
Permanent
Magnet Storage
Ring

Main Injector:
8 -120 GeV
Accelerator

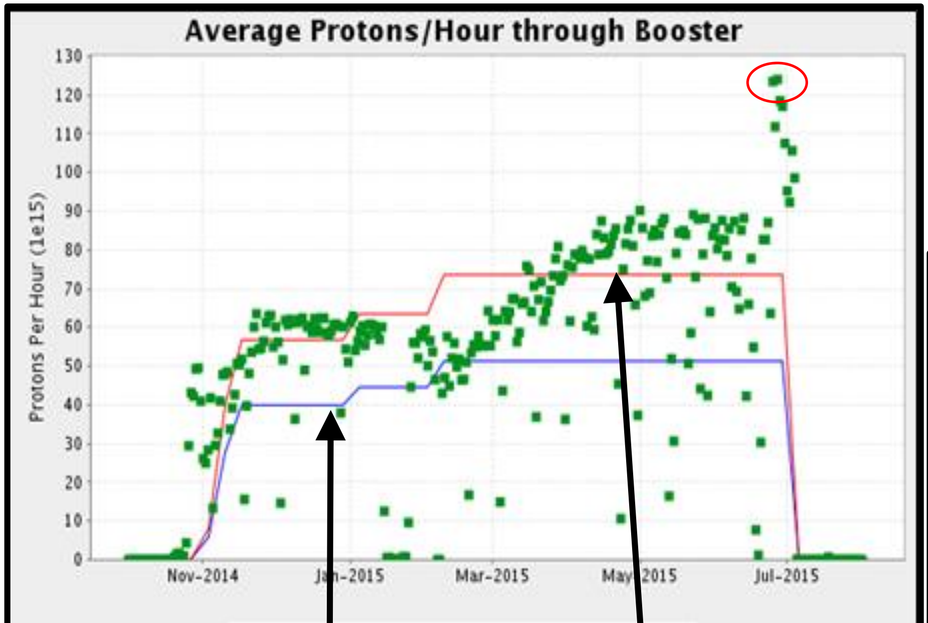
Proton Delivery Scenario from the Booster
(approximate)

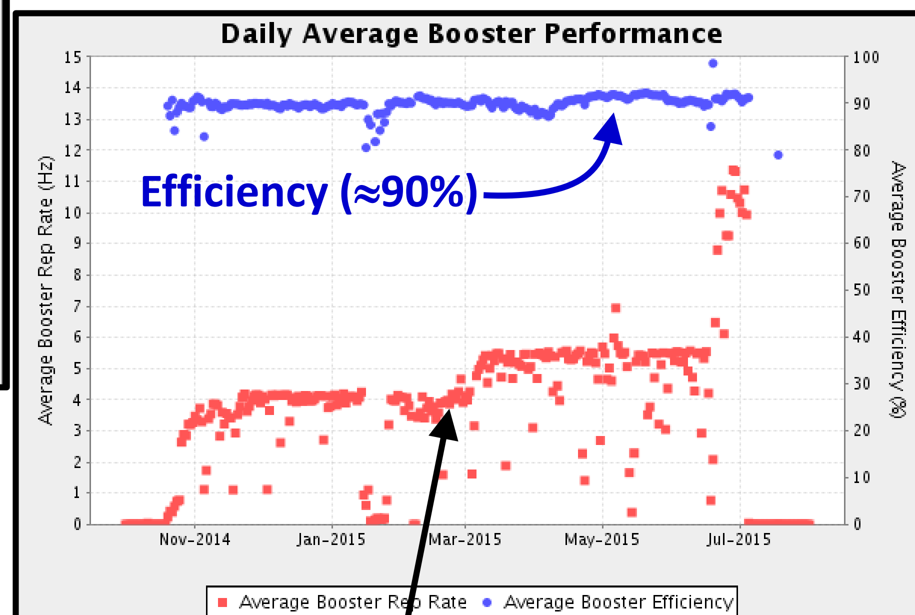


From Bill Pellico

Record 1.25x10^{17} protons/hour on July 24, 2015

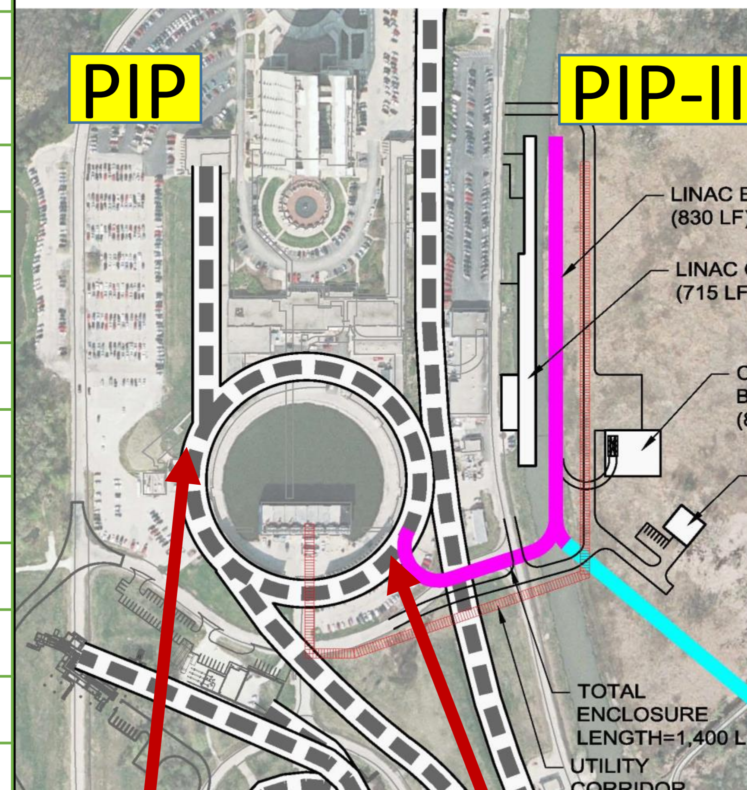
(previous record 1.1x10^{17} protons/hour)





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

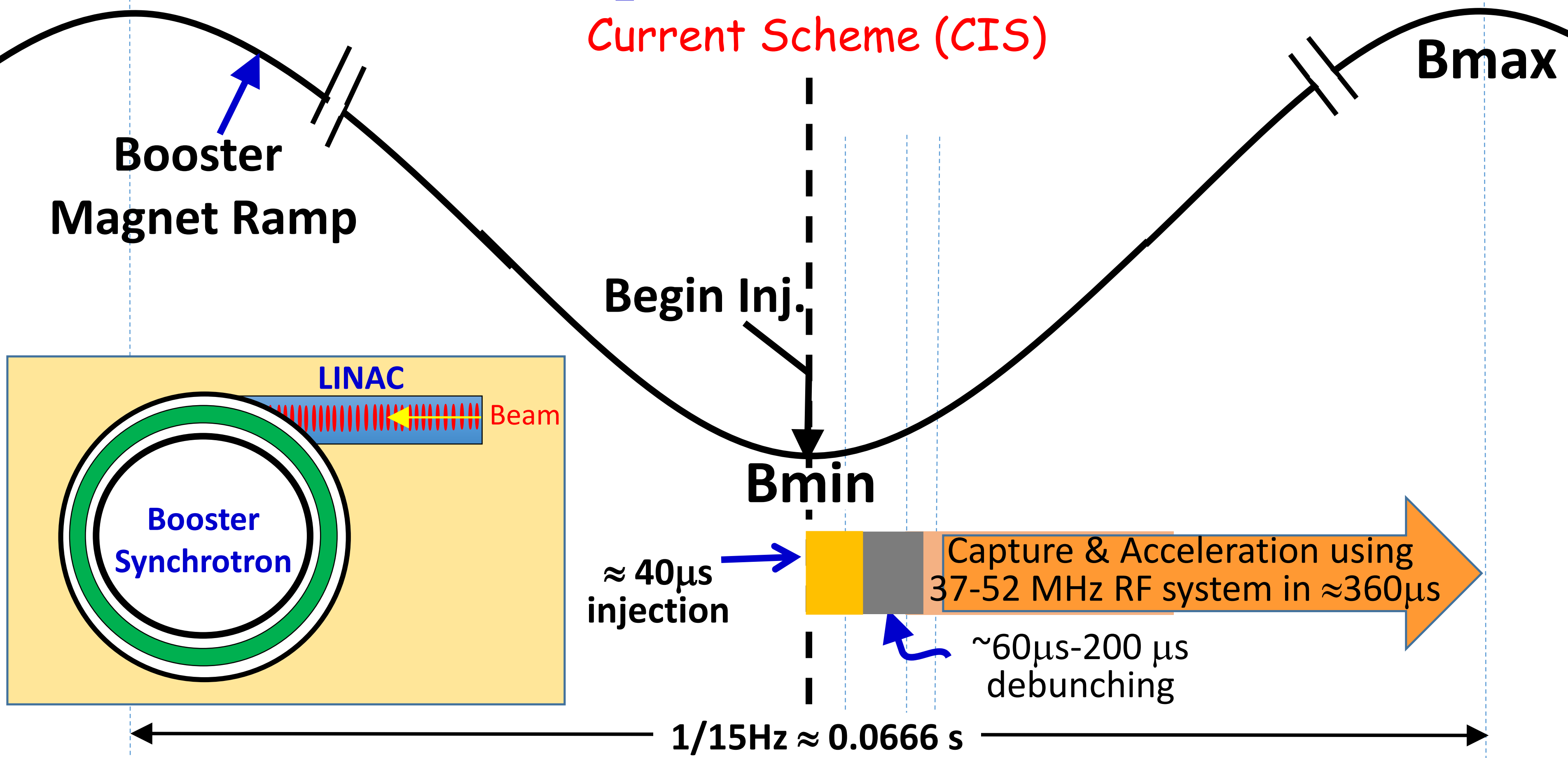
Are there innovative ways to increase the Booster beam before PIP-II era?

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

Schematic of the

Beam Injection in the Booster

Current Scheme (CIS)



<u>Issues:</u> A limited time for Beam Capture & Acceleration. RF manipulations are non-adiabatic ← ~50% emittance dilution, 10% beam loss and large RF power

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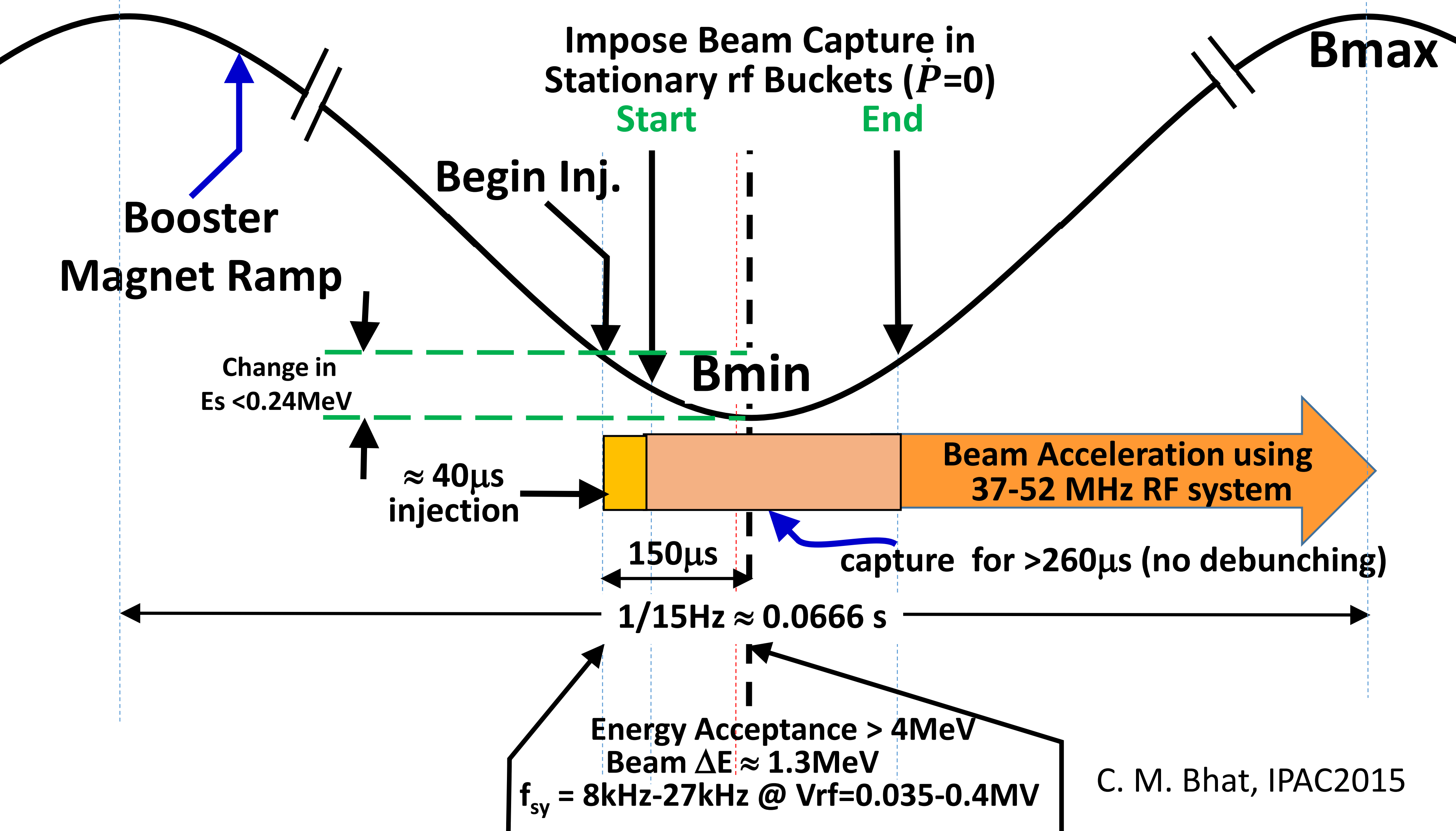
Schematic of the
Early Injection Scheme for the Booster



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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.

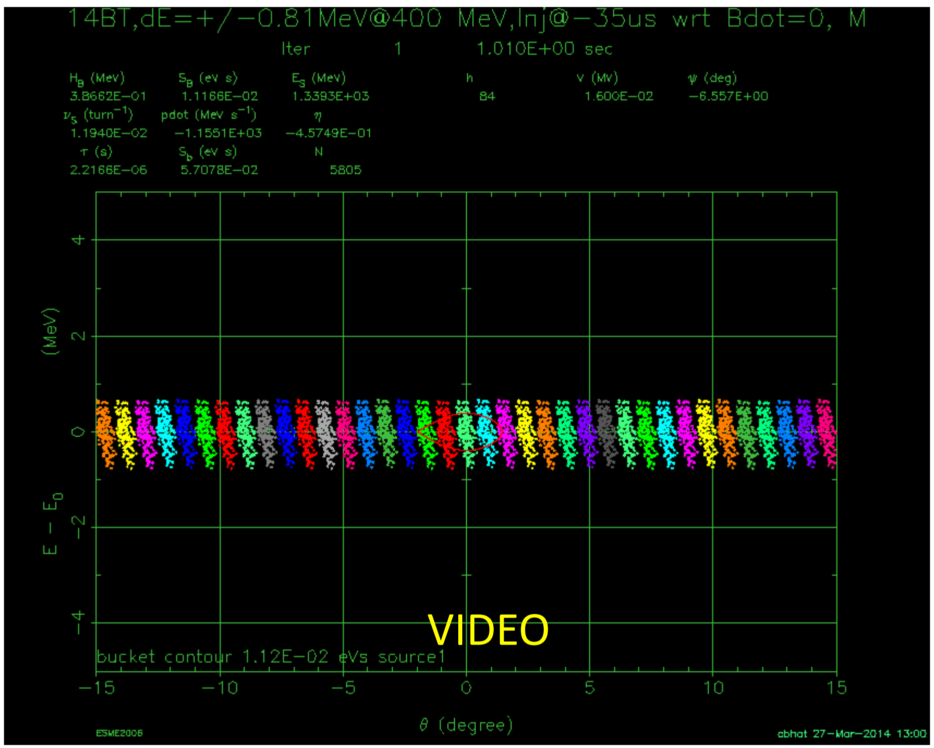
  Historically, it was believed that the capture and acceleration efficiencies in the Booster will be optimal if beam is injected close to $\dot{B}$ = 0.

- 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 ≈ 8-27kHz for Vrf=0.034-0.34MV, iso-adiabatic capture of all beam needs only ≈ 260μs.
  - Preserving the longitudinal emittance at capture means less rf voltage through the acceleration cycle ← Lesser RF power
  - Better beam for slip-stacking.

Beam Simulations from Injection → Extraction

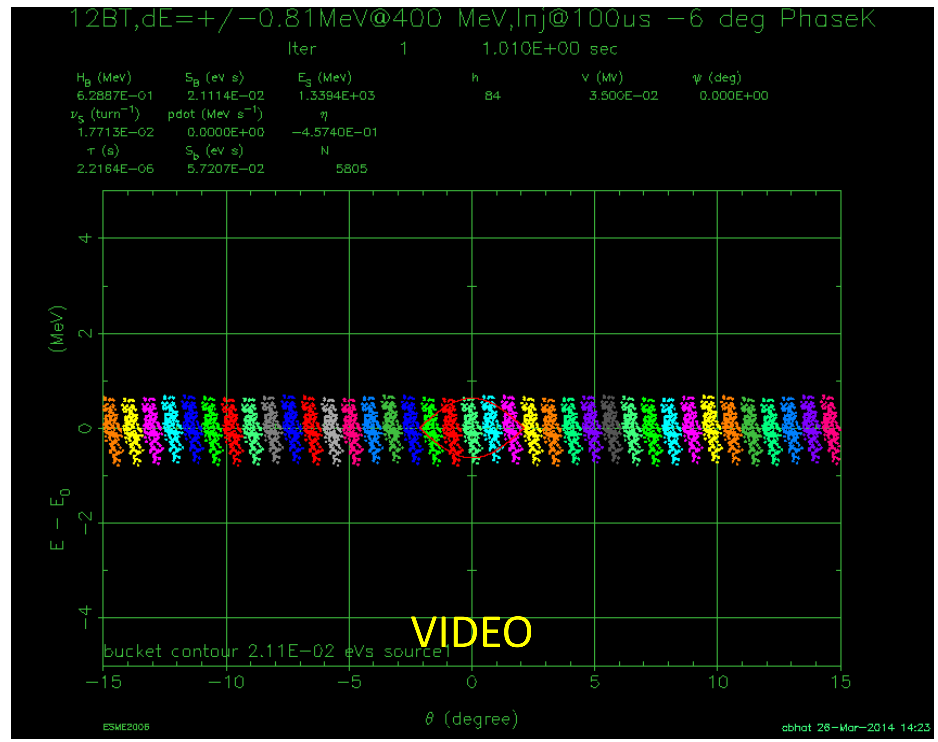
(Evolution of Phase space Distribution)

Current Injection Scheme



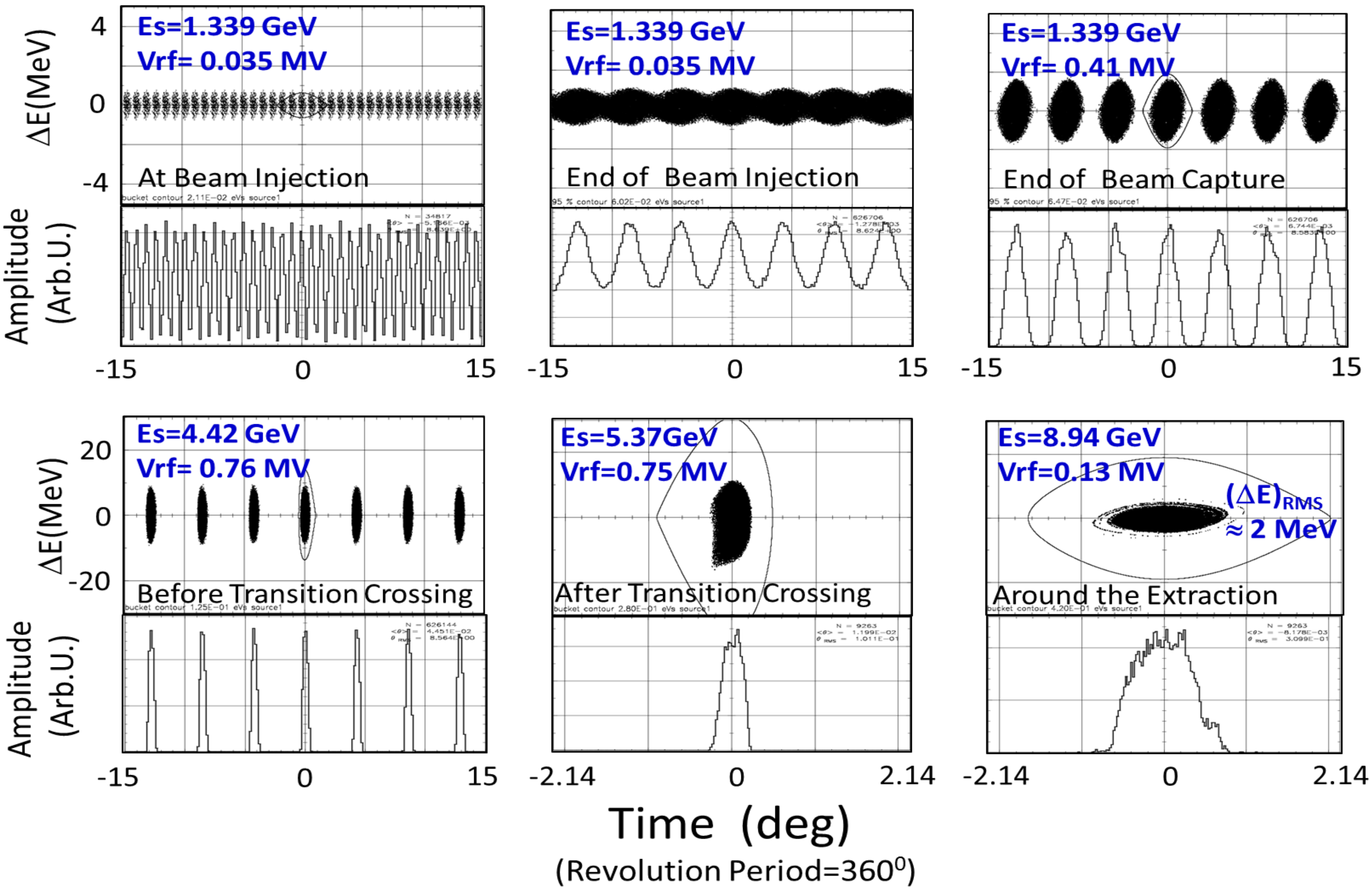
Early Injection Scheme

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.



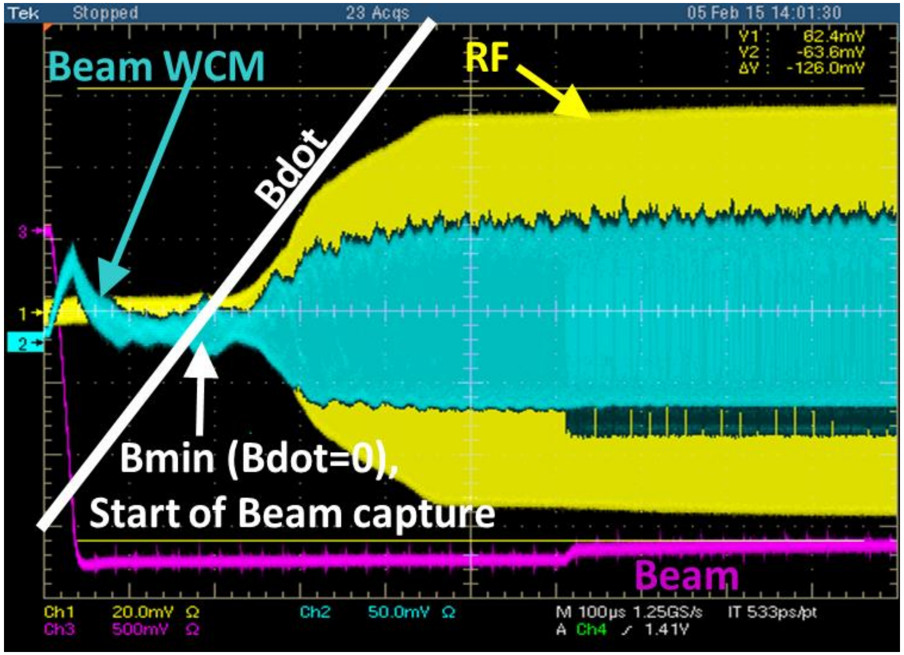
Beam Simulations from Injection → Extraction

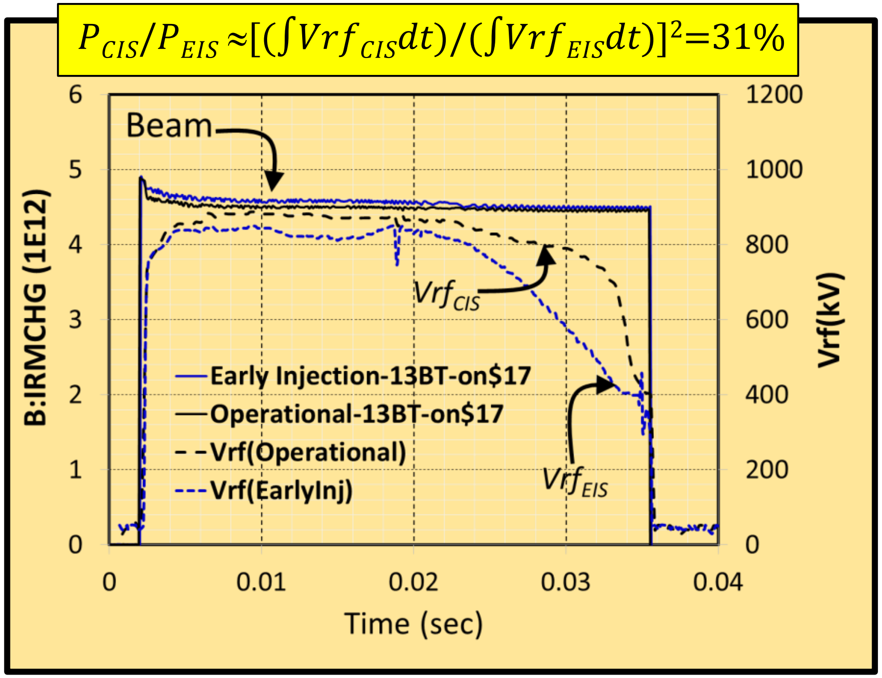
with 2E10-12E10p/bunch



"Proof of Principle" Experiment

- ❑ Beam studies were conducted in the Booster
- ❑ Beam injection at 144 μs earlier than BDOT=0.0. While in normal operation beam is injected ≈ 0.0 μs
- ❑ New Radial-position, Paraphase and Simulated Vrf curves used
- ❑ Transition crossing ← Needed additional tuning





Implications

- 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.

Tasks under Development

- Beam capture soon after the completion of the beam injection,
- A better frequency synchronization between the LLRF and real frequency.
- 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.

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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 ($2\pi R$) [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

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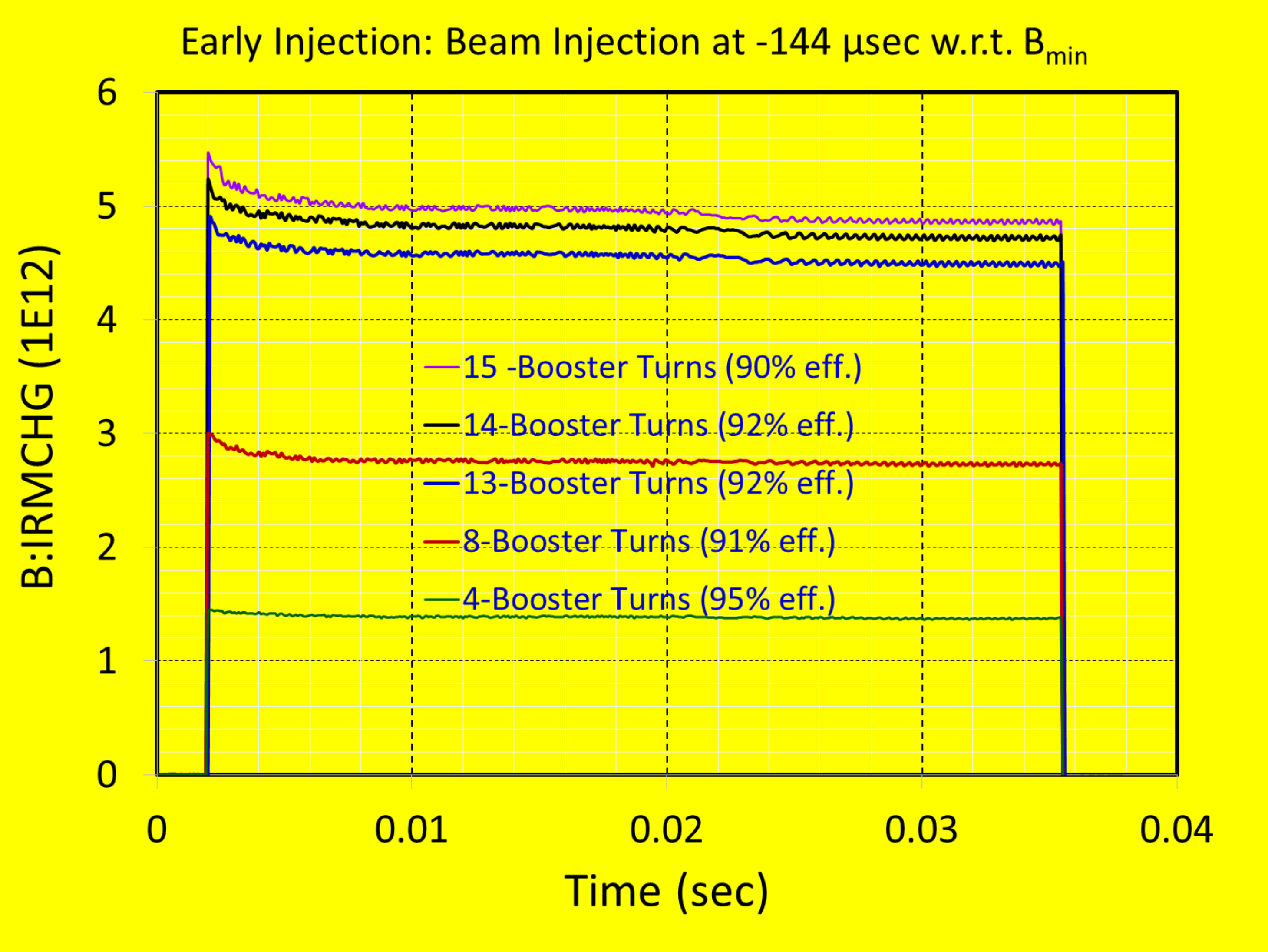
Laslett SC tune shift

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

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



Samples of Transverse Beam Sizes for the First 2 ms
(Nothing Unusual)

Data are for 14BT beam