Beam Based RF Voltage Measurements & Longitudinal Beam Tomography at the Fermilab Booster (RCS) for Intensity Upgrade

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Special Thanks to

Shreyas Bhat (SCD)

&

W. Pellico, C. Drennan, N. Eddy, K. Triplett, S. Chaurize,

B. Hendrick, F. Garcia and K. Seiya. and T. Sullivan (AD)

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Abstract

The required accelerating RF voltage during PIP-II era will need to be about 30% more than during the PIP era. Therefore, it is extremely important to find out the current RF voltage by carrying out beam-based measurements to specify the needed upgrades to the Booster RF system. During the beam cycle the magnetic field is changing all the time. Due to this, 1) measuring/calibrating the RF voltage used for beam capture and acceleration, 2) longitudinal beam tomography, are not trivial tasks. Here we present a method to accomplish both tasks near injection and extraction energies of the Booster. Python/Matlab programs* have been developed which use wall current monitor data to measure synchrotron frequencies and extract the RF voltage with an accuracy of ~3%. We have also attempted to obtain the beam tomography in the longitudinal phase space using these data. The method developed here is applicable to any similar RCSs in the world.

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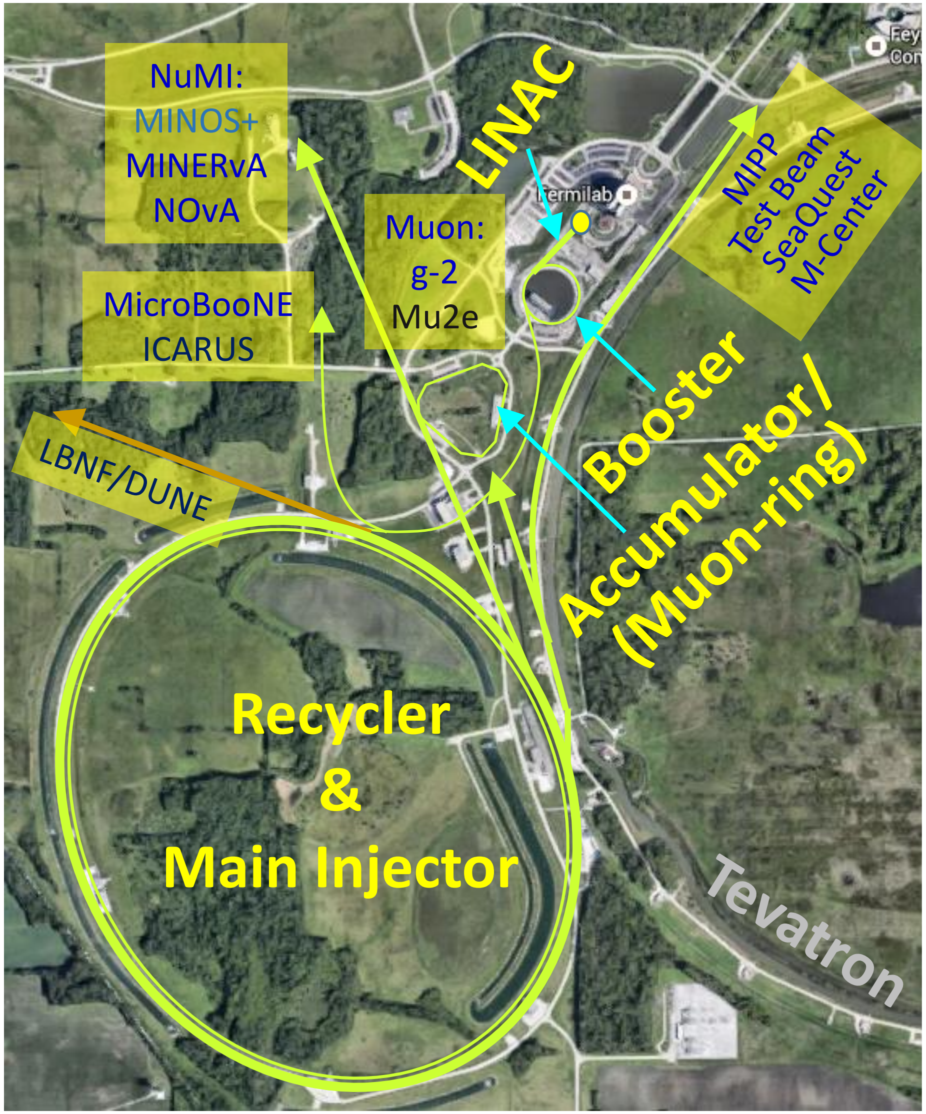
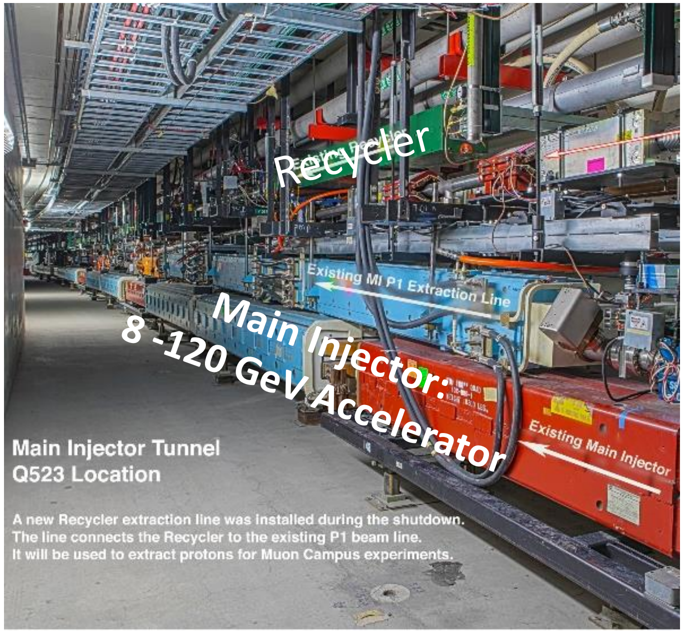


**Booster:
0.4-8 GeV
RCS
Accelerator**



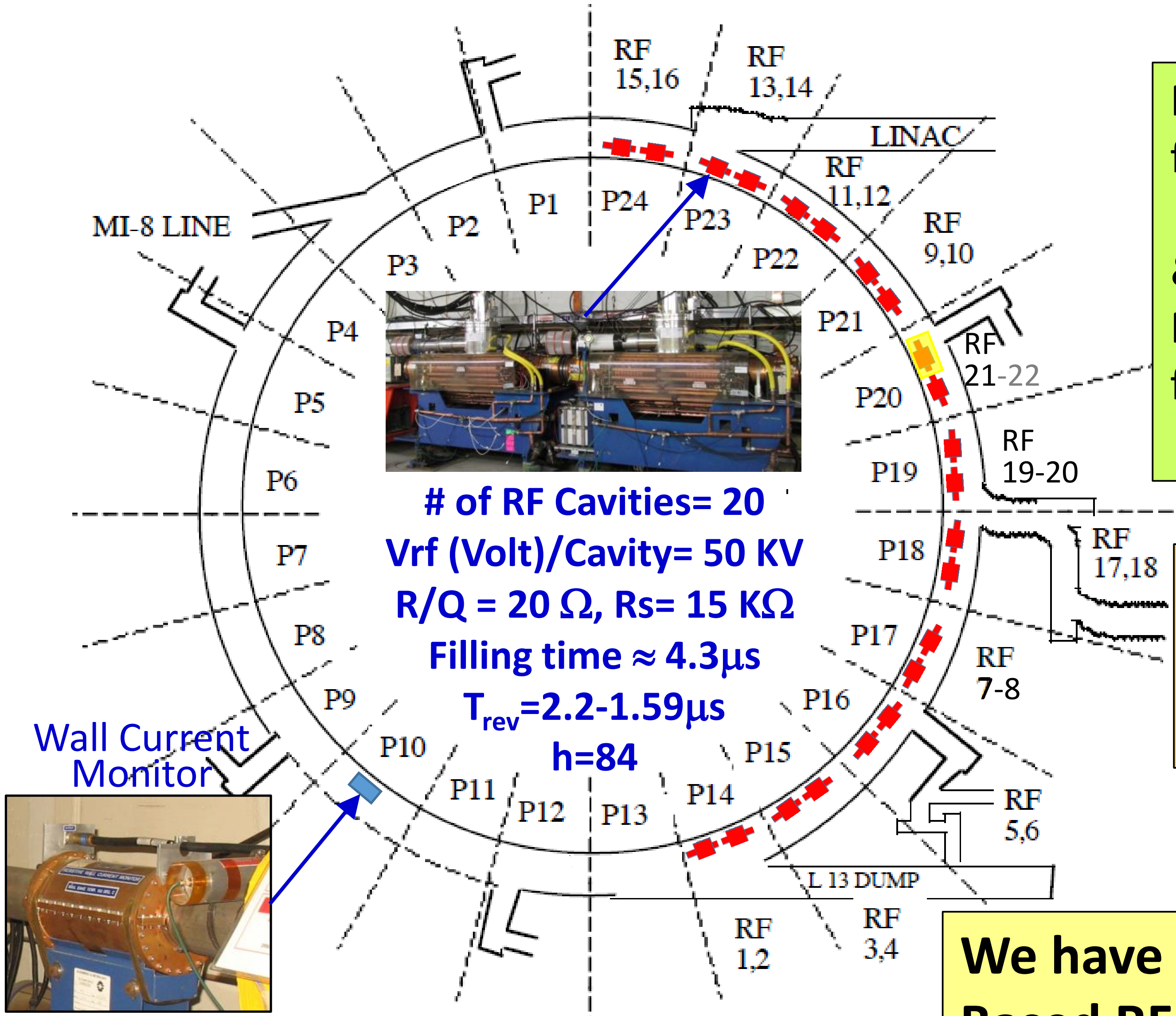
Current & Future Intensity Goals and Booster RF Requirements

Parameter	PIP-I (current)	PIP-I+ (projected)⊗	PIP-II (2026)
Inj. & Extraction Energy (KE) (GeV)	0.4, 8.0	0.4, 8.0	0.8, 8.0
Injector to the Fermilab Booster	Existing LINAC	Existing LINAC	New LINAC
Inj. & Extraction (p/pulse)(xE12)	4.52, 4.3	4.52, 4.3 (x ≈1.25)	6.63, 6.44
Number of Booster Turns	12-14	up to 20	300
Efficiency (%)	95	≈96♣	97
Booster repetition rate (Hz)	15	15	20
Beam Power at Extraction (kW)	94	115	184
Booster batches for MI	12/1.33 s	12/1.33 sec	12/1.2 sec
NOvA beam power (kW)	**700**	~900	>1200
Rate availability for other users (Hz)	5	5	8
Booster flux capability (protons/hr)	~ 2.3E17	~2.9E17	~ 3.5E17
Booster Vrf (MV)	**1**	**1.1**	**1.3**
Number of Booster RF cavities	**20**	**22**	**--**
Beam loading/Booster cavity (kV)	**12**	**16**	**18**

⊗ Assuming many upgrades in Booster, RR & MI related to PIP-II are done a head of time

♣Assuming the same number of proton loss/Booster cycle as expected during PIP.

Booster Beam Accelerating RF Cavities



# of RF Cavities= 20
Vrf (Volt)/Cavity= 50 KV
R/Q = 20 Ω, Rs= 15 KΩ
Filling time ≈ 4.3μs
T_{rev}=2.2-1.59μs
h=84

PIP Specification
f_{RF}=37.8 MHz-52.8 MHz
Vrf(total) = 1 MV
&
PIP-II Specification
f_{RF}=44.7 MHz-52.8 MHz
Vrf(total) = 1.3 MV

Do we have 1.1 MV out of these 22 RF cavities?

We have carried out Beam Based RF Voltage Calibration

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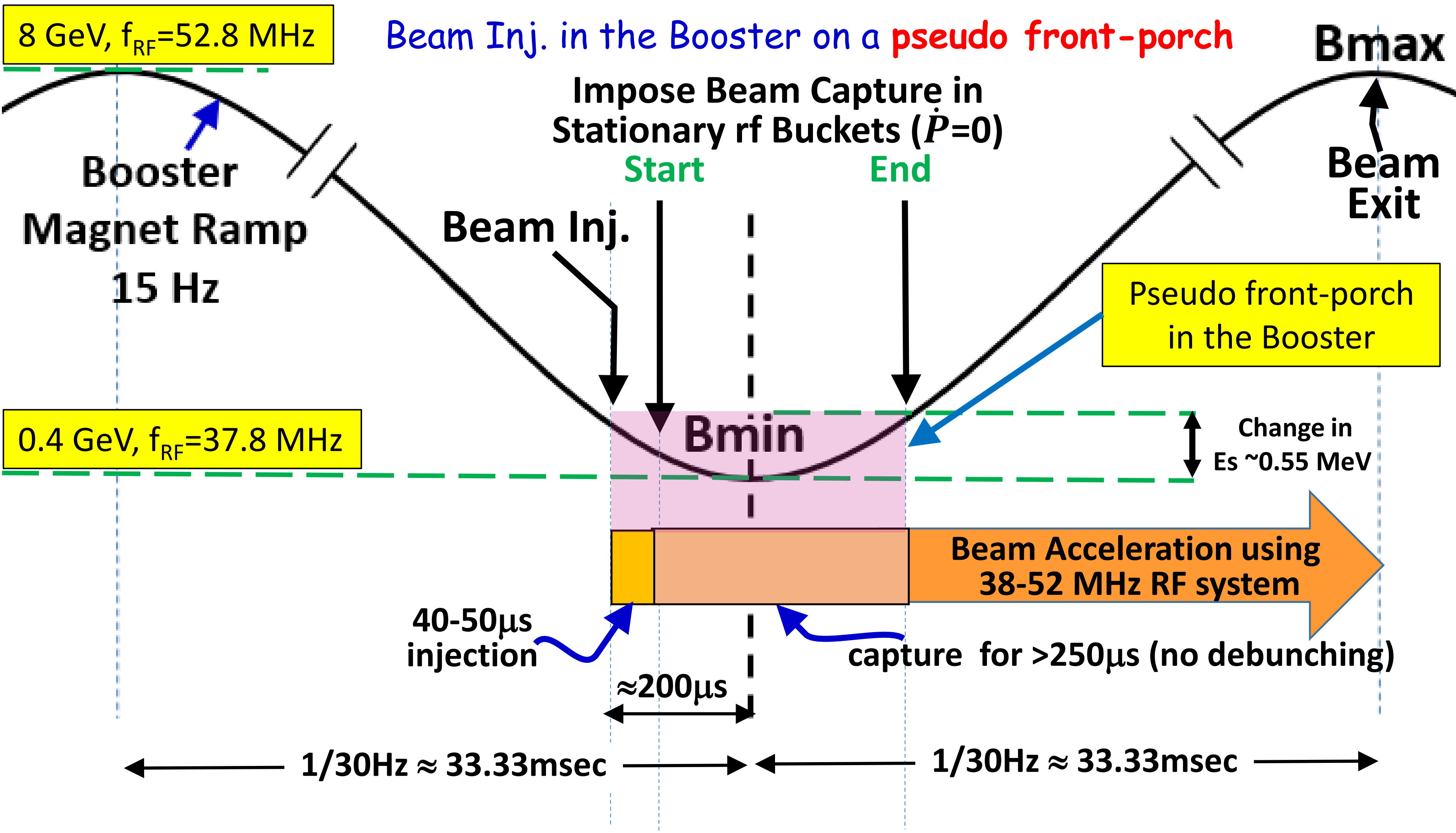
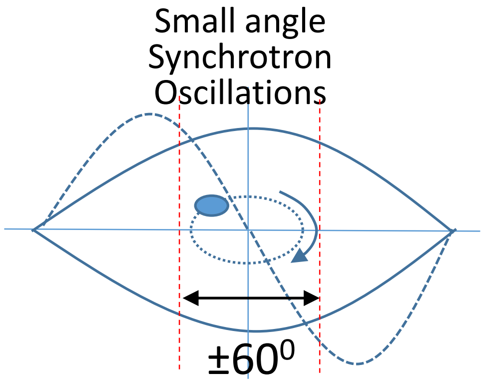
Schematic of the Booster Beam Cycle



Principle of Beam Based RF Voltage Calibration

Measure Vrf by measuring the small angle synchrotron frequency, f_{sy} of the beam in stationary rf bucket.



$$f_{sy} = f_{rev}\sqrt{\frac{V_{rf}h|\eta|}{2\pi\beta^2E_s}} \quad \text{or} \quad V_{rf} = \left\{\frac{f_{sy}}{f_{rev}}\right\}^2 \frac{2\pi\beta^2E_s}{h|\eta|}$$

frev = Revolution frequency of the beam

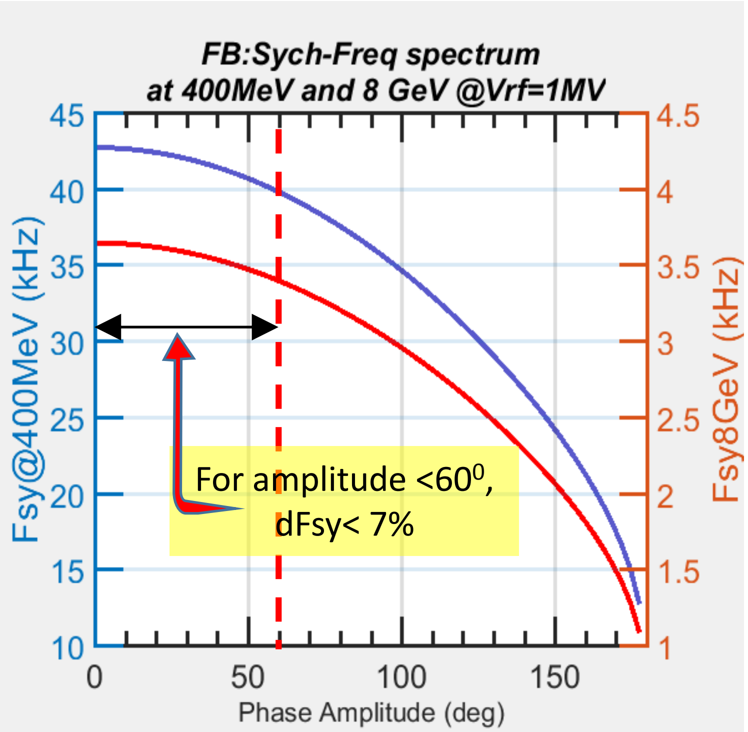
β= 0.713 @ Inj, 0.994 @ Extraction.

Es = 1.332 GeV (@ Inj.) and 8.938 GeV (@Exit)

η= 0.458 (@Inj) and 0.0223 (@Exit)

h = 84, Harmonic number

fsy = Measured synchrotron frequency



In the case of RCS like the Fermilab Booster, the beam will hardly be in stationary buckets because it gets accelerated or decelerated all the time in the Sinusoidally varying Dipole Magnetic field (@15Hz). In the absence of accurate RF phase info. Vrf calibration with *fsy* measurements is not a trivial task.

fsy Measurements in the Booster

Here, *fsy* of the beam is measured by studying the time evolution of the line-charge distribution in rf buckets using a **wall current monitor**. We adopt two different methods

- 0.4 GeV DC: By running the Booster in DC mode at injection energy. Performing FFT of the line-charge distribution of the captured beam at 38 MHz at different rf voltages. ←This method is straight forward. Good for Vrf up to 730KV.
- @8 GeV: Accelerate the beam close to 8 GeV. At ≈3 msec before the end of the beam cycle,
  - Hold the Vrf at a desired value
  - Turn off the radial feedback gain.
  - Hold the rf frequency at a fixed value
  - Excite small angle oscillations with a Vernier cavity← Thanks to Nathan Eddy

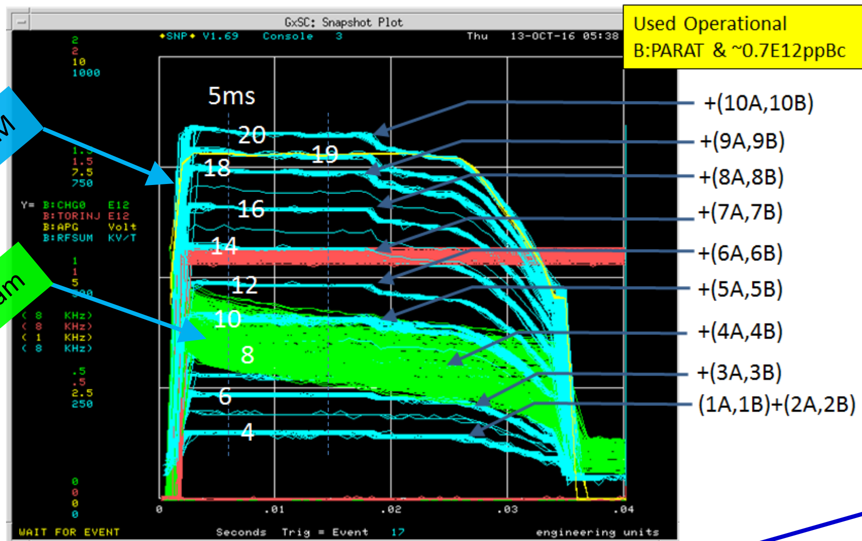
    Or phase mismatch arising from transition crossing

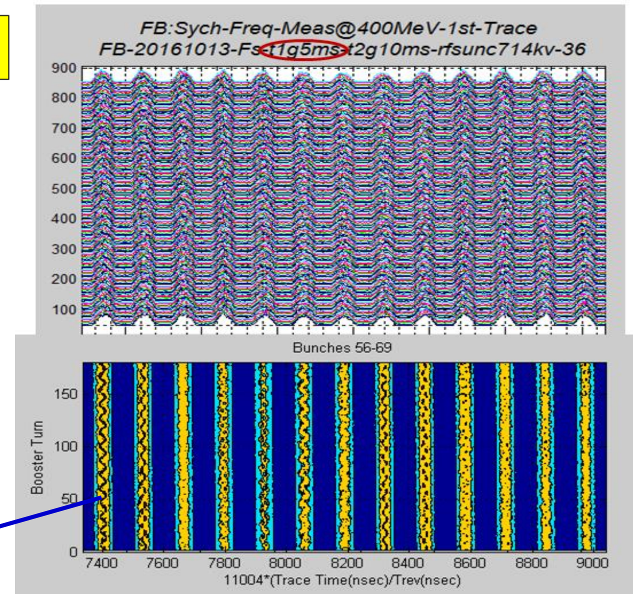
  Measure line-charge distribution for several synchrotron periods and perform FFT ←This method is more complicated.

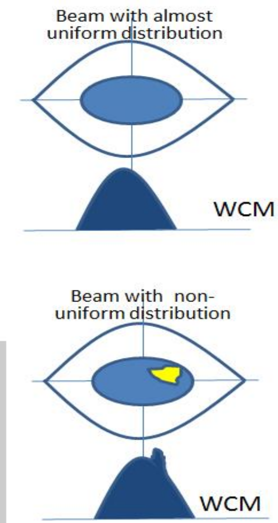
Computer programs were developed in MATLAB and in Python for data analysis.

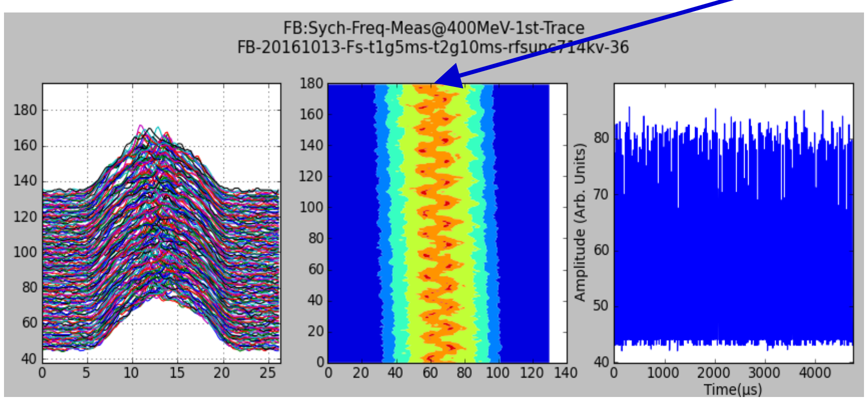
0.4 GeV (DC) data- sample

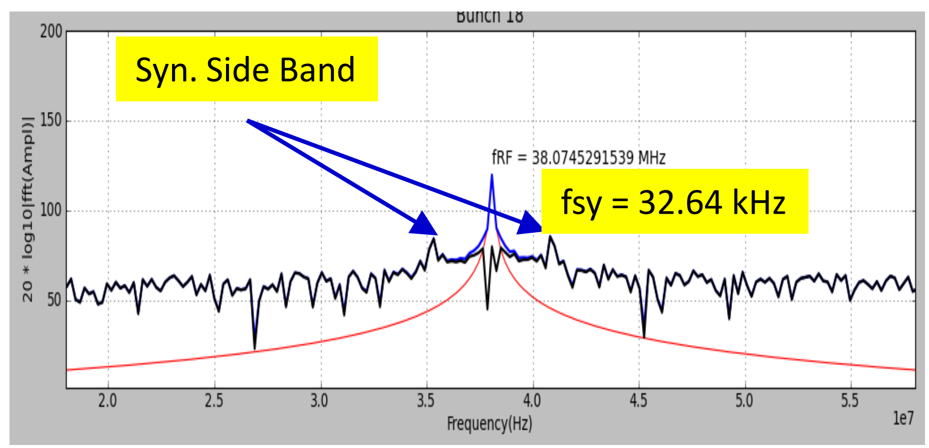
Data analysis by using PYTHON Code developed by Shreyas Bhat (SCD)







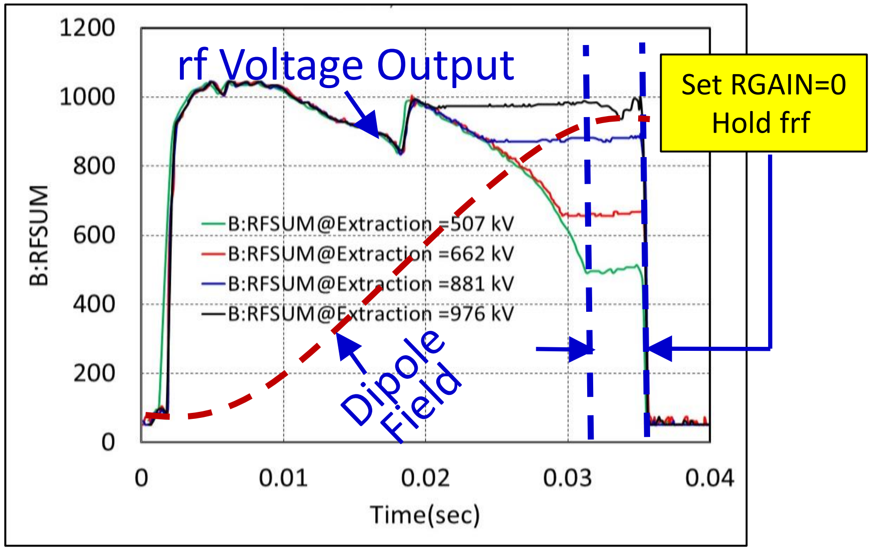


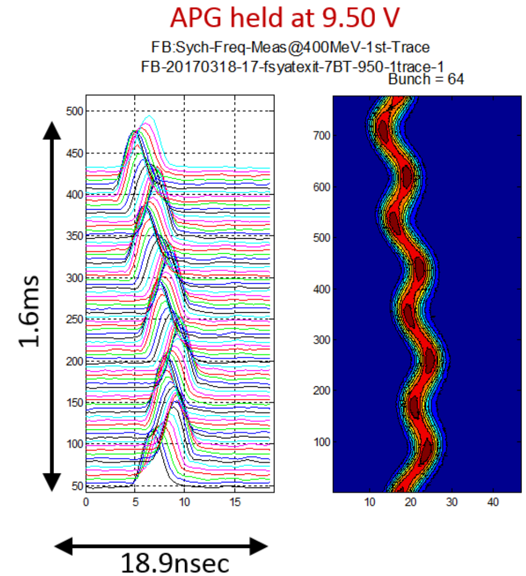


MR Plot **Contour Plot** **Concatenated WCM data**

8 GeV Data Sample

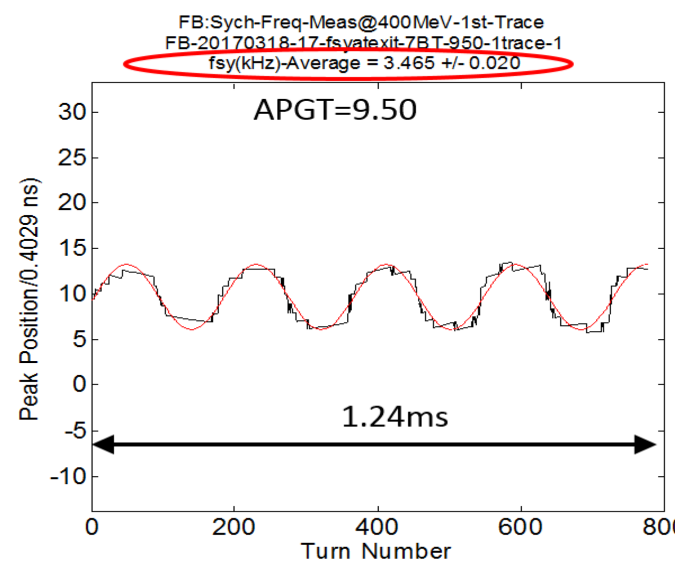
Data analysis using MATLAB code





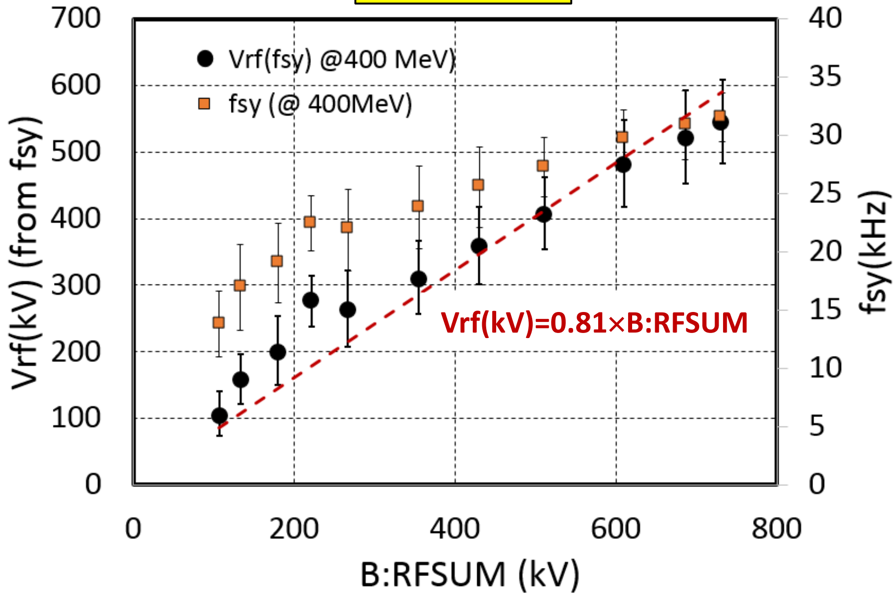
fsy from the fit to the peak position

$$F(t) = \underbrace{b_1 \sin(2\pi b_2 t + b_3) + b_4}_{\text{Back Ground (changing magnetic field)}} + \underbrace{b_5 \sin(2\pi b_6 t + b) + b_8}_{\text{Synchrotron Oscillations}}$$

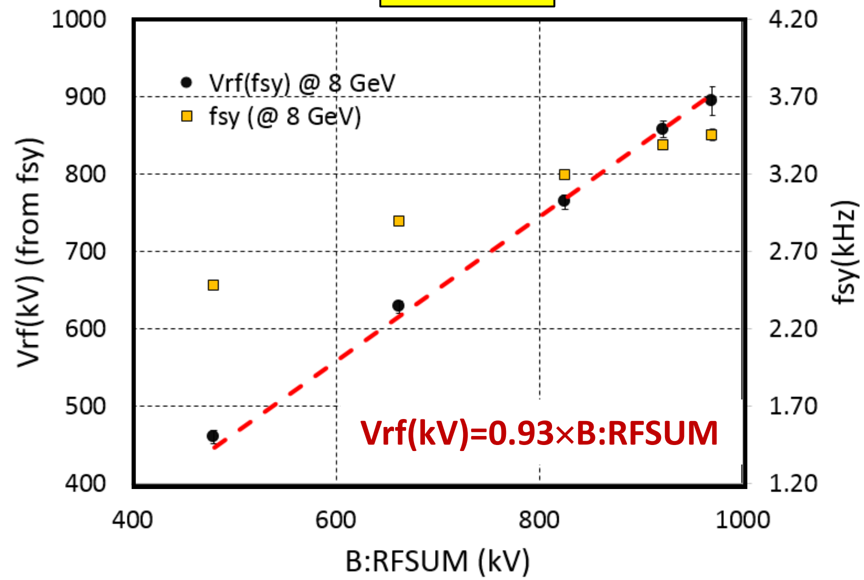


Vrf from fsy

0.4 GeV



8 GeV

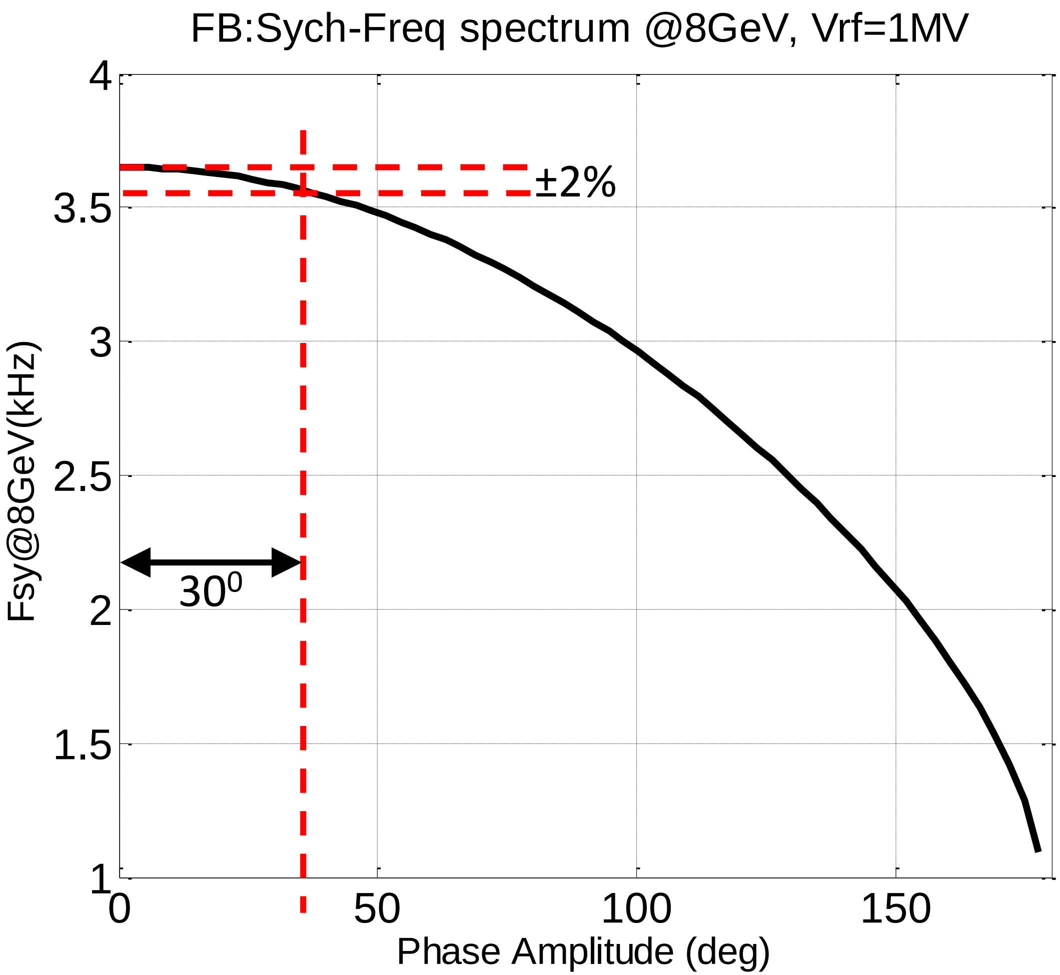


- ❑ At 0.4 GeV the buckets are almost full after the beam capture and the large spread in the measured *fsy* observed.
- ❑ Also, we could go only up to B:RFSUM=730kV due to anode limit program.

So, time being, we ignore the 0.4 GeV (DC) analysis.

- ❑ At 8 GeV, the beam size is small. Small angle synchrotron oscillations are induced either by transition crossing phase mismatch or by turning ON a dedicated RF kicker. Hence the error in *fsy* is small. This method also gives us the ability to measure *fsy* all the way up to B:RFSUM=1 MV.

Error in the Measured fsy and Vrf at 8 GeV



fsy(Total Error)=

±2% (Systematic)

±.5% (Statistical)$_{Ave}$

Vrf(Total Error)=

±3% (Systematic)

±.5% (Statistical)$_{Ave}$

For example, with 20 RF cavities

B:RFSUM=1000kV

VRF(fsy) = 930 kV+30 kV (+ve error only)

$\Rightarrow$ (930/1000) ≈ 0.93+0.03

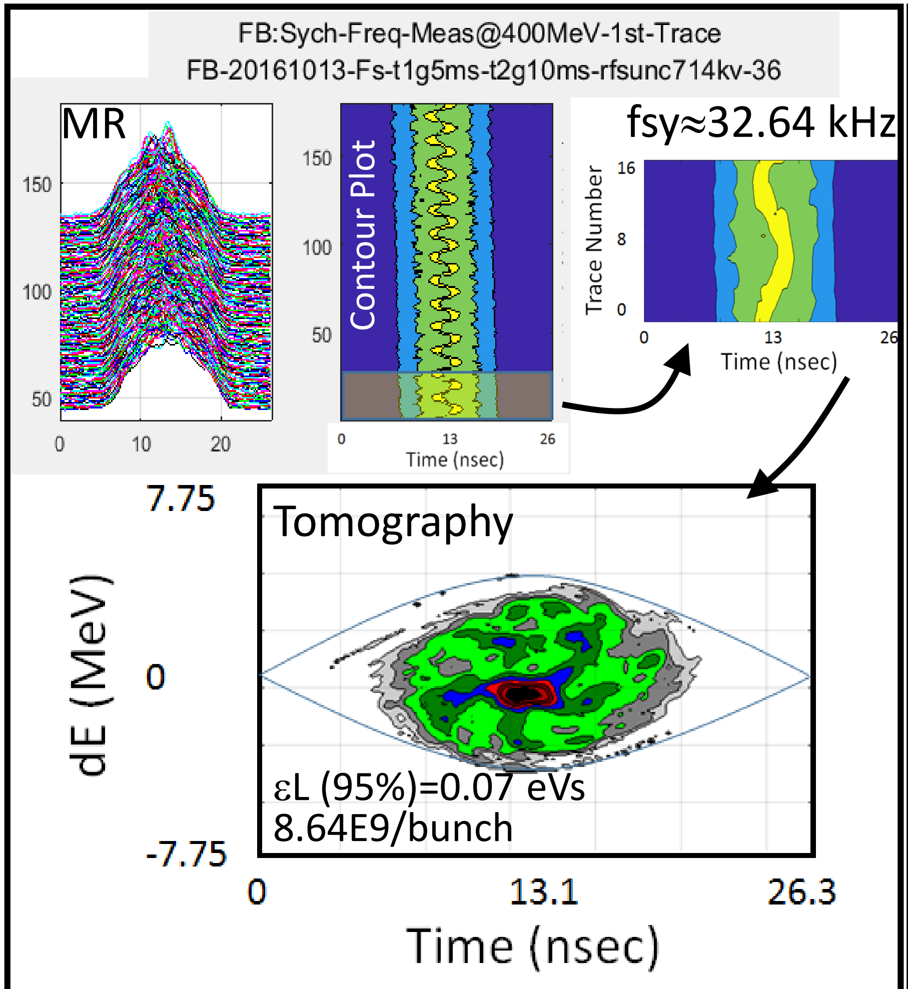
$\Rightarrow$ We have lower Vrf by ≈ 5%

Longitudinal Tomography for the Booster Beam

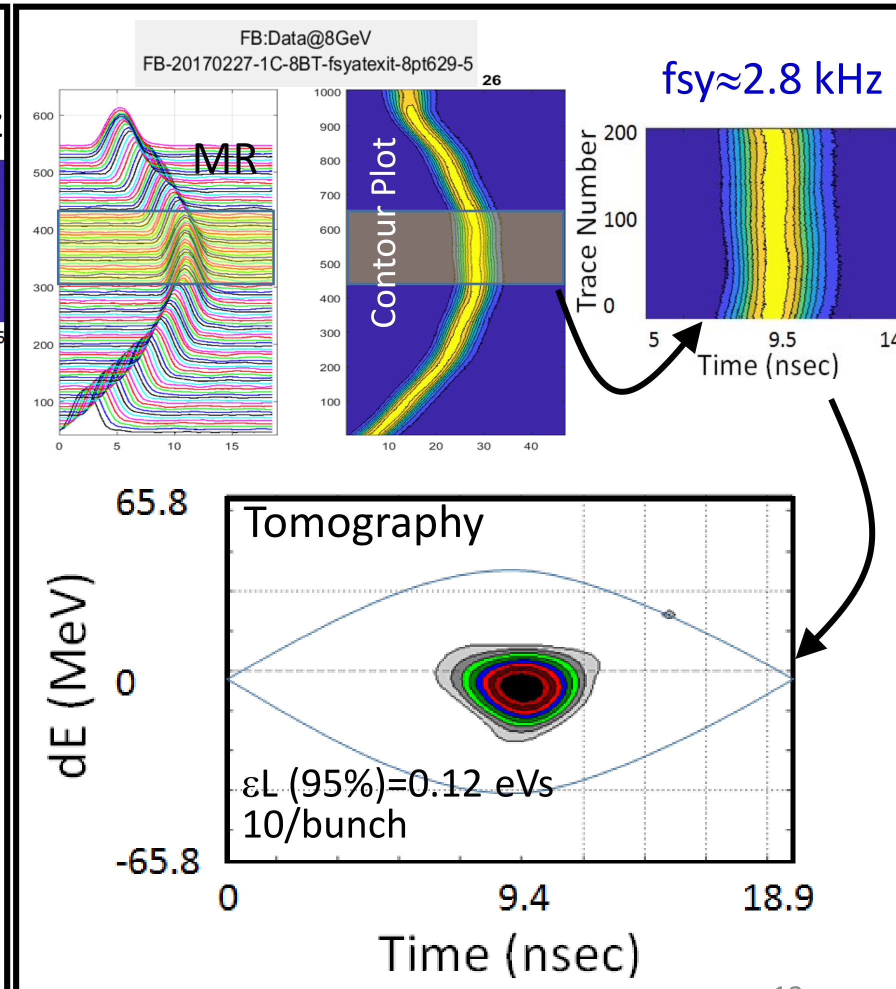
Special thanks to Steven Hancock (CERN) for Tomography code

- ❑ Have enough information for longitudinal tomography

0.4 GeV Vrf=0.68 MV, 0.7E12ppBc

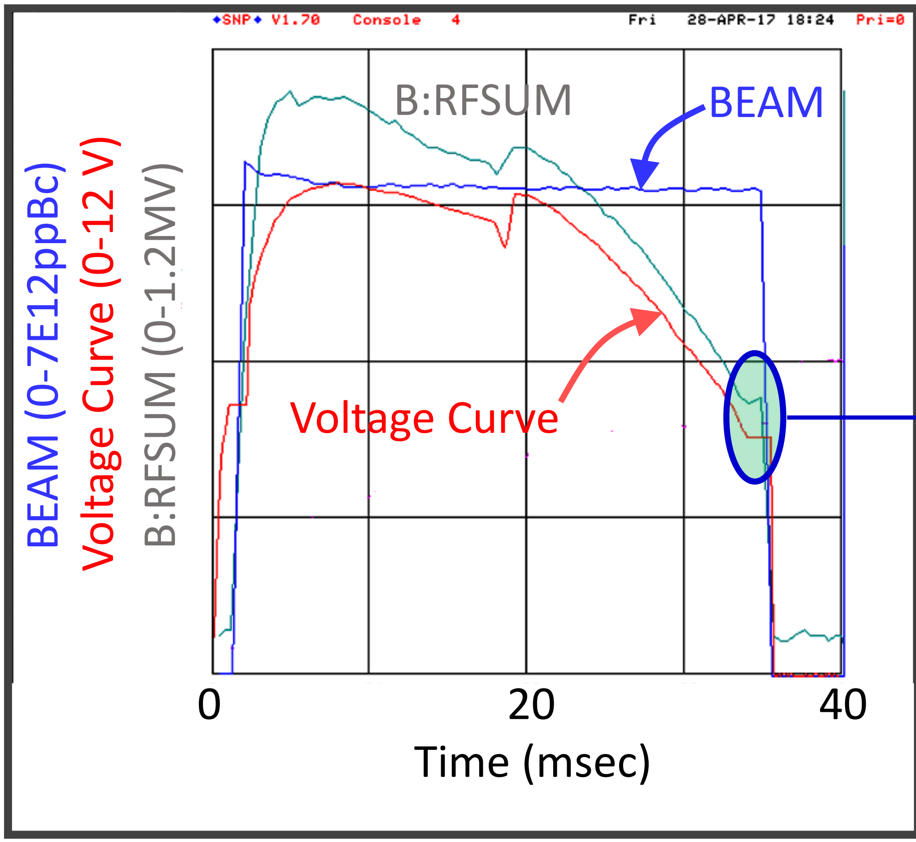


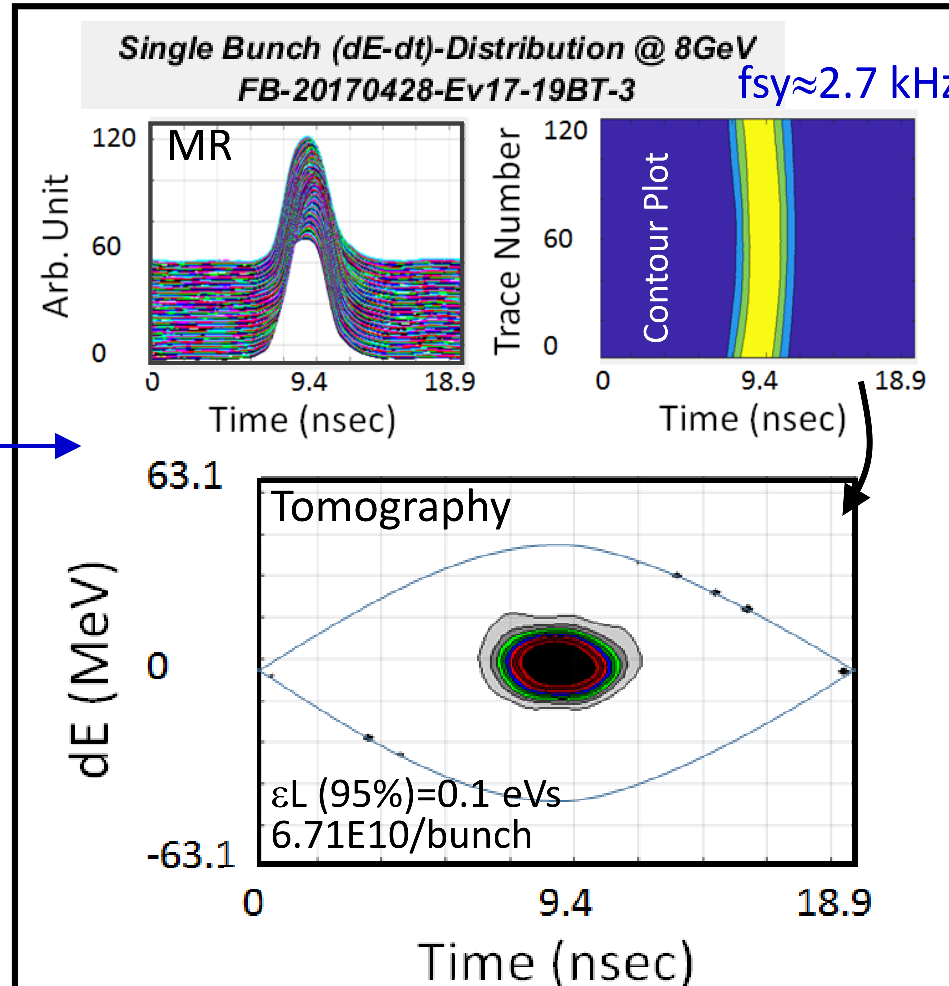
8 GeV Vrf=0.59 MV, 2.29E12ppBc



Longitudinal Tomography for the High Intensity Booster Beam@ 8GeV

Vrf=0.54 MV, 5.4E12ppBc





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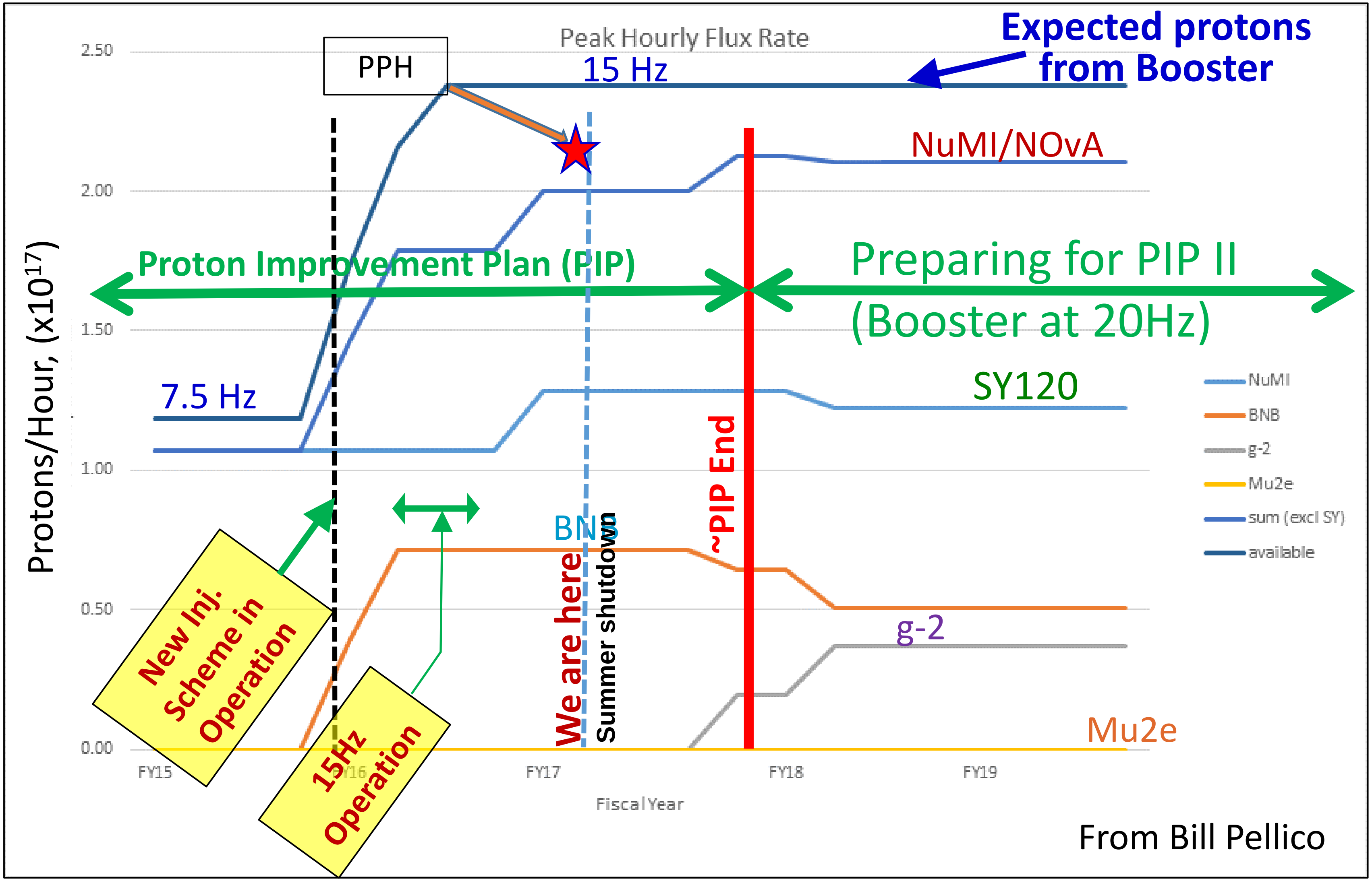
Summary and Conclusions

- Fermilab Booster will play a critical role in future intensity upgrade programs at the lab at least for next two decades.
- As a part of the PIP program (to provide 700kW beam power on NOvA neutrino target), we have refurbished all Booster RF cavities and installed new cavities for a total of 20+1 RF cavities in the ring.
- Here we have presented beam based Vrf measurement and we find that Vrf is about 5% smaller than the expected. This needs to be taken into account in future efforts as beam power increases and beam loading plays a very important role.
- We have done longitudinal beam tomography for the first time for the Fermilab Booster beam. We plan on developing a program to make beam tomography a routine diagnostic tool in our machine operations.

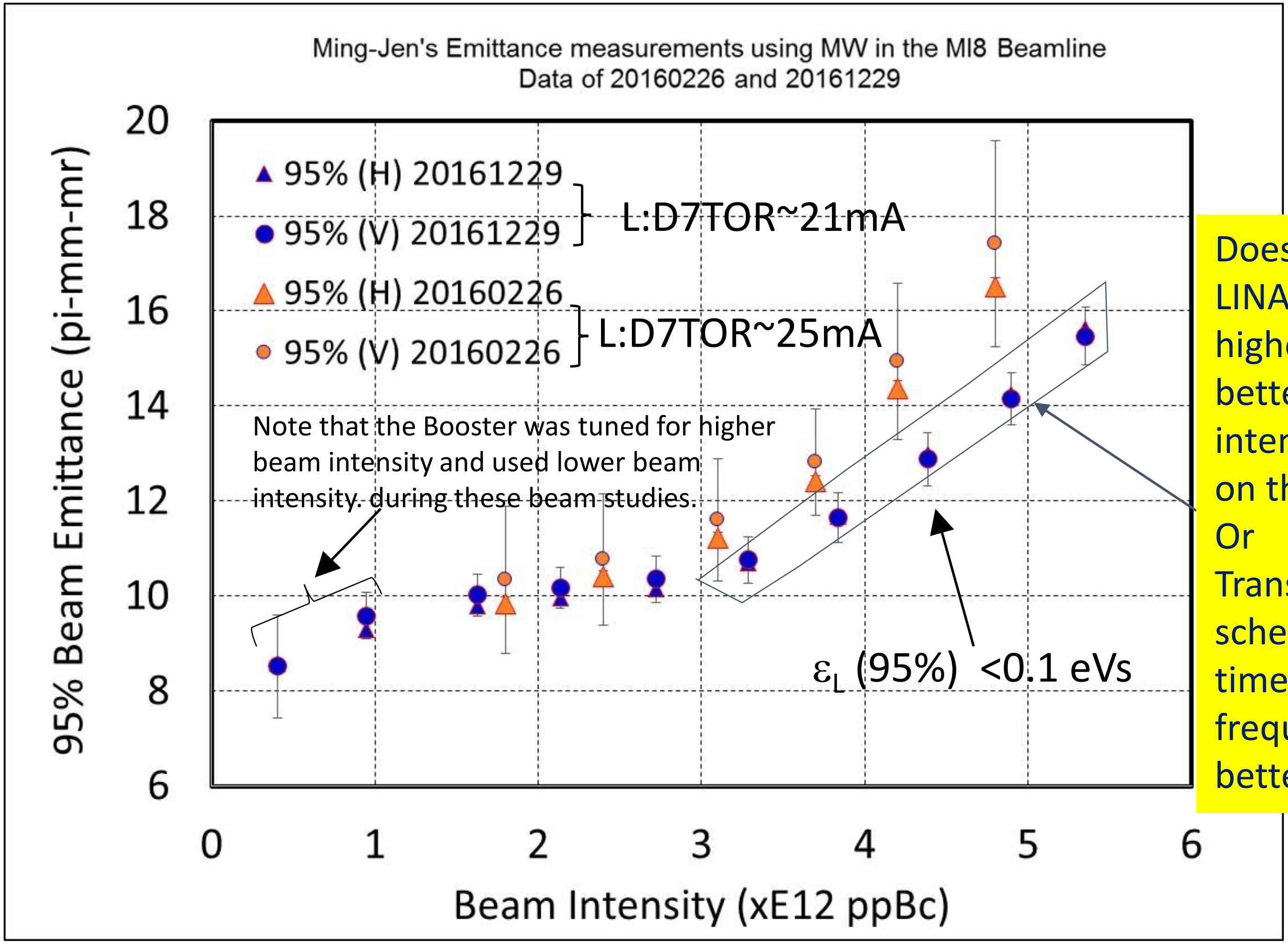
Backup Slides

Planned Proton Delivery Scenario for the Booster during PIP-era
(approximate)



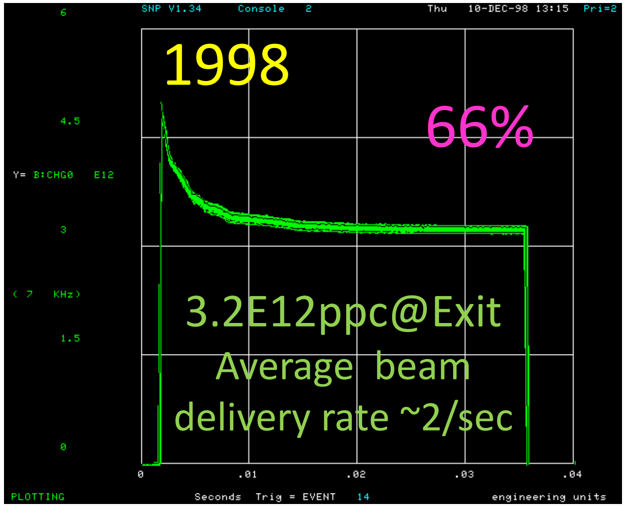
Transverse Emittance in the MI8 Beamline

(MW Data by Ming-Jen Yang)

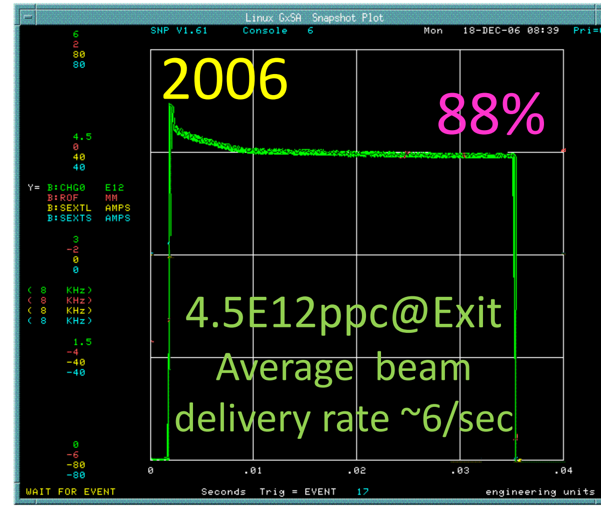


Does this imply, lower LINAC current and higher number of BT is better for higher intensity beam power on the neutrino target?
Or
Transition crossing scheme changed from time based to rf frequency based and better Booster tuning?

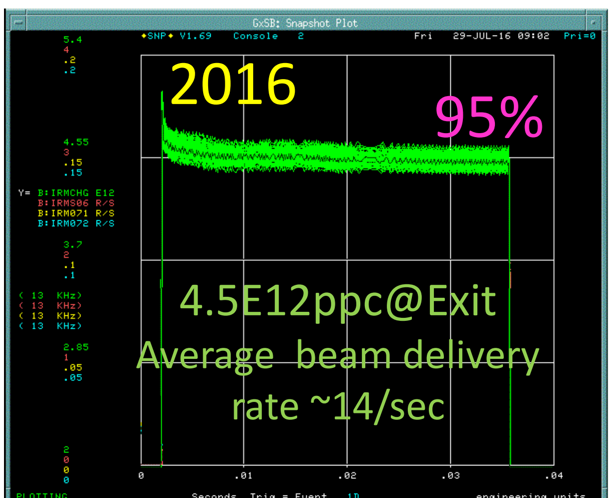
History of Beam Acceleration Efficiency in the Booster over the past ≈ two decades with the 400 MeV LINAC beam Injection



Usual Suspect were
Space Charge Effects at
- **Injection** &
- **Transition Crossing.**

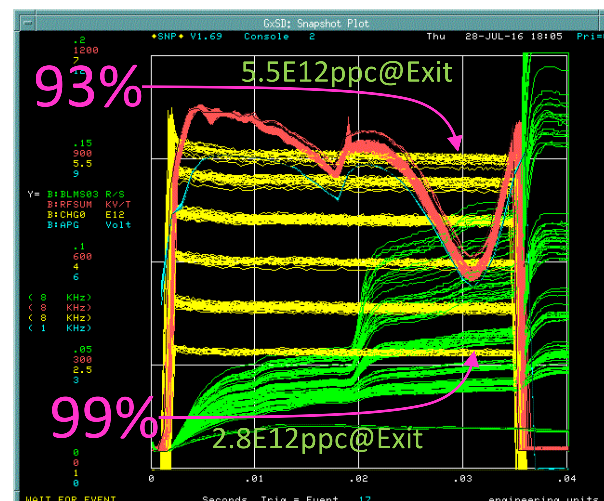


Now with a **New Injection and Bunching Scheme** (EIS)



&

with many Hardware and Operational Improvements



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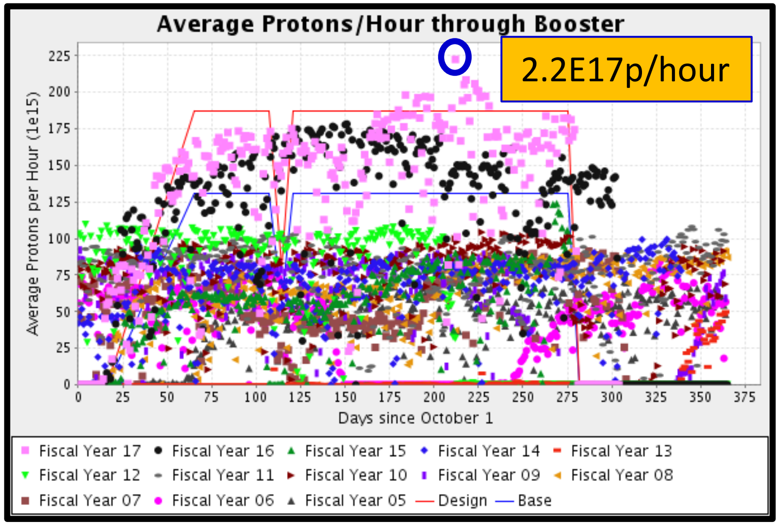
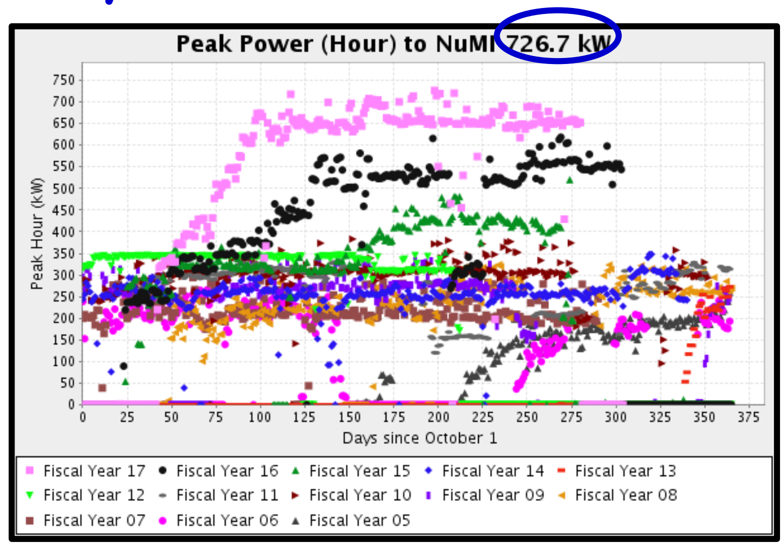
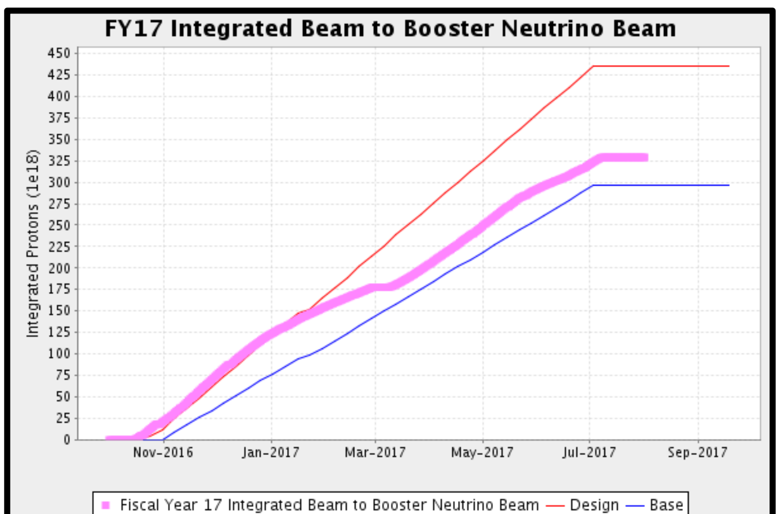
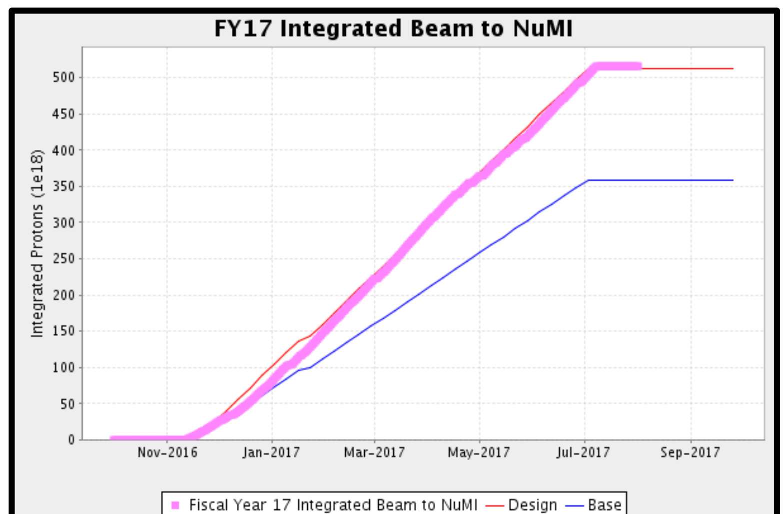
Accelerator Performance

Beam On Neutrino Targets for the past one year

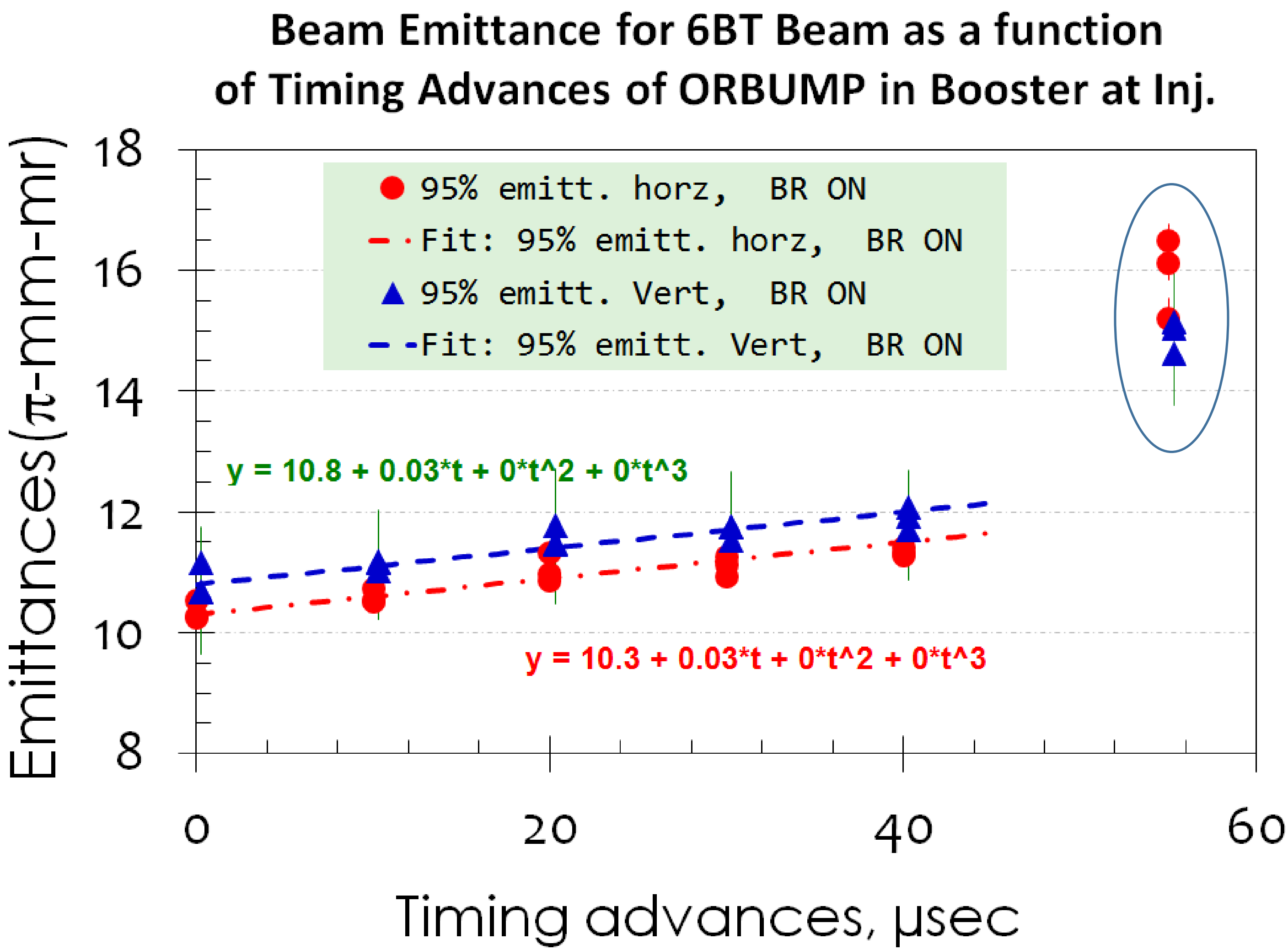




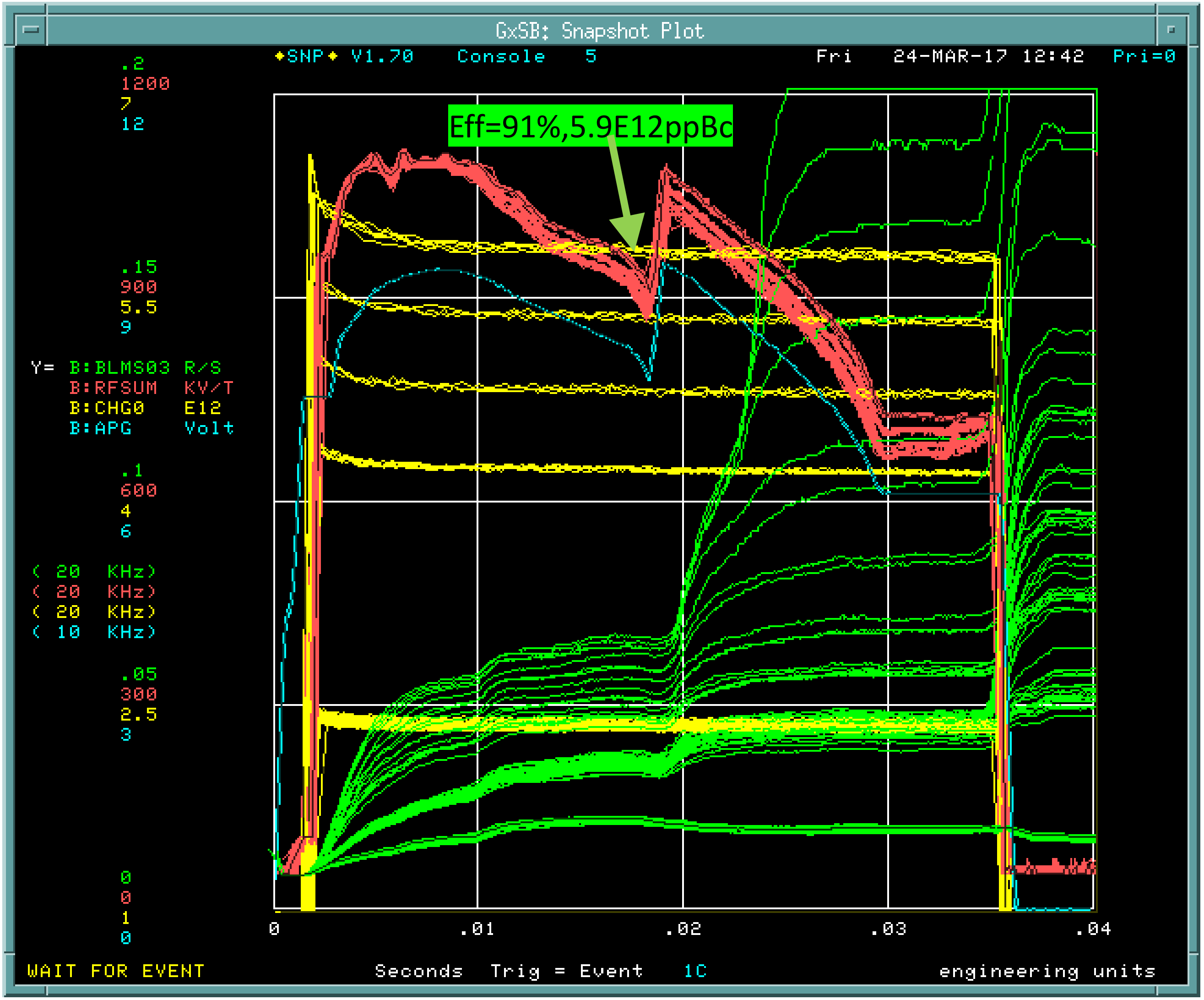




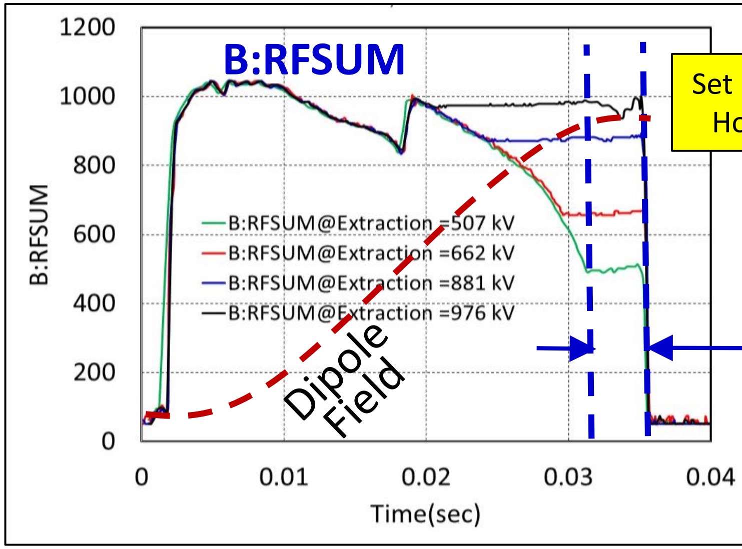
Ming-jen Yang, 20160222

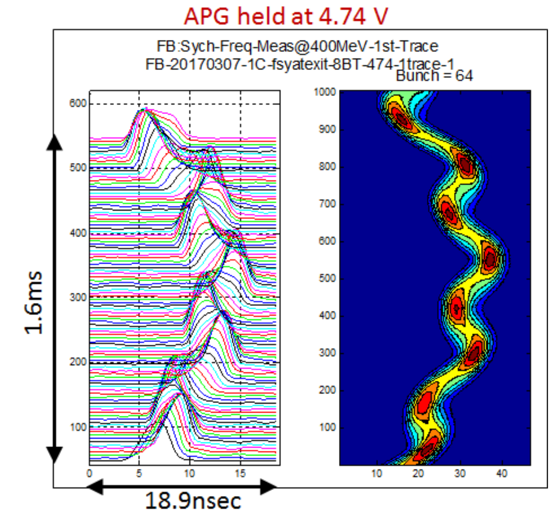


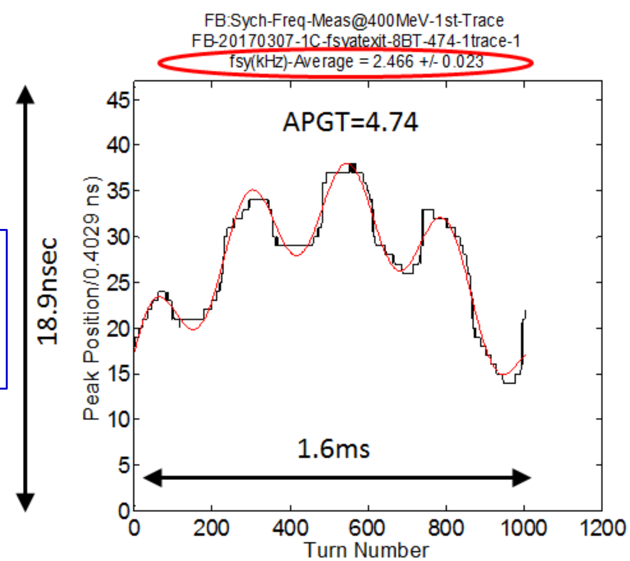
Studies with Different Intensities



8 GeV Data Sample



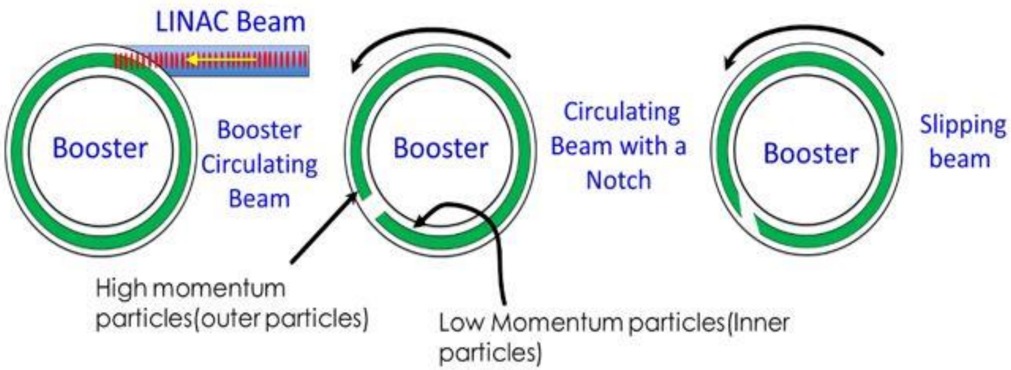




fsy from the fit to the peak position

$$F(t) = \underbrace{b_1 \sin(2\pi b_2 t + b_3) + b_4}_{\text{Back Ground (changing magnetic field)}} + \underbrace{b_5 \sin(2\pi b_6 t + b) + b_8}_{\text{Synchrotron Oscillations}}$$

ΔE at Injection on Multi-turn Beam



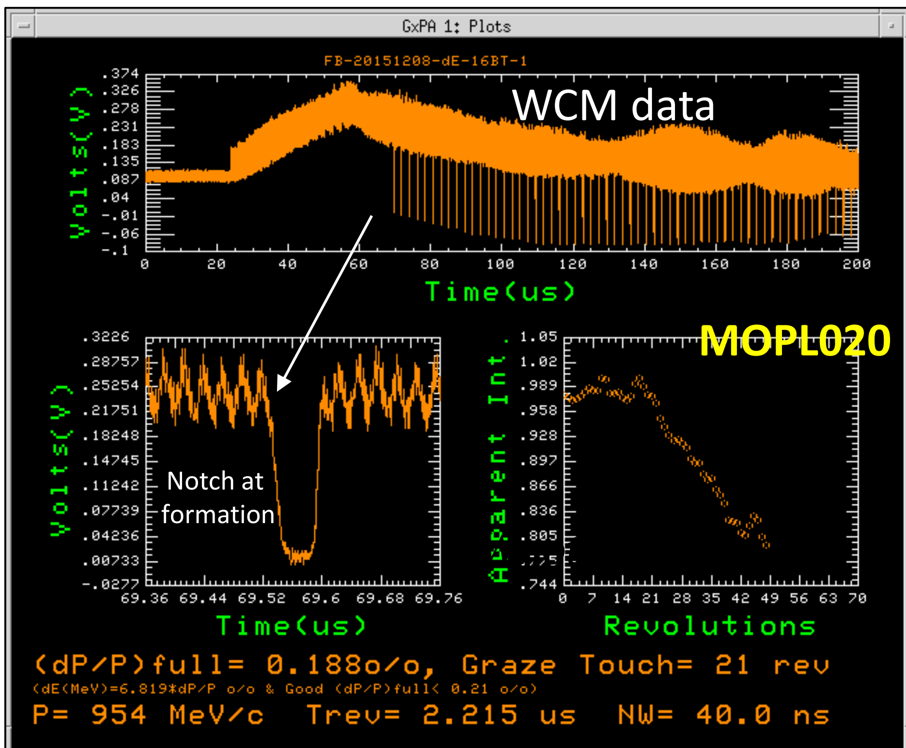
$$\Delta E = \frac{\beta^2 Es}{|\eta|} \frac{Wnotch}{Tgraze}$$

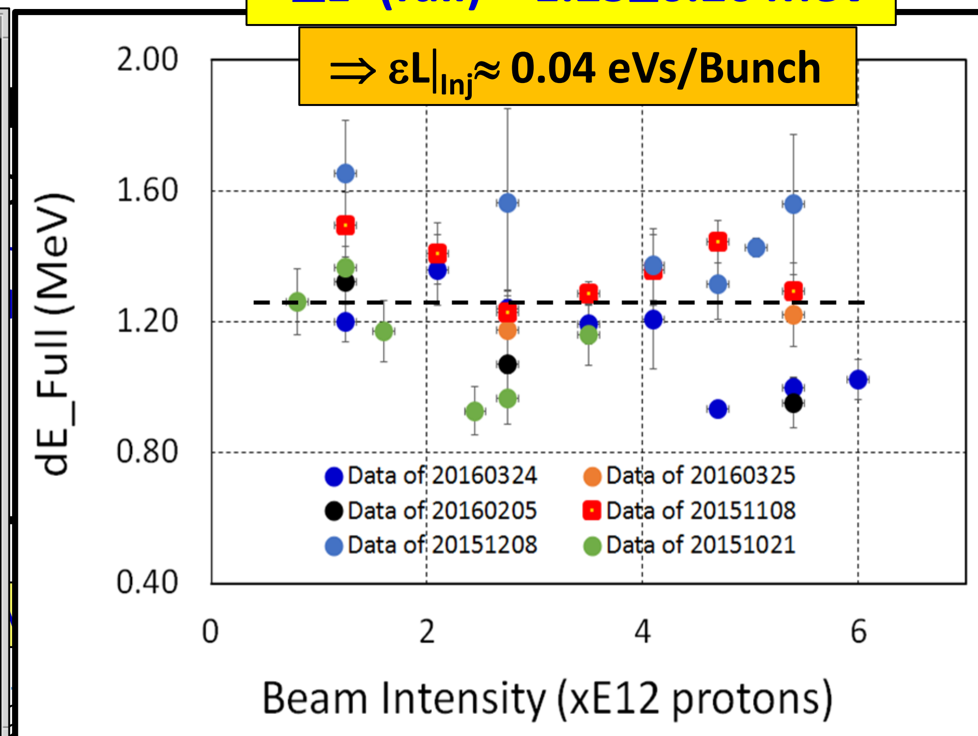
Wnotch = Width of the Notch

Tgraze = Time for grazing touch

<ΔE>(full) = 1.25±0.20 MeV

$\Rightarrow \varepsilon L|_{Inj} \approx$ 0.04 eVs/Bunch





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.