



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

Chandra Bhat

Fermi National Accelerator Laboratory

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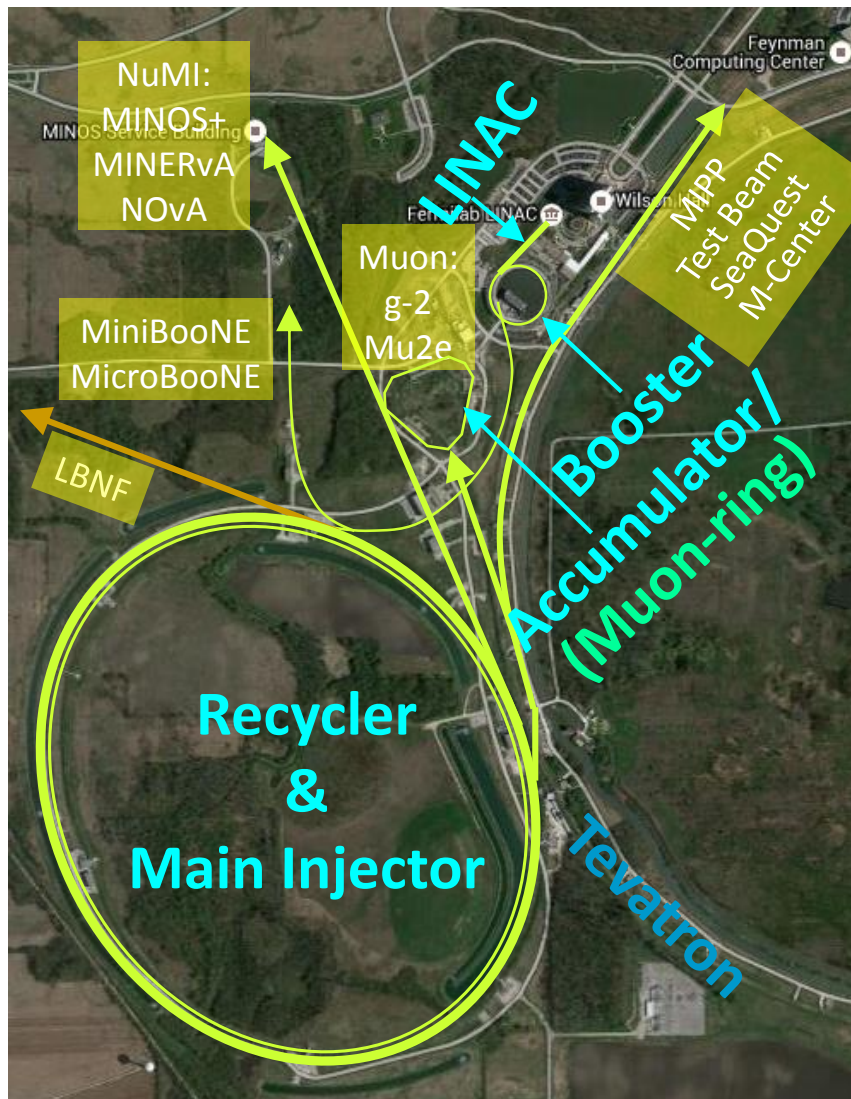
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# Acknowledgements



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K. Triplett, S. Chaurize,  
B. Hendrick, and  
T. Sullivan

# Fermilab, US Premier Particle Physics Laboratory



**Booster:**  
0.4-8 GeV  
Accelerator



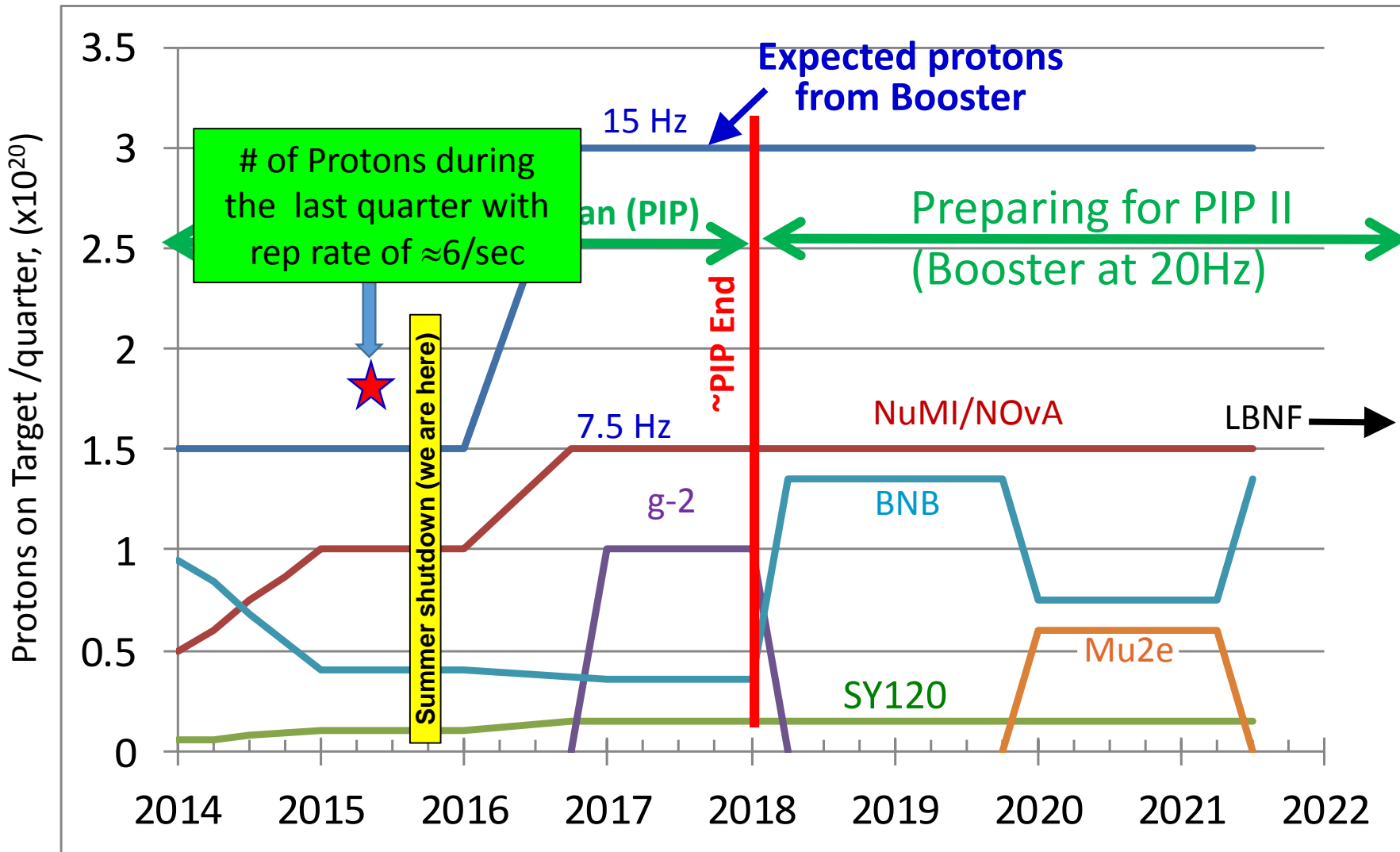
**Recycler:**  
8 GeV  
Permanent  
Magnet Storage  
Ring



**Main Injector:**  
8 -120 GeV  
Accelerator

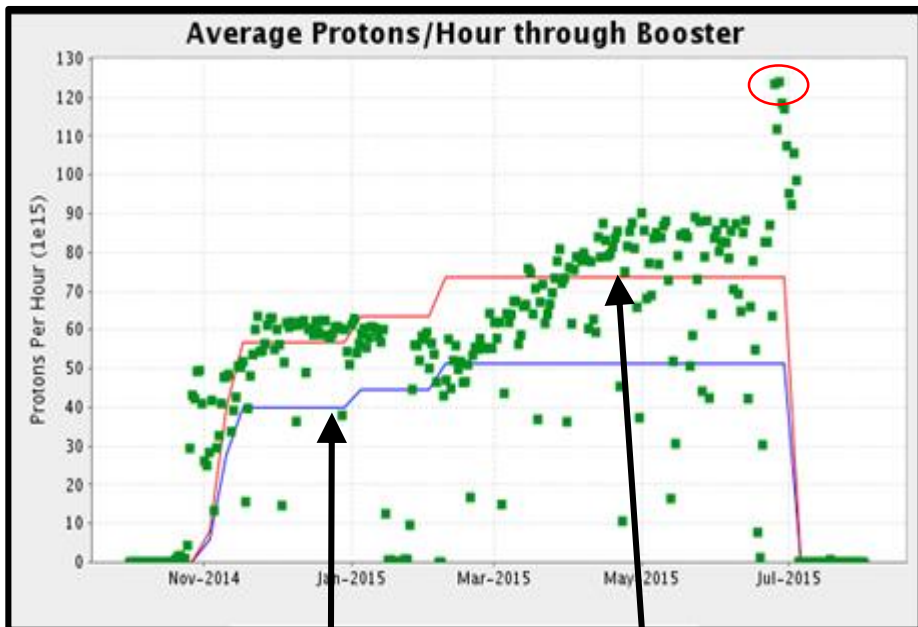
# Proton Delivery Scenario from the Booster

(approximate)



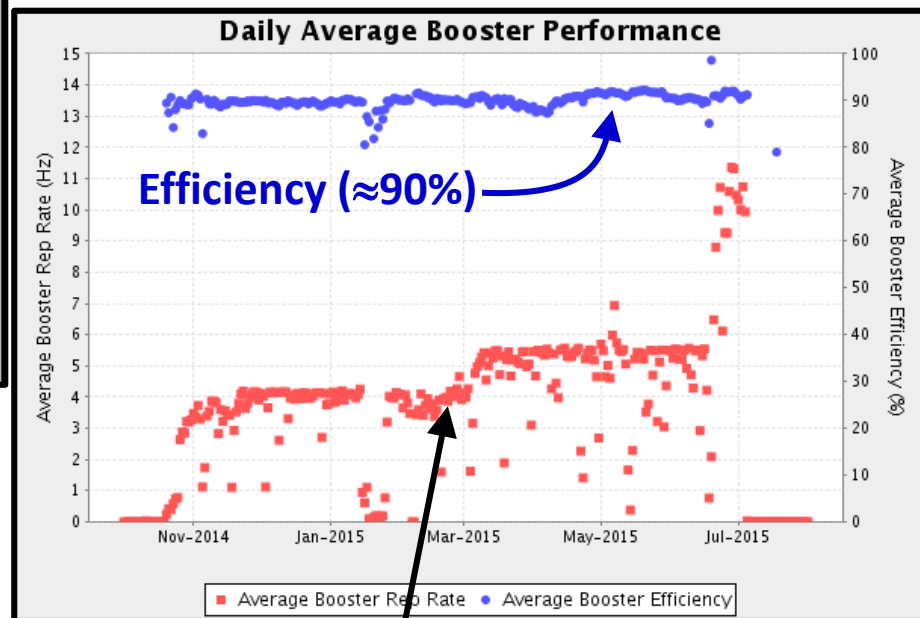
# Record $1.25 \times 10^{17}$ protons/hour on July 24, 2015

(previous record  $1.1 \times 10^{17}$  protons/hour)



**Base**

**Design**



**Efficiency (≈90%)**

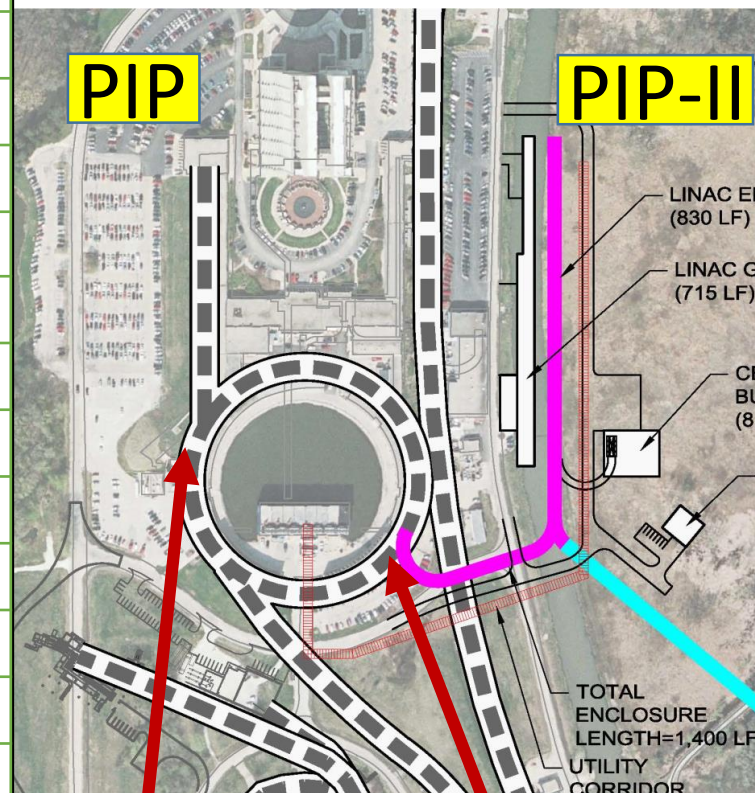
**Average rep. Rate**



# 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 per 1.33 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



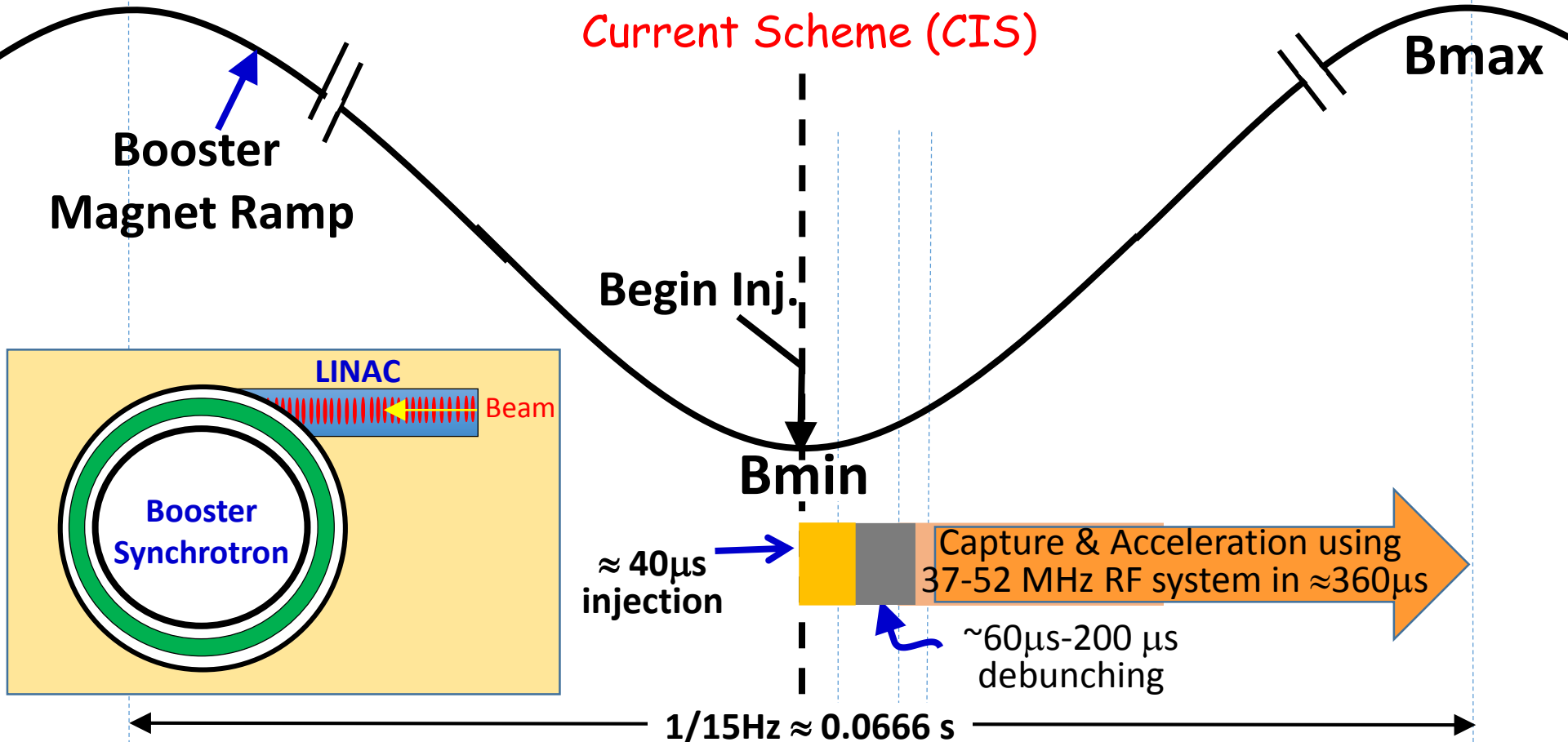
# Are there innovative ways to increase the Booster beam before PIP-II era?

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



# Schematic of the Beam Injection in the Booster

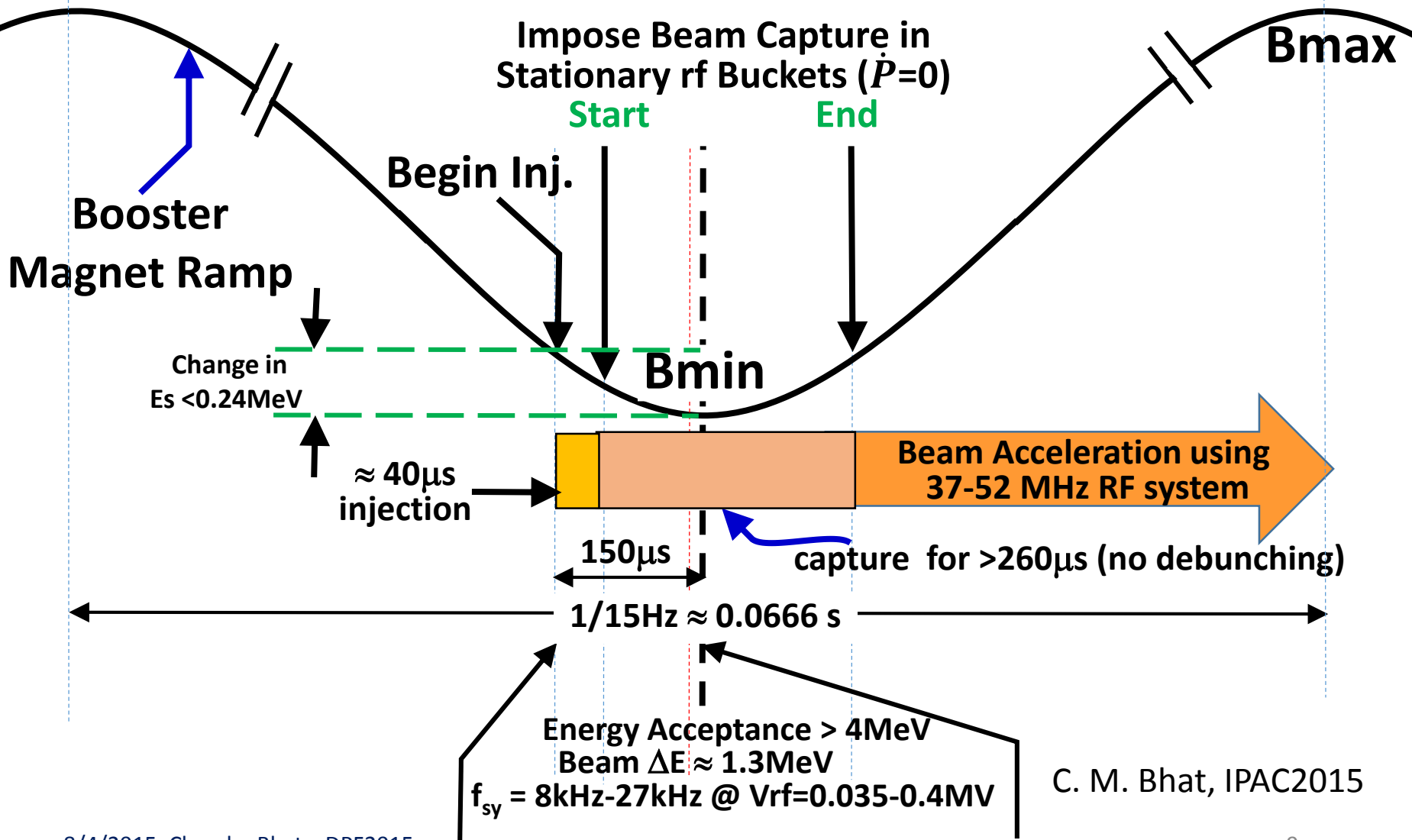
Current Scheme (CIS)



**Issues:** A limited time for Beam Capture & Acceleration. RF manipulations are non-adiabatic  $\leftarrow$   $\sim 50\%$  emittance dilution, 10% beam loss and large RF power



# Schematic of the Early Injection Scheme for the Booster



C. M. Bhat, IPAC2015

# 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  $f_s \approx 8\text{-}27\text{kHz}$  for  $V_{rf}=0.034\text{-}0.34\text{MV}$ , iso-adiabatic capture of all beam needs only  $\approx 260\mu\text{s}$ .
- 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 $\rightarrow$ Extraction

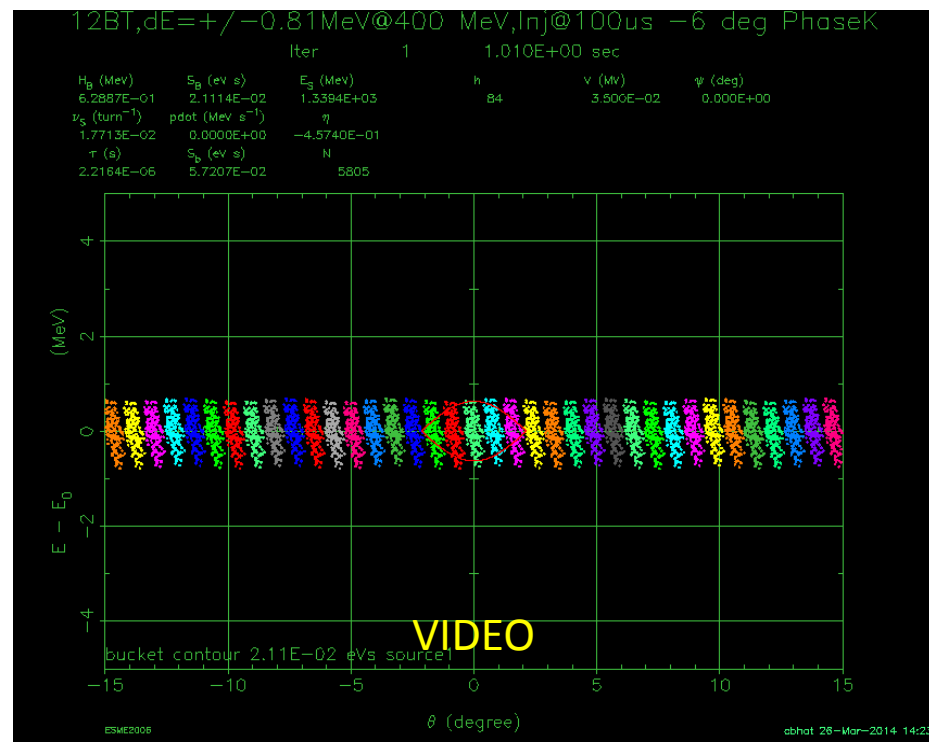
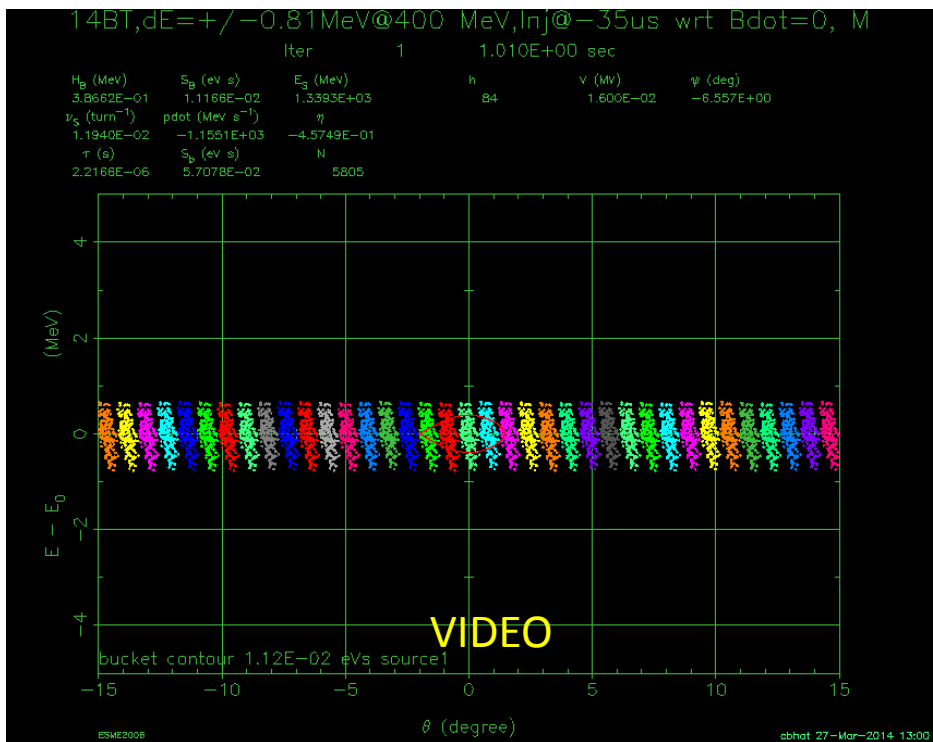
(Evolution of Phase space Distribution)



## Current Injection Scheme

## Early Injection Scheme

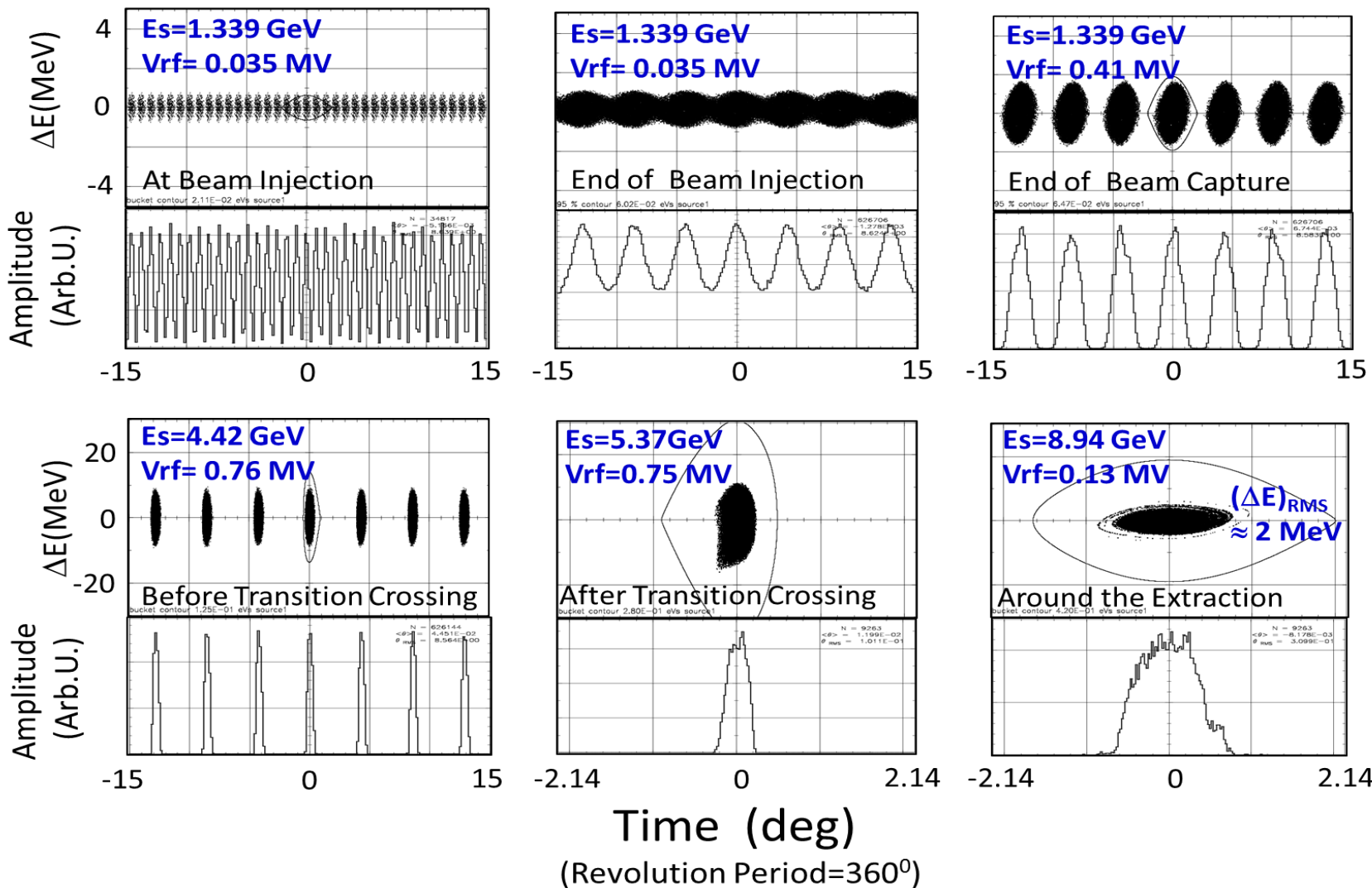
Inj. @ at  $-100\mu\text{s}$  w.r.t.  $\dot{B} = 0$ , Capture from  $-64\mu\text{s}$  to  $135\mu\text{s}$ , with a phase kick of  $\sim 6$  deg after transition crossing.



# Beam Simulations from Injection $\rightarrow$ Extraction



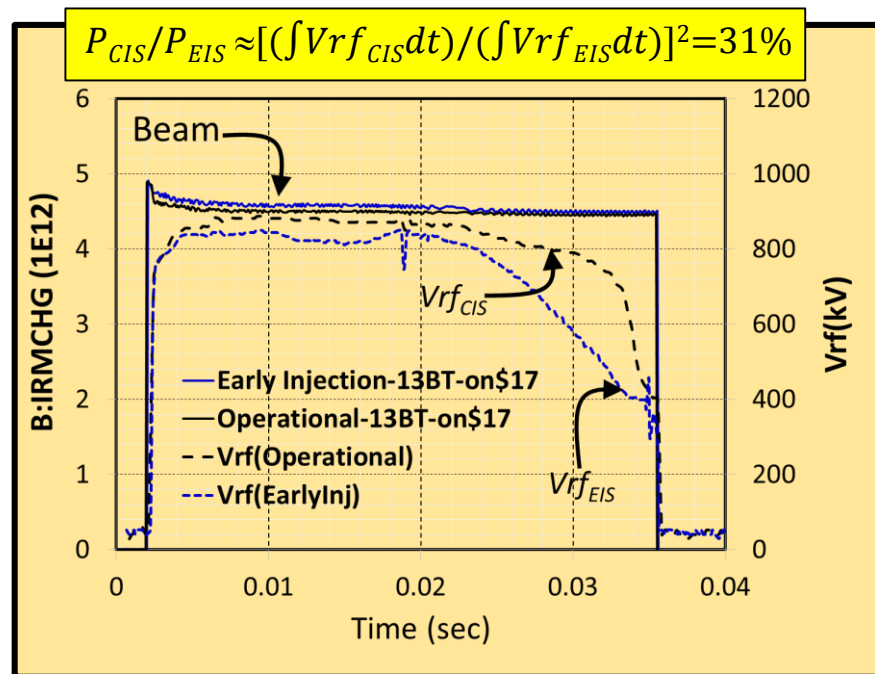
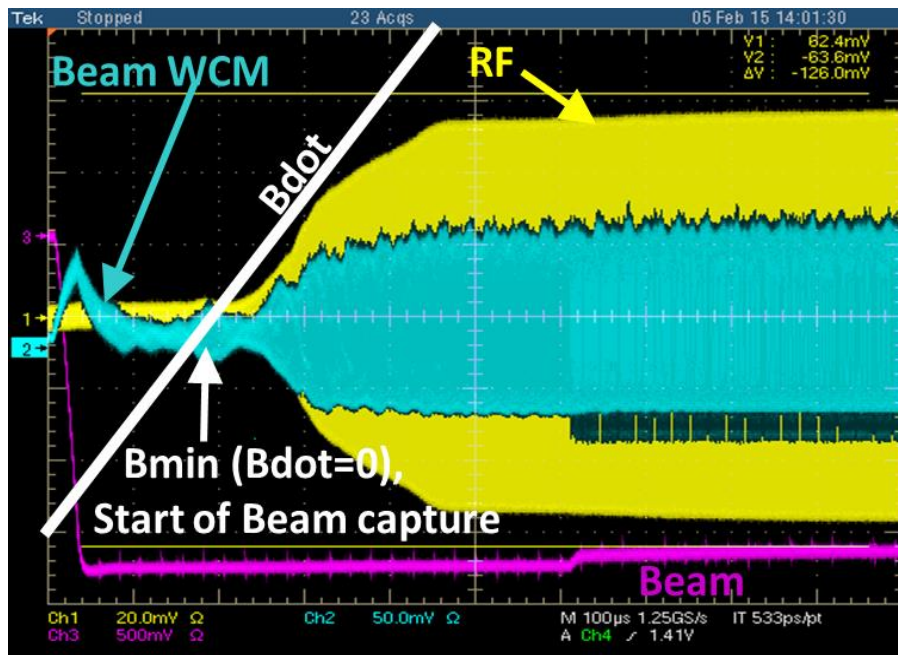
with  $2E10$ - $12E10$ p/bunch



# "Proof of Principle" Experiment



- ❑ Beam studies were conducted in the Booster
- ❑ Beam injection at 144  $\mu\text{s}$  earlier than  $\text{BDOT}=0.0$ . While in normal operation beam is injected  $\approx 0.0 \mu\text{s}$
- ❑ New Radial-position, Paraphase and Simulated Vrf curves used
- ❑ Transition crossing  $\leftarrow$  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.

# 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 $\rightarrow$ 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. $\dot{B} = 0$ [ $\mu$ sec]	0, -90, -144
Harmonic Number	84
Transition Gamma $\gamma_T$	5.478
$\Delta E$ at Injection [MeV]	1.6
Longitudinal Emittance [eV sec]	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



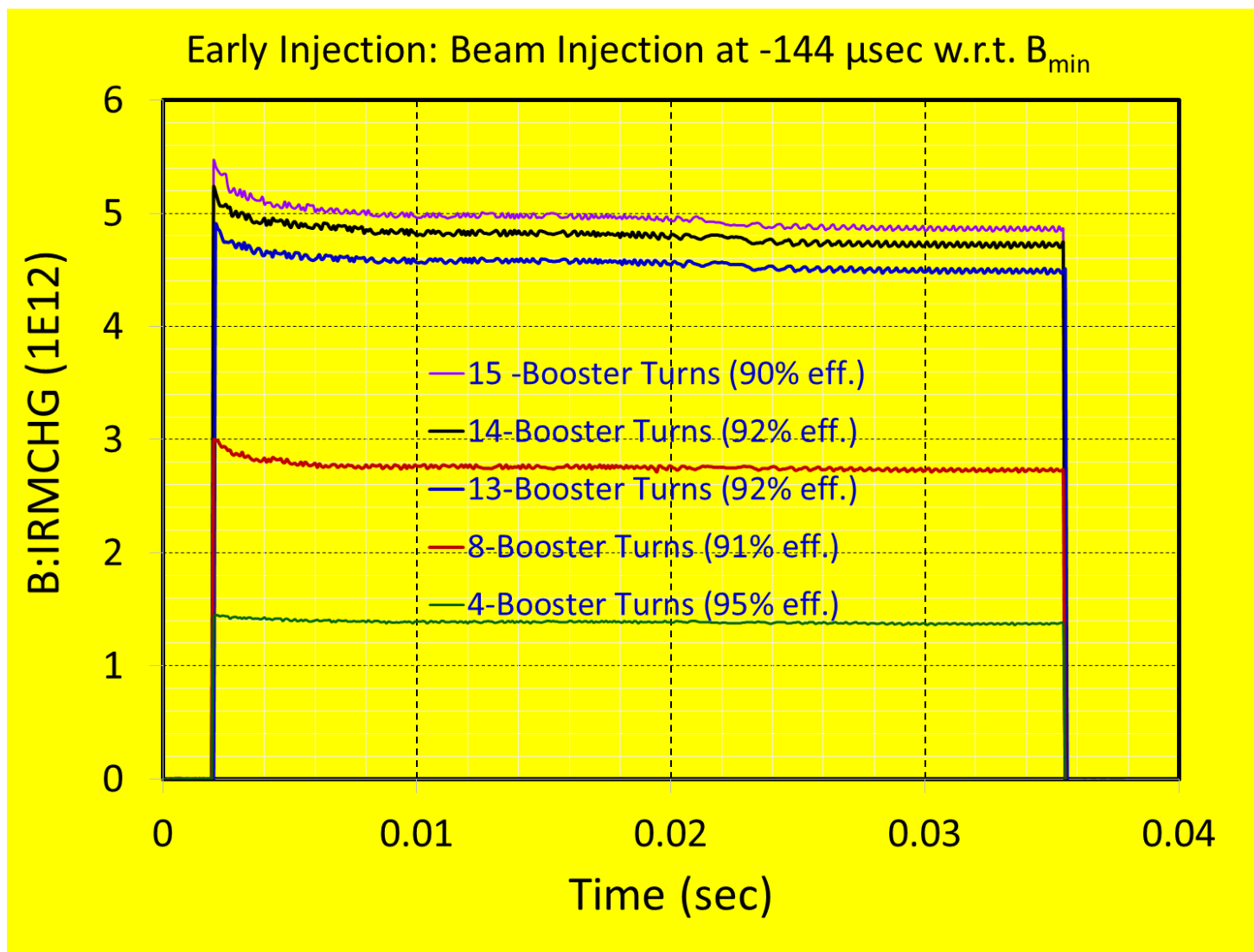
# Laslett SC tune shift



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

where  $N_{tot}$  is total number of particles in the ring,  $r_c = 1.53 \cdot 10^{-18}$ m for protons,  $\varepsilon_n$  is rms normalized emittance,  $\beta_p = v_p/c$  and  $\gamma_p$  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

