Stochastic Cooling of High Energy Bunched Beams

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Instrumentation, Controls and RF groups at BNL

- History
- The RHIC System
- Results and Comparison with Simulations
- Possibilities for cooling Pb in LHC

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).

Cooling rate scales as 1/N, Z=79 for Au

Cooling of long bunches in FNAL recycler.

Proton cooling experiment in RHIC (2006).

Operational longitudinal cooling of gold in RHIC (2007).

Transverse cooling in RHIC (2010).

Voltage considerations

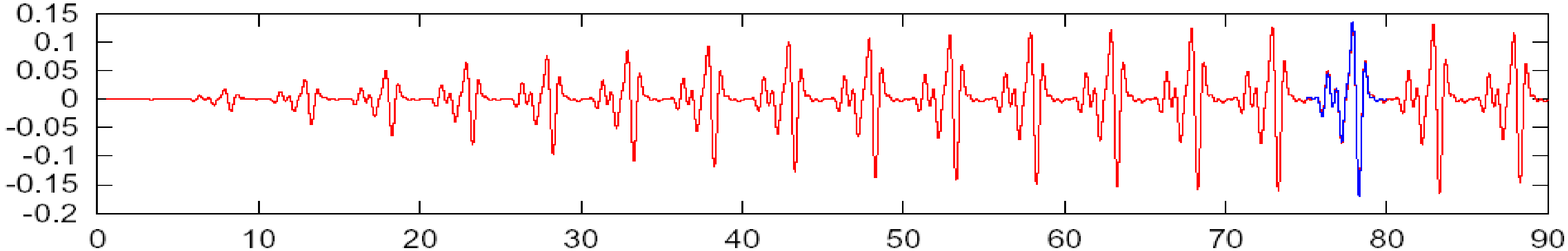
$$V(t) = \sum_n A_n \sin(2\pi nt / \tau_b + \theta_n)$$

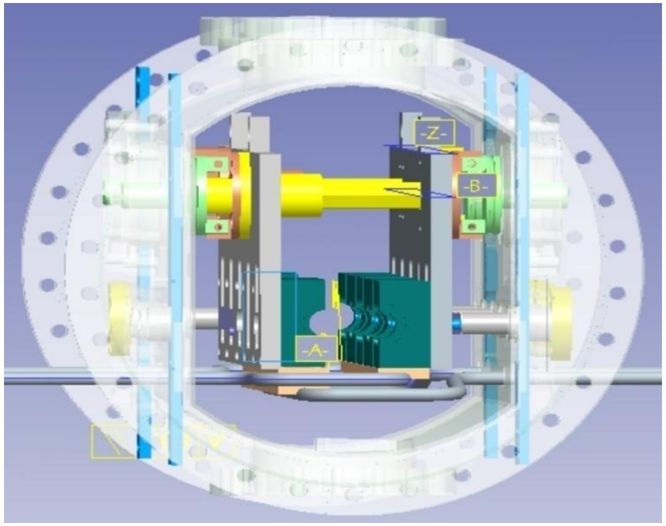
For 5-8 GHz longitudinal system we need 3 kV rms.

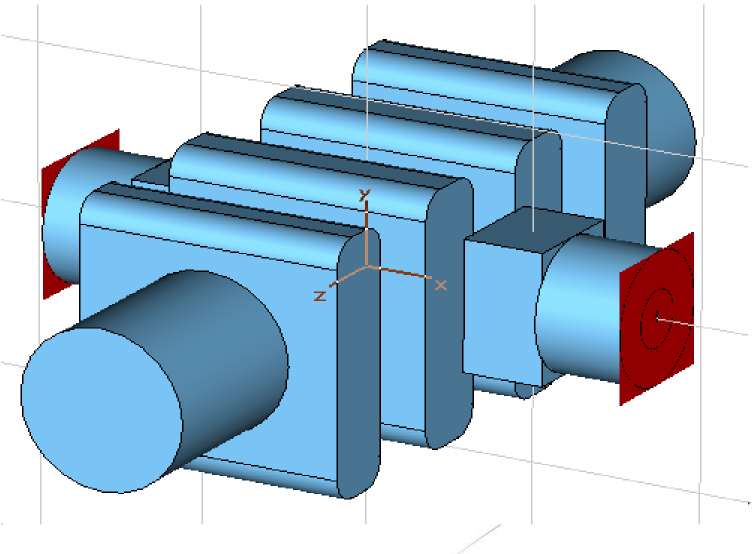
Bandwidth-Voltage product sets the cost scale.

Bunches are 5 ns long spaced by 100 ns.

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







Transverse Cooling system

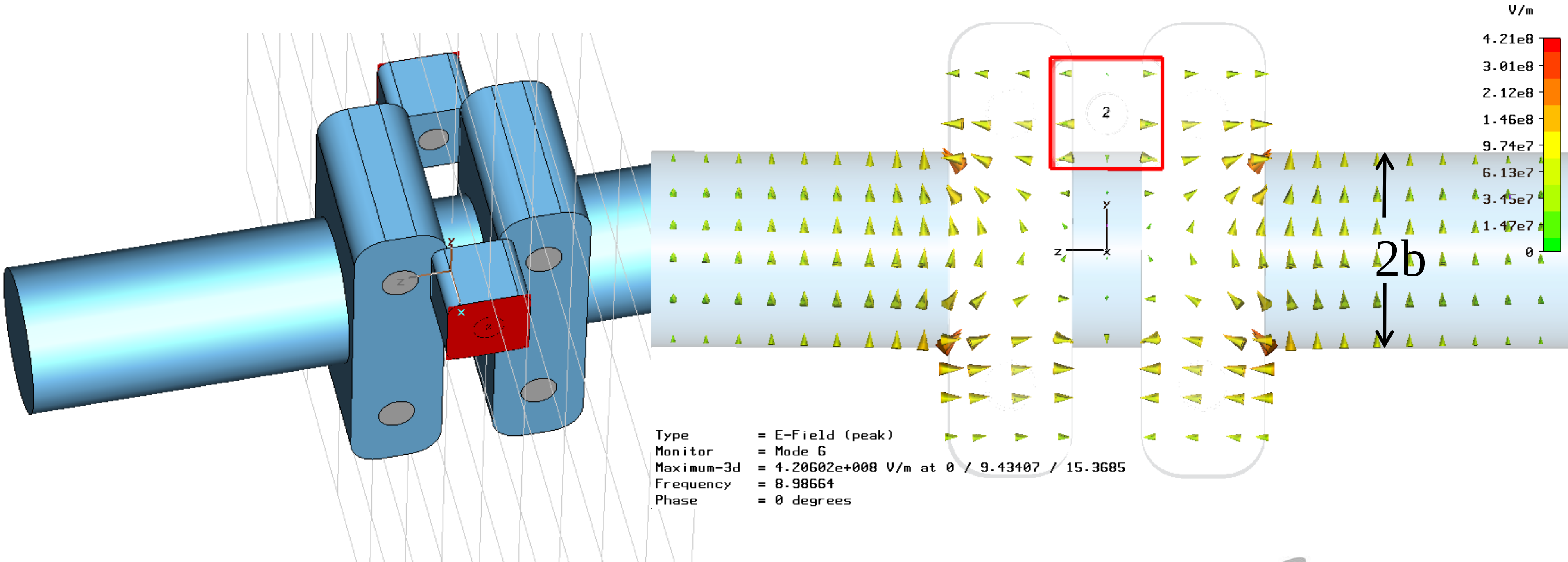
Similar cavities.

40 Watt amplifiers are sufficient.

4.8-7.8 GHz keeps aperture reasonable.

Panofsky-Wenzel theorem relates transverse kick to standard voltage

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



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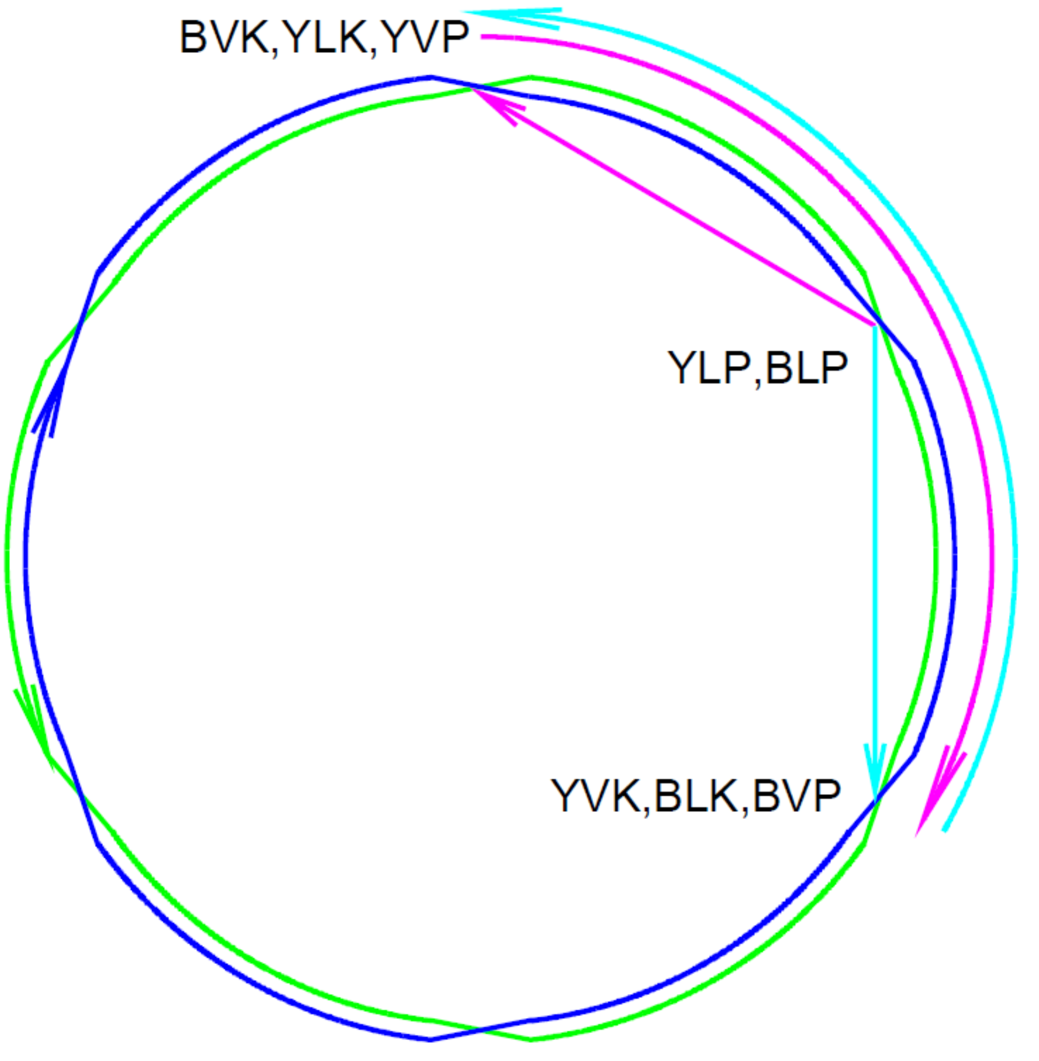
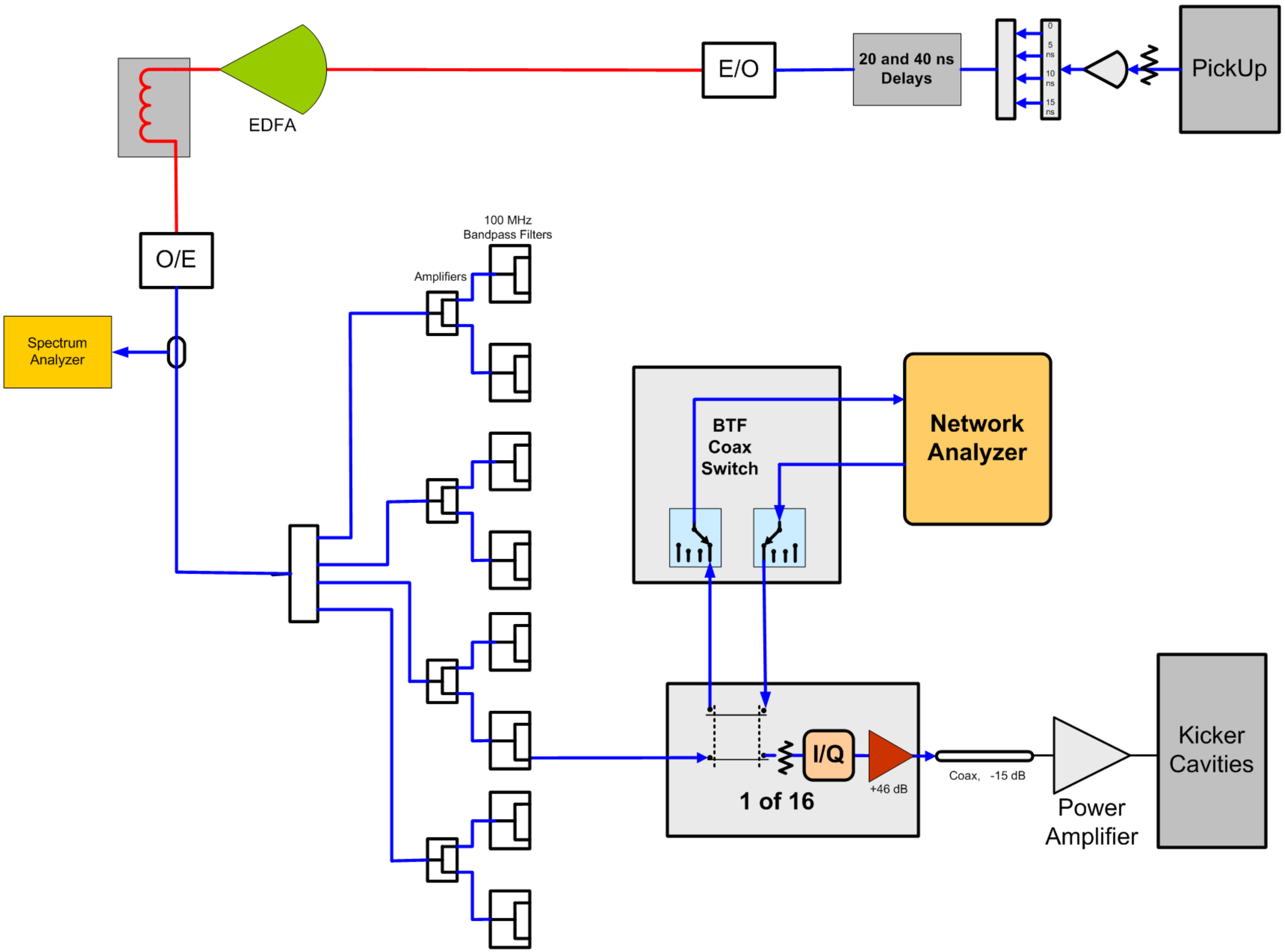
The RHIC system layout

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

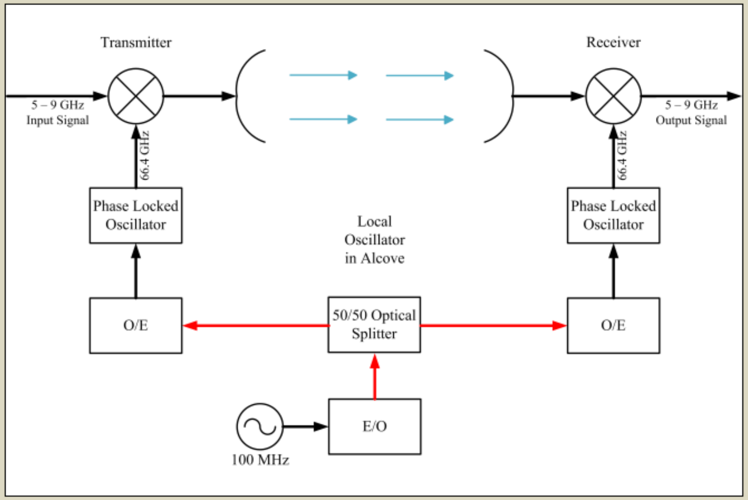


Stochastic Cooling Low Level Block Diagram

blue vertical

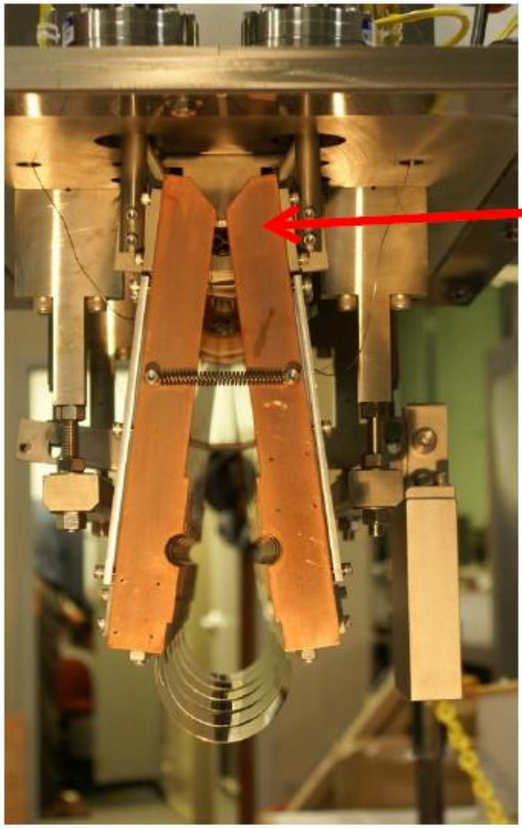


Longitudinal signals sent via 70 GHz microwave link.



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.

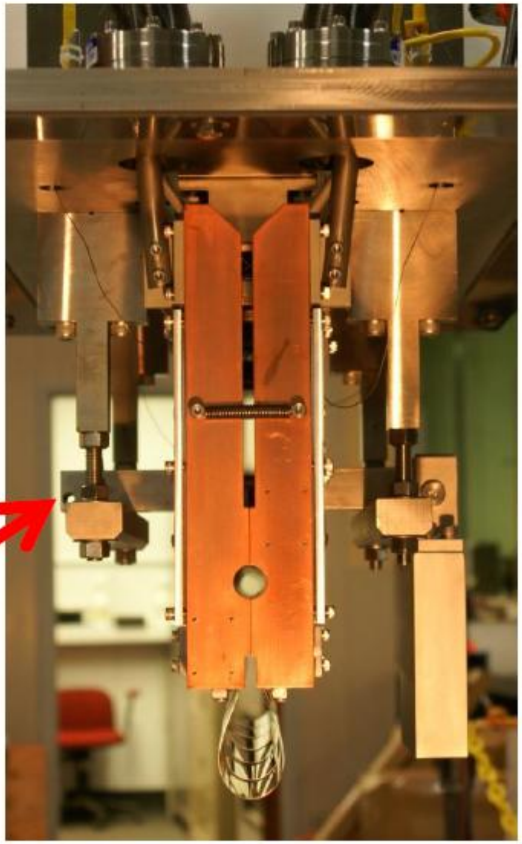
Transverse kickers



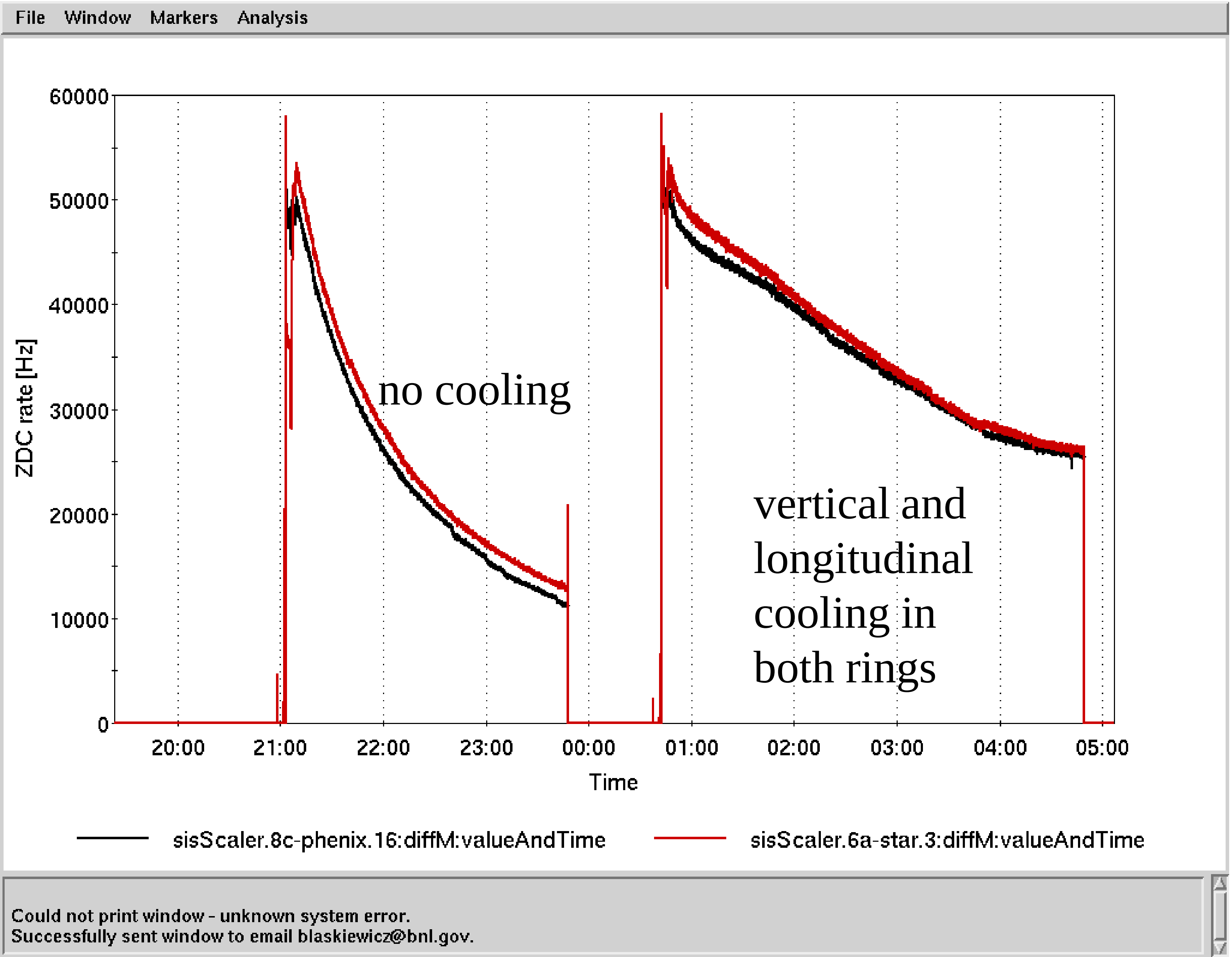
Structures open and close using a device called a "Flexi-hinge". It has no sliding parts, is bakeable for high vacuum, and operates for many 10e5 cycles.

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



Luminosity with and without cooling. Is it what we deserve?



Stochastic cooling theory on (almost) one page

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

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

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

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

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

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

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

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

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

Mixing and signal shielding are fully accounted for.

Fokker-Planck approach is several pages.

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

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

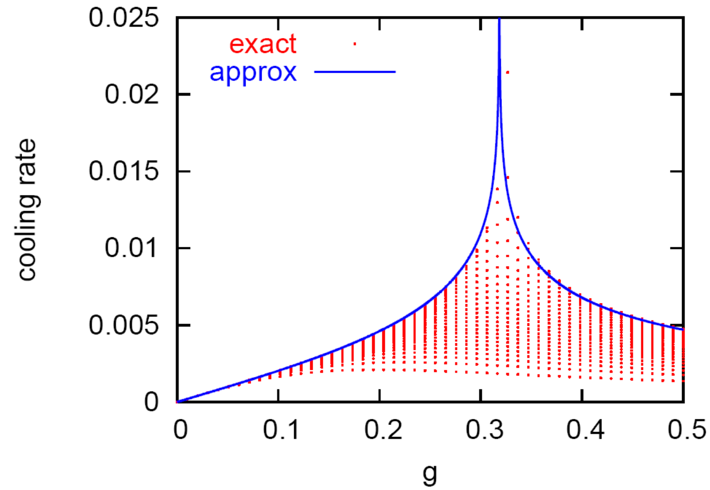


Figure 4: Comparison of actual values of $Re(\lambda)$ versus gain with those obtained from equation (14) with $X = 0$ for a rectangular frequency distribution with $N = 51$. The numerical solution had one eigenmode with a monotonically growing eigenvalue, which is not fully shown.

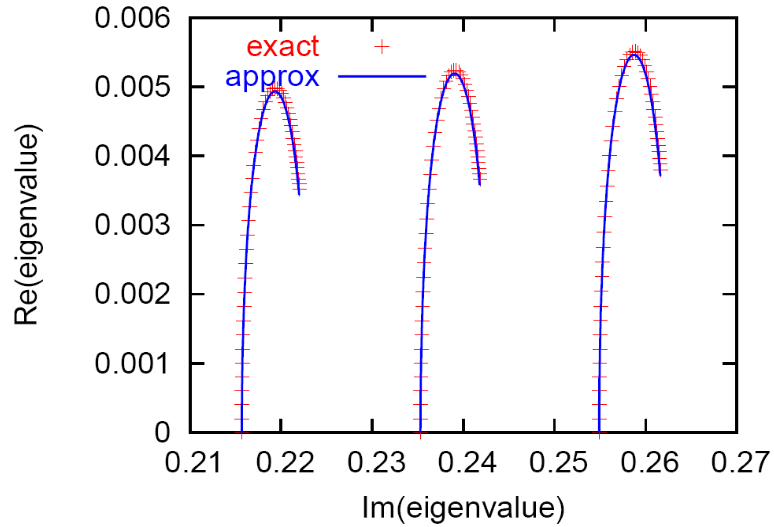


Figure 5: Evolution of λ as a function of gain for the exact, numerical solution and equation (14). The oscillator frequencies were uniformly spaced with $\omega_j = j/N$ and $N = 51$.

Bunched Beam Simulations

Time domain model of filter cooling.

Very similar to coherent stability problem.

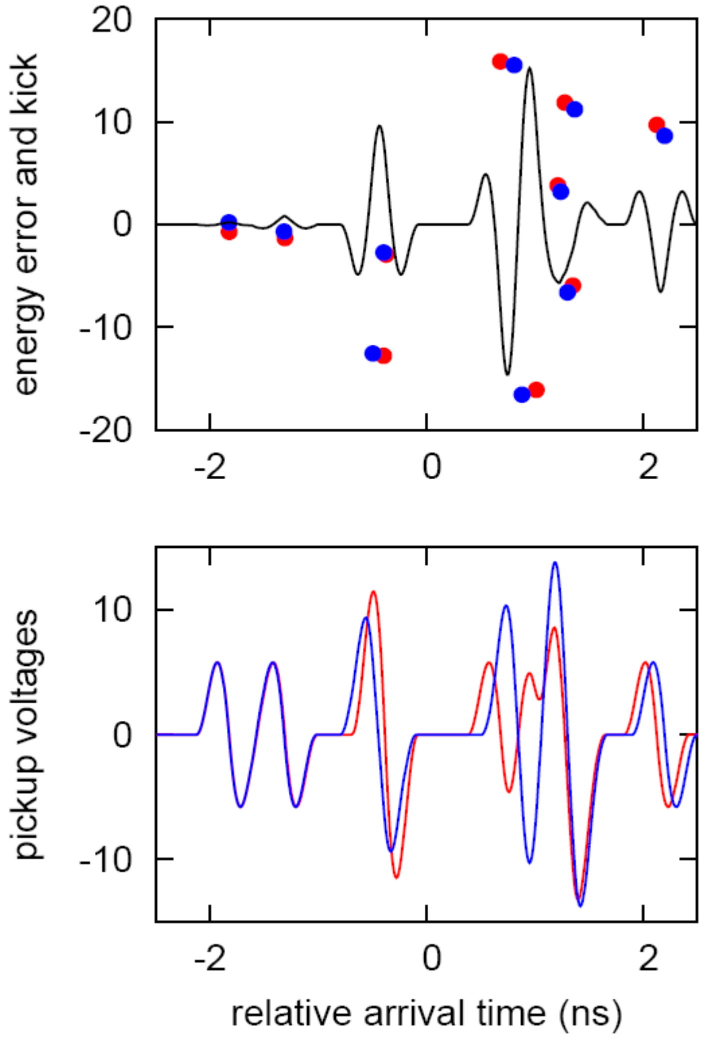
For cooling

$$T_{cool} \approx 2 N_{true} M / W$$

In a Simulation $N_{macro} << N_{true}$

So,

$$T_{sim} = \frac{N_{macro}}{N_{true}} T_{cool} << T_{cool}$$



Bunched Beam Simulations II

Dealing with intra-beam scattering

1) Start with Piwinski's formulae

$$\frac{1}{\sigma_p^2}\frac{d\sigma_p^2}{dt} = \alpha_{p0}$$

2) Correct for number of macro-particles

$$\alpha_{p1} = R\alpha_{p0}$$

3) Correct for non-gaussian profile

$$F(t) = I(t)\sigma_t 2\sqrt{\pi}/Q$$

4) Langevin kick

$$\Delta p = \sigma_p \sqrt{\alpha_{p1} T_0 F(t)}\chi$$

5) Track all 3 dimensions and use skew quads for coupling.

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, simple rf, no ibs or longitudinal cooling

Longitudinal IBS leads to diffusion in H_s.
For RHIC, transverse cooling is nearly independent of H_s.
LHC is not so lucky.

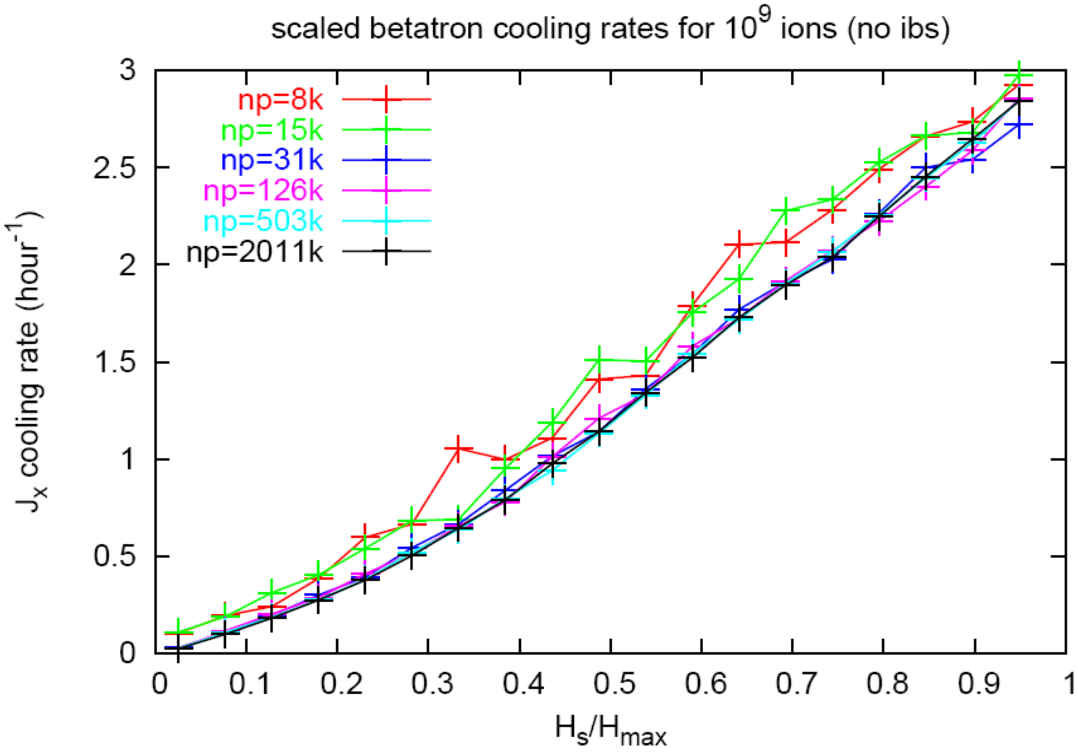
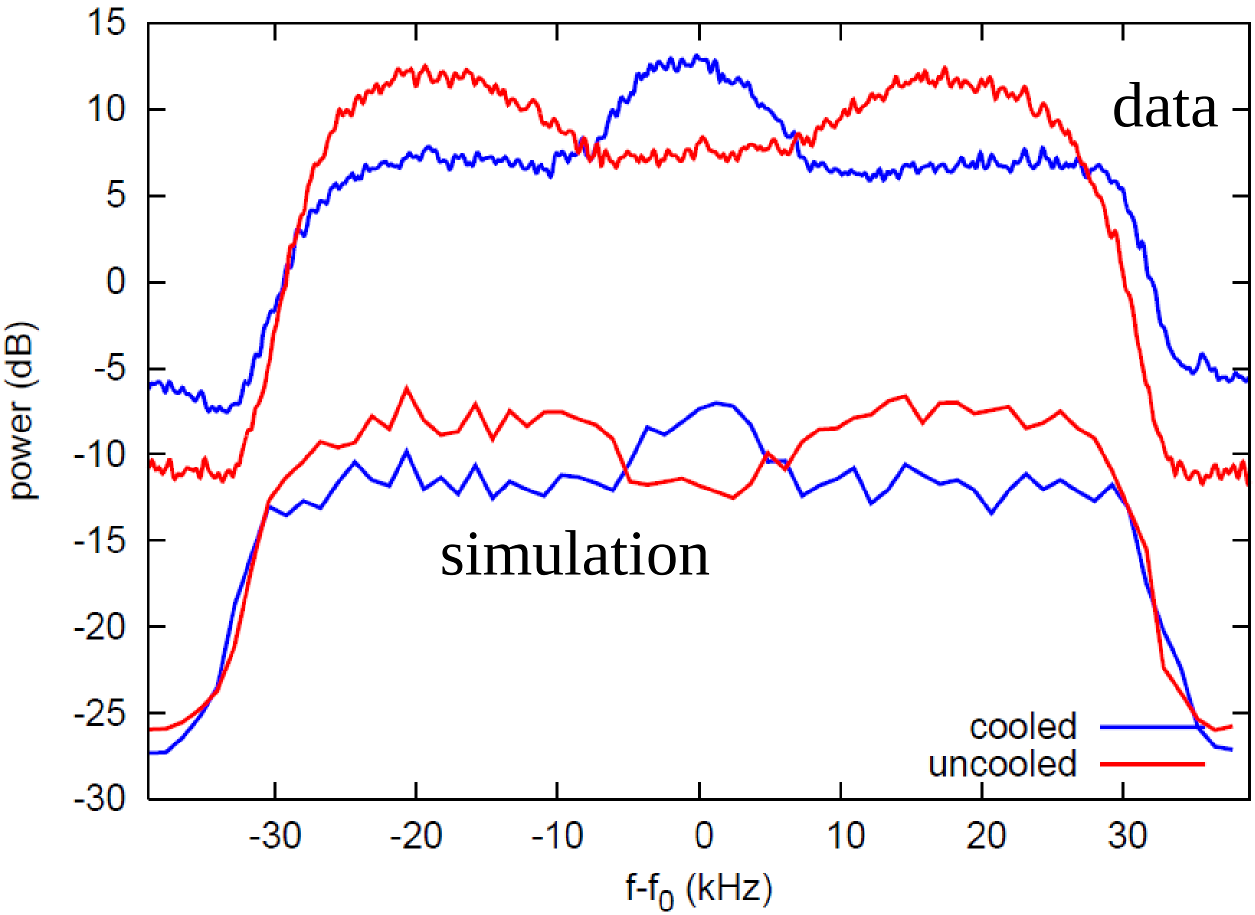


Figure 5: Transverse cooling rate versus the value of the longitudinal hamiltonian. Similar results are shown in [6, 7]

Gain adjustment in simulations

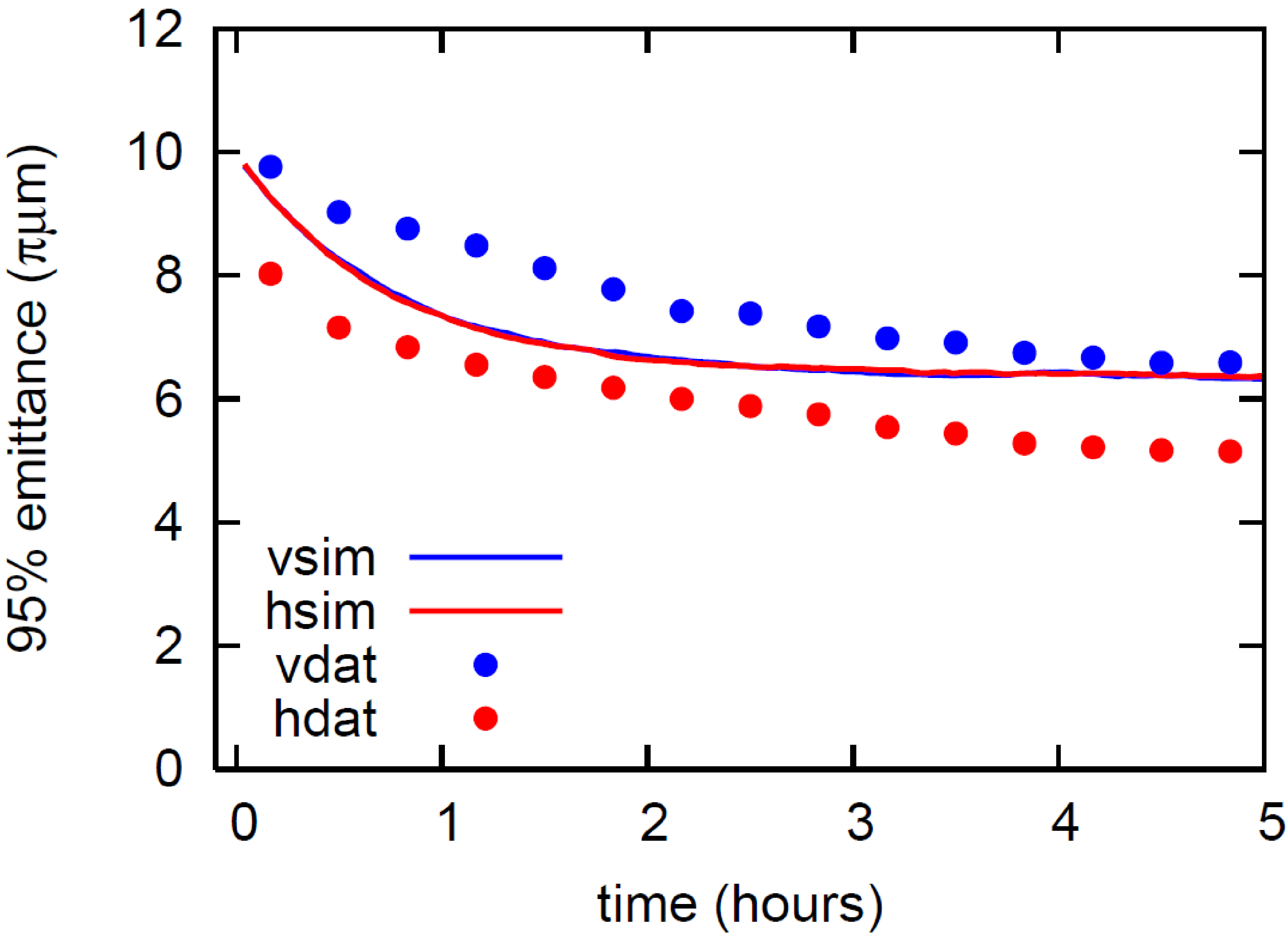
5.7 GHz center frequency



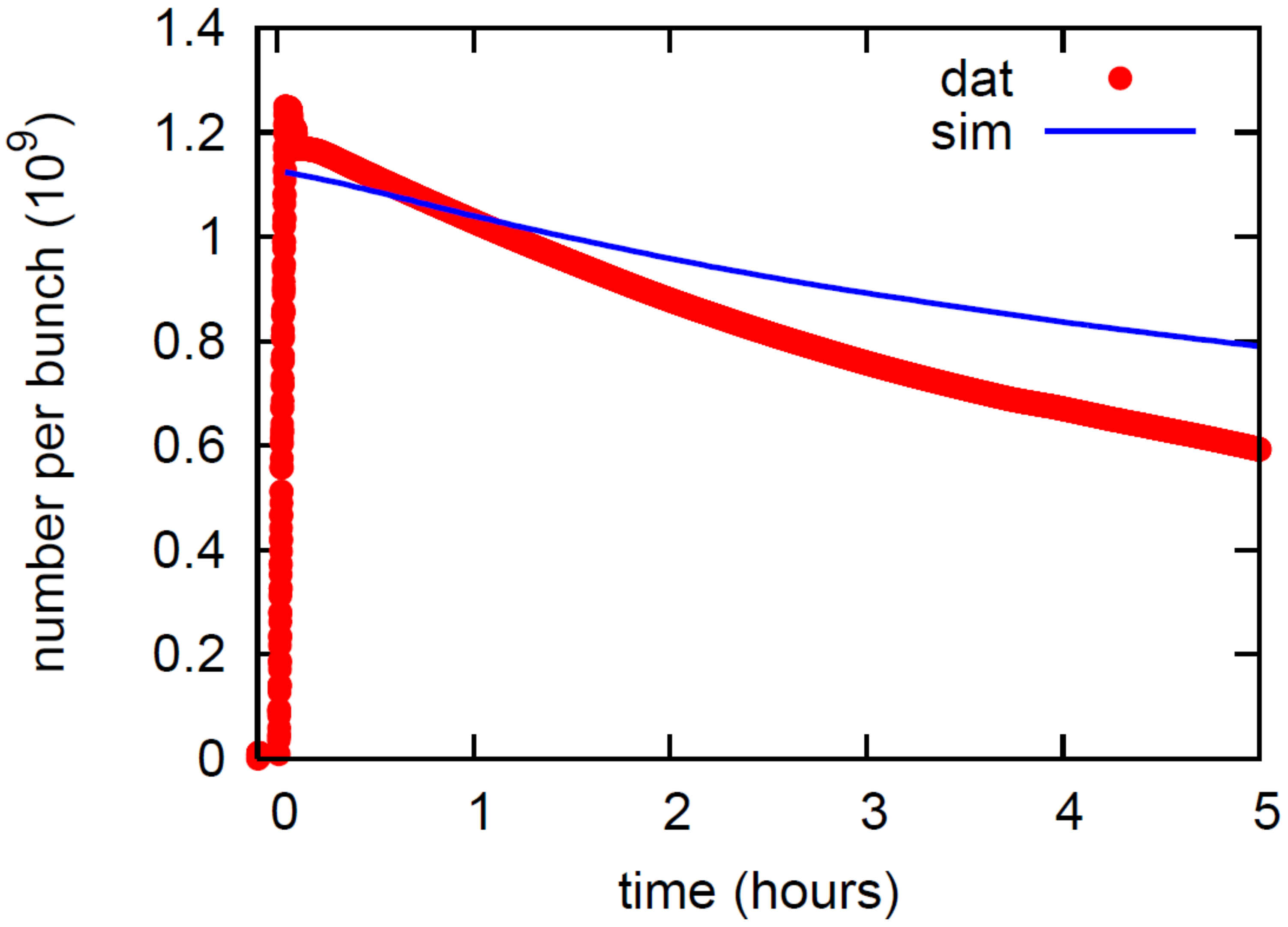
$$z_n = \sum_{k=1}^{N_p} x_k(n) e^{i\omega_c \tau_k(n)}$$

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

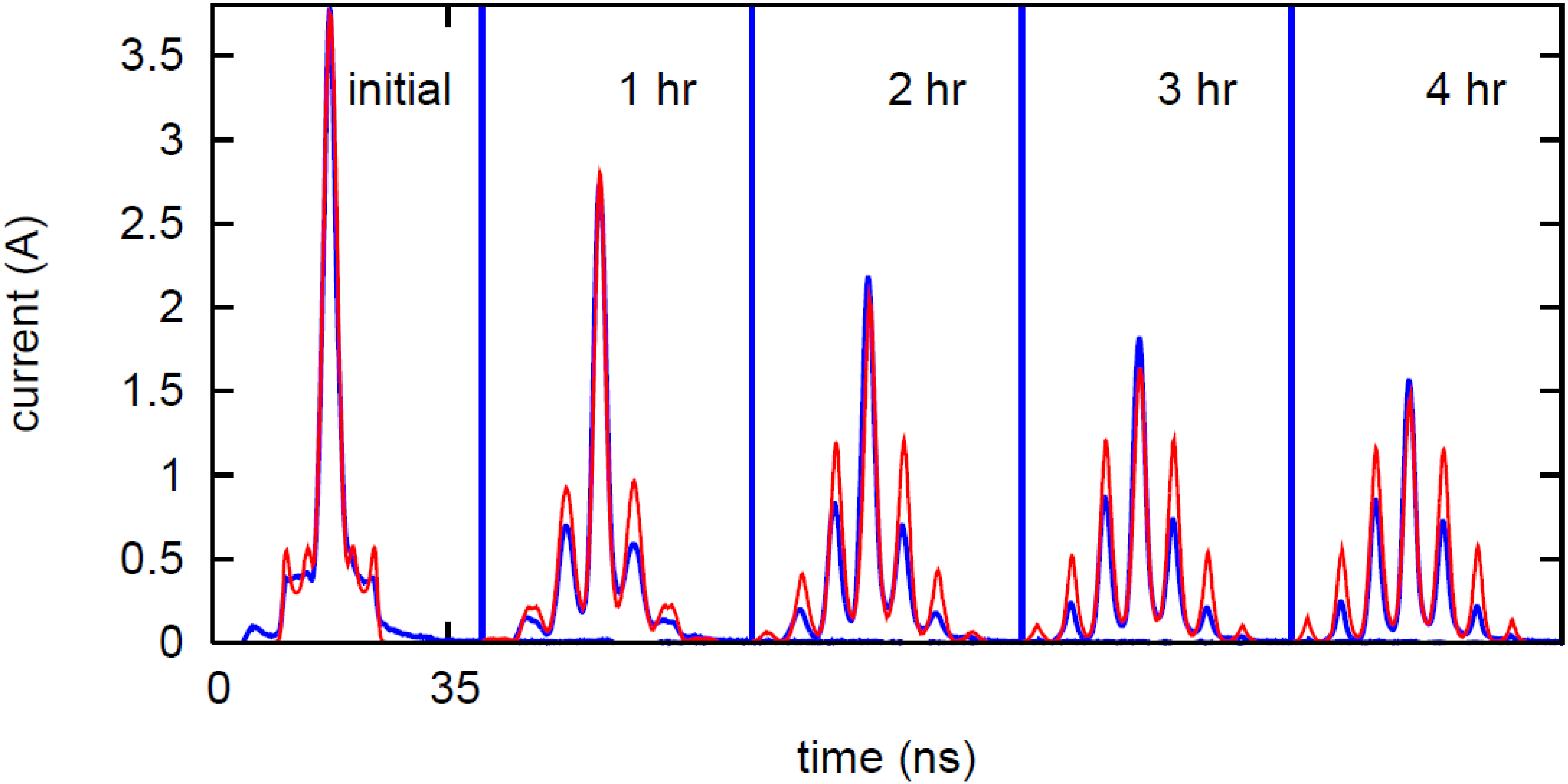
Cooling in blue, data and simulation, yellow similar



Real loss rates are faster than simulation.



Blue longitudinal suggests simulation (red) misses a momentum aperture.



Achieved 70% of simulated improvement. Extrapolating data to 5 hours shows that cooling doubles integrated luminosity.

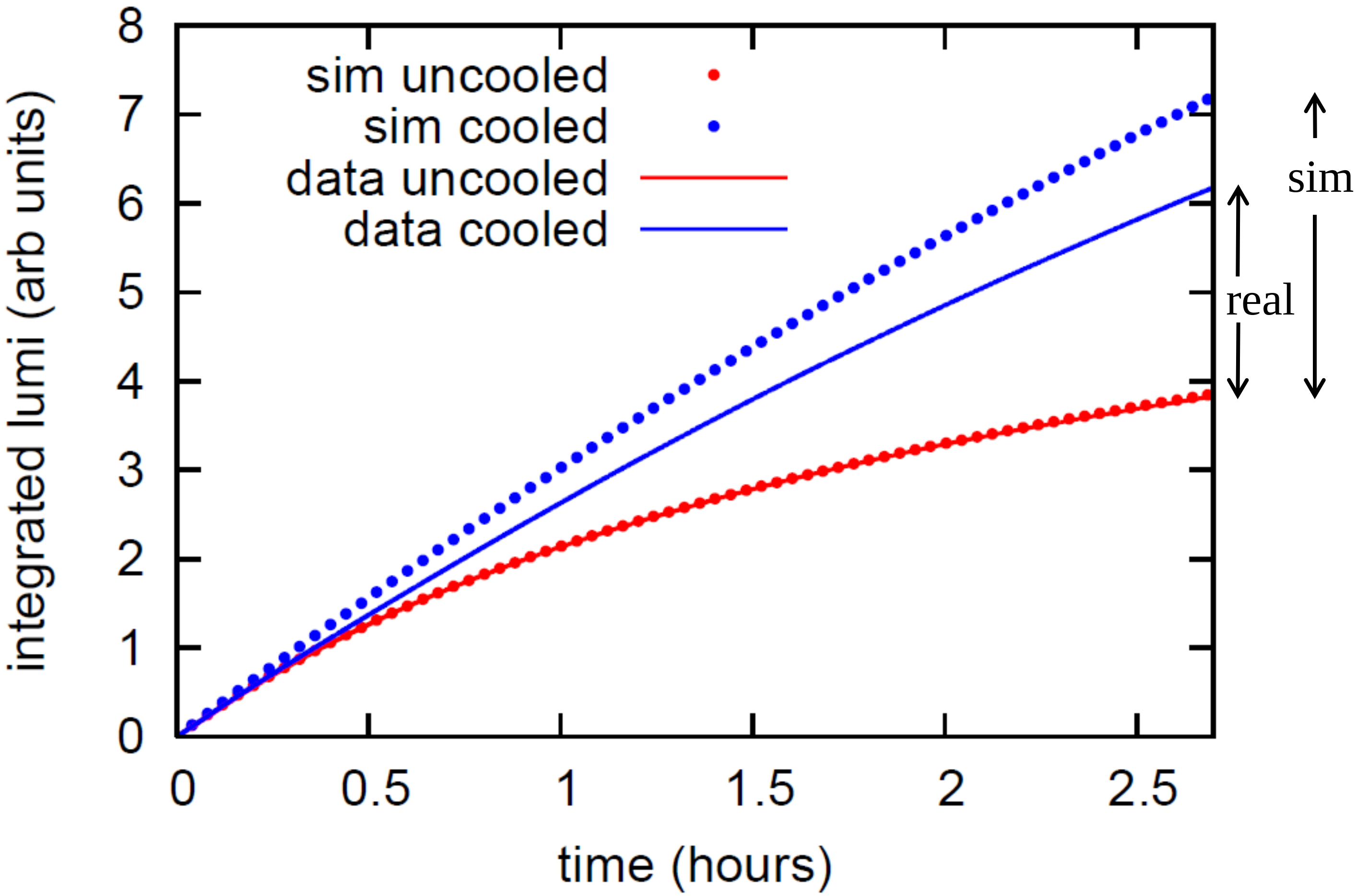
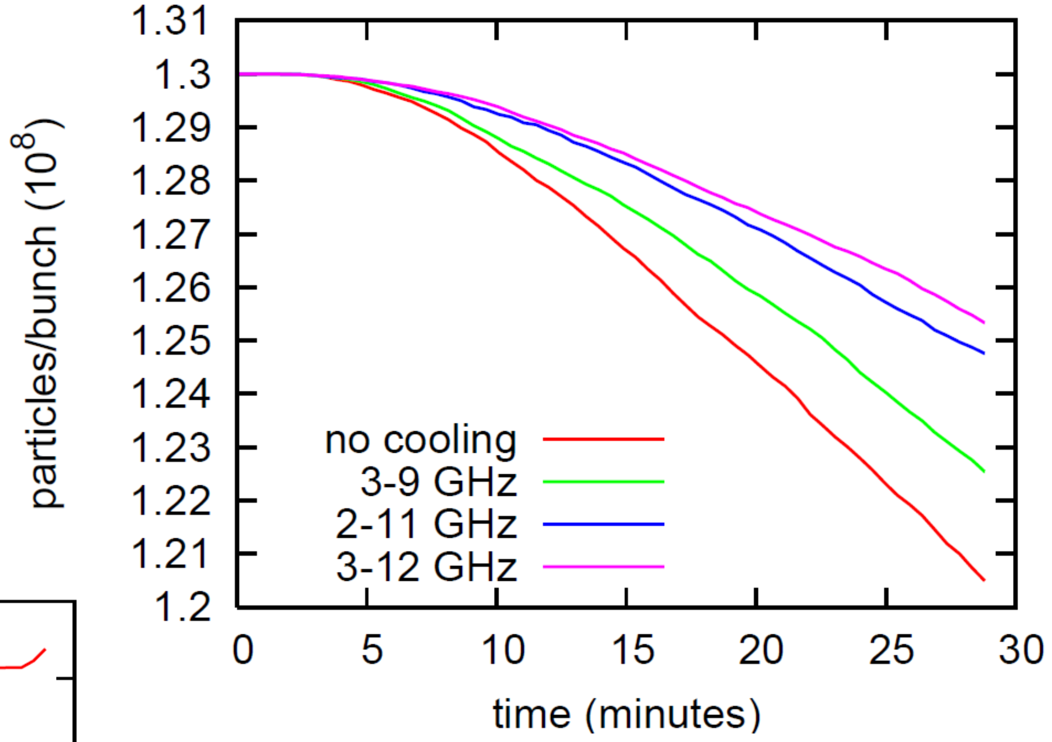
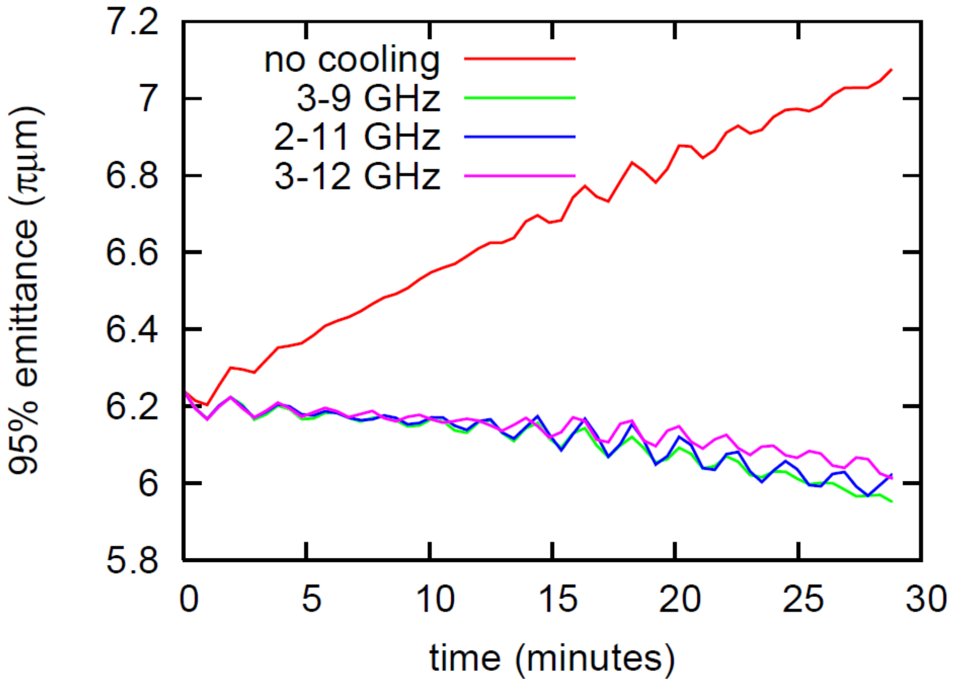


Figure 7: Comparison of integrated luminosity with and without cooling. The simulations were scaled to give good agreement for uncooled beams.

LHC Pb possibilities at injection

Single vertical system employing betatron coupling. FO link in tunnel, 5-8 GHz band.





Longitudinal systems use cascaded one turn delays with FO link in the tunnel, 2/3rd turn delay.

Conclusions

1) Stochastic cooling worked.
2) Lifetime was improved.
3) Luminosity was doubled.
4) Horizontal cooling will increase flexibility and improve things a bit.
5) Transverse cooling in LHC looks straightforward.

Voltage and Power continued

Take 16 cavities, 5-8 GHz bandwidth 40 Watts/cavity (10 K each)

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 with 10 MHz $(1/T_b)$wide peaks,

spaced by 200 MHz $(1/\tau_b)$.

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.

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.

Only had 5 branches this run.