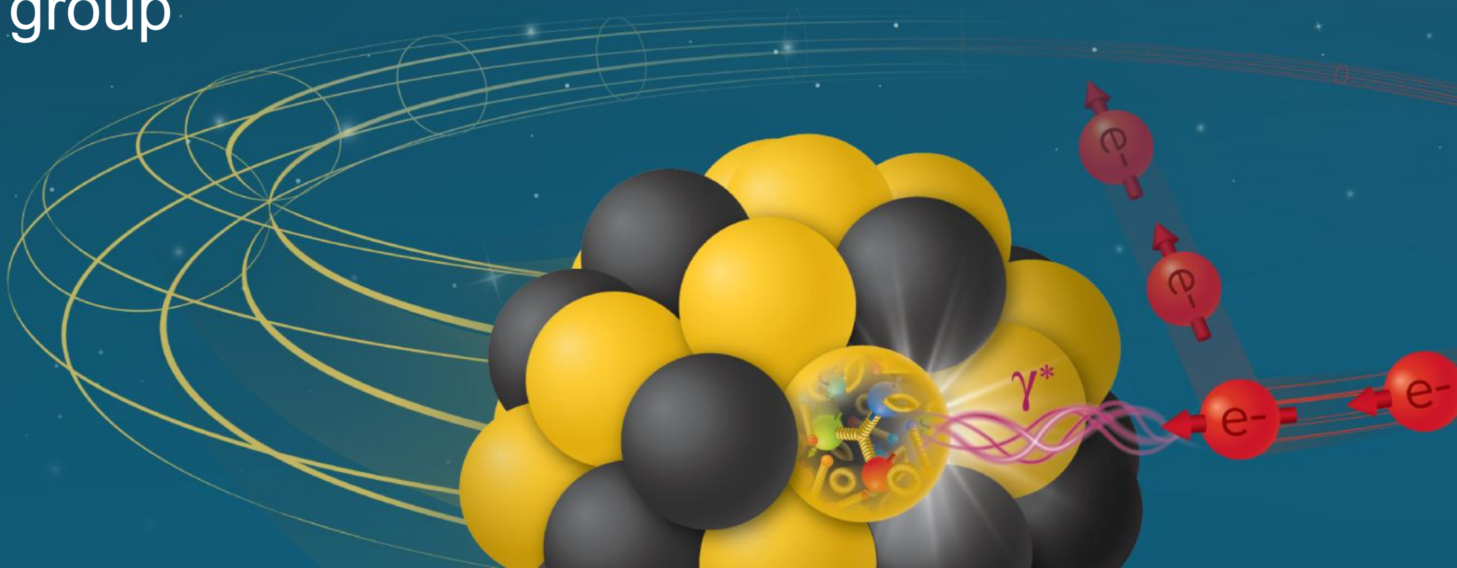
Stochastic cooling in the RHIC and the EIC

Mike Blaskiewicz for the cooling group

RHICfest

July 9-10 2026



Electron-Ion Collider

History

Herr and Mohl reported cooling bunched beams in ICE (1978)

Chattopadhyay develops bunched beam cooling theory (1983)

$$\theta - \omega_0 t = \varphi(t) \approx a \sin[\omega_s(a)t + \psi_0]$$

Stochastic cooling considered for SPS, RHIC and Tevatron (80s).

Unexpected RF activity swamps the Schottky signal (~85).

Cooling rate scales as 1/N, Z=79 for Au. Fast IBS, microwave technology.

Cooling of long bunches in FNAL recycler (2005).

Proton cooling experiment in RHIC (2006).

Operational longitudinal cooling of gold in RHIC (2007).

Transverse cooling in RHIC (2010).

Have cooled several species from 30 GeV/nucleon to 100 GeV/nucleon.

Early RHIC work

Longitudinal kickers were hard.

RHIC-AP-9

STOCHASTIC COOLING IN RHIC

S. Van der Meer

BNL, September 10, 1984

Dear Dr Lee,

As promised, I had a further look at the cooling for your planned heavy-ion machine. Unfortunately, I am not quite sure of one of the parameters you gave me: the emittance ε. Is the initial value of 10π mm mrad the real emittance or the normalized value (i.e. multiplied by βγ)? In the first case, the power required for betatron cooling would be rather high. If it is the normalized emittance, this problem would not exist, although there are still a number of other difficulties.

In particular, it turns out that the power needed for longitudinal cooling would severely restrict the obtainable cooling rate.

REPORT OF THE STOCHASTIC COOLING SUBGROUP OF THE RHIC WORKSHOP

D. Boussard, J. Claus, G. DiMassa,

J. Marriner, J. Milutinovic and R. Shafer

Received SEP 1 3

1988

Overview

We have considered the possibility of stochastic cooling of beams for the RHIC collider. Similar studies have been carried out previously for RHIC and other bunched beam proton machines (1-4). The major motivation for cooling at RHIC is to stabilize the growth from intrabeam scattering (see Table). We find that cooling rates of the order of 500 sec are theoretically possible for beams of gold ions with γ = 100 if a cooling bandwidth of 10 GHz is used. However, the amount of microwave power which is required is large for momentum cooling and probably not practical. Considerably less power is required for slower rates. We believe that cooling times of 5000 sec for momentum cooling and 1000 sec for betatron cooling might be possible.

LONGITUDINAL STOCHASTIC COOLING IN RHIC

June 1990

J. Wei and A.G. Ruggiero

Accelerator Development Department

Brookhaven National Laboratory

Upton, New York 11973

full RF buckets similar to coasting beams

Voltage considerations

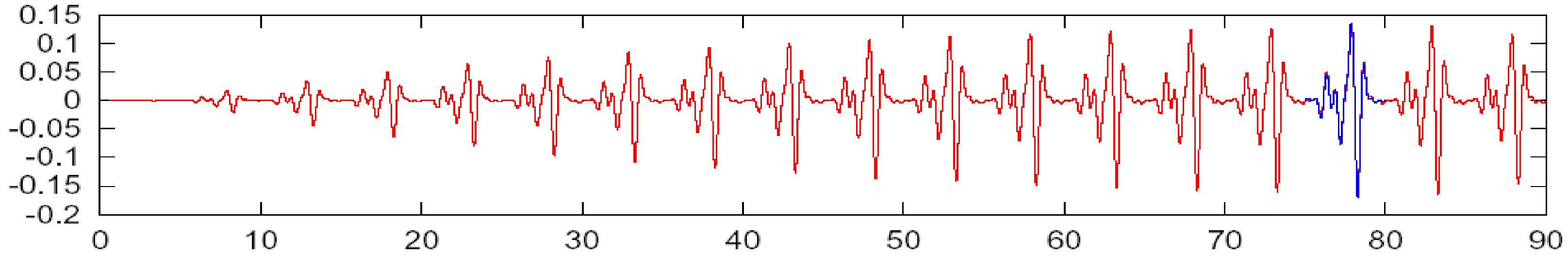
$$V(t) = \sum_n A_n \sin(2\pi nt/\tau_b + \theta_n)$$

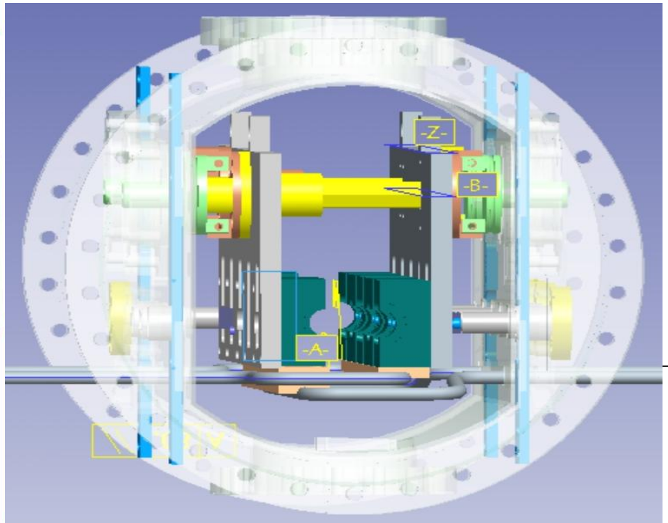
For 5-8 GHz need 3 kV rms which is large by stochastic cooling standards

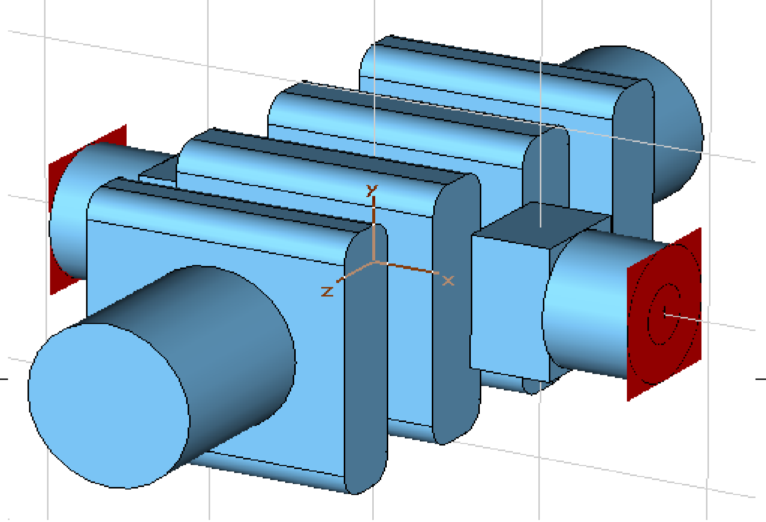
Bandwidth-Voltage product sets the cost scale

Bunches are 5 ns long spaced by 100 ns

The value of the kicker voltage matters only when the bunch is present. By using harmonics we cheat the voltage bandwidth product.







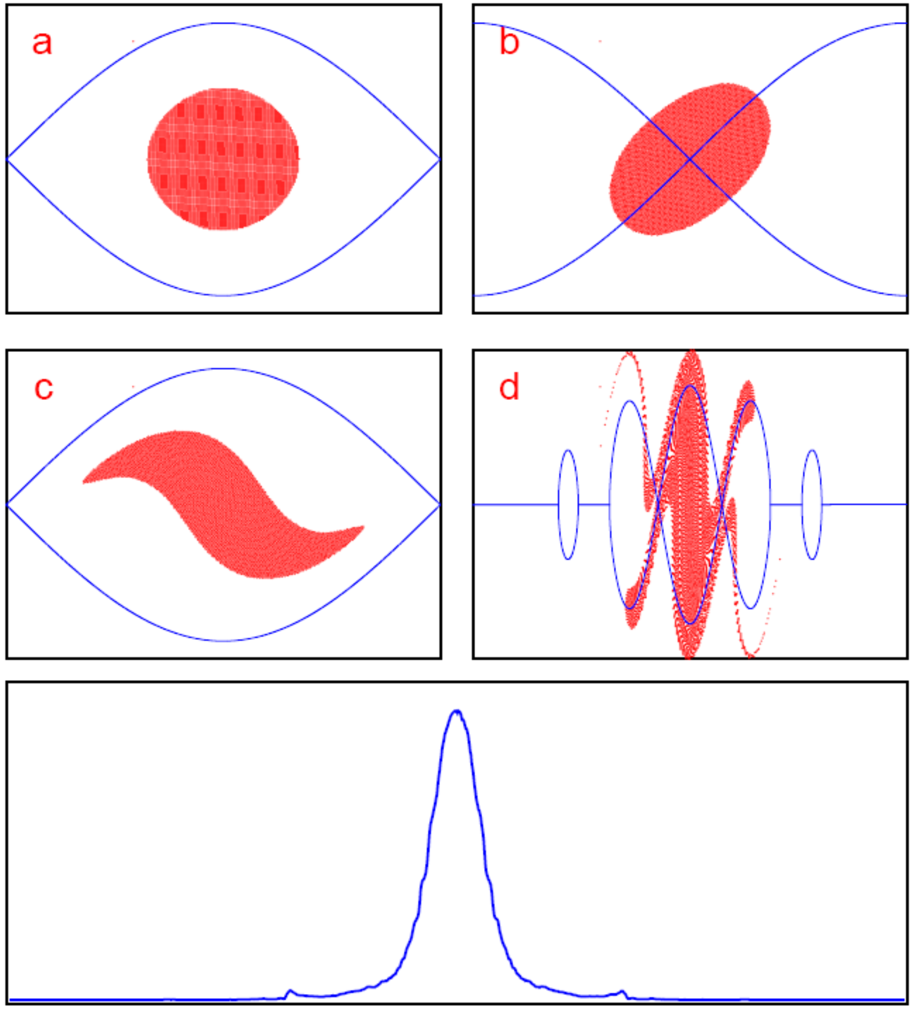
RF Activity (anomalous high frequency power)

Two distinct types:

1) Strong revolution lines
2) Strong signals associated with synchrotron motion

Heavy ions are rebucketed to shorten the bunch and combat IBS. Lots of type 1) present.

In the beginning we used torque wrenches on sma connectors to minimize signal leaks. Every connection was an antenna.

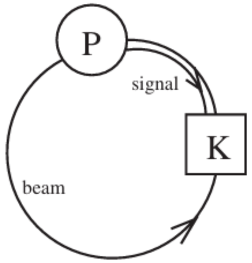


Low Level Drive for longitudinal halo cooling

For cooling we need a force that reduces the energy error.

The lattice mandates filter cooling.

$$S(\omega) = G[1 - \exp(i\Delta\omega T_{rev})]^n \exp(i\Delta\omega T_{delay})$$

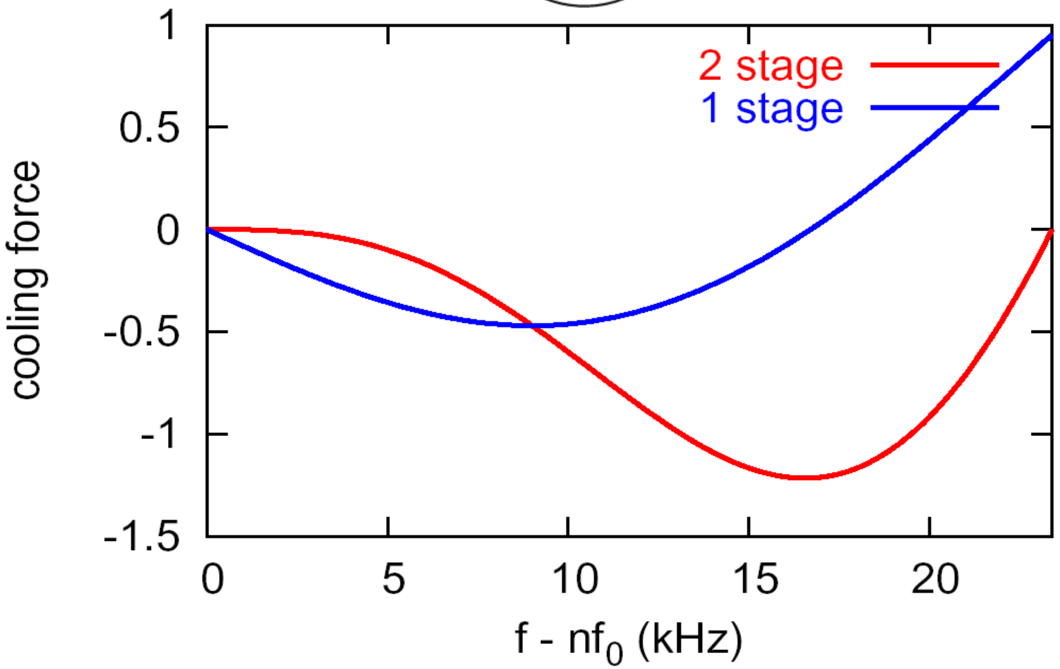


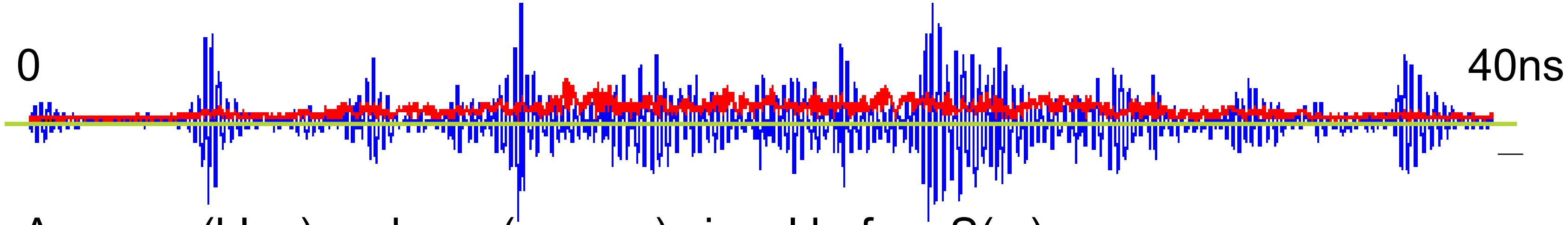
Initially used fiber optic in the tunnel from 12 to 4.

$T_{delay}=2T_{rev}/3$ and n=2 works OK for 8 GHz in RHIC

Next step was a 70 GHz microwave link $T_{delay}=T_{rev}/6$, n=1

Good at 9 GHz



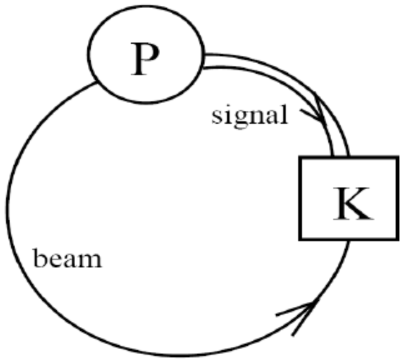


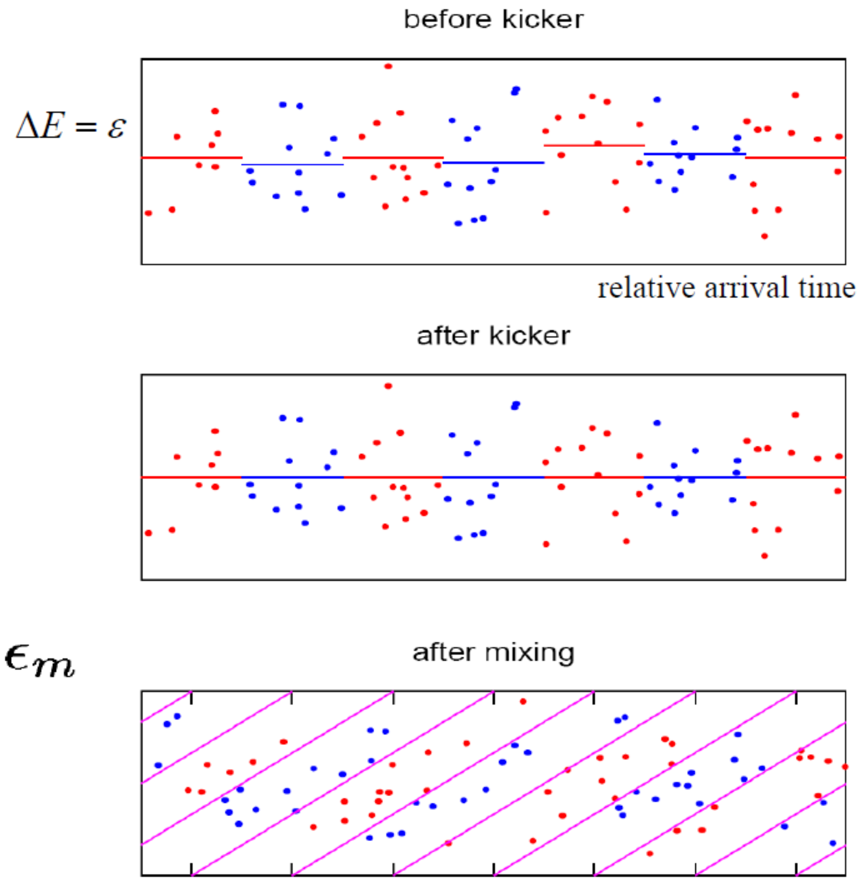
Average (blue) and rms (orange) signal before S(ω)

Simulation Algorithm

- For longitudinal cooling we measure energy offsets and correct them with a kick.
- The kick voltage scales as $1/\sqrt{N_p}$ and the cooling time scales as N_p.
- The number of simulation macroparticles satisfies $N_m << N_p$.
- The number of turns needed to simulate the system is reduced by a factor N_m/N_p.
- By keeping the total beam charge the same fluid effects are unchanged.
- Allows for a scaling law.

Basic idea





$$\bar{\epsilon}_k = \epsilon_k - \frac{g}{N_s}\sum_{m=1}^{N_s}\epsilon_m$$

$$<\varepsilon_k \varepsilon_m> = <\varepsilon^2> \delta_{k,m}$$

$$<\bar{\epsilon}^2> - <\epsilon^2> = (-2g + g^2) <\epsilon^2> / N_s$$

$N_s \approx N_p/(4\Delta f \sigma_t)$

Algorithm test: transverse cooling

- Check of scaling, single harmonic RF, no IBS or longitudinal cooling.
- Strong effect of cooling rate on H_s first noted by Chattopadhyay (Thesis 1983)
- For RHIC and EIC longitudinal IBS leads to sufficient H_s diffusion to smooth out transverse cooling.
- Figure from Blaskiewicz and Brennan, COOL07, WEM2I05

$$H_s(\epsilon, \tau) = \frac{T_0 \eta}{2\beta^2 E_0}\epsilon^2 - \int_0^{\tau} dt q V_{rf}(t)$$

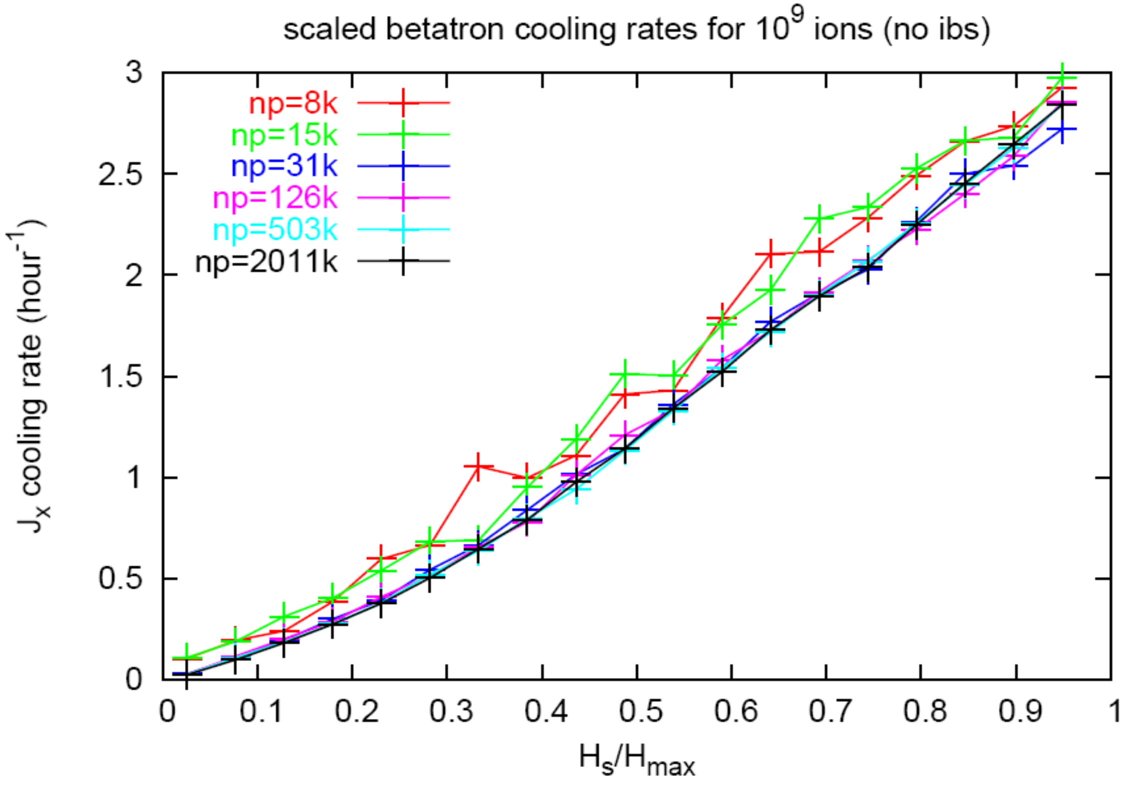


Figure 5: Transverse cooling rate versus the value of the longitudinal hamiltonian. Similar results are shown in [6, 7]

Beautiful signals

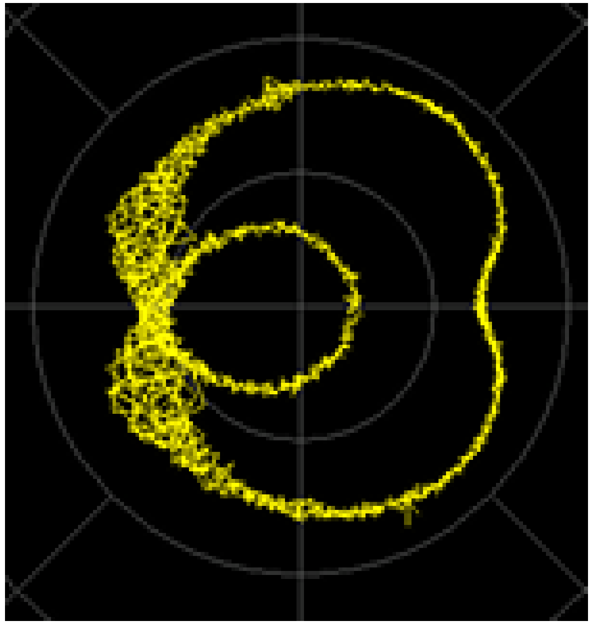


Figure 1: System transfer function of horizontal cooling in polar coordinates at 7.2 GHz.

In the end the network analyzer ran the system.

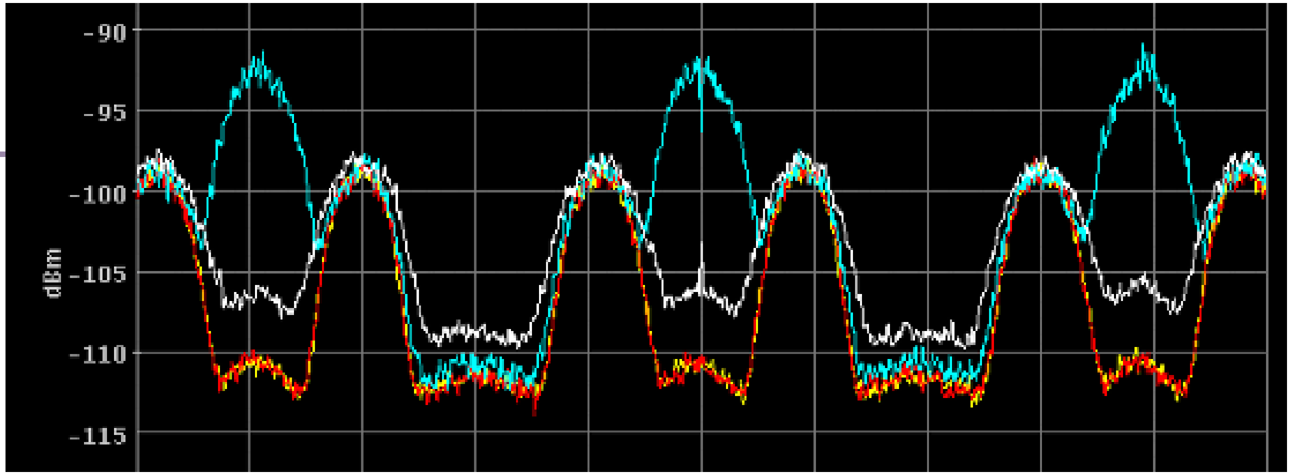


Figure 3: Common mode rejection from transverse pickup at 3 frequencies. Best, worst, and typical.

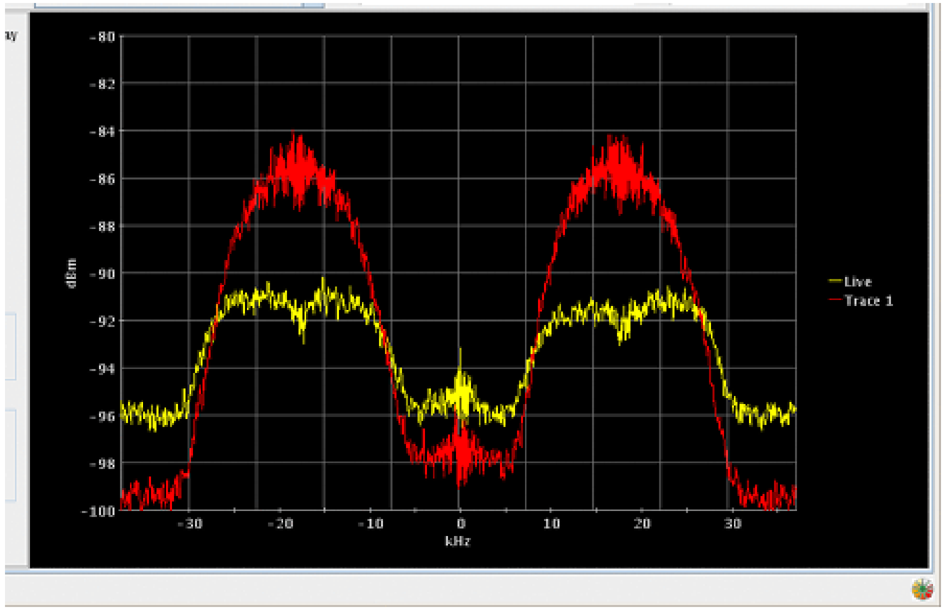


Figure 2: Betatron sidebands from pickup at 5.8 GHz Red, cooling off. Yellow, 6 dB signal suppression.

STOCHASTIC COOLING IN RHIC*

J. M. Brennan#, M. Blaskiewicz, K. Mernick, BNL 911B, Upton, NY 11973, USA

INTRODUCTION

The full 6-dimensional [x,x′; y,y′; z,z′] stochastic cooling system for RHIC was completed and operational for the FY12 Uranium-Uranium collider run. Cooling enhances the integrated luminosity of the Uranium collisions by a factor of 5, primarily by reducing the transverse emittances but also by cooling in the longitudinal plane to preserve the bunch length. The components have been deployed incrementally over the past several runs [1,2,3],

You can't argue with success.

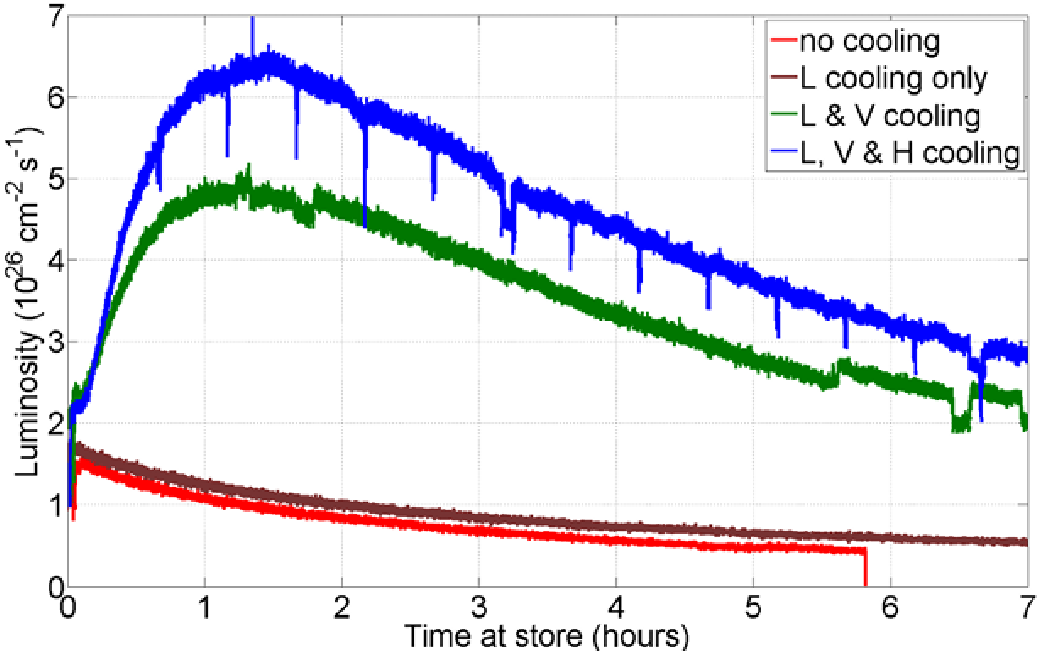
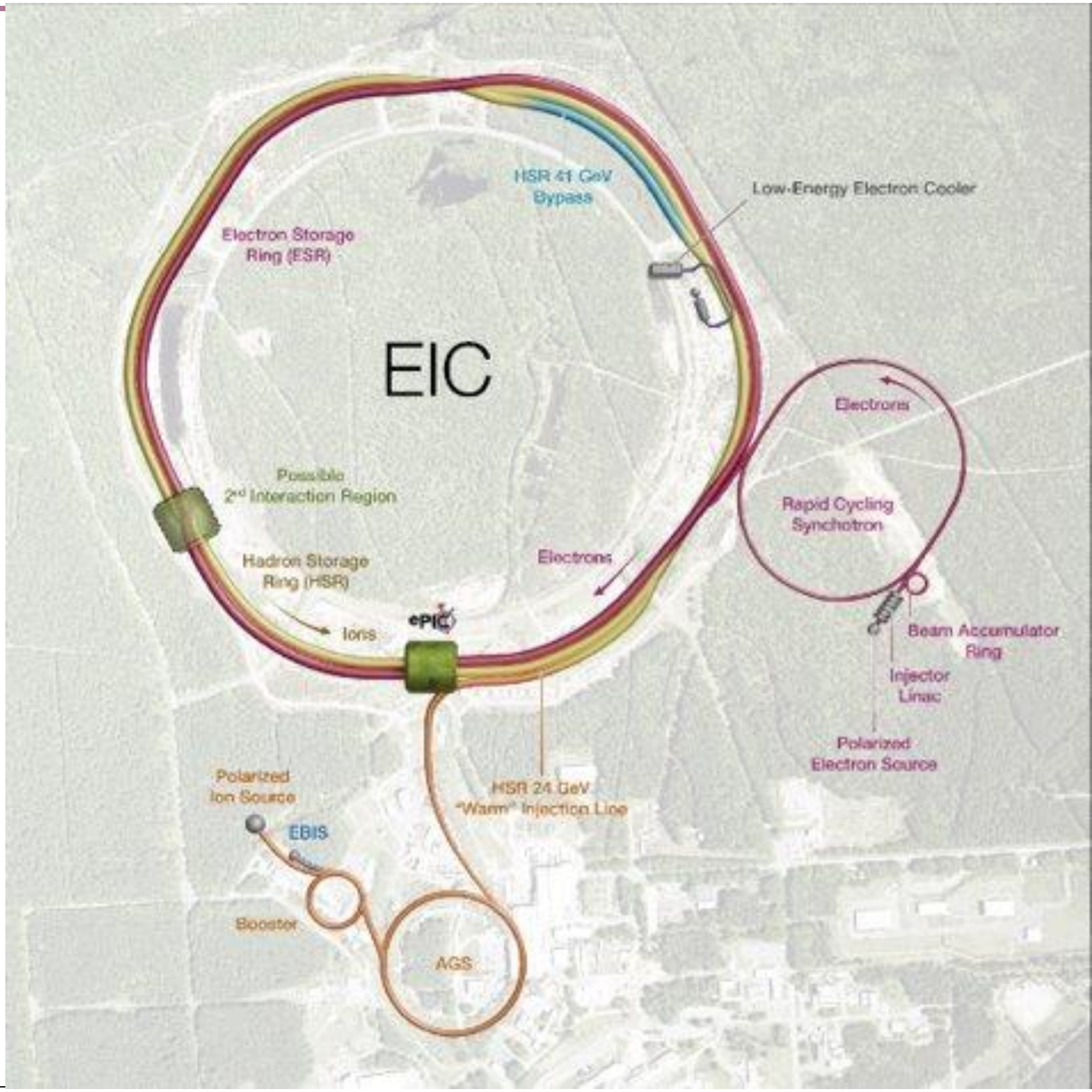


Figure 4: Effect of different cooling configurations on the luminosity. No cooling is shown in red, longitudinal only in brown, longitudinal and vertical in green, and all 3 systems in blue. The initial luminosity for these stores varies slightly due to other improvements in RHIC and the injectors.

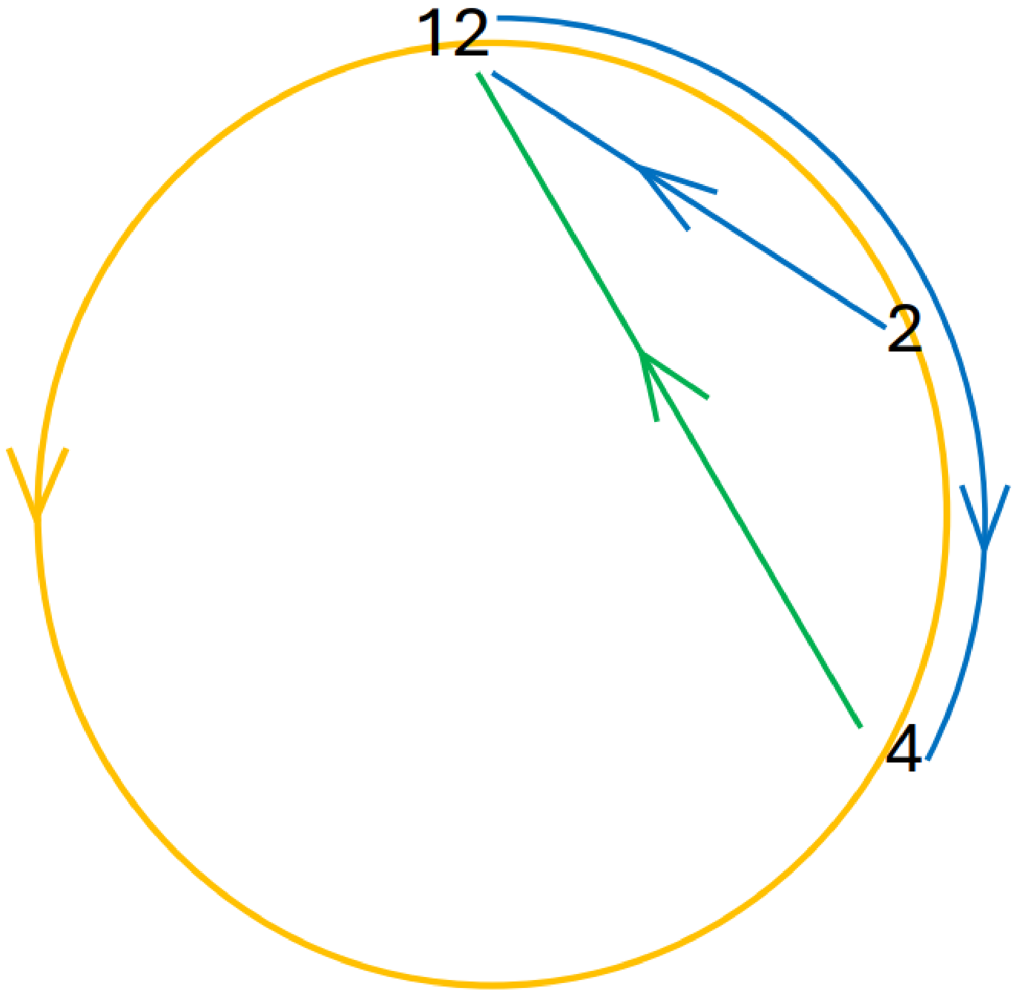
Cooling Ions in the Electron Ion Collider

- 13 nC bunches of Au from 41 to 110 GeV/nucleon. Others Nb, Ag, Cu, U,…
- Can we adapt the RHIC system to the EIC?
- Existing system works with 80ns bunch spacing.
- Injection harmonic in Hadron Storage Ring is 315, 40ns bunch spacing. Double up kickers.
- Two bunch splits used to reduce the BB tune shift of the electrons, 10ns spacing.
- For 18 GeV the electron current is power limited. No bunch splitting is used.
- Initial RF in ESR ~1/4 of final design and bunch splitting may be unnecessary.



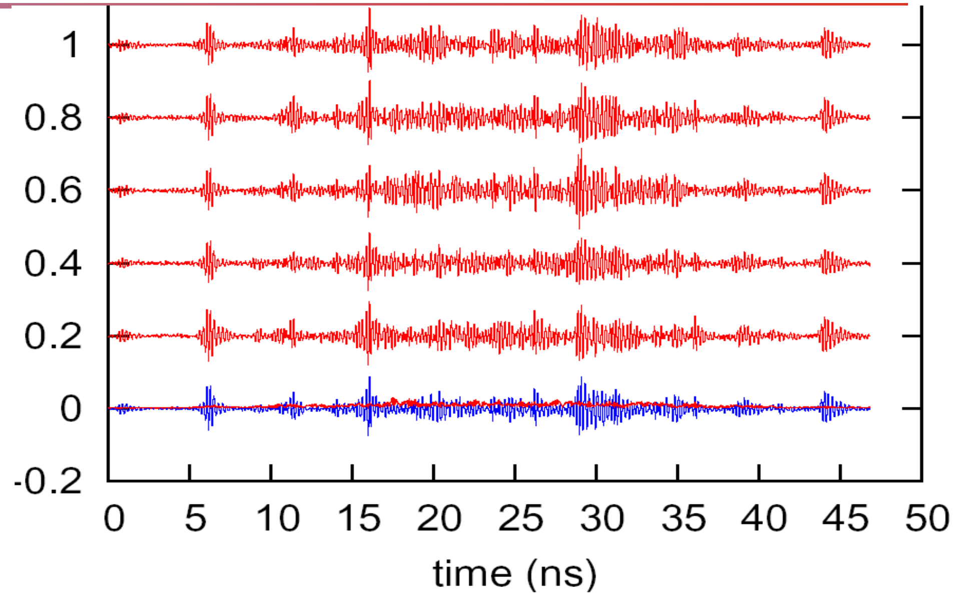
System Layout for Yellow Ring

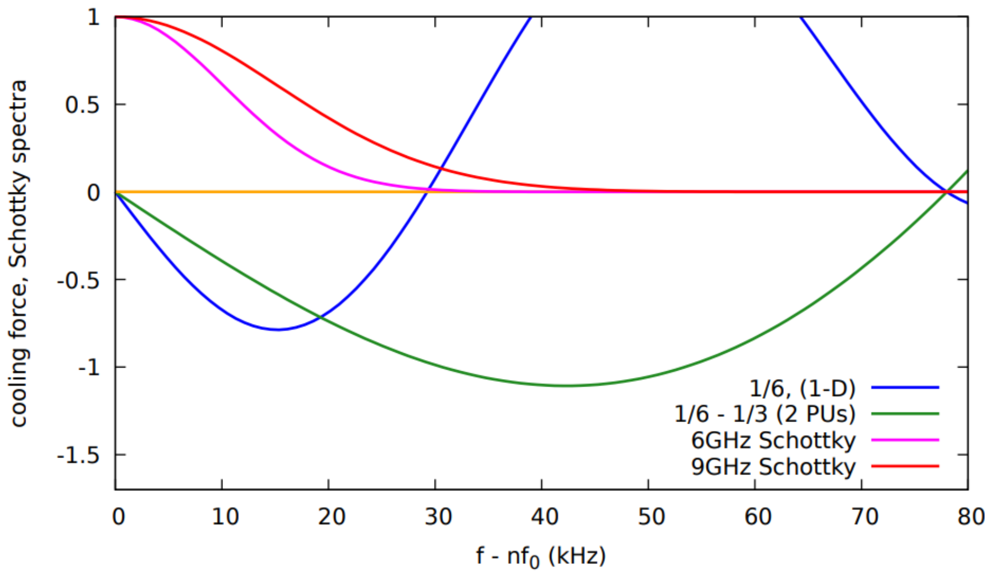
- The existing RHIC system has longitudinal kickers and transverse pickups in the 12 o'clock straight section.
- A microwave link is used to send the longitudinal pickup signal from 2 to 12, arrives before beam. 1/6 turn delay with previous turn subtracted.
- In 4 there are transverse kickers receiving their signal via fiber optic link. The signal arrives before the beam. 2/3 turn delay.
- For EIC an additional longitudinal pickup in 4 o'clock will send its signal to 12 via a microwave link, arriving before the beam. Take 1/3 turn minus 1/6 turn.



Signal Processing

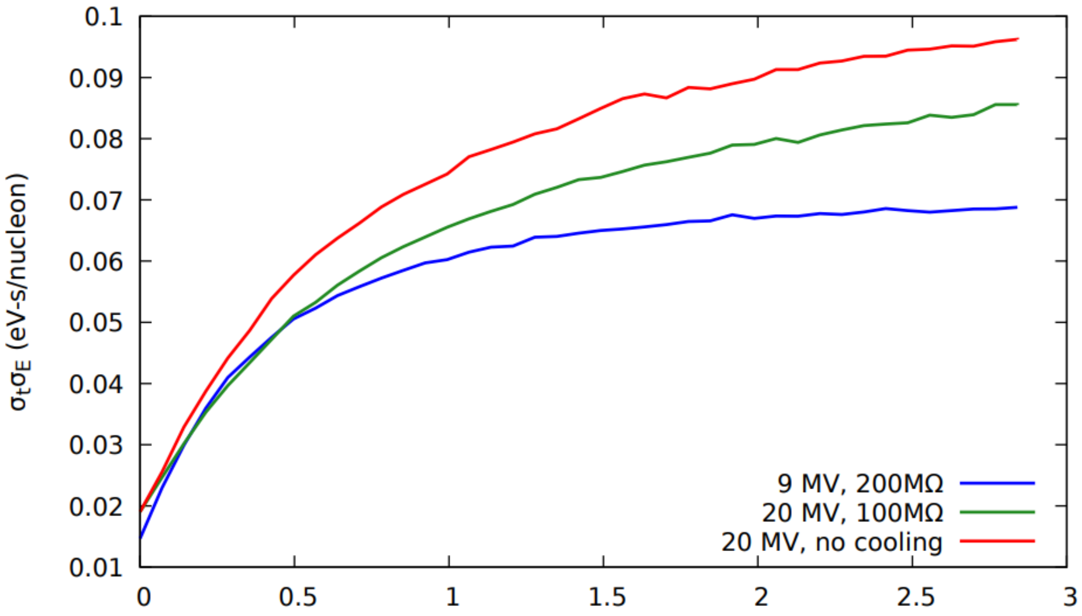
- The coherent lines at the bunching frequency must be filtered out or the system will saturate.
- Figure is 5 turns of data with 40 ns filter, blue is average, orange is standard deviation.
- For the existing longitudinal system the cooling range is in blue. Not OK for 9 GHz in EIC due to large dp/p.
- The two pickup EIC case is shown in green.
- The upper end of 9 GHz Schottky spectrum is near the max of the cooling gain.

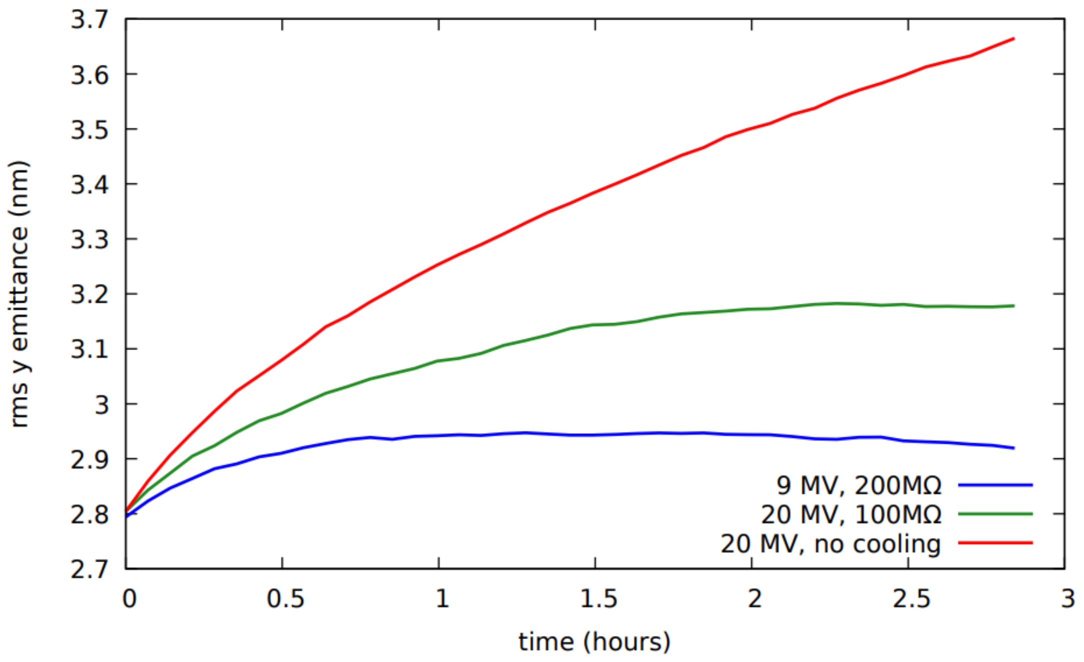


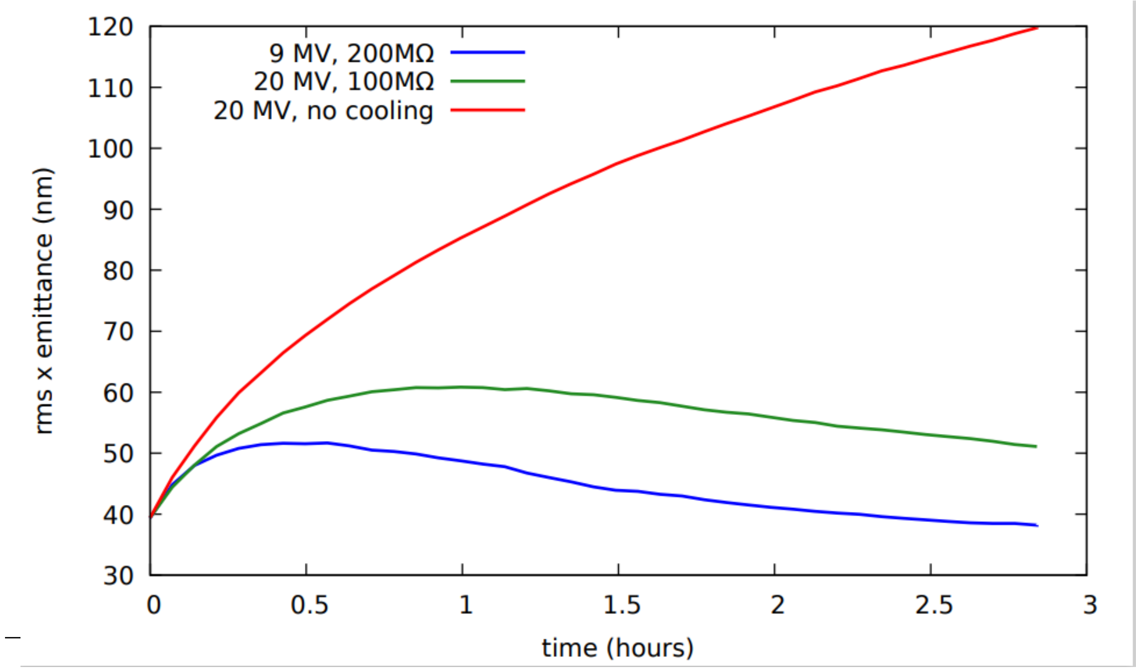


Performance for Ag

- Did some simulations using code developed for RHIC but adapted to the two pickup scheme.
- Simulation parameterized by voltage on 591 MHz system and effective impedance of longitudinal cooling.



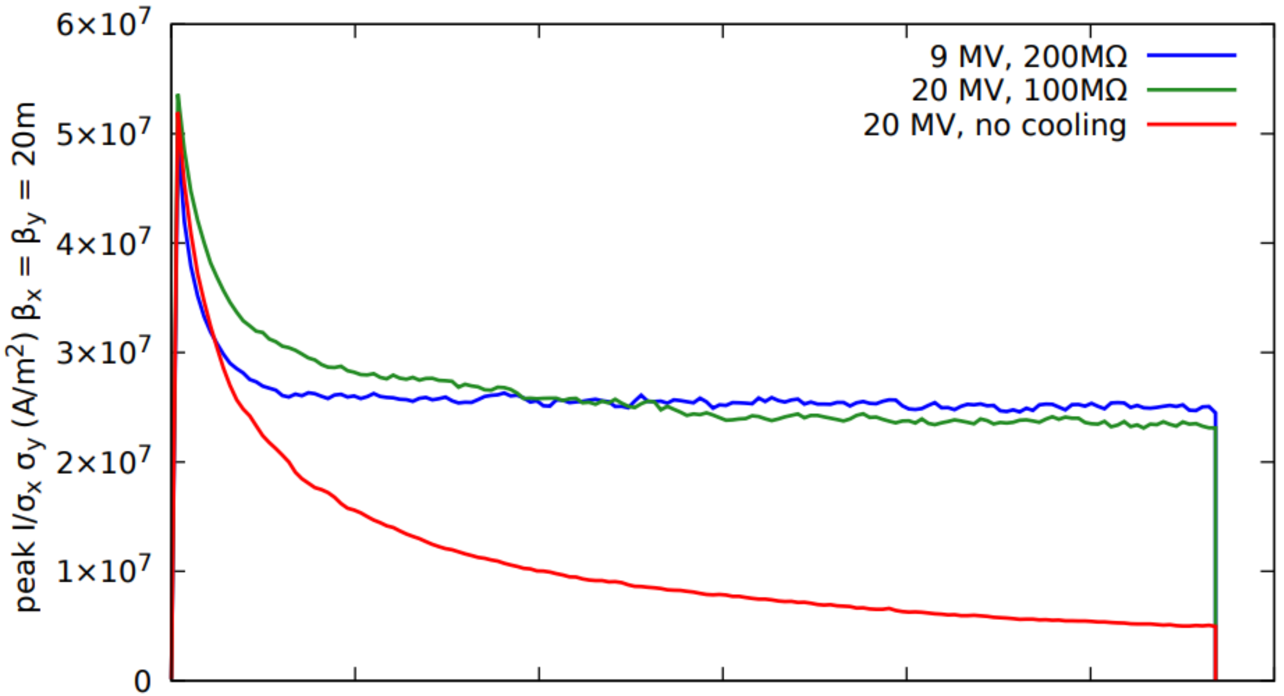




Performance for Ag

- The central density of the beam is good for both cooling scenarios.
- The improvement in luminosity is significant for these parameters.

$\gamma=127$, $\sigma_t=340\text{ps}$, $N=10^9$, $A=108$, $N=47$, $Z_x=1400\text{M}\Omega/\text{m}$, $Z_y=100\text{M}\Omega/\text{m}$



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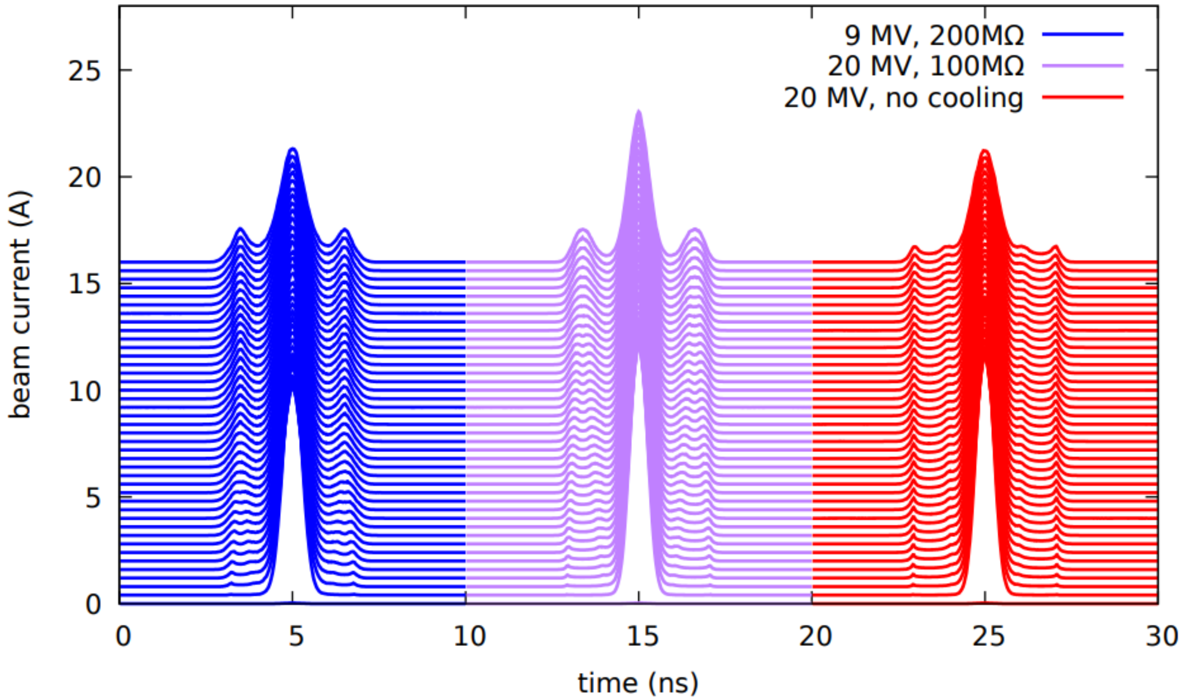

A short derivation of cooling

$$\ddot{x}_j + \Omega_j^2 x_j = -\frac{2g\Omega_0}{N}\sum_{k=1}^{N}\dot{x}_k$$

$$\Omega_j = \Omega_0 + \omega_j, \qquad |\omega_j| << \Omega_0$$

$$x_j = a_j \exp(-\lambda t - i\Omega_0 t)$$

$$(\lambda - i\omega_j)a_j = \frac{g\Omega_0}{N}\sum_{k=1}^{N} a_k$$

$$1 = \frac{g\Omega_0}{N}\sum_{k=1}^{N}\frac{1}{\lambda - i\omega_k}$$

$$\int_{-\infty}^{\omega_k} f(\omega)d\omega = \frac{k-1/2}{N}$$

$$\lambda \approx i\omega_K, \quad \Delta\omega = \frac{1}{Nf(\omega_K)}$$

$$\sum_{m=1}^{N}\frac{1}{\lambda - i\omega_m}$$

$$= \sum_{|m-K|<M}\frac{1}{\lambda - i\omega_m} + \sum_{|m-K|\geq M}\frac{1}{\lambda - i\omega_m}$$

$$\approx \sum_{|m|<M}\frac{1}{\lambda - i\omega_K - im\Delta\omega} + \sum_{|m-K|>M}\frac{i}{\omega_m - \omega_K}$$

$$\approx \sum_{k=-\infty}^{\infty}\frac{1}{\lambda - i\omega_K - ik\Delta\omega}$$

$$+ \; iN\int_{-\infty}^{\infty}\frac{\omega - \omega_K}{0^+ + (\omega - \omega_K)^2} f(\omega)d\omega. \qquad (13)$$

$$\lim_{M\to\infty}\sum_{k=-M}^{M}\frac{1}{z - ik} = \pi\frac{\exp(2\pi z)+1}{\exp(2\pi z)-1},$$

A short derivation of cooling, II

Mixing and signal shielding are fully accounted for.

$$R(\omega_K) = \pi \Omega_0 f(\omega_K) \qquad X(\omega_K) = \Omega_0 \int_{-\infty}^{\infty} \frac{\omega - \omega_K}{0^+ + (\omega - \omega_K)^2} f(\omega) d\omega$$

$$\exp[2\pi N f(\omega_K)(\lambda - i\omega_K)] = \frac{1 + gR - igX}{1 - gR - igX}$$

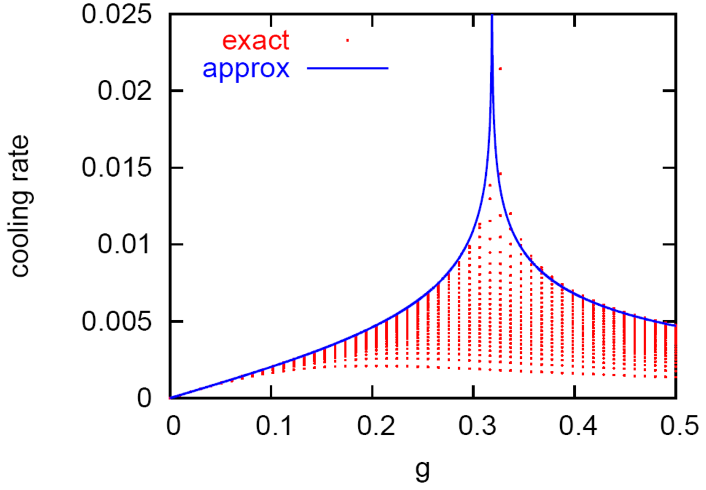

Figure 4: Comparison of actual values of $Re(\lambda)$ versus gain with those obtained from equation (14) with $X = 0$ for a rectangular frequency distribution with $N = 51$. The numerical solution had one eigenmode with a monotonically growing eigenvalue, which is not fully shown.

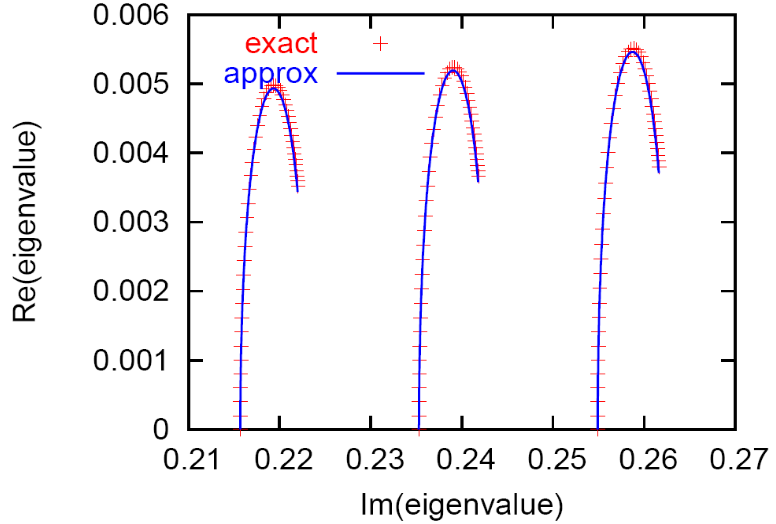

Figure 5: Evolution of λ as a function of gain for the exact, numerical solution and equation (14). The oscillator frequencies were uniformly spaced with $\omega_j = j/N$ and $N = 51$.

Wrap up

- Working on stochastic cooling was fantastic!
- Mike Brennan, Roger Lee, Kevin Mernick, Freddy Severino, other engineers and scientists, technicians, programmers, and management all worked together to make this happen.
- I thank them and the laboratory for giving me this wonderful opportunity.
- Going forward, significant luminosity gains for EIC are possible.
- During early times I think it is likely that cooling will help all ion runs.
- The system will always be useful when working with 18 GeV electrons since they always use 290 bunches.