Space charge effects and machine resonances CERN Injectors for LHC (LIU project)

Alexander Molodozhentsev (KEK)
(CERN Space Charge Group / ICE)

August 22, 2012

CONTENT of the talk

→ CURRENT status of the group activity for the period March – July 2012

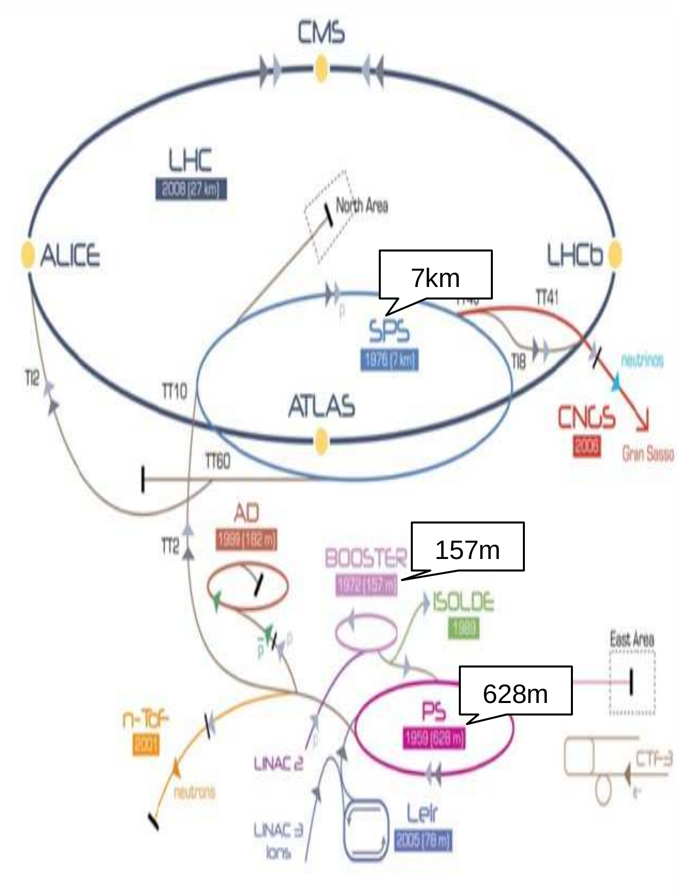
- Motivations
- Computational tools and hardware
- Convergence study
- MDs and benchmarking activity (PSB, PS, SPS)

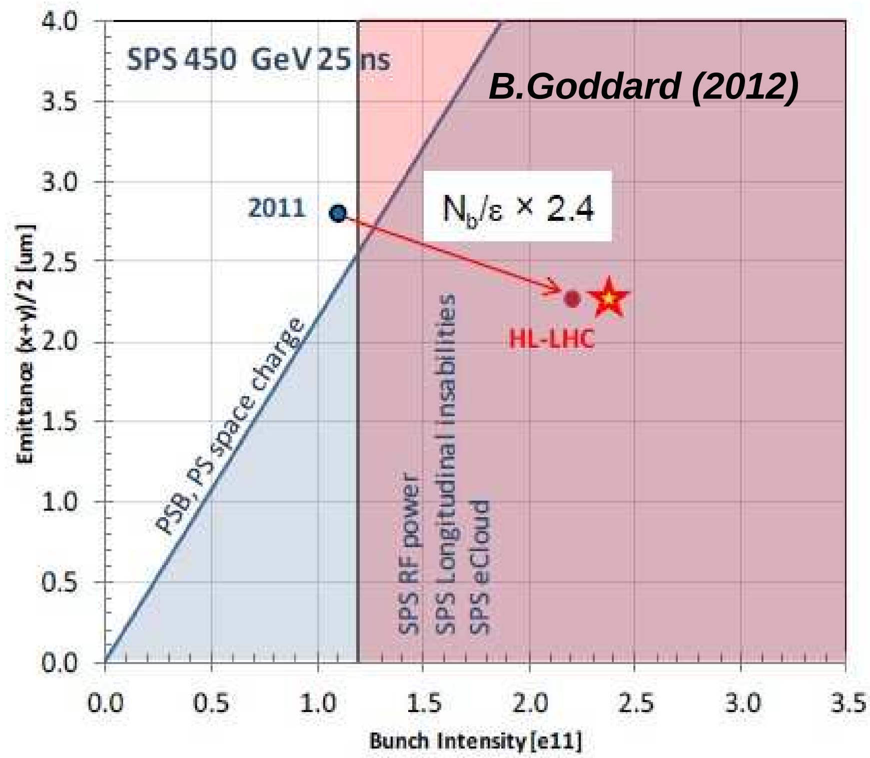
This presentation is based on results, obtained by the CERN 'Space-charge' group.

CERN Space charge Group

Group manager	Frank Schmidt
PS Booster	Vincenzo Forte Michel Martini Elena Benedetto Nicolas Mounet Christian Carli
PS	Raymond Wasef Cedric Hernalsteens Simone Gilardoni
SPS	Hannes Bartisik
‘RCS’ design	Miriam Fitterer Christian Carli

Motivations … LHC 25 nsec





2011: ~ 1.1e11 with 2.8μm for 25nsec has been extracted from SPS

Post LS2 (2019): → × 2.4 times in brightness for 25nsec

Motivations … key-points

- **LINAC**2 (p^+ 50MeV) → LINAC4 (h^- 160MeV)
- **PS Booster** → W_{inj} = 160 MeV

… **very confident** to run with $\Delta Q_y \approx -0.3$ (and **reasonable hope** for $\Delta Q_y \approx -0.36$)

- **PS** → W_{inj} = 2 GeV

… **very confident** to run with $\Delta Q_y \approx -0.26$ (with **reasonable hope** for $\Delta Q_y \approx -0.30$ with 180nsec long bunches)

- **SPS** (Q20 lattice)

… present **assumption** is to run with $\Delta Q_y \approx -0.15$

… need to increase $\Delta Q_y \approx -(0.20 … 0.25)$

GOAL

25 ns	PSB inj	PSB extr/PS inj	PS extr/SPS inj	SPS extr/LHC inj	LHC top
Energy GeV	0.16	2	26	450	7000
Nb	1	1	72	288	2808
Ib [e11 p+]	35.2	33.5	2.7	2.4	2.2
Ib in LHC [e11 p+]	2.9	2.8	2.7	2.4	2.2
Exyn [mm.mrad]	1.9	2.0	2.1	2.3	2.5

Motivations … key-points

❑ Assumptions made on emittance blowup and beam loss:

	PSB	PS	SPS	LHC
loss %	5	5	10	10
blowup %	5	5	10	10

❑ Total assumed beam losses ~ 30% (PSB flat-bottom to LHC flat-top),
❑ Total emittance growth ~ 30%

→ For comparison: '2011 operation' saw about 13% beamloss (PS injection to LHC flat-top) with the emittance growth about 60%

Computational tools …

Alexander Molodozhentsev (KEK) ICE meeting / CERN / June 1, 2011

What is this code?

- **PTC** → Etienne Forest (KEK)
- **ORBIT** → SNS-BNL code (Jeff Holmes, SNS)

  Idea to 'glue' these two codes was generated by A.Molodozhentsev and discussed during the HB ICFA06 Workshop

---

- ***PTC-ORBIT*** *combined code (from 2007, KEK-SNS)*

… use for J-PARC Main Ring to study the space-charge effects in combination with the machine resonances …

→ ***compiled*** *for the KEK super computers (Hitachi & IBM, 2007) and for the CERN CLIC cluster (CERN, November 2010)*

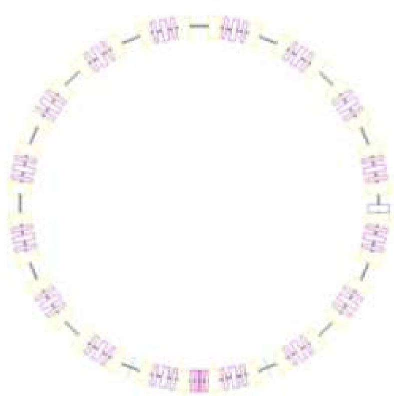
MADX-PTC → convenient way to prepare realistic machine description including user's matching procedures …

Computational tools …

Alexander Molodozhentsev (KEK) ICE meeting / CERN / June 1, 2011

Why PTC-ORBIT ?

Real machine *with field Imperfections and alignment data*

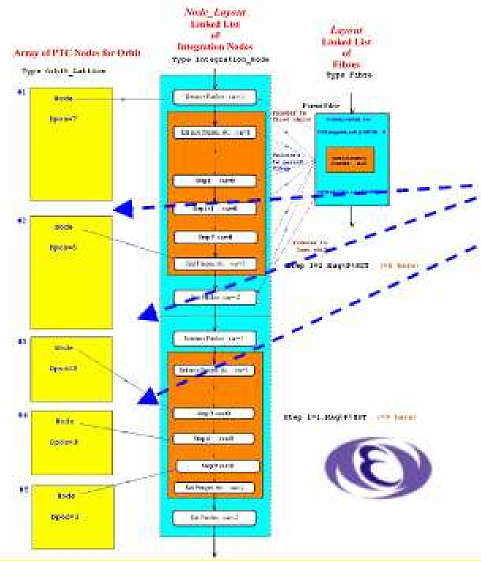


PTC *lattice representation*

→ Comprehensive lattice analysis

→ RF cavities (acceleration)

→ NEW !… Time dependent magnets



ORBIT *node*

PTC *as the tracker (6D integrator)*

'ORBIT' staff:

- *Injection foil.*
- *Space charge model.*
- *Transverse and longitudinal impedance.*
- *Feedback for stabilization.*
- *Aperture and collimation.*
- *Electron cloud model.*

Main feature:

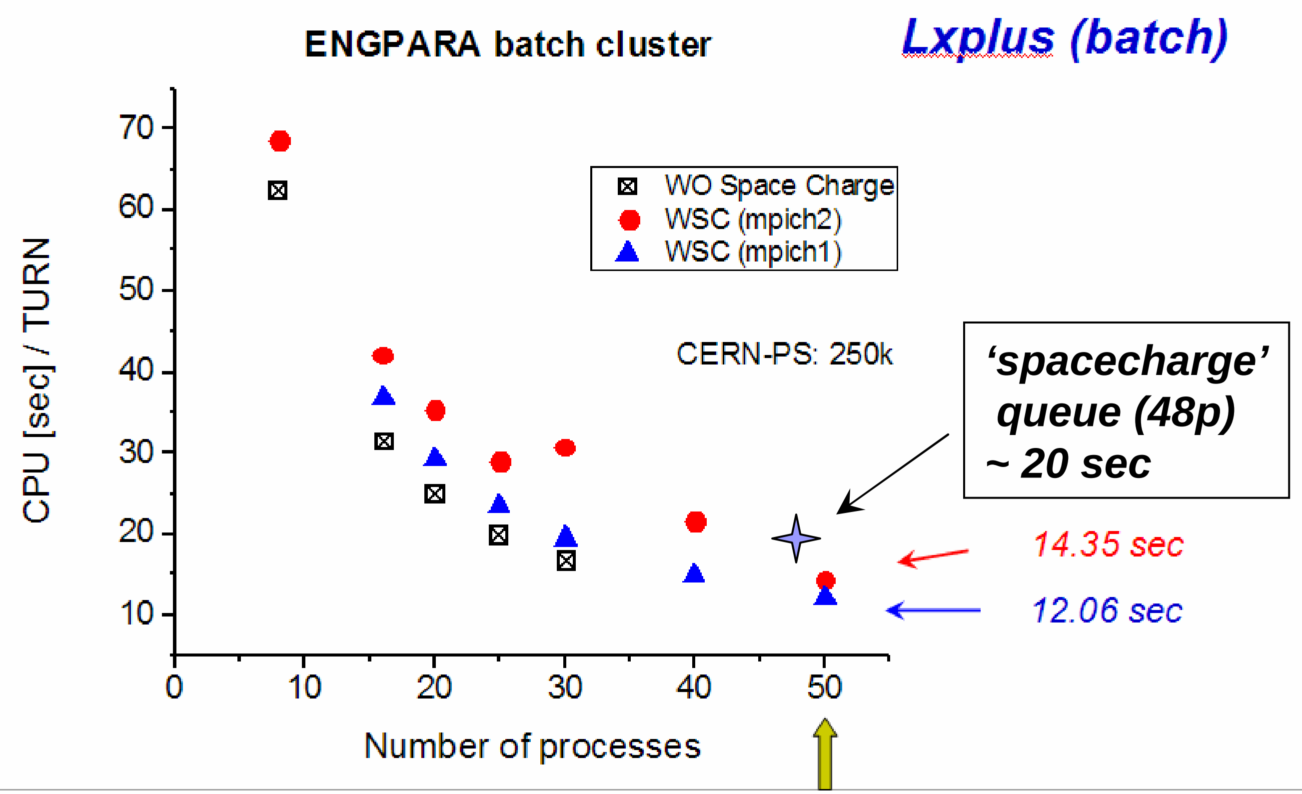
Common environment *for the single particle dynamics (lattice analysis and resonance compensation) and multi particle dynamics (collective effects).*

Computational tools …

- PTC-ORBIT(MPI) **is installed** on the CERN cluster
- PTC update **is synchronized** with the MADX update
- **PTC-ORBIT user notes** (04-25-12, p30) has been prepared and uploaded into the Space-charge Group home-page
- **Basic PTC-ORBIT scripts** have been prepared and uploaded into the Space-charge Group home-page
- **Batch script** has been prepared and tested for the ‘spacecharge’ queue

Dedicated 'spacecharge' queue …

CERN PS / CPU time



Machine's name

lxbsu2107
lxbsu2207
lxbsu2306
lxbsu2307
lxbsu2406
lxbsu2407
lxbsu2606
lxbsu2607
lxbsu2706
lxbsu2707

Convergence study

ORBIT(MPI) is the PIC code
→ in particular, FFT Particle-In-Cell without (adapted grid) or with (fixed grid) the boundary

→ Optimum set of the required parameters for the 'space-charge' model

o *… avoid artificial emittance growth ('core' and 'halo' parts of the beam)*

o *… reasonable CPU time per the '1 turn' tracking*

o *… N_{mesh} (X&Y), N_{mp}, L_{bin}, N_{spch} should be optimized for beams with different parameters (LHC type or CNGS type)*

Machine lattice:

PSB → basic IDEAL lattice without any errors <u>(static lattice)</u>
PS → basic IDEAL lattice → NO any correctors
SPS → basic IDEAL lattice
RCS → basic IDEAL lattice

Convergence study → *main parameters*

LHC type beam

	Beam intensity $\times 10^{12}$ *ppb*	Bunching factor	Tunes	Normalized emittances 1σ / π μm	Estimated $\Delta Q^{INC}_{sc,\,V}$
PSB 160MeV *LHC25*	*2.475 (1.5 nominal) (MTInj-20bl)*	*0.6 (τ_σ = 185ns)* *RF: 2nd harmonic*	*4.26 / 4.43*	*3 / 2* [official Excel datasheet]	*~ -0.26*
PS 1.4GeV *LHC50*	*0.81* *1.15*	*0.174 (T_F = 90ns)* *0.35 (T_F= 180ns)*	*6.21 / 6.23*	*1.45 / 1.32* *2.0 / 1.7*	*~ -0.26* *~ -0.23*
SPS 26GeV *LHC25*	*0.27*	*0.5 (τ_σ = 3 ns)*	*20.15 / 20.23*	*2.1 / 2.1*	*~ -0.16*
RCS 160MeV	*1.2$\times 10^{12}$ (1/2 nominal)*	*0.3*	*4.29 / 3.38*	*2.5 / 2.5*	*~ -0.15*

Convergence study

Optimized setting for main parameters of the 2.5D space charge model

PTC-ORBIT(MPI)

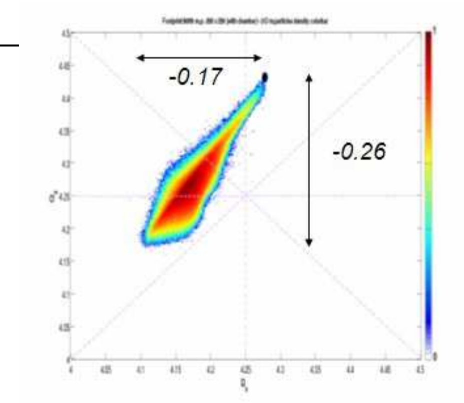
	Method	Lmax / N_{sp}	N_{mesh} (x=y)	$N_{macro} \times 10^3$	L_{bin}
PSB	*Fixed grid*	*1m / 199*	*256*	*1000*	*128*
	Adapted grid	*1m / 199*	*64*	*500*	*128*
PS	*Fixed grid **	*10m / 70*	*1024*	*250*	*128*
SPS	*Adapted grid*	*3.32m / 2688*	*64*	*200*	*128*
RCS	*Adapted grid*	*1m / 157*	*128*	*500*	*128*

** H: ± 73mm / V: ± 35mm*

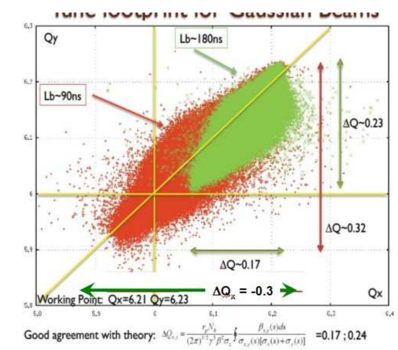
Convergence study

→ Simulated incoherent space-charge detuning
(beam parameters … Table “Main Parameters”)

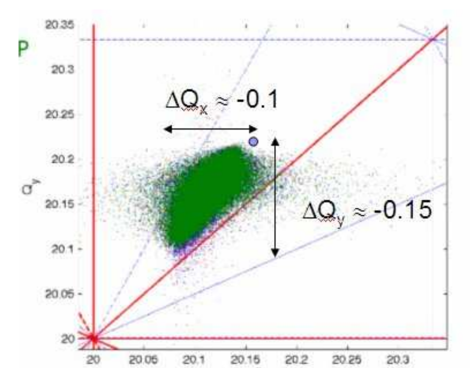
PSB



PS



SPS



… obtained space charge detuning is in good agreement with the performed estimation

MDs and code's benchmarking

Motivations:

- machine representation by using **a realistic lattice description** (including field and alignment imperfections of the machine magnets) …

- **reproduce the measured beam evolution** by the PTC-ORBIT tracking (including the particle losses during injection/acceleration process at different locations around the machine)
  … including the implemented resonance compensations

- **better understanding** the reasons for the observed effects

- to be sure that **predictions** of the beam evolution (losses) at different stages **are usable** to improve the machine performance during the machine upgrades …

MDs for the code's benchmarking

Goal:
→ Reproduce the measurements by the PTC-ORBIT tracking …
→ Improve the machine description (field and alignment errors) …

2012	PSB	PS	SPS
June	Tune scan: Integer resonance Montague resonance	RDT measurements	Tune scan: Integer resonance
	LHC25 type beam CNGS type beam		RDT measurements
	Longitudinal space charge effects		
August		Tune scan: Skew Sextupole [2,1,19] Montague resonance [2,2,0] Sextupole resonance [3,0,19] Linear coupling [1,1,0]	

PSB: MDs
… data for the benchmarking

☐MD#1: May 22-23, 2012
→ 'CNGS' (Bf=0.47) beam … tune scan

☐MD#2: June 4, 6-7
→ 'LHC25' (Bf=0.24, Bf=0.40) beam … tune scan

☐MD#3: June 18, June 20
→ Space Charge effects in the longitudinal plane
→'LHC25' beam (Bf=0.4) … Montague resonance study

☐MD#4: June 28
→ 'CNGS' beam (Bf=0.47) … Montague resonance study (checking MD#1)

Estimated incoherent space charge detunning*:

'CNGS' type beam
~900e10 ppb, 15/7.5μm
~ 1eV.sec
Bf=0.47 → ΔQ_{INC} ~ -0.25

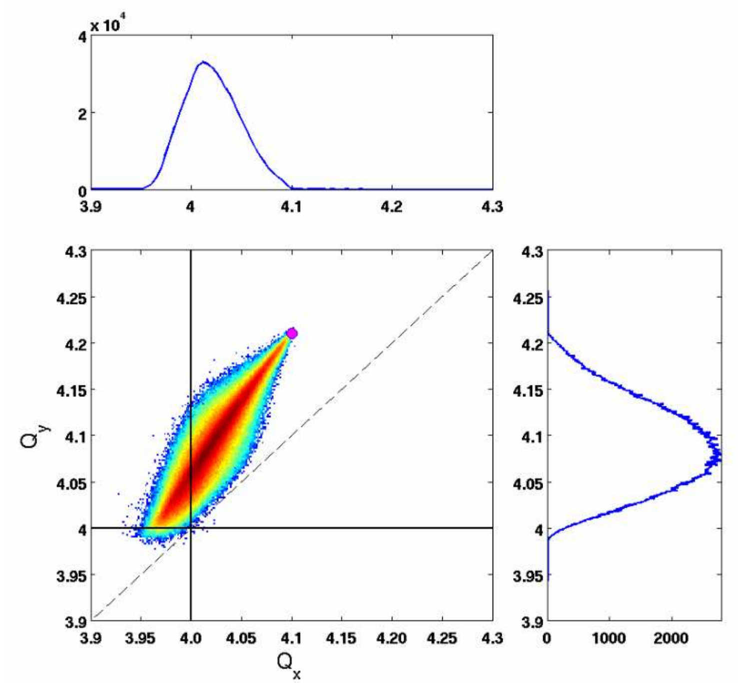
'LHC' type beam
~170e10 ppb, 3.4/1.8 μm
~ 0.6eV.sec
Bf=0.24 → ΔQ_{INC} ~ -0.45
Bf=0.40 → ΔQ_{INC} ~ -0.25

* *vertical detuning*

LHC25 type beam (B_f=0.40)

Q_x = 4.10, Q_y = 4.21

Footprint after 1000 turns

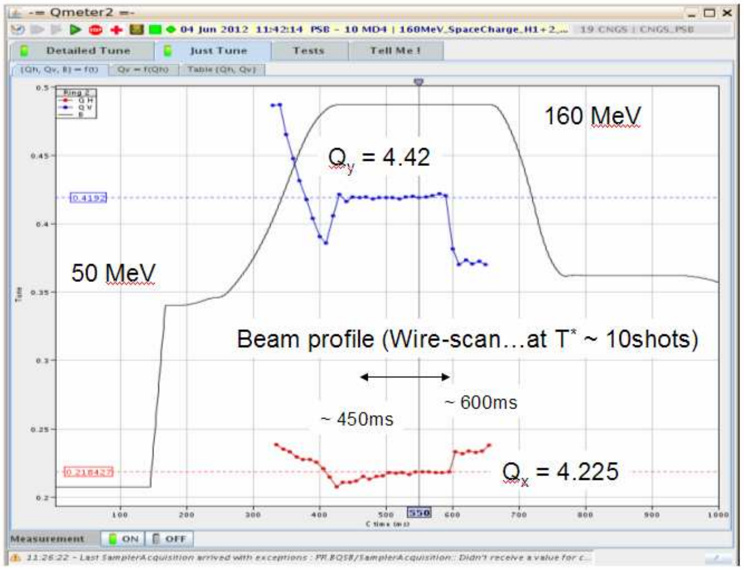


CERN PS booster

MDs for the code's benchmarking

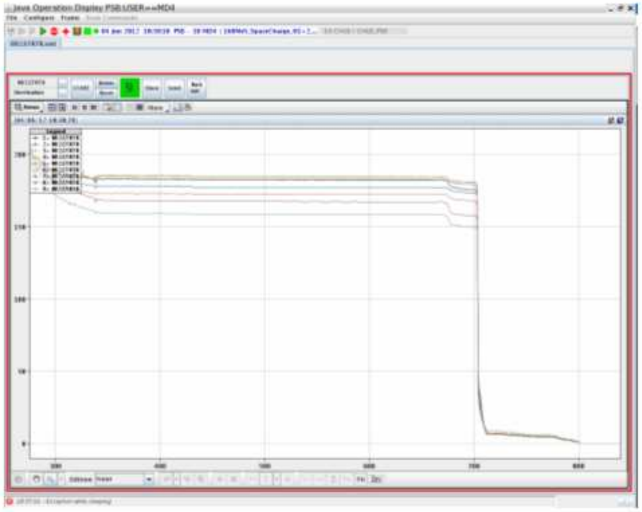
CERN PS booster setting

MD(PSB) setting: QM pattern



$Q_x = 4.11$, $Q_y = 4.21$

$B_f = 0.241$, $N_b = 149\times10^{10}$



> ➢ to reproduce the measured emittance evolution by the PTC-ORBIT tracking the emittance growth near the integer resonance Q_x=4 should be visible during < 50 msec … 50'000 turns …

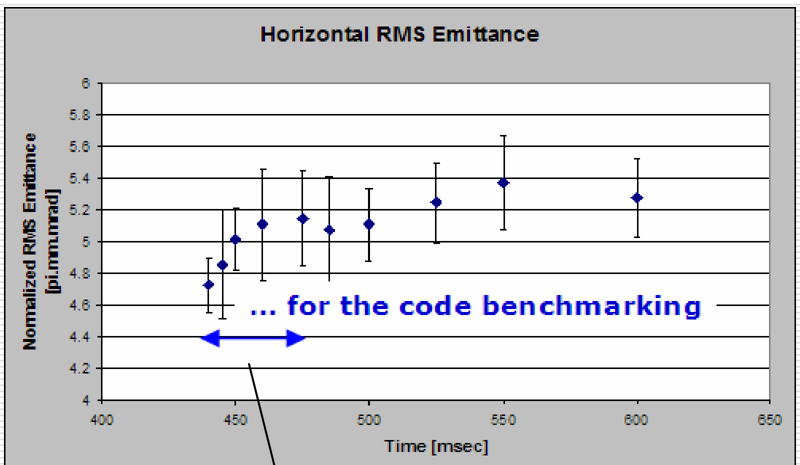
MDs for the code's benchmarking

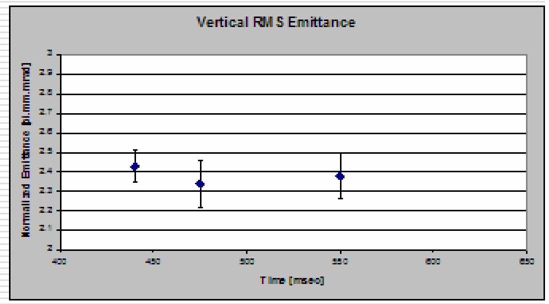
MD#2

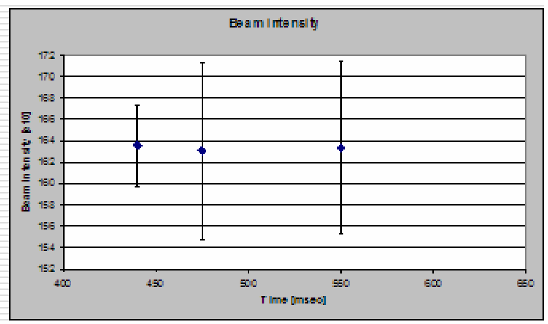
'LHC25' type beam

$B_f \sim 0.40$, $N_b \sim 170\times10^{10}$
$N_{inj} = 2.8$
ε_H(norm) ~ 3.4π mm.mrad
ε_V (norm) ~ 1.8π mm.mrad

$Q_x = 4.10$, $Q_y = 4.21$





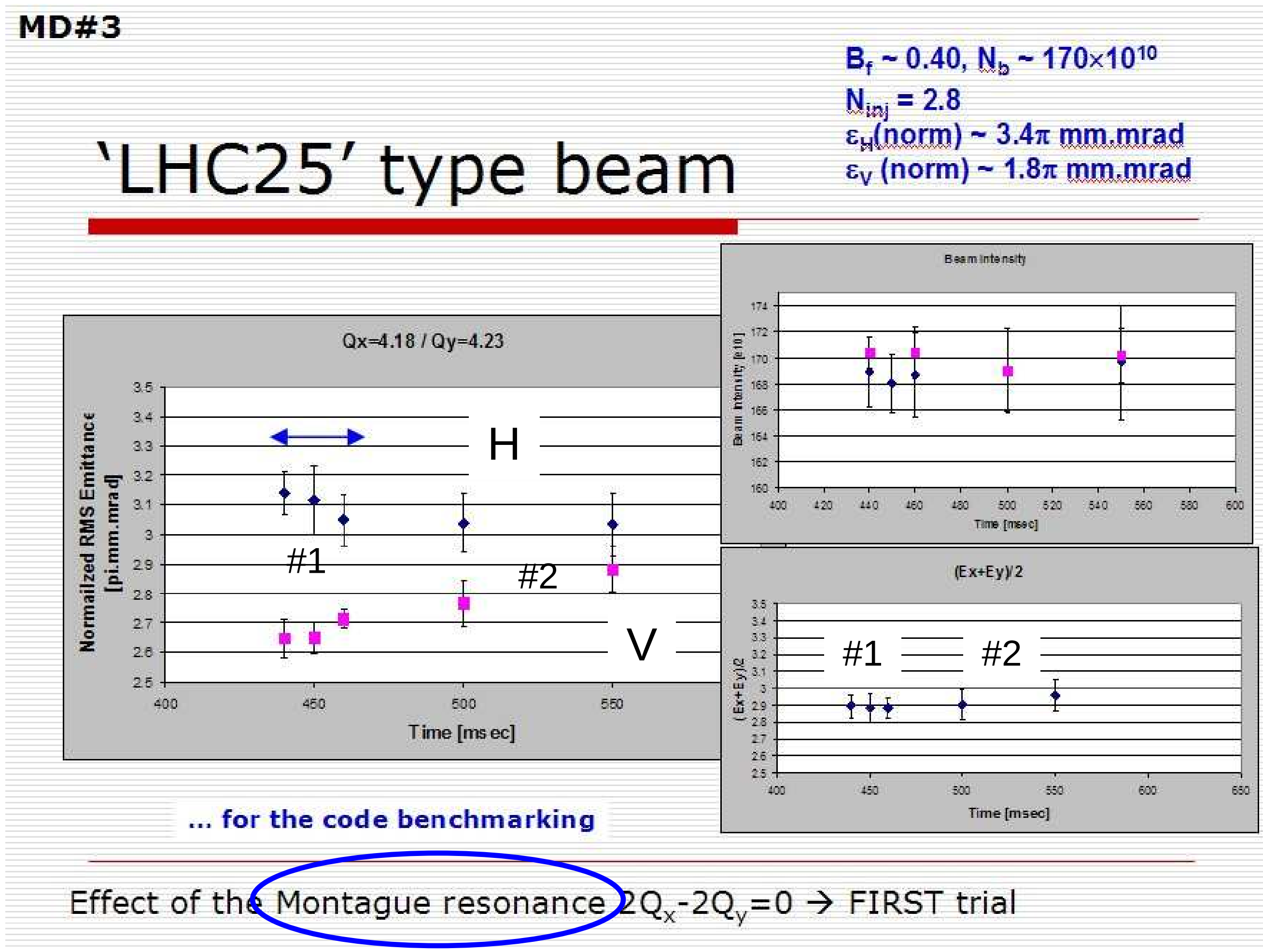


~ 50 msec

Effect of the INTEGER resonance $Q_x = 4$ (systematic)

CERN PS booster

MDs for the code's benchmarking



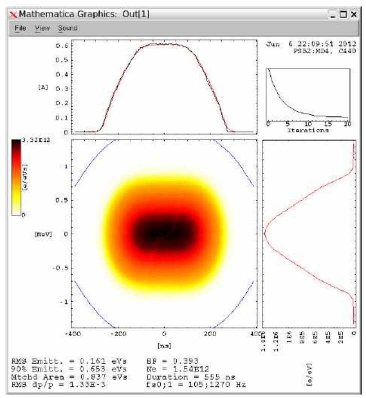
#1 → exchange of the H & V emittances
#2 → increasing the V emittance

CERN PS booster

PTC-ORBIT benchmarking

MD - Beam characteristics – longitudinal

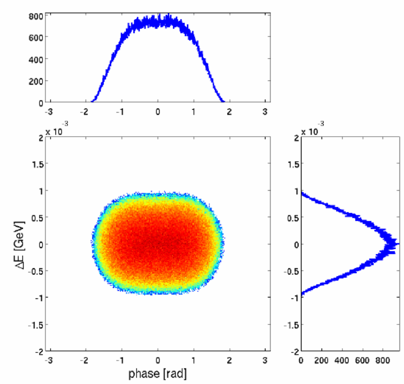
- h=1 - double harmonic RF +8kV & +4kV in antiphase
- Long bunch – B.f. ~0.39
- RMS emittance = 0.161 eVs
- RMS $\Delta p/p$ = 1.33e-3



Simulations - Beam characteristics – longitudinal

- 500e3 m.particles
- Long bunch – B.f. ~0.39
- RMS emittance ~ 0.16 eVs
- RMS $\Delta p/p$ ~ 1.33e-3

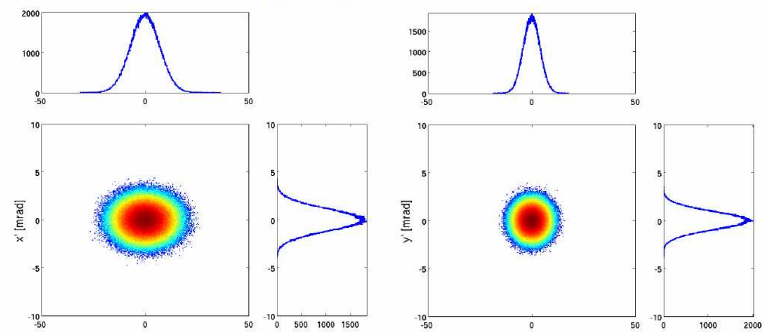
Thanks to Alexander for the longitudinal distribution



Simulations - Beam characteristics – transverse

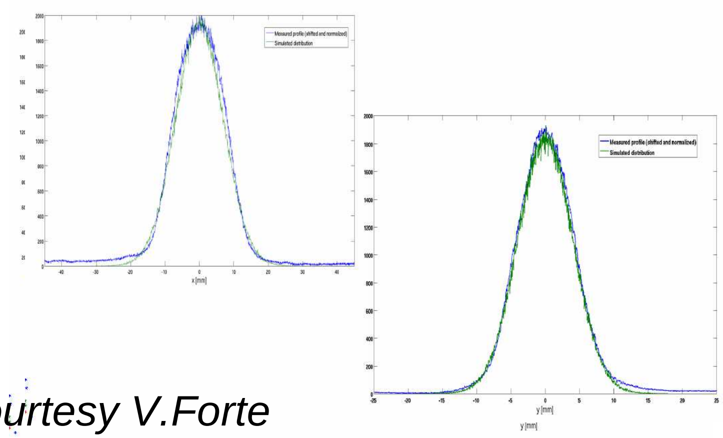
	αx	βx	αy	βy	Dx
Lattice (PTC)	-0.1889E-14	5.8138	-0.22351e-3	4.2509	-1.5215
500e3 (Matlab post p.)	-5.7985e-4	5.805	-7.7873e-4	4.2485	-1.5238

- εx (1 sigma – normalized) ~ **4.7235** mm-mrad
- εy (1 sigma – geometrical) ~ **2.3392** mm-mrad
- BetaGamma = 0.614



2D gaussian distribution

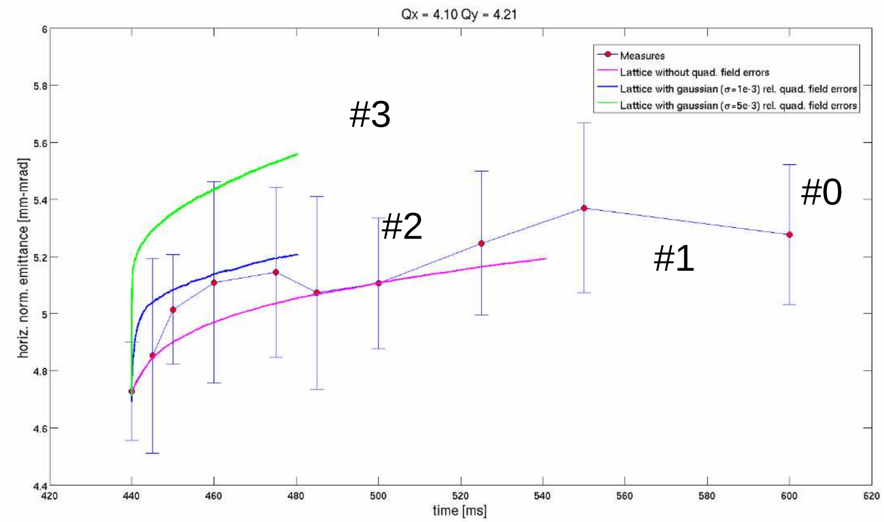
Profiles comparison – measured and simulated

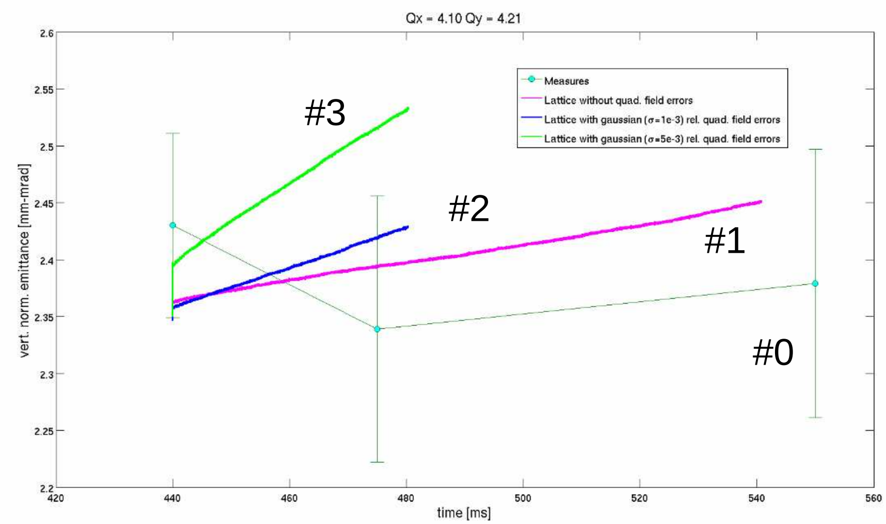


Courtesy V.Forte

CERN PS booster

PTC-ORBIT benchmarking





Effect of [1,0,4] resonance

W_{kin} = 160MeV

LHC25 beam
B_f ~ 0.4
$Q_x = 4.10$ / $Q_y = 4.21$

#0 → measurements
#1 → ideal lattice

#2, #3 → lattice with RANDOM errors $\{\delta K1\}_{QM}$
#2 : 1Sigma = 1.0×10^{-3} (relative value)
#3 : 1Sigma = 5.0×10^{-3}
Gaussian generator (no cut)

Courtesy V.Forte

CERN PS booster

Acceptable agreement between experimental data and simulation results (LHC25 beam)

Maximum random error of the PSB quadrupole magnets ~ 1.0×10^{-3} (1σ)

PTC-ORBIT benchmarking

CERN PS booster

Effect of the Montague resonance [2,-2,0]

W_{kin} = 160MeV

<u>LHC25 beam</u>

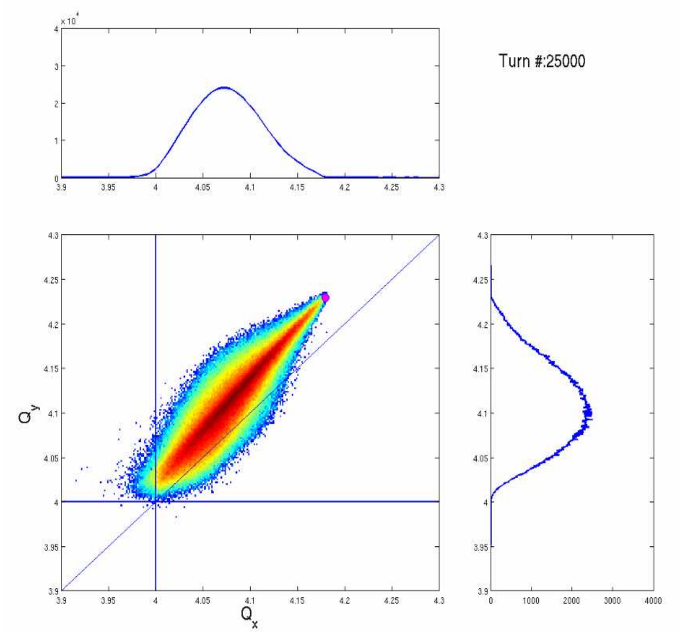
B_f ~ 0.4

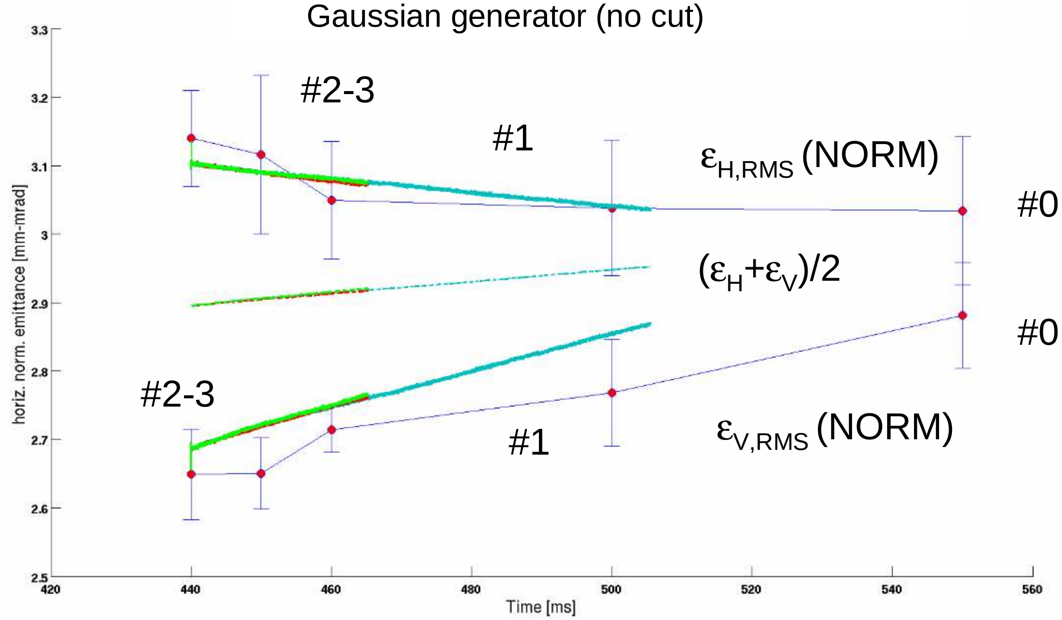
Q_x = 4.18 / Q_y = 4.23

#0 → measurements
#1 → ideal lattice

#2, #3 → lattice with RANDOM TILT of {QM}
#2 : 1Sigma = **2.17×10^{-5} rad**

#3 : 1Sigma = **4.28×10^{-5} rad**
Gaussian generator (no cut)





Courtesy V.Forte

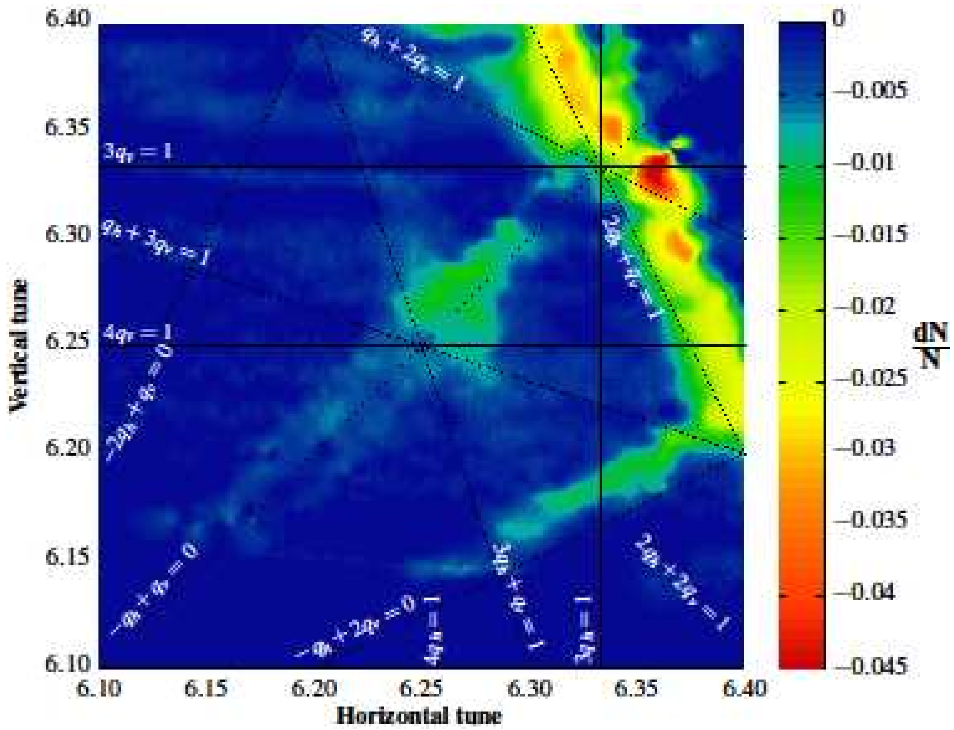
PS MDs for the code's benchmarking

PS dedicated MDs to study the machine imperfection ('pure' lattice) at the injection energy of 1.4GeV …

CERN PS

- ❑ Skew sextupole coupling resonance
- ❑ Linear coupling resonance
- ❑ Montague resonance
- ❑ $3Q_x$ resonance

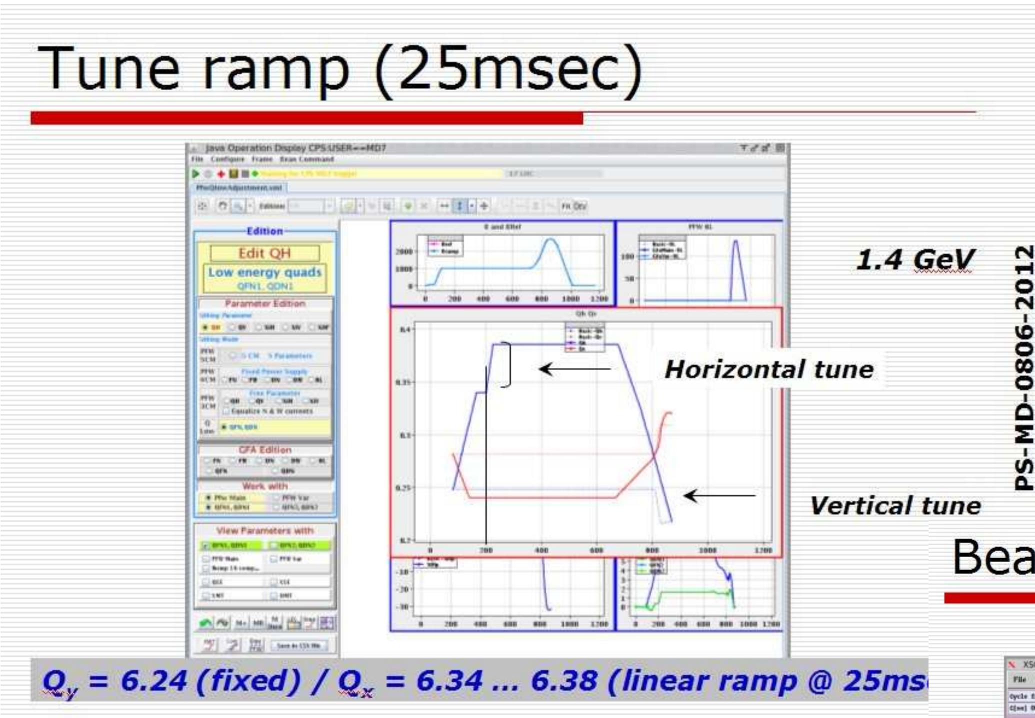
Different beam parameters:
- ▪ EASTB → $\Delta Q_y \sim -0.09$
- ▪ LHC_INDIV → $\Delta Q_y \sim -0.015$



Courtesy Alexander Huschauer

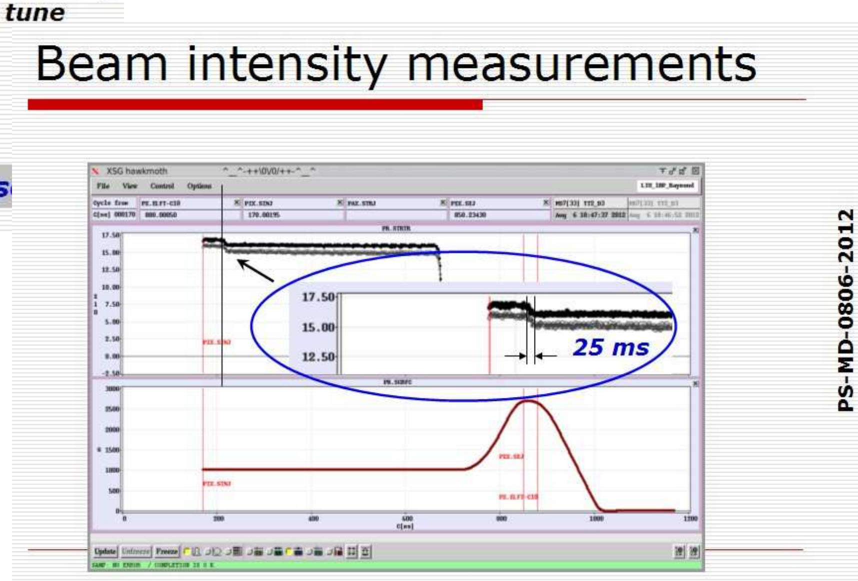
→ Data accumulation for future simulations …

PS MDs for the code's benchmarking



'EASTB' beam

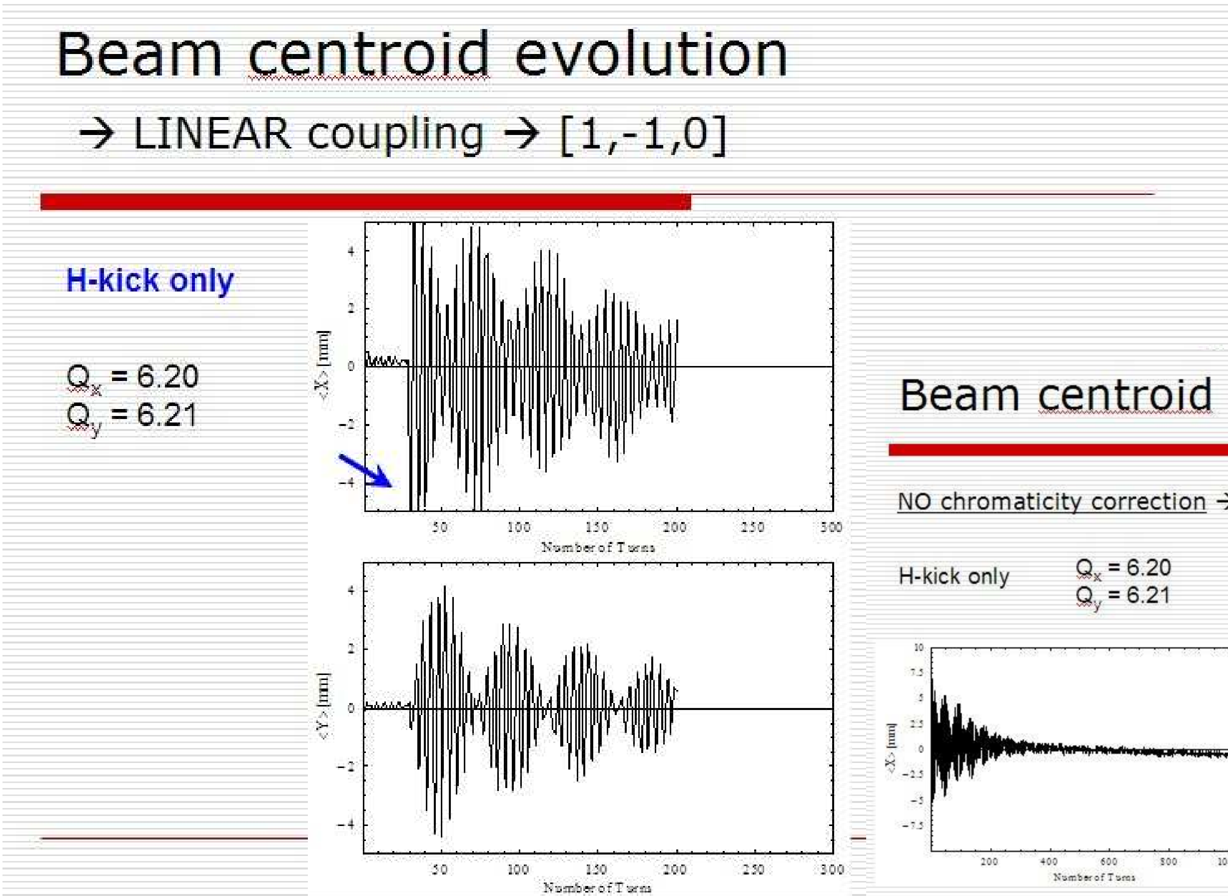
CERN PS

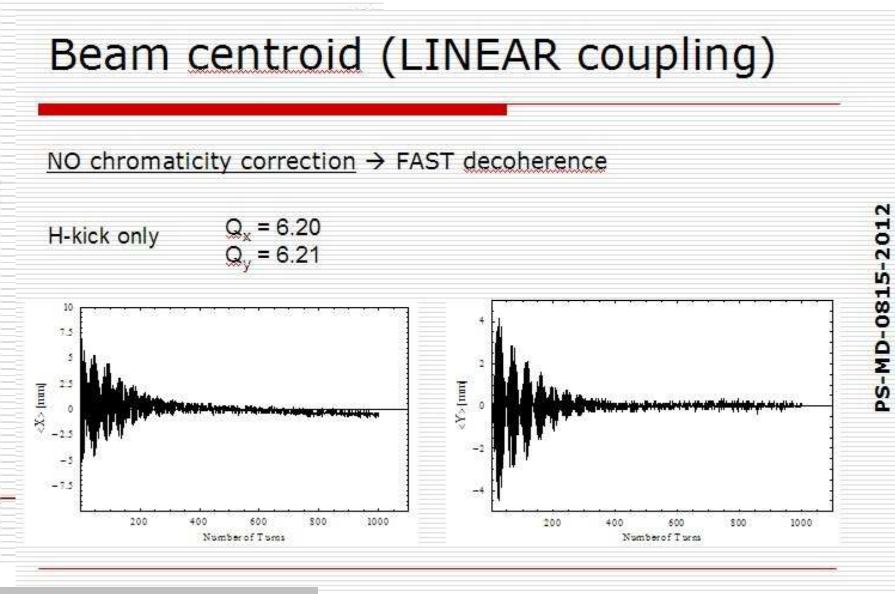


CERN PS setting and observations …

PSW MDs for the code's benchmarking

LHC_INDIV beam





CERN PS

TODO: *implementation the skew-field components in the lattice to reproduce these observations*

SPS MDs for the code's benchmarking

CERN SPS

- Effect of the INTEGER resonance for the PTC-ORBIT code benchmarking

Single bunch injection (Q20 optics)

Intensity ~ 2.7×10^{11} ppb (maximum acceptable)
Bunch length at the injection into SPS ~ 4nsec
Transverse emittance, measured at extraction from PS ~ 1.2μm
Estimated incoherent space-charge detuning (ΔQ_H~ -0.15, ΔQ_V~ -0.25)

Intensity ~ 1.2×10^{11} ppb (LHCindiv)
Transverse emittance, measured at extraction from PS ~ 1.2μm
Estimated incoherent space-charge detuning (ΔQ_H ~ -0.07, ΔQ_V ~ -0.11)

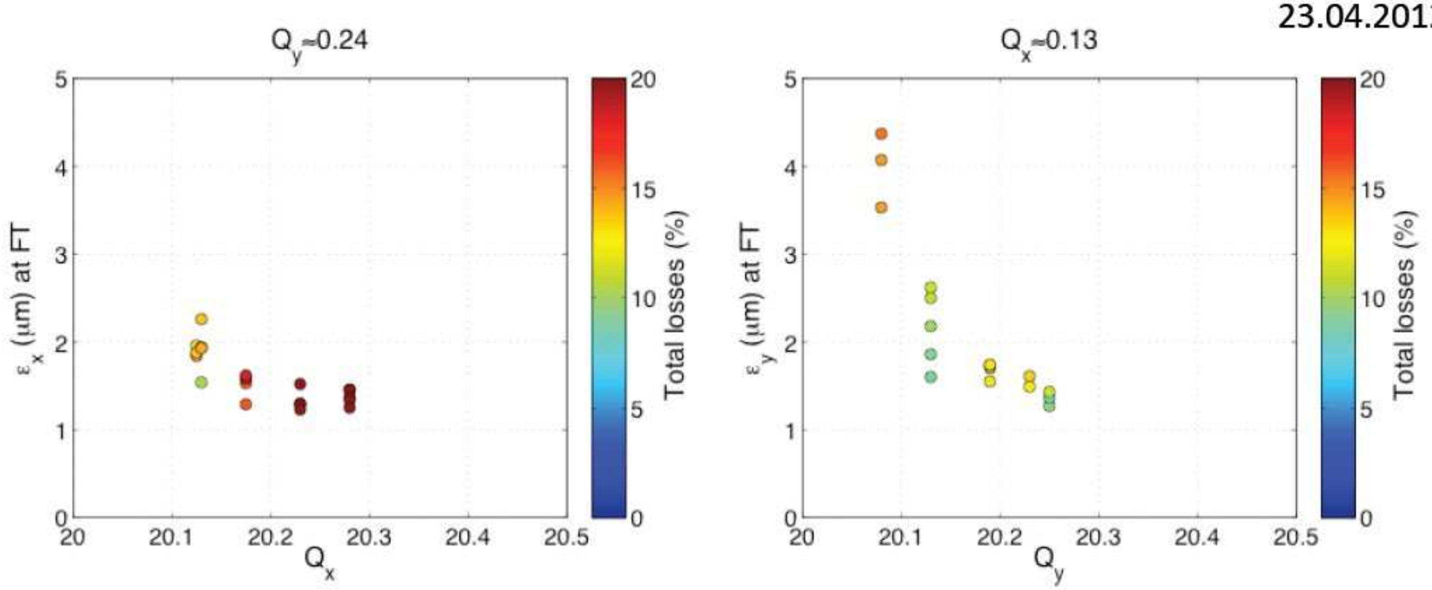
Dedicated MDs using the long cycle:
10.8sec flat bottom and ramp to 450GeV

- Emittance and Losses measurements for different tunes …

SPS MDs for the code's benchmarking

Estimation of space charge tune spread

23.04.2012



- **Approaching the integer resonances leads to**
  - Emittance blow up in the respective plane
  - A reduction of losses in the horizontal plane (
  - Increasing losses in vertical plane aperture restriction
- **For 2.7e11p/b and about $(\varepsilon_x+\varepsilon_y)/2$~1.0-1.2µm injected**

6

$\Delta Q_x \approx 0.15$ / $\Delta Q_y \approx 0.25$

Courtesy H.Bartosik

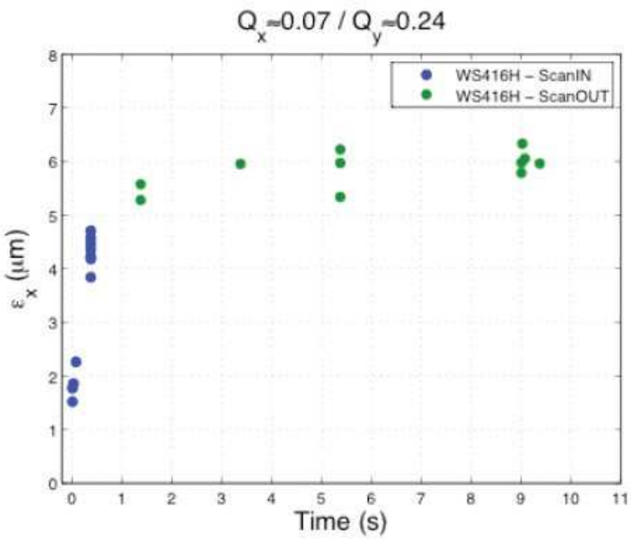
High-intensity beam

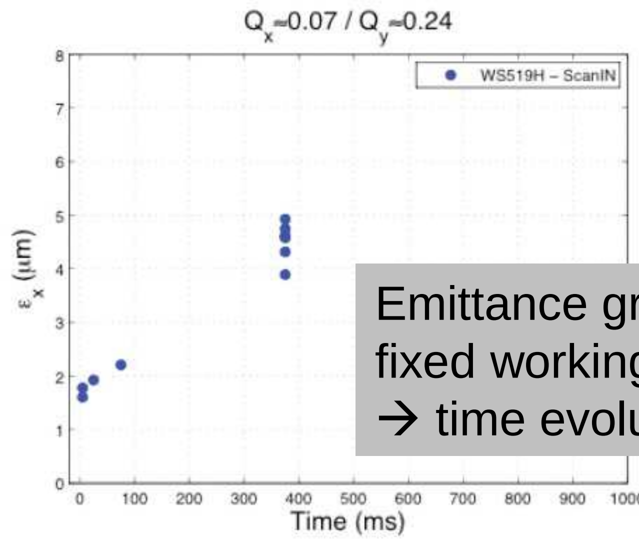
CERN SPS

SPS MDs for the code's benchmarking

Emittance growth for Qx close to integer

26.04.2012





Emittance growth for the fixed working point
→ time evolution …

CERN SPS

- **Same beam parameters as on 24.05.2012 (see above) initial tune spread is about ΔQ_x≈0.15 / ΔQ_y≈0.25**
- **(lossless) blow up of the core**
  - εx>2μm after 40ms
  - εx~4-5μm after 400ms

Courtesy H.Bartosik

SPS MDs for the code's benchmarking

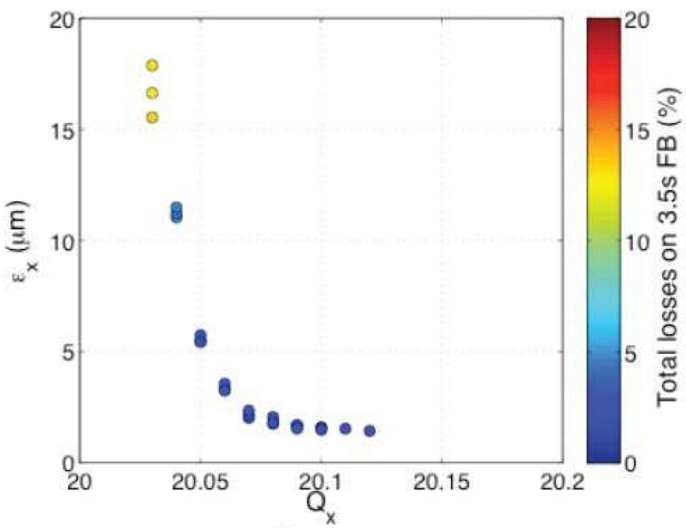
Behavior close to integer resonances

04.05.2012

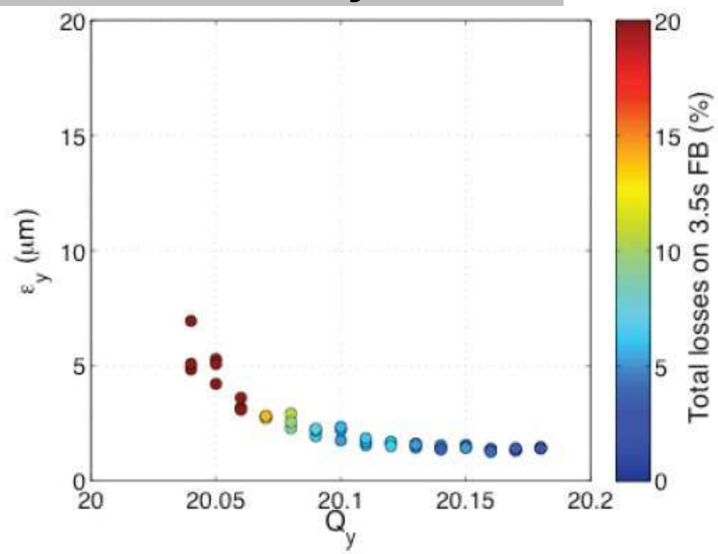
- **Parallel MD** **short flat bottom cycle**
- **Standard LHCindiv bunch** **1.2e11p/b with $(\varepsilon_x+\varepsilon_y)/2$~1.2μm**
  - Expect ΔQ_x~0.07/ΔQ_y~0.11

Courtesy H.Bartosik

Low-intensity beam



9



Large aperture in horizontal plane allows for huge emittance blow-up without losses

Aperture limitations in vertical plane lead to increasing losses with vertical beam size

CERN SPS

Conclusion

→ *short summary of activity*

- many items for different CERN machines (including the conceptual RCS design / Miriam Fitterer) have been performed successfully during this short period of time (March-July)

TODO

- ❑ continue this activity to improve the machines representation
- ❑ continue MDs to accumulate data for the benchmarking and for better understanding the beam dynamics
- ❑ by using the improved lattices (based on MDs and benchmarking simulations by the PTC-ORBIT code) study different scenarios for the LHC Injectors Upgrade

Items in consideration …

- **PSB:**

- MT injection process (with double harmonic RF system) for the high beam intensity (ΔQ_V up to -0.36) by using the dynamic chicane variation with ‘active’ compensation the half-integer resonance

- Effects of the short bending magnets

- Conceptual **RCS** design

- effects of the space charge at the injection energy