Intra-beam Scattering --

a RHIC Perspective

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Outline

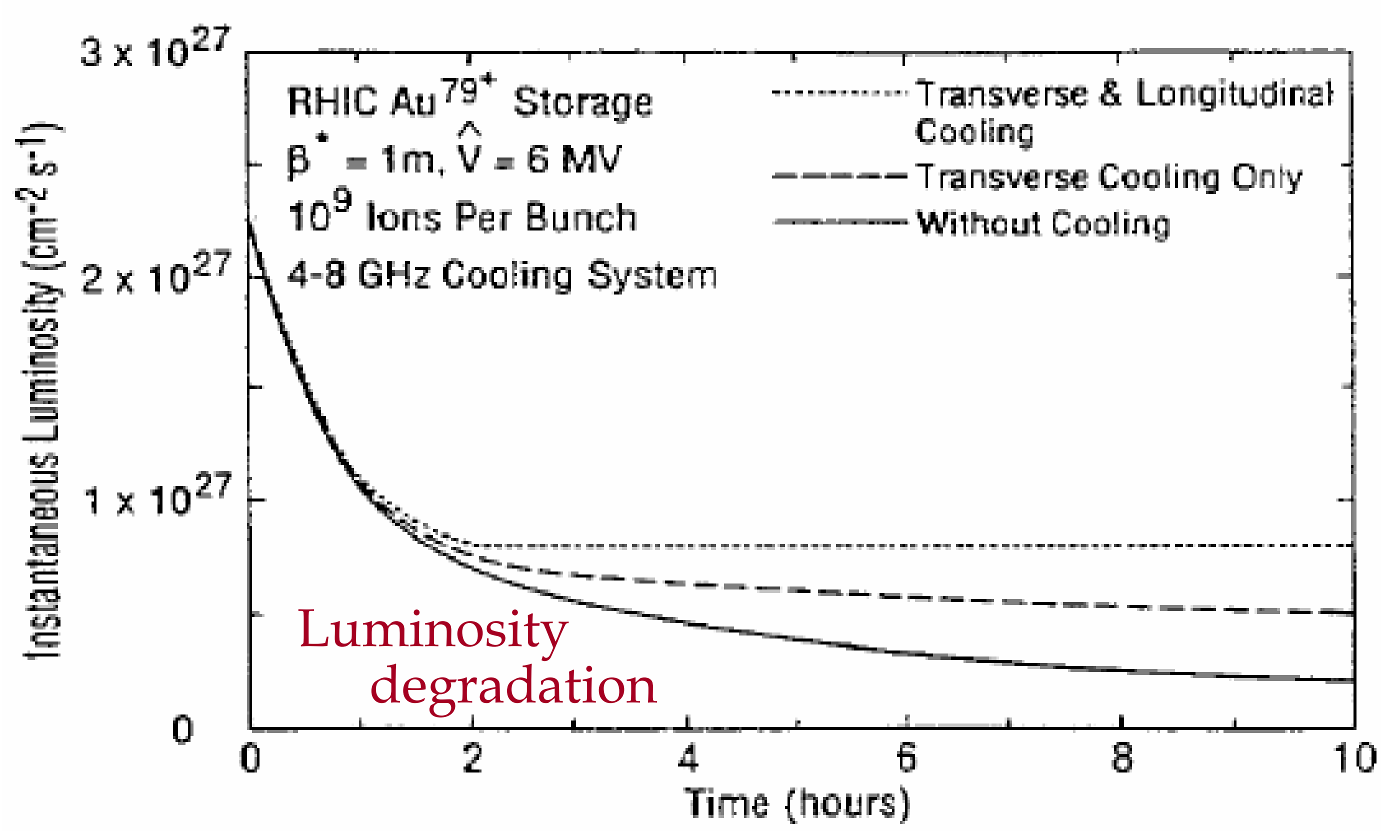
- IBS phenomena in RHIC
- A view from the beam rest frame
- IBS scaling behavior
  - Below transition
  - Above transition (negative-mass regime)
- Comparison on growth rates
- Fokker-Planck equation on density distribution evolution
- Counter measures: beam cooling

Intra-beam phenomena in RHIC

- IBS: intra-beam small-angle Coulomb scattering

→ primary luminosity limiting factor in an heavy-ion storage ring

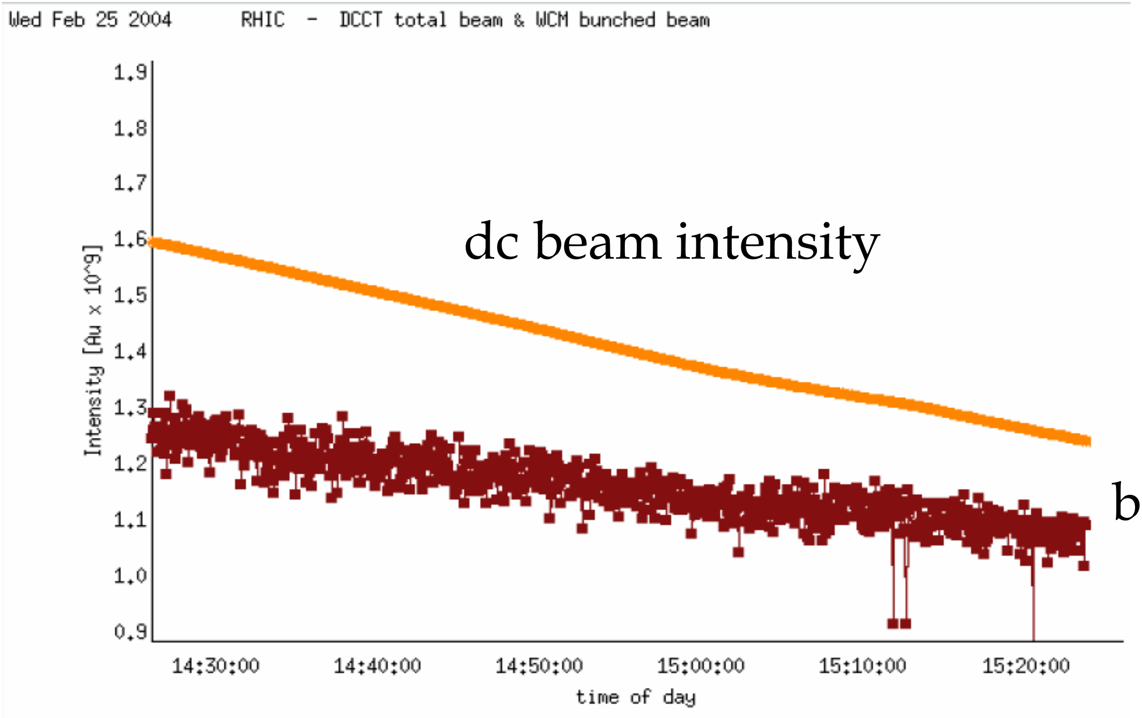
Rutherford scattering cross section ~ Z^4 / A^2



Luminosity degradation

Impact at both collision & injection

- Collision:
  - Design store time 10 hours
  - Expected longitudinal beam loss escaping RF bucket ~ 40%
  - Expected transverse emittance growth ~ 3 times
- Injection:
  - Design filling time ~ 2 minutes; much faster IBS growth

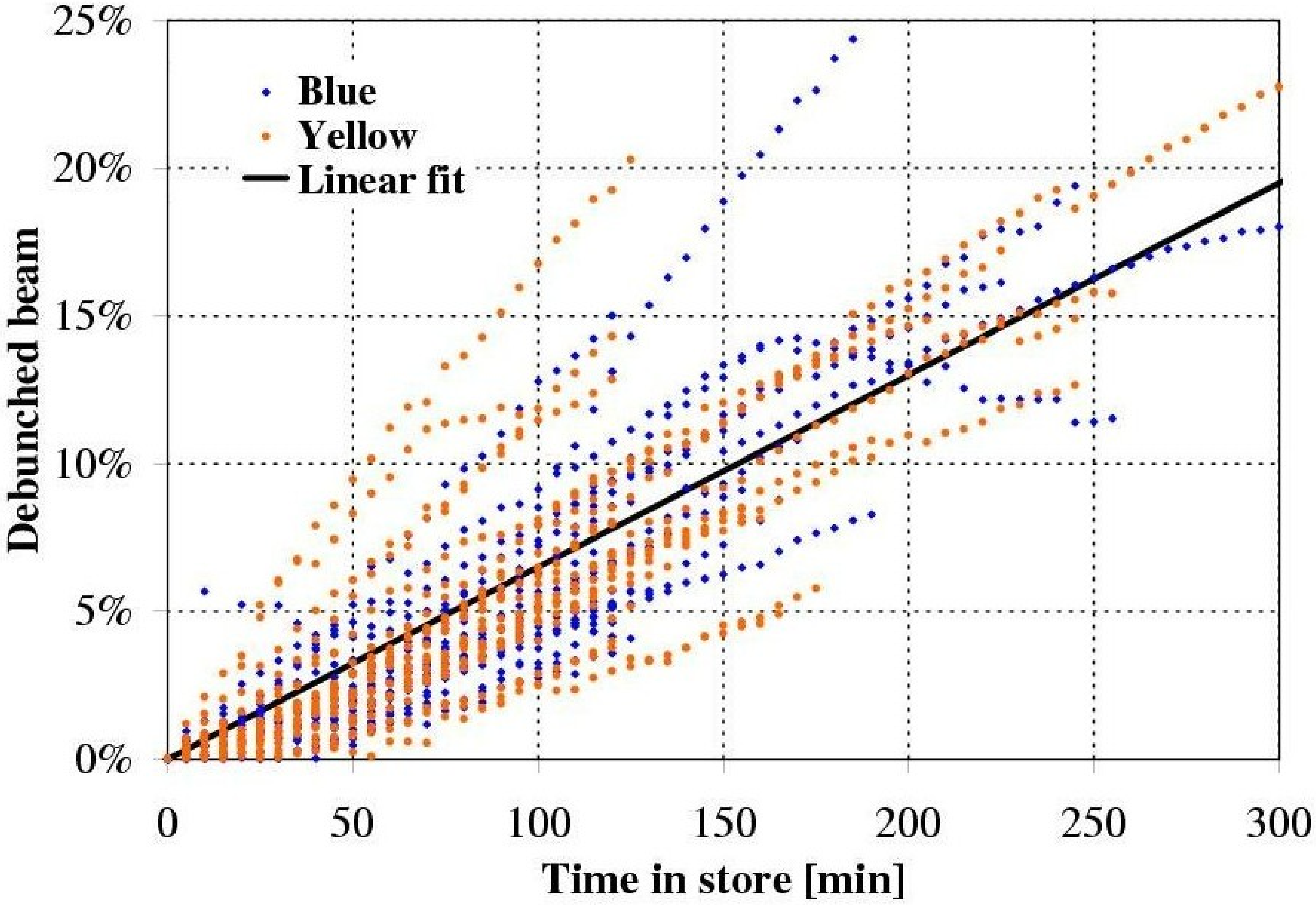


dc beam intensity

bunched beam intensity

Debunching during store

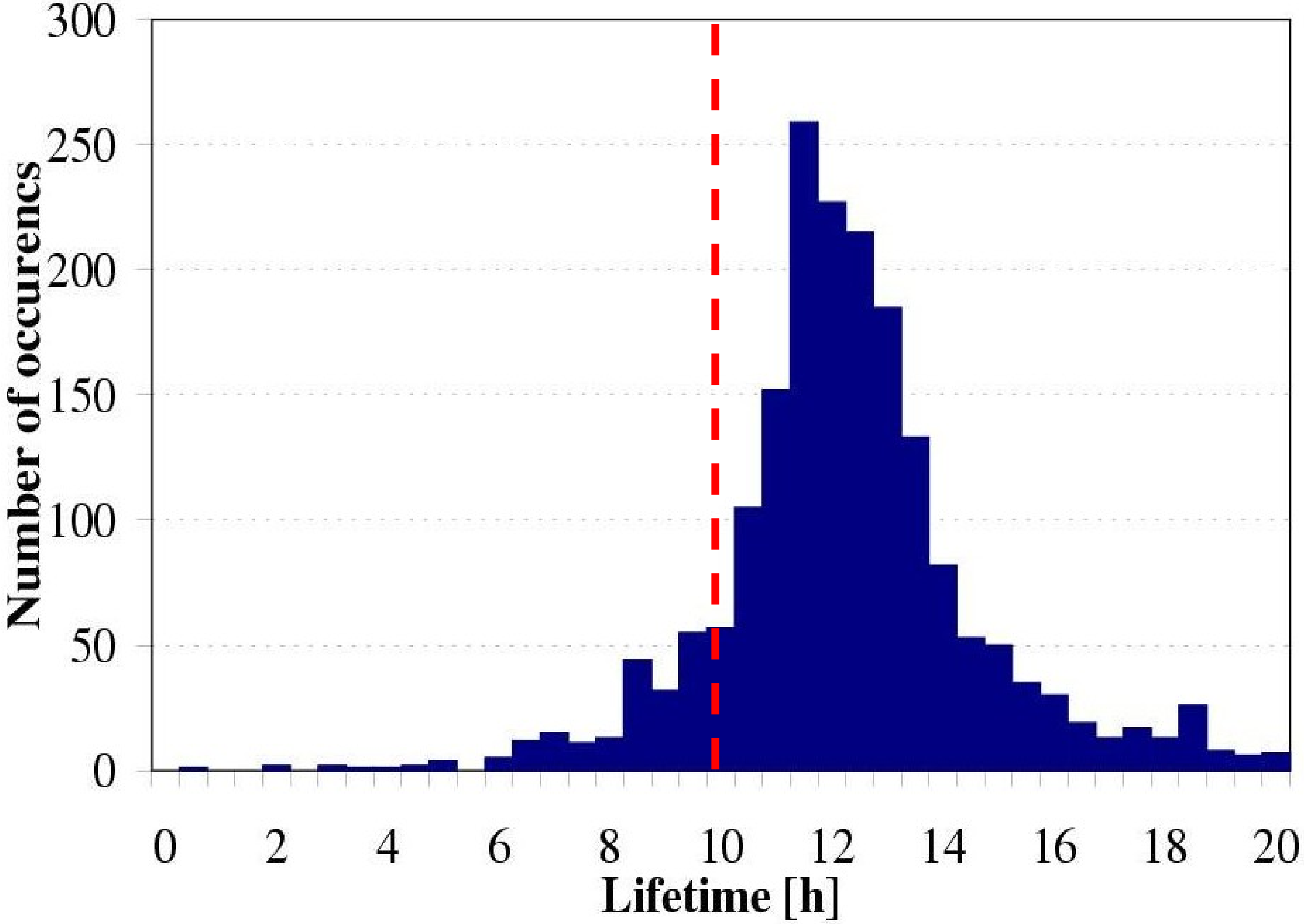
Au^{79+} stores, β^*=5m, N_b=0.25…0.4 · 10^9/bunch, storage rf system



20% of beam debunched after 5 hours

Bunched beam lifetime

Au^{79+} stores, β*=2(1)m, storage rf system, Blue only



Wei, March 16, 2004

A view from the beam rest frame

- Observe particle motion in the rest frame of the beam
- Transformed Hamiltonian

$$H\left(x_\beta, P_x, y_\beta, P_y, z, P_z, \tau\right) = \frac{P_x^2}{2} + \frac{K_x(\tau)x_\beta^2}{2} + \frac{P_y^2}{2} + \frac{K_y(\tau)y_\beta^2}{2} + \frac{1-\gamma^2 F_z(\tau)}{2} P_z^2 + V_C(x, y, z)$$

$$F_z = \begin{cases} D + DD'' + D'^2 & (bends) \\ DD'' + D'^2 & (straights) \end{cases} \qquad \left\langle F_z \right\rangle = \frac{1}{\gamma_t^{\,2}}$$

- Coulomb potential (now non-relativistic)

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

- Time-dependent Hamiltonian in beam rest frame

Below transition: positive-mass regime

- In the ideal case of uniform focusing, the Hamiltonian is positive definite
  - There exists an equilibrium state
  - In the equilibrium state, the beam has equal temperature in all three directions (isotropic in the velocity space)

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

- In general, the Hamiltonian is time-dependent; system is not conserved (AG focusing)
- <u>Quasi-equilibrium state</u>: approaching equilibrium yet still allows growth in beam size

Above transition: negative-mass regime

- The Hamiltonian is NOT positive definite in any case
  - There exists NO equilibrium state
  - All beam dimension can grow
  - Asymptotic relation exists between different dimension

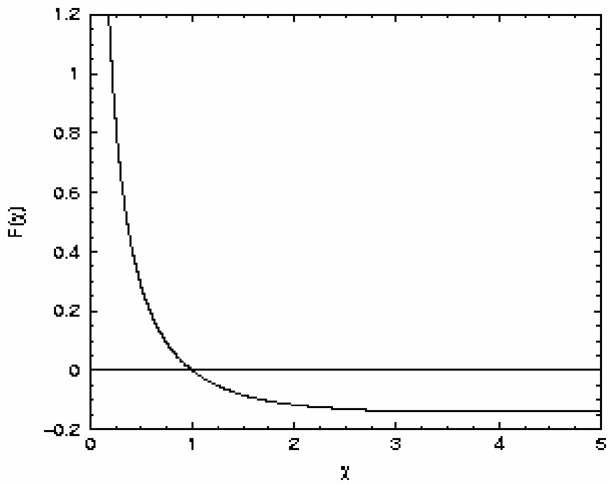
$$\sigma_x^2 \approx D_p^2 \sigma_p^2$$

- Typically vertical dimension grows only through transverse coupling

Beam growth scaling law

- IBS beam size growth rates

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

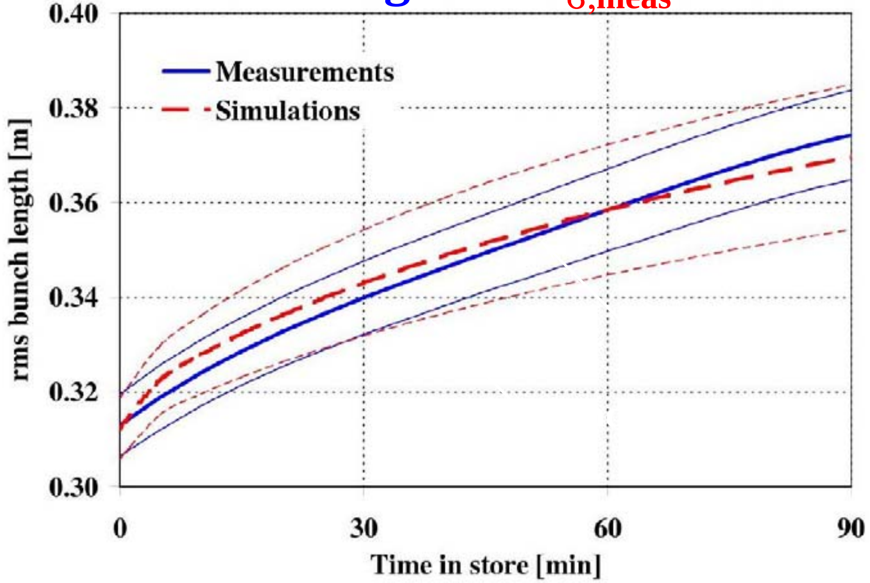


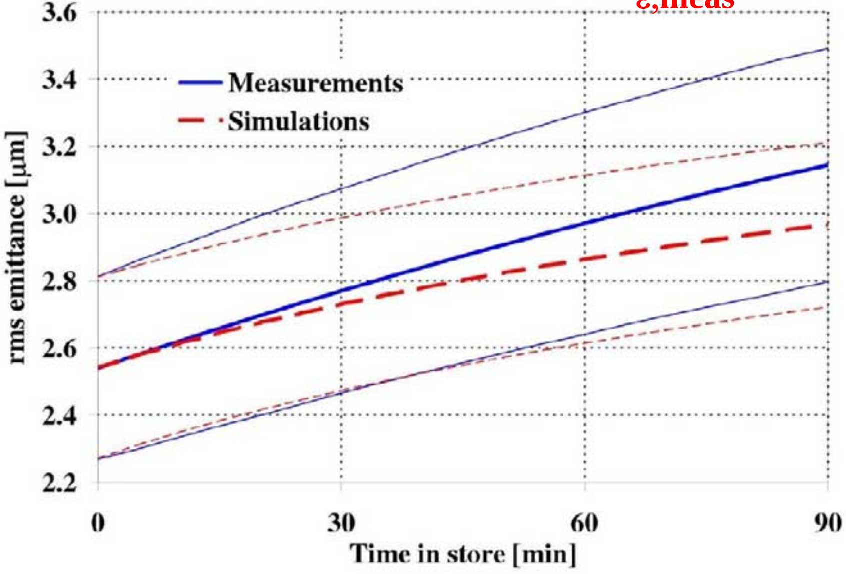
- Proportional to Z^4/A^2
- Proportional to 6-D phase-space density
- Analytic expression obtained for regular (e.g. FODO) lattice; derived by assuming a Gaussian distribution

(A. Piwinski, J. Bjorken, S. Mtingwa, G. Parzen …)

Comparison (above transition)

(W. Fischer, R. Connolly, S. Tepikian, J. v. Zeijts, K. Zeno)

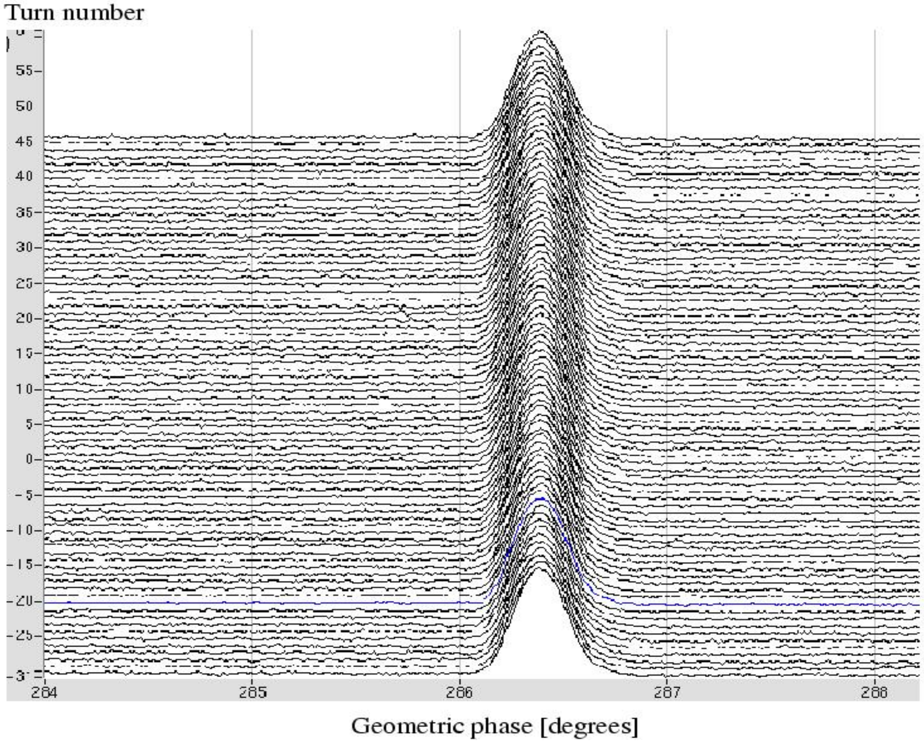

Bunch length σ $\tau_{\sigma,meas} \approx 8h$


Transverse emittance ε $\tau_{\varepsilon,meas} \approx 6h$

After 90 min	$\Delta\sigma/\sigma$	$\Delta\varepsilon/\varepsilon$
Measured Au	20%	24%
Computed Au	18%	17%
Measured p		5%

(EPAC 2002)

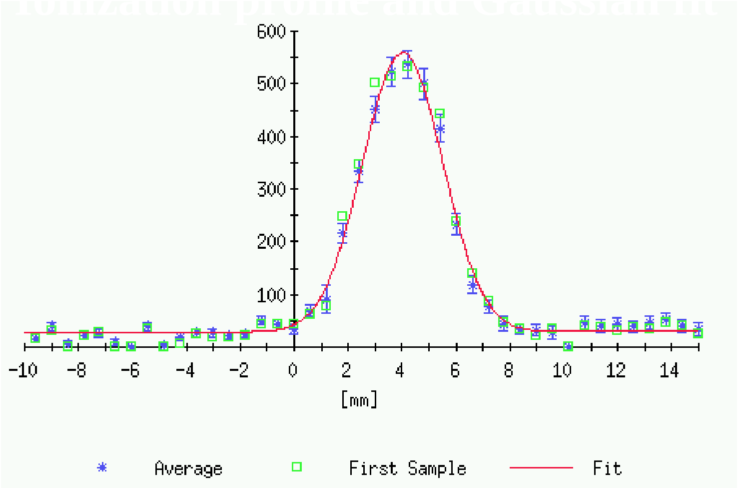
Longitudinal profile measurements

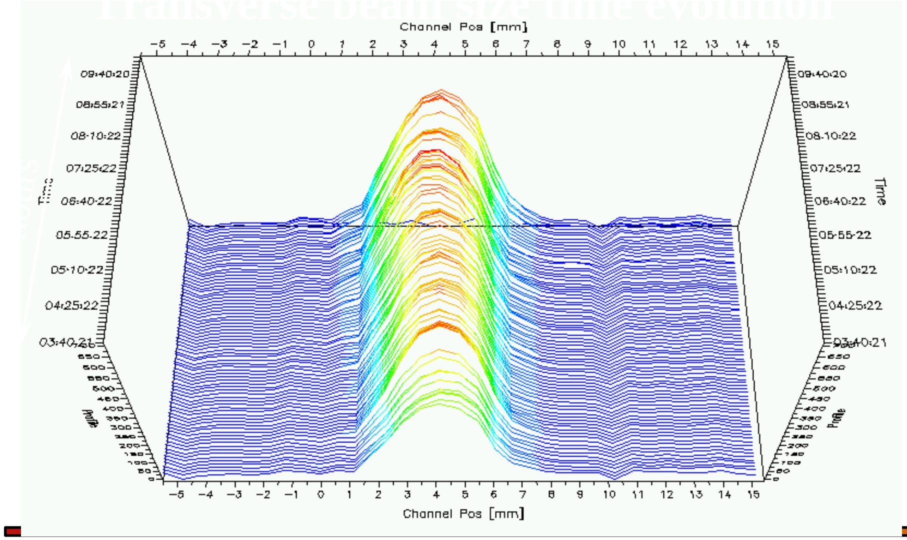


Wall Current Monitor

- time resolution 0.25 ns
  (buckets: 35 ns and 5 ns)
- recording period 0.1…5 min
- used for:
  - bunched current
  - bunch length
    (Gaussian fit)

Transverse emittance measurements



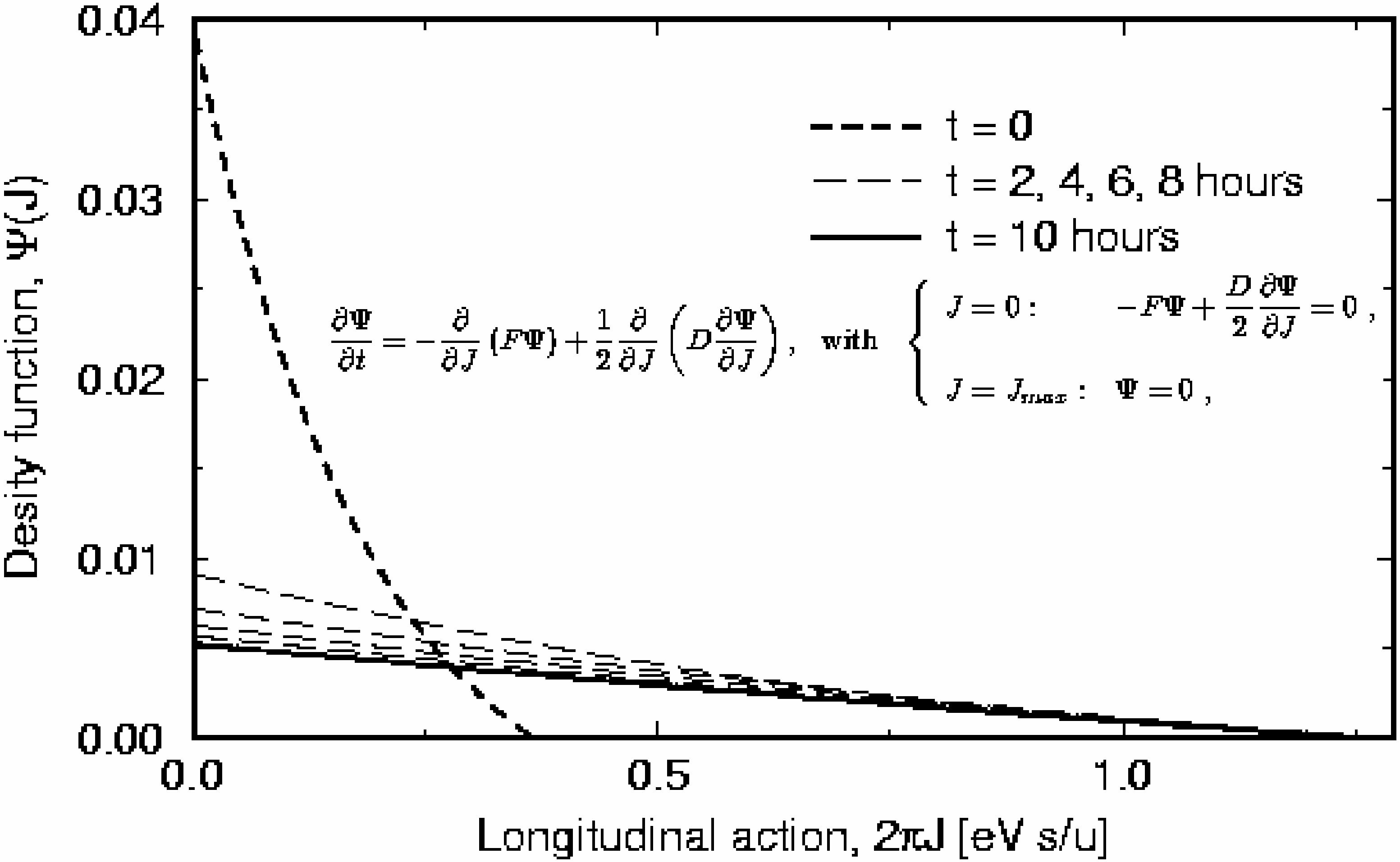


Ionization Profile Monitor

R. Connolly, S. Tepikian

- recording period 0.5…5 min
- data of improved reliability
  - multi-channel plates recessed to avoid stray electrons
  - small rest gas ionization with protons
- used:
  - at injection
  - calibration at store

Fokker-Planck approach on density evolution



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

Fokker-Planck equation

- Drift and diffusion mechanisms
  - Collision: dominated by diffusion process
  - Injection: contributed by both drift and diffusion process

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

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

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

Counter-measure example: stochastic cooling

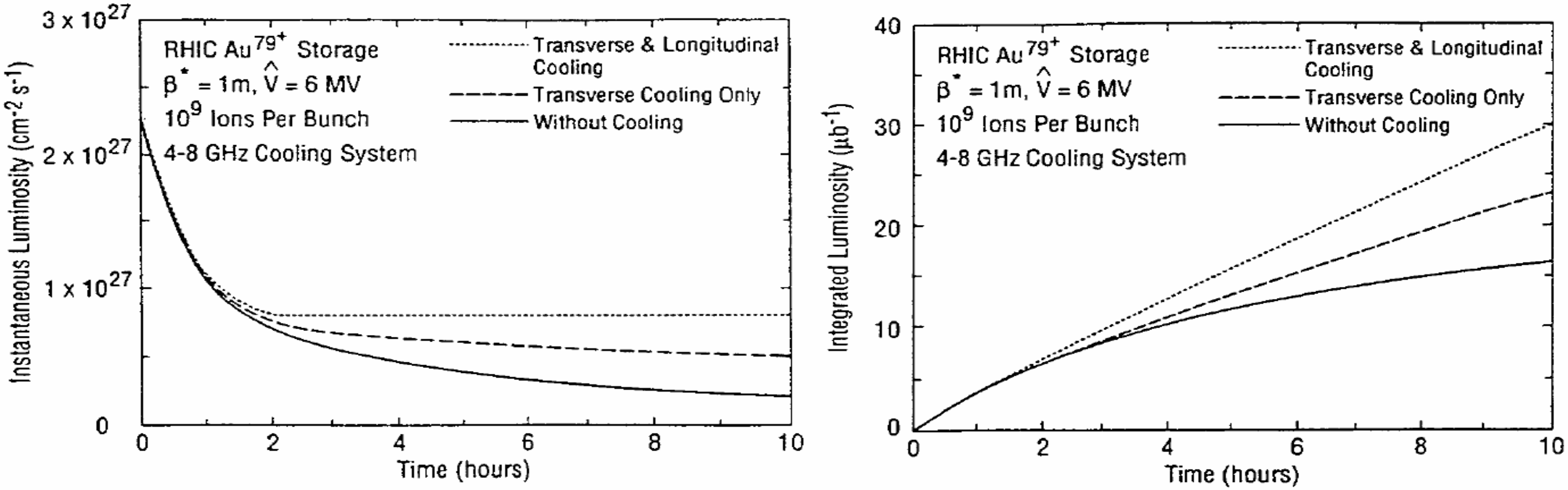


Figure 3: Improvements on a) instantaneous and b) integrated luminosity in RHIC when stochastic cooling is applied.

Key for bunched-beam stochastic cooling in a collider:

→ eliminate coherent spikes at GHz range that may saturate the cooling system

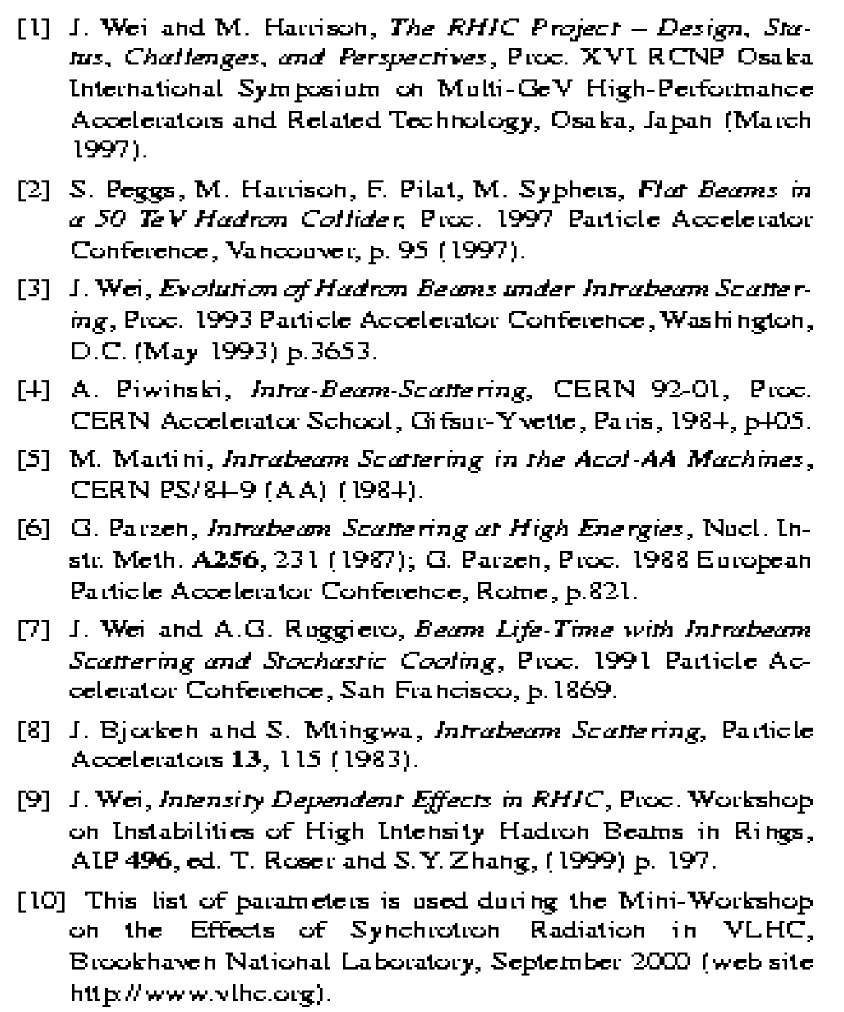
IBS among gold ions in RHIC may diffuse possible soliton mechanism

(M. Brennan, M. Blaskiewicz, et al …)

Summary

- Intra-beam scattering is the leading mechanism that limits beam luminosity in RHIC
- At storage, theoretical estimates qualitatively agrees with experimental measurements
- Counter-measures like stochastic cooling and electron cooling are under development

References



[1] J. Wei and M. Harrison, *The RHIC Project – Design, Status, Challenges, and Perspectives*, Proc. XVI RCNP Osaka International Symposium on Multi-GeV High-Performance Accelerators and Related Technology, Osaka, Japan (March 1997).

[2] S. Peggs, M. Harrison, F. Pilat, M. Syphers, *Flat Beams in a 50 TeV Hadron Collider*, Proc. 1997 Particle Accelerator Conference, Vancouver, p. 95 (1997).

[3] J. Wei, *Evolution of Hadron Beams under Intrabeam Scattering*, Proc. 1993 Particle Accelerator Conference, Washington, D.C. (May 1993) p.3653.

[4] A. Piwinski, *Intra-Beam-Scattering*, CERN 92-01, Proc. CERN Accelerator School, Gifsur-Yvette, Paris, 1984, p405.

[5] M. Martini, *Intrabeam Scattering in the Acol-AA Machines*, CERN PS/84-9 (AA) (1984).

[6] G. Parzen, *Intrabeam Scattering at High Energies*, Nucl. Instr. Meth. **A256**, 231 (1987); G. Parzen, Proc. 1988 European Particle Accelerator Conference, Rome, p.821.

[7] J. Wei and A.G. Ruggiero, *Beam Life-Time with Intrabeam Scattering and Stochastic Cooling*, Proc. 1991 Particle Accelerator Conference, San Francisco, p.1869.

[8] J. Bjorken and S. Mtingwa, *Intrabeam Scattering*, Particle Accelerators **13**, 115 (1983).

[9] J. Wei, *Intensity Dependent Effects in RHIC*, Proc. Workshop on Instabilities of High Intensity Hadron Beams in Rings, AIP **496**, ed. T. Roser and S.Y. Zhang, (1999) p. 197.

[10] This list of parameters is used during the Mini-Workshop on the Effects of Synchrotron Radiation in VLHC, Brookhaven National Laboratory, September 2000 (web site http://www.vlhc.org).