IBS suppression lattice in RHIC:
theory and experimental verification

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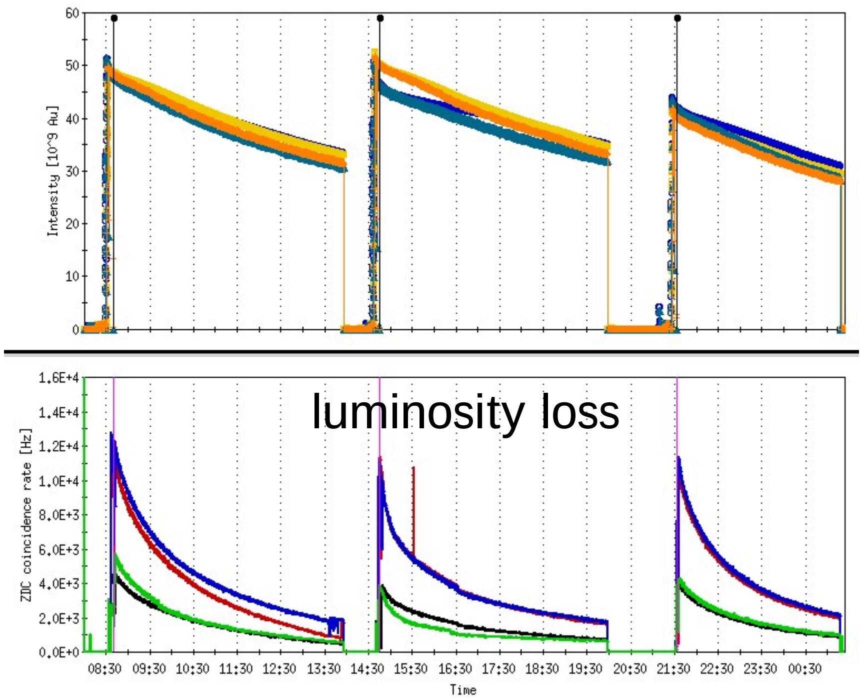
Outline

- IBS in RHIC
- Development of IBS-suppression lattice
- IBS models/simulations
- Dedicated IBS measurements
- Comparison of simulations and measurements

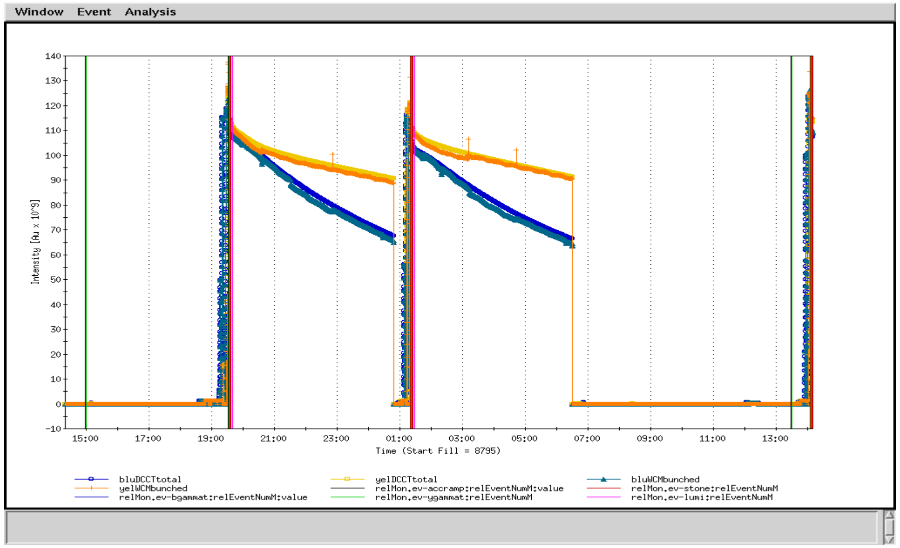
RHIC performance for Au ions

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).

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.

Approximate longitudinal IBS diffusion rate:

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

Additional heating:

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

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

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

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.

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

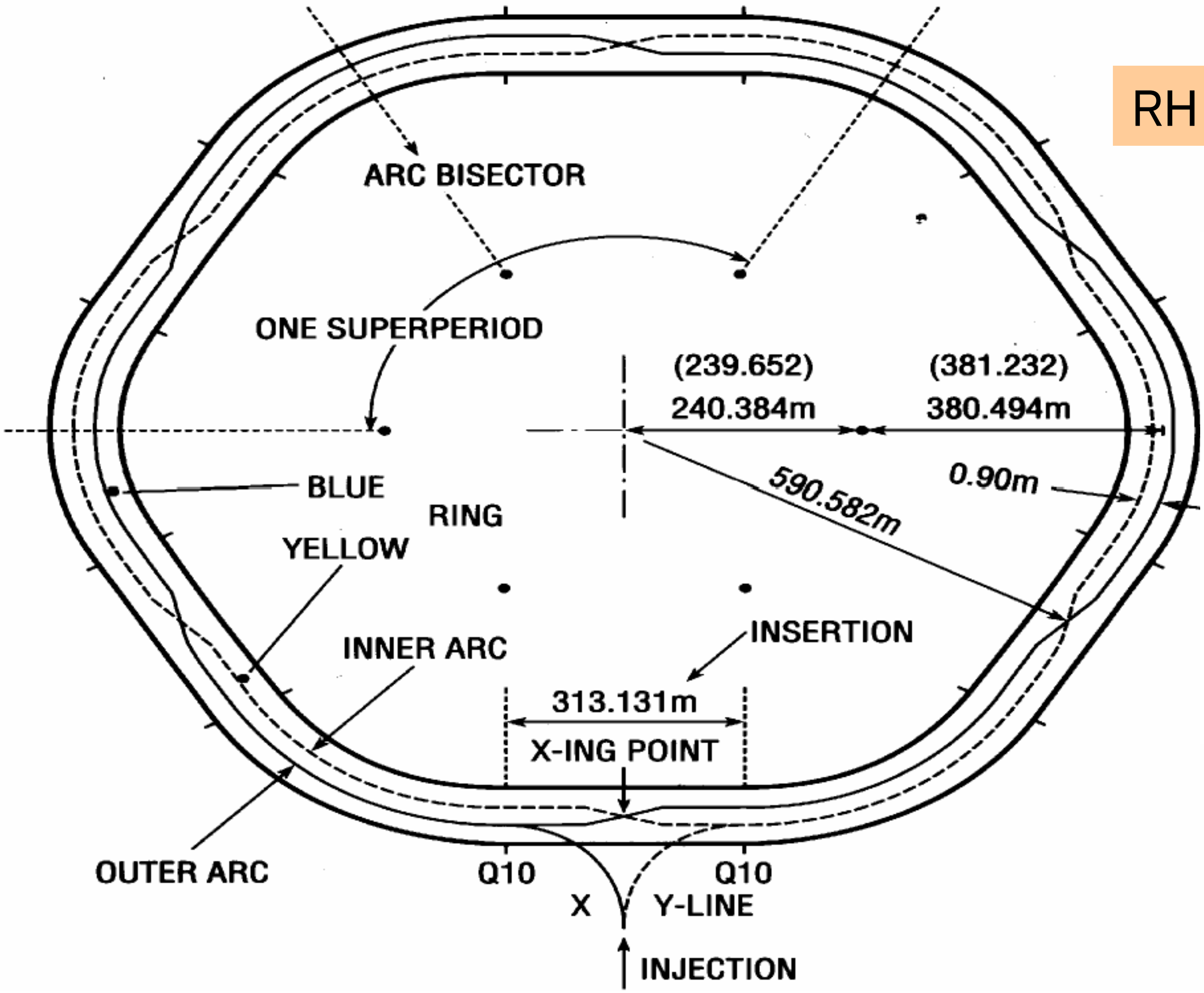
Reduction of transverse IBS

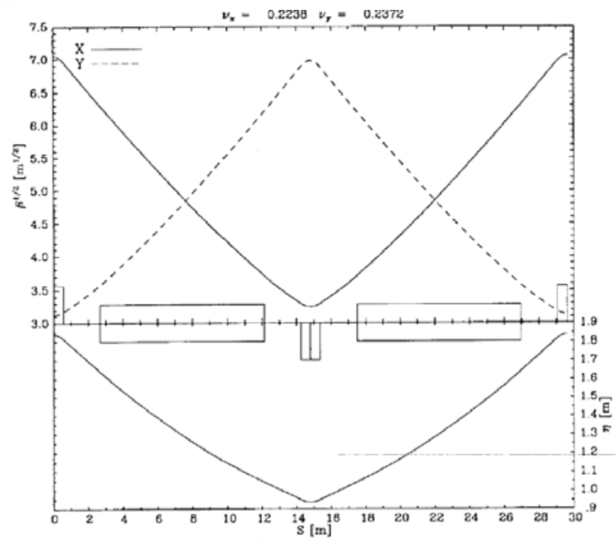
$$H_x = \gamma_x D_x^2 + 2\alpha_x D_x D_x' + \beta_x D_x'^2$$

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

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

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





Lattice functions for arc cell

Layout of RHIC collider: The collider is composed of 2 identical non-circular rings oriented to intersect with one another at 6 crossing points.

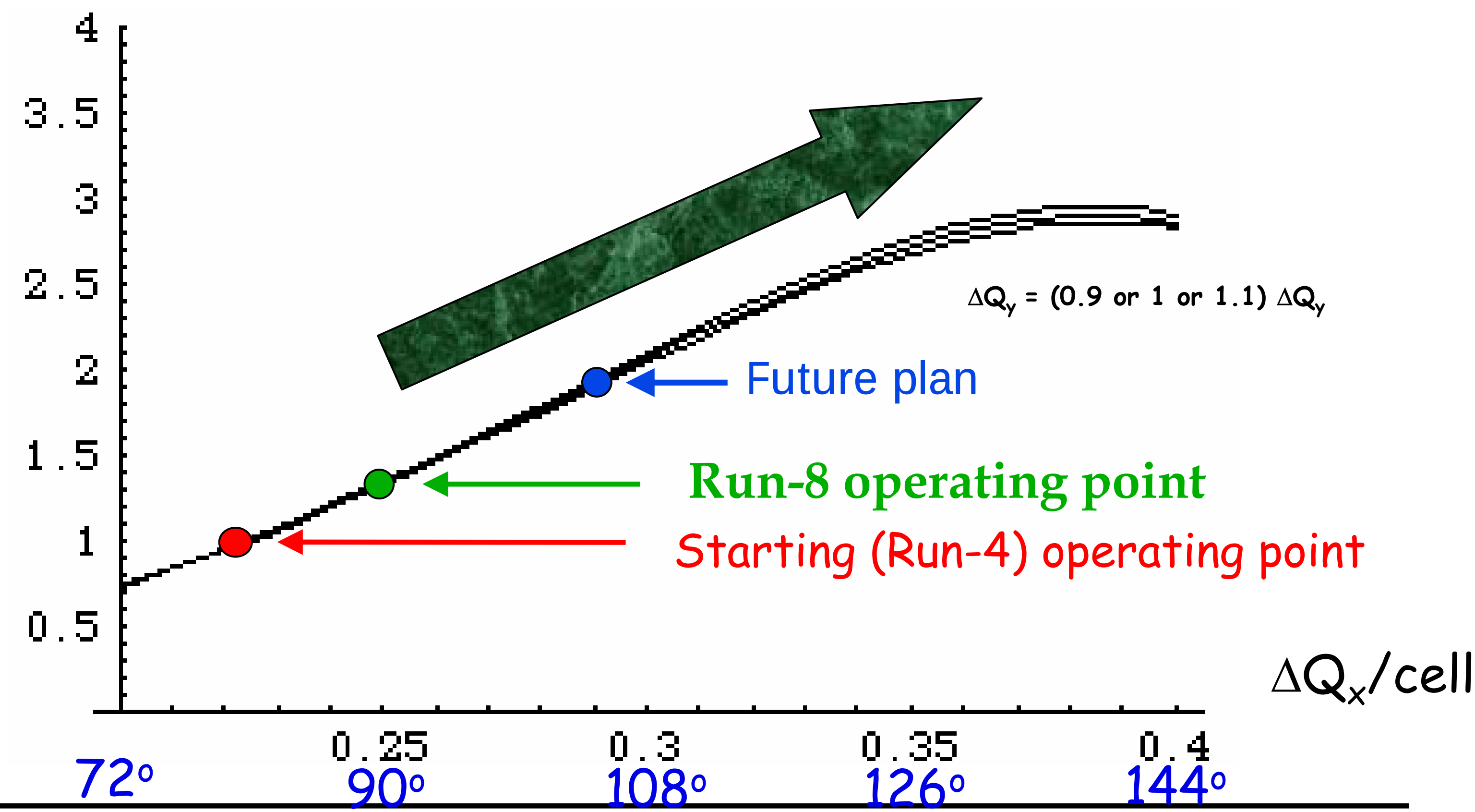
Each arc is composed of 11 FODO cells.

Reduction of the IBS rate

V.N. Litvinenko (2004)

IBS(0.22)/ IBS(ΔQ_x)

NOTE: ΔQ_x are tune advances per FODO cell

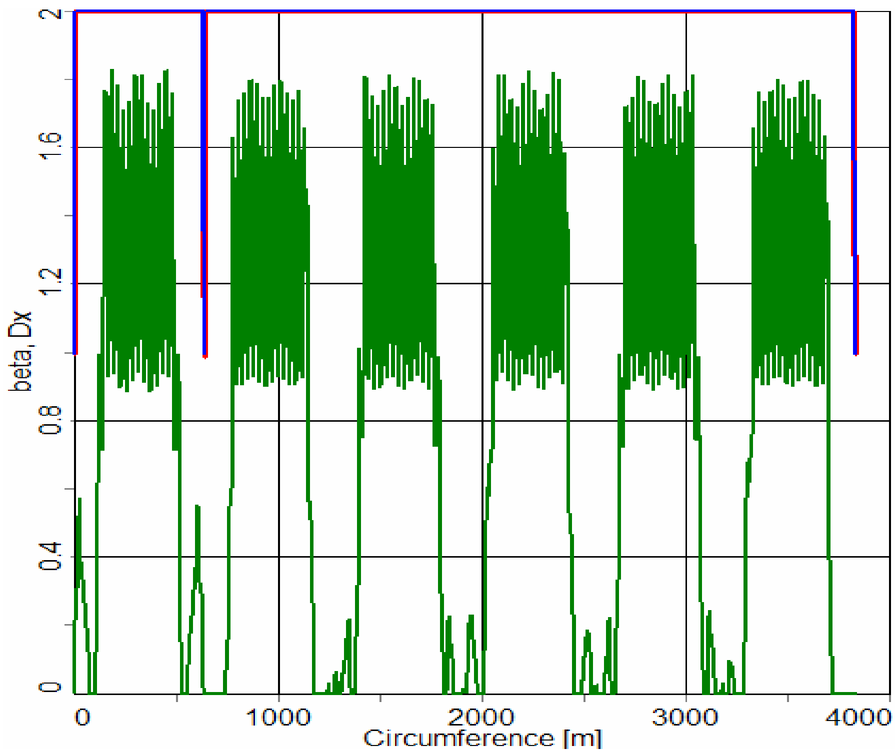


Stronger focusing and limits

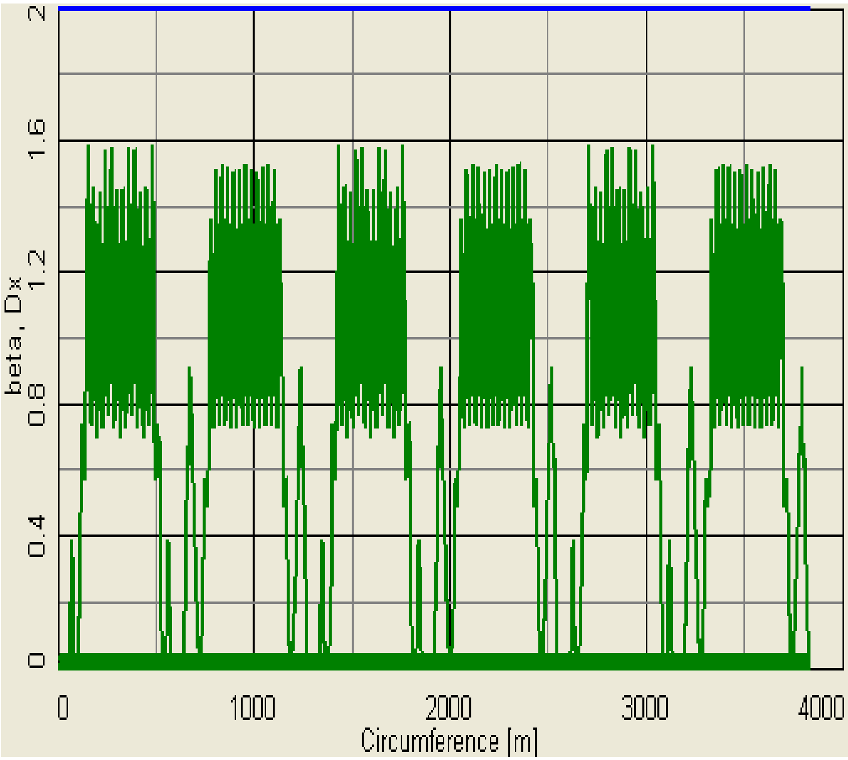
- When built, RHIC was already the collider with the shortest and strongest focusing FODO cell of all the hadron machines. The most important consideration in this regard was Intra-beam Scattering.
- However, for the beam parameters and machine performance in 2004, operational lattice with 82° phase advance appeared to be not fully optimized with respect to IBS growth and thus maximum luminosity.
- Therefore, it was suggested to explore RHIC performance with higher phase advance per cell.
- Practical range of achievable phase advances per cell is determined by existing feeding system for RHIC superconducting magnets which have multiple inter-connections and current limits imposed by feeders and power supplies. As well as interplay with other effects.
- It was decided to start with the test "IBS-suppression" lattice with 92° horizontal phase advance per cell.

Test IBS lattice (2005) for APEX experiments

lattice development by S. Tepikian

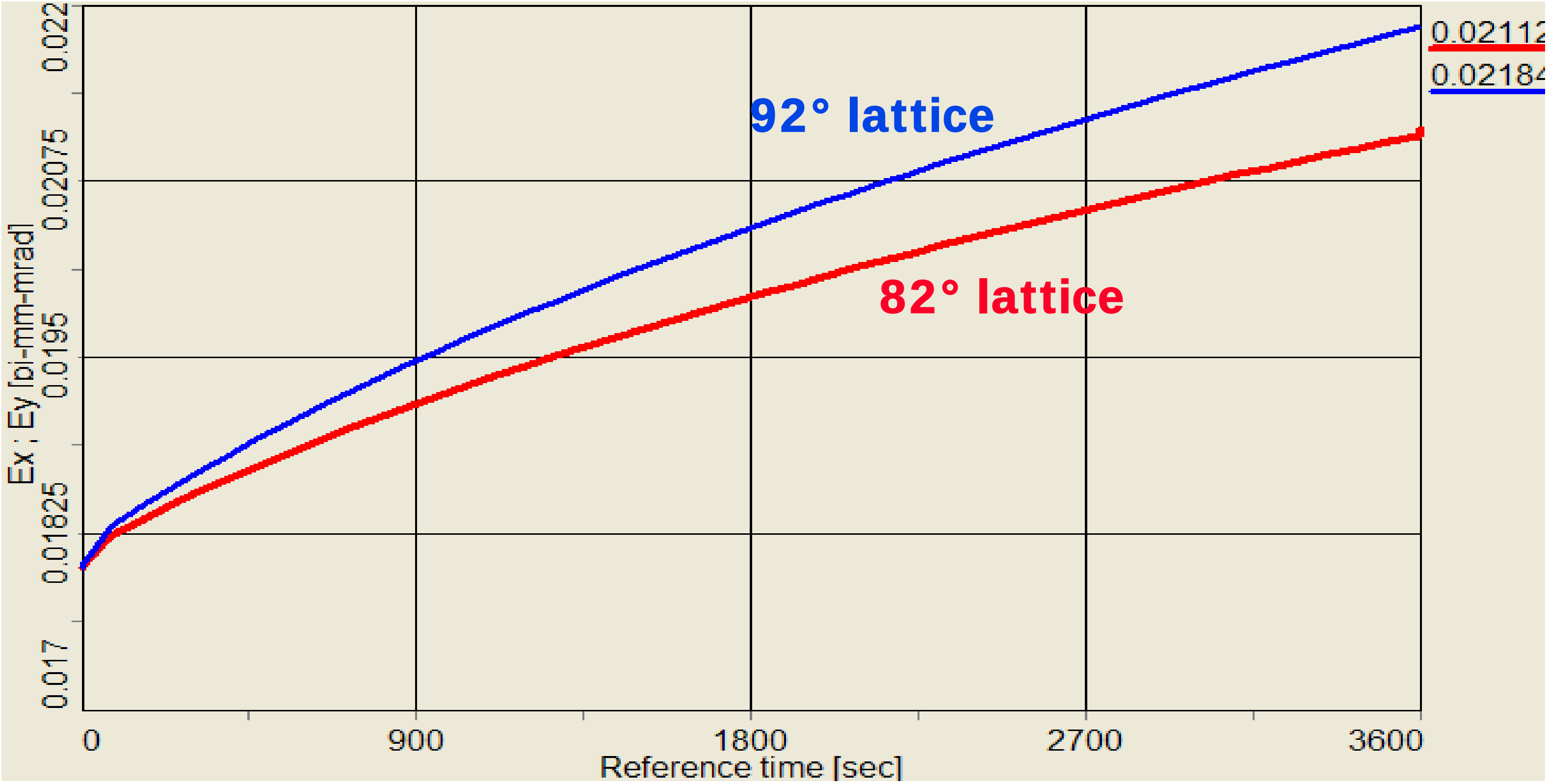


Dispersion function for RHIC-4 lattice (82° phase advance)



Dispersion function for test IBS lattice (92° phase advance)

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)



$\tau^{-1}_{rhic\text{-}4}/\tau^{-1}_{92}$=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.

Dedicated measurements of IBS in RHIC

For accurate comparison of measurements with simulations, IBS studies in RHIC were performed in dedicated beam mode under APEX.

1. **To ensure accurate benchmarking, collisions were turned off. In addition, h=360 rf system was used to avoid loss of particles from the bucket.**
2. **Six bunches of different intensity with different initial emittance were injected, which allowed us to test expected scaling with intensity and emittance.**
3. **Measurements of the bunch length were done using Wall Current Monitor (WCM).**
4. **Measurements of the horizontal and vertical emittance in each individual bunch were done using Ionization Profile Monitor (IPM).**

2004 – with Au ions

2005 – with Cu ions

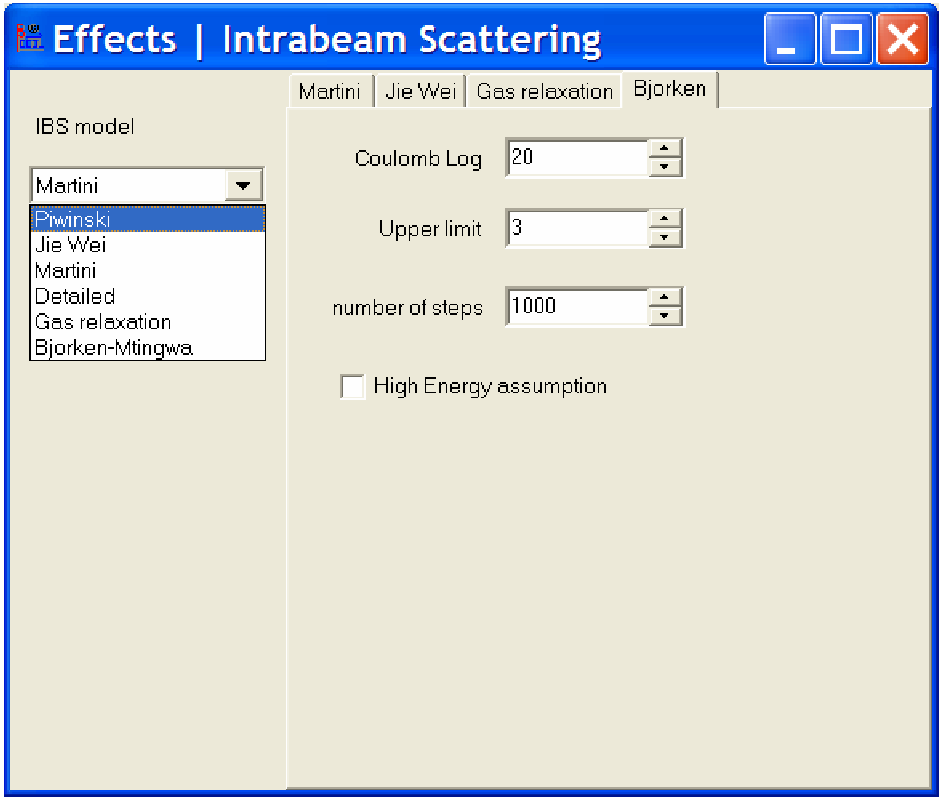
2007 – Au ions with IBS-suppression lattice

2008 – Au ions with operational IBS-suppression lattice

IBS models in BETACOOL code (JINR, Dubna, Russia) – Gaussian distributions

I. *Analytic models for Gaussian distribution:*

- Piwinski's model
- Martini's model (including derivatives of lattice functions)
- Bjorken-Mtingwa's model (including vertical dispersion)
- Wei's, Parzen's models (high-energy approximation)
- Gas-relaxation model (high-energy approximation)



For comparison with experimental measurements in RHIC at 100 GeV/n, we use Martini's or Bjorken-Mtingwa's models (which give the same results for RHIC parameters).

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.

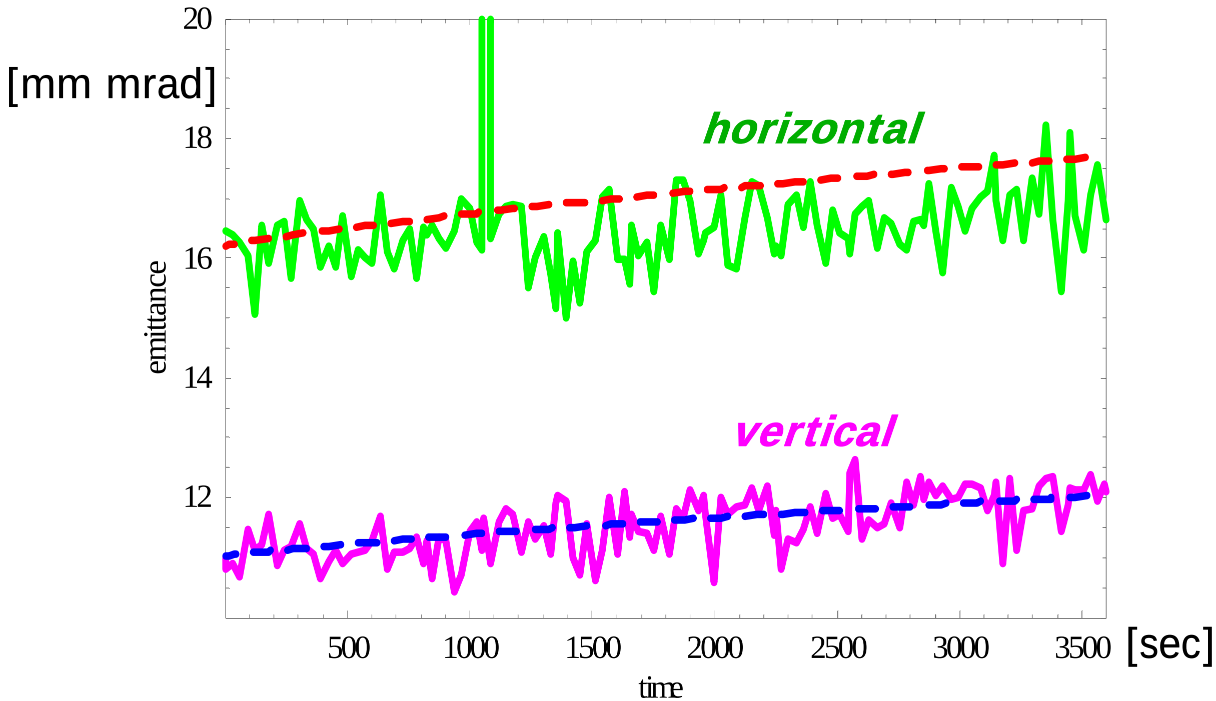
-“Core-tail”: different diffusion coefficients for particle in the core and tails of the distribution.

-“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).

IBS in RHIC – measurements vs. theory
Example of 2005 data with Cu ions (82°/cell phase advance)

Simulations (BETACOOL) – Martini's model of IBS for exact designed lattice of RHIC (82°/cell), including derivatives of the lattice functions.

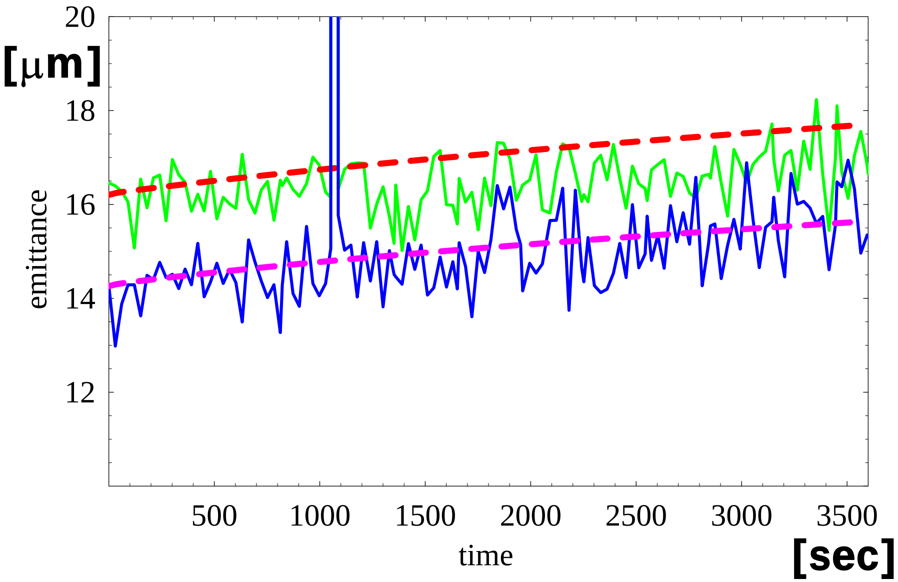


Growth of 95% normalized emittance [μm] for bunch with intensity $N=2.9\cdot10^9$

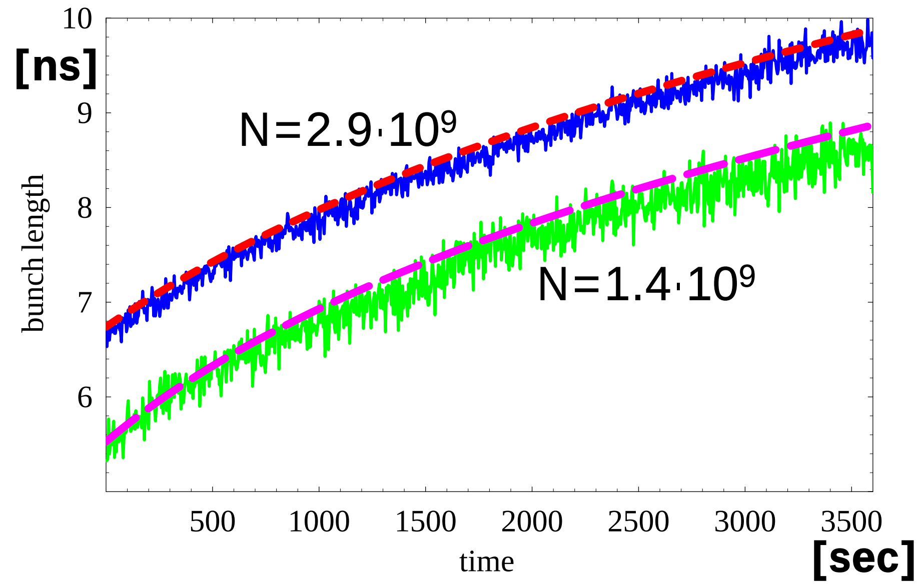
Emittance measurements were done with Ionization Profile Monitor (IPM).

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

Two bunches with different intensity.



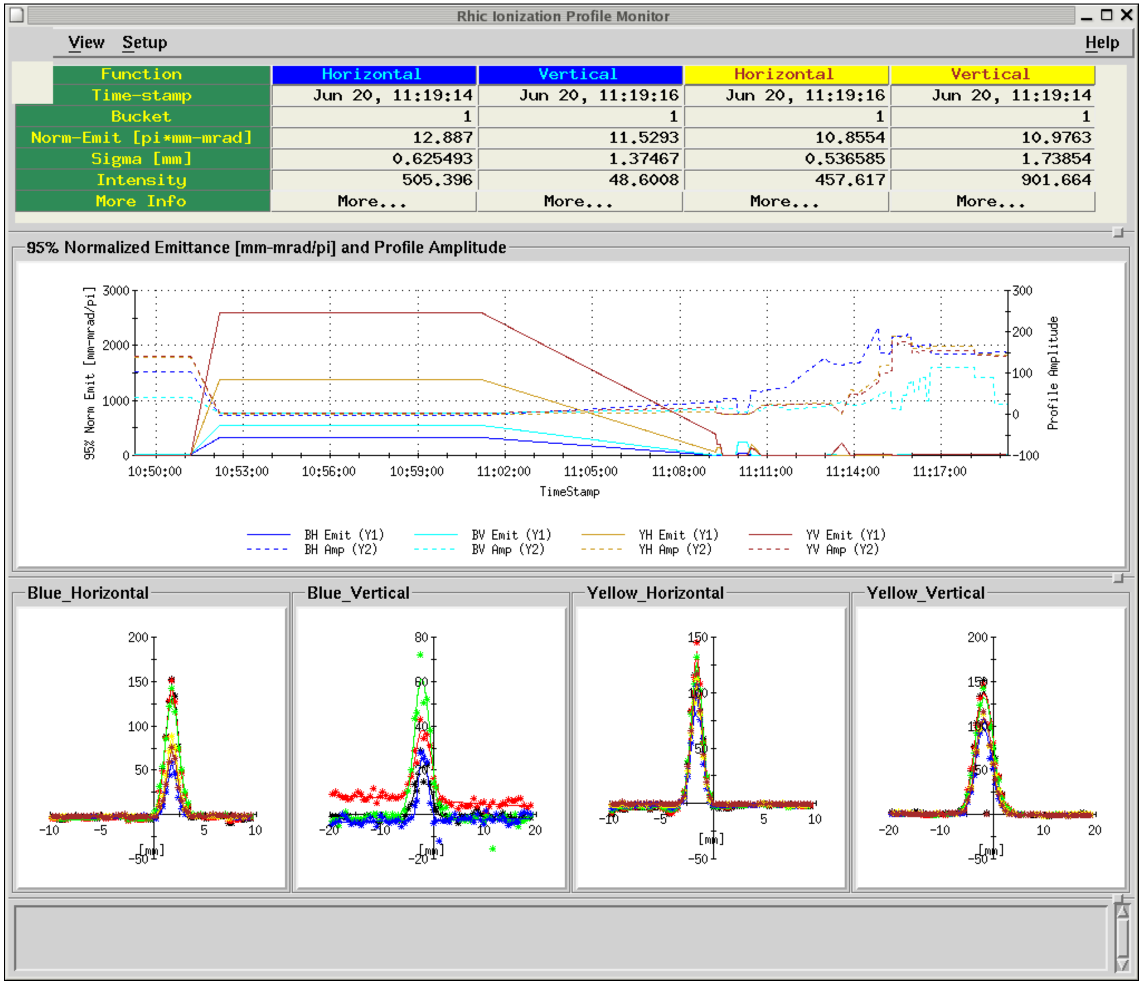
Growth of 95% normalized horizontal emittance [μm] for two bunch intensities N=2.9 ·10^{9} (upper curve) and 1.4 ·10^{9}. Dash lines – simulations; solid lines – measurements.



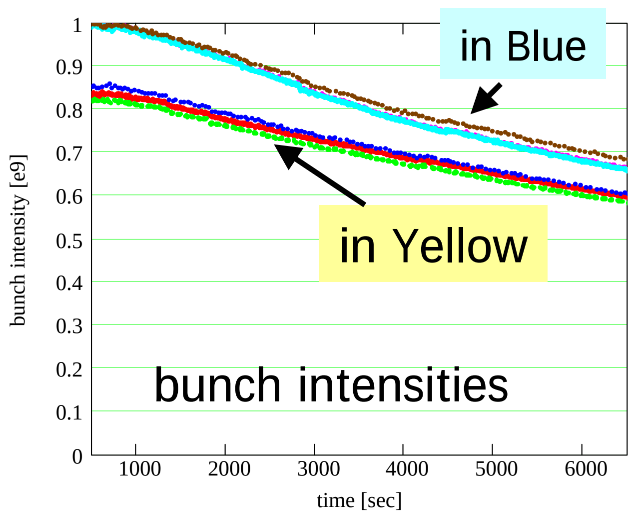
FWHM [ns] bunch length growth for intensities N=2.9 ·10^{9} and 1.4 ·10^{9}.

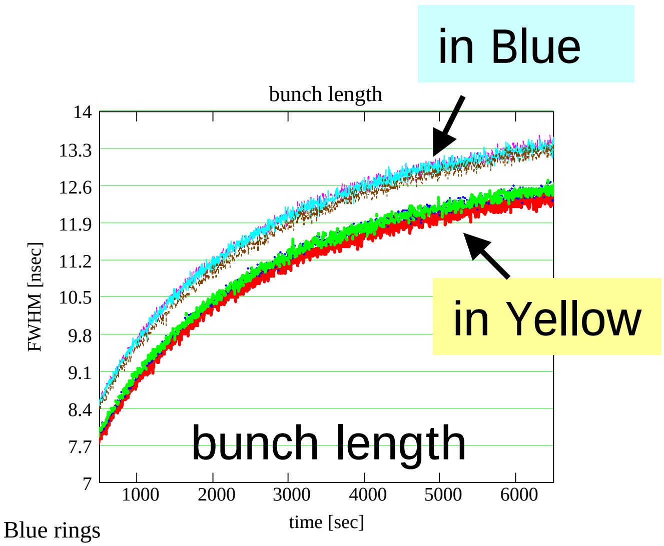
IPM measurements of transverse emittance

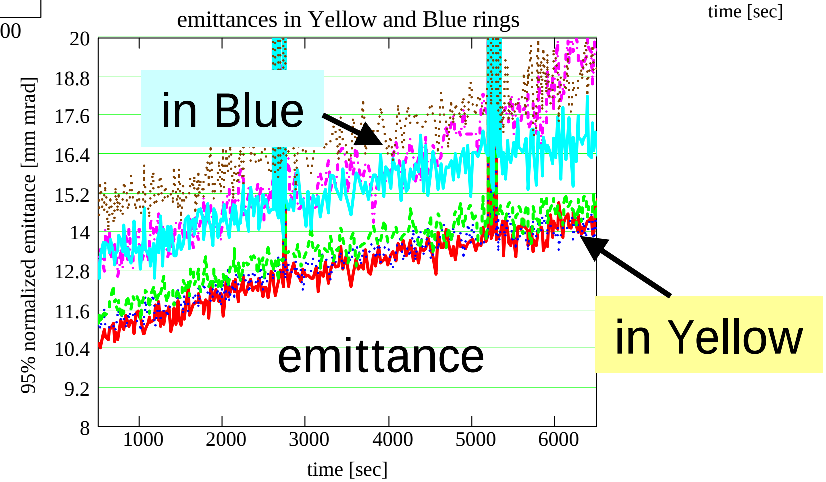
(June 2007, APEX data for Au ions)



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)







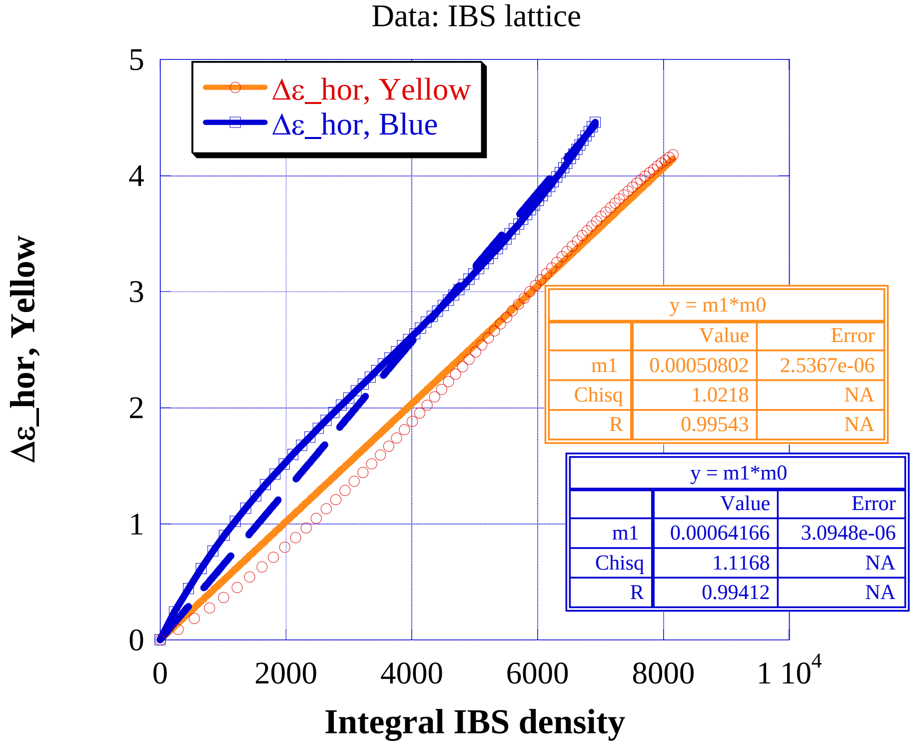
We had 6 bunches in each ring.

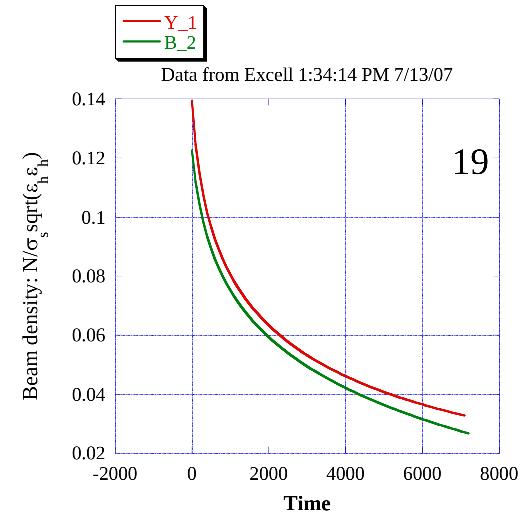
Only 3 bunches per ring are shown.

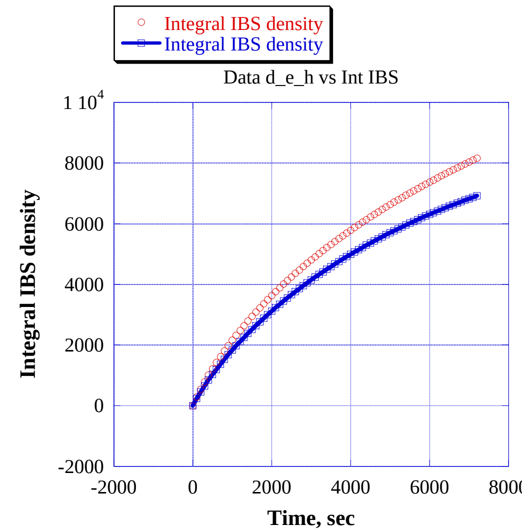
IBS suppression lattice APEX experiment – June 2007

(V. Litvinenko et al.)

$$IBS\ \ Integral\ (t) = \int_{o}^{t} \frac{N(t')dt'}{\sigma_z \sqrt{\varepsilon_h \varepsilon_v (\varepsilon_h + \varepsilon_v)}}$$







- **Conclusions**
  - **Transverse IBS emittance growth is suppressed by 30±10%**

January 9, 2008 APEX measurements, using operational Run-8 IBS lattice (95° phase advance) in Yellow ring

Goal of the experiment:

To understand what portion of vertical emittance growth comes from x-y coupling.

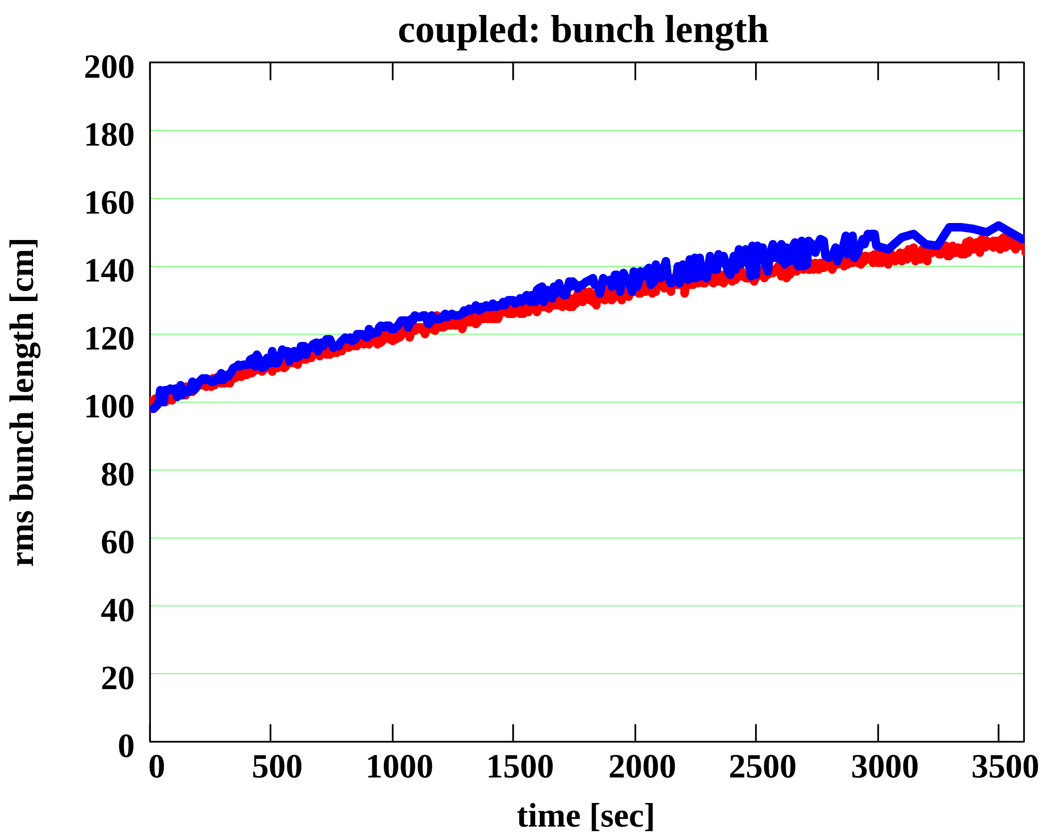
Quantitative understanding of emittance growth in horizontal and vertical planes should help us to conclude whether single-plane transverse stochastic cooling will be sufficient to counteract both horizontal and vertical emittance growth.

Measurements (at γ=107):

1. **Decoupled case: dQmin=0.001, tunes were separated by 0.018**

2. **Fully coupled case: dQmin=0.018, tunes were separated by 0.018**

Longitudinal bunch length growth due to IBS (simulations vs. measurement, bucket #121)



red – measurement

blue – simulation

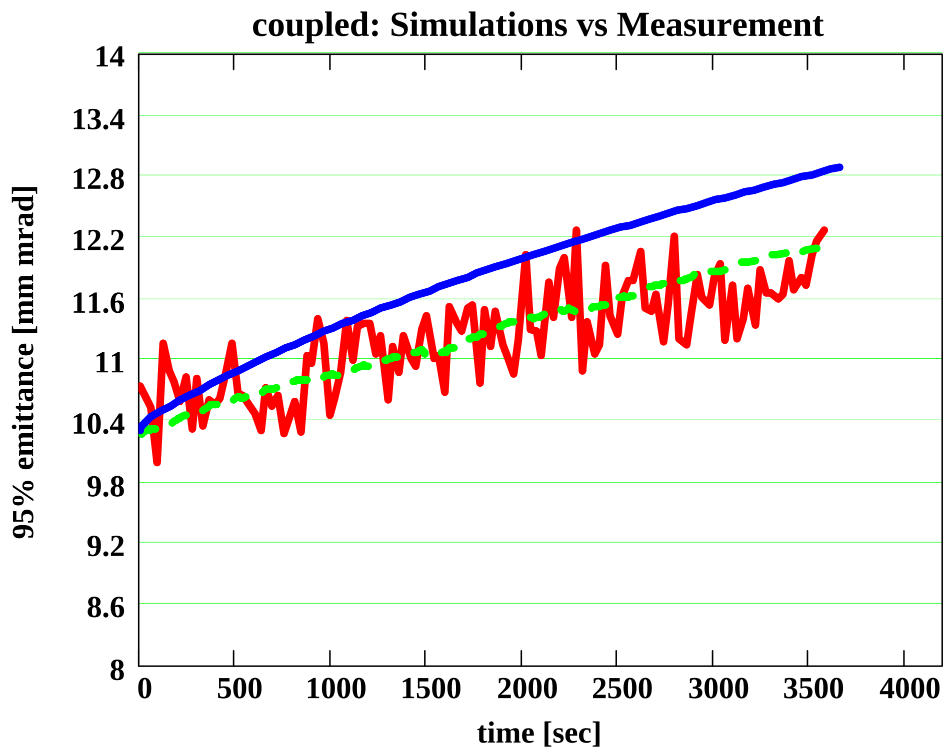
95°/cell phase advance lattice

Fully coupled case (January 9, 2008 APEX data):
Horizontal emittance growth (simulation vs. measurement, bucket #121)

red – Horizontal emittance (measurement)

blue – expected (simulation) with Run-7 lattice (82°/cell)

green – expected (simulation) for Run-8 “IBS-suppression” lattice (95°/cell)



Reduction in horizontal IBS emittance growth rate, as predicted.

For simulations with 82° and 95° lattice, longitudinal beam parameters (momentum spread and bunch length) were chosen the same.

IBS lattice summary

Clear advantages:

- reduced transverse emittance growth – confirmed by dedicated beam experiments
- increased RF bucket area, due to higher γ_t (by 13%) –better rebucketing
- shorter bunch length – better vertex luminosity

Additional advantages:

- helps to achieve lower β^* due to slower emittance growth
- more relaxed PS current at the beta squeeze

Concerns:

- new lattice, more time for development – no problem in Run-8.
- higher main quad current (reliability issue) – seems not a problem in Run-8.
- nonlinear characteristics of the lattice, the dynamic aperture and its possible effects on beam lifetime – to be explored in simulations

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.**

Acknowledgements

Development and implementation of RHIC lattice with higher phase advance per cell became possible as a result of dedicated work of large group of people at Collider-Accelerator Department.

We are grateful to I. Ben-Zvi, D. Kayran, G. Parzen, and J. Wei for many very useful discussions on this subject.

We used BETACOOL code developed at JINR, Dubna, Russia.

Thank you