CODE REQUIREMENTS FOR LONG-TERM TRACKING WITH SPACE CHARGE

1. **CERN Injector Upgrade**

2. **Create a SC Working Group at CERN**

3. **World-wide Collaboration & Workshops**

4. **Codes**

   - **CERN Requirements**
   - **Code Bench-marking**
   - **Noise Issues**
   - **Code Bench-marking with Experiment**
   - **Computing Facilities**

Acknowledements

The work being presented here is based on our discussions during the SC-13 joint CERN/GSI workshop April 2013:
http://indico.cern.ch/event/221441/

And the SC-14 CERN collaboration meeting May 2014:
http://indico.cern.ch/event/292362/

The most active CERN and external participants are:

H. Bartosik, E. Benedetto, M. Bodendorfer, V. Forte, S. Gilardoni, N. Hoimyr, A. Huschauer, M.A. Kowalska, M. Martini, E. Metral, A. Oeftiger,
B. Panzer-Steindel, F. Schmidt, E.G. Souza, M. Titze, R. Wasef, CERN,
Y. Alexahin, J. Amundson, V. Kapin, L. Michelotti, E. Stern, Fermilab,
S.M. Cousineau, J. Holmes, A.P. Shishlo, SNS,
O. Boine-Frankenheim, G. Franchetti, I. Hofmann, F. Kesting, GSI,
S. Machida, RAL, C. Montag, BNL, J. Qiang, LBNL

PSB (E. Benedetto et al.)

- Goal: Improve understanding of current Space Charge limits and predict PSB performance with the new H- injection
  - LHC (high brightness) beams → focus on emittance preservation (see Elena’s talk)
  - High Intensity beams → focus on losses control
- We need:
  - Optics model: studies ongoing kick response matrix and driving terms
  - Benchmark code vs. measurements show that the knowledge of optics model is fundamental for accurate estimates

PS (S. Gilardoni et al.)

Today max acceptable: $\Delta Qy \sim |0.3|$ @ 1.4 GeV
HL-LHC max needed: $\Delta Qy > |0.3|$ @ 2 GeV

Goal: demonstrate that it is possible to inject a beam with $\Delta Q > |0.3|$ with limited emittance blowup (max 5%)

- **Experimental studies**:
  - ✓ Tune scan to identify via beam losses dangerous resonances
  - ✓ *Driving terms measurements and compensation*
  - ✓ Understanding of Integer Resonances
  - ✓ 4^{th} (actually 8^{th}) order resonance + mitigation
  - ✓ Qx+2Qy coupled sextupole resonance with space charge
- **Non-linear Model: Lack of good magnetic error model**
  - No error tables from magnetic measurements (à la LHC) available from 1958
  - Opera©-based magnetic error simulations
- **Simulation studies:**
  - **PTC–Orbit simulations**
  - **IMPACT – MADX-SC simulations**

SPS (H. Bartosik et al.)

- Regime of strong space charge for future LHC beams in the SPS
  - Long storage time at injection energy for multiple injections from PS
  - Tight budgets for losses and emittance blow-up
  - Space charge tune shift of $\Delta Q_y = -0.21$ for baseline 25 ns scenario already demonstrated feasible
  - Expected space charge tune shift of $\Delta Q_y = -0.24$ for alternative 50 ns scenario to be studied
- Experimental studies
  - Tune scans performed in 2012 → achieved SPS record space charge tune shift
  - Main goal of studies in 2014/15: determine maximum tune shift acceptable in the SPS within emittance growth and loss budgets
  - Interplay of space charge and other collective effects
- Space charge and machine modeling strategy
  - Short term space charge effects with pyOrbit (slice-by-slice)
  - Long term effects with MADX frozen space charge
  - Rely on beam based measurements for modeling of machine nonlinearities
  - Interplay with other collective effects using PyHEADTAIL

Codes 1/3

1. At CERN we have decided not to develop our own PIC code

2. Instead we collaborating closely with PIC code developers:
   A. CERN Requirements for Codes
      - Fully functional and bench-marked optics code including Maps, NormalForm ➔ Example below
      - Documentation!
      - Magnet fringe fields
      - Time varying fields
      - Double RF
      - Acceleration
      - Take part in development of code
   B. More than one code
   C. Code Bench-mark suite to be fully passed
   D. Bench-mark with experiments
3. Develop frozen SC in MAD-X (V. Kapin et al.)

Codes 2/3

- **We have 3 potential PIC codes: pyORBIT, SYNERGIA and IMPACT and MADX-SC which includes frozen SC.**

- **pyORBIT (PYTHON frontend upgrade of PTC-ORBIT) is our operational future workhorse after all CERN teams have converted to use it. This is the only PIC code presently with all debugged features for our CERN studies. Our optic code PTC which is integrated into MAD-X has been prepared for integration in ORBIT by E. Forest & A. Molodozhentsev.**

- **We have a friendly collaboration with the SYNERGIA team but we are still fighting issues about combined function magnets. Most CERN features are implemented into CHEF a rough equivalent of PTC but not yet debugged nor bench-marked.**

- **IMPACT is developing a full blown optics part. Apparently well adapted to super-computers.**

Codes 3/3

- **MADX-SC has been put under OPENMP, scaling well only for a few cores due to its structure ➔ In typical cases a factor of slightly more than 2 of speed-up has been gained on 4 core machines. Simulation over 800’000 for the PS take 10 days on CERN’s LXPLUS batch.**

- **GSI Benchmarking Suite: MADX-SC has been done several years ago; SYNERGIA done; pyORBIT lacks the 100’000 turn tracking part; IMPACT still needs to get started.**

- **GOAL: Releases of all 3 PIC codes at end of the year:**
  - **All CERN features debugged**
  - **Complete benchmarking**
  - **Documentation!**

Interlude: Create matched 6D distributions

- **Create independent 2D polar Gaussian distributions via the Box-Muller transform.**
- **Multiplied by the square root of the emittance of the horizontal, vertical and longitudinal phase space respectively.**
- **The ε_z can be obtained by the beam-size σ_z and the β_z in the longitudinal plane. The latter can be obtained by the generalized 6D TWISS parameters ➔ PTC:**

$$\sqrt{(\varepsilon_z)} = \sigma_z / \sqrt{(\beta_z)}$$

- **Method can be extended to higher order NormalForm and the initial distributions could be different from Gaussian.**

➔ Good example how non-linear tools can help in SC world!

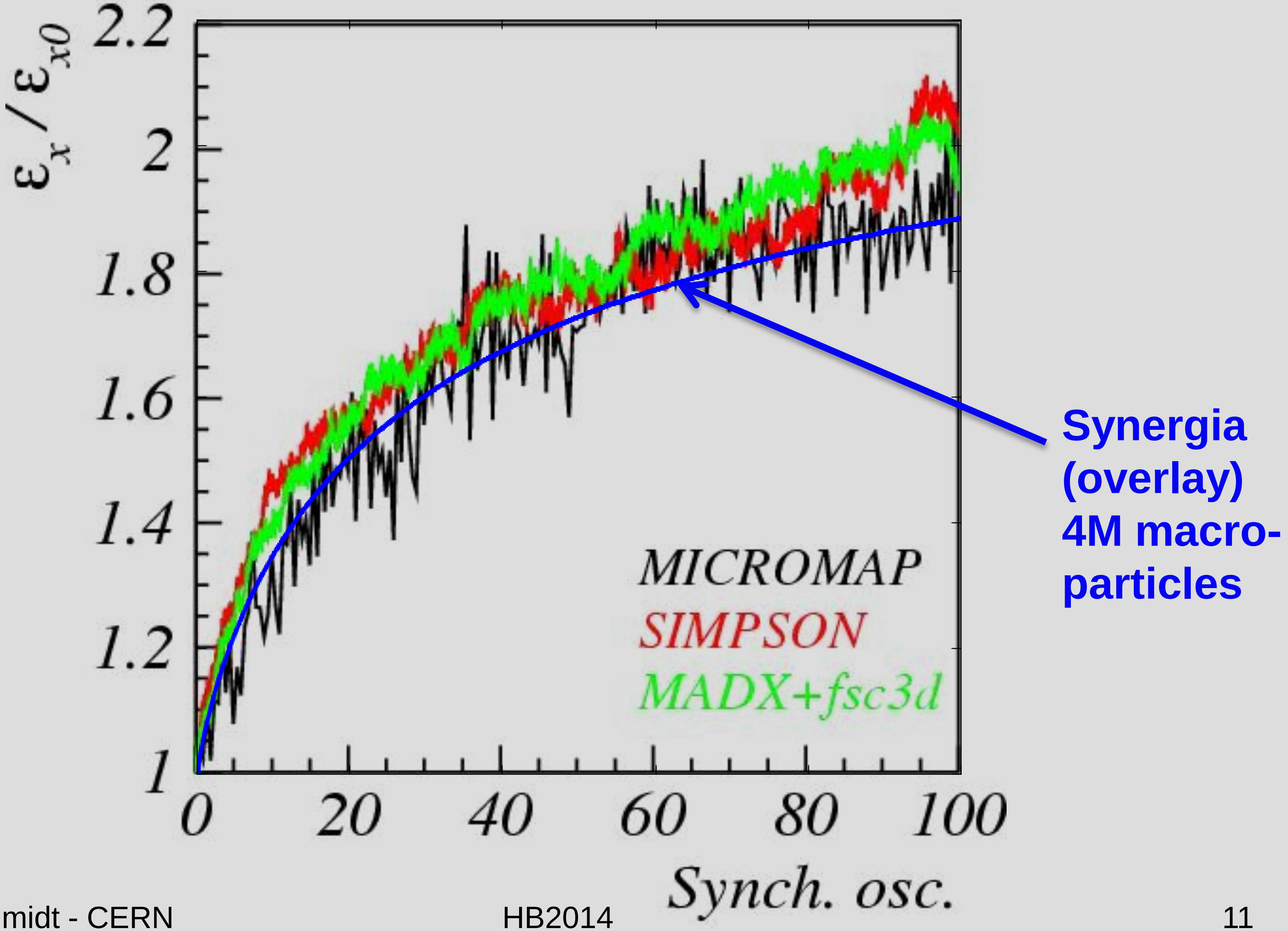
GSI Bench-Mark Suite

- **During the SC-13 workshop we have decided to include the PIC codes in the well-established GSI SC bench-marking suite fostered by G. Franchetti:**

http://web-docs.gsi.de/~giuliano/research_activity/trapping_benchmarking/main.html

- **Considerable work has been done for SYNERGIA & pyORBIT with IMPACT still on its way.**
- **As stated before we at CERN see this as a precondition for trusting the results of any code we will use for SC simulations.**
- **We expect this work to finish before the end of the year and we are planning to update the Bench-mark website and publish a report about it to inform the SC community.**

100'000 Turn SIS18 Bench-marking (Step 9)

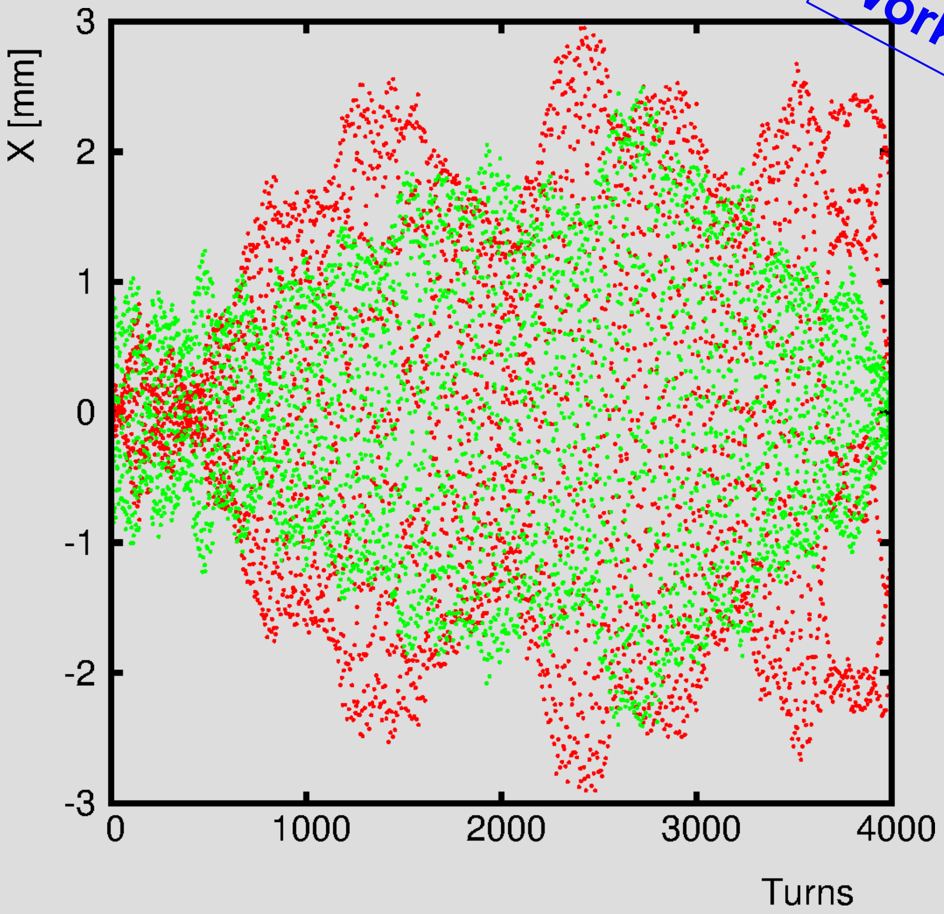


Noise

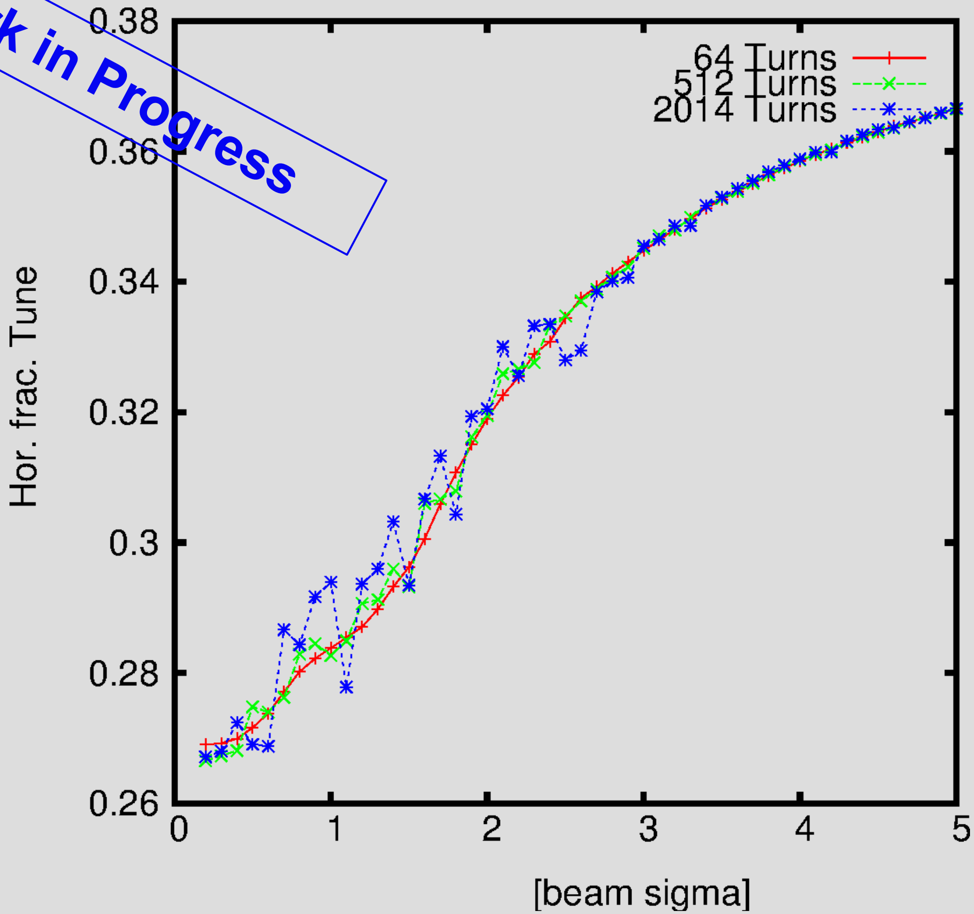
- **Theoretical models by Struckmeier manage to relate IBS to PIC noise. Recently this theory has been reviewed and extended (O. Boine-Frankenheim & I. Hofmann).**
- **The question remains how this theory relates to PIC noise effects found in actual simulations ➔ I. Hofmann (this conference).**
- **I. Hofmann has proposed a simulation experiment with trapping phenomena in which a code-generated noise level is introduced to check how much noise can be tolerated and if the codes can handle it.**
- **Due to PIC noise the motion of all particles in the distribution appear to exhibit chaotic behavior in "real" simulations.**
- **Despite this fine grain noise, long-term PIC simulations over 100'000 turns agree on bulk quantities as emittance growth in the SIS18 benchmarking with frozen SC codes. A precondition is that the convergence tests are done over the full time scale of the simulations.**

Single Particles (SIS18 Bench-marking)

PTC-ORBIT

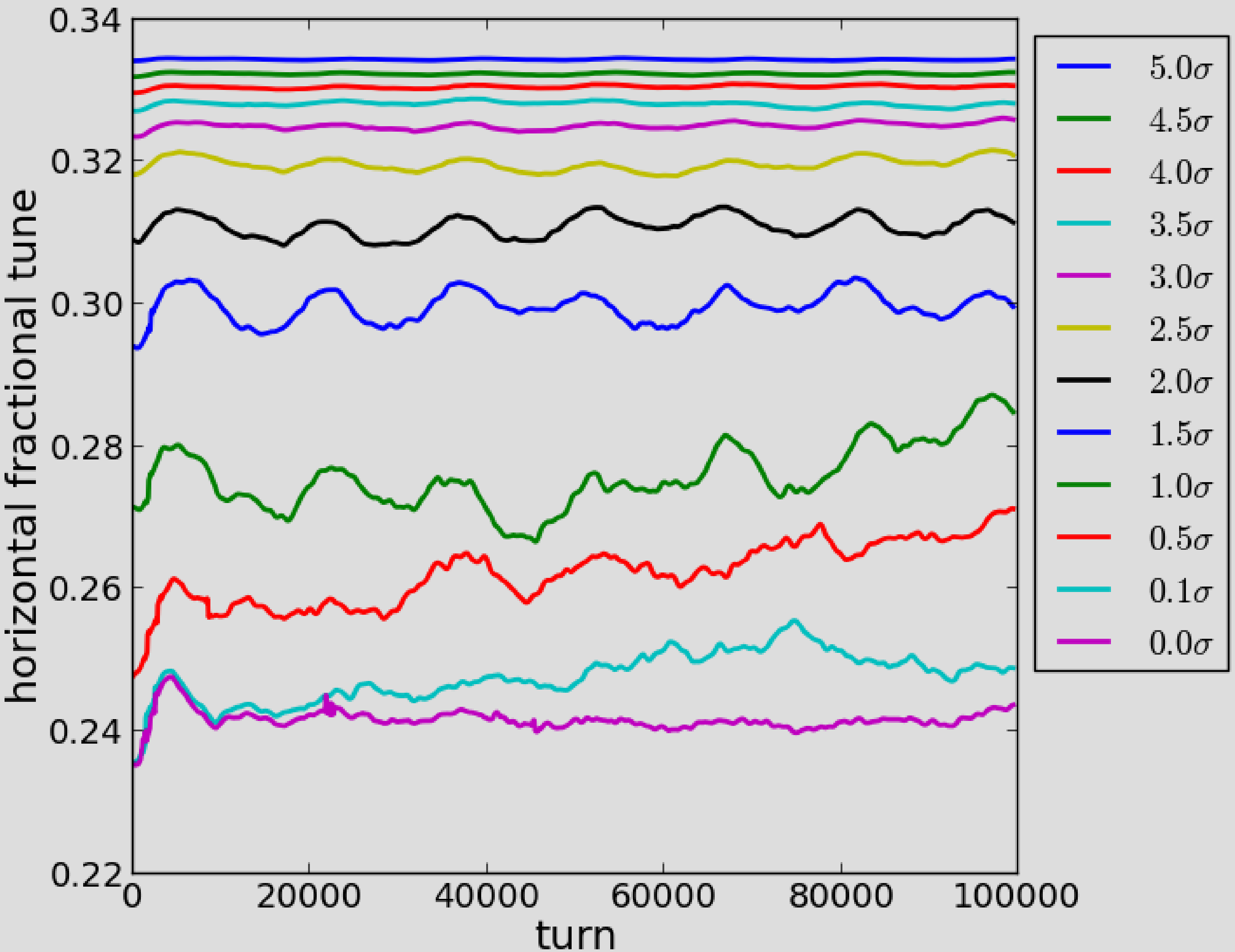


Work in Progress



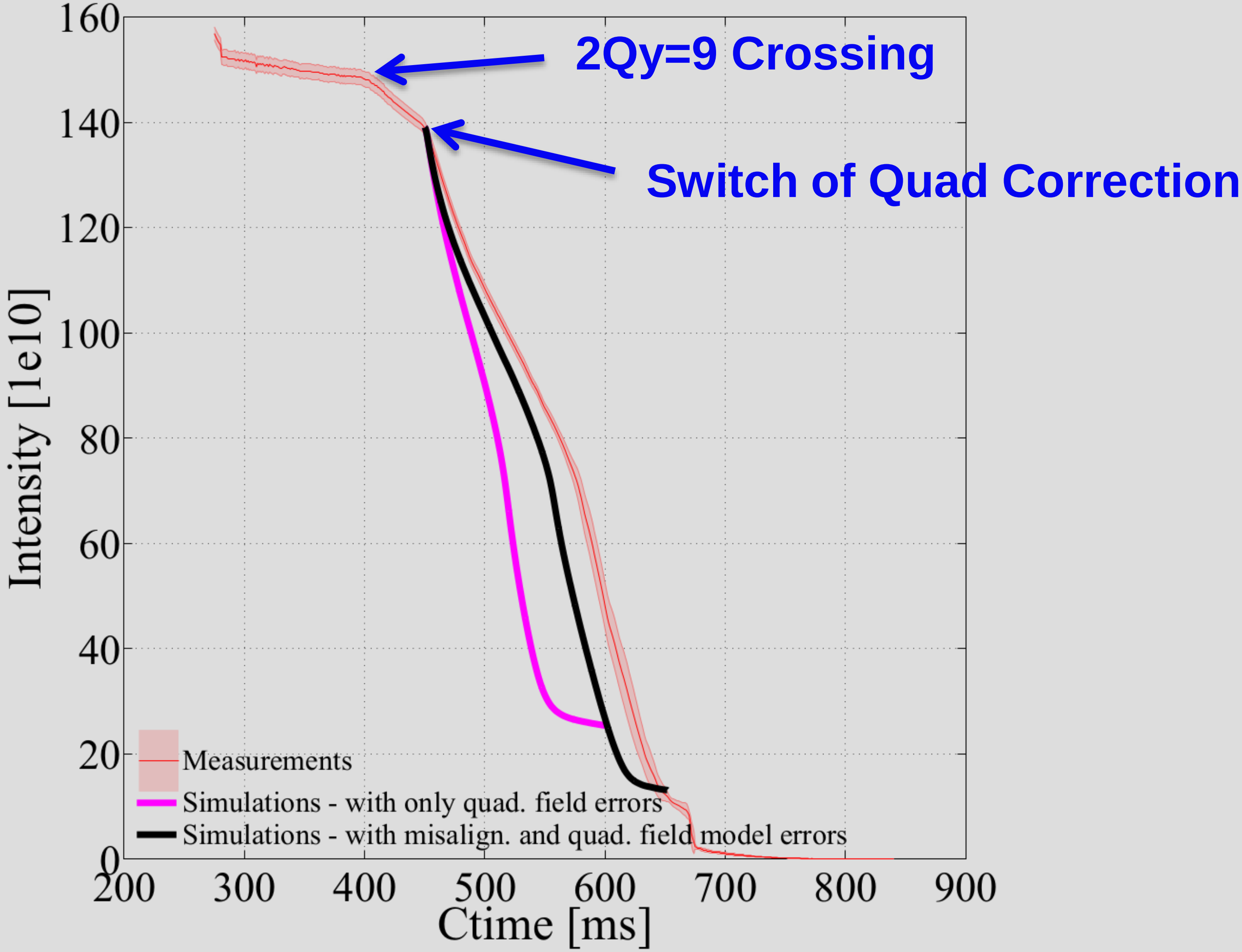
Sliding 1024 Turn Tunes (SIS18 Bench-marking)

Synergia



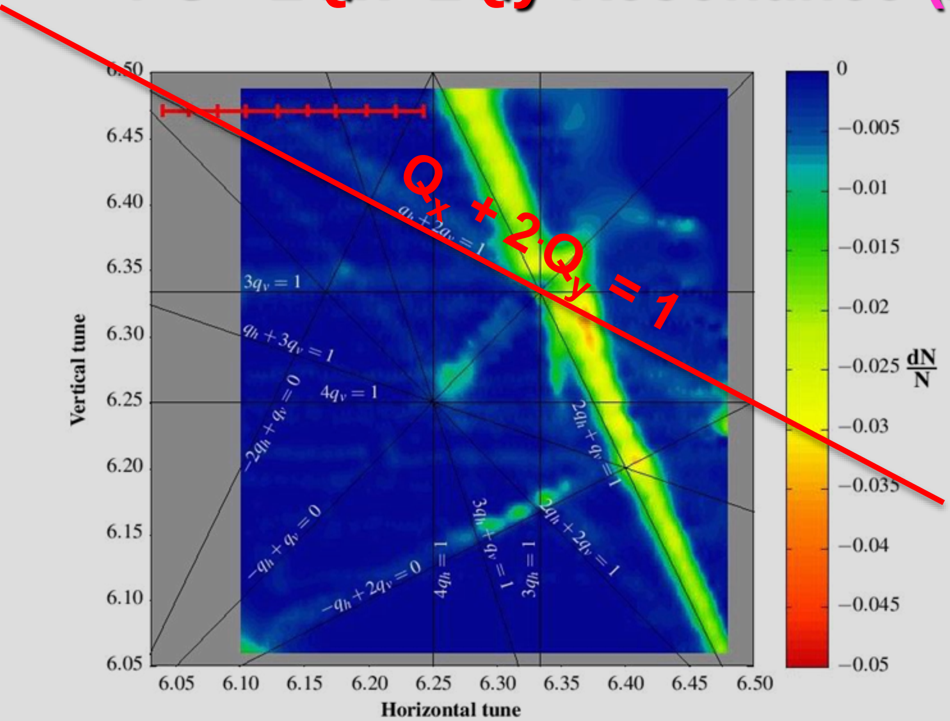
Code Bench-marking with Experiment 1/2
PSB ½ Integer Resonance

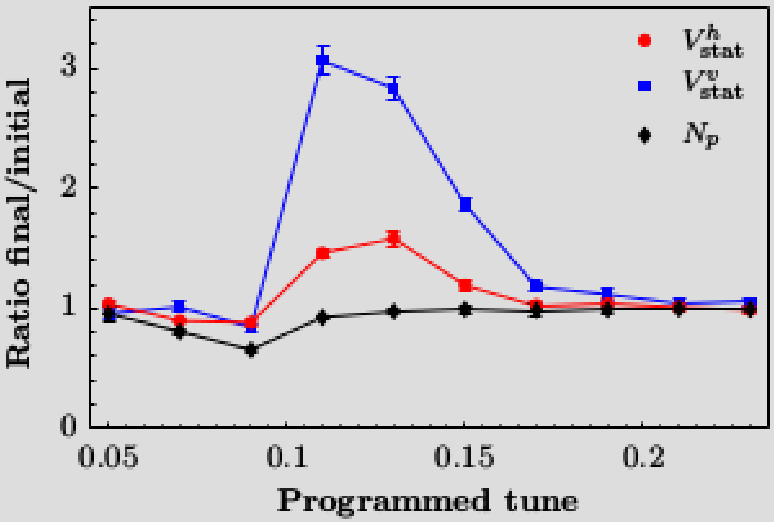
V. Forte et al.

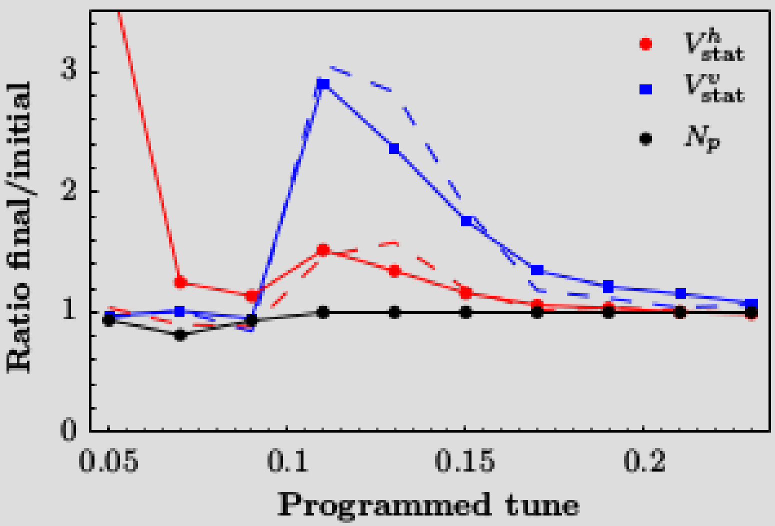


Code Bench-marking with Experiment 2/2

PS - 2Qx+2Qy Resonance (A. Huschauer, R. Wasef et al.)







MADX-SC is being applied over 800'000 turns using a turn-by-turn update of the emittances (Y. Alexahin) and a recalculation of the TWISS parameters every 1'000 turns. Techniques still needs full justification, in particular concerning potential "noise".

Computing Resources

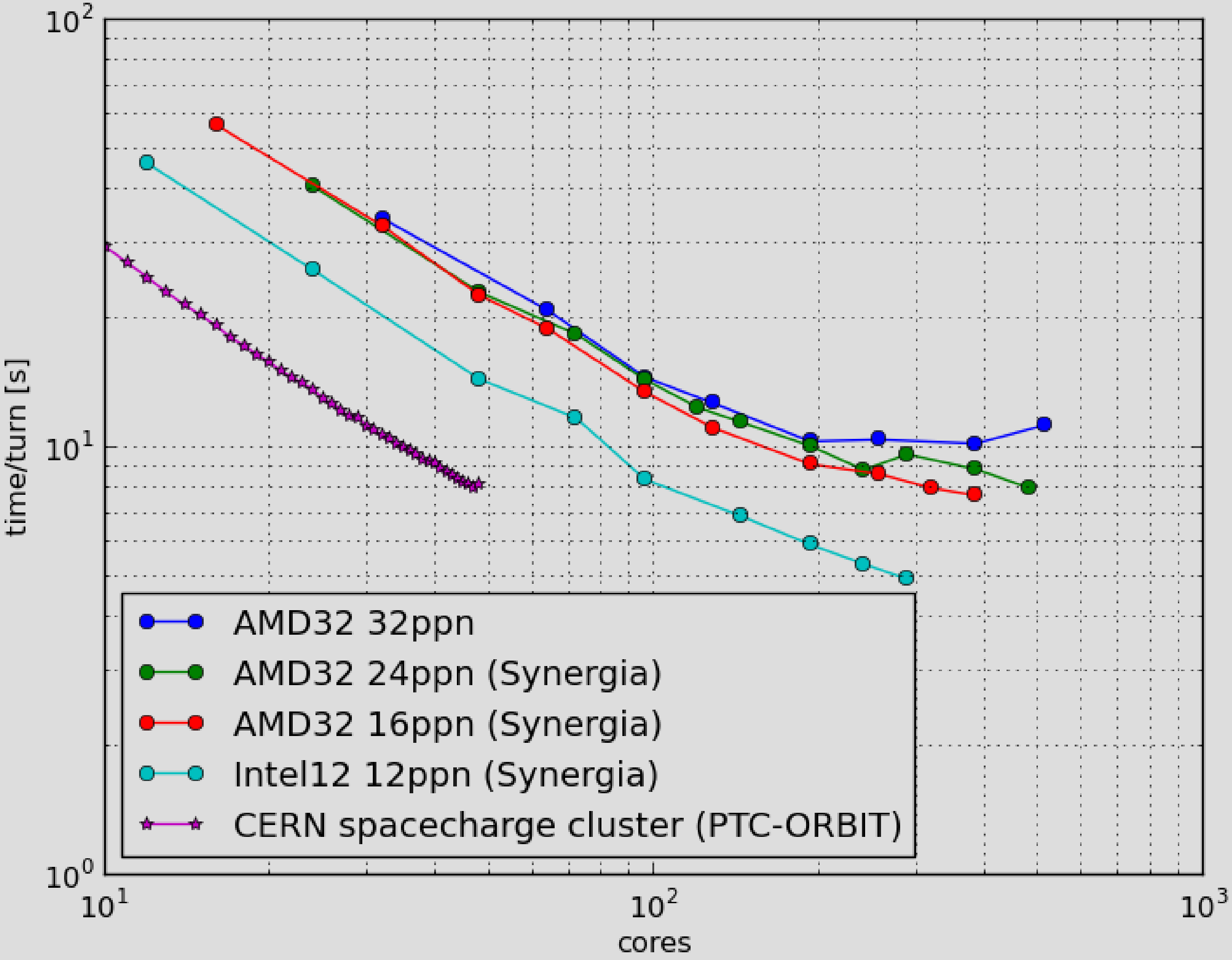
- The MPI simulation with PIC codes tend to be very time-consuming, E.G. typical PSB tracking (201 SC nodes, Grid: 128^3, 500’000 MP, 5000 Turns) take some 11h on a 48 core machine.
- What are the potential options to improve turn-around time?
  - Large clusters of some 100s of nodes of typically 12 core systems with good raw speed. Good scaling over ~(100-200) cores. Most importantly with excellent network speed!
  - Super-computers many more cores with good scaling.
  - Could the GPU approach be an alternative? Is such a system feasible at this moment in time? How would it compared with conventional system in terms price, code development, machine maintenance and speed performance?
- Frozen SC codes are much better in terms of performance, E.G. MADX-SC, PS (1000 SC kicks, 1000 MP, 800’000 Turns) take 10 days on modern 4 core PCs under OPENMP (twice speed-up). Scaling gets better for larger # of MP which may not be necessary.

Scaling on Clusters (PSB)

V. Forte (CERN) /E. Stern (Fermilab)

A prequisite is:

• Codes must be prepared to allow for good Scaling!
• Case Dependent
• Larger # of macro-particle always helps!

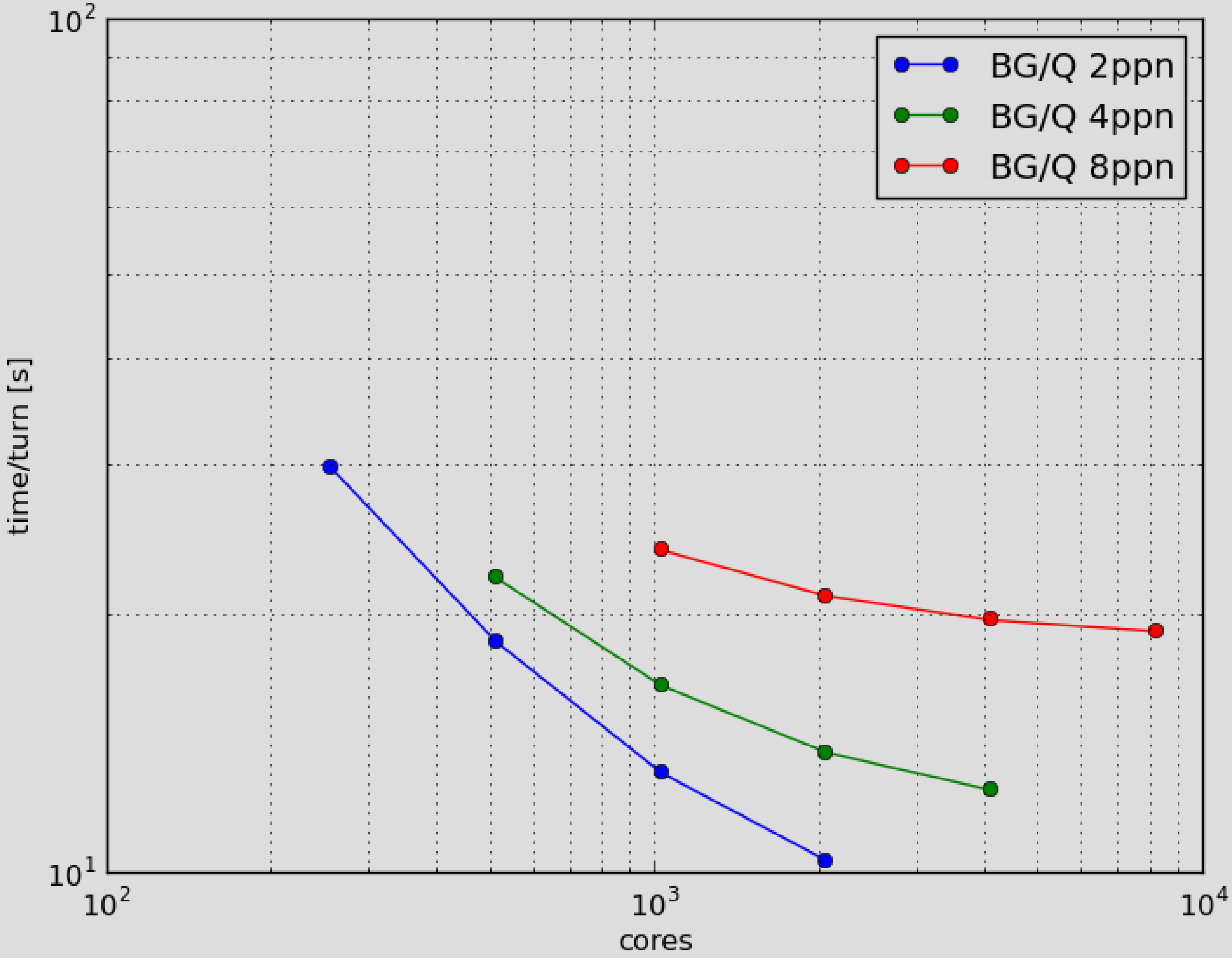


Super-Computer which Super-Computer?

- There are various variants, generations of super-computers so what is require in our applications? Moreover, results may vary from case to case and general statements may be difficult to state.
- At Fermilab we tested the BlueGene/Q IBM. But this machine would be most adequate for weakly coupled studies (see below).
- What would be required is a machine with:
  - Fast raw speed on one core
  - Scaling to very large number of codes >>100
- Apparently CRAY super-computer based on 12 core AMD Opteron chips or other machines based on the 60 core INTEL Xeon processors seem to the adequate choices.
- At CERN we are in investigating with HPC cluster at CNAF (Bologna) and EPFL (Lausanne) to look for feasible solutions for our simulation needs.

Scaling on Blue Gene (PSB)

E. Stern



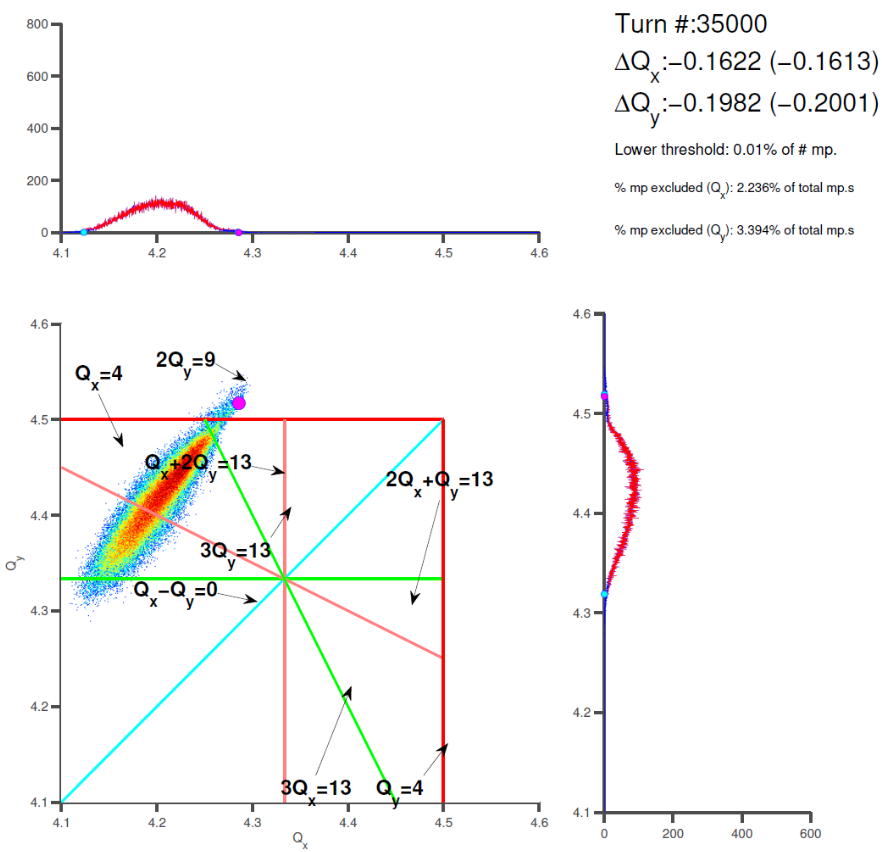
Conclusion

- A world-wide collaboration has been started to tackle SC issues related to the upgrade of the CERN pre-LHC injector chain.
- Both PIC codes and frozen SC codes are being bench-marked and by the end of 2014 we expect the release of up to 3 PIC codes that cover the CERN requirements.
- Progress has been made concerning the PIC noise phenomenon but we still need to understand the effect in practice.
- For the frozen SC simulations one needs to justify the continuous emittance re-normalization which is needed to explain PS experimental results.
- New physical understanding of Qx+2Qy resonance is being prepared. ➔ G. Franchetti
- Code bench-marking with experiment has been started and for the PSB & PS we find remarkable agreement once the model of the machine is know sufficiently well.
- Choice of best computing resources are being discussed.

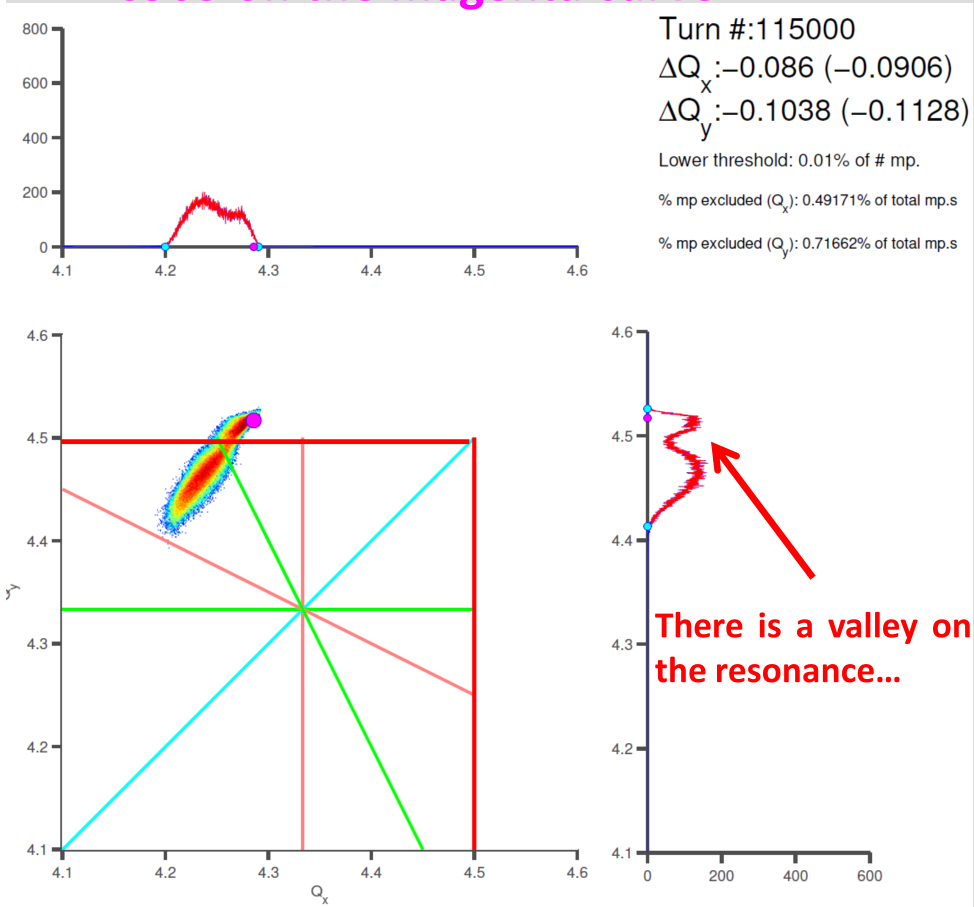
Reserve

Tunes Simulations (with quad field errors): after ~35ms and ~115ms

C485 on the magenta curve



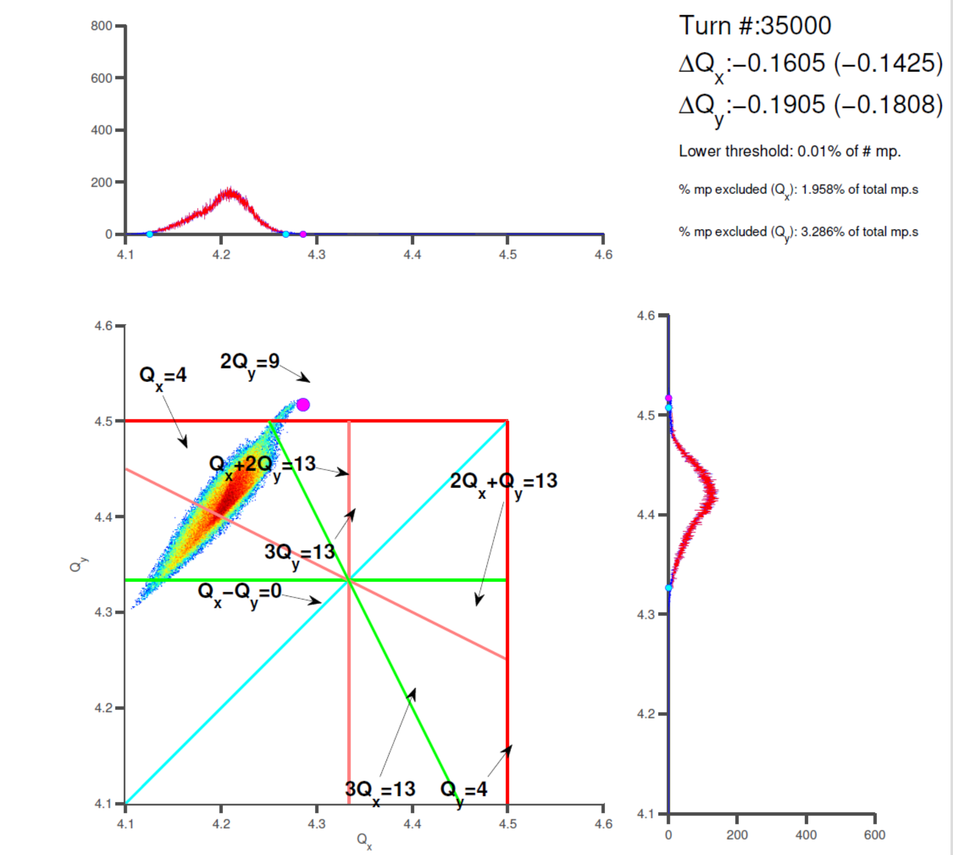
C565 on the magenta curve

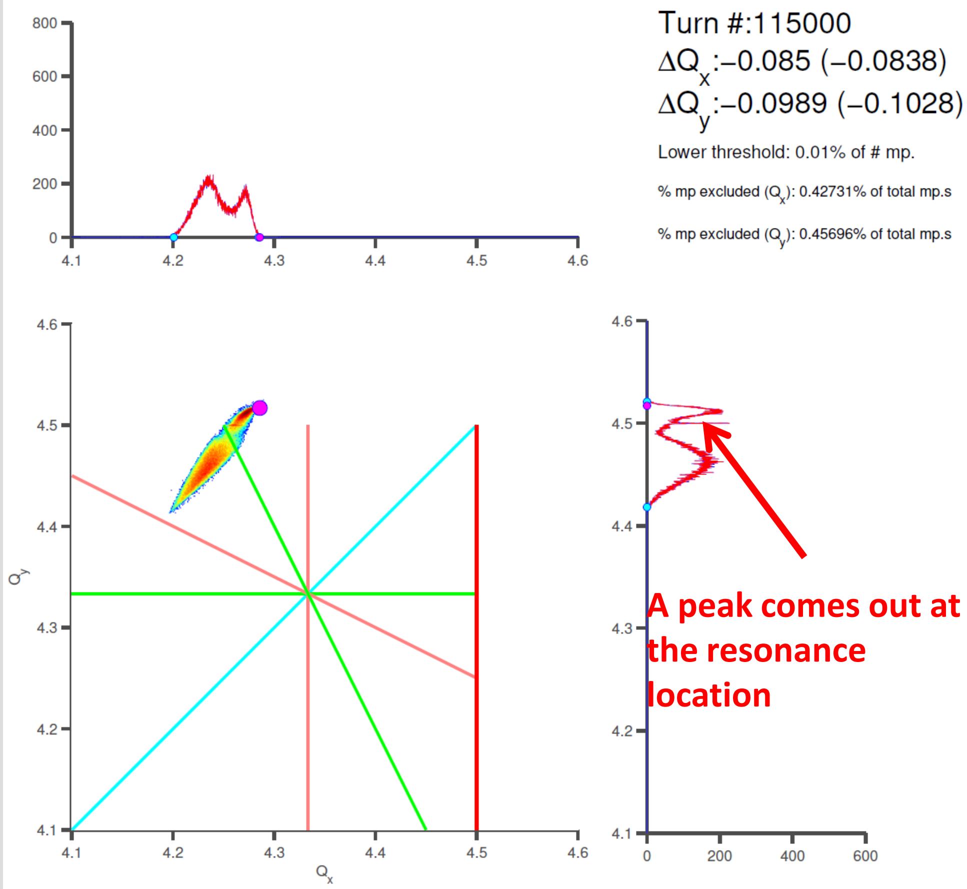


There is a valley on the resonance…

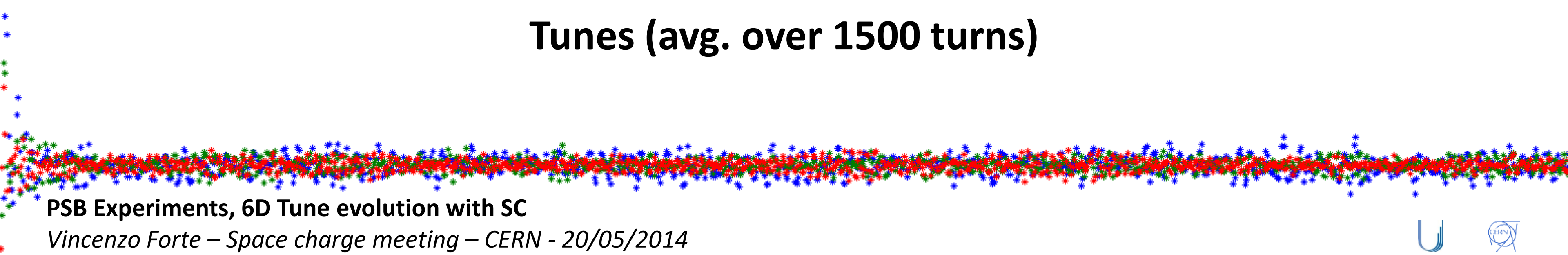
Tunes computation (phase advance per turn)

Tunes Simulations (with quad fields): after ~35ms and ~115ms



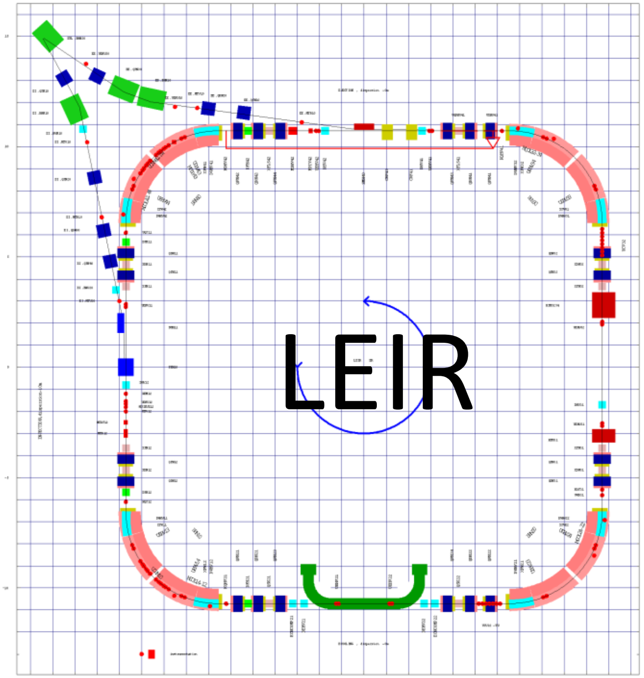


Tunes (avg. over 1500 turns)



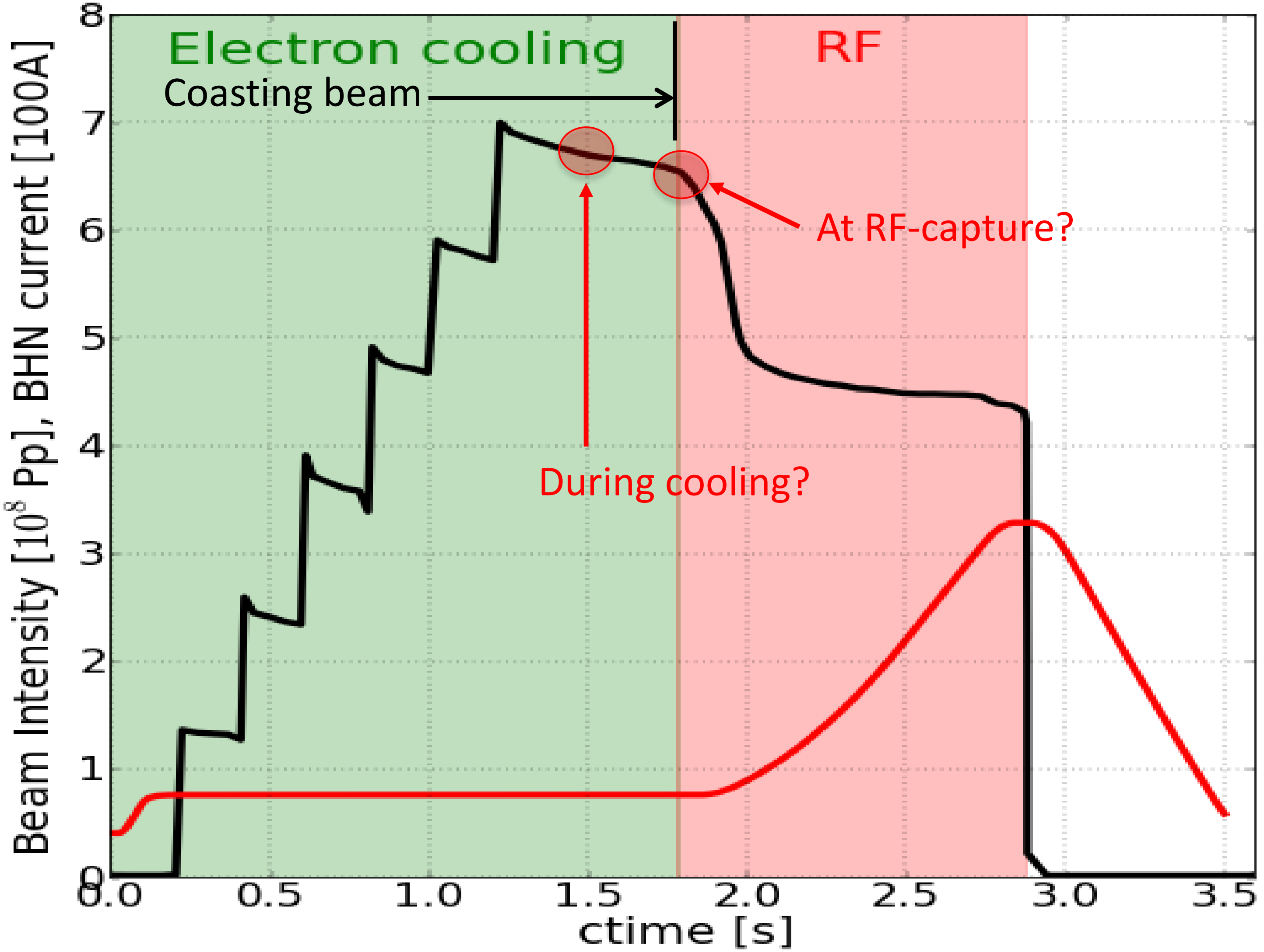
Overview

Machine	Output Energy	Charge state
ECR ion source	2.5 keV/n	…,29+,…
LINAC3	4.2 MeV/n	29+/54+
LEIR	**72.2 MeV/n**	**54+**
PS	5.9 GeV/n	54+/82+
SPS	176.5 GeV/n	82+



LEIR Design Parameter	Value	
	Injection	Extraction
Length	78m	
$\beta_{rel.}$(Inj. | Ej.)	0.095	0.392
$\gamma_{rel.}$ (Inj. | Ej.)	1.0045	1.087
$\gamma_{transition}$	2.84	
$\Sigma^{*}_{transv.}$ (Hor.|Vert.)	6µm|4µm	0.65|0.7µm
$\Sigma_{long.}$ (Inj. | Extr.)	0.015eVs/u	0.1eVs/u
Tune (Hor. | Vert.)	1.82|2.72	1.82|2.72

Space charge limitation in LEIR?



PSB parameters

Circumference:	157m
Super-periodiciy:	16
Injection:	conventional Multi-Turn → upgrade to H-
Injection energy:	50 MeV → upgrade to 160 MeV
Extraction energy:	1.4 GeV → upgrade to 2 GeV
Cycle length:	1.2s
# bunches:	1 x 4 Rings
RF cavities:	h=1+2 (double harmonics), h=16
Tunes at injection:	4.30, 4.45, ~1e-3
Rev. freq. (160 MeV):	~1MHz
# protons/bunch:	50 → 1000 x 1e10 (wide range for different users)
H. emittance:	2 →15 um
V.l emittance:	2 → 9 um
Longitud. emittance:	1 → 1.8 eVs

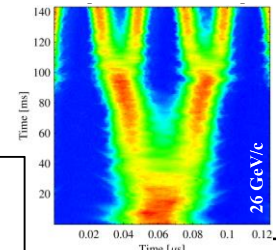
Upgrade will allow to double the brightness, i.e. for LHC beams go from 170e10 to 340e10

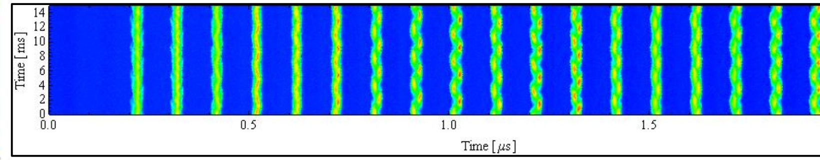
Conclusions

- Goal: Improve understanding of current Space Charge limits and predict PSB performance with the new H- injection
  - LHC (high brightness) beams → focus on emittance preservation (see Elena's talk)
  - High Intensity beams → focus on losses control

- We need:
  - Optics model: studies ongoing kick response matrix and driving terms
  - Benchmark code vs. measurements show that the knowledge of optics model is fundamental for accurate estimates

Challenges in the PS



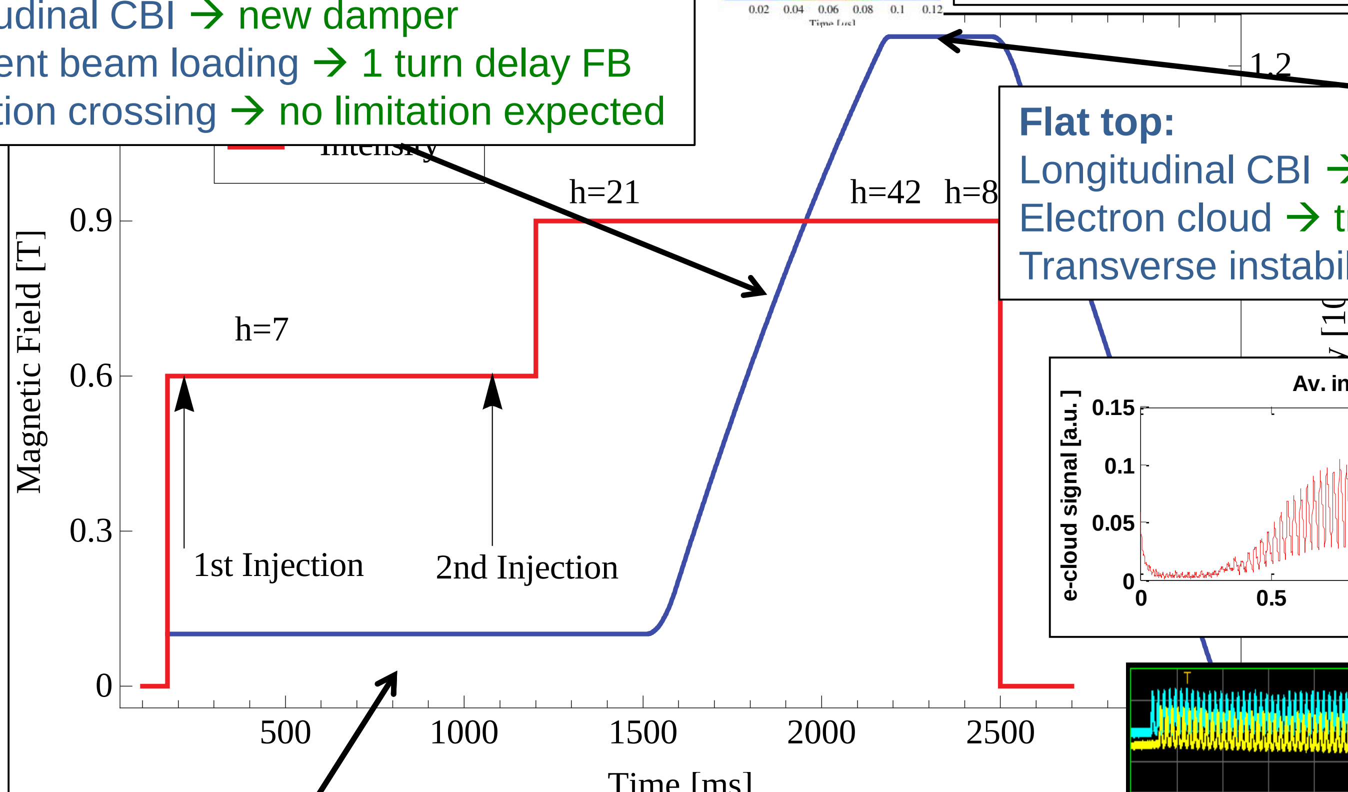


Acceleration/Bunch splittings

Longitudinal CBI → new damper

Transient beam loading → 1 turn delay FB

Transition crossing → no limitation expected

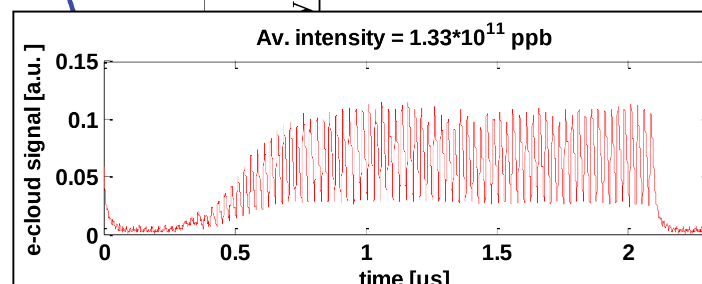


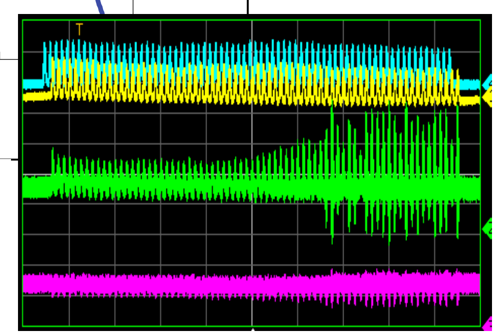
Flat top:

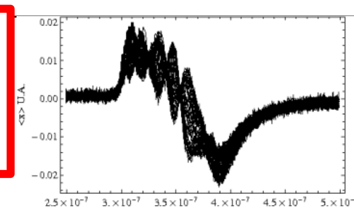
Longitudinal CBI → new damper

Electron cloud → transverse FB

Transverse instabilities → transverse FB







Injection flat bottom:

Space charge → 2 GeV injection upgrade

Headtail instability → transverse FB

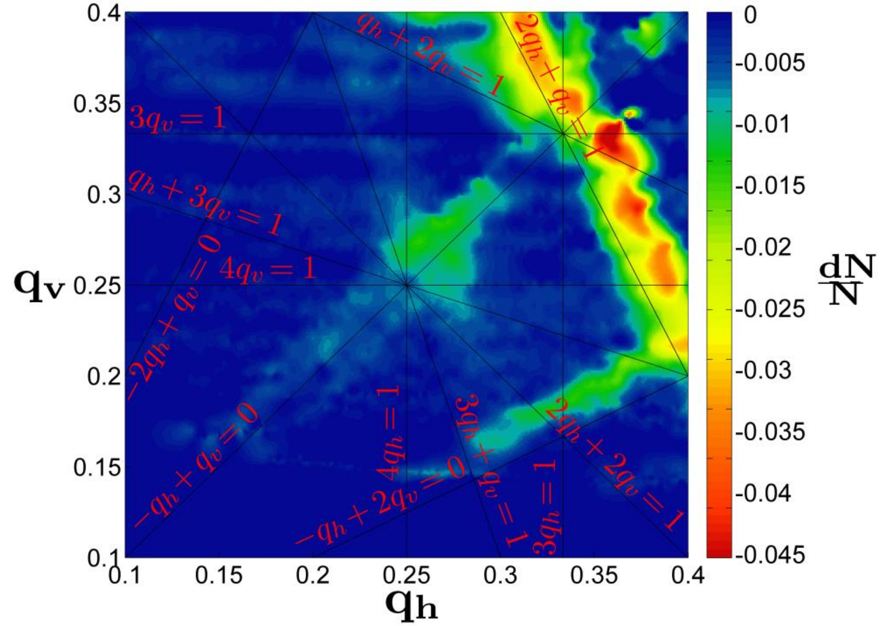
Space Charge at injection (1.4 GeV - 2 GeV)

Study to determine largest acceptable tune spread.

Today max acceptable: ΔQy ~|0.3| @ 1.4 GeV
HL-LHC max needed: ΔQy > |0.3| @ 2 GeV

Goal: demonstrate that possible to inject a beam with ΔQ>|0.3| with limited emittance blowup (max 5%)

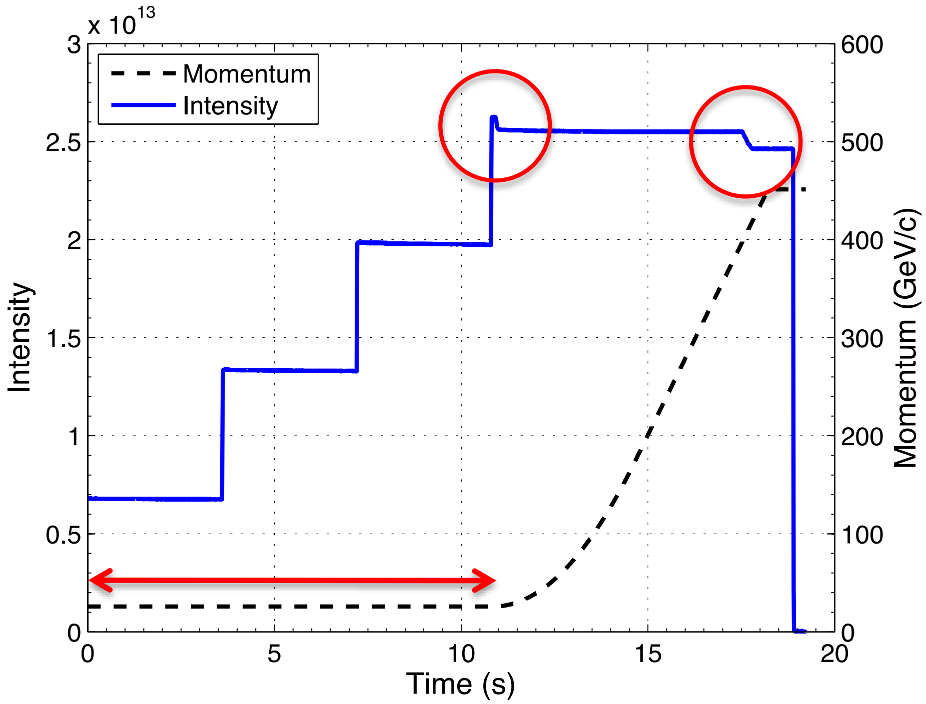
- **Experimental studies**:
  - ✓ Learn from operational beams experience. Current Laslett at about -0.28 with Qy<0.25
  - ✓ Tune scan to identify via beam losses dangerous resonances
  - ✓ *Driving terms measurements*
  - ✓ Compensate resonances (as done already in 1975 with injection at 50 MeV)
- **Simulation studies:**
  - – **PTC–Orbit simulations**
  - – **IMPACT – MADX-FZM simulations**
  - ✓ Lack of good magnetic error model
    - No error tables from magnetic measurements (à la LHC) available from 1958
    - Opera©-based magnetic error simulations



2013-2014 important results:

- Better understanding of integer resonance
- Better understanding of 4th (or 8th) order resonance

Introduction - SPS cycle for LHC beam



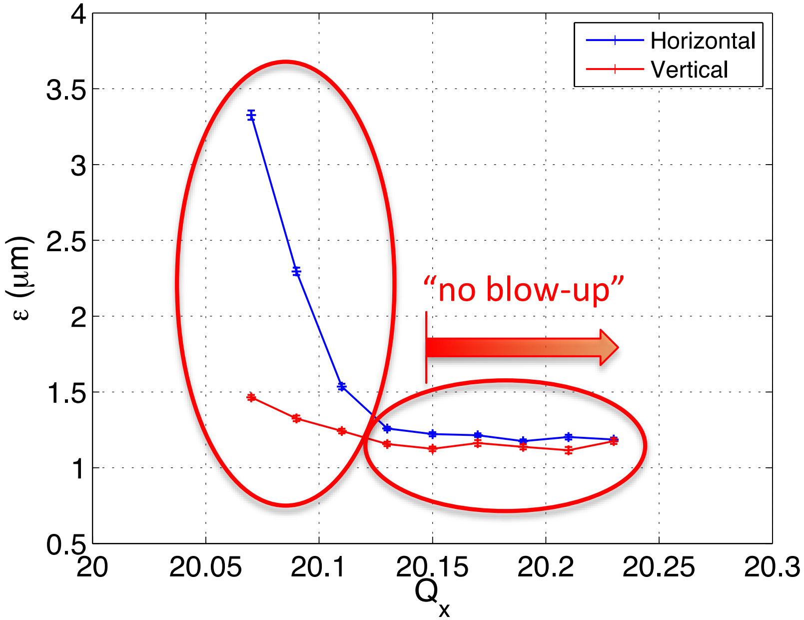
- **Long injection plateau (10.8s)**
  - 4 injections, 26 GeV/c
  - Maybe even longer in case of BCMS beam
- **Budget for total losses: 10%**
  - Losses at start of acceleration ~3-5%
  - Scraping at flat top ~3%
- **Budget for emittance growth: 10%**
  - Small optics mismatch at injection
  - Avoid different emittance per batch

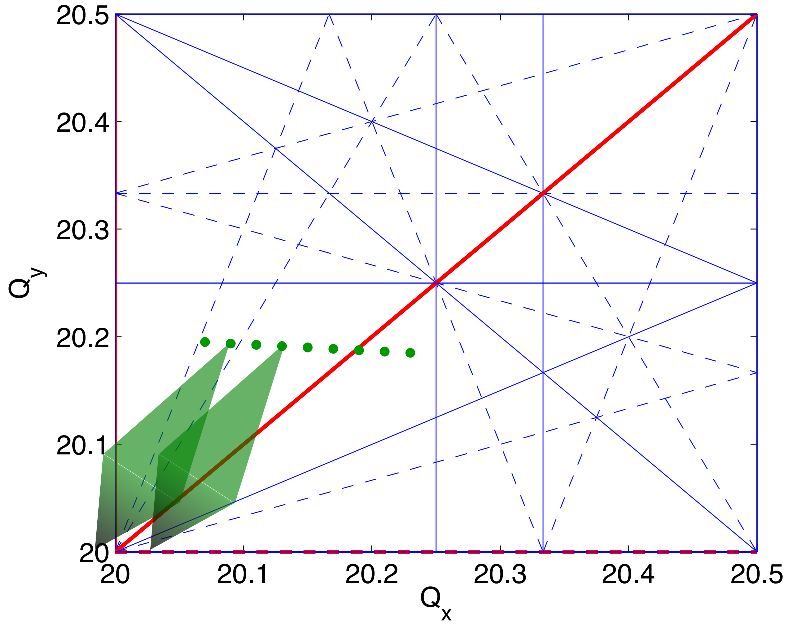
⇒ Need to preserve high brightness for >10s with ΔQ>0.2 with “practically no degradation”

Experimental tune scan

- **High brightness 50ns BCMS beam**
  - N = 1.95×10^{11} p/b (at injection)
  - ε ~ 1.15μm
  - Transmission up to flat top around 94% without scraping (very small losses on flat bottom)
  - Emittance measurement at the end of flat bottom

$\Delta Q_x/\Delta Q_y$ ~ 0.10/0.18





Summary

- **Regime of strong space charge for future LHC beams in the SPS**
  - Long storage time at injection energy for multiple injections from PS
  - Tight budgets for losses and emittance blow-up
  - Space charge tune shift of ΔQ_y= –0.21 for baseline 25 ns scenario already demonstrated feasible
  - Expected space charge tune shift of ΔQ_y= –0.24 for alternative 50 ns scenario to be studied

- **Experimental studies**
  - Tune scans performed in 2012 (BCMS beam) → achieved SPS record space charge tune shift
  - Main goal of studies in 2014/15: determine maximum tune shift acceptable in the SPS within emittance growth and loss budgets
  - Interplay of space charge and other collective effects

- **Space charge and machine modeling strategy**
  - Short term space charge effects with PTC-pyOrbit (slice-by-slice)
  - Long term effects with MADX frozen space charge
  - Rely on beam based measurements for modeling of machine nonlinearities
  - Interplay with other collective effects using PyHEADTAIL