R&D on Beam Injection and Bunching Scheme in the Fermilab Booster

Chandra Bhat
Fermilab

Acknowledgements
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K. Seiya, F. Garcia, B. Hendricks, T. Sullivan and A. Waller

“HB2016, Malmö, Sweden, 3-8 July 2016”

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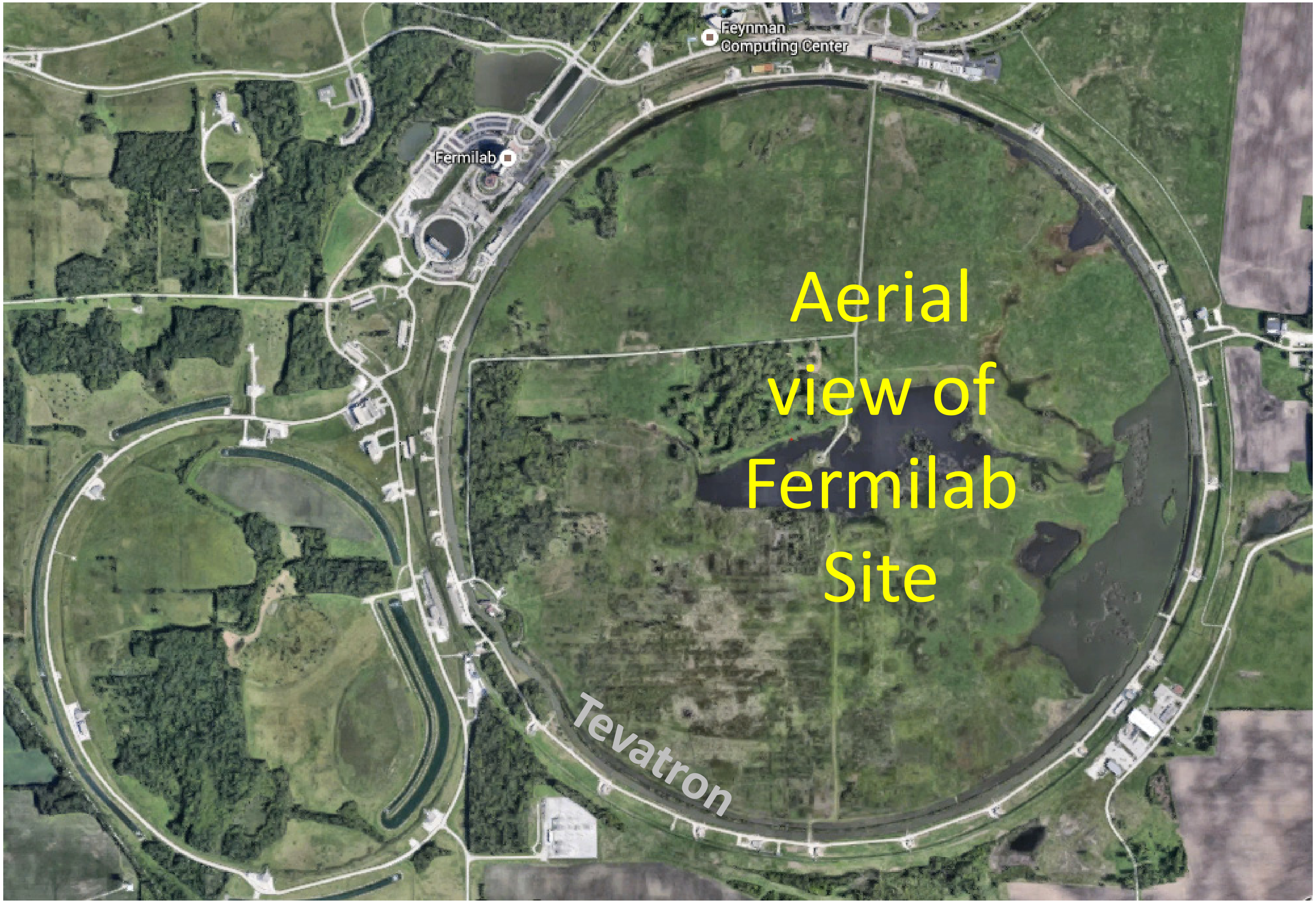

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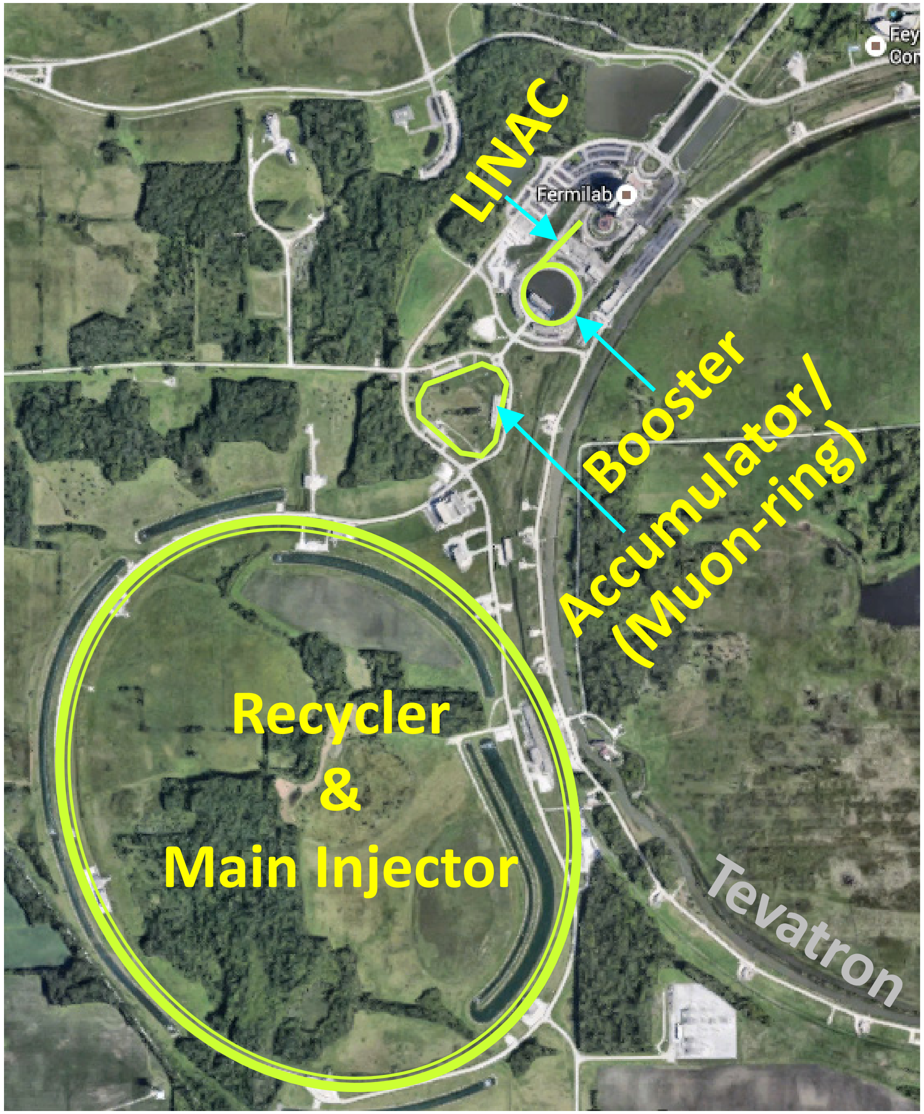
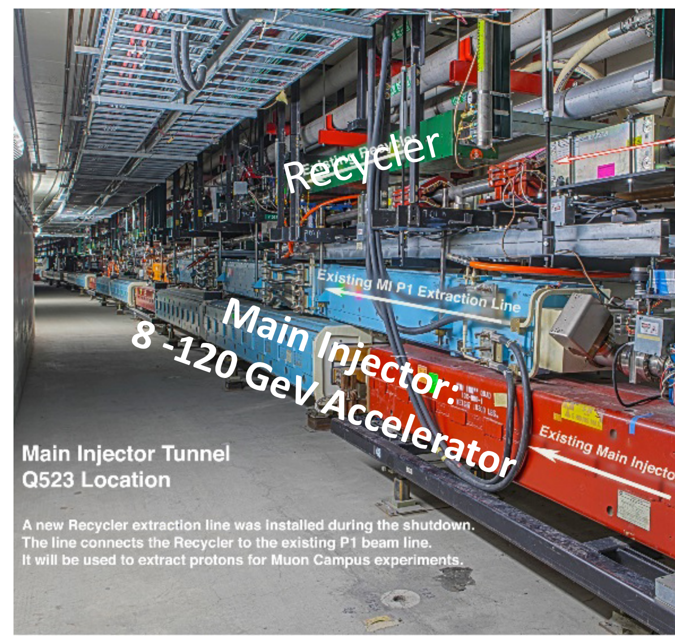


Booster: 0.4-8 GeV Accelerator



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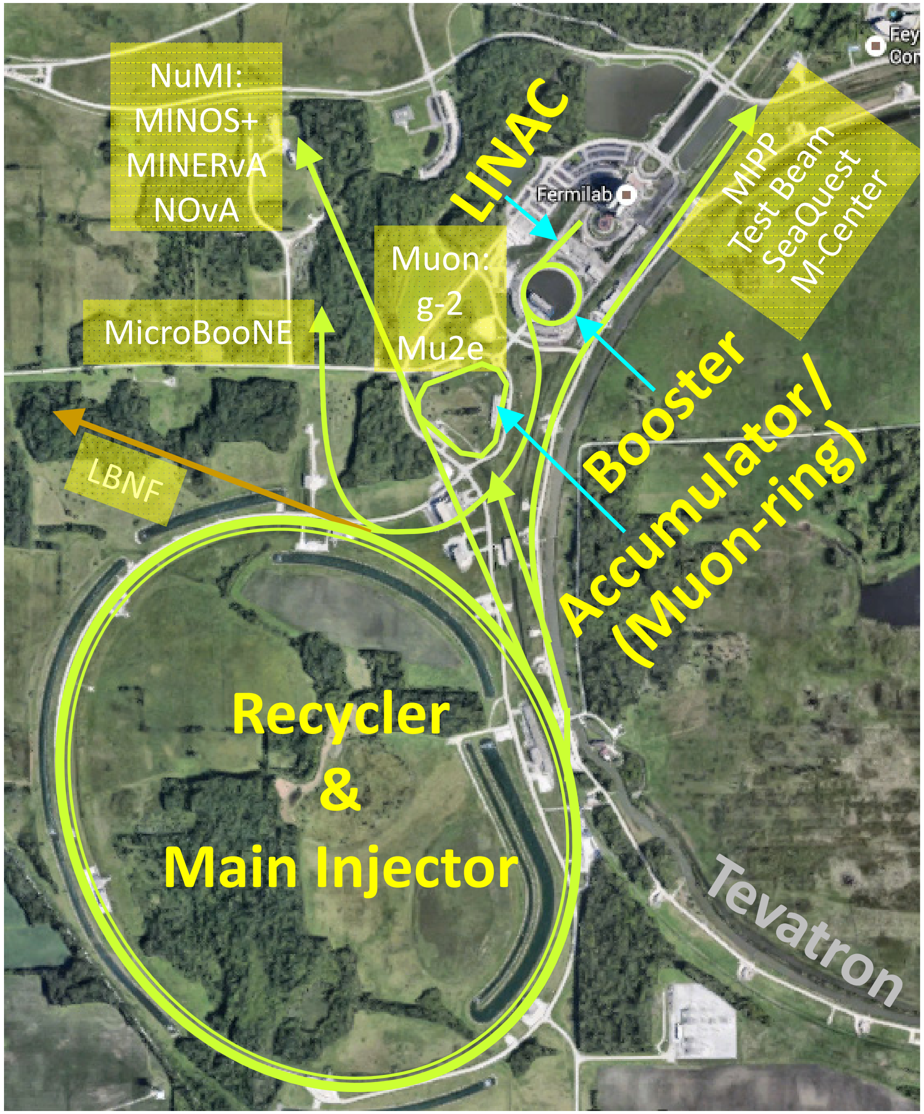

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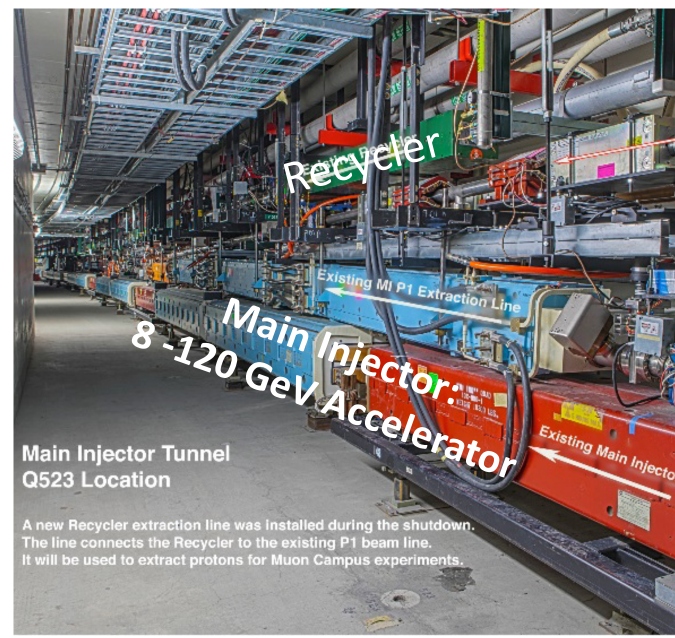
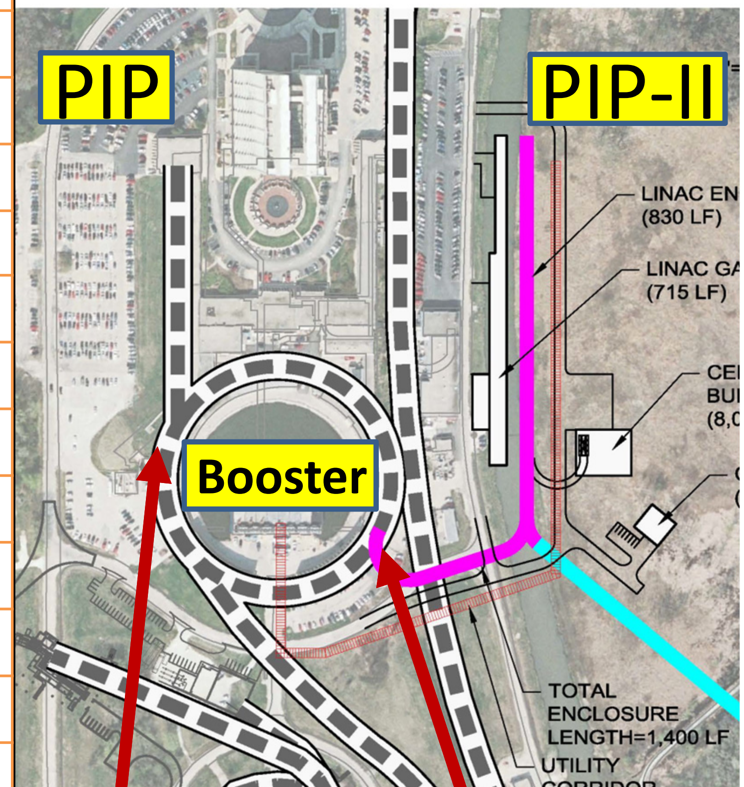


Upgrade Path for Power on Target

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	15 Hz	20 Hz
Booster Beam Power at Exit (kW)	94	184
MI batches	12 per1.33 sec	12 per 1.2 sec
NOvA beam power	700 kW	1200 kW
Rate availability for other users (Hz)	5	8
Booster flux capability (protons/hr)	~ 2.3E17	~ 3.5E17
Laslett Tune shift at Injection	≈- 0.072	≈ -0.105
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

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Booster repetition rate	15 Hz	20 Hz
Booster Beam Powe	[illegible]	[illegible]
MI batches	12 per1.33 sec	12 per 1.2 sec
NOvA beam power	**701 kW**	1200 kW
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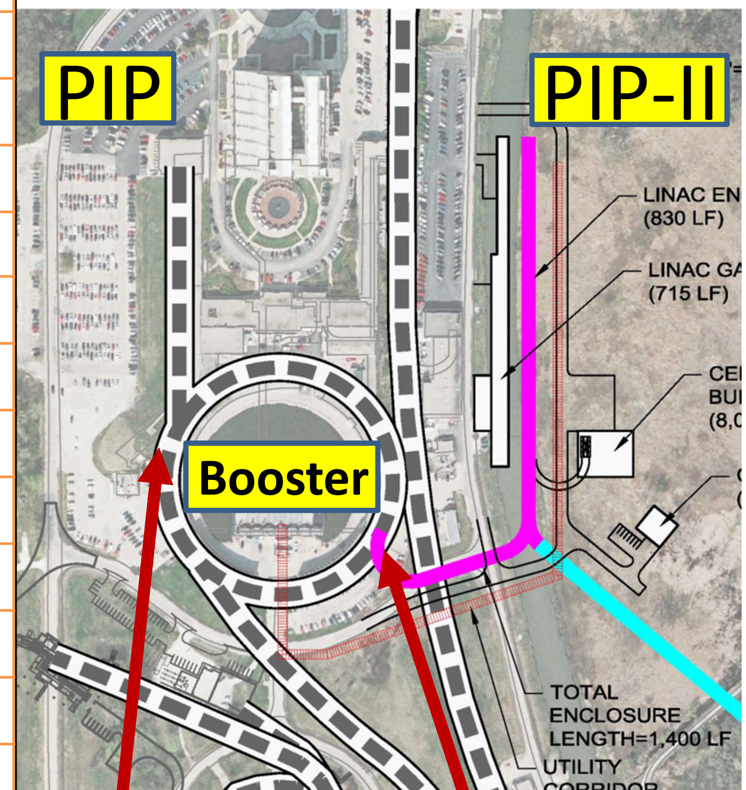
As of June 23 with & **EIS** in Operation we have reached



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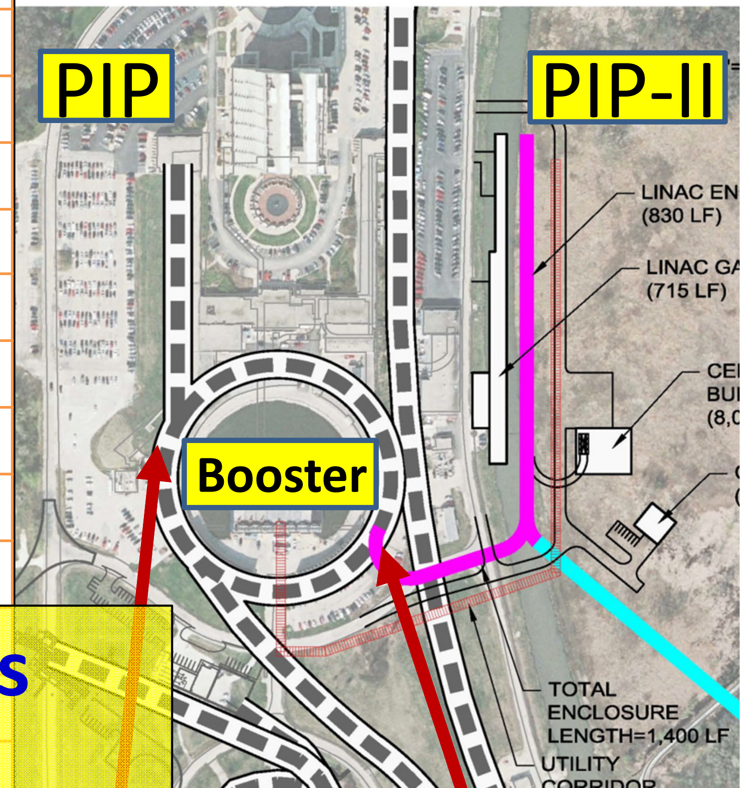
As of June 23 with & **EIS** in Operation we have reached

The Booster will remain as the workhorse in the Fermilab Accelerator Complex at least for next two decades



Present inj. point at L1

New inj. point at L11

Are there Innovative ways to Increase the Booster Beam Intensity beyond PIP?

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Are there Innovative ways to Increase the Booster Beam Intensity beyond PIP?

- New Injection and Bunching Scheme
- Beam Simulations
- New Scheme in Operation
- Issues and Mitigation ← Also Relevant to PIP-II
- Projections
- Summary

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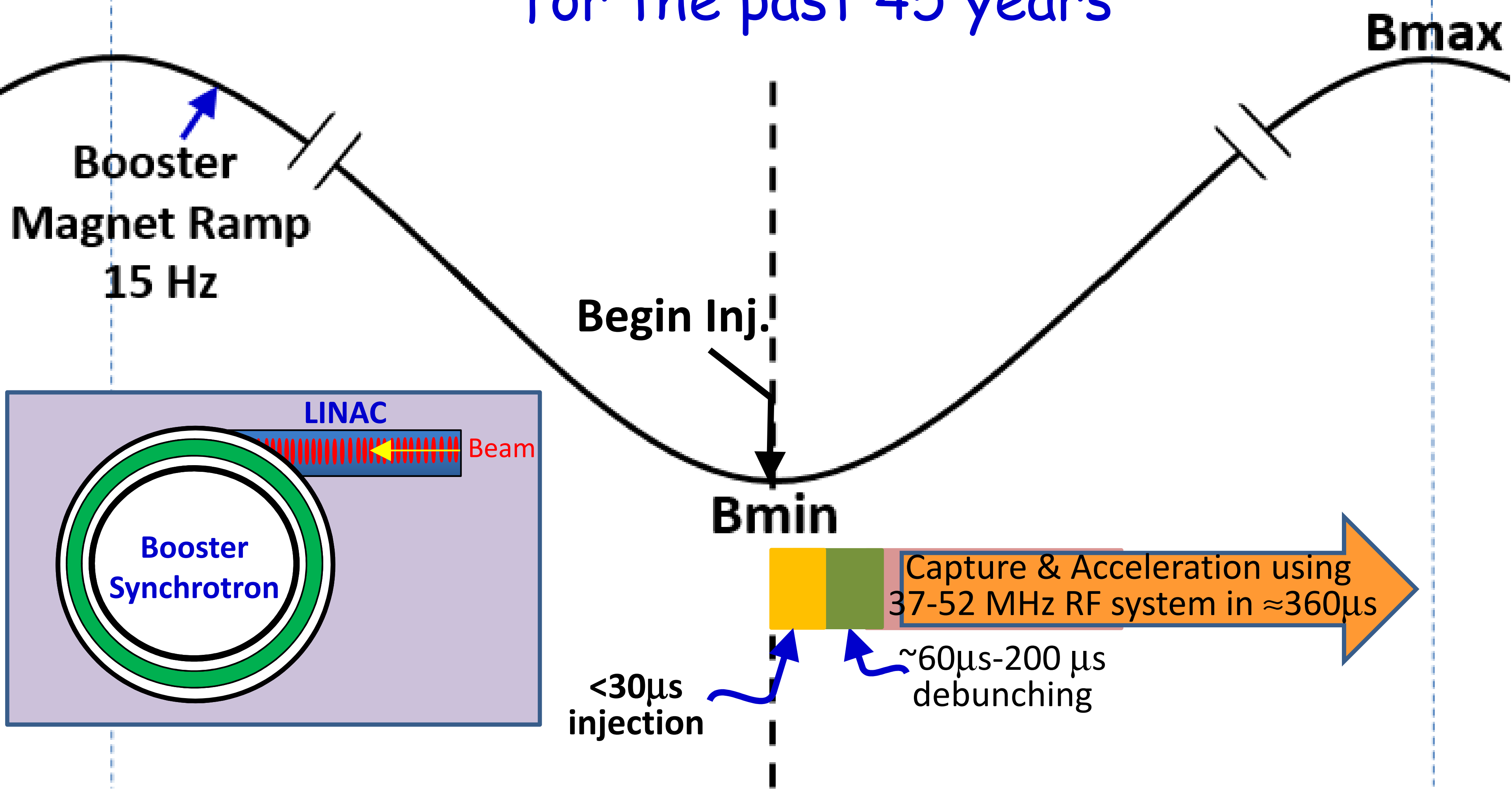
Beam Injection in the Booster for the past 45 years



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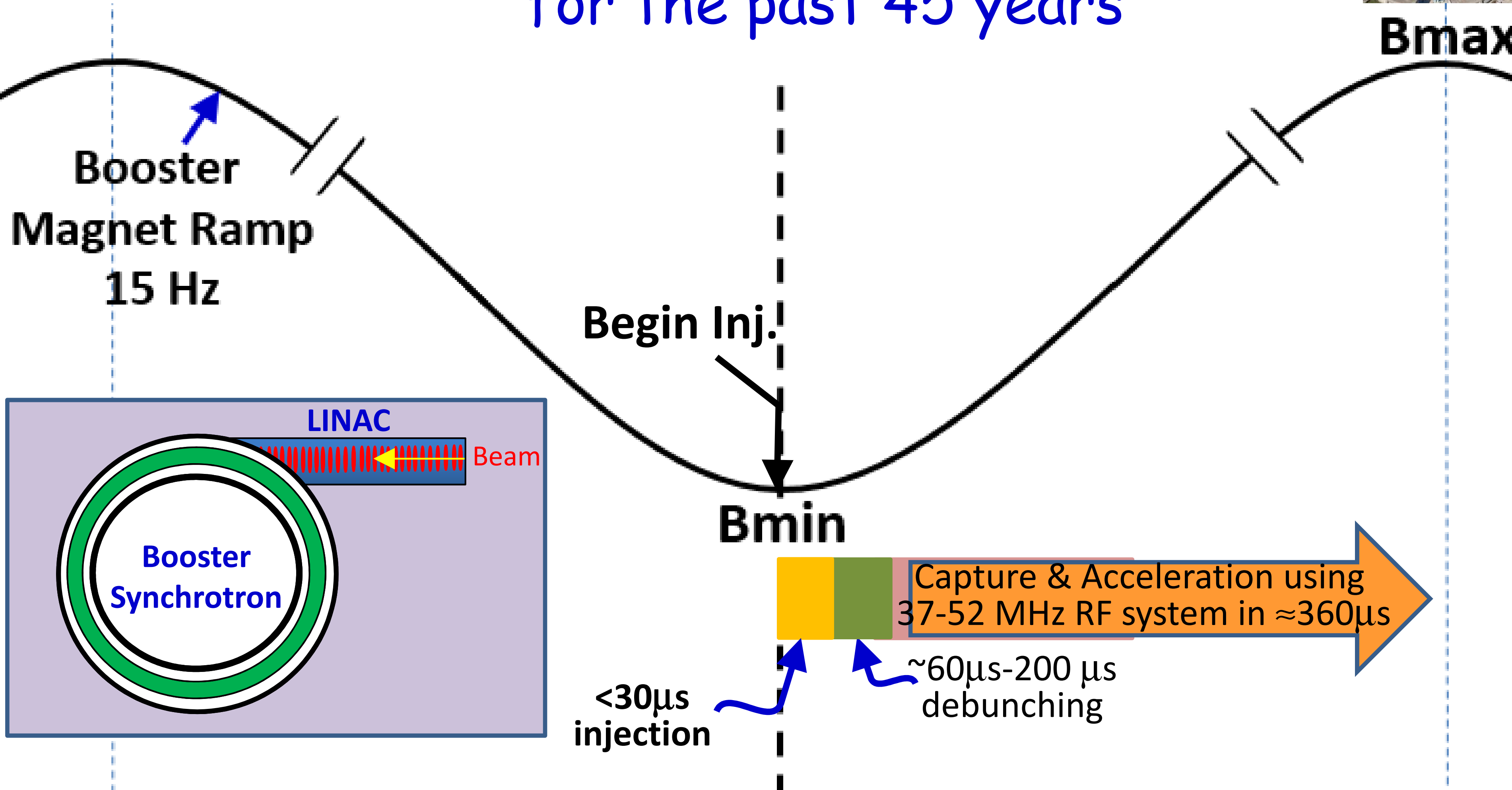
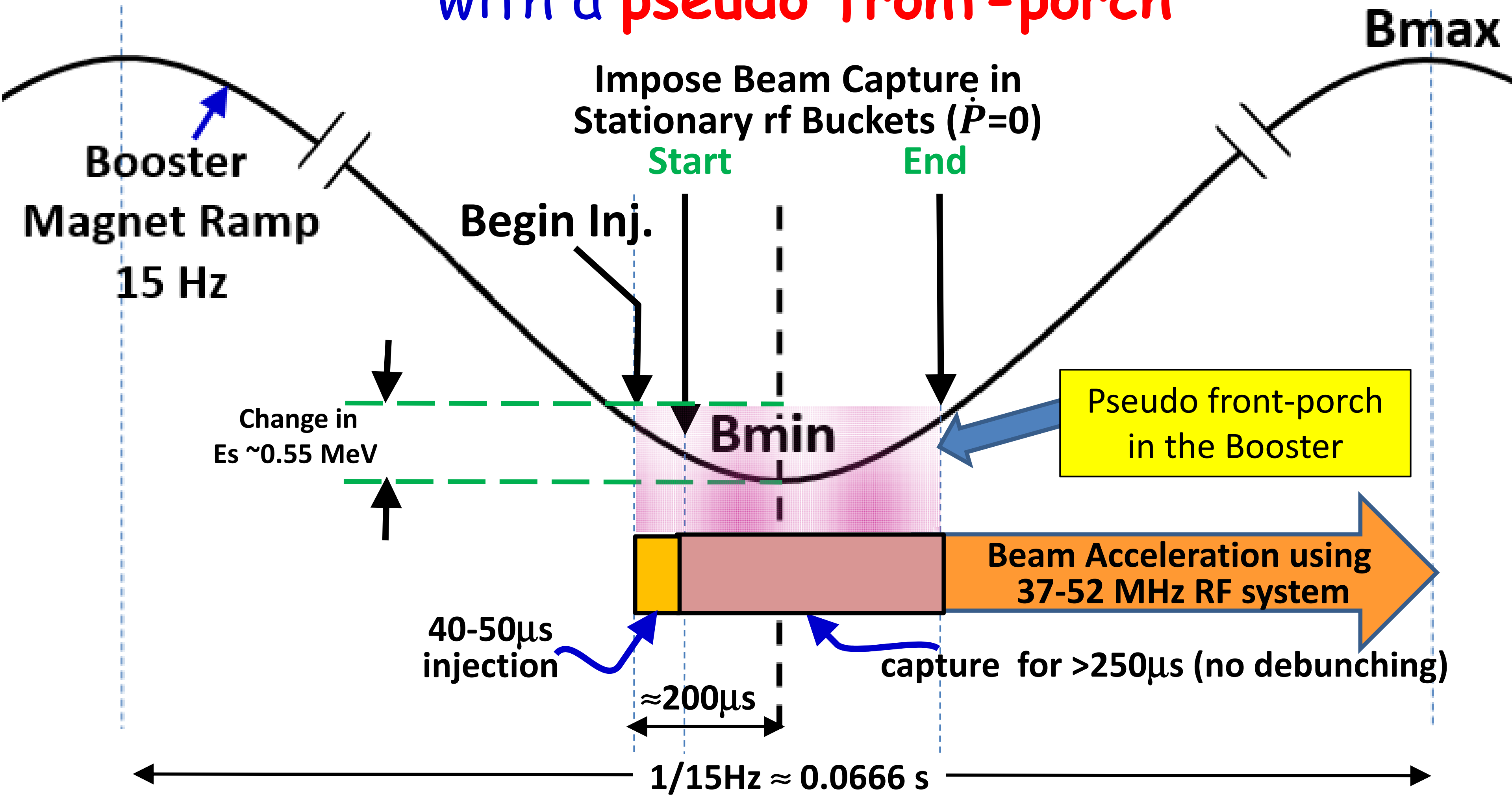


<u>Issues:</u> A limited time for Beam Capture & Acceleration. RF manipulations are non-adiabatic ← >100% emittance dilution, ~8-10% beam loss and large RF power

Schematic of the

Early Injection in the Booster with a pseudo front-porch



C. M. Bhat, IPAC2015

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Beam Injection & Capture

- Needs a good understanding of
  - Properties of the beam from the LINAC
    - Beam Energy Spread, *ΔE (full)*
    - H and V Transverse Emittances
  - Acceptance at Injection
    - Momentum Acceptance in the Booster
    - Transverse Acceptance

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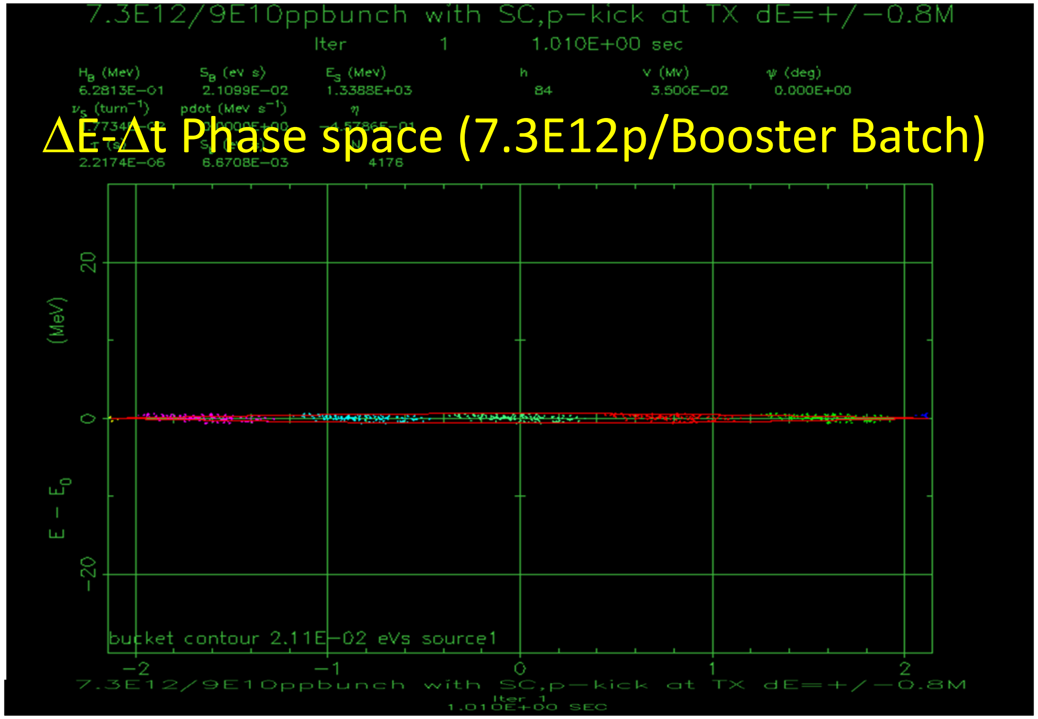
Beam Injection & Capture

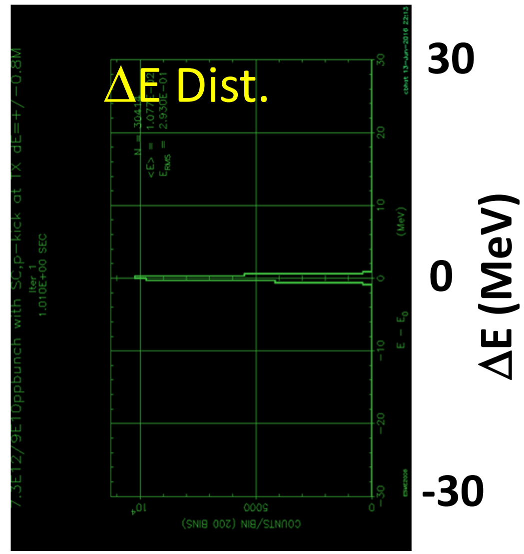
- Needs a good understanding of
  - Properties of the beam from the LINAC
    - Beam Energy Spread, *ΔE (full)* ⇐ =1.25 MeV
    - H and V Transverse Emittances

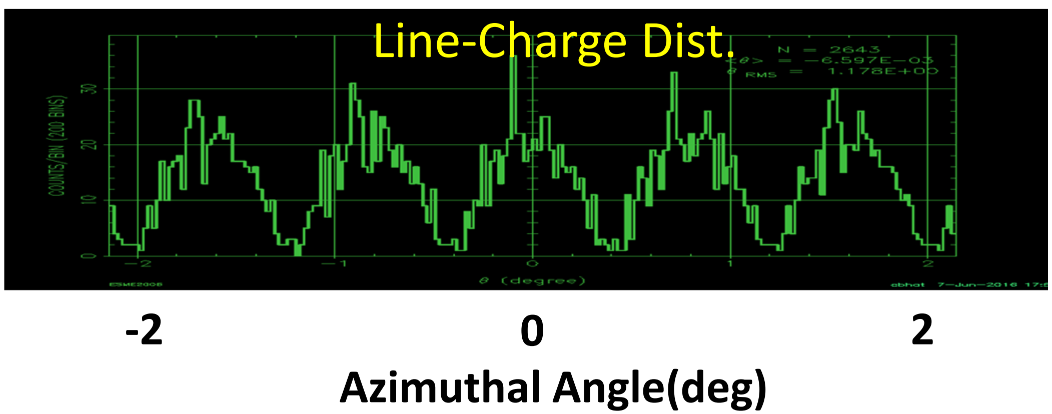
    i.e., εl(Inj)≈ 0.033 eVs/Bunch

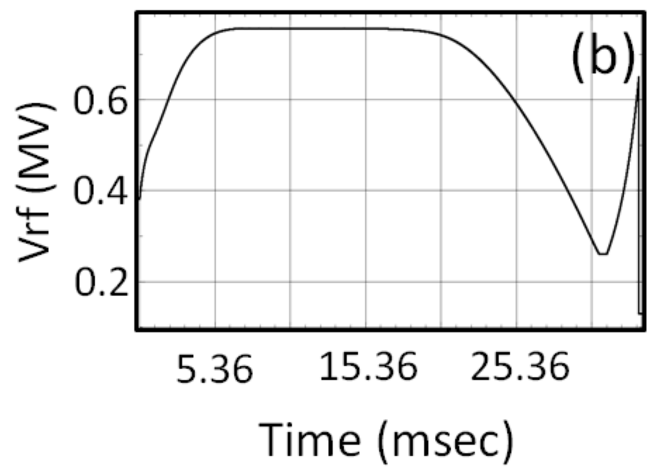
    HB2016 MOPL020
  - Acceptance at Injection
    - Momentum Acceptance in the Booster ⇐ **5.4 MeV (±0.4 MeV)**
    - Transverse Acceptance ⇐ **H: 50 π-mm-mr**, **V: 30 π-mm-mr**

ESME Simulations of EIS



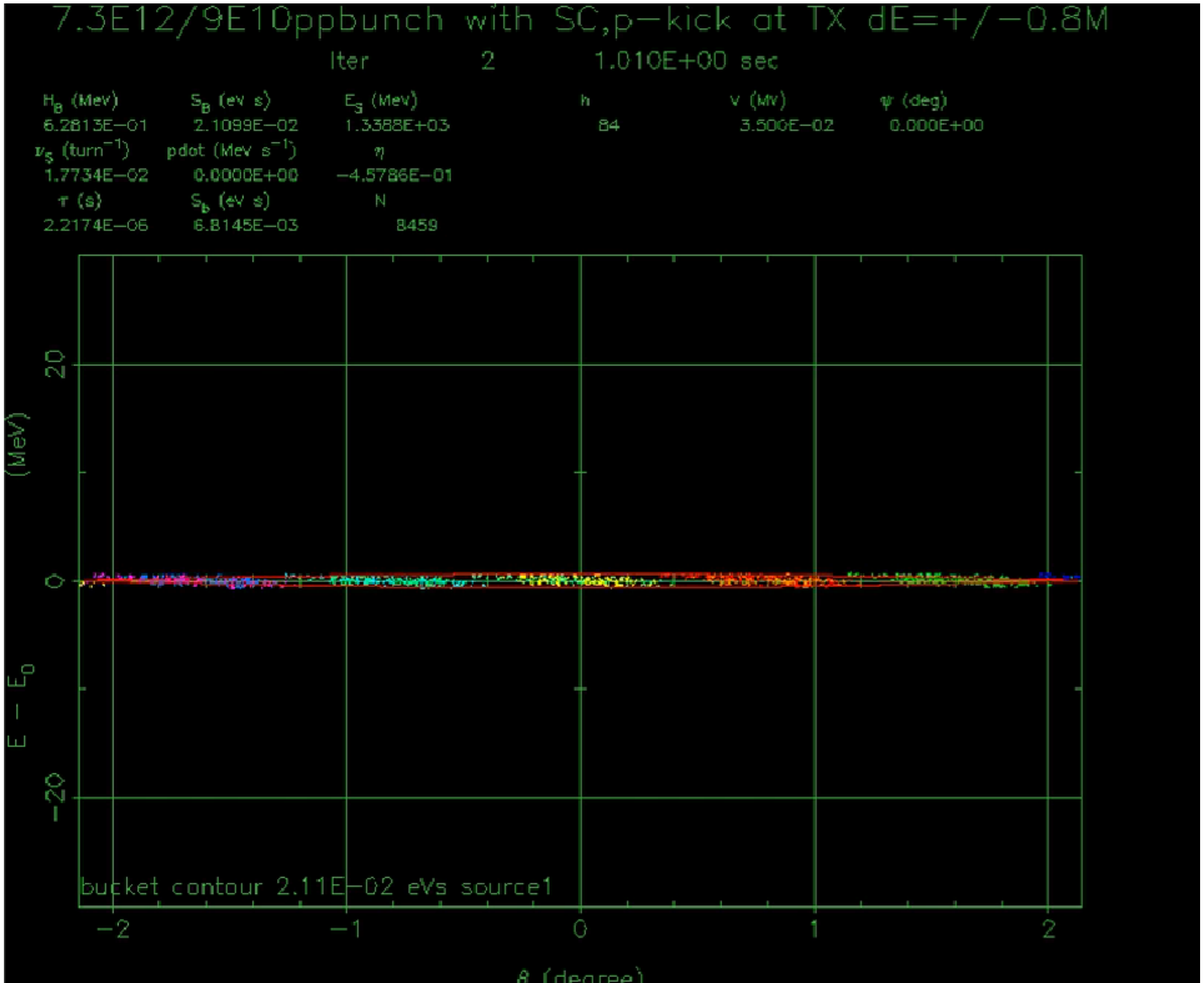






ESME Simulations of EIS

ΔE-Δt Phase space (7.3E12p/Booster Batch)



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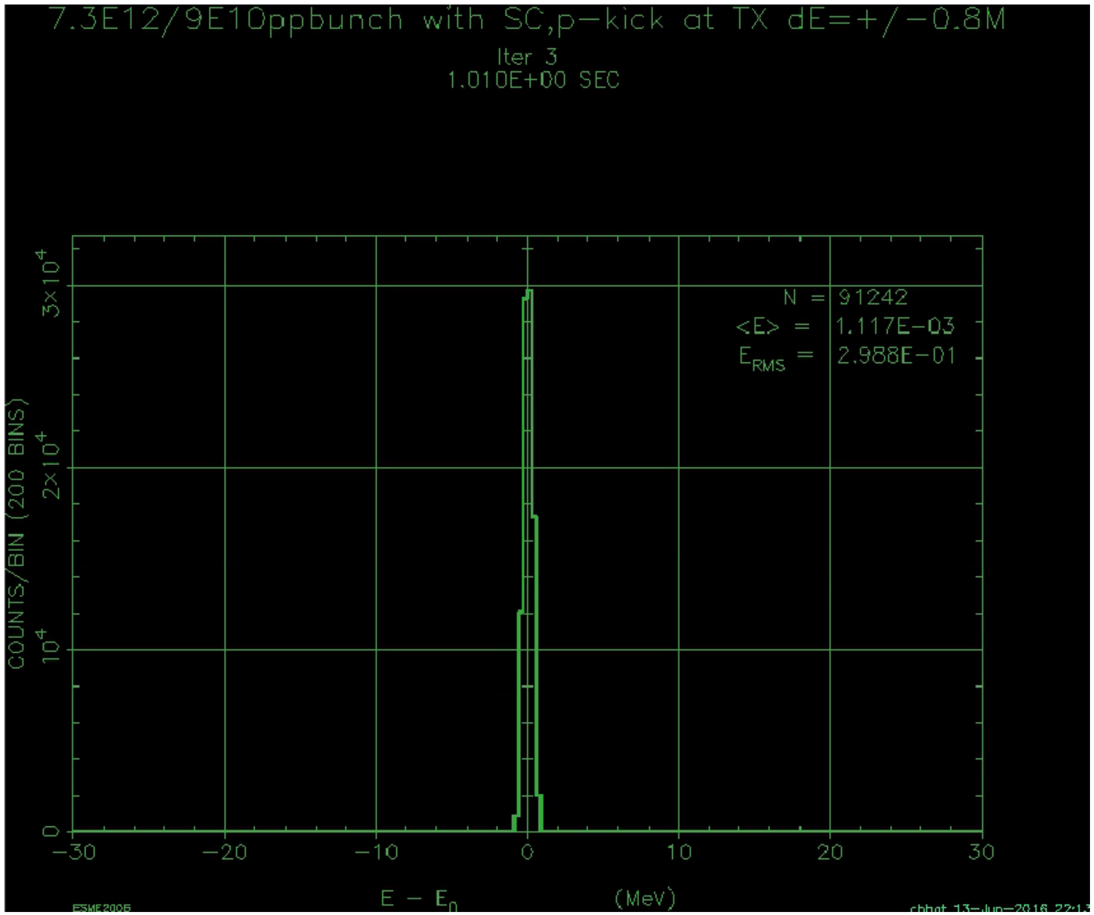
ESME Simulations of EIS

ΔE Dist.

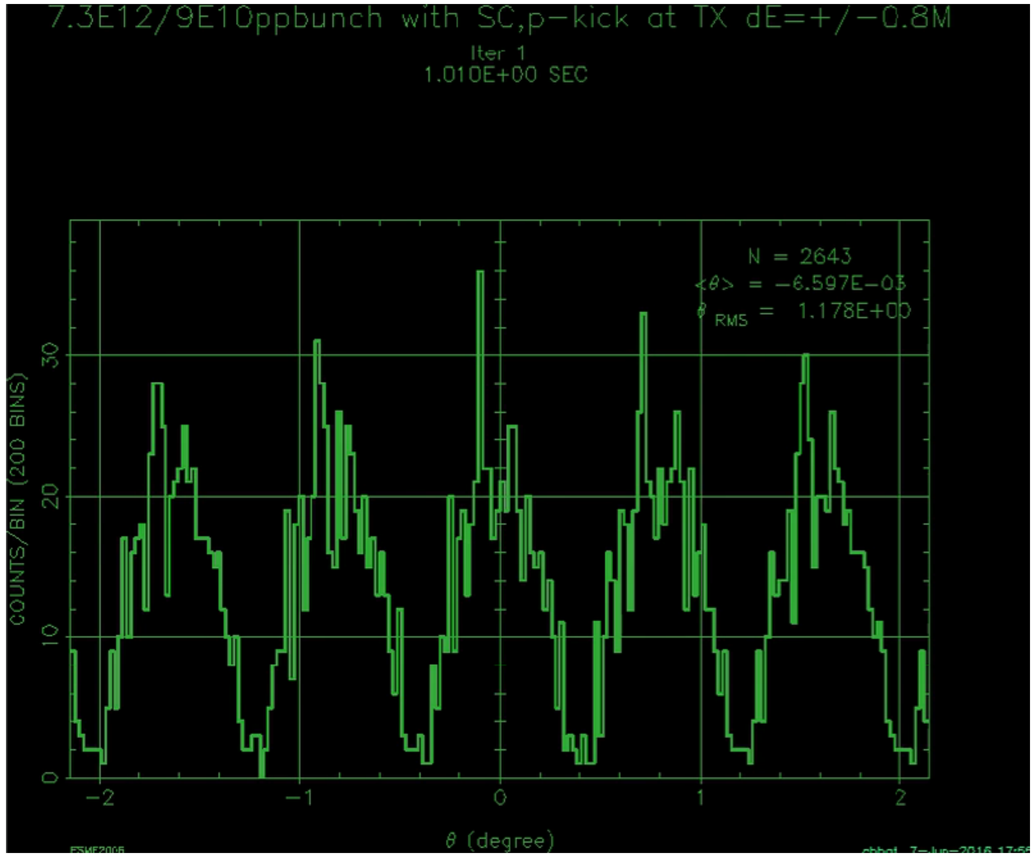


-30 0 30

Δ E (MeV)

ESME Simulations of EIS

Line-Charge Dist.



-2 0 2

Azimuthal Angle(deg)

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Beam Experiments

- We revisited many LLRF parameters
  - Curves: Radial-position feedback, Voltage and RF frequency etc.
  - Turn-on time for many parameters
- Transition crossing ← Needed additional tuning
- Bunch rotation to reduce the dp/p for transfer to the Recycler/MI
- Measured Beam Transmission Efficiency and Emittances @Inj & @Exit

Beam Experiments & EIS in Operation

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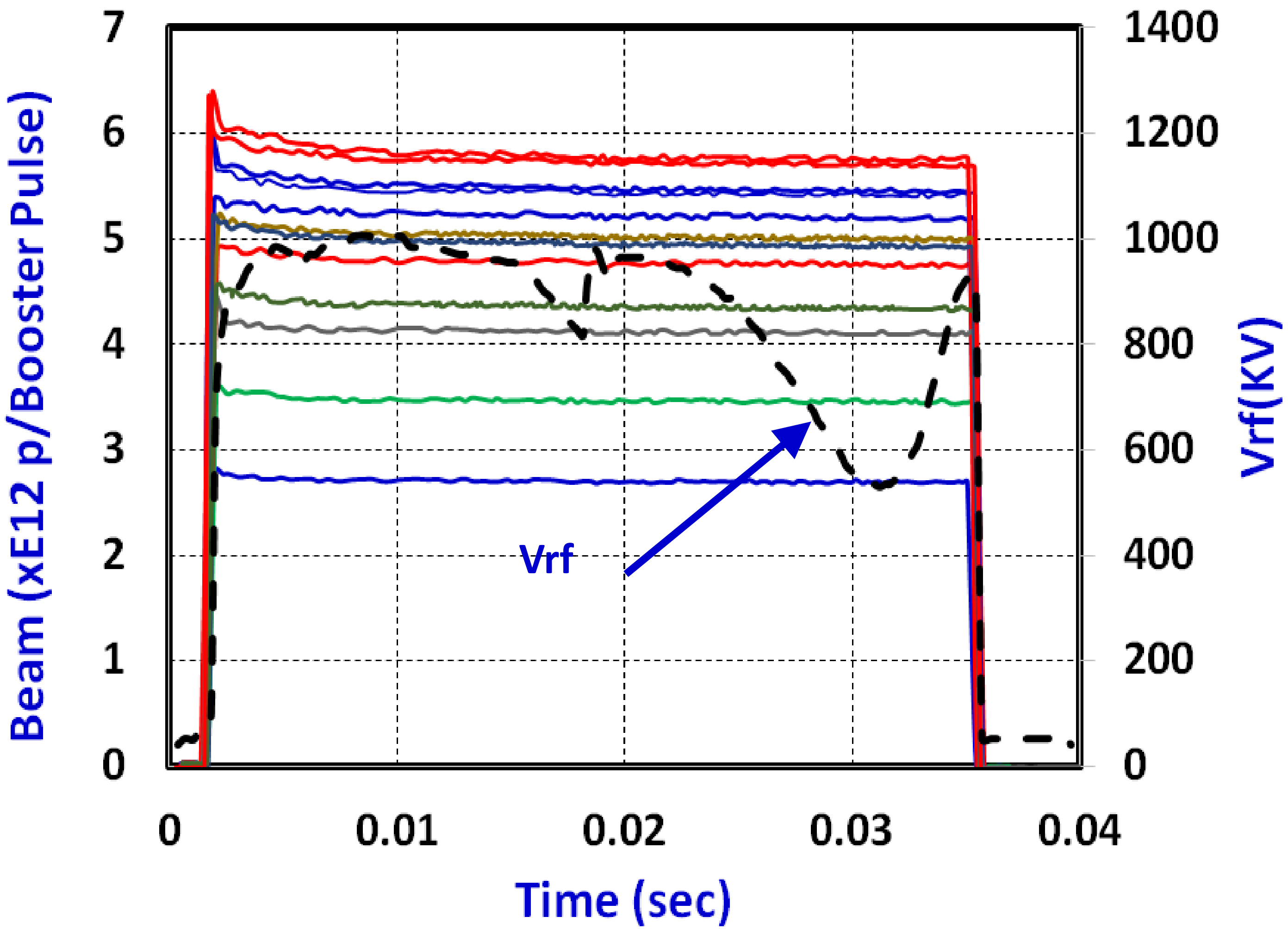
  - Turn-on time for many parameters
- Transition crossing ← Needed additional tuning
- Bunch rotation to reduce the dp/p for transfer to the Recycler/MI
- Measured Beam Transmission Efficiency and Emittances @Inj & @Exit

Late 2015 we have made the EIS in operation
Made many progress and
seen many benefits.

EIS: Acceleration Efficiencies (Beam and Vrf)



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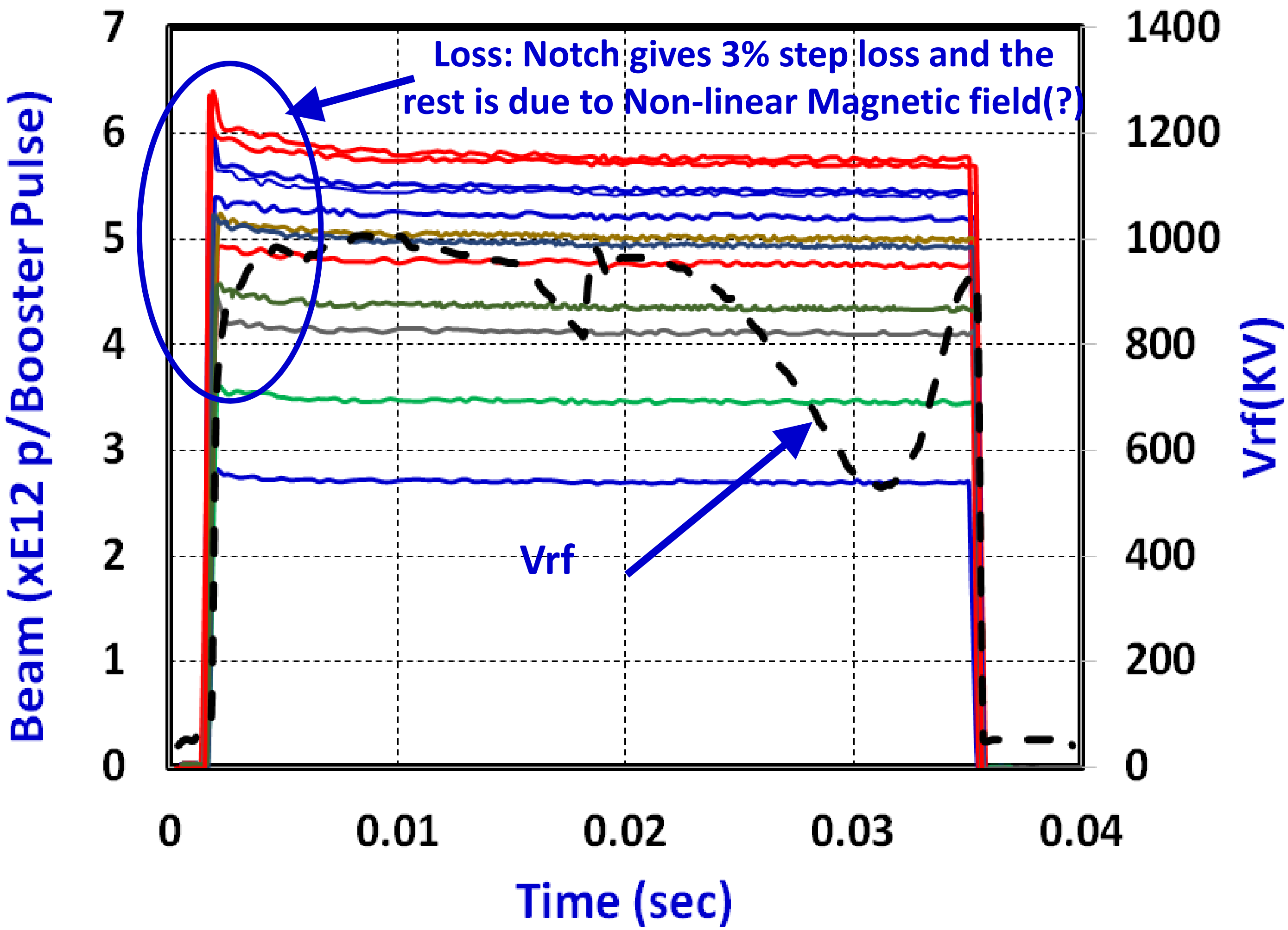

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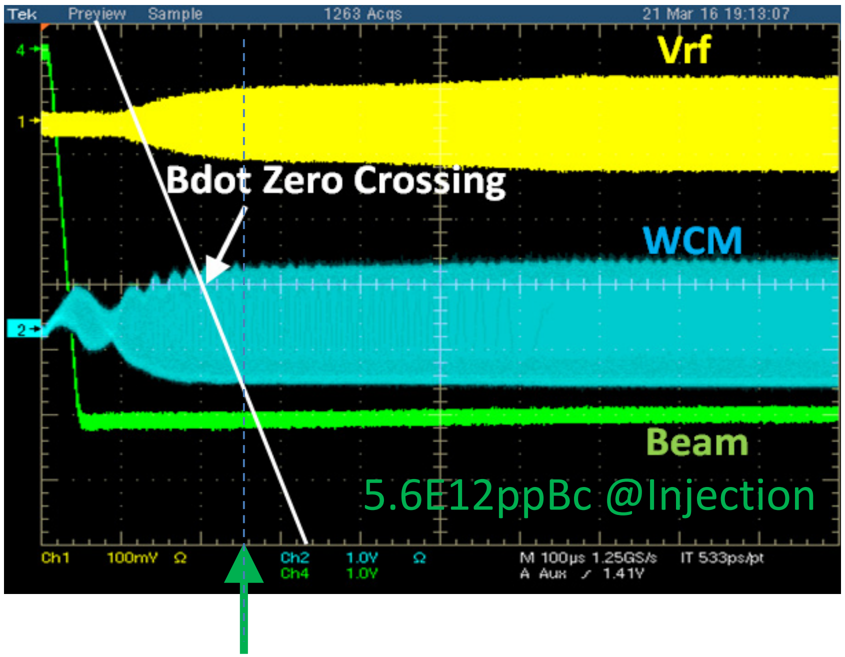
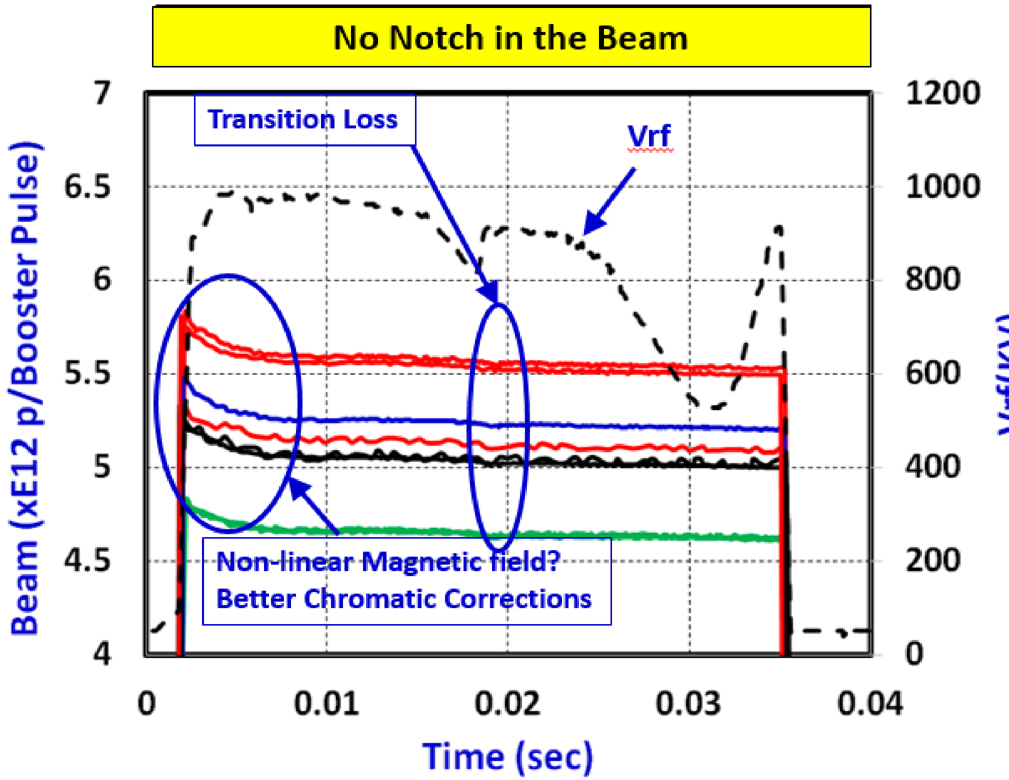
EIS: Acceleration Efficiencies (Beam and Vrf)

Scope Data for 1st 1ms at Injection

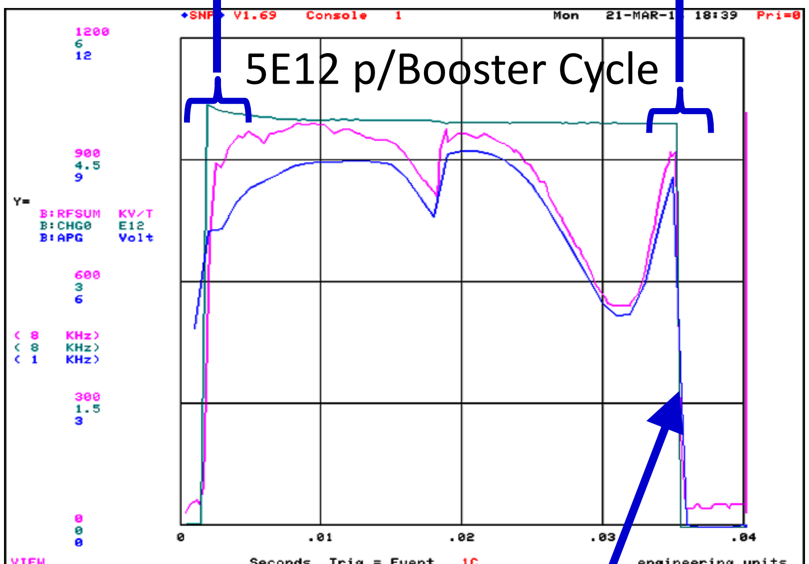


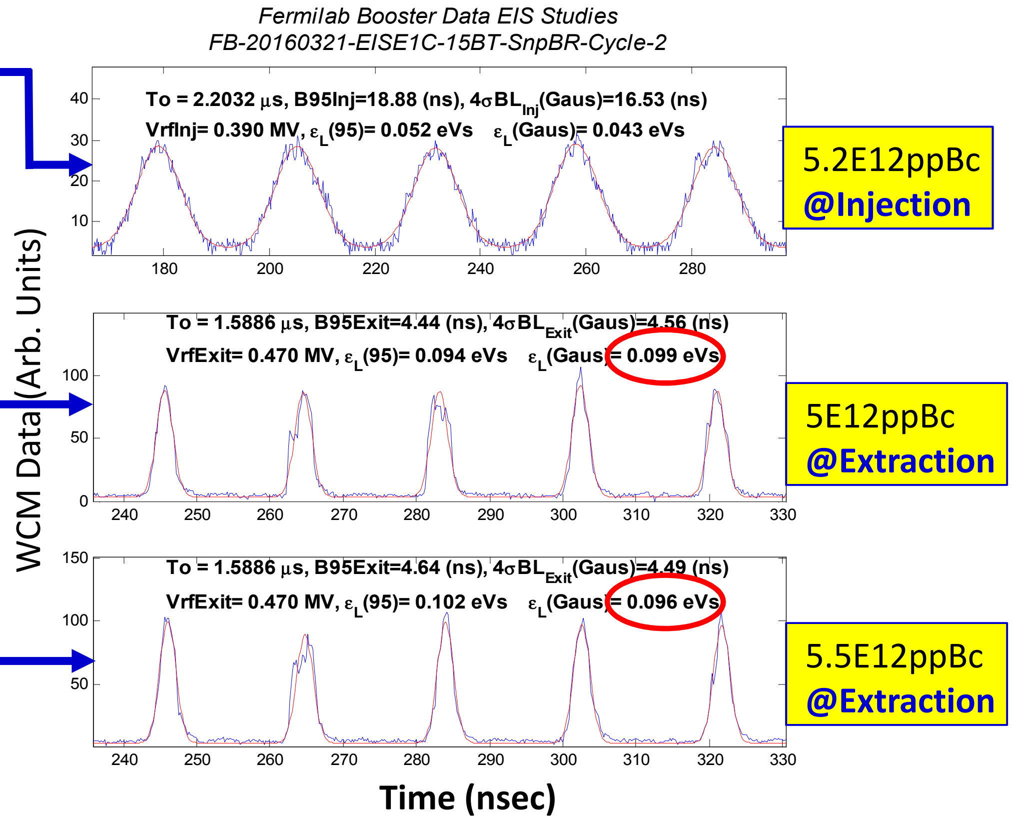
Capture and Transmission efficiency for the first 1ms ~98%

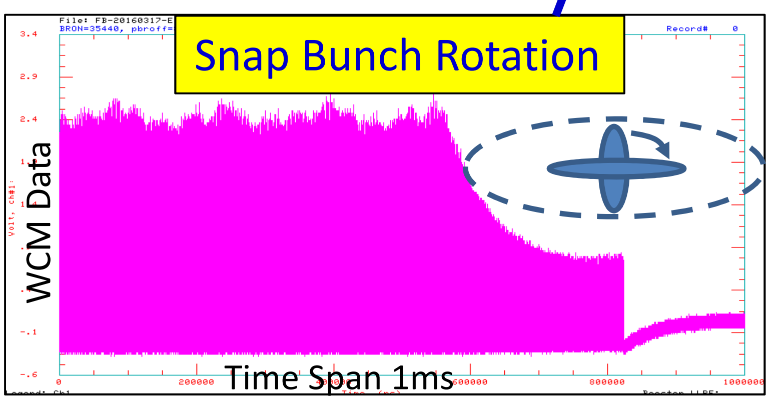


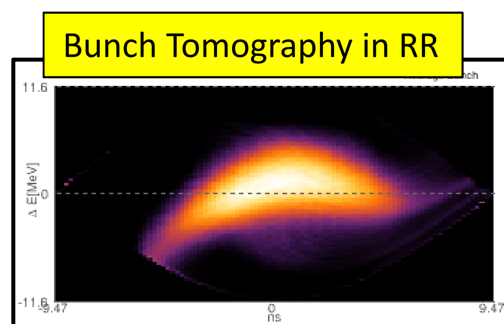
Transmission Efficiency over the cycle ~95%

Some Samples of Emittance Measurements









$\sigma_E \approx 2.8$ MeV

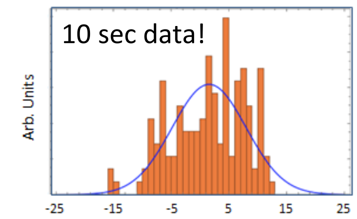
$\sigma_T \approx 2.75$ns

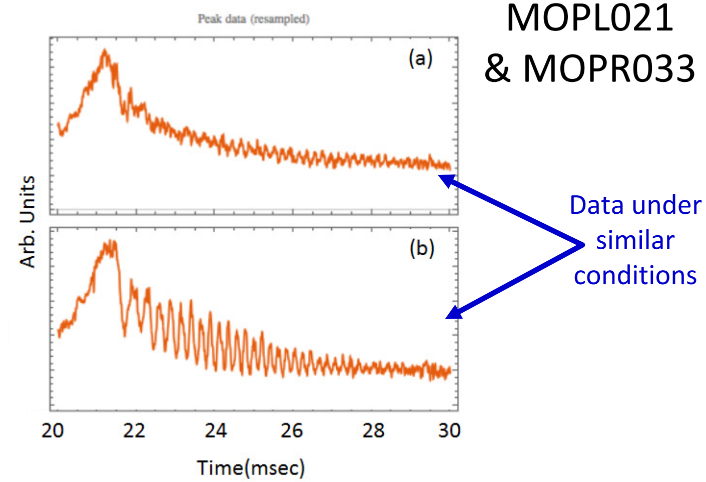
$\varepsilon_L(4\sigma) \approx 0.097$eVs

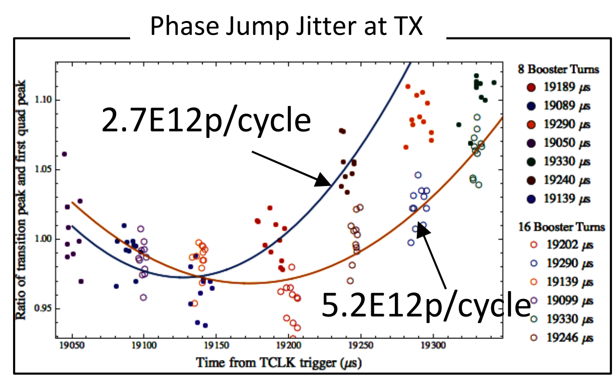
Issues and Mitigation

- There are a number of issues that we are working on in order to exploit the EIS fully
  - The time jitter in the *Bmin* relative to the beam injection clock event is ~30µsec. This jitter is random and arises from ComEd power line frequency. ← Introduces emittance dilution @Inj.
  - A better RF voltage regulation is needed at injection.
  - The transition crossing phase jump is delayed w.r.t. clock event. So jitter as large as ~30 µsec. ← unacceptable for Booster.
  - The RF frequency does not follow the Booster dipole magnetic field ramp.
  - Bunch rotation at extraction for reduced dp/p

Bmin Jitter at Injection







Addressing these Issues also Important to PIP-II

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PIP and PIP-II parameters

Parameter	PIP	PIP-II (After 2022)
Injection Energy (KE) (GeV)	0.4	0.8
Extraction Energy KE (GeV)	8	8
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Repetition Rate	15 Hz	20 Hz
Efficiency (%)	95	97
Booster repetition rate (Hz)	15	20
Booster Beam Power at Extraction	94 kW	184 kW
MI batches	12 every 1.33 sec	12 every 1.2 sec
NOvA beam power	700 kW	1.200MW
Rate availability for other users (Hz)	5	8
Booster flux capability (protons/hr)	~ 2.3E17	~ 3.5E17

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PIP and PIP-II parameters with EIS

Potential of 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
Repetition Rate	15 Hz **(15 Hz)**	20 Hz
Efficiency (%)	95 **(≥ 97)**	97
Booster repetition rate (Hz)	15	20
Booster Beam Power at Extraction	94 kW **(~130 kW)**	184 kW
MI batches	12 every 1.33 sec	12 every 1.2 sec
NOvA beam power	700 kW **(~950kW)**	1.200MW
Rate availability for other users (Hz)	5	8
Booster flux capability (protons/hr)	~ 2.3E17 **(3.2E17)**	~ 3.5E17