RHIC Luminosity Increase with Bunched Beam Stochastic Cooling and Initial Estimates for LHC

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Acknowledgements

Dave McGinnis (ESS), Ralph Pasquinelli (FNAL)
Fritz Caspers, Flemming Pedersen, John Jowett, Manfred Wendt (CERN)
Wolfram Fischer, Vladimir Litvinenko, Derek Lowenstein, Thomas Roser (BNL)
Jie Wei (FRIB)
Instrumentation, Controls and RF groups at BNL

- History
- The RHIC System
- Results and Comparison with Simulations

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 (85s).

Boussard et.al. use channels for data transmission.

Signal Suppression in the Tevatron (95).

Cooling of long bunches in FNAL recycler, mixing via IBS.

Proton cooling experiment in RHIC (2006).

Operational longitudinal cooling of gold in RHIC (2007).

Transverse cooling in RHIC (2010).

Solution of cross talk problem by cavity frequency offset (2011).

Full 3-D cooling in RHIC (2012).

Voltage considerations

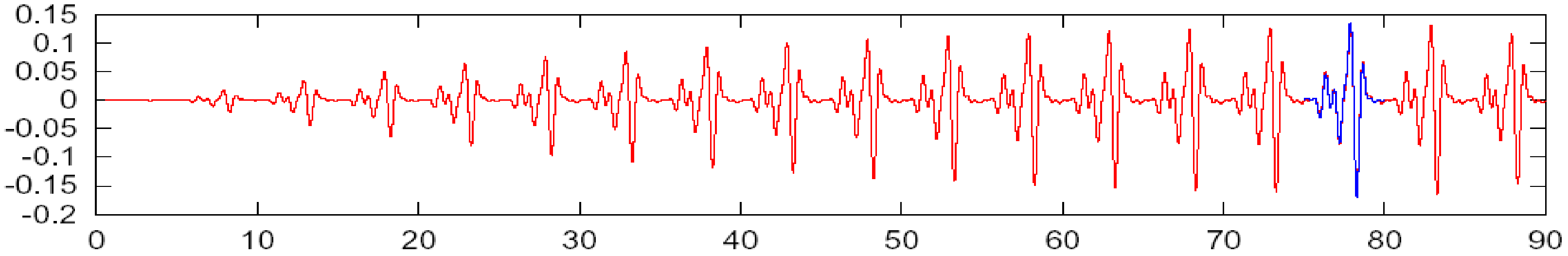
$$V(t)=\sum_n A_n(t_{slow})\sin[2\pi nt/\tau_b+\theta_n(t_{slow})]$$

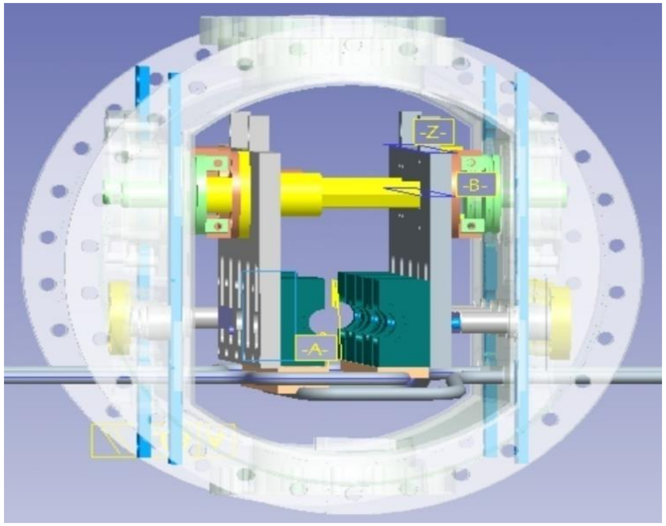
For 6-9 GHz longitudinal system we need 3 kV rms.

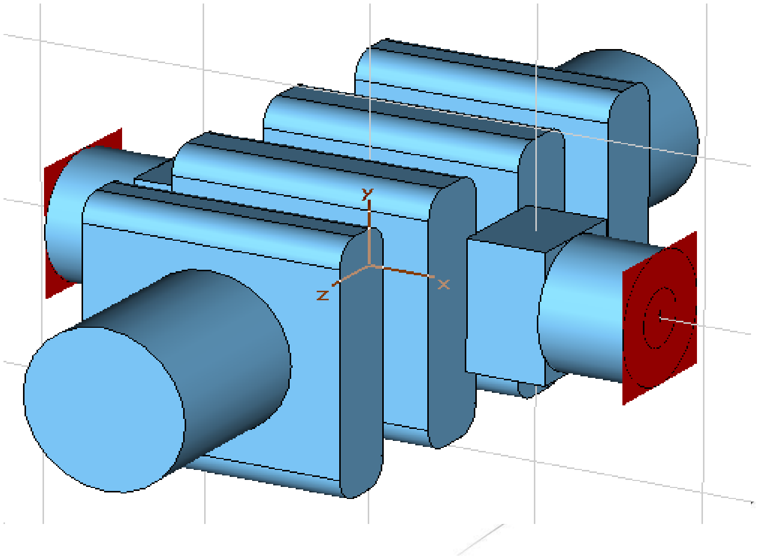
Bandwidth-Voltage product sets the cost scale.

Bunches are 5 ns long spaced by 100 ns.

The value of the kicker voltage matters only when the bunch is present.







Voltage and Power continued

Take 16 cavities, 6-9 GHz bandwidth 40 Watts/cavity

R/Q=100Ω, 10 MHz FWHP bandwidth, R ≥ 50 kilo-Ohm

gives 1 to 1.4 kV rms per cavity, or 5.6 kV total

Cavity drive signal needs to be roughly sinusoidal for R (not R/Q) to matter

Suppose $S_0(t)$ is the drive signal for a broad band kicker (like a resistor).

Periodically extend

$$S(t) = \sum_{k=0}^{N-1} S_0(t - k\tau_b)$$

This creates a signal spectrum with peaks spaced by $1/\tau_b = 200 MHz$ with width $1/N\tau_b = 10 MHz$

Split and pass through 100 MHz filters, centered on cavity resonance, before power amps. In this way each amplifier sees a piecewise sinusoidal input.

Combination of transmission lines and fiber optic technology for the delay line (traversal) filter.

Transverse Cooling system

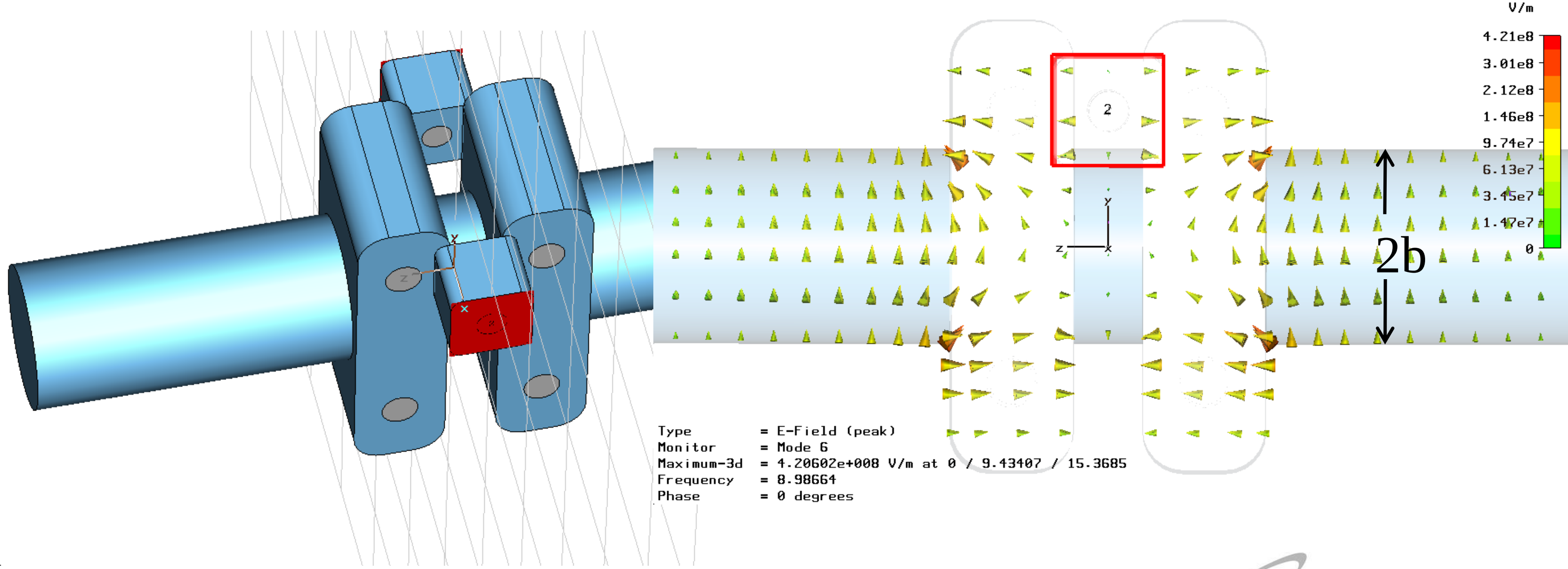
Similar cavities.

40 Watt amplifiers are sufficient.

4.8-7.8 GHz keeps aperture reasonable.

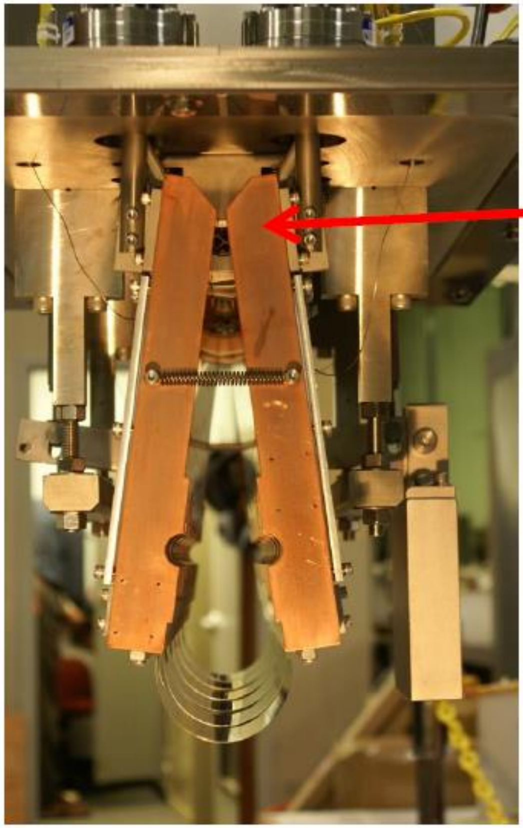
Panofsky-Wenzel theorem relates transverse kick to standard voltage

$$V_\perp = \frac{c}{\omega b} V_{z,wall}$$



```
Type          = E-Field (peak)
Monitor       = Mode 6
Maximum-3d    = 4.20602e+008 V/m at 0 / 9.43407 / 15.3685
Frequency     = 8.98664
Phase         = 0 degrees
```

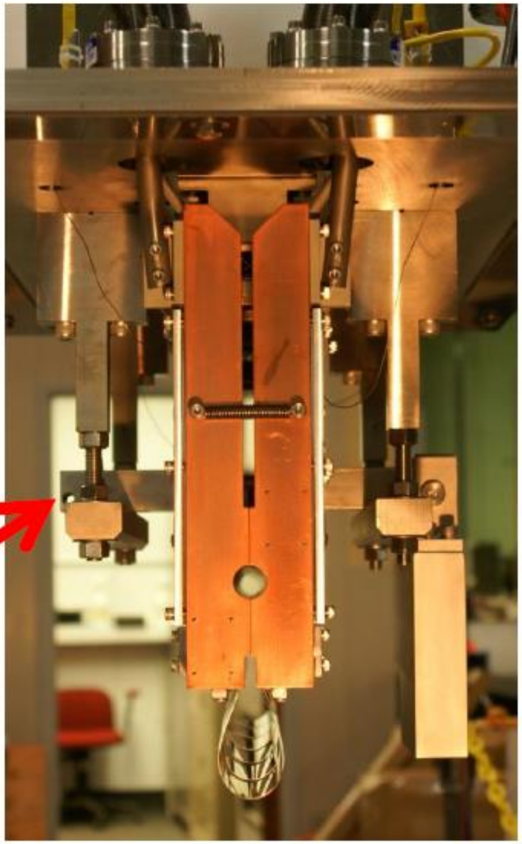
Transverse kickers



Structures open and close using a device called a “Flexi-hinge”. It has no sliding parts, is bakeable for high vacuum, and operates for many 10e5 cycles.

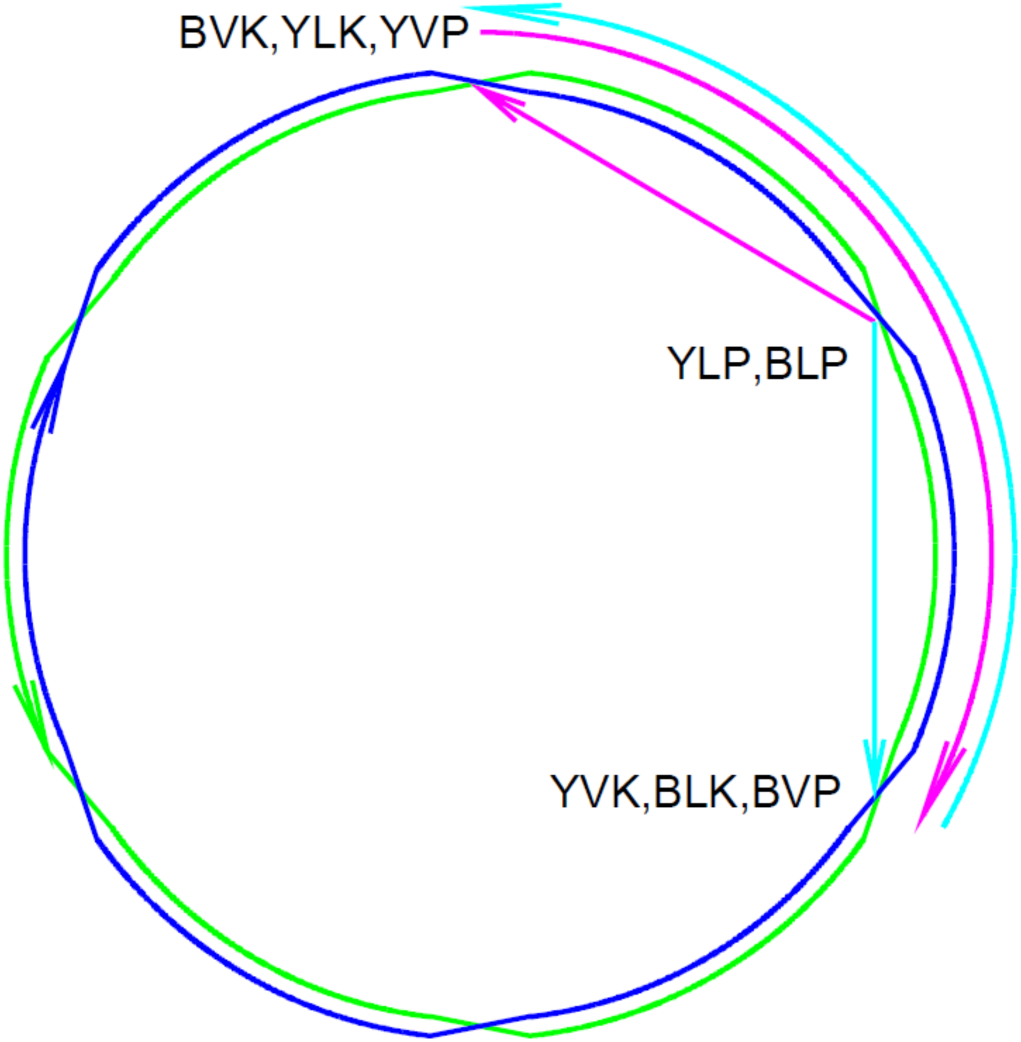
The actuating motors do not determine the size or location of the beam aperture, “positive stop”

Survey fiducials on the top plate, outside the vacuum reference the beam axis



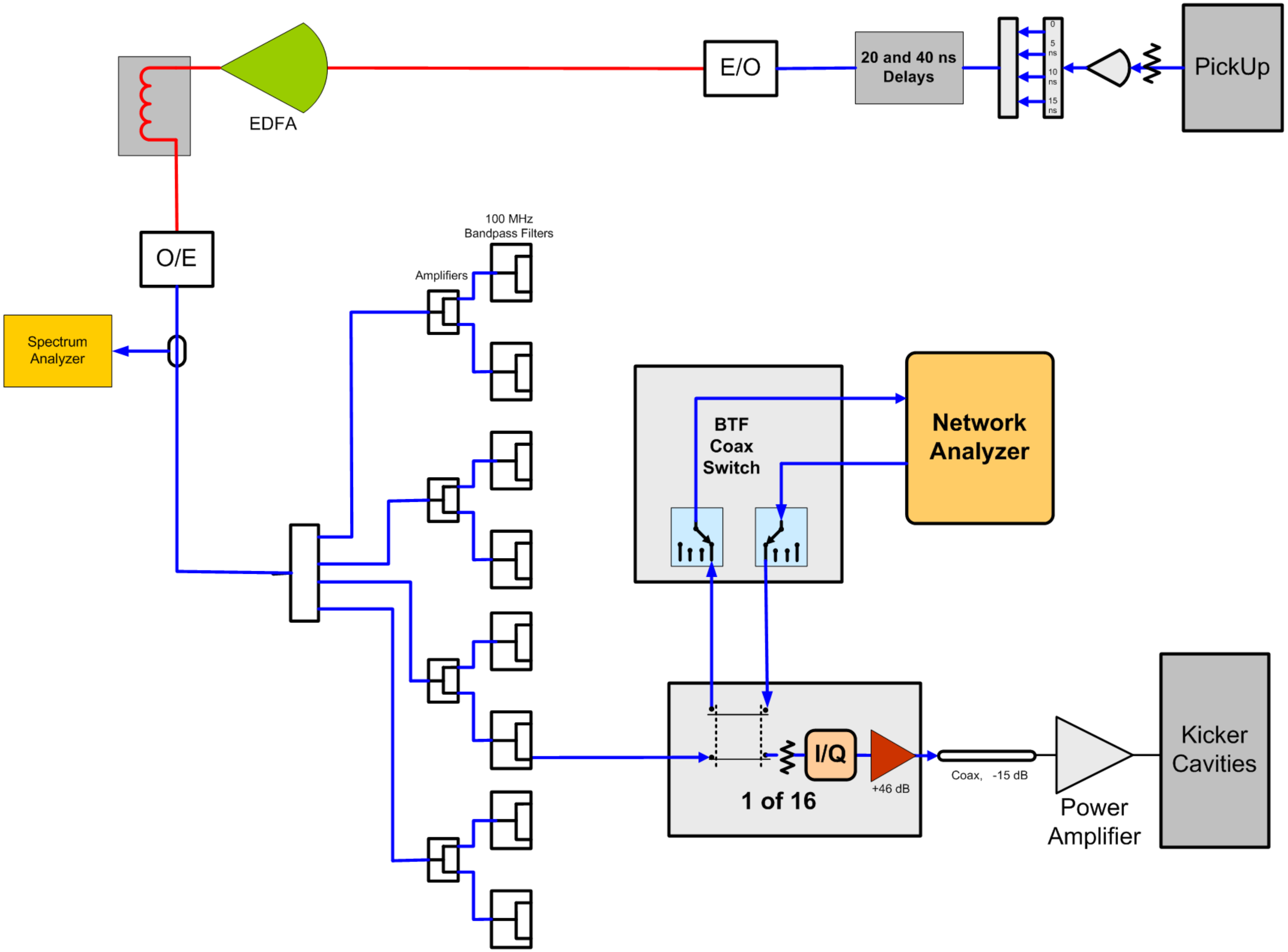
The RHIC system layout

Longitudinal cooling uses 70 GHz microwave links. Transverse cooling uses fiber optics. Yellow transverse 4.8,5.0,..7.8 Blue transverse 4.7,4.9,..7.7 to avoid cross-talk through IRs

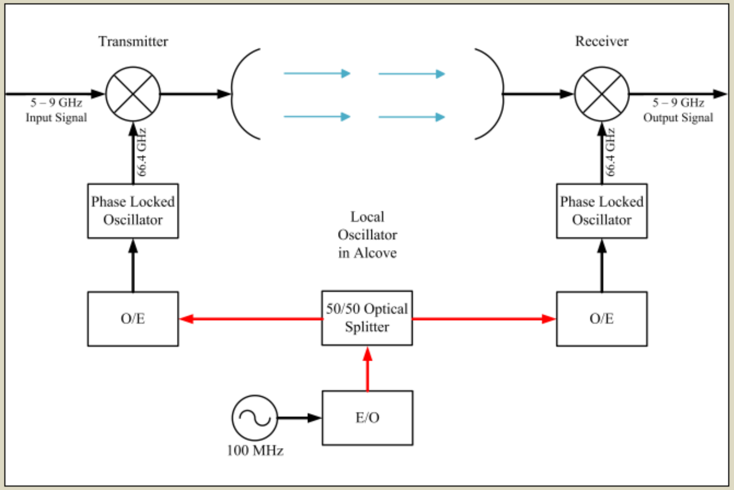


Stochastic Cooling Low Level Block Diagram

blue vertical

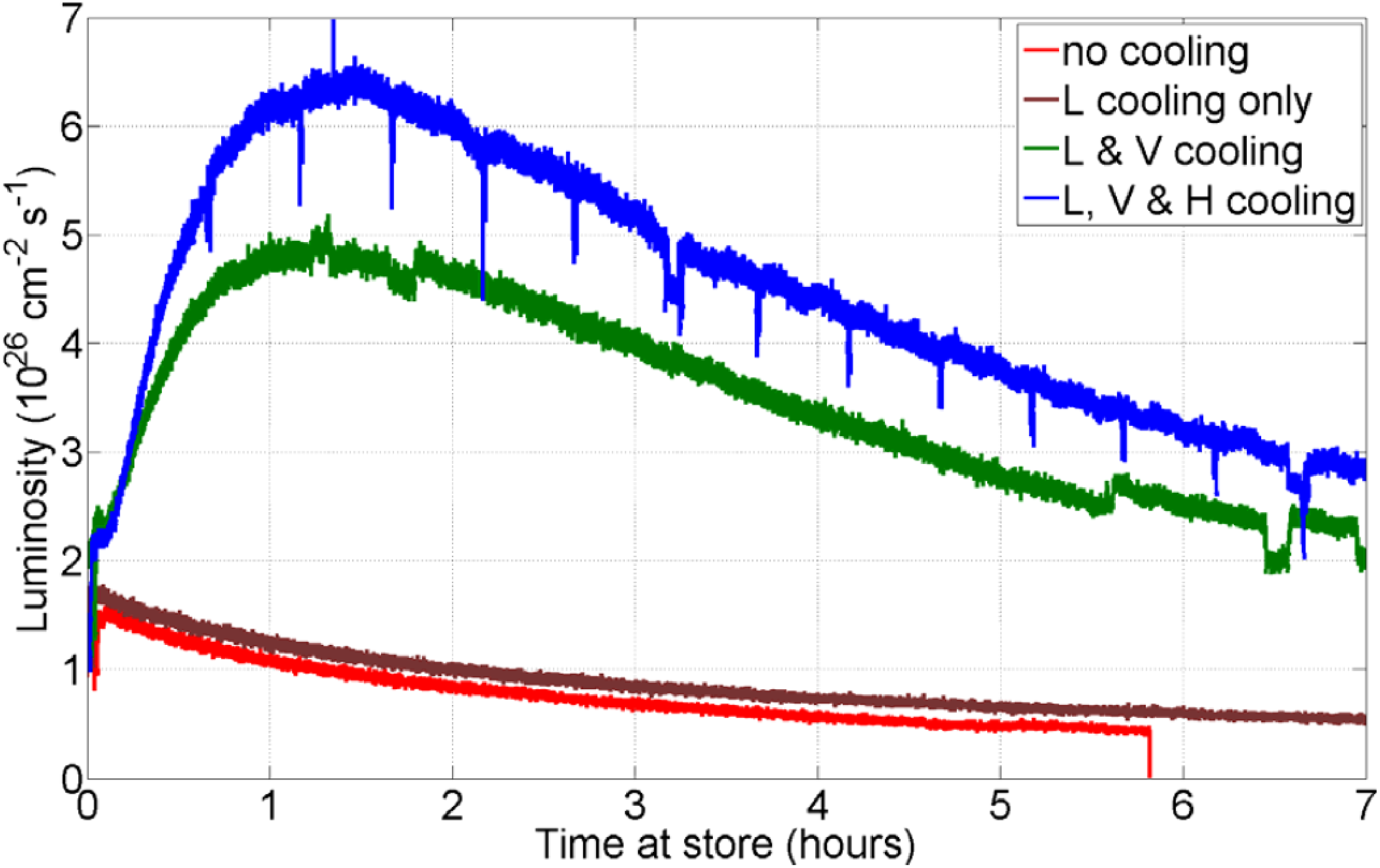


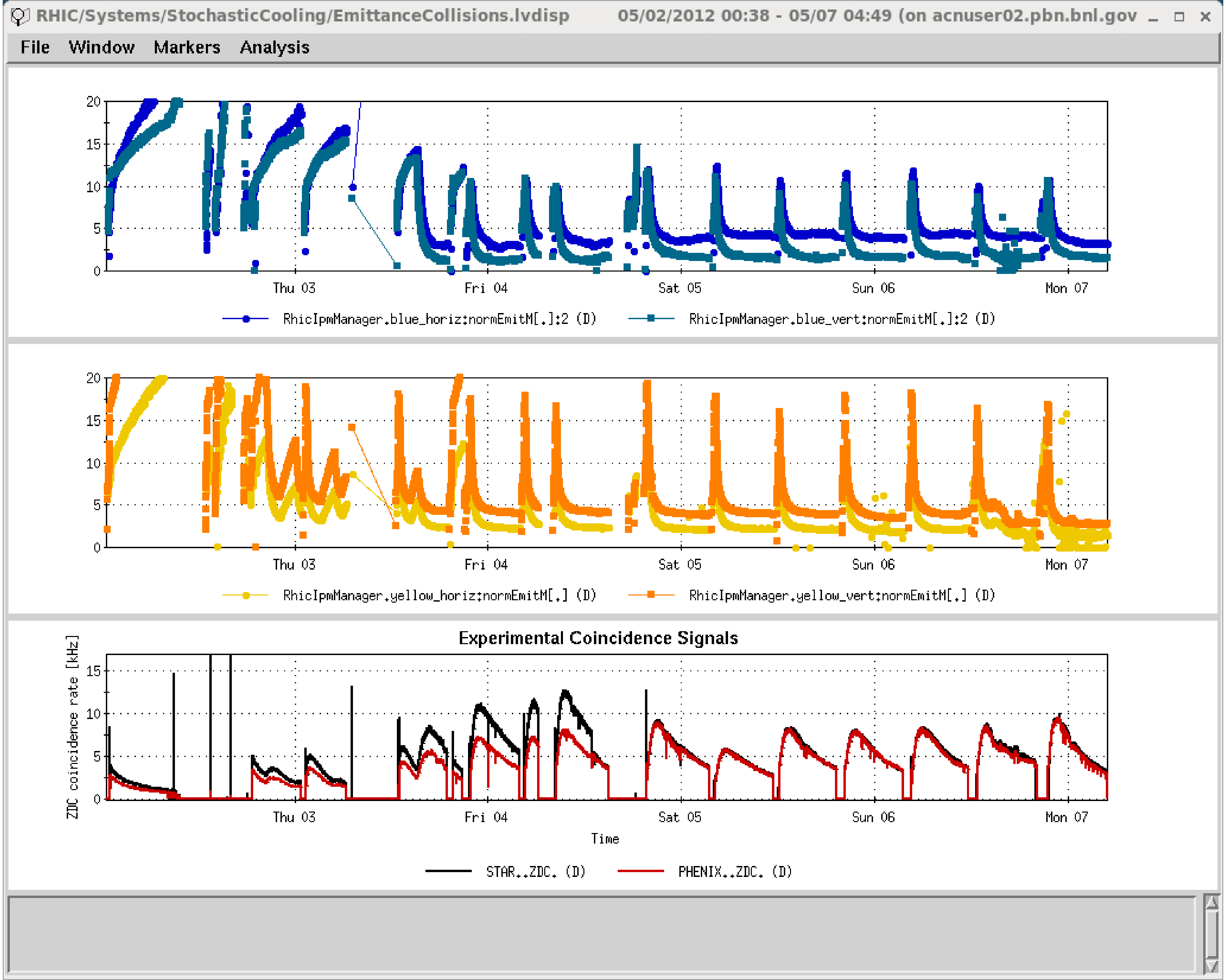
Longitudinal signals sent via 70 GHz microwave link.



The microwave link introduces phase modulation in the received signal due to variations in the time of flight and differences in the phase of the local oscillator at the transmitter and receiver. We found that the local oscillator was the dominant source of phase shifts.

Integrated uranium luminosity improved 5 fold with cooling. Is it what we deserve?




RHIC/Systems/StochasticCooling/EmittanceCollisions.lvdisp
05/02/2012 00:38 - 05/07 04:49 (on acnuser02.pbn.bnl.gov
File
Window
Markers
Analysis
20
15
10
5
0
Thu 03
Fri 04
Sat 05
Sun 06
Mon 07
RhicIpmManager.blue_horiz:normEmitM[.]:2 (D)
RhicIpmManager.blue_vert:normEmitM[.]:2 (D)
20
15
10
5
0
Thu 03
Fri 04
Sat 05
Sun 06
Mon 07
RhicIpmManager.yellow_horiz:normEmitM[.] (D)
RhicIpmManager.yellow_vert:normEmitM[.] (D)
Experimental Coincidence Signals
ZDC coincidence rate [kHz]
15
10
5
0
Thu 03
Fri 04
Sat 05
Sun 06
Mon 07
Time
STAR..ZDC. (D)
PHENIX..ZDC. (D)

- Quick reminder of how stochastic cooling works

$$\bar{\varepsilon}_n = \varepsilon_n - \frac{g}{N}\sum_{k=1}^{N}\varepsilon_k$$

$$<\bar{\varepsilon}_n^2> = <\varepsilon_n^2 - 2\frac{g}{N}\sum_{k=1}^{N}\varepsilon_n\varepsilon_k + \frac{g^2}{N^2}\sum_{k,m}\varepsilon_m\varepsilon_k>$$

$$<\varepsilon_m\varepsilon_k> = \sigma^2\delta_{m,k}$$ perfect mixing

$$\frac{\bar{\sigma}^2 - \sigma^2}{\sigma^2} = \frac{g^2 - 2g}{N} \rightarrow -\frac{1}{N}$$

- So, reducing N increases cooling rate.
- A simulation with M<N macro-particles reaches the same macroscopic parameters in M/N the updates. $M < 10^{-3} N$

Stochastic cooling theory II

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

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

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

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

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

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

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

$$\begin{aligned}
&\sum_{m=1}^{N}\frac{1}{\lambda - i\omega_m} \\
= \;& \sum_{|m-K|<M}\frac{1}{\lambda - i\omega_m} + \sum_{|m-K|\geq M}\frac{1}{\lambda - i\omega_m} \\
\approx \;& \sum_{|m|<M}\frac{1}{\lambda - i\omega_K - im\Delta\omega_K} + \sum_{|m-K|>M}\frac{i}{\omega_m - \omega_K} \\
\approx \;& \sum_{k=-\infty}^{\infty}\frac{1}{\lambda - i\omega_K - ik\Delta\omega_K} \\
+ \;& iN\int_{-\infty}^{\infty}\frac{\omega - \omega_K}{0^+ + (\omega - \omega_K)^2} f(\omega)d\omega. \qquad (5)
\end{aligned}$$

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

Mixing and signal shielding are fully accounted for.
Fokker-Planck approach is several pages.

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

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

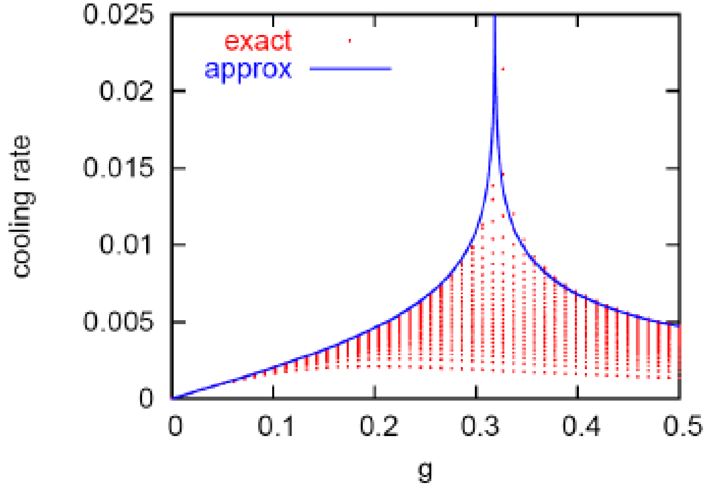


Figure 4: Comparison of actual values of $Re(\lambda)$ versus gain with those obtained from equation (14) with $X = 0$ for a rectangular frequency distribution with $N = 51$. The numerical solution had one eigenmode with a monotonically growing eigenvalue, which is not fully shown.

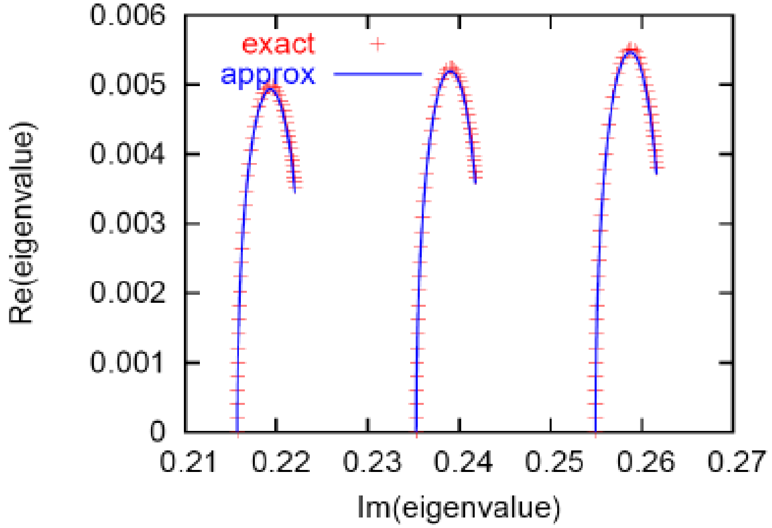
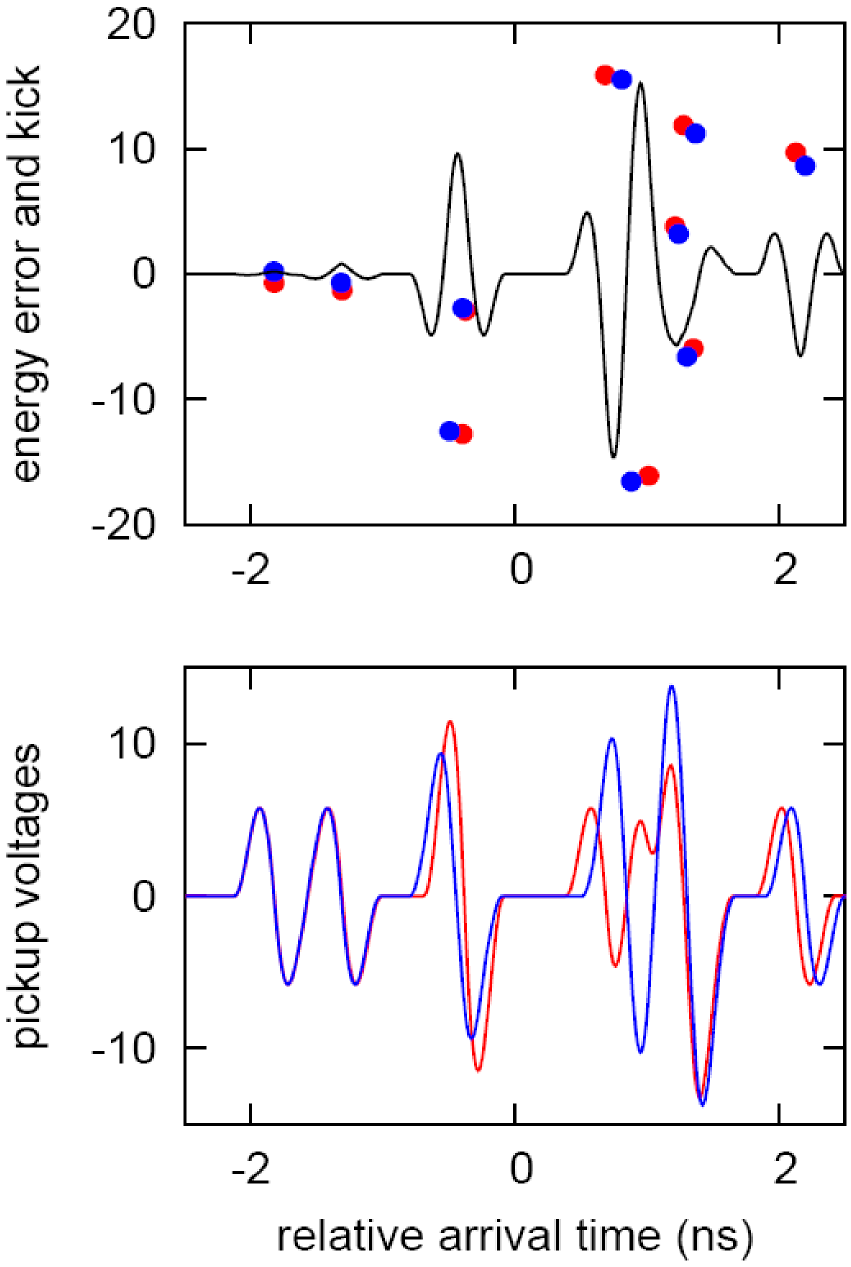


Figure 5: Evolution of λ as a function of gain for the exact, numerical solution and equation (14). The oscillator frequencies were uniformly spaced with $\omega_j = j/N$ and $N = 51$.

Bunched Beam Simulations

- Time domain model of filter cooling.
- Very similar to coherent stability problem.
- Need to have pickups and kickers in different locations to correctly account for phase slip and betatron phase advance.
- Signal to noise addressed by adding noise in the pickup.
- 200 MHz cavity spacing addressed by folding all data into 5 ns interval before FFT and convolution.
- Need to add IBS, which is done as random kicks modulated by line density.



Transverse Cooling Simulations

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

Check of scaling, single harmonic rf, no IBS or longitudinal cooling

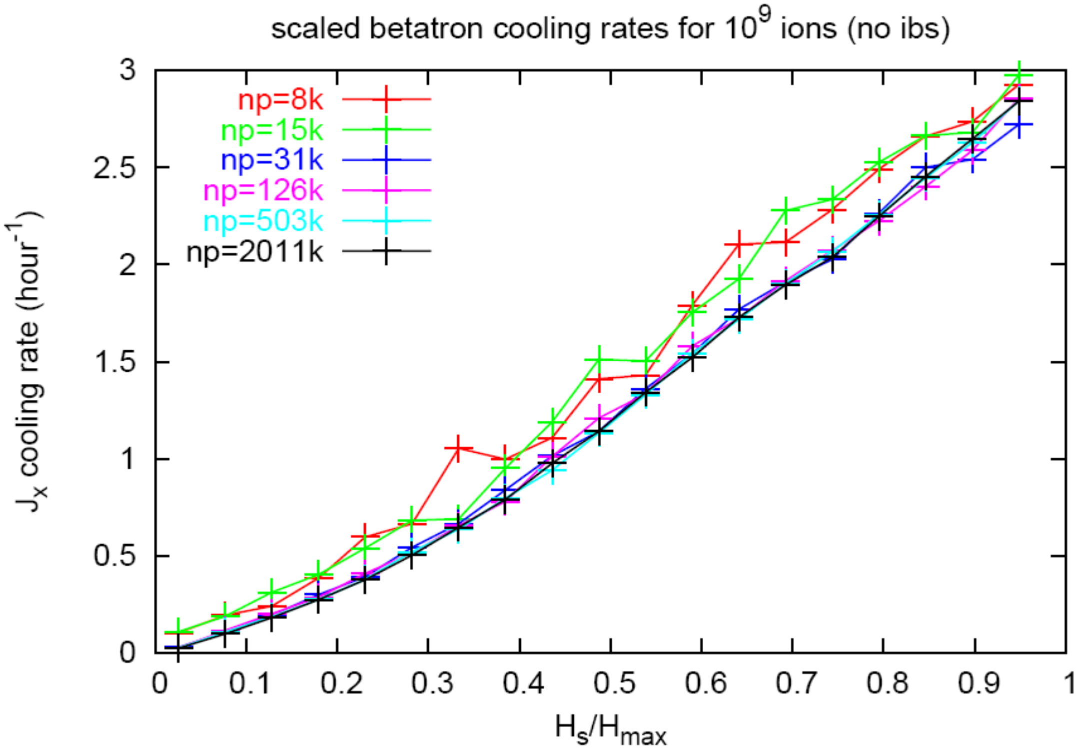


Figure 5: Transverse cooling rate versus the value of the longitudinal hamiltonian. Similar results are shown in [6, 7]

Intra-beam scattering helps transverse cooling

IBS causes diffusion in longitudinal action. Physically important for FNAL Recycler, it’s a major source of mixing.

For RHIC, longitudinal cooling keeps the distribution in the bucket, but a given particle will wander in synchrotron amplitude.

The net effect is that all particles have good transverse cooling.

This gives a new simulation time scale to worry about.

One must make sure that the fast mixing from IBS is small compared to the fast mixing from synchrotron motion.

Inclusion of burn-off (luminosity losses)

Spatial density for gaussian beam traveling to left

$$n(x_\perp, z, t) = \frac{\lambda(t + z/c)\exp[-x_\perp^2/2\varepsilon\beta(z)]}{2\pi\varepsilon\beta(z)}$$

Particle traveling to right $x(z) = x_0 + \theta_x z, \quad z = c(t - t_0)$

Probability particle interacts $P = 2\sigma \int n(x_\perp(z), z, t_0 + z/c)dz$

Average over betatron phase

$$P = \sigma F(\alpha_x)F(\alpha_y)\int dz\,\frac{\lambda(2z + ct_0)}{\pi\varepsilon\beta(z)}$$

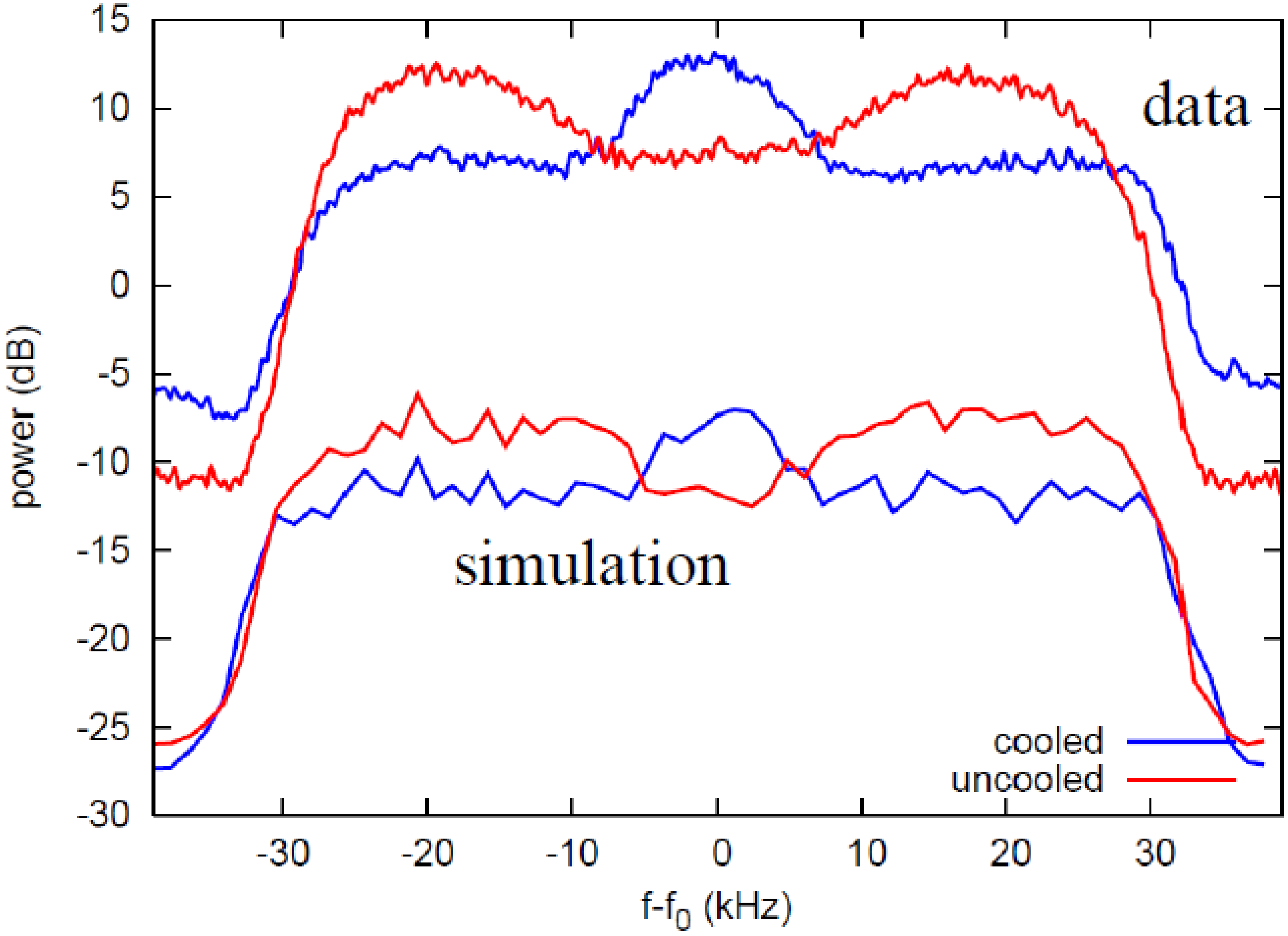
$$F(\alpha) = e^{-\alpha}I_0(\alpha), \quad \alpha_x = \frac{x_0^2 + \beta_*^2\theta_x^2}{4\beta_*\varepsilon}$$

Gain adjustment in simulations

5.7 GHz

center

frequency

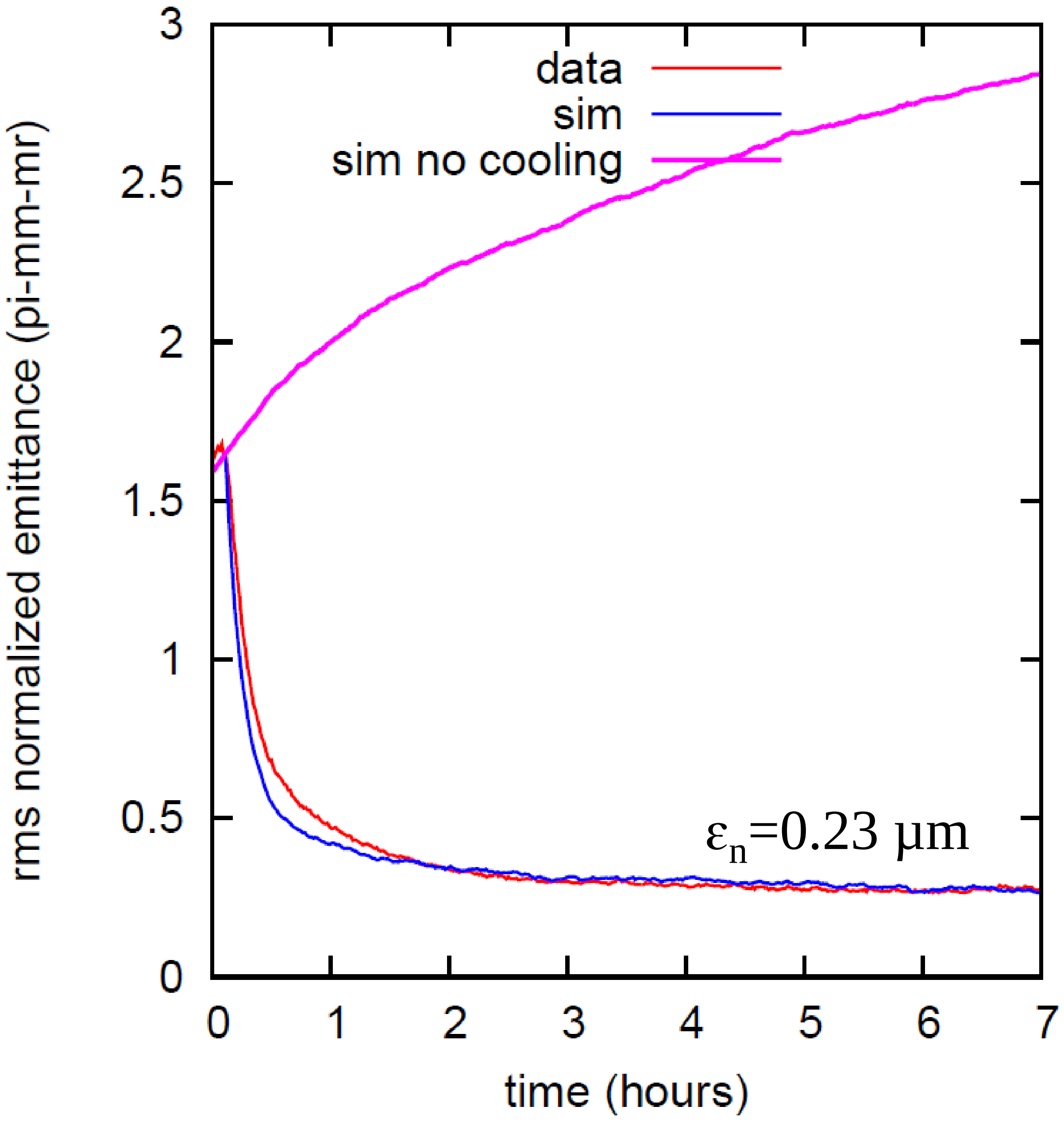


$$z_n = \sum_{k=1}^{N_p} x_k(n) e^{i\omega_c \tau_k(n)}$$

$$S(\omega) = \left\langle \left| \sum_{n=1}^{N_{spec}} z_n e^{i(\omega-\omega_c)nT_{rev}} \right|^2 \right\rangle$$

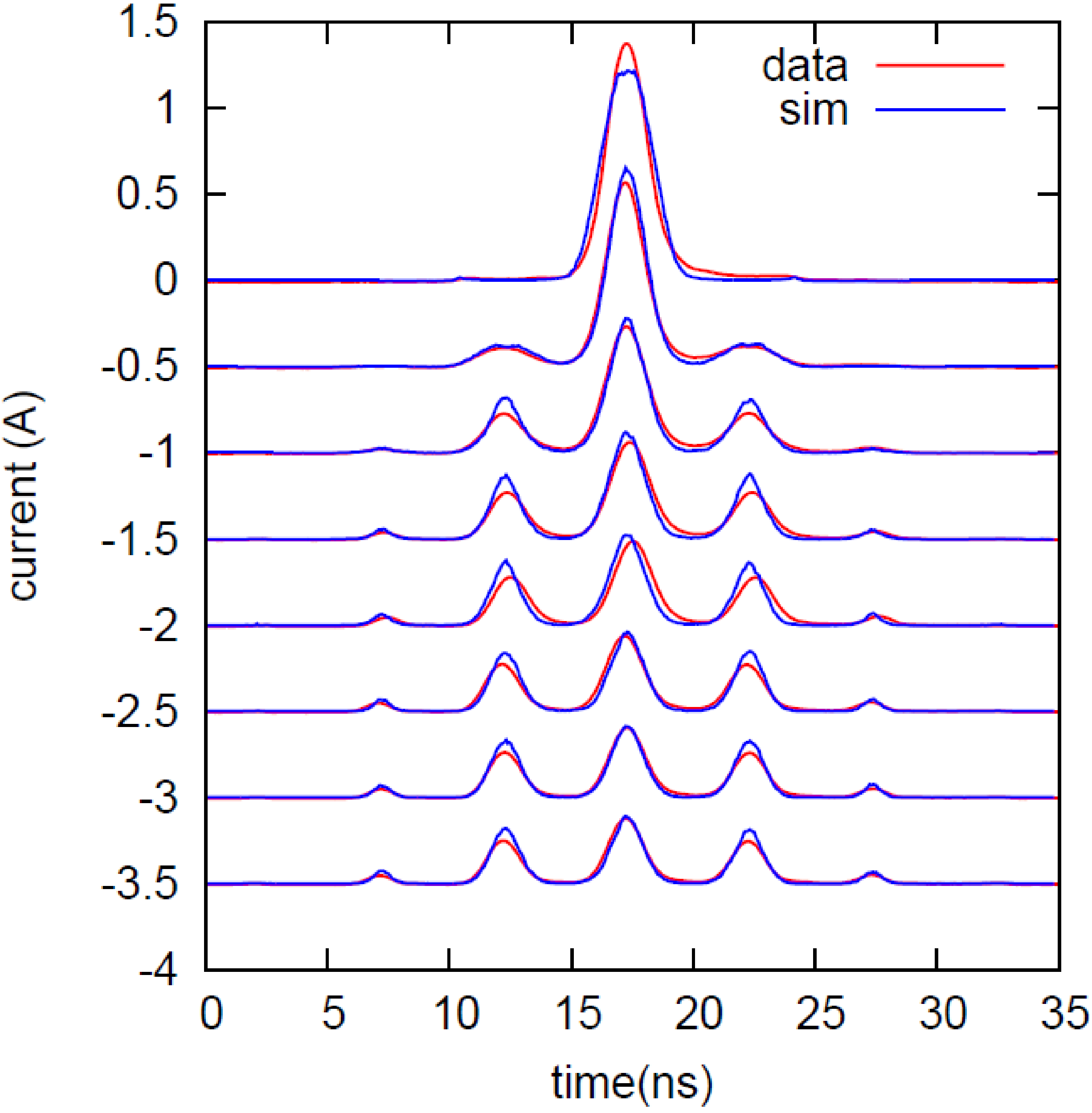
- Uranium beam size reduced

2.2×10^8 U ions

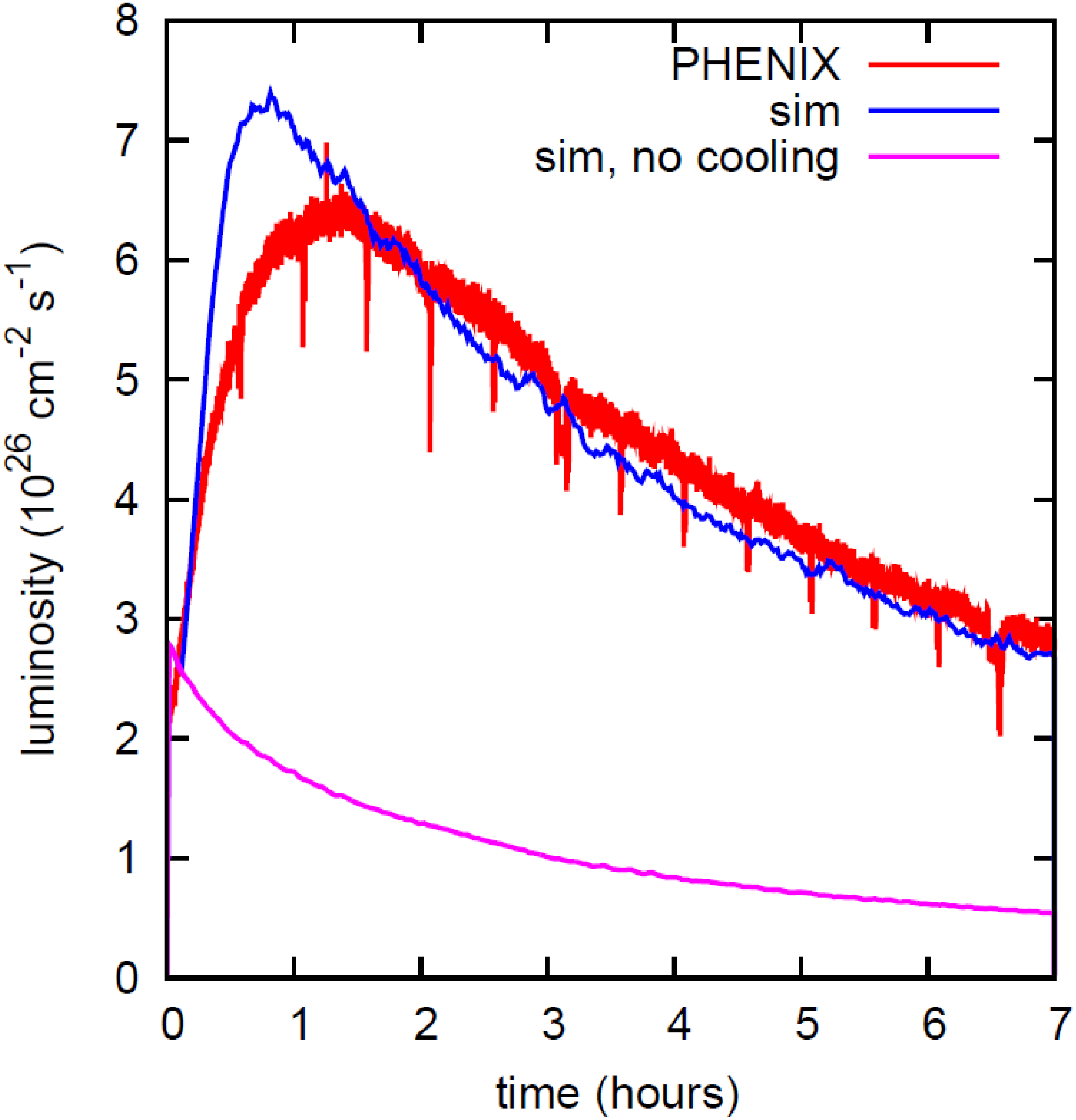


- Longitudinal evolution for uranium
- Dual harmonic RF

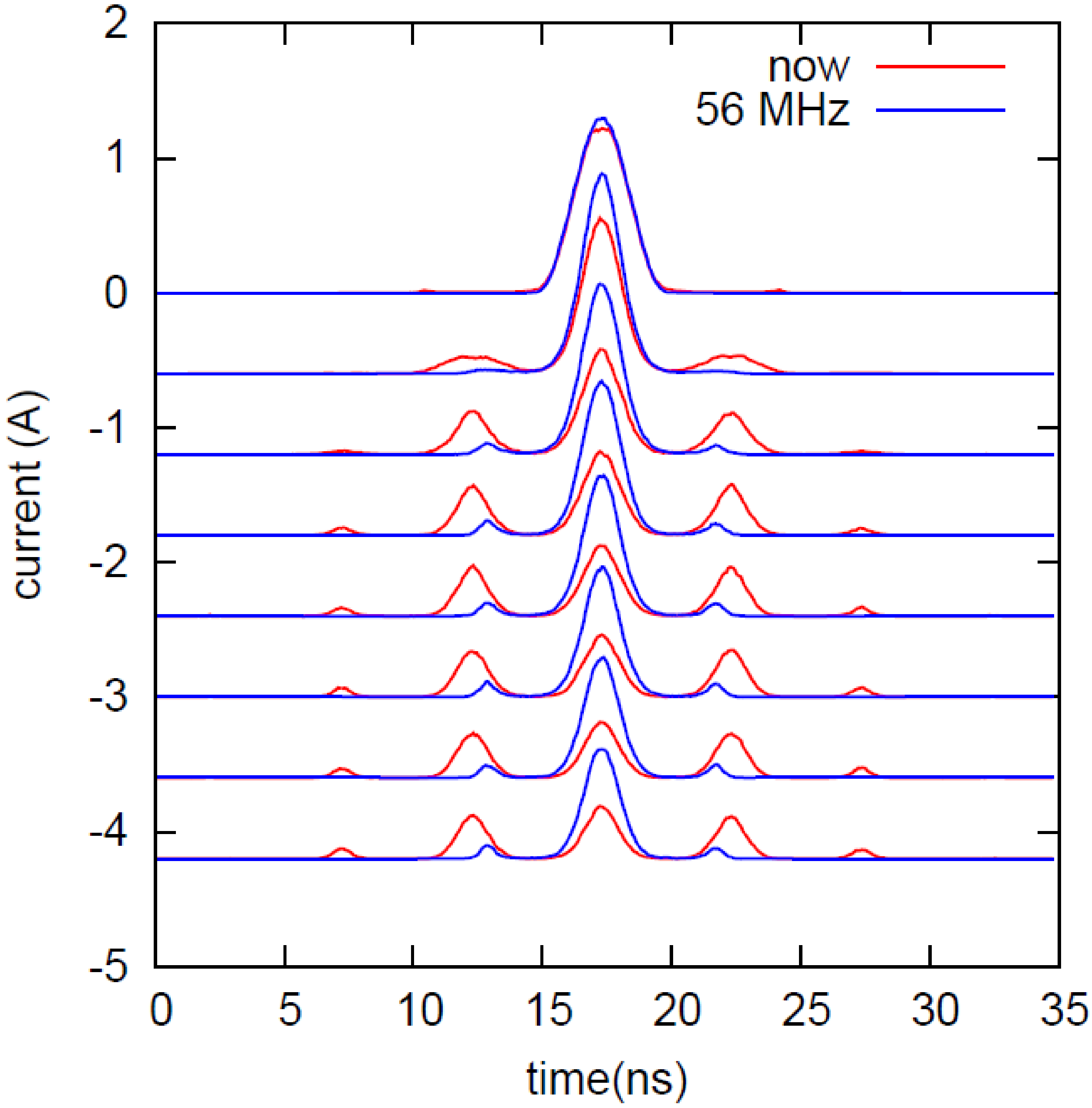
Profiles each hour



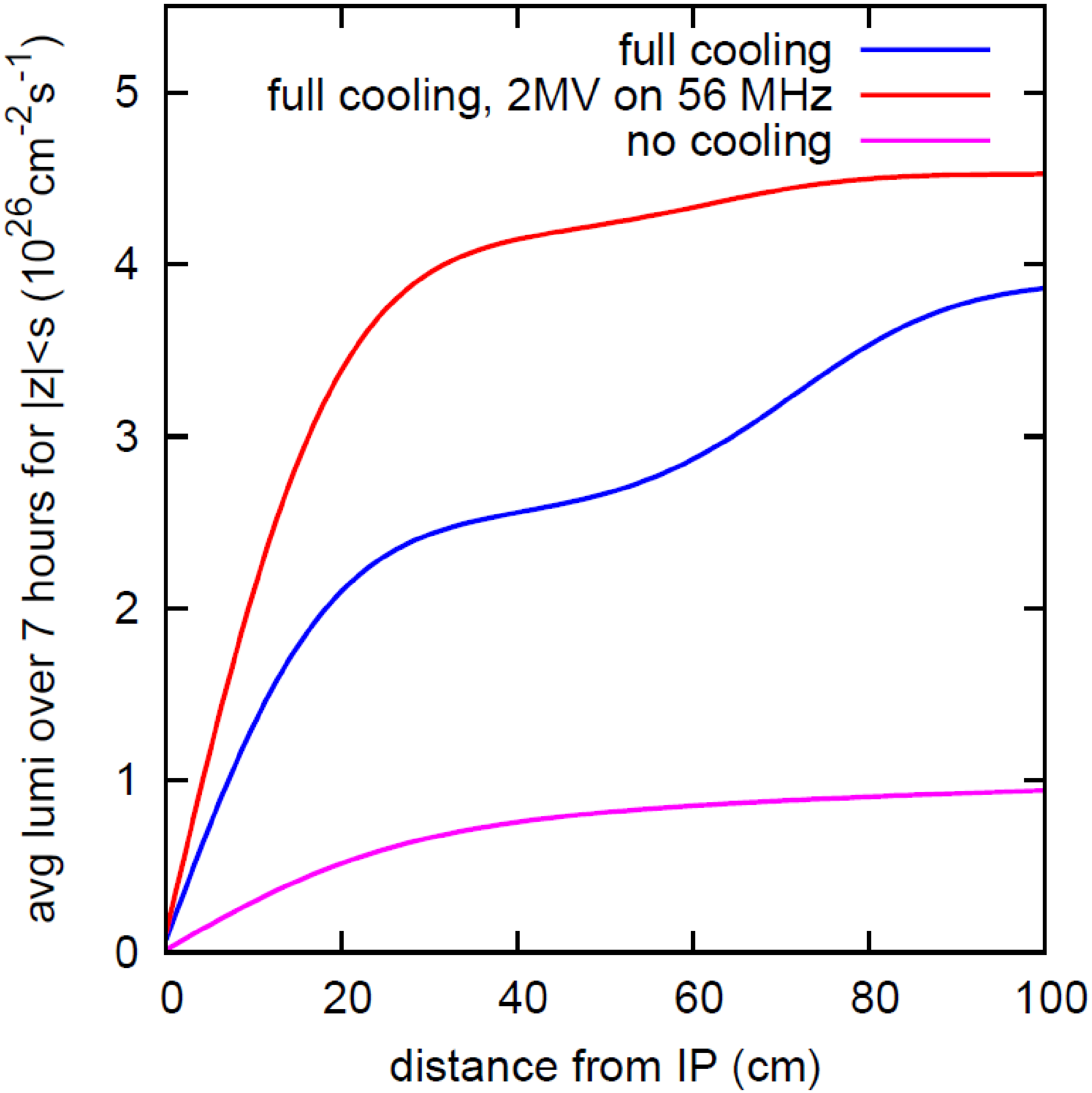
- Luminosity evolution with constant gain
- Integrals agree within 1%



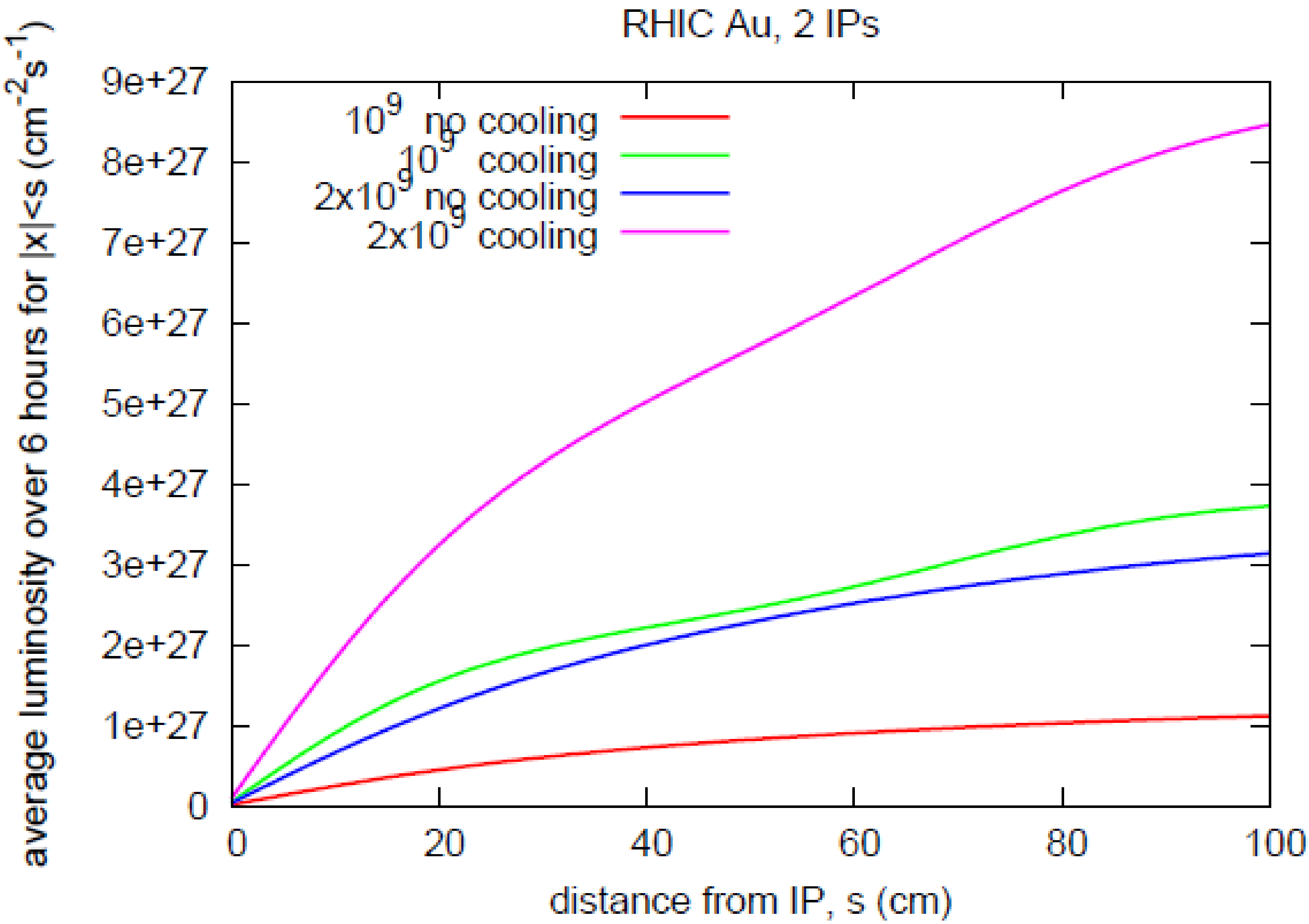
- 56 MHz reduces debunching



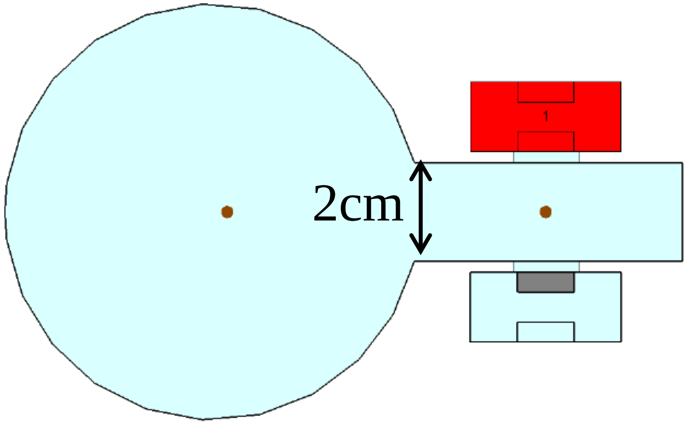
- 56 MHz cavity improves performance near IP

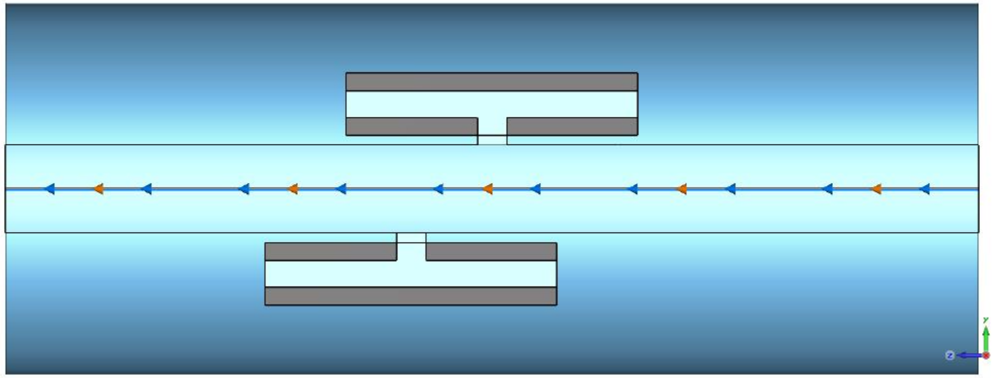


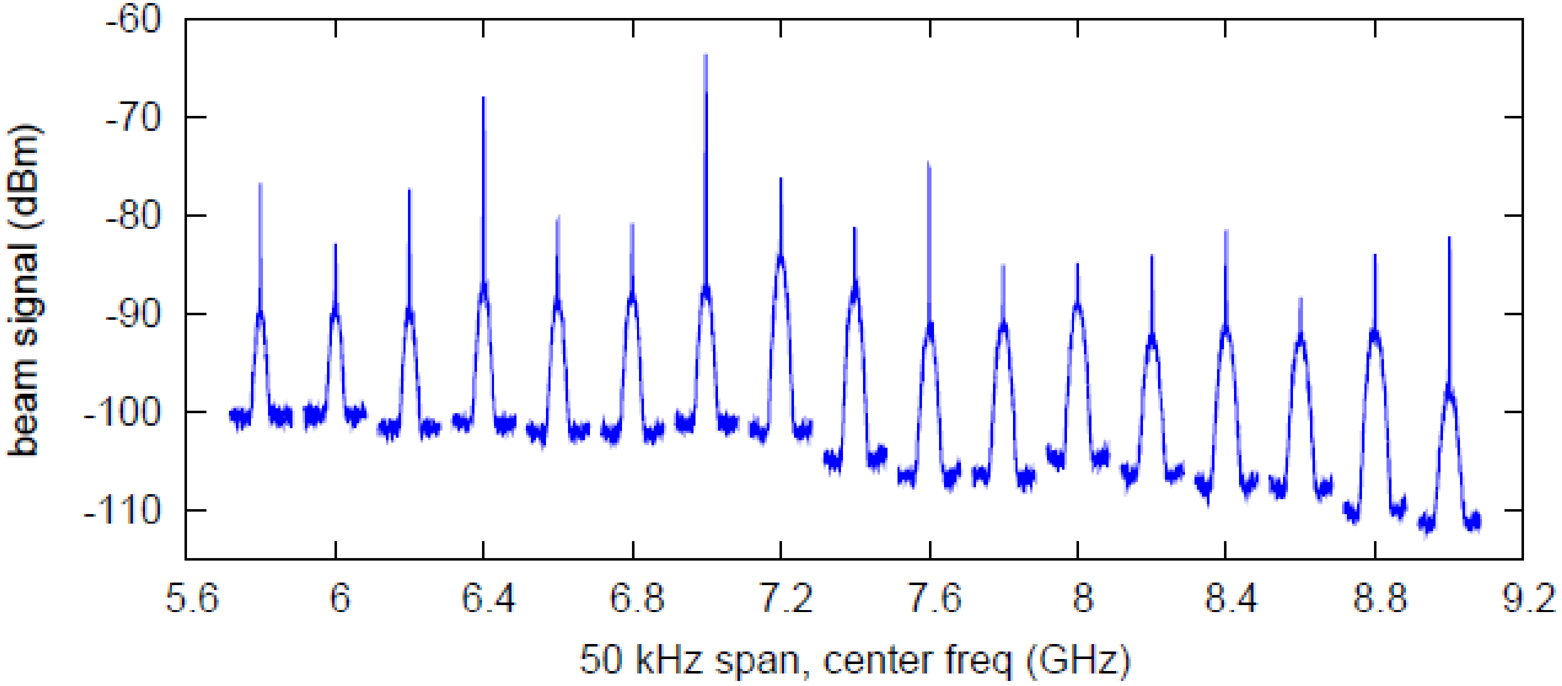
Full cooling more than doubles integrated luminosity for typical gold intensities.



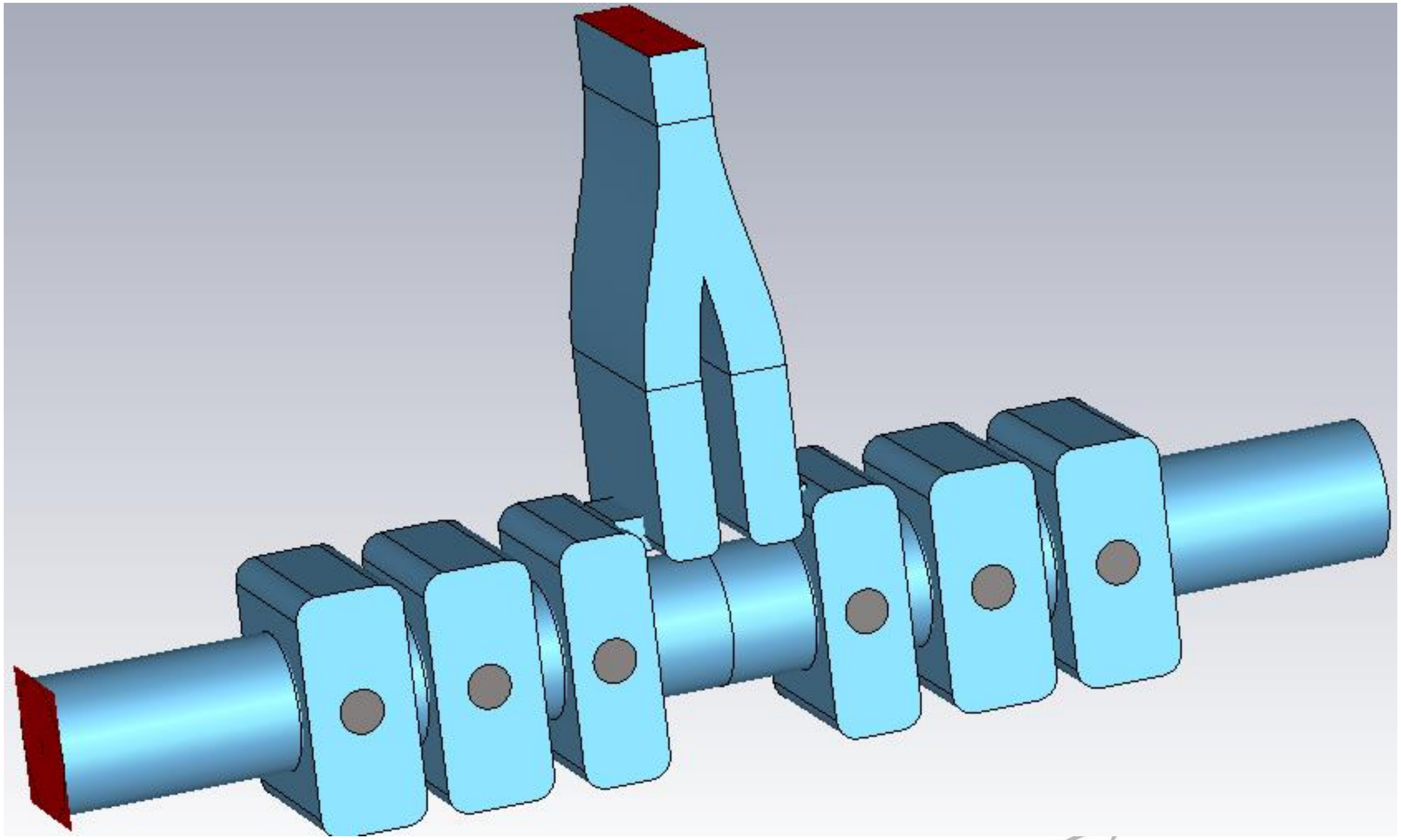
New keyhole longitudinal pickup





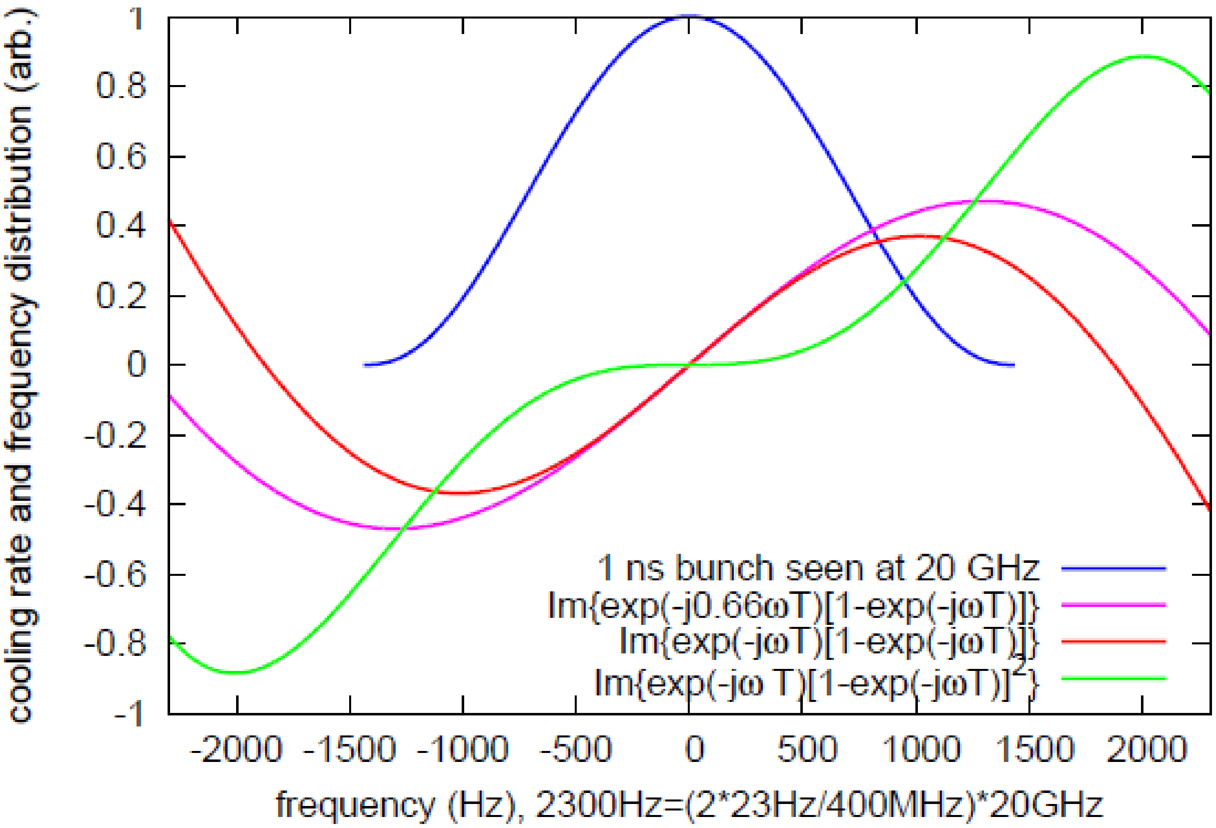


Updating longitudinal kickers to scissor design.
2x3 Cell longitudinal kickers increase voltage.
Waveguide coupler eliminates coaxial cables.
Work very well.

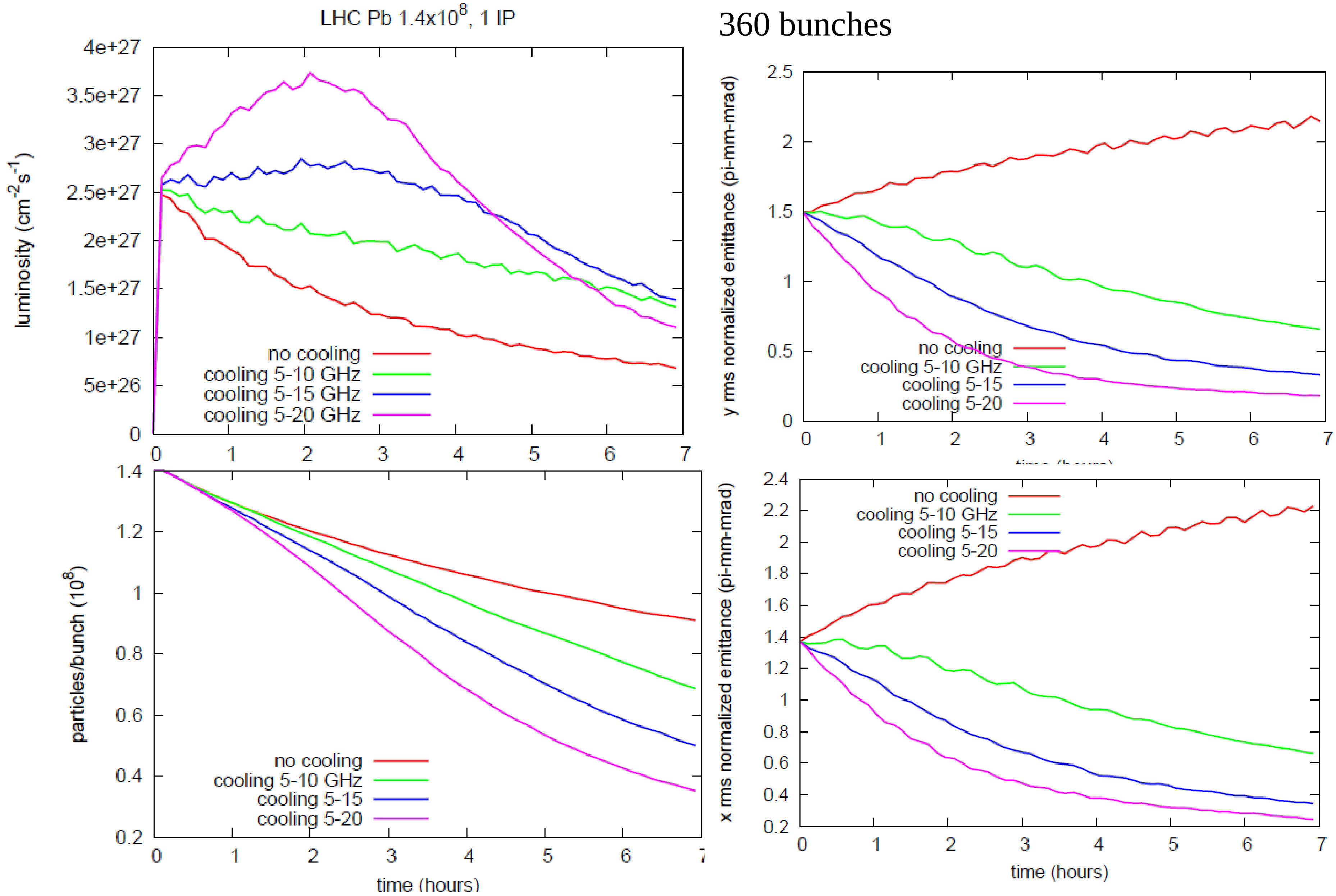


Considerations for LHC

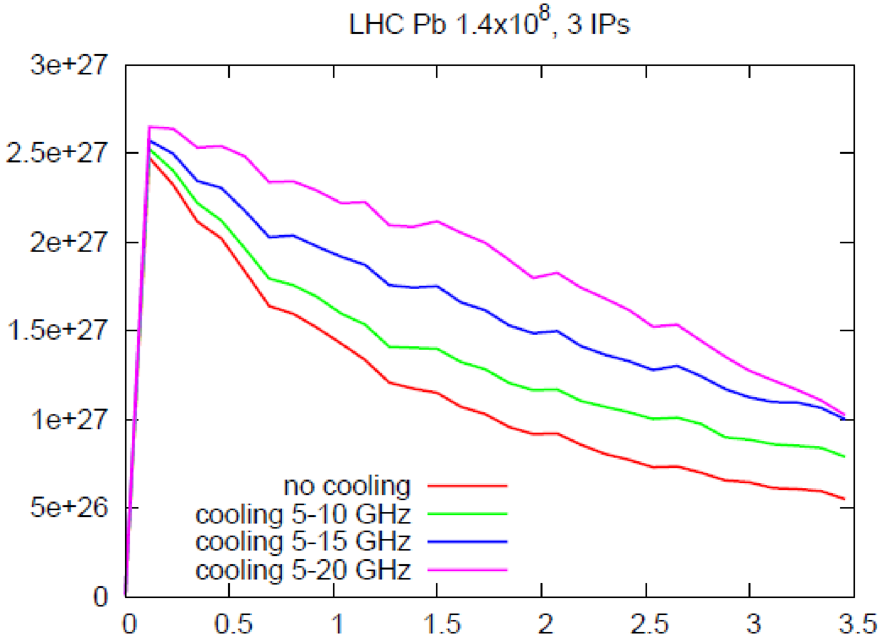
Took 2/3 turn delay and single one turn delay filter.

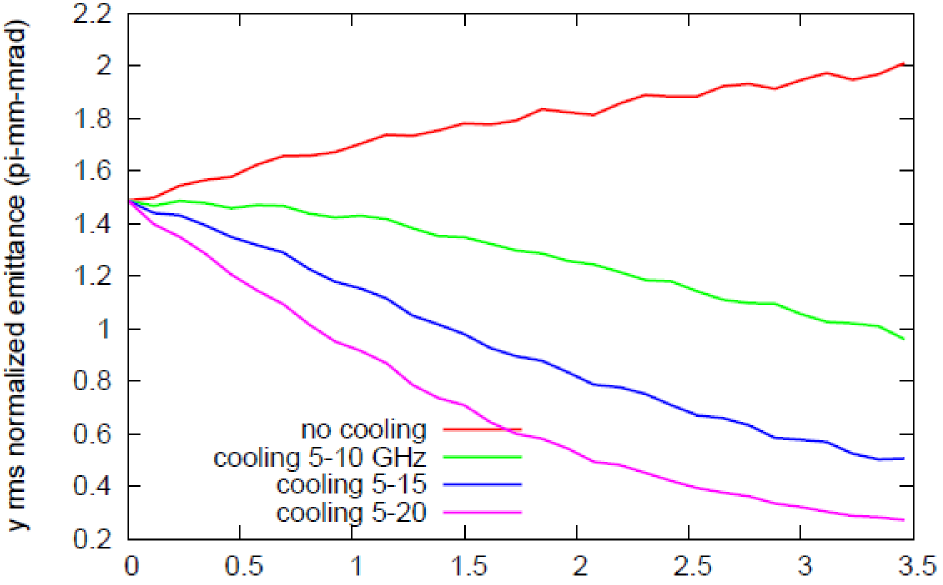


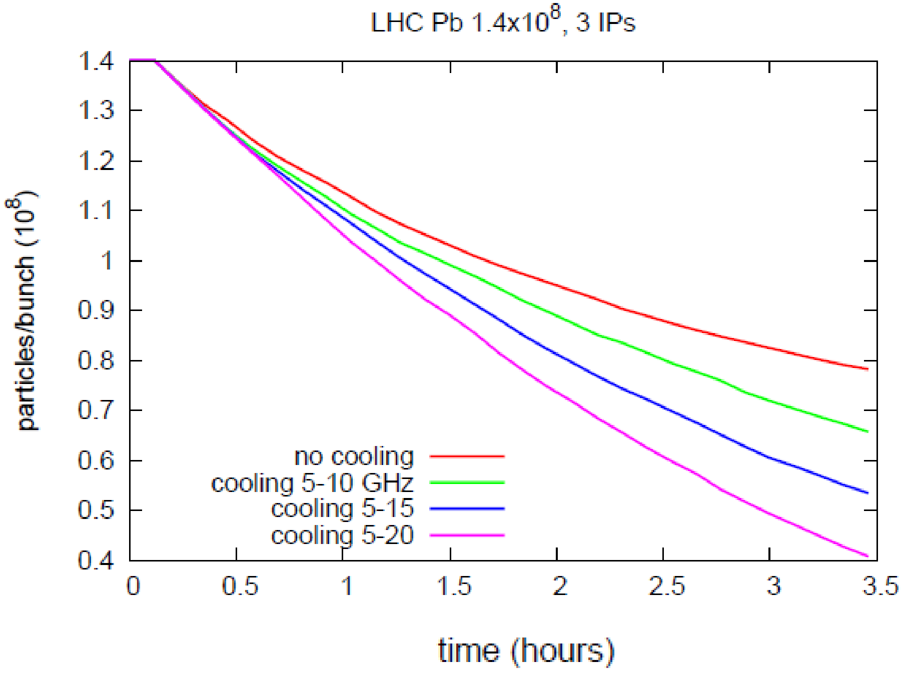
360 bunches

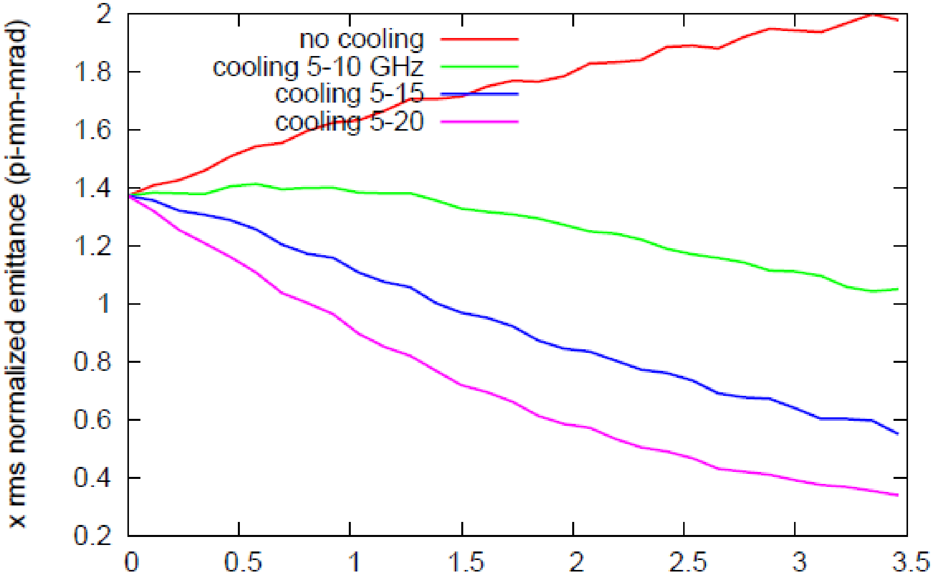


$$\Delta Q_{bare} = 0.01, \quad \Delta Q_{\min} = 0.02$$


LHC Pb 1.4x10^8, 3 IPs
3e+27
2.5e+27
2e+27
1.5e+27
1e+27
5e+26
0
0
0.5
1
1.5
2
2.5
3
3.5
no cooling
cooling 5-10 GHz
cooling 5-15 GHz
cooling 5-20 GHz


y rms normalized emittance (pi-mm-mrad)
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.5
1
1.5
2
2.5
3
3.5
no cooling
cooling 5-10 GHz
cooling 5-15
cooling 5-20


LHC Pb 1.4x10^8, 3 IPs
particles/bunch (10^8)
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0
0.5
1
1.5
2
2.5
3
3.5
time (hours)
no cooling
cooling 5-10 GHz
cooling 5-15
cooling 5-20


x rms normalized emittance (pi-mm-mrad)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.5
1
1.5
2
2.5
3
3.5
no cooling
cooling 5-10 GHz
cooling 5-15
cooling 5-20

Voltage and power Considerations, 1GHz cavity spacing

$$W = 15GHz, \quad I_{peak} = 4A, \quad \sigma(\gamma) = 0.22$$

$$N_{sample} = \frac{I_{peak}}{2Wq} = 7.6\times10^{6}$$

$$\frac{\sigma(E)}{q} = \sigma(\gamma)\frac{mc^{2}}{q} = 0.52GV$$

$$M = \frac{\tau_{damp}}{T_{rev}} = \frac{1}{T_{rev}\pi\Delta f_{FWHP}} \approx 8 \text{ at 12 GHz}$$

$$\sigma(V_{cav}) = \frac{1}{\sqrt{16}}\frac{1}{\sqrt{N_{sample}}}\frac{\sigma(E)}{q}\frac{1}{M} = 5.9kV$$

Results from simulations give near optimal luminosity For 2kV rms, which was adopted.

With 1 GHz spacing the voltage per cavity does not depend on band width

Transverse voltage of 200V rms per cavity.

Conclusions

1) First implementation of 3D cooling in a collider worked as predicted.

2) Integrated luminosity in U-U improved 5 fold.

3) Cooling led to first increase of instantaneous luminosity and smallest emittance ever in a hadron collider.

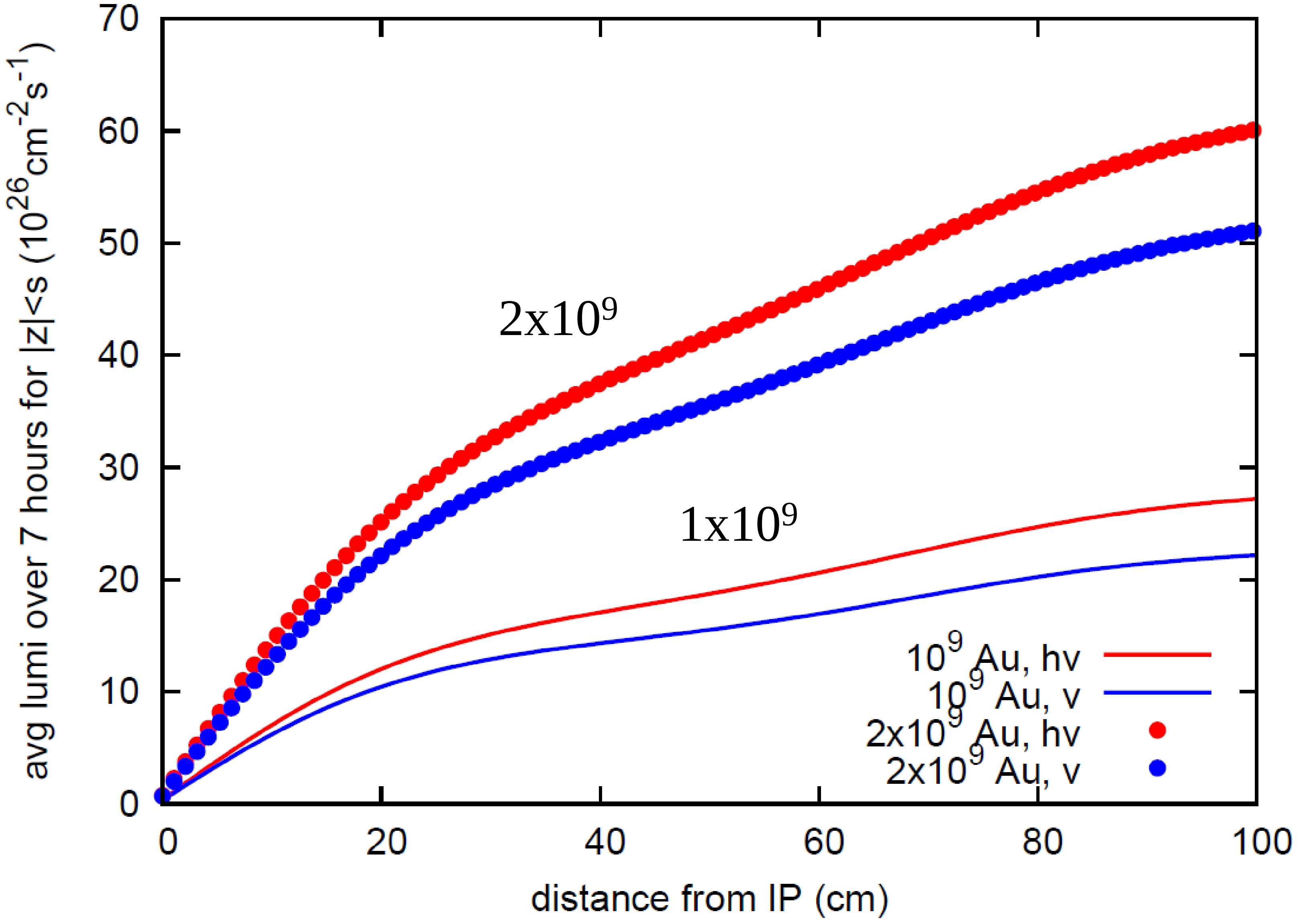
4) Simulations have adequate predictive power to design with confidence.

5) For 1.3E9/bunch, cooling will improve integrated luminosity by a factor of 2 or more, system allows operation up to 2.E9/bunch

6) 56 MHz yields an additional 30 to 50% luminosity depending on vertex cut.

7) Preliminary results for LHC are promising.

Au luminosity versus acceptance



Voltage and power 2

Our cavities typically have R/Q = 100 Ohm (circuit def.)

At 12 GHz Q = 600 for 20 MHz band width, R=60kOhm

Power = $(V_{rms})^2/R$=66 Watts, rms.

Probably want 200 or more watts.

Saturation has been simulated.

Limiters that saturate without introducing a phase shift would be very useful.

Transverse voltage of 200 V rms per cavity.

Need to follow up on power requirements.

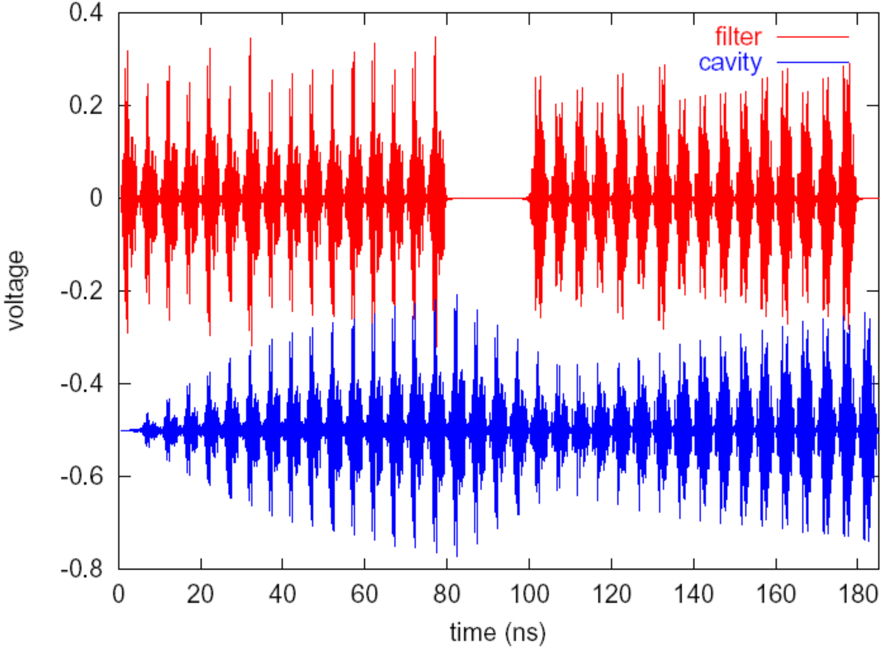
Error Limit Simulations

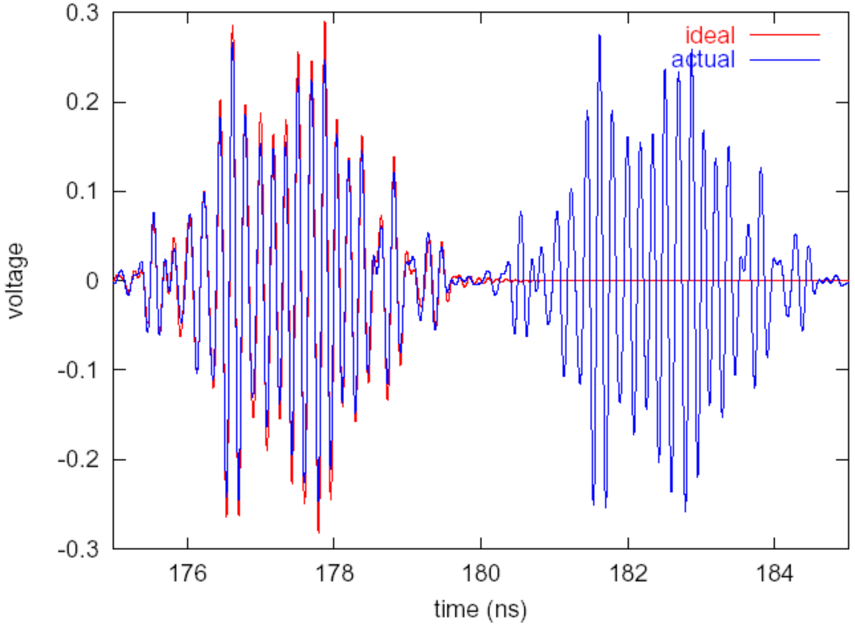
Took conservative errors.

- 2 ps timing error
- 20% amplitude errors
- 2 MHz cavity frequency errors

Desired cooling voltage is modeled as band limited noise.

System is well behaved with these errors.





portion of assembly

Choke joints allow for gap without loss.

Use lights to elevate temperature and turn them down to keep fixed temperature during operation.