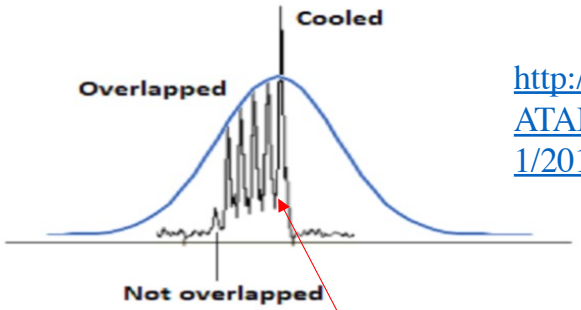
APEX on Recombination studies at LEReC

D. Kayran, A. Drees, A. Fedotov, P.Harvey, R. Hulsart , A. Marusic,
P. Thieberger, S. Seletskiy and others.

CEC-X group meeting Nov 12, 2021

Introduction and Motivation

- Radiative recombination of ions was extensively studied experimentally. Perfect agreement between measurements and theoretical prediction for the recombination coefficient was found in a wide range of relative energies between the electrons and ions (>10meV).
- However, in the region of extremely small relative energies (which is the region typically used for electron cooling), the measured recombination coefficient for experiments with bare ion was found significantly higher than predicted by standard theory of radiative recombination.
- At RHIC during LEReC setup in 2019 the recombination enhancement **was observed first time without continues** solenoidal field. The goal of this experiment is the systematic study beam losses due to recombination for different energy offsets and energy spread.



Bunch by bunch loss signal data. The best matched energy MB

http://www.cadops2.bnl.gov/elogs/entryList.jsp?DATABY=day&ELOG=LEReC_2019&DATE=04/11/2019&DIR=none#968776

© P. Thieberger

Recombination signal was used to match RHIC and LEReC beams velocities during LEReC commissioning in 2019

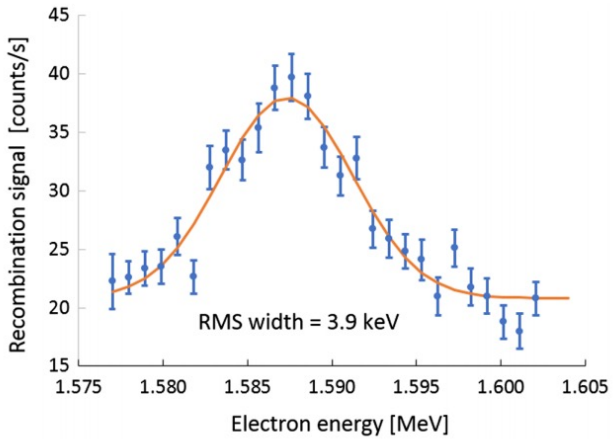


FIG. 7. The recombination signal (blue dots) dependence on beam energy (as measured by spectrometer) during the scan. The error bars for each point represent the rms of the recombination signal at each energy setting averaged over two scans. RMS width of the measured trend is calculated from Gaussian fit of the data (orange solid line).

Phys. Rev. Accel. Beams 22, 111004 – Published 27 November 2019

Summary of April 2019

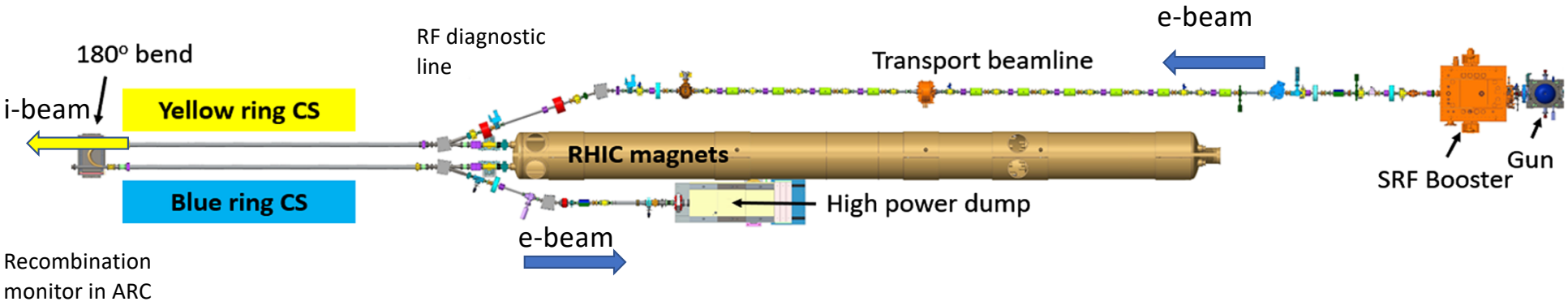
- It seems that bunch by bunch loss rate near recombination monitor location is well correlated with:
  - Presents of electrons
  - Energy of electrons
- For this RHIC/LEReC parameters the loss rate was about 10-15 events/minute.

- The energy dependance distribution of the losses looks not exactly Gaussian.
  - Should try to scale with ion bunch intensity to get more accurate curves

Plan for APEX June 2021:

- ~~Use more intensity per bunch RHIC and LEReC~~
- Try LEReC 76kHz mode with 6MB (or 10MB if possible)
- Preferable configuration: several bunches in RHIC overlapping with one (or two) less numbers of the LEReC Mbunches.
- Initial Question
  - Should we restore Au19-4GeV-25m rec. lattice or try regular RHIC run21 Au21?
    - We decided to keep regular RUN21 lattice **and apply local bump, instead.**

LEReC layout



- The e-bunches are produced at the photo-cathode illuminated by a green 704 MHz laser modulated with the 9 MHz frequency to match the frequency of RHIC ion bunches.
- The electrons are accelerated to 375 keV in the dc gun followed by a 704 MHz superconducting rf accelerating cavity bringing the beam energy to 1.6–2. MeV.
- The e-beam is transported in a 40 m long transport line and merged to the cooling section (CS) in the “Yellow” RHIC ring . After passing the Yellow CS, the beam is sent to the cooling section in the “Blue” RHIC ring by a 180° bend.
- Finally, the electron beam is extracted and sent to the beam dump.

Equations to calculate recombination rate

Recombination cross section for an electron to be captured by an ion:

$$\sigma(v) = A\frac{2h\nu_0}{m_e v^2}\left[\ln\left(\sqrt{\frac{2h\nu_0}{m_e v^2}}\right) + \gamma_1 + \gamma_2\left(\frac{m_e v^2}{2h\nu_0}\right)^{1/3}\right]$$

v: relative velocity between an electron and an ion

$$A = 2.11\times10^{-22}\,cm^2$$

$$\gamma_1 = 0.1402$$

$$\gamma_2 = 0.525$$

To calculate recombination rate of an ion bunch moving together with an electron bunch, the following formula is used

$$h\nu_0 = Z^2\alpha^2 m_e^2/2 = Z^2\times13.6eV$$

$$Z = 79$$

$$\alpha_r = \frac{\int_{-\infty}^{\infty} d^3v_i d^3v_e f_e(v_e) f_I(v_i)|\vec{v}_e - \vec{v}_i|\sigma(|\vec{v}_e - \vec{v}_i|)}{\int_{-\infty}^{\infty} d^3v_i d^3v_e f_e(v_e) f_I(v_i)}$$

Slides from Gang Wang's presentation on Aug 27, 2021:
http://case.physics.stonybrook.edu/images/f/f9/Dependance_of_recombination_rate_on_energy_deviation.pdf
https://arxiv.org/pdf/2109.13980.pdf

LEReC parameters

Electrons and ions distributions for transversely axial symmetrical distribution with longitudinal velocity offset $\Delta v_{e,z}$:

$$f_e(v_e) = \frac{1}{(2\pi)^{3/2}\beta_{e,\perp}^2\beta_{e,z}} \exp\left(-\frac{v_{e,x}^2+v_{e,y}^2}{2\beta_{e,\perp}^2} - \frac{(v_{e,z}-\Delta v_{e,z})^2}{2\beta_{e,z}^2}\right)$$

$$f_i(v_i) = \frac{1}{(2\pi)^{3/2}\beta_{i,\perp}^2\beta_{i,z}} \exp\left(-\frac{v_{i,x}^2+v_{i,y}^2}{2\beta_{i,\perp}^2} - \frac{v_{i,z}^2}{2\beta_{i,z}^2}\right)$$

Where β –s are velocities rms spread in the COF

$$\beta_{i,x} = \beta_{i,y} = \beta_{i,\perp} \text{ and } \beta_{e,x} = \beta_{e,y} = \beta_{e,\perp}$$

	gamma	e-Angular spread, urad	i-Angular spread, urad	e-Energy spread	i-Energy spread	e-Transvers velocity, m/s	i-Transvers velocity, m/s	e-long velocity, m/s	i-long velocity, m/s
CEC-X	28.5	300	140	5E-4	1.3E-4	$2.6\text{x}10^6$	$1.2\text{x}10^6$	$1.5\text{x}10^5$	$3.9\text{x}10^5$
LEReC	4.1	150	130	3E-4	5E-4	$1.8\text{x}10^5$	$1.5\text{x}10^5$	$0.9\text{x}10^5$	$1.5\text{x}10^5$

Few more steps

Redefine:

$\beta_\perp^2 = \beta_{i,\perp}^2 + \beta_{e,\perp}^2$ and $\beta_\parallel^2 = \beta_{i,z}^2 + \beta_{e,z}^2$

$$\alpha_r(\Delta v_{e,z}) = \frac{\int_{-\infty}^{\infty} d^3v_i d^3v\, f_i(v_i) f_e(v_i+v) v\sigma(v)}{\int_{-\infty}^{\infty} d^3v_i d^3v\, f_i(v_i) f_e(v_i+v)} = \frac{1}{(2\pi)^{\frac{3}{2}}\beta_\perp^2\beta_\parallel} \int_{-\infty}^{\infty} d^3v\, \exp\left\{-\frac{v_x^2+v_y^2}{2\beta_\perp^2} - \frac{(v_z-\Delta v_{e,z})^2}{2\beta_\parallel^2}\right\} v\sigma(v)$$

LEReC

$\beta_\parallel^2/\beta_\perp^2 = 0.56$

CeC-X

$\beta_\parallel^2/\beta_\perp^2 = 0.02$

For LEReC parameters transvers and longitudinal velocities are comparable no “COLD” approximation is possible

$$\sigma(v) = A\frac{v0^2}{v^2}\left[\ln\left(\frac{v0}{v}\right) + \gamma_1 + \gamma_2\left(\frac{v}{v0}\right)^{2/3}\right], \text{ where } v0^2 = \frac{2hv_0}{m_e}$$

$$\alpha_r(\Delta v_{e,z}) = \frac{Av0^2}{(2\pi)^{1/2}\beta_\perp^2\beta_\parallel}\int_0^{\infty}\left[\ln\left(\frac{v0}{v}\right) + \gamma_1 + \gamma_2\left(\frac{v}{v0}\right)^{2/3}\right] exp\left(-\frac{v^2}{2\beta_\perp^2}\right) dv \int_{-v}^{v} \exp\left\{\frac{u^2}{2\beta_\perp^2} - \frac{(u-\Delta v_{e,z})^2}{2\beta_\parallel^2}\right\} du$$

Recombination calculated curve for LEReC setup

angular spread

energy spread

Electrons Parameters

$\theta_e := 0.150 \cdot 10^{-3} = 1.5 \times 10^{-4}$

$\delta e := 3 \cdot 10^{-4}$

$\Delta_t := \gamma \cdot \beta \cdot c \cdot \theta_e = 1.788 \times 10^{5}$ $\quad \frac{\Delta_t}{c} = 5.964 \times 10^{-4}$ $\quad \Delta_z := c \cdot \delta e = 8.994 \times 10^{4}$

Transvers and longitudinal velocities in COF are about the same

Ions Parameters

$\theta_i := \sqrt{\frac{\varepsilon_i}{\gamma \cdot \beta \cdot \beta_i}} = 1.269 \times 10^{-4}$

$\delta e\_i := 5 \cdot 10^{-4}$

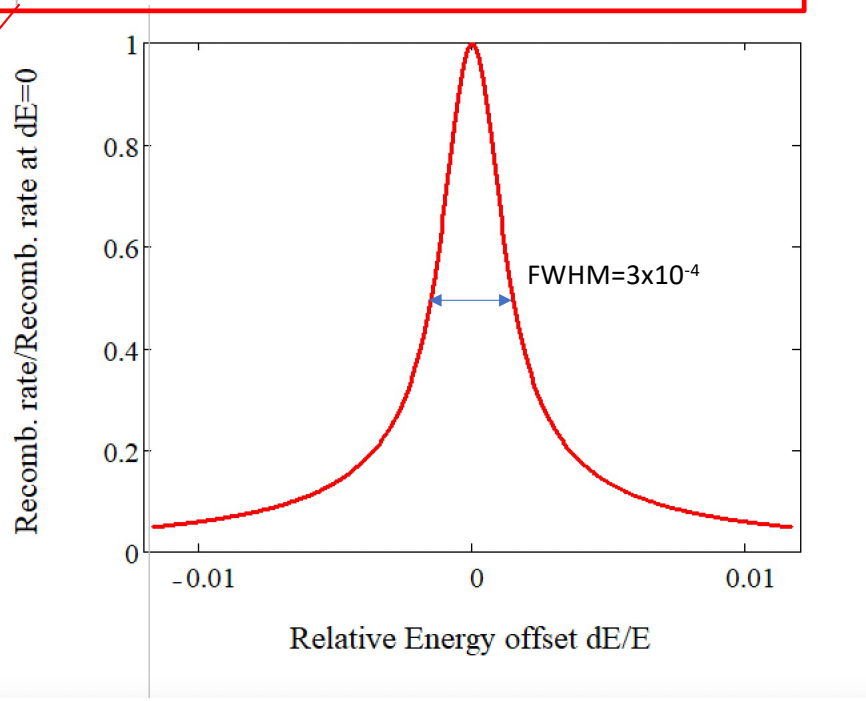
$v_t := \gamma \cdot \beta \cdot c \cdot \theta_i = 1.512 \times 10^{5}$ $\quad \frac{v_t}{c} = 5.045 \times 10^{-4}$ $\quad v_z := c \cdot \delta e\_i = 1.499 \times 10^{5}$

$\beta_t := \sqrt{\beta_{ex}^{\,2} + (\beta_{ey})^2} = 8.435 \times 10^{-4}$

$\beta_z := \sqrt{(\beta_{ez})^2 + (\beta_{iz})^2} = 5.831 \times 10^{-4}$

$y0 := \sqrt{\frac{2h\upsilon_0}{m_e}} = 0.576$

$$f0(y,\Delta u,bt,bz) := \frac{y0^2}{\sqrt{2\pi}\cdot bz\cdot bt^2}\left[-\ln\left(\frac{y}{y0}\right)+\gamma_1+\gamma_2\cdot\left(\frac{y}{y0}\right)^{\frac{2}{3}}\right]\cdot\left(e^{-\frac{y^2}{2bt^2}}\right)\cdot\int_{-y}^{y} e^{-\frac{(u-\Delta u)^2}{2\cdot bz^2}+\frac{u^2}{2\cdot bt^2}}\,du$$

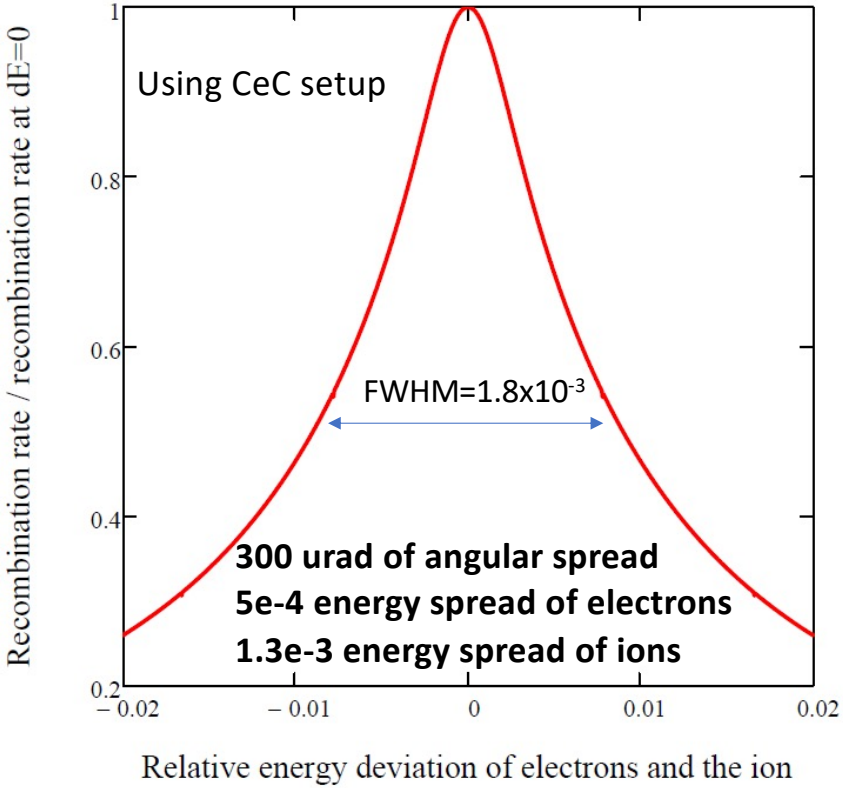


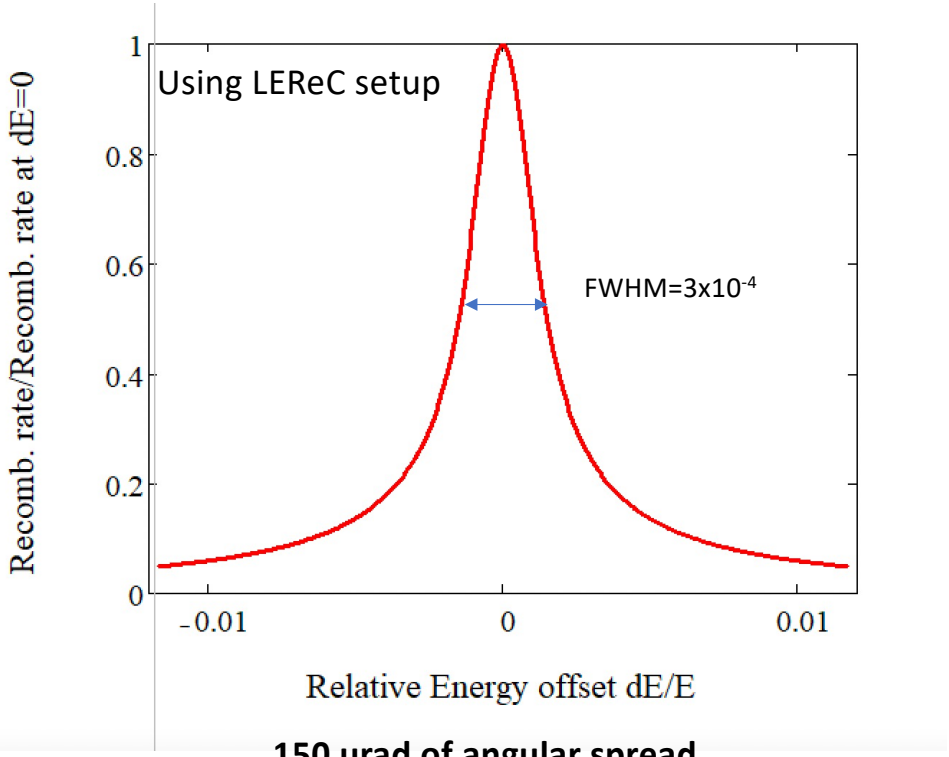
Rec. rate

$$ff(\Delta u,bt,bz) := \int_{y\_min}^{y\_max} f0(y,\Delta u,bt,bz)\,dy$$

Side by side comparison of CeC and LEReC

While CEC rec. signal is less sensitive to energy mismatch in comparison with LEReC setup, it still provides good tool for i-e gamma matching





150 urad of angular spread
3e-4 energy spread of electrons
5e-4 energy spread of ions

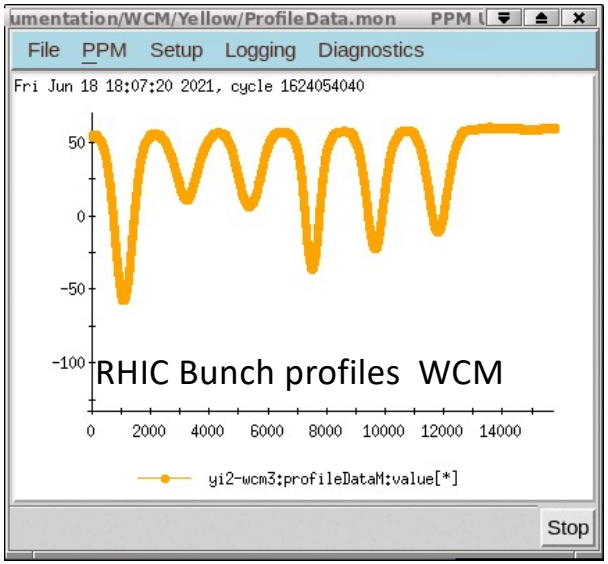
See full presentation for CEC-X parameters:

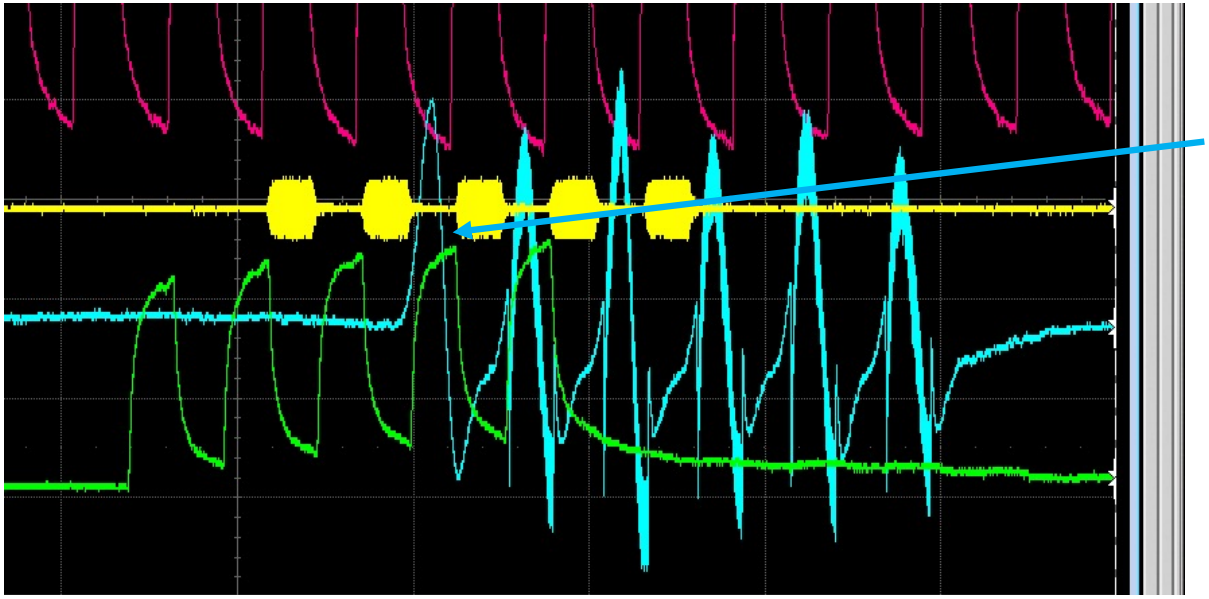
http://case.physics.stonybrook.edu/images/f/f9/Dependance_of_recombination_rate_on_energy_deviation.pdf

RHIC/LEReC setup:

On June 18

- We used regular RHIC lattice with and without local bump
  - 6 bunches per store with intensity 0.4-1.5e9 per bunch
- For LEReC we used regular 5 MB with 3 and 2nC per MB
  - beam loading per MB 3.3keV for charge of 3nC per MB





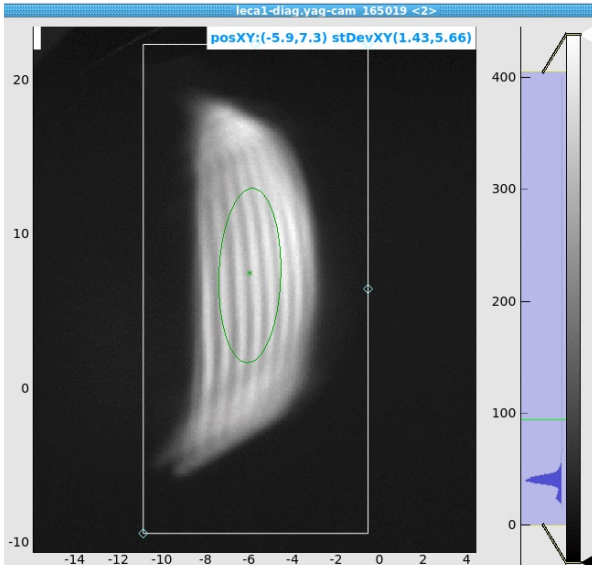
Cyan trace is signal from BPM in the cooling section

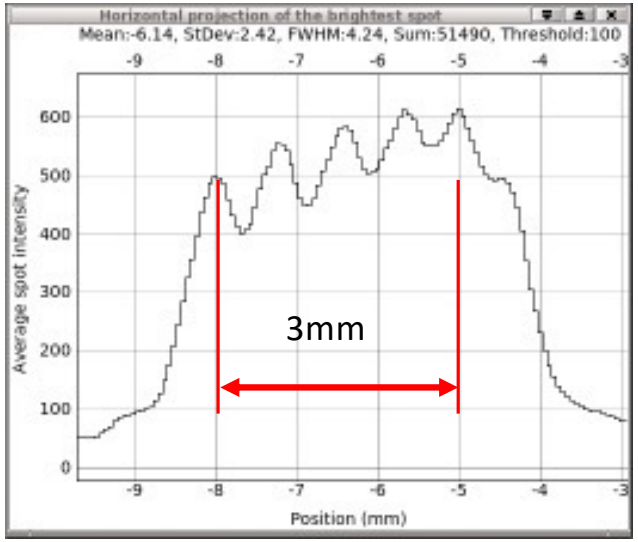
1st RHIC bunch is not overlapping with LEReC bunches

5 followed bunches are overlapped with LEREC bunches

Bunch to bunch energy difference due to beam loading effect

- MB profiles image at PM in RF diagnostic line
- Train of 5 MBs with charge of 1.3 nC per MB
- Distance between 4 peaks =3 mm, dispersion= 800 mm
- MBunch by MBunch energy shift $\Delta E/E=3/800/4=9.4E-4$

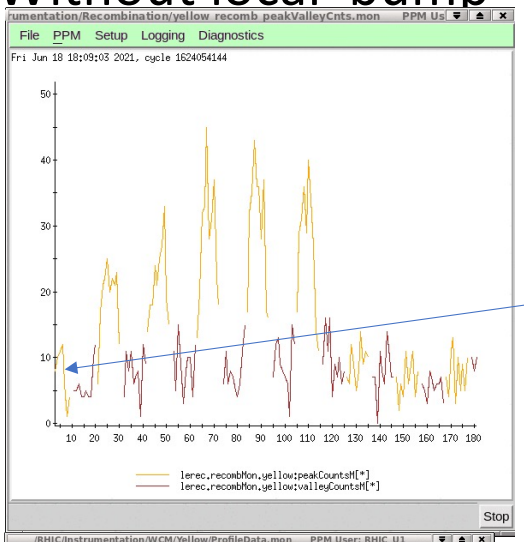


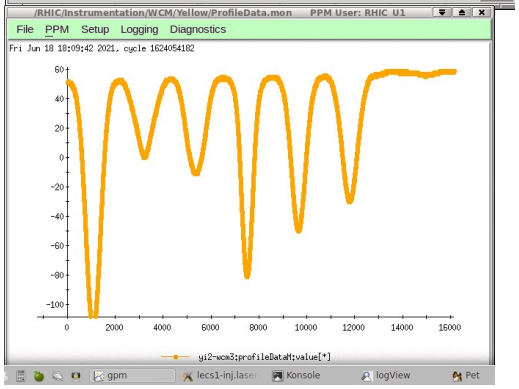


http://www.cadops2.bnl.gov/elogs/entryList.jsp?DATABY=day&ELOG=LEReC_2021&DATE=06/24/2021&DIR=none#1481011

Bunch by bunch recombination loss signal

Without local bump



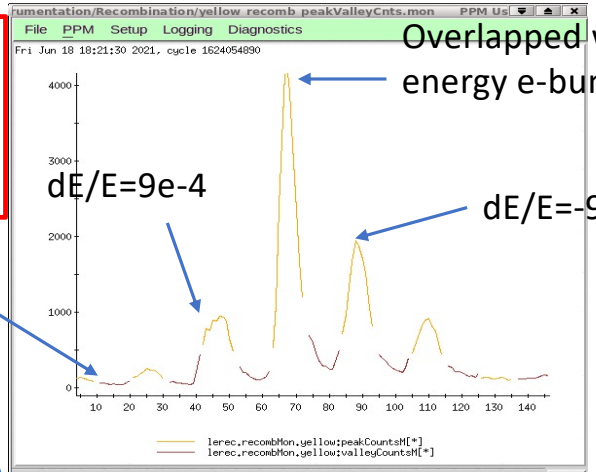


Local bump (8.5mm at yo1-bh14) helped to increase recombination signal/noise level significantly

Non interacted bunch #1

WCM profiles

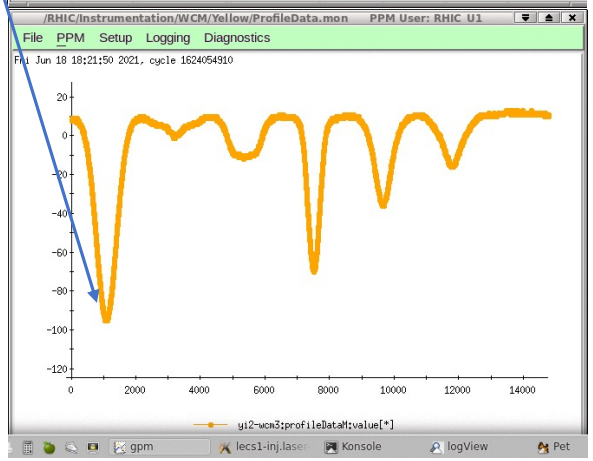
With local horizontal bump



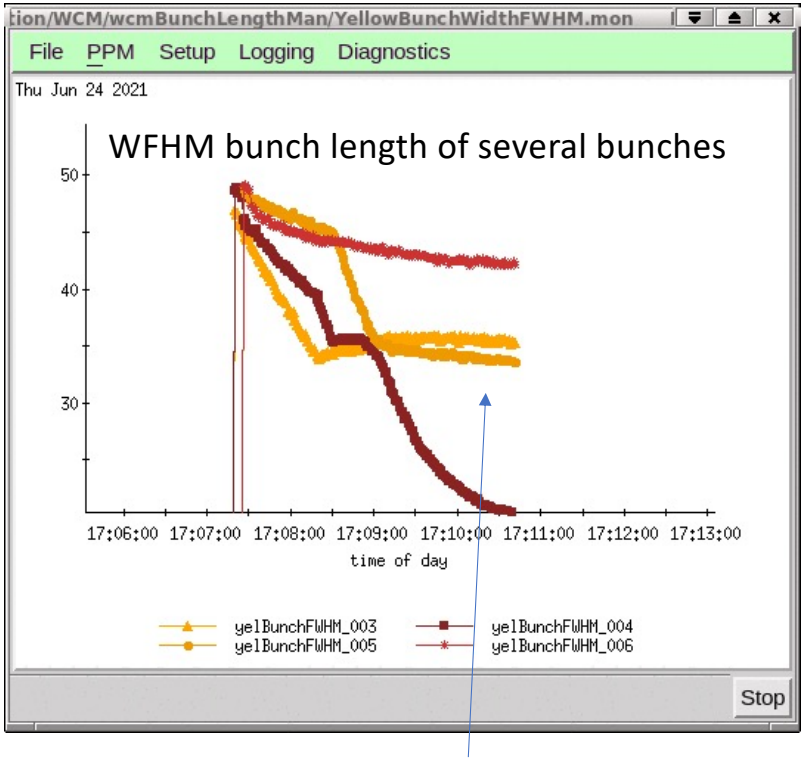
Overlapped with optimized energy e-bunch

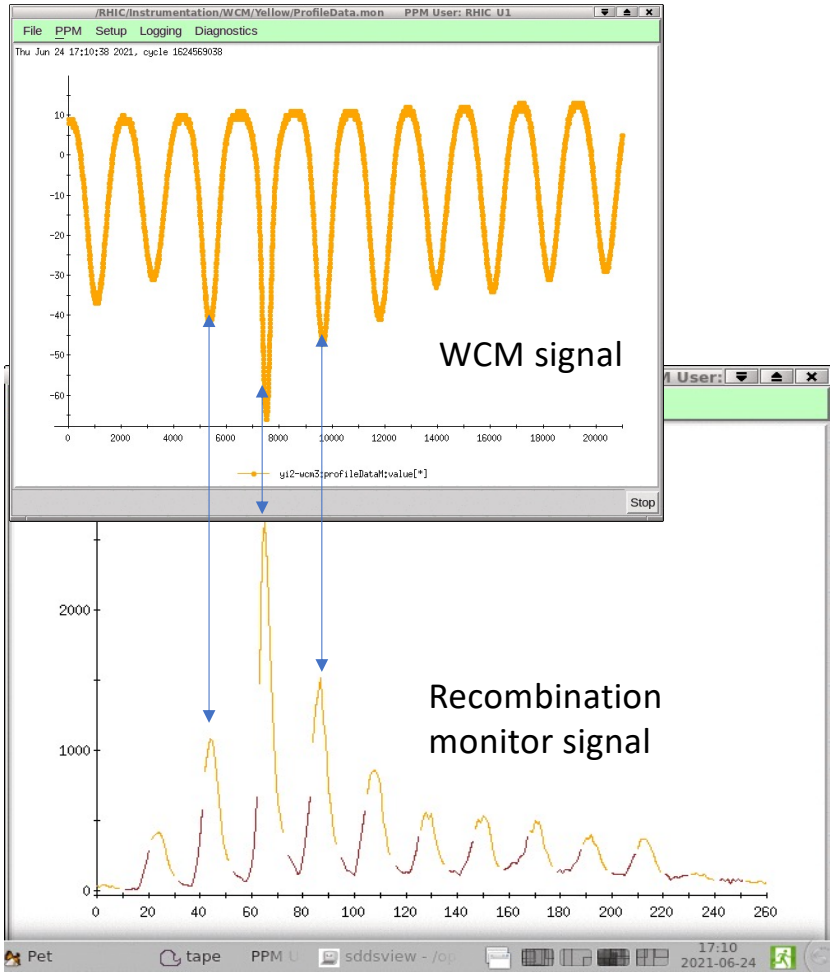
dE/E=9e-4

dE/E=-9e-4



Fine LEReC energy tuning by optimizing cooling of the selected ion bunch





RHIC Bunch #4 is optimally cooled while two neighbor Bunches #3 and #5 are weaker but equally cooled as well

http://www.cadops2.bnl.gov/elogs/entryList.jsp?DATABY=day&ELOG=LEReC&DATE=06/24/2021&DIR=none#1481257

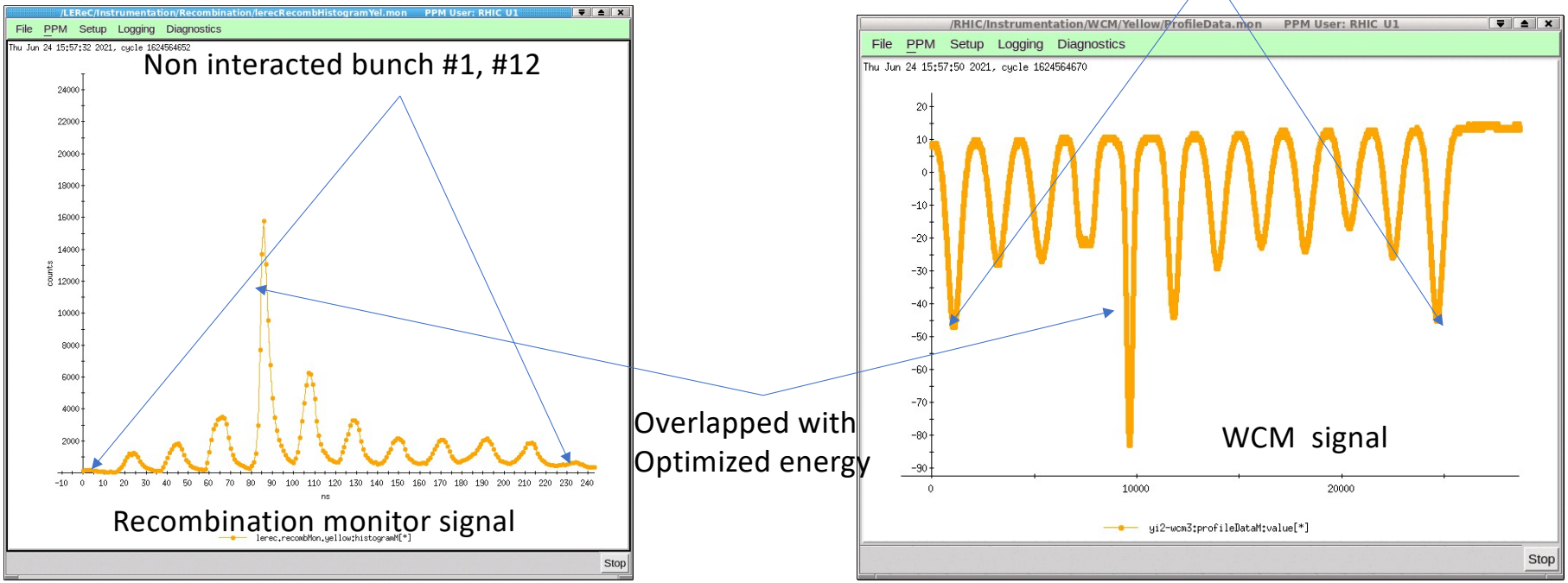
APEX June 24

We used regular RHIC lattice with local bump:

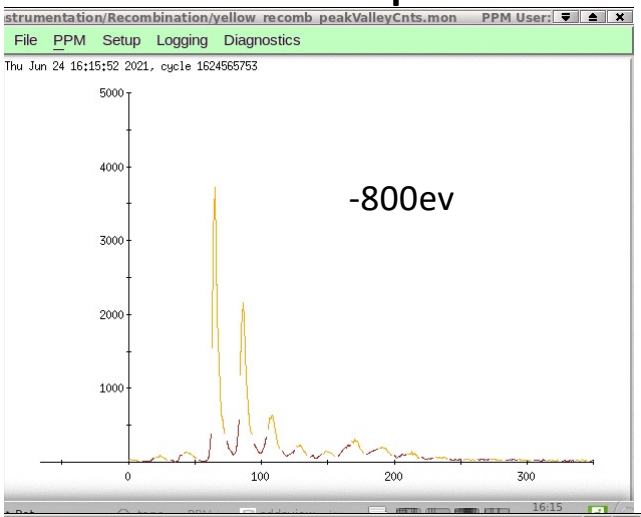
12 bunches per store with intensity 0.4-1.5e9 per bunch

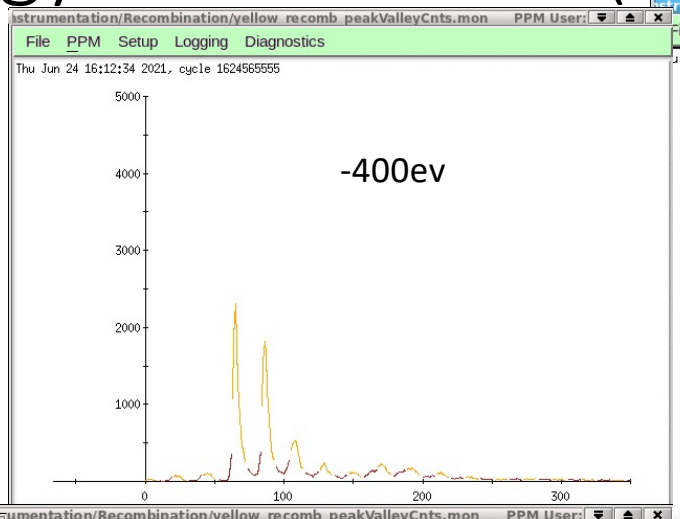
For LEReC we used regular 10 MBs with 1.3 nC per MB

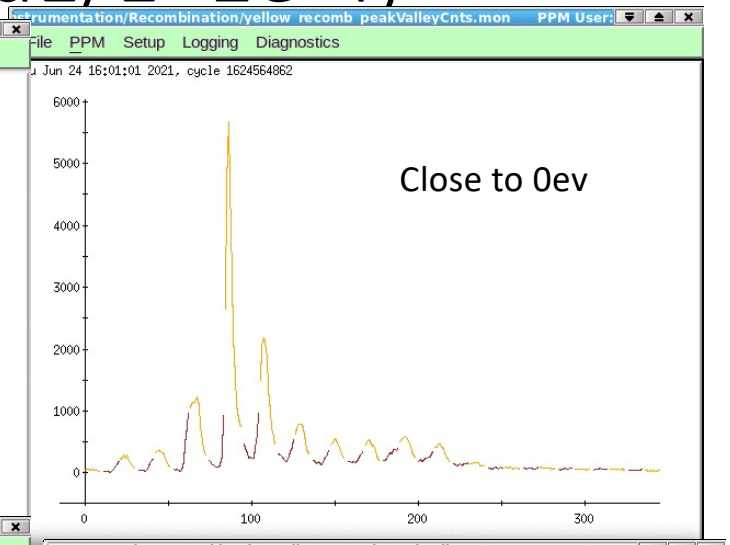
beam loading ~2 keV per MB

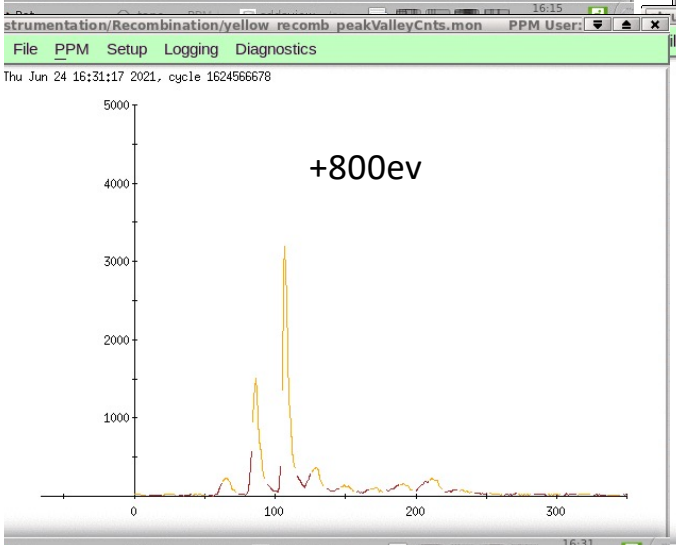


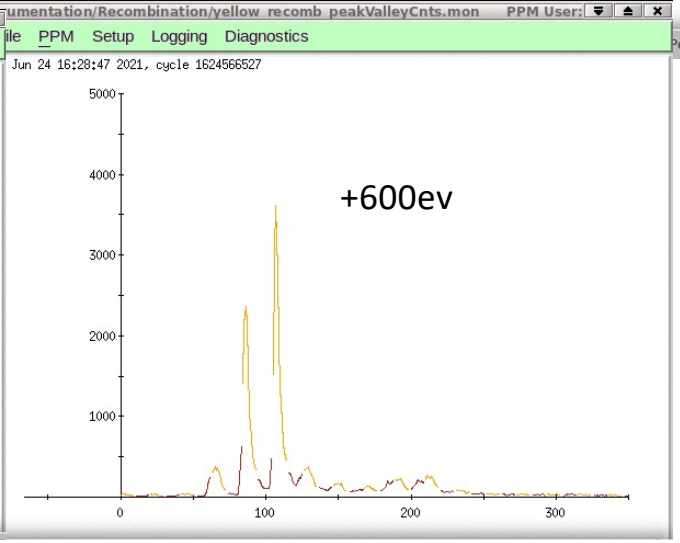
Small steps energy scan ~200eV (dE/E=1e-4)

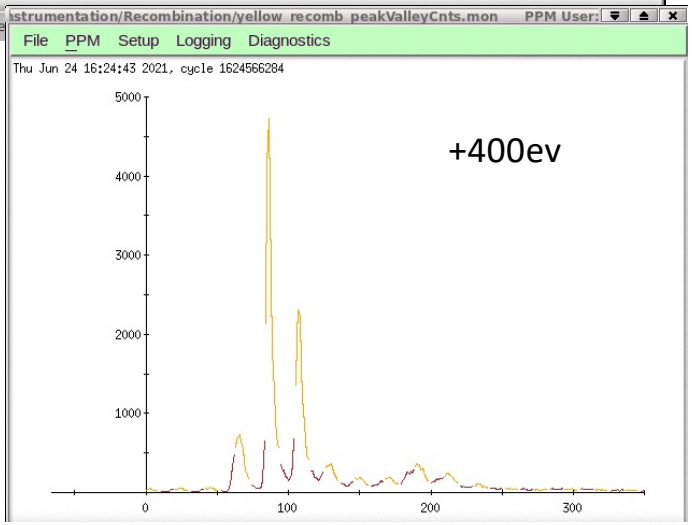






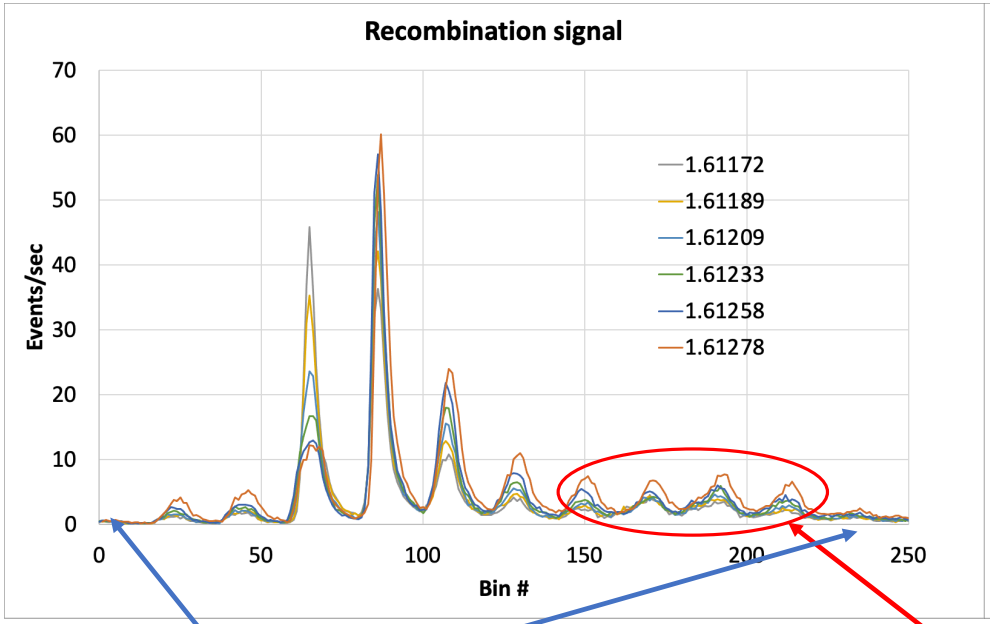




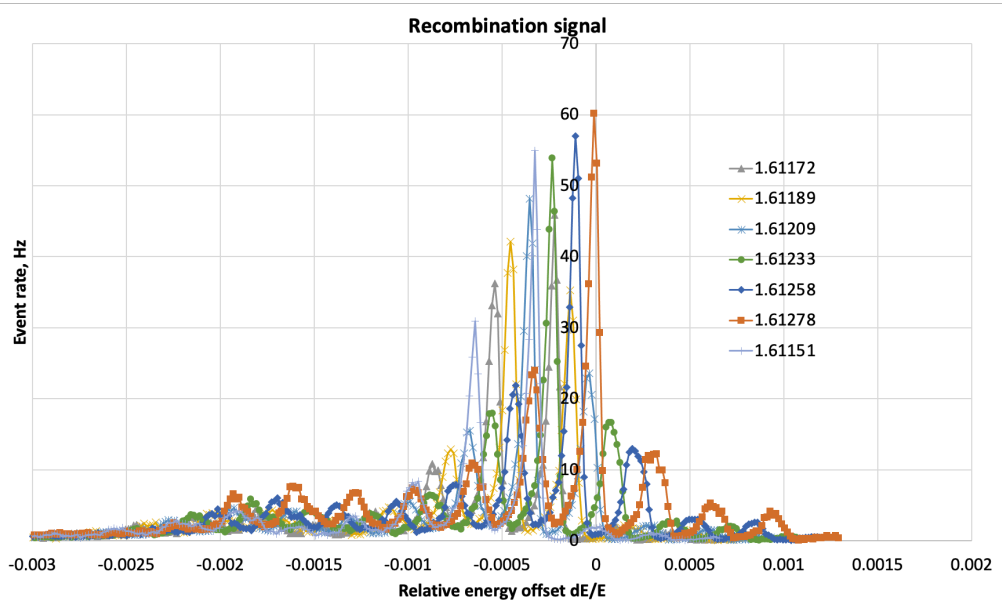


Loss event rate per seconds for different LEReC average energy (200 eV step)

Raw data



Function of energy offset



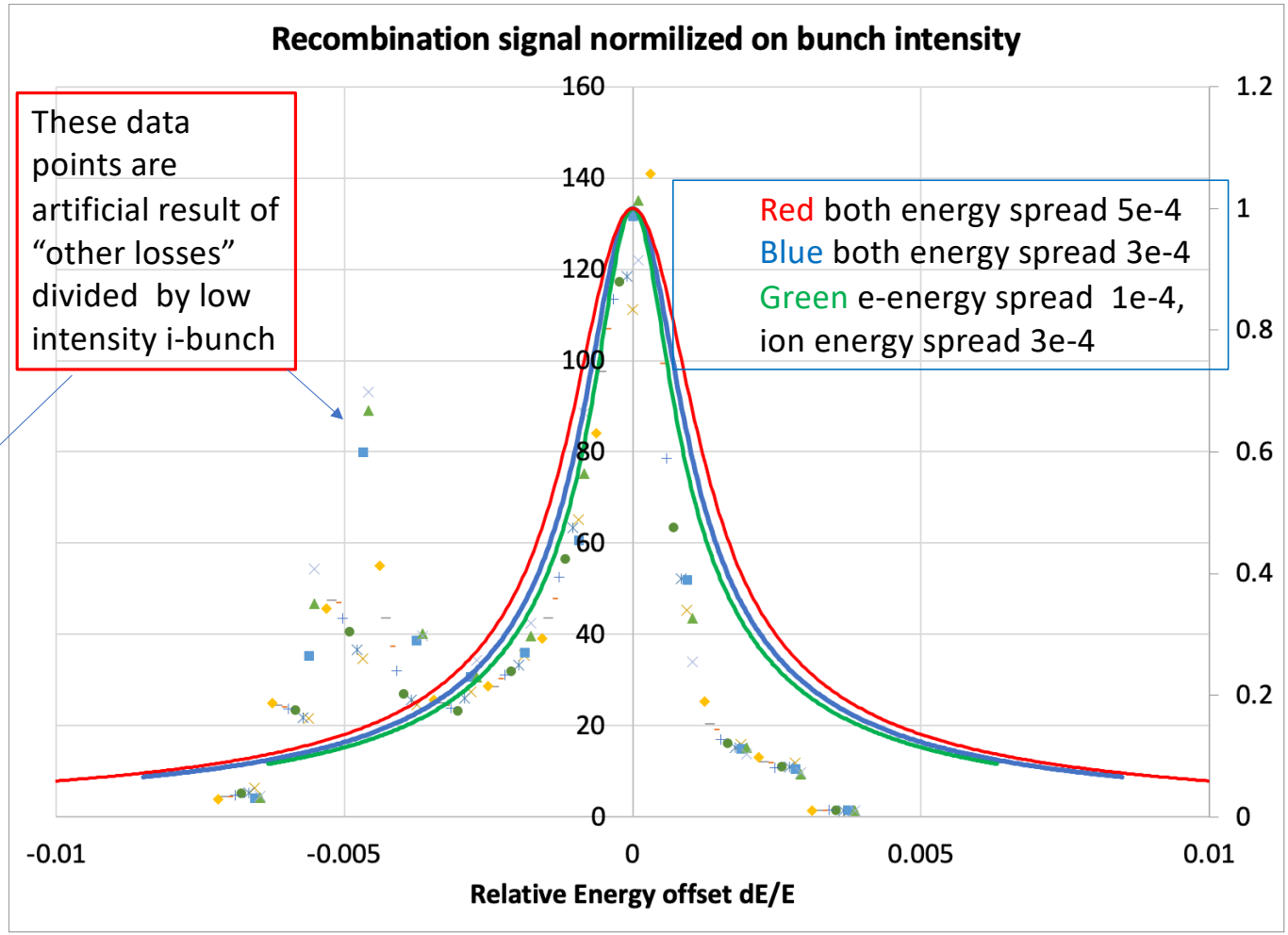
Very low background signal, losses from non interacted bunches

Regular losses dueto LEReC –RHIC interaction and results of signal reflection

More data from each bunch normalized to the individual i-bunch intensity

- Markers are for measured data points at different average LEReC energy settings
- Lines are calculated recombination signal

Ion bunches intensity



LEReC Recombination studies summary

- We observed and measured energy dependence of recombination signal
- Introducing local bump significantly improved statistic
- Measured energy dependance of recombination signal is well matched with textbook formulas for LEReC bunch energy spread ~ 1e-4

Back-up material

RHIC dispersion and resulted bunch separation

RHIC dispersion

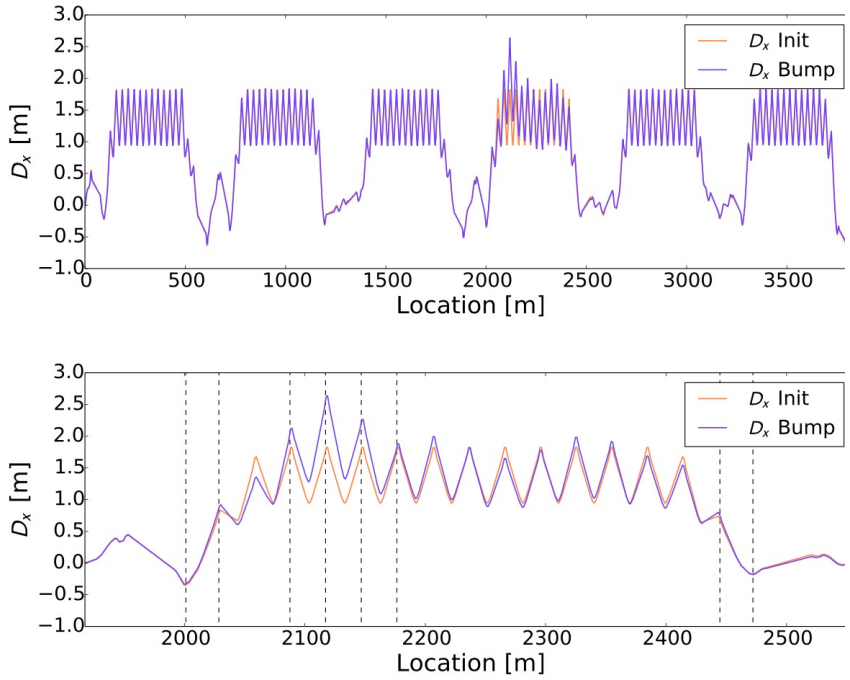


Figure 3.7: The horizontal dispersion for the initial lattice, in orange, and for the lattice with the dispersion wav for the BLUE beam. The dispersion is increased by almost 1 m in BI12_QF13 and by 0.5m in BI12_QD14.. Th dispersion wave closes at the end of the arc, and no distortions are observed

Au79 vs Au78 bunch separation in Arcs

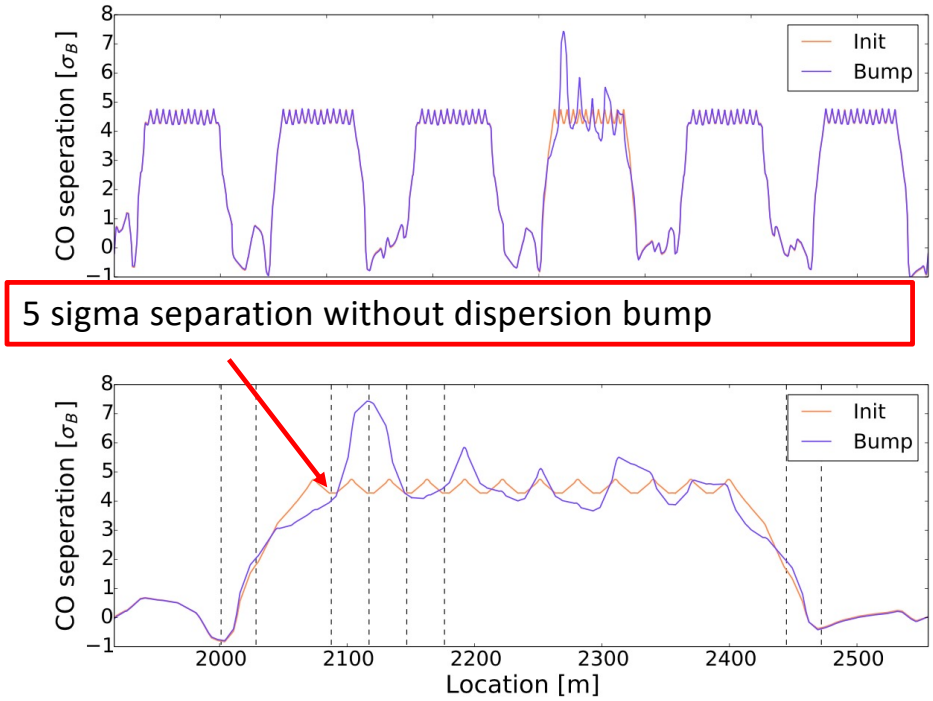


Figure 3.8: separation between the closed orbit of the fully stripped ions and the recombined ions. The upper figure shows the separation for the complete RHIC, while the lower figure shows the separation for the arc between IP12 and IP2. A maximum separation of 7.8 σ_B is obtained in the

F.S. Carlier “Detectors for low energy electron cooling in RHIC” C-A/AP/557 February 2016

LEReC parameters

- gamma= 4.1
- e-bunch energy spread is <3e-4
- average e-bunch angular spread ~150 urad
- I-bunch energy spread 5e-4
- I-bunch angular spread 130 urad

CEC-X parameters

300 urad of angular spread
5e-4 energy spread of electrons
1.3e-3 energy spread of ions