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Booster Beam Studies 2019
S.09: Tune Scans, Instensity Scans

J.Eldred, K.Seiya, V.Shiltsev

June 27 (whole day) and June 28 (PM), 2018

S.09: Dependencies of SC effects – Original Plan

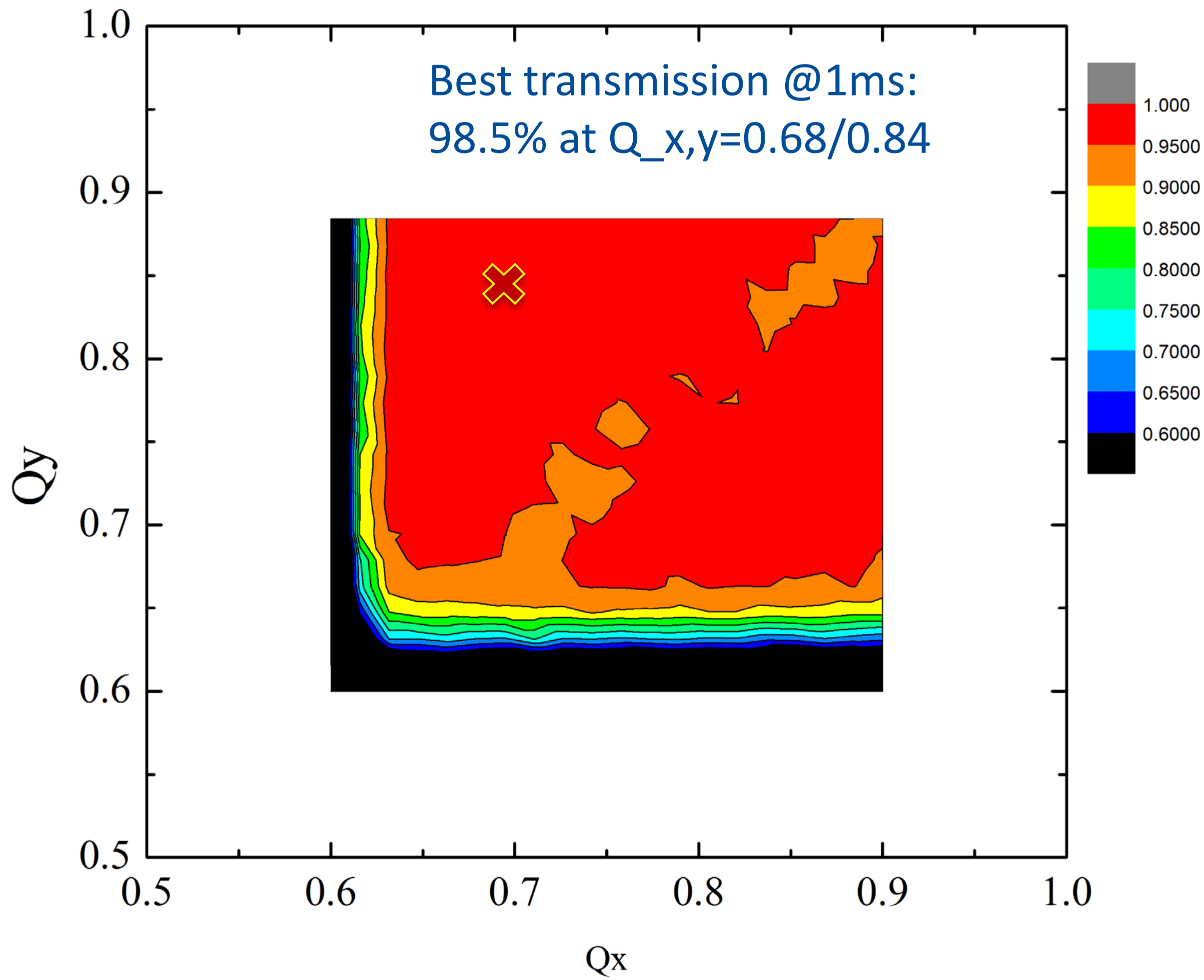
- *Objective:* systematic study of the evolution of transverse emittance growth and beam loss over the ramp; effects of the space-charge, tunes, Q', octupoles, known magnet nonlinear errors// will use of RWM and IPM to carry out corresponding scans (~400)
- *PI's (Fermilab and non-Fermilab):* K.Seiya and V.Shiltsev
- *Participants:* (J.Eldred), K.Seiya, V.Shiltsev, CERN, GSI
- *Est. duration:* **2 shifts parasitic, 1 shift dedicated**
- *Comments:* all instruments have to be available (built and installed); small loss scans at the rate 2-10/min (0.1-1% effect on proton timeline), larger loss results in PA trips and 10-15 min recovery – will be minimized to about 10-15.

S.09: Dependencies of SC effects – Actual Plan

- *Thur. June 27* - 2D tune scans:
  - Q_x,Q_y scan: Low N_p 4T, low Q' (-6)
  - Q_x,Q_y scan: Low N_p 4T, high Q' (-20)
  - Q_x,Q_y scan: High N_p 14T, high Q' (-20)
  - Q_x,Q_y scan: High N_p 14T, medium Q' (-12)
- *Fri. June 28* – 2 D tune scans, 1D scans:
  - Q_x,Q_y scan: Medium N_p 9T, medium Q' (-12)
  - Q_x,Q_y scan: Medium N_p 9T, high Q' (-20)
  - N_p scan, standard optics: nominal Q' *, -12, -20

* nominal operational Q_x,y = 6.78/6.88; Q'_x,y=-4/-16

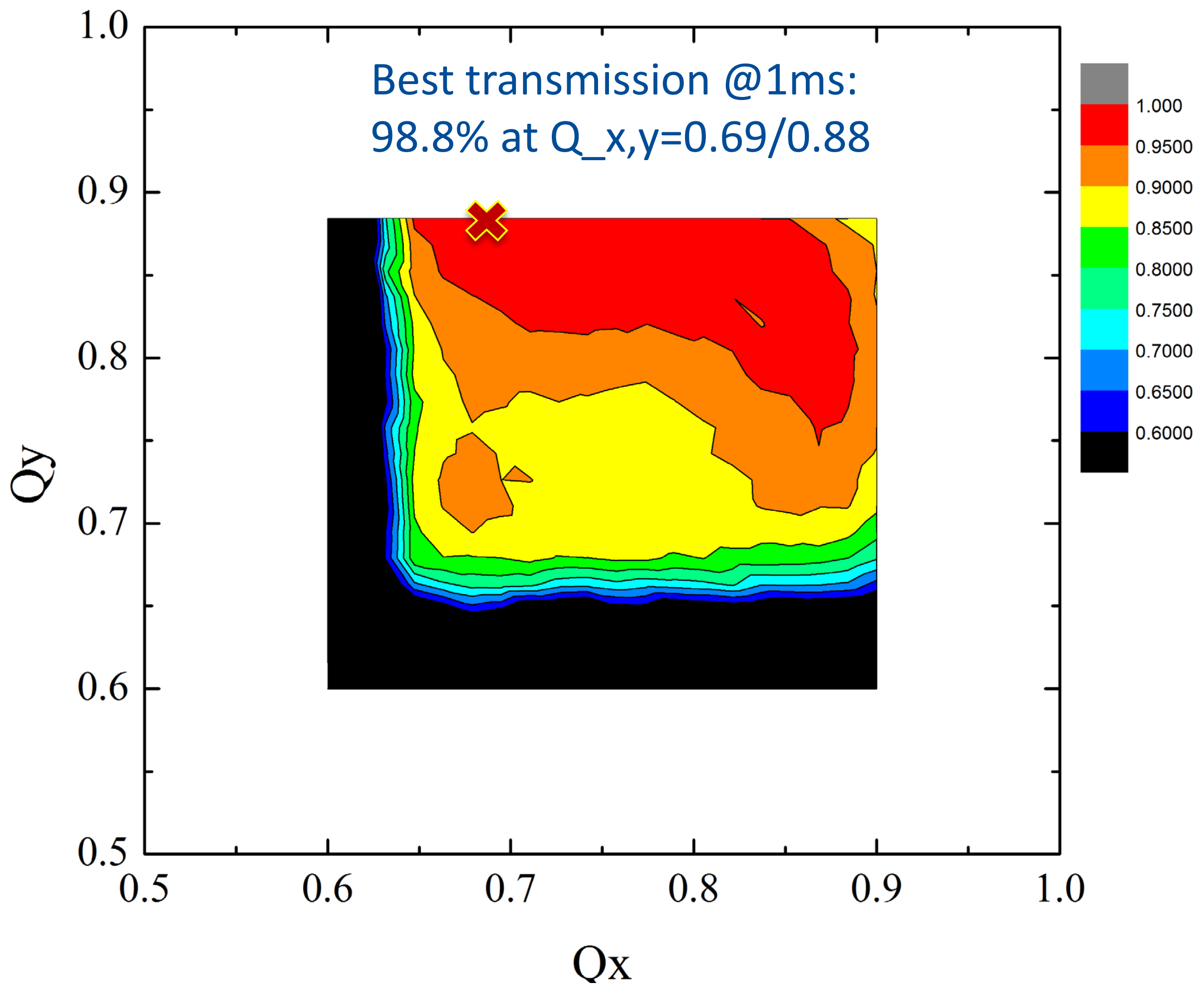
S.09: (Thur 06/27 data) Q'=-6 N_p=4 turns



Best transmission end of cycle: 96.5% at Q_x,y=0.82/0.81

- Intensity transmission after 450 turns ("point A", +1 ms)

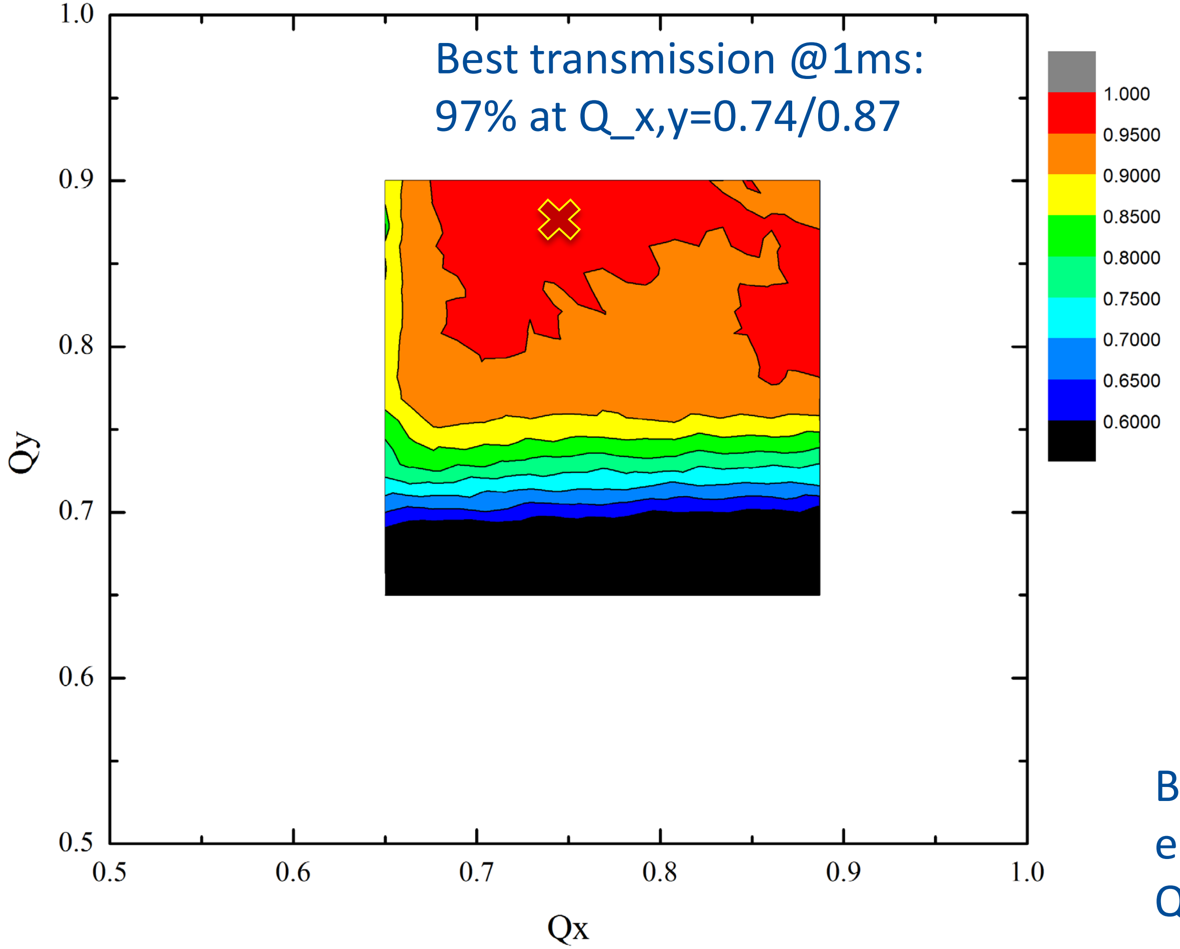
S.09: (Thur data) Q'=-20 N_p=4 turns



Best transmission end of cycle: 97.4% at Q_x,y=0.77/0.88

- Intensity transmission after 450 turns ("point A", +1 ms)

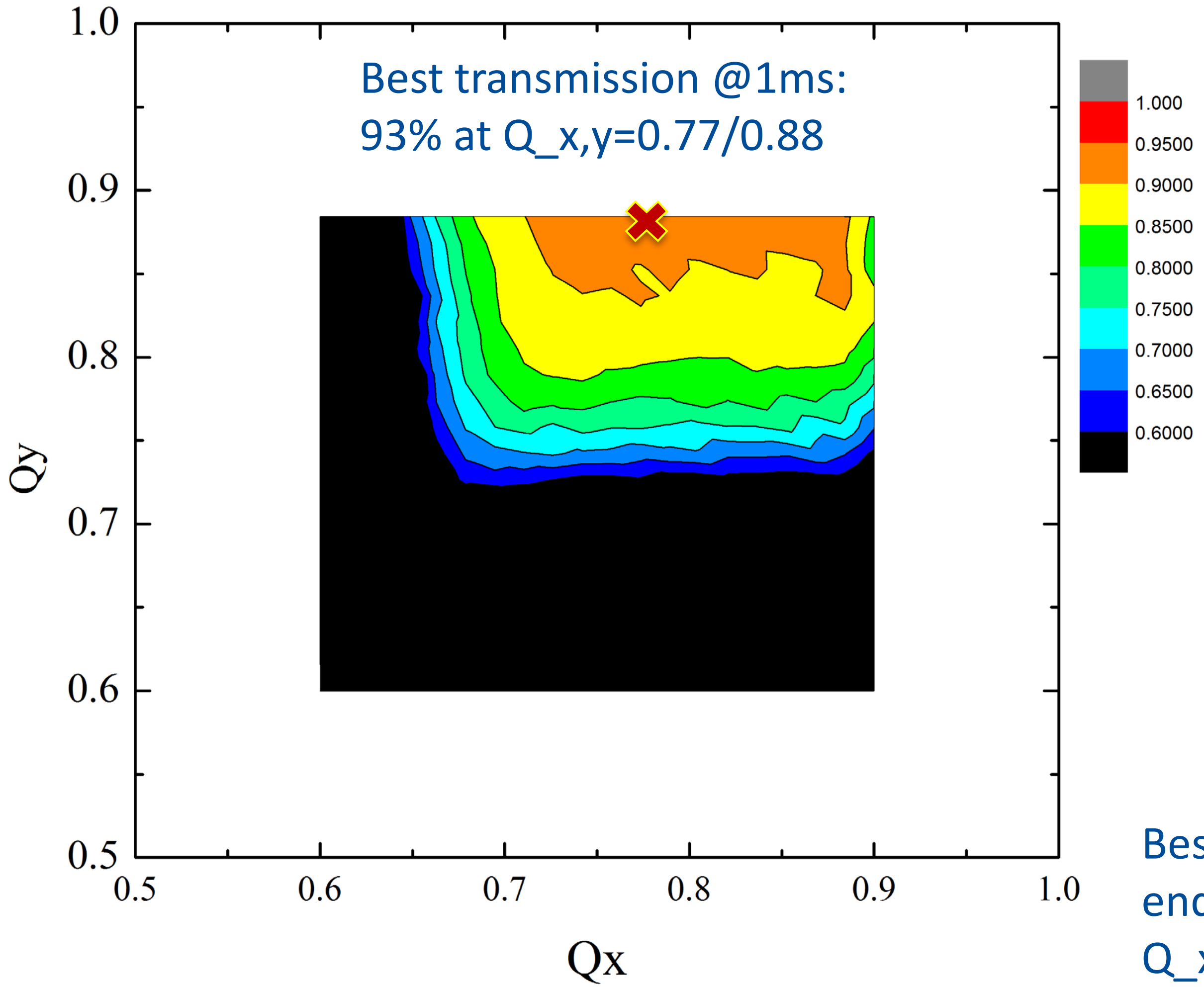
S.09: (Thur data) Q’=-12 N_p=14 turns



Best transmission end of cycle: 93% at Q_x,y=0.8/0.9

- Intensity transmission after 450 turns (“point A”, +1 ms)

S.09: (Thur data) Q'=-20 N_p=14 turns



Best transmission end of cycle: 84% at Q_x,y=0.77/0.88

- Intensity transmission after 2000 turns ("point A", +1 ms)

Approx. Scaling *dN/N* vs *N* and *Q'*

	Q'=-4	Q'=-12	Q'=-20
N=4 turns	1.5% (1ms) (3.5 % extr.)		1.2% (1ms) (2.6 % extr.)
N=14 turns		3.0% (1ms) (7.0 % extr.)	7.0% (1ms) (16 % extr.)

i.e. for losses after 1 ms

$$\frac{dN}{N}[\%] = (1.5 \pm 0.5) + 5.5 \cdot \left(\frac{Q'}{20}\right)^{2 \pm 0.5} \cdot \left(\frac{N}{14\ turns}\right)^{1.5 \pm 0.5}$$

Compare with the Tevatron at inj, ramp and squeeze (long-range beam-beam)

$$\frac{\Delta N_{\mathrm{a,p}}}{N_{\mathrm{a,p}}} = 1 - \frac{N(t)}{N(t=0)} \propto \sqrt{t} \cdot \varepsilon^2_{\mathrm{a,p}} \frac{N_{\mathrm{p,a}}}{\varepsilon_{\mathrm{p,a}}} {Q'}^2{}_{\mathrm{a,p}} \cdot F\left(\varepsilon_{\mathrm{L}}, Q_{x,y}, S_{\mathrm{a-p}}\right)$$

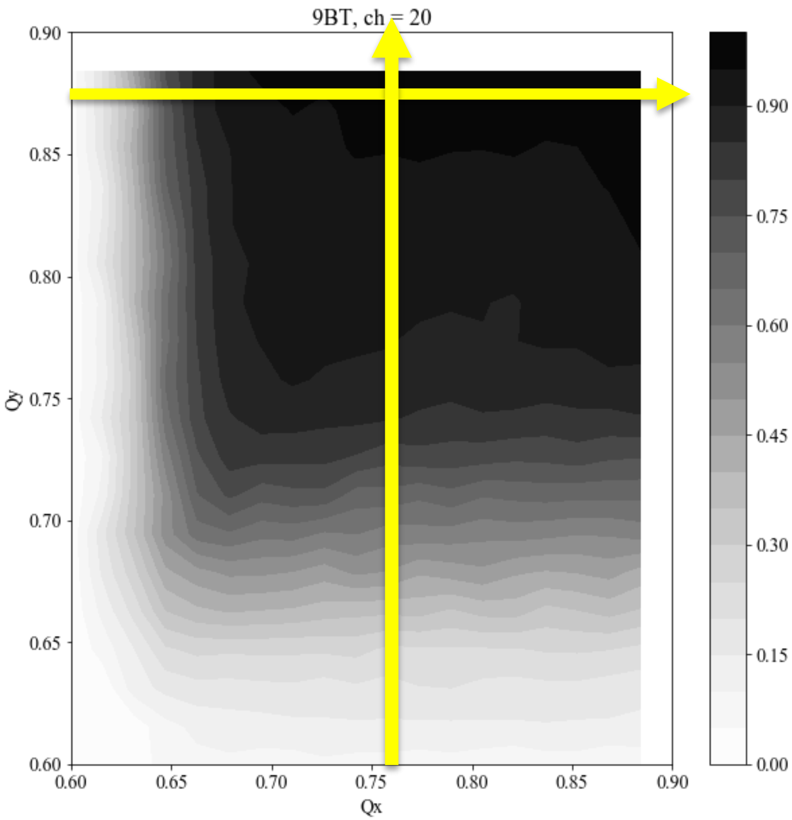
Also : is the footprint "shrinkage" = (dP/P)xQ' ?

- For N=4 turns:
  - Change of chromaticity dQ'=20-6=14 units
  - Reduction of the 90% transmission tune area dQ_x=0.02, dQ_y=0.05
  - Rms energy spread at inj ~0.0017
  - So, in the units of dQ'(dP/P) : dQ_x=0.8 and dQ_y=2.1
- For N=14 turns:
  - Change of chromaticity dQ'=20-12=8 units
  - Reduction of the 90% transmission tune area dQ_x=0.05, dQ_y=0.1
  - Rms energy spread at inj ~0.0017
  - So, in the units of dQ'(dP/P) : dQ_x=3.7 and dQ_y=7.4

Why dQ_x << dQ_y? Why does Q' footprint reduction scale with N_turns?

Three effects: dQ due to Q', dQ due to SC for particles off center due to D_x(dP/P), dQ_SC tuneshift due to long oscillations along the bunch for particles with dP/P…

Kyiomi looked at 9BT CH=-20, IPM data from 0 to 512 turns (first 1msec)

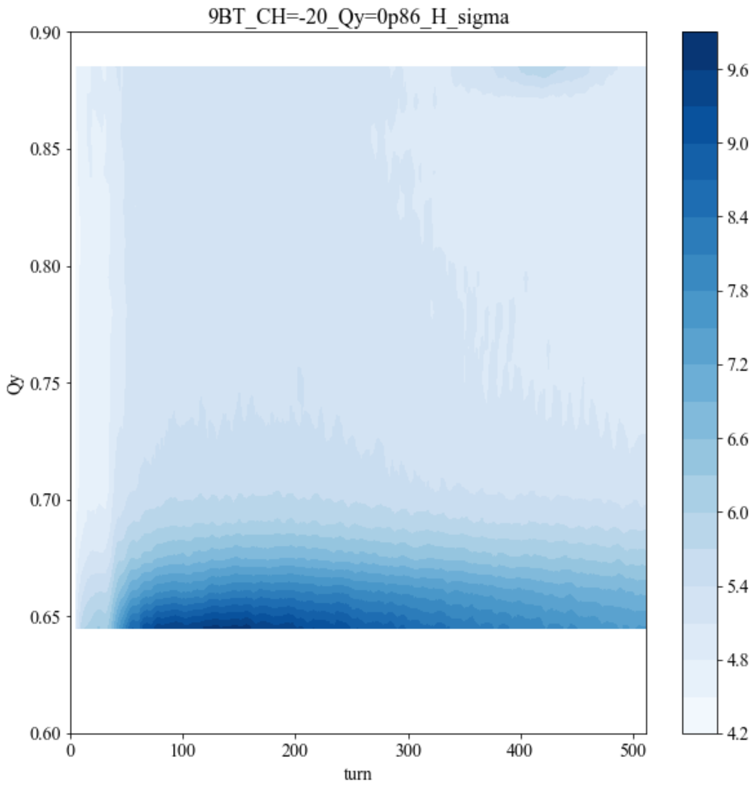


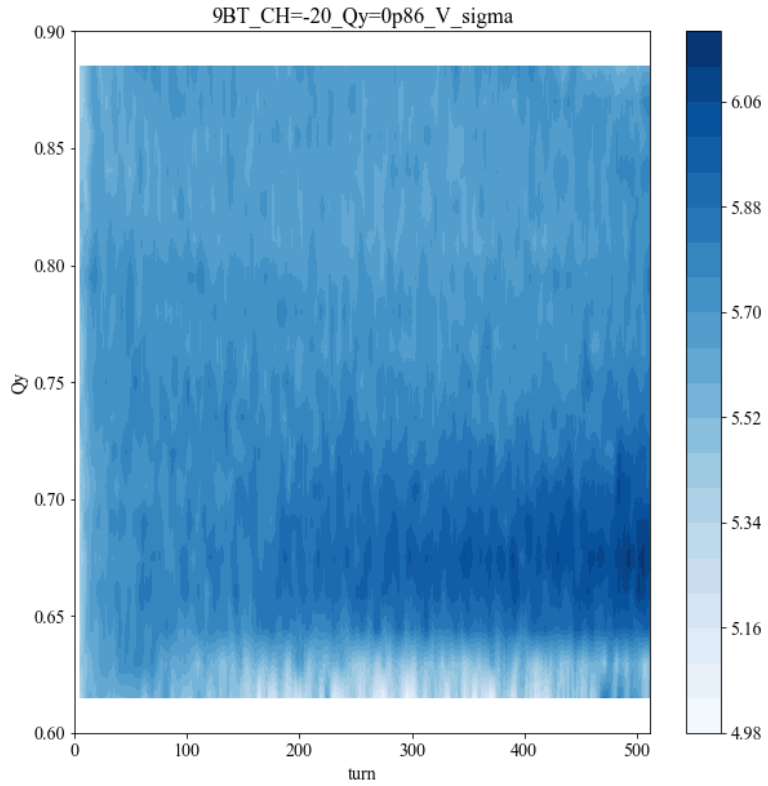
1: I looked at first 512 turn IPM data.
2: The data is the beam size (sigma) which is averaged over 6 turns.
3: I fixed Qx=0.76 and scanned vertical tune and plotted BPM data in horizontal and vertical in slide2.
4: I fixed Qy=0.86 and scanned horizontal tune and plotted BPM data in slide3
5: Beam size was increased first 200 turns in Horizontal and vertical probably due to multiturn injection and adiabatic capture.
6: Intensity kept decreasing from 0 turn to 512 turn.
*I have not made this plot, but slide 4 show an example.
7: The slide4 shows the horizontal position moved more than 5 mm in 512 turns
*I have not made this plot
8: * I have to do same analysis with different chromaticity.

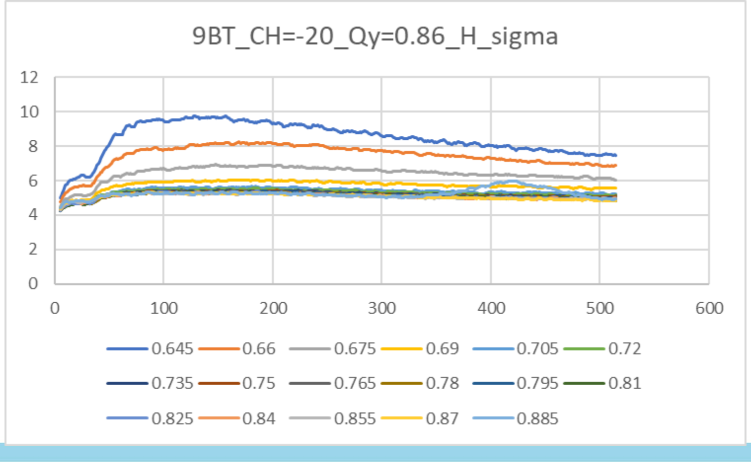
****Question****

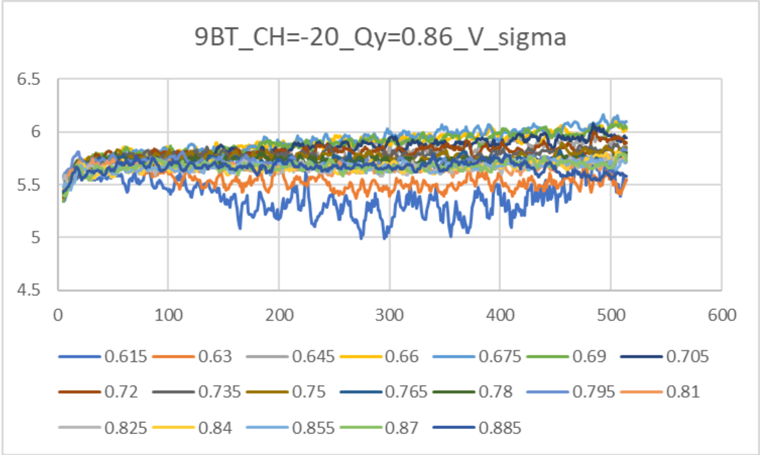
If beam size is not increasing, why are we loosing beam for 1 msec?

Why is the horizontal position moving?


9BT_CH=-20_Qy=0p86_H_sigma
Qy
turn


9BT_CH=-20_Qy=0p86_V_sigma
Qy
turn

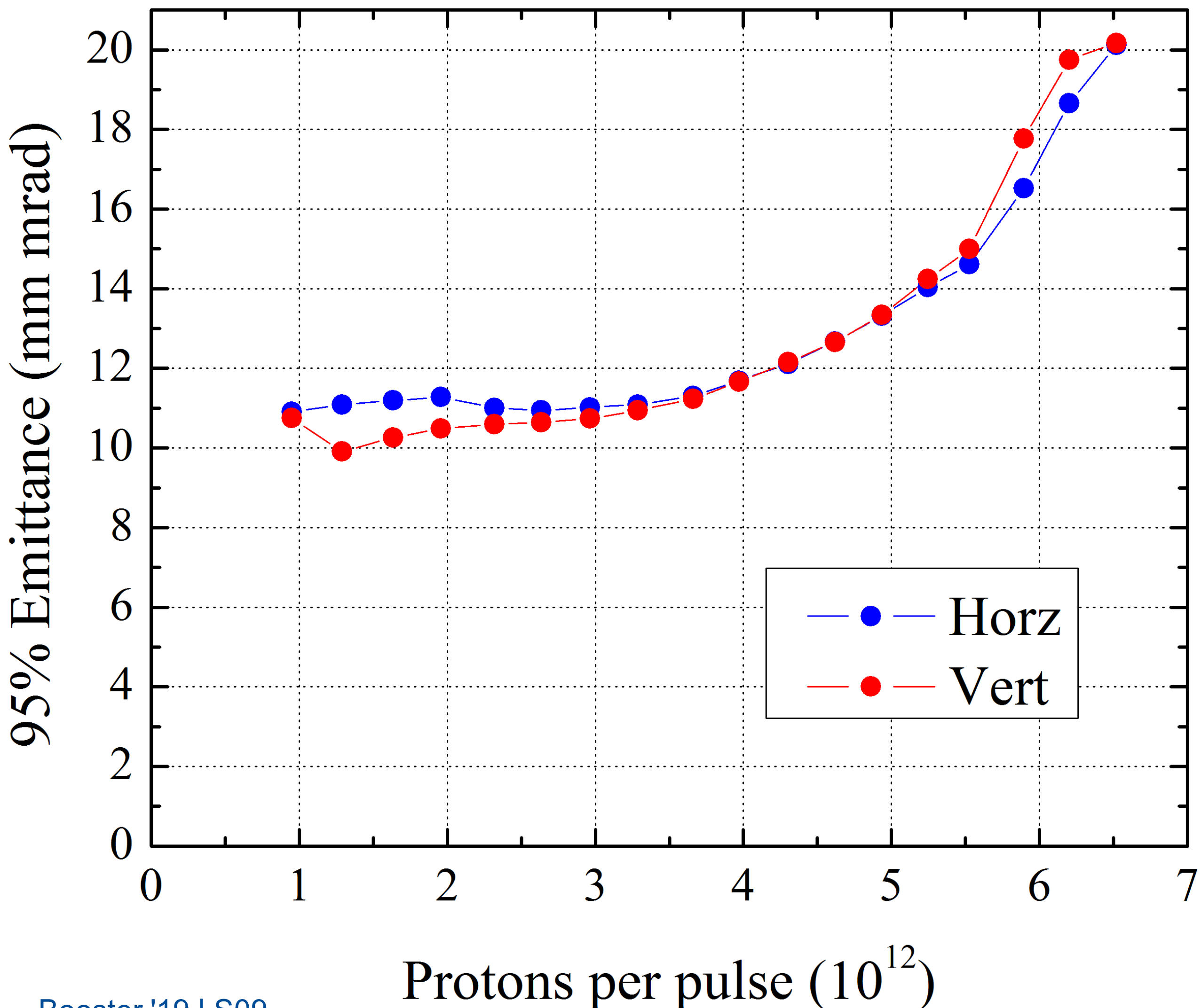

9BT_CH=-20_Qy=0.86_H_sigma
0.645 0.66 0.675 0.69 0.705 0.72
0.735 0.75 0.765 0.78 0.795 0.81
0.825 0.84 0.855 0.87 0.885


9BT_CH=-20_Qy=0.86_V_sigma
0.615 0.63 0.645 0.66 0.675 0.69 0.705
0.72 0.735 0.75 0.765 0.78 0.795 0.81
0.825 0.84 0.855 0.87 0.885

Intensity Scans: MW Emittances (8 GeV, extr. beam, 95%)

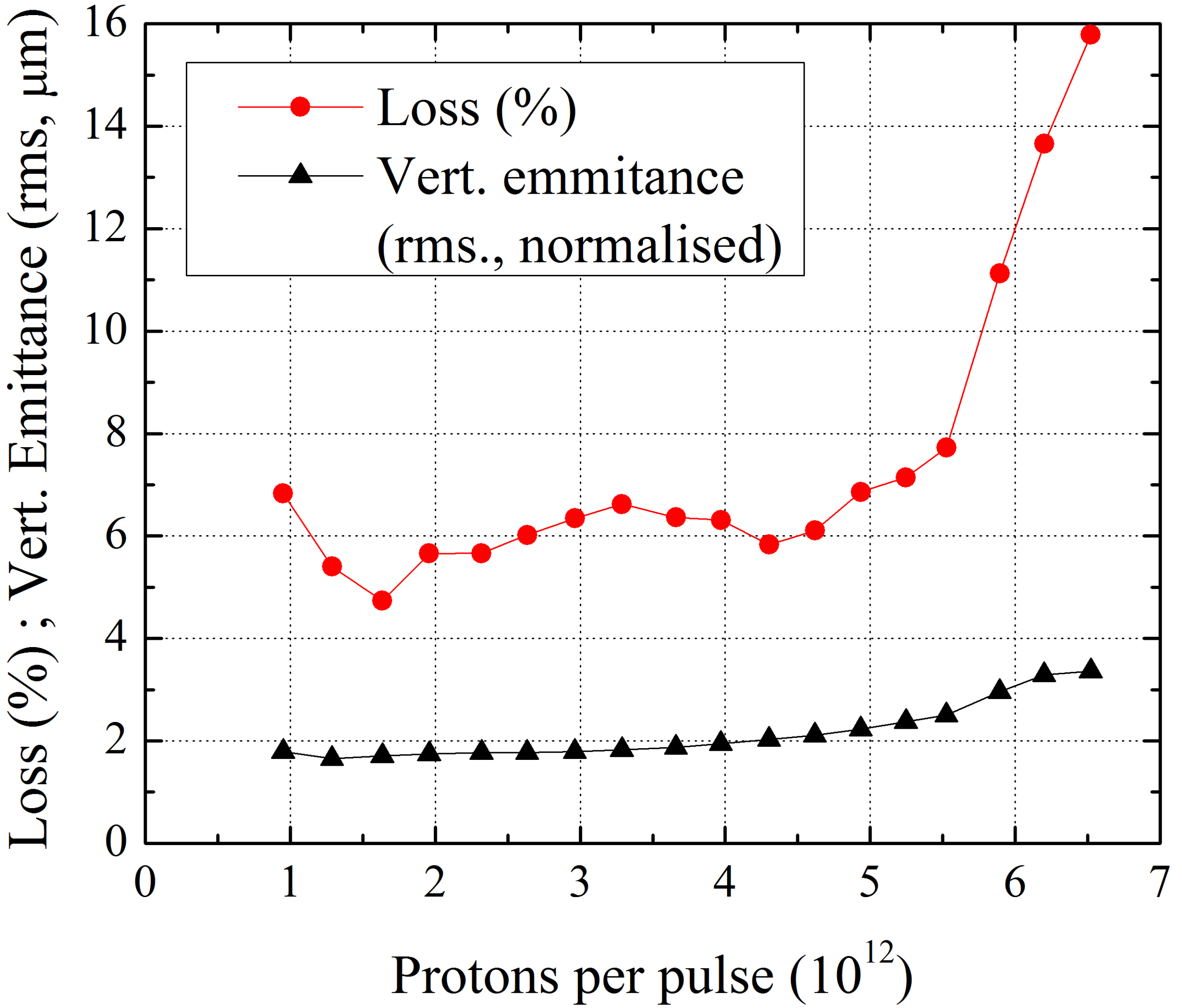
HEP tunes and Chromaticity (-4/-16)

Signs of scraping?



Intensity Scans: Losses and MW Emittances (rms)

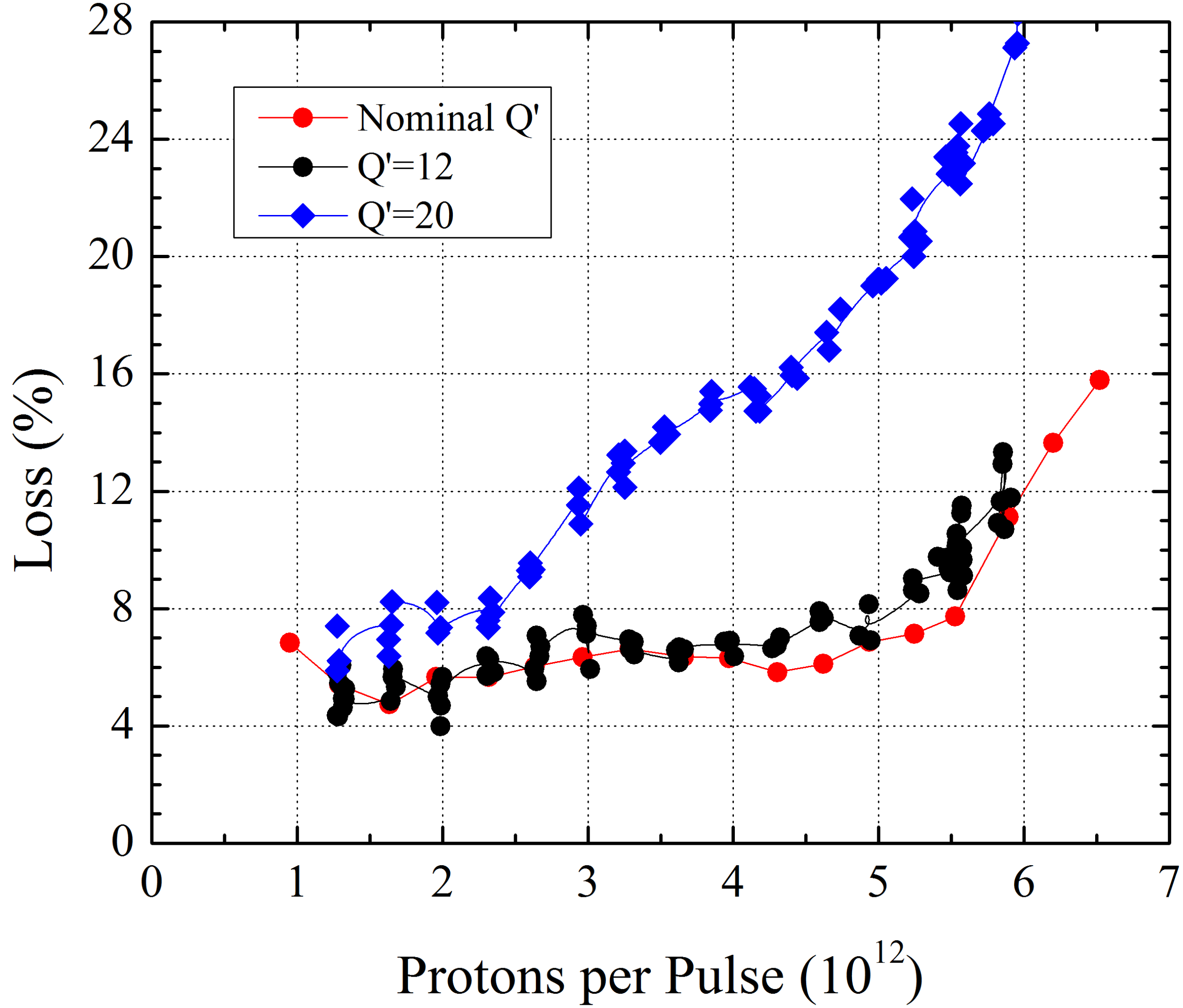
HEP tunes and Chromaticity (-4/-16)



Scraping indeed…

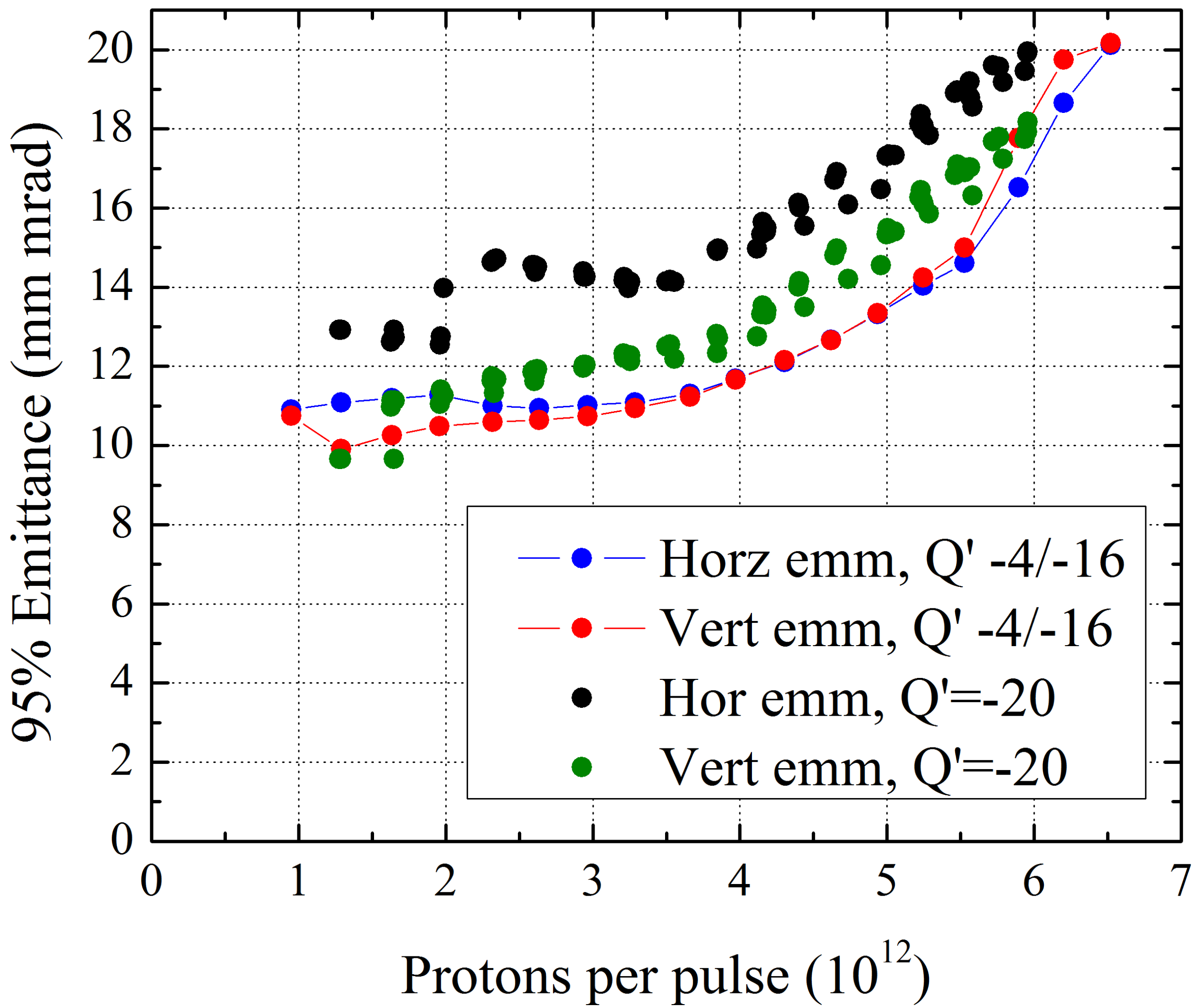
Fermilab

Intensity Scans: Losses and Chromaticity



Things get much worse (~2-3) with higher Q’

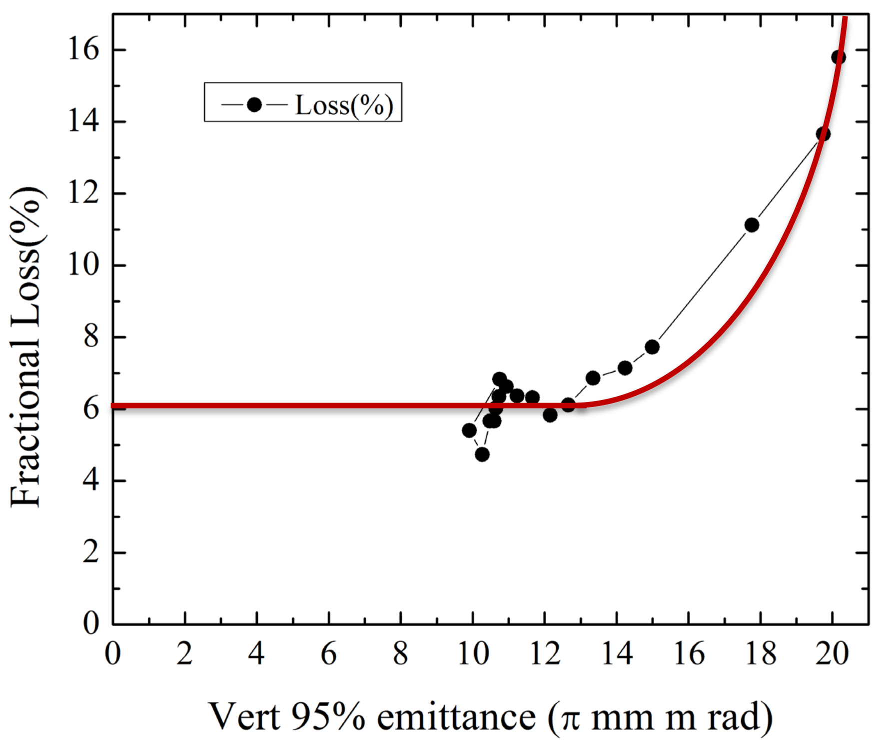
Intensity Scans: Emittances and Chromaticity



Emittances get somewhat lager at higher Q’, but show “scraping”

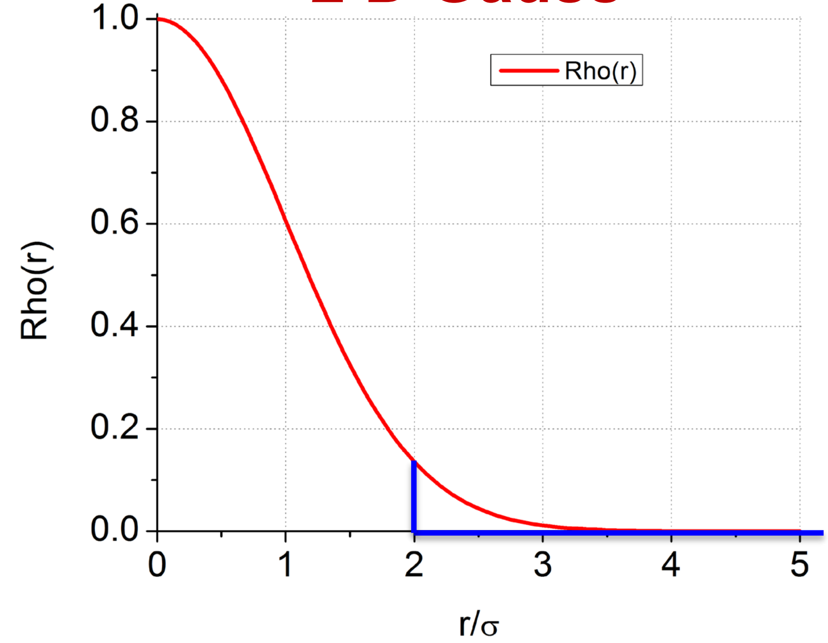
Acceptance

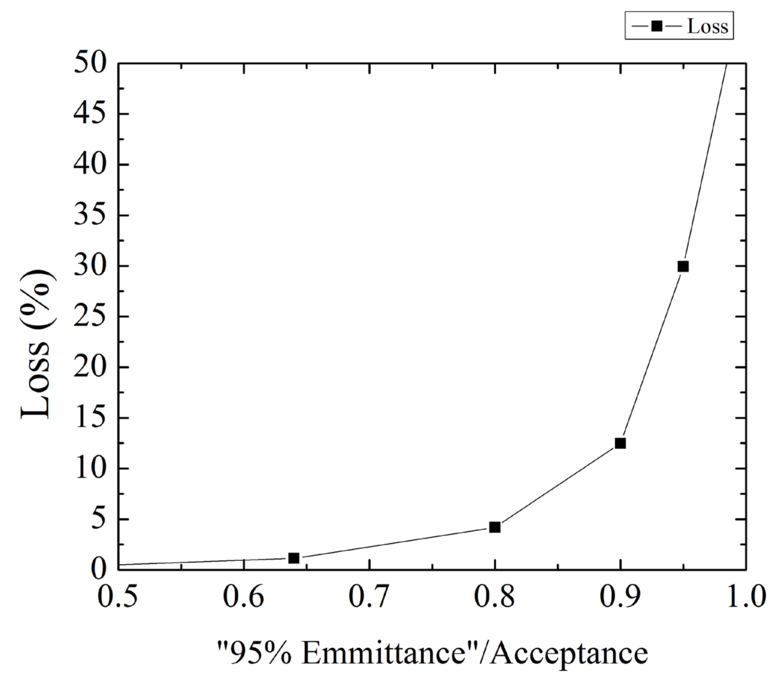
Booster Loss



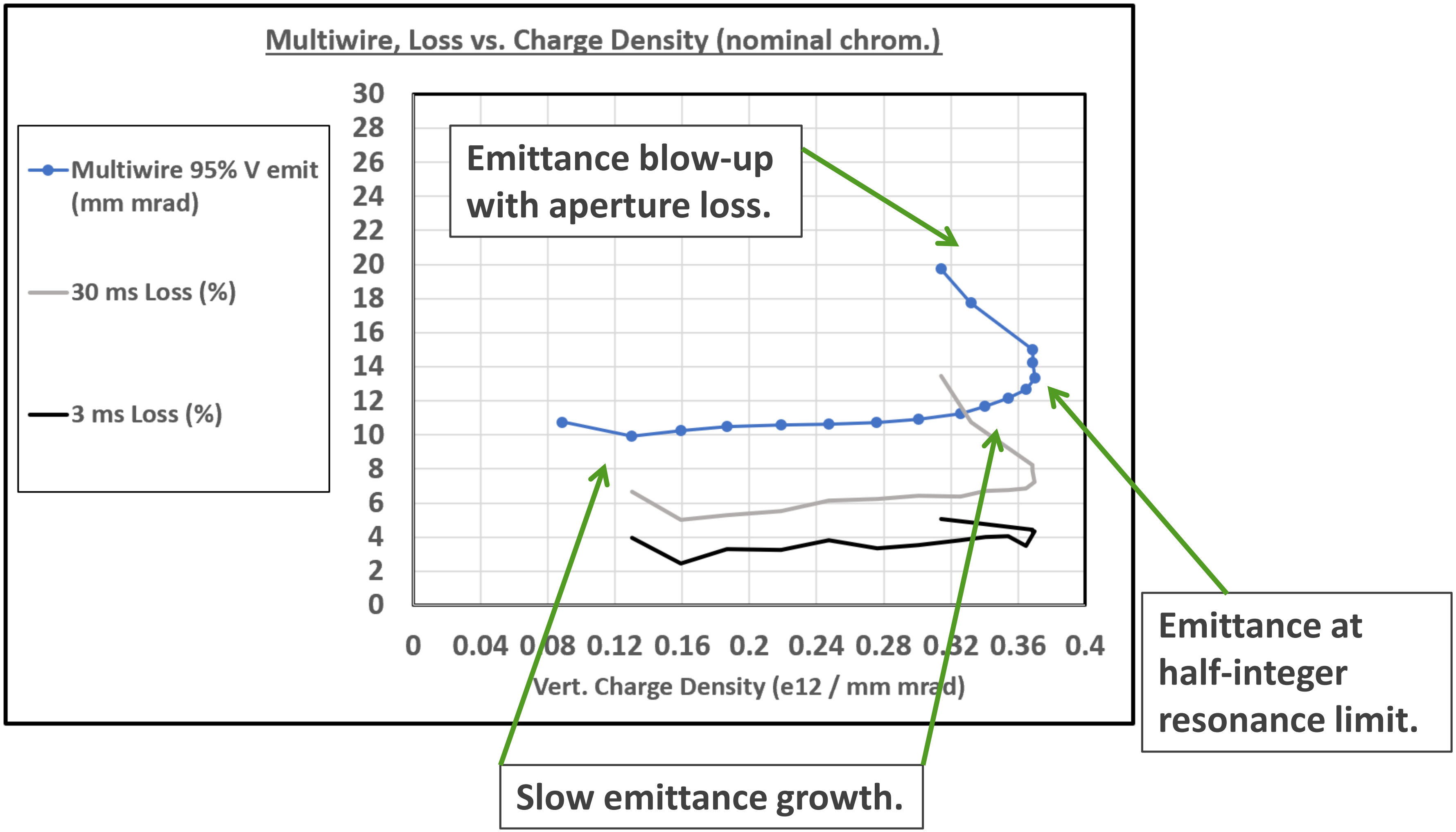
Booster Acceptance is about 22+-2 pi (mm mrad , normalized)

2 D Gauss





Nominal Chromaticity – Emit Loss vs Charge Density



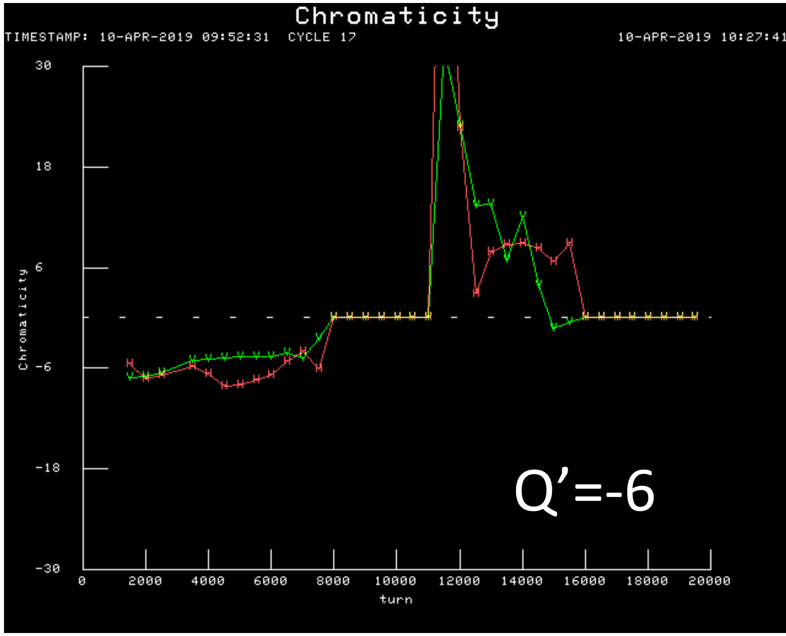
Important issues/notes :

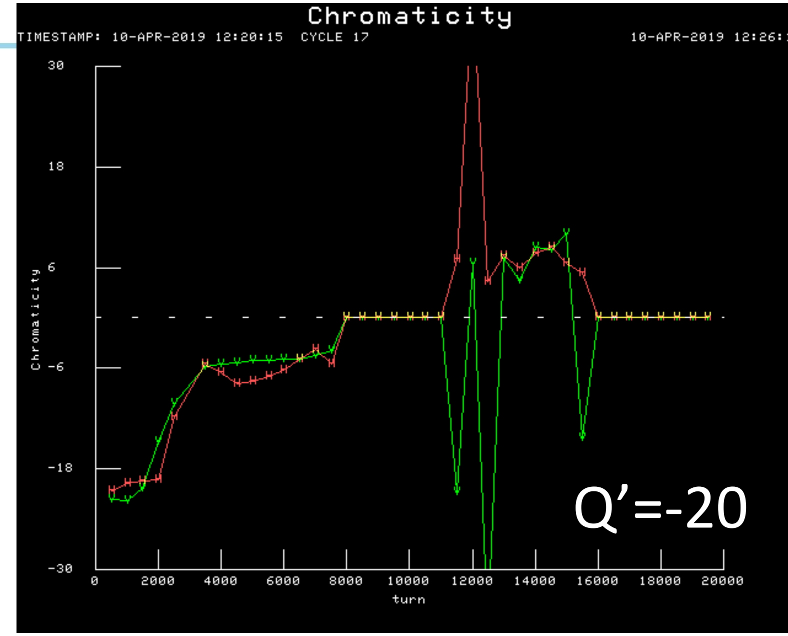
a) on chromaticity Q'

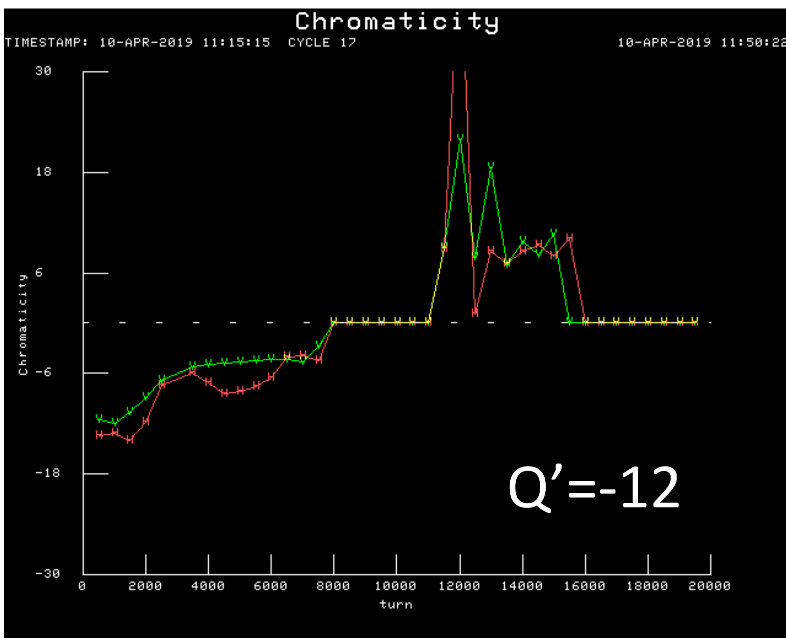
b) on the ionization profile monitor (IPM)

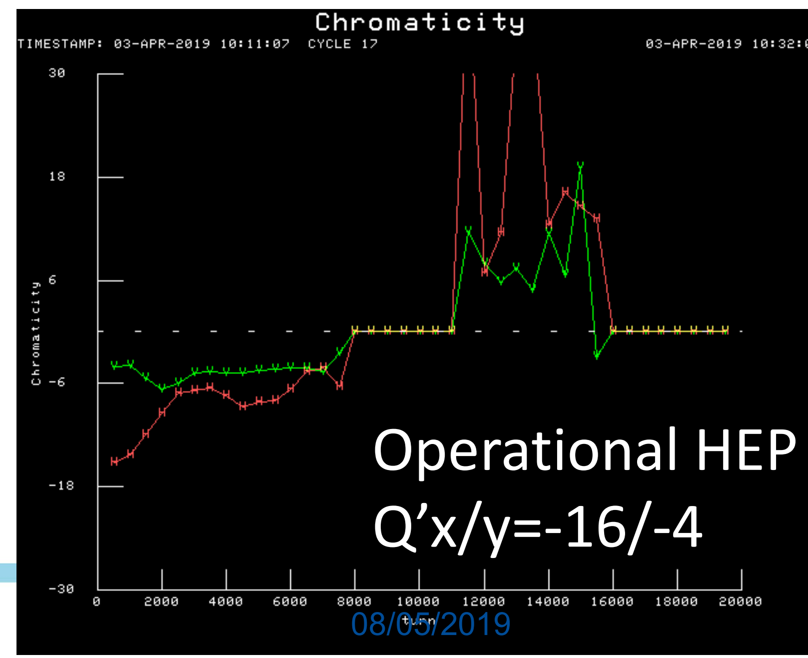
c) on ultimate beam out of Booster "now and then"

Measured Q' (Jeff)

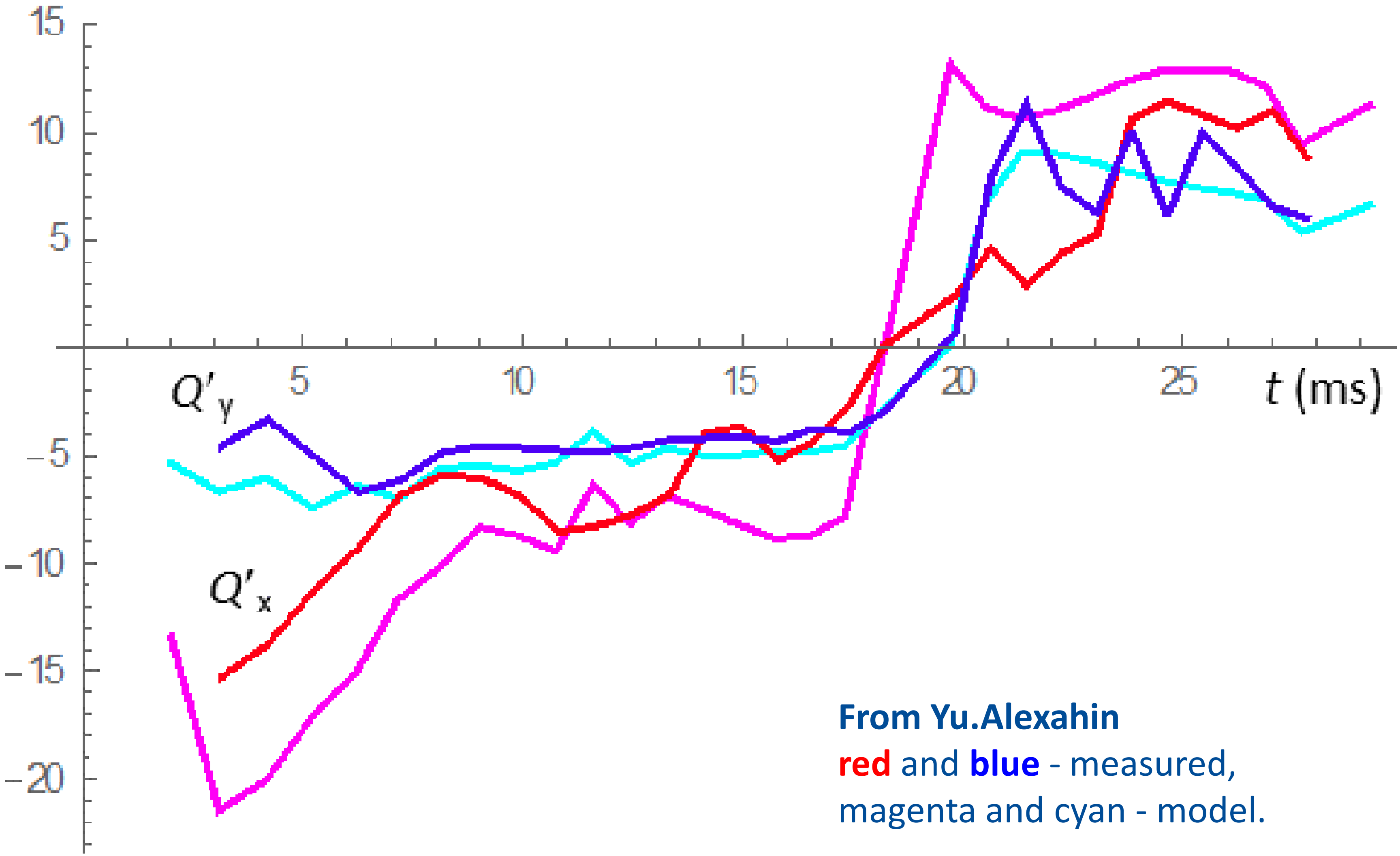








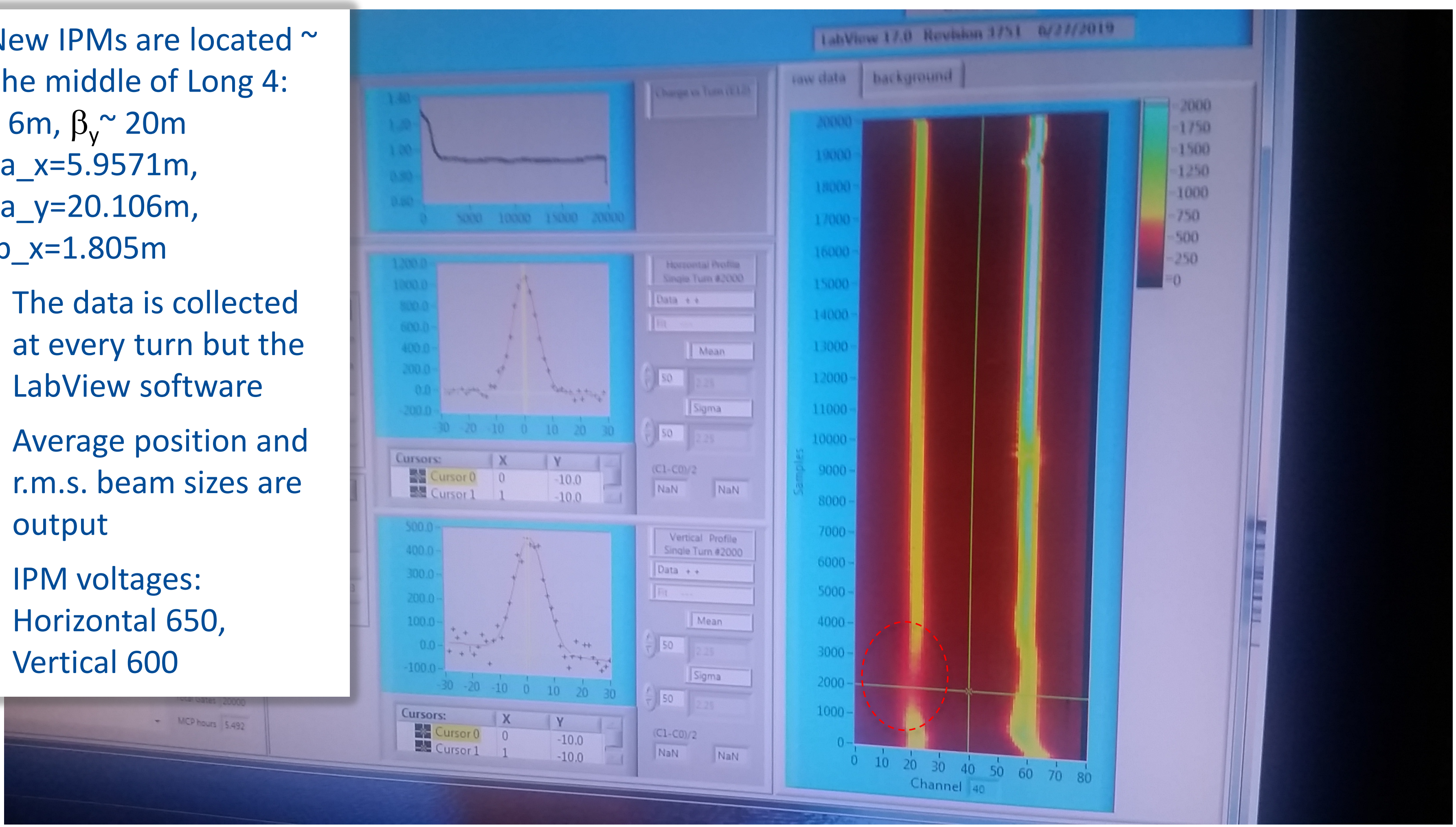
On the Booster chromaticity : model vs reality



From Yu.Alexahin
red and **blue** - measured,
magenta and cyan - model.

S.09: (Thur data) gap in IPM V data stream – very helpful!

- New IPMs are located ~ at the middle of Long 4: β_x~ 6m, β_y~ 20m beta_x=5.9571m, beta_y=20.106m, disp_x=1.805m
  - The data is collected at every turn but the LabView software
  - Average position and r.m.s. beam sizes are output
  - IPM voltages: Horizontal 650, Vertical 600

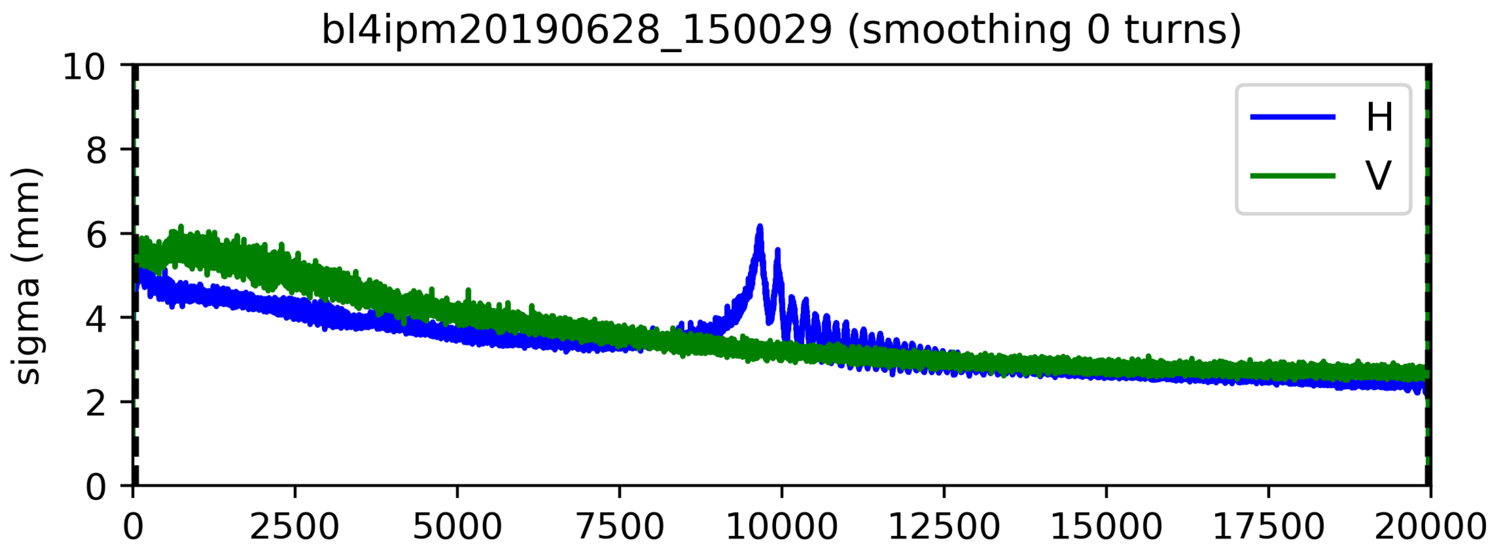


- See around 2000th turn

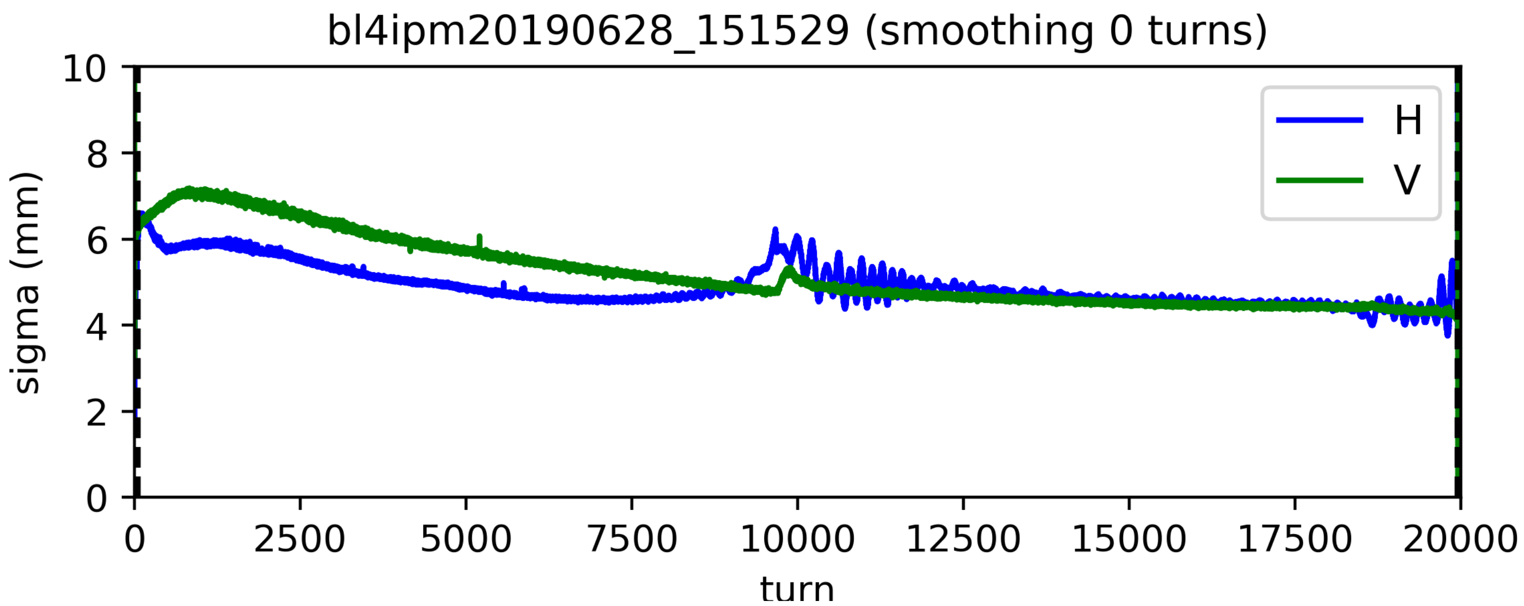
Fermilab

IPM

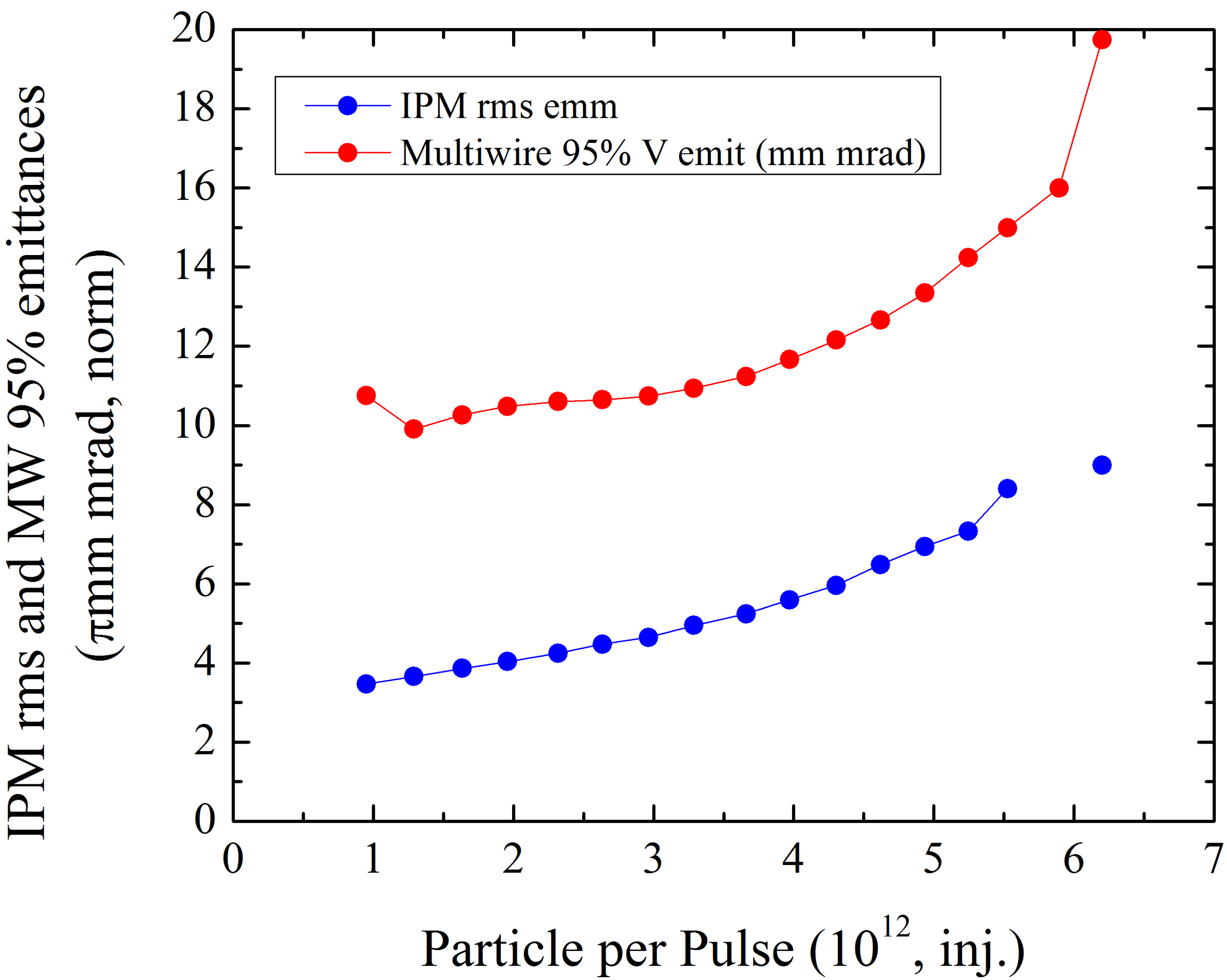
4 turn injection



20 turn injection

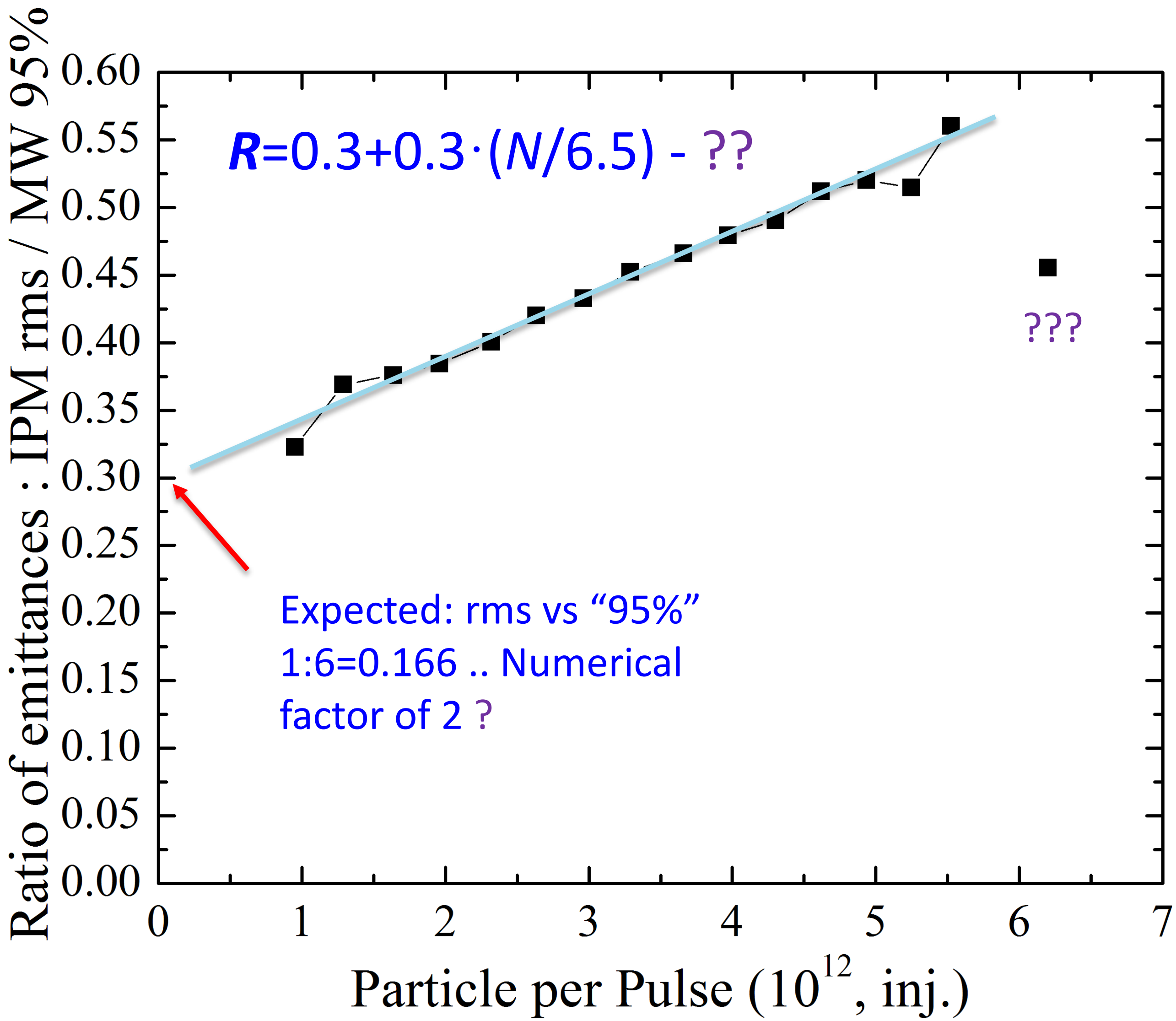


IPM and MW Emittances vs Intensity



Both show growth, but …(see next slide)

Ratio of IPM / MW Emittances : Three questions



IPM vs MW (ionization profile monitor vs multiwire chamber)

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME 6, 102801 (2003)

Calibration of the Fermilab Booster ionization profile monitor

J. Amundson, J. Lackey, and P. Spentzouris
Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA

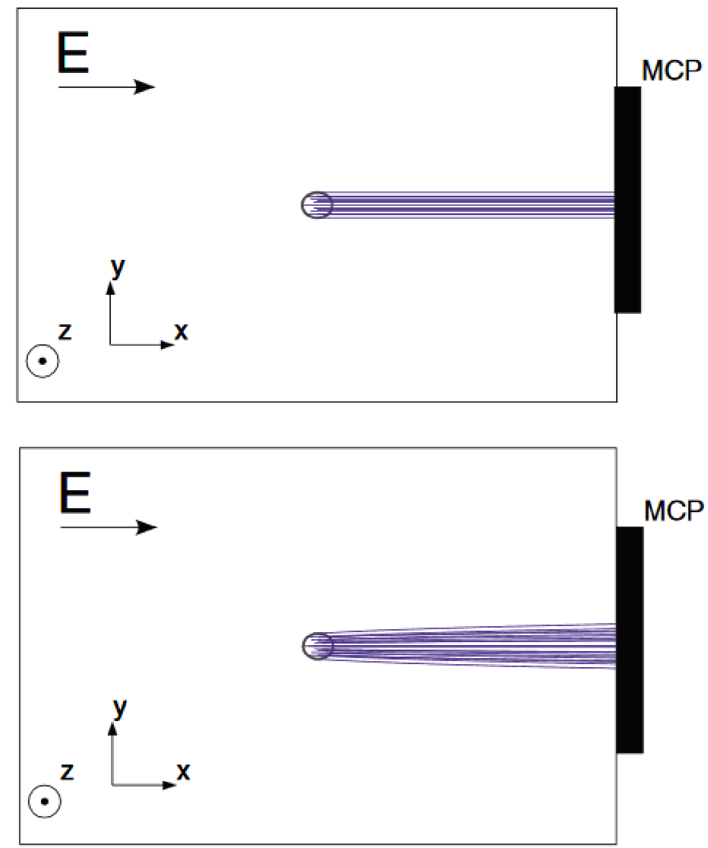
G. Jungman
Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

L. Spentzouris
Department of Biological, Chemical, and Physical Sciences, Illinois Institute of Technology, Chicago, Illinois 60616, USA
(Received 20 May 2003; published 9 October 2003)

relation between the raw beamwidth seen in the IPM and the real width is well described by the function

$$\sigma_{\text{measured}} = \sigma_{\text{real}} + C_1 N \sigma_{\text{real}}^{p_1}, \tag{8}$$

where N is the current in units of 10^{12} protons in the machine, $C_1 = (1.13 \pm 0.06) \times 10^{-5}\ \text{m}^{1-p_1}/10^{12}$, and $p_1 = -0.615 \pm 0.013$. The range of validity in



While AGS IPM (PAC1987):

SPACE-CHARGE DISTORTION IN THE BROOKHAVEN IONIZATION PROFILE MONITOR*

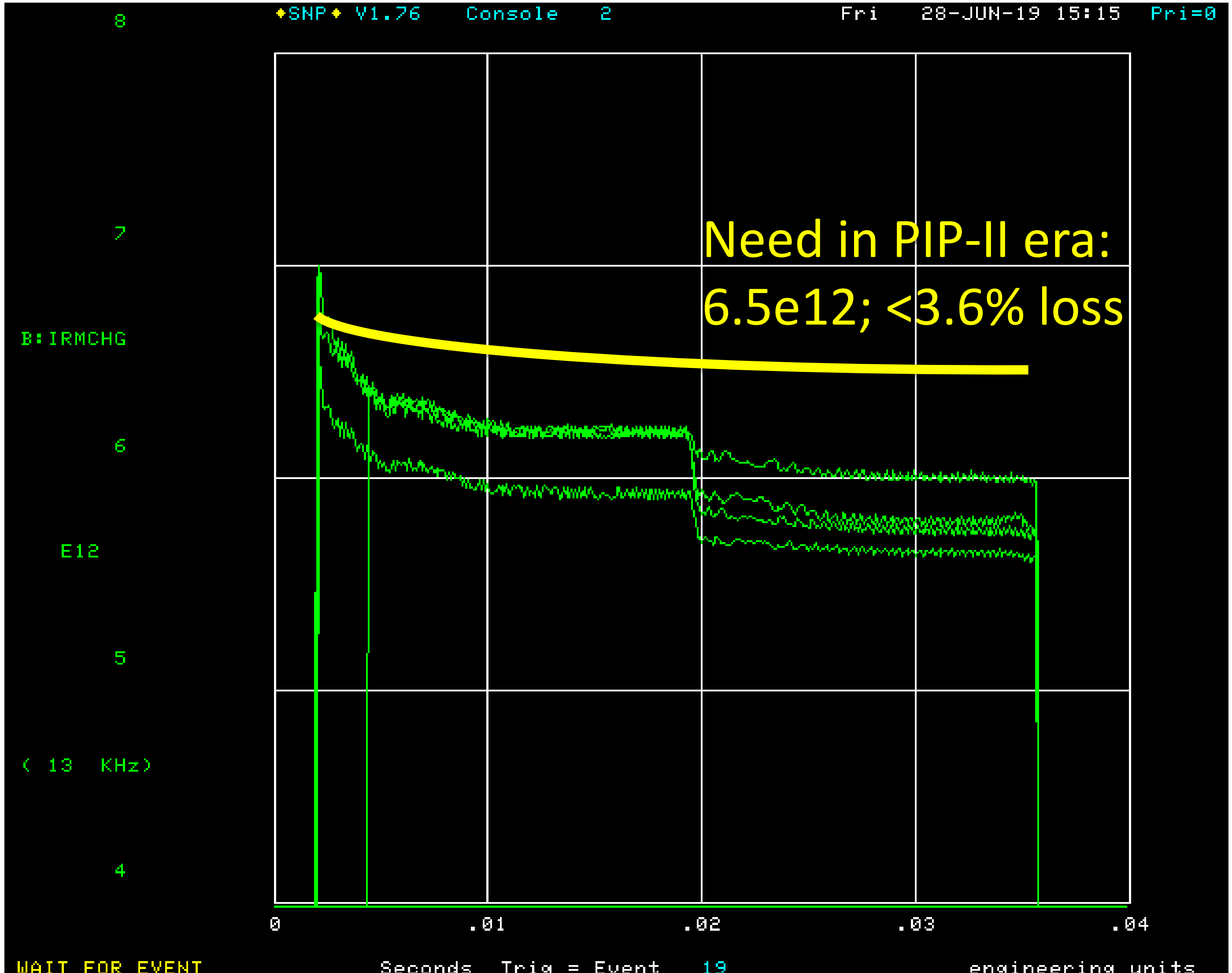
R.E. Thern
AGS Department,

$$\sigma_m = \sigma + 0.302 \frac{N^{1.065}}{\sigma^{2.065}} (1 + 3.6 R^{1.54})^{-0.435}$$

S.09: (Fri data) 6e12 ppp – Booster record?

(per Jeff)

"…I went through some Elog history and Datalogger data, and I think it is a record.
I could not find any prior occasion in which the Booster successfully extracted above 6e12."



6e12/7e12=
86%
Transmission efficiency

(Tentative) Summary of S09 Study :

- 2 D tune scans show that :
  - Operational tunes are close to optimal at high Np
  - Losses in optimal tunes scale approx. as Np x Q' ^2
  - Min loss @1 ms at low N_p ~1-2%, grows to 7% at 14 turns
- 1 D Intensity scans from 4 to 21 turns show that:
  - dN/N Losses grow with N
  - Q' is a huge factor (x2-3 from ~12 to ~20) – for the total loss
  - Emittances grow too, by ~60% from 1 to 6 e12
- Max extracted N_p is 6.0 e12 , with 14% loss (worst)
  - vs required 3.6% at 6.5e12 during PIP-II era (long way to go)
- IPM is calibrated vs MW :
  - Great tool – fast! … though have some unresolved issues
  - Absolute values wrt MW (off by ~2)
  - Strong intensity dependence (~x2 from 0 to 6e12)

Back up slides

(Chandra to Kornilov) On the end of Capture parameters

- dE_rms = dE_95 / 4 ~ 4.6MeV / 4 = 1.15MeV (@inj., maximum over the years)
- dp/p_rms=(dE_rms/E)*(1/beta**2)=(1.15/1338.27)*(1/0.713**2) = 1.7E-3
- V_rf ~0.7 MV (at the end of capture)
- frequency_rf = 37.899 MHz
- Bunch length BL(4sigma) ~17- 19 ns (end of capture)
- Emittance_longitudinal LE (95%) ~0.06-0.07 eVs (end of capture)
- Emittance_xy_95: meas'd in 400 MeV transfer line is ~7pi-mm-mr; ~11 pi-mm-mr (at 1e12, IPM sizes 4.7/6.0) and ~13.5 pi-mm-mr (at 4.5e12) - measured at extraction (divide by 6 for rms)

Tunes vs currents (VS and Kyiomi)

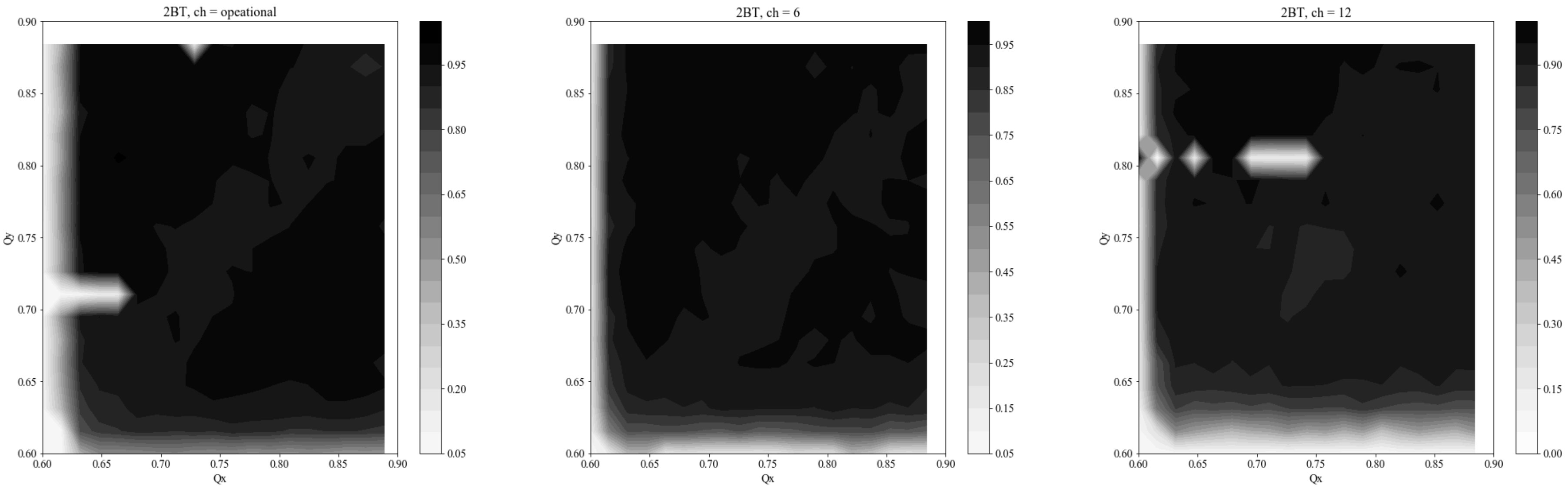
- Booster fractional tune vs IQS/IQL Amps:
  QX = IQS*0.0449 + IQL*.0096 + 0.77945
  QY = -0.0277*IQS - 0.0078*IQL + 0.88

Extra Analysis by Kiyomi

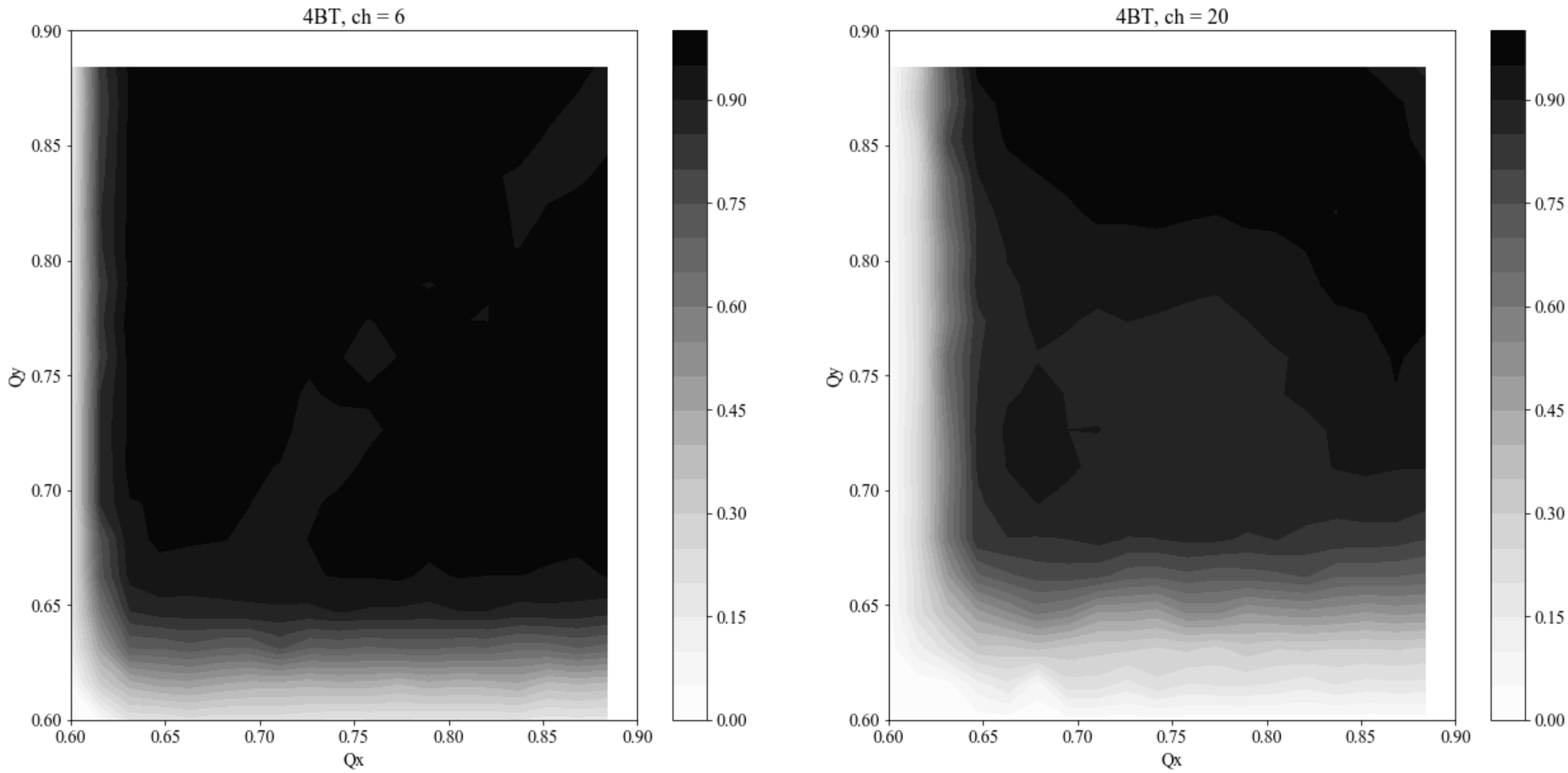
Scan data

	Ch = 6	Ch = 12	Ch = 20	Ch = Op
2BT	TS	TS		TS
4BT	TS		TS	
9BT		TS	TS	
14BT		TS	TS	

2BT

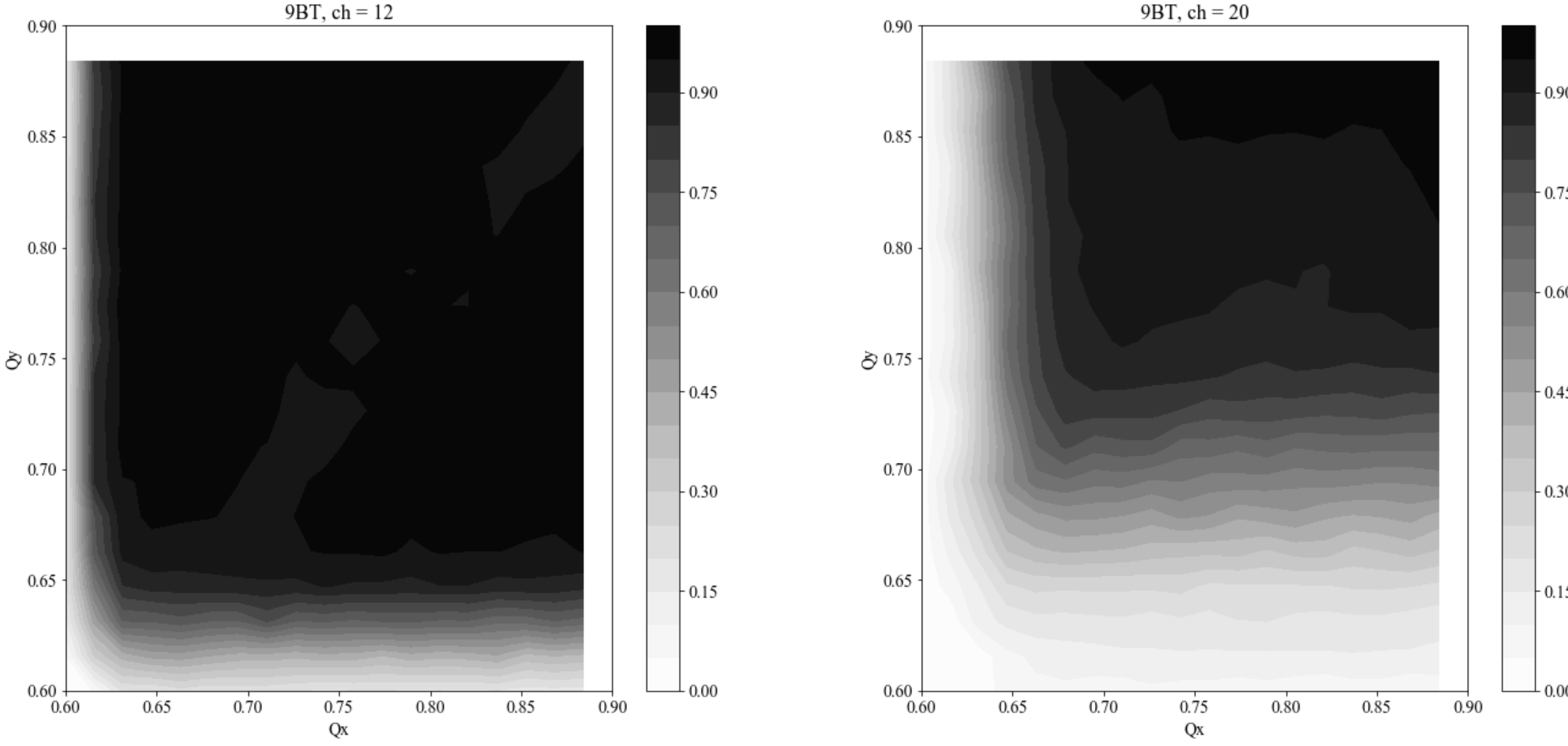


4BT

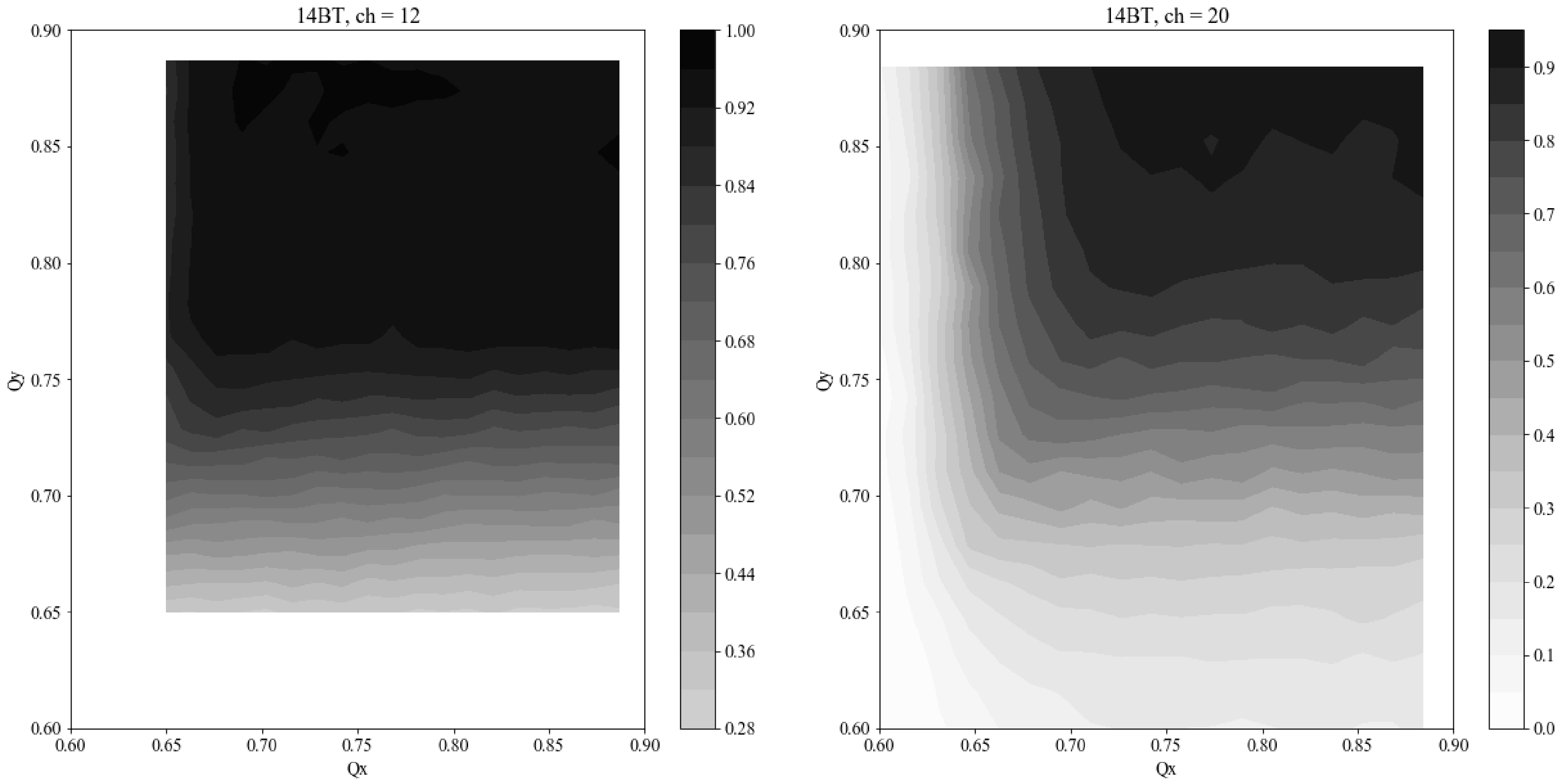


4BT, ch = 6
4BT, ch = 20
Qx
Qy
0.60
0.65
0.70
0.75
0.80
0.85
0.90
0.00
0.15
0.30
0.45
0.60
0.75
0.90

9BT

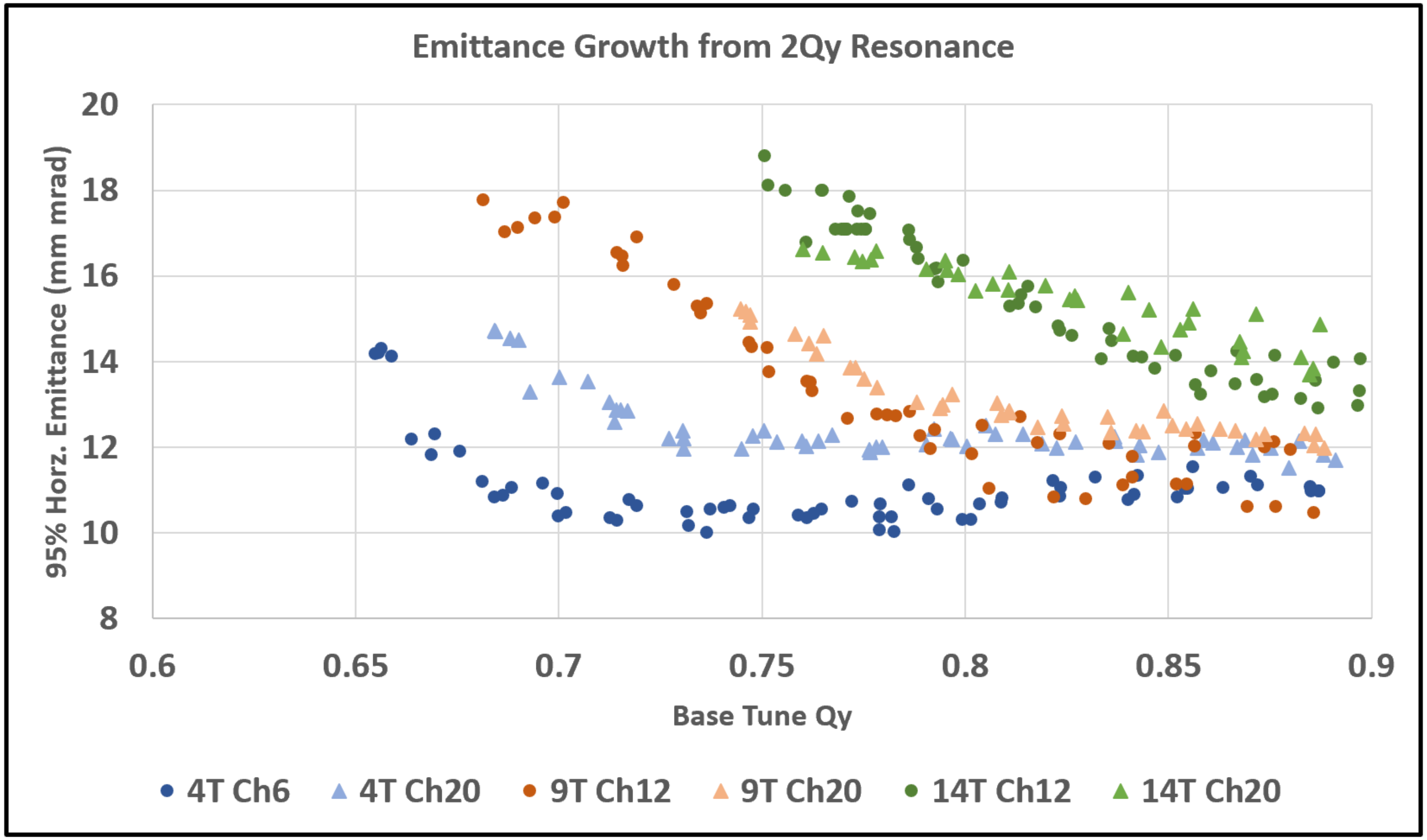

9BT, ch = 12
Qy
Qx
0.60
0.65
0.70
0.75
0.80
0.85
0.90
0.00
0.15
0.30
0.45
0.60
0.75
0.90
9BT, ch = 20
Qy
Qx

14BT


14BT, ch = 12
Qy
Qx
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.60
0.65
0.70
0.75
0.80
0.85
0.90
1.00
0.92
0.84
0.76
0.68
0.60
0.52
0.44
0.36
0.28
14BT, ch = 20
Qy
Qx
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0

Jeff Slides

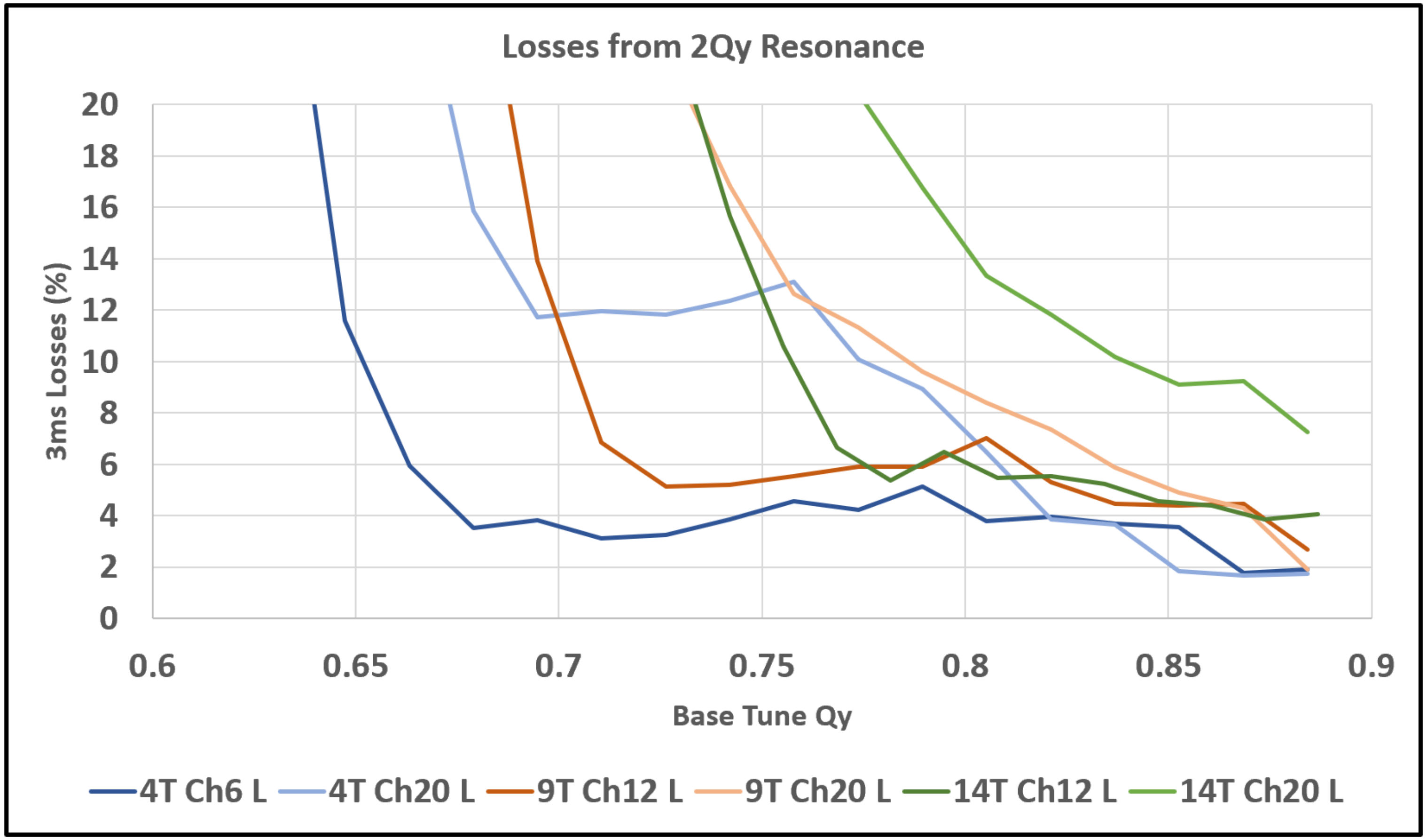
Emittance & Losses, Nominal Chromaticity



Emittance increases near half-integer, no tune-space is left.

At high-intensity, emittance growth not very sensitive to chromaticity.

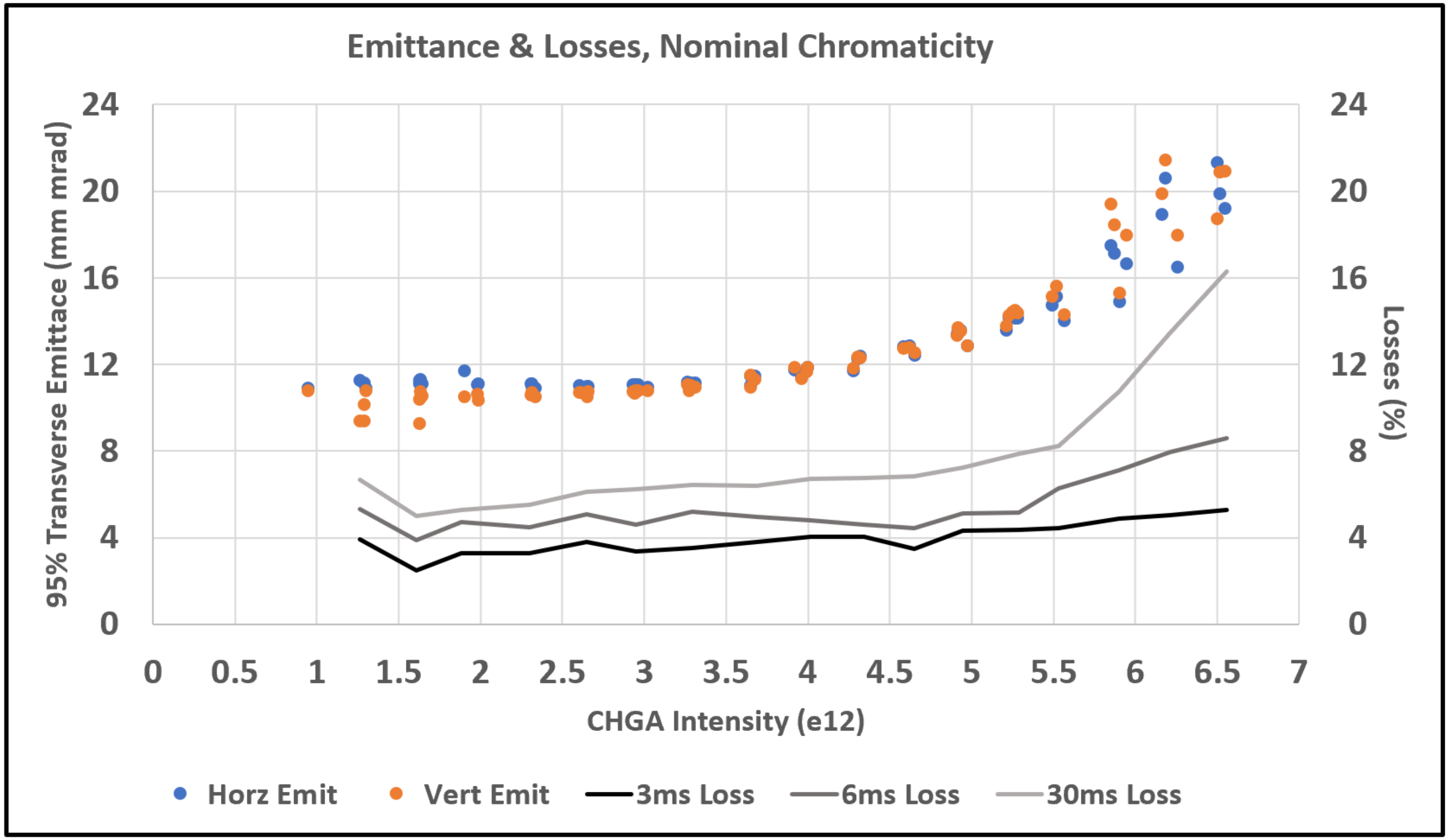
Emittance & Losses, Nominal Chromaticity



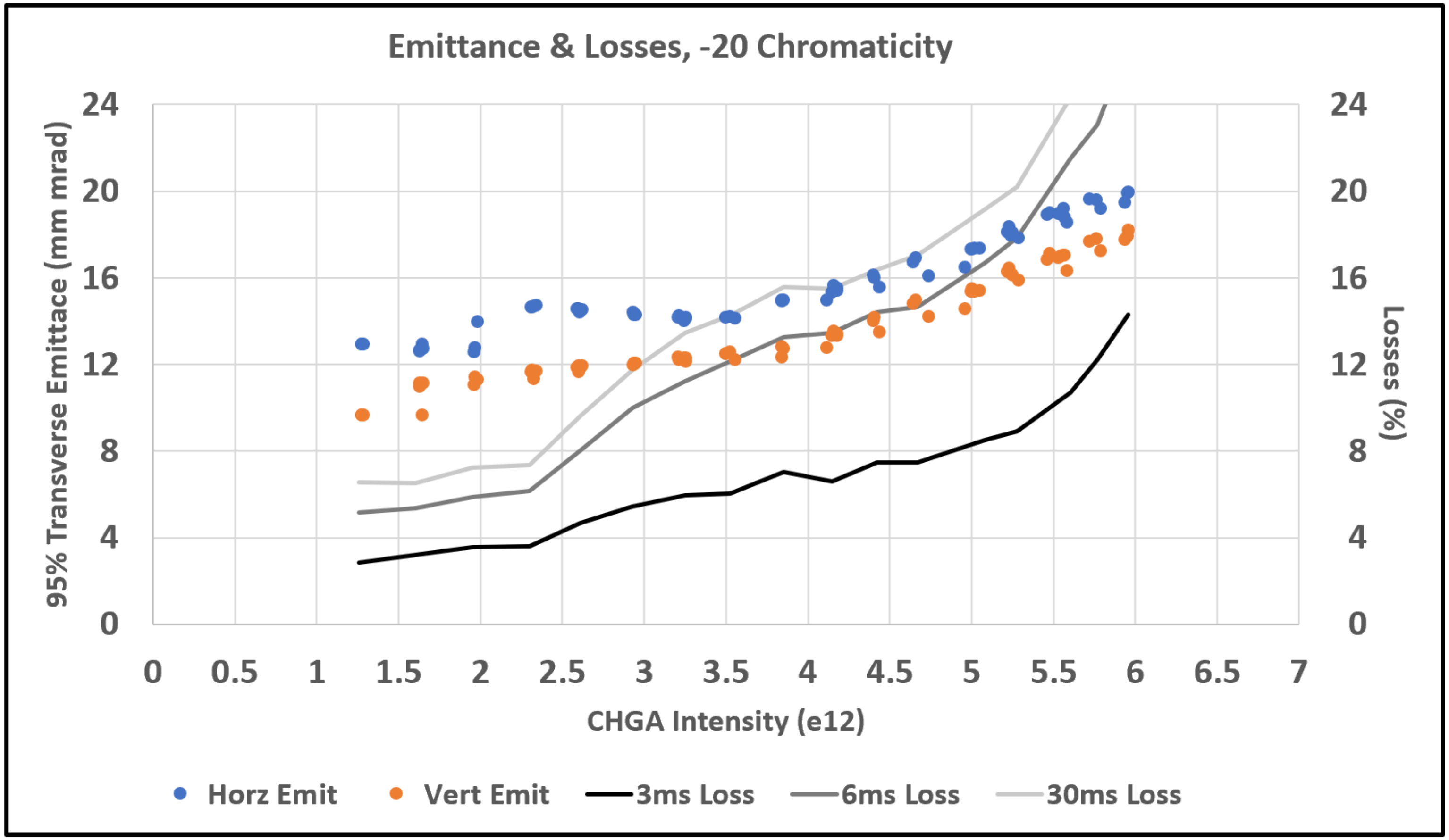
Practical loss limits are encountered immediately, dramatic losses follow.

Losses are much more sensitive to chromaticity.

Emittance & Losses, Nominal Chromaticity

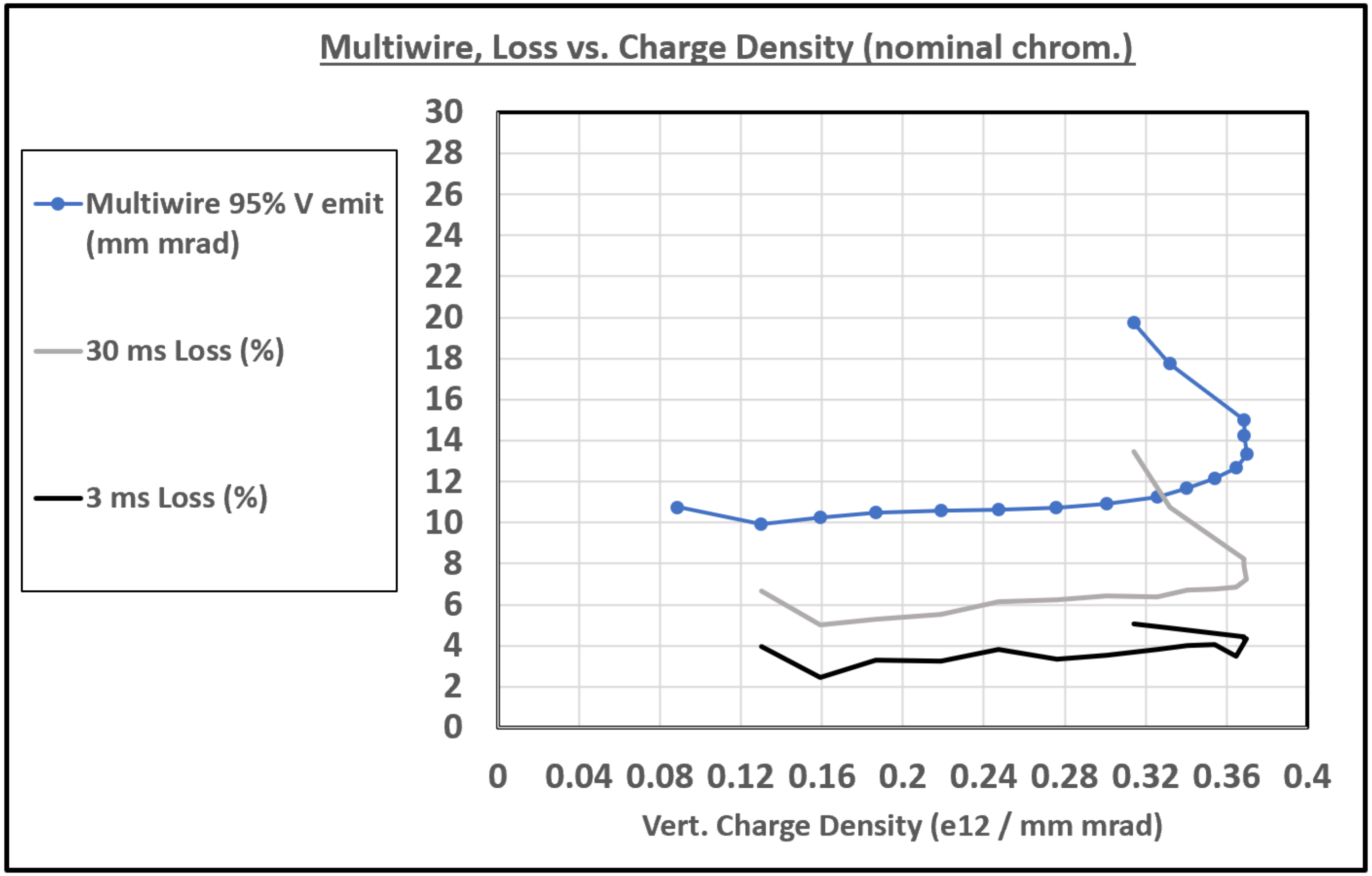


Emittance & Losses, -20 Chromaticity

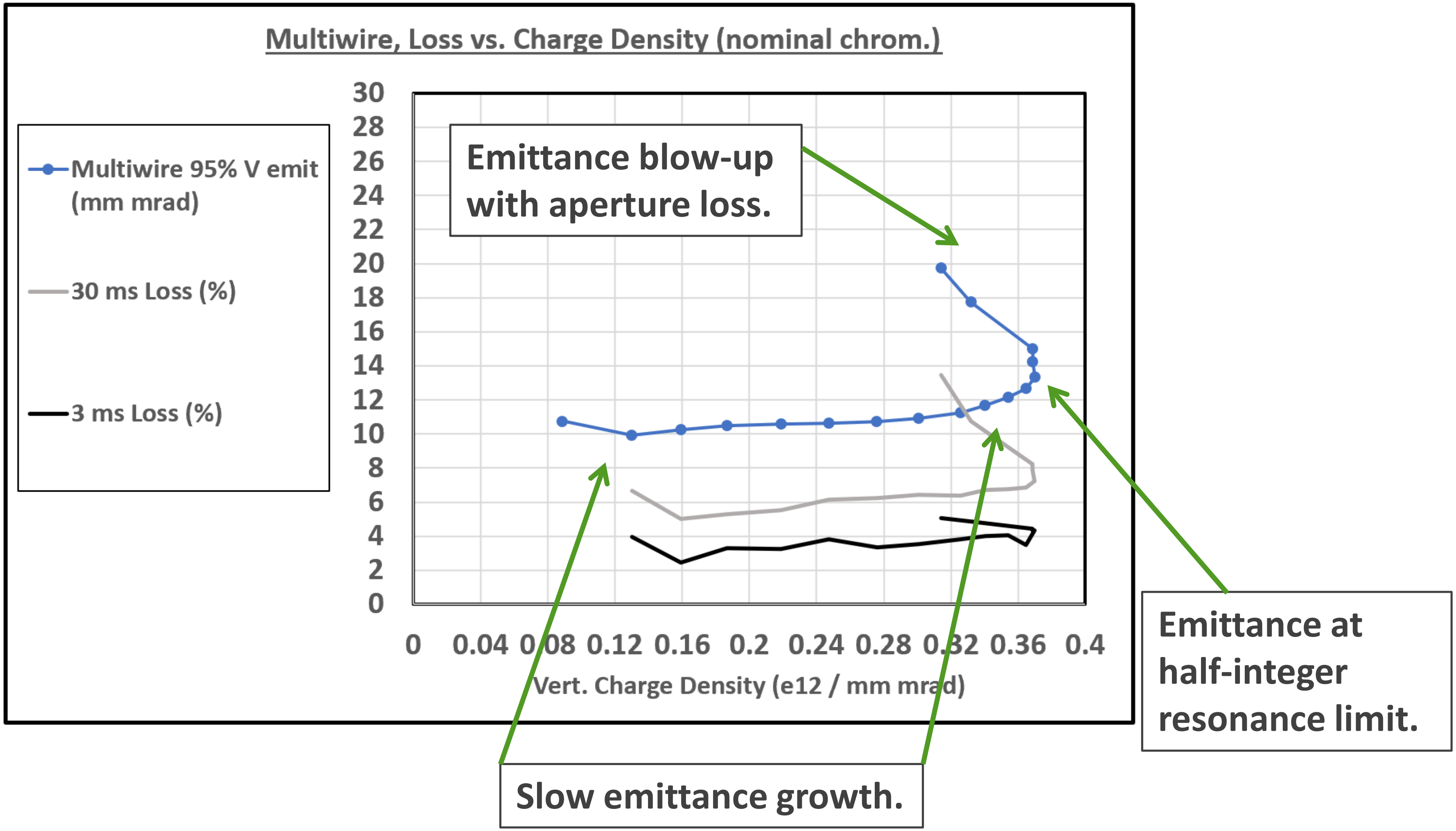


Fermilab

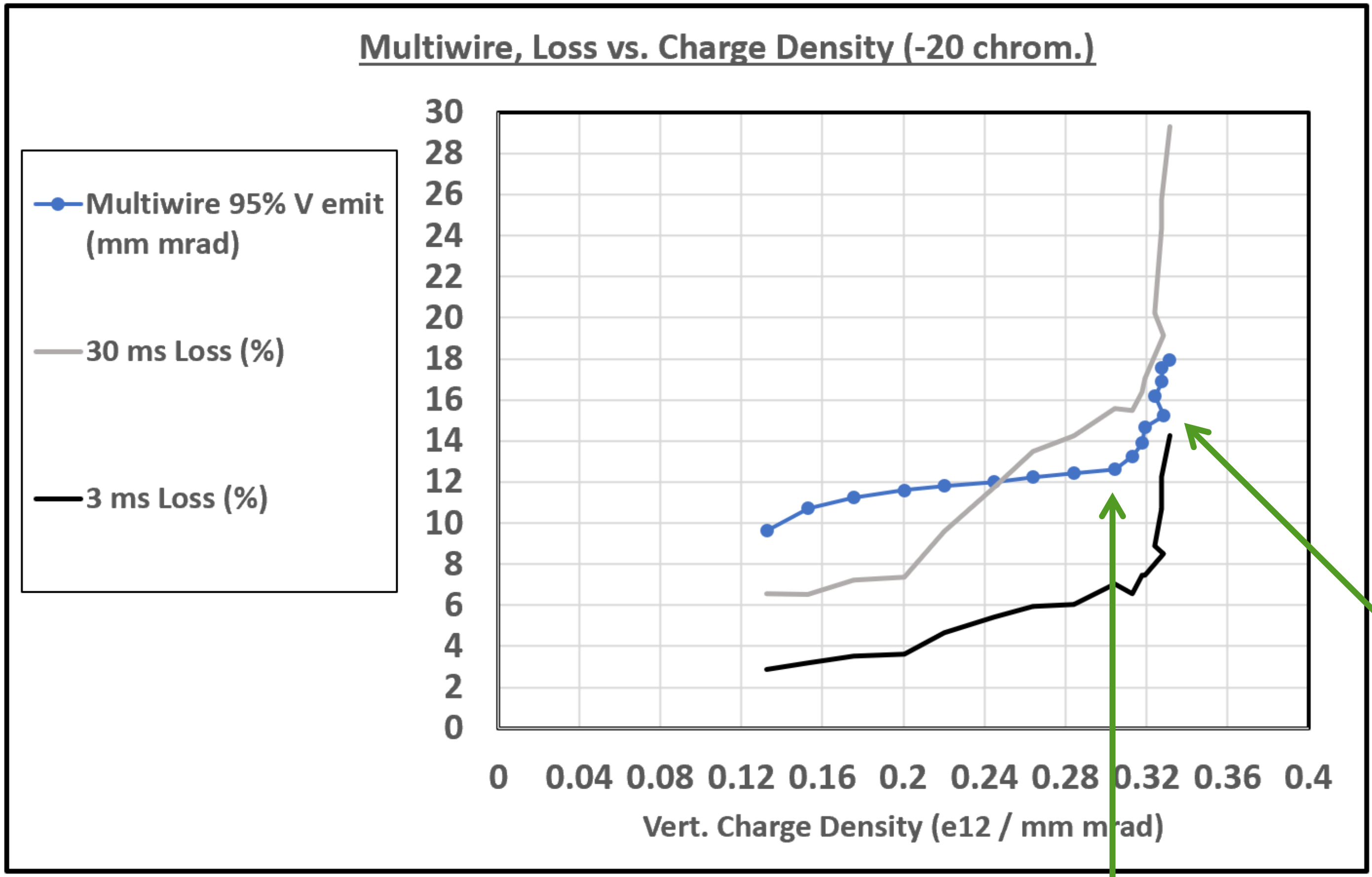
Nominal Chromaticity – Emit Loss vs Charge Density



Nominal Chromaticity – Emit Loss vs Charge Density



-20 Chromaticity – Emit Loss vs Charge Density

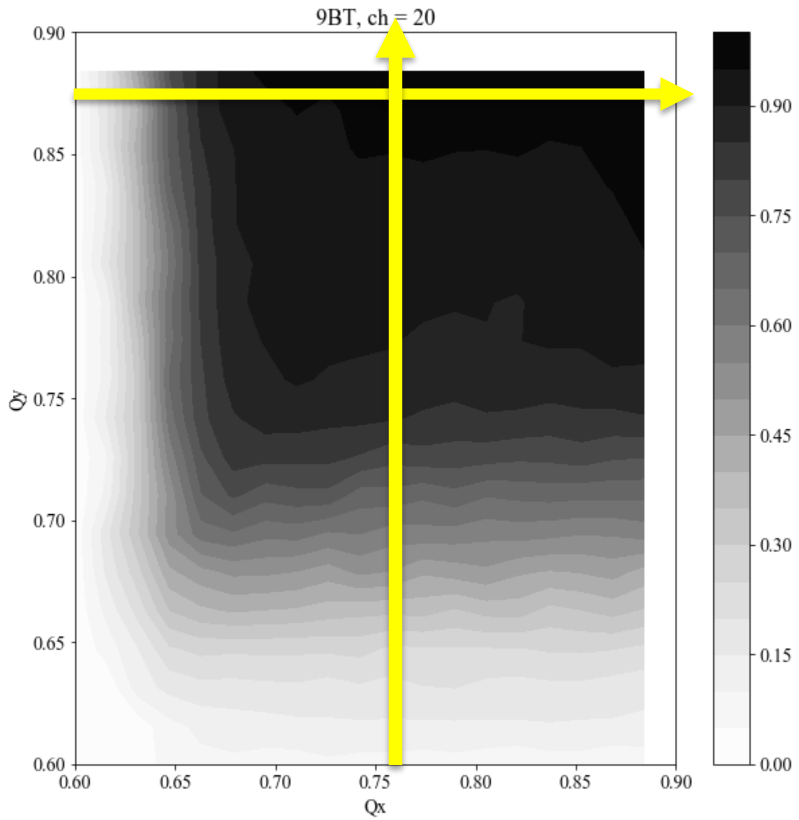


Half-integer resonance limit encounted earlier.

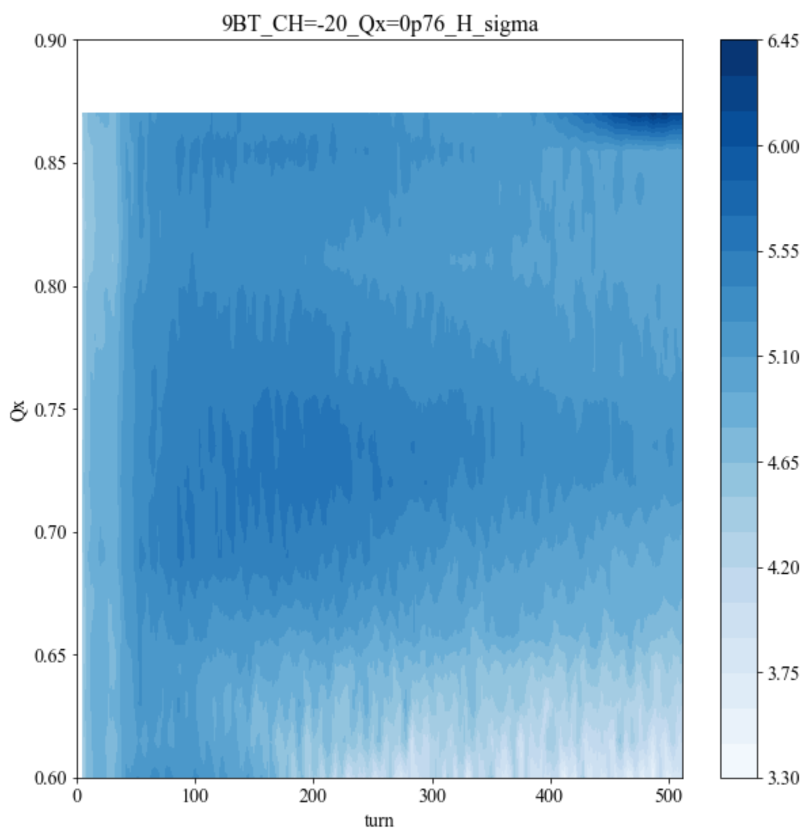
Faster emittance growth?

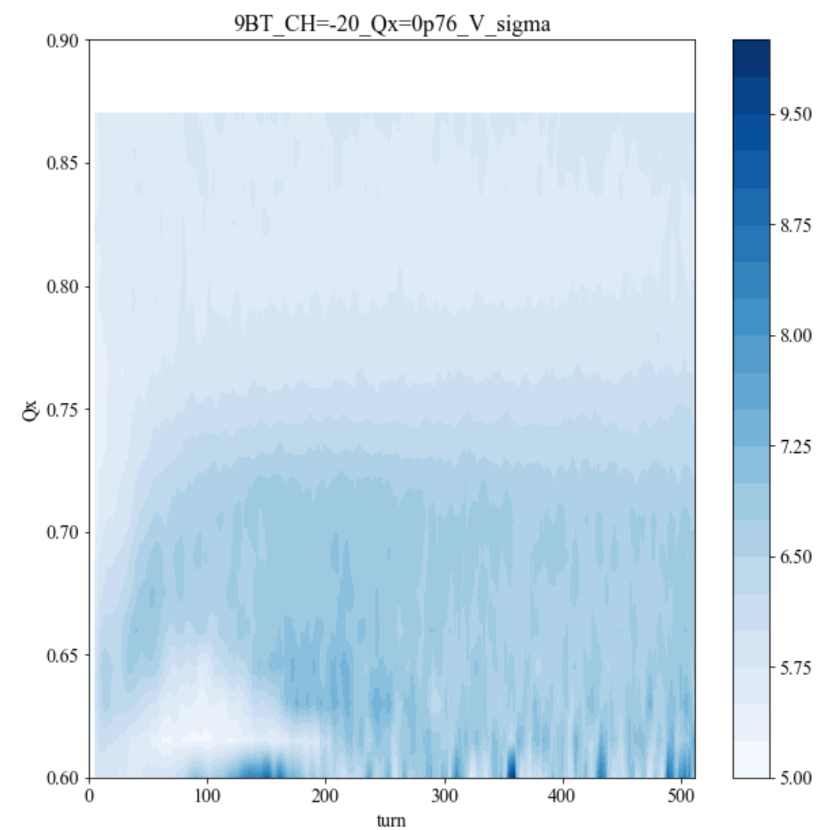
Kyiomi analysis #2

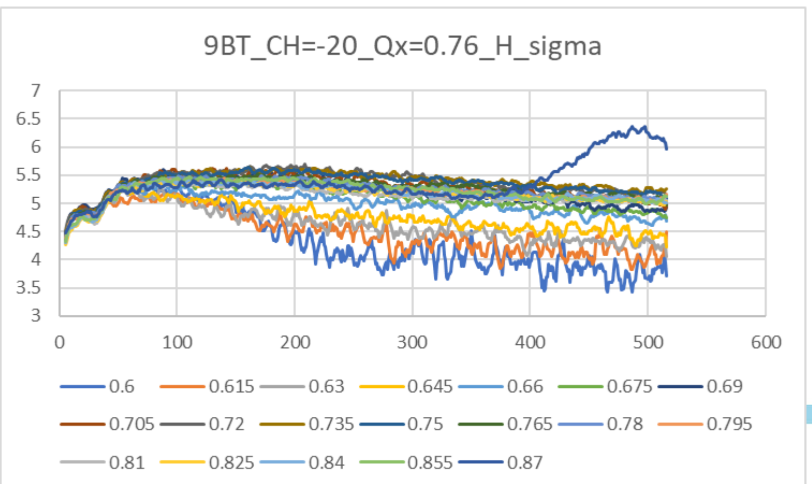
Looked at 9BT CH=-20, IPM data from 0 to 512 turns (first 1msec)

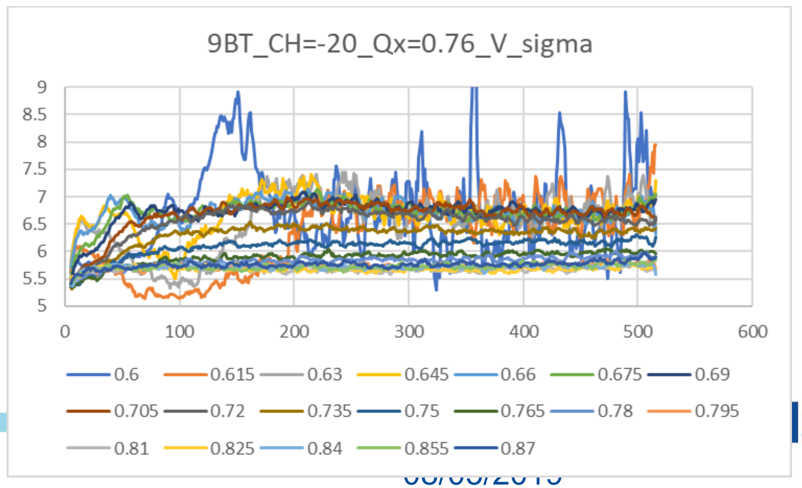


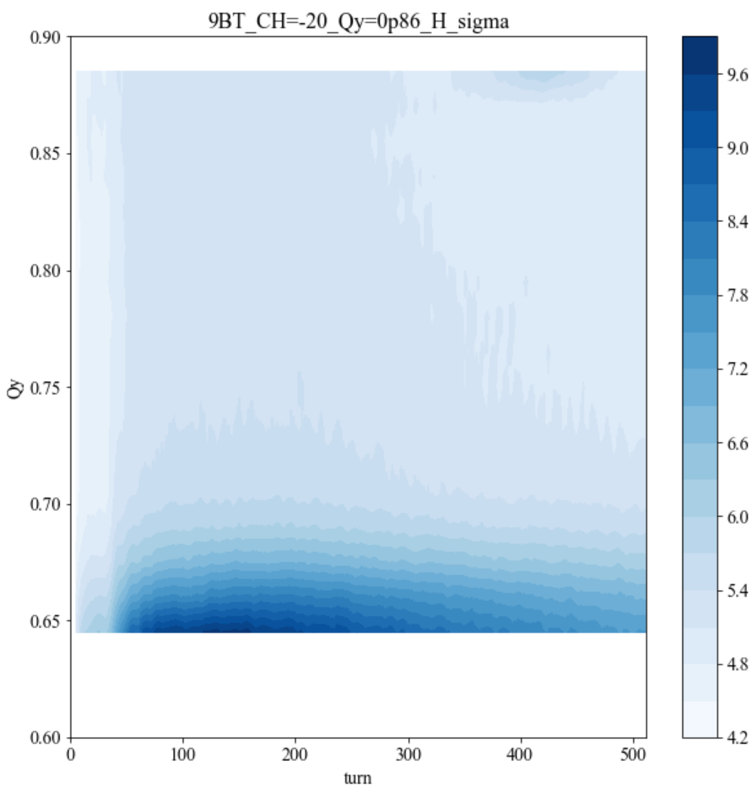
1: I looked at first 512 turn IPM data.
2: The data is the beam size (sigma) which is averaged over 6 turns.
3: I fixed Qx=0.76 and scanned vertical tune and plotted BPM data in horizontal and vertical in slide2.
4: I fixed Qy=0.86 and scanned horizontal tune and plotted BPM data in slide3
5: Beam size was increased first 200 turns in Horizontal and vertical probably due to multiturn injection and adiabatic capture.
6: Intensity kept decreasing from 0 turn to 512 turn.
*I have not made this plot, but slide 4 show an example.
7: The slide4 shows the horizontal position moved more than 5 mm in 512 turns
*I have not made this plot
8: * I have to do same analysis with different chromaticity.
Question
If beam size is not increasing, why are we loosing beam for 1 msec?
Why is the horizontal position moving?

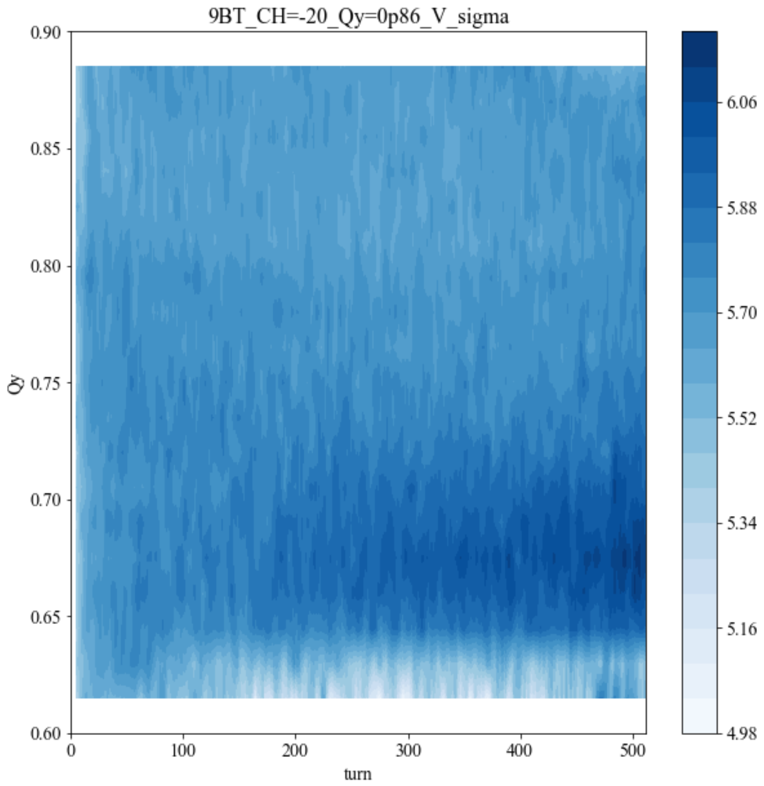

9BT_CH=-20_Qx=0p76_H_sigma
Qx
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0
100
200
300
400
500
turn
6.45
6.00
5.55
5.10
4.65
4.20
3.75
3.30

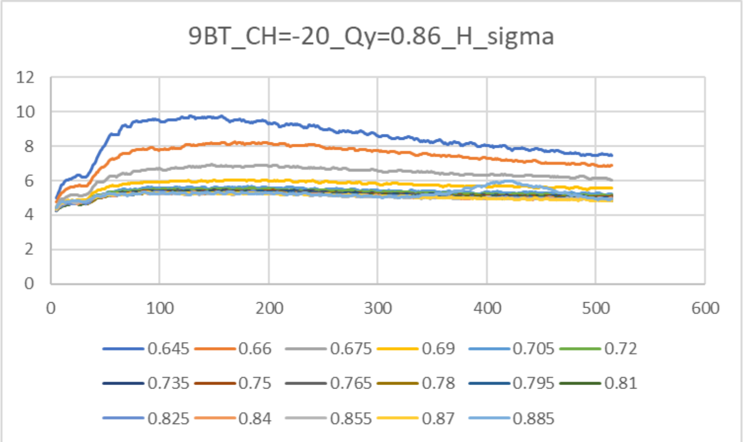

9BT_CH=-20_Qx=0p76_V_sigma
Qx
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0
100
200
300
400
500
turn
9.50
8.75
8.00
7.25
6.50
5.75
5.00

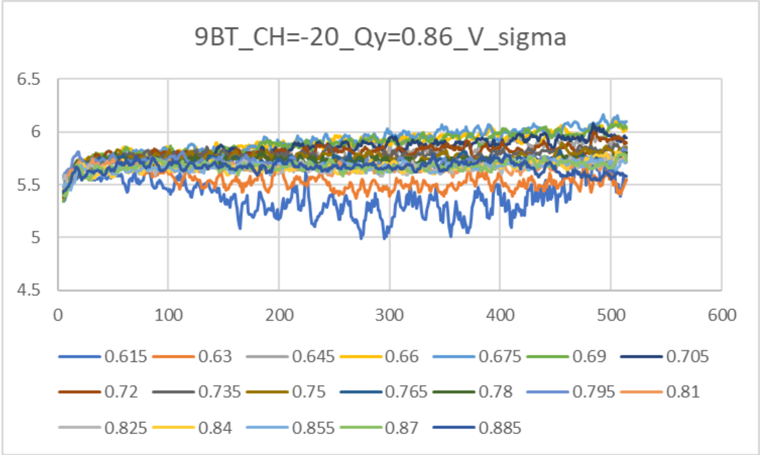

9BT_CH=-20_Qx=0.76_H_sigma
7
6.5
6
5.5
5
4.5
4
3.5
3
0
100
200
300
400
500
600
0.6
0.615
0.63
0.645
0.66
0.675
0.69
0.705
0.72
0.735
0.75
0.765
0.78
0.795
0.81
0.825
0.84
0.855
0.87


9BT_CH=-20_Qx=0.76_V_sigma
9
8.5
8
7.5
7
6.5
6
5.5
5
0
100
200
300
400
500
600
0.6
0.615
0.63
0.645
0.66
0.675
0.69
0.705
0.72
0.735
0.75
0.765
0.78
0.795
0.81
0.825
0.84
0.855
0.87


9BT_CH=-20_Qy=0p86_H_sigma
Qy
turn


9BT_CH=-20_Qy=0p86_V_sigma
Qy
turn


9BT_CH=-20_Qy=0.86_H_sigma
0.645 0.66 0.675 0.69 0.705 0.72
0.735 0.75 0.765 0.78 0.795 0.81
0.825 0.84 0.855 0.87 0.885


9BT_CH=-20_Qy=0.86_V_sigma
0.615 0.63 0.645 0.66 0.675 0.69 0.705
0.72 0.735 0.75 0.765 0.78 0.795 0.81
0.825 0.84 0.855 0.87 0.885

Example of IPM signals