Precise beam velocity matching for the experimental demonstration of ion cooling with a bunched electron beam

S. Seletskiy, M. Blaskiewicz, A. Drees, A. Fedotov, W. Fischer, D. M. Gassner, R. Hulsart, D. Kayran, J. Kewisch, K. Mernick, R. Michnoff, T. Miller, G. Robert-Demolaize, V. Schoefer, H. Song, P. Thieberger, P. Wanderer

NAPAC 2019

BROOKHAVEN NATIONAL LABORATORY

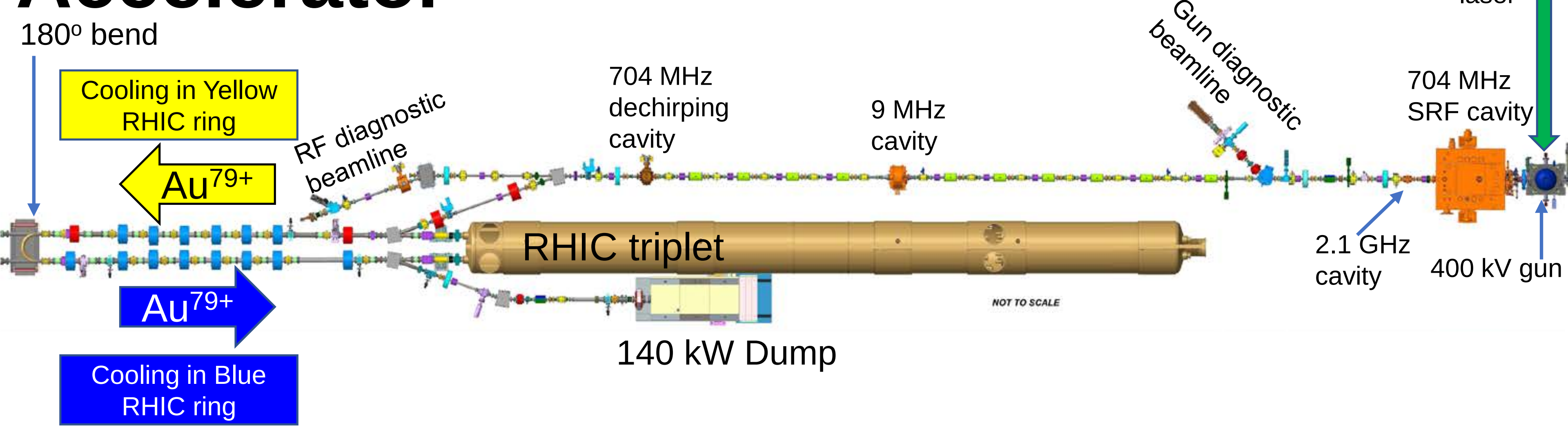
U.S. DEPARTMENT OF ENERGY

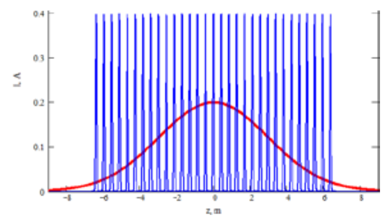
LEReC highlights

- Low Energy RHIC electron Cooler (LEReC) is world's first RF-based ("bunched") electron cooler
- LEReC is the first electron cooler which is applied directly to the ions in the collider at top energy
- LEReC is the first electron cooler that utilizes the same electron beam for cooling ions in two consecutive cooling sections in two rings of the collider

- LEReC is an important part of low energy RHIC run dedicated to search of the QCD critical point in the nuclear matter phase diagram
- Since LEReC uses RF acceleration of the bunched beam it can be easily scaled for high energy applications

Accelerator





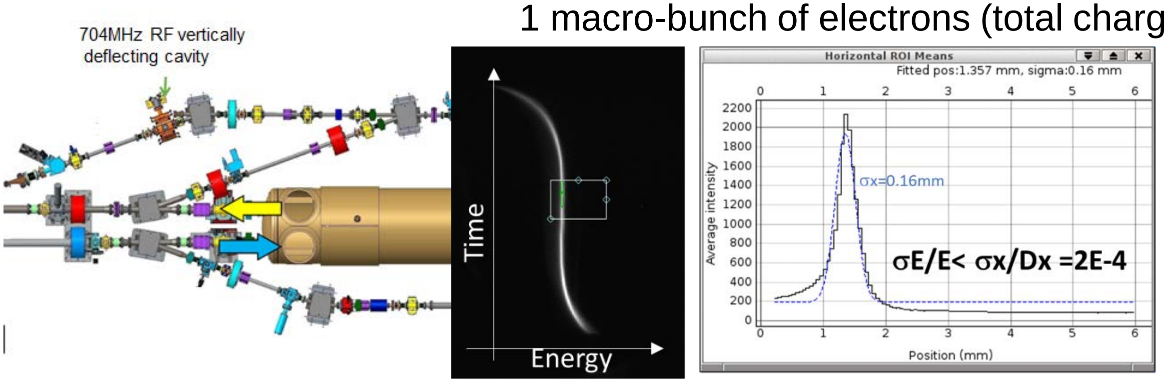
- 704 MHz e-bunches (chopped into 9 MHz macrobunches) are produced from photocathode and accelerated in gun to 400 keV
- Electrons are accelerated to design energy (1.6 MeV, 2 MeV, 2.6 MeV) in 704 MHz SRF Booster

- 3rd harmonic (2.1 GHz) cavity is used to reduce the curvature of e-bunches longitudinal phase space, 9 MHz cavity compensates macrobunch to macrobunch beam loading, warm 704 MHz cavity removes energy chirp introduced in Booster
- e-bunches are brought to Yellow and then Blue RHIC cooling sections (20 m long) where they co-travel with ion bunches with the same average velocity
- LEReC is designed to produce up to 85 mA of CW current, and to conserve the high quality of e-bunches throughout ~100 m of the beamline.

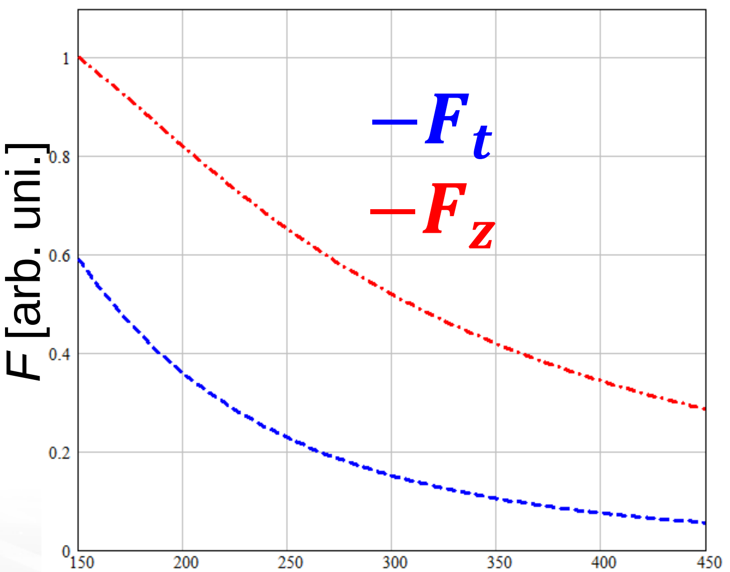
Requirements to electron bunches

- To have a linear 3D cooling effectively counteracting IBS in RHIC ion bunches the e-bunches are required to have
  - $\sigma_{\delta e}$=5e-4
  - γ_e and γ_i must be matched with accuracy better than 5e-4 relative to each other
  - $\sigma_{\theta e}$=150 urad
- High quality e-bunches (with charge/bunch up to 130 pC) satisfying LEReC requirements were successfully obtained during 2018 accelerator commissioning.

1 macro-bunch of electrons (total charge 3nC)



- Presence of ions doesn't affect relative momentum spread of the e-bunch, it does severely affect its angular spread though.
- Yet longitudinal friction force is relatively strong even for high e-bunch angular spread. Hence setting E_e with 5e-4 accuracy shall allow one to observe longitudinal bunched cooling.



Approach to γ-matching

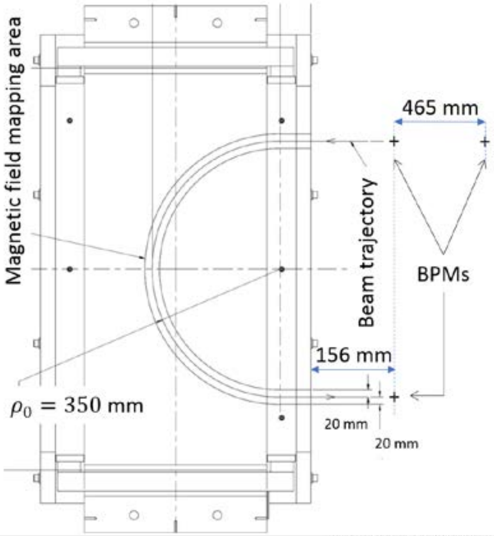
- Initially the energy of e-beam is set based on RF calibration (a few % error is highly possible)
- High accuracy low energy spectrometer measurements are used to find e-beam energy with 0.5 % accuracy
- Energy scan with 1 keV steps and recombination monitor is used match γ_e and γ_i within 0.1% with respect to each other
- Energy scan with sub-keV steps is used to observe and optimize longitudinal cooling

U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY

High accuracy low energy spectrometer

To measure electrons absolute energy with accuracy better than 8 keV we utilized 180º bending magnet located between the Yellow and the Blue cooling sections.



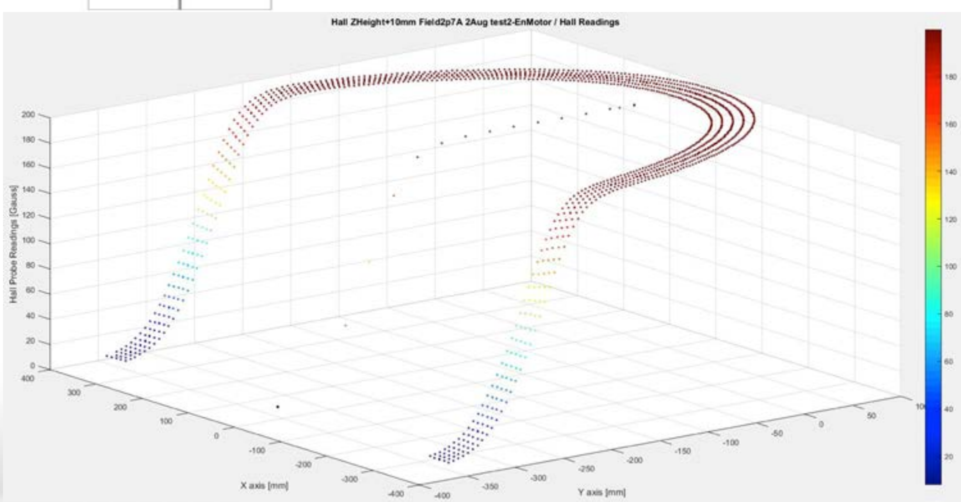
$$\delta = E/E_0 - 1$$

$$\Delta \equiv B/B_0 - 1$$

$$x_{out} = -x_{in} - 2\rho_0 \frac{E_0 + mc^2}{E_0 + 2mc^2}\delta + 2\rho_0 \Delta$$

$$x_{in} = x_2 + S_b \frac{x_2 - x_1}{S_{12}} \qquad x_{out} = x_3 + S_b \frac{x_2 - x_1}{S_{12}}$$

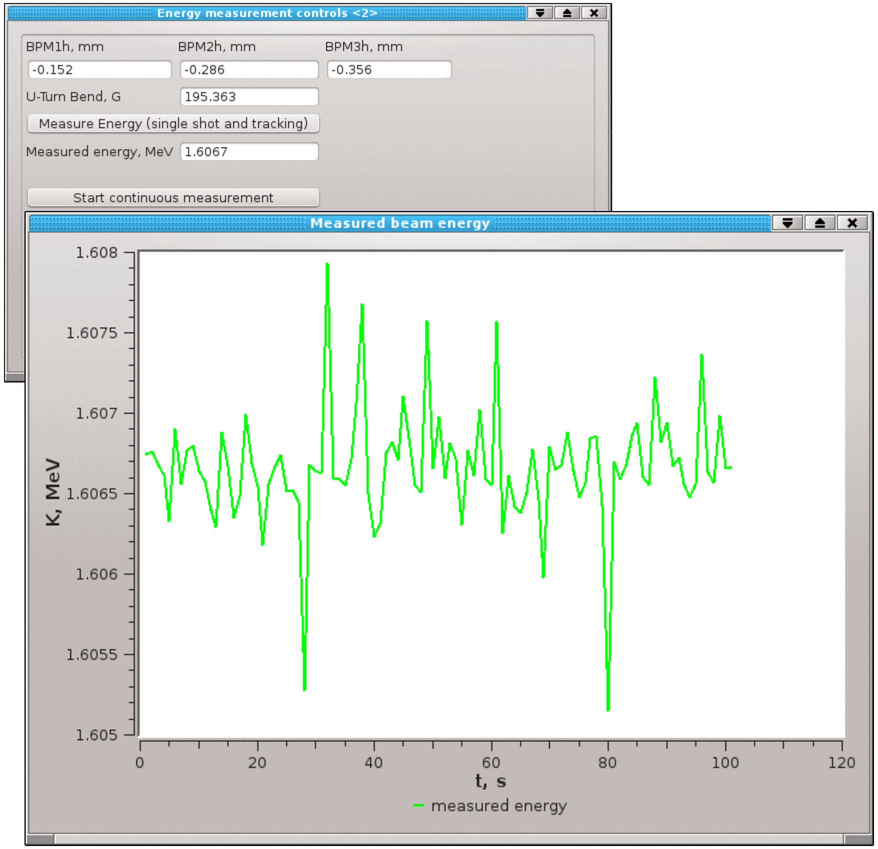
$$B\rho = \frac{mc}{e}\sqrt{\left(\frac{E_0(1+\delta)}{mc^2} + 1\right)^2 - 1} \approx B_0\rho_0\left(1 + \frac{E_0 + mc^2}{E_0 + 2mc^2}\delta\right)$$

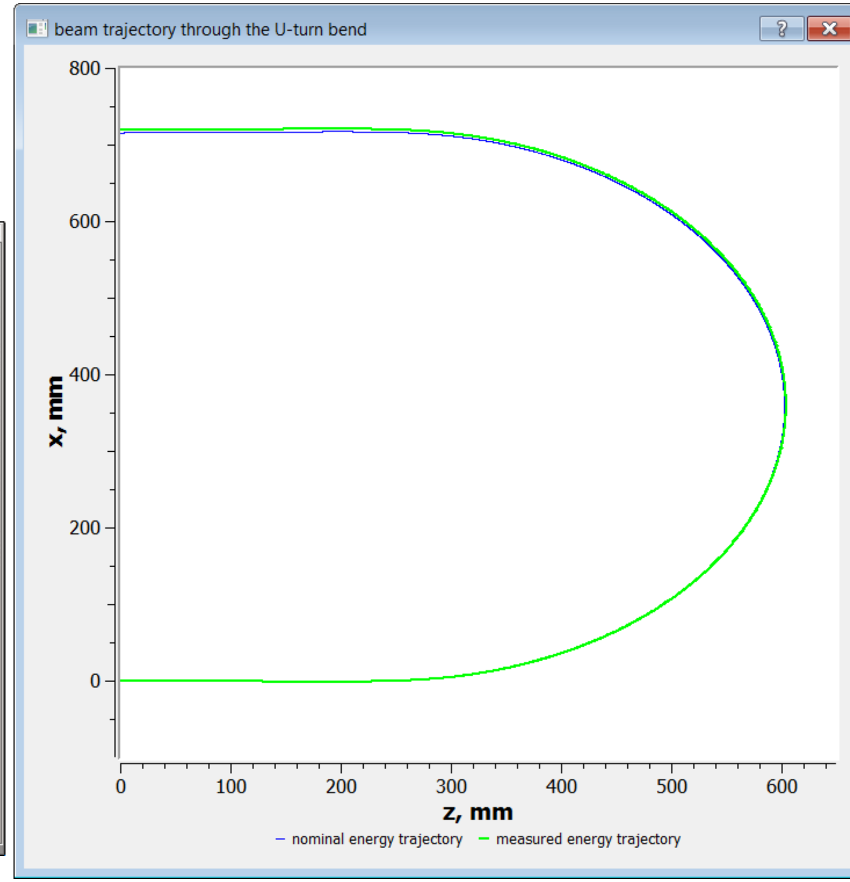


The field of the U-turn bending magnet was mapped in +/-20 mm range around the design beam trajectory. The field was measured with a probe combining Hall sensor and a customized high-accuracy NMR probe capable of measuring fields as low as 140 G. The resulting field map has an accuracy of 0.02 G.

Measuring E_e with spectrometer

- Spectrometer showed that energy set based on RF calibration had 100 keV error.





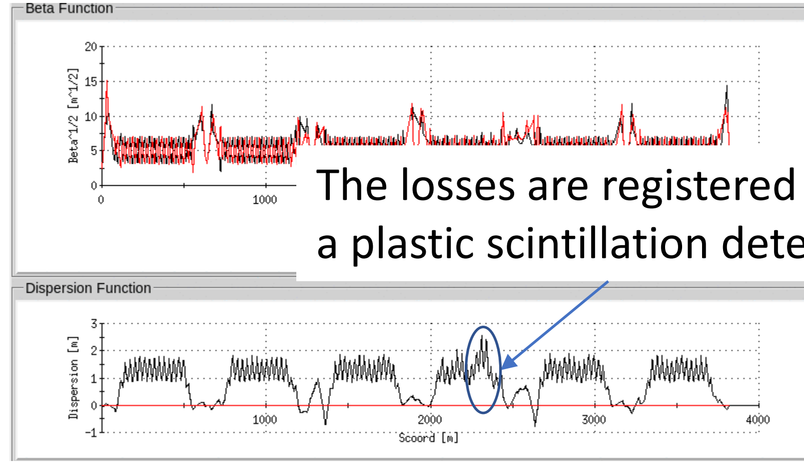
- Both simulations and experiment showed perfect agreement between beam tracking in mapped field and a hard-edge approximation results. We used energy measured in the hard edge approximation for routine energy monitoring and setting while tracking was performed sometimes to double-check the results.

Recombination monitor

$$Au^{79+} + e^{-} \rightarrow Au^{78+} + \gamma$$

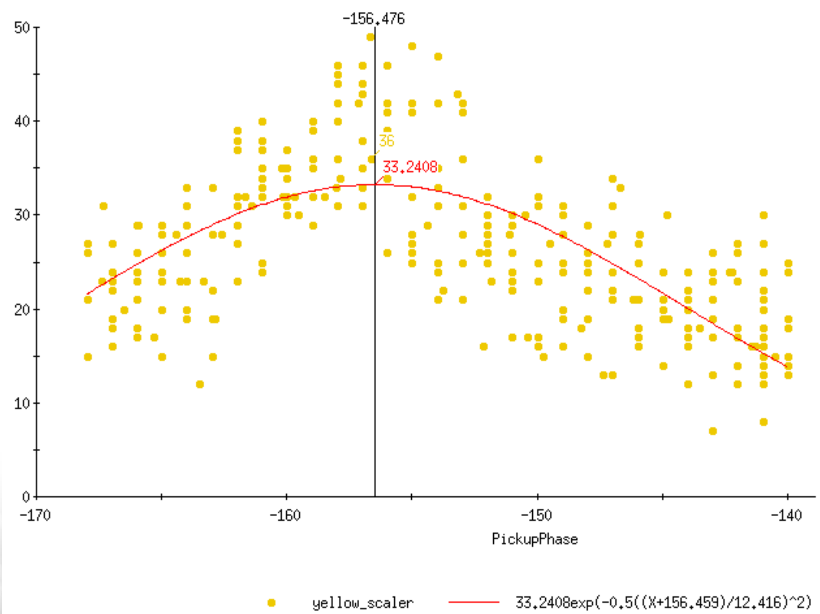
- Some of Au^{79+} ions recombine with electrons via radiation recombination process in the CS, become Au^{78+} and get lost in the high dispersion RHIC region.
- The recombination rate is the highest when the electron and ion γ-factors are matched.

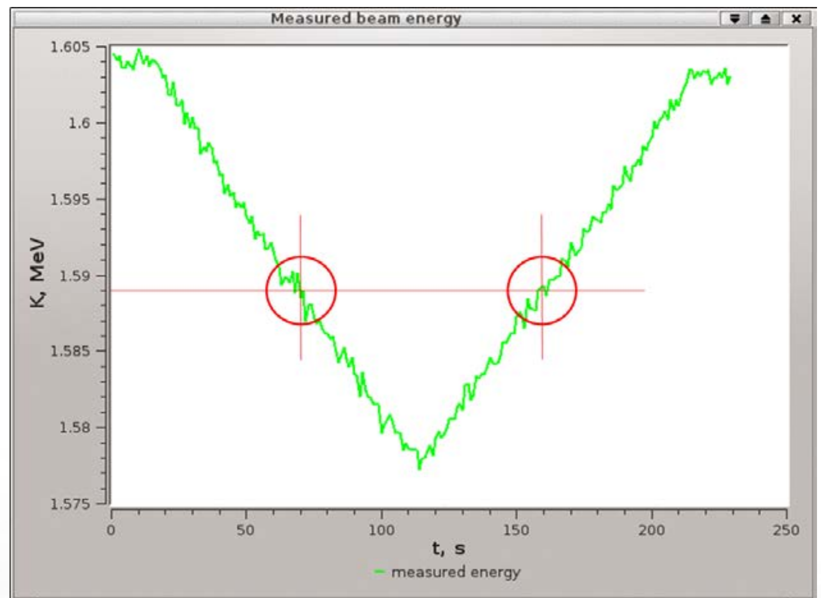
Dedicated lattice with high dispersion downstream of the CS



The losses are registered with a plastic scintillation detector

Night of **March 28, 2019** – γ_e and γ_i are matched

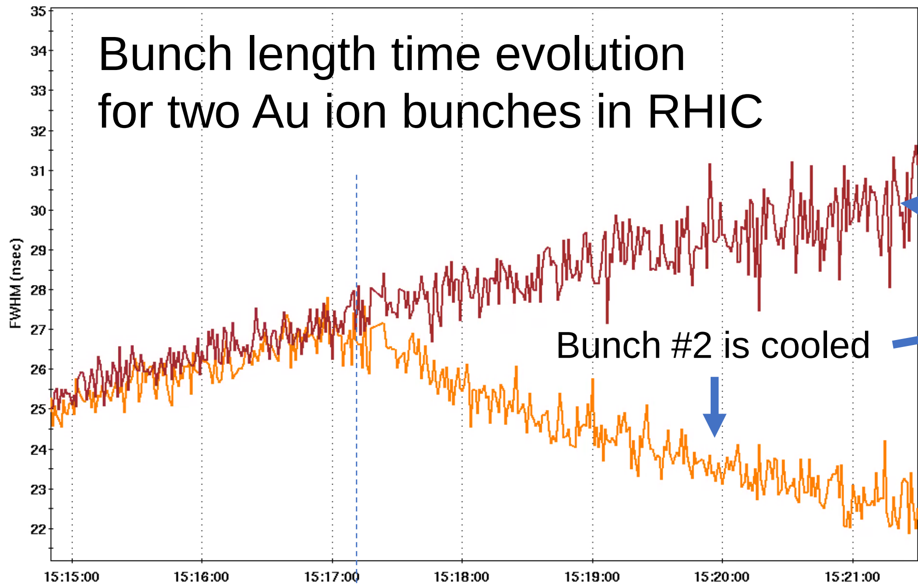


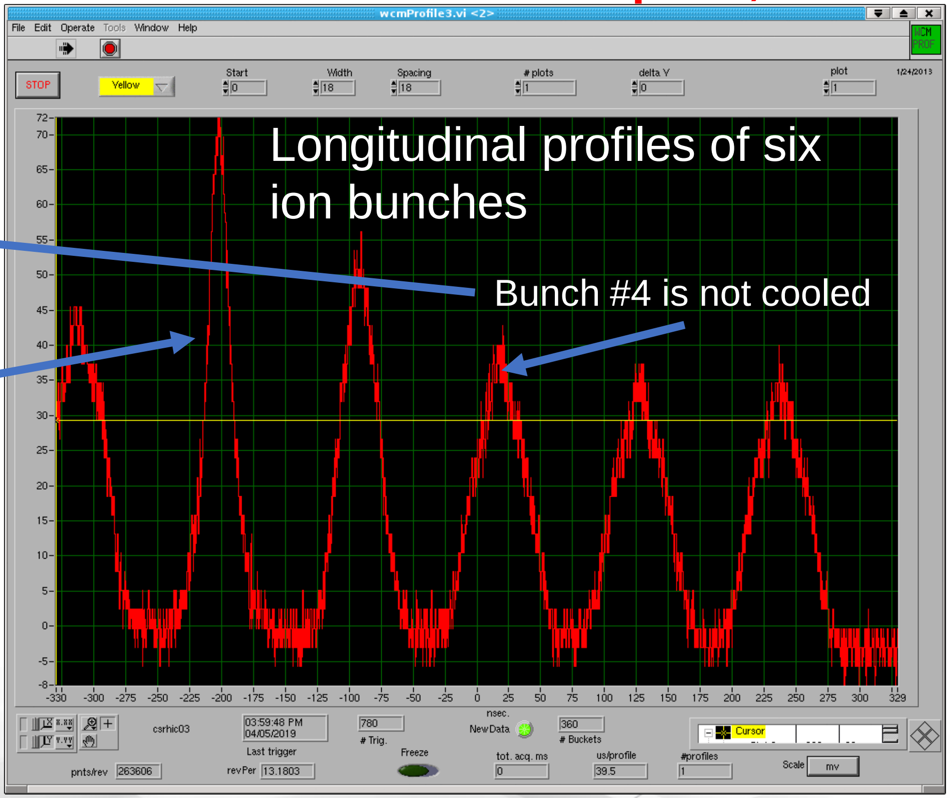


Obtaining cooling

- After rough matching of electron and ion γ-factors based on recombination rate maximization, we engaged in an electron energy scan with sub-keV steps aimed to observe bunched beam cooling.
- In the absence of electrons, the ion bunch length increases due to IBS. On the other hand, electron cooling must keep ion bunch length at a constant value determined by the balance of the IBS the cooling.
- The shape, length and peak current of the ion bunches are continuously read by the RHIC wall current monitor (WCM).

First electron cooling using bunched electron beam was observed on **April 5, 2019**

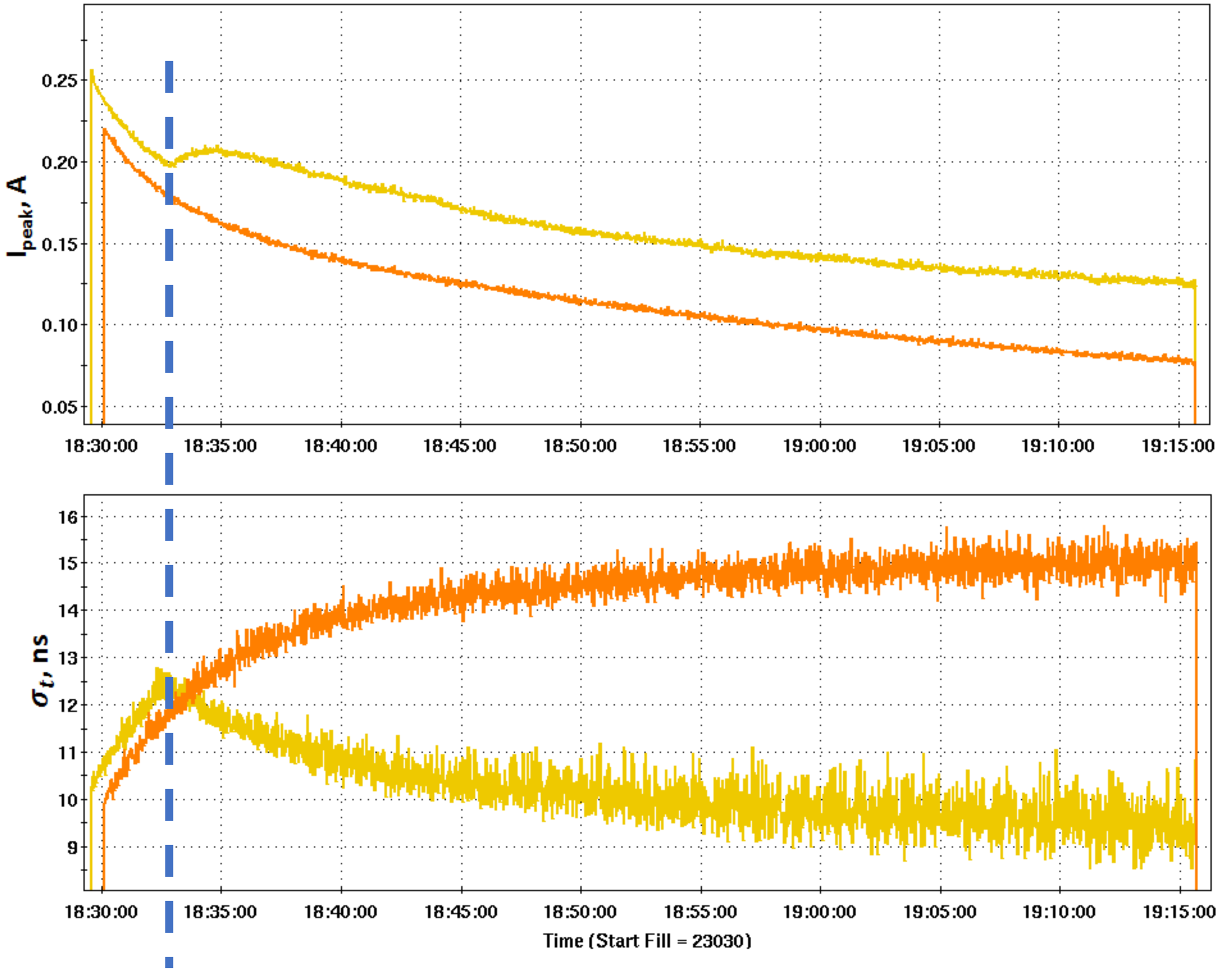




γ-factors of ions and 2nd e-macrobunch are matched at this moment

U.S. DEPARTMENT OF ENERGY

Typical cooling observation



γ-factors of ions and electrons are matched at this moment

The upper plot shows evolution of peak current of cooled (yellow trace) and test (orange trace) ion bunches. The lower plot shows evolution of the rms bunch length of the cooled and the test ion bunches during RHIC store.

γ-matching at new energy

- Since our spectrometer was providing a good energy measurement accuracy and the longitudinal cooling was easily detectable during the energy scan, we decided to skip the recombination scan for 2 MeV energy settings.
- We set LEReC RF based on the spectrometer readings and scanned electron energy monitoring ion bunch length and peak current.
- The whole process of precise γ-matching at 2 MeV took us just a few hours

Conclusion

- The critical step in obtaining first bunched beam cooling was matching the average longitudinal velocities of electron and ion beam so that γ-factor of two beams coincide with precision better than 5e-4. This required setting electrons energy with accuracy better than 0.8 keV.
- We used three complimentary techniques
  - Our high accuracy low energy spectrometer allowed us to set electron energy with 4e-3 accuracy
  - Recombination monitor confirmed the spectrometer settings and improved electron-ion γ-matching to 1.3e-3
  - Finally, fine-step energy scan allowed us to obtain the longitudinal cooling which is easily detectable from the monitoring of the length and peak current of ion bunches.