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Studies of Beam Intensity Effects in Fermilab Booster Synchrotron

Part II: Beam Emittance Evolution

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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 campaign*).

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.

See APT Seminar 08/25/2020

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

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

Part I Summary: 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
  - Mb as high as *O*(10%) at higher intensities if not tuned up
- **Losses at extraction**
  - Usually small *O*(0.1%)

Booster Emittance Diagnostics : Multi Wires

Vertical and horizontal MWs are installed in the extraction beam line

β_x=16.2m, β_y=25.9m, D_x=-1.65m

(one measurement per cycle at best)

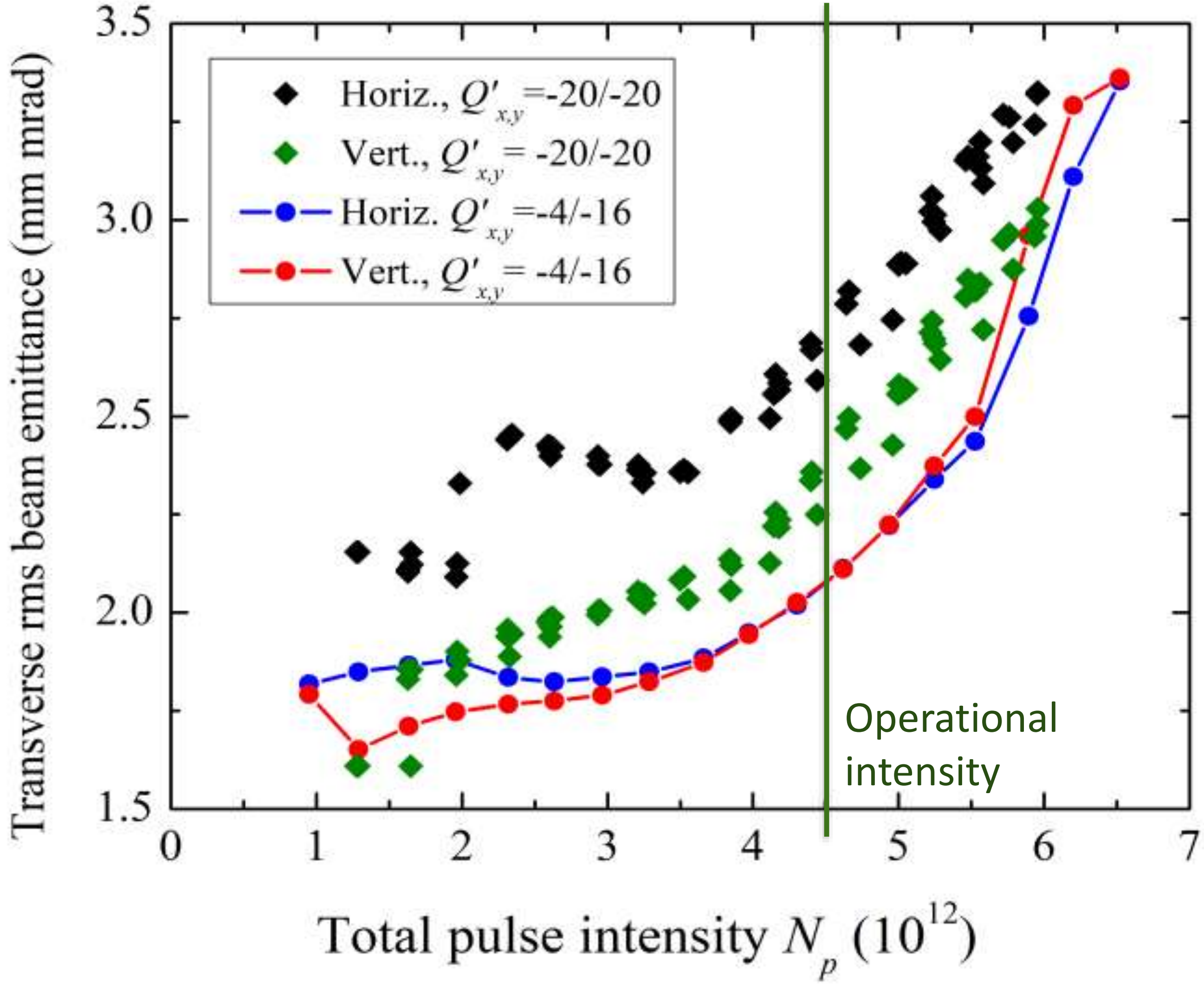
(readings supposed to be intensity independent)

There are 48 wires in each instrument, spaced by 1 mm.

Statistical rms error of the MW **rms norm** emittance measurement is about 0.05 mm mrad (out of ~2 mm mrad)

NB: here and in TM-2741 we always use rms normalized values, unless specifically mentioned otherwise

Emittance at Extraction vs total proton intensity *N*

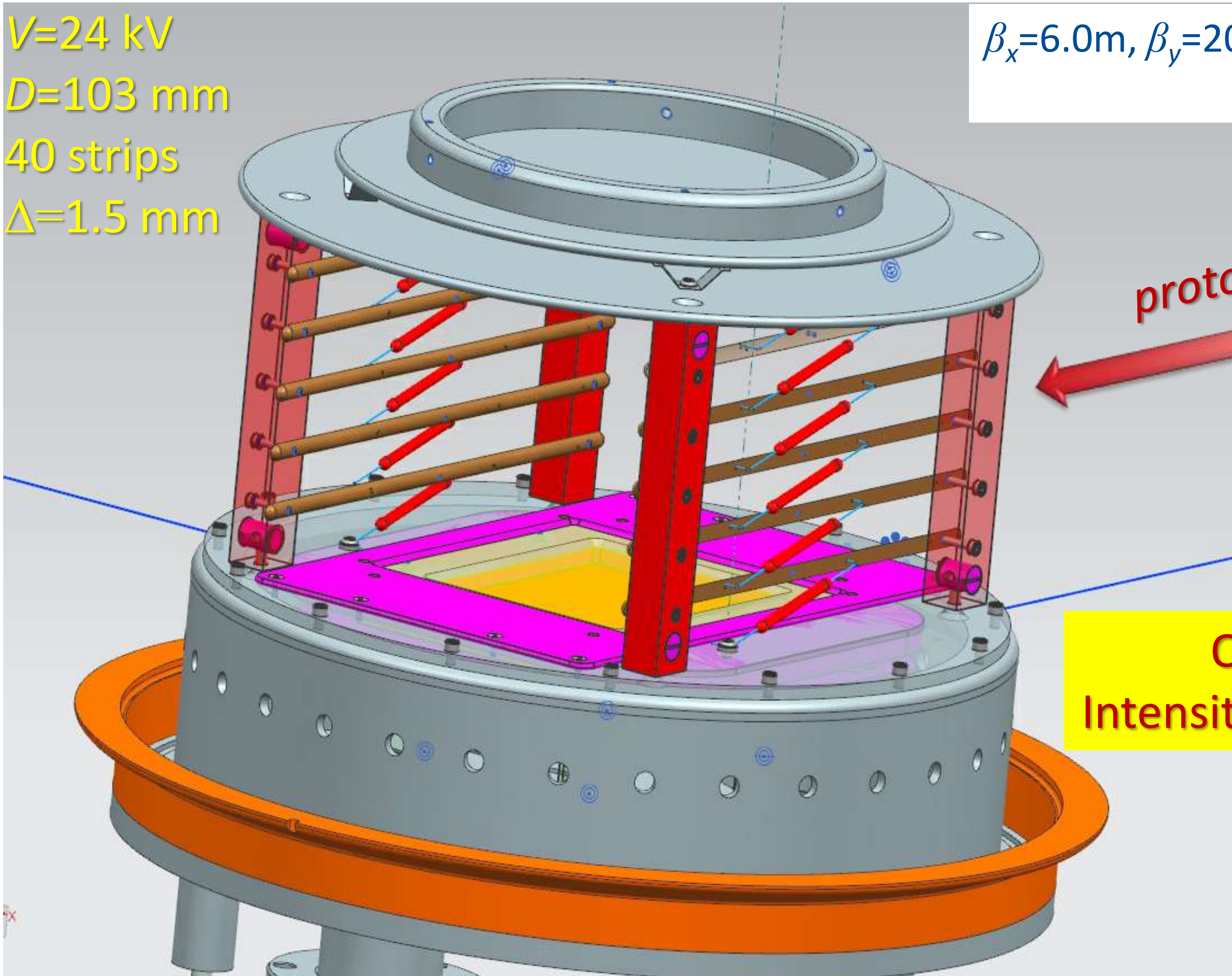


2 mm mrad
rms norm =
12 mm mrad
95% norm

$$\varepsilon_{y,extr}\ [\pi \text{ mm mrad}] \approx 1.7 + 1.20 \cdot (N_p/6\ 10^{12})^{4\pm0.3}$$

$$\varepsilon_{x,extr}\ [\pi \text{ mm mrad}] \approx 1.8 + 1.03 \cdot (N_p/6\ 10^{12})^{4\pm0.3}$$

Ionization Profile Monitors: *V* and *H*

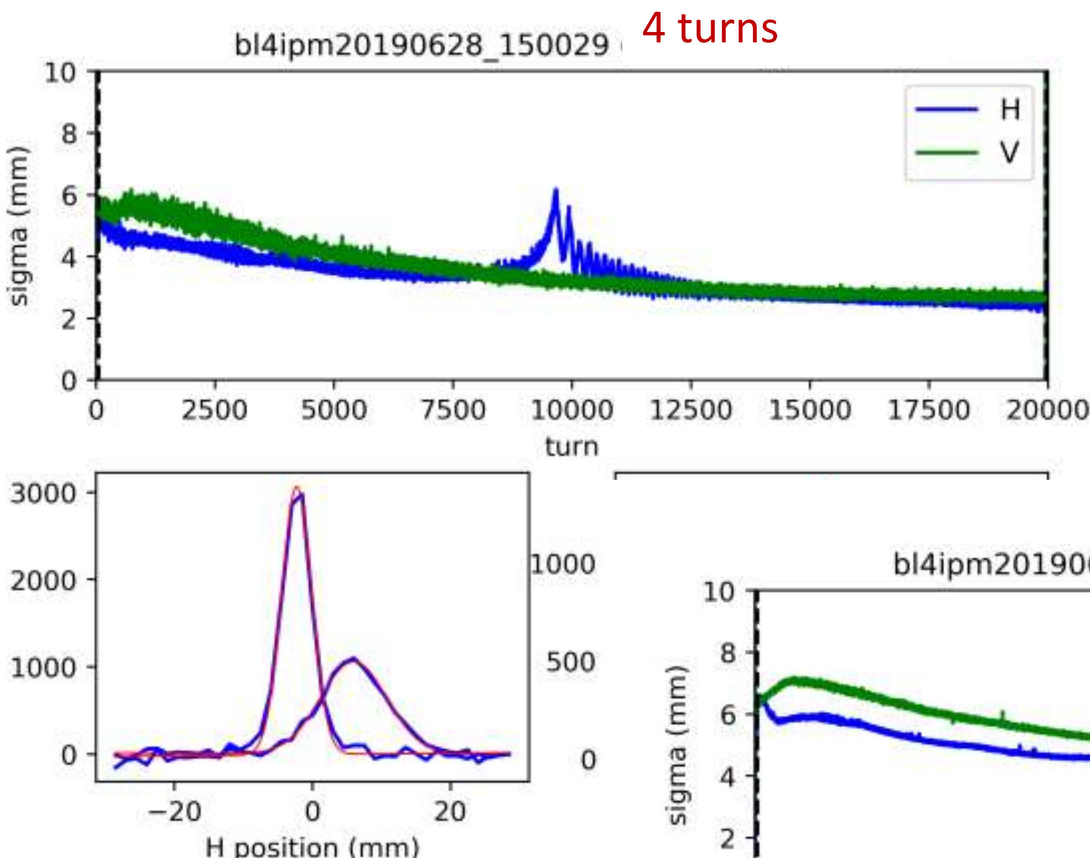


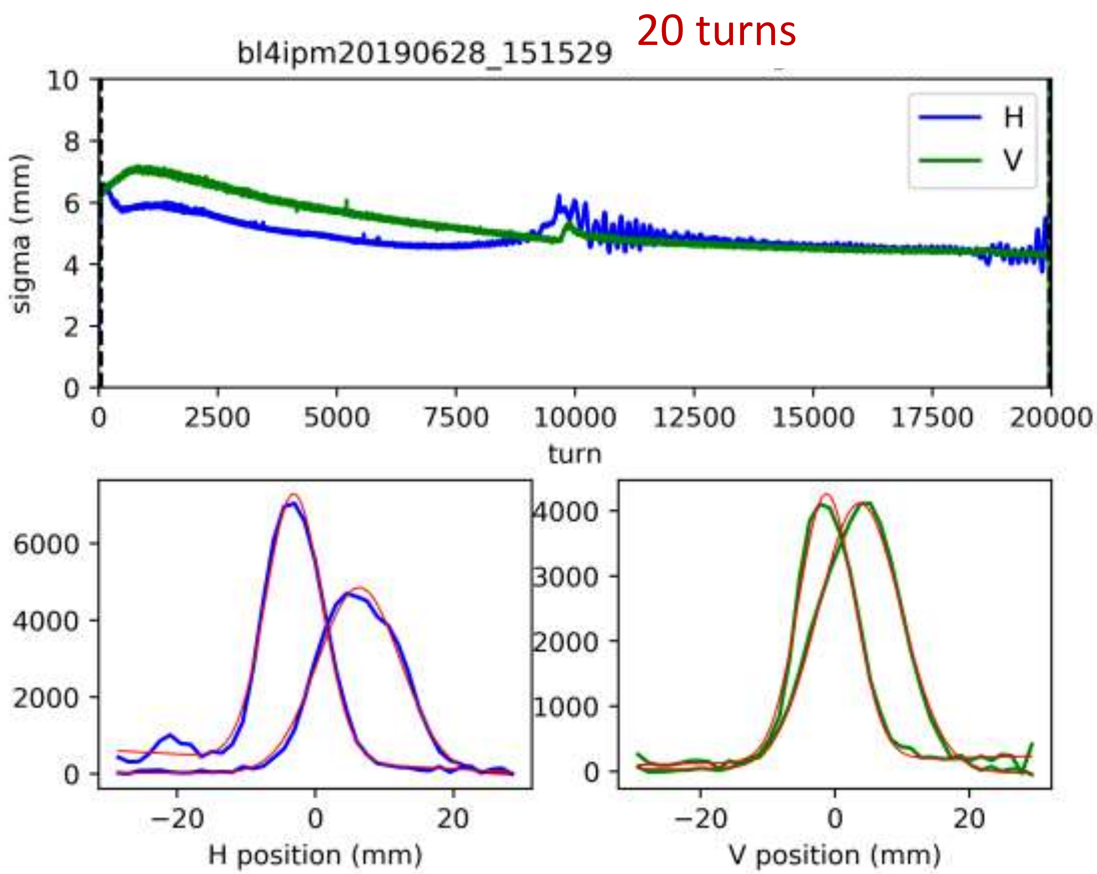
β_x=6.0m, β_y=20.8m, D_x=-1.8m
in Long 04

Once per turn
Intensity dependent

IPM signals

for 4 and 20 turns injection cycles





Note:

a) Noisier at 4 turns

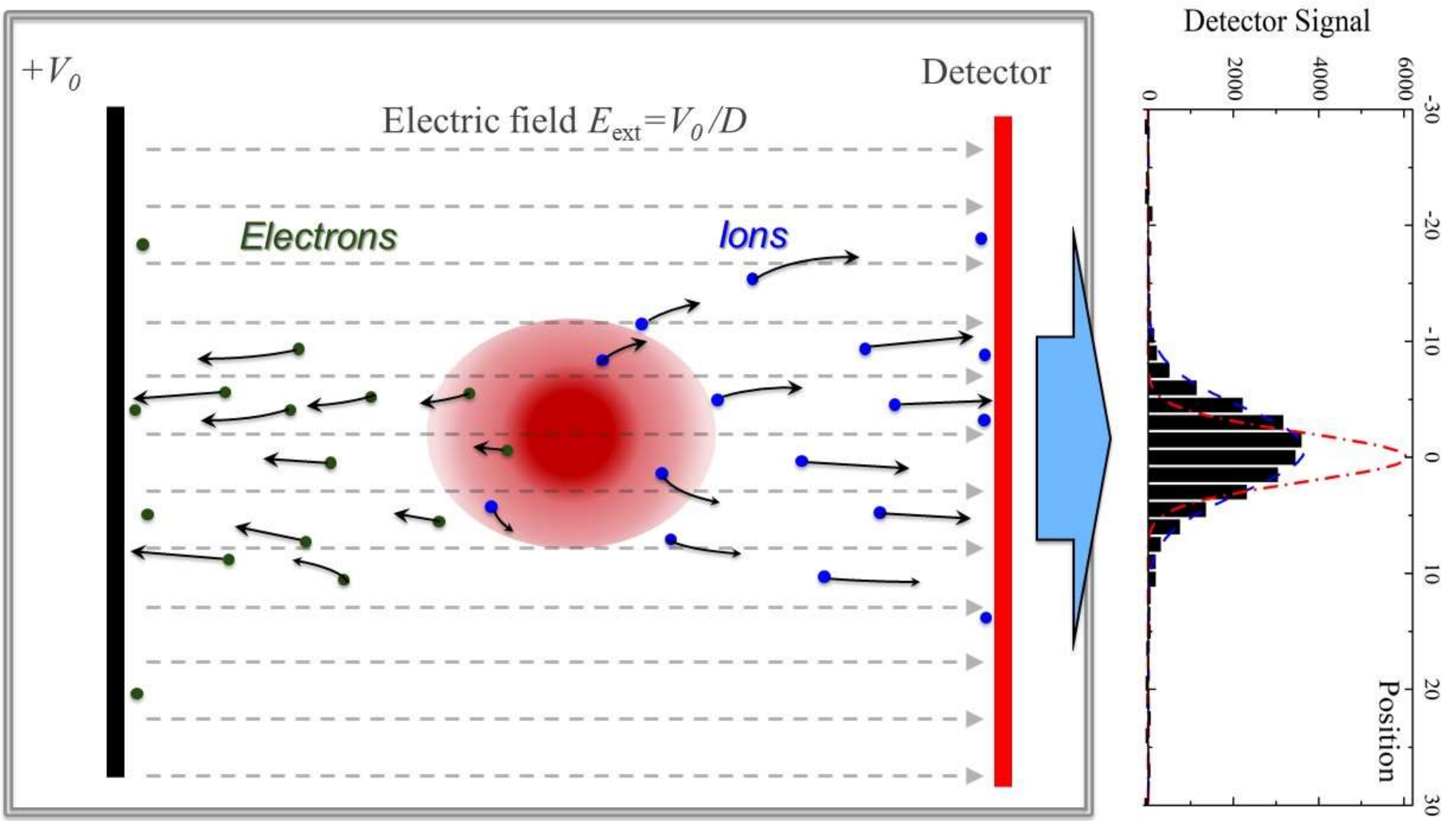
b) H/V differences

- 600/650 V

c) No saturation

d) Complex dynamics

IPM Principle of Operation



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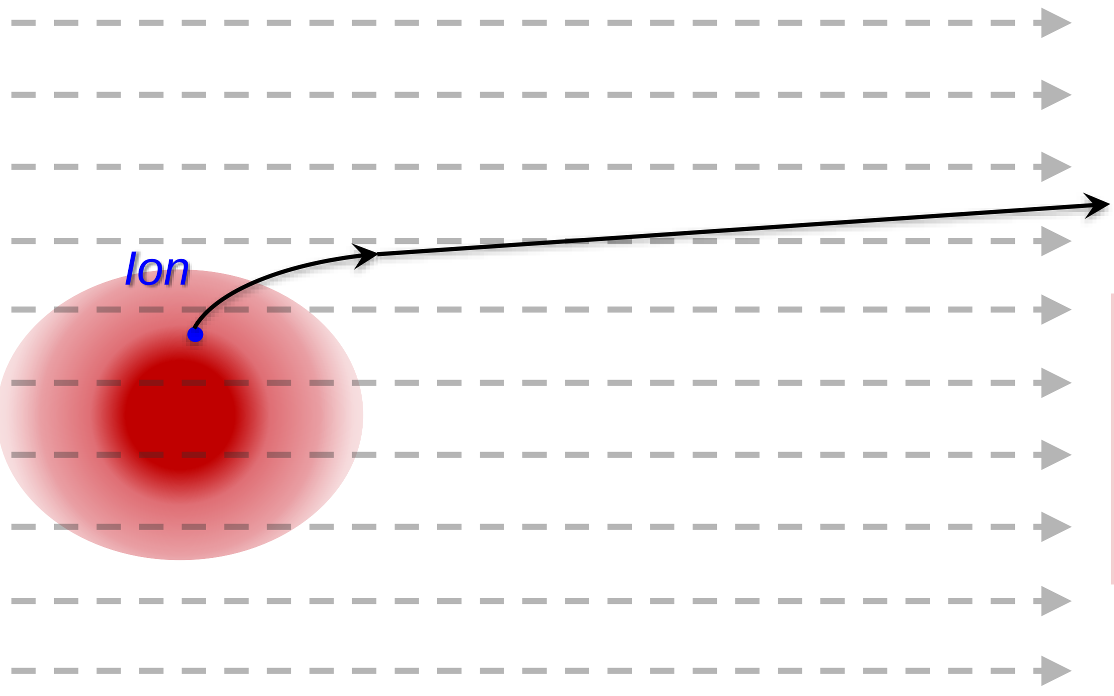
IPM Transverse Profile Expansion

Step I: Ion is born

Step II: Ion gets out of beam in time τ_0



$$V_y \sim Force \cdot \tau_0 = \\ = y_0\,(N/\sigma^2) \cdot \sqrt{\sigma}$$

$\tau_0 \sim 20ns$

Step III: Ion reaches MCP "ballistically" in time $\tau_2 \sim (d/E_{ext})^{1/2}$

$\tau_2 \sim 100ns$

$$y = y_0 + V_y \cdot \tau_2 = y_0\,(1 + \alpha N/\sigma^{3/2})$$

Electric field $E_{ext} = V_0/D$

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Main Equation and Solutions – Uniform Beam

arXiv:2003.09072

$$d^2y/dt^2 = \frac{1}{\tau_1^2} y \qquad r < a$$

$$d^2y/dt^2 = \frac{1}{\tau_1^2} y \frac{a^2}{y^2+x^2} \qquad r > a$$

$$x(t) = \frac{ZeE_{ext}}{2M} t^2 = \frac{ZeV_0}{2MD} t^2$$

$$\boldsymbol{y(t) = y_o h(t)}$$

$$U_{SC} = \frac{30 I_p}{\beta_p} \approx [18.3\ V] \frac{N_p}{6 \cdot 10^{12}}$$

$$\frac{1}{\tau_1^2} = \frac{2ZeU_{SC}}{Ma^2}$$

Characteristic SC blowup time ~50 ns

$$\tau_0 = \sqrt{\frac{2MaD}{ZeV_0}}$$

Time to get out of beam ~20 ns

$$\tau_2 = \sqrt{\frac{2MdD}{ZeV_0}}$$

Time to reach MCP (d ≈50 mm) ~100 ns

$$y(t) = y_0 \frac{t}{\tau_0} \left[\mathrm{ch}(\alpha) \left(\mathrm{ch}(\tilde{\alpha}) - \frac{\mathrm{sh}(\tilde{\alpha})}{\alpha} \right) + \mathrm{sh}(\alpha) \mathrm{sh}(\tilde{\alpha}) \right]$$

where $\alpha = \tau_0/\tau_1$ and $\tilde{\alpha} = \alpha(1 - \tau_0/t)$

$$h(t = \tau_2) \approx 1 + \frac{4}{3} \frac{\tau_2 \tau_0}{\tau_1^2} = 1 + \frac{16 U_{SC} D}{3 V_0 a} \sqrt{\frac{d}{a}}$$

Gaussian Beam …and Bunched Beam

arXiv:2003.09072

$$y_{[1]}(t) = y_0 \cdot \Big[1 + \frac{\tau_0^2}{\tau_1^2}\Big(\frac{t}{3\tau_0}(\Gamma(\frac{1}{4}) - \Gamma(\frac{1}{4}, \frac{t^4}{\tau_0^4})) - \frac{1}{2}\sqrt{\pi}\mathrm{erf}(\frac{t^2}{\tau_0^2}) + \frac{\tau_0^2}{6t^2}(1 - \exp(-\frac{t^4}{\tau_0^4}))\Big)\Big]$$

$$\sigma_m = \sigma_0 \cdot h \approx \sigma_0 \cdot \Big[1 + \frac{2U_{SC}}{E_{\mathrm{ext}}\sigma_0}\Big(\frac{\Gamma(\frac{1}{4})}{3}\sqrt{\frac{d}{\sigma_0}} - \frac{\sqrt{\pi}}{2}\Big)\Big]$$

$\Gamma(\frac{1}{4}) \approx 3.625$

… if the beam consists of short bunches space by t_b, extra correction factor is applied:

$$h = 1 + \frac{2U_{SC}}{E_{\mathrm{ext}}\sigma_0}\Big(\frac{\Gamma(\frac{1}{4})}{3}\sqrt{\frac{d}{\sigma_0}} - \frac{\sqrt{\pi}}{2}\Big) \cdot [1 + t_b/\tau_0]$$

That's not All: "Zero Intensity" Correction

There are also intensity independent effects leading to the IPM profile smearing:

a) the initial velocities of the ions;

b) IPM charge collection strips distance 1.5 mm;

c) angular misalignment of the IPM long and narrow strips with respect to the high energy proton beam orbit;

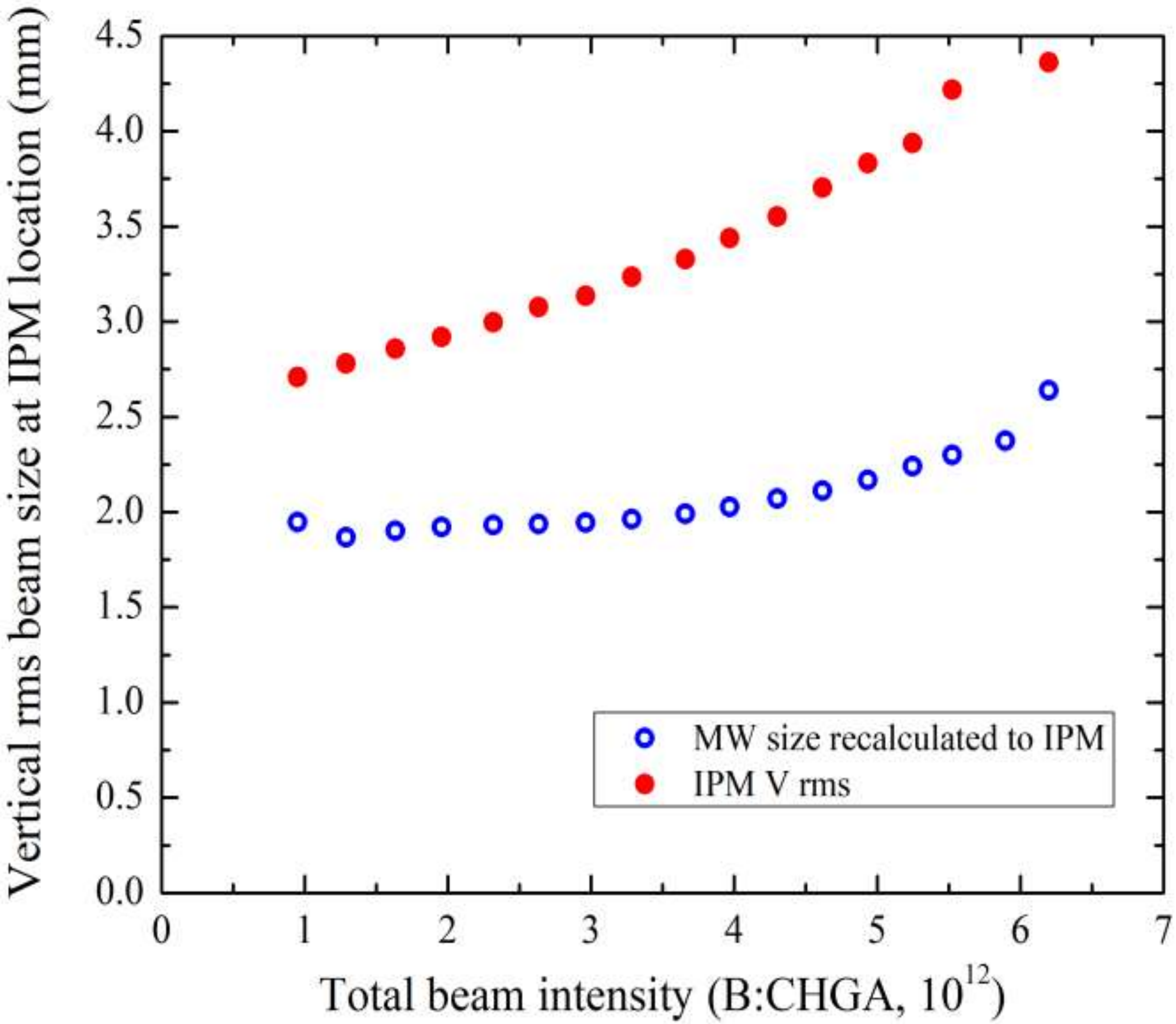
d) charging of dielectric material in between the strips or strip-to-stripe capacitive cross talk;

e) non-uniformity of the extraction electric field in the operational IPM aperture….

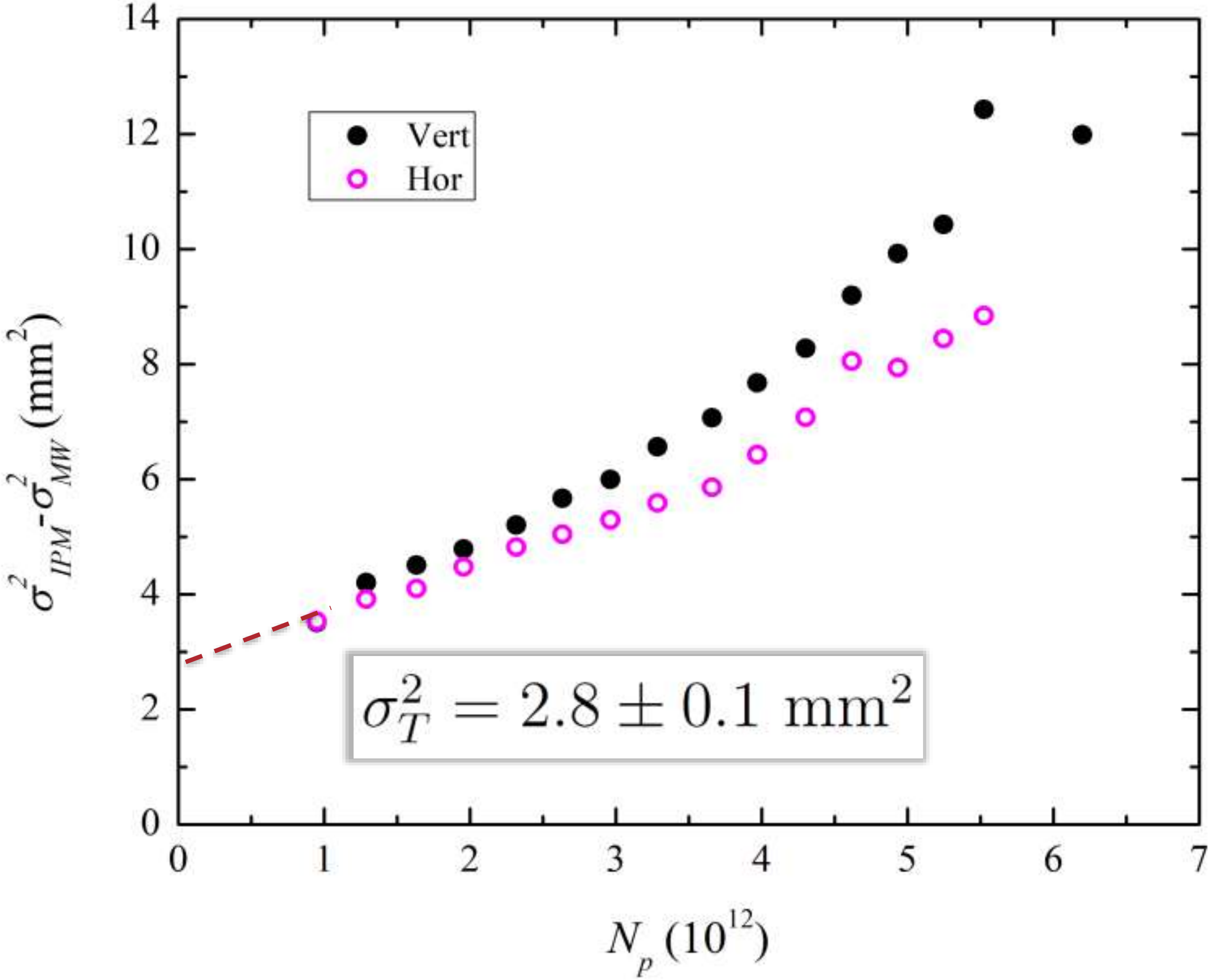
They all add in quadrature… eg, initial kinetic energy $\mathcal{E}_i$ results in

$$\sigma_m^2 = \sigma_0^2 h^2(U_{SC}, \sigma_0, E_{\rm ext}, d) + \left(\frac{4\mathcal{E}_i d}{ZeE_{\rm ext}}\right)$$

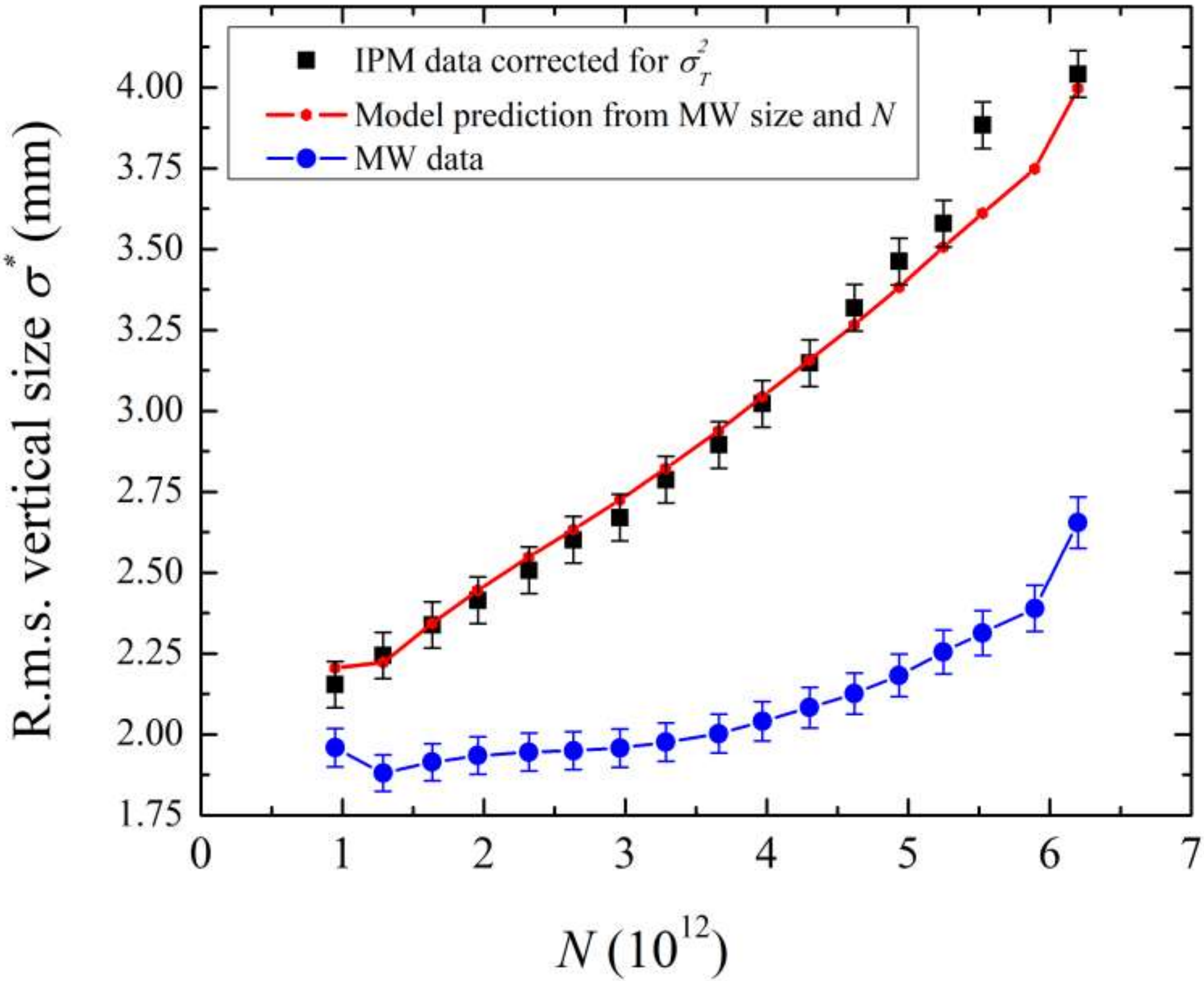
Let's start with the latter effect : MW vs IPM at *N*=0



Same “Smearing” Effect in Horiz and Vert IPMs

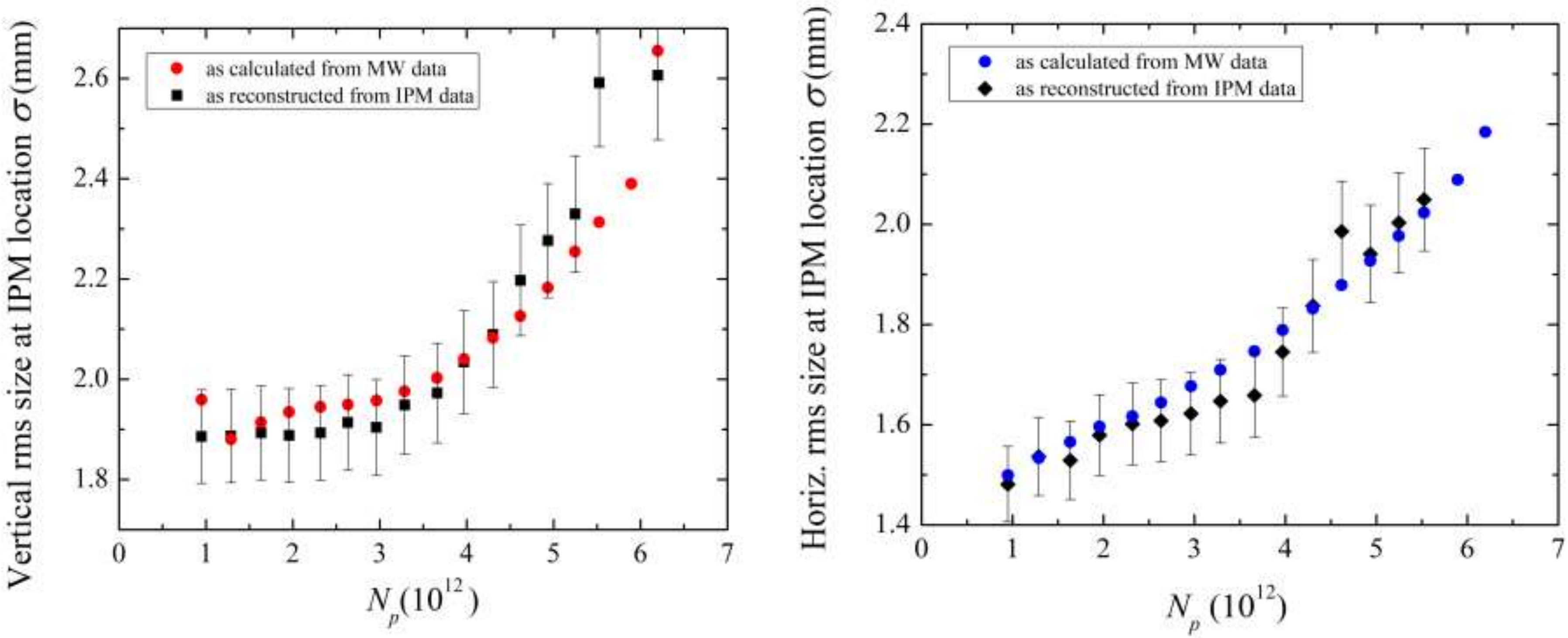


SC Expansion and “Smearing” in IPM



Vertical mean squared IPM size σ^* as measured at extraction (V=24 kV, D=103 mm, black squares) vs the total proton beam intensity N_p. The theoretical predication of Eq.(3) (with $d=D/2$=52 mm, red line) is calculated using the initial beam sizes σ_0 as measured by the Multi-Wires monitor (blue line). The measured IPM rms sizes $\sigma^2_{m,IPM}$ are corrected for the intensity independent smearing as $\sigma^* = (\sigma^2_{m,IPM}(N_p) - \sigma^2_T)^{1/2}$ with σ^2_T=2.7 mm².

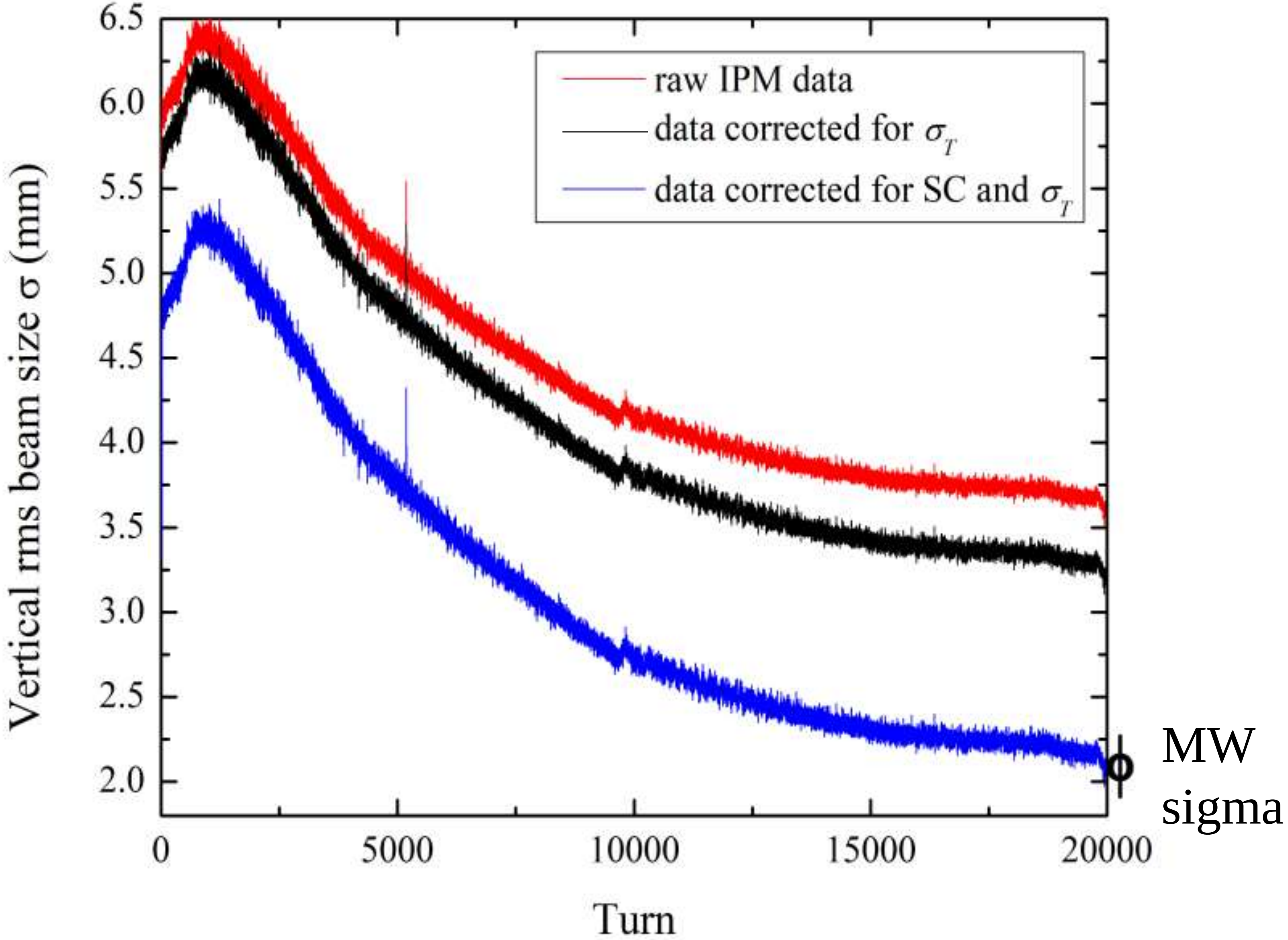
Finding the Original σ_0 from the IPM σ_m



Comparison of the vertical (left) and horizontal (right) rms beam sizes at extraction for a range of total proton beam intensities N_p. Red and blue dots are as measured by MWs and recalculated for the IPM location. Black squares with error bars are for the rms beam sizes reconstructed from the IPM data correction for σ^2_T and for the space-charge expansion $h(N_p, V, D, d)$

$$\sigma_0 \cong \frac{\sigma^*}{\left(1+\frac{c}{\sigma^{*\frac{3}{2}}}\right)\left(1+\alpha\frac{c^2}{\sigma^{*2}}\right)}$$

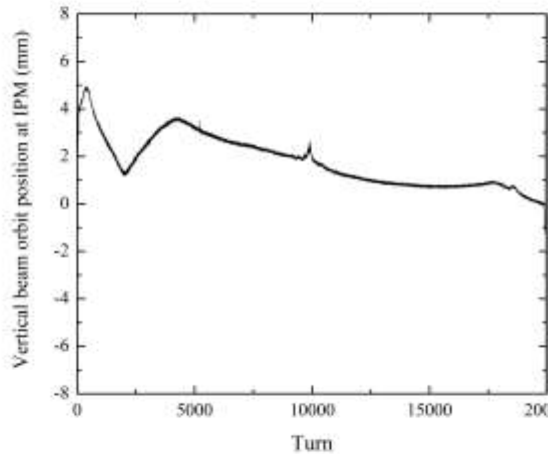
Apply the Method to the Entire Booster Cycle

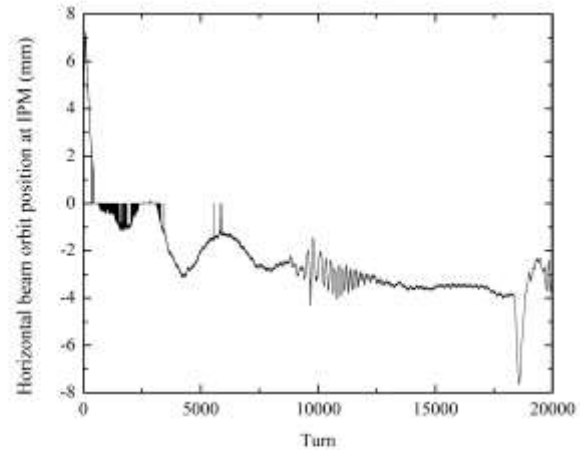


Emittances : Effects to Keep in Mind

1) Obits move while the space-charge expansion depends on the distance *d* from the beam orbit to the IPM collection plate.

O(10%)



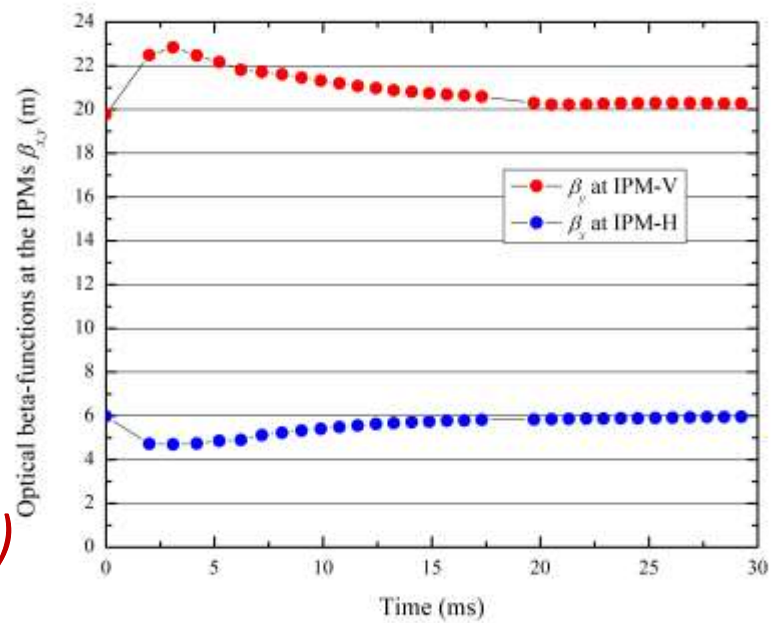


2) Beta-functions at the IPM locations vary in the cycle – see Fig. – as well as the space-charge forces which somewhat distort the optical focusing lattice functions

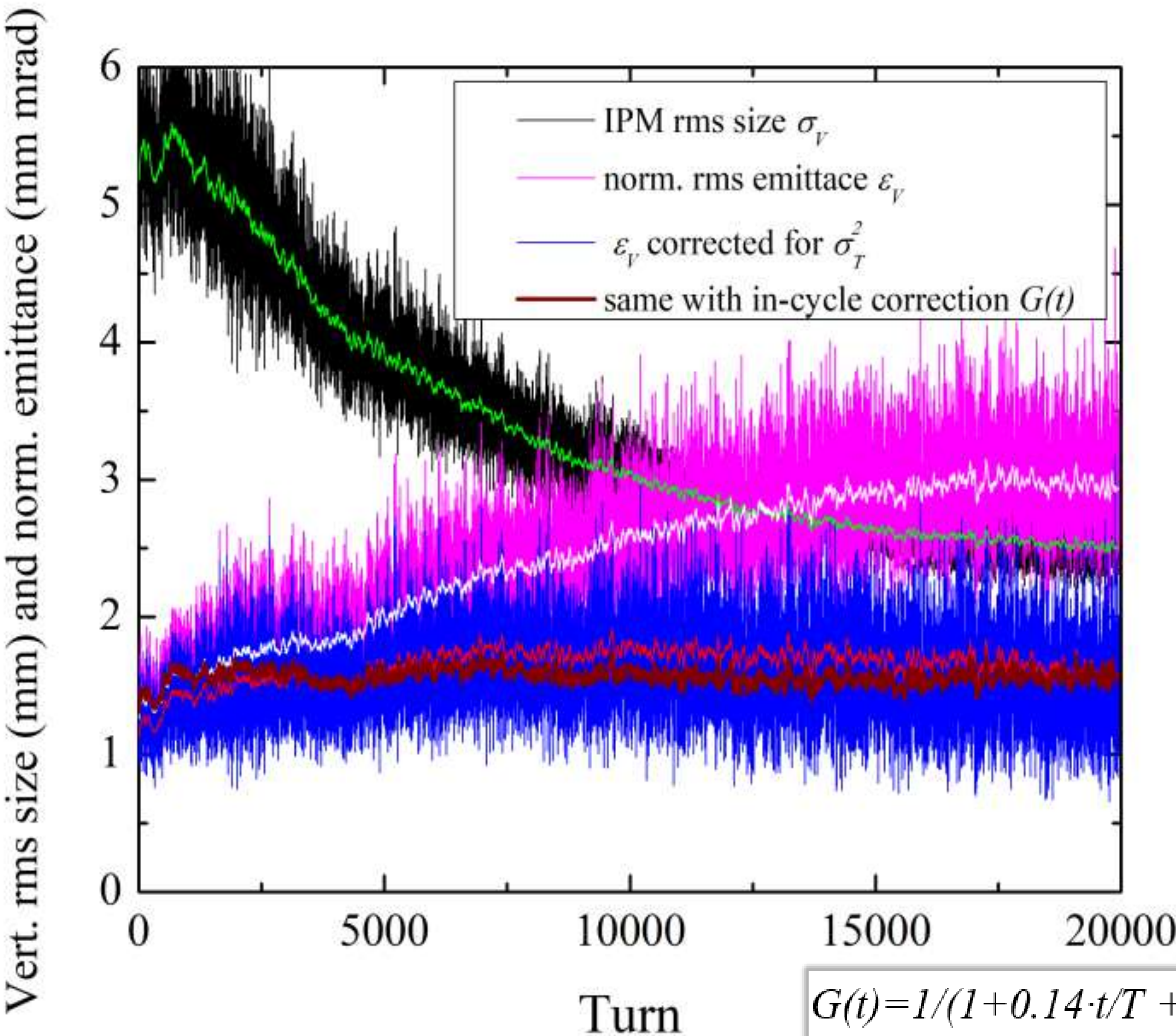
O(10%)

3) Bunching varies (smaller effect)

O(5%)



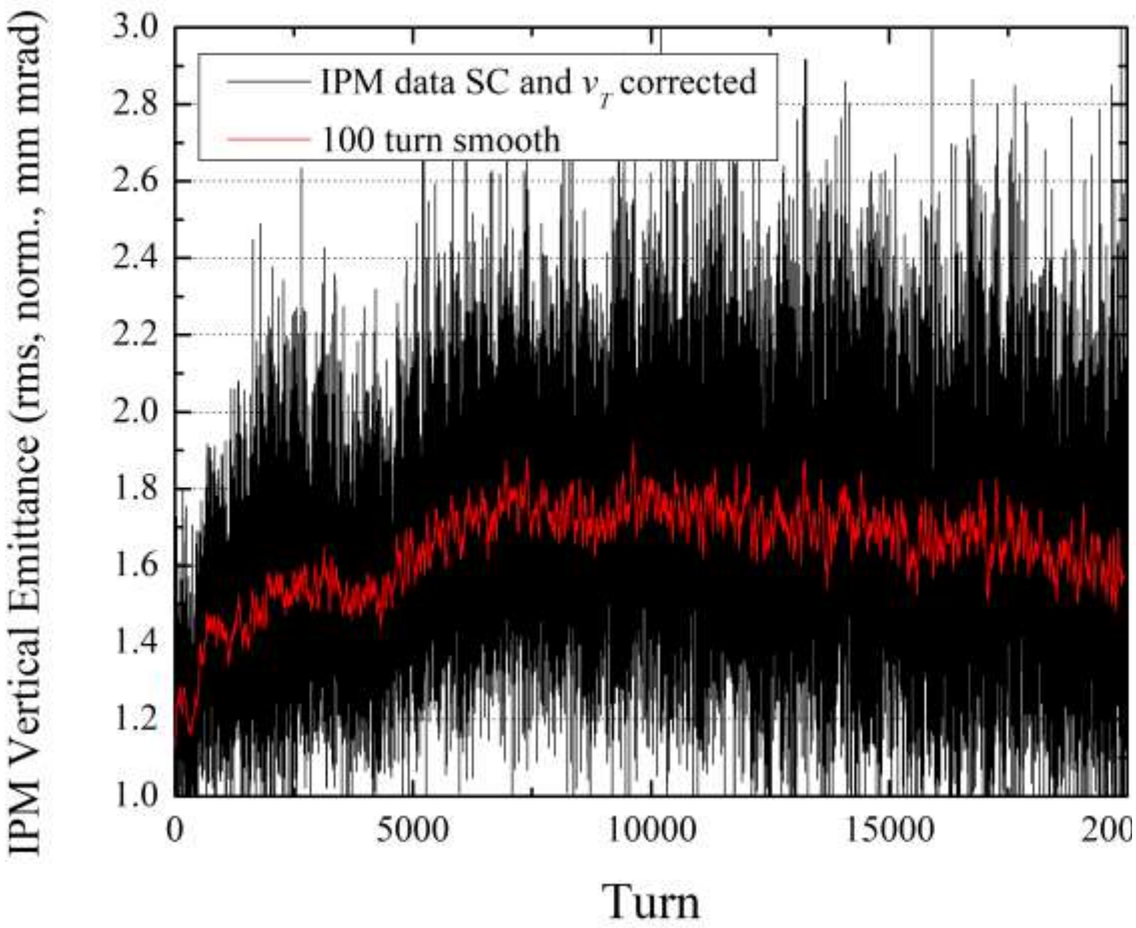
Method: Assume no Emittance growth at *N*=0



Vertical rms proton beam size and emitance at low intensity $N_p=0.5\cdot10^{12}$: black – raw IPM data, green – 100 turn window average of the raw IPM data; pink and white – vertical rms normalized emitances calculated from the raw IPM data; blue and red – same, but corrected for intensity independent smearing; brown – same with additional fudge factor $G(t)$

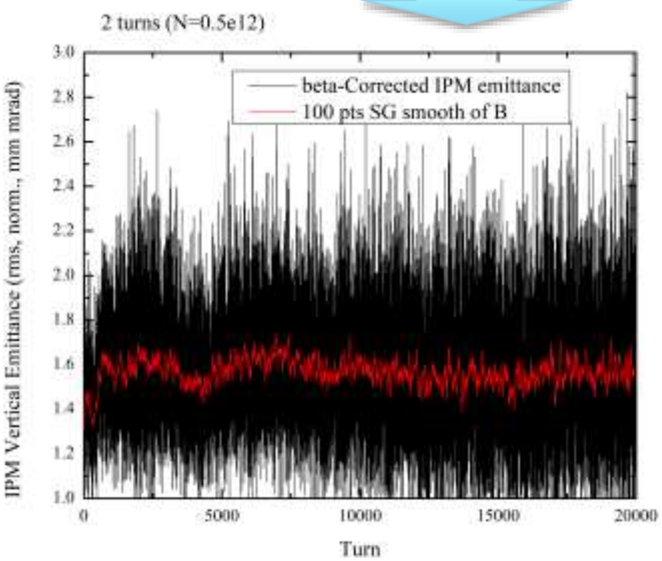
$$G(t)=1/(1+0.14\cdot t/T+0.018\cdot(1-T/2)^2/(T/2)^2)$$

Emittance Arguments to Account for β–function Variations

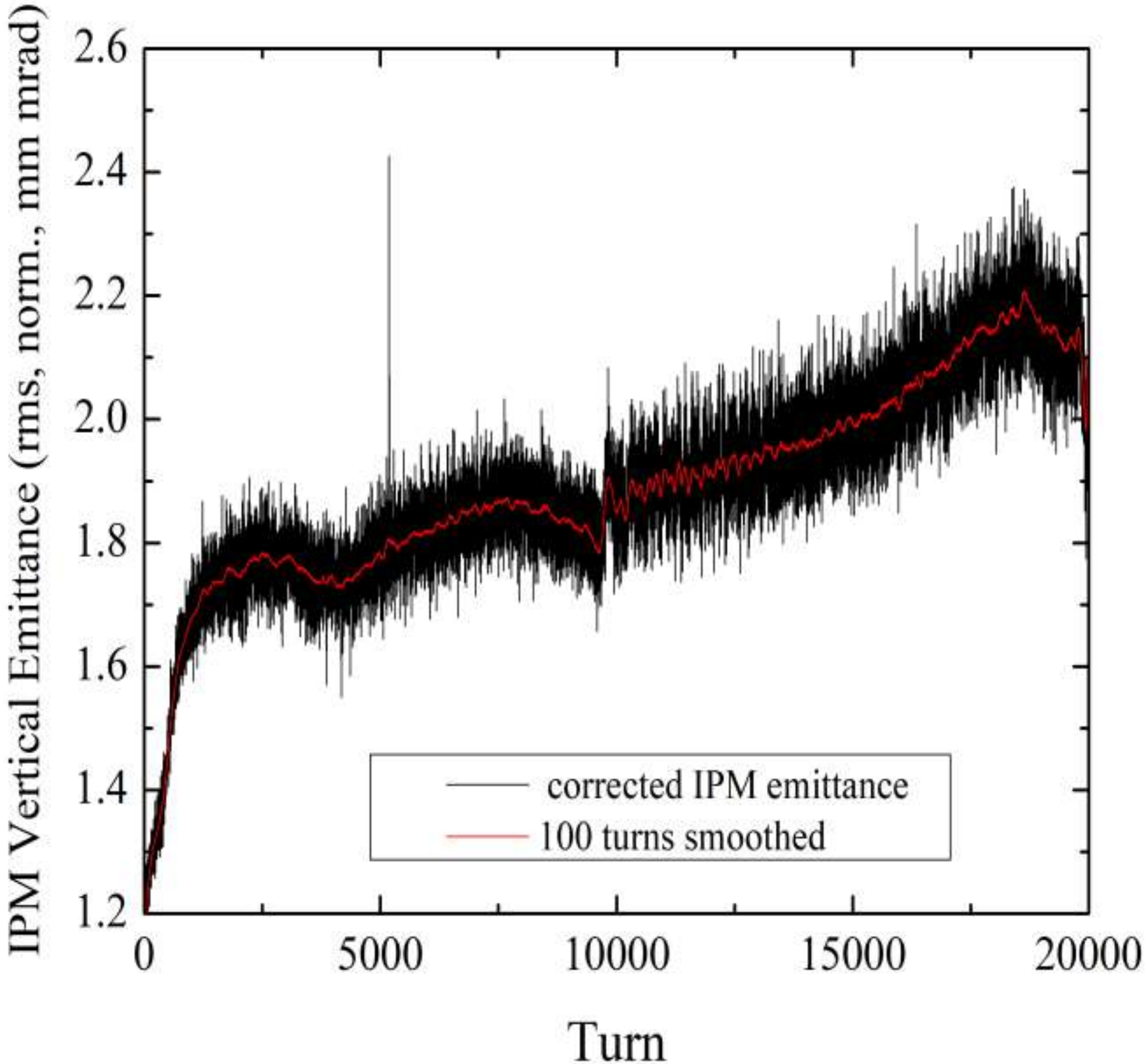


F(t)=(0.86+0.14*t/T+0.18*4*(1-(t-T/2)^2/T^2)

1) to avoid appearance of emittance growth at low intensity (2 turns injection)
2) to avoid decrease of emittance in the cycle
3) still to be matched to MW sizes at extraction



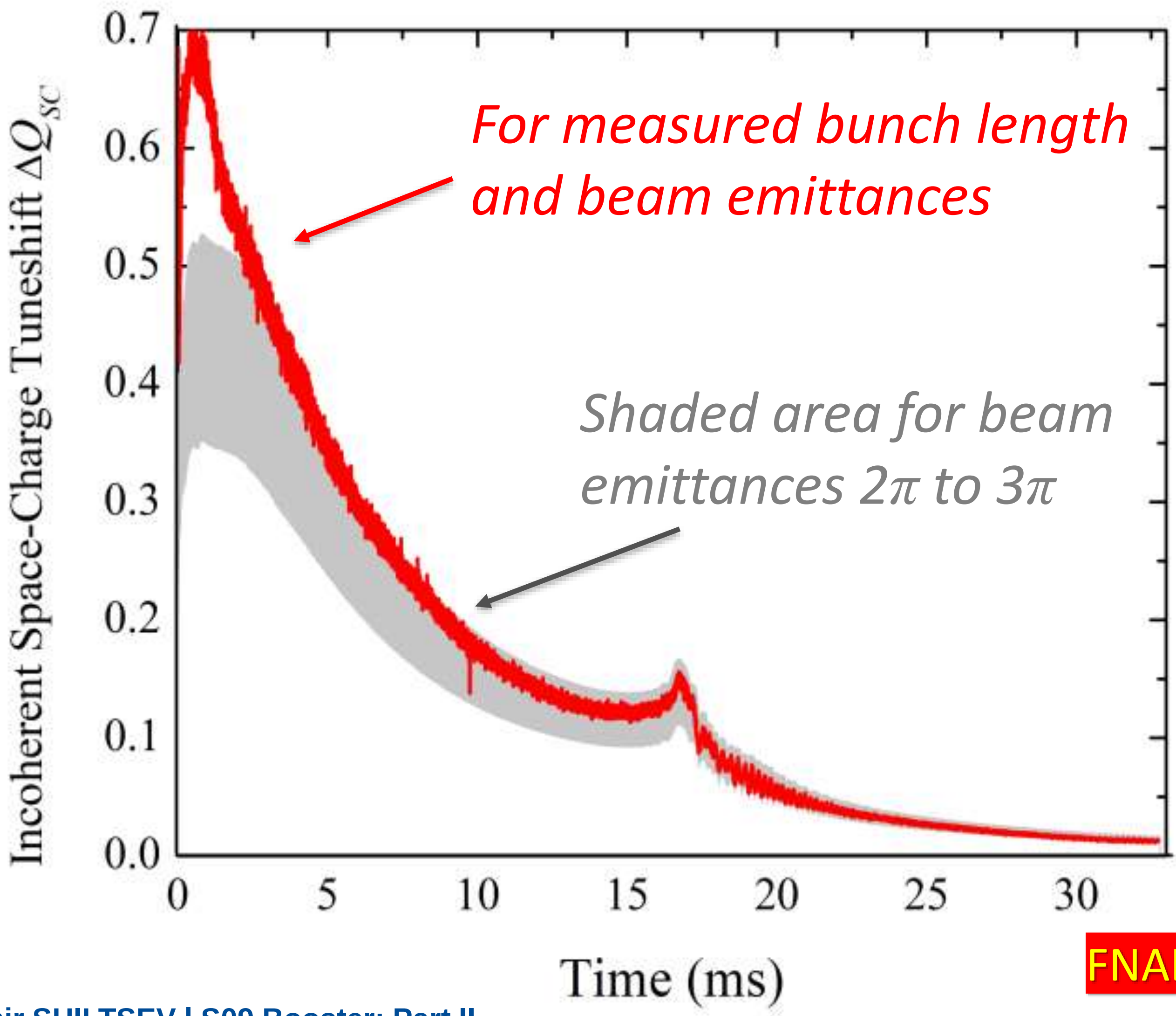
Emittance in Cycle (With All the Corrections In)



Vertical emittance at $N_p=4.6\cdot10^{12}$

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

at nominal intensity N_p=4.5e12



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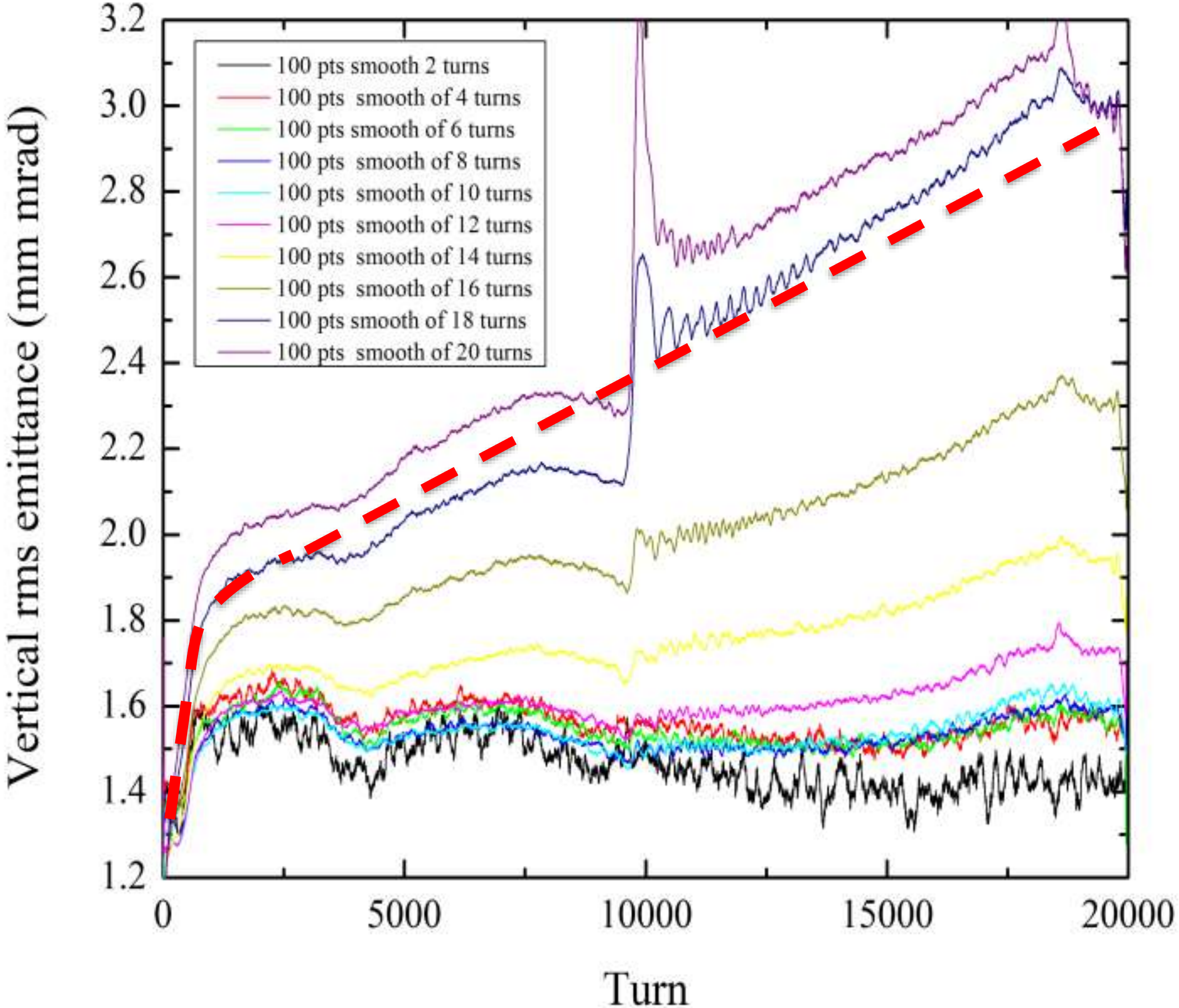
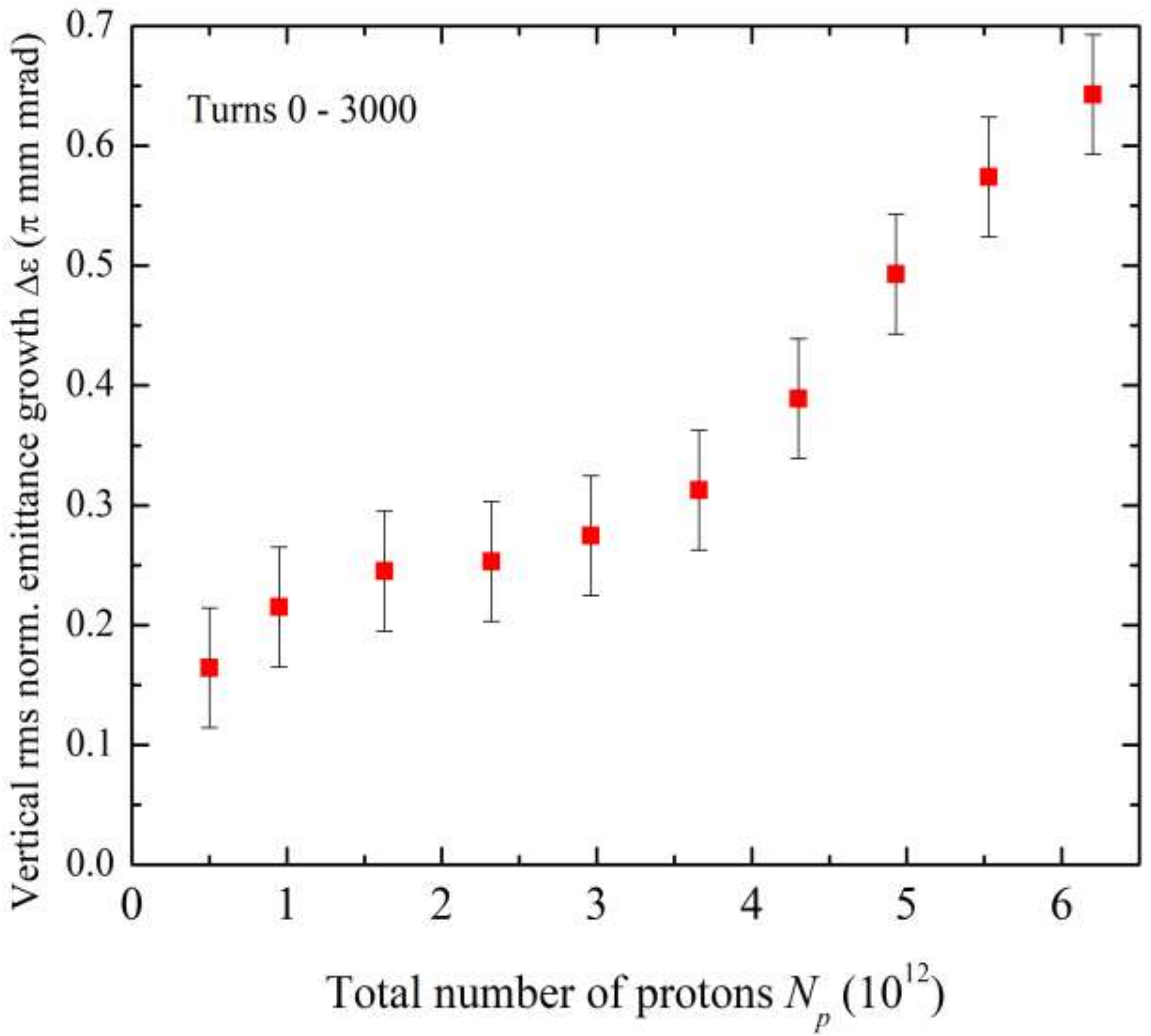
Emittance Evolution at Various Intensities *N*



Emittance Increase over 0-3000 turns

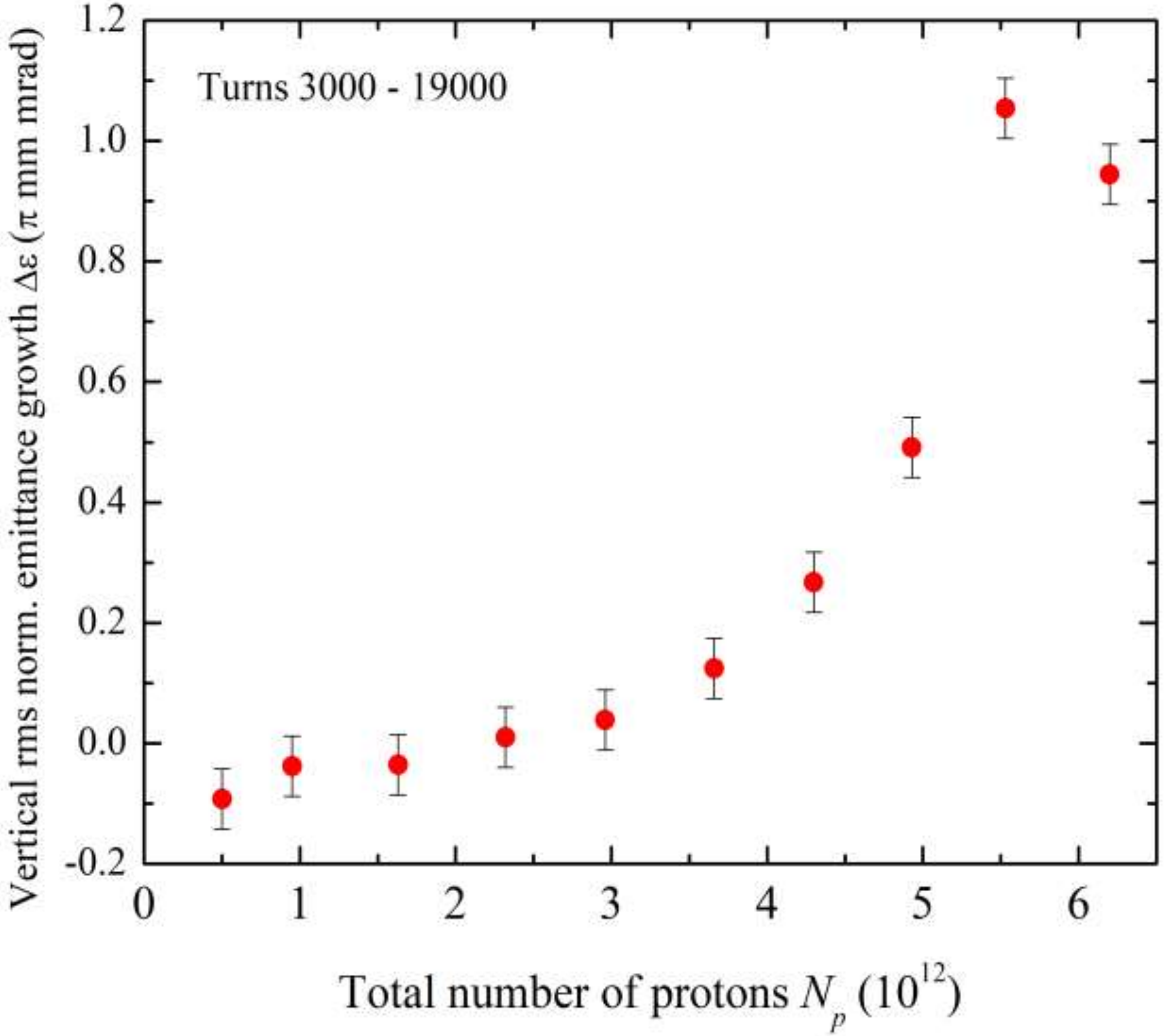
averaged over five hundred turns 3000-3500 minus averaged over 0-500



Presumably due to space-charge effects

Emittance Increase over 3000-19000 turns

averaged over five hundred turns 19000-19500 minus averaged over 3000-3500



WHY ?

1) Incoherent noise excitation? Multi-pacting/e-cloud?
2) Coherent effect?
3) Instrumental ?

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Can IPM/MW info shed extra light on the Booster losses?

Losses depend on apertures, beam sizes and orbit position

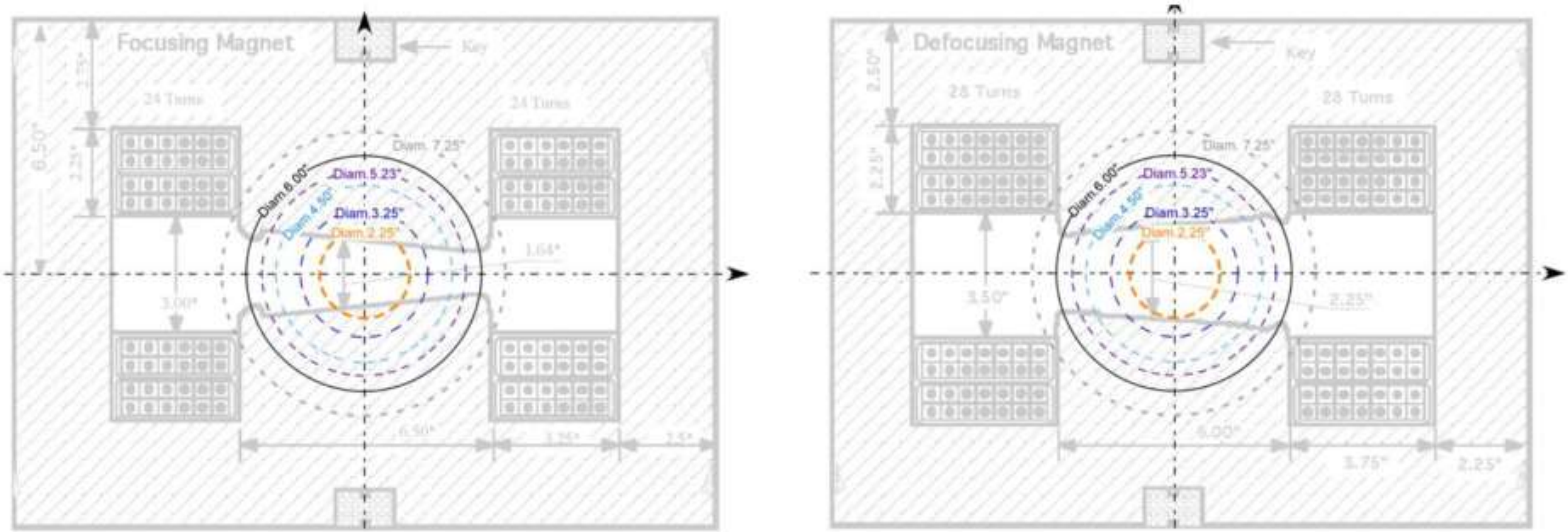
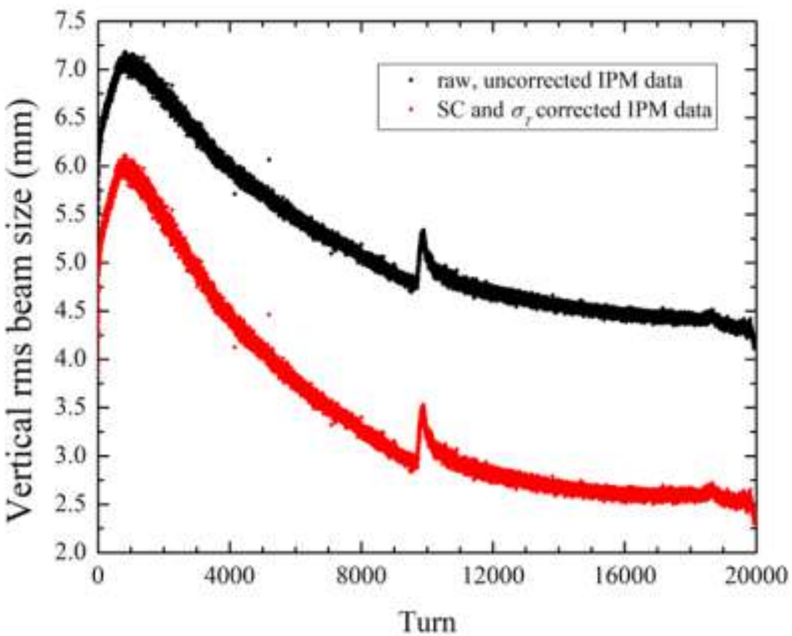


Figure 16: Cross Sectional View of a "F" magnet (left) and a "D" magnet [5] overlapped by apertures of some typical Booster elements implying possible aperture restrictions on the beam: a) RF-cavities (Diam. 2.25"); b) regular beam pipes (Diam. 3.25"); c) corrector package (Diam. 4.5"); d) special aperture in short straight 12 (Diam. 5.23" shifted horizontally by 2 cm outwards); e) 0.5 meter pipes between F and magnets (Diam. 6.00"); f) flanges of combined-function magnets (Diam. 7.25") – from Ref. [6].

Beam sizes over the Booster cycle

Losses depend on apertures, beam sizes and orbit position



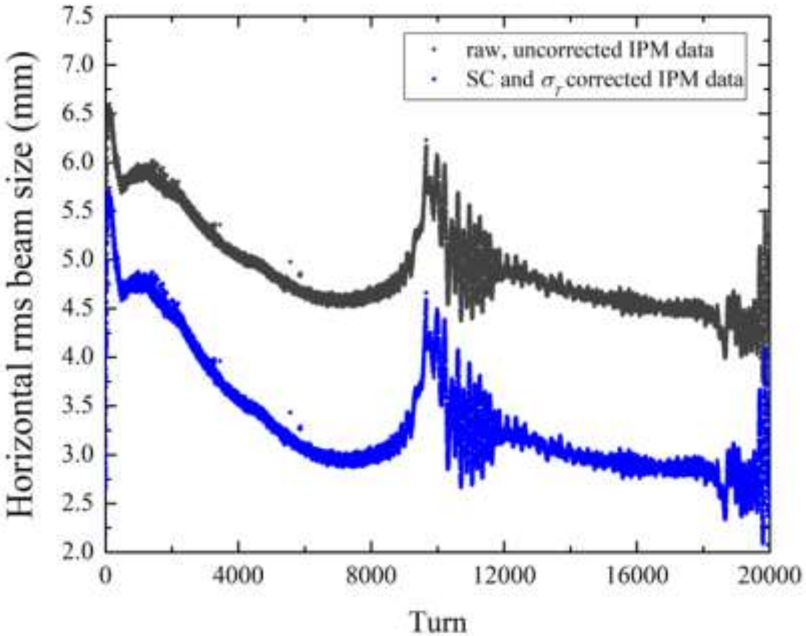


Figure 15: Vertical and horizontal rms IPM beam sizes' evolution over the Booster cycle at $N_p = 6.2 \cdot 10^{12}$ (raw data – black line).

Losses depend on apertures, beam sizes and orbit position

Table I: Booster beam sizes and half-apertures without collimators.

element	β_y, β_x, D_x (m)	A_y / Ax (mm)	σ_y, σ_x (mm, inj.)	σ_y, σ_x (mm, tr.)	$(A/\sigma)_y$, $(A/\sigma)_x$ inj.	$(A/\sigma)_y$, $(A/\sigma)_x$ tr.
IPM	20.3 / 5.9 / 1.8	n/a	5.4 / 4.4	2.7 / 5.0	n/a	n/a
F magnet	10.8/33.8/3.2	21.8 / 54.6	3.9 / 8.8	2.0 / 8.6	5.6 / 6.2	11 / 6.3
D magnet	20.5/17.3/2.1	28.6 / 38.1	5.4 / 6.2	2.7 / 5.8	5.3 / 6.1	10.6 / 6.5
RF cavity	20.5 / 7.6 / 1.9	28.6 / 28.6	5.4 / 4.7	2.7 / 5.2	5.3 / 6.1	10.6 / 5.5

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@ injection: losses on vertical aperture

@ transition: losses on horizontal aperture

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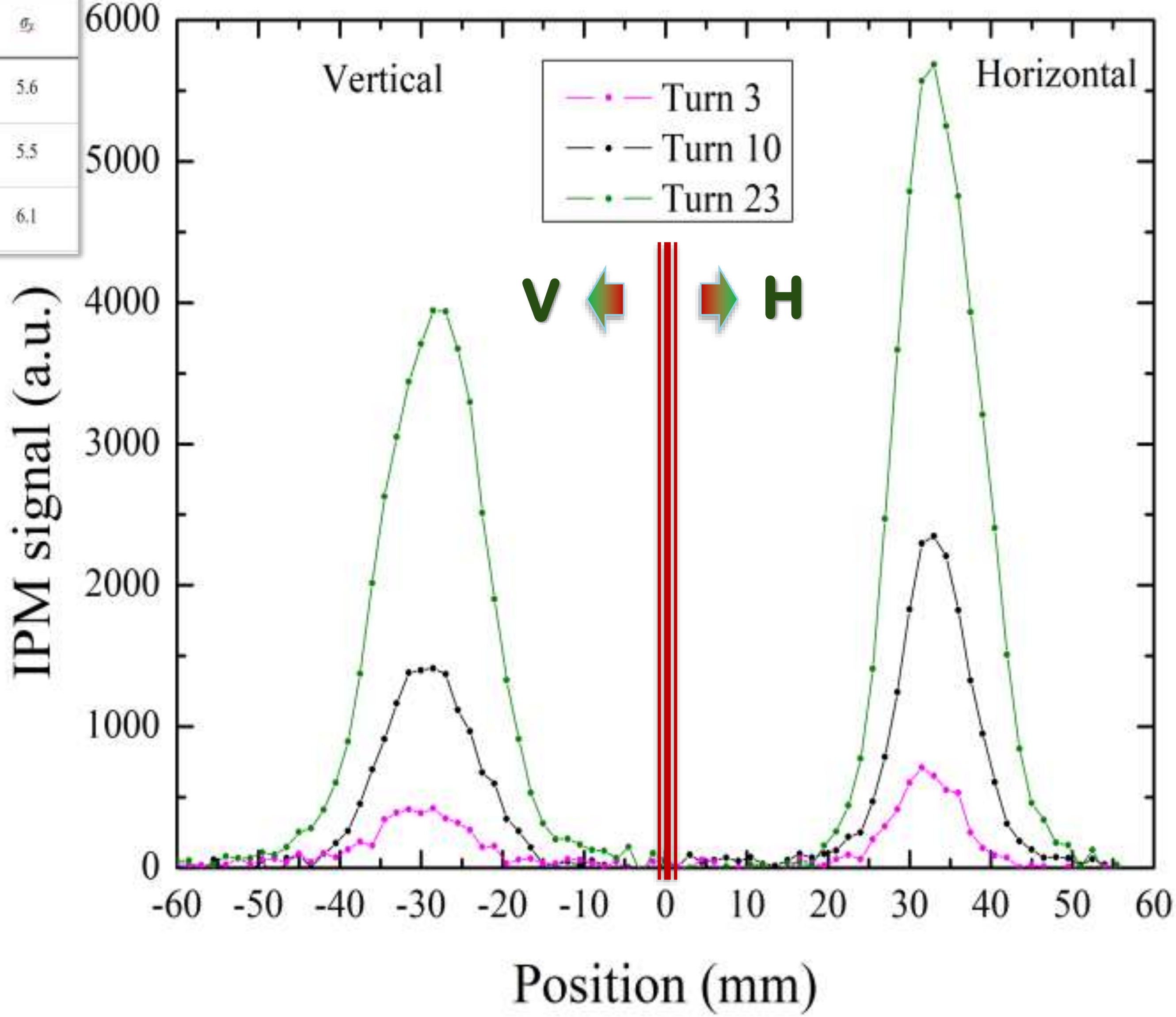
How do losses affect IPM profiles (1)

at N_p=6.2·10[12] (uncorrected, raw IPM data)

Turn #	Y	σ_y
3	-1.4	5.6
10	-0.5	5.5
23	0	6.1

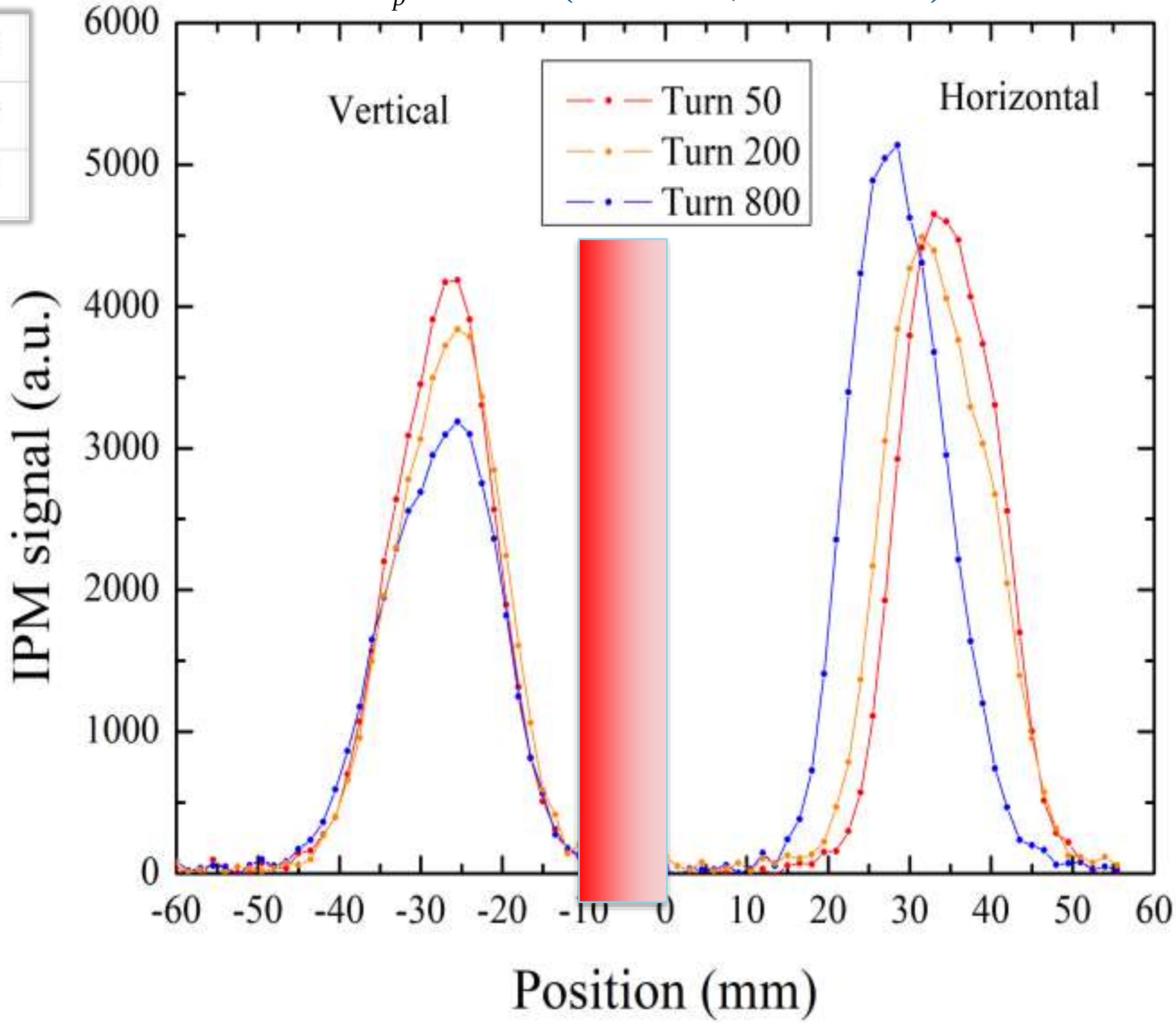


X	σ_x
-1.2	3.9
-0.3	4.2
0	5.0

How do losses affect IPM profiles (2)

at N_p=6.2·10^{12} (uncorrected, raw IPM data)

50	1.5	6.2
200	2.2	6.5
800	3.0	7.0



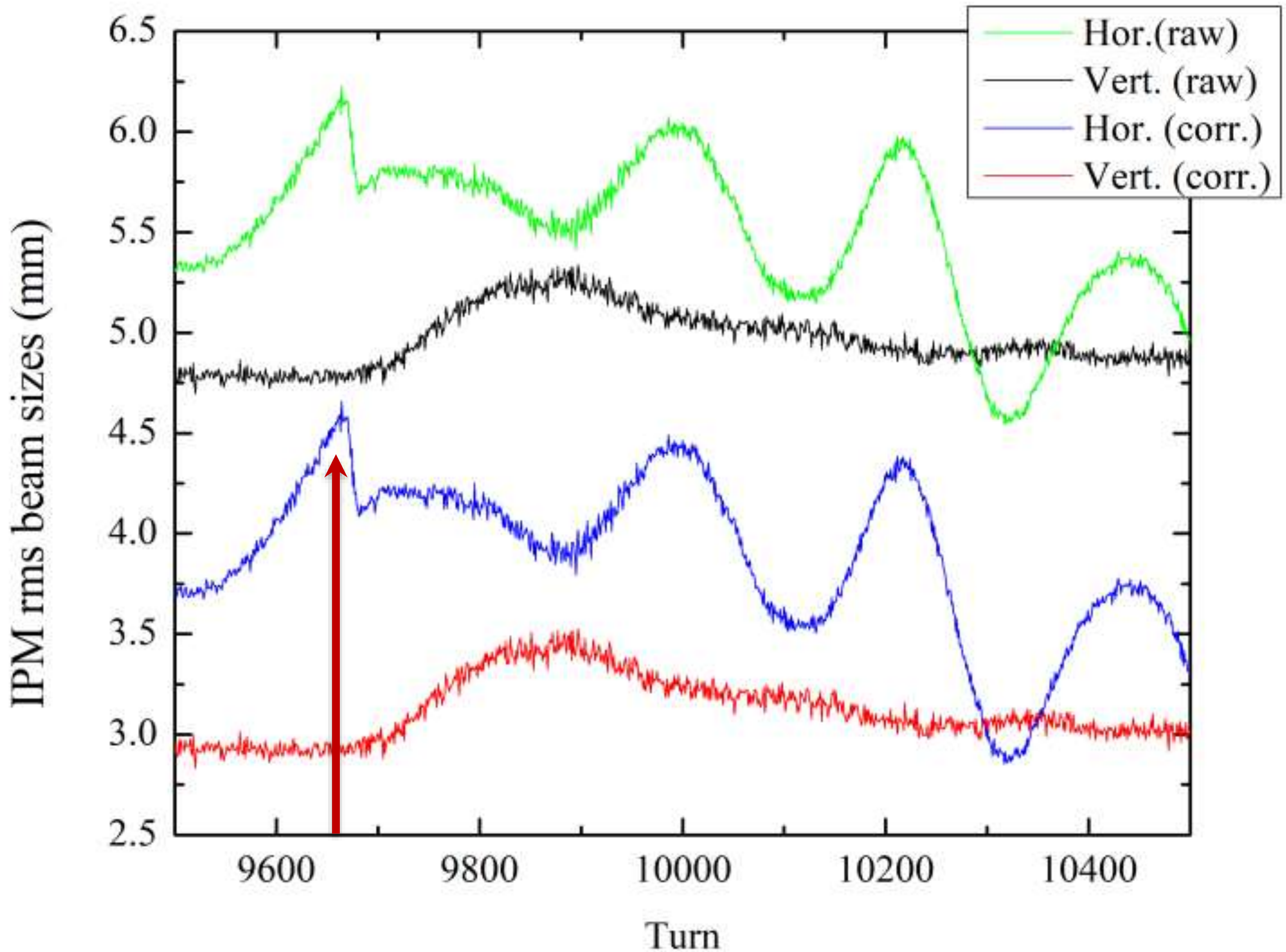
1.4	5.9
-0.2	6.5
-5.1	5.8

WHY ?

Nonlinear optics?
Nonlinear IPM?
Coherent motion?

IPM Profiles at Transition

NB: raw data (upper curves V, H) , corrected data (lower); peak at turn #9664



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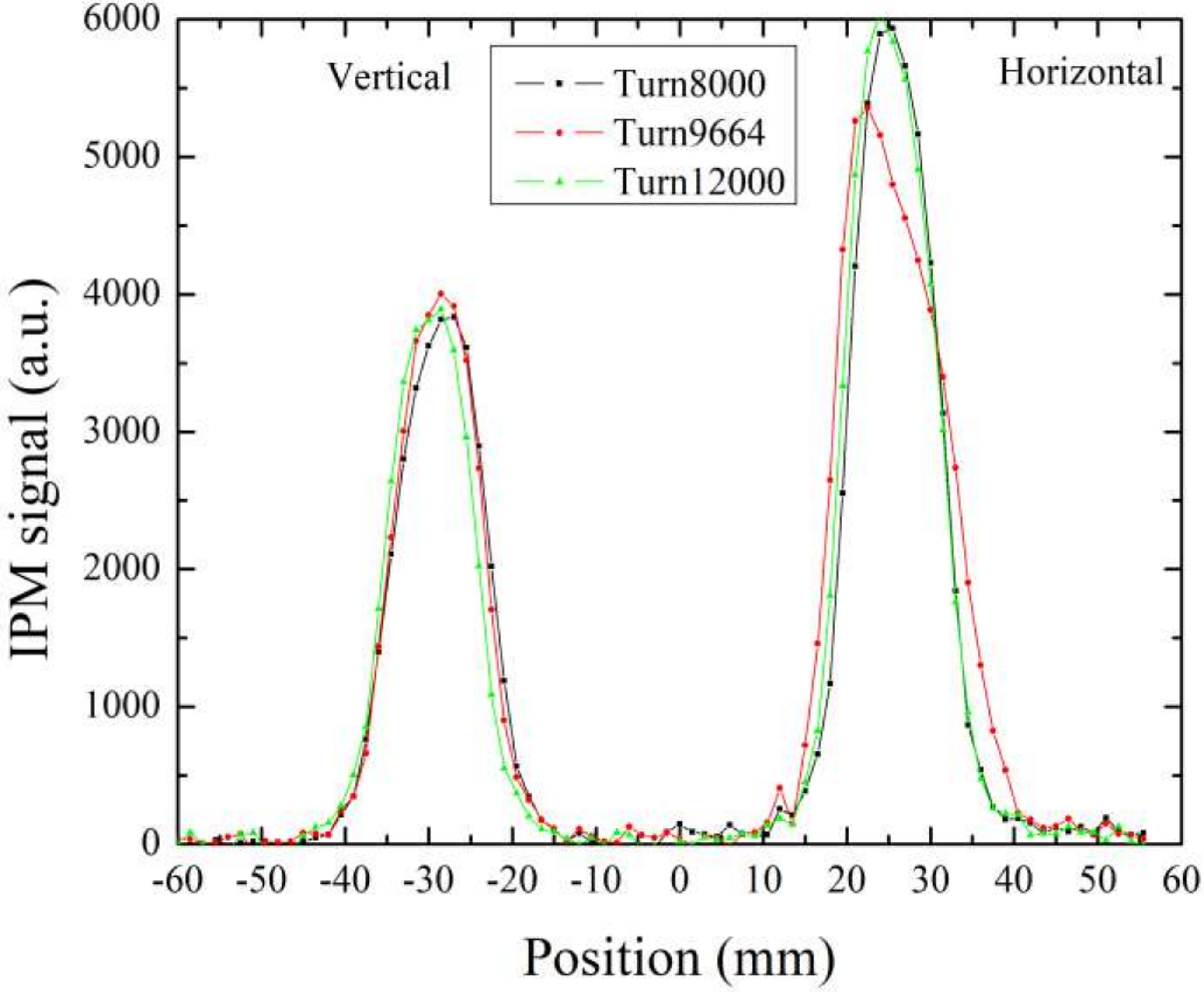
IPM Profiles Before-At-After #9664

NB: skewed H peak at turn #9664



Part II Summary: Booster Emittances

- **Linac *H-* beam comes with small emittance**
  - ~(0.7-1) π mm mrad (i.e., up to 6 pi "95%")
- **Scattering while crossing the foil**

$$\Delta\varepsilon_{foil} \cong (\beta\gamma)_p \frac{\beta_{x,y}}{2}\left(\frac{d}{X_0}\right)\left(\frac{13.6\,MeV}{pc}\right)^2 \times N_{turns}$$

  - $+(0.2_H - 0.6_V)$ π mm mrad , scales approx (BT+29)/2
- **Growth few ms after injection**
  - $\Delta\varepsilon_{y,3000} \approx 0.2+0.4\cdot(N_p/6\ 10^{12})^2$ …space-charge (*N*,*Q'*)
- **"Steady" growth thru the rest of the cycle**
  - $\Delta\varepsilon_{y,3000\text{-}19000} \approx 0.97 \cdot (N_p/6\ 10^{12})^3$ … why?
  - there other minor features $O(0.2\pi)$ – mb instrumental?
- **All that results in (*MW/IPM*) extraction values of**
  - $\varepsilon_{y,extr}$ [π mm mrad] $\approx 1.7 + 1.20 \cdot (N_p/6\ 10^{12})^{4\pm0.3}$
  - $\varepsilon_{x,extr}$ [π mm mrad] $\approx 1.8 + 1.03 \cdot (N_p/6\ 10^{12})^{4\pm0.3}$

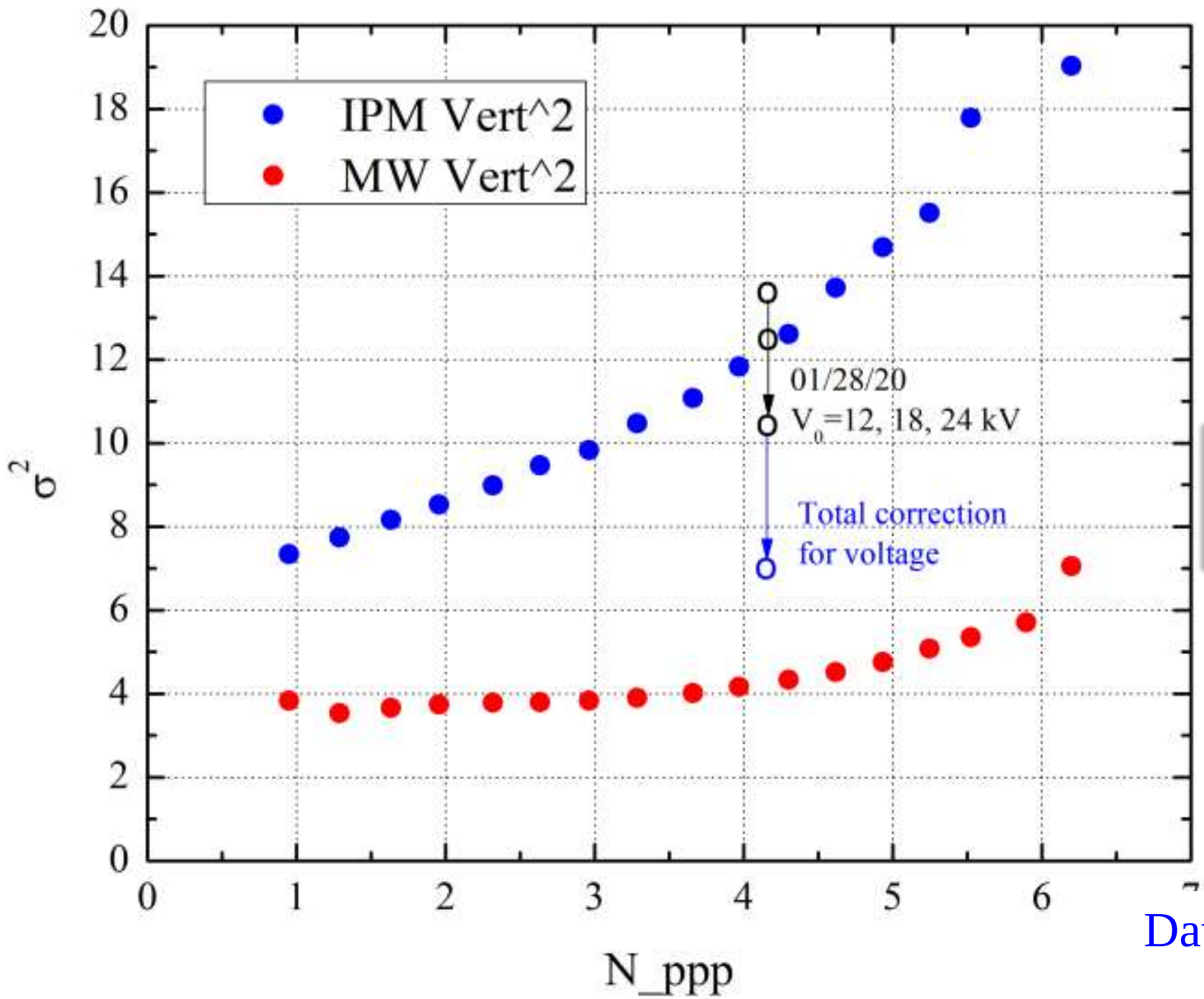
strongly dependent on the chromaticity

Seminar #2 : Discussion/Conclusions (1)

- Booster *Ionization Profile Monitors* are extremely valuable tools for fast beam size diagnostics:
  - operate in the ion collection mode without external magnetic field
  - there are strong systematic space-charge effects in the IPMs leading to significant, factor of 2 or more, expansion of the rms beam size reported by the IPMs w.r.t. to the original proton beam size.
- We accounted these effects following theoretical recipes arXiv:2003.09072
  - Resulting in acceptable systematic error *O(10-20%)*
  - Corrections can be/should be implemented online
  - Some subtle effects, e.g. those due to variable bunching factor need further exploration and experimental studies, e.g. →

IPM Profiles vs IPM High Voltage

Vertical mean squared beam size as reported by the Booster IPM with voltages V=12, 18 and 24 kV at nominal $N_p=4.5\cdot10^{12}$, red and blue dots – MW and 24 kV IPM data taken in 2019 S09



Theory scaling: $h \sim$

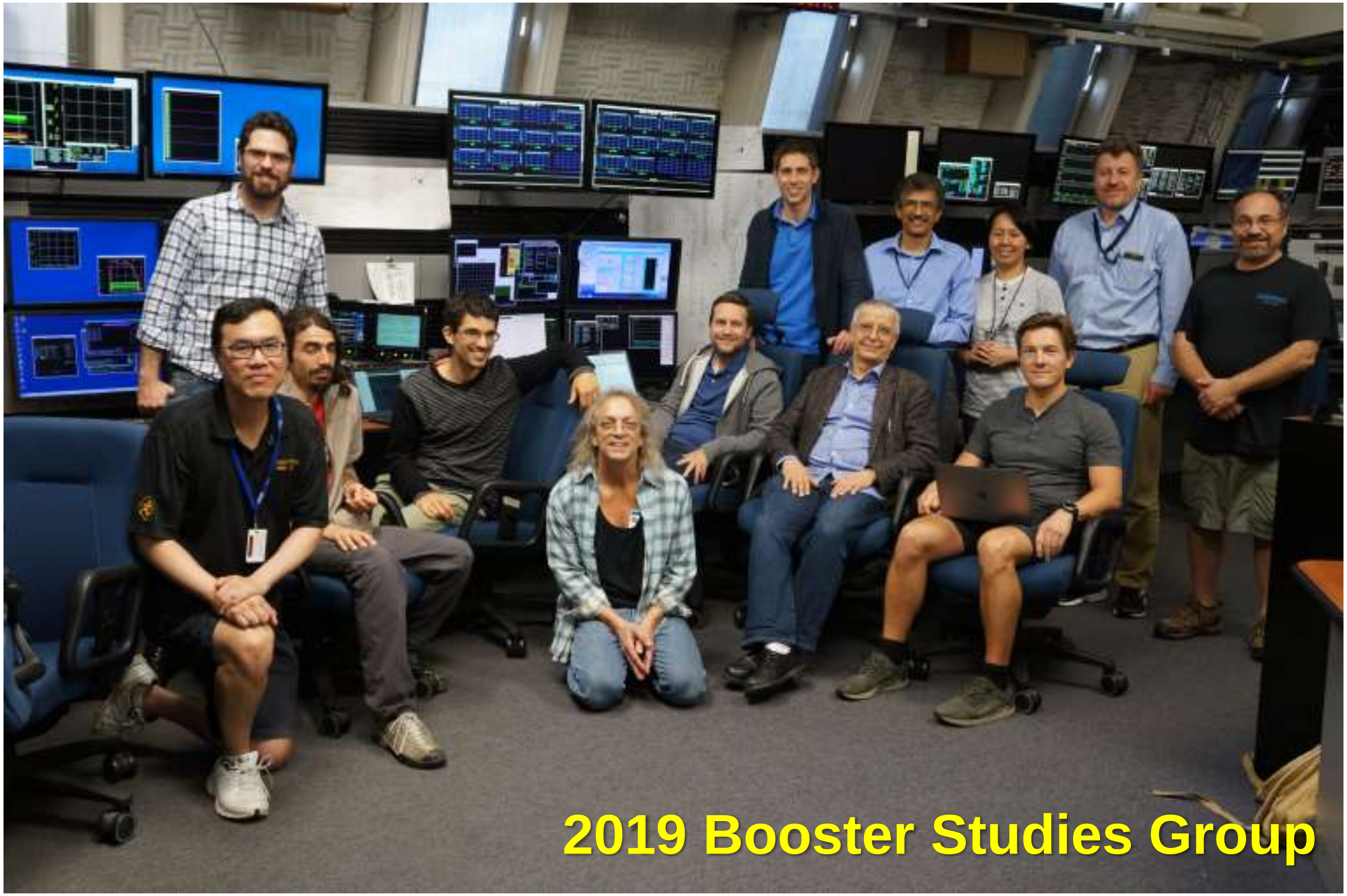
$$\left(\frac{2U_{SC}\,D}{\sigma_0\,V}\right)\left[\frac{\Gamma(1/4)}{3}\left(\frac{d}{\sigma_0}\right)^{\frac{1}{2}}-\frac{\sqrt{\pi}}{2}\right]$$

Data courtesy V.Kapin

Seminar #2 : Discussion/Conclusions (2)

- Further IPM studies/improvements:
  - the differential IPM profile measurements at several values of *V* may allow to estimate the actual proton beam size σ_0 as approximation for *V* going to infinity using theory Eq.
  - arrival times from the beam to the MCP plate depend on the ion species $\tau_0=(2MD\sigma_0/ZeV)^{1/2}$ *- so,* IPM signals at ~10ns resolution can allow quantitative analysis of the Booster vacuum
- **Beam effects to study further**
  - *Origin of the "steady emittance growth" over the cycle*
    - *Exclude instrumental explanation*
    - *See signs of e-cloud (simulate Booster …like RR/MI)*
    - *Special tests with extra gap in the Booster beam*
    - *Detect coherent motion (why there is no instability?)*
  - *Why IPM profiles are skewed at the times of losses?*

Thank You for Your Attention !



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

Backup Slides and Slides from Seminar #1