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Studies of ion beam heating by electron beam

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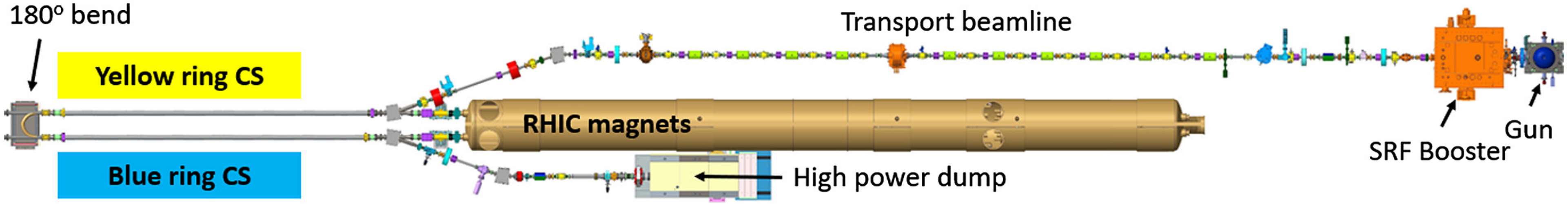
Outline

- Introduction: Low Energy RHIC electron Cooler (LEReC)
- Electron-ion heating (e-i heating) in LEReC
- Technique of the e-i heating measurements
- Results of the experiment
- Possible explanations
- Summary

Introduction to LEReC



- **LEReC was designed to cool colliding gold ions @ $\gamma = 4.9$ and @ $\gamma = 4.1$ and was successfully operated in 2020-2021 low energy RHIC run routinely providing a substantial luminosity increase.**

- In LEReC 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 SRF cavity bringing the beam energy to 1.6–2. MeV. Next, the e-beam is transported o the cooling section (CS) in the “Yellow” RHIC ring and to the cooling section in the “Blue” RHIC ring. Finally, the electron beam is extracted at the exit of the blue CS through the extraction dogleg and sent to the beam dump.

- LEReC is the first:
  - RF-based electron cooler
  - cooler using neither e-beam magnetization nor continuous solenoidal field in the cooling section.
  - electron cooler which is applied directly to the ions in the collider at top energy
  - electron cooler that utilizes the same electron beam for cooling ions in two consecutive cooling sections in two rings of the collider

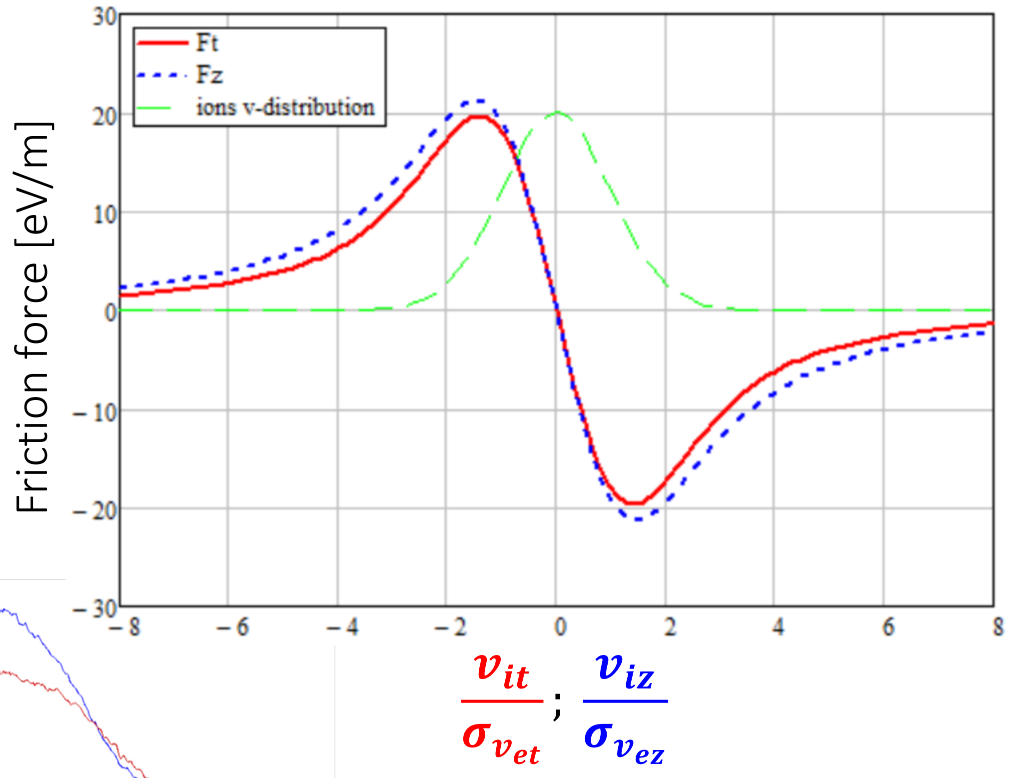
- LEReC publications:

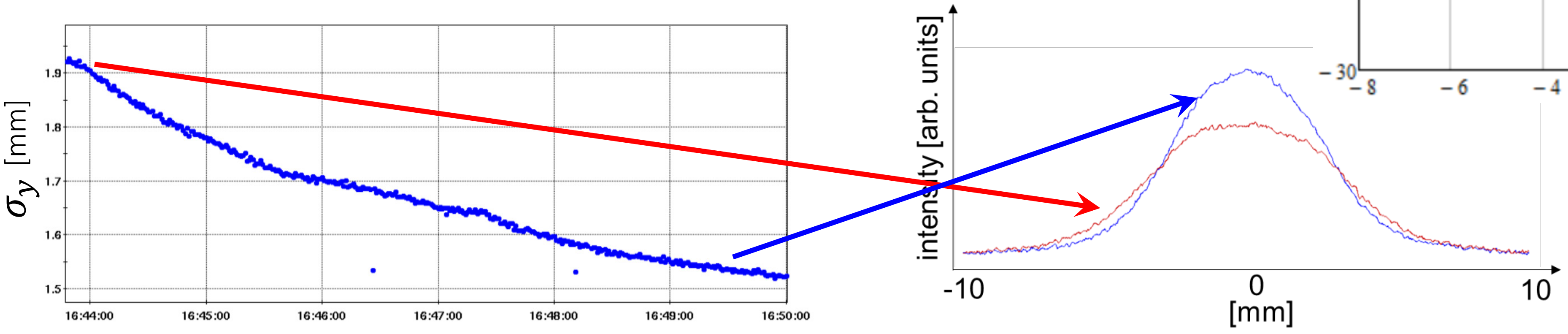
A. Fedotov et al., PRL 124, 084801 (2020).
D. Kayran et al., PRAB 23, 021003 (2020).
S. Seletskiy et al., PRAB 21, 111004 (2019).
X. Gu et al., PRAB 23, 013401 (2020).
H. Zhao et al., PRAB 23, 074201 (2020).
S. Seletskiy et al., PRAB 23, 110101 (2020).

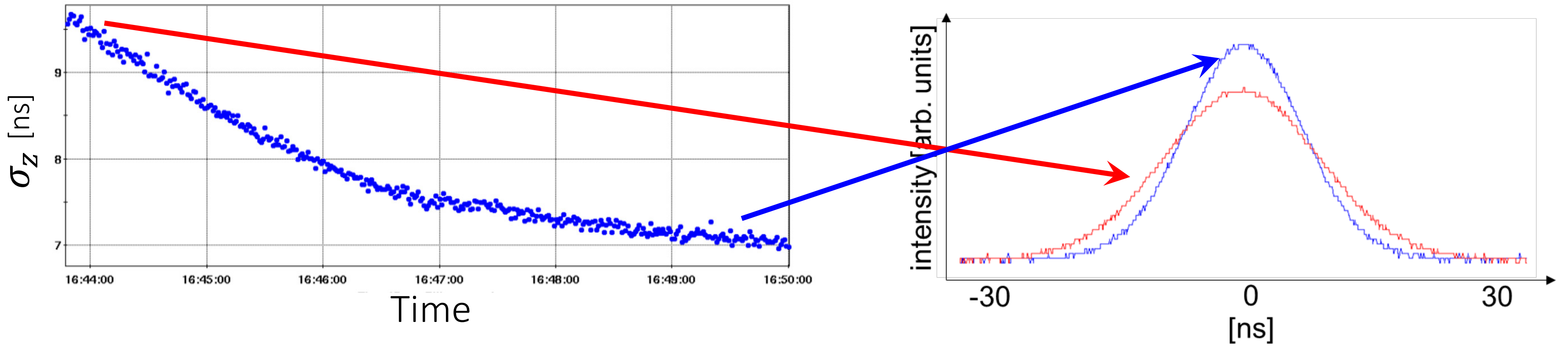
Cooling in LEReC

Typical 3D cooling for optimized e-beam parameters

- e&i-beams γ-factors are matched
- e-bunch energy spread is ~5e-4
- average e-bunch angular spread ~150 urad

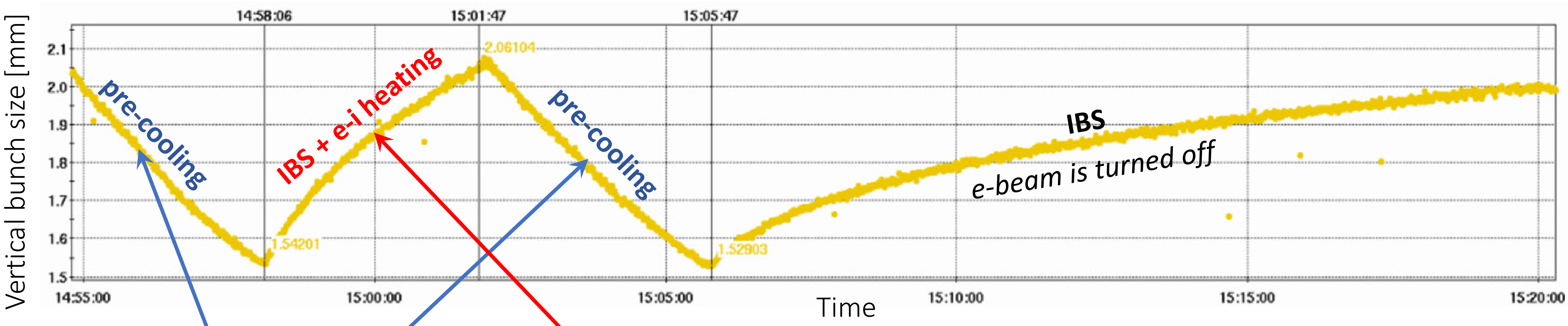


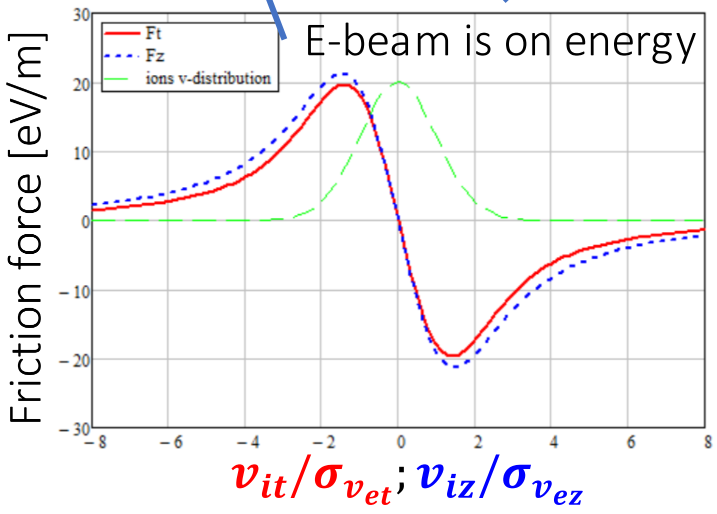




Electron-ion heating

- In the presence of e-beam and with the “zeroed” cooling we observe a much faster growth of the transverse size of the i-bunch than the IBS driven size growth.
- We call this additional growth of the emittance “the electron-ion heating”

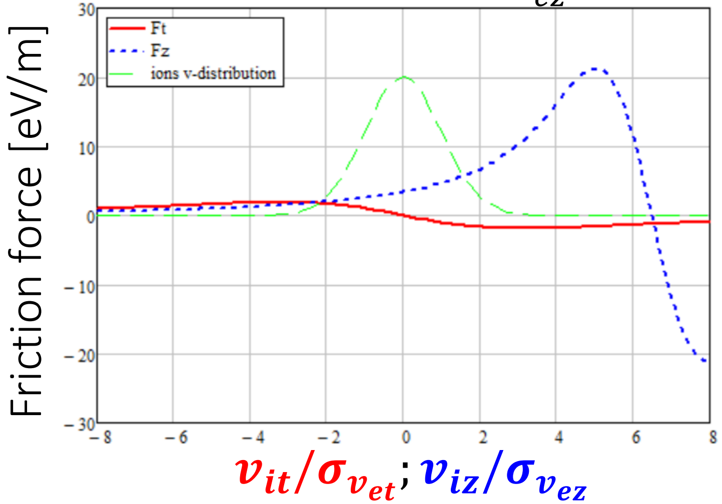




E-beam is on energy

$v_{it}/\sigma_{v_{et}}; v_{iz}/\sigma_{v_{ez}}$

E-beam is 5 kV ($\mu_{iz} \approx 6.3\sigma_{v_{ez}}$) off energy



$v_{it}/\sigma_{v_{et}}; v_{iz}/\sigma_{v_{ez}}$

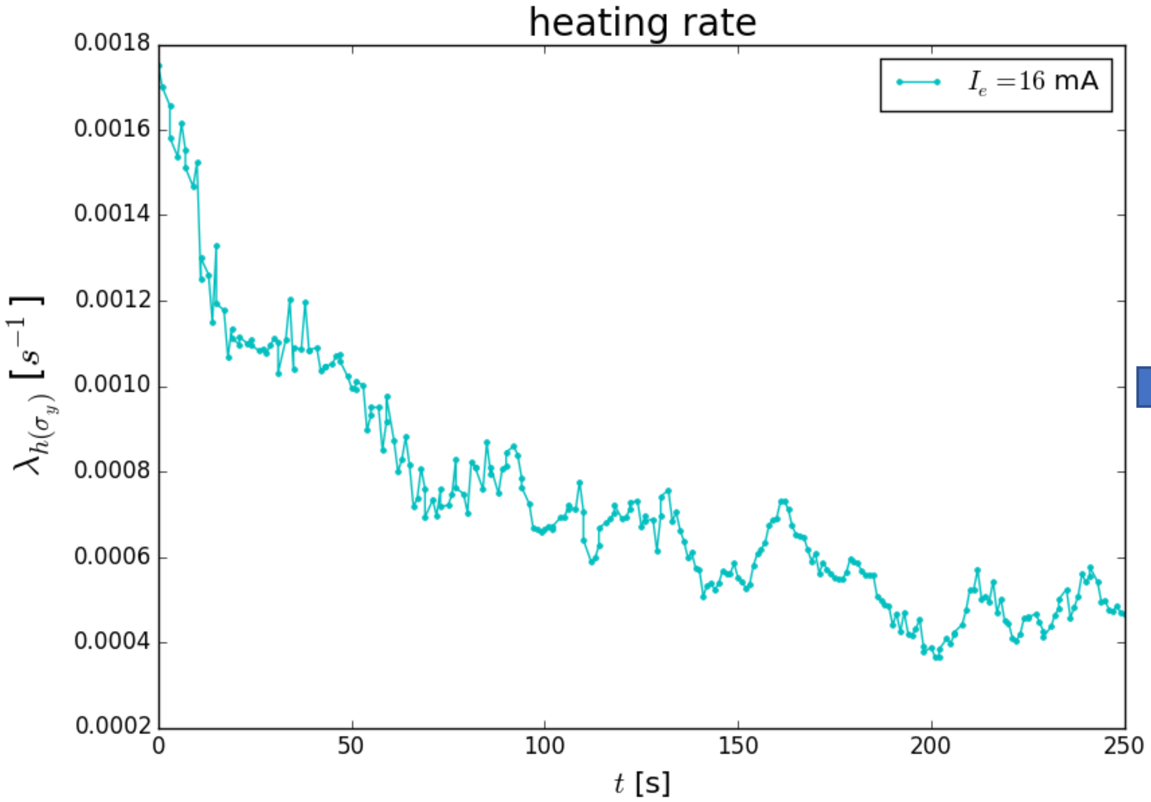
We suppress the cooling while keeping the electron beam in the CS by detuning the electron beam energy by a few kV

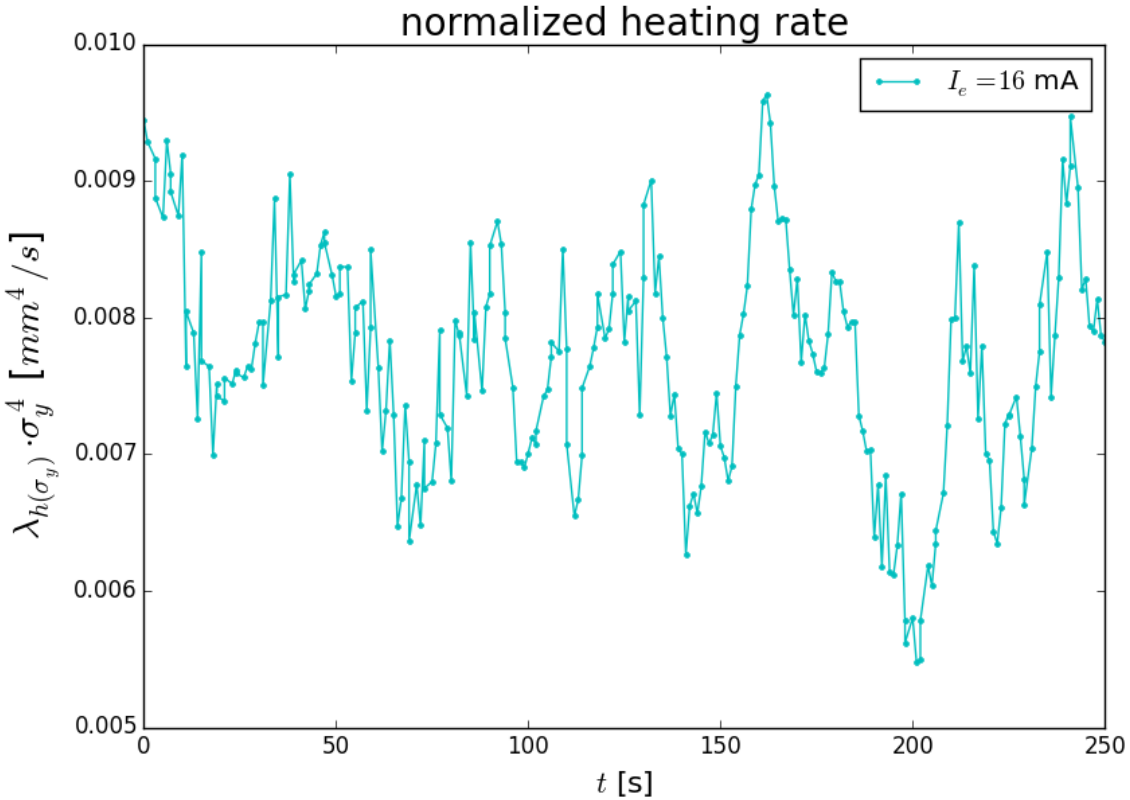
Measurement procedure

- We perform the studies with the low intensity ion bunches in one ring only
- We always precool the i-bunches to approximately the same transverse and longitudinal size
- Next, we “switch off” the cooling by detuning the e-beam energy by 5-6 kV
- In a heating measurement for given parameters we record the evolution of the ion bunches transverse and longitudinal sizes and the intensity of the ion bunches
- Measurement-to-measurement we vary the charge of electron bunches, and/or the settings of the cooling section solenoids.
- For each electron bunch charge used in the heating measurements we fully characterize the longitudinal and the transverse phase space of the electron bunch at the entrance to the cooling section in dedicated measurements.
- We perform several control measurements of the IBS-driven size growth of the i-bunches throughout each shift. The i-bunch parameters in these measurements cover the whole parameters’ range used in the heating measurements

Heating process invariant

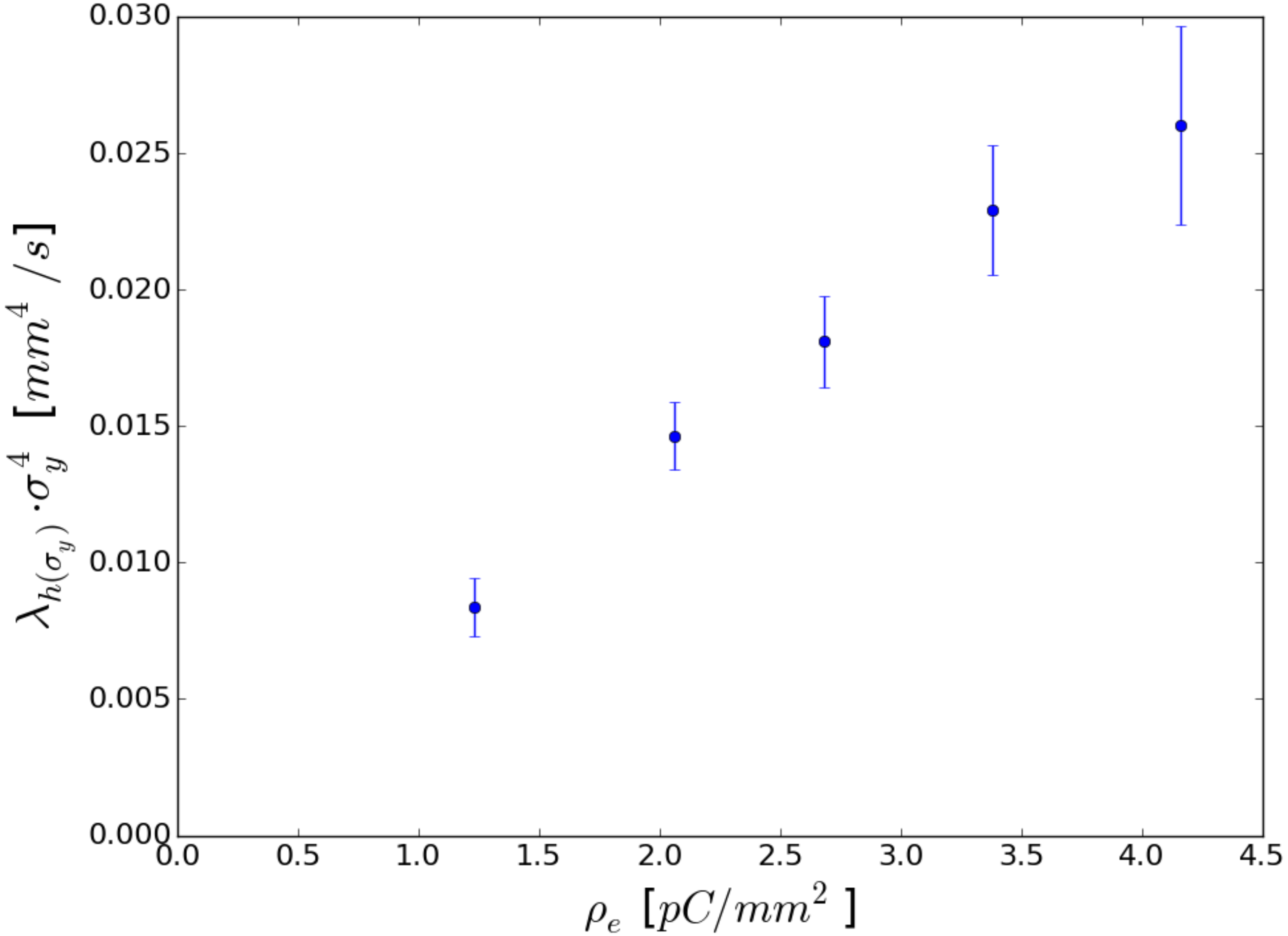
We found that in every measurement: $\lambda_\sigma \sigma^4 = \text{const}$





Typical measurement result for a constant e-beam current

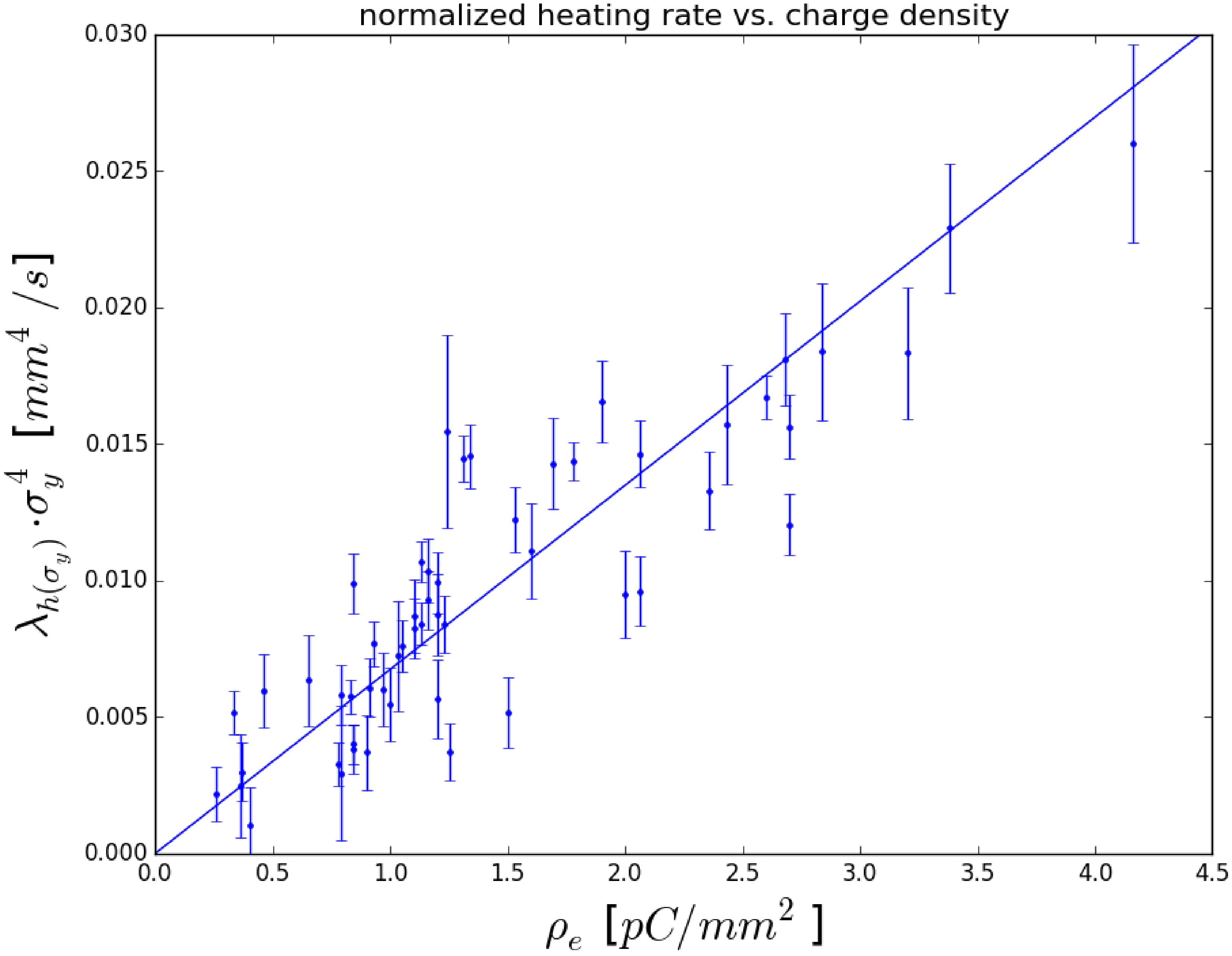
- This measurement was performed with electron bunch charge of 62 pC ($I_e = 20$ mA)
- The average electron bunch density in the cooling section was varied by adjusting the CS solenoids (in the range of 3A-9A)
- In this measurement the “initial conditions” for the e-bunch at the entrance to the cooling section stayed unchanged.



Combining all datapoints

We observed a linear dependence of the heating rate on the electron bunch density

$$\lambda_{h(\sigma_y)}\sigma_y^4 = C_0\rho_e$$



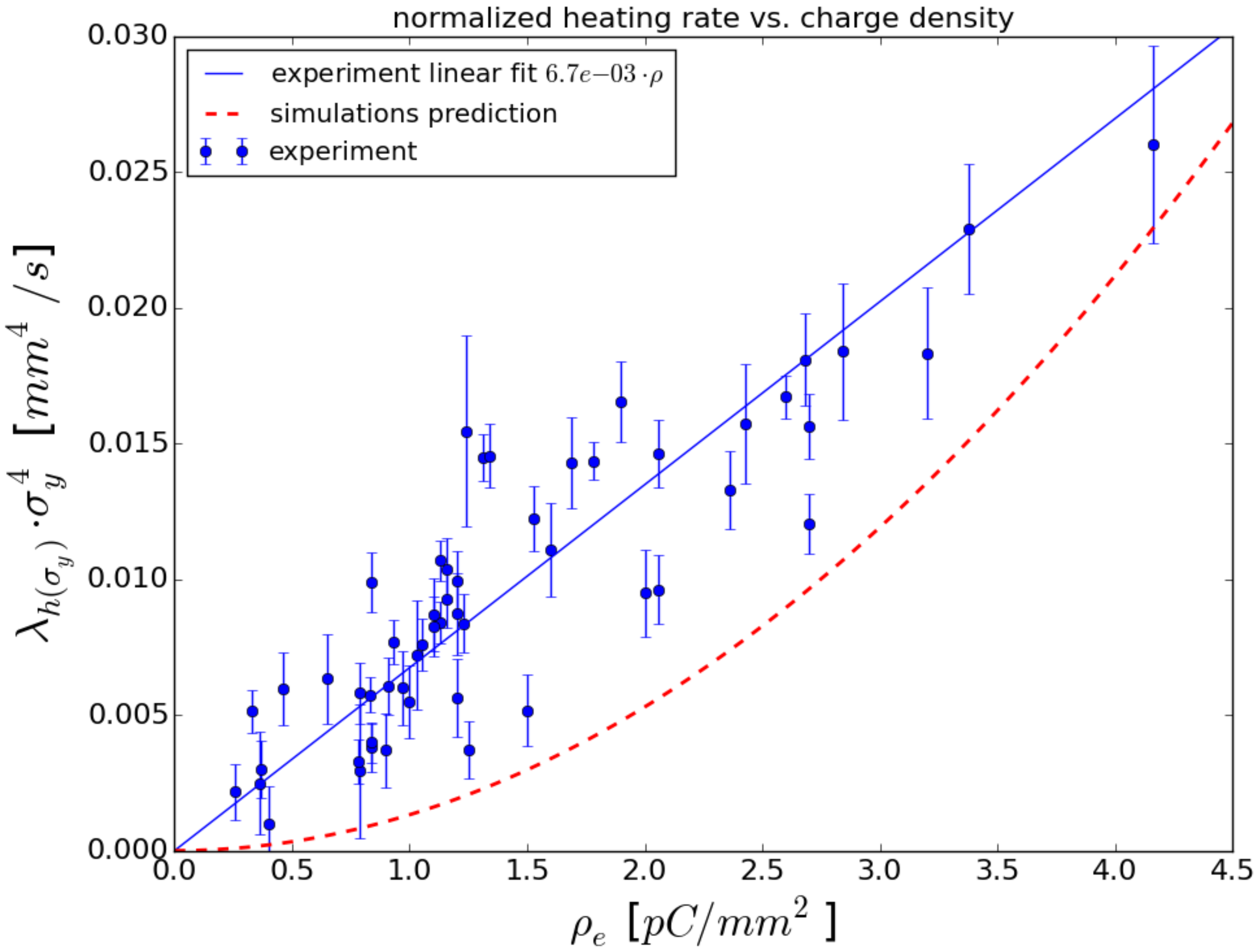
Comparison to models

- We applied several theories to the observed data, but none of them predict experimentally observed dependence:

$$\lambda_{h(\sigma_y)}\sigma_y^4 = C_0\rho_e$$

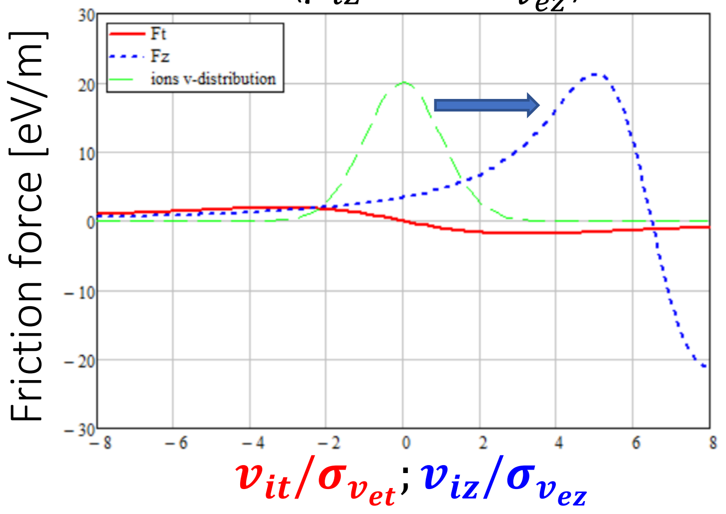
- A simple "random walk model" with either dipole or focusing kicks.
- In a more sophisticated model the focusing kicks from the space charge of e-bunches drive synchro-betatron resonances and the heating effect occurs due to the longitudinal IBS continuously "dragging" individual ions through the resonance conditions.

- The red dashed line shows the model's prediction for the heating rate on the average e-beam density. The simulations are based on a one-turn map and a thin lens treatment of the electron-ion interaction, and include the cooling force, intra-beam scattering, ion-electron focusing and electron-ion focusing kick.



Does energy offset produce heating?

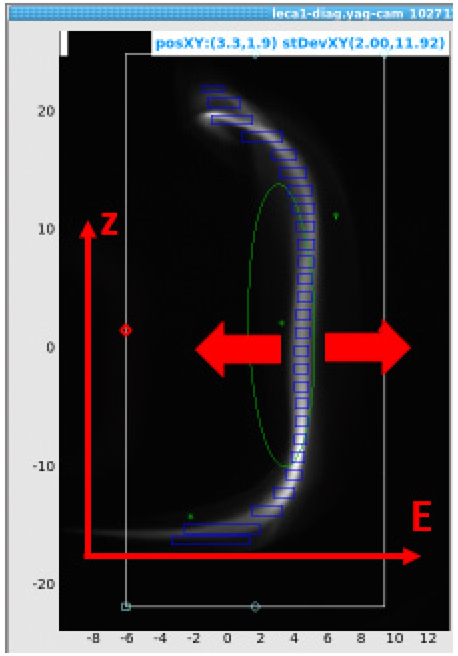
E-beam is 5 kV ($\mu_{iz} \approx 6.3\sigma_{v_{ez}}$) off energy



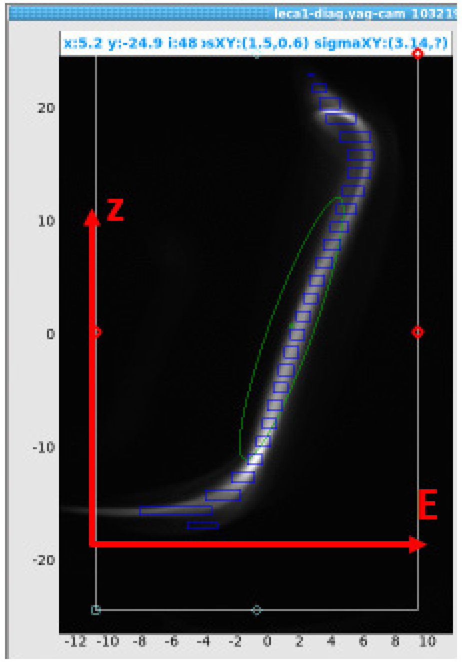
- A substantial enough offset in electron beam energy creates a mechanism of longitudinal heating
- This heating can be partially redistributed to transverse direction through coupling
- To check whether we “create” transverse heating by offsetting beam energy we performed measurements with chirped e-bunch.

We compared the heating measured for the e-beam with energy offset and the beam with the chirp, large enough to produce a similar cooling force suppression

offset

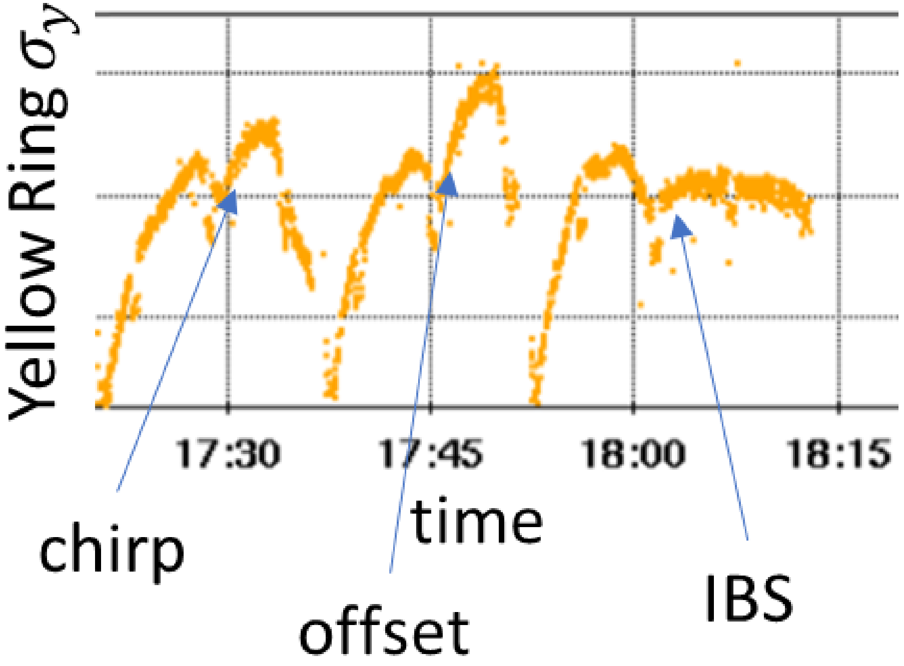


chirp



Chirp vs. offset

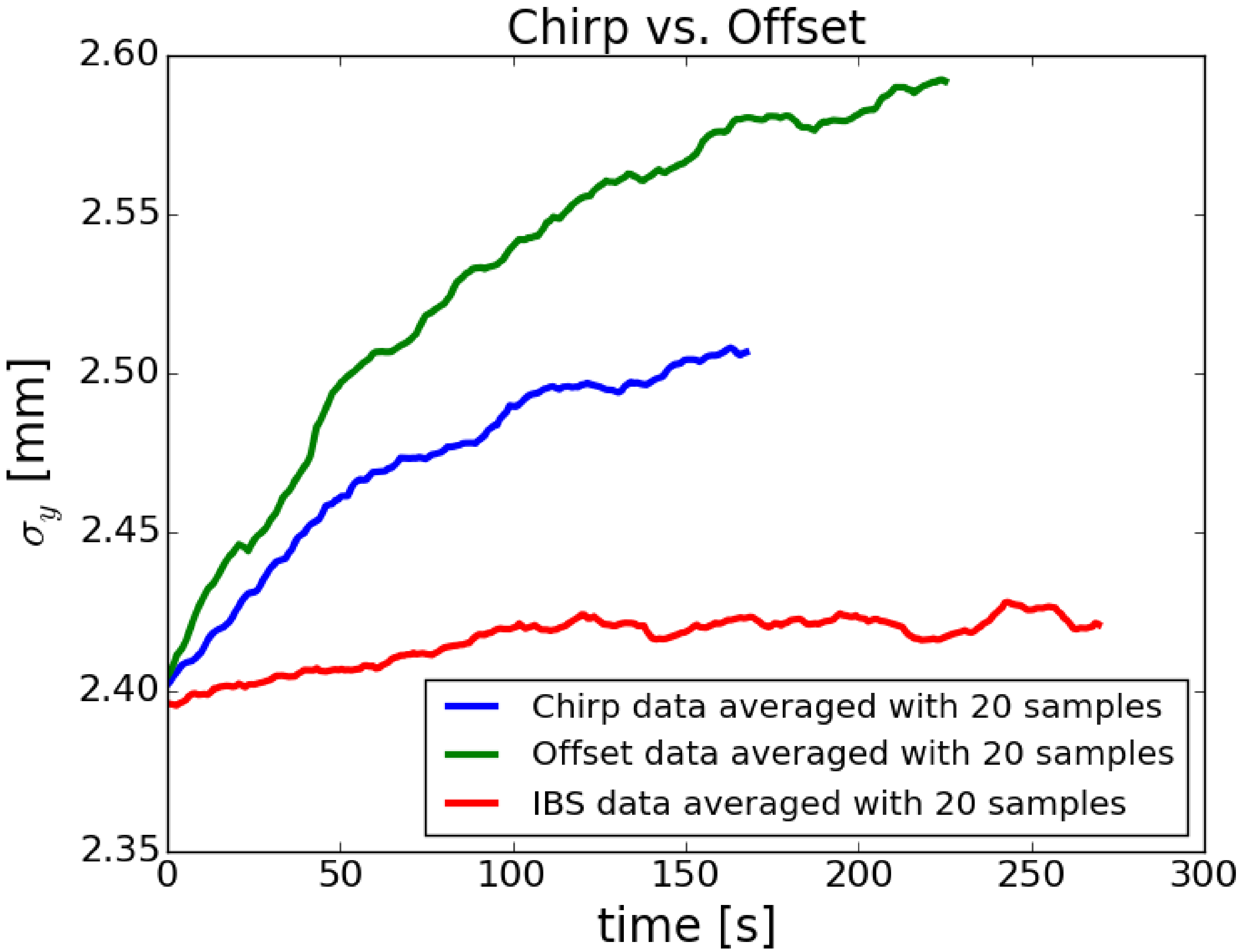
- The offset-driven size growth rate is ~1.5 times larger than the chirp-driven one.



chirp

offset

IBS



Summary

- In presence of electron beam in the cooling section of the RHIC electron cooler (and in the absence of cooling) we observe a noticeable transverse heating of the ion bunches - a much faster growth of the transverse size of the i-bunch than the IBS driven size growth.
- The optimized electron cooling overcomes both the heating and the IBS. The e-i heating was not a limiting factor for RHIC operations with the cooler.
- Dedicated studies of the electron-ion heating showed that the heating rate grows linearly with the average density of electron bunches.
- It was found that the extra-heating “created” by energy-offset is a substantial part of the overall emittance growth.
- Further studies are planned for the RHIC run of 2023.

Acknowledgements

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