Beam-beam Effects in RHIC

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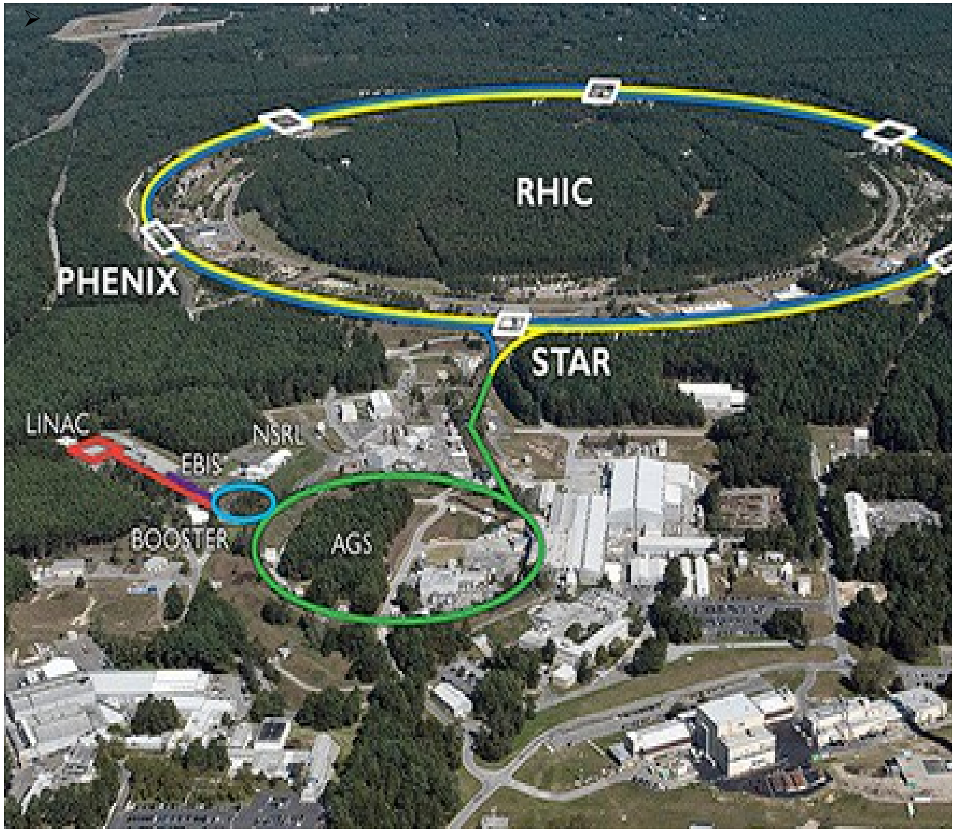
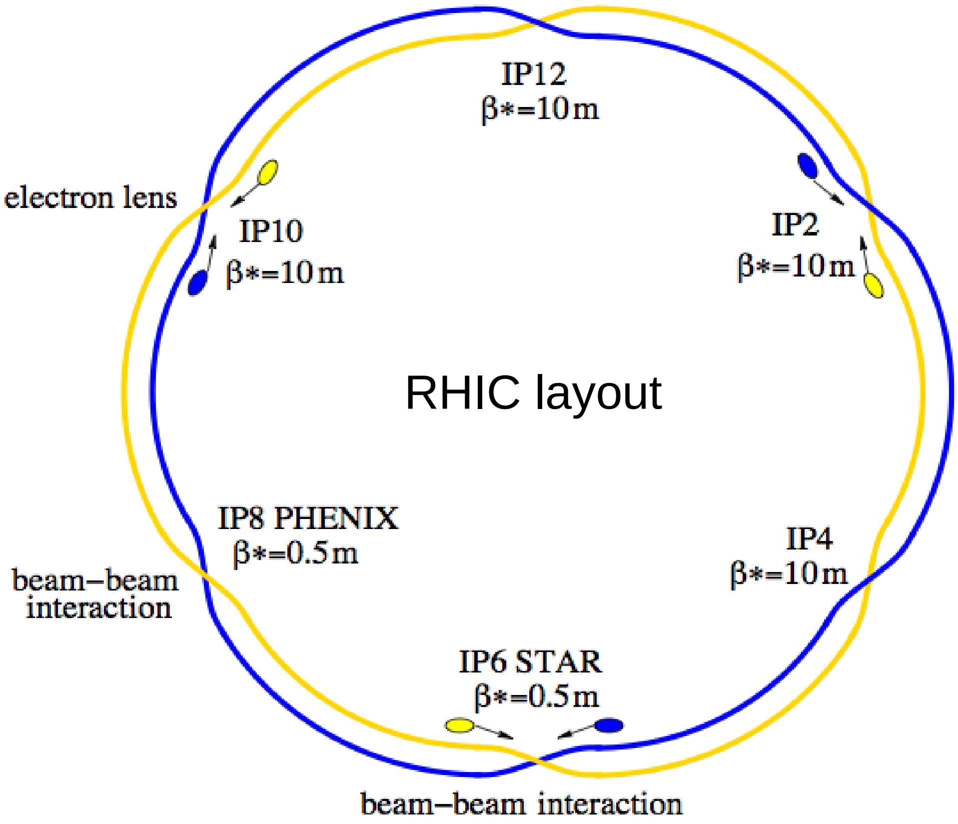
Content

RHIC : Relativistic Heavy Ion Collider

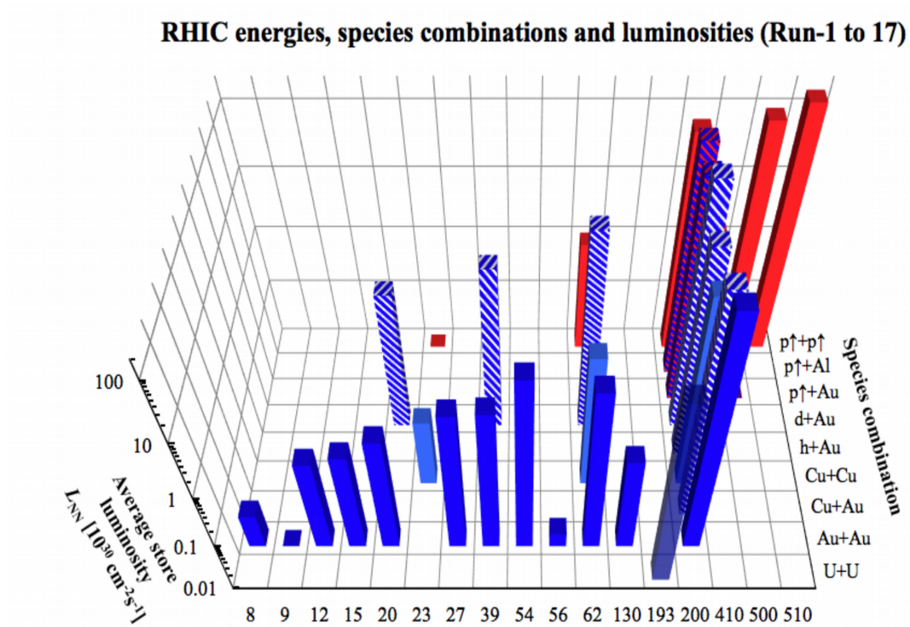
- **Two super-conducting rings**: circumference 3.8 km, side by side with 6 sextants
- RHIC is capable of accelerating **proton up to 275 GeV**,
  heavy ion up to 100GeV/nucleon
- **Two detectors: STAR at IP6 , PHENIX at IP8**
- **RHIC operation modes**: heavy ion collision, heavy-light ion collision
  polarized proton collision, proton-ion collision

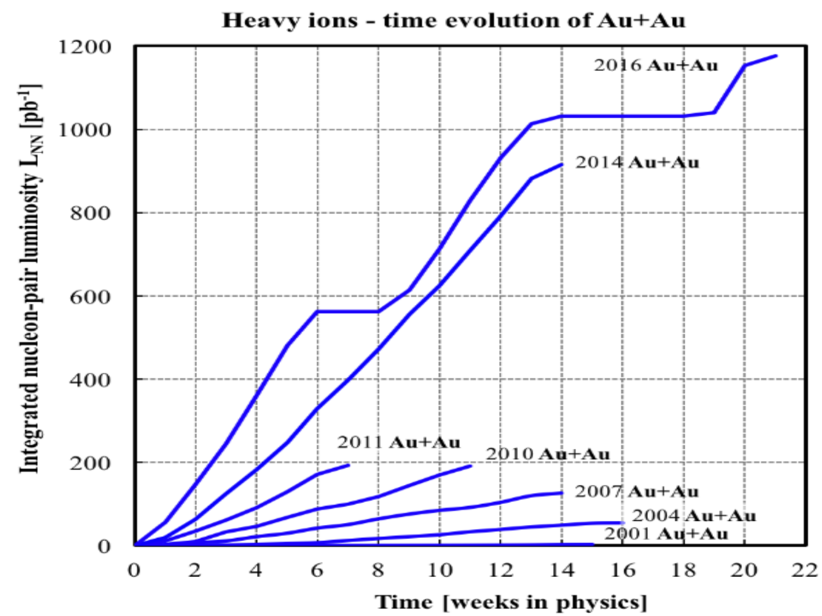


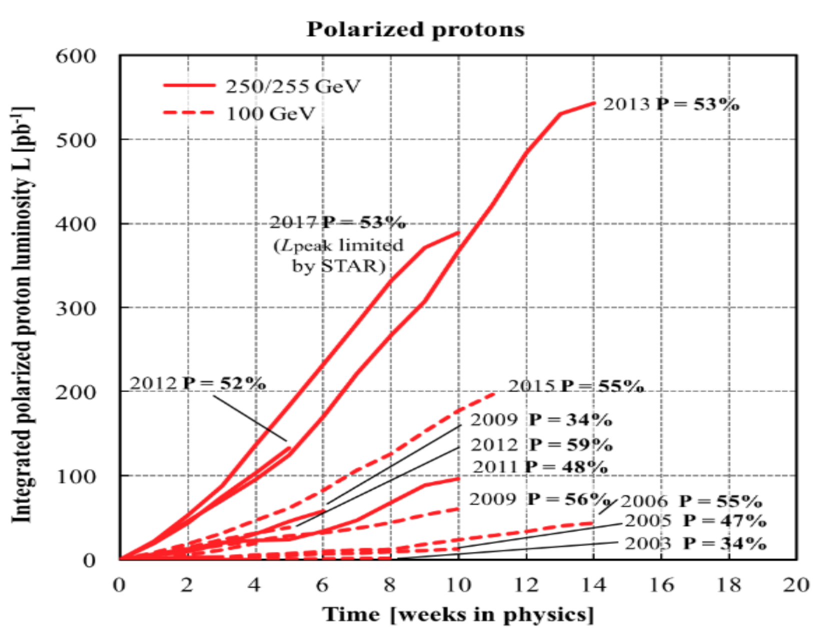


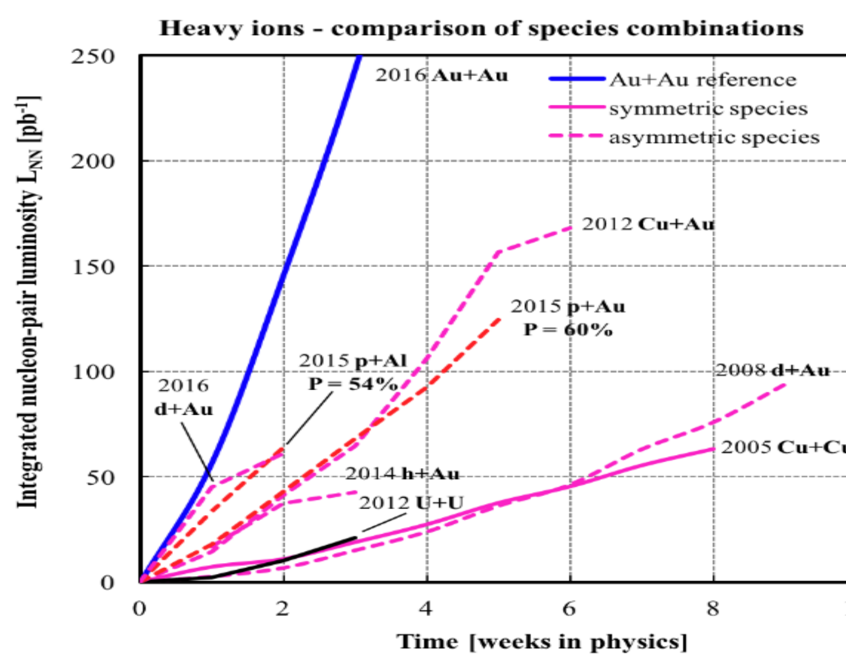
RHIC Run History & Luminosity

http://www.agsrhichome.bnl.gov/RHIC/Runs/ W. Fischer









RHIC Heavy Ion Runs

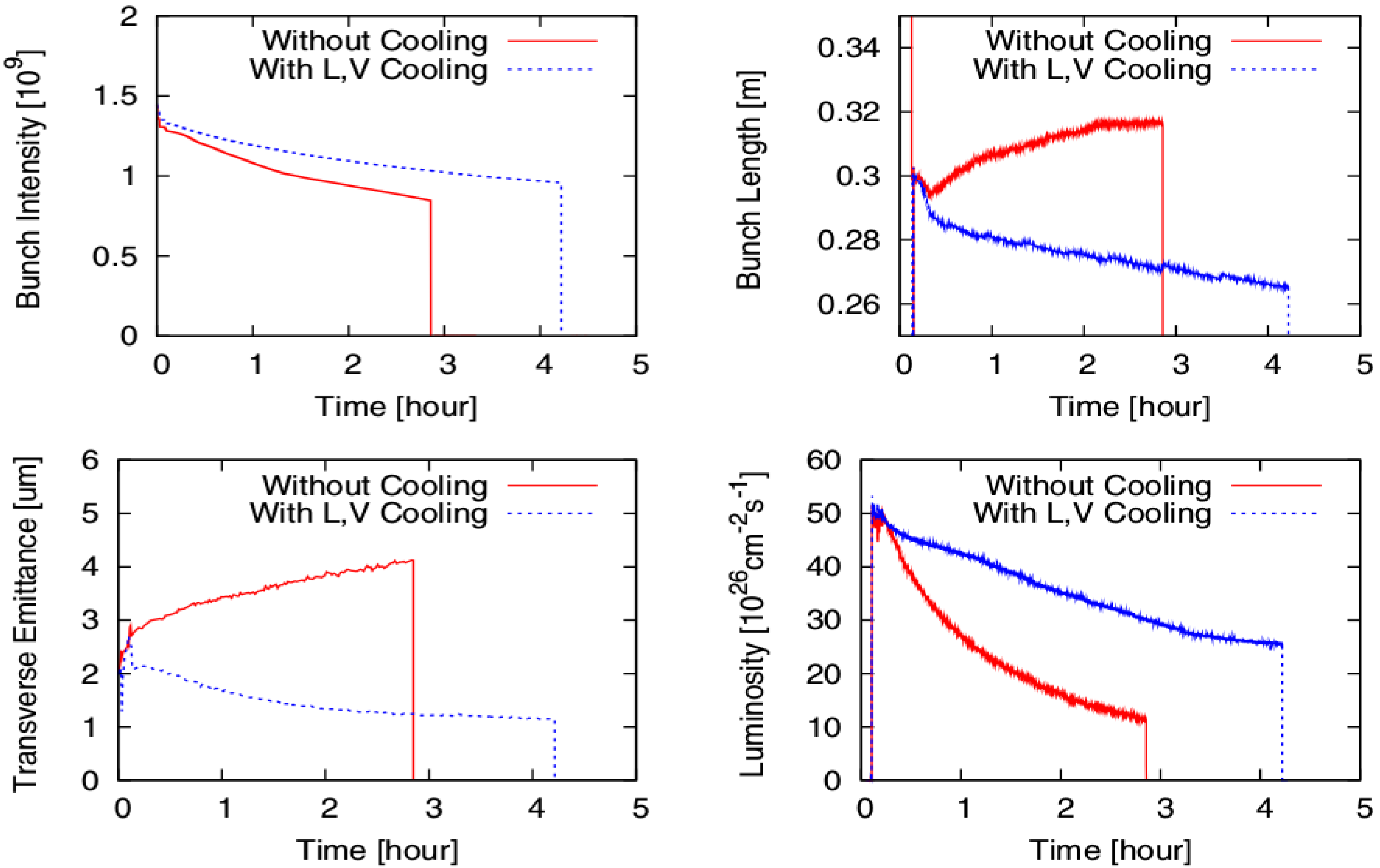
$$\tau_{\mathrm{IBS},\parallel}^{-1} = \frac{1}{\sigma_p^2}\frac{d\sigma_p^2}{dt} = \frac{r_i^2 c N_i \Lambda}{8\beta^{3/2}\gamma^{3/2}\epsilon_{n,\mathrm{rms},x}^{3/2}\langle\beta_x^{1/2}\rangle\sigma_l\sigma_p^2},$$

$$\tau_{\mathrm{IBS},x,y}^{-1} = \frac{1}{\epsilon_{n,\mathrm{rms},x,y}}\frac{d\epsilon_{n,\mathrm{rms},x,y}}{dt} = \frac{1}{2}\frac{\gamma\beta\sigma_p^2}{\epsilon_{n,\mathrm{rms},x}}\left\langle\frac{H_x}{\beta_x}\right\rangle\tau_{\parallel}^{-1}.$$

- **IBS** blows up beam emittance & bunch length

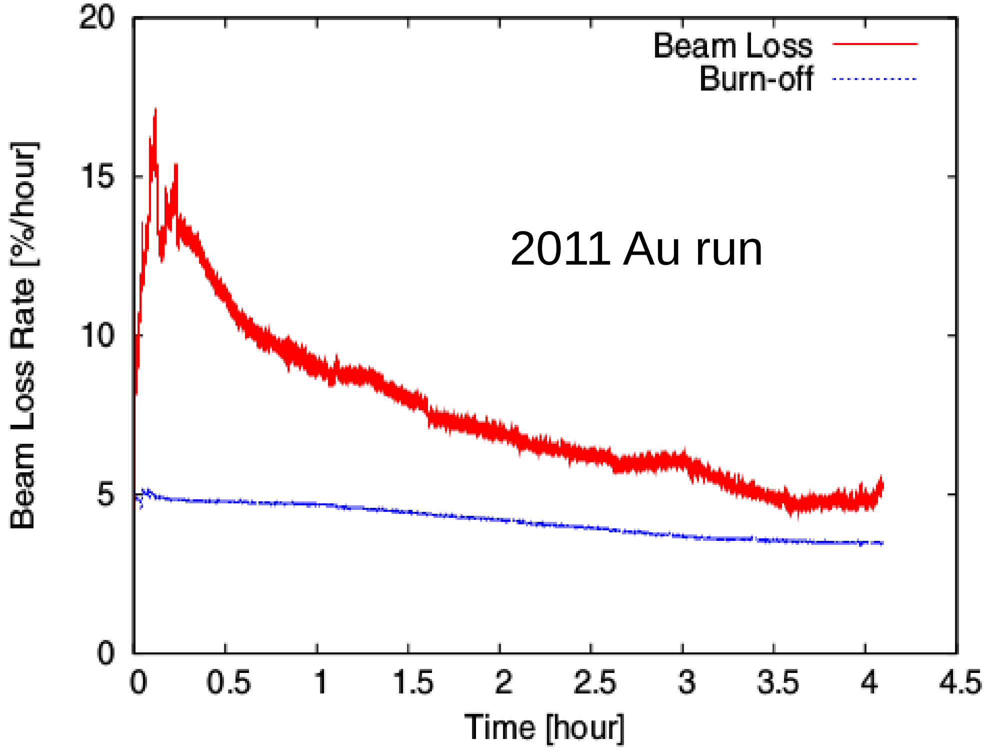
  Counter-measure: **Stochastic cooling**
- **Operational concerns**:
  - → luminosity & beam lifetime (bigger N_i, smaller emittance, bigger DA)
  - → luminosity leveling (separation bump, beta* adjusting)
  - → narrow vertex collision rate (stronger longitudinal focusing)
- **Beam-beam interaction**:
  - → without cooling, BB parameter ~ 0.003
  - → with cooling, BB parameter ~ 0.01
  - → mostly interplay between BB and stochastic cooling

Observations: Au Ion Run (2011)



- **IBS-suppression lattices** (with higher integer tunes, first used in 2008 d-Au run, until 2011 Au-Au run) **were used to reduce the transverse IBS rate.**
- **Stochastic cooling available** in RHIC in 2007 (L plane). In 2011, L & V plane cooling available. In 2012, 3-d cooling implemented.

Au Ion Loss Rate

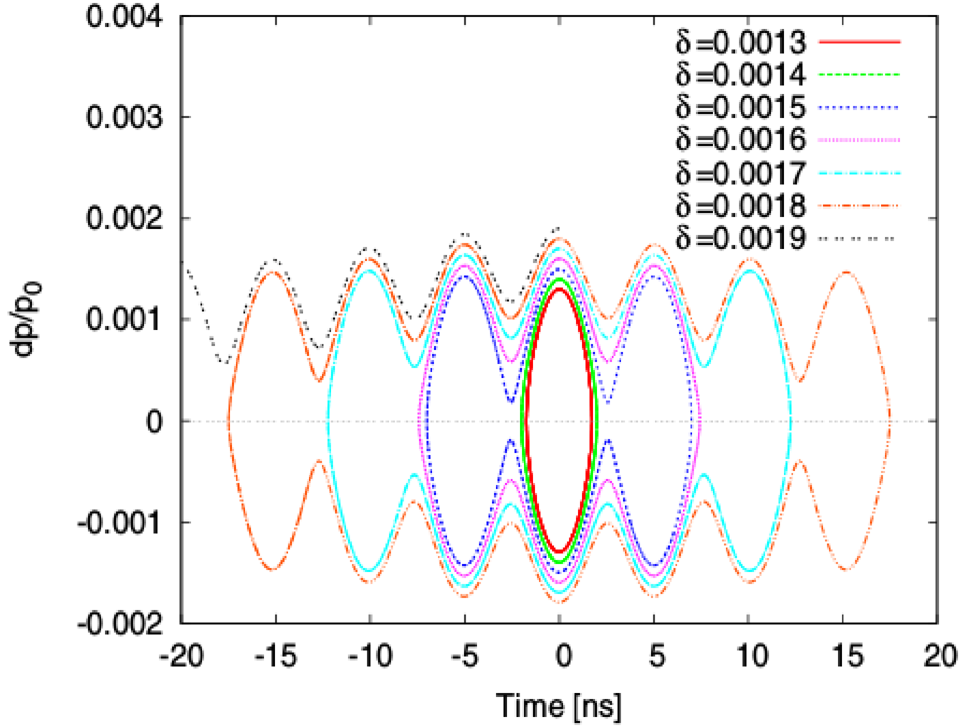


$$\tau^{-1}_{\text{burn-off}}(t) = \frac{(L_{\text{IP6}}(t) + L_{\text{IP8}}(t))\sigma_{\text{coll}}}{N_{\text{tot},i}(t)}$$

- This plot shows that **the measured particle loss rate**, together with the calculated particle loss rate due to **luminosity burn-off** (The total cross section Au-Au collision at 100 GeV is 218.46 b)
- From the plot, **there were a large amount of particle loss (~46%) whole store due to non-luminous losses.**

Au Ion Loss Mechanism (I)

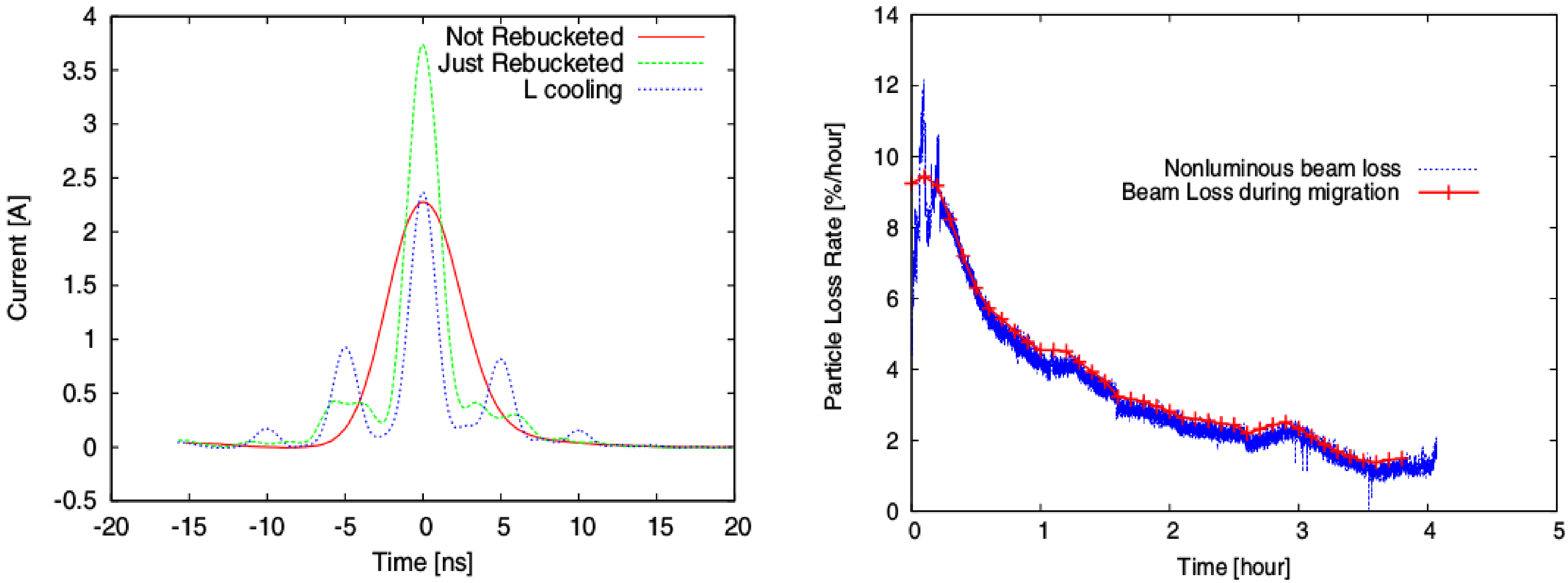
Longitudinal phase space



central bucket dp/p0 acceptance is **0.0014**, while adjacent bucket dp/p0 accepatnce is **0.0019**.

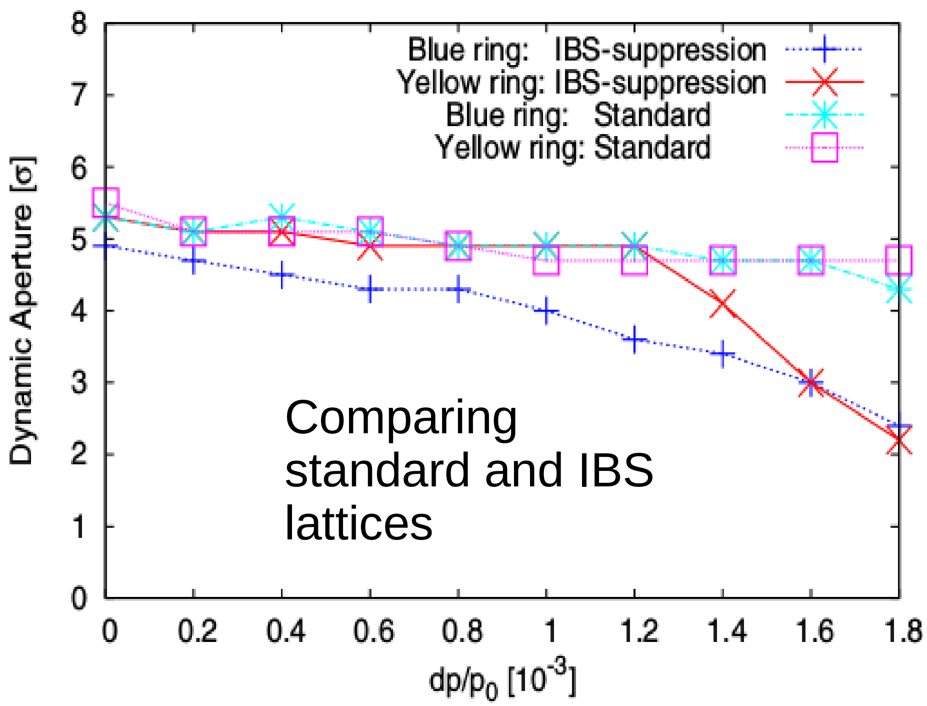
- **RF re-bucketing** from 28MHz to 197MHz is required for stochastic cooling.
- **Experimentally**, 1) with BB without RF re-bucketing, we only observed ~5% particle loss rate. 2) With RF re-bucketing without BB, we observed ~10% particle loss rate.
- **Numerical simulation** shows BB interaction does not reduce the dynamic aperture.
- **Therefore**: The non-luminous particle loss rate was linked to RF re-bucketing.

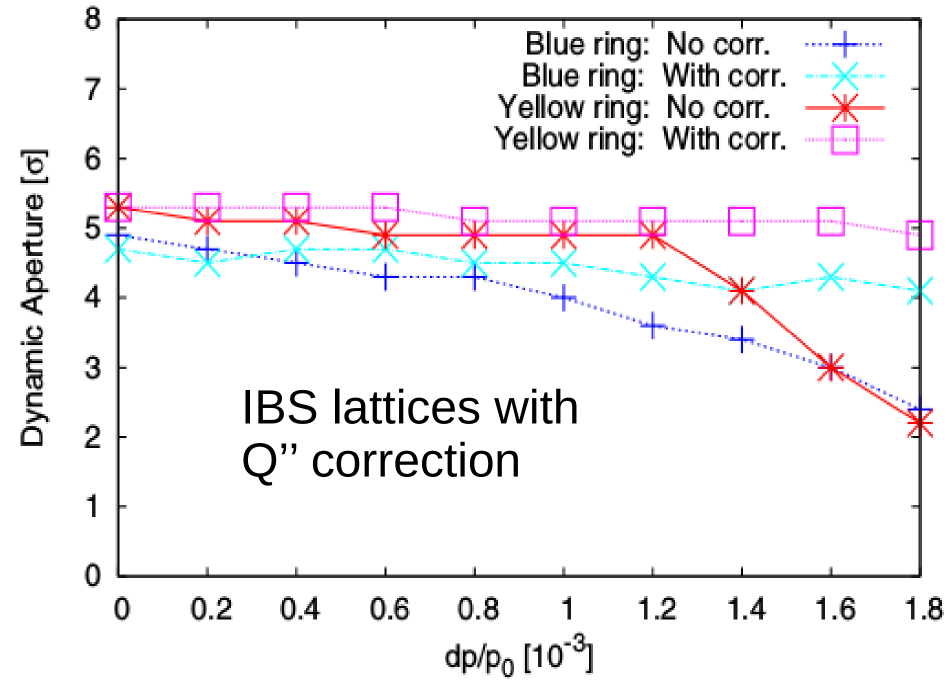
Au Ion Loss Mechanism (II)



- From the **wall-current monitor** (wcm), we are able to measure the particle populations in each 197 RF bucket (5ns width) and therefore the longitudinal particle migration.
- We noticed that there were particles leaking out of central RF bucket, even with L cooling.
- We further found that **not all the particles leaking out of the central 197 RF bucket ended in the adjacent buckets**.
- Stunningly, we found that **the particle loss during migration was very close to the non-luminous beam loss**.

Off-momentum Dynamic Aperture

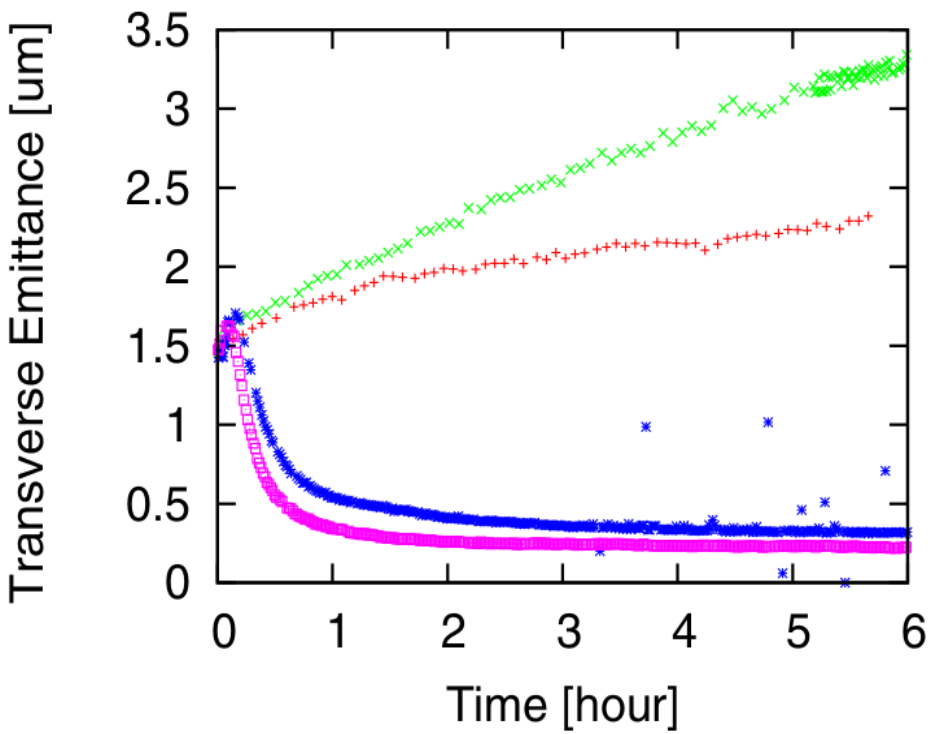


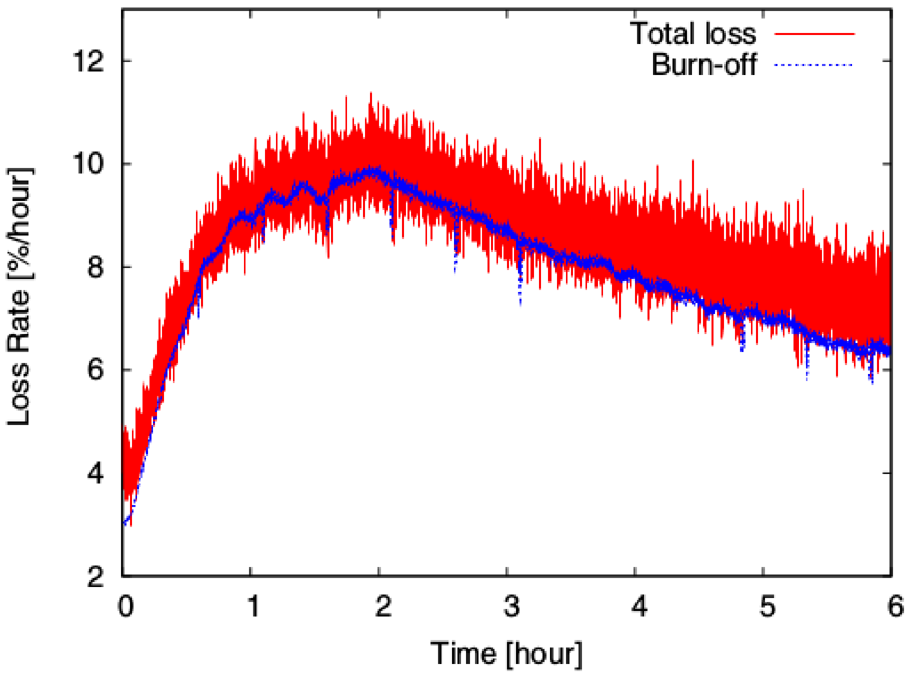


- The reason why the particles got lost during migration was **the small off-momentum aperture** (dp/p0 < 0.0019). Simulation shows that **the IBS suppression lattices** have smaller off-momentum dynamic apertures.
- Therefore, we decided to adopt **the standard lattices** (with 1 unit lower integer tunes) since 2012. These lattices give larger off-momentum dynamic apertures.

With Improved Off-momentum DA

2012 U-U run

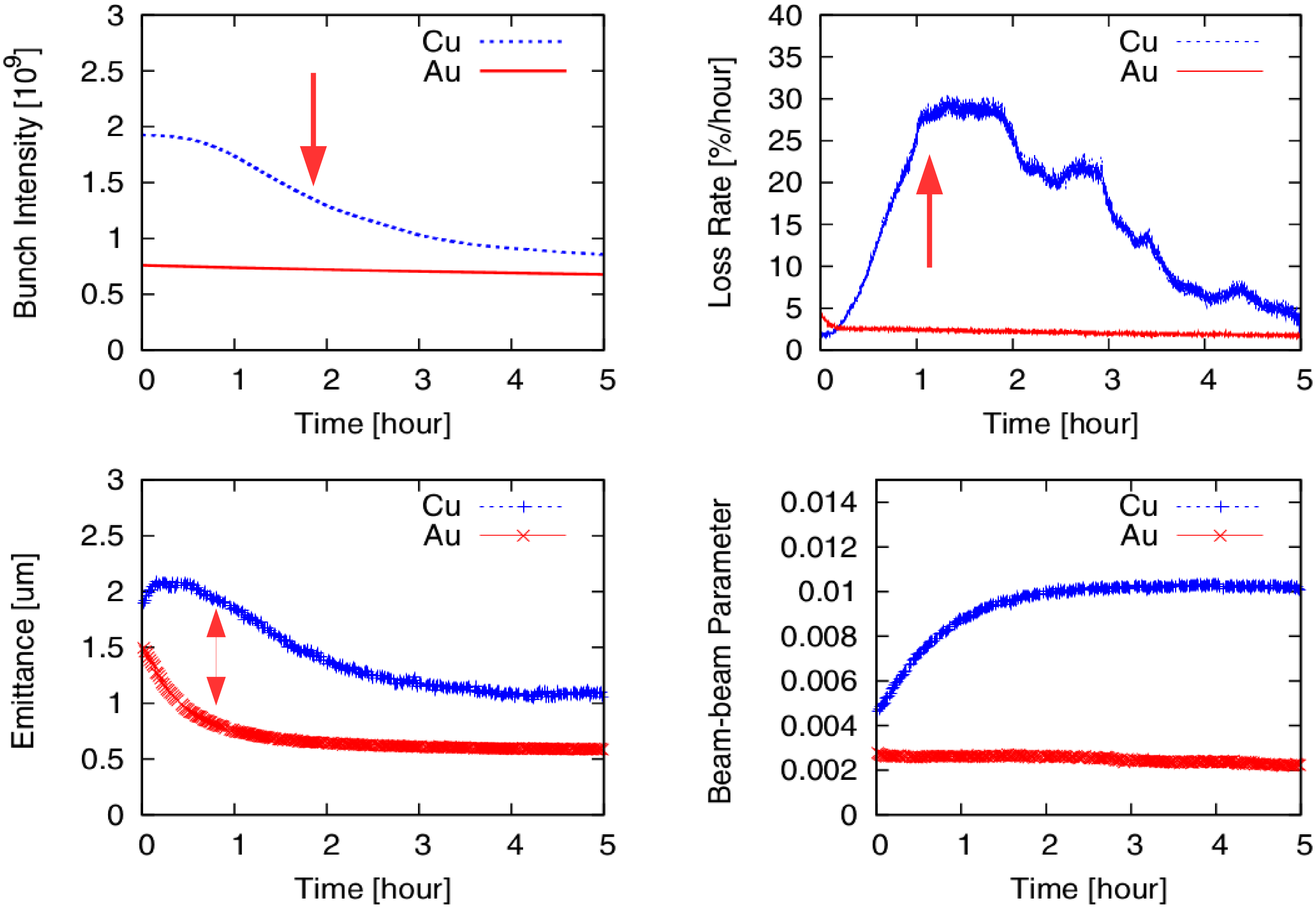




- With the standard lattices, the off-momentum DA was improved. The non-luminous particle loss were largely eliminated. In the 2012 U-U ion run, **97% of particle loss were from burn-off**.
- In the 2014, 2016 Au-Au runs, more tha 90% of particle loss were from burn-off.

Asymmetric Ion Run

2012 Cu-Au Run



- In the 2012 asymmetric Cu-Au run, with **full cooling speed** for both beams, we observed an enormous Cu beam loss (30%/h) at the beginning of store and a very bad luminosity lifetime.

Unbalanced IBS & Cooling Rates

- The **IBS growth rate** is proportional to (N_i Z^2 r_p /A), since $N_{i,\ Cu}$ ~ 3 $N_{i,\ Au,}$ we have

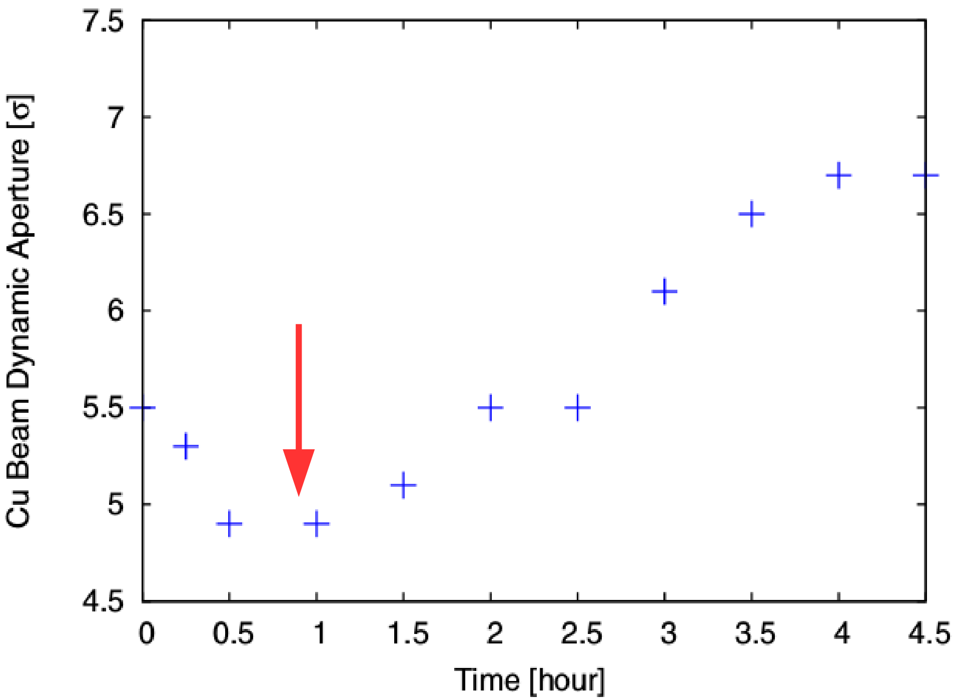
$$\tau^{-1}_{\mathrm{IBS,Cu}} \approx \frac{1}{2}\tau^{-1}_{\mathrm{IBS,Au}}.$$

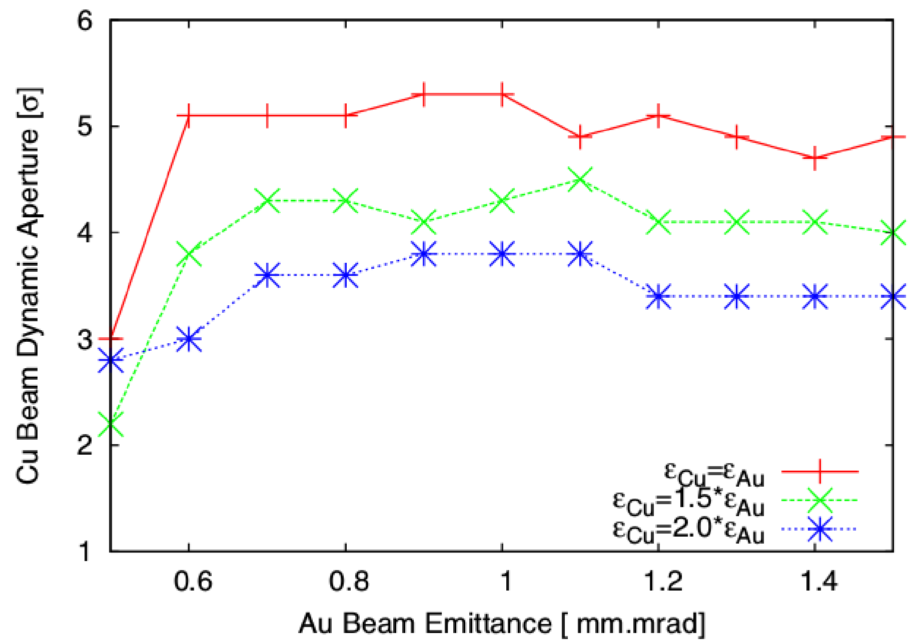
- The **stochastic cooling rate** is inversely proportional to $N_{i,}$ we have

$$\tau^{-1}_{\mathrm{cooling,Cu}} \approx \frac{1}{3}\tau^{-1}_{\mathrm{cooling,Au}}.$$

- The initial Cu beam's transverse emittance was 30% larger than the Au beam. **It took ~1 hour to cool down Au beam but ~3 hours to cool down Au beam.**
- With full cooling power for both beam, the transverse beam sizes differed at IP with a same beta*=0.7m at IP.

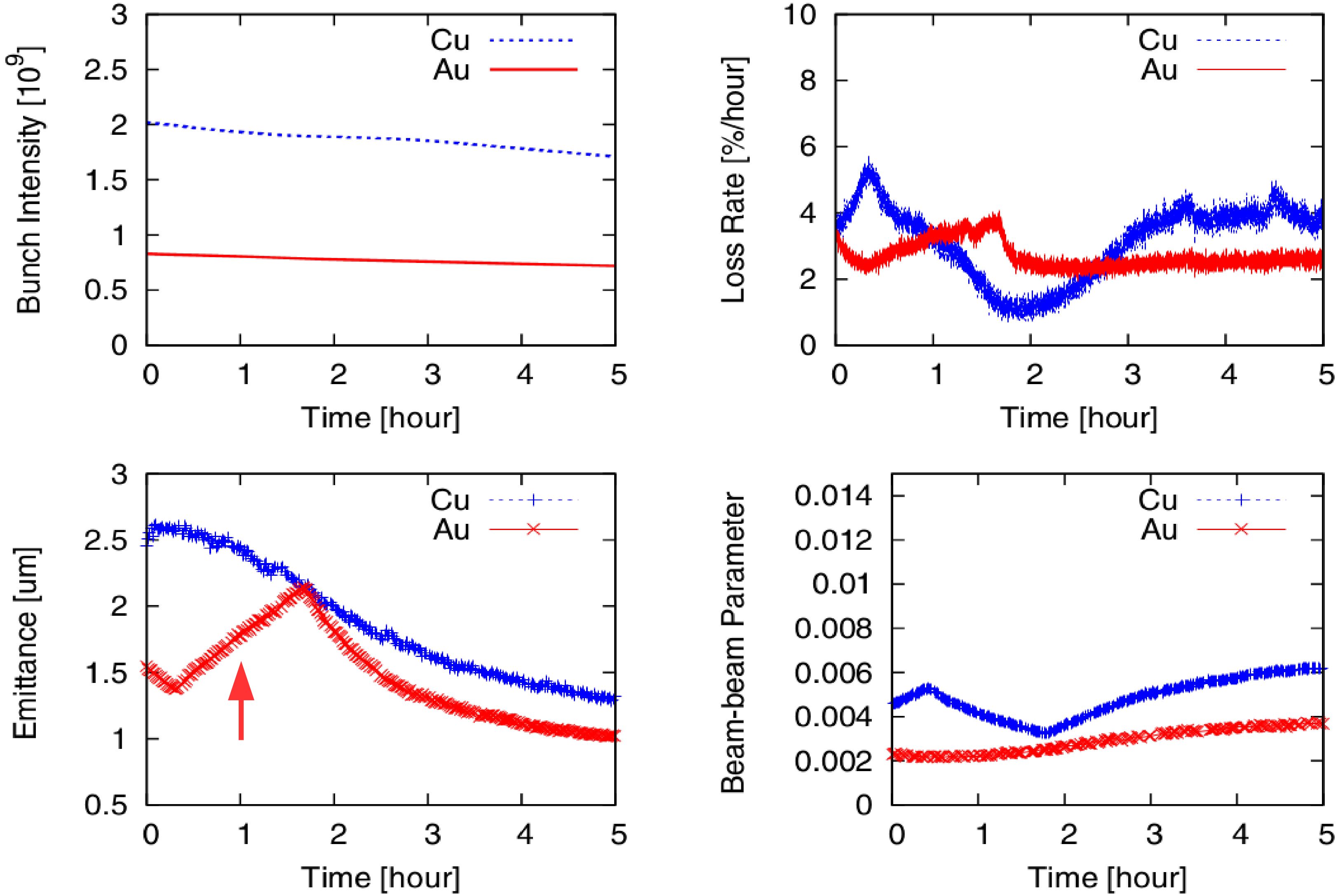
Dynamic Aperture Calculation





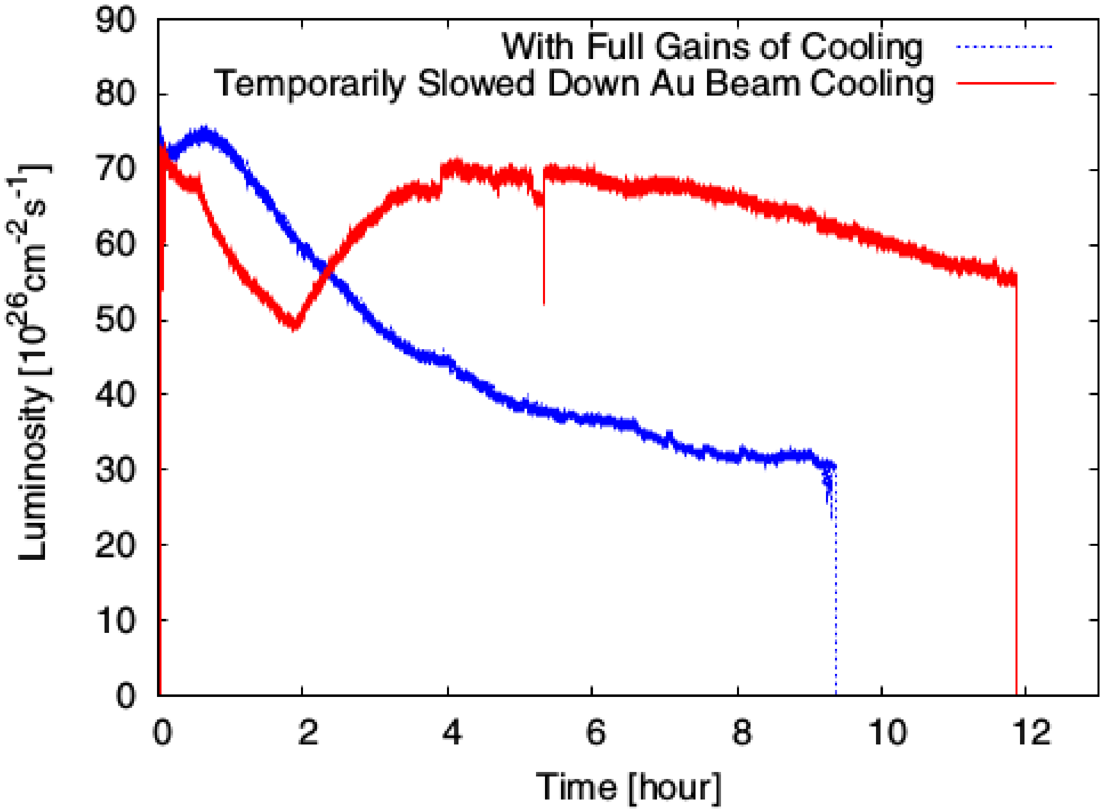
- Left plot shows **the calculated Cu beam DA with the actual measured beam emittances**. With full speed cooling for both beams, the Cu beam's DA first went down then slowly went up.
- Right plot shows that to maintaining a good Cu beam DA, the emittance difference between the Cu and Au beams should not be smaller than 50%.

Maximizing Integrated Luminosity



- Based on the above analysis, we decided to defer the cooling to the Au beam at the beginning of store to maintain the Cu beam intensity. After both beam cooled down, we applied full cooling speed to both beams.

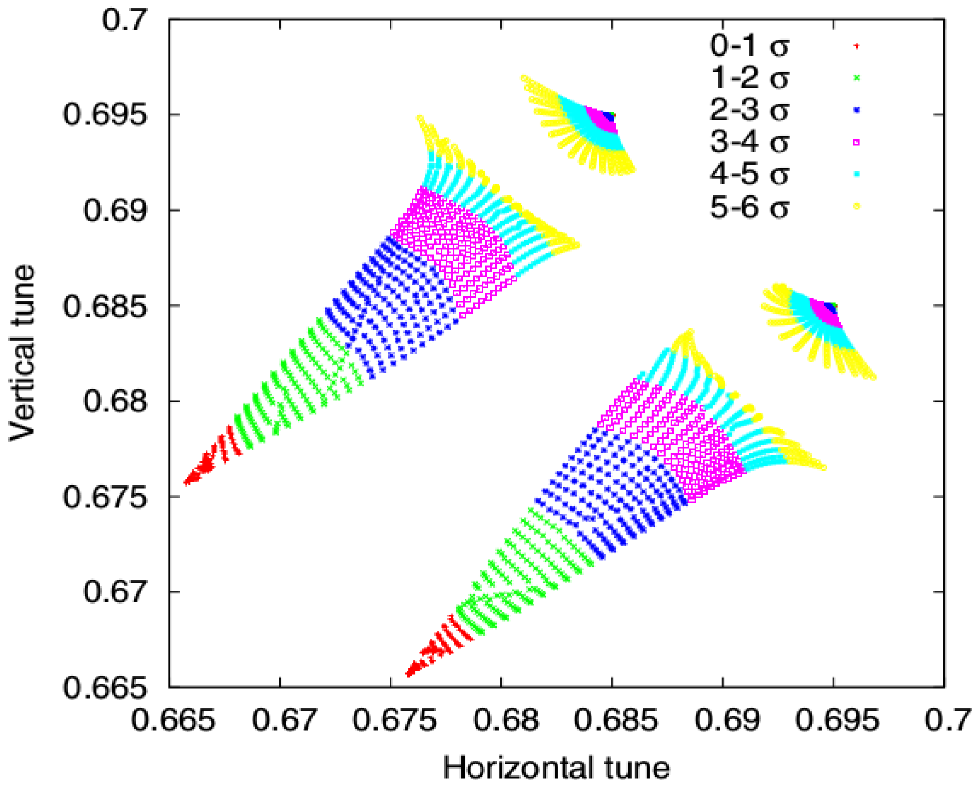
Maximizing Integrated Luminosity (II)



- By doing that, we minimized the Cu beam loss rate at the beginning of store and maximized the integrated luminosity per store (**increased by 74%**).
- The regular store length was extended to 14 hours. Almost flat luminosity lasted several hours.

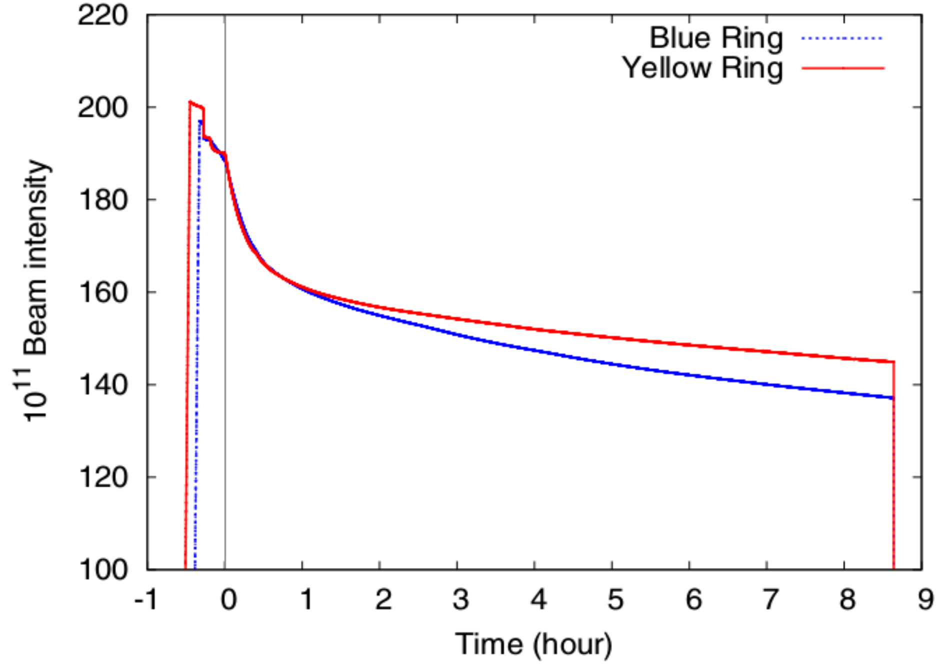
RHIC Polarized Proton Runs

- **Operational concerns**:
  → **Luminosity** and beam lifetimes (increase $N_{p,}$ small emittance, good DA)
  → Proton **polarization** and lifetime
- **Beam-beam concerns**:
  → **Limited tune space**
  spin & betatron resonances
  → **Other complications**:
  IR non-linearities,
  low beta* lattices,
  chromatic effects,
  IR 10Hz orbit oscillation,...

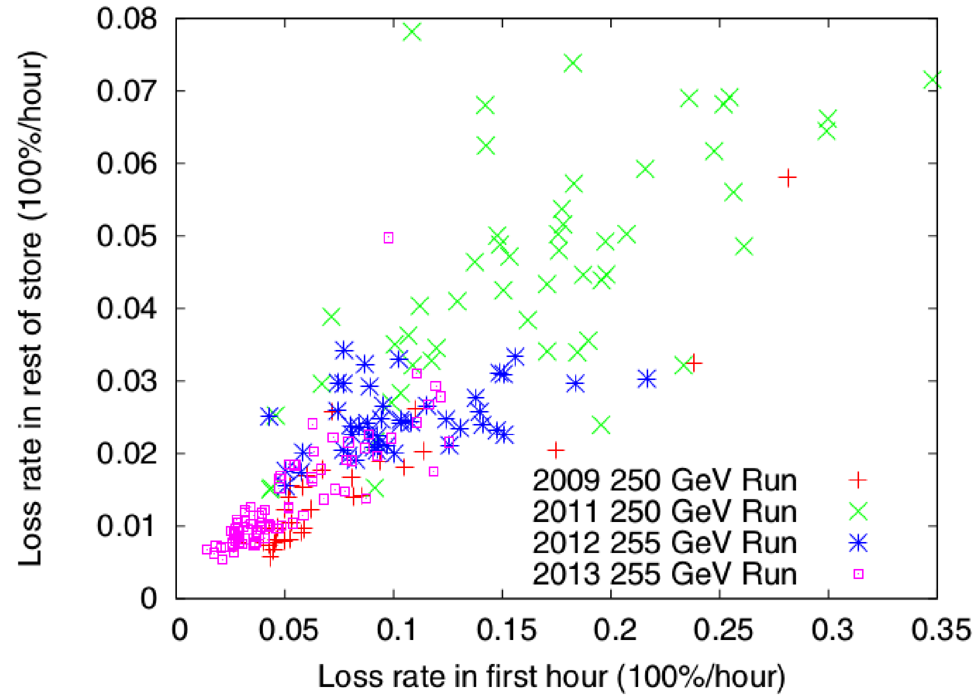


Operational Observations (I)

2012 p-p run

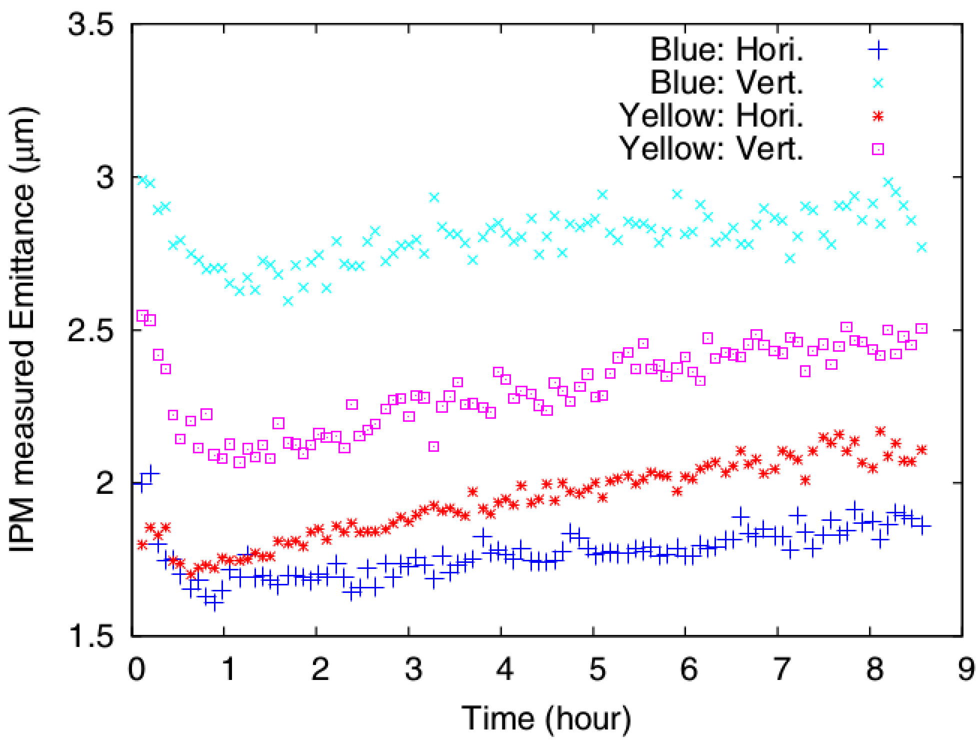


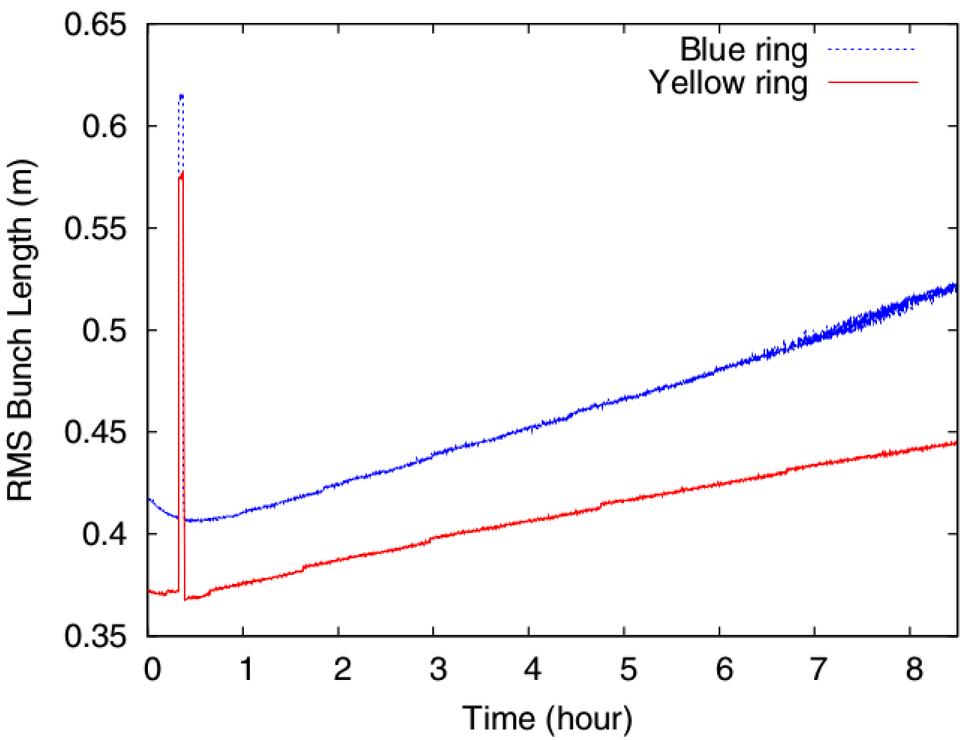
Statistics



- Large loss at the beginning of store, much slower loss after 1 hour into the store.
- Different equations are used to fit the overall beam intensity at store.
- Experimentally, **without BB at store**, proton loss only about 1%/hour with fine tuning. **Therefore**, **the large beam loss was linked to BB interaction.**

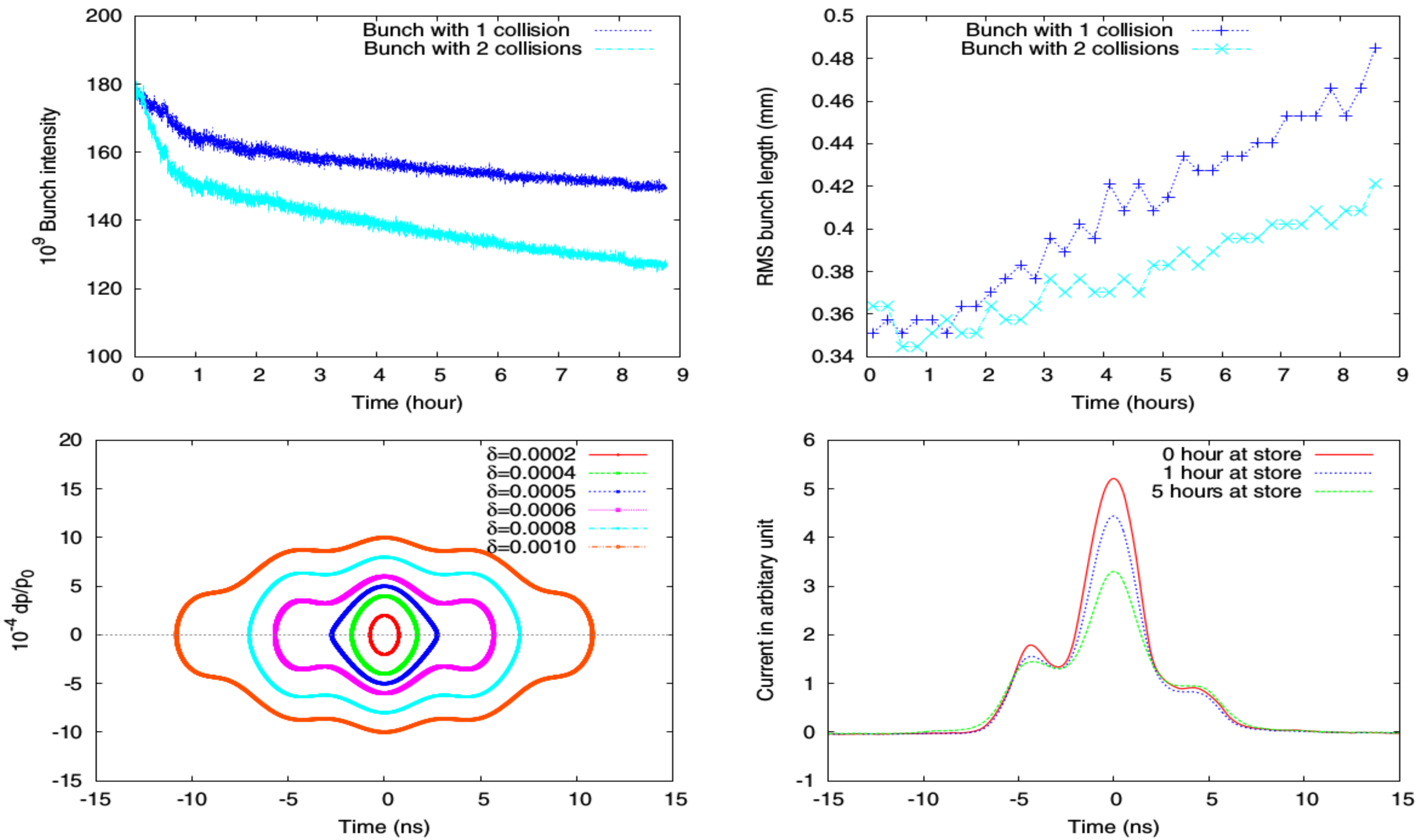
Operational Observations (II)





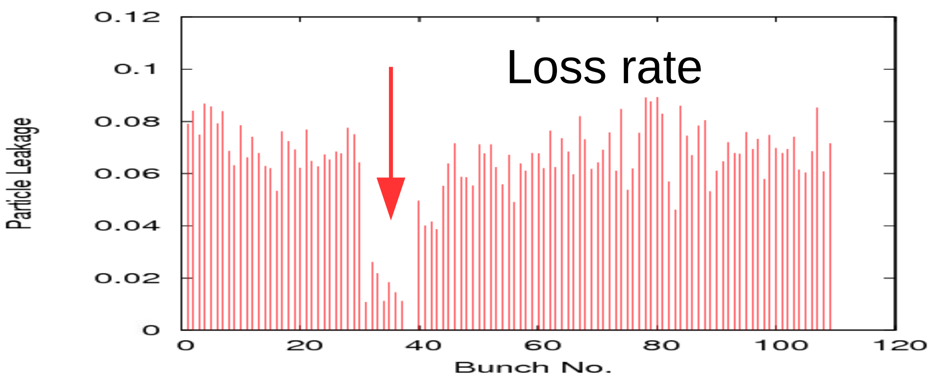
- We observed **reduction in emittance and bunch length at the beginning of store**. After 1 hour into store, the emittance and the bunch length began to grow with a small rate.
- We link the **emittance and bunch length reduction** at the beginning of store to the **large particle loss** at that time.

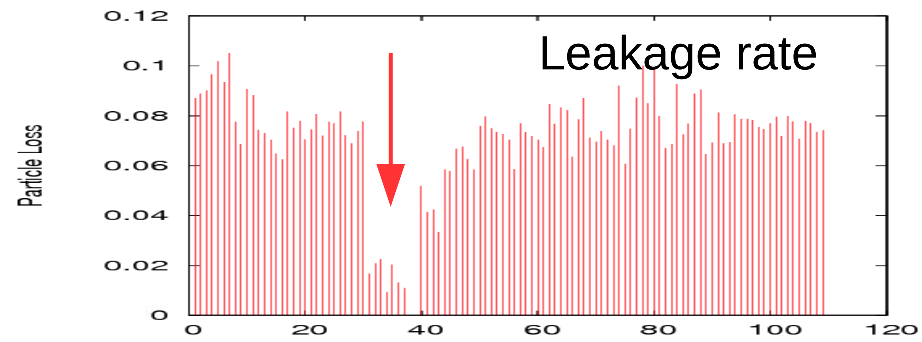
Proton Loss Mechanism (I)

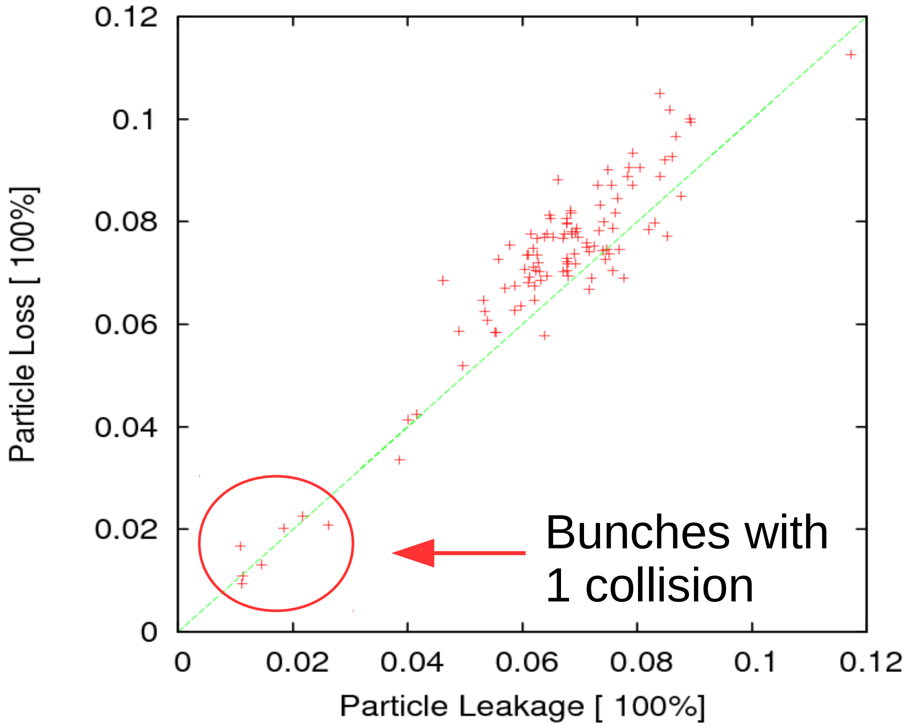


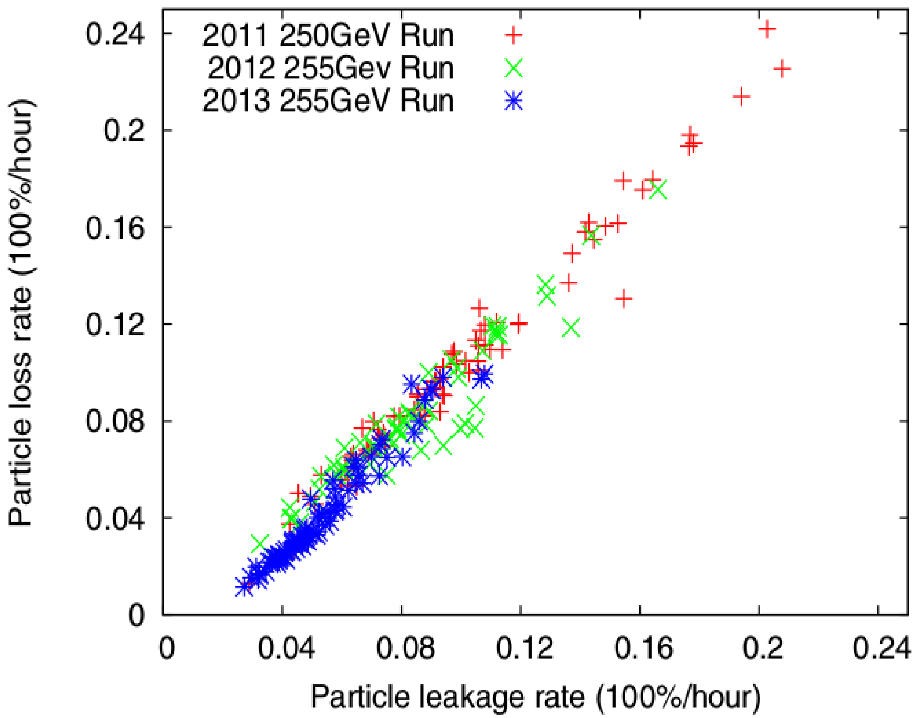
- We found bunches **with 1 collision per turn** had less beam loss than those bunches with **2 collisions per turn**. We also found the bunch length of bunches with 2 collisions grow more slowly than the bunch with 1 collision per turn. **BB must play a role here.**
- Dual RF cavities were used. Into the store, we did not observe the particle population grow in the adjacent 197MHz RF bucket. **Particle loss happened with a large dp/p0.**

Proton Loss Mechanism (II)





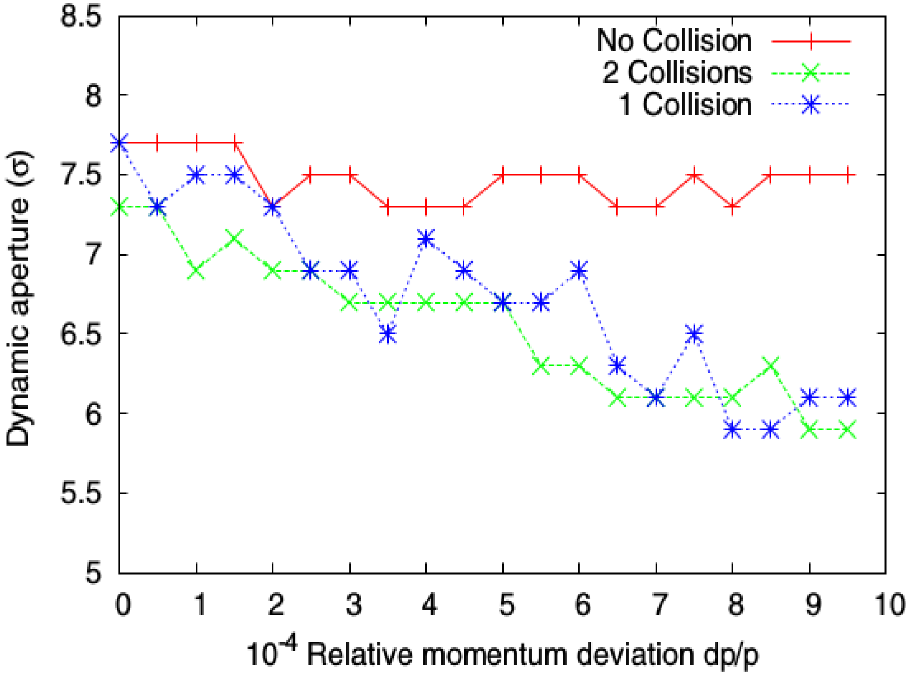




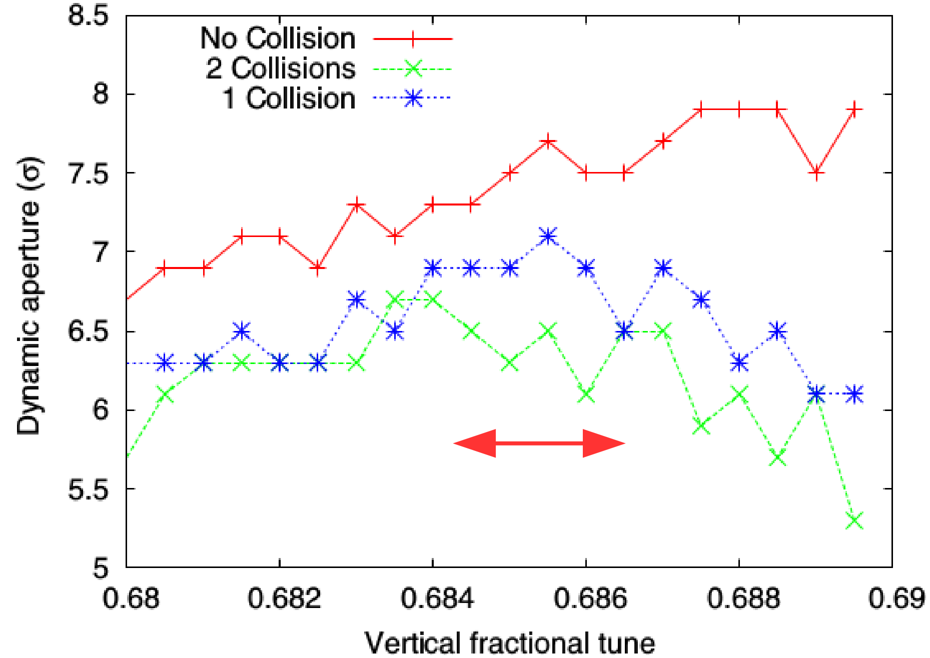
- We further found **a good linear correlation** between the particle loss rate and the particle leak rate from the central 197MHz RF bucket, no matter at the beginning of store or 1 hour into the store, no matter which p-p run.

Off-momentum DA

dp/p0 scan



tune scan

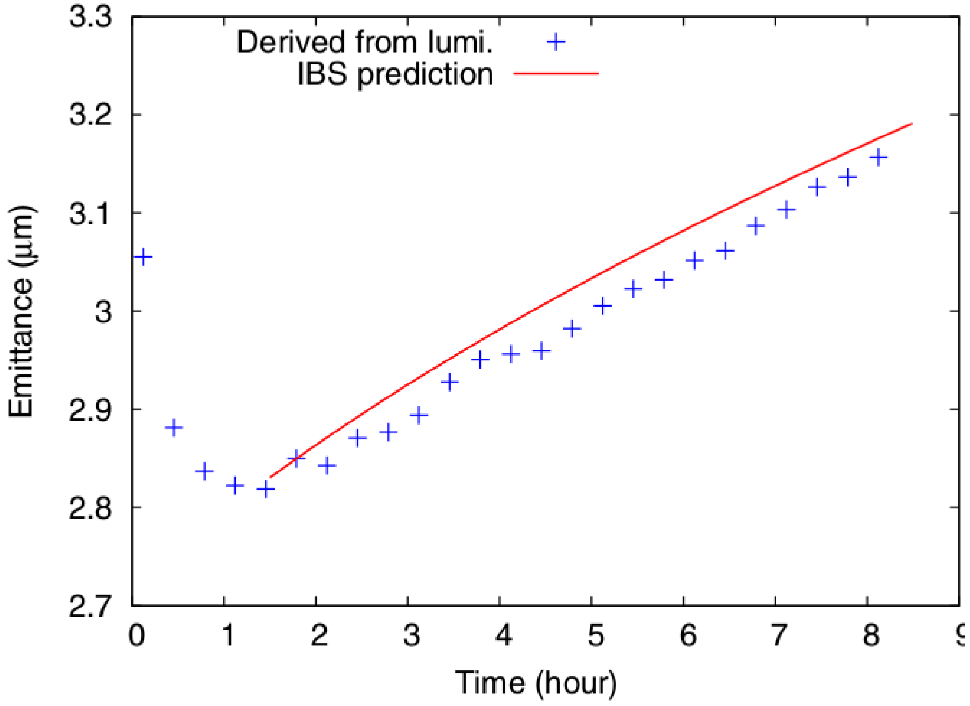


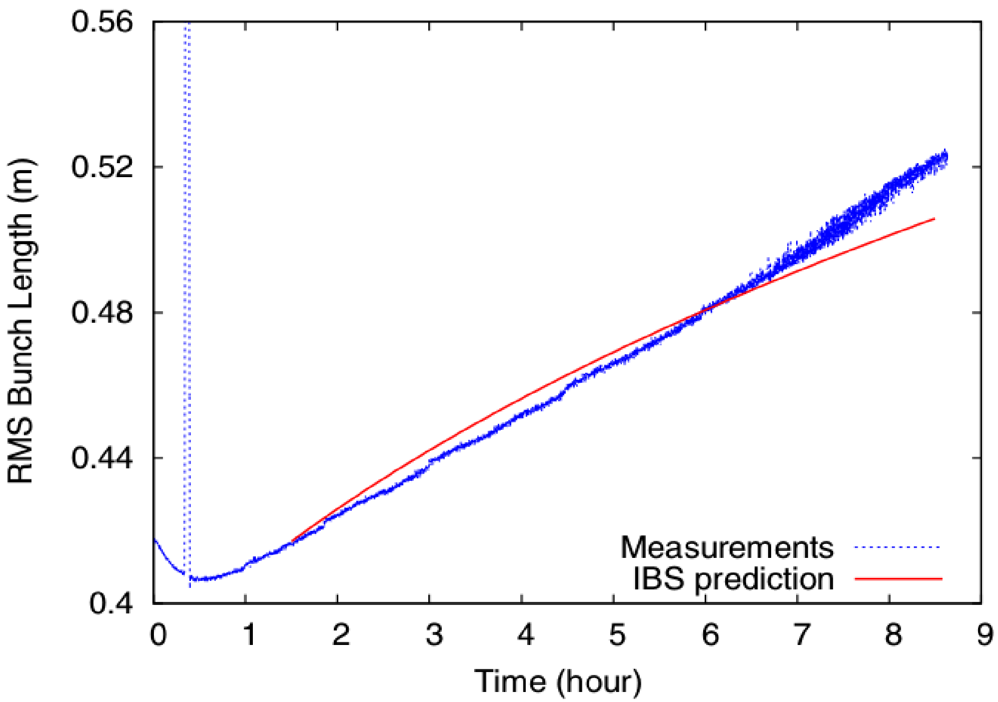
- Left plot shows **off-momentum DA vs. dp/p0**. The DA with 1 collision per turn is slightly better than with 2 collisions per turn.
- Right plot shows **DA tune scan with dp/p0=6e-4**. The DA with 1 collision per turn is 0.5 sigma larger than with 2 collisions per turn in the operation tune range.
- **Conclusion:**
  Beam-beam interaction reduced the off-momentum DA. Particles got lost with a large dp/p0, either from re-bucketing at beginning of store, or from IBS into store.

Emittance Growth Modeling

$$\tau_{\mathrm{IBS},\parallel}^{-1} = \frac{1}{\sigma_p^2}\frac{d\sigma_p^2}{dt} = \frac{r_i^2 c N_i \Lambda}{8\beta^{3/2}\gamma^{3/2}\epsilon_{n,\mathrm{rms},x}^{3/2}\langle\beta_x^{1/2}\rangle\sigma_l\sigma_p^2},$$

$$\tau_{\mathrm{IBS},x,y}^{-1} = \frac{1}{\epsilon_{n,\mathrm{rms},x,y}}\frac{d\epsilon_{n,\mathrm{rms},x,y}}{dt} = \frac{1}{2}\frac{\gamma\beta\sigma_p^2}{\epsilon_{n,\mathrm{rms},x}}\left\langle\frac{H_x}{\beta_x}\right\rangle\tau_{\parallel}^{-1}.$$

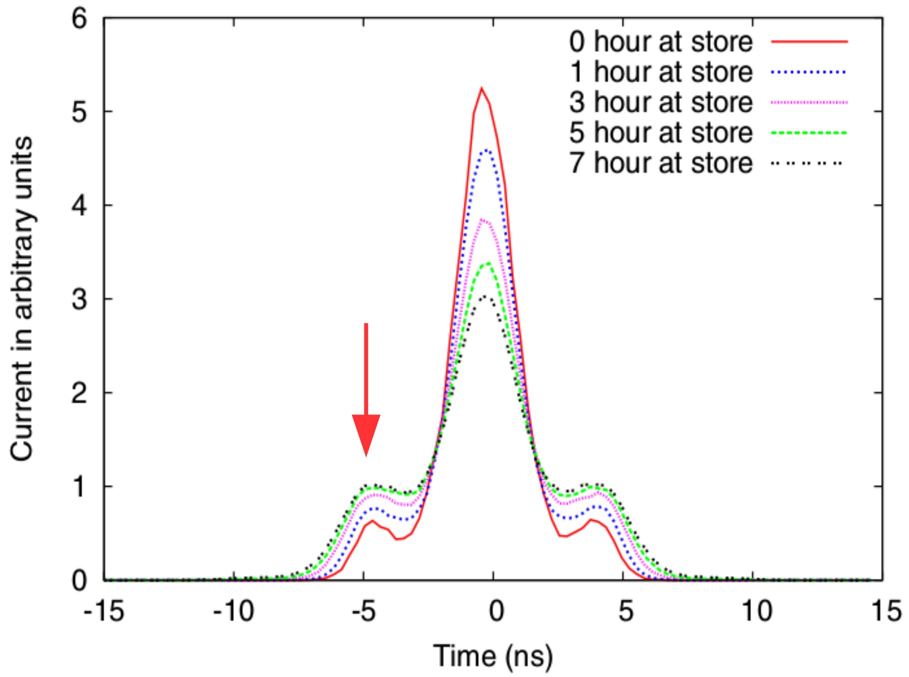




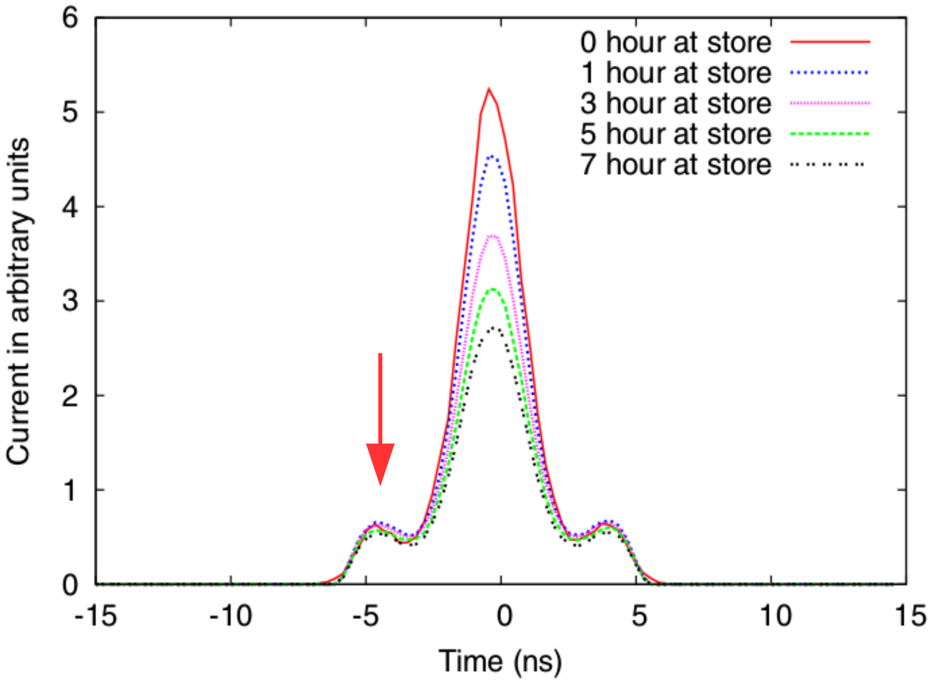
- Emittance and bunch length growth can be largely reproduced by IBS effect **with actual intensity evolution** (see later, we can’t model intensity evoluation well).
- Without BB (therefore without beam loss), the experimental emittance and bunch length growth can be reproduced by IBS too.

Multi-particle Tracking (I)

Without BB, no dp/p0 limit

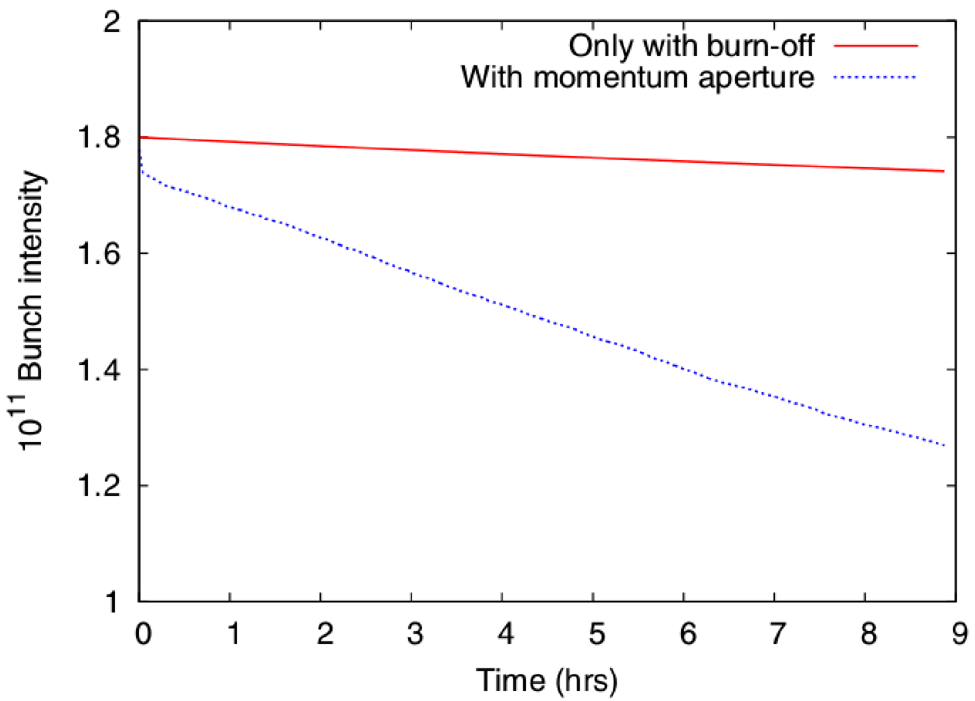


With BB, with dp/p0 limit



- Multi-particle tracking was used to benchmark the observed longitudinal particle population distribution. IBS and a **hard** transverse momentum aperture are included.
- **Simulation reproduced the observed longitudinal profiles** with and with BB interaction.

Multi-particle Tracking (II)



- **However, We can’t reproduce the early particle loss rate**.
- One reason is a hard momentum deviation limit was used. The actual particle loss in longitudinal plane is much complicated.
- Secondly, we don’t know how to reproduce the exactly initial longitudinal particle distribution with RF re-bucketing.

Summary

- We analyzed the mechanism of beam loss in the ion run. After adopting a new lattice with a better off-momentum DA, the ion loss was mostly from burn-off. During the asymmetric ion run, unbalanced beam sizes at IP caused a large beam loss. By adjusting cooling speeds, we minimized the beam loss and maximized the integrated luminosity.
- We analyzed and modeled the beam loss, emittance and bunch length growth in the proton runs. The large beam loss at beginning of store was due to a limit off-momentum DA which was reduced by the BB interaction. The observed emittance and bunch length can be largely reproduced by IBS with the actual bunch intensity evolution.