Why Strong Hadron Cooling Is Needed

Thomas Roser

Coherent electron Cooling WS

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BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY

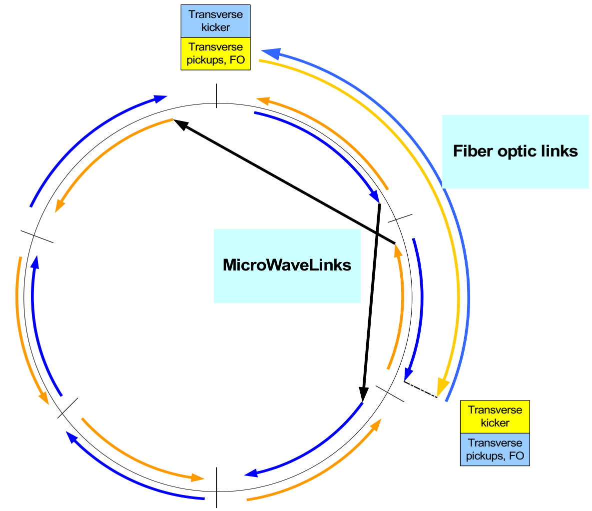
Luminosity of Storage Ring Colliders

$$\mathcal{L} = f_c \frac{N_1 N_2}{4\pi\sigma_x\sigma_y} = f_c\gamma \frac{N_1 N_2}{4\pi\sqrt{\beta_x^*\beta_y^*}\sqrt{\varepsilon_x^n\varepsilon_y^n}}$$

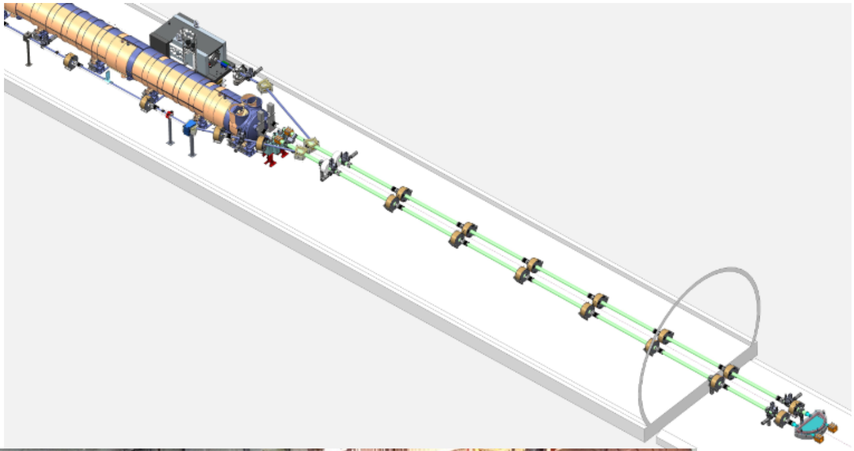
- Luminosity is inversely proportional to transverse beam size ($\sigma_x\sigma_y$) at the collision point
- Extreme focusing to reach small transverse beam size is limited by short focal length, short vertex length (hour glass effect) needing short bunches and high peak current and large non-linear optical effects
- Full energy beam cooling gives small transverse beam size without the need for extreme focusing. Beam cooling can also reduce beam halo and reduces beam losses and detector background.

Strong high energy hadron cooling at RHIC

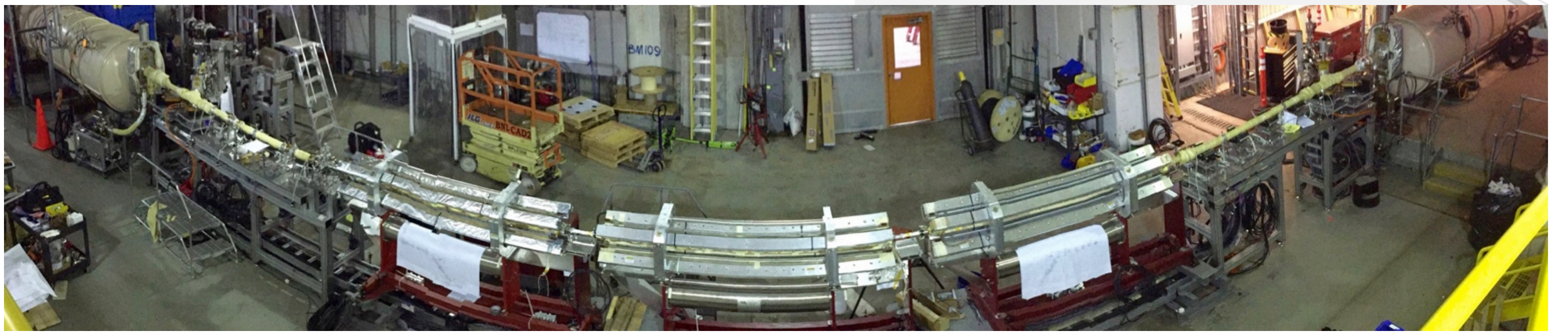
- First high energy, bunched beam stochastic cooling gives record heavy ion collision rates



- First bunched beam electron cooling for luminosity upgrade of "low" energy heavy ion collisions



- Experimental demonstration of Coherent electron Cooling, a combination of stochastic and electron cooling, for fast cooling of high energy hadron beams

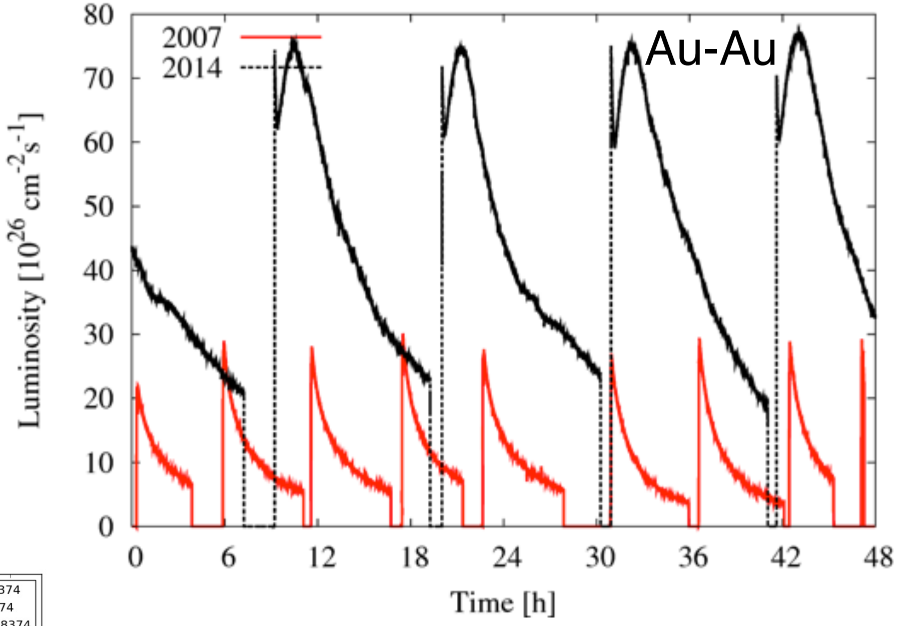


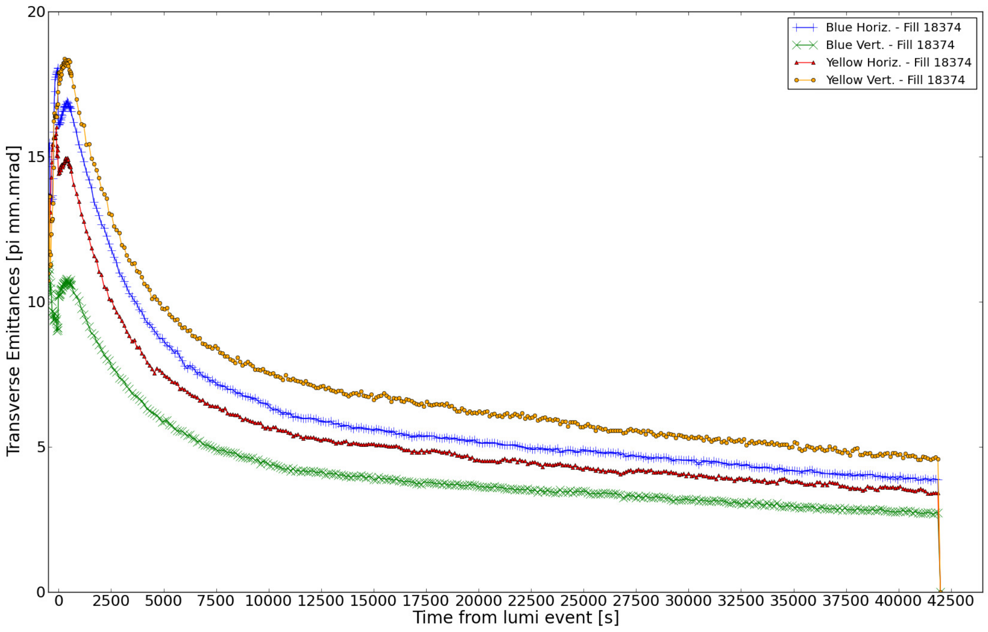
Luminosity limits with hadron cooling – burn-off

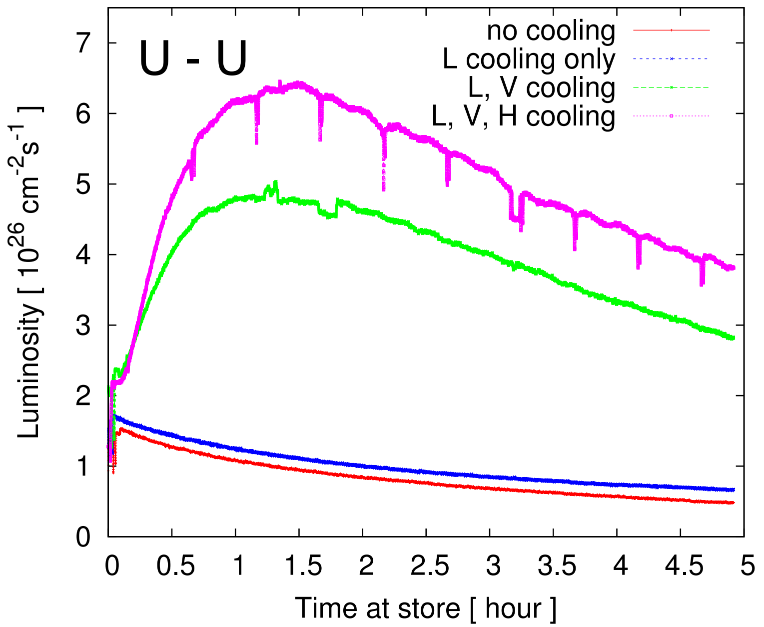
- Burn-off: particles are lost from beam intensity due to collision interaction (total cross section)
  - For Au-Au collisions (total cross section ~ 400 barns) maximum luminosity is about 1 x 10^{28} $cm^{-2}s^{-1}$ at RHIC
  - For proton-proton collisions (total cross section ~ 60 mb) maximum luminosity is about 1 x 10^{34} $cm^{-2}s^{-1}$ at RHIC
- LHC and particularly HL-LHC would not benefit much from full energy beam cooling
- For electron-ion colliders the total cross section is much smaller and burn-off is not a problem. This is the primary application for strong hadron cooling.

Heavy ion stochastic cooling – reaching burn-off

- First high energy, bunched beam stochastic cooling gives record heavy ion collision rates
- Reached normalized emittances of 0.3 - 0.8 μm







Luminosity limits with hadron cooling – beam-beam

$$\xi_{1;x,y} = \frac{N_2 r_0 \beta^*_{1;x,y}}{2\pi\gamma\sigma_{2;x,y}\left(\sigma_{2;x}+\sigma_{2;y}\right)} = \frac{N r_0}{4\pi\varepsilon^n} \text{ (for equal round beams)}$$

$$= \frac{N_2 r_0 \beta^*_{1;x,y}}{2\pi\gamma\sigma_{2;x,y}\sigma_{2;x}} \text{ (for flat beams)}$$

- Beam-beam interactions: emittance growth from collision interactions cannot be cooled fast enough.

- Beam-beam limitation is greatly reduced for linac (or ERL-ring) colliders with only a single interaction

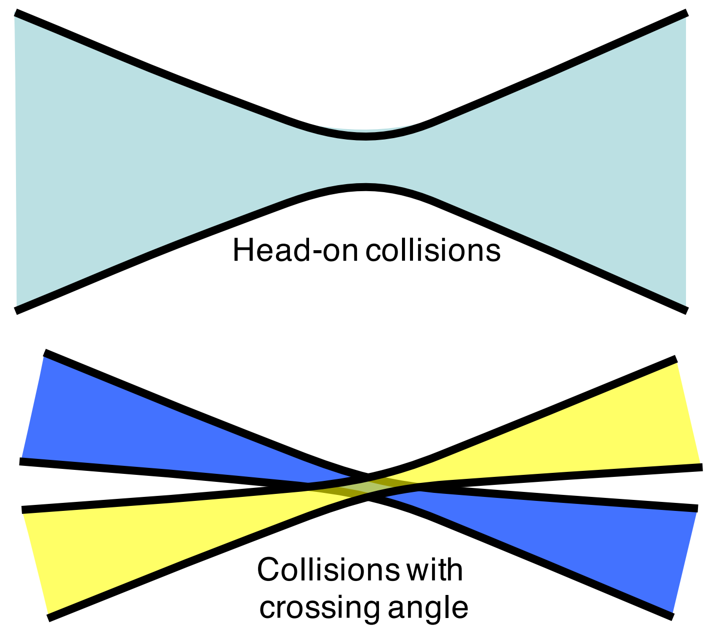
High bunch frequency and beam cooling

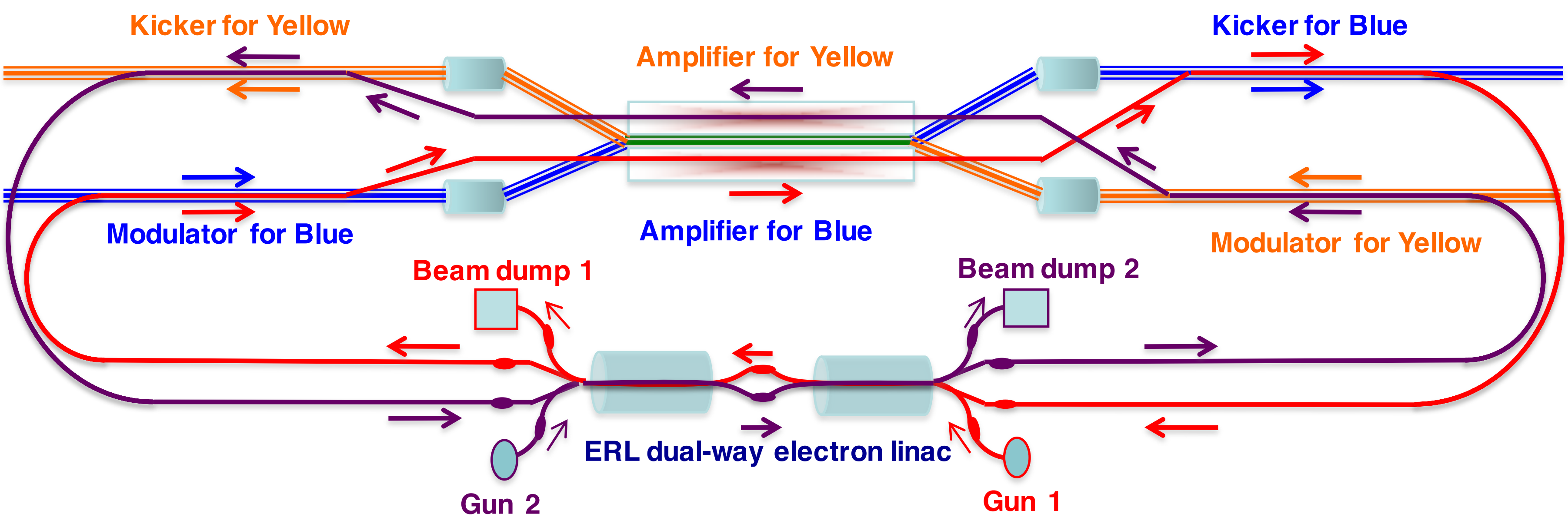
$$\mathcal{L} = f_c \frac{N^2}{4\pi\sigma^2} = f_c \gamma \frac{N^2}{4\pi\beta^* \varepsilon^n}$$

- Increase bunch frequency and reduce bunch charge with constant beam current
- Cool beam emittance at lower bunch charge to get the same beam-beam parameter (N/ε)
- This results in the same luminosity
- Now reduce β^*, which is possible because of the smaller emittance, to get increased luminosity
- This requires large crossing angle to avoid parasitic collisions and crab cavities

CeC for RHIC: High Luminosity with large Piwinski angle

- If head-on collisions are at beam-beam limit large Piwinski angle collisions of long bunches with very small emittance can increase luminosity (Super B factory)
- Needs strong cooling: synchrotron rad. or **CeC**
- Separate bunches outside high luminosity region to avoid beam-beam from low luminosity region.
- Reducing beam emittance back to beam-beam limit
- Smaller emittance and shorter overlap region allows for smaller beta-star
- RHIC: overlap length ~ 10 cm, ε^n (rms) ~ 0.2 μm , β^* ~ 10 cm gives ~ x10 luminosity increase (~ 5 x10^{33} cm^{-2} s^{-1} !)





Summary

- Strong hadron beam cooling can increase collider luminosities up to the fundamental limit of burn-off and beam-beam interactions

- Strong hadron beam cooling is particularly useful for electron-ion colliders because of the absence of the burn-off limit

- High bunch frequency with large crossing angle or long bunches with large Piwinski angle can use of strongly cooled beams to increase luminosity