Intra-beam Scattering: benchmarking and predictions

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RHIC Beam Experiment Workshop

September 16 - 17, 2004

BROOKHAVEN NATIONAL LABORATORY

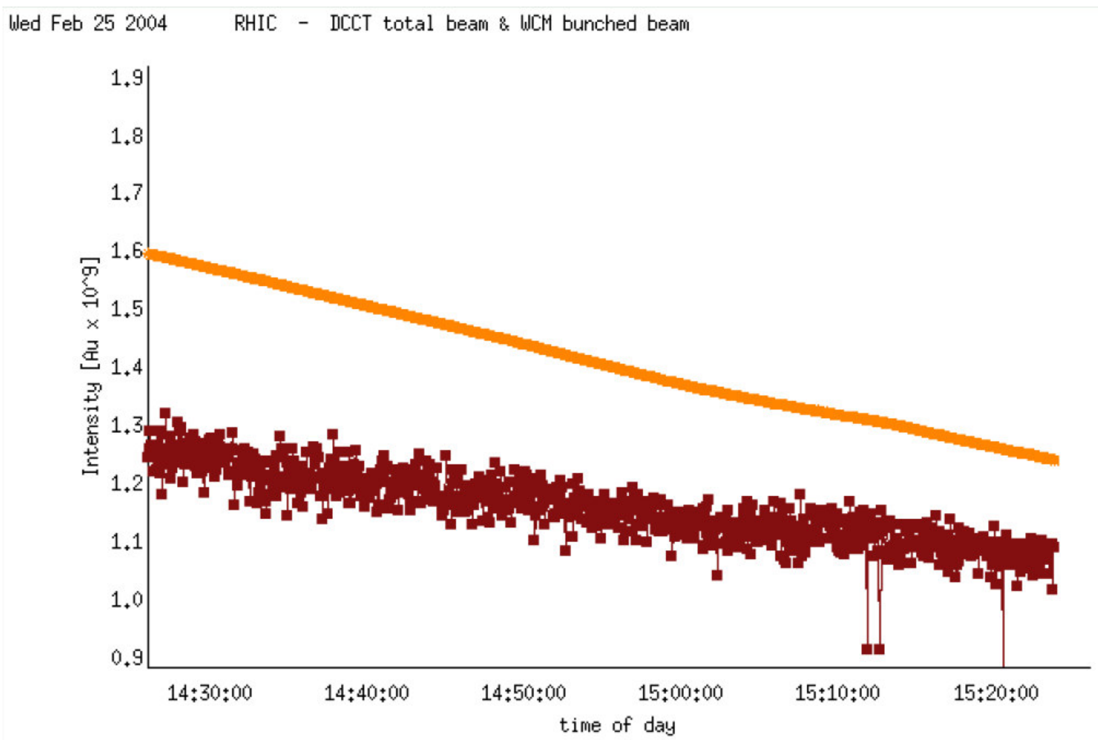
Outline

- Introduction
  - IBS effects, mechanism, scaling laws
  - IBS beam experiment goals
- IBS study results from Run 4
  - beam emittance growth
  - Beam loss & de-bunching
  - Beam distribution evolution: Gaussian-like vs. hollow beams
- IBS predictions for Run 5 Cu operation

- Acknowledgements: M. Blaskiewicz, M. Brennan, R. Connolly, V. Litinenko, T. Satogata, S. Tepikian, J. van Zeijt …

IBS effects

- Luminosity degradation
  - Transverse emittance growth
  - Longitudinal growth & beam loss due to RF bucket limitation
- De-bunching & experimental background



Mechanism

- Particle motion in the beam rest frame

$$H = \begin{cases} \frac{1}{2}\left(P_x^2 + P_y^2 + P_z^2\right) + \frac{1}{2}x^2 - \gamma x P_z + V_C & \text{(bending section)} \\ \frac{1}{2}\left(P_x^2 + P_y^2 + P_z^2\right) - \frac{n_1}{2}\left(x^2 - y^2\right) + V_C + U_z & \text{(straight section)} \end{cases}$$

- Intra-beam Coulomb scattering among particles of the same bunch

$$V_C = \sum_j \frac{1}{\sqrt{(x_j - x)^2 + (y_j - y)^2 + (z_j - z)^2}}.$$

- IBS: Rutherford scatting + Lorentz transformation + averaging

Positive- and negative-mass regime

- Transformed Hamiltonian

$$\overline{H} = \omega_{\beta_x} J_x + \omega_{\beta_y} J_y + \frac{1-\gamma^2 F_z}{2} P_z^2 + V_C \qquad \langle F_z \rangle = \frac{1}{\gamma_t^{\,2}}$$

$$F_z = \begin{cases} D + DD'' + (D')^2 & \text{(bending section)} \\ DD'' + (D')^2 & \text{(straight section)} \end{cases}$$

- Below transition: positive-mass regime dominated by “drift”
  - Quasi-equilibrium (equal velocity in beam rest frame)

$$\left\langle \frac{\sigma_x}{\beta_x} \right\rangle \approx \left\langle \frac{\sigma_y}{\beta_y} \right\rangle \approx \frac{\sigma_p}{\gamma}, \quad \gamma \ll \gamma_T$$

  - Temperature exchange between different directions towards equilibrium
  - Actual growth due to AG potential (time-dependent in beam rest frame)

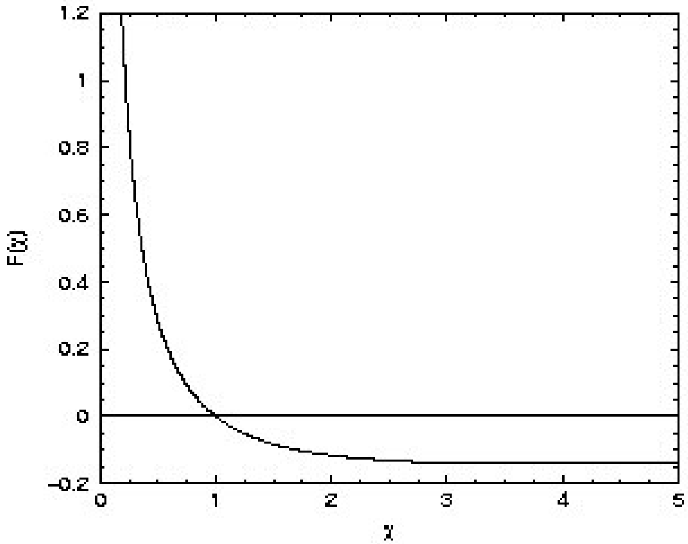
- Above transition: negative-mass regime dominated by diffusion; continuous growth in longitudinal & transverse directions

$$\sqrt{n_b n_c}\,\langle \sigma_x \rangle \approx \langle D \rangle \sigma_p, \quad \gamma \gg \gamma_T$$

IBS growth scaling

- IBS beam size growth rates assuming an unbounded Gaussian beam

$$\begin{bmatrix} \frac{1}{\sigma_p}\frac{d\sigma_p}{dt} \\ \frac{1}{\sigma_x}\frac{d\sigma_x}{dt} \\ \frac{1}{\sigma_y}\frac{d\sigma_y}{dt} \end{bmatrix} = \frac{Z^4 N}{A^2}\frac{r_0^2 m_0 c^2 L_c}{8\gamma\epsilon_x\epsilon_y S}F(\chi)\begin{bmatrix} n_b(1-d^2) \\ -a^2/2+d^2 \\ -b^2/2 \end{bmatrix}$$



- Proportional to Z^4 / A^2
- Proportional to 6-D phase-space density
- Analytic expression for FODO lattice; integral formula for actual lattice
- Inadequate when beam loss occurs / for non-Gaussian beams

Intra-beam scattering study goals

- Verify the growth of rms beam sizes under IBS
  - Early theories by Piwinski, Bjorken/Mtingwa
  - Detailed lattice implementation by Martini
  - Asymptotic behavior analysis/approximation by Parzen
  - Approximation model by Wei
  - Recent compilation by the Russian collaborators / Fedotov
- Verify the beam de-bunching behavior under IBS
  - Predictions by Wei using the Fokker-Planck approach
- Verify the longitudinal bunch profile evolution under IBS
  - Predictions by Wei using the Fokker-Planck approach
  - Similar approach used in stochastic cooling analysis/predictions

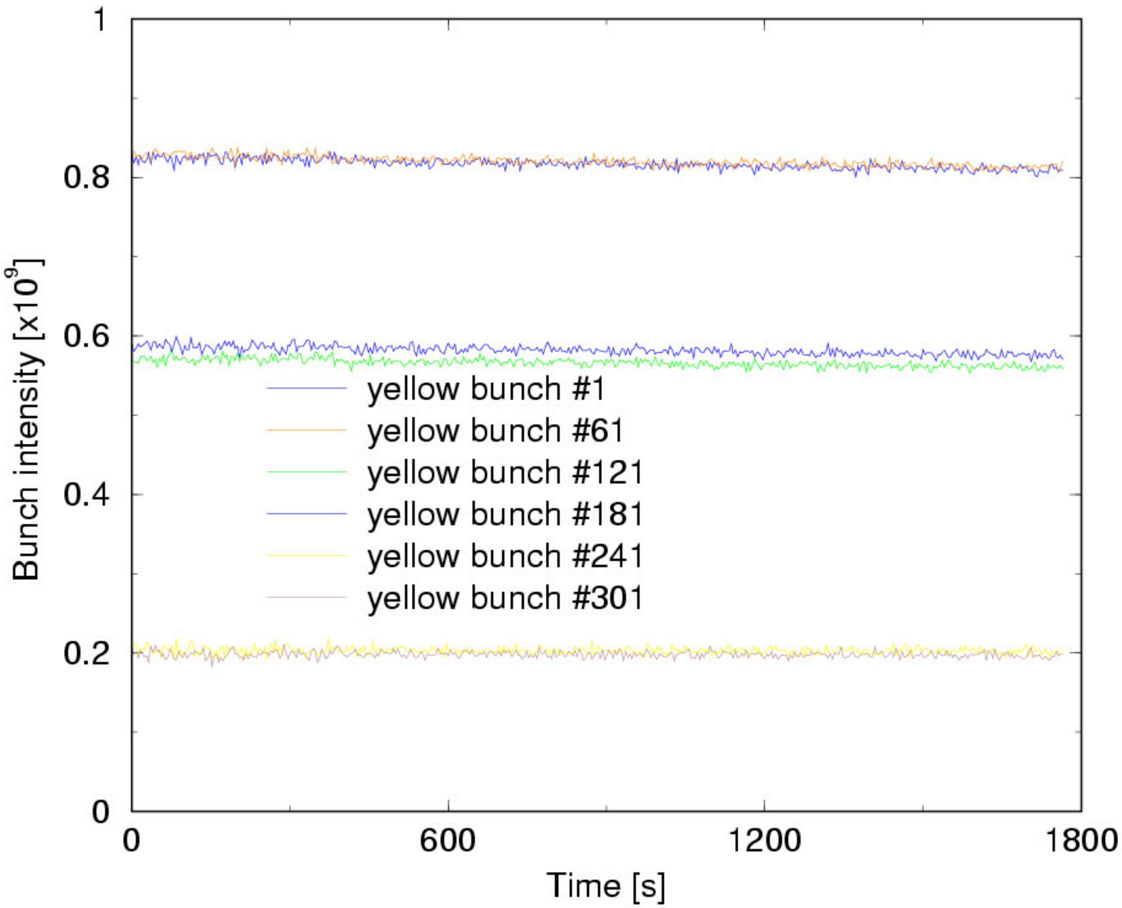
→ Help to determine RHIC II performances

IBS observables

- rms beam sizes (bunch length, transverse emittances)
  - Many early studies performed
  - Need to single out IBS from other processes
  - (beam-beam, tune kicker, Landau cavity, dual RF, RF noise …)
  - Need to calibrate Ionization Profile Monitor readings
- Beam loss
  - Wall Current Monitor and DCCT readings
  - De-bunching with a single vs. a dual RF (28 MHz and 200 MHz)
- Beam profiles (longitudinal)
  - Hollow bunch profile evolution
  - Gaussian-like bunch profile evolution & asymptotic shape

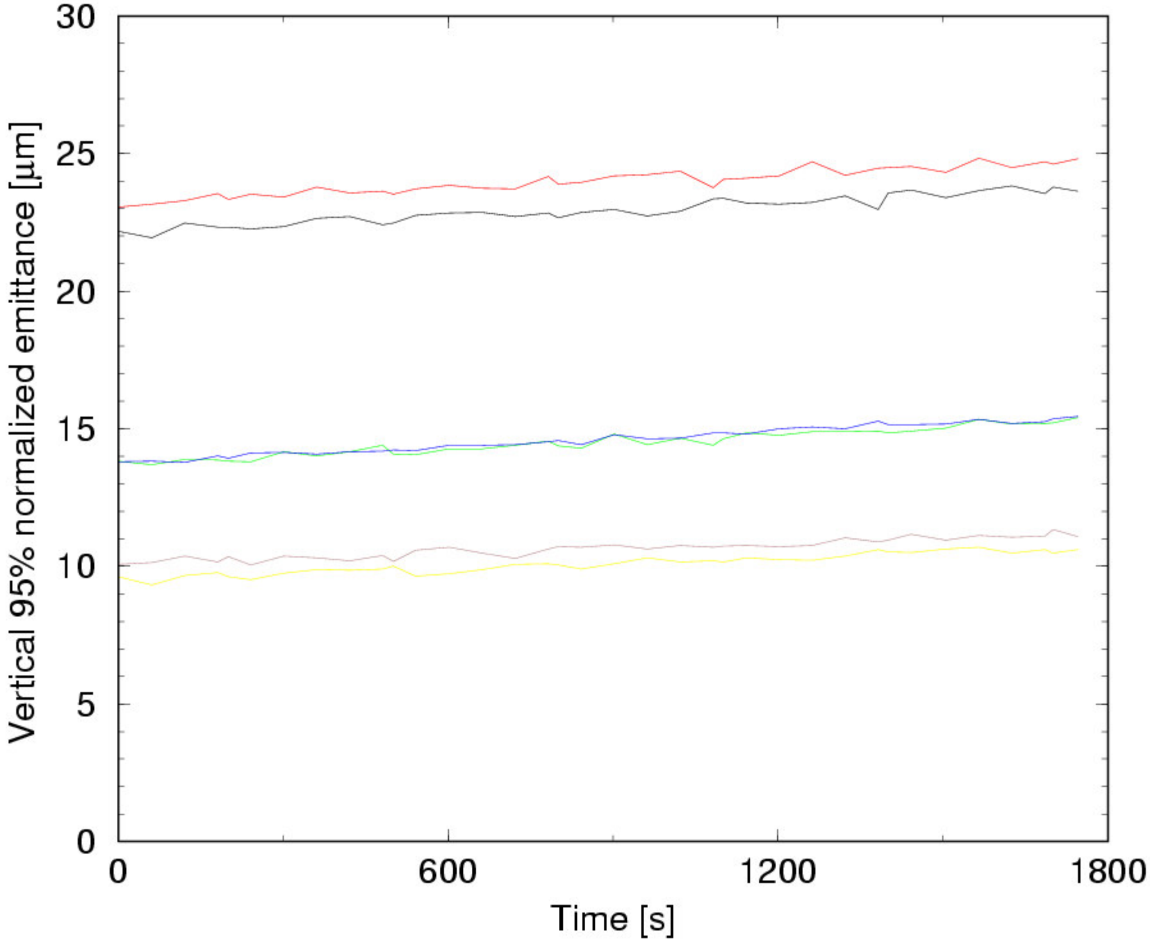
Dedicated IBS studies during Run 4

- January - March, 2004
- Simultaneous IBS measurement under different intensities



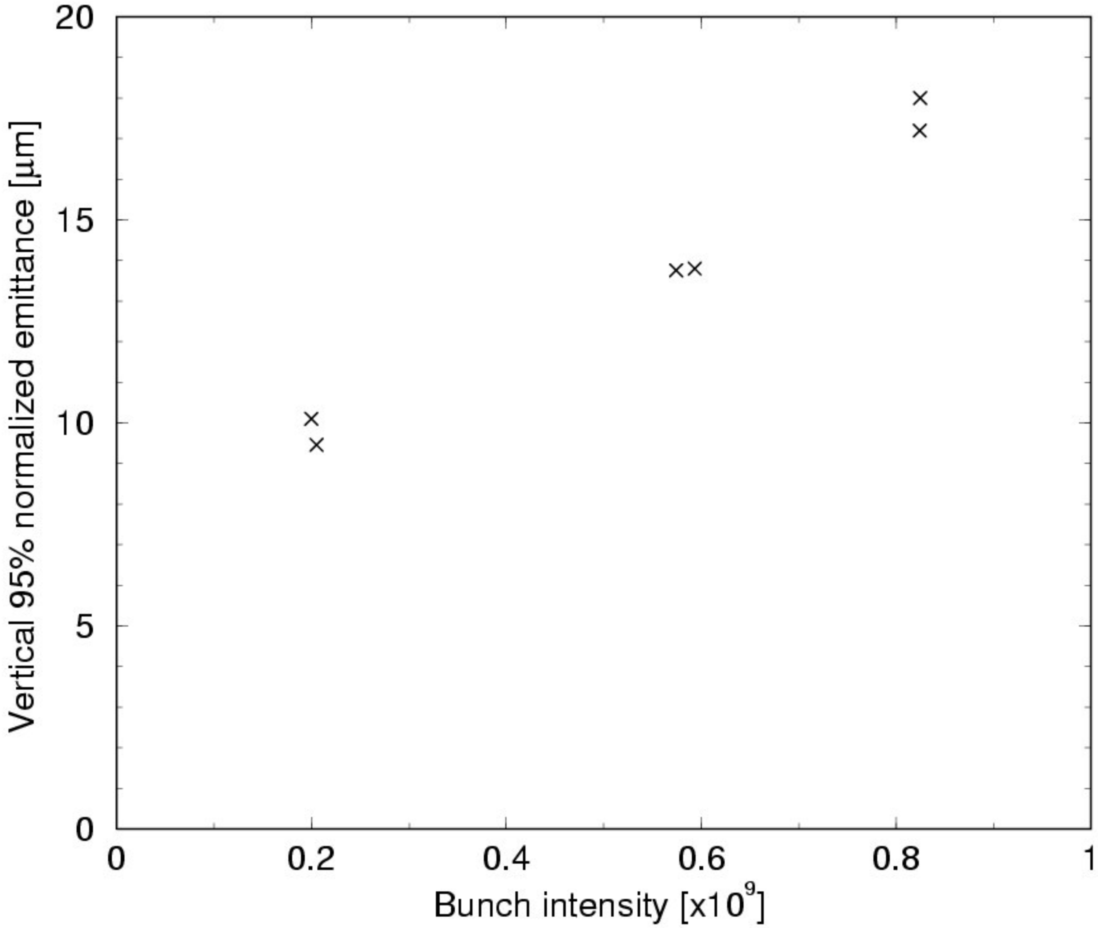
Observation of emittance growths

- Initial transverse emittance depends on intensity
- Overall scaling agrees with IBS theory (Fedotov)



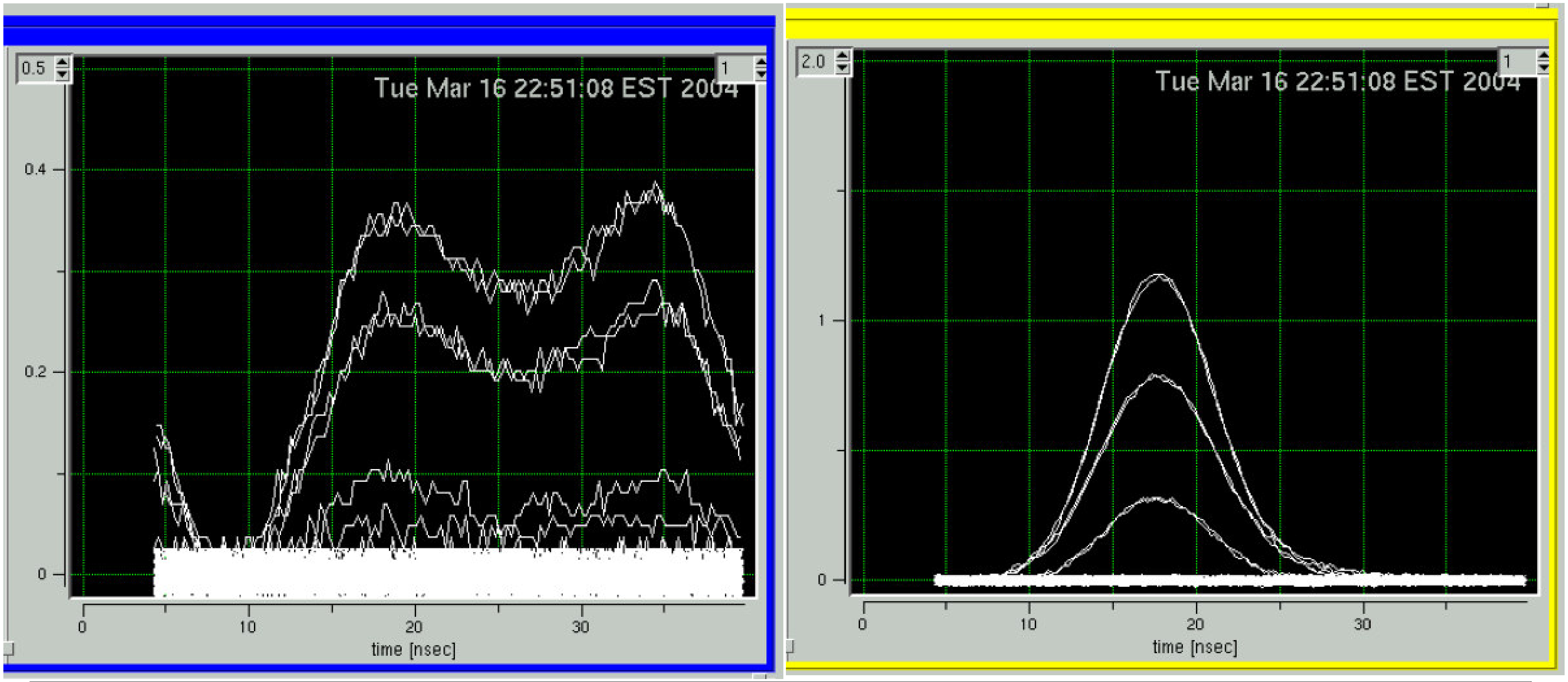
Intensity dependence of emittances

- Possible space-charge effects at Booster/AGS
- Measurement in AGS can confirm IPM calibration in RHIC



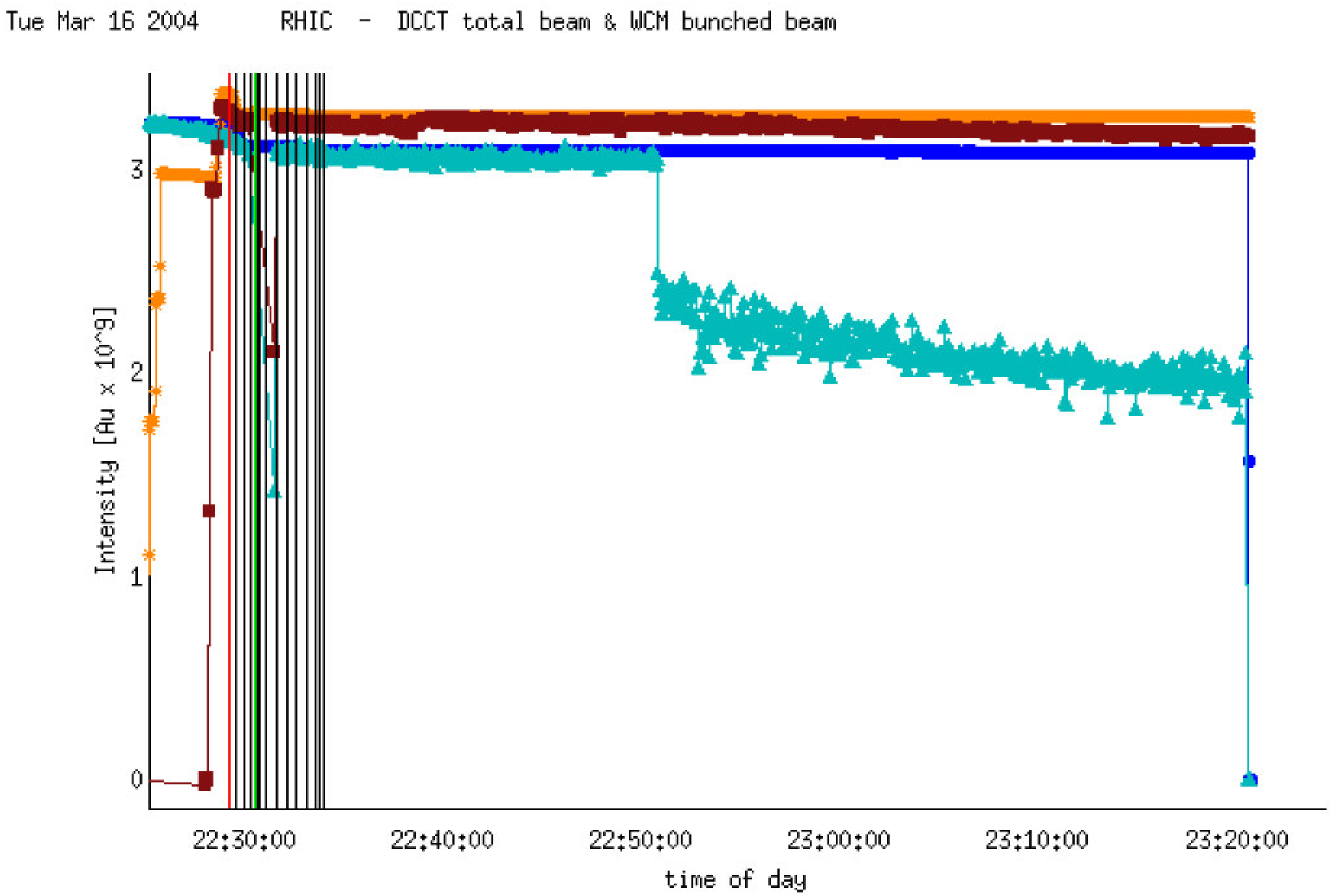
March 16, 2004: run #4790

- Gold beam, store at 100 GeV/u with h=360 RF system; no beam collision
- No Landau cavity, no dampers, no kickers
- Hollow beam in blue (phase jump), normal beam in yellow



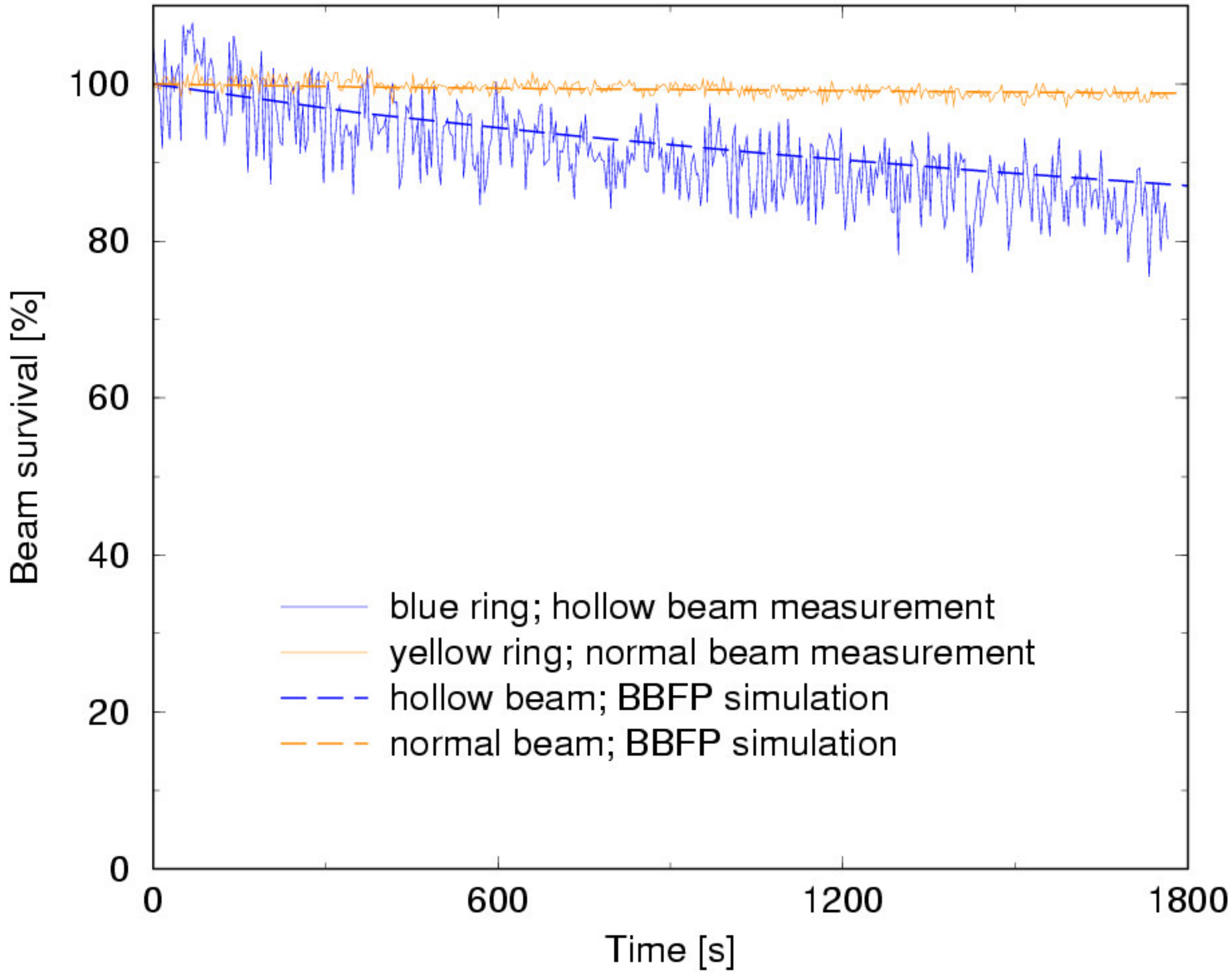
Wall current monitor intensity readings

- Distinctively different beam loss (de-bunching) behavior



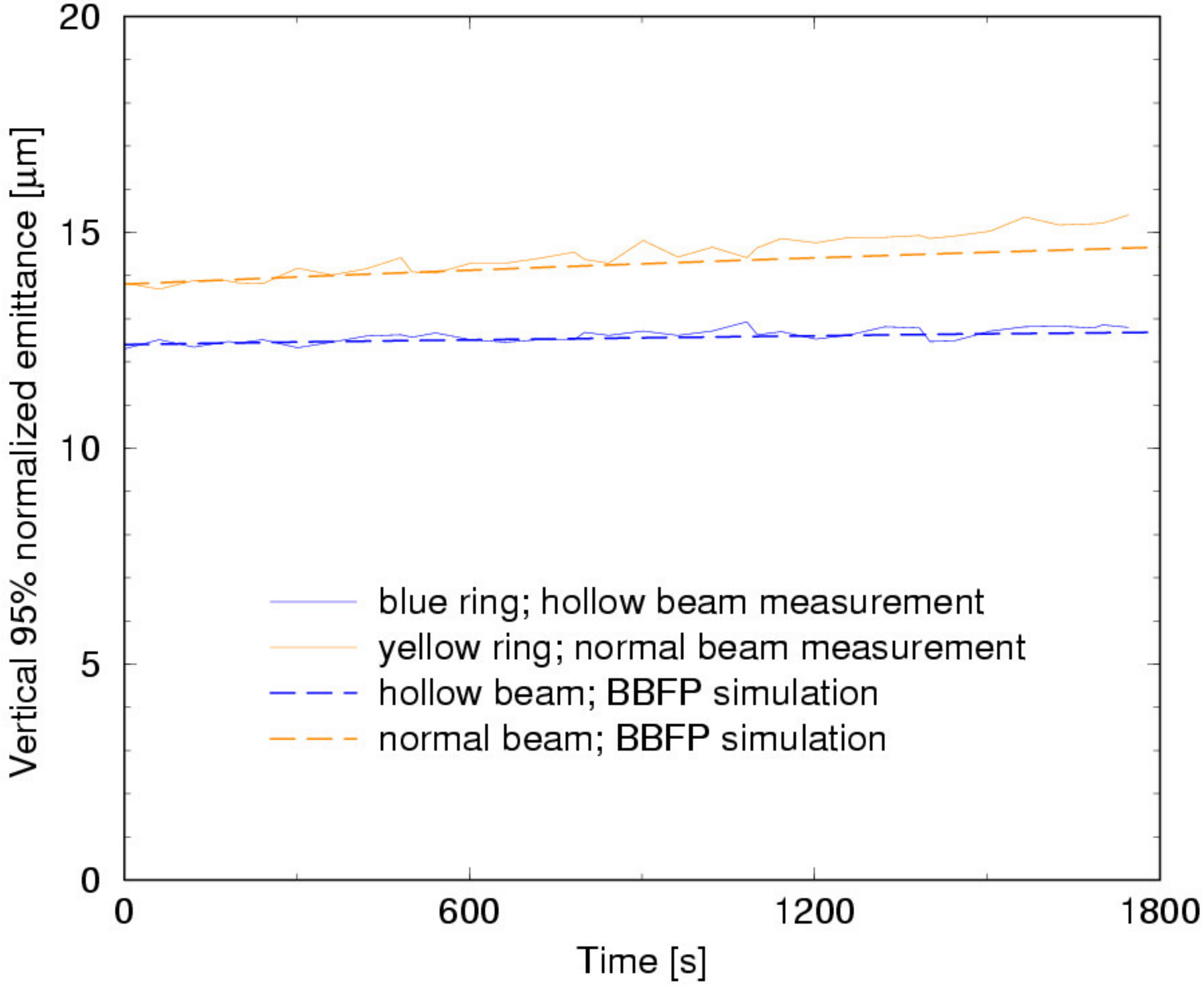
Beam de-bunching loss benchmarking

- Run #4790, 30 minute WCM measurement vs. BBFP code simulation



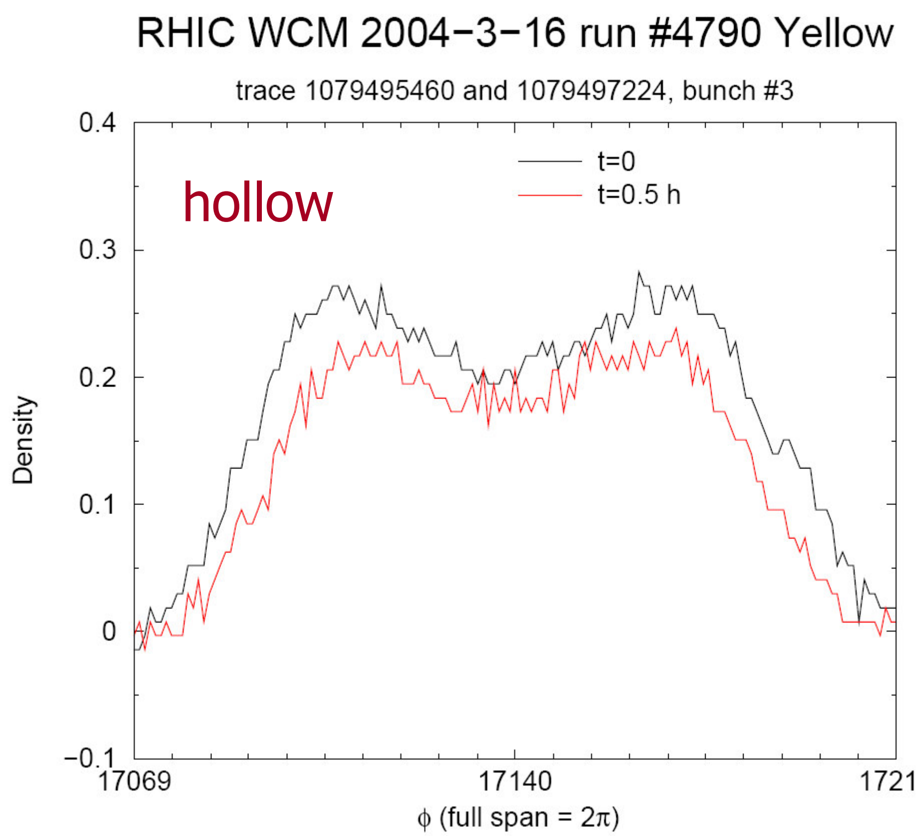
Transverse emittance growth benchmarking

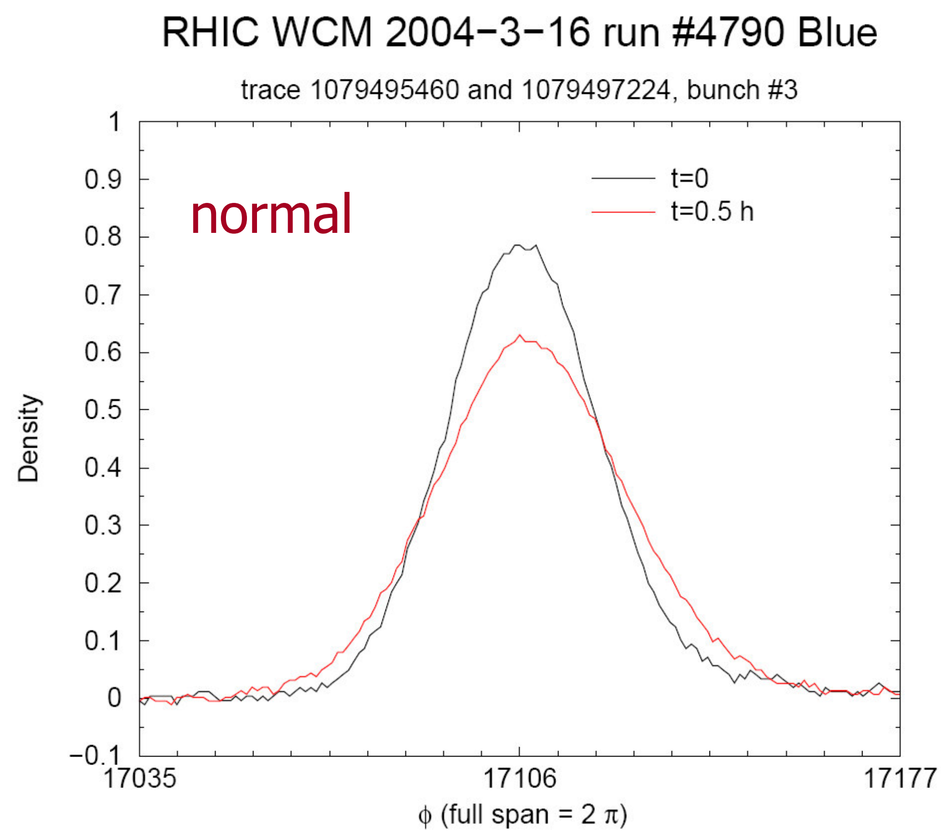
- Run #4790, 30 minute IPM measurement vs. BBFP code simulation



Processed WCM data

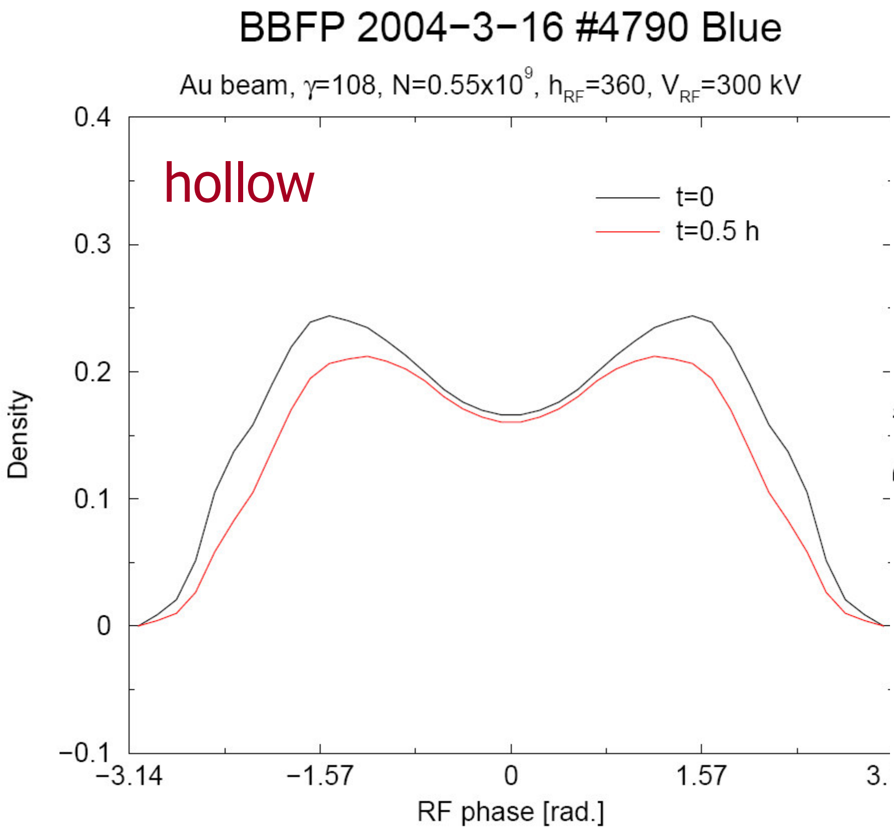
- Normal beam: Gaussian-like shape
- Hollow beam: reducing depth of the hole -> approaching Gaussian

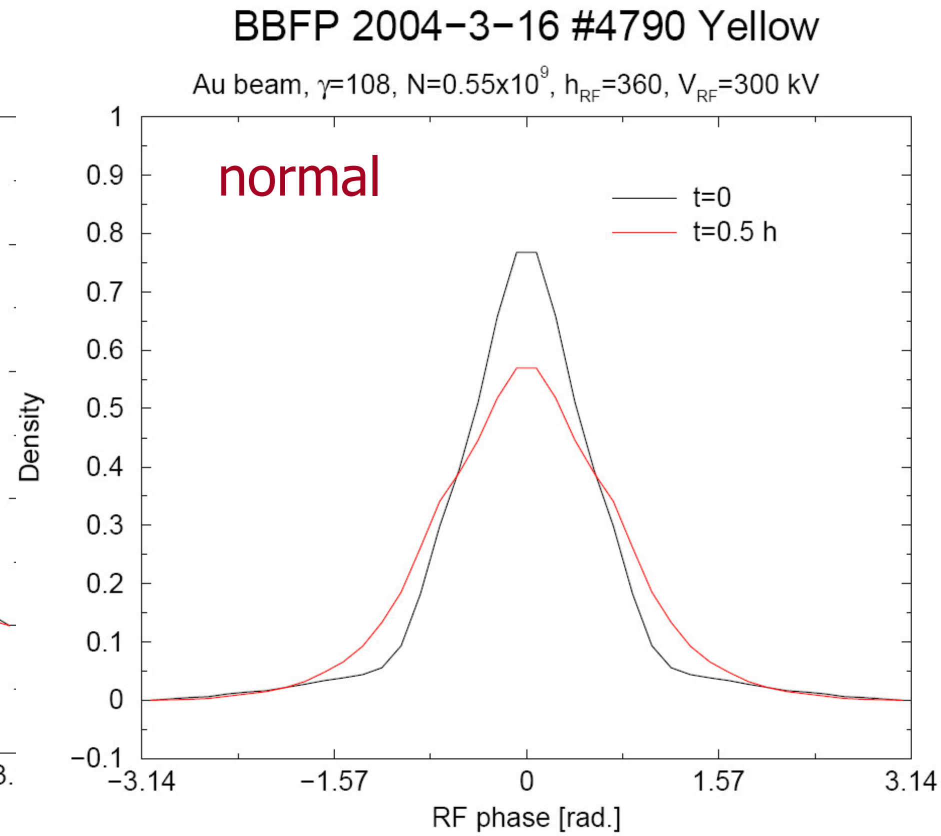




BBFP simulation of the beam profiles

- Good agreement
- Details to be refined





BBFP: Fokker-Planck equation solver

- Drift and diffusion

$$\frac{\partial \Psi}{\partial t} = -\frac{\partial}{\partial J}(F\Psi) + \frac{1}{2}\frac{\partial}{\partial J}\left(D\frac{\partial \Psi}{\partial J}\right), \quad \text{with} \quad \begin{cases} J = 0: & -F\Psi + \frac{D}{2}\frac{\partial \Psi}{\partial J} = 0\,, \\ J = J_{max}: & \Psi = 0\,, \end{cases}$$

where the drift coefficient is given by

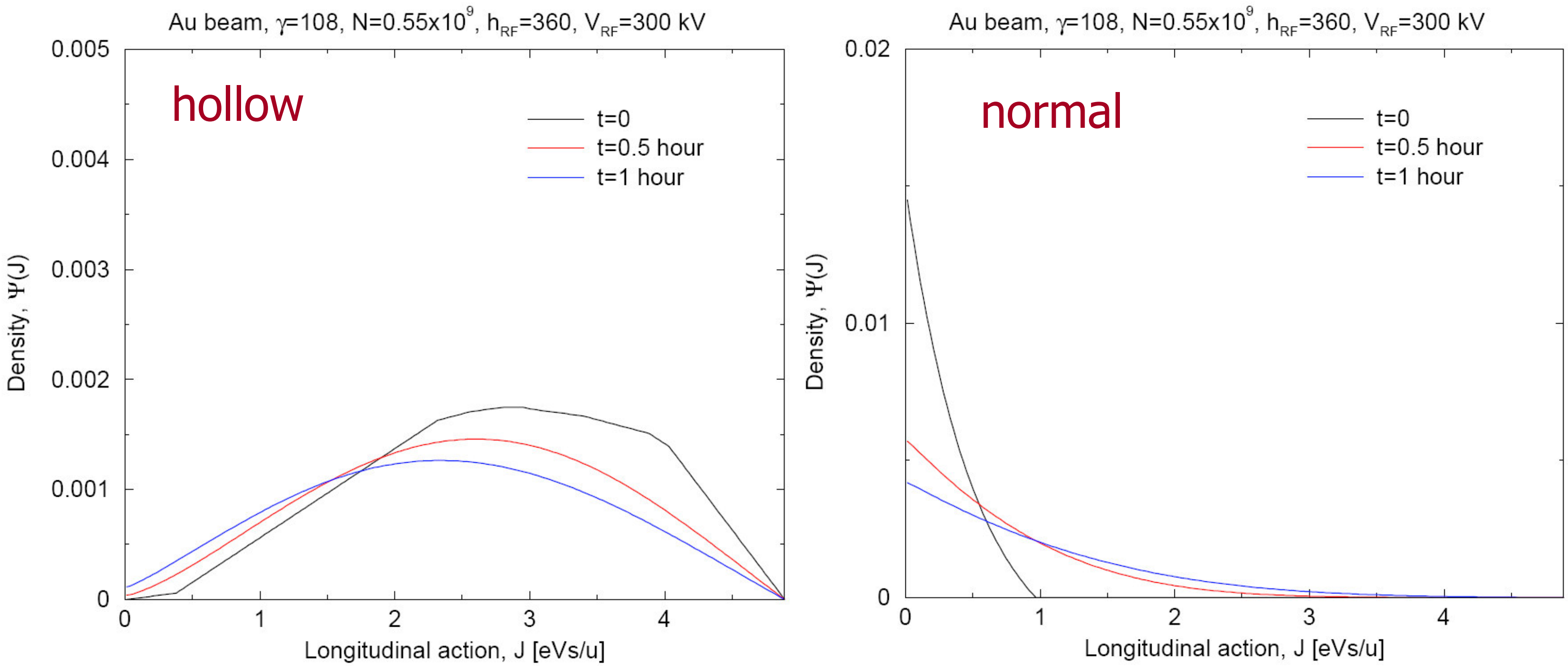
$$F(J) = \oint \frac{2dz}{\pi R} \int_0^{\frac{1}{4}} dQ \left.\frac{\partial W}{\partial J}\right|_{\phi}^{-1} (Q, J) \int_{J_{min}}^{J} \left.\frac{\partial W}{\partial J}\right|_{\phi} (Q', J')\,[A_F(\lambda_1) + A_F(\lambda_2)]\,\Psi(J')dJ'$$

and the difusion coefficient is given by

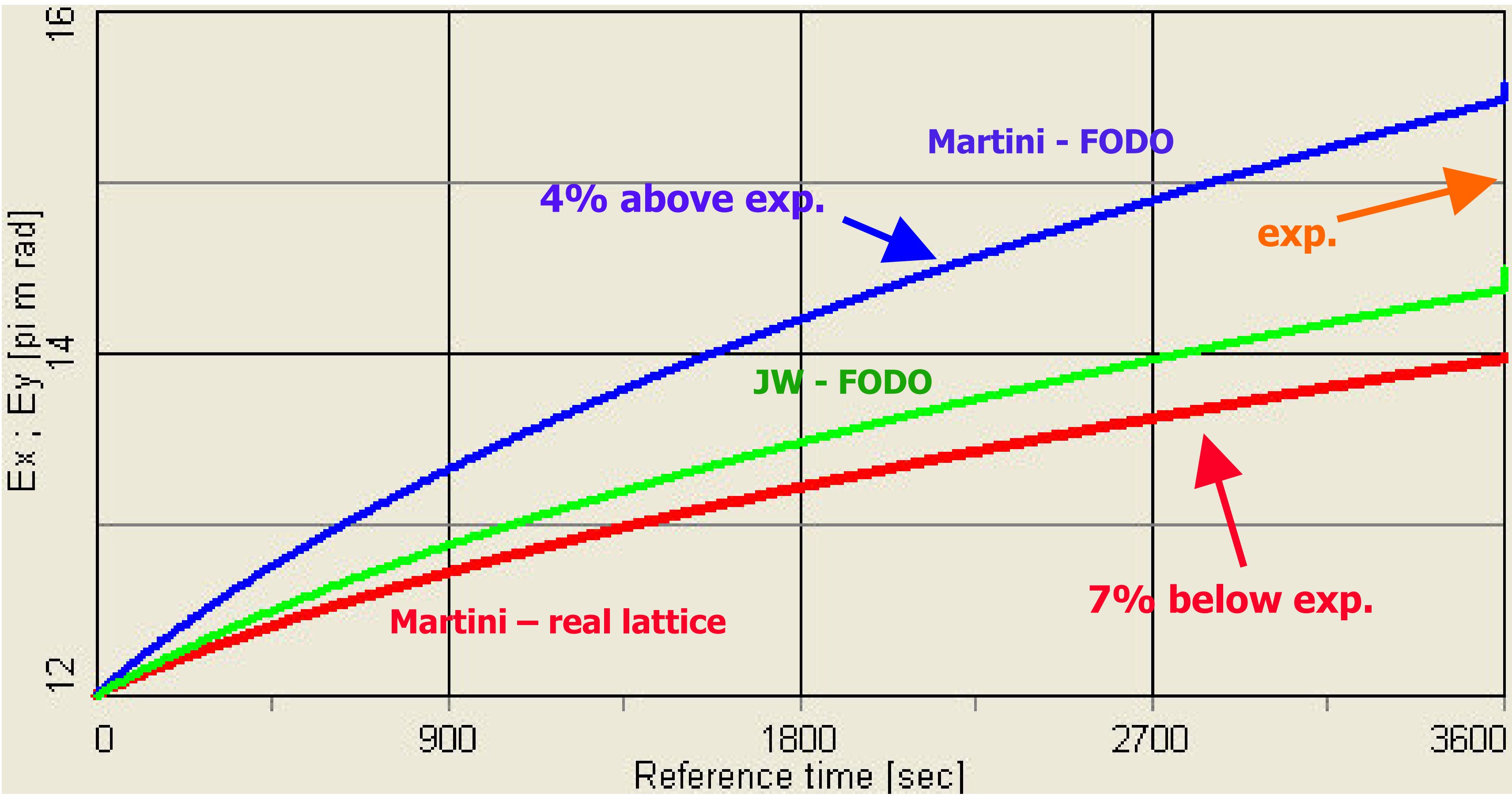
$$D(J) = \oint \frac{2dz}{\pi R} \int_0^{\frac{1}{4}} dQ \left[\left.\frac{\partial W}{\partial J}\right|_{\phi}^{-1} (Q, J)\right]^2 \int_{J_{min}}^{J} \left.\frac{\partial W}{\partial J}\right|_{\phi} (Q', J')\,[A_D(\lambda_1) + A_D(\lambda_2)]\,\Psi(J')dJ'$$

BBFP simulation of beam evolution

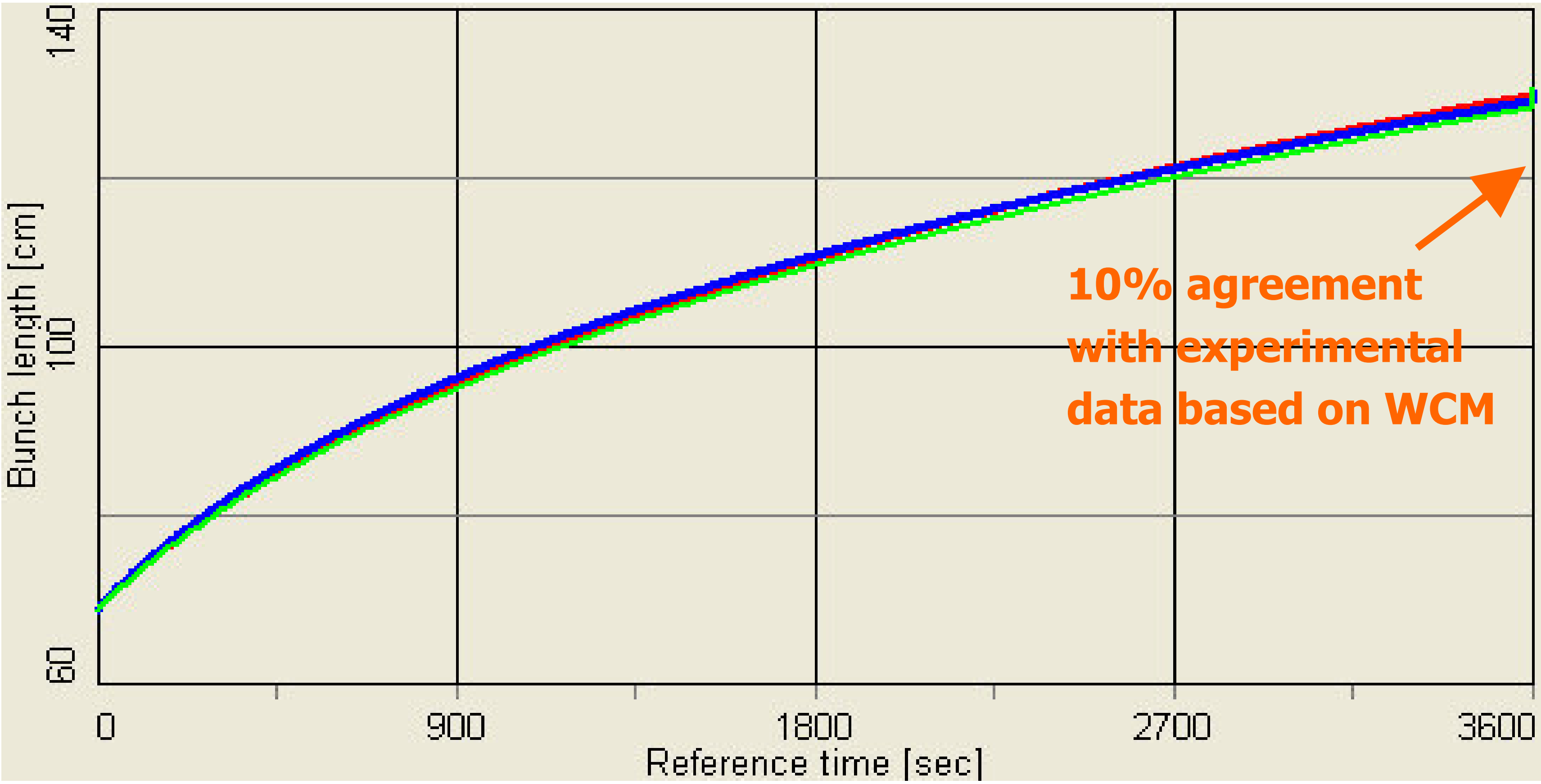
- Density projection in longitudinal action
- Convertible to the phase / momentum planes



Transverse emittance & lattice dependence



Run #4790 – rms bunch length growth



Transverse emittance comparison issues

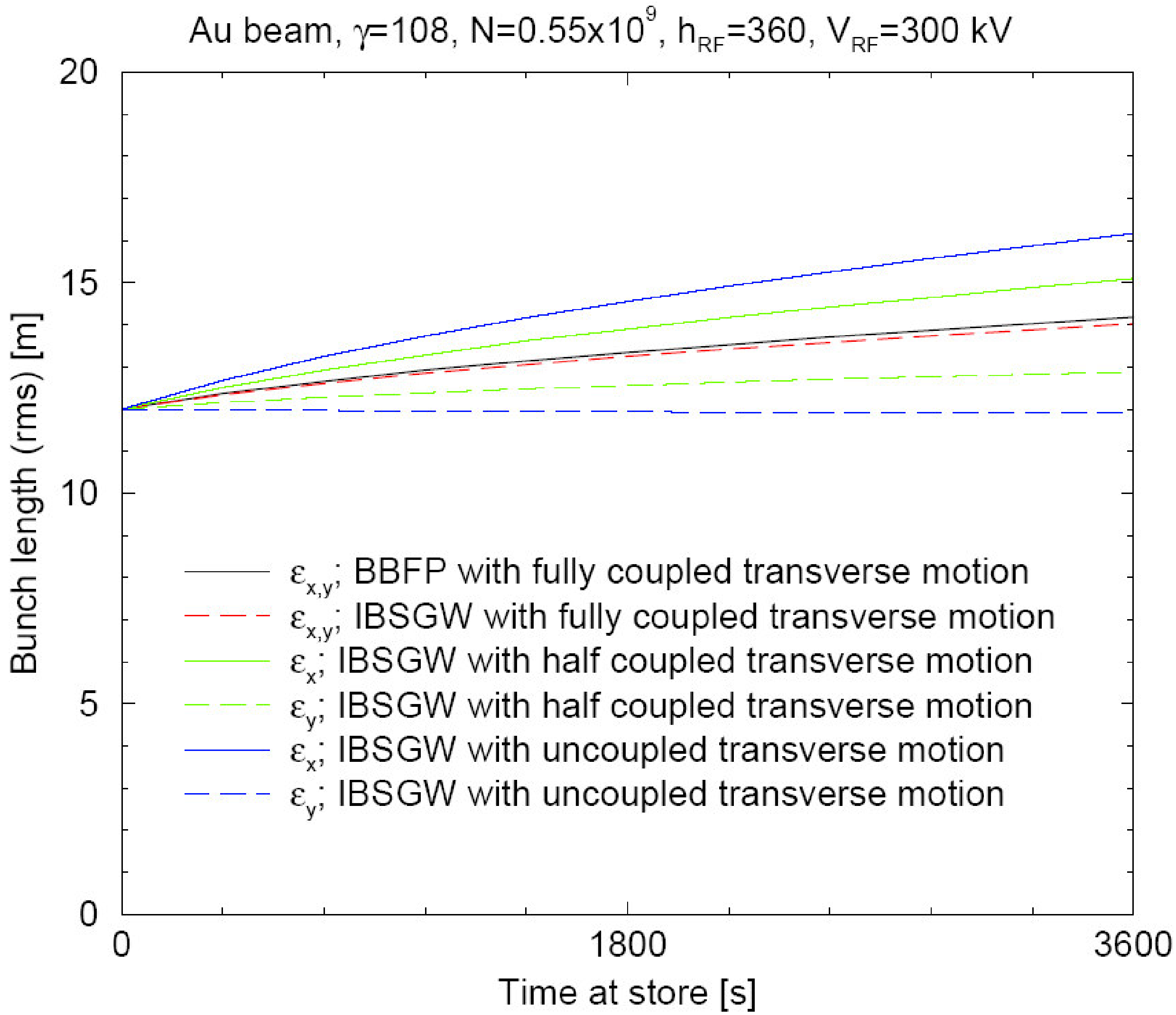
- Strong dependence on average dispersion
  - Need an accurate estimate of dispersion and dispersion wave
  - Asymptotically $\sigma_x^2 \approx D_p^2 \sigma_p^2$

  (Johannes promised to get an estimate from online model)
- Calibration of IPM at store
  - Calibration was done only for lattice at injection
  - Possible IPM electronics degradation/peak suppression may result in falsely large measured emittance value
- Verify source of intensity dependence in Booster / AGS

Puzzles and clues

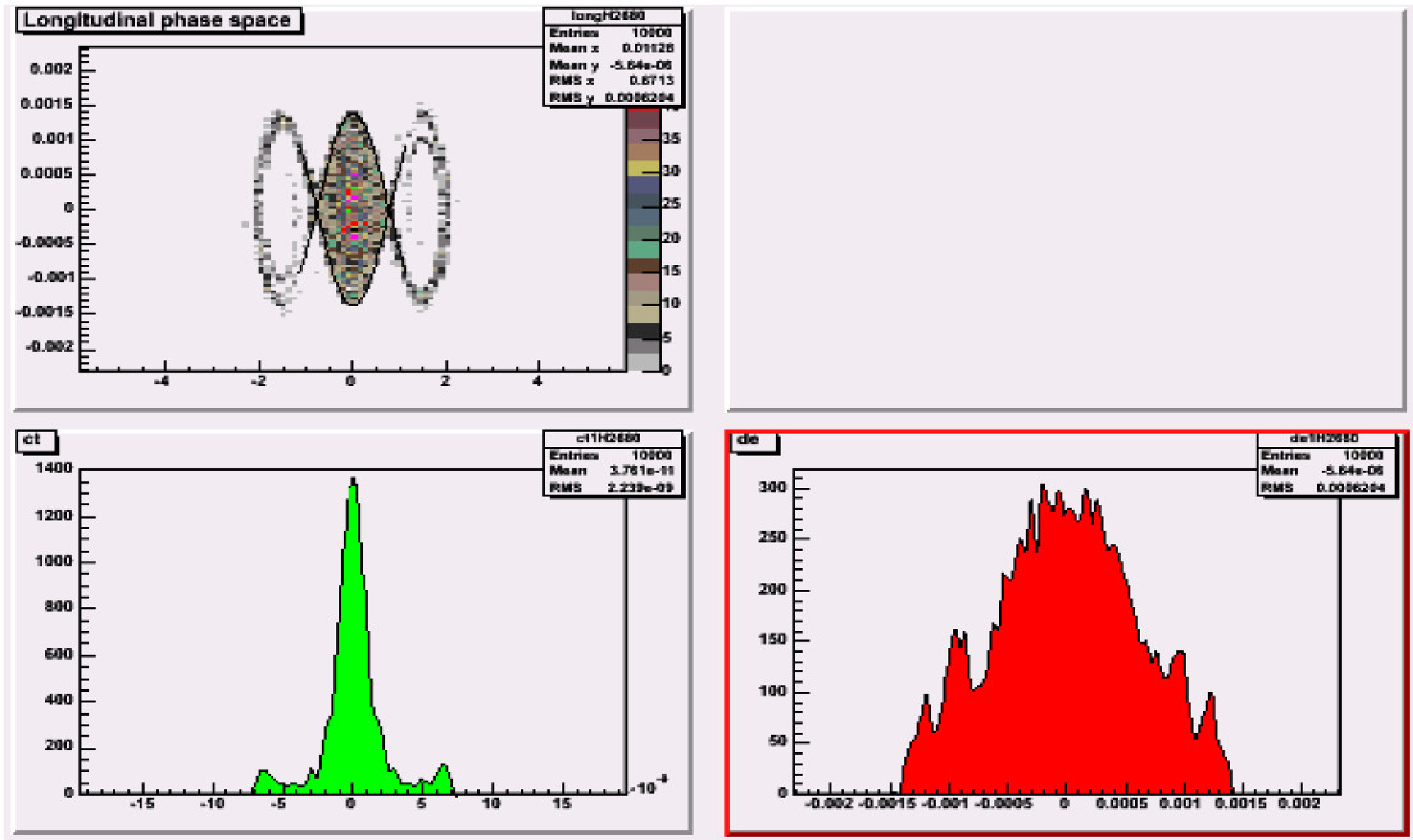
- Transverse emittance under-estimation
  - Simulations now converging; within a factor of 2 of the measurement result
  - Dispersion dependence needs study
  - Transverse coupling effect needs study
- Measured bunch length exceeding those of Fokker-Planck solver
  - Malitsky's re-bucketing simulation: satellite beam contribution
  - Estimation using measured rms bunch size underestimates IBS growth!
- Strange Fokker-Planck behavior at injection
  - Under investigation – work to be done

Transverse coupling



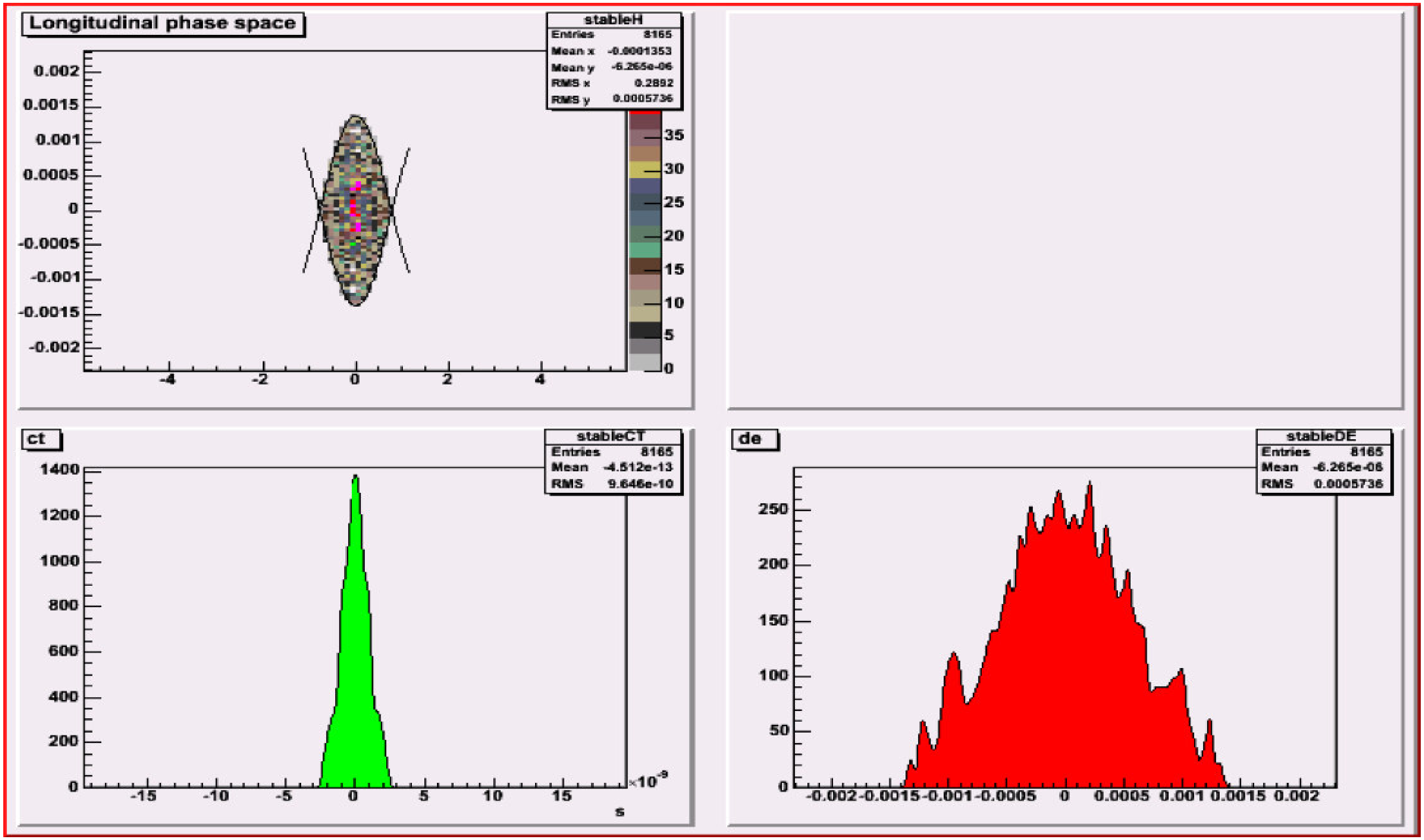
Re-bucketing with a full beam: satellites

- Large rms bunch length (2ns) due to satellite beams



Re-bucketing with a full beam

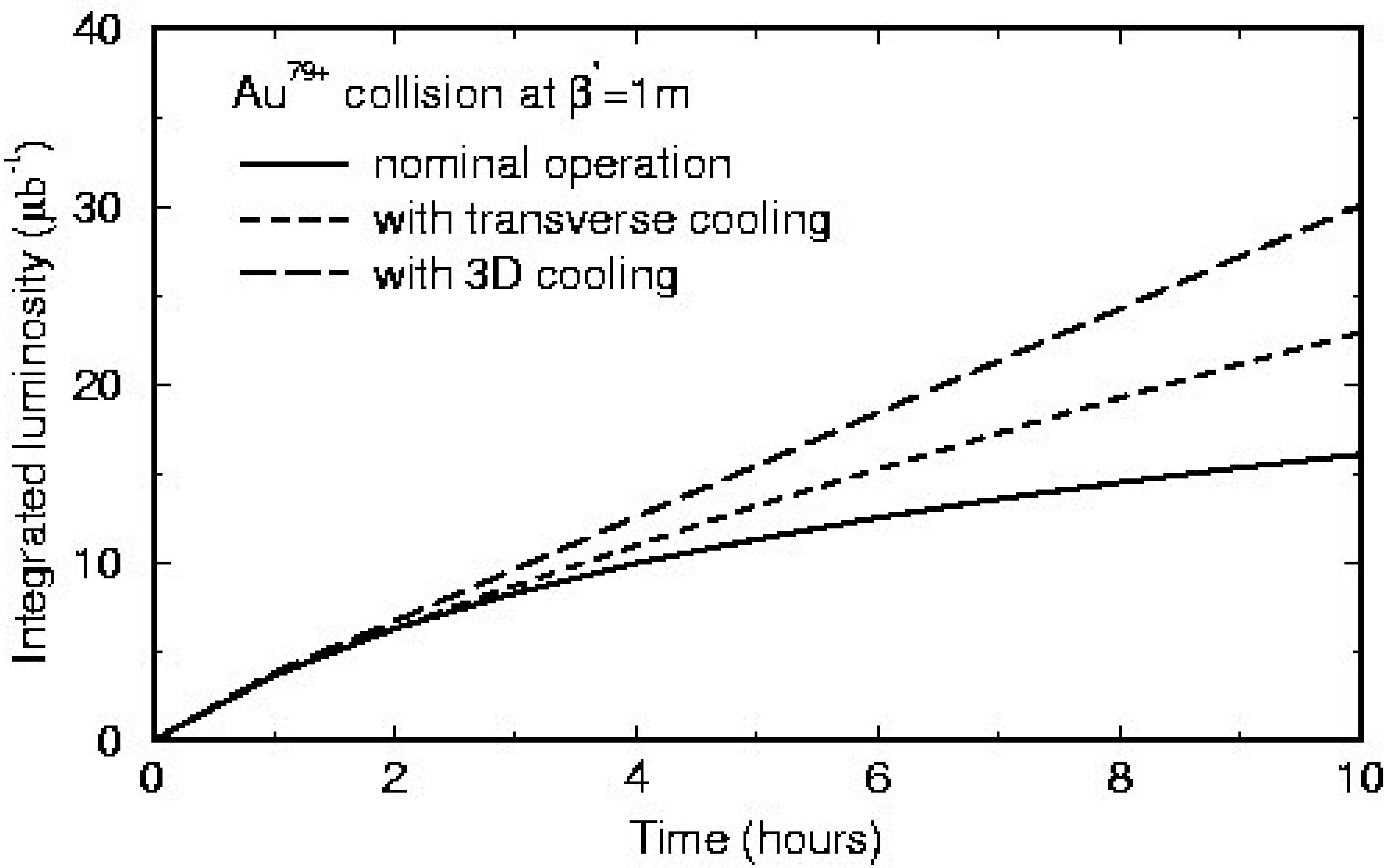
- Maximum rms bunch length is < 1 ns (bucket width > 5 σ)



Summary

- The IBS benchmarking study at store is promising
  - Agreement on rms beam size growth is converging
    - » Longitudinal: agreement is within 10%
    - » Transverse: surely within a factor of 2
  - Agreement on de-bunching beam loss is good
  - Agreement on longitudinal profile is good
- Further studies needed
  - More accurate dispersion model & measurement
  - IBS under different transverse coupling conditions
  - IPM device calibration & lattice (beta-function) measurement
  - IBS study at injection

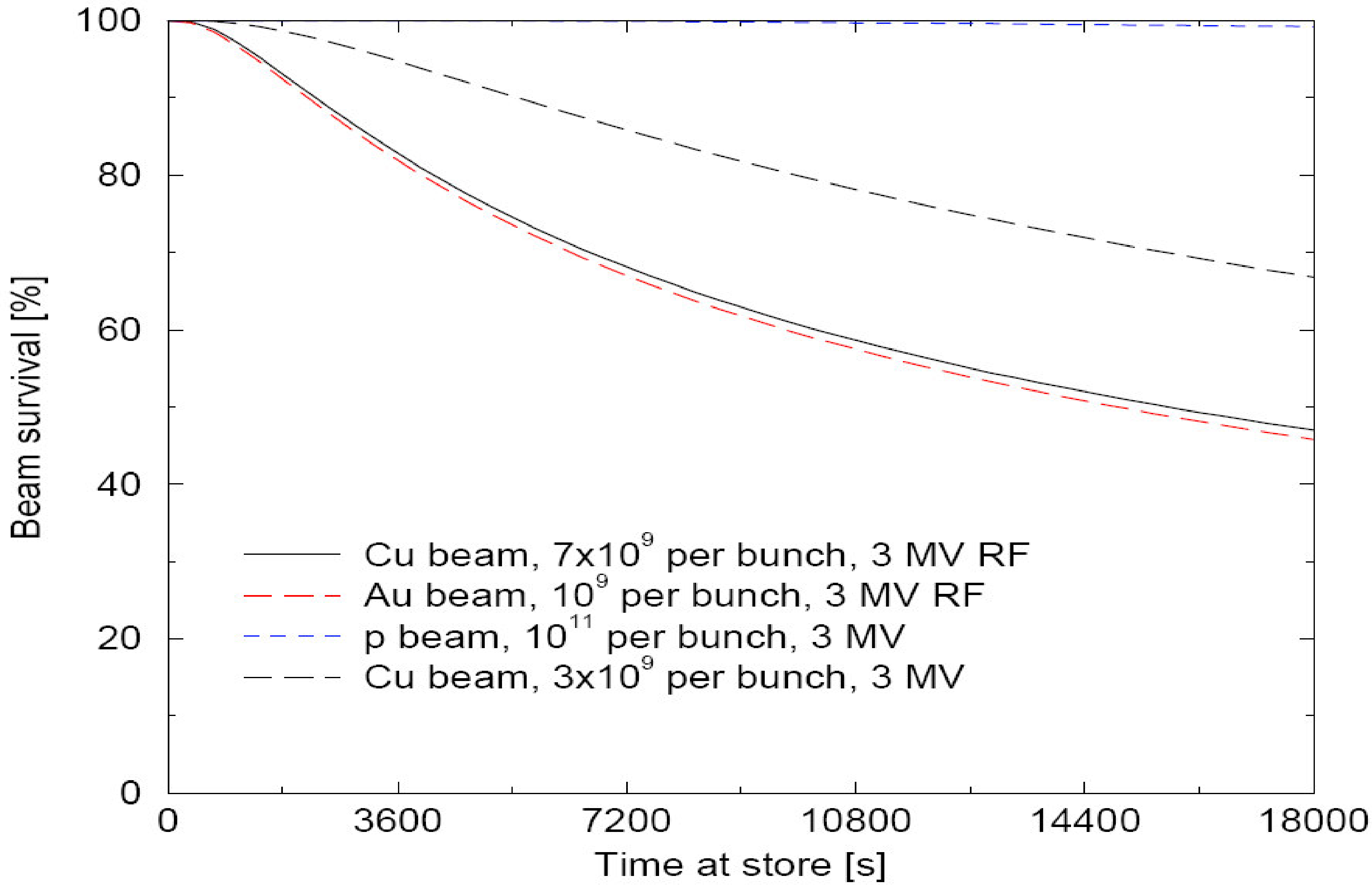
Predictions on beam cooling to counter IBS



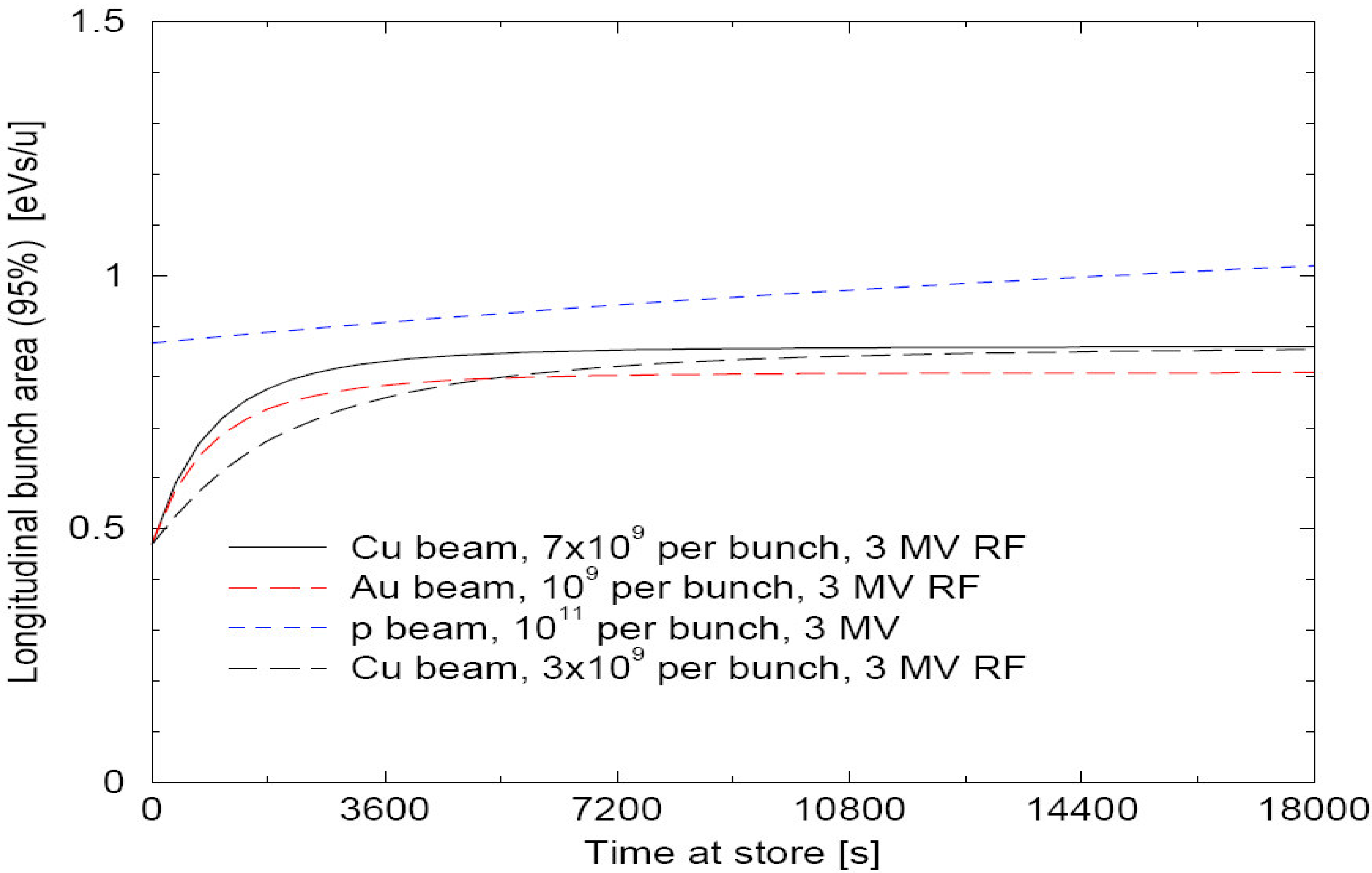
Predictions for the 2005 Cu run

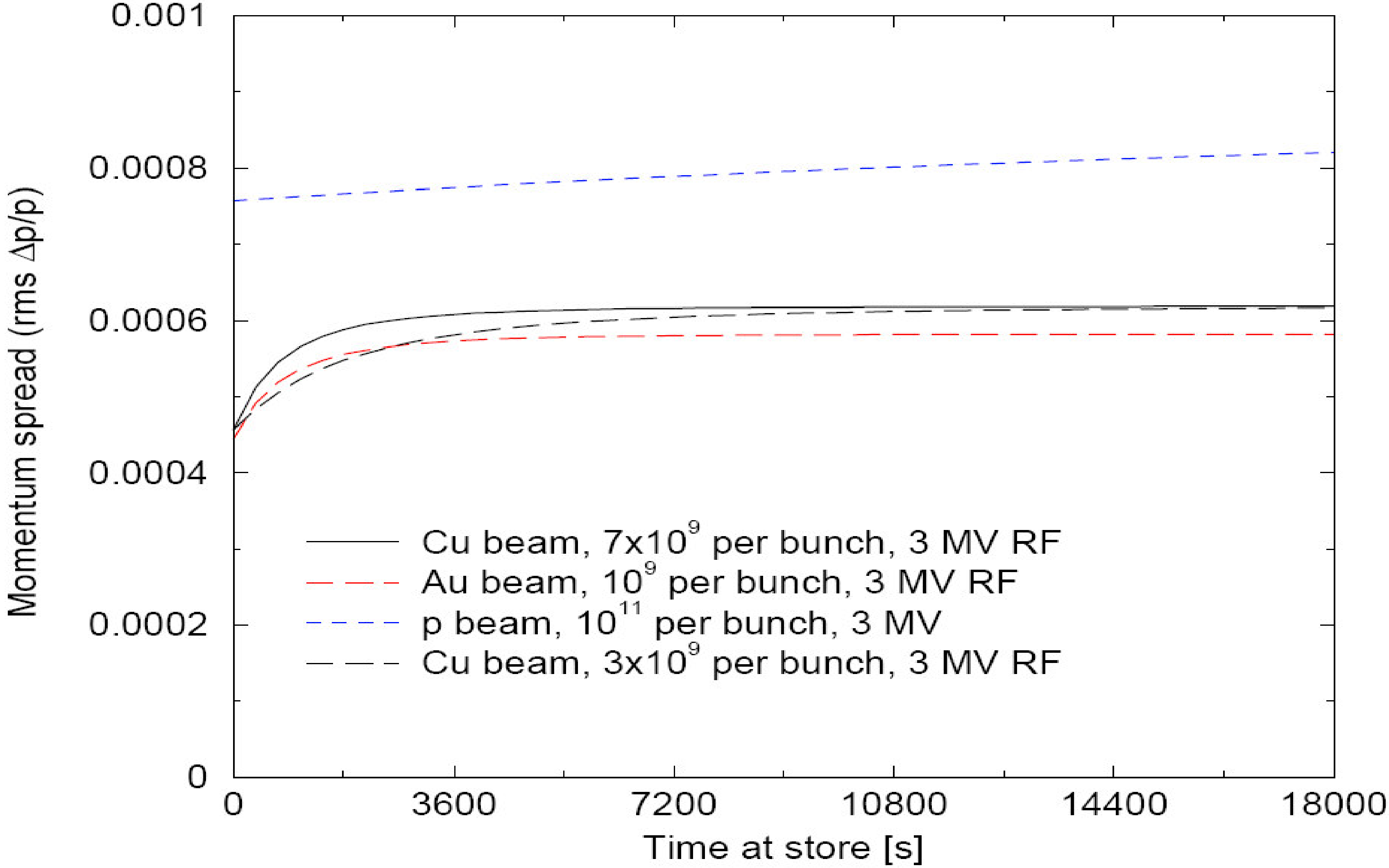
- Scale with NZ^4/A^2
- 6×10^9 Cu is equivalent to 1×10^9 Au

- IBS Expectation:
  - Similar behavior as Au store at 1×10^9 per bunch
  - Significant de-bunching expected; saturated bunch length and momentum spread
  - Usual rms growth prediction may not be adequate; BBFP can possibly better predict the IBS behavior

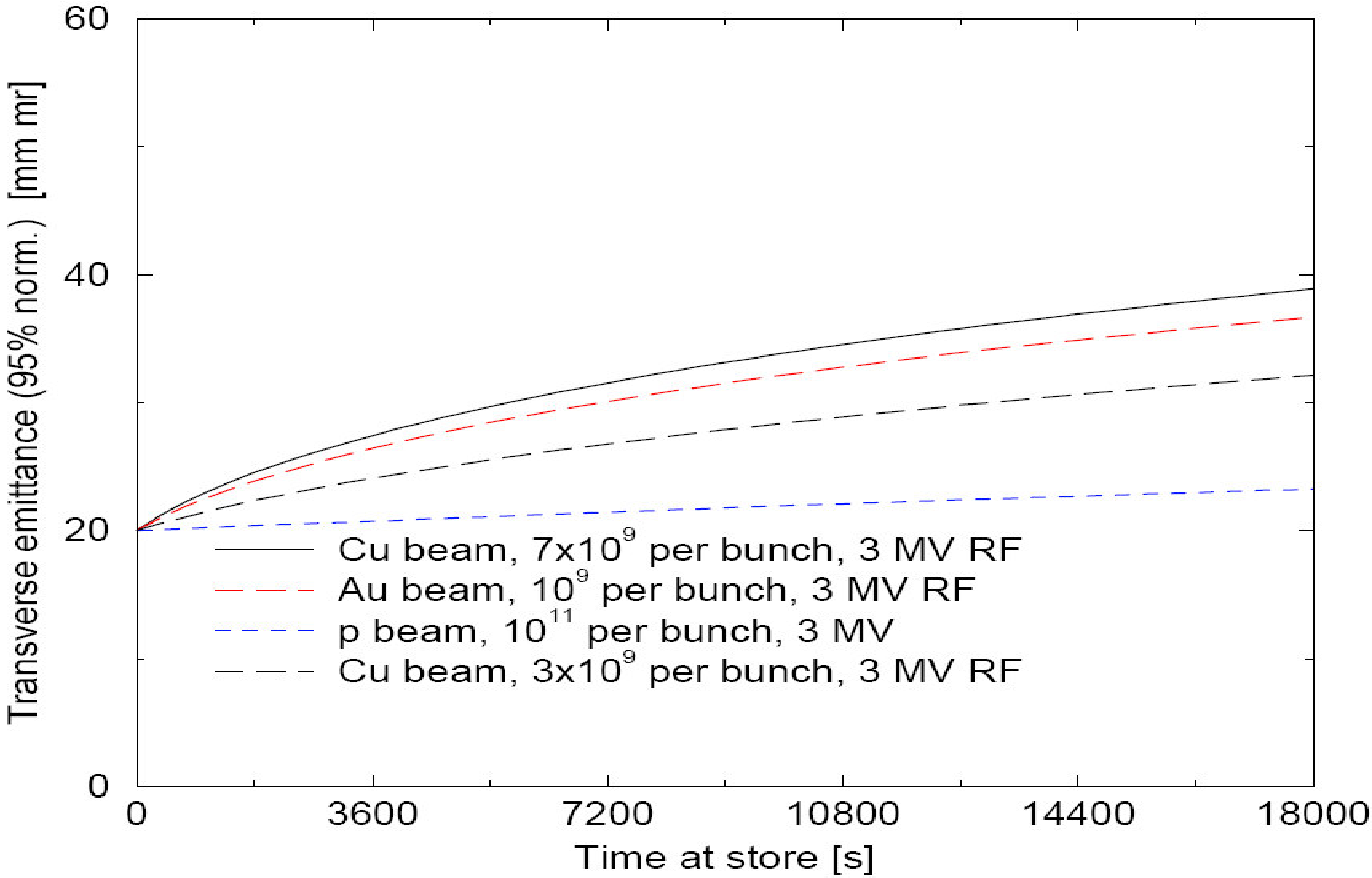


Beam survival [%]
100
80
60
40
20
0
0
3600
7200
10800
14400
18000
Time at store [s]
Cu beam, 7x10^9 per bunch, 3 MV RF
Au beam, 10^9 per bunch, 3 MV RF
p beam, 10^11 per bunch, 3 MV
Cu beam, 3x10^9 per bunch, 3 MV

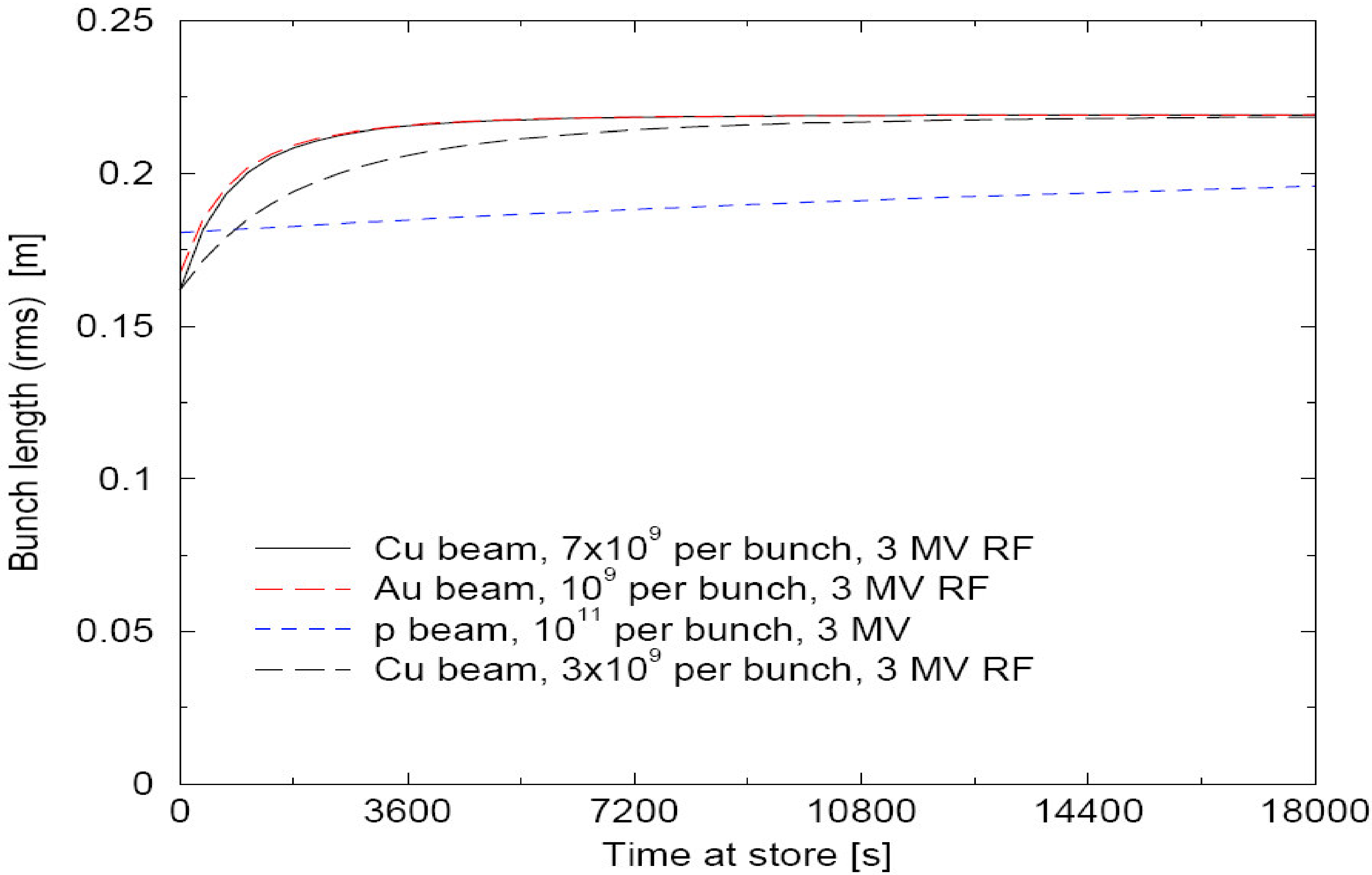

1.5
1
0.5
0
Longitudinal bunch area (95%) [eVs/u]
0
3600
7200
10800
14400
18000
Time at store [s]
Cu beam, 7x10^9 per bunch, 3 MV RF
Au beam, 10^9 per bunch, 3 MV RF
p beam, 10^11 per bunch, 3 MV
Cu beam, 3x10^9 per bunch, 3 MV RF



Momentum spread (rms Δp/p)
0.001
0.0008
0.0006
0.0004
0.0002
0
0
3600
7200
10800
14400
18000
Time at store [s]
Cu beam, 7x10^9 per bunch, 3 MV RF
Au beam, 10^9 per bunch, 3 MV RF
p beam, 10^11 per bunch, 3 MV
Cu beam, 3x10^9 per bunch, 3 MV RF



60
40
20
0
Transverse emittance (95% norm.) [mm mr]
0
3600
7200
10800
14400
18000
Time at store [s]
Cu beam, 7x10^9 per bunch, 3 MV RF
Au beam, 10^9 per bunch, 3 MV RF
p beam, 10^11 per bunch, 3 MV
Cu beam, 3x10^9 per bunch, 3 MV RF


0.25
0.2
0.15
0.1
0.05
0
Bunch length (rms) [m]
0
3600
7200
10800
14400
18000
Time at store [s]
Cu beam, 7x10^9 per bunch, 3 MV RF
Au beam, 10^9 per bunch, 3 MV RF
p beam, 10^11 per bunch, 3 MV
Cu beam, 3x10^9 per bunch, 3 MV RF

RHIC-5: estimates of IBS for Cu-Cu run

A. Fedotov and J. Wei (August 2004)

Parameters:

energy: 100 GeV

Cu: Z=29, A=64

95% normalized emittance: 20 μm

beta*=1m

RF: h=2520, V=3 MV

1. High-intensity case: $7*10^9$ per bunch, 28 bunches
2. Low-intensity case: $3*10^9$ per bunch, 45 bunches

Luminosity

- For high luminosities of Au ions, beam life time is limited by "burn-off" process of Au-Au collisions.
- Total cross section is about 212 barn (much higher than geometric cross section) due to

1) Production of electron-positron pairs (117 barn)
2) Coulomb dissociation of nucleus (95 barn)

For Cu: 1) is expected to be negligible 2) comparable to geometric cross section.

In simulation for Cu-Cu run only geometric cross section was assumed.

IBS Model

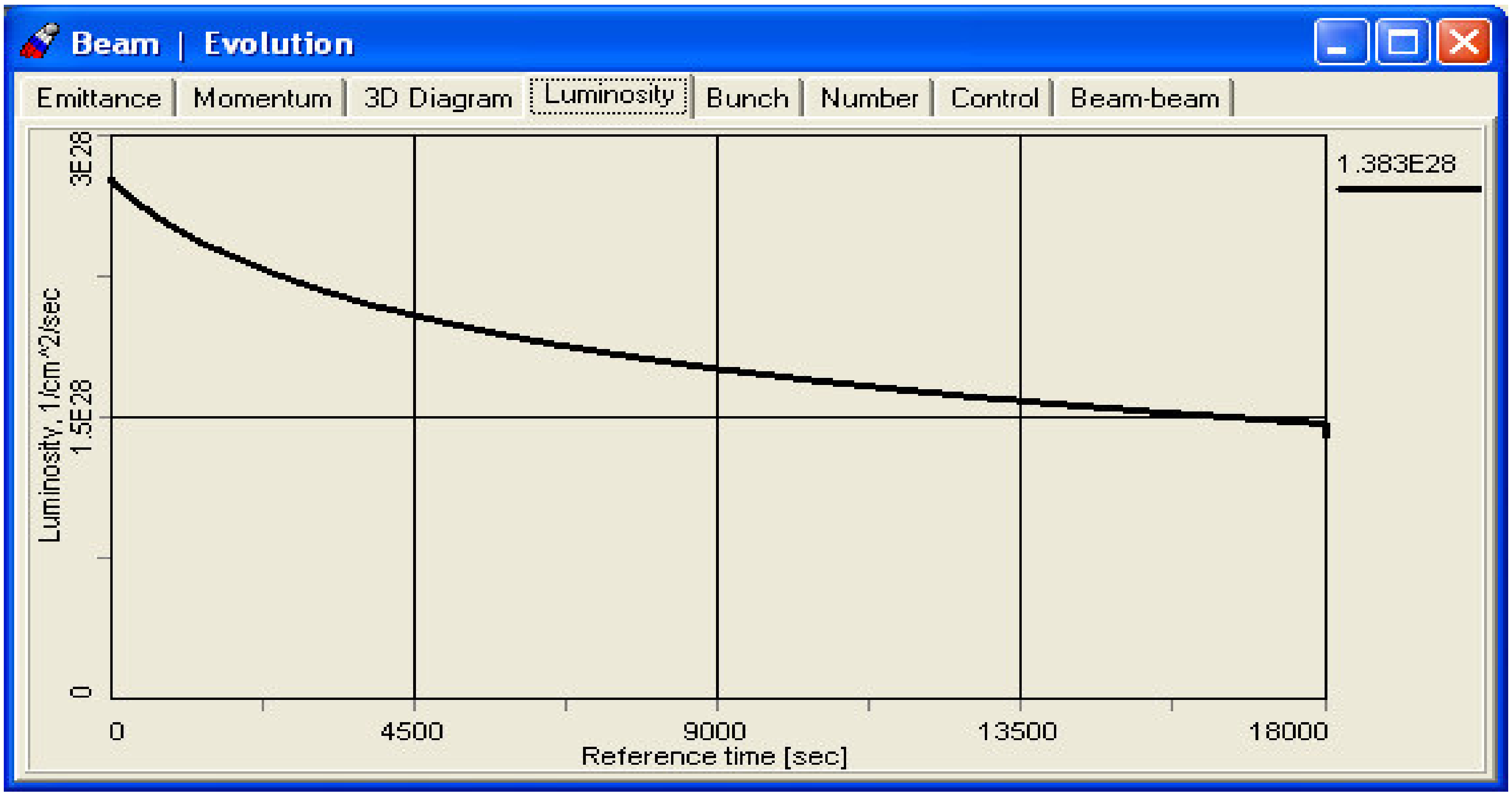
For IBS calculation of Cu-Cu run we used Jie Wei's model of IBS without high-energy approximation.

Simulations are done for:

1. Realistic RHIC lattice – under discussion.
2. FODO approximation – better describes emittance growth in RHIC (higher average dispersion) – used in present predictions for Cu run.

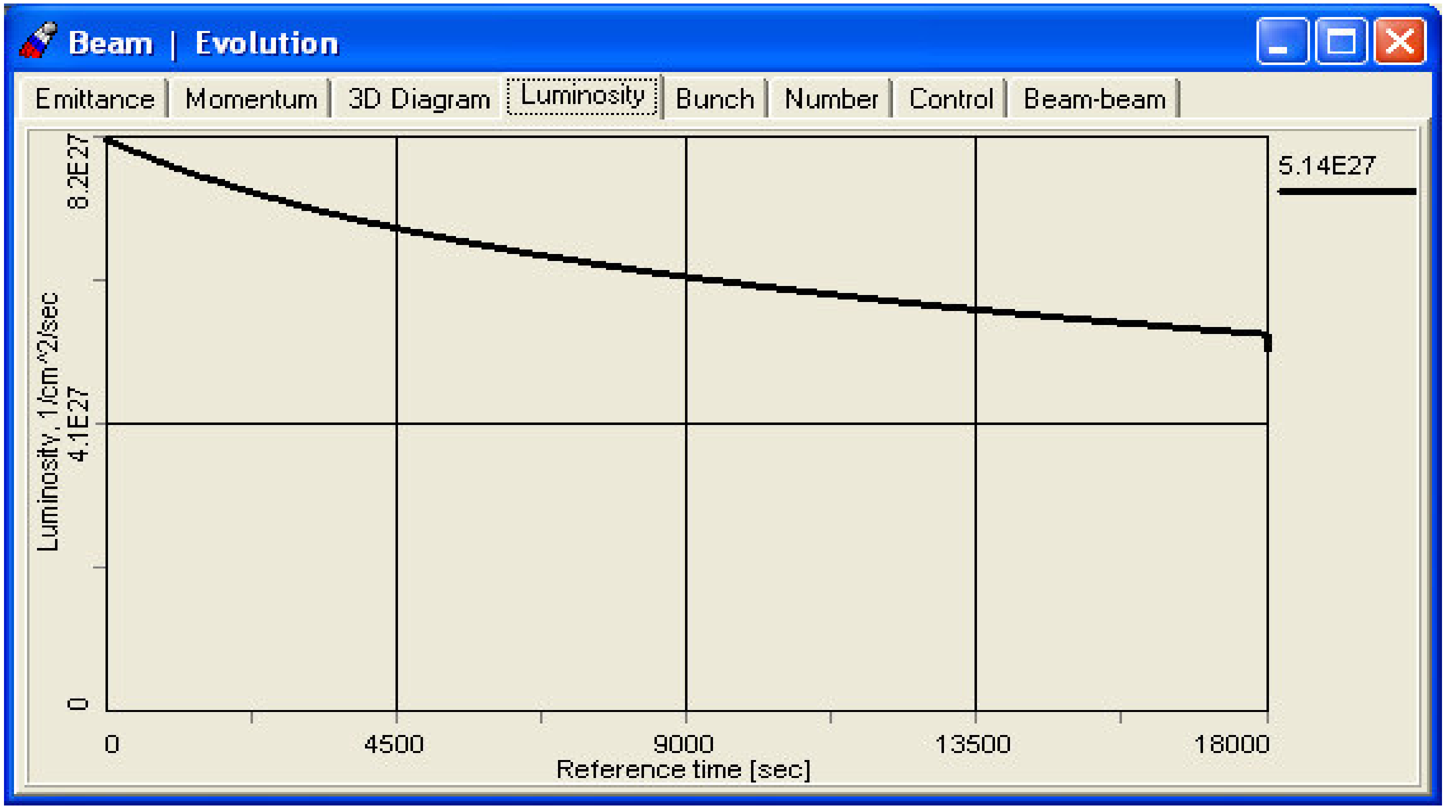
Simulations are done with the BETACOOL and J. Wei's codes.

FODO approximation
Cu-Cu, N=7e9, 28 bunches



Luminosity: 2.8e28 -> 1.4e28 in 5 hours

FODO approximation
Cu-Cu, N=3e9, 45 bunches



Luminosity: 8.2e27 -> 5.1e27 in 5 hours