Burn-off Dominated Uranium and Asymmetric Copper-gold Operation in RHIC

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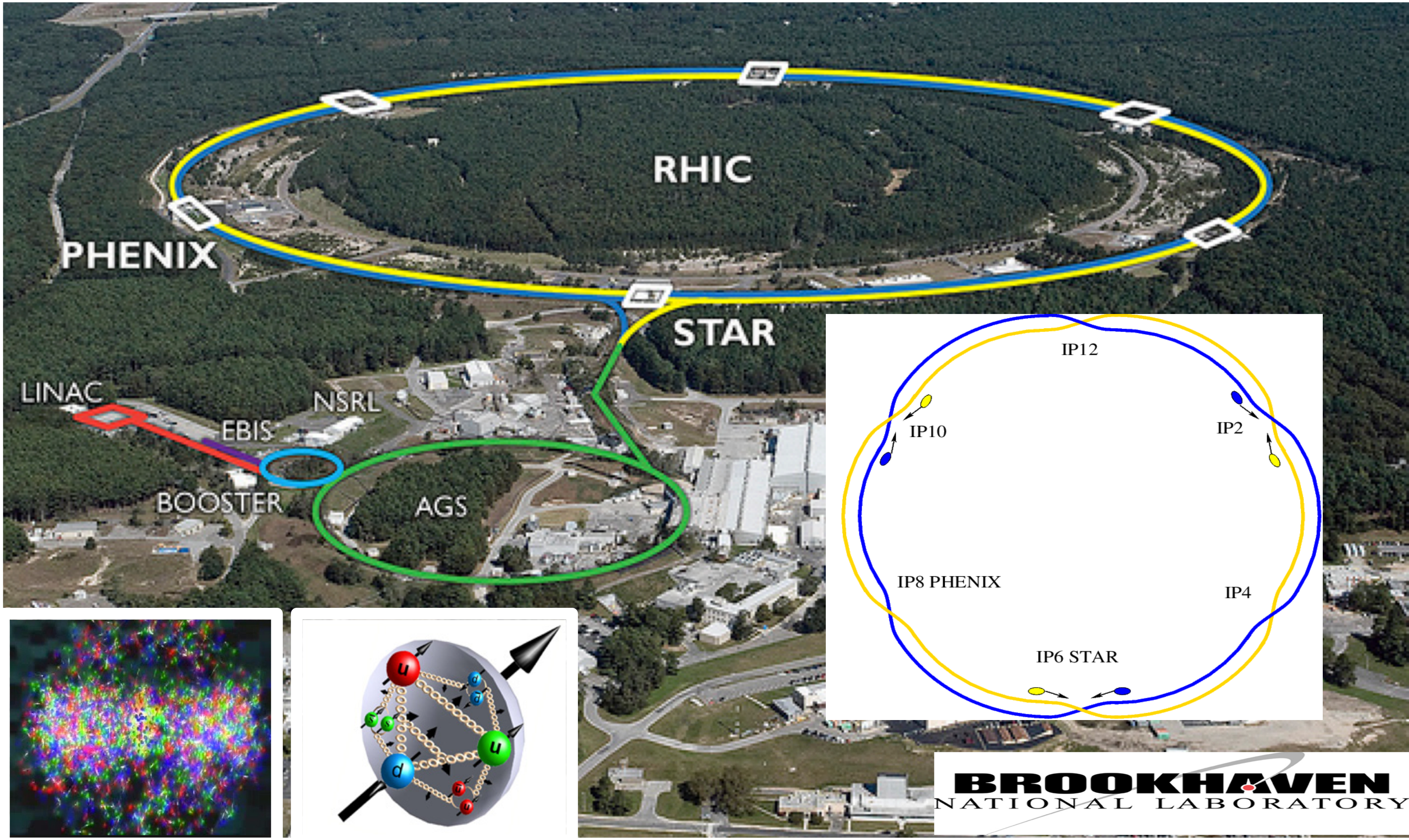
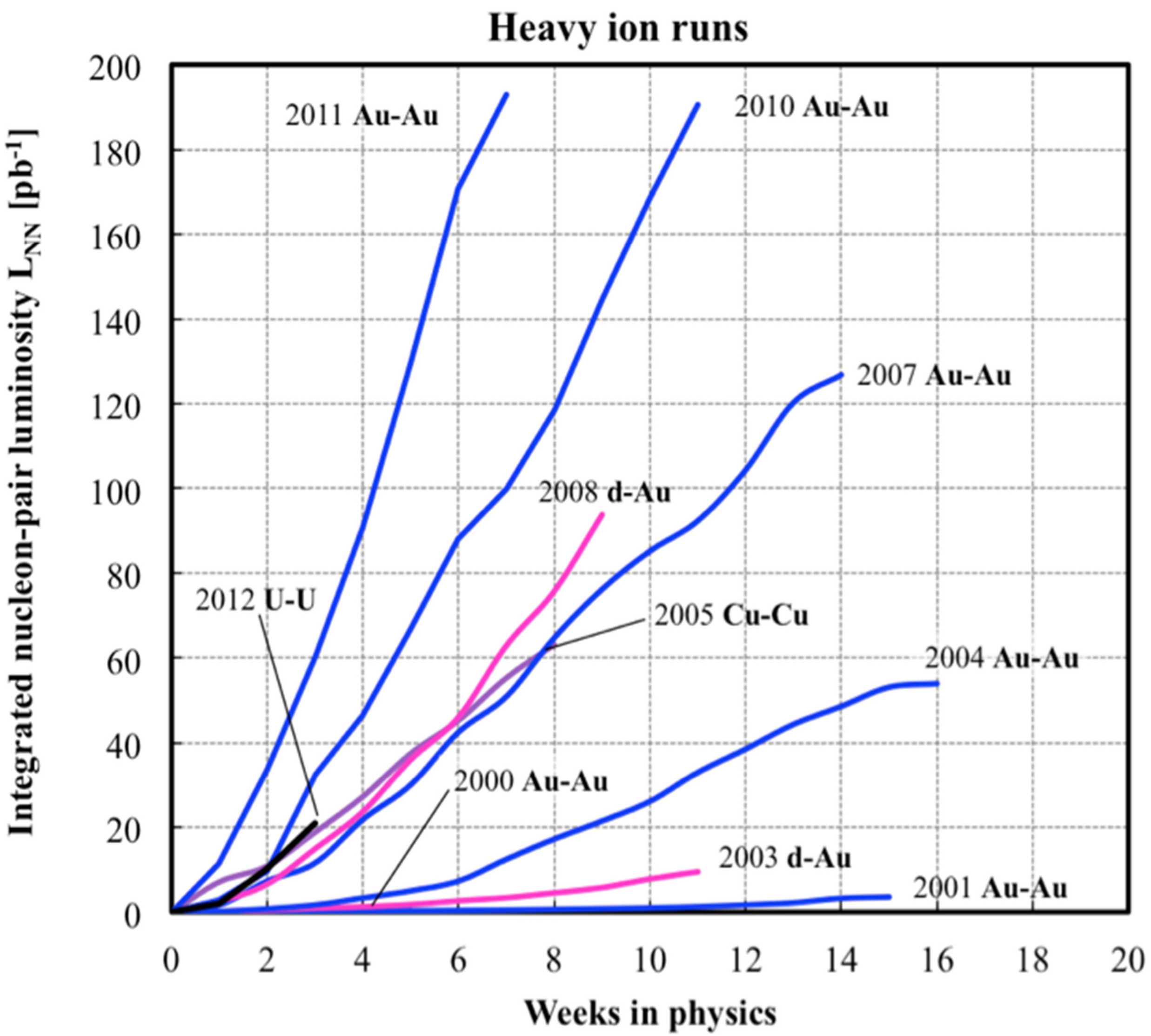
- Burn-off dominated U-U operation
- Asymmetric Cu-Au operation
- Summary

Relativistic Heavy Ion Collider (RHIC)



RHIC Heavy Ion Runs

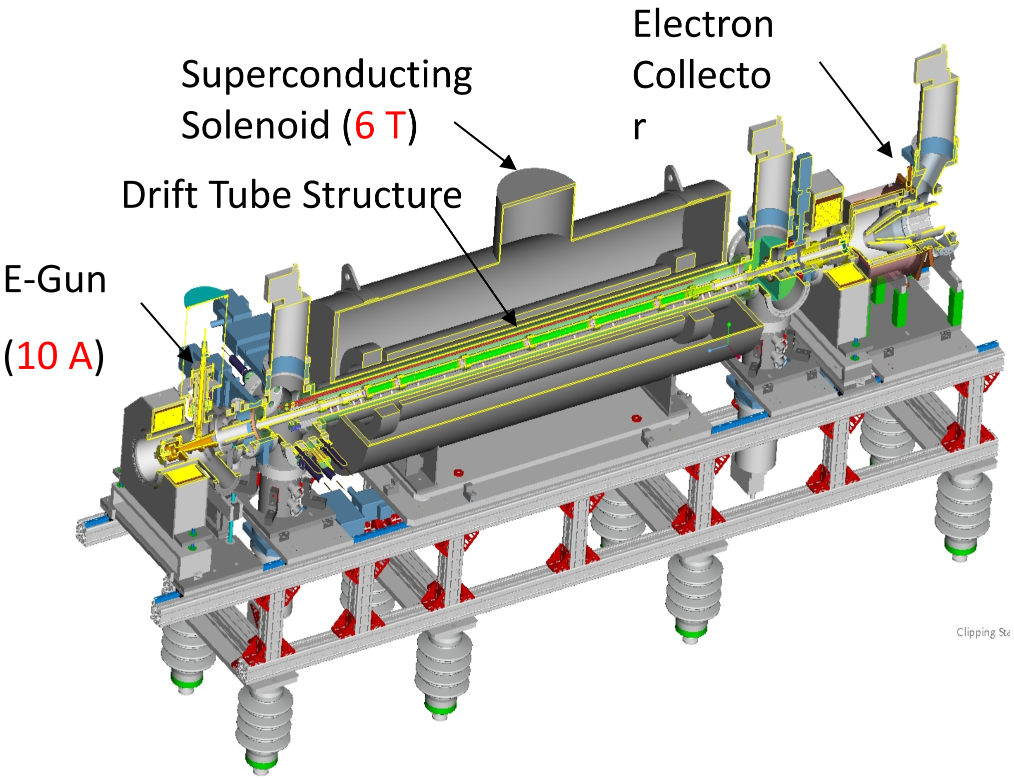


2012: collided high energy U-U and Cu-Au for the first time.

U-U 193GeV run:
- A=238 , Q= 92+
- April 19 -- May 15
- 5 day setup
- 2.9 weeks of Physics

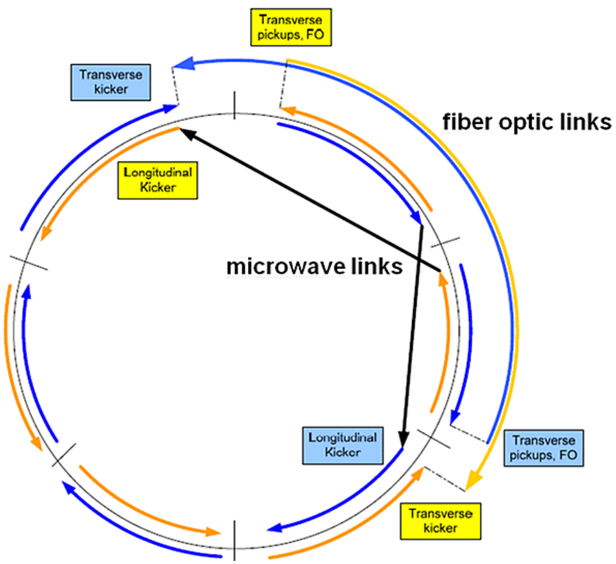
Cu-Au 200GeV run:
- Cu: A=63, Q=29+
- Au: A=197, Q=79+
- May 16 — June 25
- 4 day setup
- 5.5 weeks of Physics

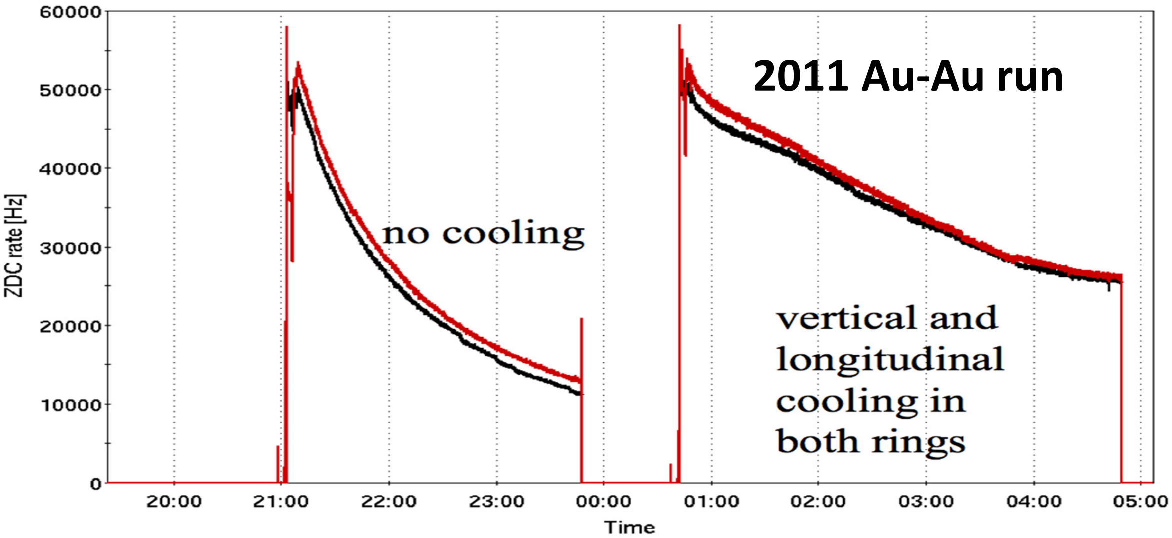
Electron Beam Ion Source (EBIS)



EBIS can produce beams of essentially any ion species, and can switch rapidly between two different species. It was used for the first time to provide ions for RHIC physics program.

3-D Stochastic Cooling





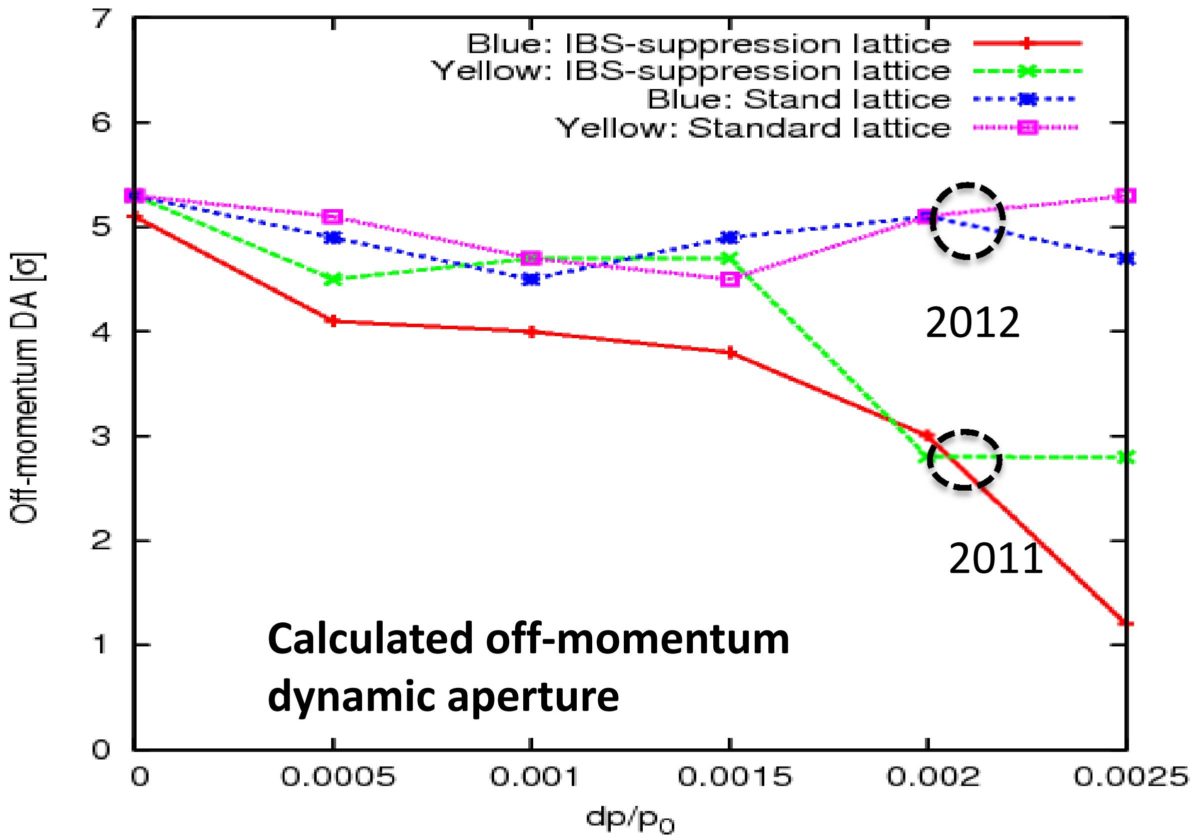
Intra-beam scattering (IBS) is the limiting factor for RHIC ion runs.

Stochastic cooling was implemented in past few years to counteract IBS effects. (For details: 3-D cooling: Mon. talk MOZAA2)

In 2011 Au-Au run we doubled integrated luminosity per store with longitudinal and vertical cooling.

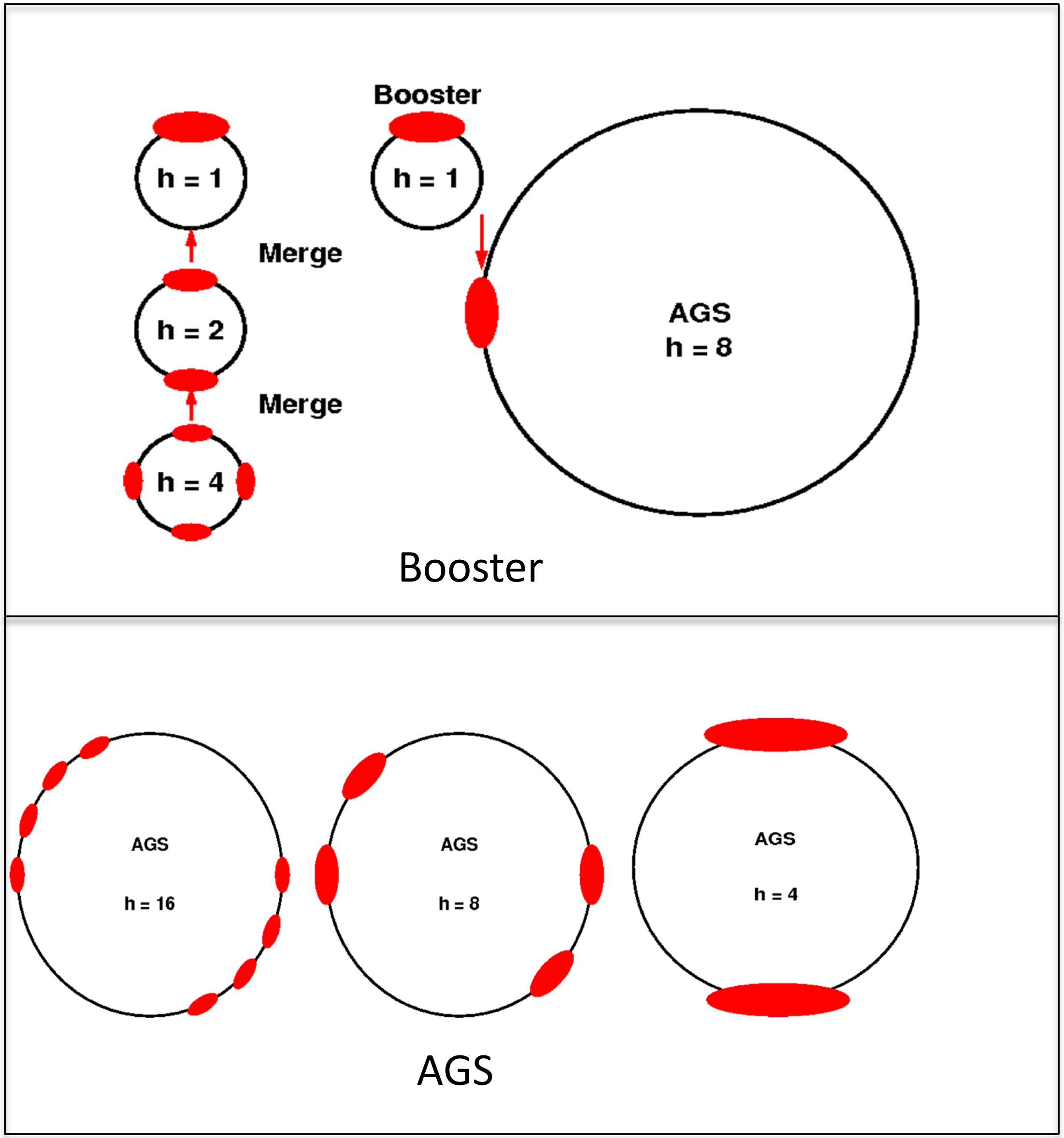
In 2012, horizontal cooling became available and full 3-D are operational.

Lattice: Larger Momentum Aperture



In RHIC 2010 and 2011 Au-Au runs, large beam loss were observed with RF re-bucketing and at store, which was caused by limited off-momentum dynamic aperture. In 2012 we chose a lattice with a much larger momentum aperture.

Bunch Merging: Increasing Bunch Intensity



In U-U run, due to lower intensity from pre-injector and lower than expected foil stripping and ion transfer efficiencies, we decided to boost the ion intensity in RHIC with extra bunch merging in Booster and AGS.

In principle they would increase bunch intensity in RHIC by a factor of 4. It was tested and finally operational two days before the end of U-U run end. Double bunch merging used for whole Cu-Au run.

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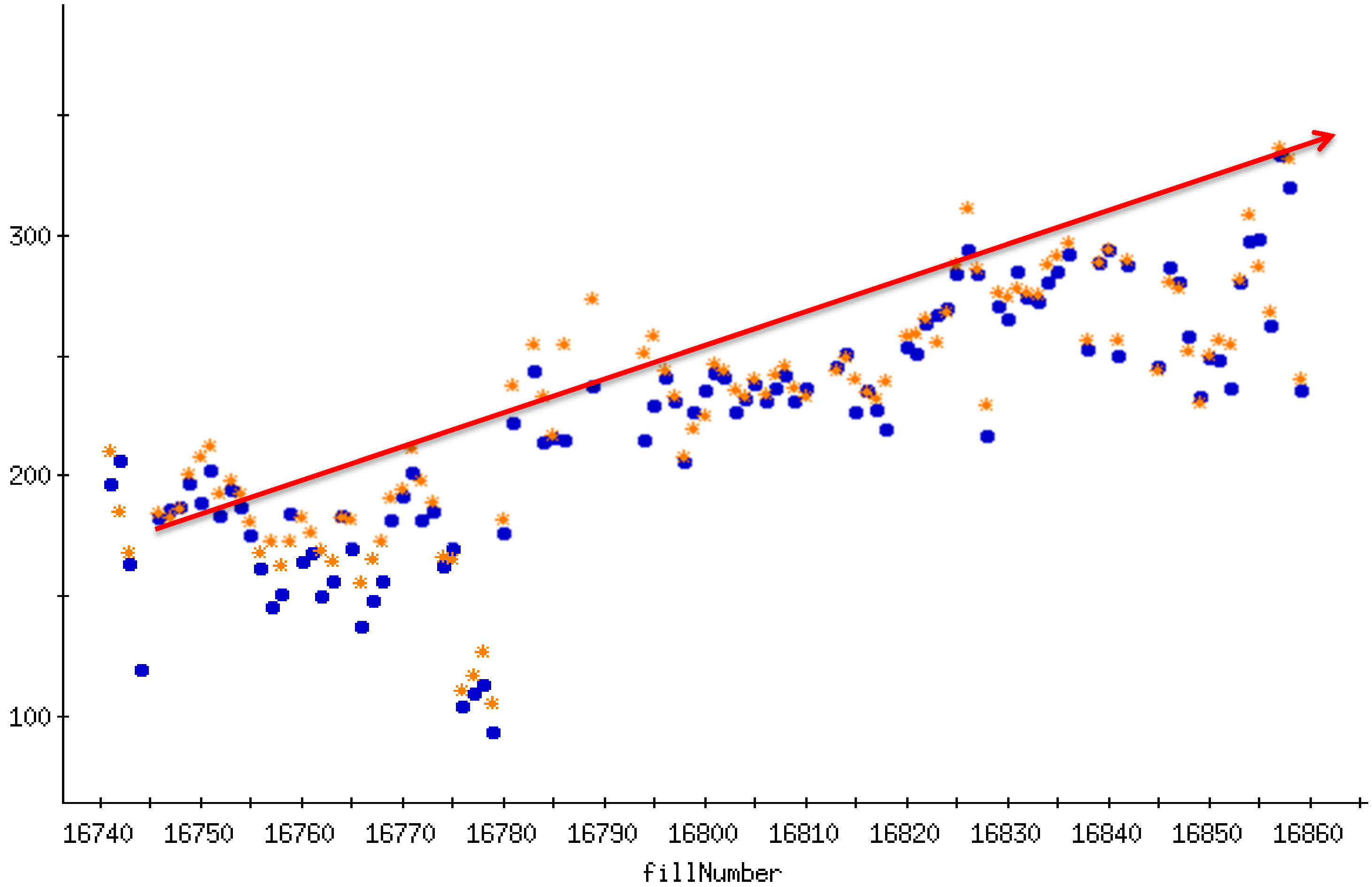
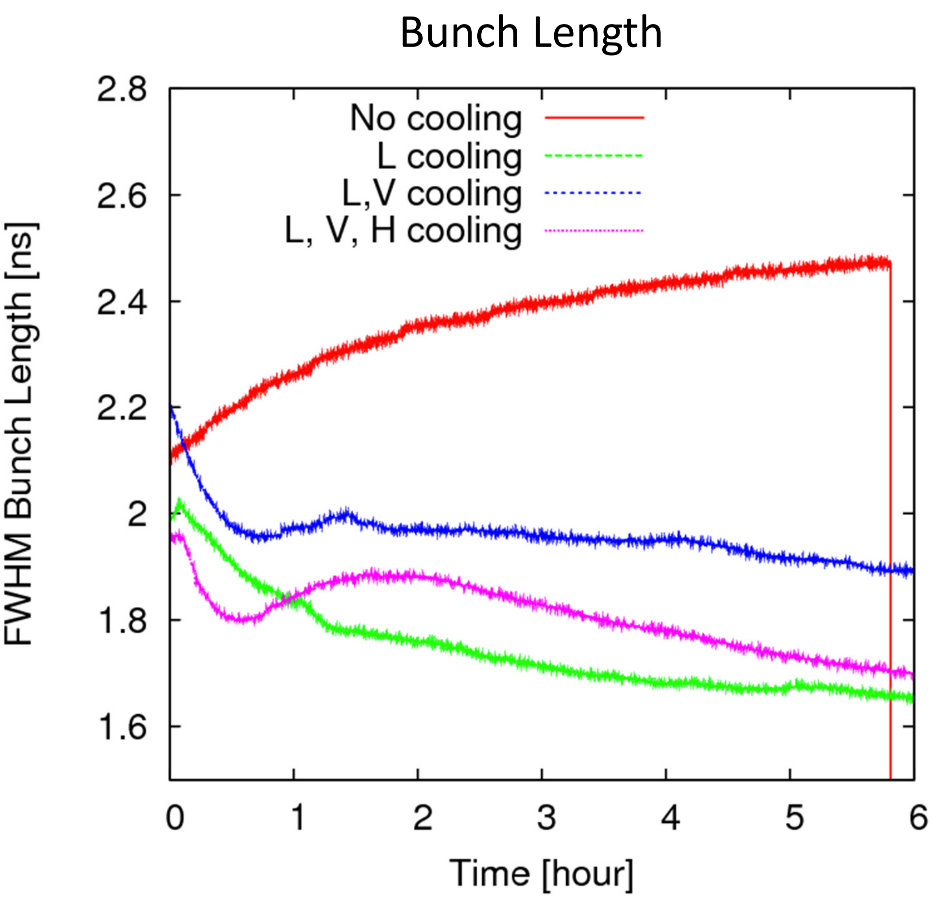
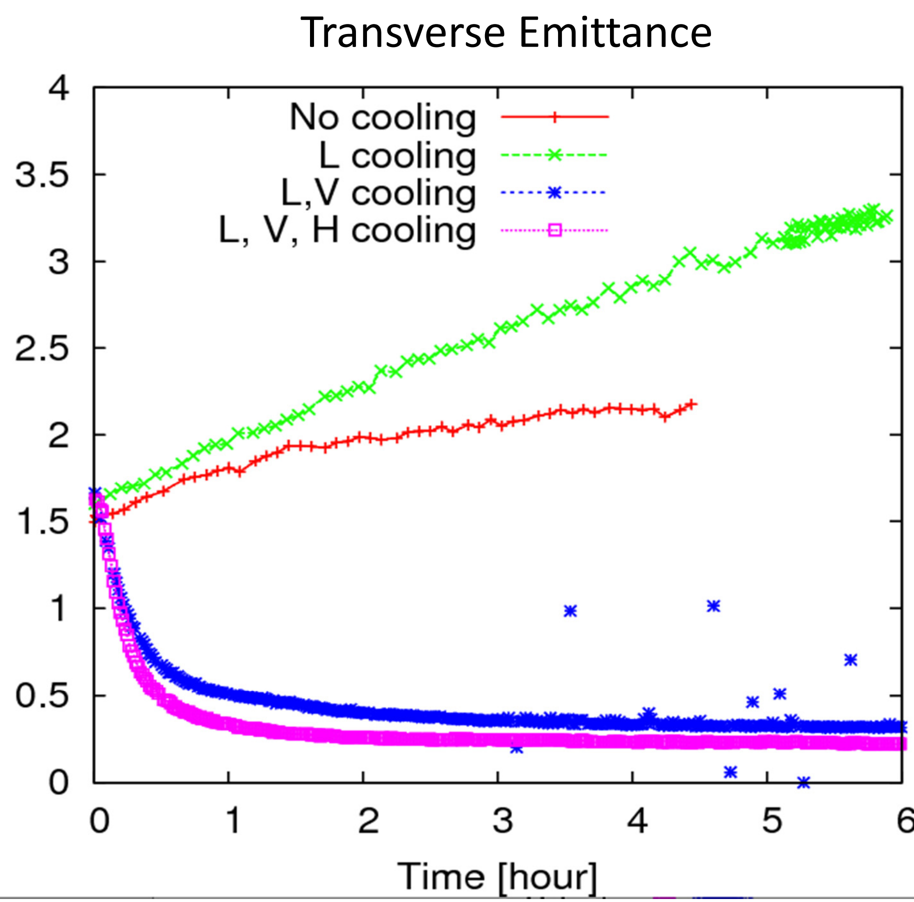
RHIC Uranium Bunch Intensity



With U ion bunch intensity 0.3e9, comparing to Au ion bunch intensity 1.3e9, IBS growth rate was smaller and stochastic cooling was more efficient.

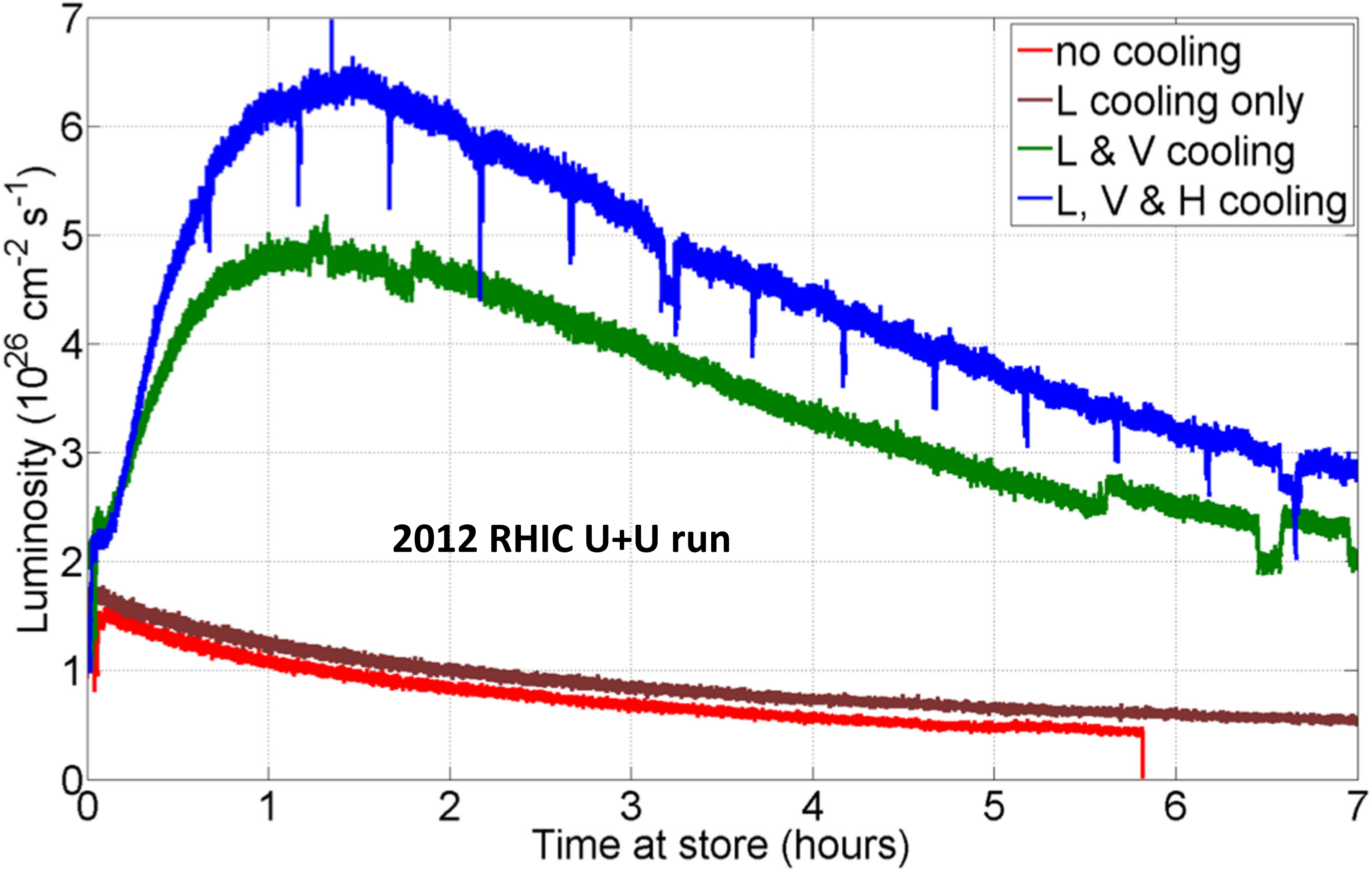
Emittance and Bunch Length





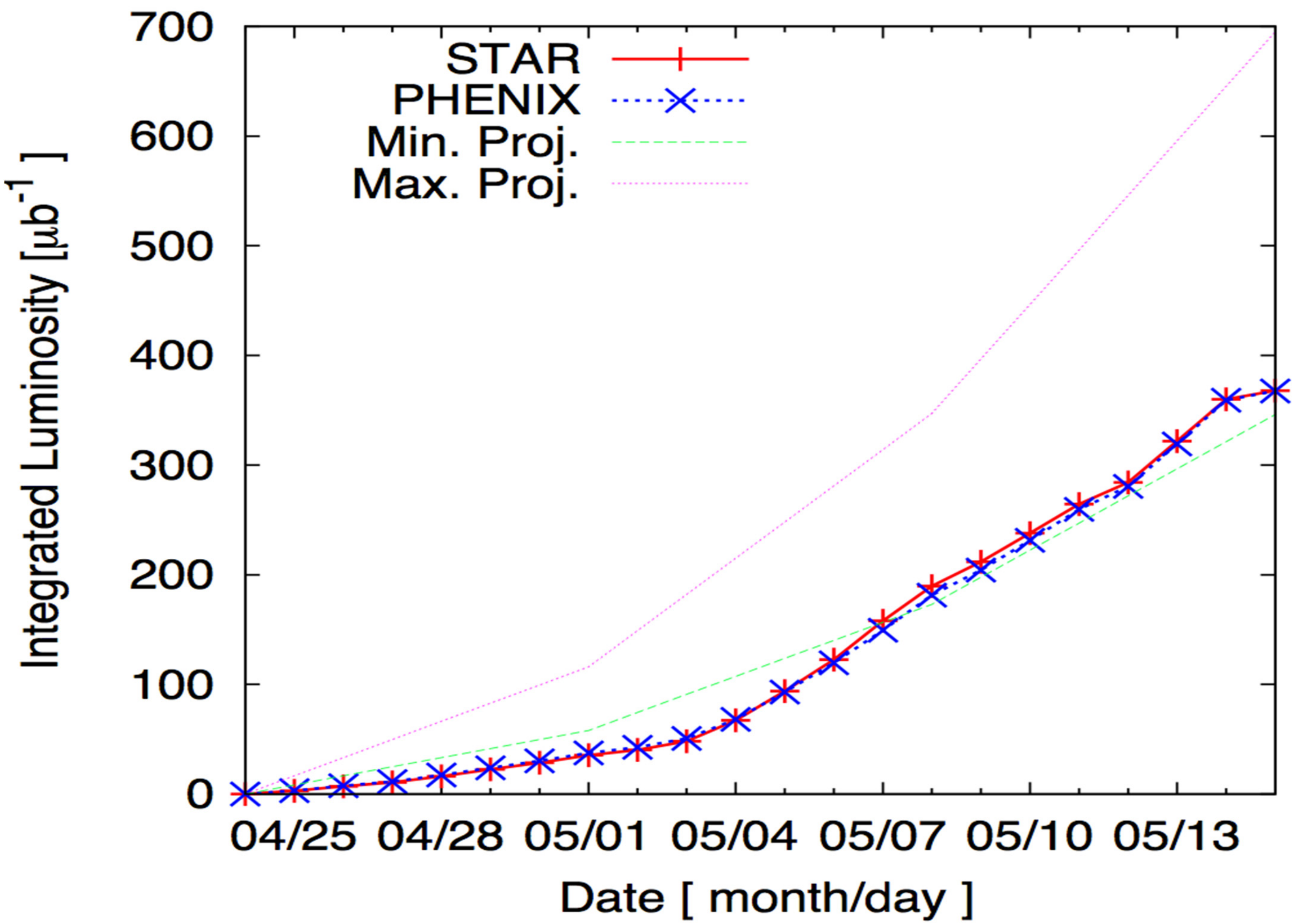
With 3-D cooling, the normalized rms transverse emittances were cooled down in 2 hours by a factor of 5, from 1.5 to 0.3 mm.mrad.

Luminosity with Stochastic Cooling



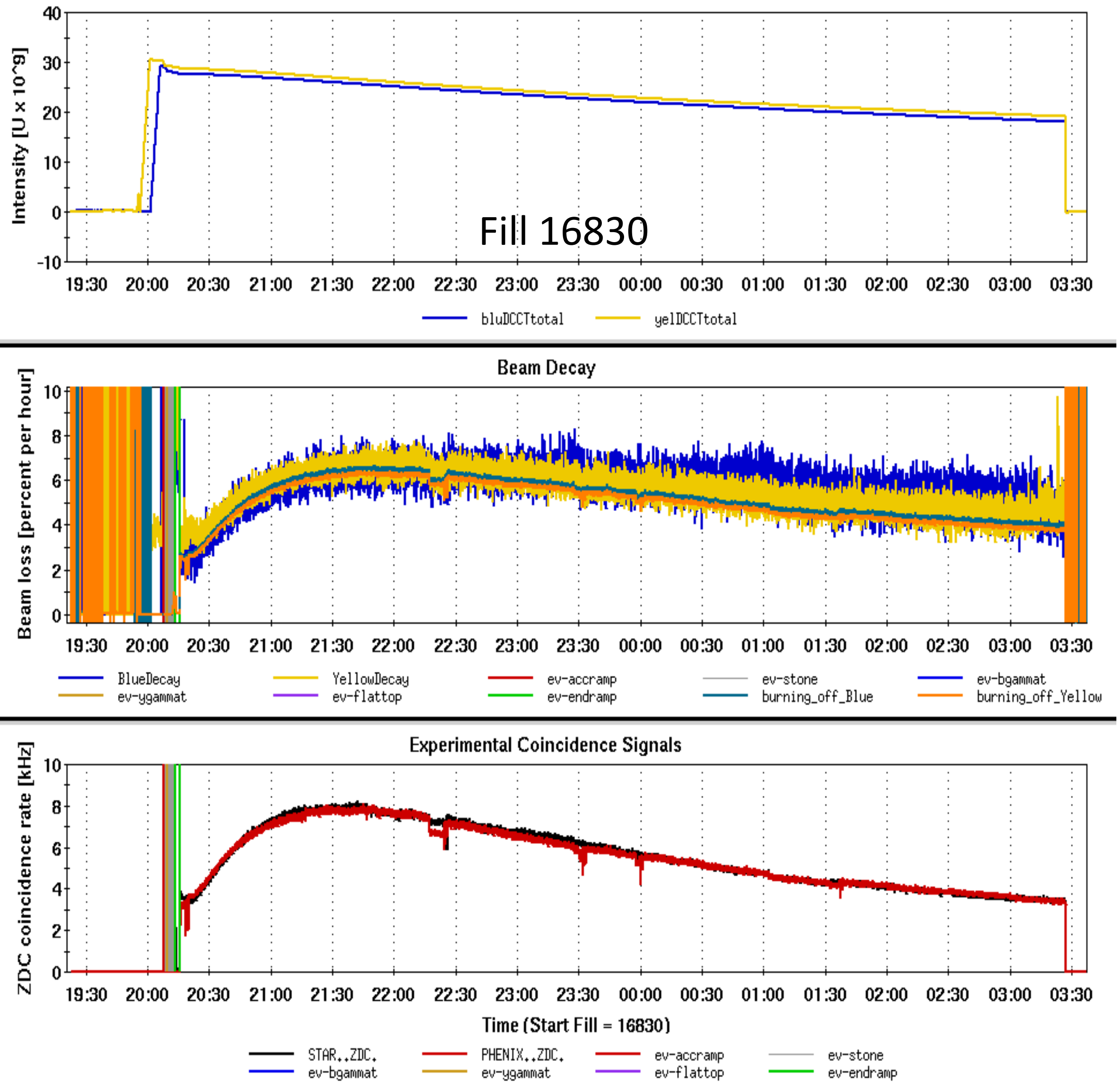
With 3-D cooling on, peak luminosity was more than 3 times the initial luminosity. Integrated luminosity per store was about 5 times of that without cooling.

Integrated Luminosity in U-U Run



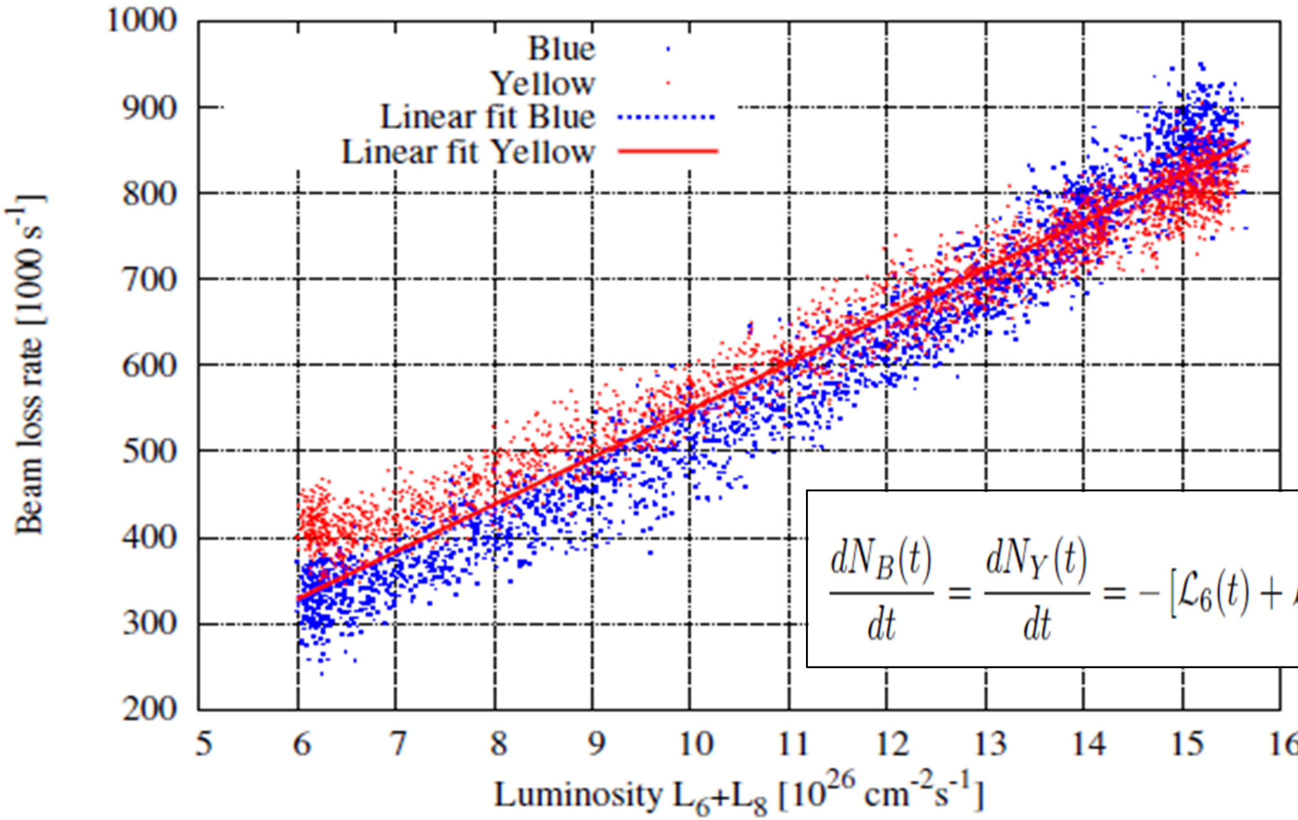
- Even with lower than projected bunch intensity 0.6e9, we reached luminosity goals set by the detectors STAR and PHENIX.
- The store time was 72% of calendar time, highest for RHIC high energy ion runs.

An Ultimate Collider



Thanks to enlarged off-momentum dynamic aperture and stochastic cooling, the beam loss in the physics stores was almost entirely from luminosity burn-off.

Total Cross Section Measurement

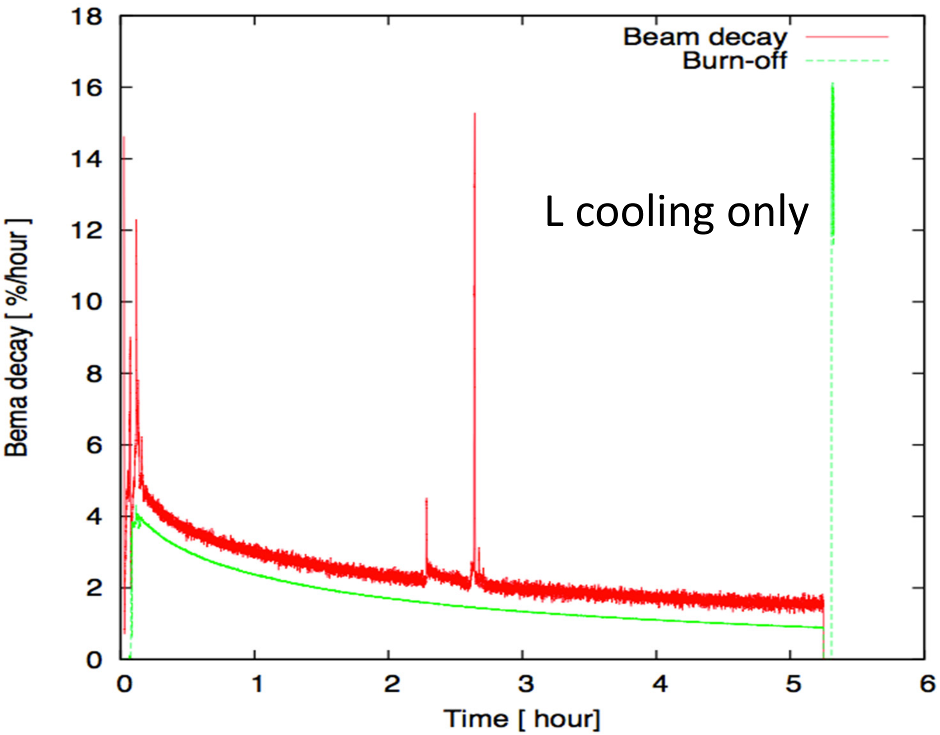


$$\frac{dN_B(t)}{dt} = \frac{dN_Y(t)}{dt} = -\left[\mathcal{L}_6(t) + \mathcal{L}_8(t)\right]\sigma_{tot}$$

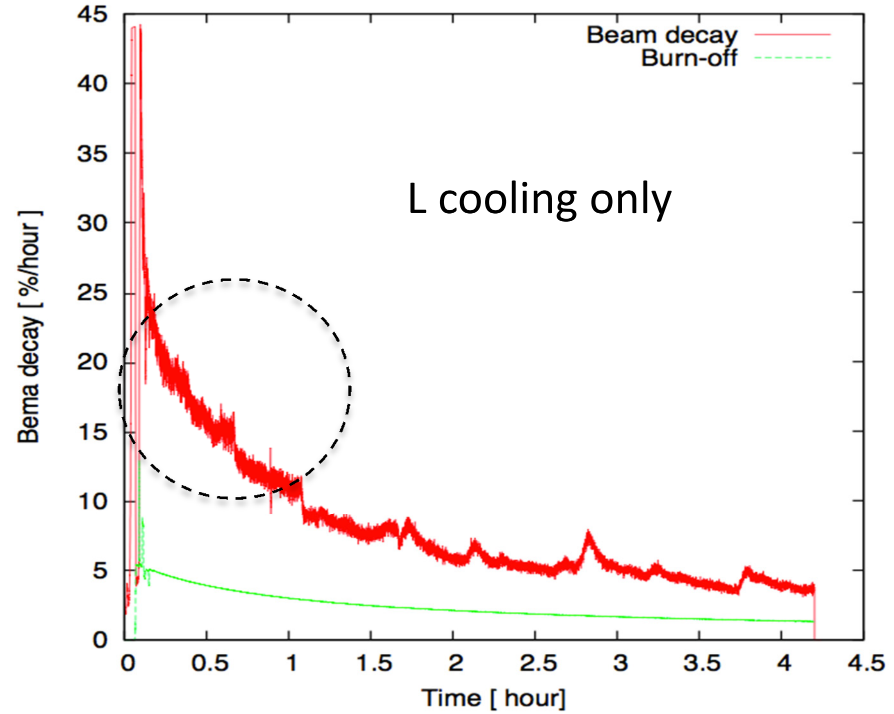
By fitting the beam loss rates against the sum of luminosities at IP6 and IP8, we measured the total cross section in the U-U collision is (506.9+/-0.21) b. The analytically calculated total cross section for U-U collision is 487.3 b. Therefore, burn-off takes up 97% of the total beam loss.

(For details: W. Fischer, et al, TUPFI078, IPAC'13. Submitted to Phys. Rev. C)

Particle Loss in Previous Au-Au Runs



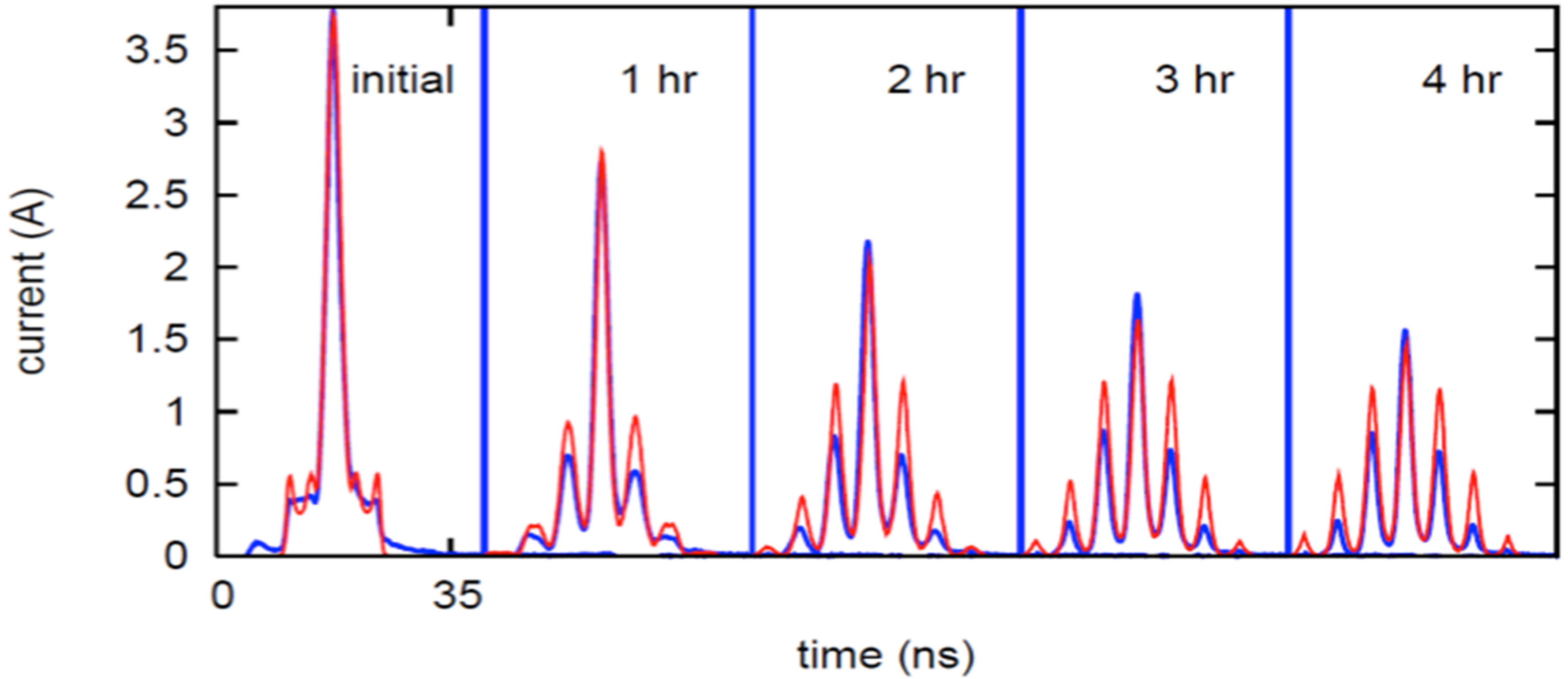
2007 Au-Au run
“Standard” lattice



2011 Au-Au run
“IBS-suppression” lattice

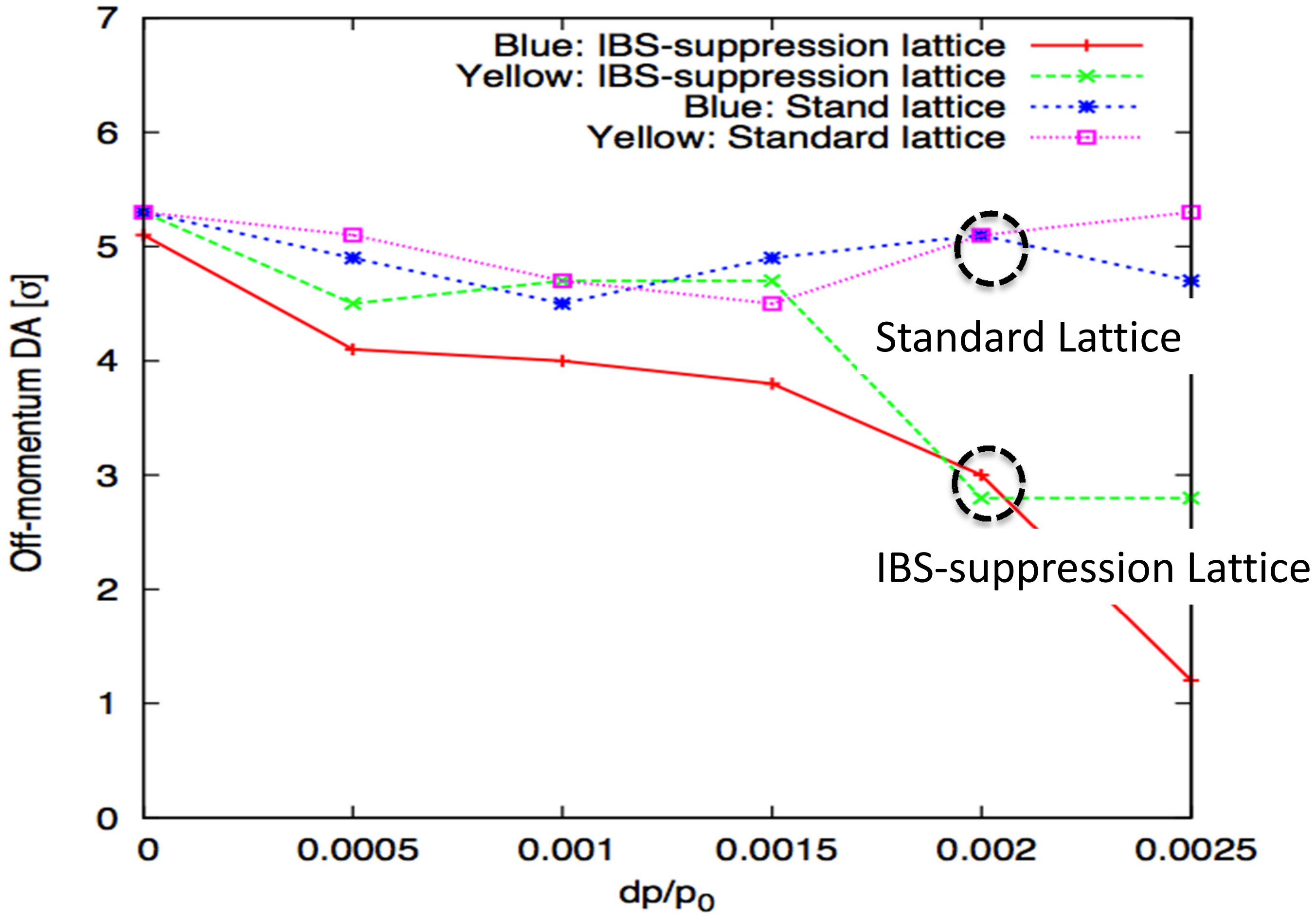
We observed large beam loss with RF re-bucketing in the 2011 Au-Au run, which hints that “IBS-suppression” lattice gives a lower off-momentum dynamic aperture.

Particle Loss with Cooling at Store



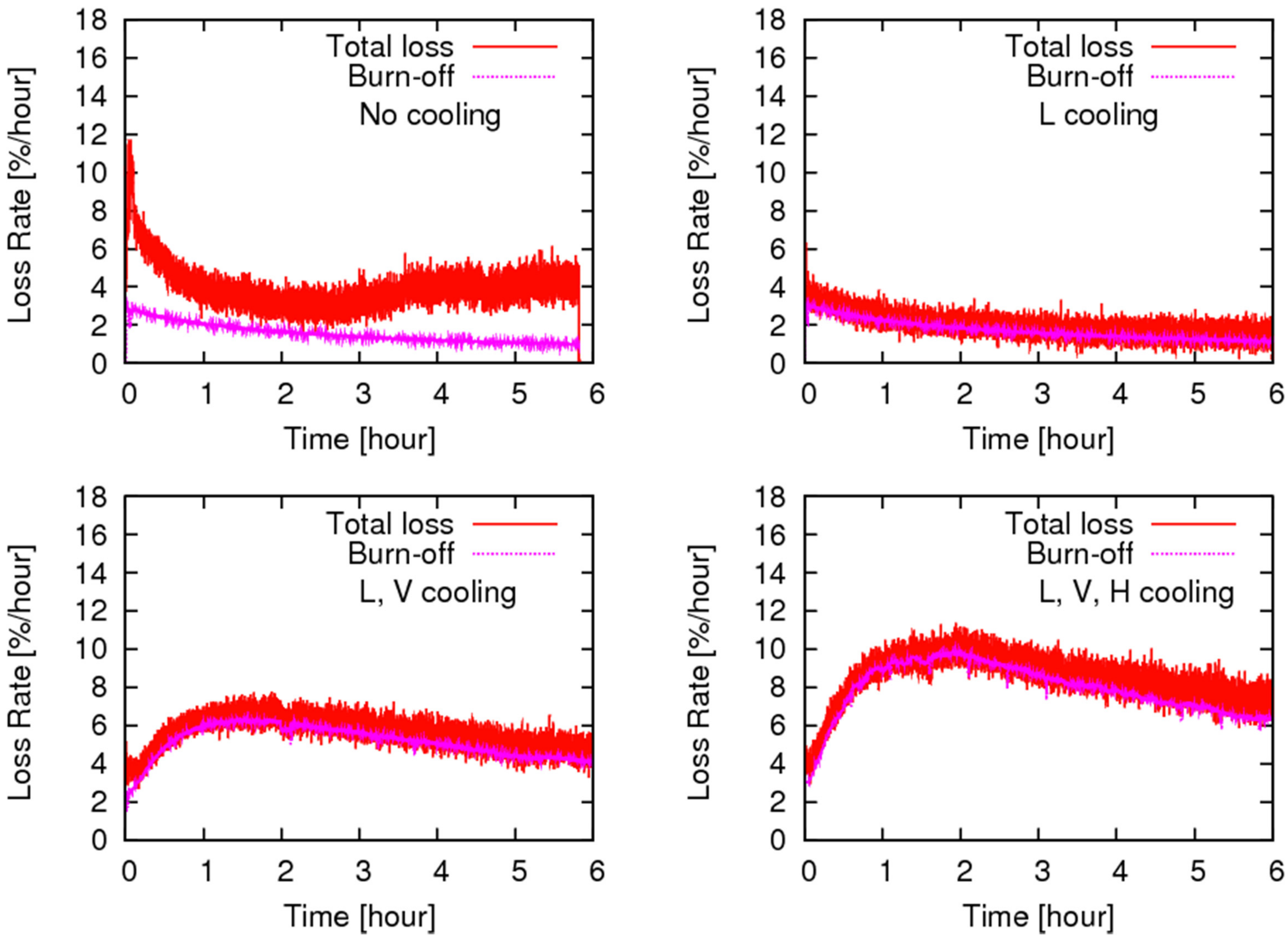
Into the store, we also observed more particle loss in 2011 Au-Au run. These particles are with larger momentum errors and get lost during leakage from center bucket to adjacent buckets due to limited off-momentum aperture.

Improving Off-Momentum Aperture



Based on observations of particle loss in the previous RHIC Au-Au runs and dynamic aperture numeric simulation, we adopted the 2007 RHIC Au-Au lattices which provides a larger off-momentum aperture.

Particle Loss Rates with Cooling



With long. cooling, burn-off dominated beam lifetime was achieved with new lattices.

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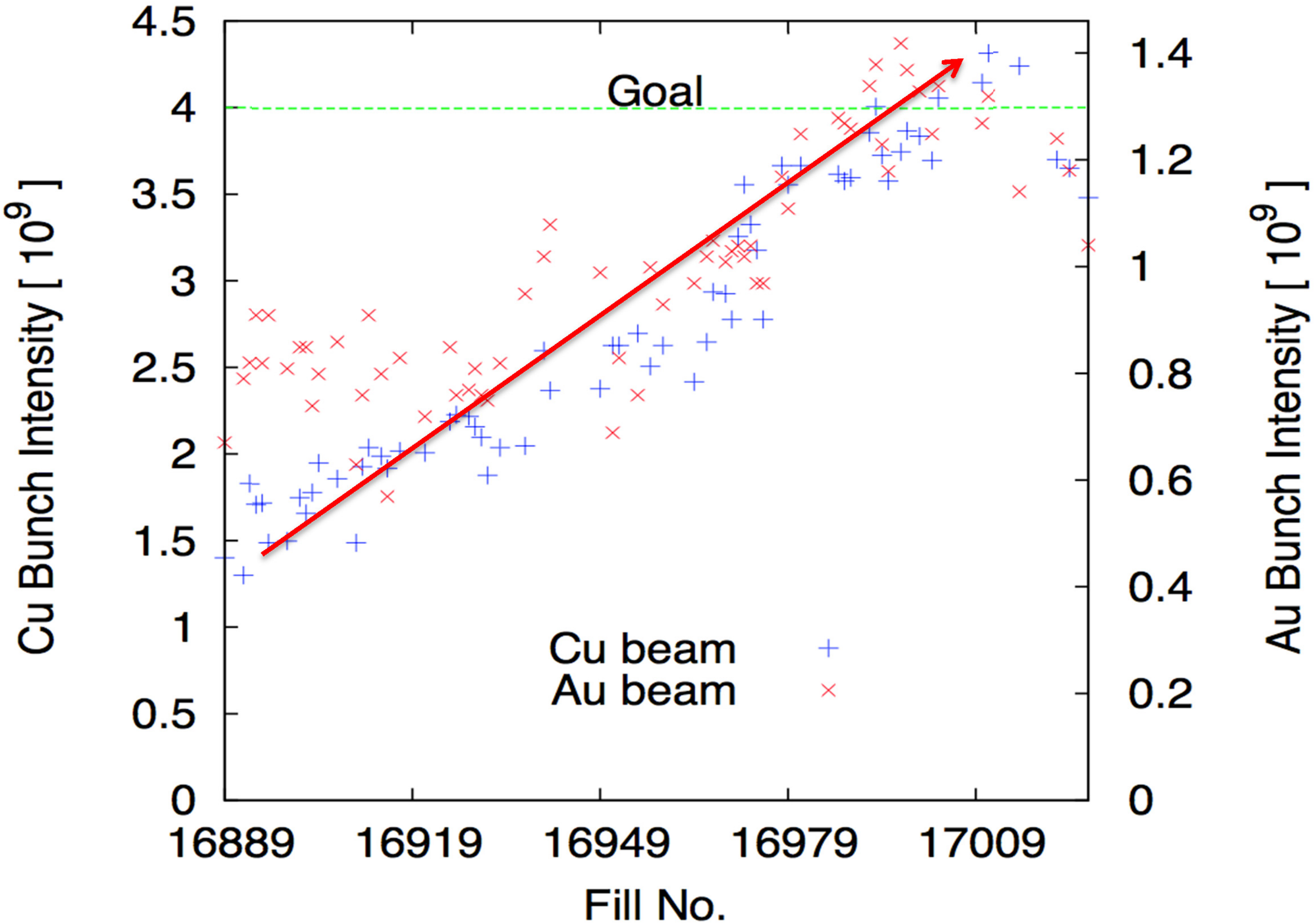
Bunch Intensities in Cu-Au Operation



Double bunch merging in Booster and AGS increased Cu and Au ion bunch intensities.
We generated the most intense ion bunch for RHIC ion runs.

Different IBS and Cooling Rates

IBS growth rates:

$$\tau_{||}^{-1} = \frac{1}{\sigma_p^2}\frac{d\sigma_p^2}{dt}\frac{r_i^2 c N_i \Lambda}{8\beta\gamma^3\epsilon_x^{3/2} < \beta_x^{1/2} > \sqrt{\pi/2}\sigma_l \sigma_p^2},$$

$$\tau_{\perp} = \frac{\sigma_p^2}{\epsilon_x} < \frac{H_X}{\beta_x} > \tau_{||}^{-1}.$$

Stochastic cooling rates:

$$\tau_{Cooling}^{-1} \propto \frac{1}{N_i}$$

Therefore:

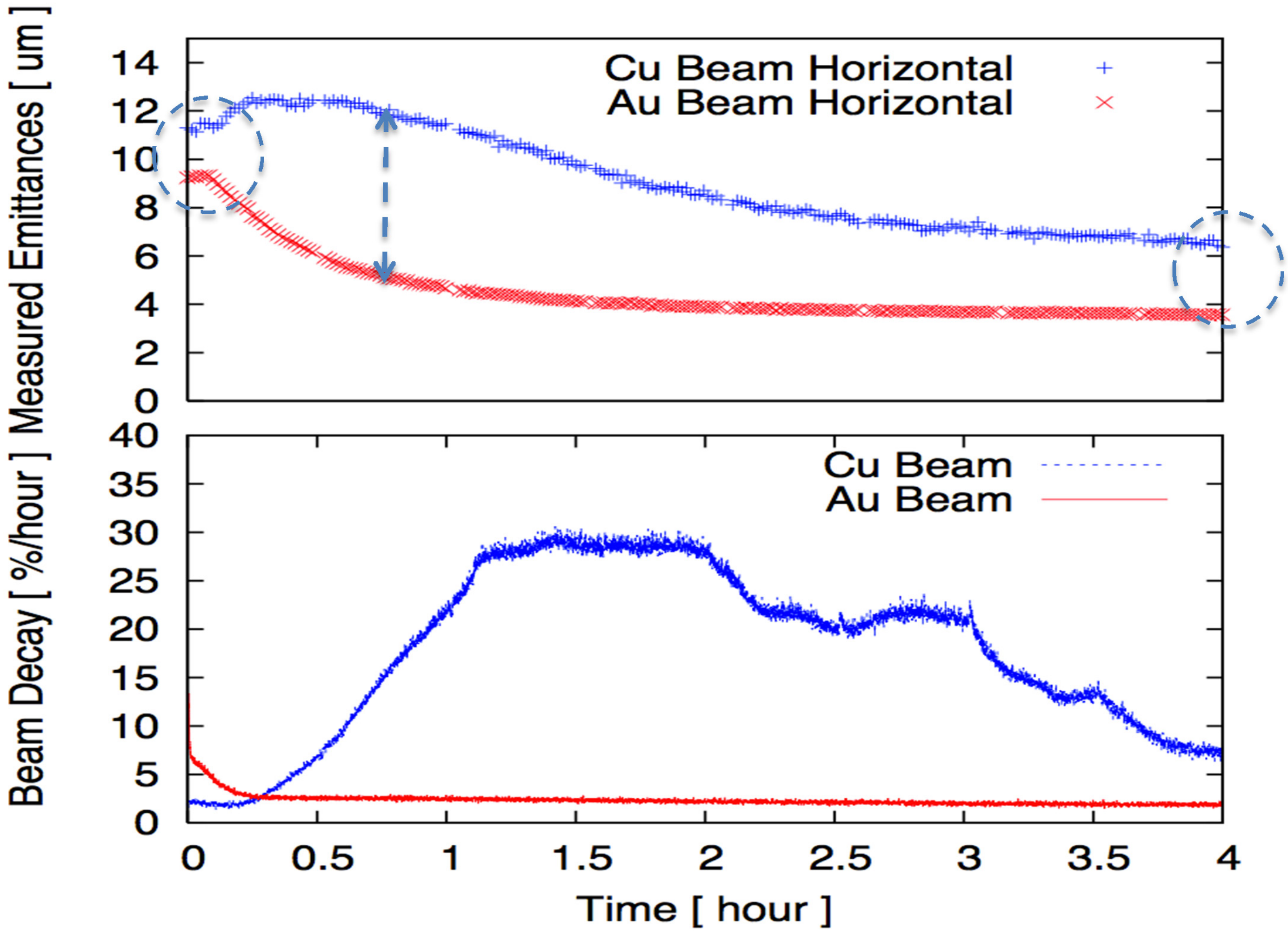
$$\tau_{IBS,Cu}^{-1} = \frac{1}{2}\tau_{IBS,Au}^{-1}$$

$$\tau_{Cooling,Cu}^{-1} = \frac{1}{3}\tau_{Cooling,Au}^{-1}$$

Cu ion:
A=63, Q=29+
Au ion:
A=197, Q=79+
Cu bunch intensity:
4.0e9
Au bunch intensity:
1.3e9

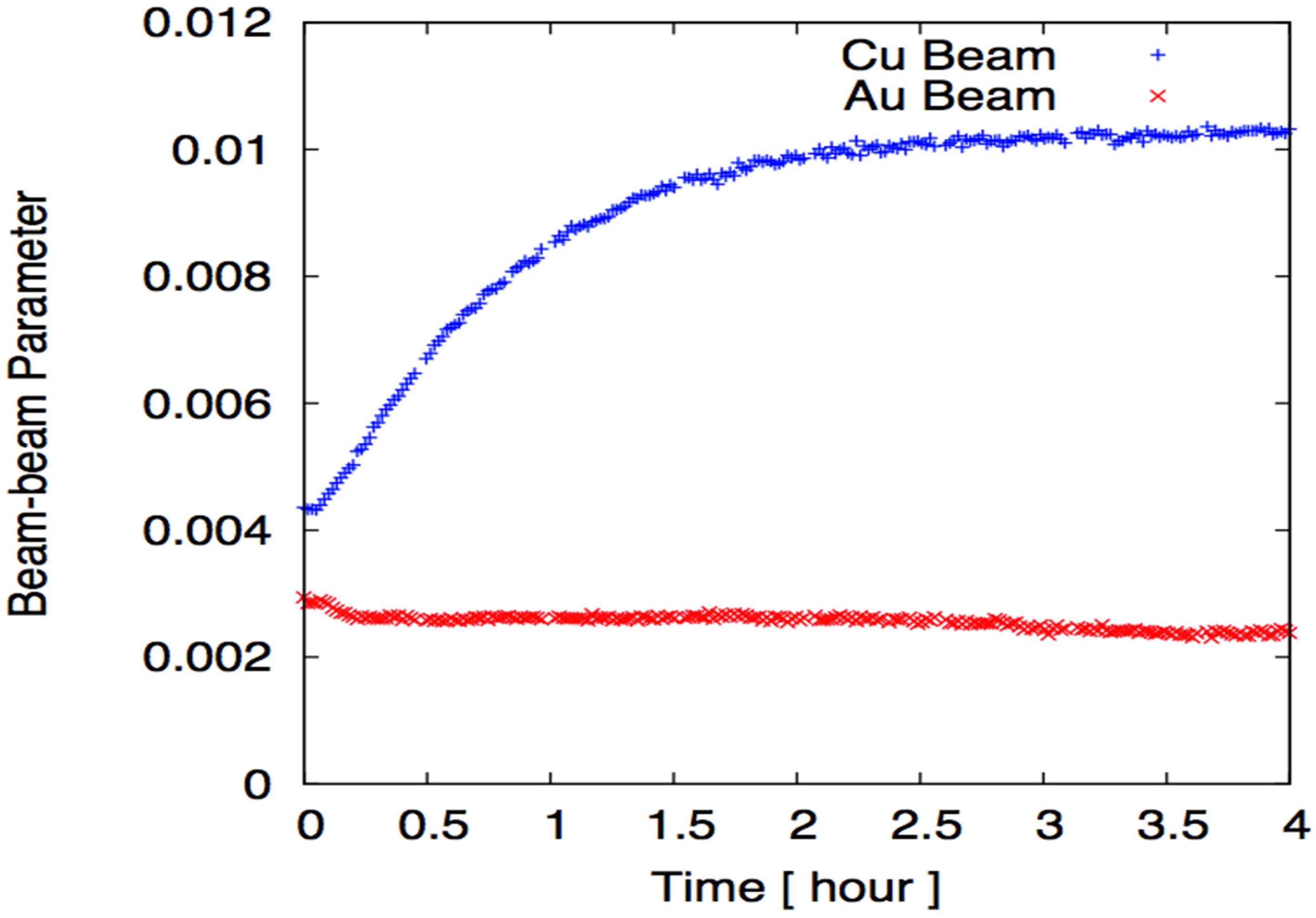
Au ion bunch IBS growth faster but cooling down faster.

Beam Loss with Full Cooling Power



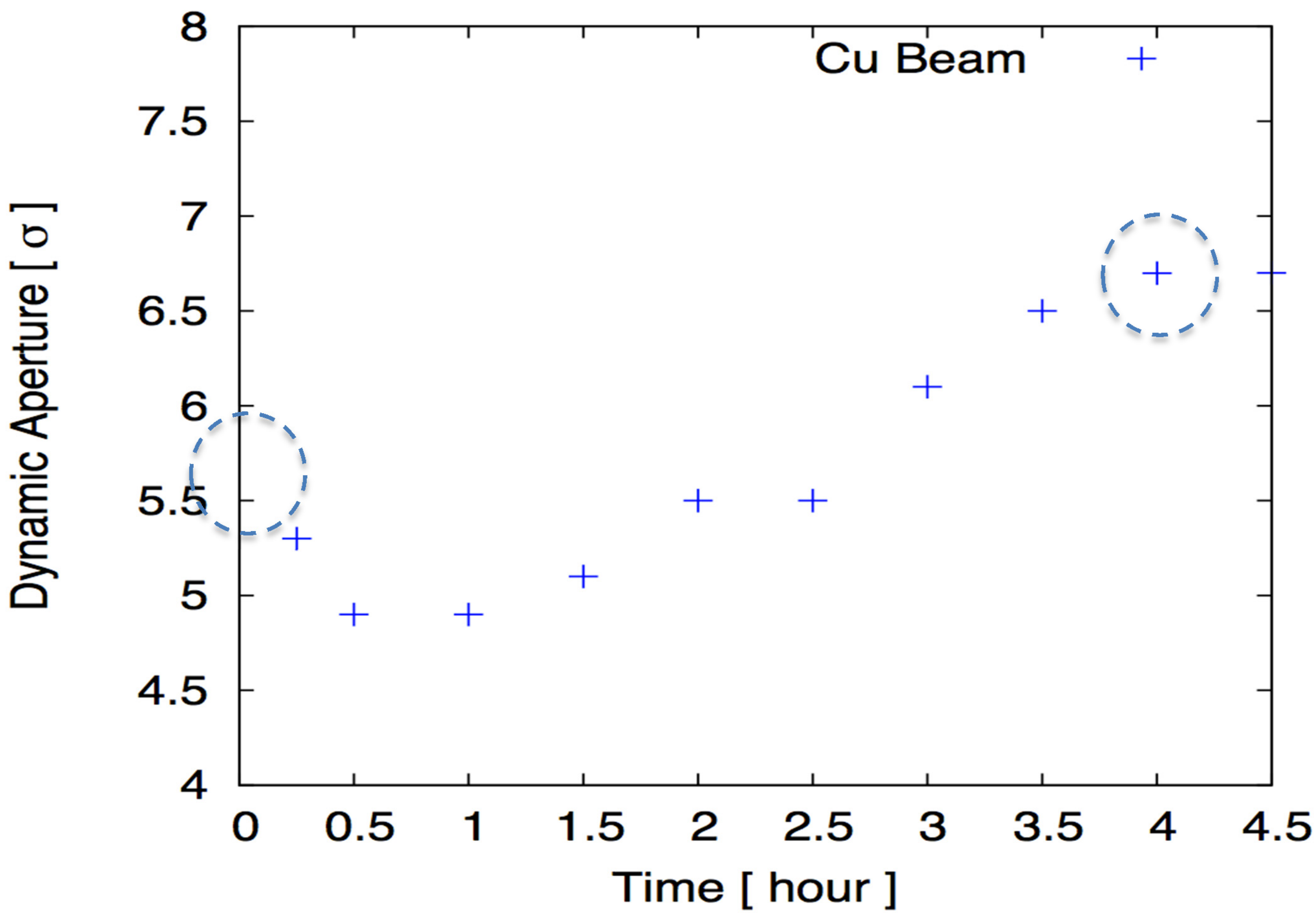
In the beginning of Cu-Au run, we observed large Cu beam loss due to different IBS and cooling rates for Cu and Au ions through beam-beam interaction with unbalanced transverse beam sizes.

Beam-beam Parameters with Full Cooling



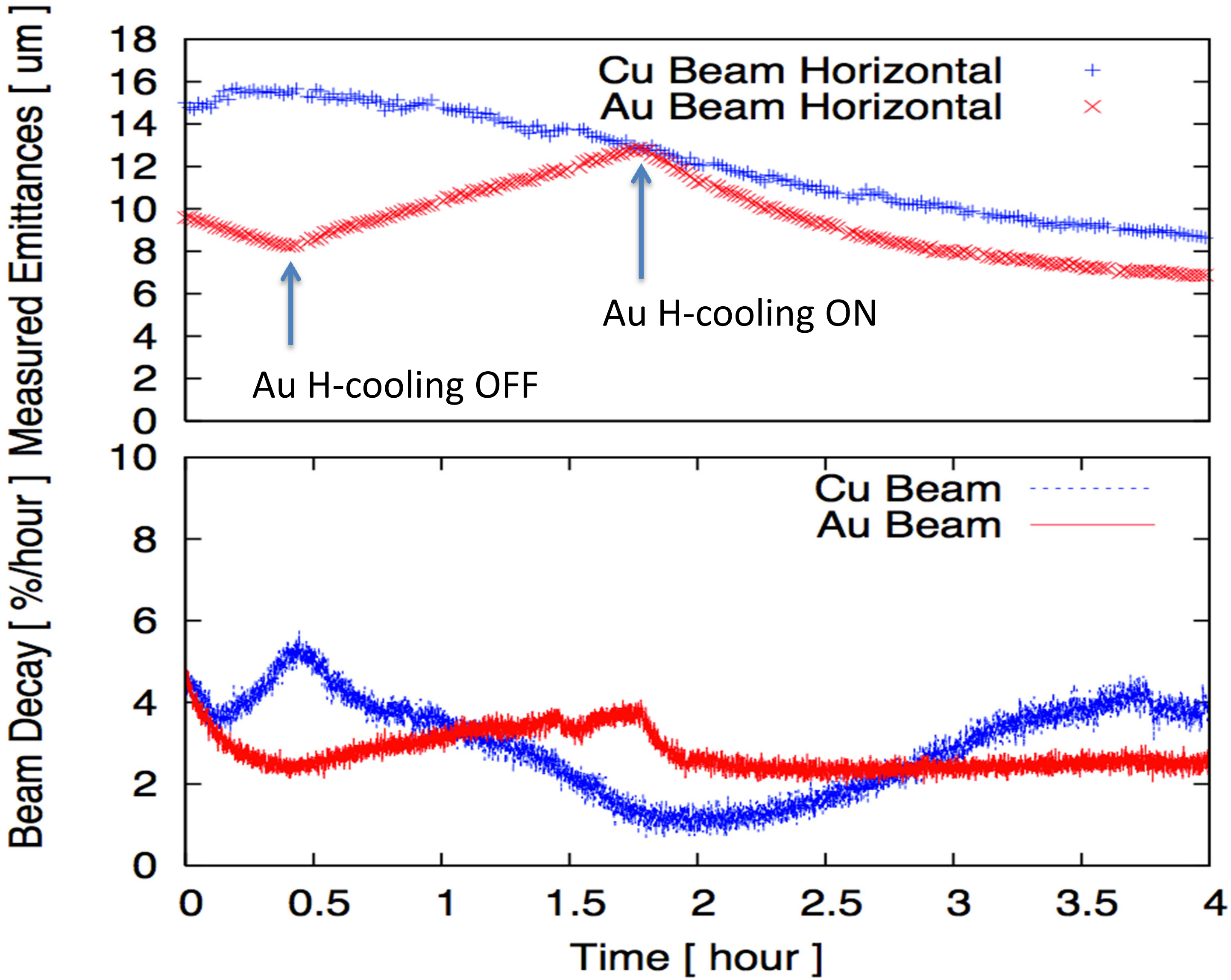
Beam-beam parameters of Cu and Au ion beams. The typical beam-beam parameters in the previous Au-Au runs are 0.003.

Dynamic Aperture Calculation

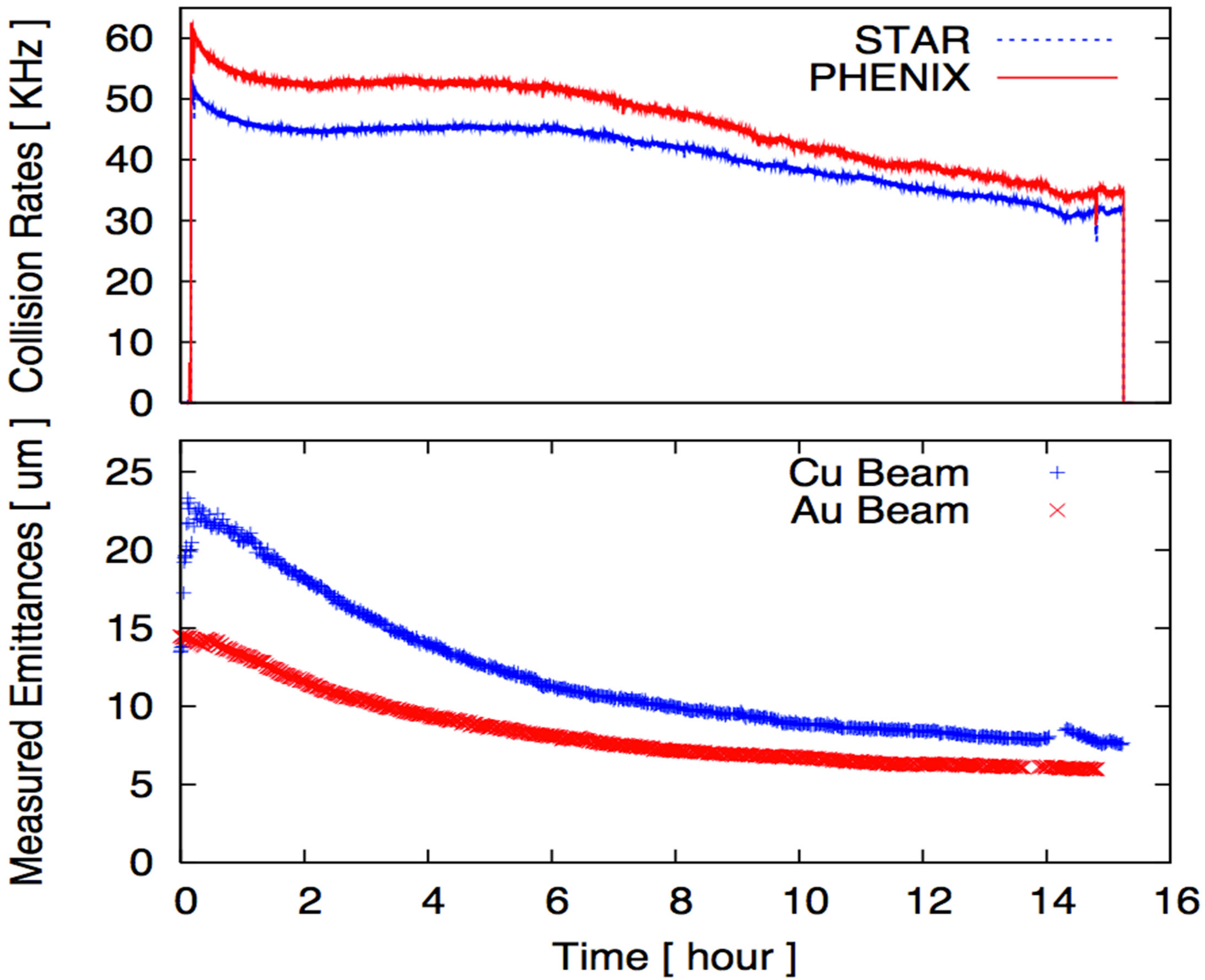


Dynamic aperture simulation with beam-beam interaction shows that Cu ions have smaller dynamic aperture when Cu beam have much larger transverse beam size.

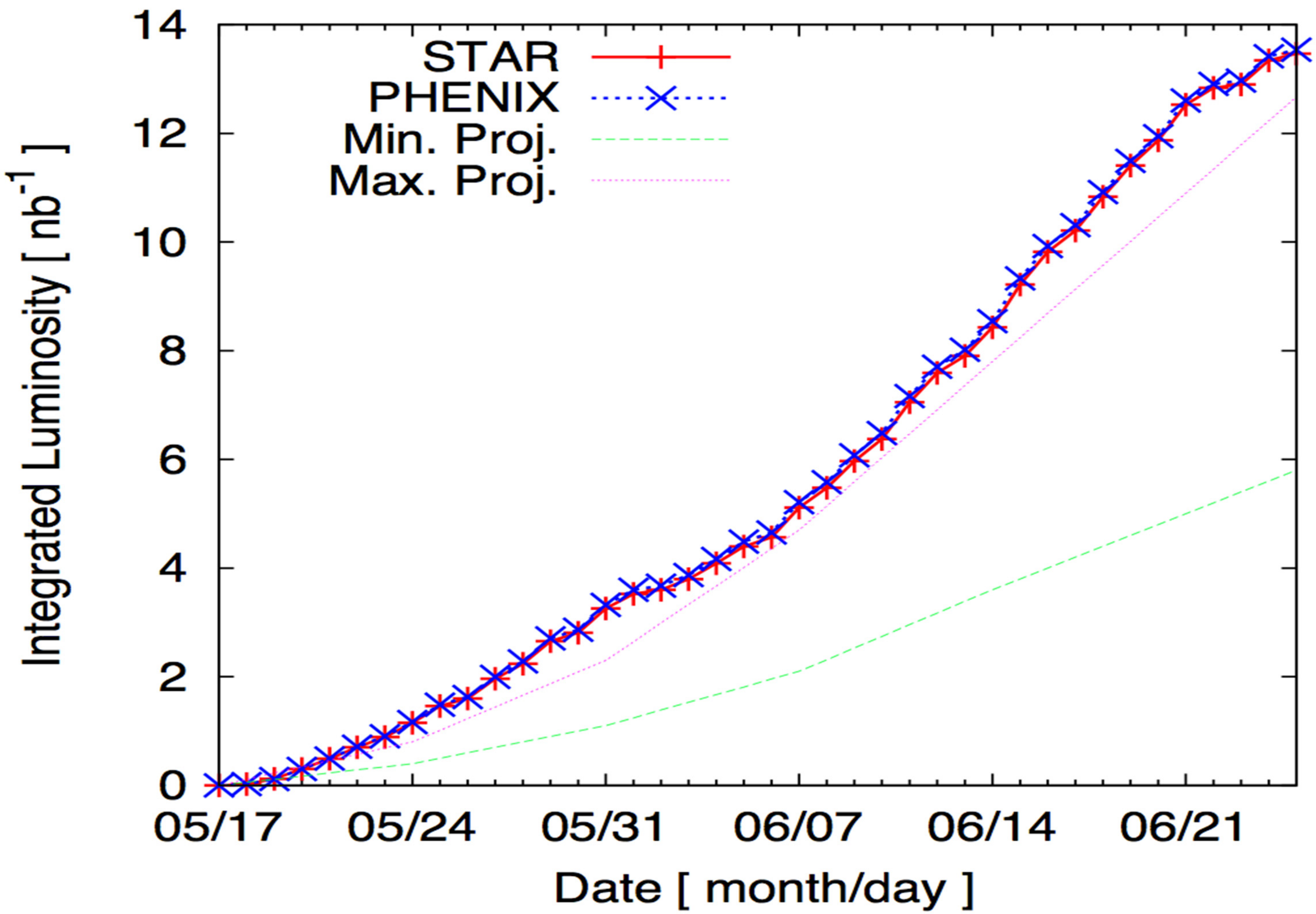
Slowing Down Au Beam Cooling



Maximizing Integrated Luminosity



Integrated Luminosity in Cu-Au Run



The integrated luminosity we delivered to experiments in the Cu-Au run exceeded their maximum projections.

Summary

- 2012 RHIC ion run was a great success. In this run, we collided 100 GeV U-U and Cu-Au ions for the first time. EBIS and 3-D cooling were operational for the first time in RHIC ion runs.

- With 3-D cooling, peak luminosity was 3 times the initial one in the U-U run. Together with a new lattice, we achieved burn-off dominated beam lifetime. Both are the first time to be observed in colliders.

- In the Cu-Au run, with double bunch merging technique, we achieved the most intense ion bunch in RHIC. By adjusting cooling gains, we reduced Cu beam loss due to different IBS and cooling rates and maximized the integrated luminosity.