RHIC Luminosity Increase with Bunched Beam Stochastic Cooling

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Acknowledgements

- 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).

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).
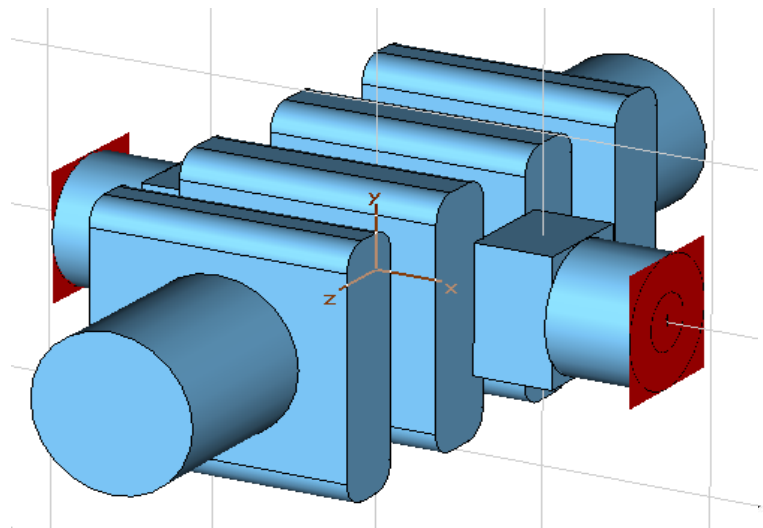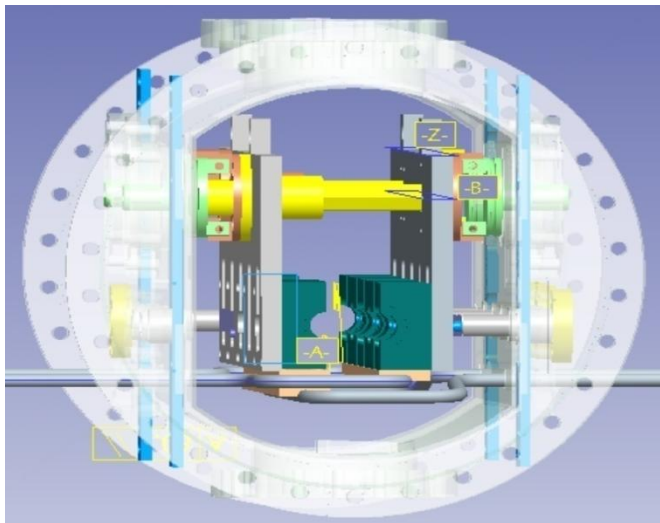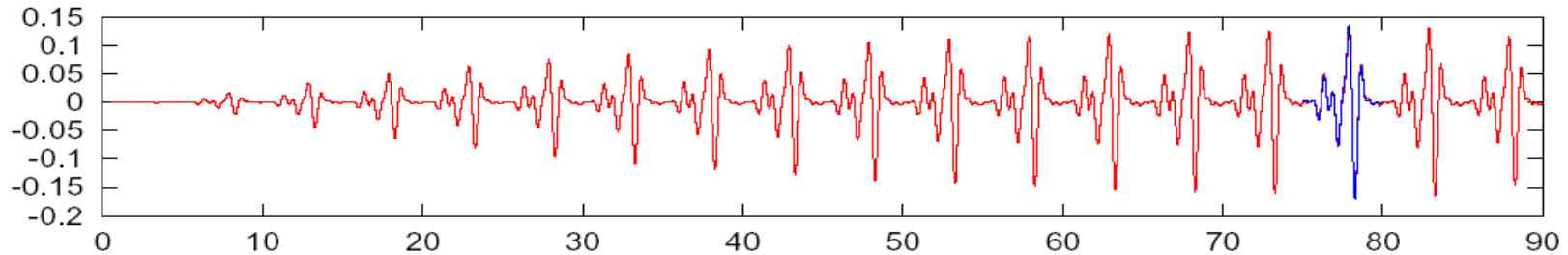
Voltage considerations

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

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.

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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.

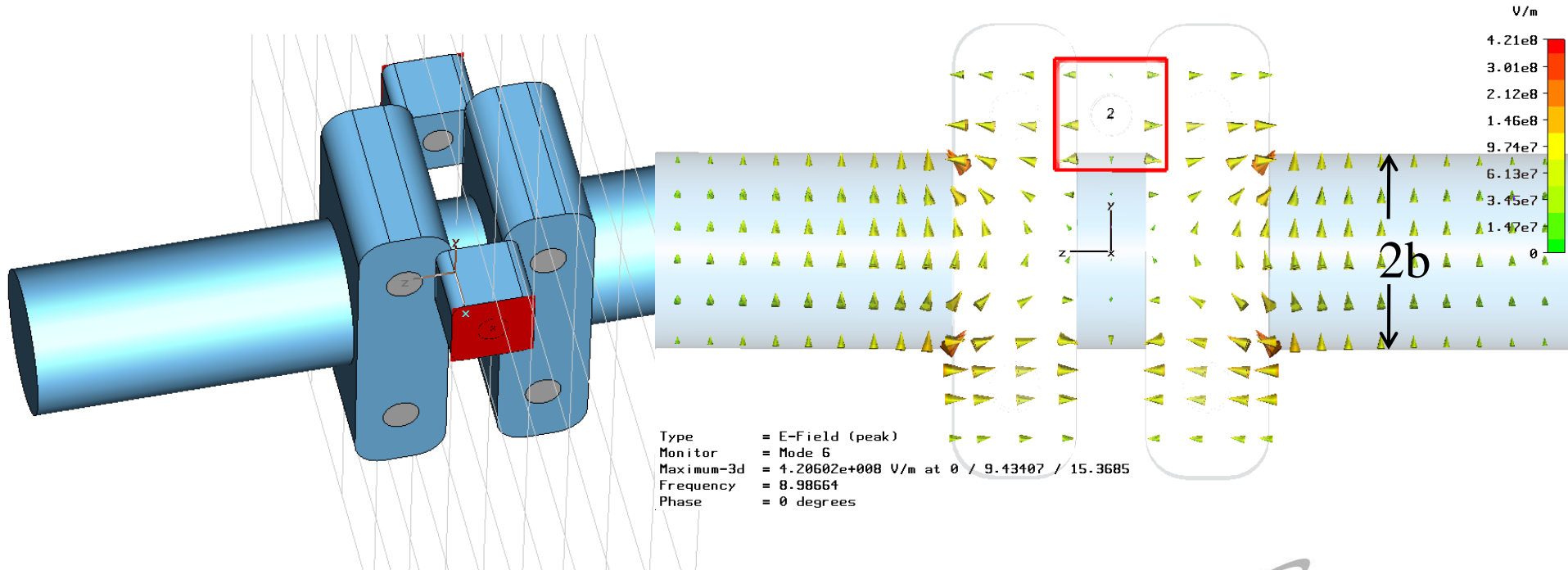# Transverse Cooling system

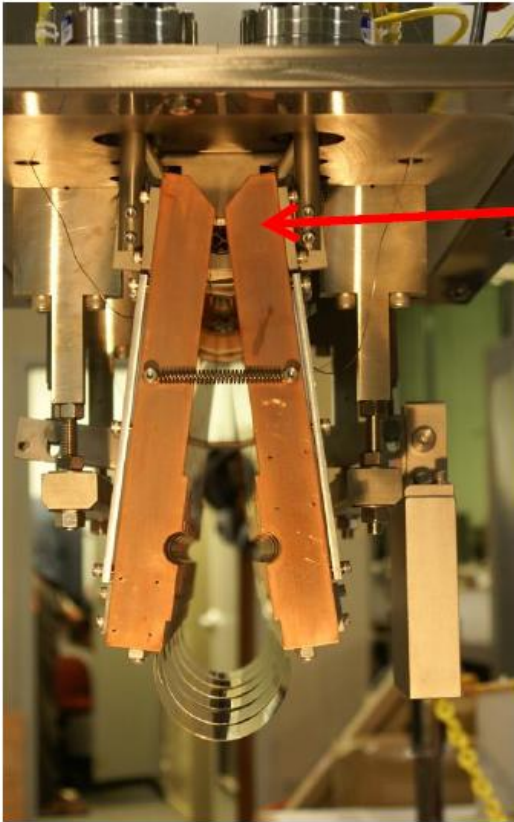Similar cavities.

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
```

```
V/m
4.21e8
3.01e8
2.12e8
1.46e8
9.74e7
6.13e7
3.45e7
1.47e7
0
```

2b

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

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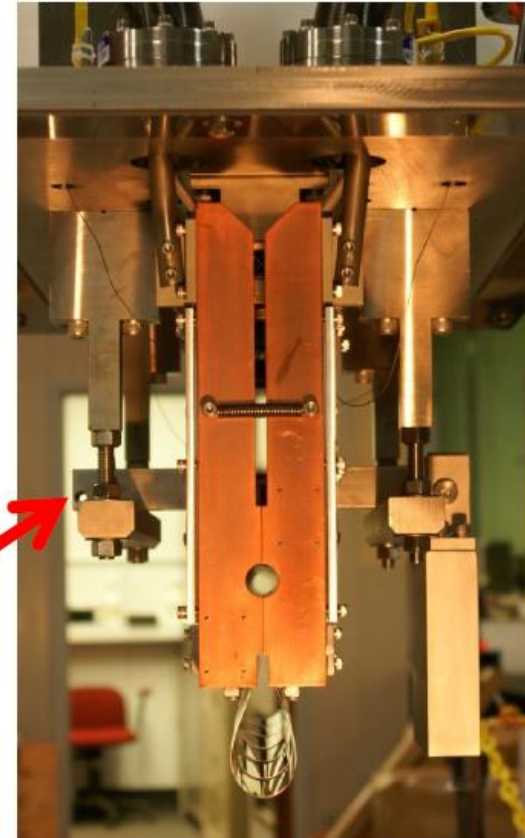
The RHIC system layout

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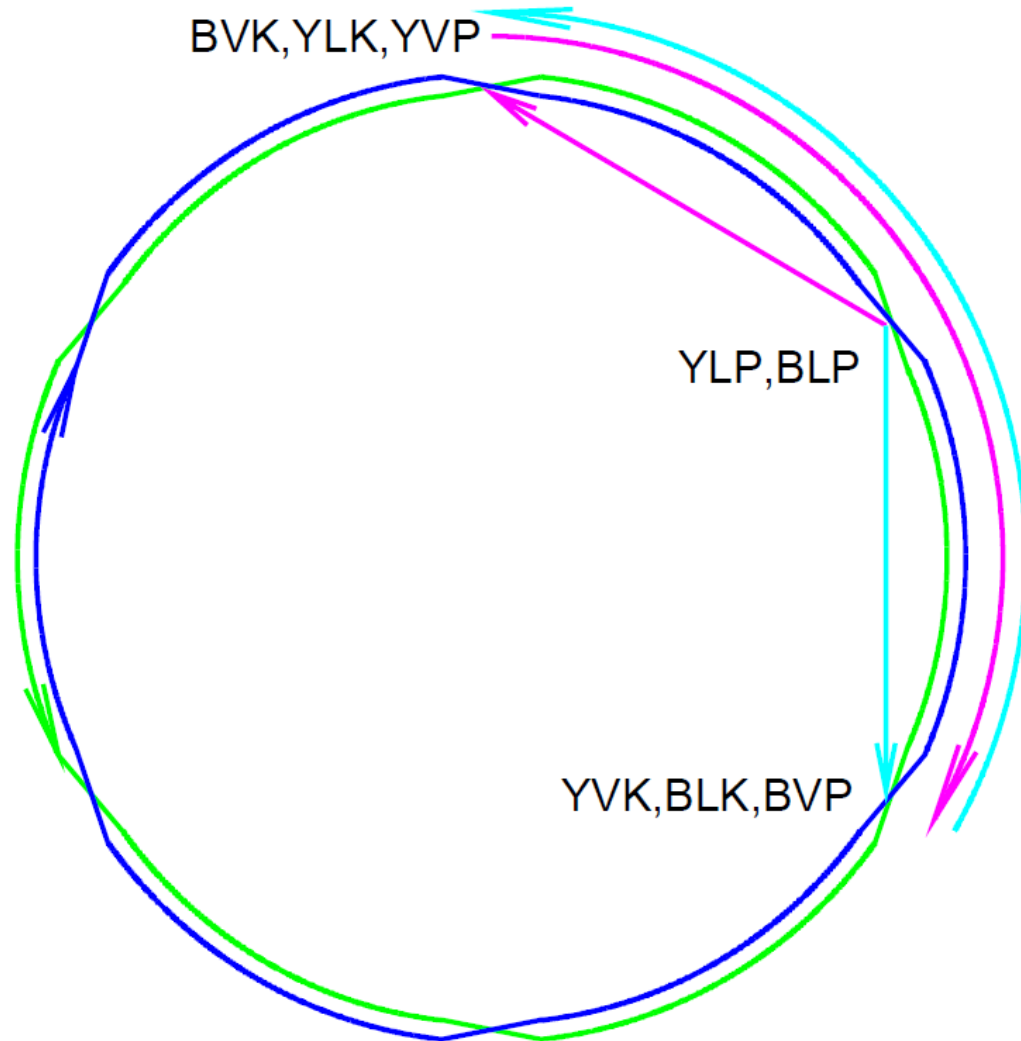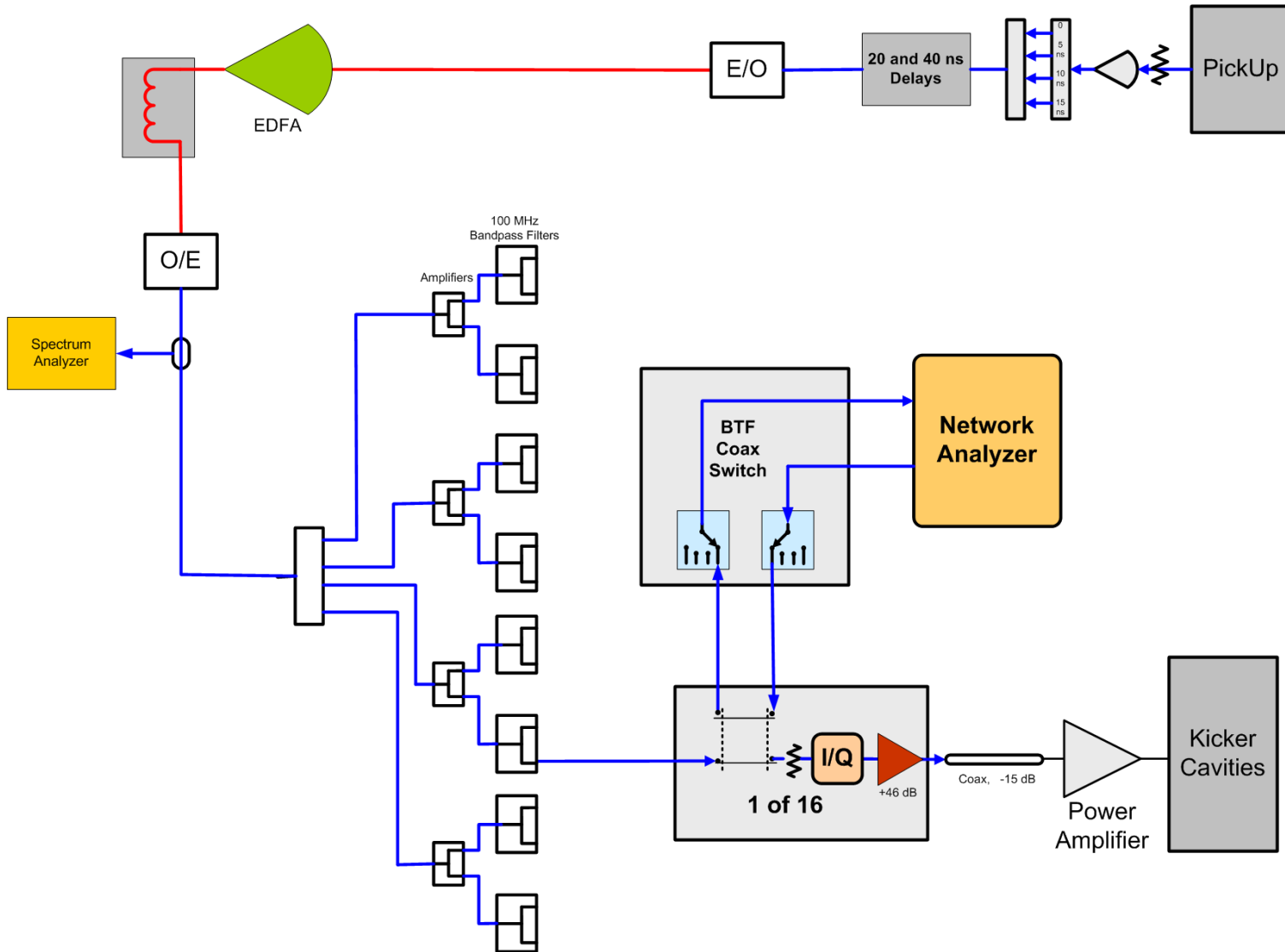Blue transverse
4.7,4.9,..7.7 to
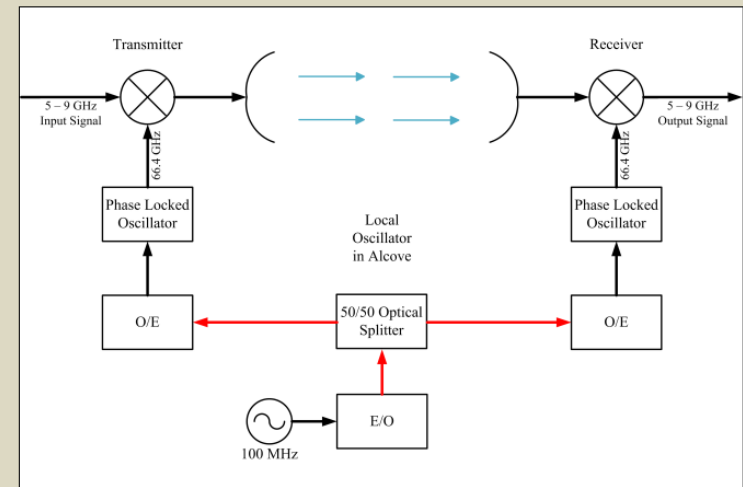avoid cross-talk
through IRs

BVK,YLK,YVP

YLP,BLP

YVK,BLK,BVP

# 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.

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Integrated uranium luminosity improved 5 fold with cooling. Is it what we deserve?
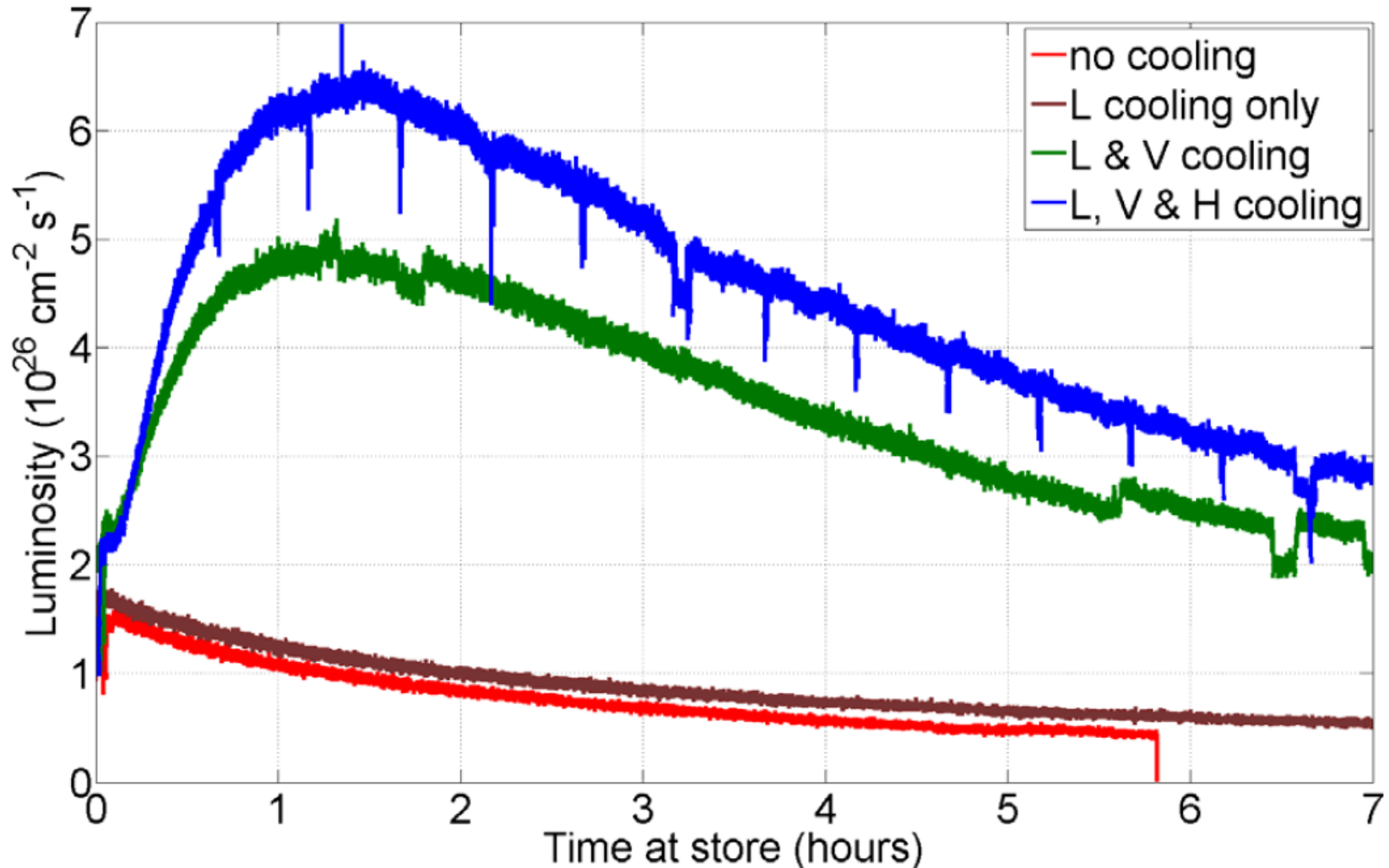
- Quick reminder of how stochastic cooling works

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

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

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

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

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

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.
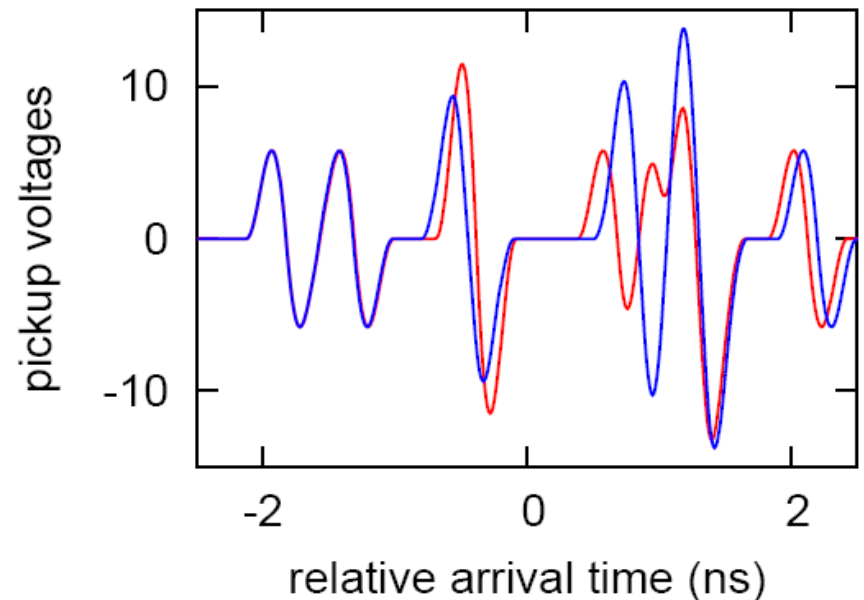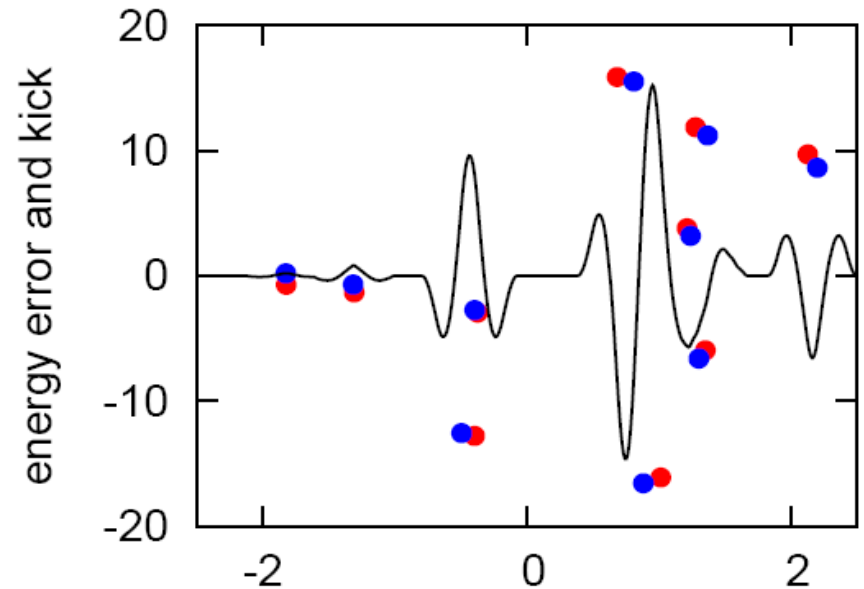
Transverse Cooling Simulations

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

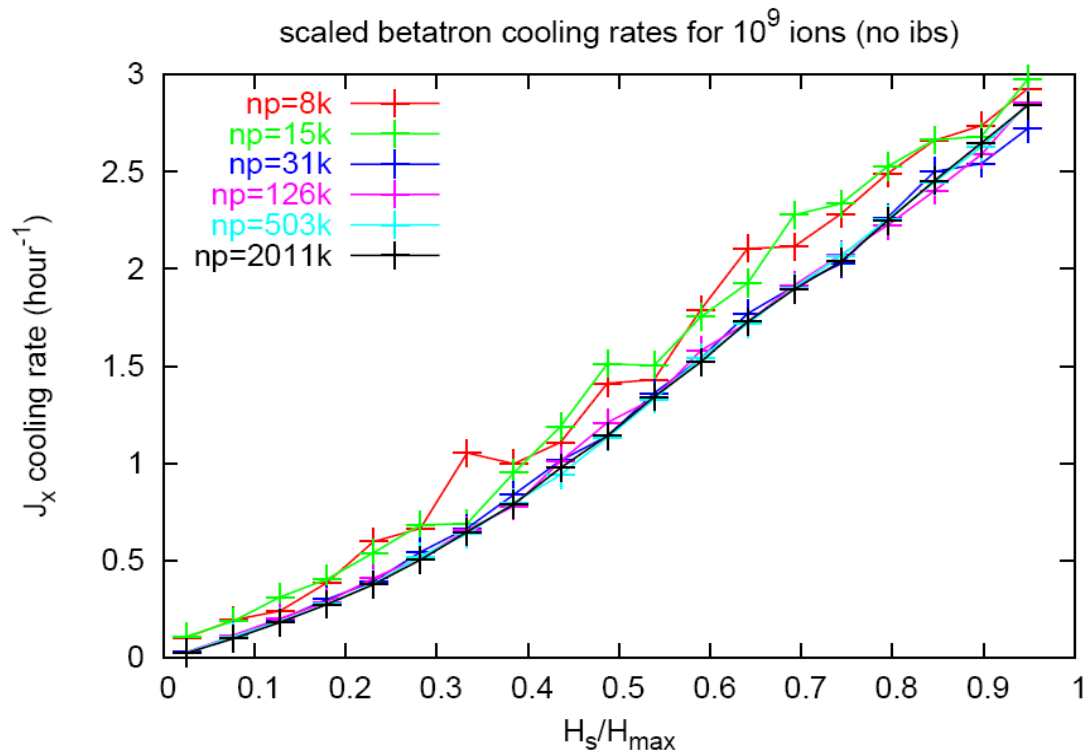Check of scaling, single harmonic rf, no IBS or longitudinal cooling

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

Spatial density for gaussian beam traveling to left

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

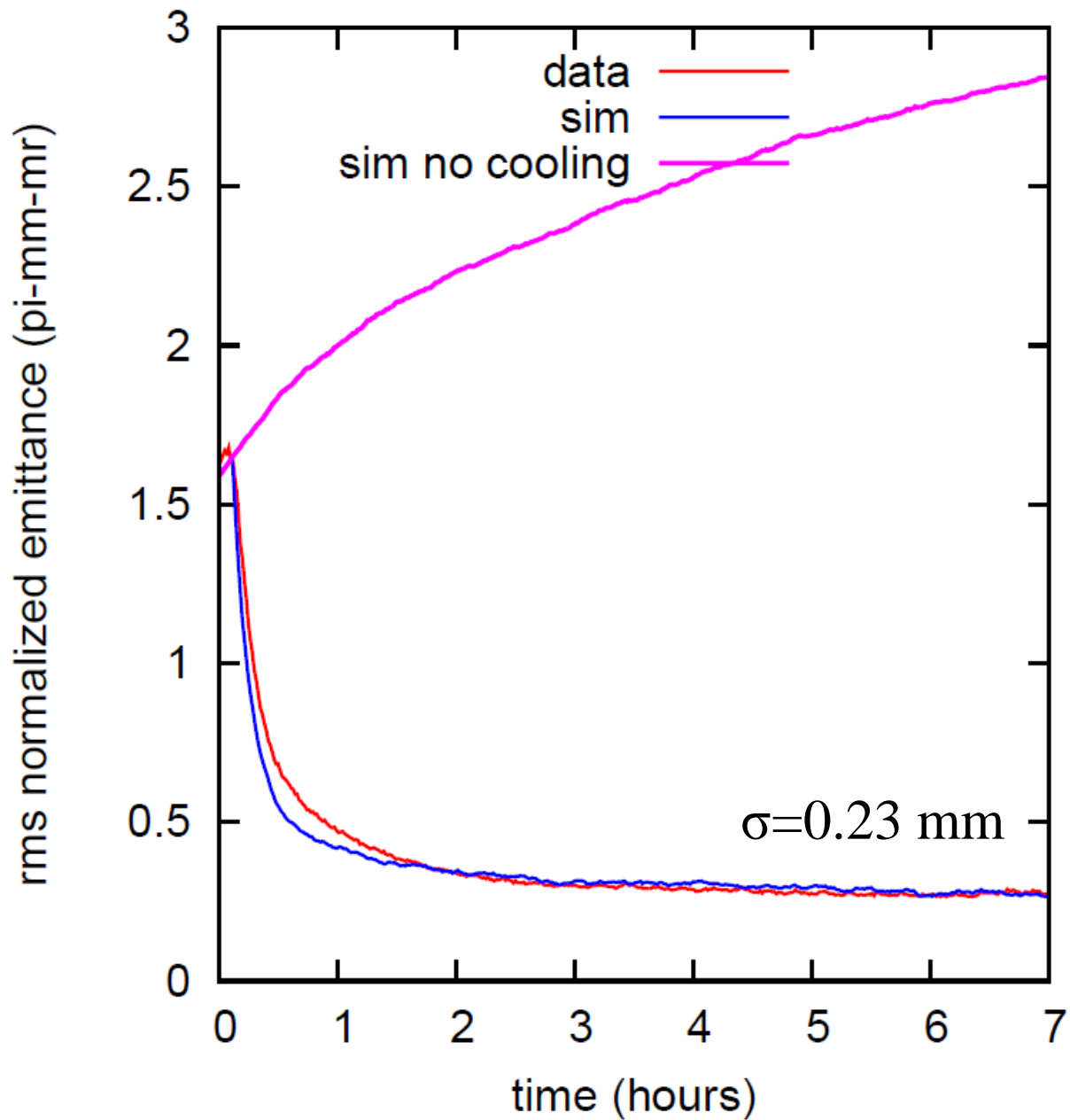Particle traveling to right $\quad x(z) = x_0 + \theta_x z, \quad z = c(t - t_0)$

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

Average over betatron phase

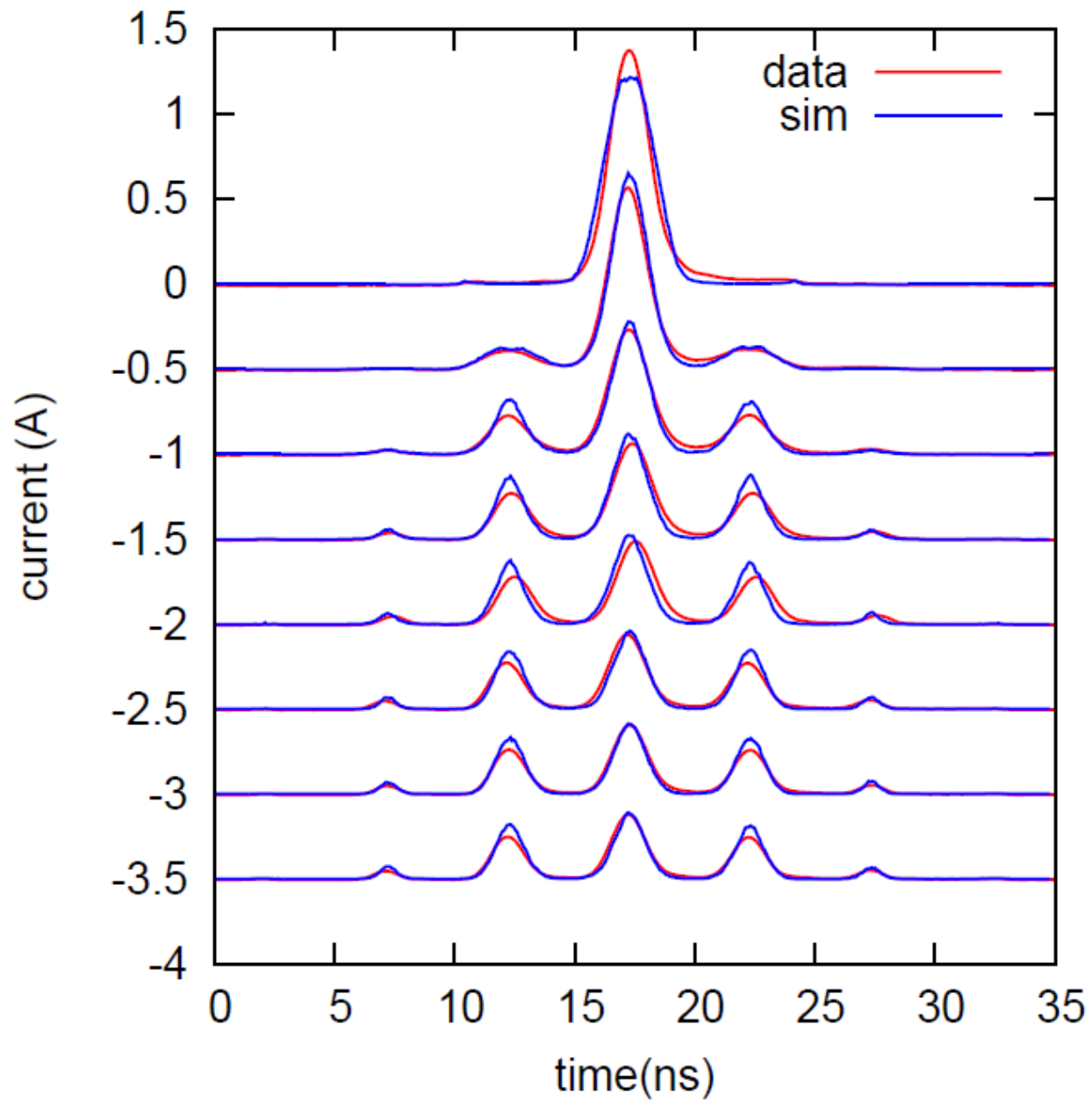$$P = \sigma F(\alpha_x)F(\alpha_y)\int dz\, \frac{\lambda(2z + ct_0)}{\pi\varepsilon\beta(z)}$$

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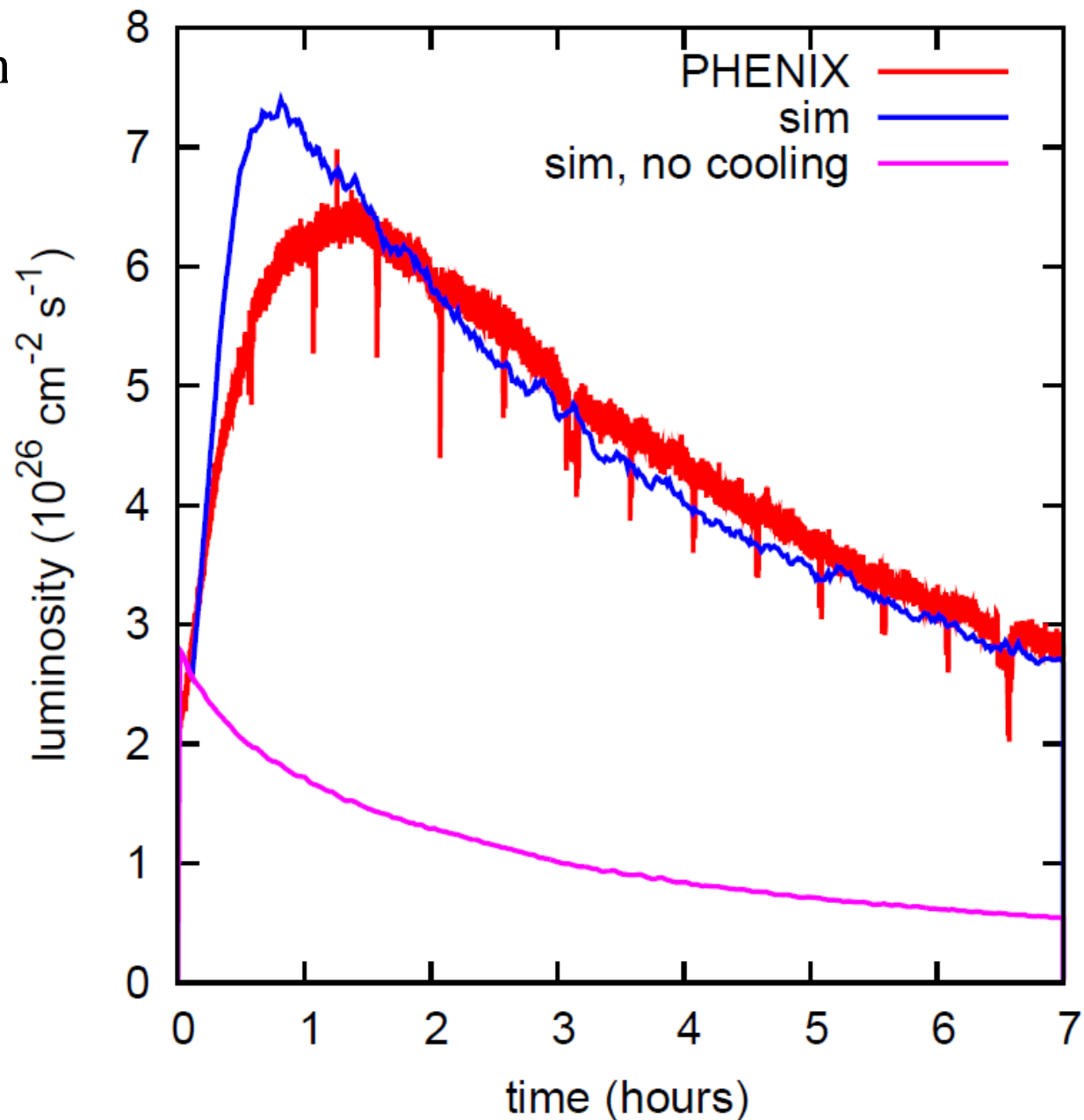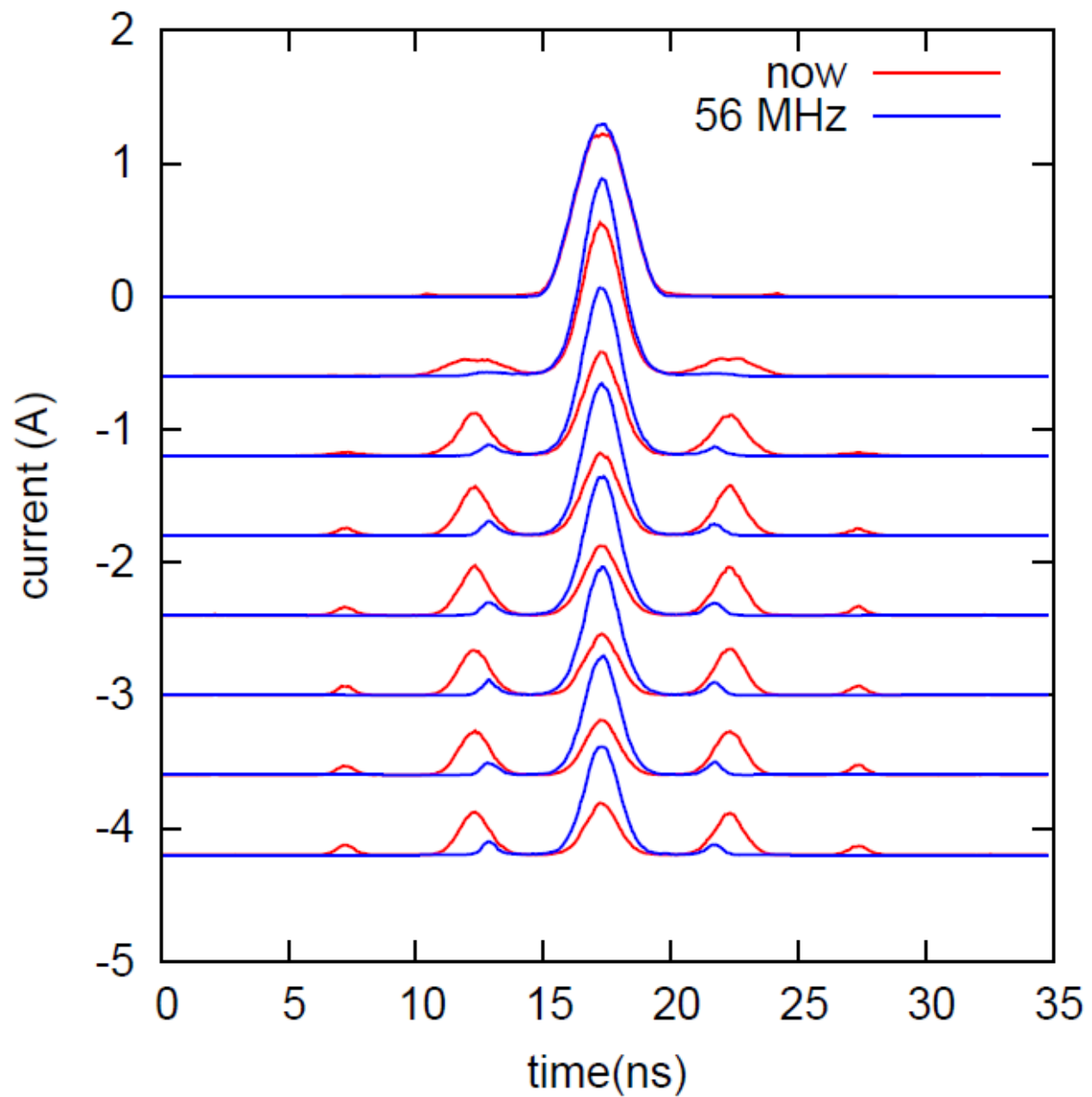
- Uranium beam size reduced

σ=0.23 mm

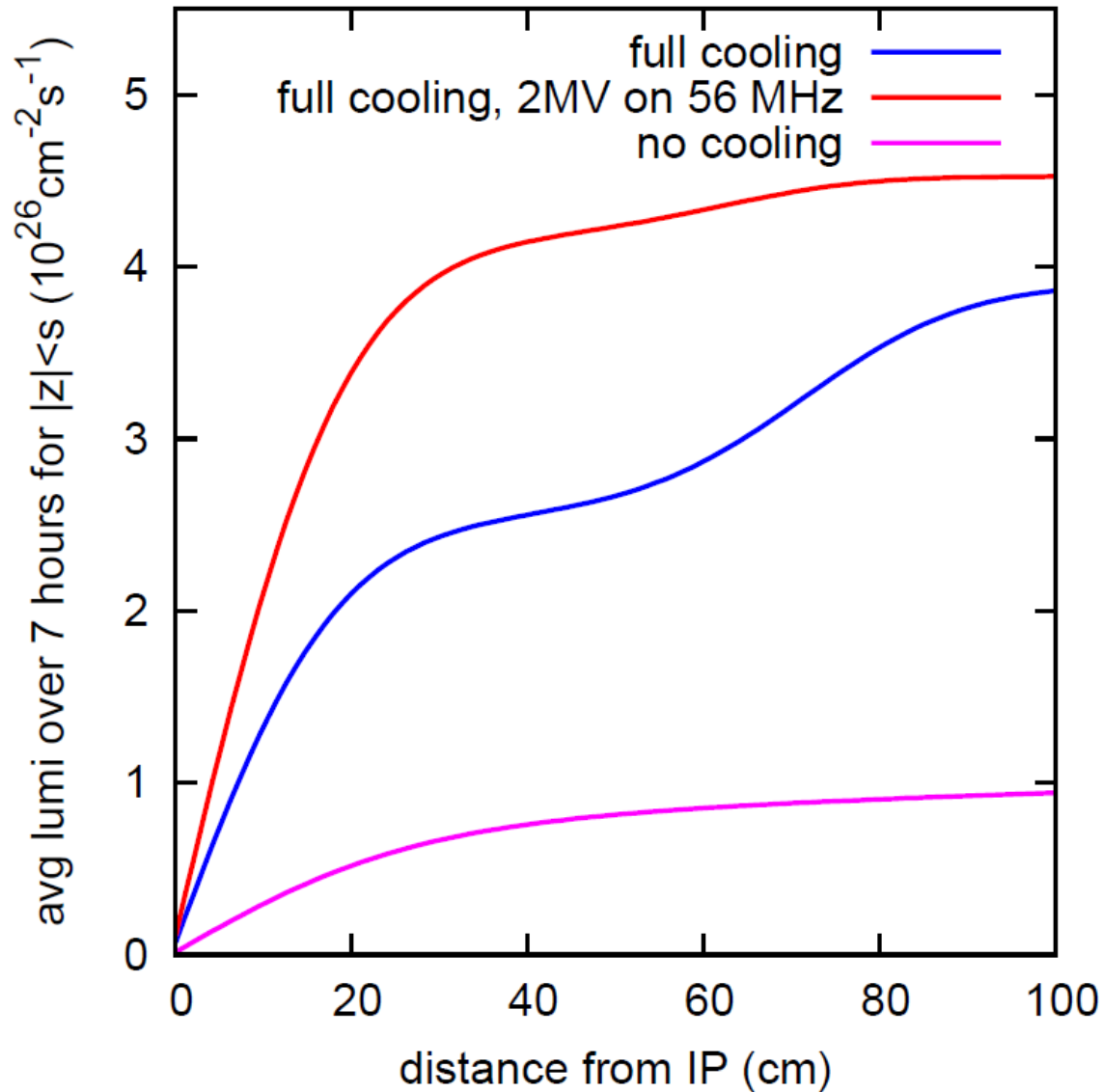- Longitudinal evolution for uranium

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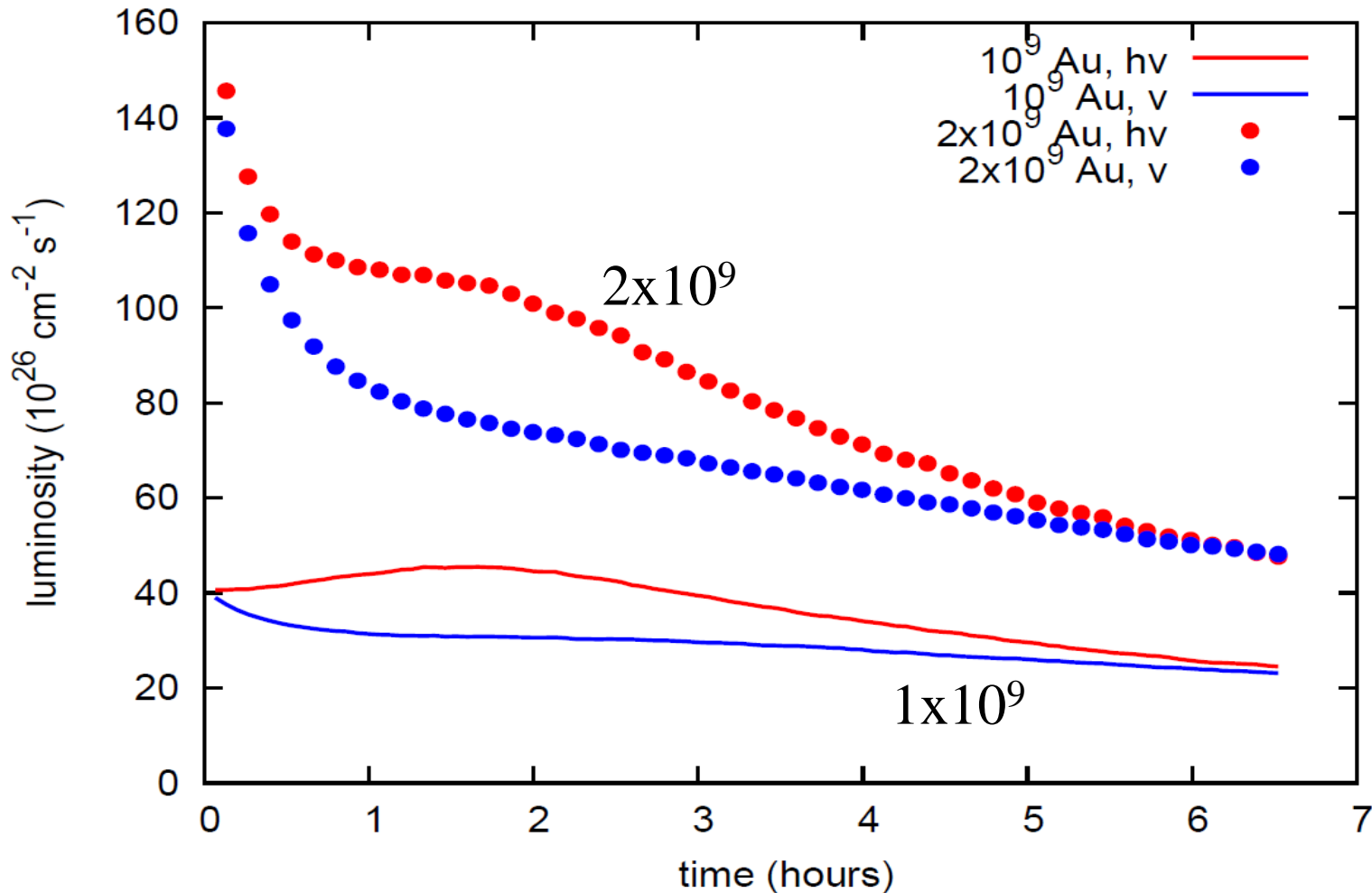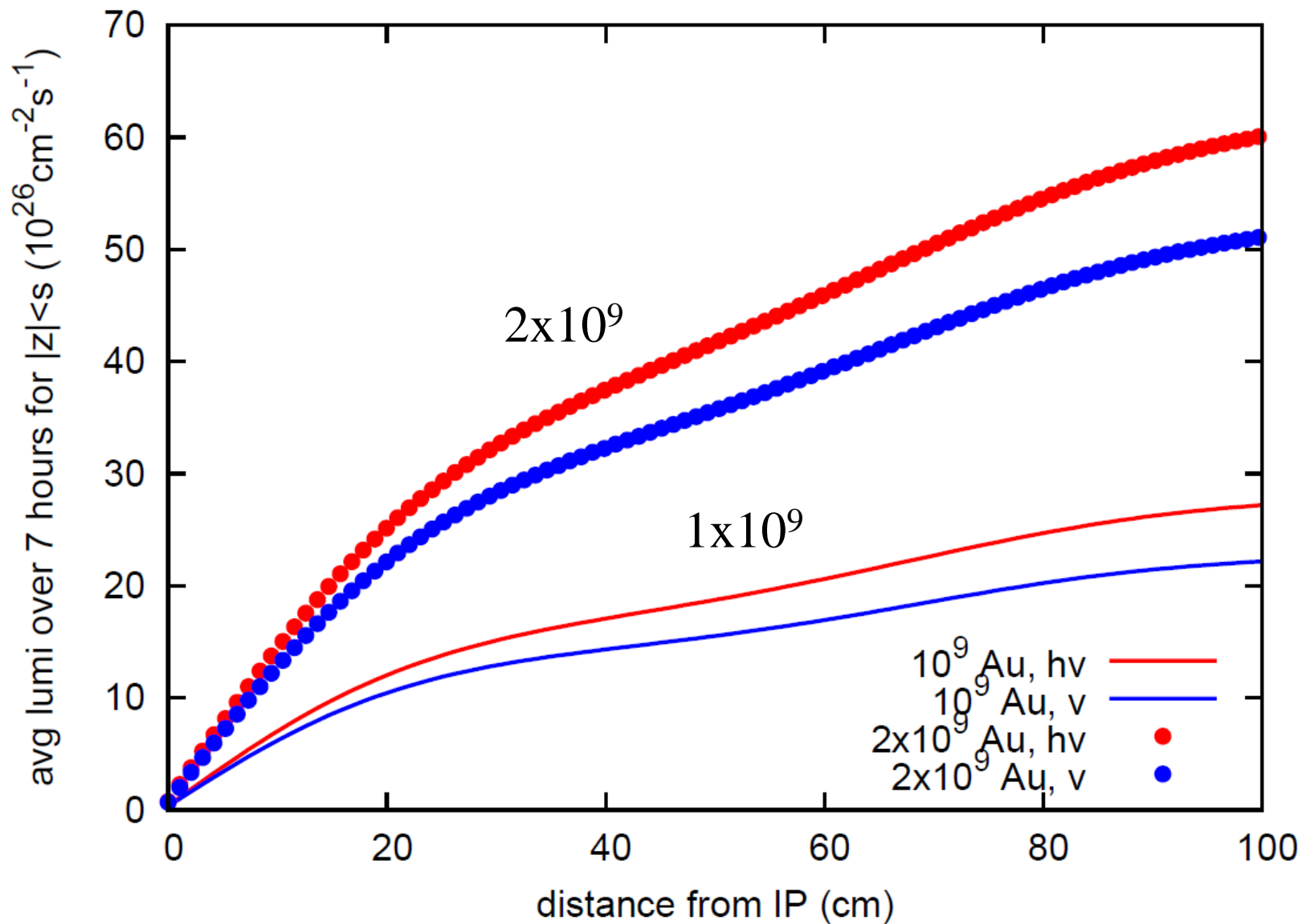- Integrals agree within 1%

- 56 MHz reduces debunching
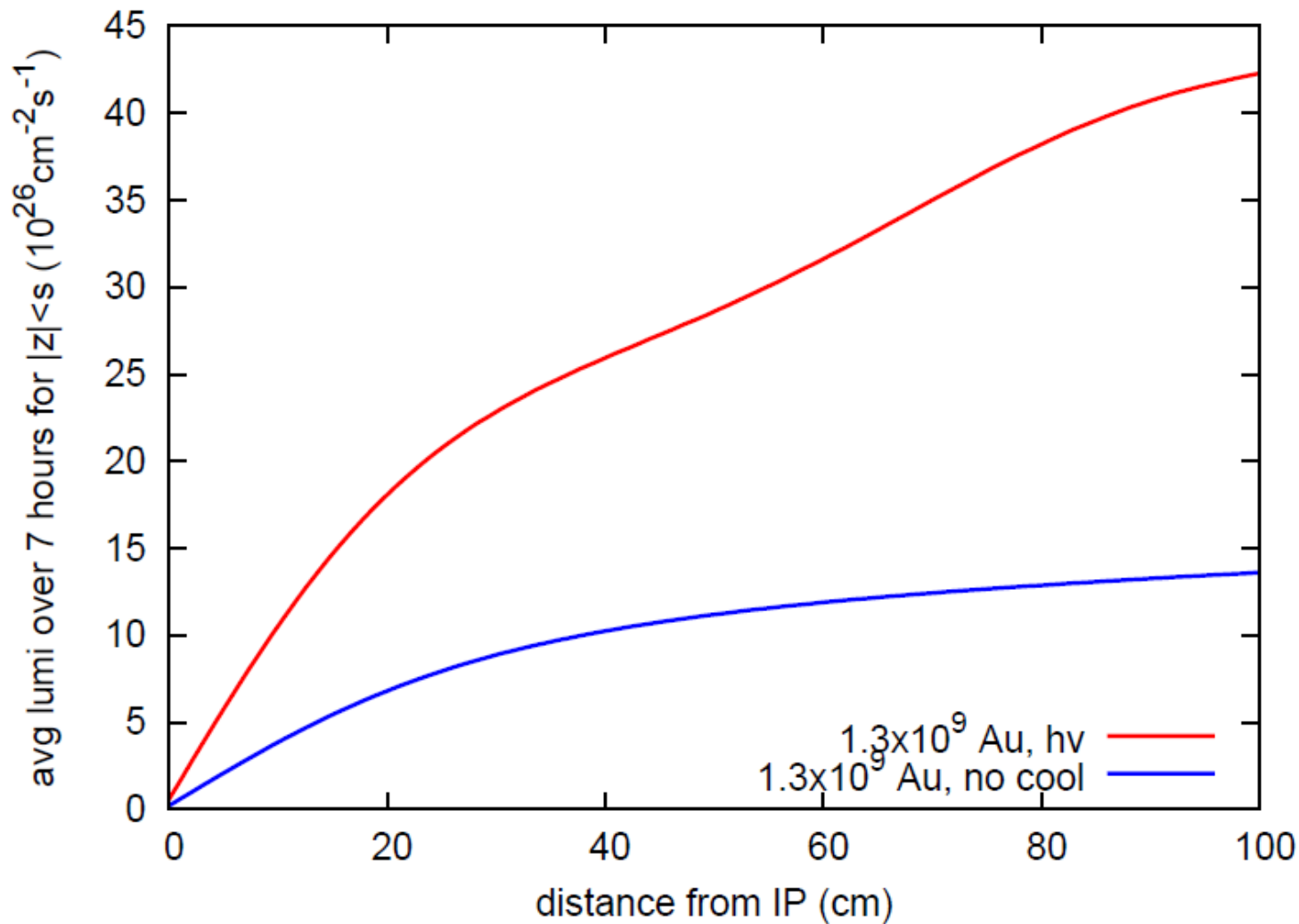
- 56 MHz cavity improves performance near IP

Au luminosity improved with horizontal cooling
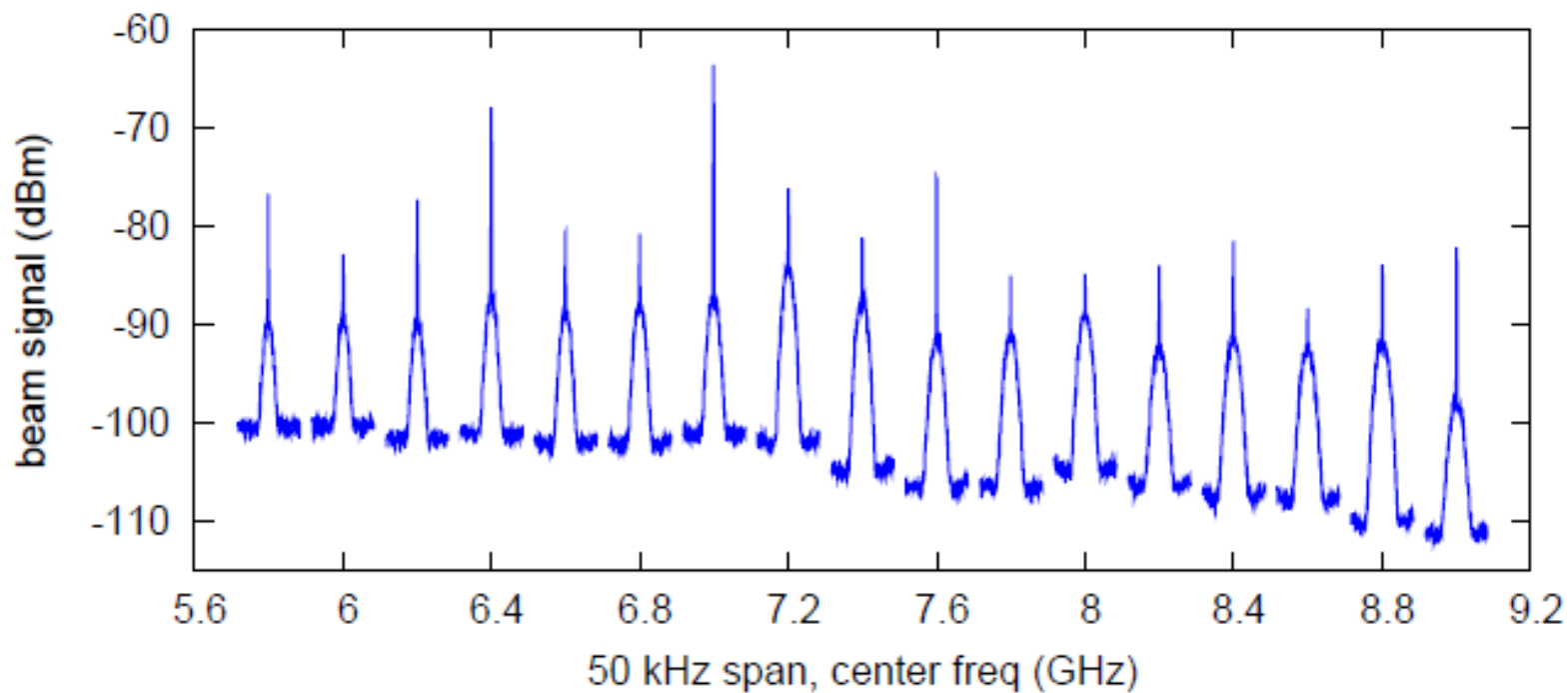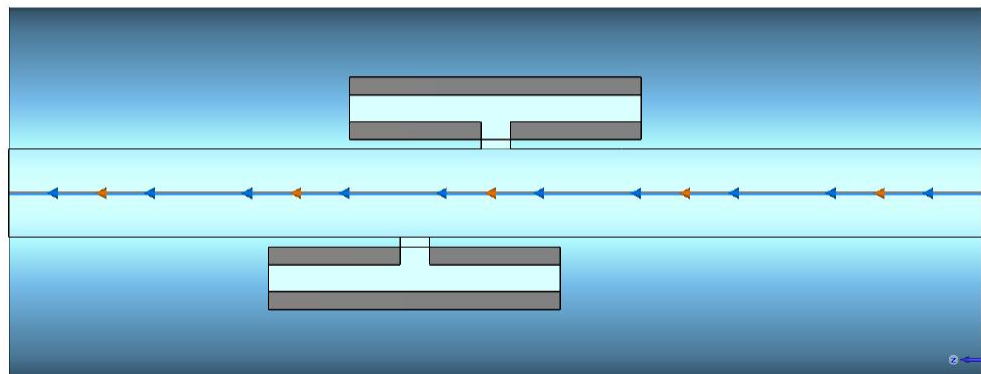Enough margin to increase from 1.3 to 2×10^9 per bunch.
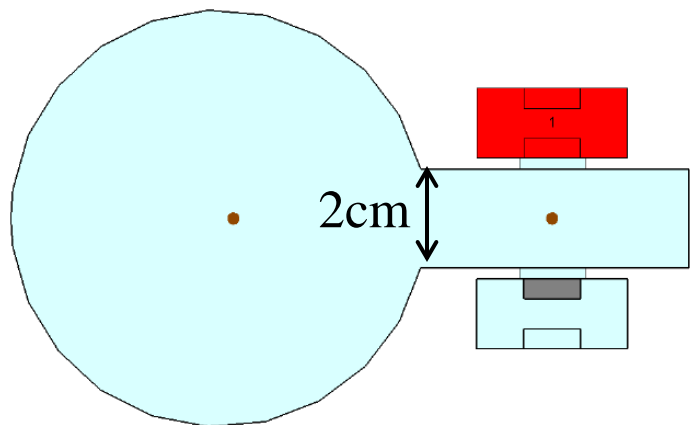
Au luminosity versus acceptance

Full cooling more than doubles integrated luminosity for typical intensities.

The y-axis is labeled "avg lumi over 7 hours for $|z| < s$ ($10^{26} \mathrm{cm}^{-2} \mathrm{s}^{-1}$)" and the x-axis is labeled "distance from IP (cm)". The legend reads: 1.3×10^{9} Au, hv (red), 1.3×10^{9} Au, no cool (blue).
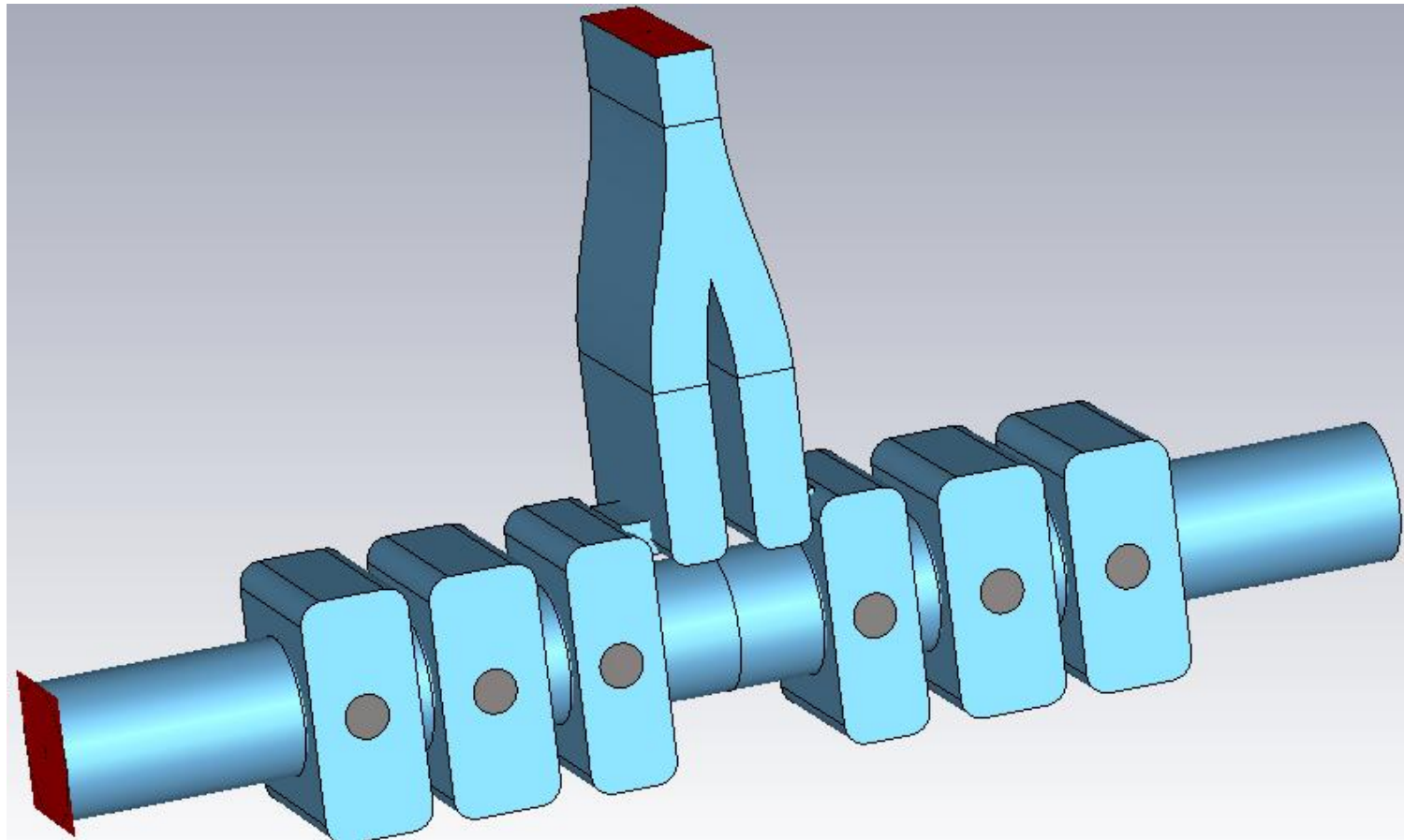
New keyhole longitudinal pickup

2cm

Updating longitudinal kickers to scissor design.
2x3 Cell longitudinal kickers increase voltage.
Waveguide coupler eliminates coaxial cables.
Prototyping in progress.

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.
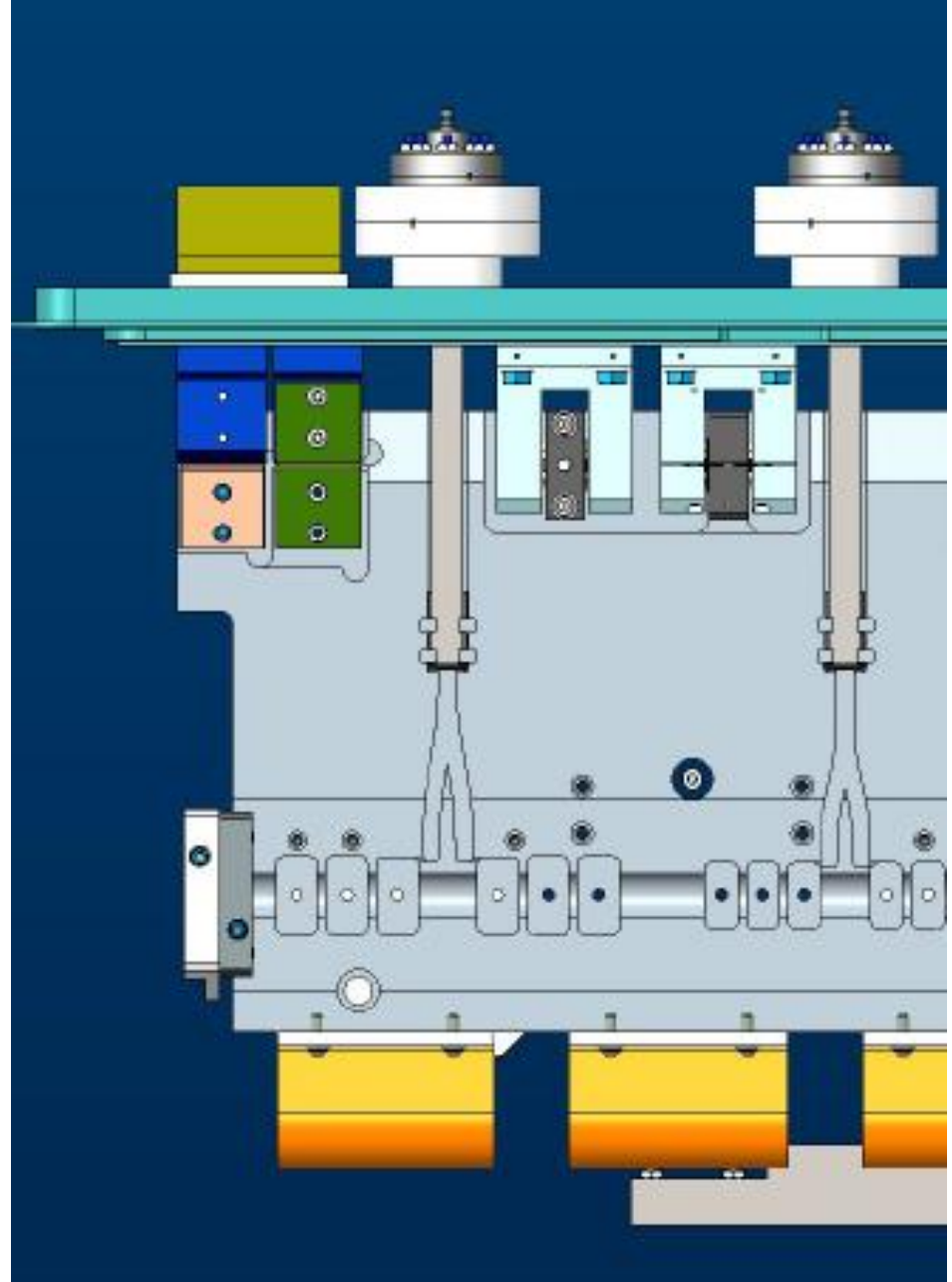
Conclusions

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.

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.