HB2012
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PTC-ORBIT Studies for the CERN LHC Injectors Upgrade Project

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KEK CERN

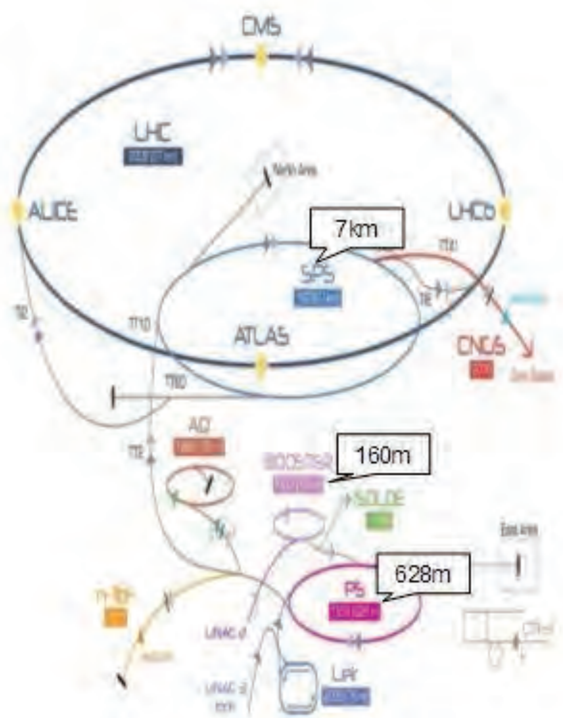
LHC Injectors Upgrade

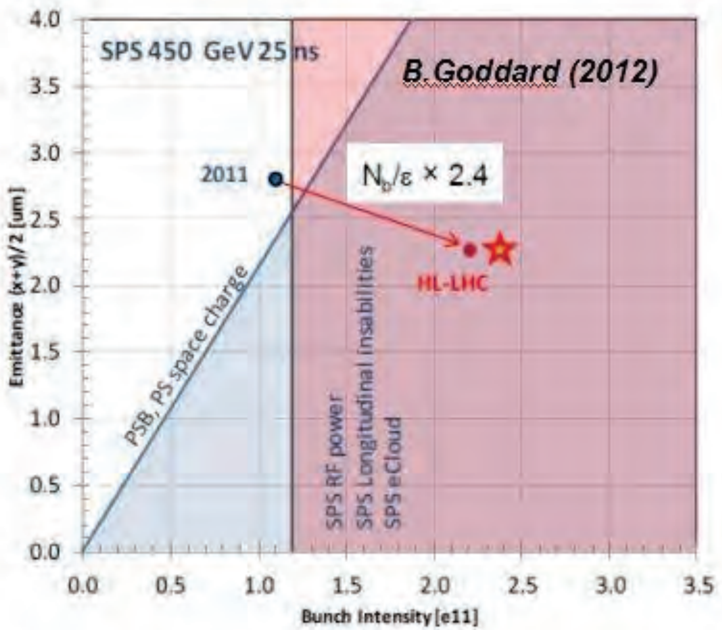
Outline

- Motivation
- Computational tools
- ‘Space-charge’ convergence study
- Machine study and the code benchmarking
- ‘Dynamic’ simulations of the Multi-turn injection for the CERN PS Booster
- Observation of the space charge effects for CERN PS and SPS
- Conceptual design of the CERN RCS

▪ Motivation

➢ *CERN LHC (25nsec) beam upgrade scenario (LIU request)*





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

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

▪ Motivation

➢ *Space charge detuning estimations for the LHC Injectors*

- **LINAC2** (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 $\Delta Q_y \approx -0.15$

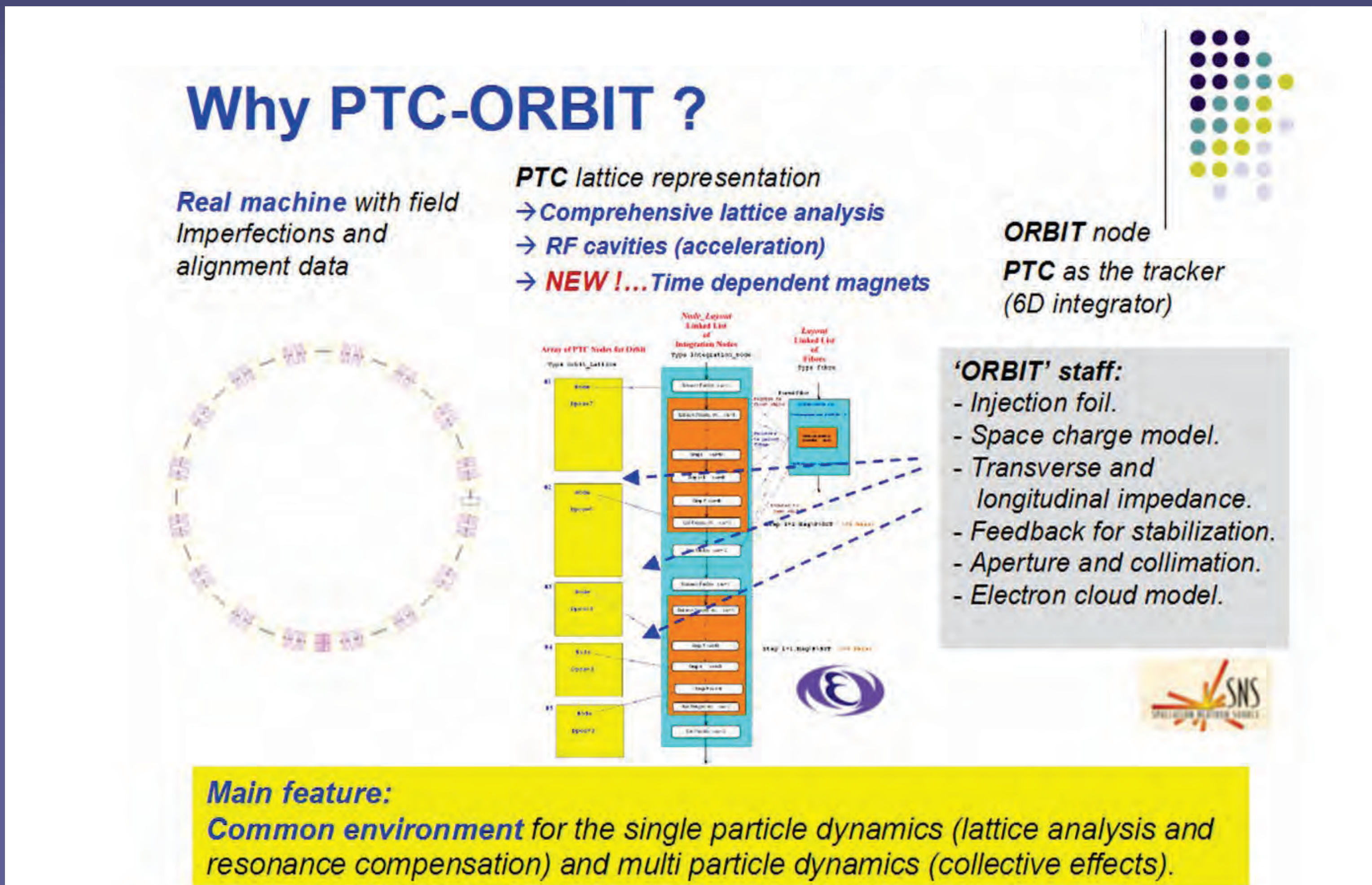
… need to increase $\Delta Q_y \approx -(0.20 \ldots 0.25)$

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

B_f=0.4 → $\Delta Q_y \approx -0.25$
B_f=0.3 → $\Delta Q_y \approx -0.37$

▪ Computational tools



▪ ‘Space-charge’ 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
- *… avoid artificial emittance growth (‘core’ and ‘halo’ parts of the beam)*
- *… reasonable CPU time per the ‘1 turn’ tracking*
- *… 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 (static lattice)
PS → basic IDEAL lattice → NO any correctors
SPS → basic IDEAL lattice
RCS → basic IDEAL lattice

LHC type beam

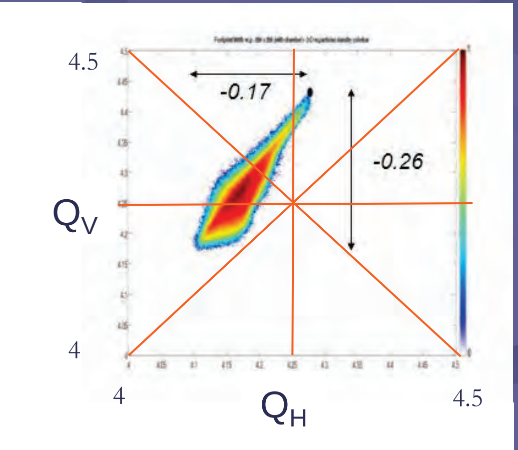
	Beam intensity $\times 10^{12}$ ppb	Bunching factor	Tunes	Normalized emittances $1\sigma / \pi$ µm	Estimated $\Delta Q^{INC}_{sc,V}$
PSB 160MeV LHC25	2.475 (1.5 nominal) (MTInj-20bl)	0.6 (τ_σ = 185ns) RF: 2nd harmonic	4.26 / 4.43	3 / 2 official Excel datasheet	~ -0.26
PS 1.4GeV LHC50	0.81 1.15	0.174 (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	1.2×10^{12} (1/2 nominal)	0.3	4.29 / 3.38	2.5 / 2.5	~ -0.15

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*

Space charge detuning
for CERN PS-Booster (160MeV)



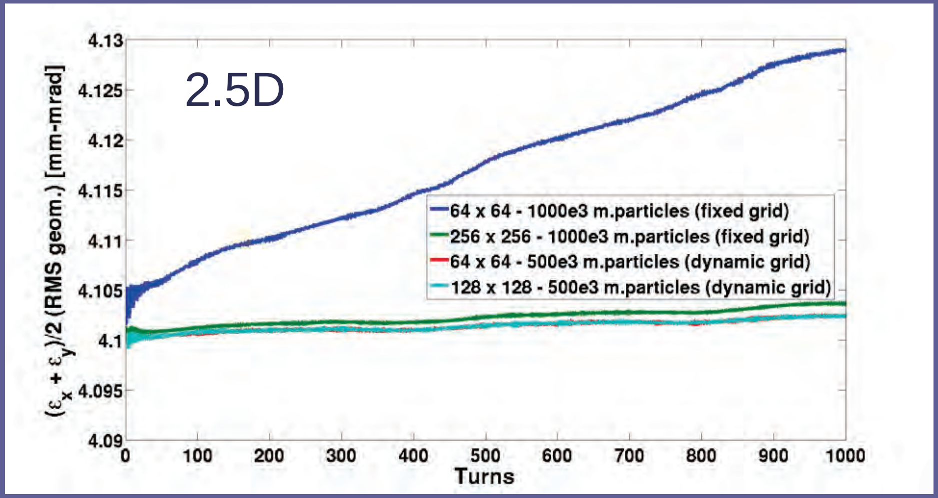
2D histogram

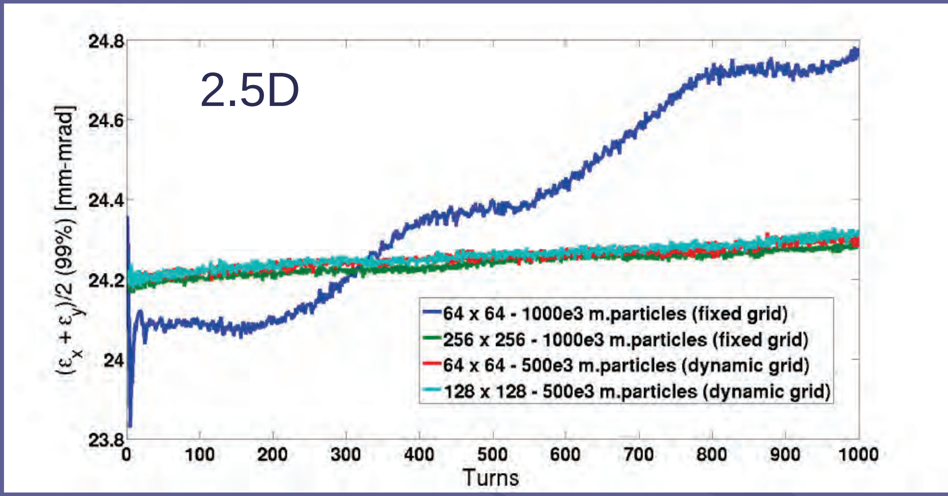
Q_H/Q_V=4.26/4.43

PTC-ORBIT(MPI)

▪ 'Space-charge' convergence study

➢ RMS and 99% emittance evolution for different sets of the 'space charge' module of the code for the case of the lattice tunes Q_H / Q_V = 4.26 / 4.43 (CERN PS Booster)





RMS emittance evolution

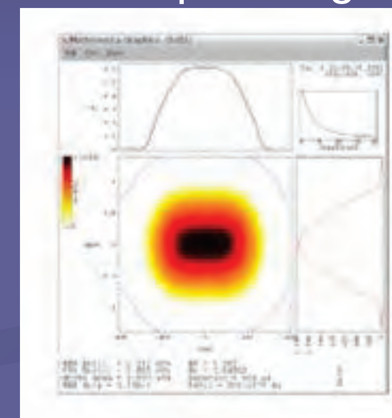
Evolution of the 'halo' part of the beam

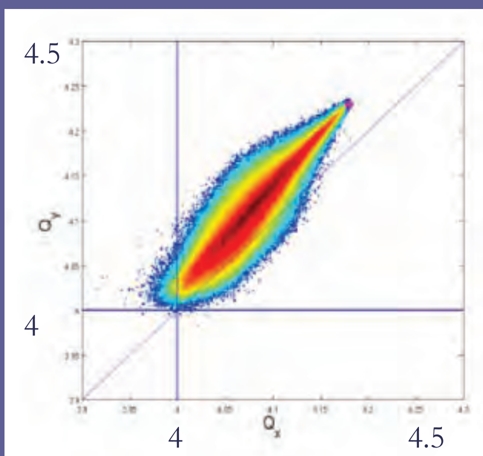
PTC-ORBIT(MPI)

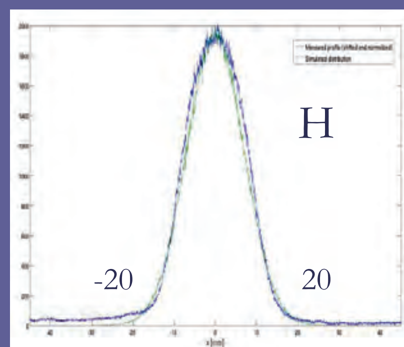
▪ Machine studies (MD-2012) and the PTC-ORBIT code benchmarking

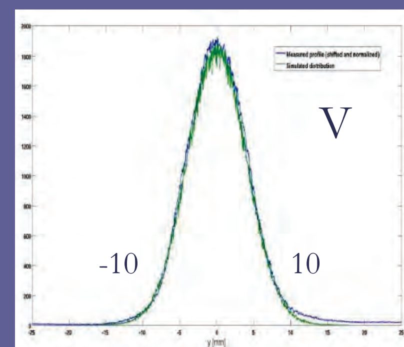
Motivation:
- **reproduce** the measured beam evolution at 160MeV by the PTC-ORBIT tracking

Measured beam profile
'Tomoscope' image

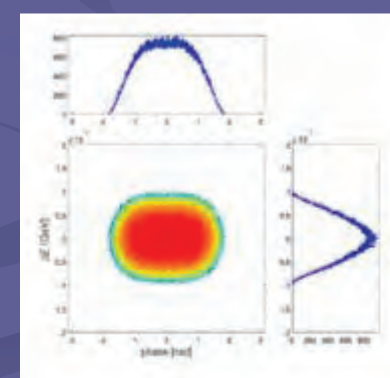








Generated beam profile



Foot print

Q_H/Q_V=4.18/4.23

<u>LHC25 beam</u>

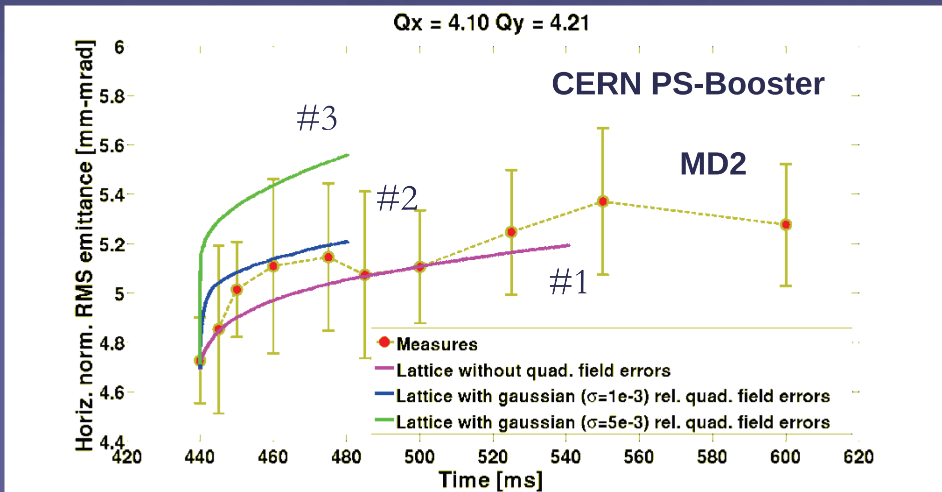
B_f ~ 0.4

PTC-ORBIT(MPI)

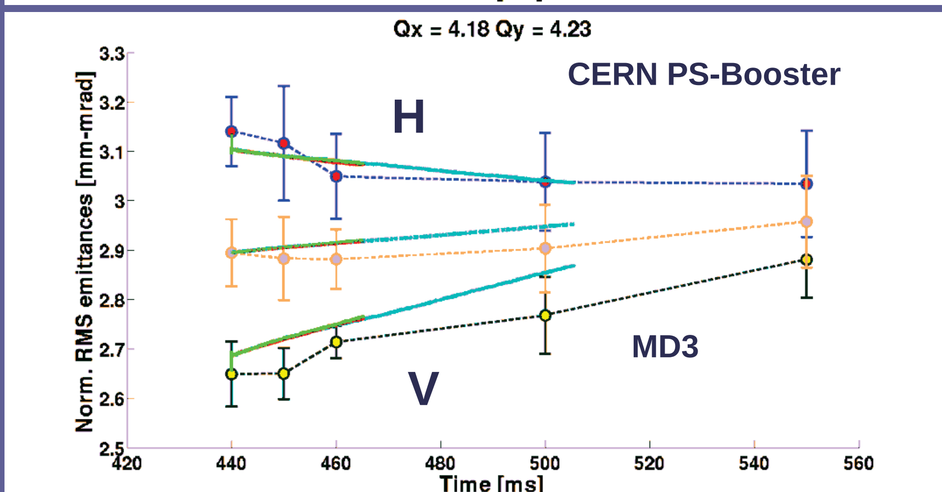
Generated and measured transverse beam profile at the 160MeV energy

▪ Machine studies (MD-2012) and the PTC-ORBIT code benchmarking

[1,0,4] resonance



[2,-2,0] resonance



→… taken into account the random error of the quadrupole strength of the PS Booster magnets

→ lattice with RANDOM errors {δK1}QM

#1: 'ideal' lattice

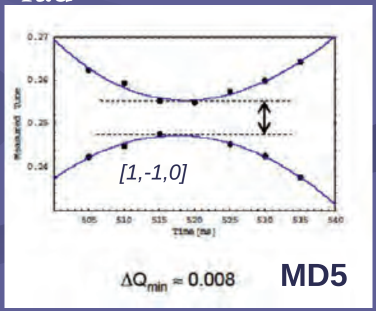
#2 : 1Sigma = 1.0×10^{-3} (relative value)

#3 : 1Sigma = 5.0×10^{-3}

→… including the random TILT of the PS Booster quadrupole magnets

Up to 1Sigma = **4.28×10^{-5} rad**

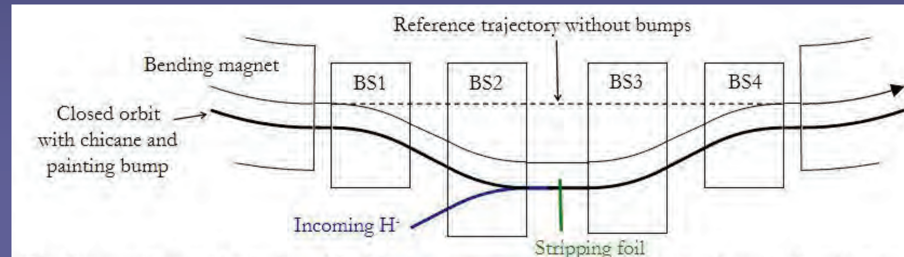
Linear coupling of the PS Booster: $\Delta Q_{MIN} \approx 0.008$



→Accuracy of the RMS emittance measurements should be improved …

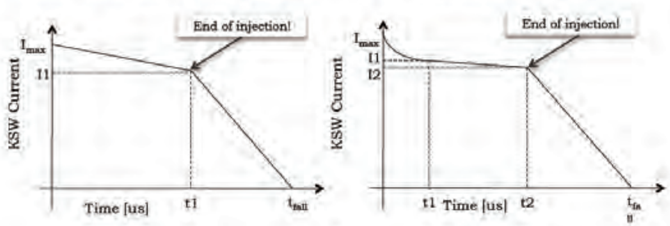
▪ Multi-turn injection for the CERN PS Booster with LINAC4

- ❑ Significant improvement of the efficiency of the MT injection by using the H$^-$ stripping injection in the H-plane
- ❑ Control over both transverse emittances
- ❑ Effects of the edge-focusing of the ‘slow’ bump-magnets, changing during the chicane reduction



Injection straight at the beginning of the injection (trajectory of incoming H$^-$ coincides with closed orbit)

KSW Decay – possible waveforms



Linear KSW Decay:

✓ Slow linear KSW decay until end of injection.

✓ Fast decay to 0 in order to move the beam away from the stripping foil (15 us)

Exponential-Linear KSW Decay:

✓ Fast exponential decay over first few turns

✓ Slow linear KSW decay until end of injection.

✓ Fast decay to 0 in order to move the beam away from the stripping foil (15 us)

KSW Parameters

	LHC Beam	CNGS Beam
I1	94% I_{max}	71% I_{max}
I2	92% I_{max}	70% I_{max}
t1	7 us	10 us
t2	20 us	49 us
t_{fall}	35 us	64 us

I_{max}: current corresponding to a bump height at the foil of -35 mm

Kicks for a 55 mm bump at the foil:
KSWP16L1: 8.74 mrad ➔ 0.045 T
KSWP1L4: 2.55 mrad ➔ 0.013 T
KSWP2L1: 2.55 mrad ➔ 0.013 T
KSWP16L4: 8.74 mrad ➔ 0.045 T

Functions have to be defined for varying the dI/dt of the KSW during injection.
Different functions for different users ➔ high flexibility is required

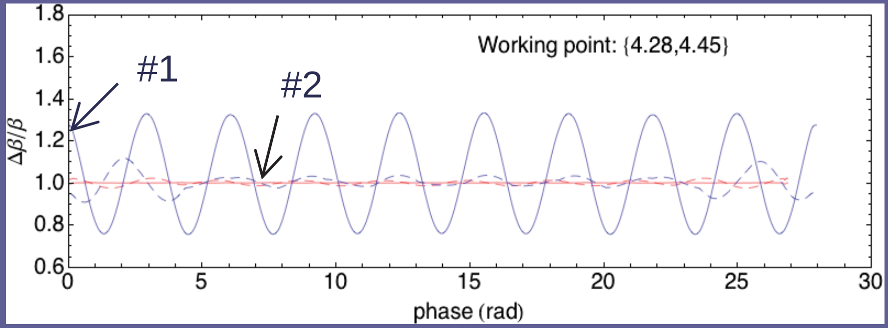
▪ Multi-turn injection for the CERN PS Booster with LINAC4

- ❑ Lattice tunes: **Q_H / Q_V =4.28/4.45**
- ❑ **Q_V could be above 4.5 …**
- ❑ **Compensation the V beta-beating effect**

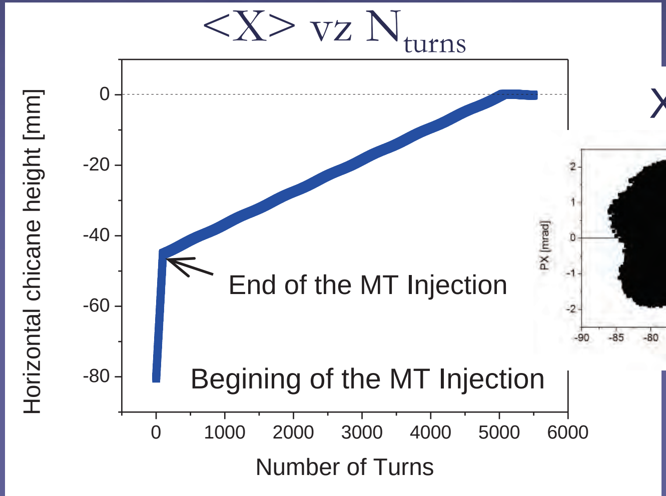
→ Active compensation scheme by using 2 independent families of quads

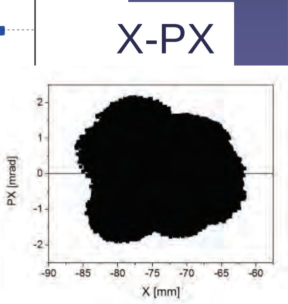
→ Reduction of the V-beta beat: 35% → 5%

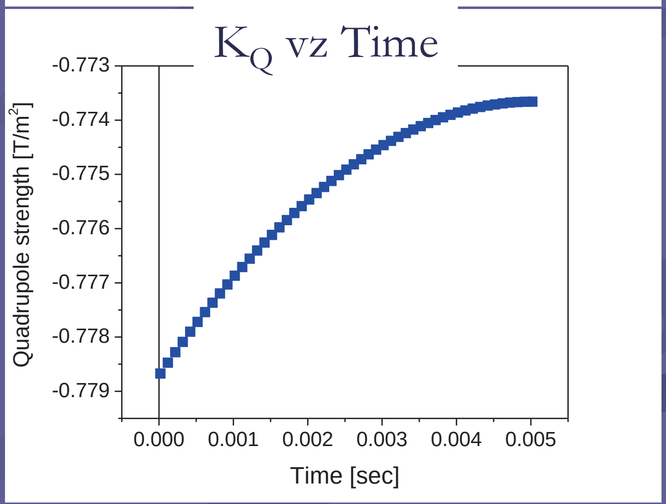
→ Dynamic changing the quad strength during the chicane's fall from MAX (≈ -80mm) to ZERO



V beta-beating around CERN PS Booster:
#1 – before; #2 – after the 'active' correction



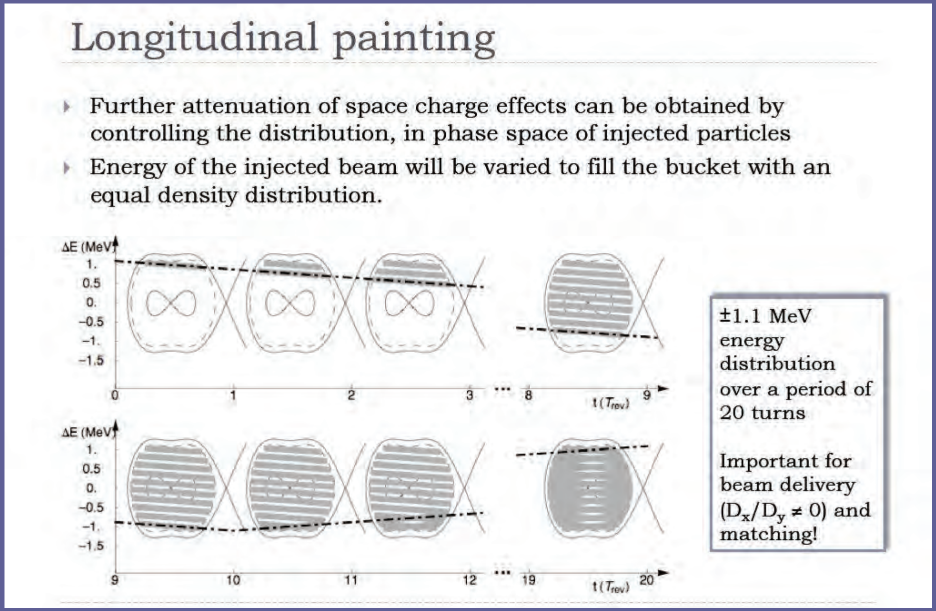




PTC-ORBIT(MPI)

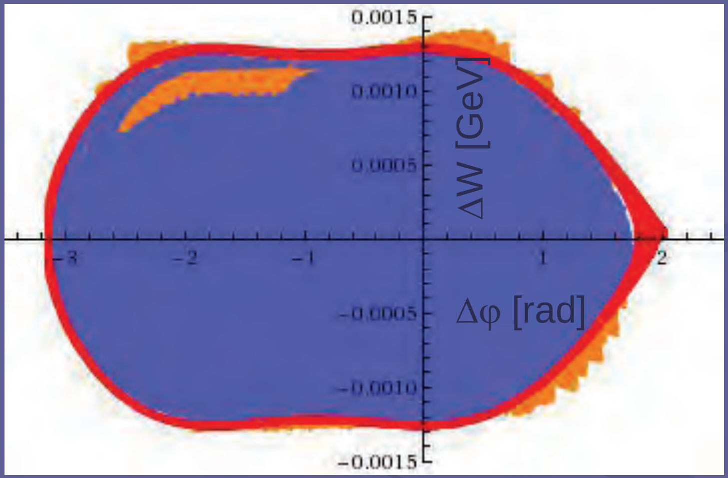
▪ Multi-turn injection for the CERN PS Booster with LINAC4

Double harmonic RF system with the longitudinal stacking of the bunches



Particle distribution after 5520t

PTC-ORBIT (space charge → ON)

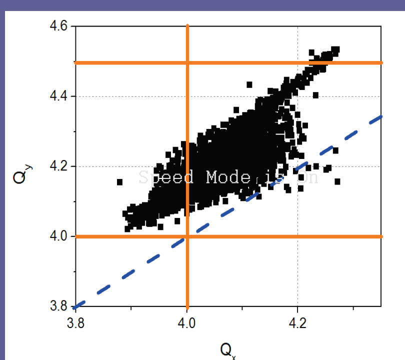


Capture efficiency ~ 98%, B_f ~ 0.6

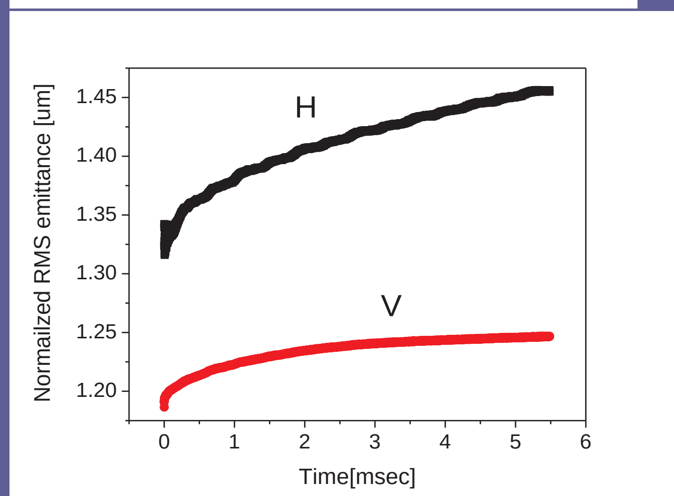
PTC-ORBIT(MPI)

▪ Multi-turn injection for the CERN PS Booster with LINAC4

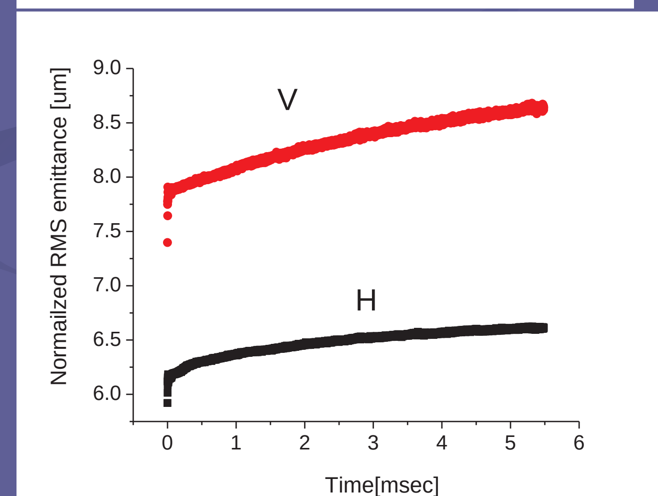
- Transverse emittance evolution (NO FOIL)
- V OFF-set (~3mm) to control the Vertical emittance
- Space Charge effects → ON (adapted grid) … 35.2e10ppb
- Incoherent space charge detuning < -0.5, Lattice tune Q_H / Q_V = 4.27 / 4.58



RMS Normalized Emittance



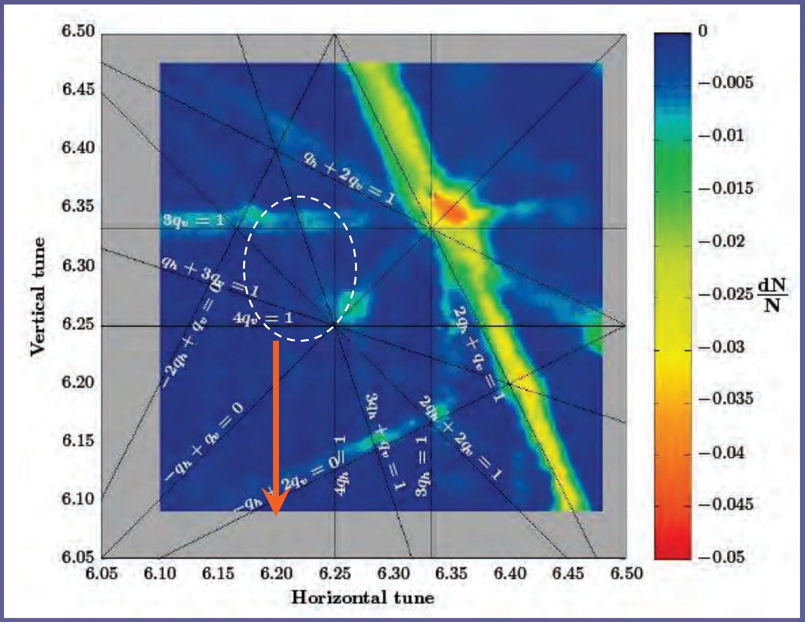
99% Normalized Emittance



✓ Effects of FOIL, Aperture limitation, machine imperfections should be analyzed

PTC-ORBIT(MPI)

▪ CERN PS: space charge effects and machine resonances



Tune scan at the energy 2.0GeV
Typical tune-spread H,V ~(-0.18, -0.28)

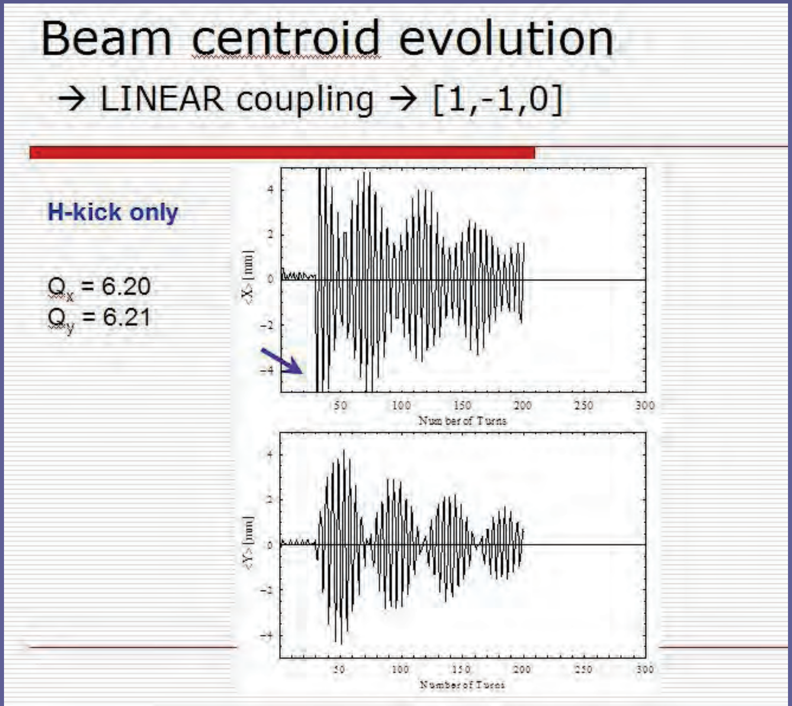
S.Gilardoni talk

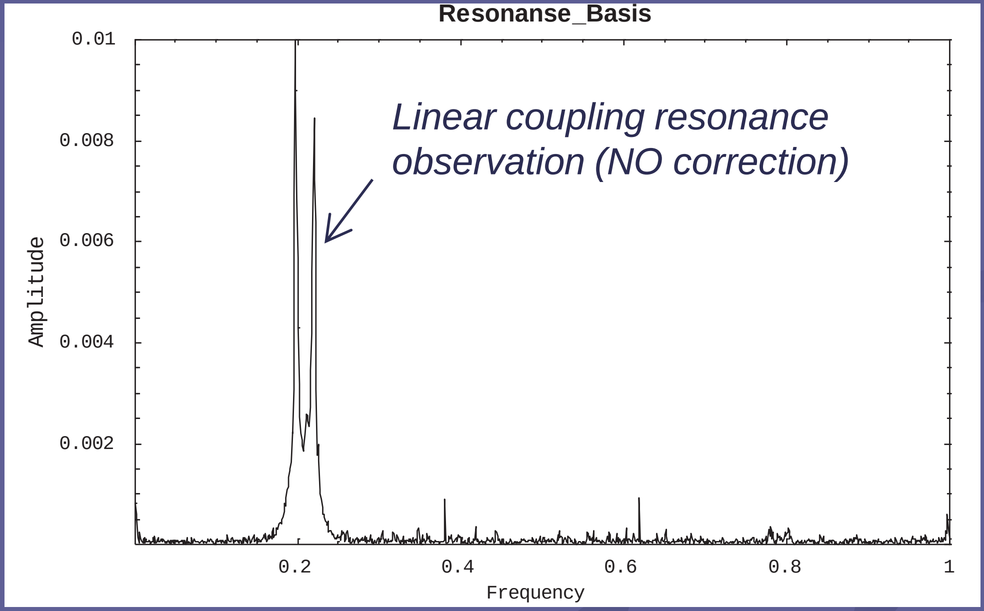
- Emittance growth near the [0,1,6] resonance has been studied experimentally … for the code benchmarking
- Resonance Driving Terms:
  → 'pencil' beam (LHC-INDIV)
  → different horizontal kick strength
- 'Realistic' machine description by using the measured field nonlinearities of the PS magnets …
  … in progress … to reproduce the experimental observations.

▪ CERN PS: space charge effects and machine resonances

'LHC-INDIV' beam

[1,-1,0] resonance observation



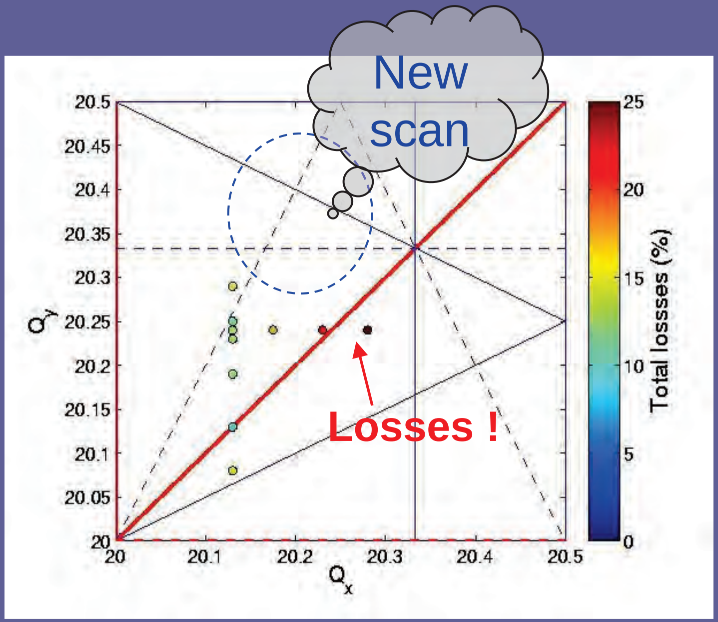


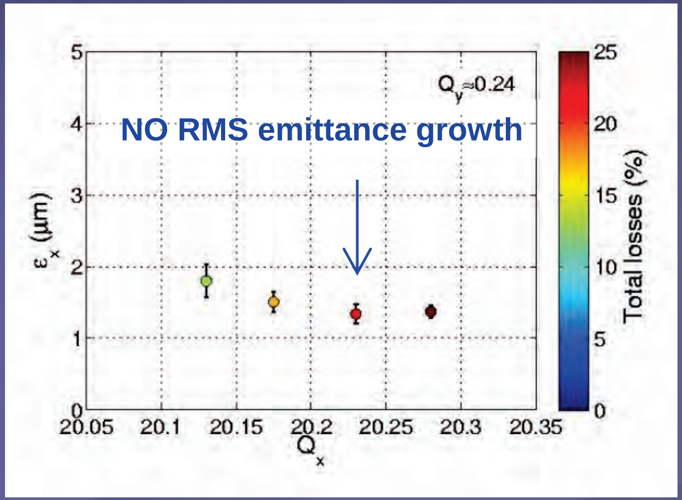
Observation of the [1,-1,0] resonance
→ turn-by-turn data acquisition …

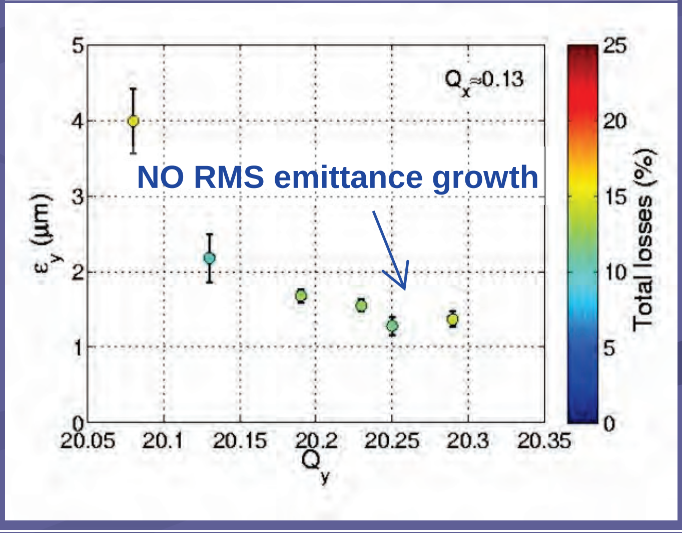
Turn-by-Turn data analysis

▪ CERN SPS: space charge effects and machine resonances

- Tune scan for the Q20 SPS optics at 26GeV
- Single bunch : 2.5-2.7e11 p/b
- Normalized RMS emittance: 1.2μm in both planes
- The incoherent space charge detuning:
  $\Delta Q_H \approx -0.15$, $\Delta Q_V \approx -0.25$.

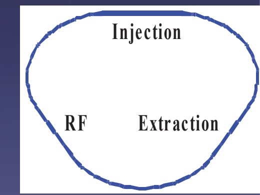






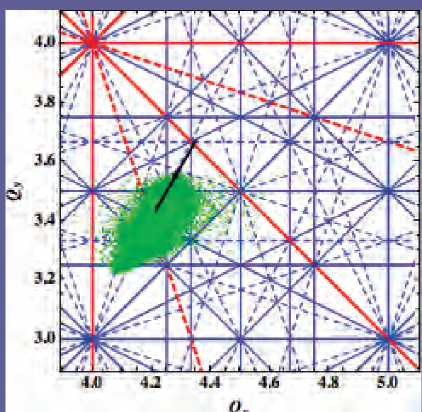
H.Bartosik talk

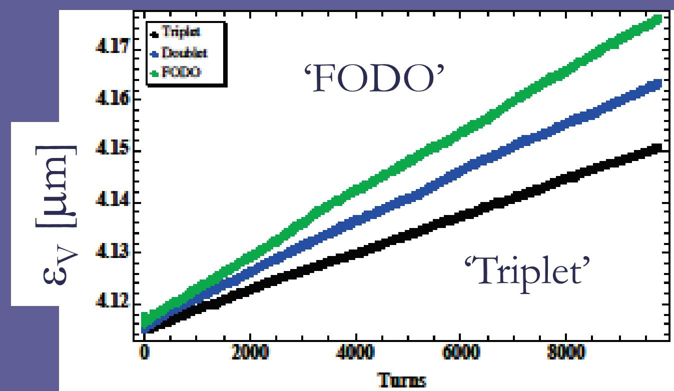
▪ RCS conceptual design

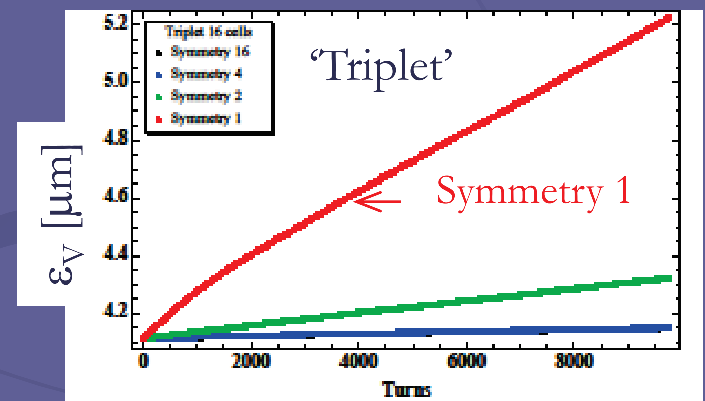


Motivations (including the space charge at injection):

- alternative to the CERN PS Booster upgrade (160MeV-2GeV, 10Hz)
- effect the beam envelope modulations on the emittance growth
- effect of the super-periodicity







$\Delta Q_y \approx -0.4$

→ Lattice tune above $2Q_y=7$
→ Including the Vertical beta-beating correction …

<u>**Variation of the beam size can lead to the emittance growth:**</u>
→ the 'TRIPLET' features smallest variation of the transverse emittance compared to the 'DOUBLET' and the 'FODO' cell

Emittance growth due to excitation of 'systematic' resonances:
→ 'weak' symmetry breaking in one cell with correcting the beat-beat

PTC-ORBIT(MPI)

Conclusions

- The performed benchmarking between the measured and simulated beam evolution for the CERN PS Booster at 160MeV shows very good agreement
- Optimization of main PS Booster setting has been performed to simulate the multi-turn injection process
- Data accumulation for the further study of the space charge effects for the LHC Injectors has been started to perform extensive simulations during the ‘Shut-Down-1’ period

Thanks for your attention