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Studies of Beam Intensity Effects in Fermilab Booster Synchrotron

Part I: Introduction; Tune and Chromaticity Scans of Beam Losses.

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Fermilab APT Seminar

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FERMILAB-TM-2740 and *FERMILAB-TM-2741*

Detrimental beam dynamics effects limit performance of high intensity rapid cycling synchrotrons (RCS) such as the 8 GeV Fermilab Booster. Here we report the results of comprehensive studies of various beam intensity dependent effects in the Booster (aka *Summer 2019 Booster beam studies campaig*n).

Part I covers the dependencies of the Booster beam intensity losses on the total number of protons per pulse and on key operational parameters such as the machine tunes and chromaticities.

In Part II we cross-check two methods of the beam emittance measurements (the multi-wires proportional chambers and the ionization profile monitors), analyze the intensity dependent emittance growth effects and discuss the ultimate performance of the machine now and after foreseen and proposed upgrades.

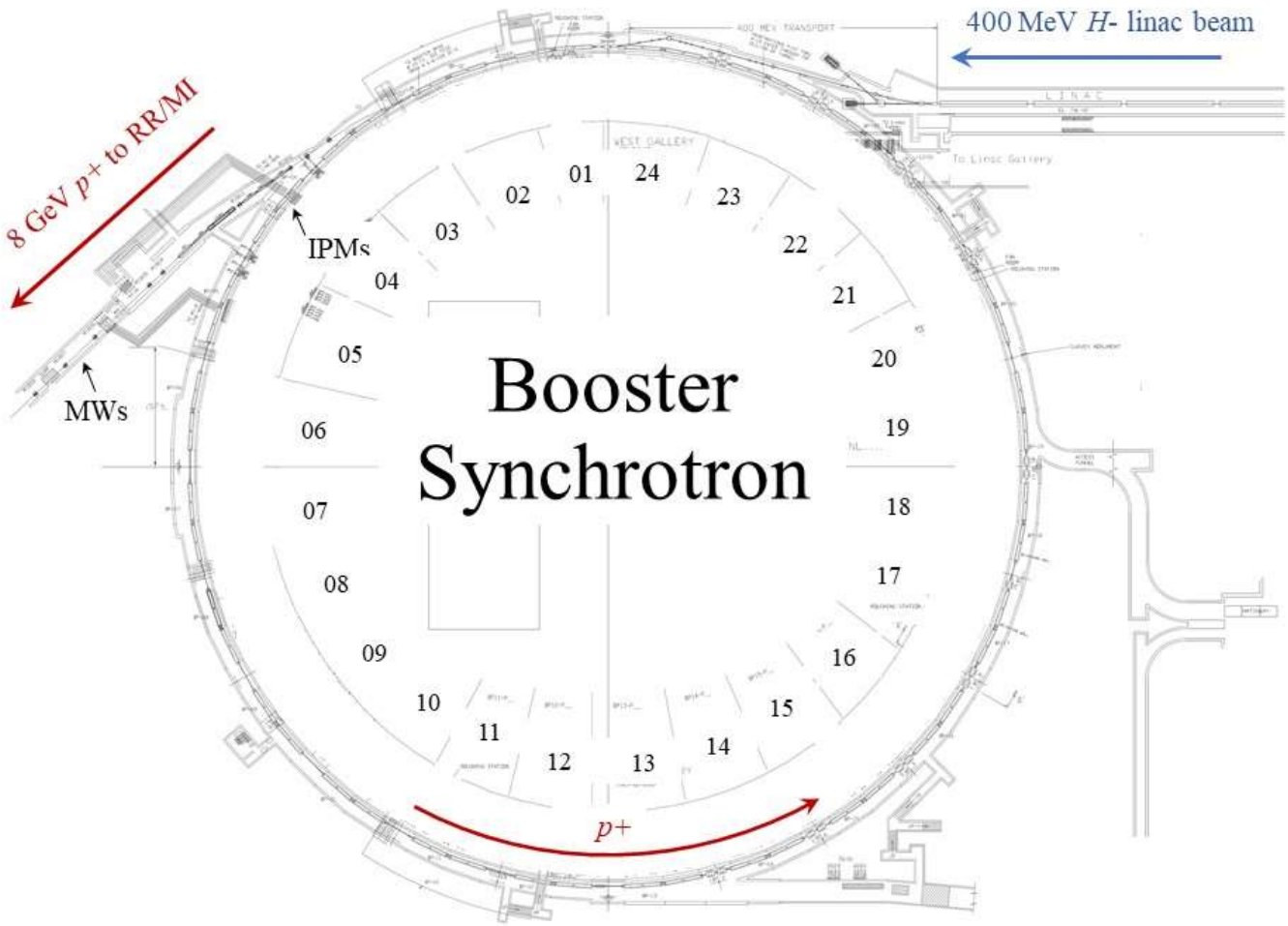
Acknowledgements

We would like to thank C.Y. Tan, C. Bhat, Yu. Alexahin, A. Burov, W. Pellico and R. Thurman-Keup for numerous discussions on the topics of this study and S. Chaurize, V. Kapin and K. Triplett for their invaluable help with experimental Booster beam studies.

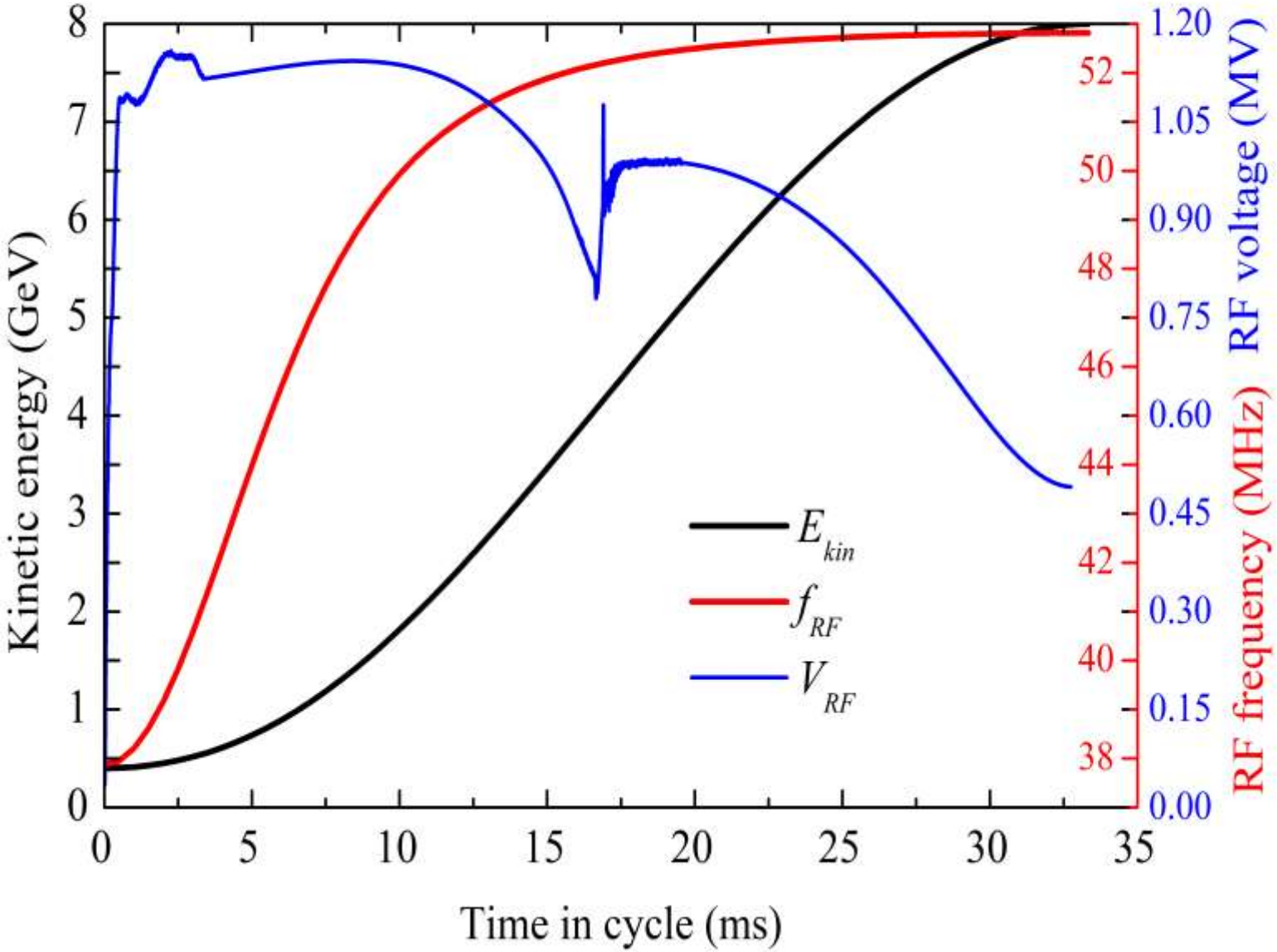
In addition, the **Summer 2019 Booster beam study campaign** involved N. Eddy, C. Jensen, J. Larson, and H. Pfeffer of Fermilab, H. Bartosik, N. Biancacci, M. Carla, A. Saa Hernandez, A. Huschauer, F. Schmidt of CERN, D. Bruhwiler, J. Edelen of the Radiasoft SBIR company and V. Kornilov of GSI.

We greatly appreciate their fruitful cooperation and the spirit of international beam physics collaboration.

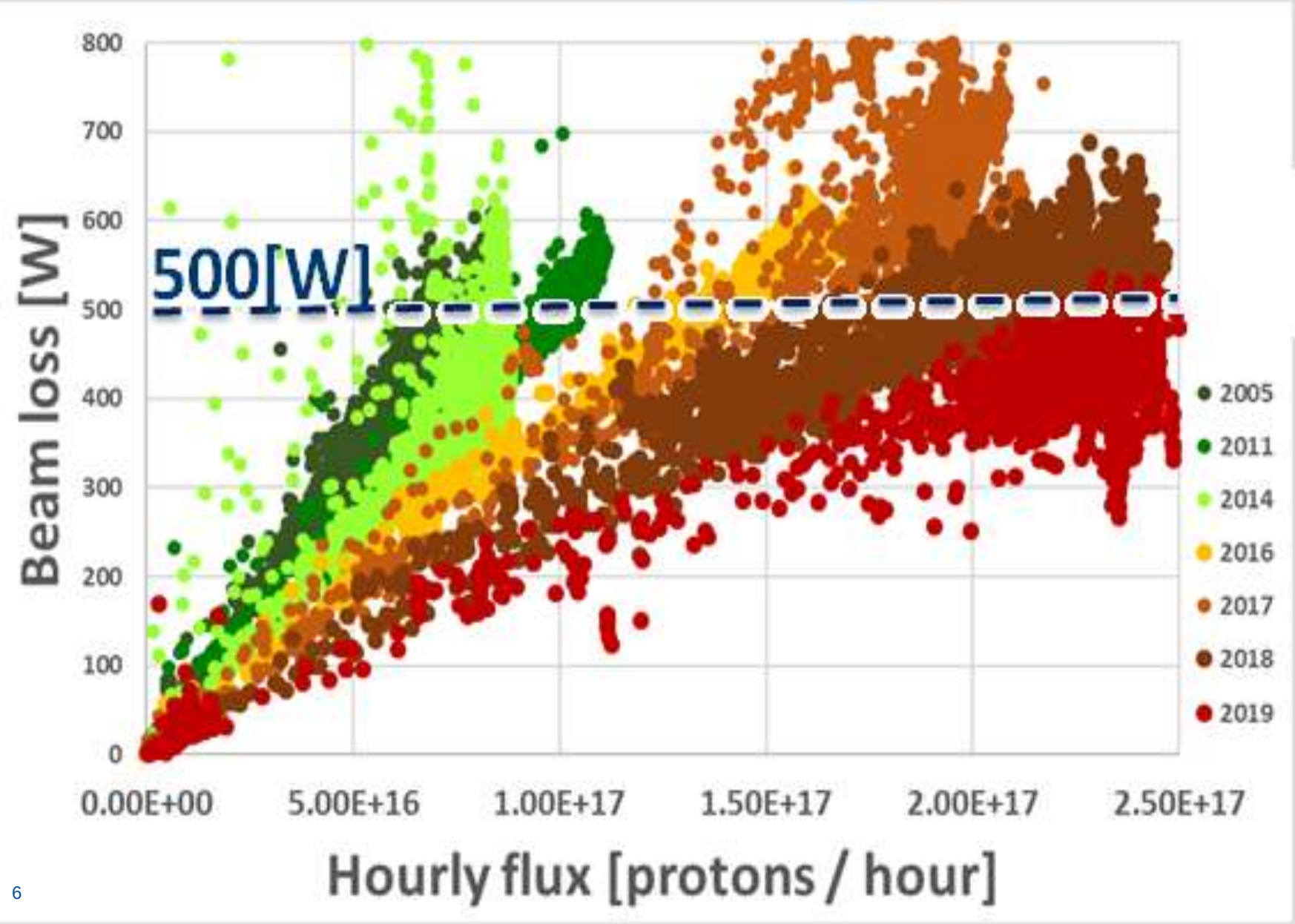
Part I - Booster : C=474 m, 400 MeV → 8 GeV, 15 Hz



Complicated Dynamics – esp. Early in the Cycle



Losses vs Flux : 1 W/m Limit → Flux Limit



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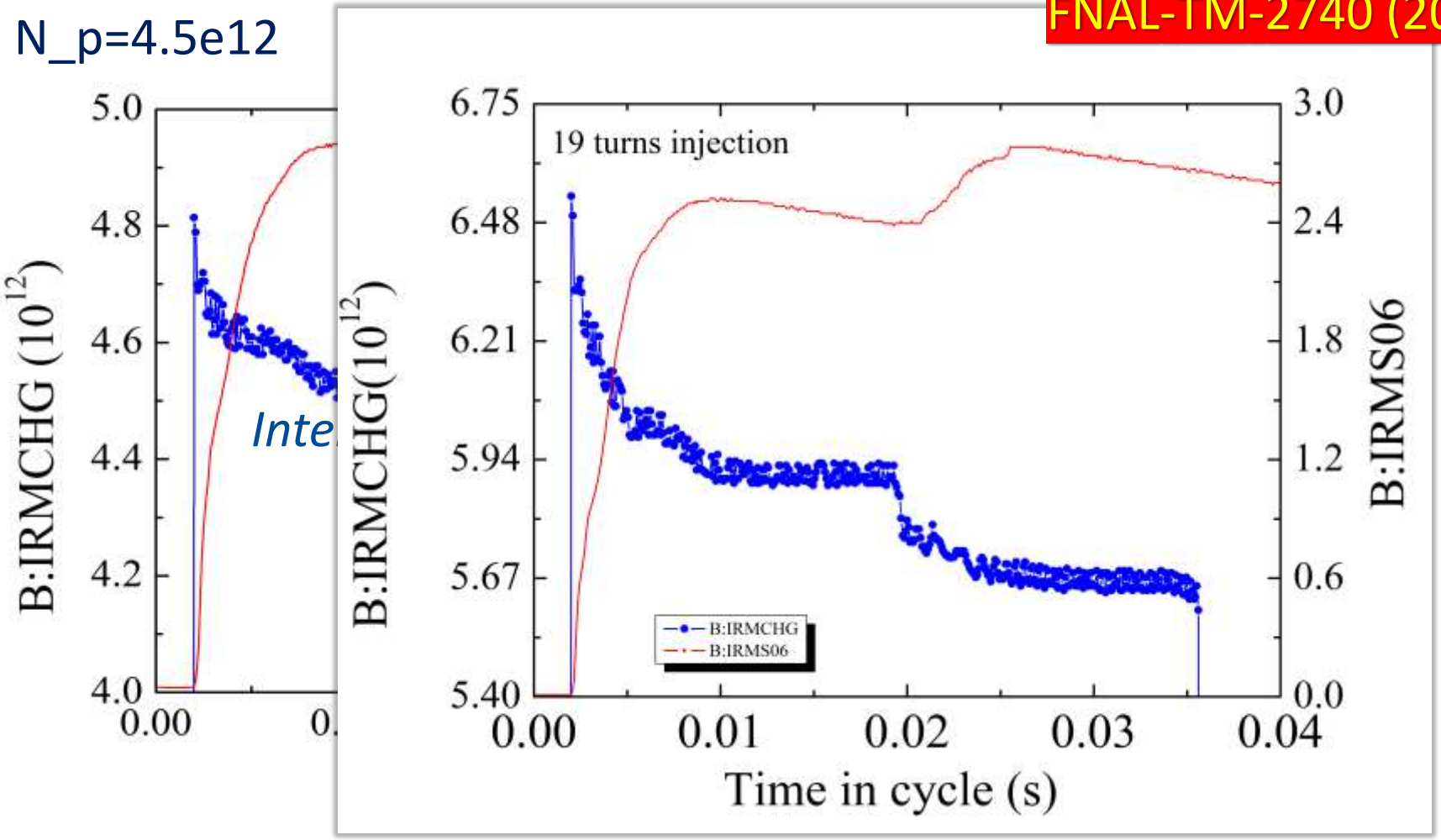
Two Occurrences of Losses in the Cycle

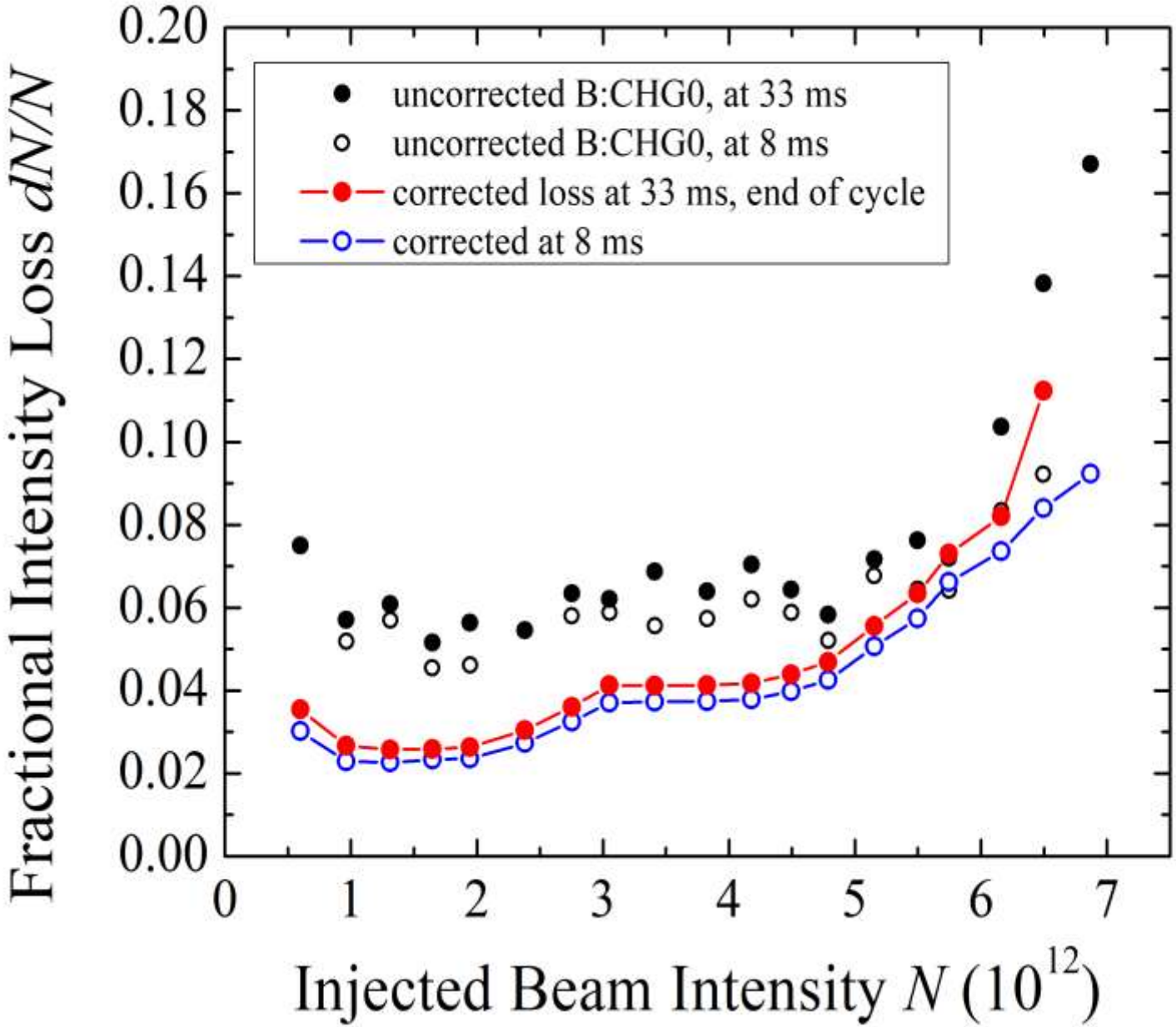
N_p=4.5e12

FNAL-TM-2740 (2020)



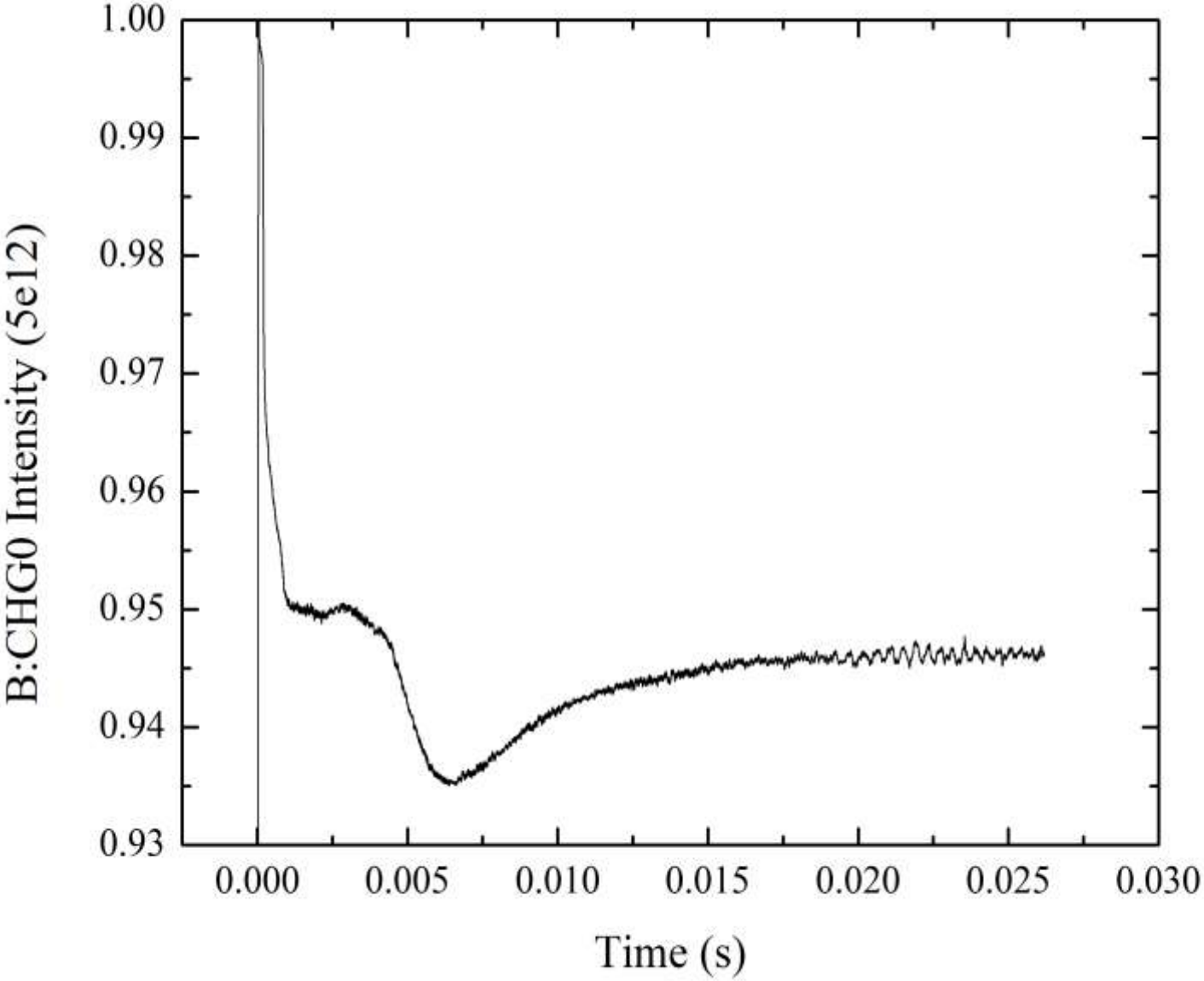
*data from the 2019 Booster Beam Studies, expt #S09

Overall Booster Efficiency *(N_in-N_out)/N_in*



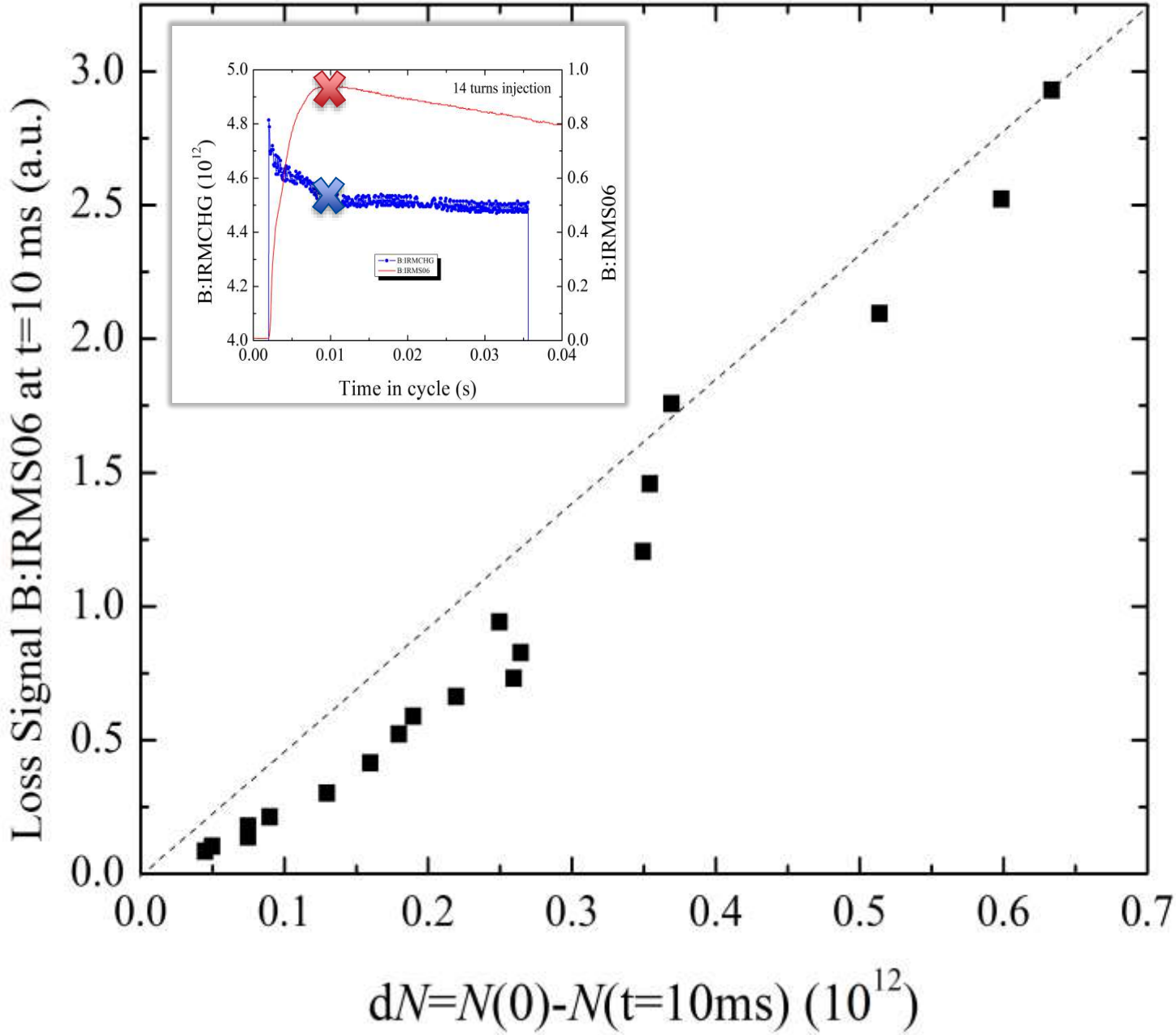
Fractional Booster beam intensity losses vs total injected number of protons: black circles and dots – for raw B:CHG0 intensity data taken at 8 ms in the cycle and at extraction, respectively; blue circles and red dots – for the data corrected for the toroid systematic error .

Raw B:CHG0 toroid intensity data



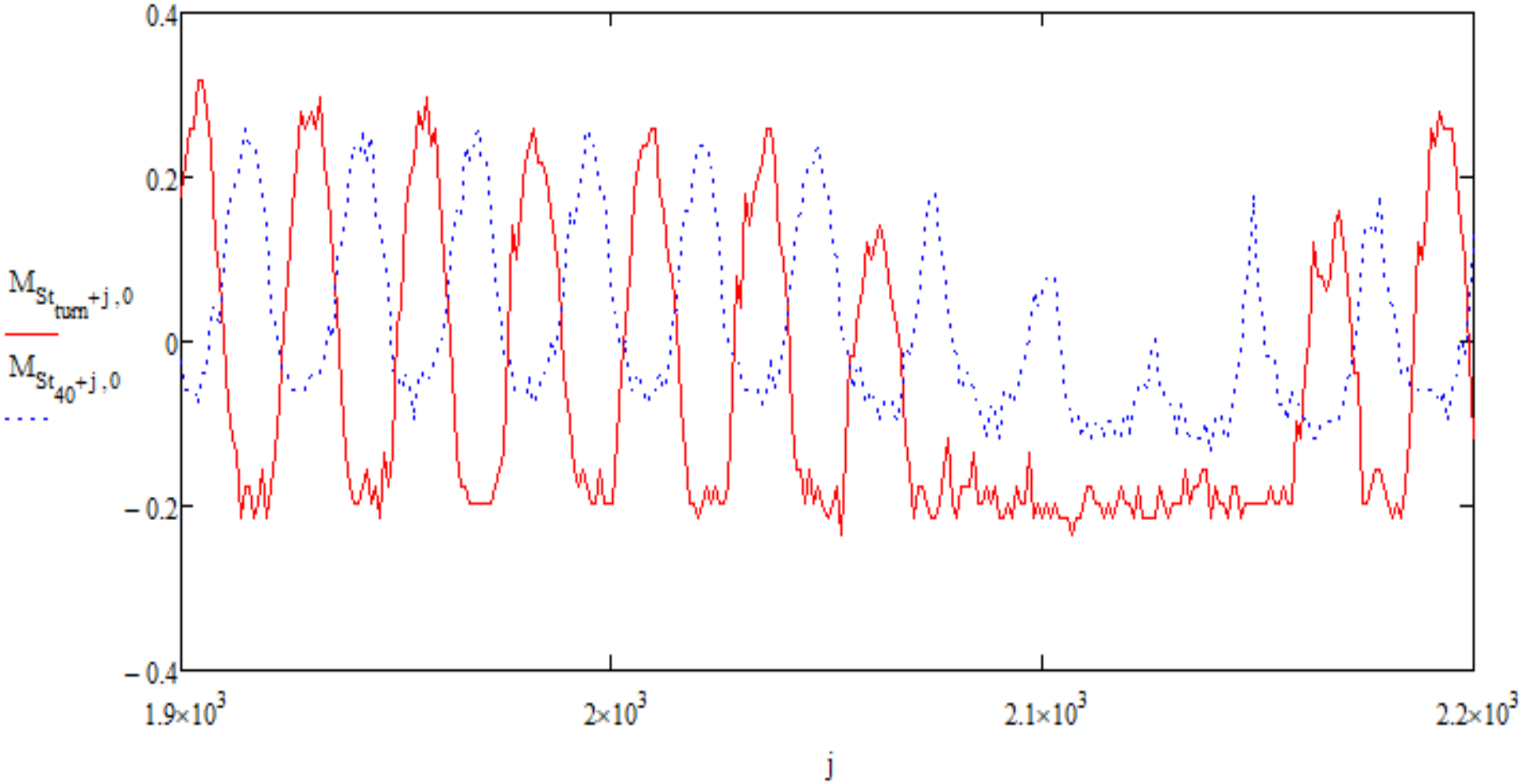
Reported B:CHG0 intensity, normalized to $5 \cdot 10^{12}$, in the Booster cycle

Cross-calibration? Wrt Booster loss monitors…



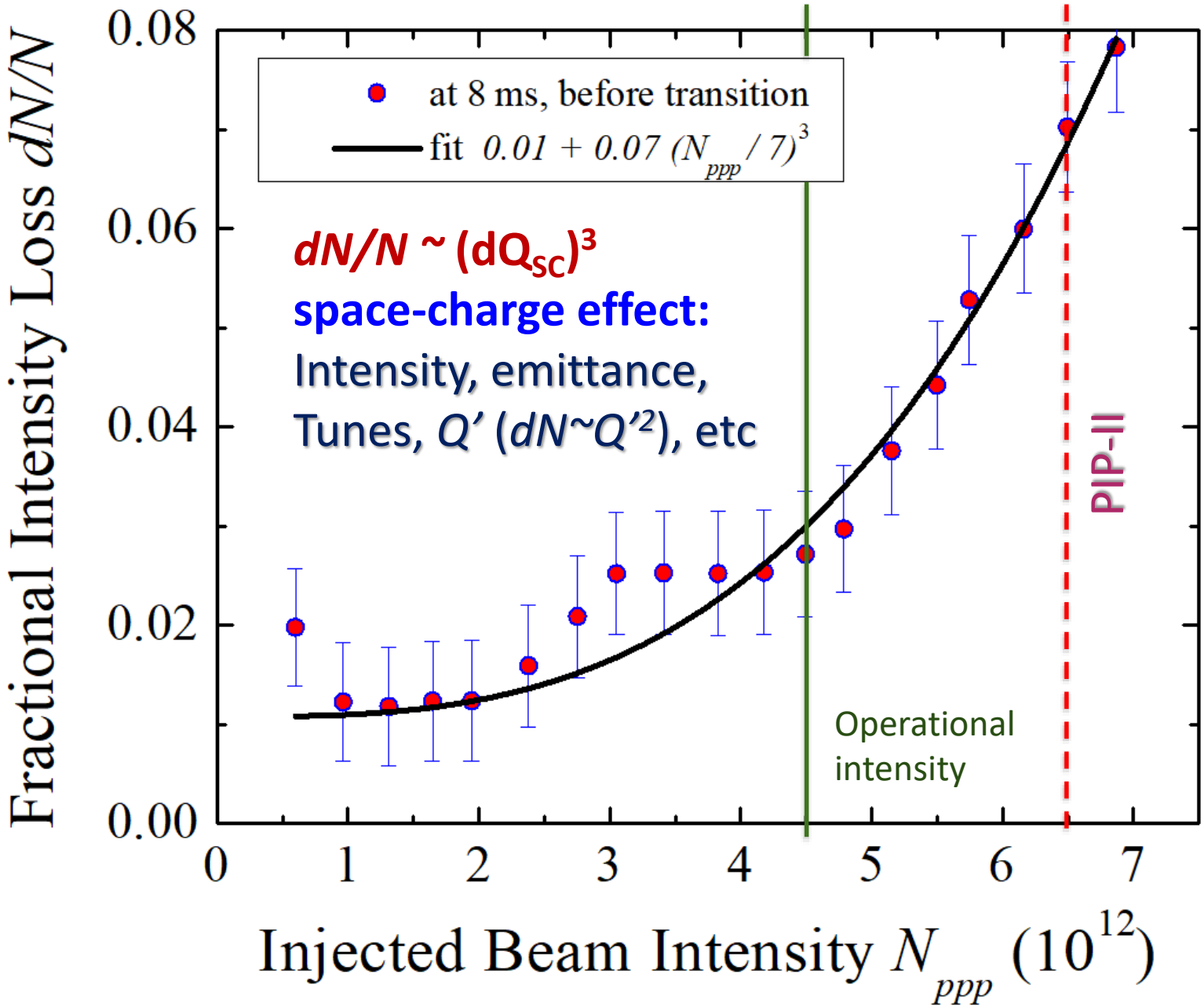
BLMS06 signal as measured at 10 ms into the Booster cycle vs the beam intensity change in the same 10 ms as measured by the B:CHG0 intensity monitor. The dashed line indicates the linear dependence anticipated from high beam intensity loss measurements.

Account the “Notcher gap” Intensity (not Booster to blame)



Booster RW monitor traces for the bunch beam current profiles right before (dashed blue) and 40 turns after (solid red) the extraction gap clearing.

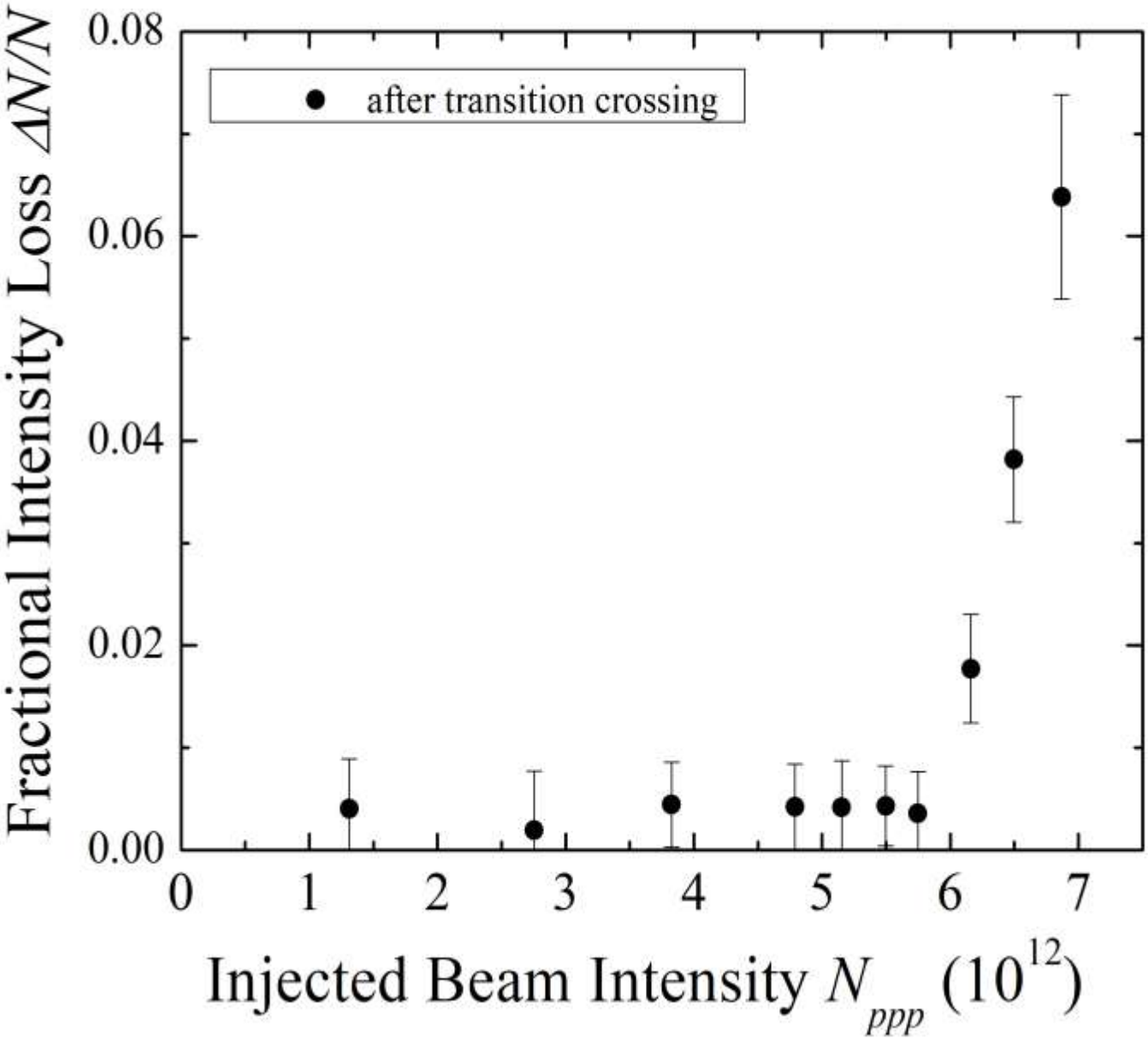
"After Injection" beam losses quickly grow with intensity *N*



Intensity-dependent fractional Booster beam intensity loss, i.e. notch losses subtracted

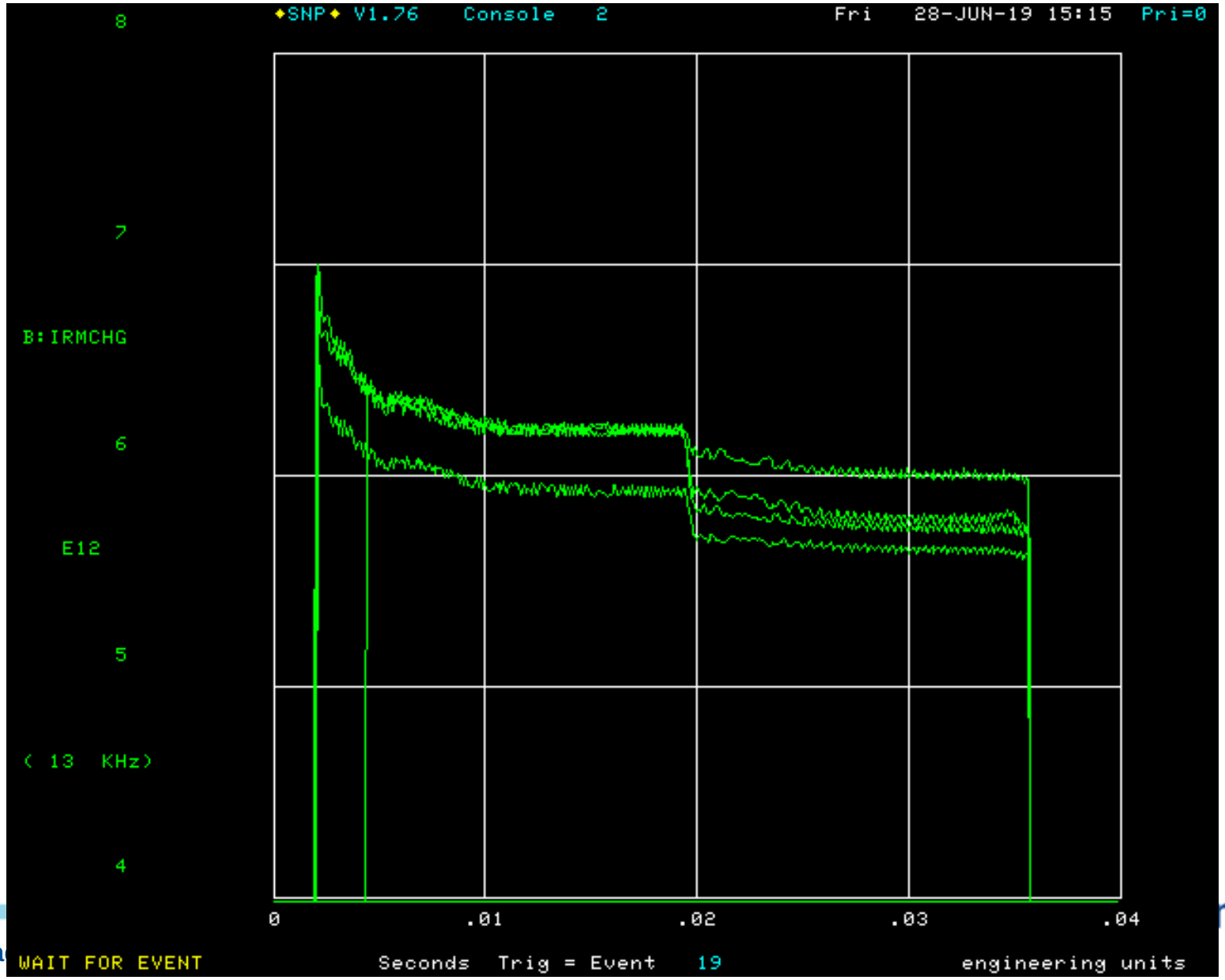
Operational chromaticities Q'(x,y)=(-4/-16)

What about transition?

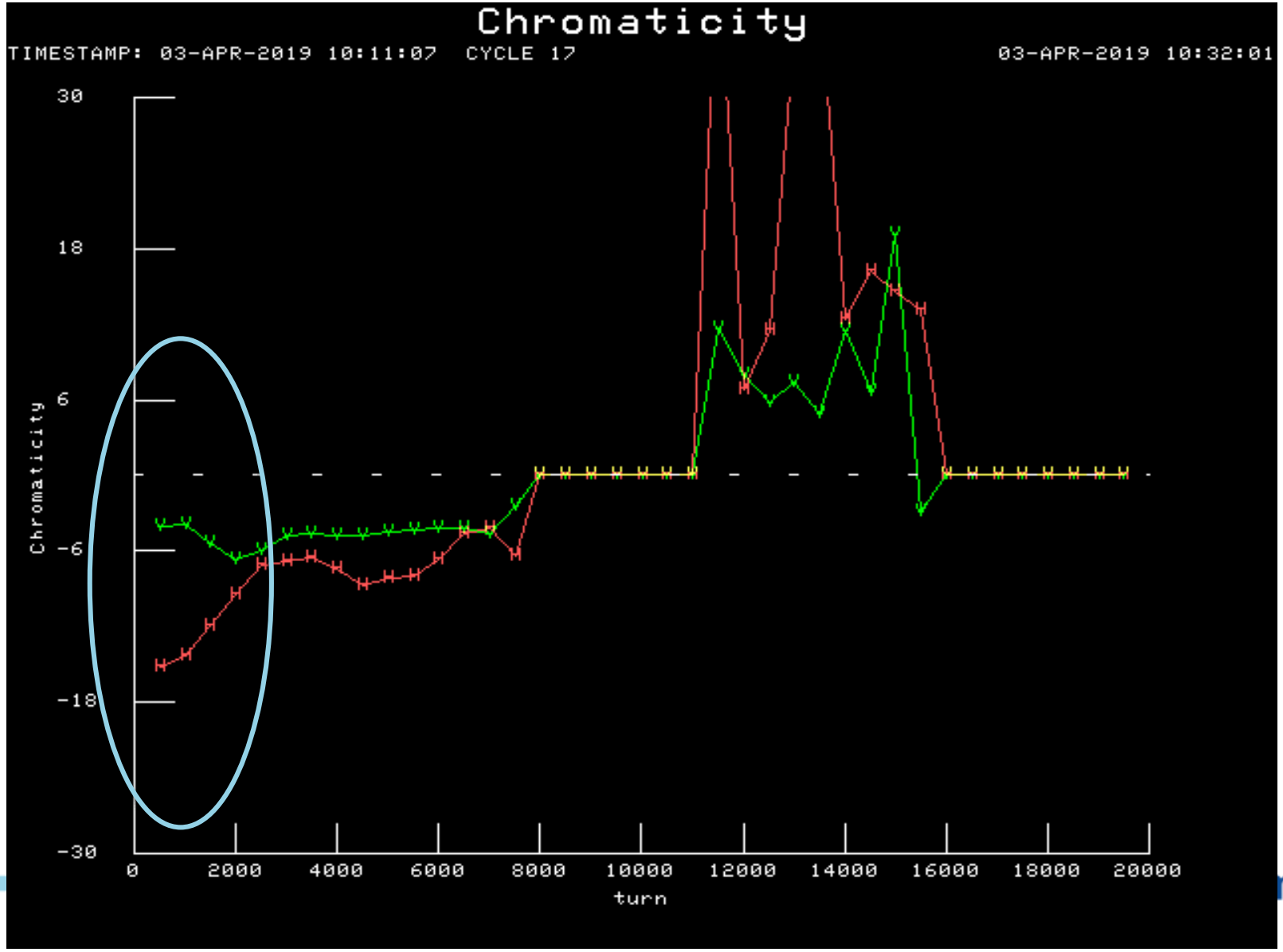


Intensity-dependent fractional beam intensity loss at transition vs total number of protons.

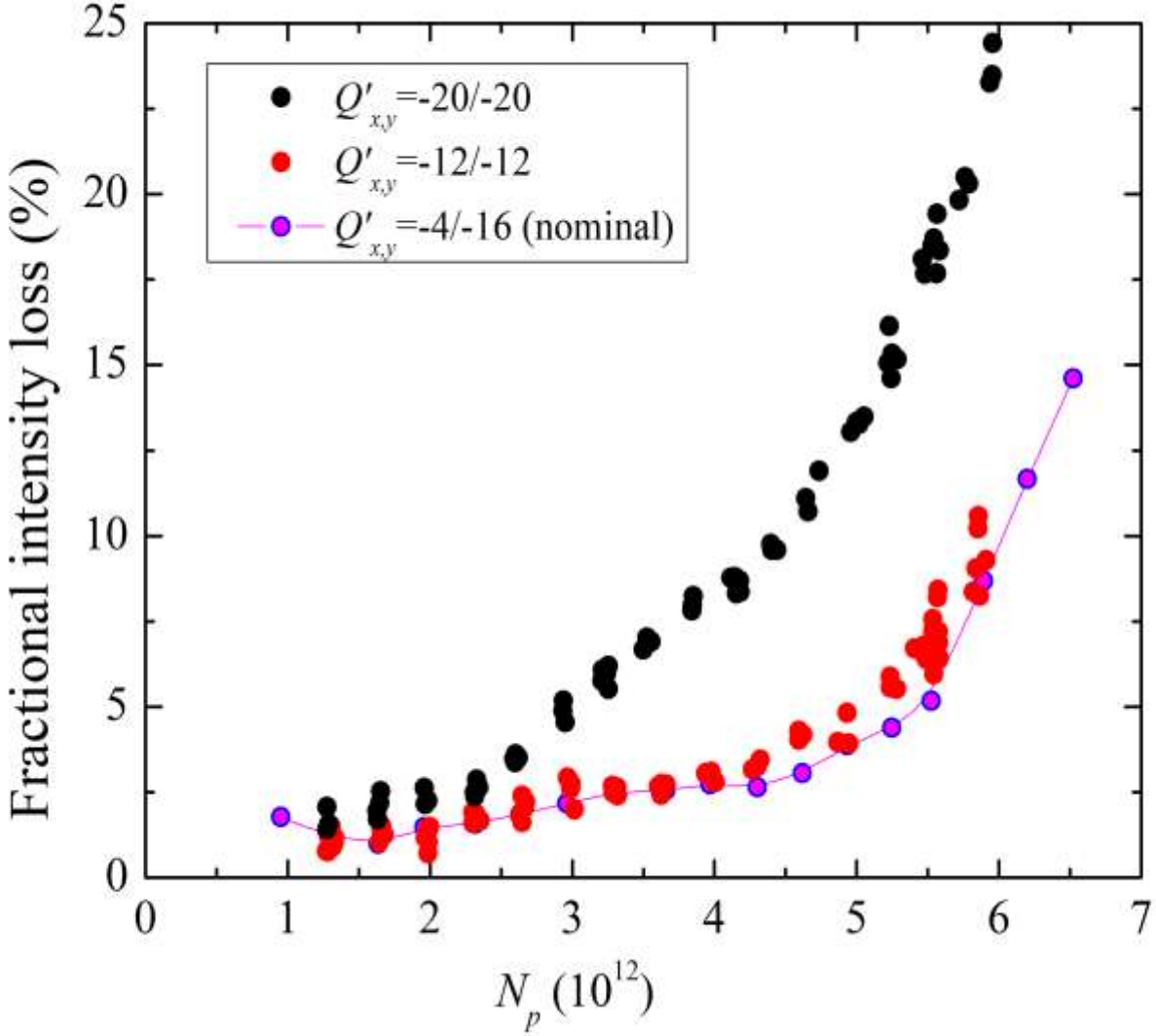
Record(?) Pulse Intensity out of Booster : 7e12 in → 6e12 out



What is the nature of the losses? Injection $Q_{x,y}$ and Q' scans



Three Chromaticity Settings : *dN/N* vs *N*



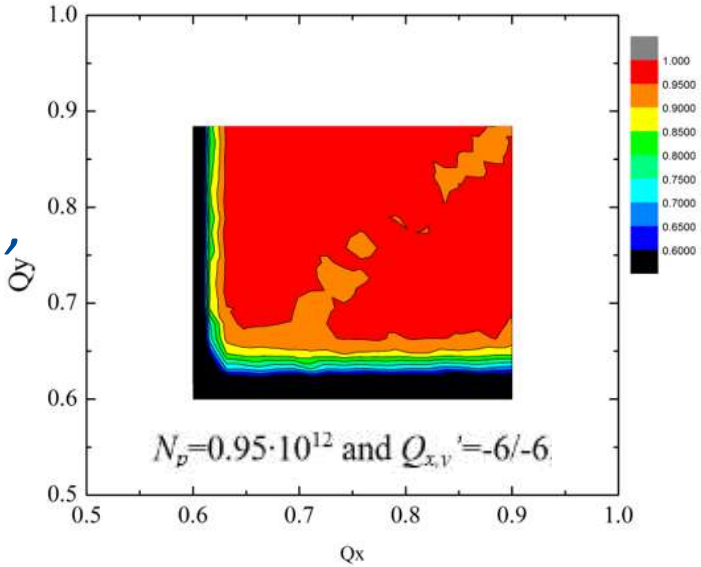
Approximation:

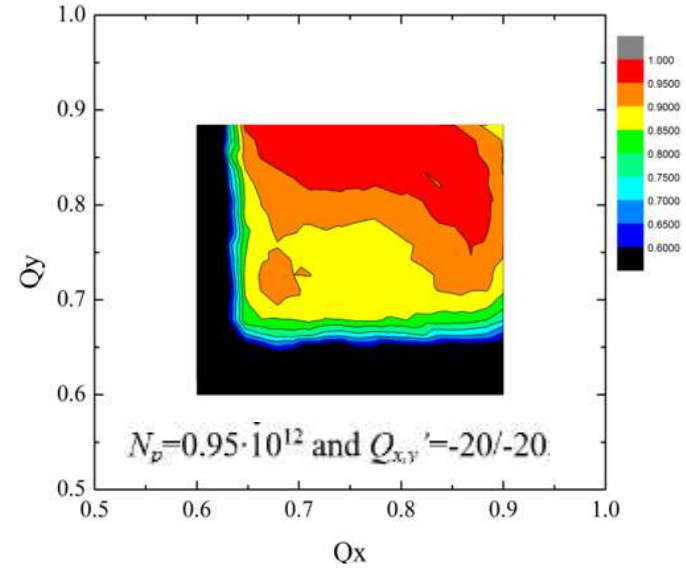
$$\frac{\Delta N_p}{N_p} = (0.013 \pm 0.003) + (0.10 \pm 0.02)\left(\frac{N_p}{7\times10^{12}}\right)^3\left(\frac{\langle Q' \rangle}{10}\right)^{1.9\pm0.2}$$

$\langle Q' \rangle = (|Q_y'| + |Q_y'|)/2$ is the average chromaticity

Tune Scans (…many – these are some examples)

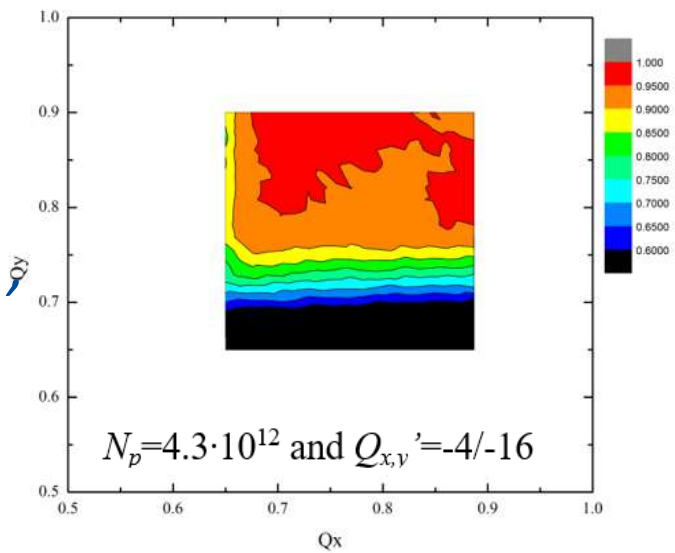
Low *N*
Low *Q'*

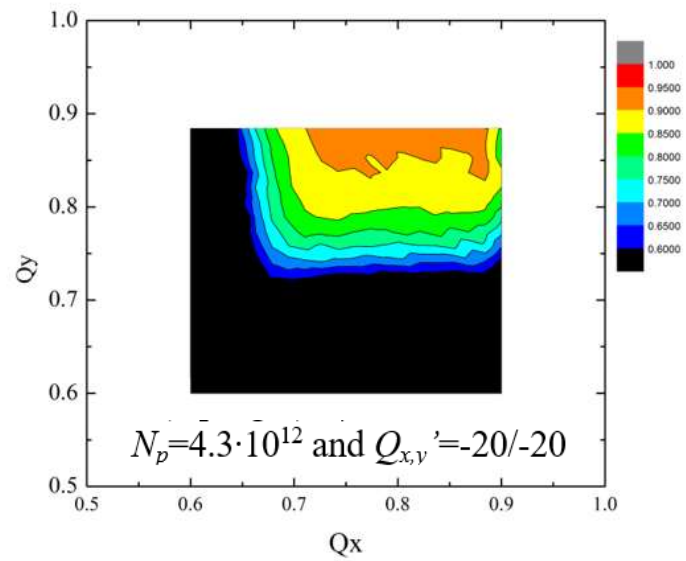




Low *N*
High *Q'*

High *N*
Med. *Q'*





High *N*
High *Q'*

Higher sensitivity of the losses to the vertical tune than to the horizontal one.

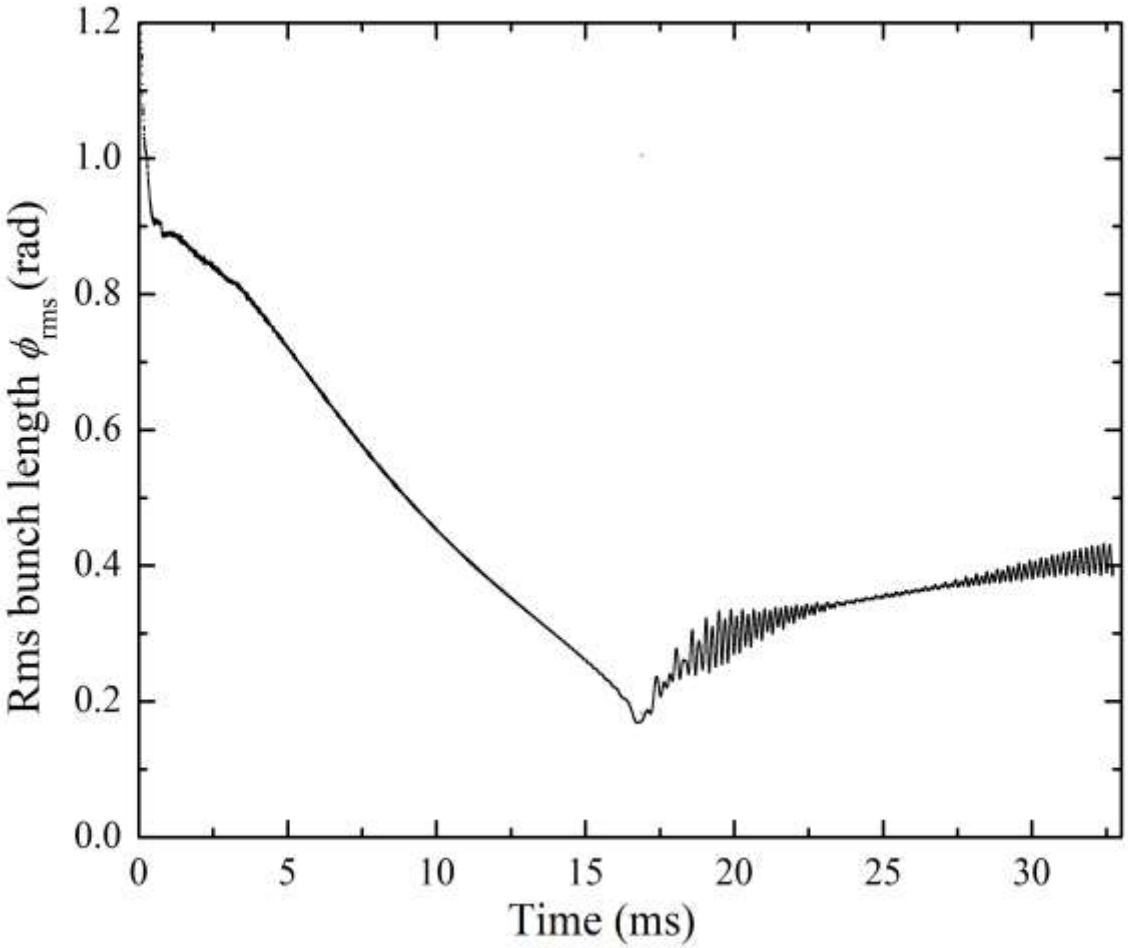
Summary of the Booster Losses

- **Losses due to crossing the foil**
  - ~1%, scale approx (BT+29)/2 arXiv:1912.02896
- **Losses out of the "three bunch gap" in the linac beam, needed for clean extraction**
  - About 1.7± 0.4% , weak dependence on intensity *N*
- **Losses few ms after injection (capture, etc)**
  - 1%+ 7% $(N/6e12)^3$ - space-charge *(N,Q,Q')*
- **Losses at the transition energy (5.2 GeV)**
  - Small (<1%) for *N*<4.6e12, *O*(10%) at higher intensities
- **Losses at extraction**
  - Usually small *O*(0.1%)

What is SC tuneshift?

$$\Delta Q_{SC} = \frac{N_p r_p B_f}{4\pi\varepsilon\beta\gamma^2}$$

$$B_f = (2\pi)^{1/2}/\varphi_{rms}$$



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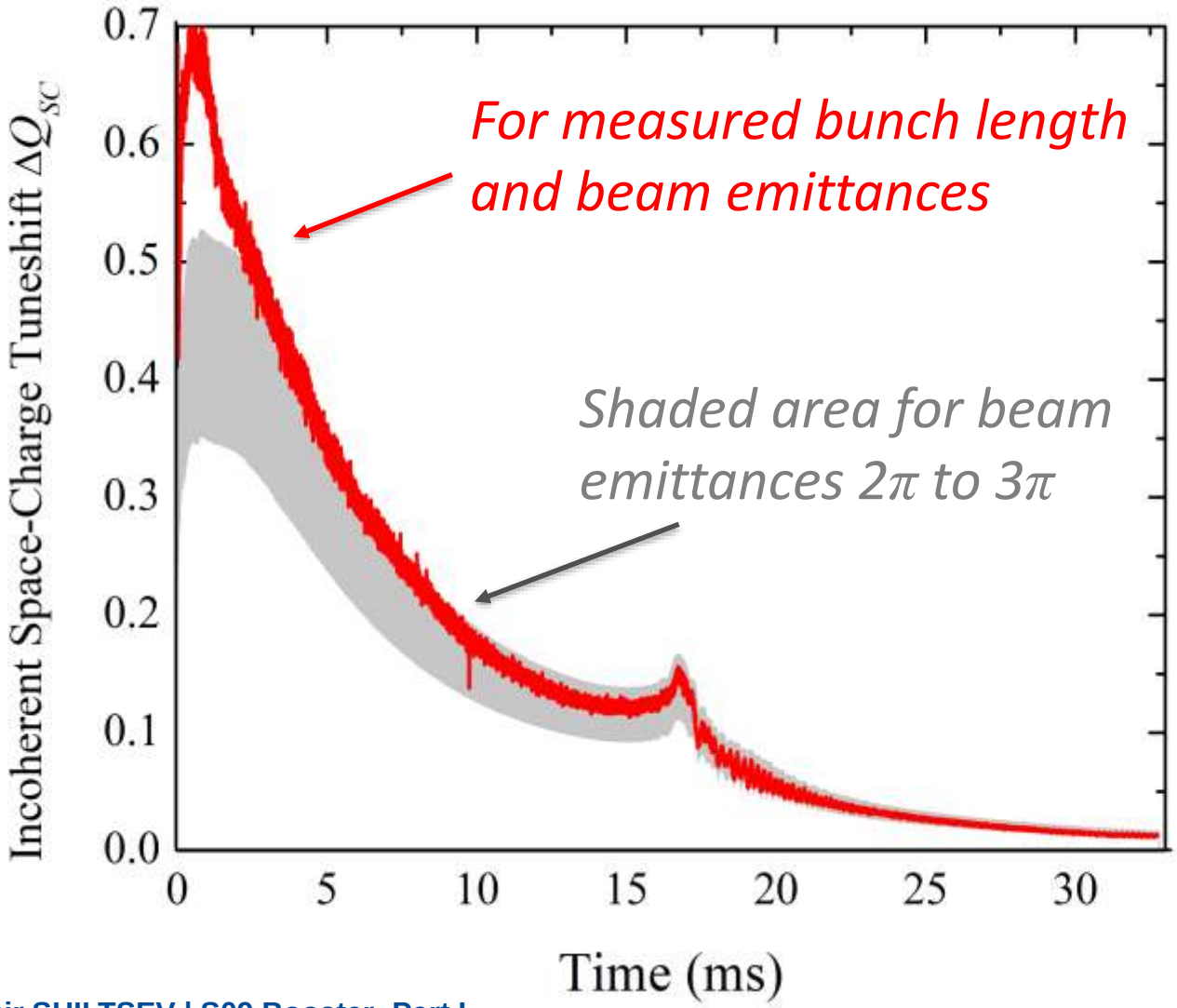
Space-Charge Tune Shift Parameter $dQ_{SC} \sim NB_f/\varepsilon\beta\gamma^2$

at nominal intensity N_p=4.4e12



See Report FNAL-TM-2741 (2020) and the Part II seminar (Sep.15)

"Booster @ PIP-II" Projections :

$N \rightarrow$ 6.5e12, 400 MeV $\rightarrow$ 800 MeV, $\beta\gamma^2$: 1.37 $\rightarrow$ 2.62

- **Losses due to crossing the foil**
  - Now ~1%
- **Losses out of the "three bunch gap" in the linac beam, needed for clean extraction**
  - Now ~1.7± 0.4%
- **Losses few ms after injection (capture, etc)**
  - Now 1%+ 7% $(N/6e12)^3$ - space-charge
- **Losses at the transition energy (5.2 GeV)**
  - Now <1% for N<4.6e12, O(7%) at higher N
- **Losses at extraction**
  - Now ~0.1%

0

?

If avg SC loss power is limited – eg *W*=500 W

$$\frac{\Delta N_p}{N_p} \leq \frac{W}{(1-\eta) N_p E_k f_0}$$

$$\frac{\Delta N_p}{N_p} \sim \alpha \Delta Q_{SC}{}^{\kappa}$$

$$\Delta Q_{SC} = \frac{N_p r_p B_f}{4\pi\varepsilon\beta\gamma^2}$$

E_k – kinetic energy (400 MeV → 800 MeV)

N_p – protons per pulse (4.4 → 6.5 e12)

f_0 – cycle rate 15 Hz → 20 Hz

η - efficiency of the collimation system (??)

κ – exponent , ≈3

0.25 0.75 1.33 -0.25

$$N_p^{max} \sim \left(\frac{W}{1-\eta}\right)^{\frac{1}{\kappa+1}} \cdot \left(\frac{\varepsilon}{B_f}\right)^{\frac{\kappa}{\kappa+1}} \cdot \gamma^{\frac{2\kappa-1/2}{\kappa+1}} \cdot (\alpha f_0)^{-\frac{1}{\kappa+1}}$$

x1.31 same? same? x1.41 x 0.93

Space-Charge Limit : Factors and Options

$$N_p^{max} \sim \left(\frac{W}{1-\eta}\right)^{\frac{1}{\kappa+1}} \cdot \left(\frac{\varepsilon}{B_f}\right)^{\frac{\kappa}{\kappa+1}} \cdot \gamma^{\frac{2\kappa-1/2}{\kappa+1}} \cdot (\alpha f_0)^{-\frac{1}{\kappa+1}}$$

To increase the maximum operational intensity one can:

i) increase the injection energy : PIP-II case → only **x1.3**

ii) better collimation to increase $\boldsymbol{\eta}$: eg 0.7→ 0.9 gives **x1.3**

iii) larger emittance (machine aperture) : +20% → **x1.15?**

iv) flatten the bunches to reduce $\boldsymbol{B_f}$: -20% → **x1.15**

v) improve the beam dynamics to make α and κ smaller

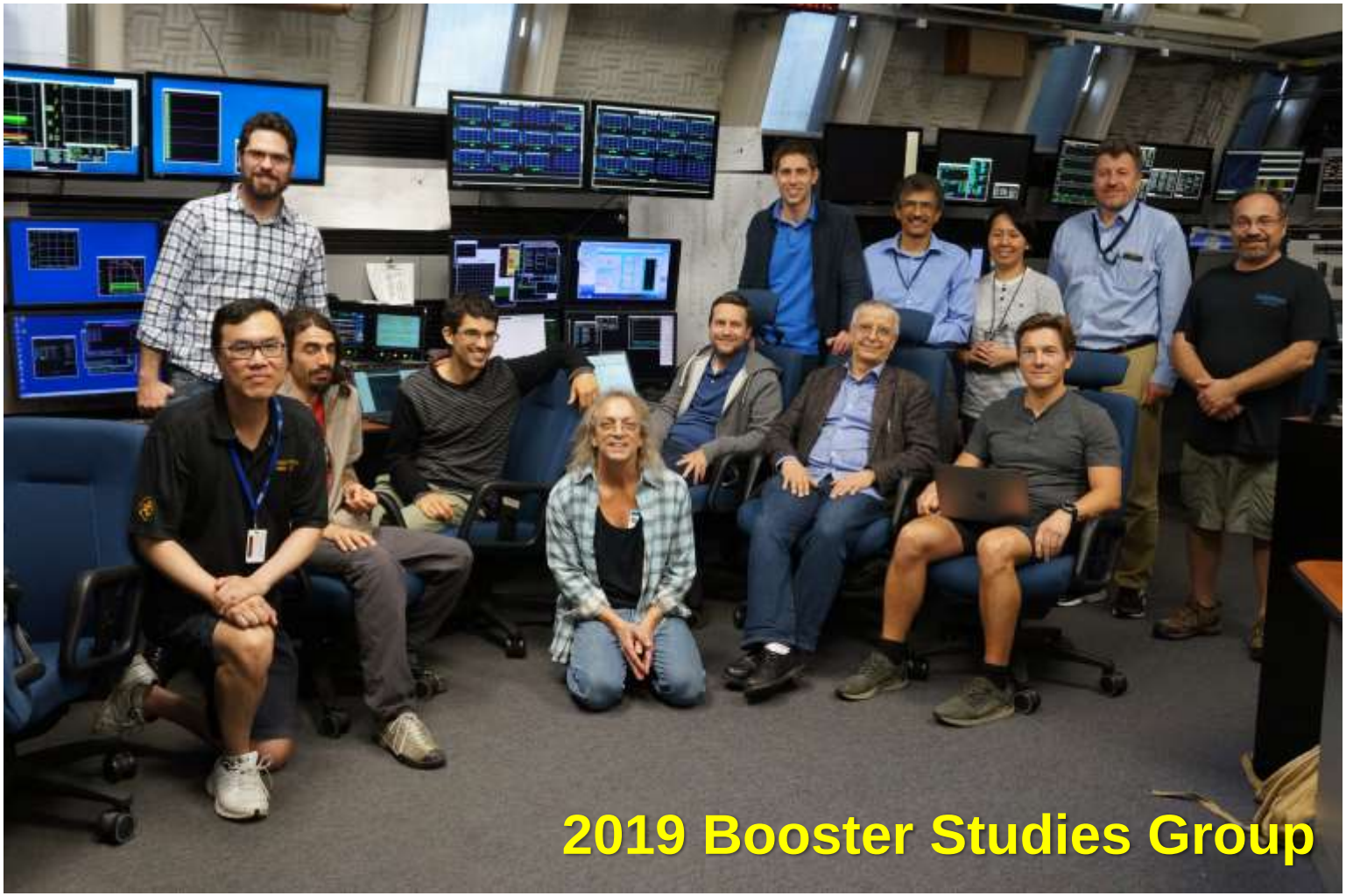
- by the *injection "painting"* to make the SC force more uniform
- via *non-linear integrable optics*
- by SC *compensation by e-lenses*, etc

x2 ?
(IOTA)

Seminar #1 : Conclusions

- The Booster beam losses are dominated by *O*(4%) losses early in the cycle at *N*<5e12 ppp and *O*(7%) losses at transition at *N*>6e12 ppp
  - Inj/capture losses are due to SC, transition loss – (instability? *dP/P*?)
  - That's on top of losses on the foil (~1%), dirty gap (~1.7%) and extraction (~0.1% at 8 GeV equivalent to 2% at injection)
- The space-charge losses at injection scale $\sim N^3 Q'^2$
  - $dQ_{SC} \sim 0.7$… Can *Q'* be further dropped? Can *P=24* periodicity help?
- The PIP-II era ops (6.5e12, 800 MeV, 20 Hz) is worrisome:
  - Control of the SC loss at injection might require additional measures
  - Losses at the transition are poorly understood (the biggest concern)
- The issues are serious and call for detail analysis:
  - of emittances (see Seminar #2 in three weeks)
  - instrumentation must be improved: B:CHG0, RWs to be good to 0.1%

Thank You for Your Attention !

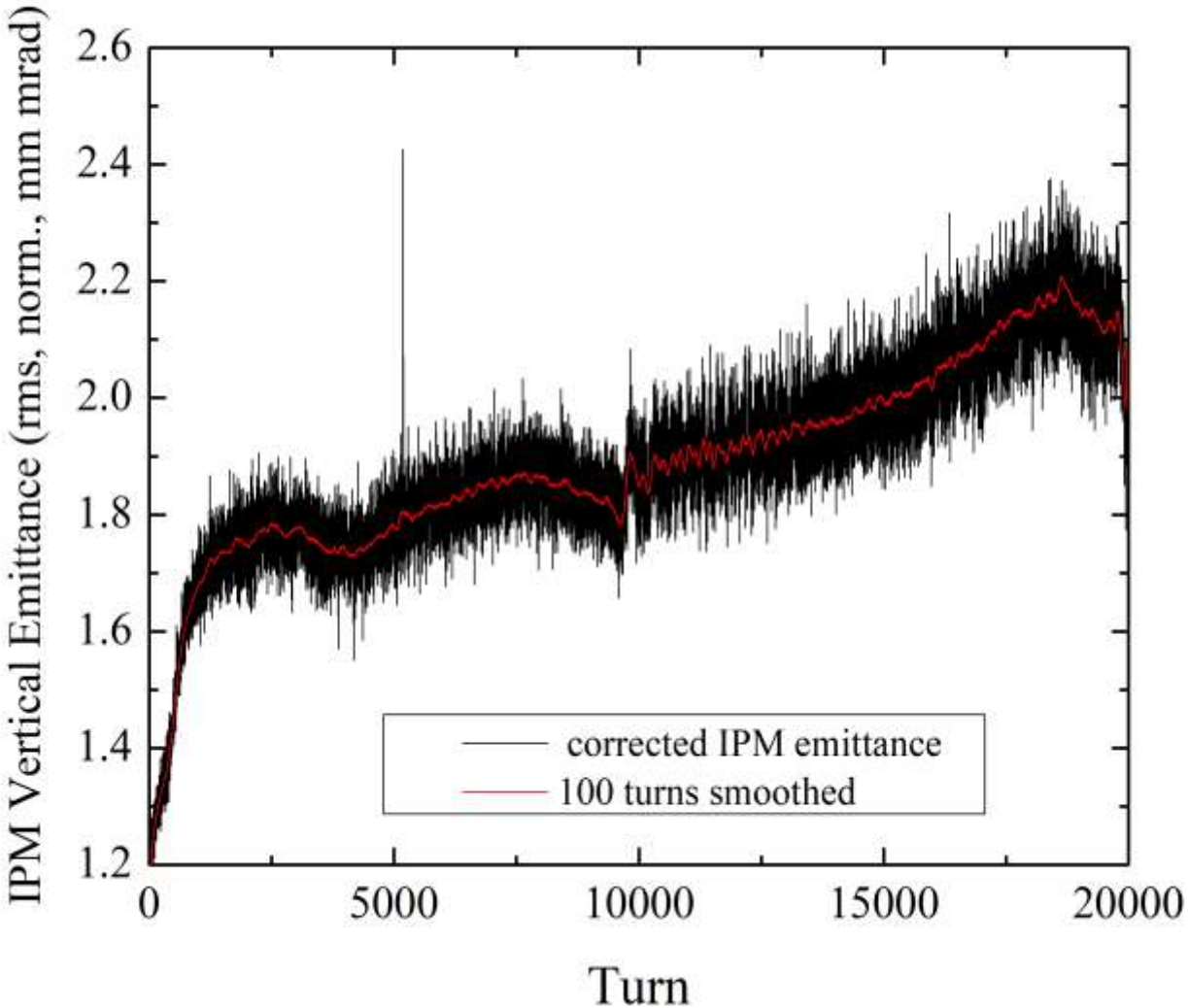


(also Angela, David, Jon, and many key Fermilab participants.)

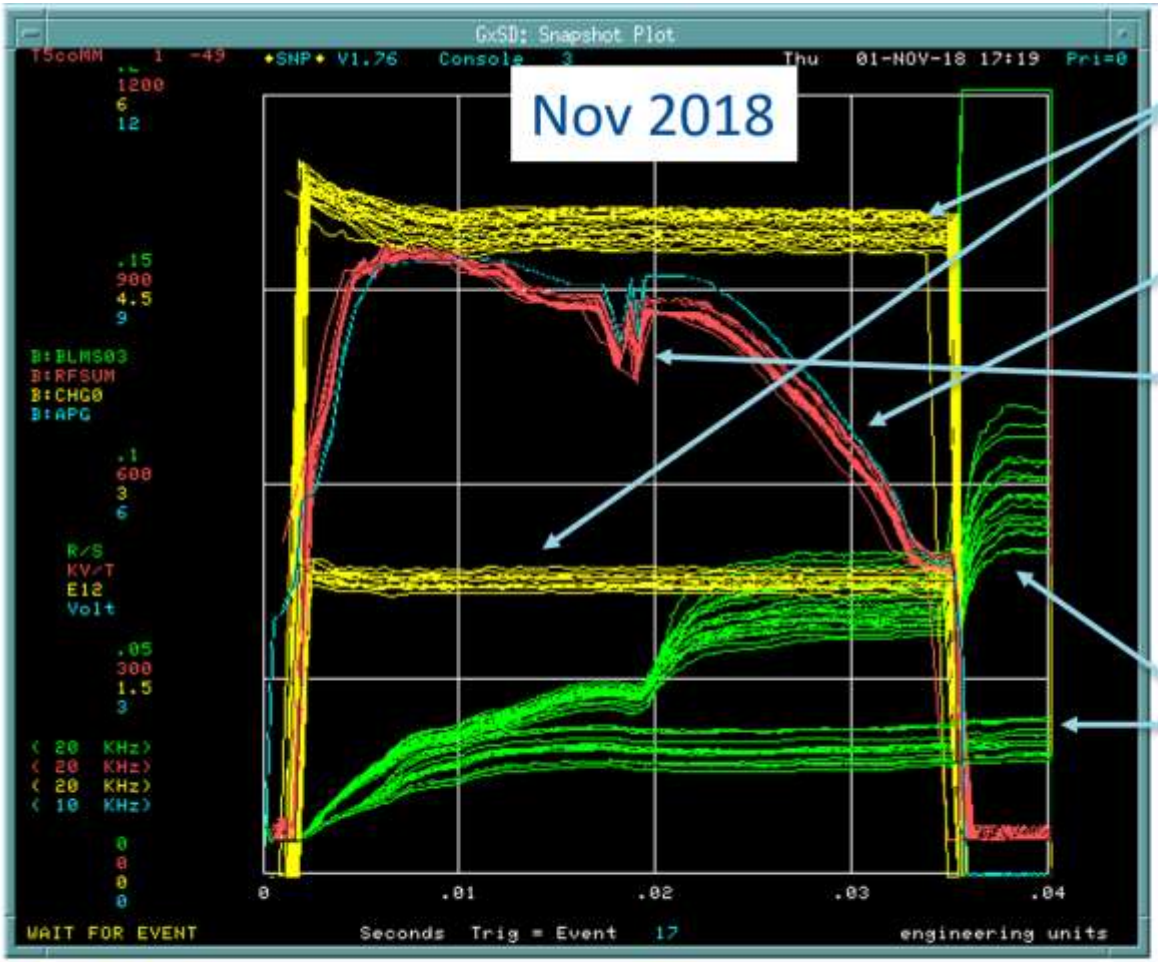
Backup

Booster emittance evolution at nominal intensity

FNAL-TM-2741 (2020)



Losses over Cycle



Beam intensity (e12)

RF sum voltage

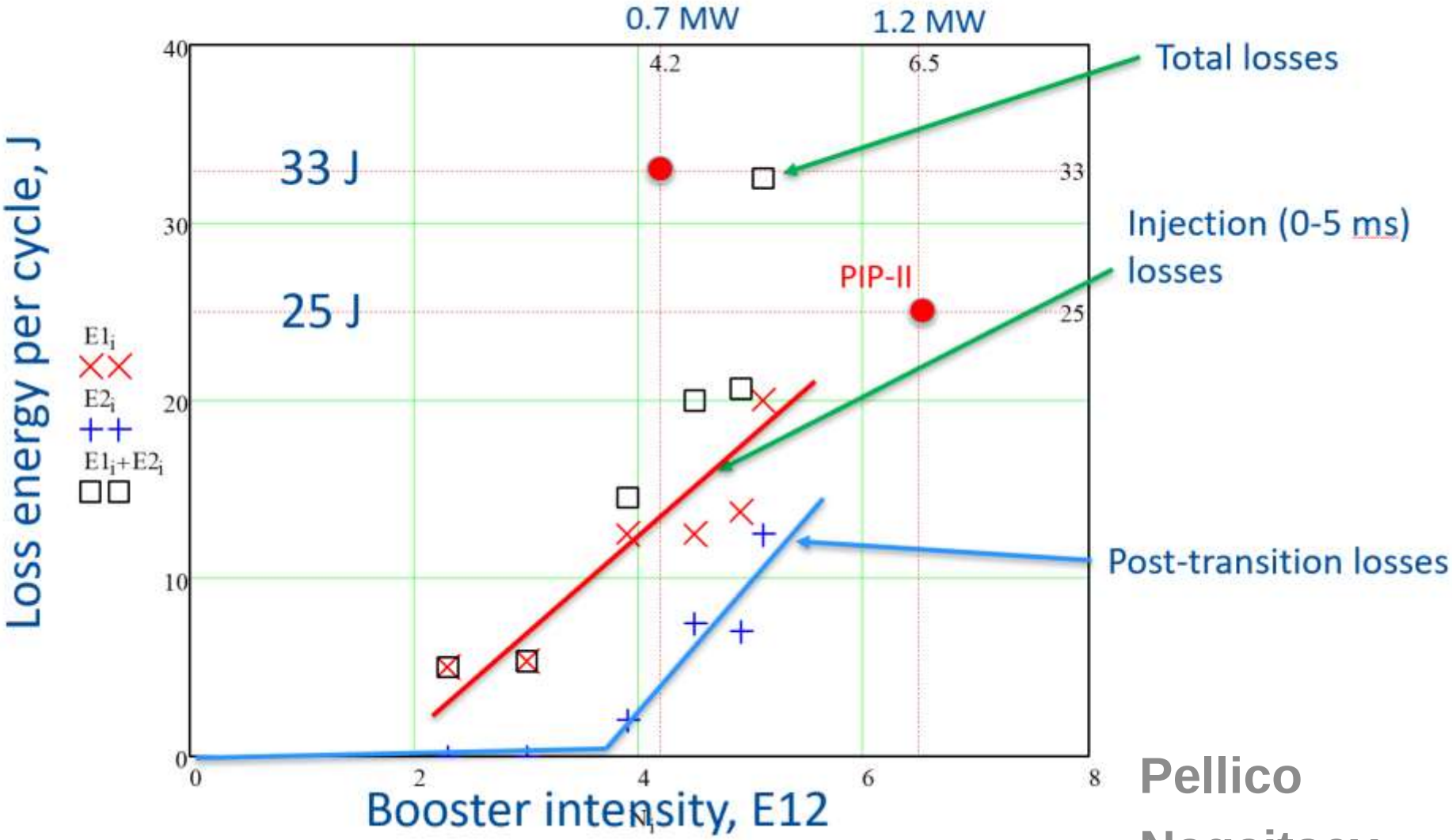
Gamma-t transition at ~5 GeV

Beam losses at one particular location

Beam losses for two different intensities (green lines).

Losses above gamma-t transition appear only above 3e12.

Injection & Transition Losses



Pellico

Nagaitsev

PIP-II at 400 MeV

Two-stage collimators – conceptual design.

Wide-bore RF cavities, 60 kV and 3-inch aperture.

GMPS regulation using ML learning (LDRD).

Flat Injection – correct dipole ramp during injection.

LLRF system upgraded to digital.

Longitudinal & transverse damper amplifier upgrades.

Booster shielding assessment

Magnet girder test-stand for 20 Hz.