Some HB2008 Highlights

- IBS suppression lattice in RHIC: theory and experimental verification A. Fedotov et al.
- State of the art of high intensity simulation codes: new algorithms and methods for rings - a personal and biased view A. Adelmann
- Evolution beam parameters during injection and storage of the high brightness beams envisaged for the Linac4 injection into the CERN PS Booster M. Martini et al.

HB2008 Workshop, Nashville, Tennessee
August 25-29, 2008

M. Martini

IBS suppression lattice in RHIC: theory and experimental verification

A. Fedotov, M. Bai, D. Bruno, P. Cameron, R. Connolly, J. Cupolo, A. Della Penna, A. Drees, W. Fischer, G. Ganetis, L. Hoff, V. Litvinenko, W. Louie, Y. Luo, N. Malitsky, G. Marr, A. Marusic, C. Montag, V. Ptitsyn, T. Satogata, S. Tepikian, D. Trbojevic, N. Tsoupas

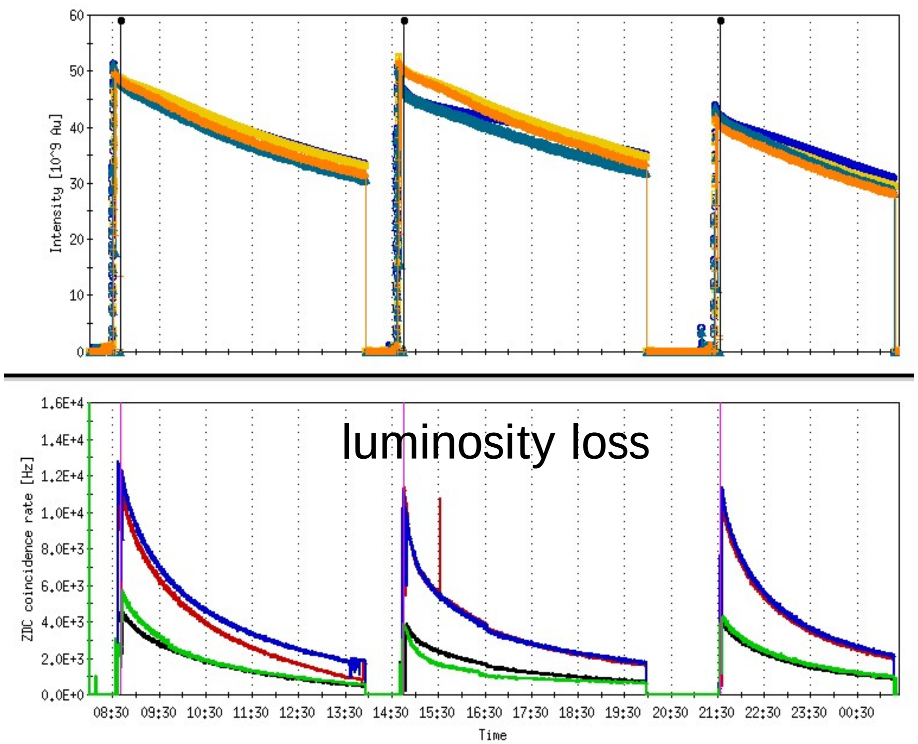
Collider-Accelerator Department, BNL

BROOKHAVEN
NATIONAL LABORATORY

RHIC performance for Au ions

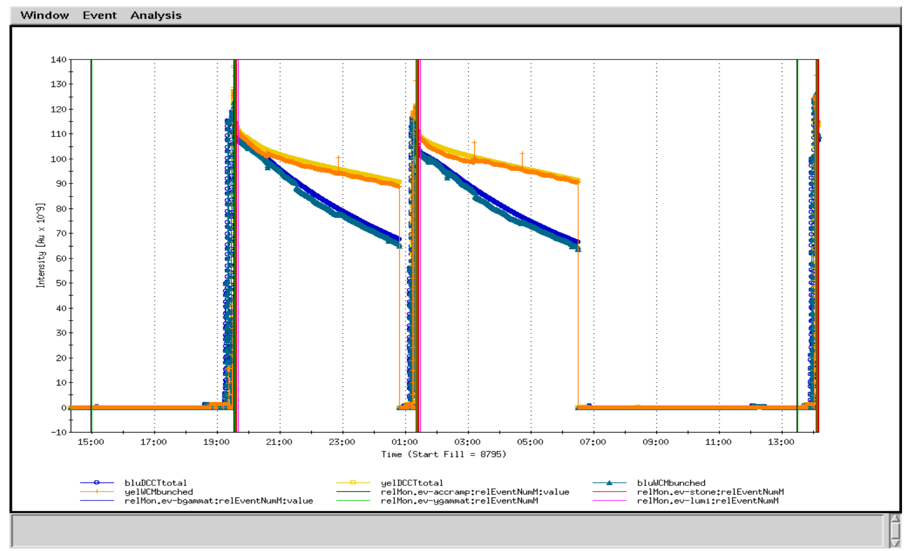
2004 run

intensity loss



2007 run

(with longitudinal stochastic cooling in Yellow ring)



Performance of RHIC collider with Au ions is limited by the process of Intra-Beam Scattering (IBS).

Beam loss in the blue & yellow rings (top) luminosity decrease at different RHIC interaction points (bottom) of a $^{197}Au^{79+}$ beam (≈5 hours per fill)

IBS in RHIC (for $\gamma >> \gamma_{tr}$)

1. For energies much higher than transition energy Intra-beam Coulomb scattering (IBS) is dominated by heating of longitudinal degree of freedom.

Additional heating:

2. At regions with non-zero dispersion, changes in longitudinal momentum change particle reference orbits, which additionally excites horizontal betatron motion.

3. Horizontal heating is shared between horizontal and vertical planes due to x-y coupling. For the case of full coupling, transverse heating is equally shared between x and y.

@γ=107; γ_t=23

Approximate longitudinal IBS diffusion rate:

$$\tau_{\parallel}^{-1} \equiv \frac{1}{\sigma_p^2}\frac{d\sigma_p^2}{dt} \approx \frac{r_i^2 c N_i \Lambda}{8\beta^3\gamma^3\varepsilon_x^{3/2}\left\langle \beta_\perp^{1/2}\right\rangle \sigma_s \sigma_p^2}$$

$$\tau_x^{-1} \equiv \frac{1}{\varepsilon_x}\frac{d\varepsilon_x}{dt} = \frac{\sigma_p^2}{\varepsilon_x}\left\langle \frac{D_x^2 + (D_x'\beta_x + \alpha_x D_x)^2}{\beta_x}\right\rangle \tau_{\parallel}^{-1}$$

$$H_x = \gamma_x D_x^2 + 2\alpha_x D_x D_x' + \beta_x D_x'^2$$

Reducing this function allows to reduce transverse IBS rate – idea behind "IBS-suppression" lattice.

The H-function can be reduced by increasing phase advance per cell.

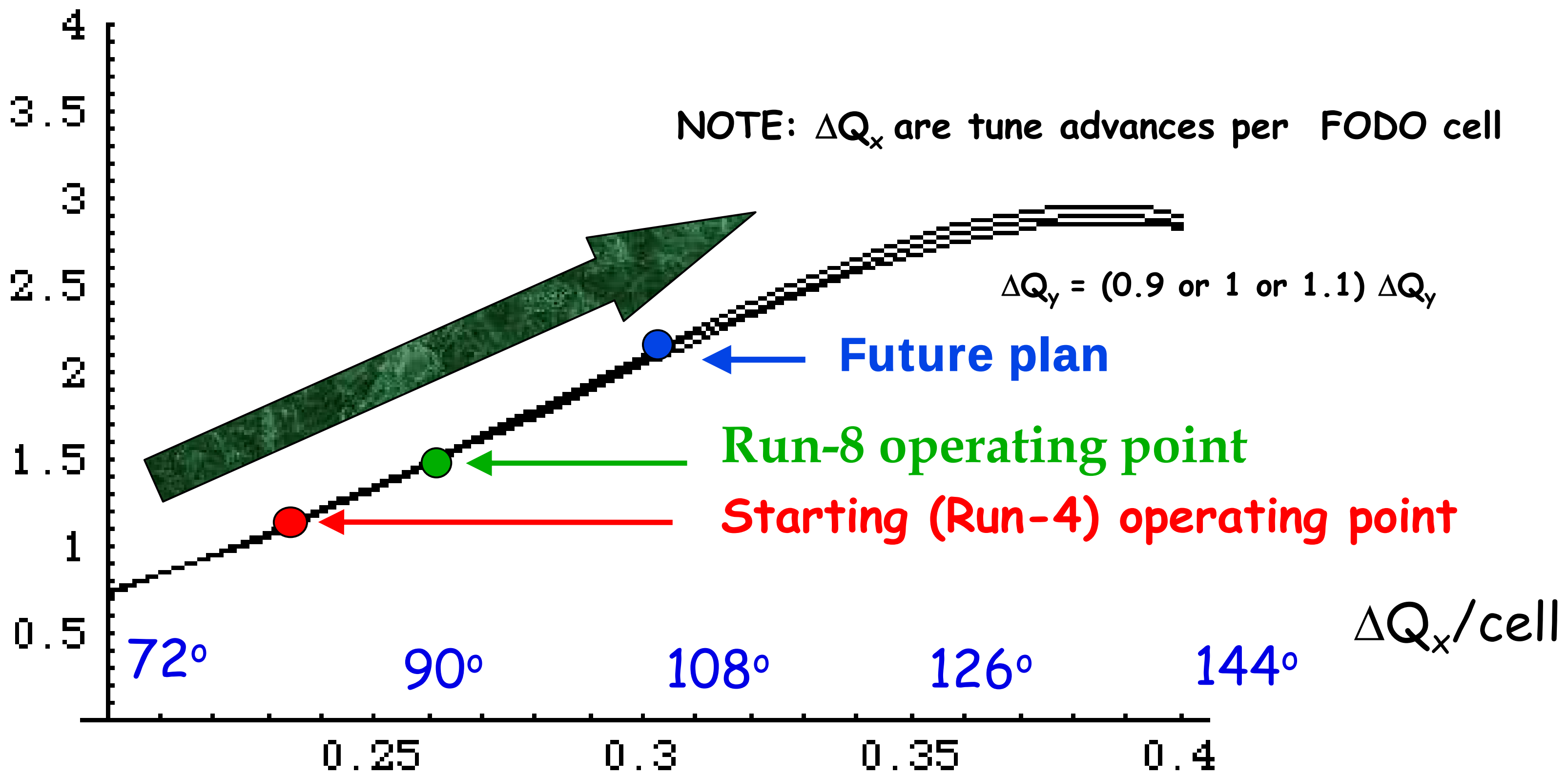
The 2004 RHIC lattice had 82° phase advance per cell.

Reduction of the IBS rate

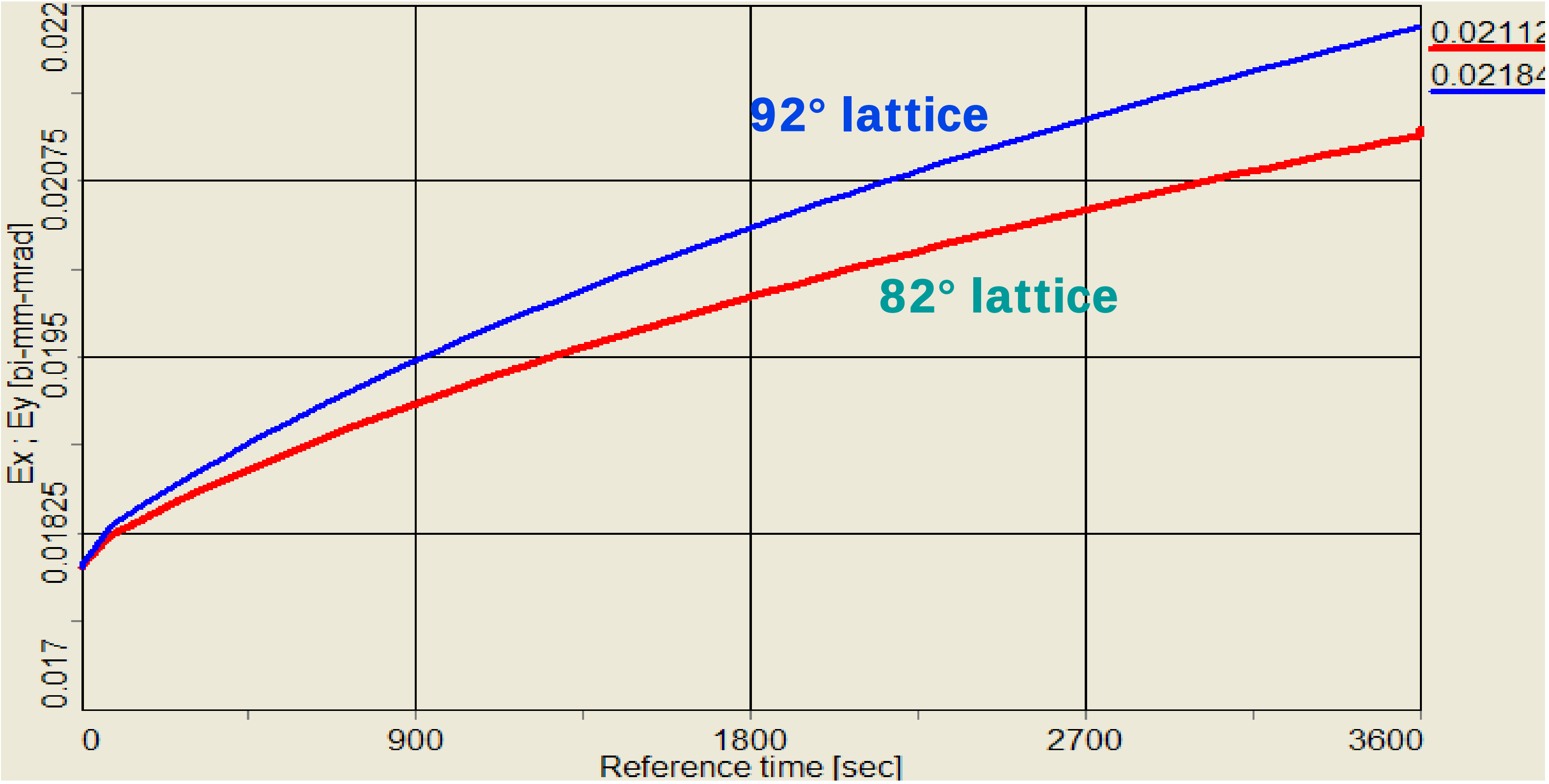
V.N. Litvinenko (2004)

IBS(0.22)/ IBS(ΔQ_x)

RHIC lattice consists of 6 insertions (IP regions), where H-function is very low and 6 arcs with regular FODO cells. Dominant contribution into transverse IBS comes from the arcs.



2005 predictions for IBS APEX experiment with the test lattice (simulations using BETACOOL code: rms unnormalized emittance growth for 82° and 92° lattice, Cu ions @100 GeV/n)



$\tau^{-1}_{rhic-4}/\tau^{-1}_{92}$=30% reduction in transverse IBS emittance growth rate

History of IBS-lattice development

1. **2004 – IBS suppression lattice proposed. It was decided to start with incremental increase of phase advance per cell (92° for the first test).**
2. **2005 – development of IBS lattice for Cu ions during Accelerator Physics EXperiments (APEX). The progress with ramp development was marginal – the main problems were related to the tune swings during the ramp. Measurements @31GeV/n and some puzzles.**
3. **2006 – no experiments, since the run was with polarized protons.**
4. **2007 – progress with tune and coupling feed-back dramatically speed-up development of the ramps. Effect of IBS suppression lattice on transverse emittance growth was directly measured during APEX in June 2007.**
5. **2008 – for d-Au run, IBS lattice was implemented as operational lattice for Au ions in Yellow ring.**

IBS models in BETACOOL – non-Gaussian distributions (mostly relevant to distributions under e-cooling)

II. *IBS for non-Gaussian distributions.*

In situations when distribution can strongly deviate from Gaussian, as for example under effect of Electron Cooling, it was necessary to develop IBS models based on the amplitude dependent diffusion coefficients.

Several models were developed:

-"Detailed" (Burov): analytic expression for longitudinal coefficient for Gaussian distribution with longitudinal temperature much smaller than transverse and smooth lattice approximation.

-"bi-Gaussian" (Parzen): rms rates for bi-Gaussian distribution; all particles are kicked based on the rms rate expression.

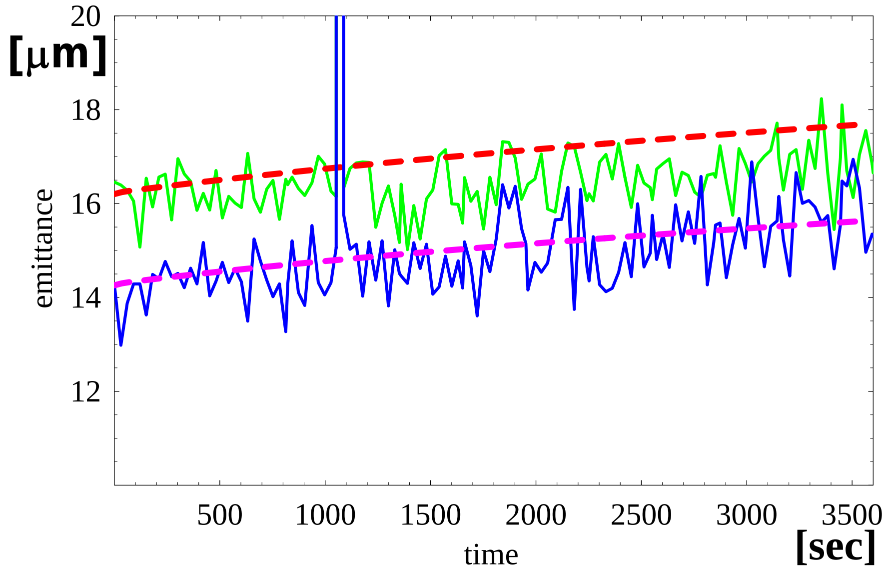
-"Core-tail": different diffusion coefficients for particle in the core and tails of the distribution.

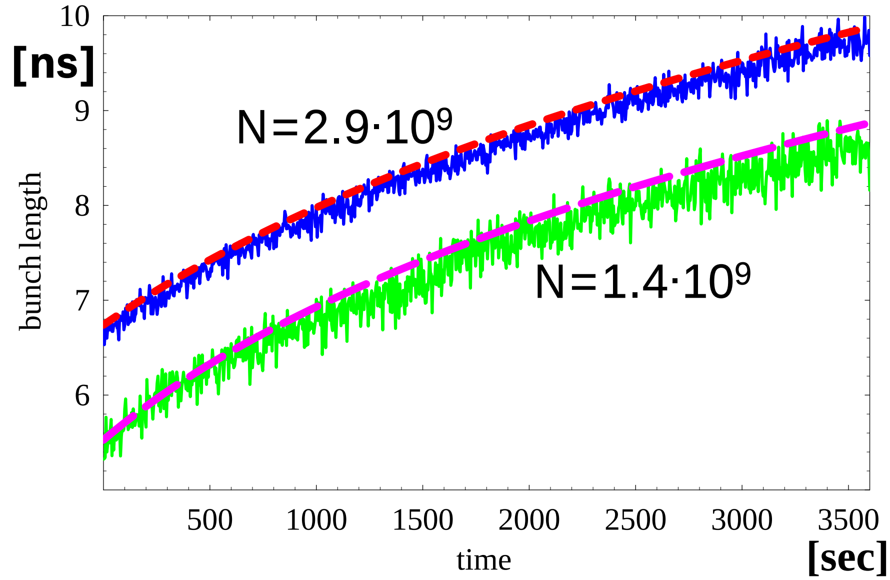
-"Kinetic model"

- "Local diffusion" – algorithm is based for numerical evaluation of amplitude dependent diffusion coefficients in 3-D. Allows to simulate evolution of arbitrary distribution due to IBS (implemented in BETACOOL in 2007).

Simulations vs. Measurements; Cu ions, APEX 2005 (82°/cell phase advance lattice; 100 GeV/n)

Two bunches with different intensity.

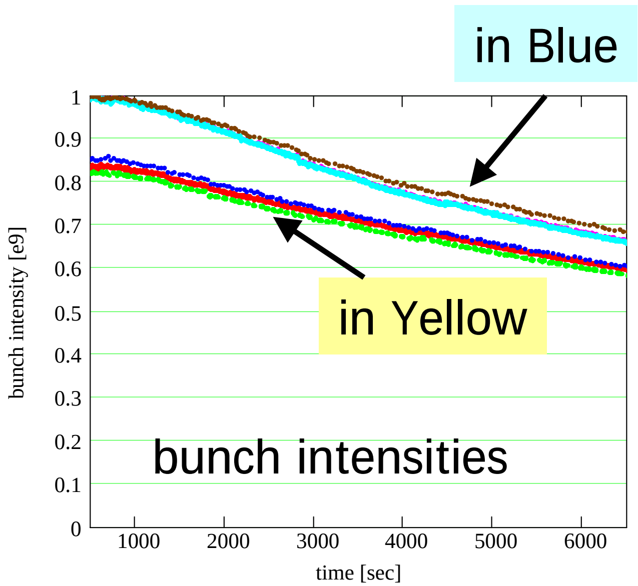


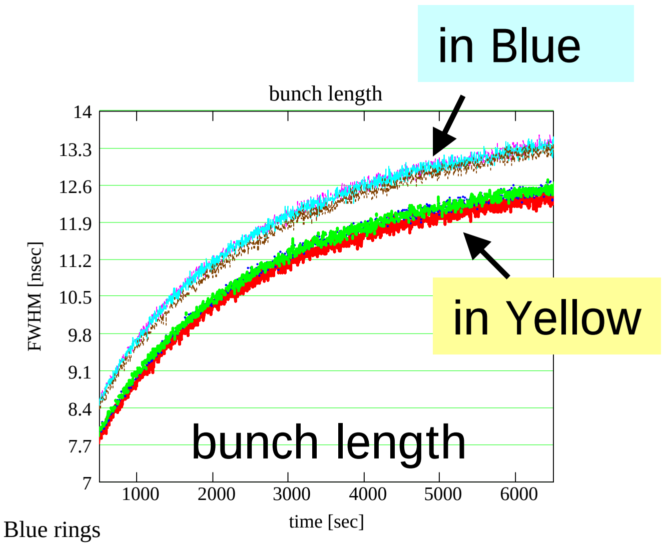


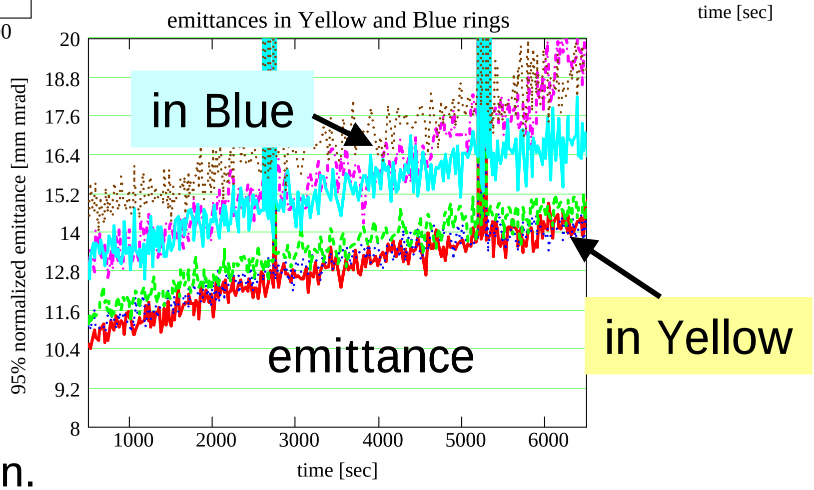
Growth of 95% normalized horizontal emittance [μm] for two bunch intensities N=2.9 $\cdot 10^9$ (upper curve) and 1.4 $\cdot 10^9$. Dash lines – simulations; solid lines – measurements.

FWHM [ns] bunch length growth for intensities N=2.9 $\cdot 10^9$ and 1.4 $\cdot 10^9$.

Au ions at 100 GeV/n (June 2007, APEX data)
(Blue ring: normal lattice with 82° phase advance per cell;
Yellow ring: IBS lattice with 92° phase advance)

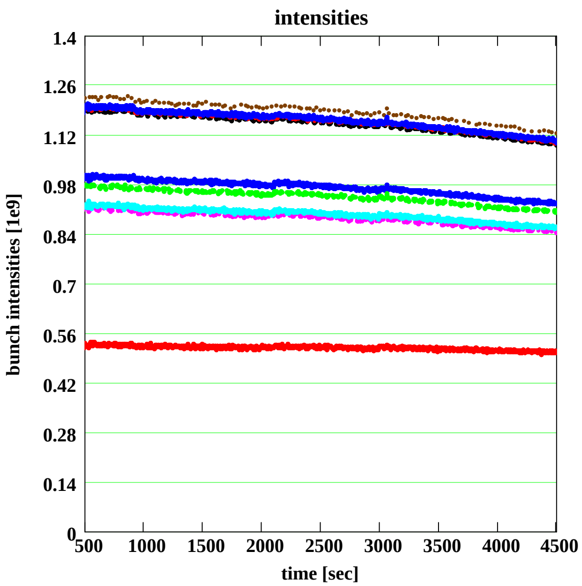


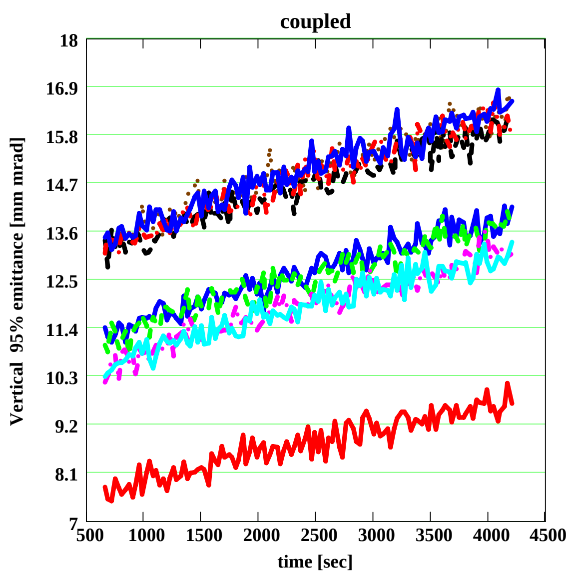


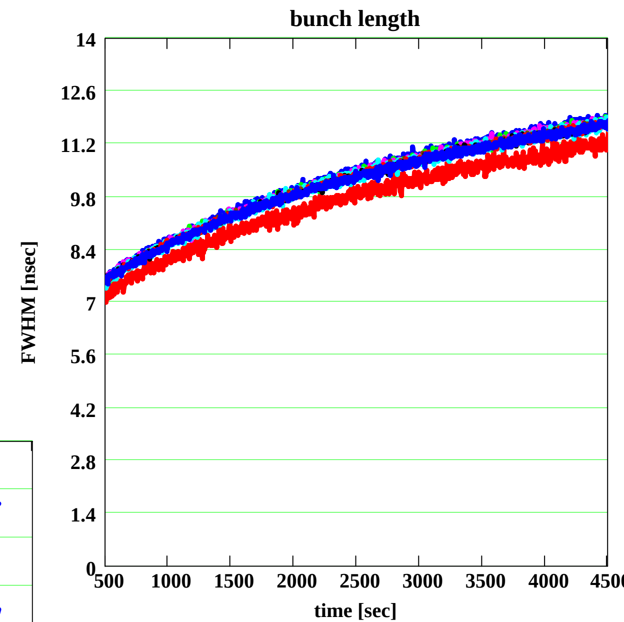


We had 6 bunches in each ring.
Only 3 bunches per ring are shown.

Au ions at 100 GeV/n (January 2008, APEX data)
(Yellow ring: operational IBS lattice with 95° phase advance)







coupled case data

Conclusions, future plans

- **Already developed lattice (95° phase advanced per cell) has expected 30% reduction in transverse IBS emittance growth rate.**
- **Significant improvement in integrated & vertex luminosity is expected.**
- **Use 95° lattice in both Blue and Yellow rings during next RHIC run with Au-Au. Push β^* down to 0.5m with 95° lattices.**
- **Develop lattice even with higher phase advance per cell. The lattice with 107° is presently under development. Test/develop this new lattice during next APEX experiments with heavy ions.**

State of the art of high intensity simulation codes: new algorithms and methods for rings - a personal and biased view

A. Adelmann

Accelerator Modelling and Advanced Simulation (AMAS), PSI

Contents

Overview

Overview of Received Contributions

Code	Author (et.al)	Space Charge	Dim	Parallel
Micromap	G. Franchetti	analyt.	2/3	no
Accsim	F.W. Jones	Hyb. FMM	2.5	no
Simpson	S. Machida	PIC	3	(yes)
Orbit	J.A. Holmes	PIC	3	yes
IMPACTx	J. Qiang	PIC	3	yes
PTC/Orbit	A. Molodozhentsev	PIC	3	yes
ML/IMPACT	R.D. Ryne	PIC	3	yes
Synergia2	J. Amundson	PIC	3	yes
OPAL	A. Adelmann	PIC	3	yes
Posinst	M. Furman	analyt. & e-cloud	2	no
Warp	D. Grothe	PIC & e-cloud	3	yes

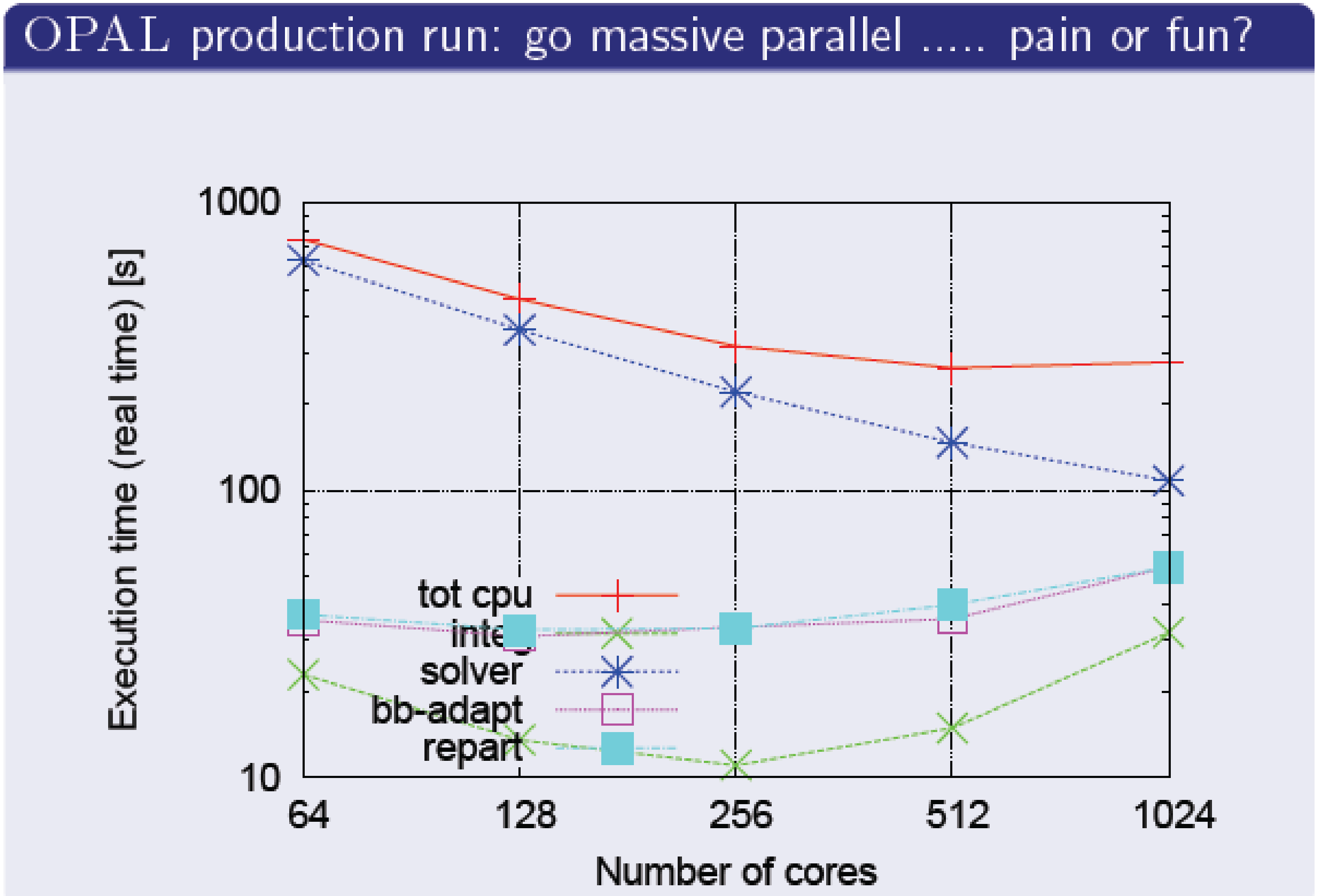
Oberservation 1: clear trend towards 3D & parallel

New development

New Development

- Physics inside: tremendous increase in the efficiency of the simulation
  - J.-L. Vay - Warp
- 3D semi-analytic space charge model (ellipsoidal symmetry)
  - G. Franchetti et.al - MICROMAP
- Iterative Methods and exact Geometry
  - J. Amundson et.al - Synergia
  - A. Adelmann et.al - OPAL
- High Performance Computing (& CS)
  - go parallel - or go massively parallel: pain or fun?

New development



Outlook

Outlook

In the MW- League it is all about *quantitative* i.e. *precise* BD simulation

1. The more precise our simulations are the more difficult and important are proper initial conditions
2. Obtain measurements (profiles) with a dynamical range of several orders of magnitude is non trivial but vital in order to fully profit from our precise simulations
3. HPC helps but we have to work hard on the weak scaling

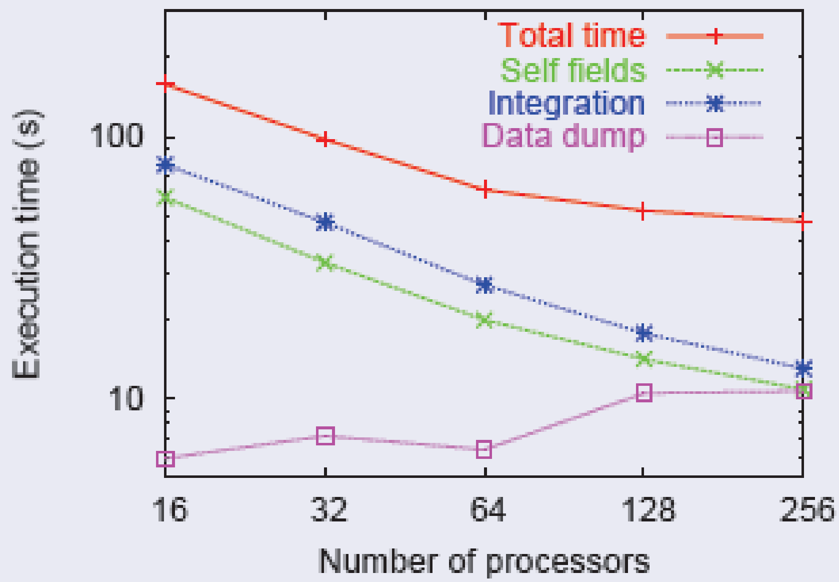
Outlook

Setup

- 10^6 particles,
- 3D FFT on a 64^3 grid,
- 2D domain decomposition
- Track 200 time steps
- Gaussian distribution
- Dump data into single H5Part file every 10 steps

Observations

- The code scales well
- Good load-balancing
- Dumping time increased



Evolution beam parameters during injection and storage of the high brightness beams envisaged for the Linac4 injection into the CERN PS Booster

M. Aiba, Ch. Carli, M. Martini
(CERN)

Acknowledgements

M. Chanel, B. Goddard, W. Weterings (CERN)
S.M. Cousineau (ORNL), F.W. Jones (TRIUMF)

Agenda

- ✓ Studies of the injection and storage of the 160 MeV Linac4 beam for LHC into the CERN PS Booster (PSB)
  - Simulations with the Orbit code of the H^- charge exchange injection and following beam emittance evolution at 160 MeV
  - Injection done via a painting scheme for optimal shaping of the initial particle distribution
- ✓ Benchmarking of the Orbit and Accsim simulations with measurements performed in the PSB on the actual high intensity beam stored at 160 MeV

Motivation for the upgrade of the PSB with Linac4:
Deliver beams for the LHC, CNGS and ISOLDE of higher intensity or brightness than presently achieved

ORBIT/ACCSIM space charge modeling

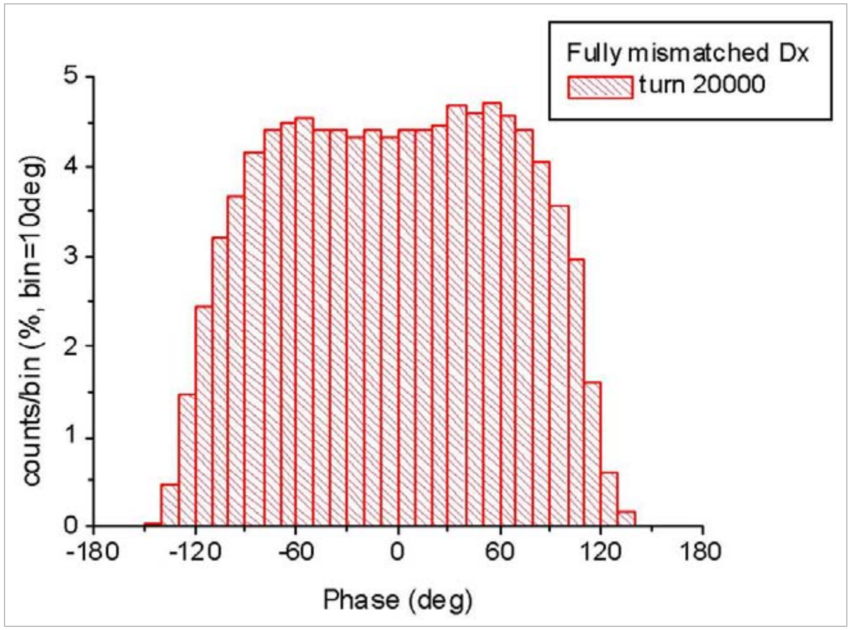
<table>
<tr><th>ORBIT</th><th>ACCSIM</th></tr>
<tr><td>Parallel processing</td><td>Non-parallel processing</td></tr>
<tr><td>2½D & 3D space charge models</td><td>2½D space charge model</td></tr>
<tr><td colspan="2">Transverse space charge techniques</td></tr>
<tr><td>Pair-wise sum: “Particle-Particle” method (computes Coulomb force on one particle by summing the force over all other particles)</td><td>Fast Multipole Method (FMM): “Particle-Particle Tree-code” method (lumping charges together)</td></tr>
<tr><td>Brute Force Particle-In-Cell (PIC): “Particle-Mesh” method (grid size automatically fitted to the beam extent)</td><td rowspan="2">Hybrid Fast Multipole (HFM): FMM is combined with elements of PIC-style methods (grid size manually fitted to the beam extent):

Overlay a proper grid on the dense beam core region, assign compound charges to the grid points, and let FMM solve the whole system of core grid + halo charges</td></tr>
<tr><td>FFT-PIC: Alike to the brute-force PIC with the aid of a FFT technique (the fastest solver)</td></tr>
</table>

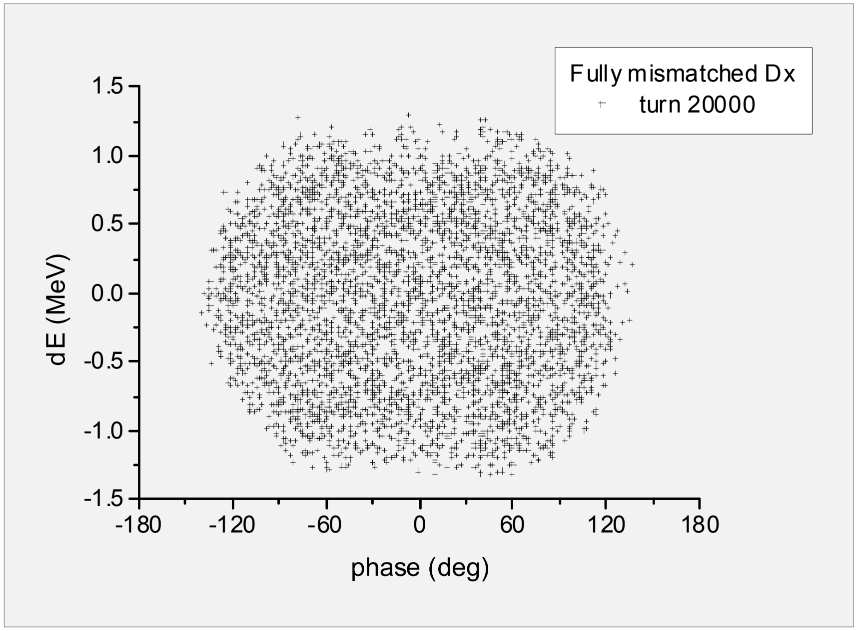
PSB injection –Painting and tracking with ORBIT

- ✓ Nominal LHC beam at 160 MeV PSB injection
  - Mismatched dispersion at injection (end line: D_{Linac4}=0m, D_{PSB}≈-1.4m)
  - Bunching factor ~0.60

FROM M. AIBA



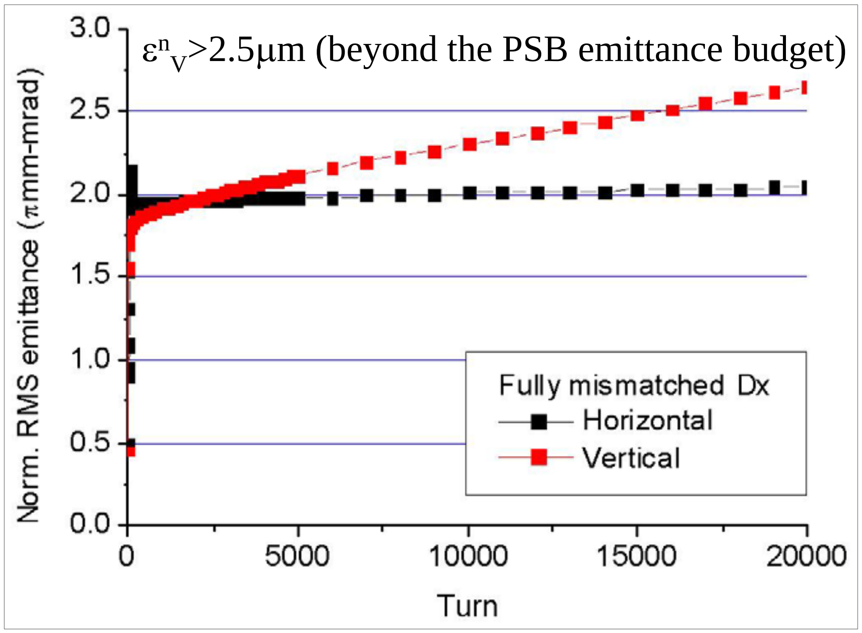
ORBIT : Longitudinal profile (flat)
(2.2×10^5 macro-particles)



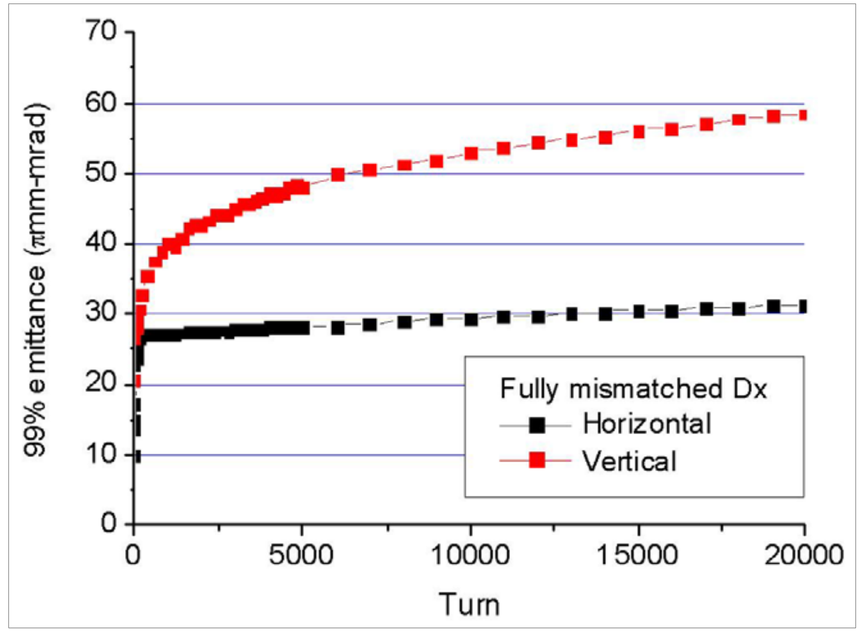
ORBIT : Longitudinal phase-space plot
ϕ-ΔE [deg-MeV] (2.2×10^5 macro-particles)

PSB injection –Painting and tracking with ORBIT

- ✓ Emittance evolution on a 160 MeV energy plateau **FROM M. AIBA**
  - – Painting and subsequent tracking up to 2×10^4 turns
  - – Simulation done with space charge, $\Delta Q_{H,V}$~-0.27/-0.32 ($Q_{H,V}$=4.28/5.45)



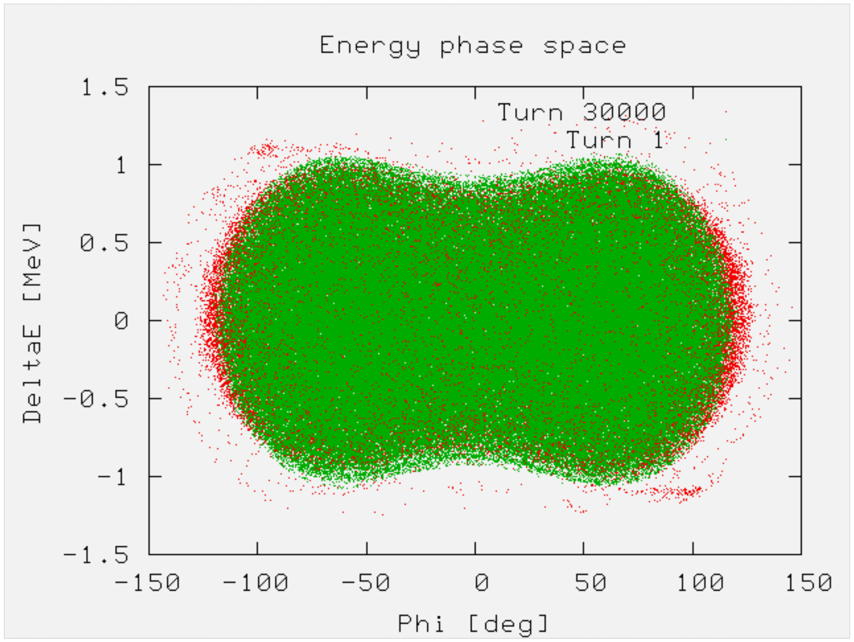
ORBIT : Emittances after injection
$\varepsilon^n{}_{H,V}(1\sigma)$ [μm] (2.2×10^5 macro-particles)



ORBIT : Emittances after injection
$\varepsilon^n{}_{H,V}(99\%)$ [μm] (2.2×10^5 macro-particles)

Remark: ~8% rms vertical emittance blow-up reduction after 10^4 turns when using 4 times more macro-particles (~9×10^5)

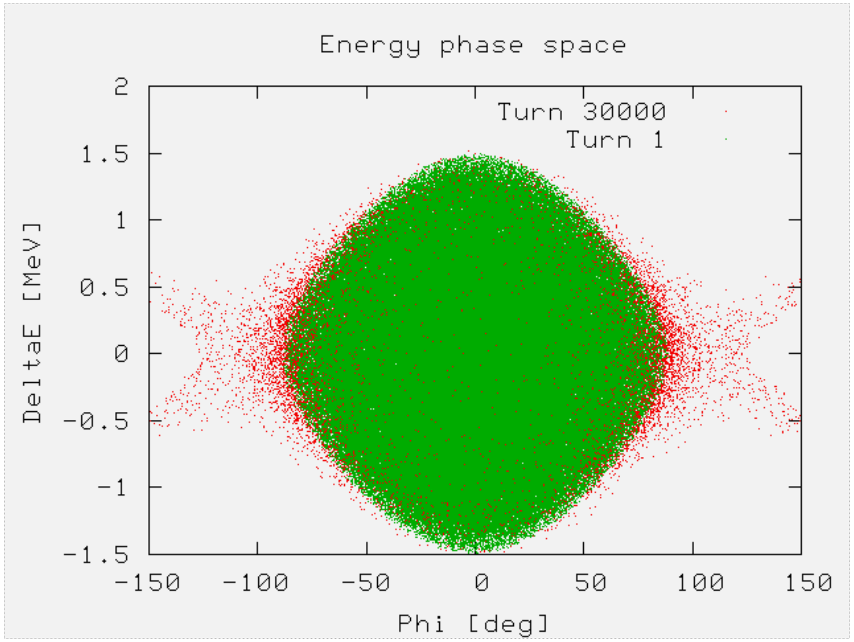
Benchmark – ORBIT/ACCSIM vs. measurements



✓ ORBIT $Q_{H,V}$=4.21/4.35
Long bunches

Longitudinal phase-space plots
ϕ-ΔE [deg-MeV] (2×10^5 macro-particles)
(green: at turn 1, red: at turn 30000)

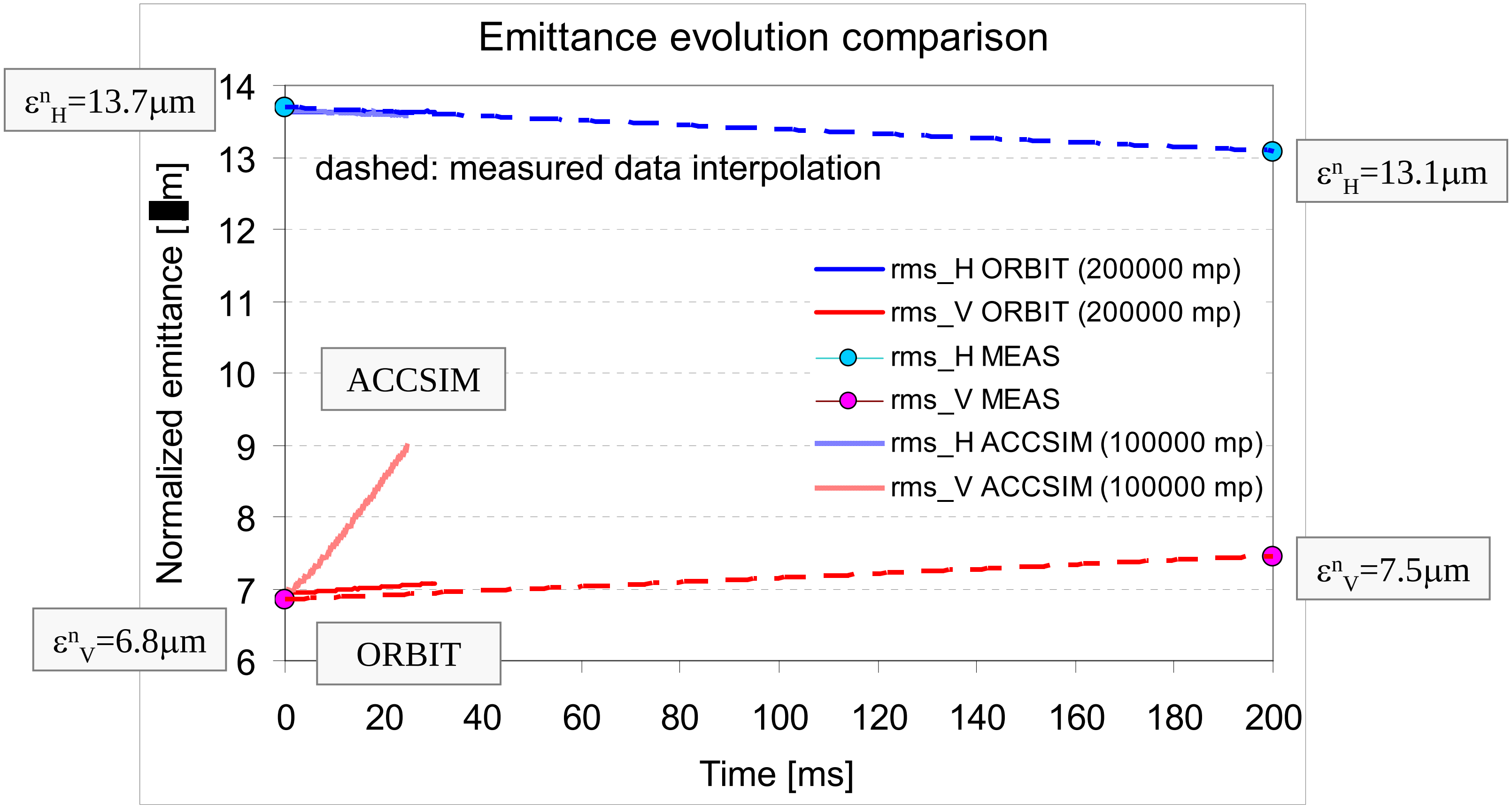
✓ ORBIT $Q_{H,V}$=4.21/4.45
Short bunches



Benchmark – ORBIT/ACCSIM vs. measurements

✓ ORBIT and ACCSIM : Long bunches – $Q_{H,V}$=4.21/4.35

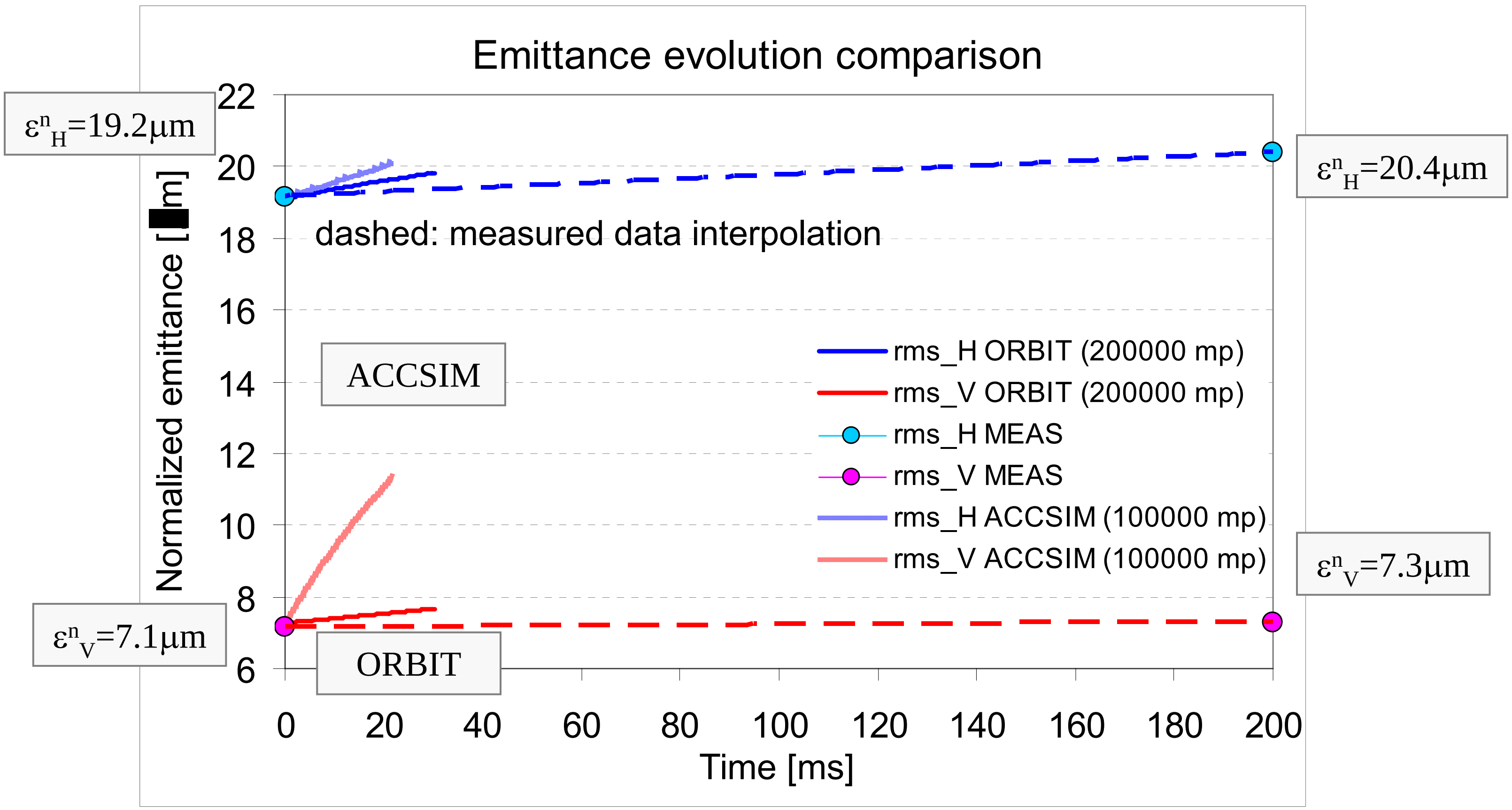
- 2^{nd} harmonic cavity in anti-phase
- ORBIT: ~30 ms, 3×10^4 turns, $\Delta\varepsilon_{H\&V}/\Delta t$~$5\times10^{-4}$ & 5×10^{-3} μm/ms
- ACCSIM: ~25 ms, 2.5×10^4 turns, $\Delta\varepsilon_{H\&V}/\Delta t$~-0.003 & 0.1 μm/ms



Benchmark – ORBIT/ACCSIM vs. measurements

✓ ORBIT and ACCSIM : Short bunches – $Q_{H,V}$=4.21/4.45

- 2^{nd} harmonic cavity in phase
- ORBIT: ~30 ms, 3×10^4 turns, $\Delta\varepsilon_{H\&V}/\Delta t$~0.024 & 0.013 μm/ms
- ACCSIM: ~22 ms, 2.2×10^4 turns, $\Delta\varepsilon_{H\&V}/\Delta t$~0.04 & 0.2 μm/ms



Summary

- ✓ PSB injection simulations
  - – Controlled longitudinal injection painting scheme based on a triangular modulation of the Linac4 output energy examined
  - – Tailoring of the longitudinal and transverse distributions to minimize peak densities is effective in lessening the transverse emittance blow-up
- ✓ PSB benchmarking simulations
  - – Benchmark of the simulations with experiments at 160 MeV seems to indicate that the simulations done with Orbit are hopeful (i.e. emittance growth rates ~similar to measurements) while those conducted with Accsim are rather pessimistic (i.e. overestimation of growth rates but horizontal plane and long bunches)