LHC Injectors Upgrade

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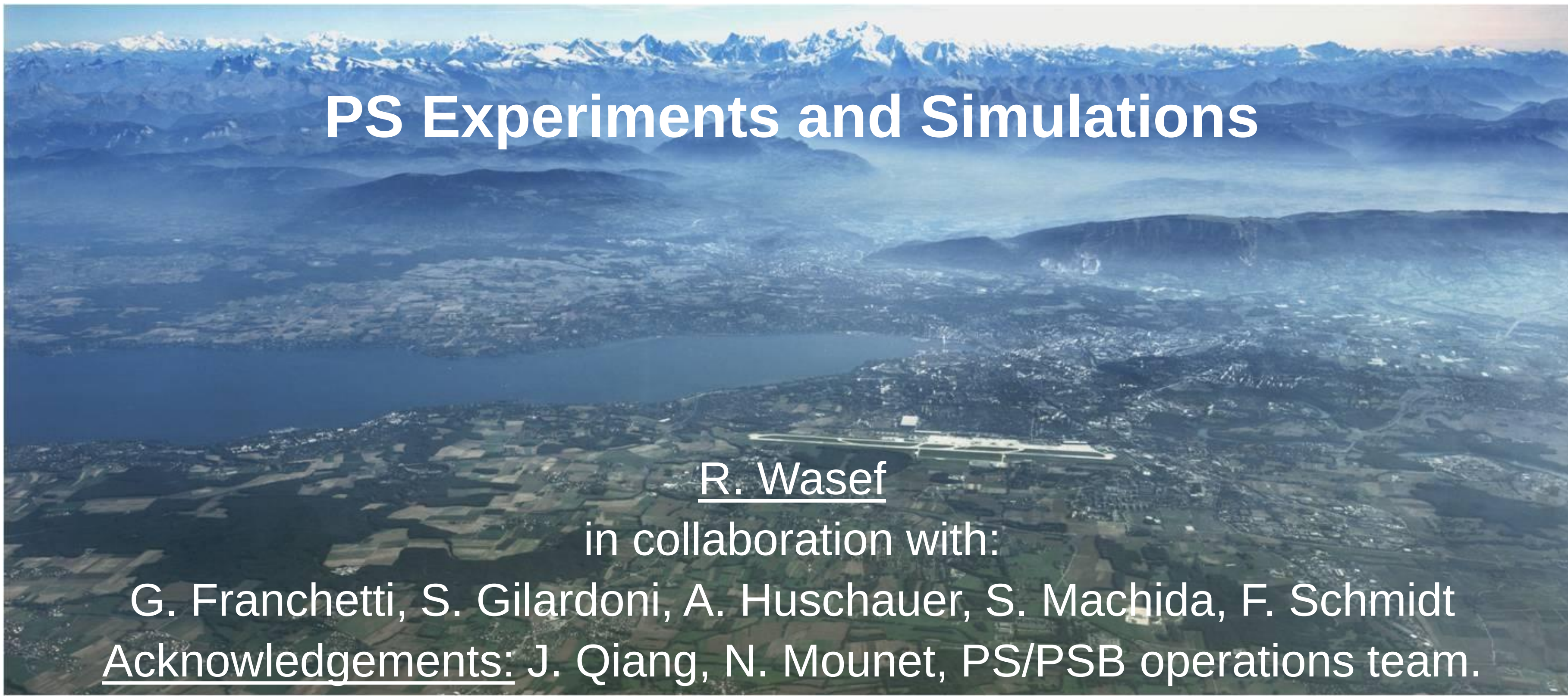

PS Experiments and Simulations

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in collaboration with:

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Acknowledgements: J. Qiang, N. Mounet, PS/PSB operations team.

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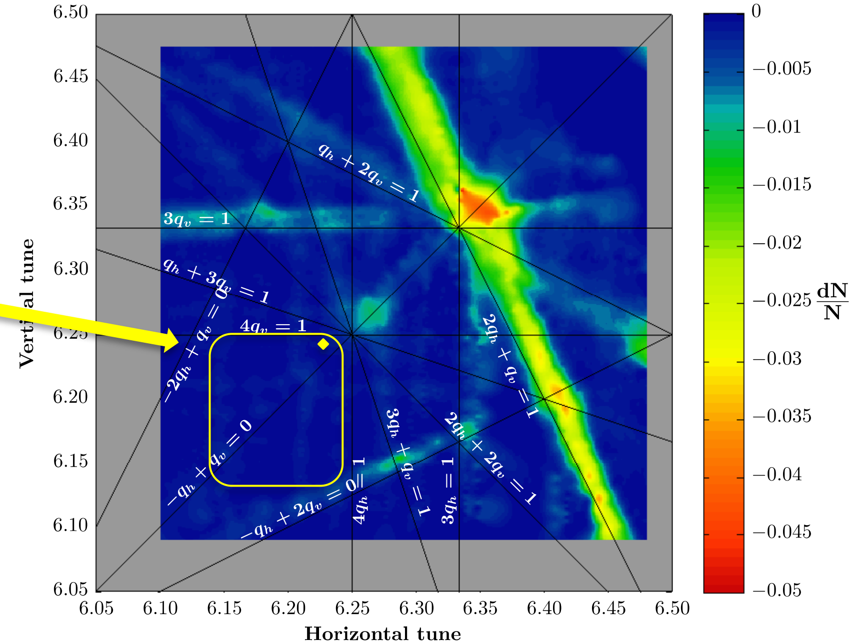
Outline

I. Space Charge at injection
II. Experimental studies of 2012/2013
III. Available simulation codes
IV. Simulations of the Qx+2Qy resonance
V. Simulations of the 4th order resonance
VI. Summary and Outlook

Space Charge at injection (1.4 GeV)

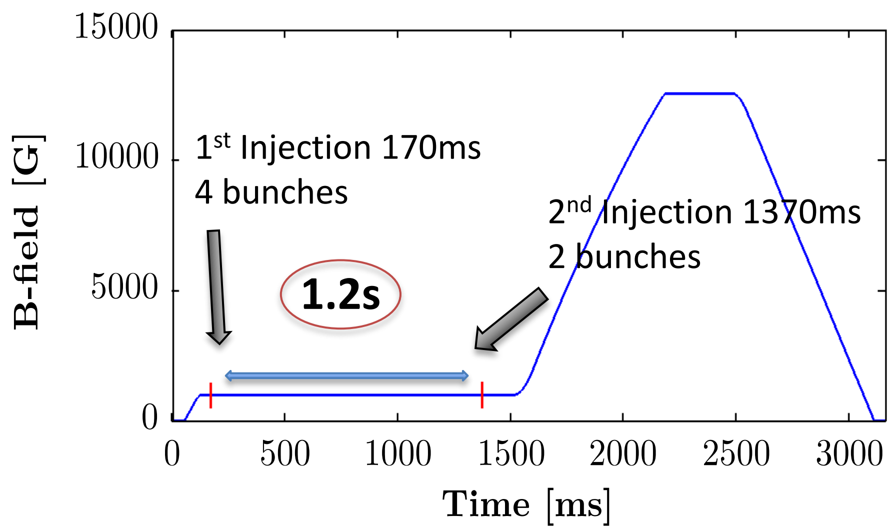
- Current injection **energy**: **1.4 GeV**
  ➔upgrad to 2GeV

Current operation area



- **Typical tune-spread** of current operational beam~**(0.2 ; 0.28)**

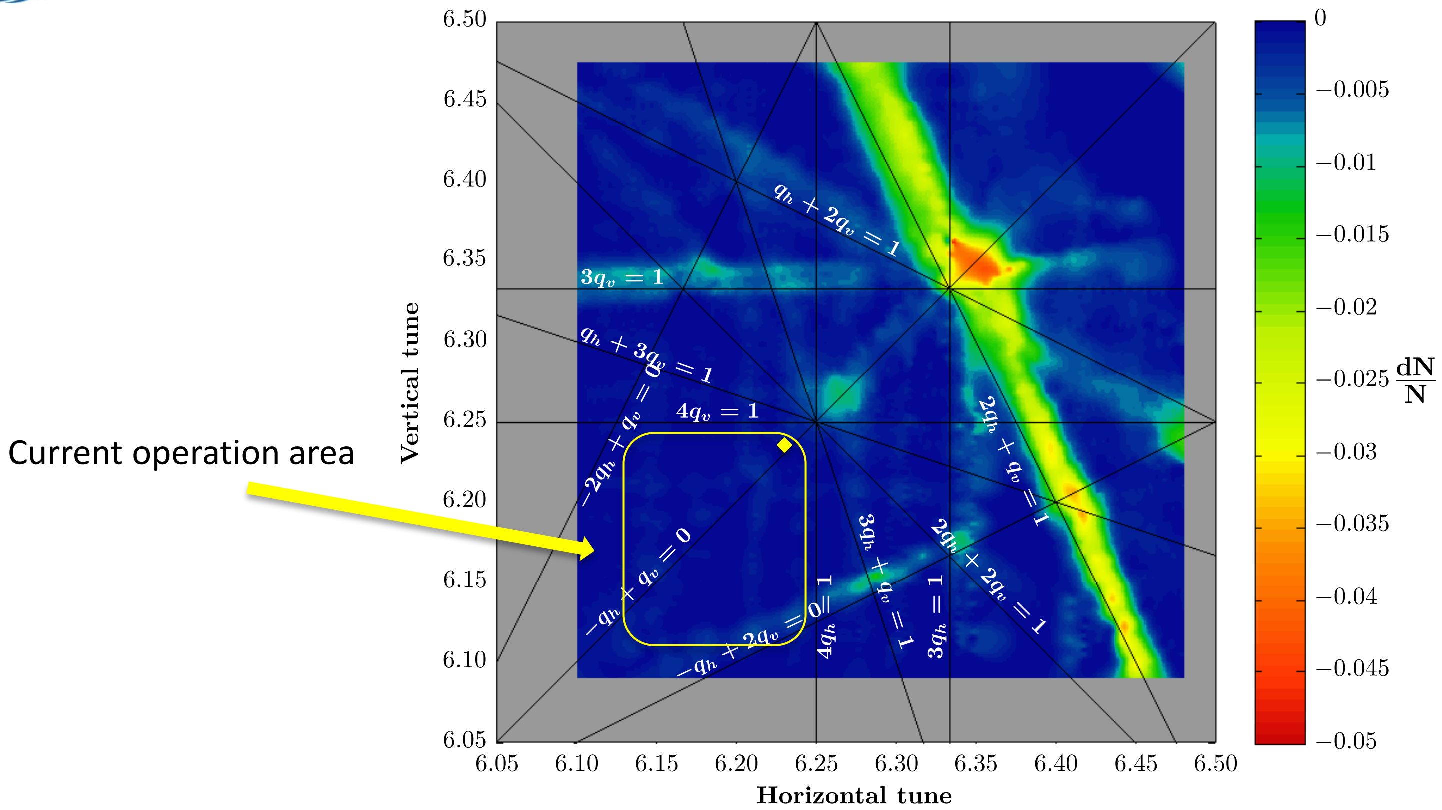
- LHC double batch injection: Long **flat bottom: 1.2s**



- HL-LHC beams requirement: **tune-spread > .3 (at 2GeV)**
- LIU Budgets: **5% losses,**
  5% emittance growth

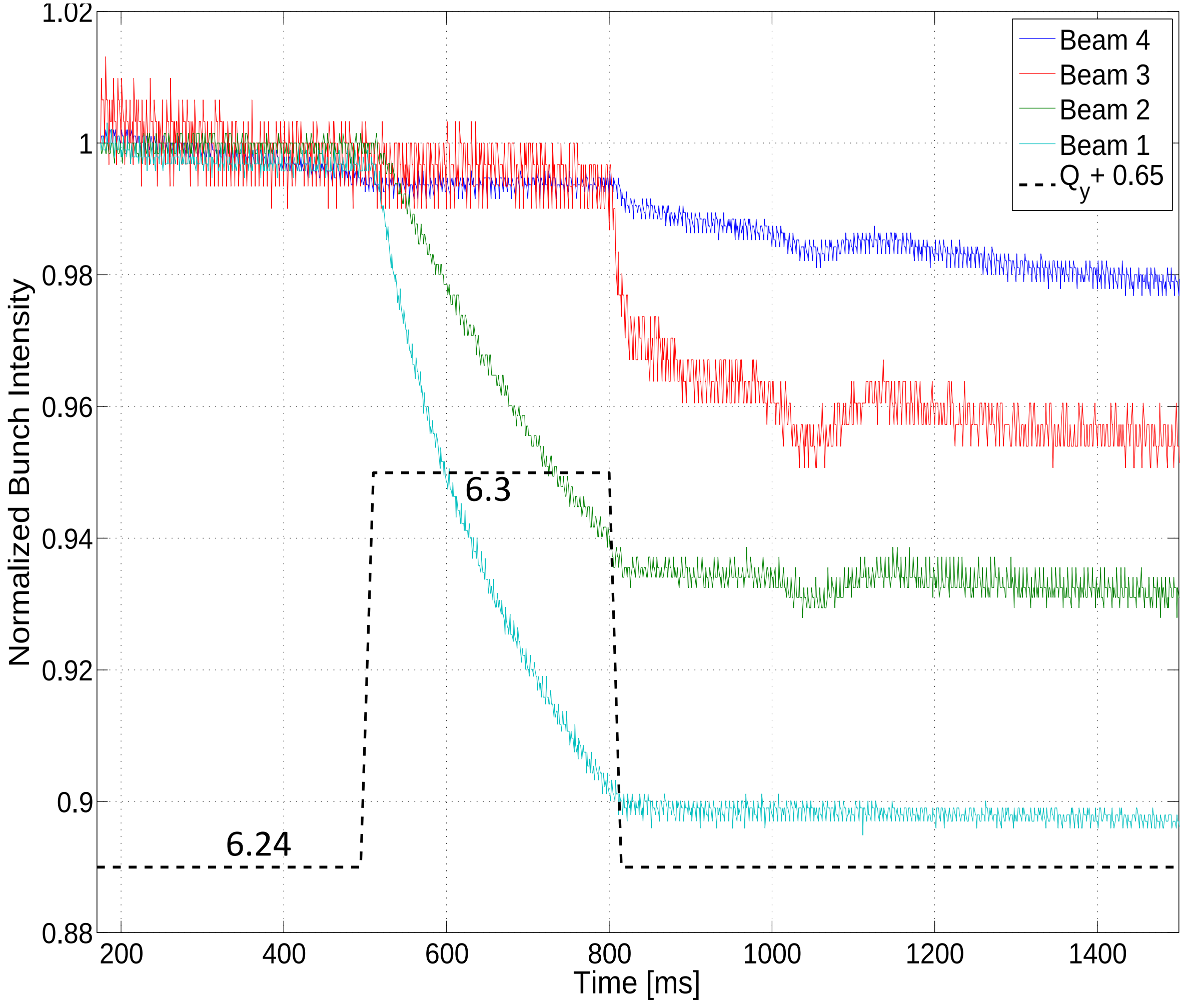
➔ Importance of the study of excited resonances and their influence on the beam.

Tune scans



- Excited resonances: 3Qy=19 and 2Qx+Qy=19 (skew sextupolar)
- Operation area very close to the integer resonances ➔ Study the effect of this resonance
- During a measurement campaign I noticed the excitation of the 4Qy=25.

4^{th} order Resonance



Horizontal tune fixed at 6.23

Vertical tune: 6.24->6.3->6.24

Maximum detuning due to space charge:

Beam 1 : (-.22 ; -.4)

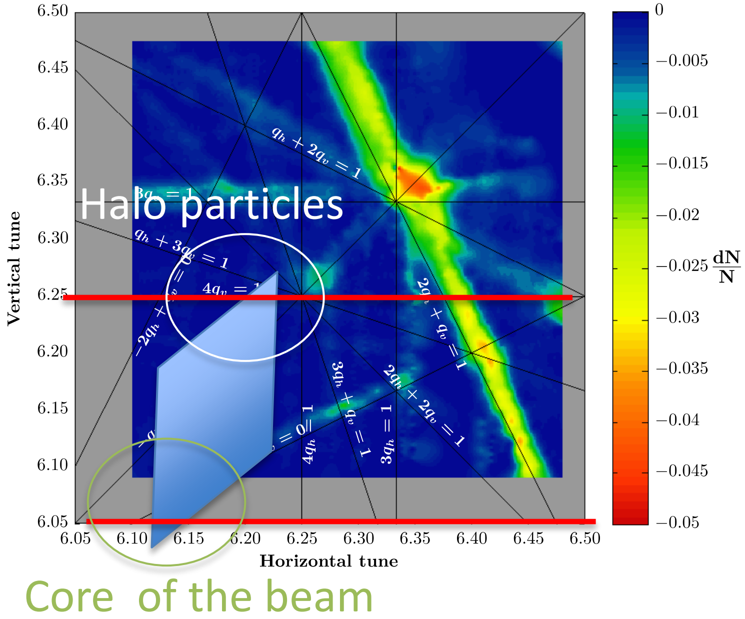
Beam 2 : (-.18 ; -.37)

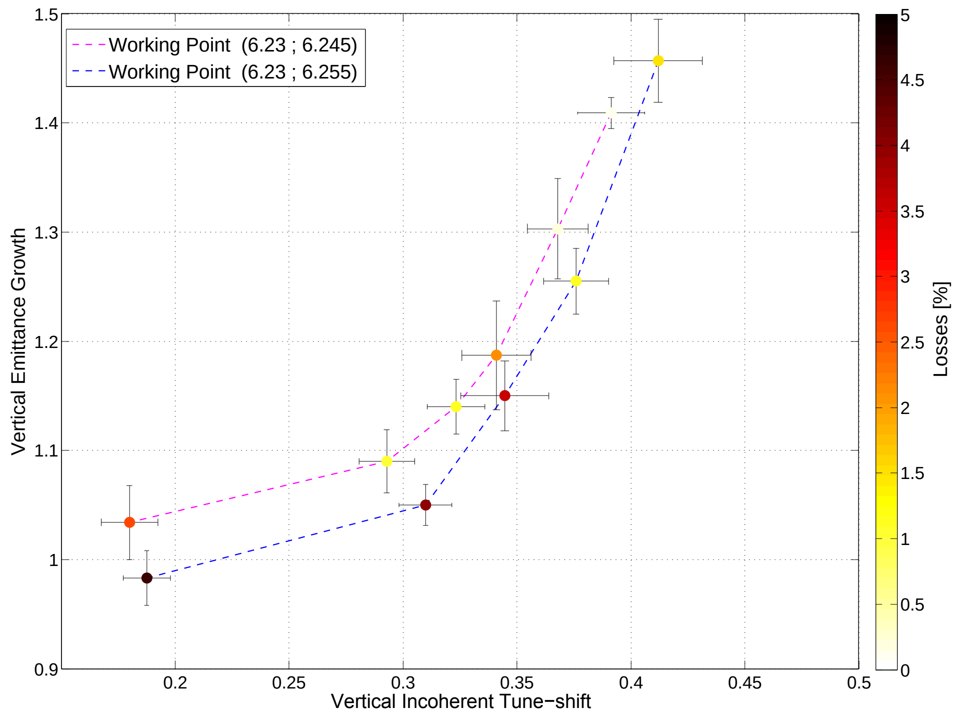
Beam 3 : (-.08 ; -.07)

Beam 4 : (-.01 ; -.01)

➔ The 4^{th} order resonance seems to be excited by space charge

Vertical growth vs. Tune-spread vs. Losses





The beam tune-spread is trapped between the 4Qy=25 and the integer.

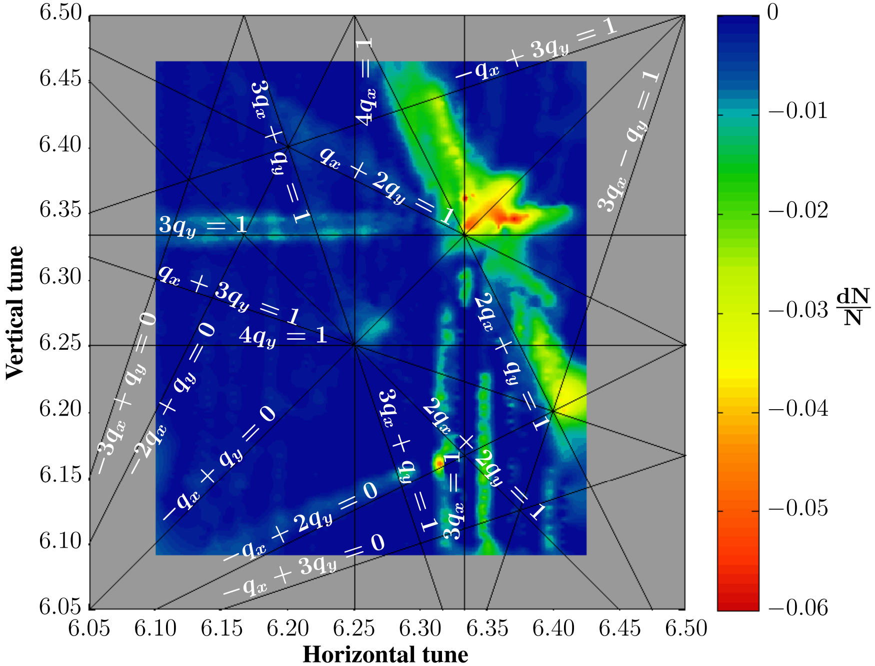
➔ If one increases the vertical tune to avoid growth due to the integer, the losses increase because of the 4th order resonance

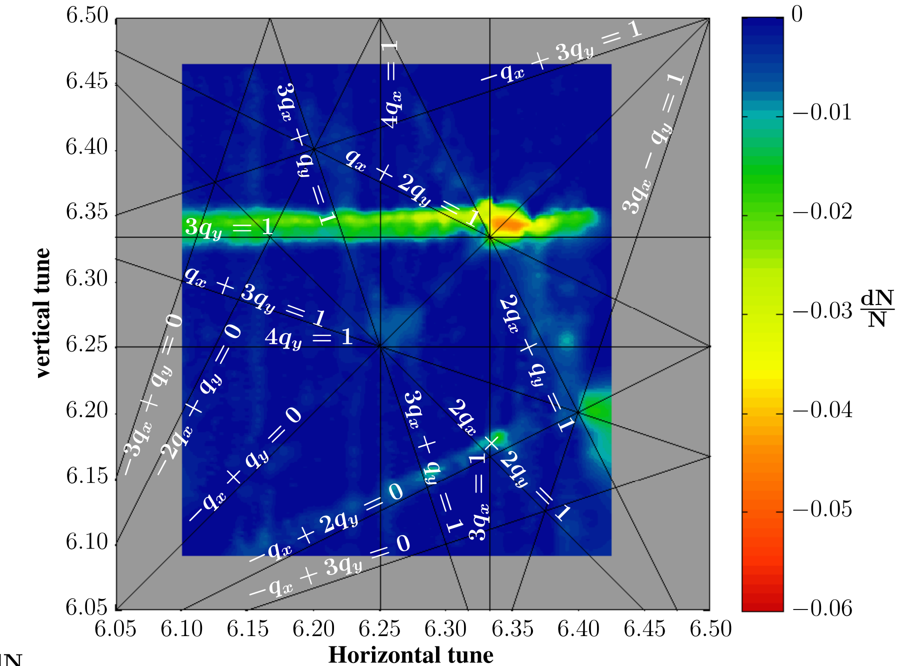
➔ There are less losses with higher tune-spread because the proton population becomes smaller on the 4Qy=25 after compression.

➔ The choice of the working point is a compromise between losses and emittance blow-up

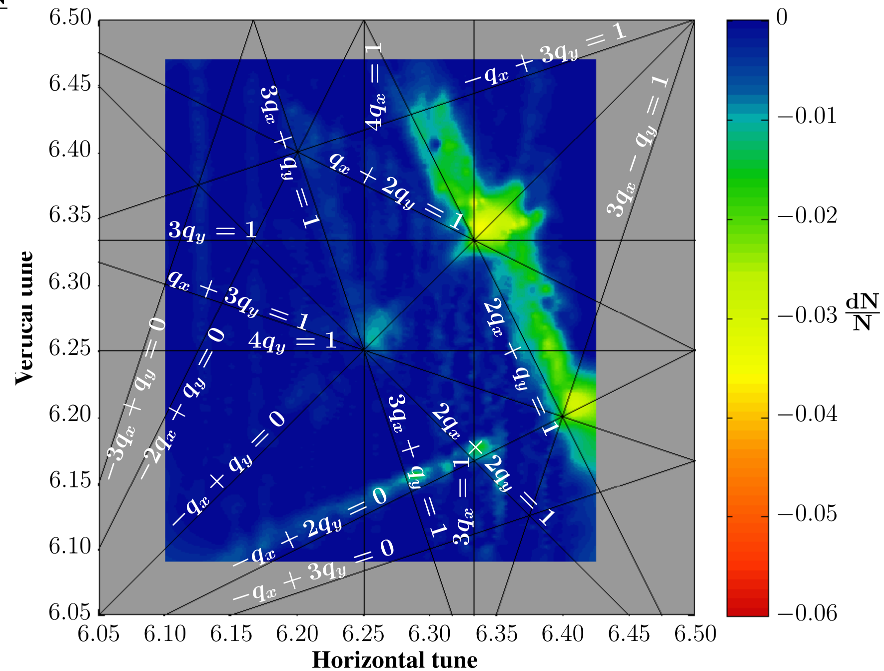
Resonance compensation

Vertical tune scan





2Qx+Qy compensation

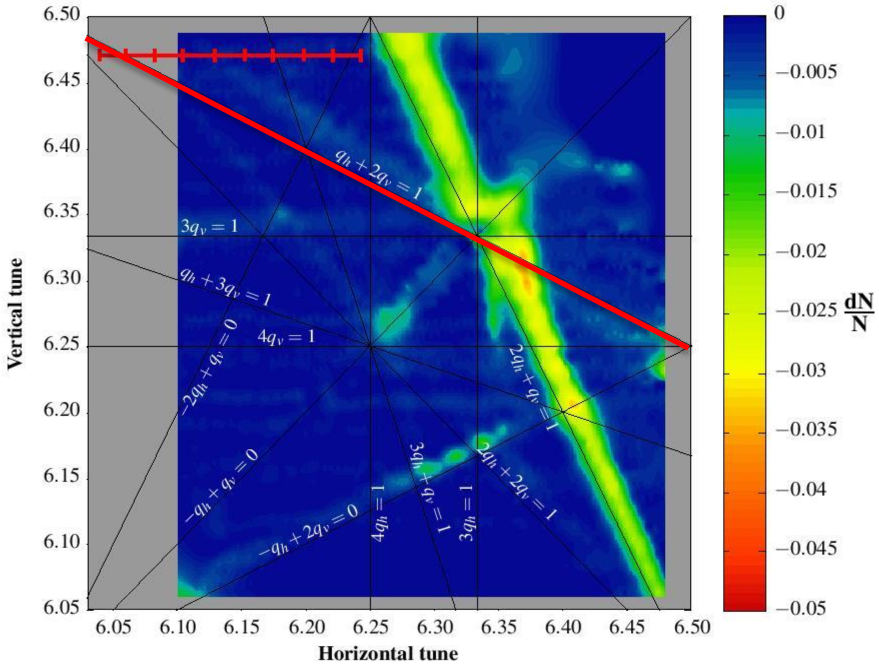


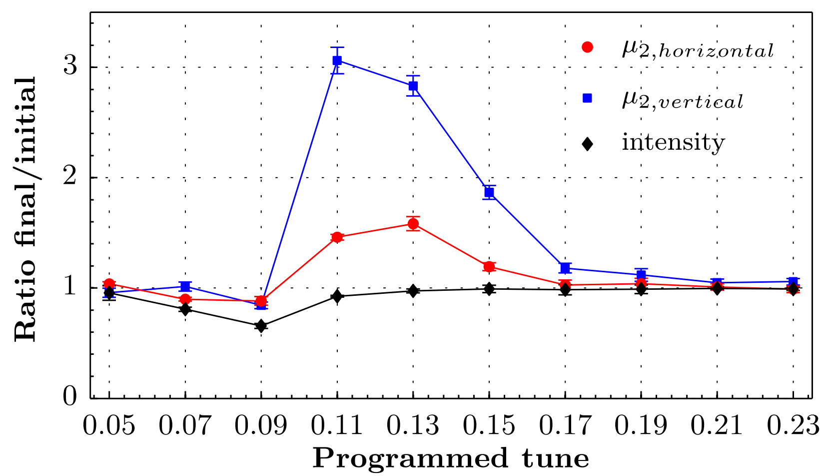
3Qy compensation

➔ Successful implementation of a resonance compensation scheme

Measurements of the Qx+2Qy resonance

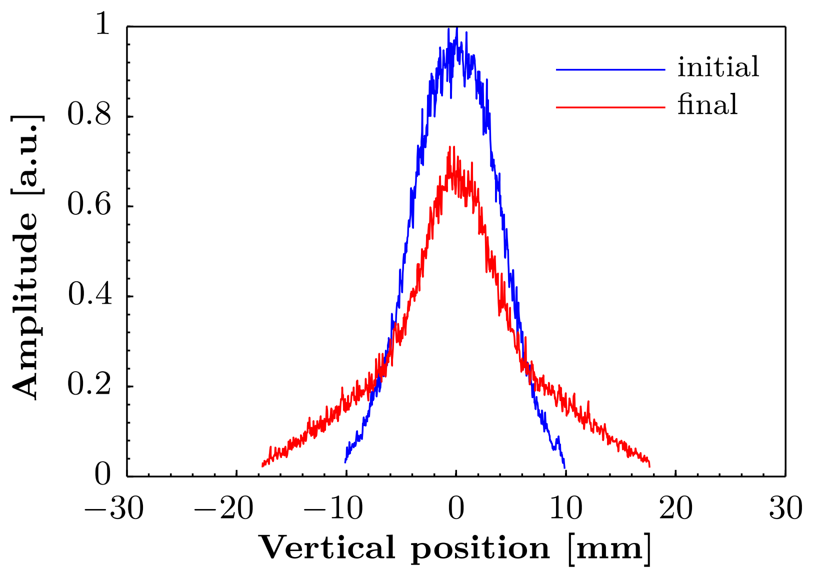
- Controlled excitation of the resonance: normal sextupole powered (2A)
- 10 static measurements of the resonance: for each measurement, Qy fixed at 6.47 and Qx fixed at a value between 6.04 and 6.24.
- Observables over 1.1s: beam loss, transverse and longitudinal profiles.
- Useful for SIS100 design



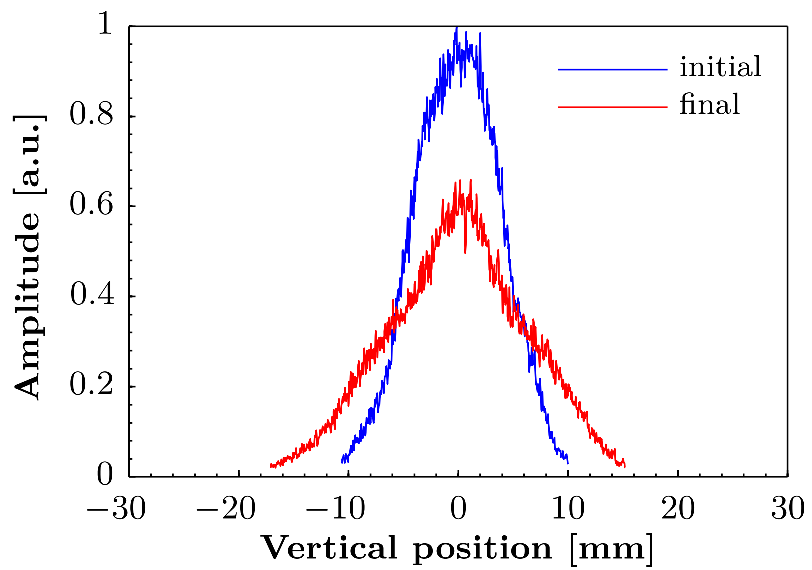


Measurements of the Qx+2Qy resonance

Tunes (6.11, 6.47)



Tunes (6.13, 6.47)



The most interesting behaviors were observed for Qx=6.11 and Qx=6.13 (programmed tune). ➔ A simulation campaign was launched, especially to see if we can reproduce such a profile deformation

Available Simulation Codes

- PTC-ORBIT
  - Advantage: benchmarked, self-consistent.
  - Limitations: slow (~1000 turns/day on "spacecharge" cluster at CERN)

  ➔ Short simulations (few 1000 turns)

- MADX-Frozen-model
  - Advantage: MADX developed and maintained at CERN, fast with ***modest cluster*** (~50k turns/day on 4 proc.).
  - Limitations: very small number of macro-particles for a convenient speed

  ➔Long-term simulations with Gaussian beams

- IMPACT
  - Advantage: fast (~ 90k turns/day, ***on NERSC cluster***), self-consistent.
  - Limitations: user interface sophisticated, runs on NERSC for ideal speed.

  ➔Long-term which needs a self-consistent code

Note: All figures are given for the PS case and the same lattice.

Simulation of Qx+2Qy resonance

- Simulations are on-going with MADX-Frozen-model.
- Preliminary results are very promising.

__Limitation and hypothesis:__

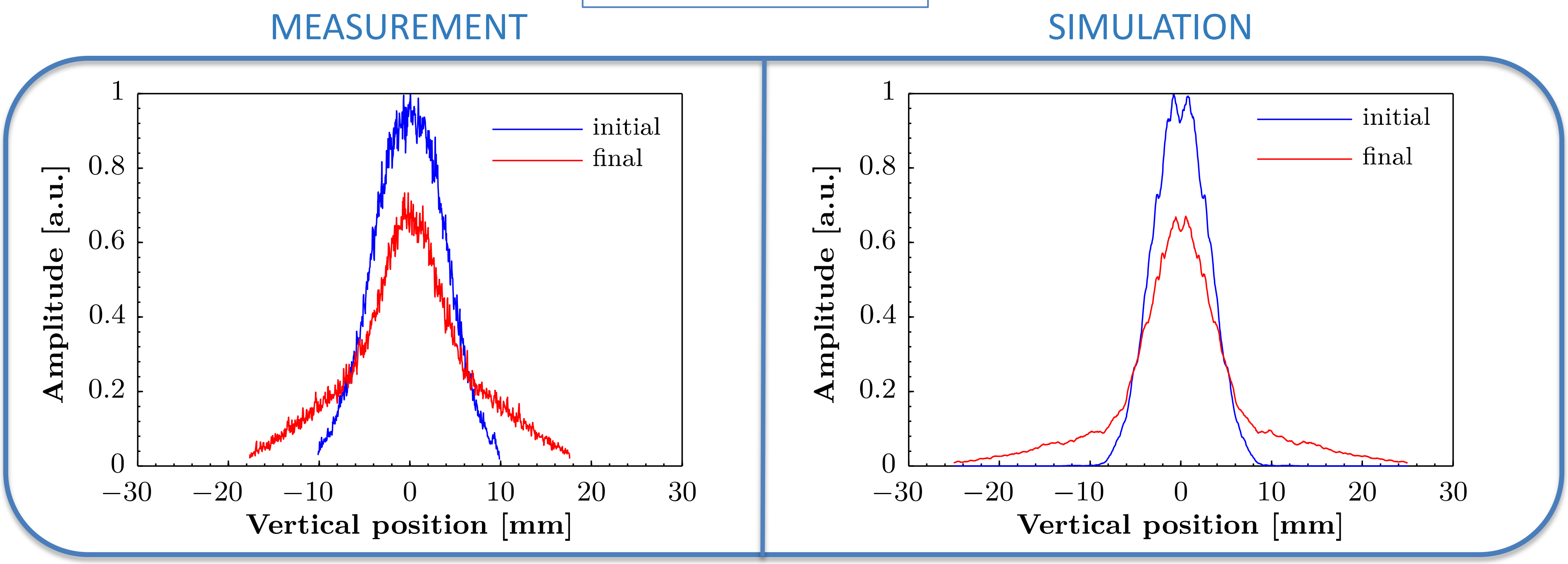
- For the frozen model introduced in MADX, the number of M.P. is limited due to simulation time issues.

- To be able to compare profiles, and specially tails, it is very difficult to use only 1000 M.P.
  ➔ It is ***supposed*** that the evolution of the profiles are negligible over 1000 turns.
  ➔ 1000 successive turns are averaged to generate the profile at a given turn.
  ➔ which induces high correlation in the distribution since it's the profile of 1000 M.P. over 1000 turns and not 1M M.P. at the given turn.

- **This assumption is also comparable to the measurement technique (wire-scanner averaging over 2ms~1000turns).**

Experiment & Simulation of Qx+2Qy resonance

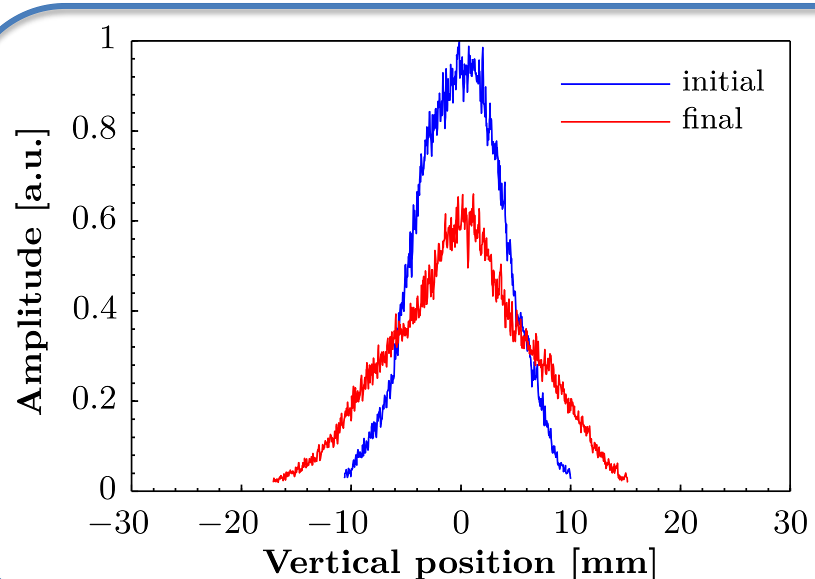
TUNES (6.11 ; 6.47)

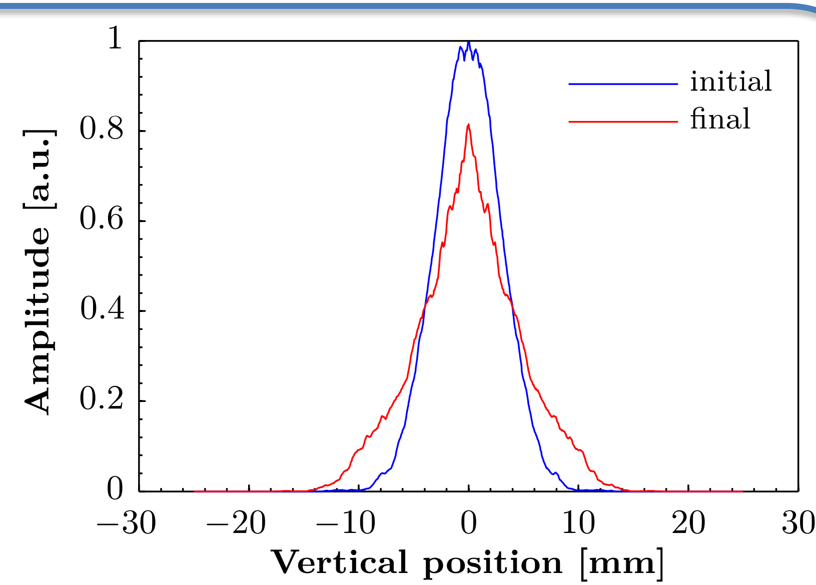


- ➔ Good agreement between measurement and simulation (same binning).
- The simulated distribution is going to be regenerated, because of a depopulation issue in the center.
- The extent of the tails is not the same between simulation and measurement, but it could be due to the "natural" excitation of the resonance, or an error on the assumed tune.

Experiment & Simulation of Qx+2Qy resonance

TUNES (6.13 ; 6.47)





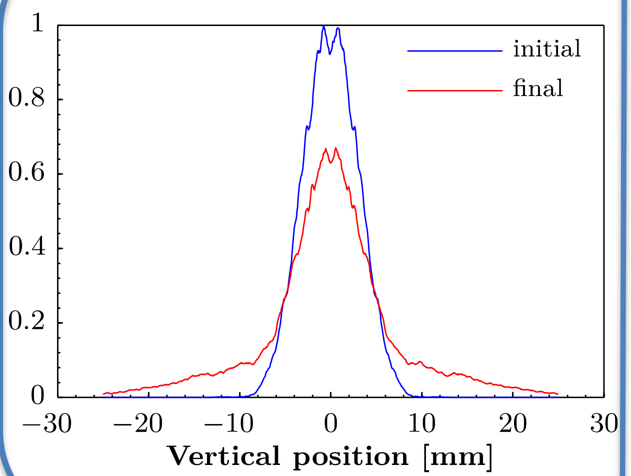
- ➔ Good agreement between measurement and simulation
- The difference between the final profiles could come from the "natural" excitation of the resonance, or an orbit oscillation/wire-scanner oscillation and/or an error of the tune settings.

Note: The simulated and measured profiles are not at the same position (~factor of 2 difference in β ➔ different sizes)

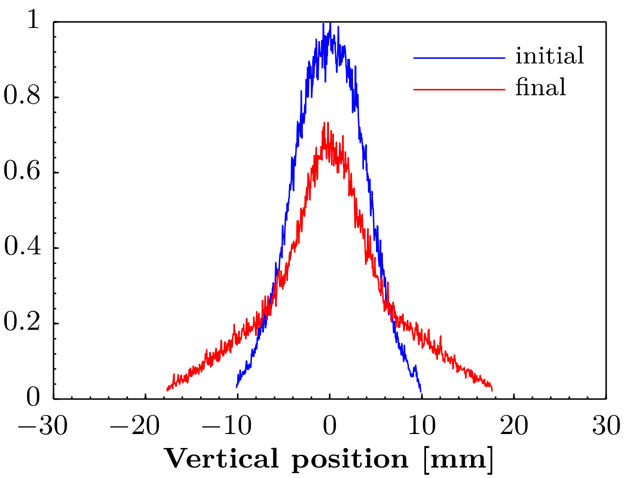
Simulation of the Qx+2Qy resonance

The difference between the simulated and measured profiles for Qx=6.11 is believed to come from the difference between measured and simulated tune.

Simulation at Tunes (6.105 ; 6.47)

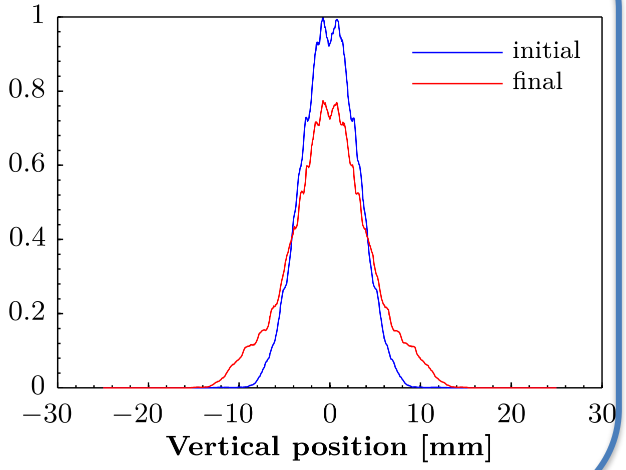


Measurement at tunes: programmed (6.11 ; 6.47) measured (6.105 ; 6.476)



Simulation at Tunes (6.105 ; 6.48)

Preliminary results (only 425k turns)



➔ Tail development is very sensitive to tune-settings.

4th order resonance

- The preferred hypothesis is that the 4th order resonance is **a structure resonance driven by space charge**.

- The resonance is driven by the space charge force modulation which has a harmonic (4*6.25=25 or 8*6.25=50) of the symmetry of the machine (25x “FD DF FD DF” or 50x ”FD DF”)

➔ If one **changes the vertical integer tune**, then the space charge harmonic should be different from the lattice one, and shouldn’t be excited anymore. (ex: 4*7.25=29)

- Another advantage, noticed during this study, is that the space charge tune spread would be reduced (because of the higher dispersion).

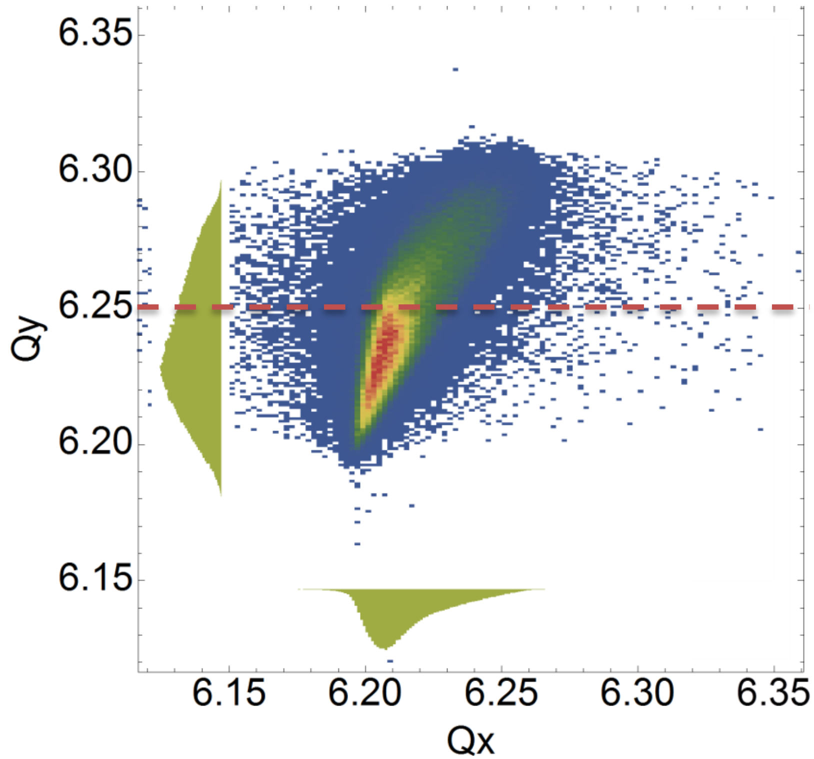
Change of vertical integer tune

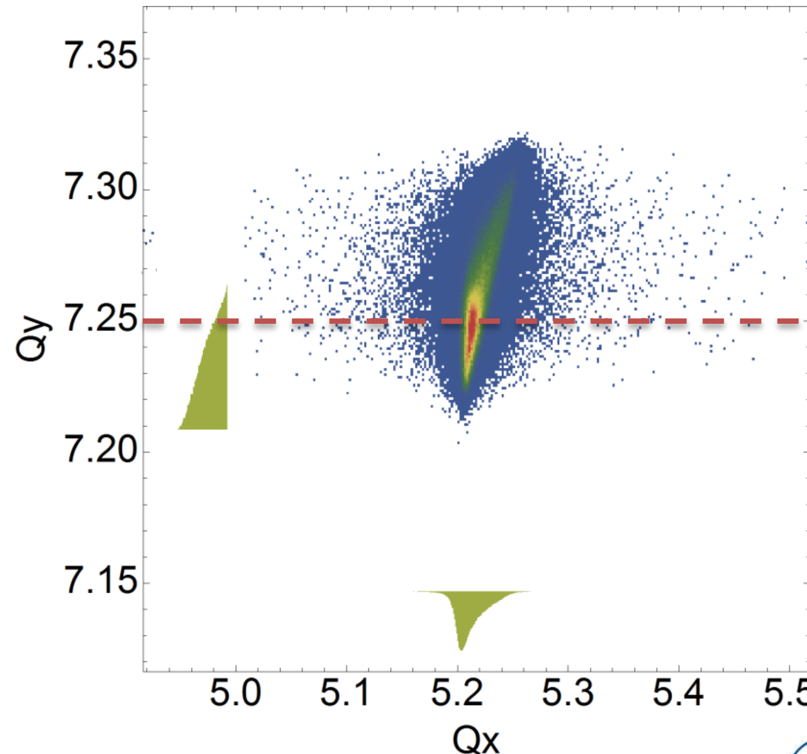
	Bare Machine	Scheme 1	Scheme 2
Tunes	Q_x=6.25 / Q_y=6.28	Q_x=7.25 / Q_y=5.28	Q_x=5.25 / Q_y=7.28
PFKI1F	0	3.38337E-04	-3.30540E-03
PFKI1D	0	3.34595E-03	-4.41205E-04
F8L	0	-130A	+130A
βx @42	11.9	10	13
βy @42	22.4	28.6	19
Dx @42	2.3	1.71	3.26
Dx RMS	2.68	2	3.79
Dx max	3.1	2.3	4.3
Average βx	17.1	14.8	20.4
Average βy	16.8	20.1	14.6
MAX βx	22.5	19.7	29.1
MAX βy	22.4	28.6	19.7
Gamma Transition	6.1218	7.0908	5.1436
ΔQx	-0.19	-0.2	-0.17
ΔQy	-0.25	-0.28	-0.21

- To change the integer, I use only the F8L (introduces only quadrupolar component).
- Going to 7 as vertical integer tune seems to be more advantageous (reduces the tune-spread due to space
- One has to verify if the injection transfer line can match these optics.
- A limitation (for large beams): the horizontal size is doubled. (For an LHC-type beam, the aperture~24σ in H and 17.5σ in V)

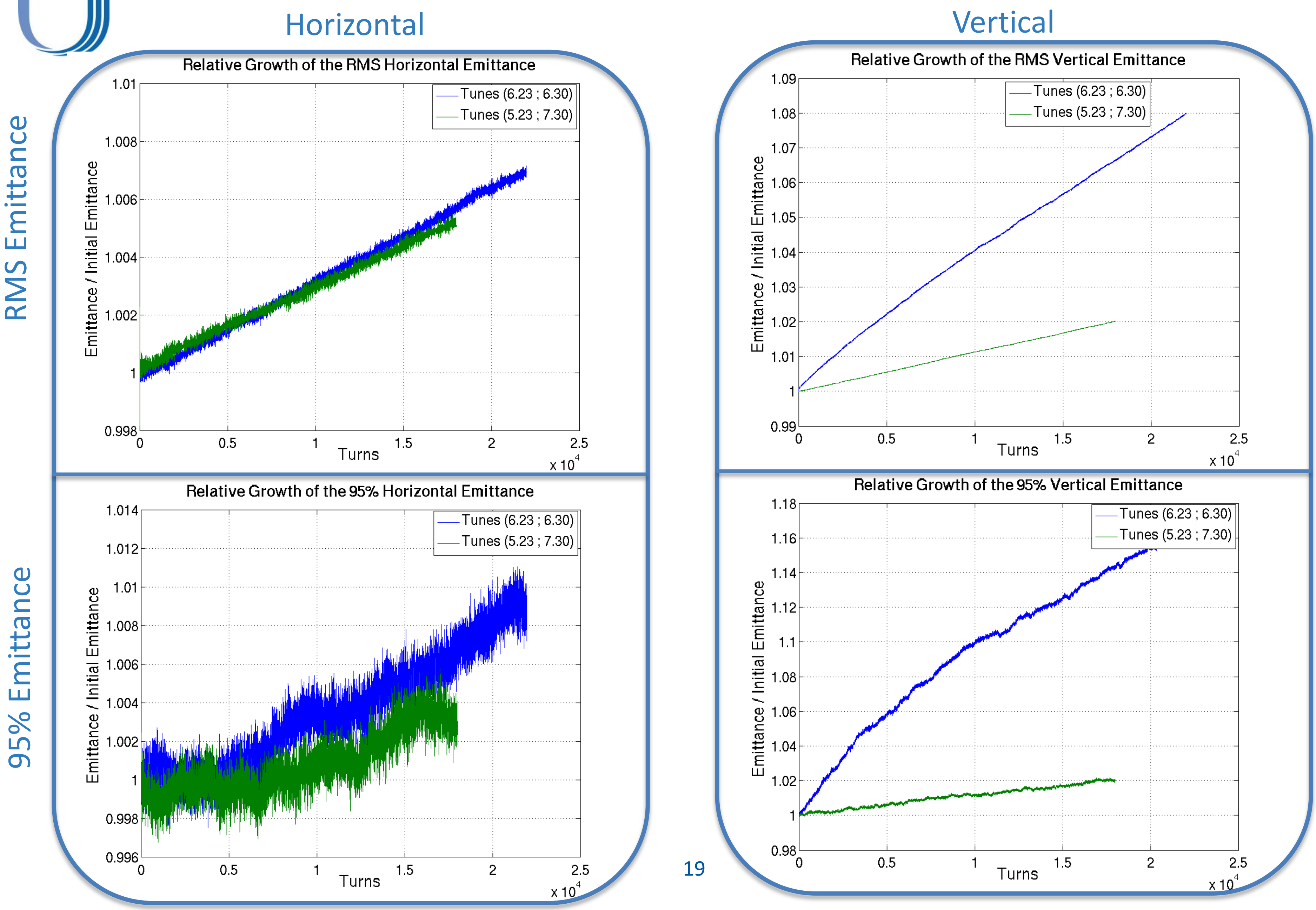
Change of vertical integer tune

- The aim of the following study is to verify the hypothesis of structure resonance driven by space charge.
- The simulated beam is different from the measured ones, to have a smaller tune-spread, to overlap only the 4Qy=25.



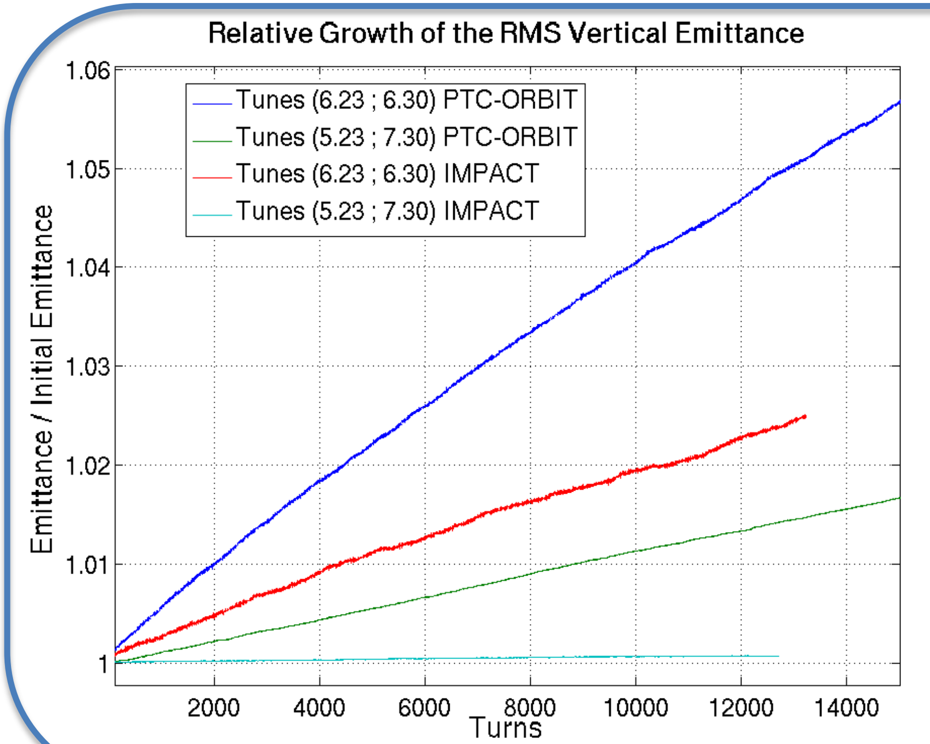


Change of vertical integer tune

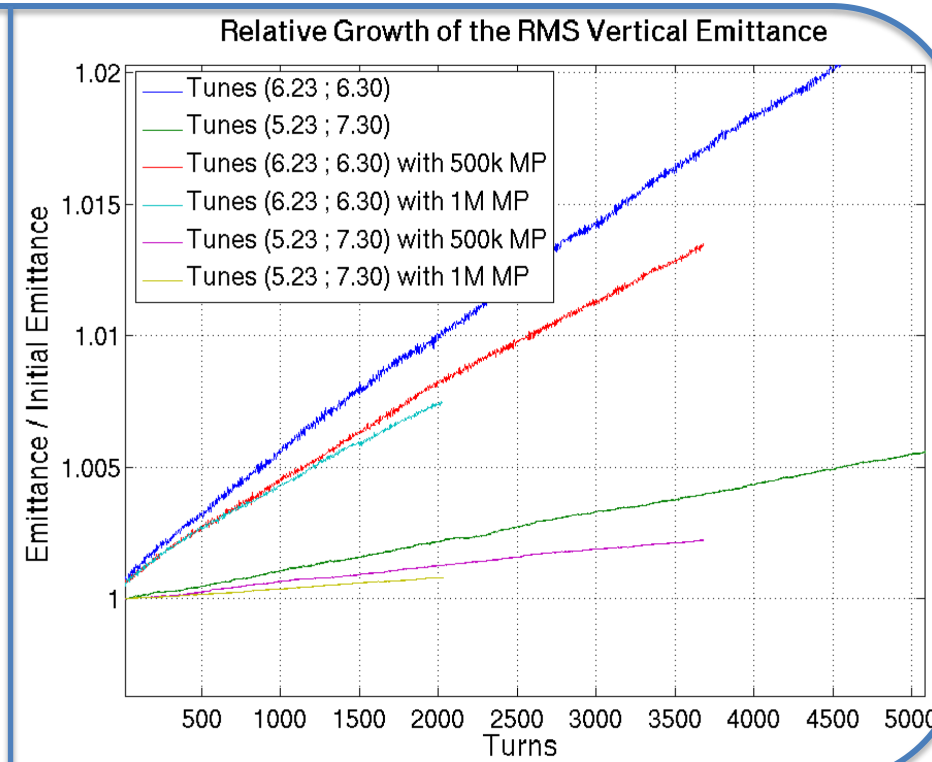


Change of vertical integer tune

PTC-ORBIT vs. IMPACT



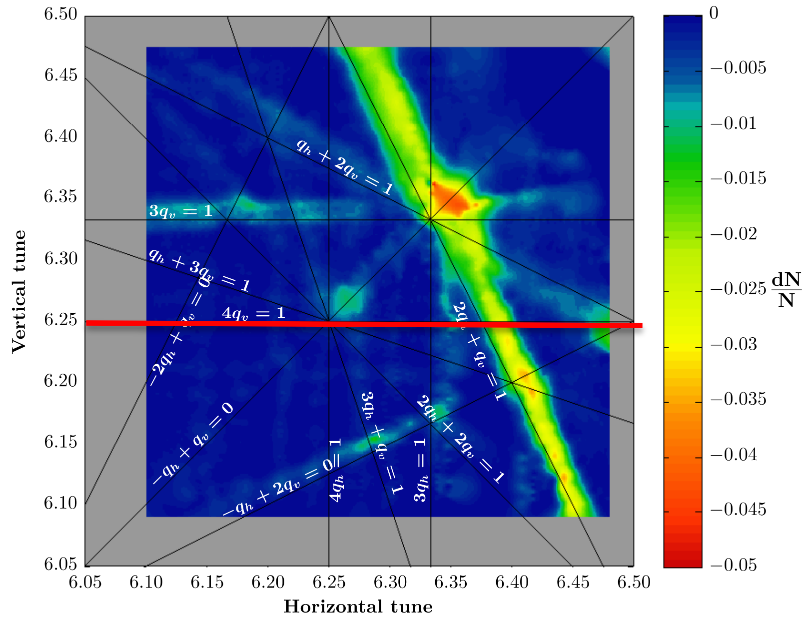
PTC-ORBIT with different # of MP



- The main goal of these simulations is not to have an absolute value of emittance growth but to verify the relative behavior with the different settings.

  ➔ Simulations tend to confirm the hypothesis of the 4th order being a structure resonance driven by space charge.

Summary and Outlook



- Excited resonances: Skew sextupolar and 4Qy=25.
- The skew sextupolar resonances have been compensated.
- Simulations are on going using PTC-ORBIT, IMPACT and MADX-SC.
- Good agreement between measurement and simulation (MADX-SC) for the case of the Qx+2Qy resonance.
- Simulations tend to confirm the hypothesis of the 4th order being a structure resonance driven by Space Charge
- Several experiments are planned at the restart of the machine (change of integer, hollow bunches, resonance compensation…etc)

➔ Potential large increase of the available tune area.

LHC Injectors Upgrade

THANK YOU FOR YOUR ATTENTION!

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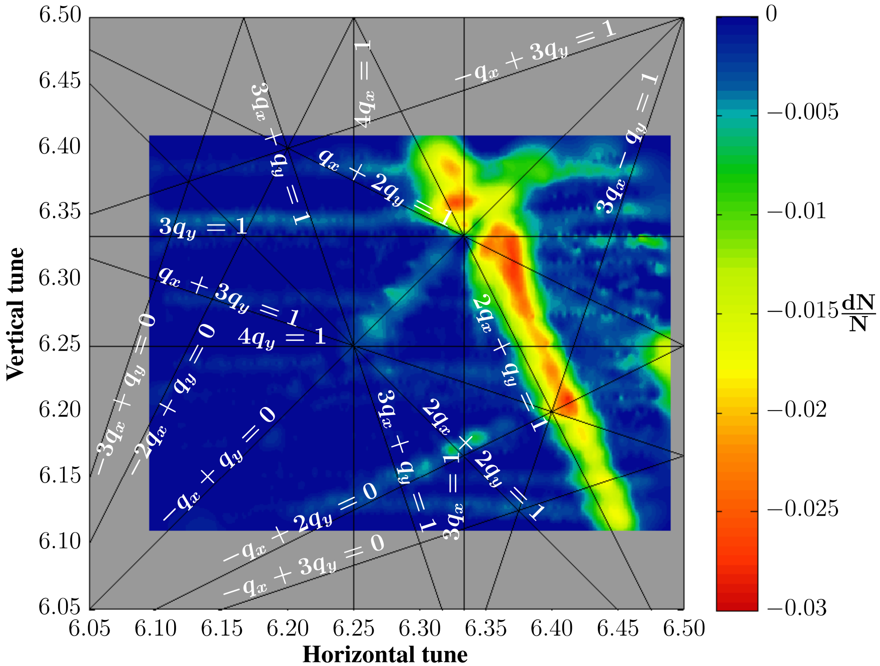
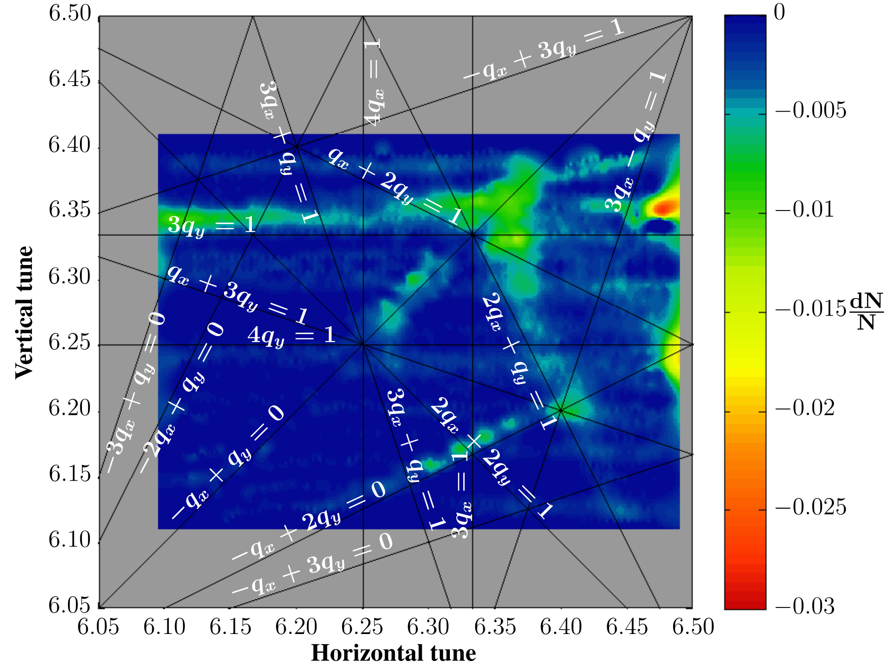
Backup Slides

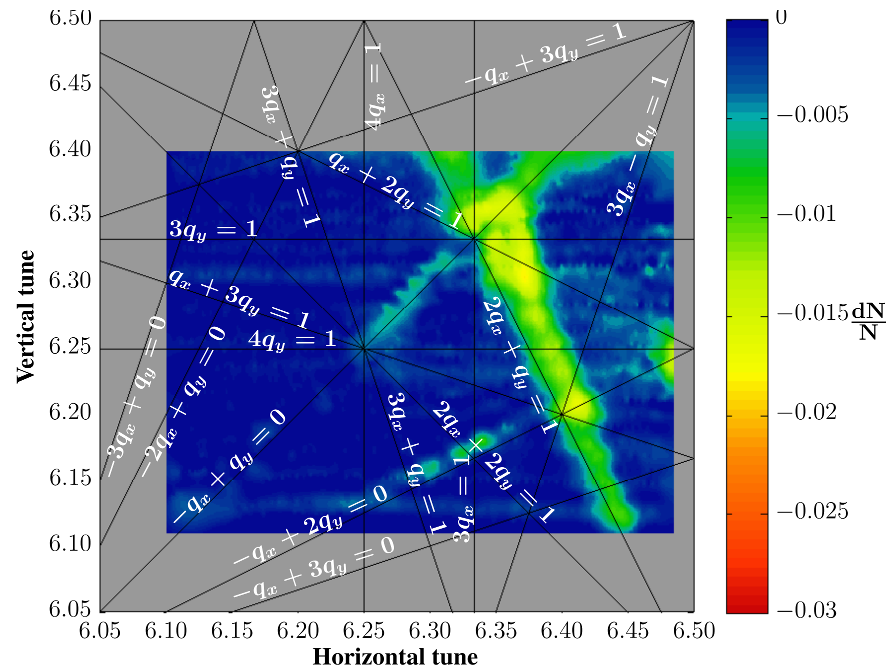
Resonance compensation

Horizontal tune scan





2Qx+Qy compensation

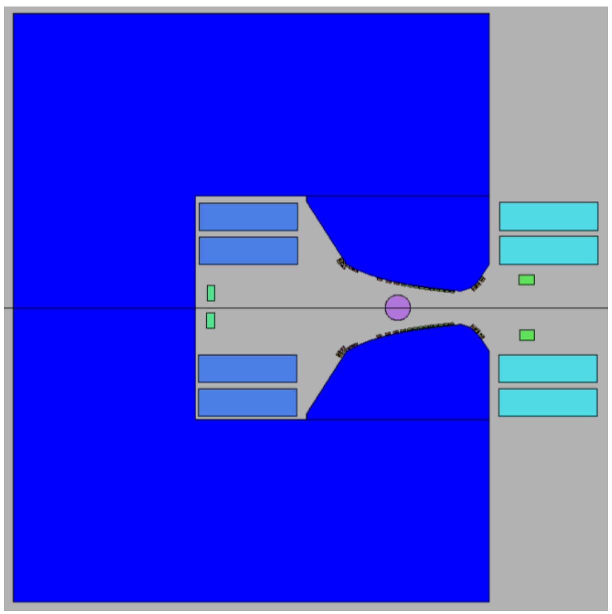


3Qy compensation

Resonance Compensation

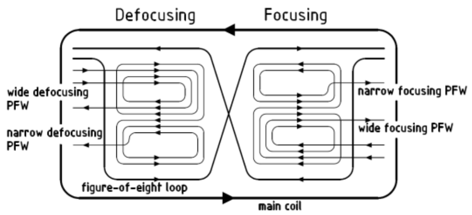
- 2D calculation including Gaussian distribution of the position of the coils and the shape of the iron with up to 22 DOFs per magnet (OPERA) were performed.

- 1000 models per magnet type (4 types) and current level have to be calculated. Performed for momentum of 2.14 GeV/c, 2.78 GeV/c, 14 GeV/c, 26 GeV/c.

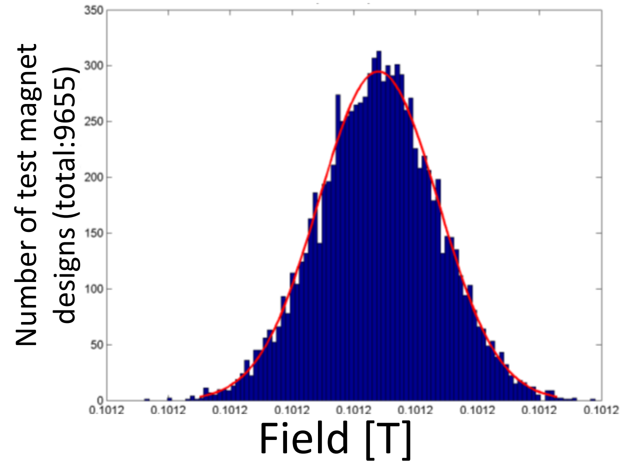


Coils can be displaced, no rotation:
Main coils (2 x 4 DOFs), σ = 3 mm
F8 (2 x 4 DOFs), σ = 1 mm
PFW (2 x 2 DOFs), σ = 0.7 mm

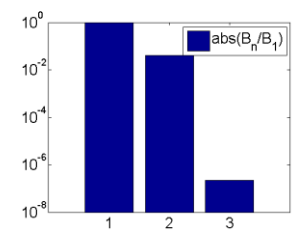
Iron is displaced in y-direction, σ = 0.02/3 mm

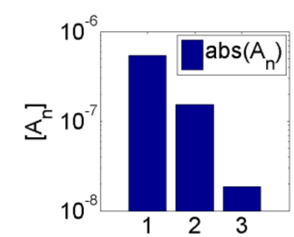


Dipolar Component



Kinetic energy: 1.4GeV
Reference radius
r = 10 mm
Vacuum chamber: 140x70mm

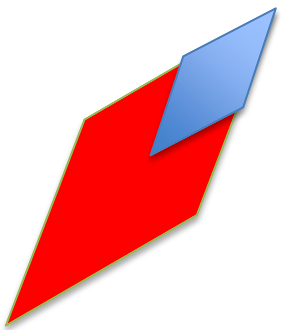




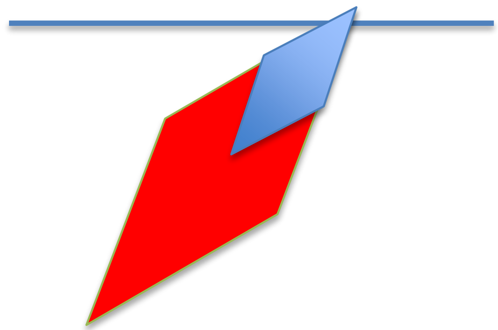
➔ These errors were randomly distributed on the magnets in the PTC model to compute the driving terms of each of the resonances.

III. 4th order Resonance

Testing the effect of the 4qy by changing the population crossing it (Bunch compression @ C1000)



Tune spread before and after compression



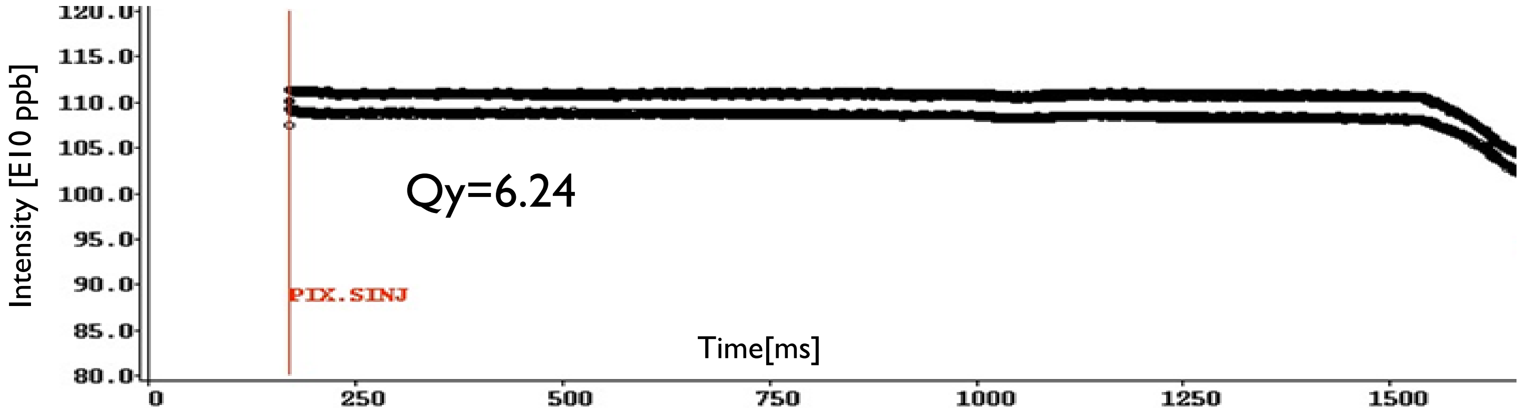
If the working point is close to the resonance, before and after the compression it is mainly the halo crossing the resonance

If the working point is relatively far from the resonance the population crossing the resonance changes after compression

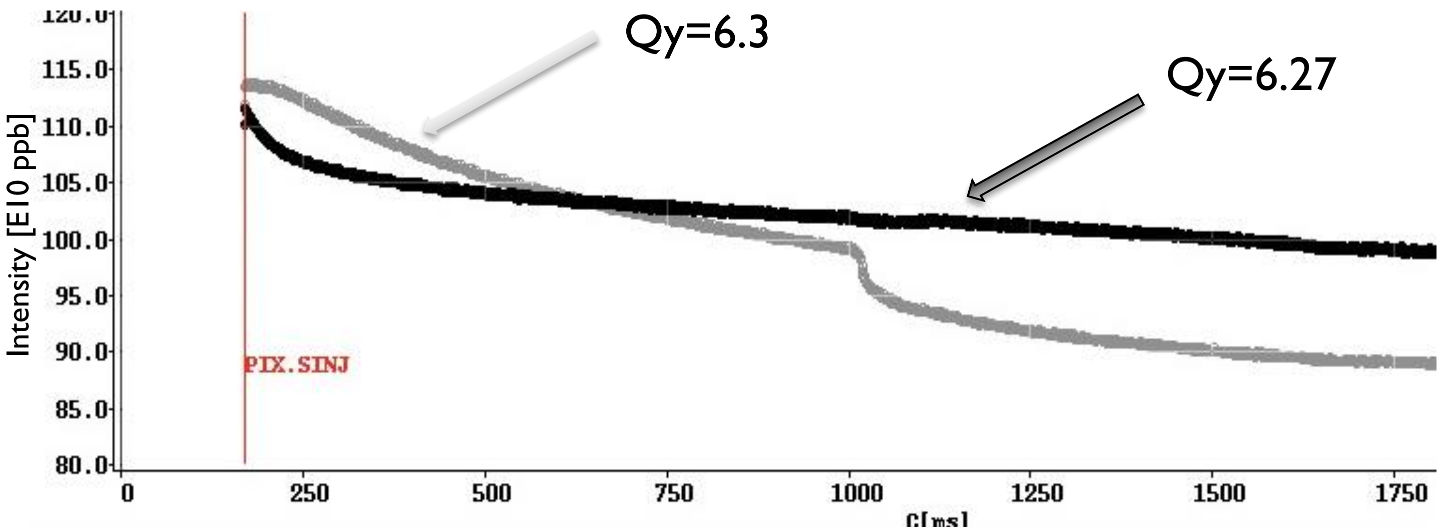
➔ Losses due to the resonance are expected to be different

III. 4th order Resonance

Bunch compression @ C1000



➔No effect of the compression (losses due to change of W.P.)



Before compression: losses are faster in the case of Qy=6.27

After compression: No effect for Qy=6.27 but faster losses for Qy=6.3

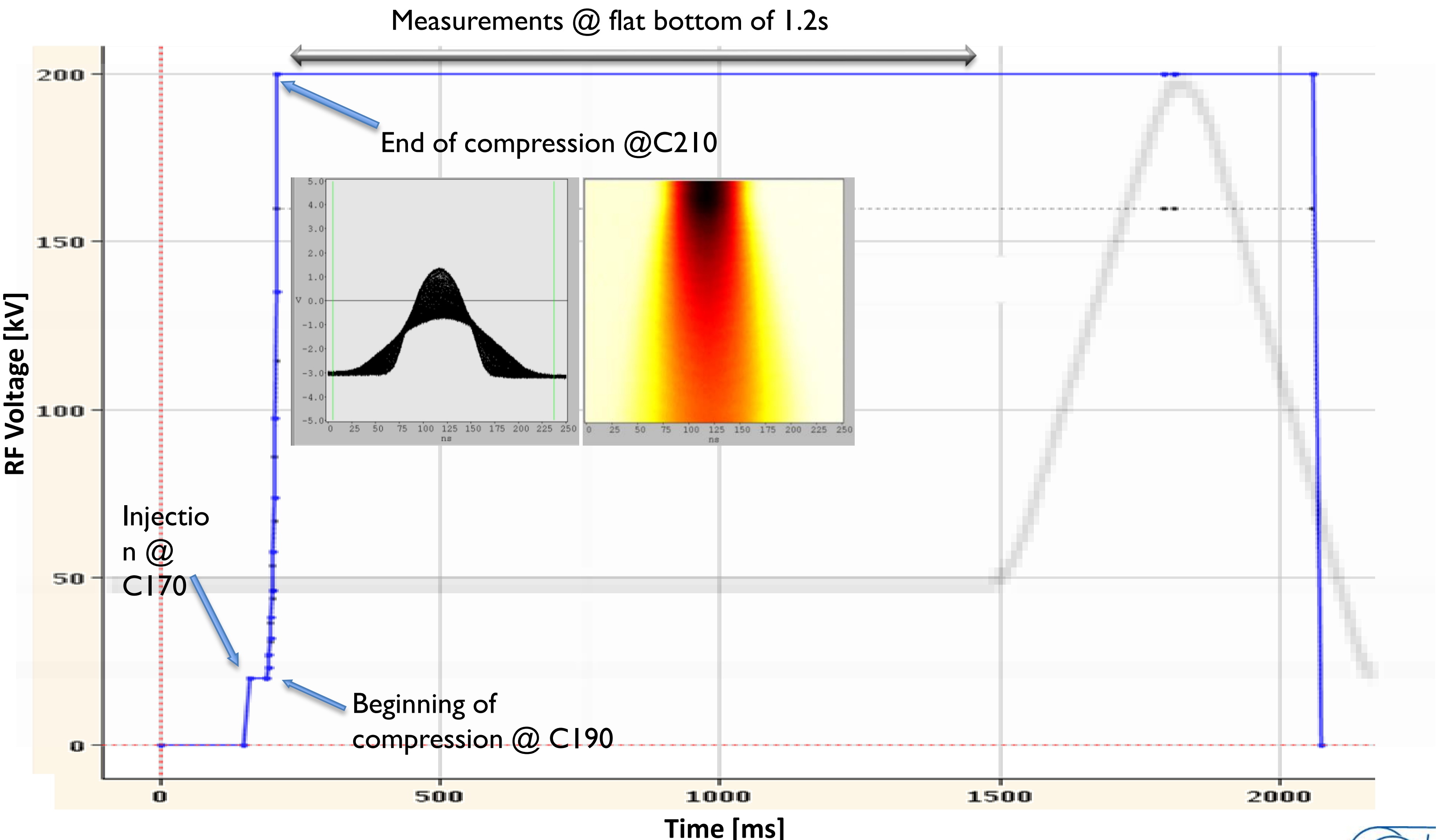
Integer resonance effect

- The **tune-spread** was varied using an **adiabatic bunch compression** (20ms).
- The effect of the integer is observed through the **longitudinal and transverse profiles** as well as **losses.**
- The transverse profile is measured using a **wire-scanner**, which averages the profile over ~2ms and it can only be used **once per cycle**.
- The **emittances** are computed using the a fit of the beam profile from the wire-scanne assuming the optics (β,dispersion) of the model.
- The maximum tune-shift due to space charge is estimated using:

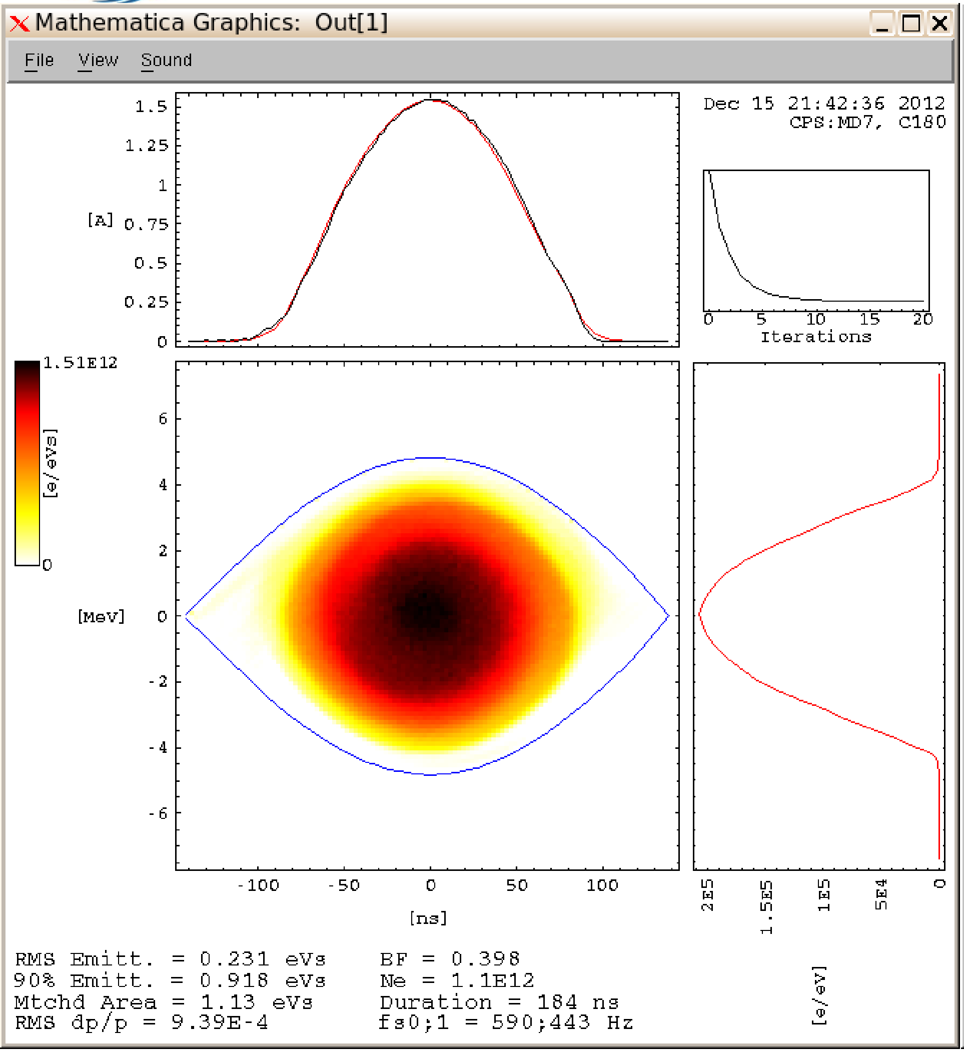
$$\Delta Q_{x,y} = \frac{r_p N_b}{(2\pi)^{3/2} \gamma^3 \beta^2 \sigma_z} \oint \frac{\beta_{x,y}(s) ds}{\sigma_{x,y}(s)[\sigma_x(s) + \sigma_y(s)]}$$

- After a quick check of the losses and emittances after compression, **(6.23 ; 6.255)** has been chosen as starting working point. (Measured ~(6.228 ; 6.253))

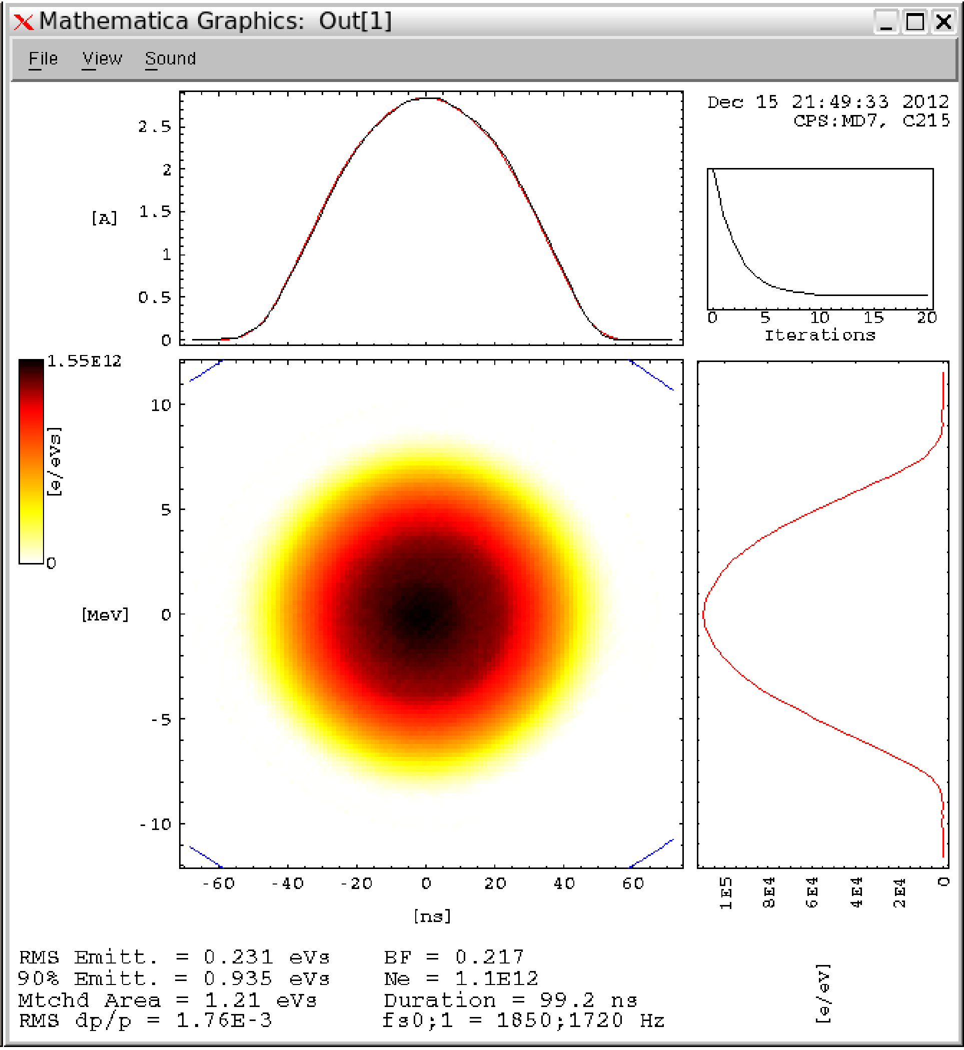
Adiabatic Bunch Compression



Longitudinal profile before/after compression

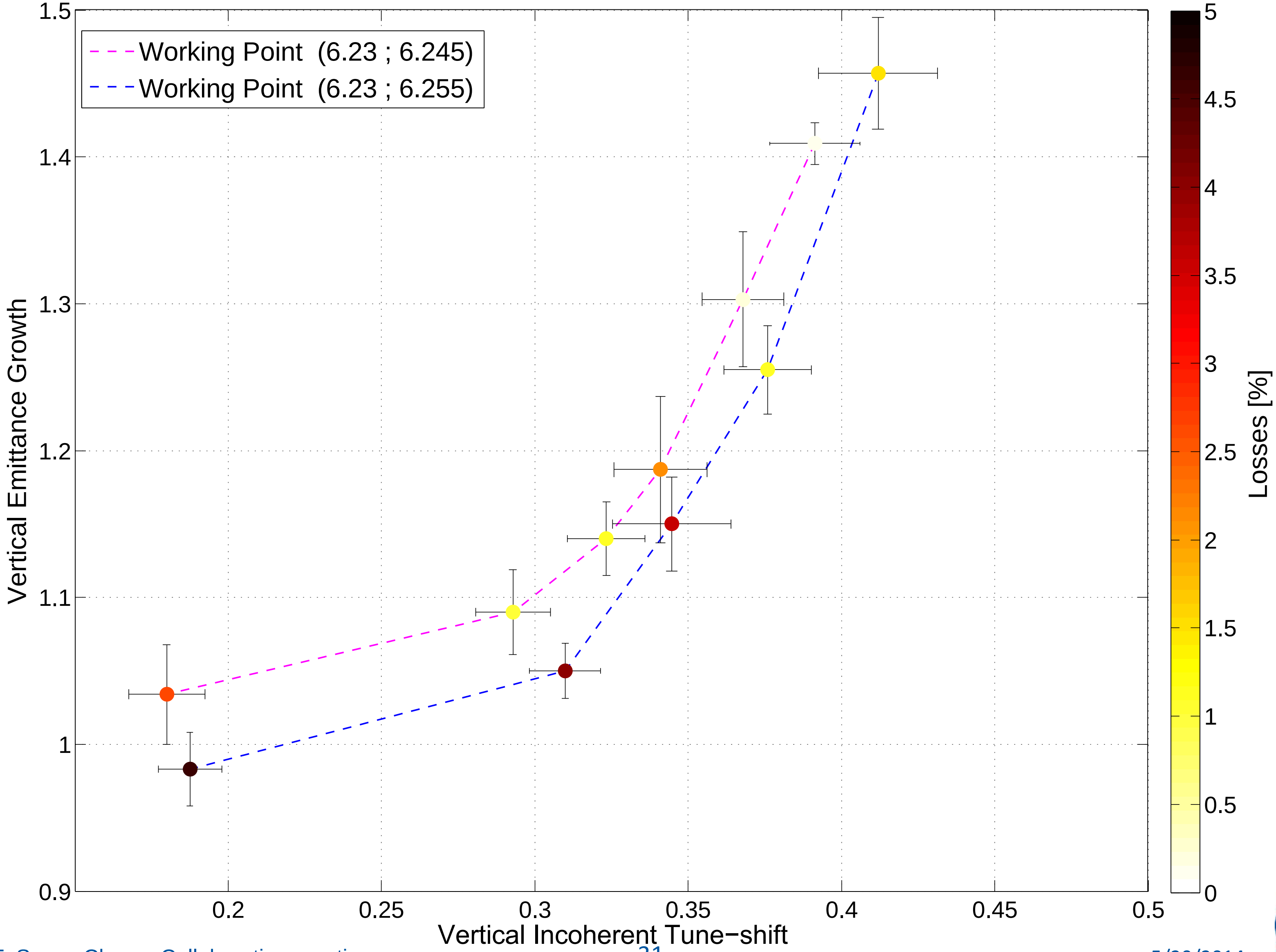


Before compression



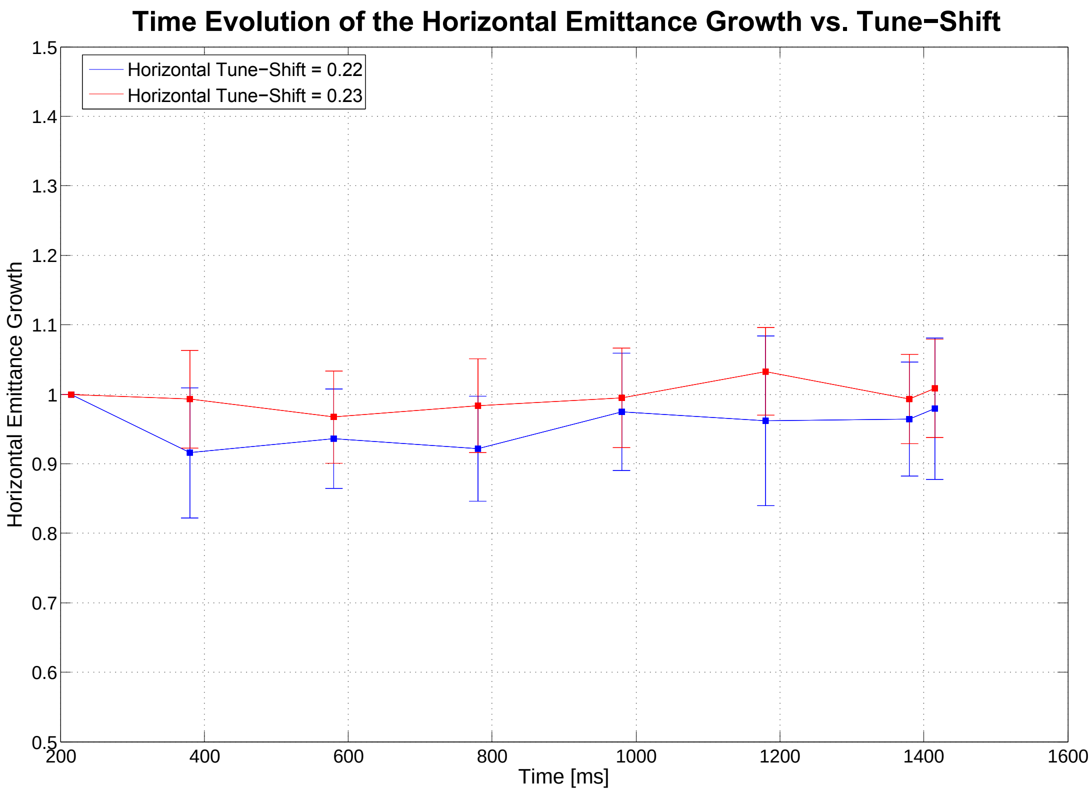
After compression

Vertical growth vs. Tune-spread vs. Losses



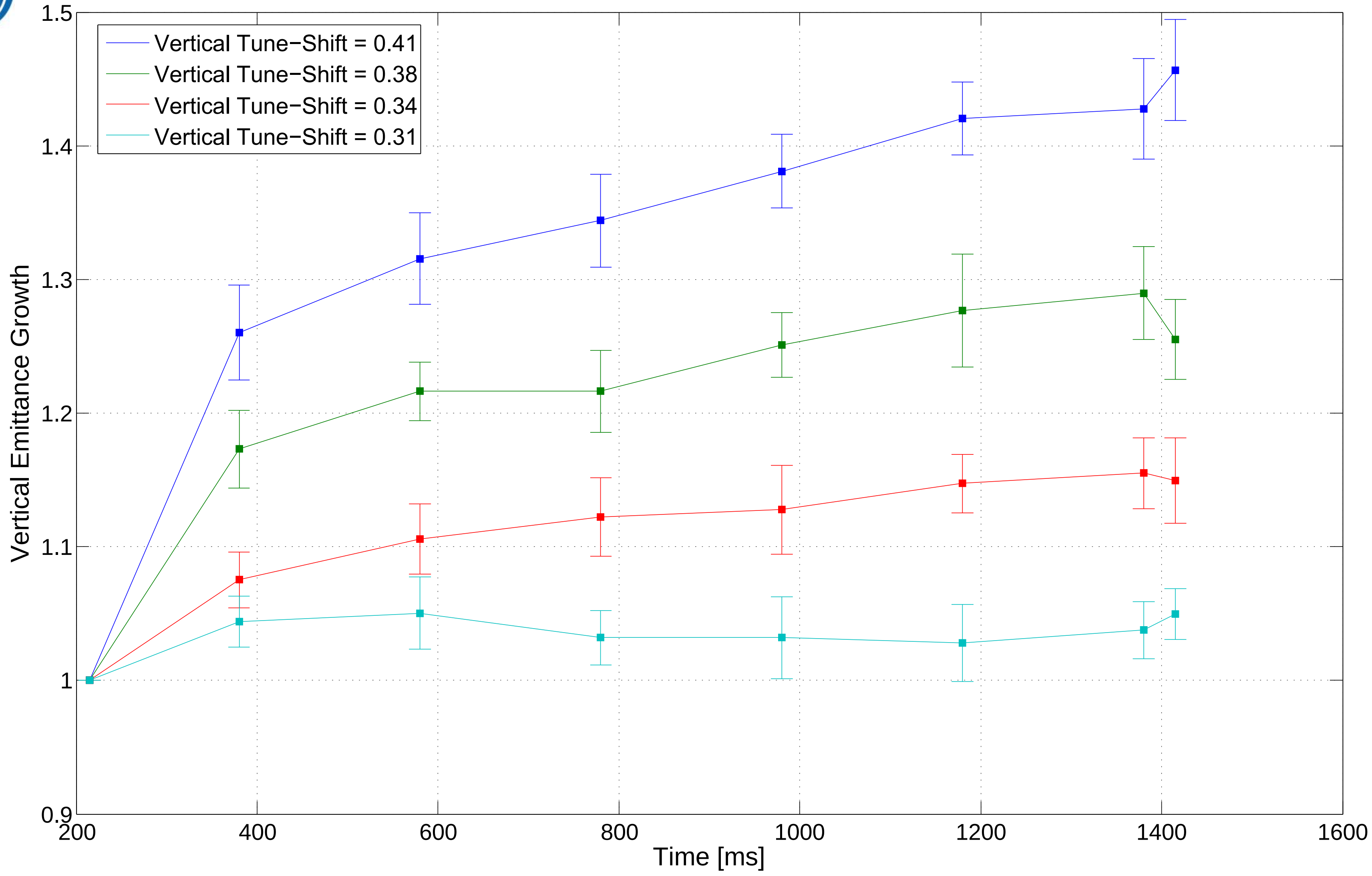
IV. Horizontal emittance behavior

- **Beam used:**
  I=1.15e12 ppb; $\varepsilon_{h,normalized}$=1.6μm; $\varepsilon_{v,normalized}$=1.25μm; Δp/p(1σ)= 0.95E-3 ; full bunch length=185ns



Since the horizontal detuning is always **less than .23** (Qx=6.23), no relevant change has been noticed in the horizontal plane. Therefore, only the vertical emittance is shown in the following results

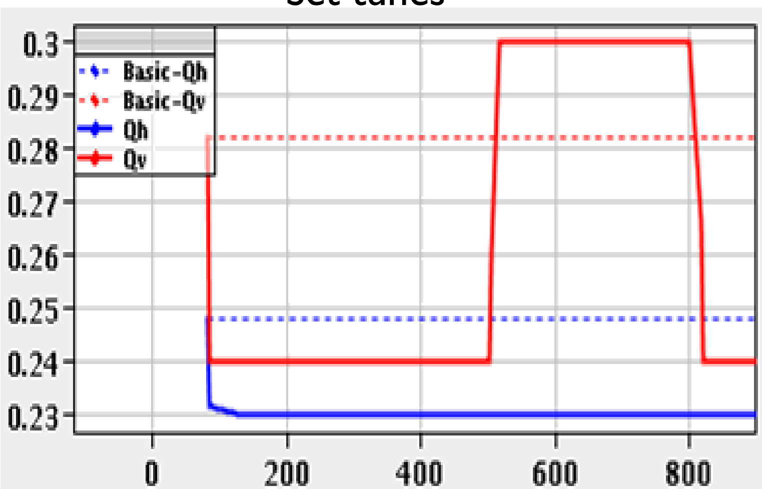
IV. Vertical growth vs. Time vs. Tune-spread



III. 4th order Resonance

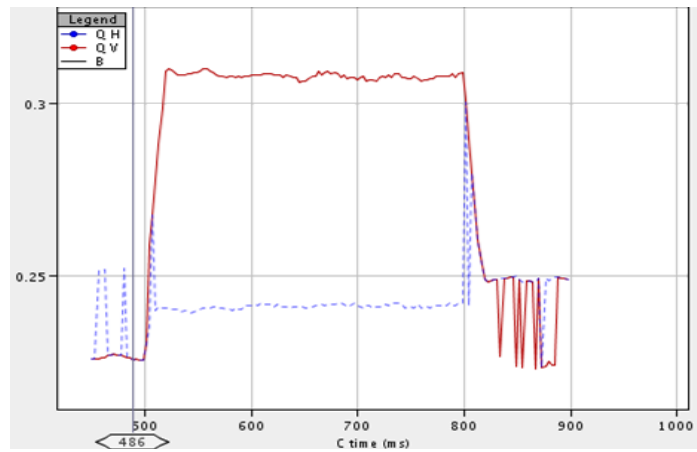
- **Testing if the 4qy=1 is excited by Space Charge:**
  - Bunch compression @ C190
  - Tune step between C500 and C800

Set tunes

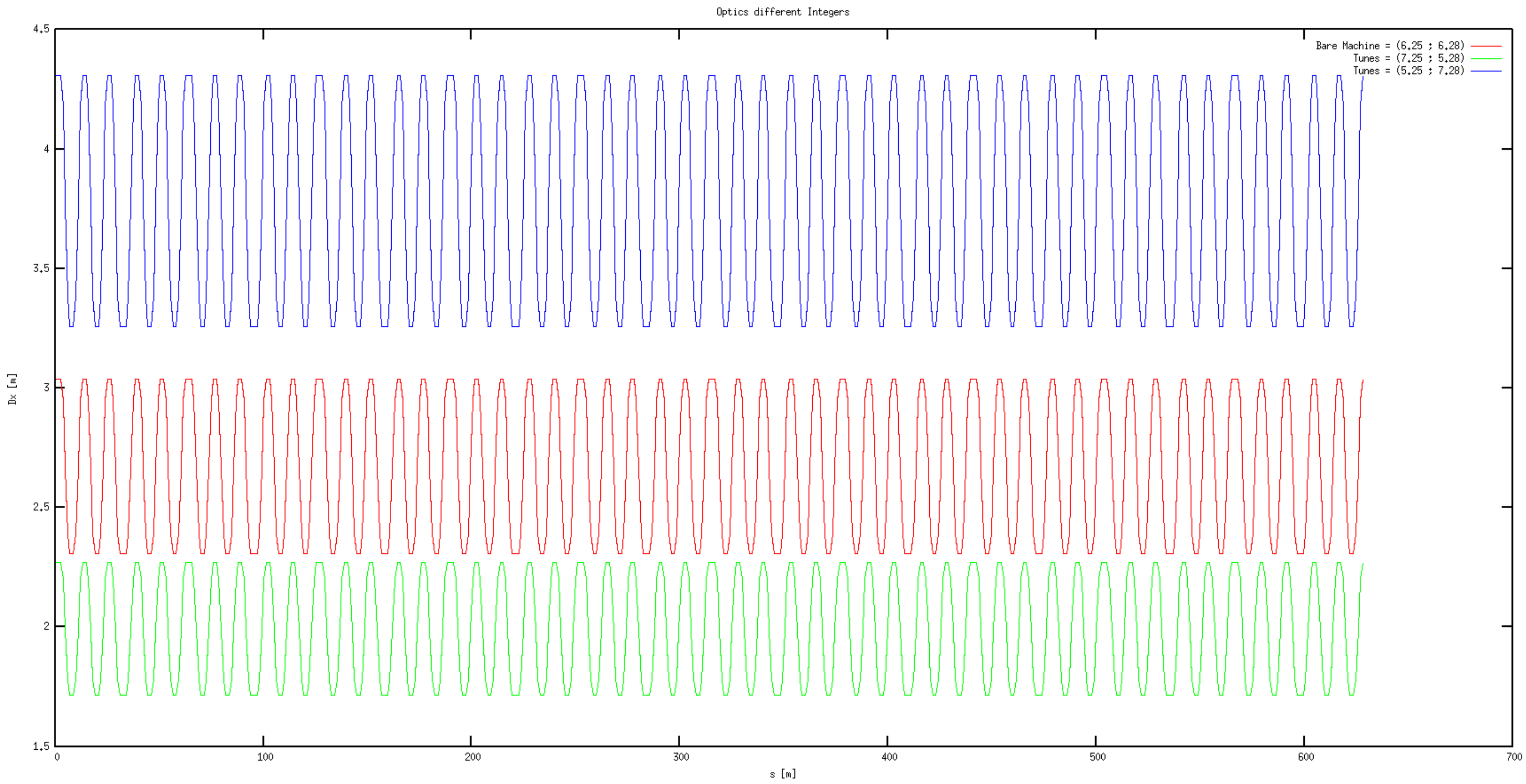


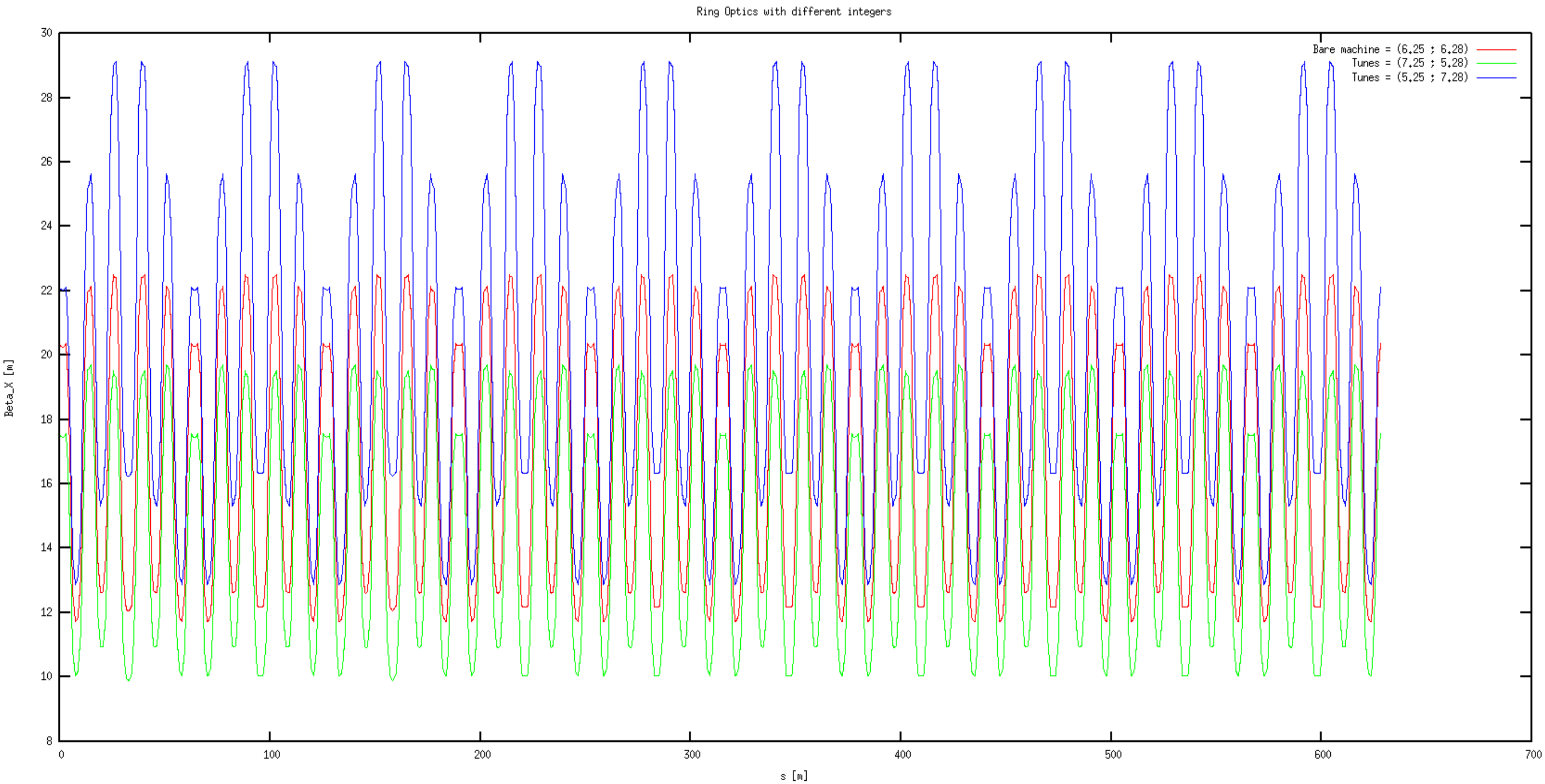
Time[ms]

Measured tunes

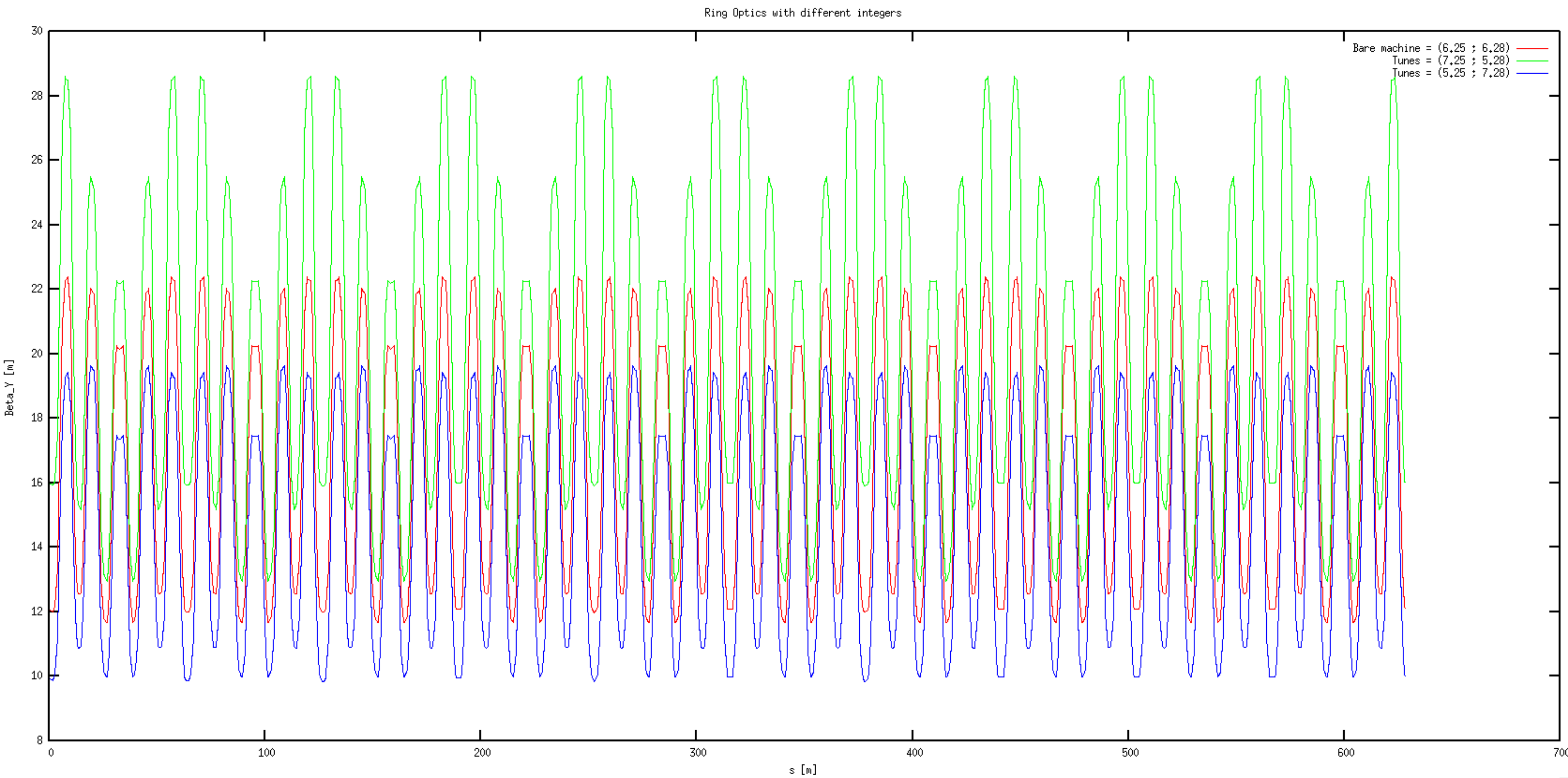


- **4 different settings**:
  - ➢ I=115 e10 ppb Tune-spread =(.22 ; .4) (for Q21Q23 optics)
  - ➢ I=80 e10 ppb Tune-spread =(.18 ; .37) (for Q21Q23 optics)
  - ➢ I=35 e10 ppb Tune-spread =(.08 ; .24) (for Q21Q23 optics)
  - ➢ I=115 e10 ppb Debunched

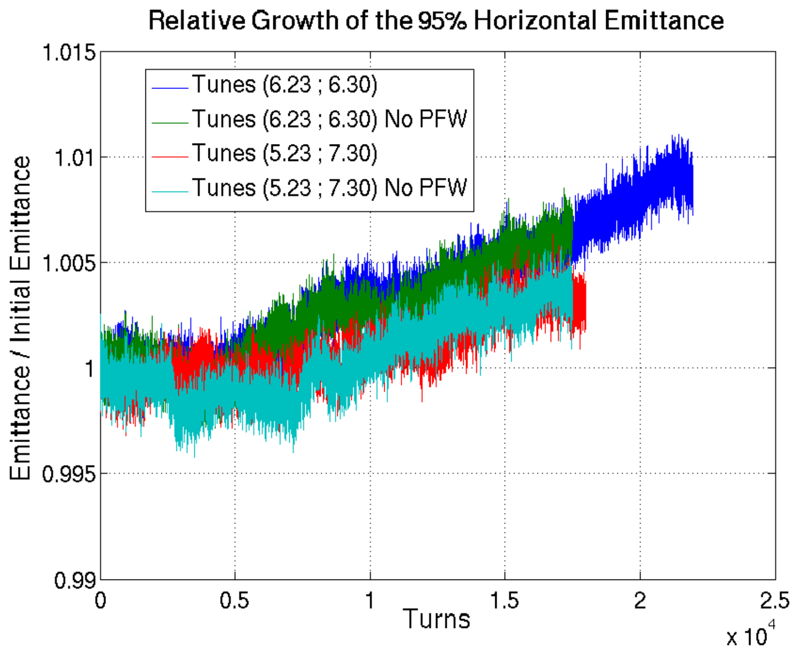

Optics different Integers
Bare Machine = (6.25 ; 6.28)
Tunes = (7.25 ; 5.28)
Tunes = (5.25 ; 7.28)
Dx [m]
s [m]
4.5
4
3.5
3
2.5
2
1.5
0
100
200
300
400
500
600
700



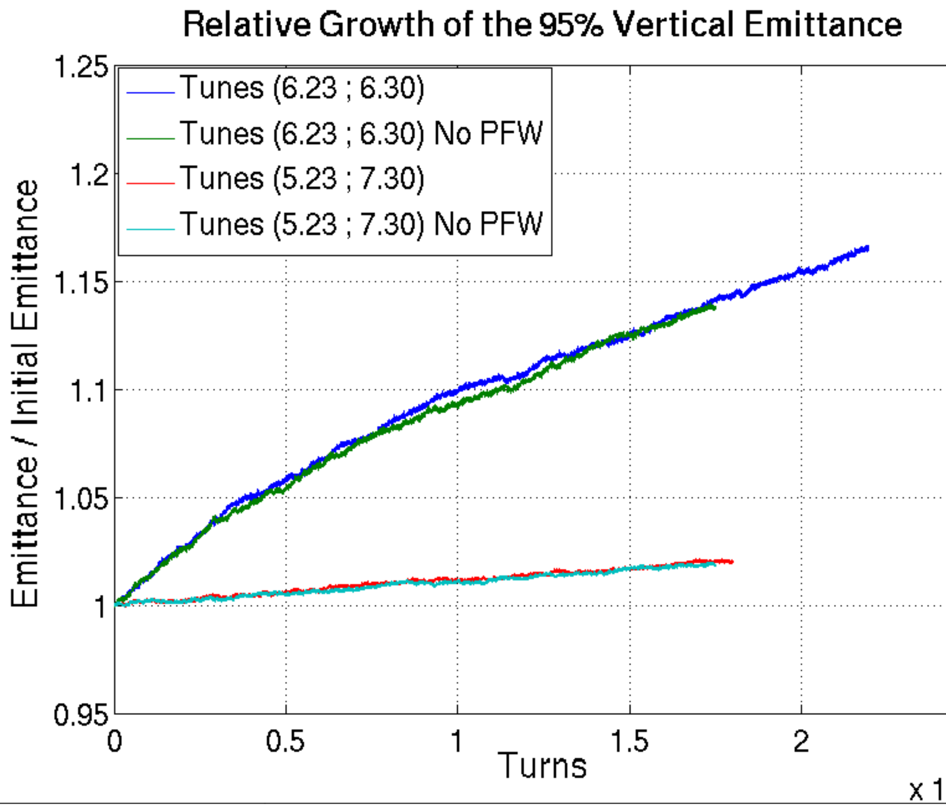
Ring Optics with different integers
Bare machine = (6.25 ; 6.28)
Tunes = (7.25 ; 5.28)
Tunes = (5.25 ; 7.28)
Beta_X [m]
s [m]
30
28
26
24
22
20
18
16
14
12
10
8
0
100
200
300
400
500
600
700



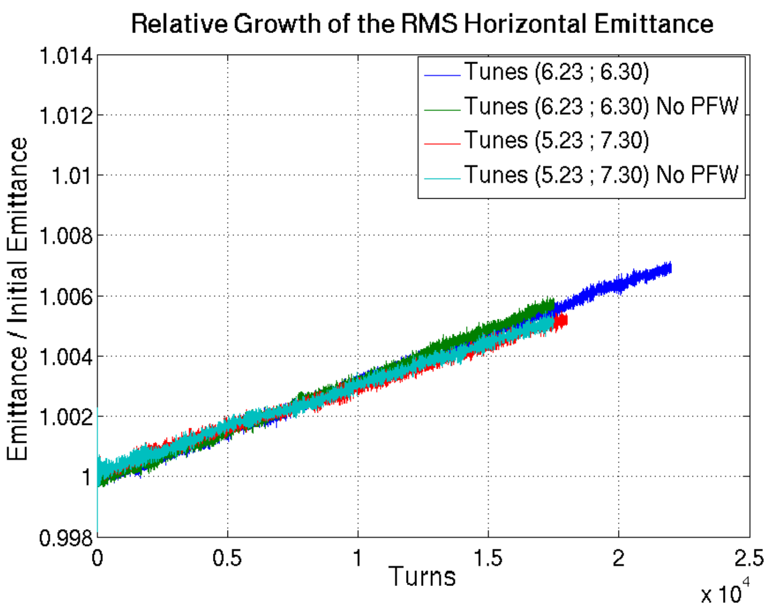
Ring Optics with different integers
Bare machine = (6.25 ; 6.28)
Tunes = (7.25 ; 5.28)
Tunes = (5.25 ; 7.28)
Beta_Y [m]
s [m]
30
28
26
24
22
20
18
16
14
12
10
8
0
100
200
300
400
500
600
700



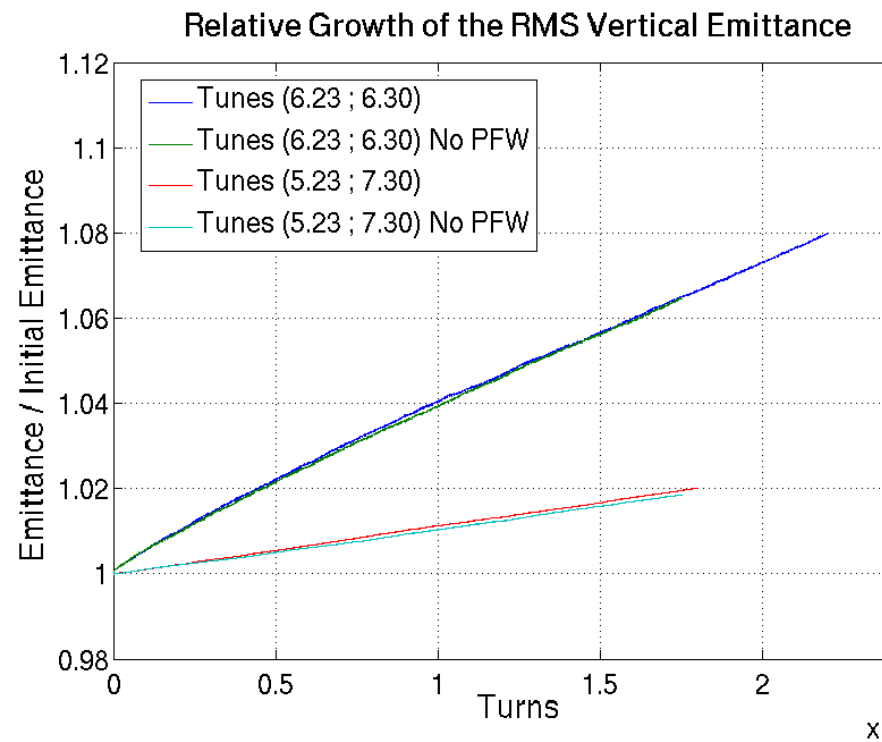
Relative Growth of the 95% Horizontal Emittance
Tunes (6.23 ; 6.30)
Tunes (6.23 ; 6.30) No PFW
Tunes (5.23 ; 7.30)
Tunes (5.23 ; 7.30) No PFW
Emittance / Initial Emittance
Turns
x 10^4
1.015
1.01
1.005
1
0.995
0.99
0
0.5
1
1.5
2
2.5



Relative Growth of the 95% Vertical Emittance
Tunes (6.23 ; 6.30)
Tunes (6.23 ; 6.30) No PFW
Tunes (5.23 ; 7.30)
Tunes (5.23 ; 7.30) No PFW
Emittance / Initial Emittance
Turns
1.25
1.2
1.15
1.1
1.05
1
0.95
0
0.5
1
1.5
2



Relative Growth of the RMS Horizontal Emittance
Emittance / Initial Emittance
Turns
x 10^4
Tunes (6.23 ; 6.30)
Tunes (6.23 ; 6.30) No PFW
Tunes (5.23 ; 7.30)
Tunes (5.23 ; 7.30) No PFW



Relative Growth of the RMS Vertical Emittance
Emittance / Initial Emittance
Turns
Tunes (6.23 ; 6.30)
Tunes (6.23 ; 6.30) No PFW
Tunes (5.23 ; 7.30)
Tunes (5.23 ; 7.30) No PFW