Summary for Session I

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ICFA Workshop on CeC
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Outline

- Why Strong Hadron Cooling is Needed

  Thomas Roser

- How the CeC was Conceived

  Yaroslav Derbenev

- Discussions

Why Strong Hadron Cooling Is Needed

Thomas Roser

Coherent electron Cooling WS

July 24, 2019

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.

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

Luminosity limits with hadron cooling – beam-beam

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

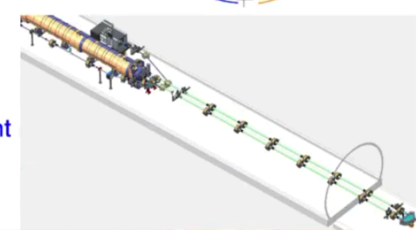
$$= \frac{N_2 r_0 \beta_{1;x,y}^*}{2\pi\gamma\sigma_{2;x,y}\sigma_{2;x}} \text{ (for flat beams)}$$

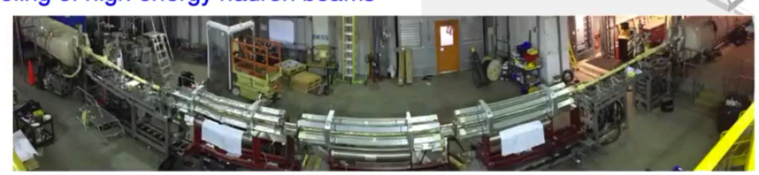
- Beam-beam interactions: emittance growth from collision interactions cannot be cooled fast enough.
- Beam-beam limitation is greatly reduced for linac (or ERL-ring) colliders with only a single interaction

Strong high energy hadron cooling at RHIC

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

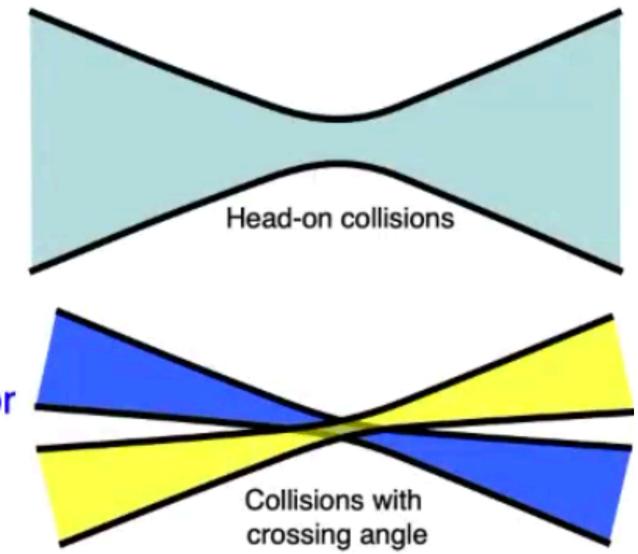
- First bunched beam electron cooling for luminosity upgrade of “low” energy heavy ion collisions
- Experimental demonstration of Coherent electron Cooling, a combination of stochastic and electron cooling, for fast cooling of high energy hadron beams

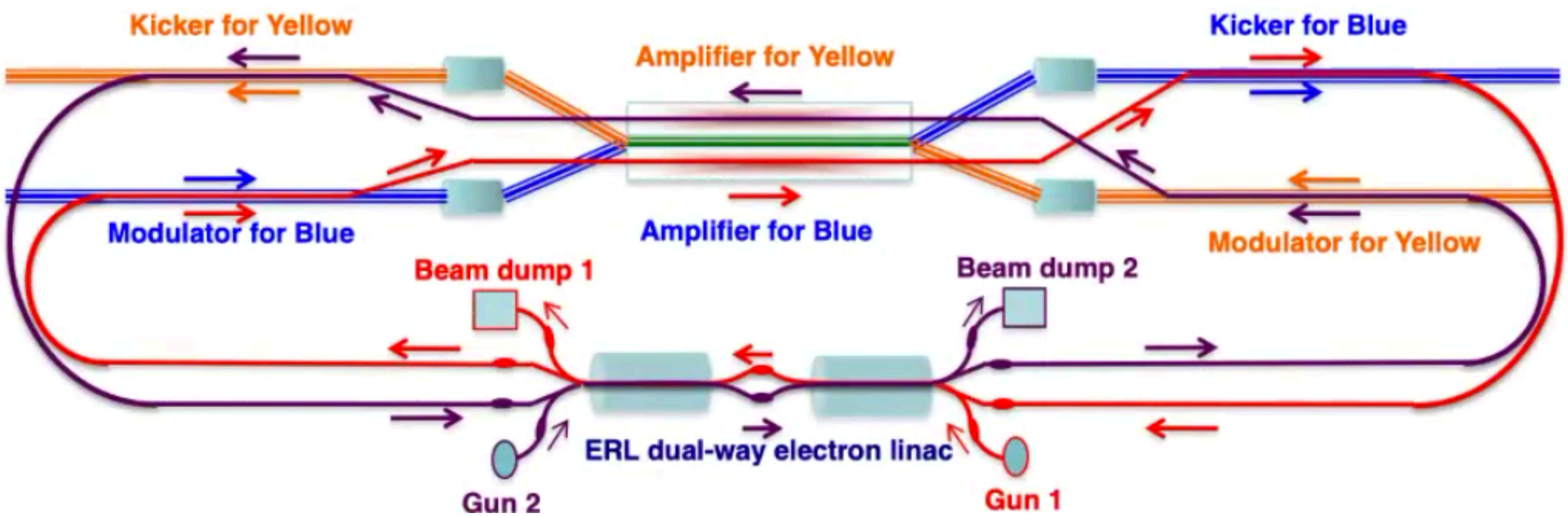




CeC for RHIC: High Luminosity with large Piwinski angle

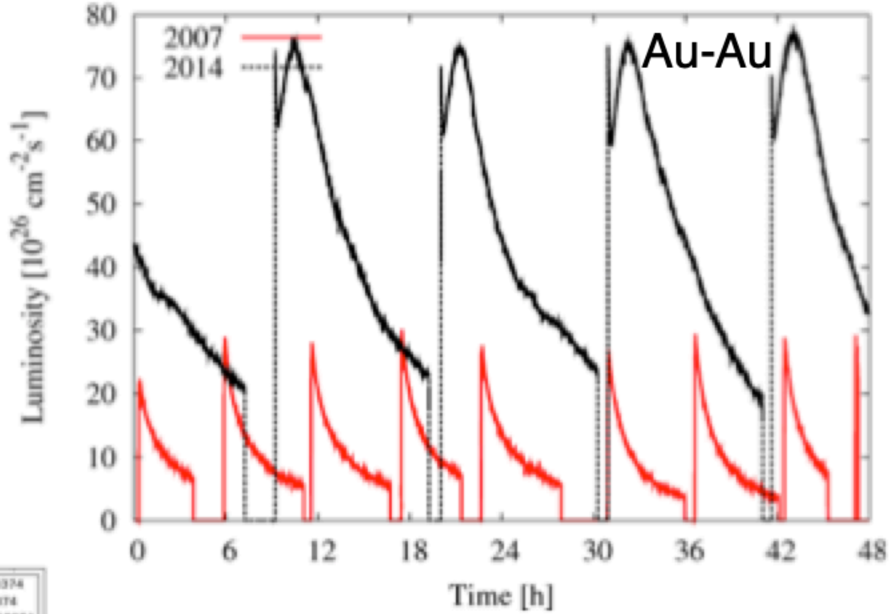
- If head-on collisions are at beam-beam limit large Piwinski angle collisions of long bunches with very small emittance can increase luminosity (Super B factory)
- Needs strong cooling: synchrotron rad. or **CeC**
- Separate bunches outside high luminosity region to avoid beam-beam from low luminosity 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} !)

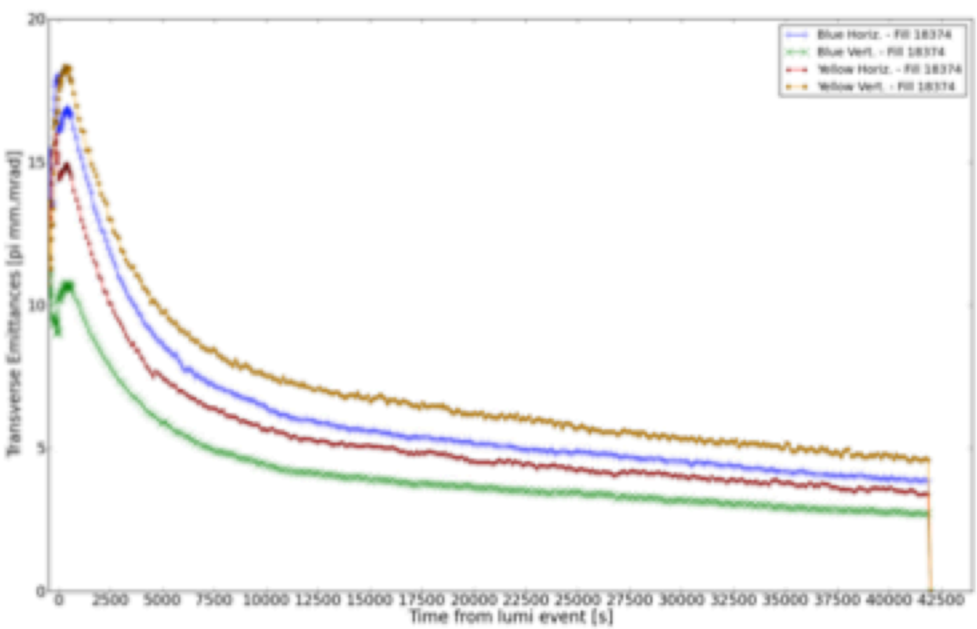


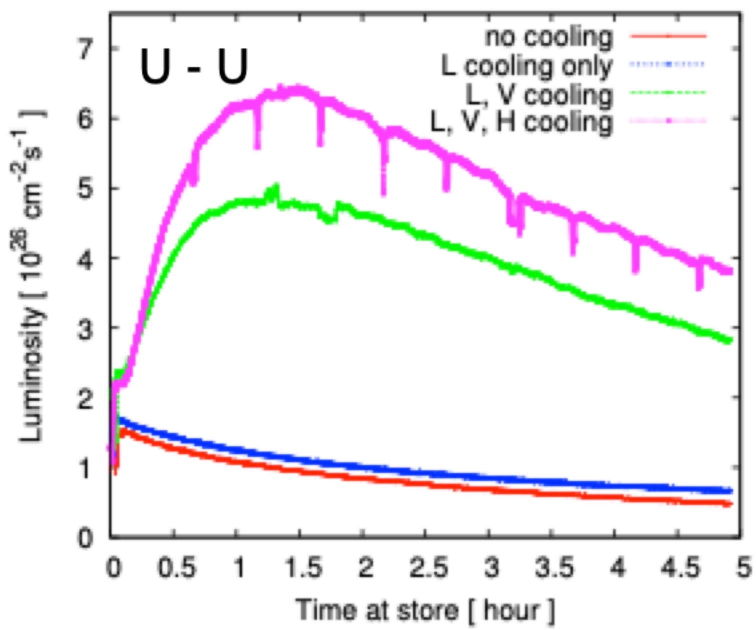


Heavy ion stochastic cooling – reaching burn-off

- 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 – 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 1×10^{28} $cm^{-2}s^{-1}$ at RHIC
  - For proton-proton collisions (total cross section ~ 60 mb) maximum luminosity is about 1×10^{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.

How the CeC was conceived

Yaroslav Derbenev, *Jlab*

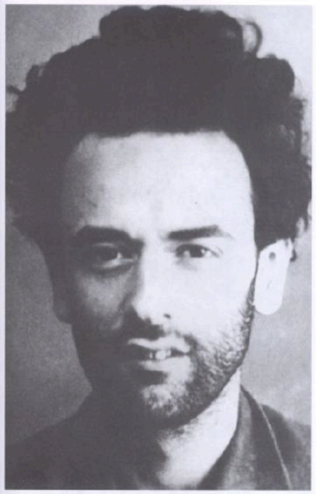
ICFA Workshop on Coherent Electron Cooling

Stony Brook, NY

July 24 – 25, 2019

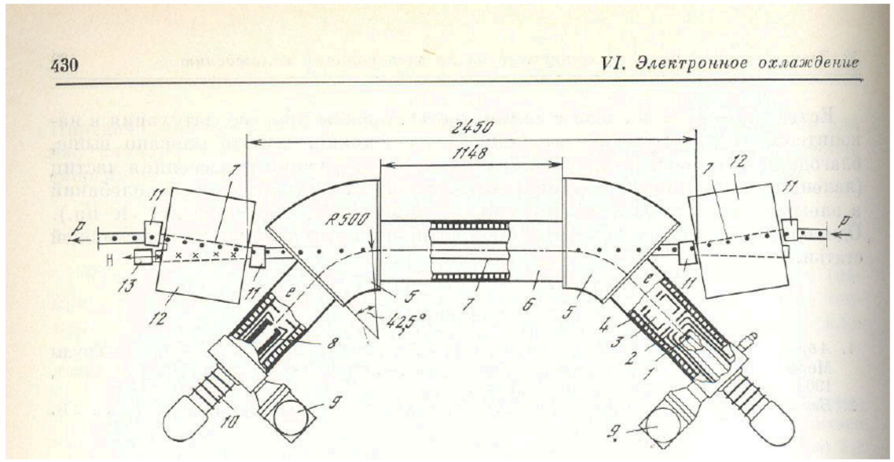
ELECTRON COOLING:

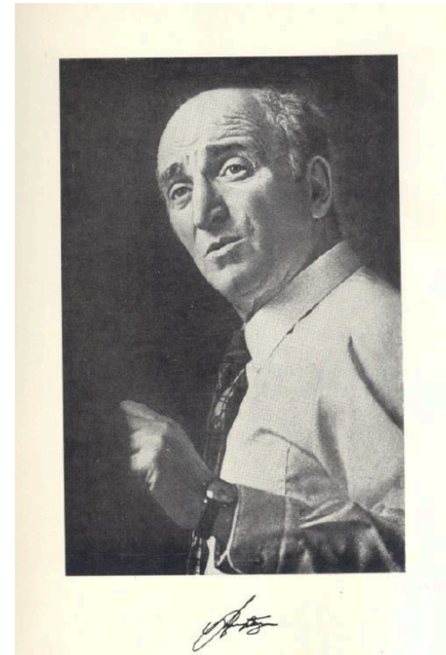
The thermostat of a relativistic engineer



Фотография сделана во внутренней тюрьме НКВД СССР на Лубянке, 1938 год.

Do not renounce from prison and money bag…





Landau liked to call me "The relativistic engineer". I am very proud of that.

Gersh Budker

- **<u>Kinetic equation</u> (plasma relaxation) was derived by Landau in 1937. But… can it work for charged beams? It does! Yet very interesting and important phenomena have been discovered (magnetized cooling, super-deep cooling, cristaline beams…)**
- **<u>EC and IBS</u>: similar equations…**

EC as plasmas relaxation

Boltzman →Fokker-Plank equation with binary collisions integral of Landau results in thermal relaxation between ions and electrons:

$$\frac{dT}{dt'} = -\frac{8\sqrt{2\pi}}{3}\eta \frac{n_e' Z^2 e^4 L}{mM} \frac{T - T_e}{\left(\frac{T}{M} + \frac{T_e}{m}\right)^{3/2}}$$

Drag force of a fast ion

- $\vec{F}(\vec{v}) = -\frac{4\pi Z^2 n_e' e^4 L}{mv^3}\vec{v} \quad for \quad v \gg v_{eT}$

$$L(u) = \log\frac{mu^3\tau_{eff}}{Ze^2}, \qquad \tau_{eff} = \min\left\{\frac{1}{\omega_e}, \frac{l}{\gamma\beta c}\right\}$$

- Magnetized cooling: $r_L << \sigma_\perp$

$$\vec{F}(\vec{v}) \sim -\frac{4\pi Z^2 n_e' e^4 L}{mv^3}\vec{v} \qquad for \quad v \gg \frac{\Delta\gamma_e}{\gamma}c$$

Is the EC 100% same process as plasma relaxation?

- Interaction time is limited by the cooling section length
- While an ion excites electron plasma effectively in dynamical shield radii which can be much larger compared with electron Debay parameter

BALESCUE-KLIMONTOVICH THEORY FOR DRAG FORCE IN PLASMAS

- *Taking into account stability of a normal plasma, these professors have derived the following formula for the drag force:*
- $\vec{F} = -\frac{Z^2 e^2}{2\pi^2} \int d^3 k \frac{\vec{k}}{k^2} \frac{\operatorname{Im} \varepsilon_{\vec{k}}(\vec{k}\vec{v})}{\left|\varepsilon_{\vec{k}}(\vec{k}\vec{v})\right|^2}$
- Assumption about Landau damping of the ignited plasma waves is valid for the conventional real plasmas
- But it is not so in our case of the cooling electron beam…

VLASOV- LANDAU THEORY OF THE PLASMAS WAVES

- Prof. Vlasov has incepted his the self-consistent method to describe plasma waves
- Prof. Landau has found damping of the plasma waves
- However, this damping is not effective in the area beyond the electron Debay radii – during the flight time of our beams through the cooling section…
- Namely , this circumstance is forcing one to take into account the wave mode of electron plasma excitation by an individual ion… - effectively in the sphere of the dynamical shield for a fast ion…

CONTRIBUTION OF THE TRANSIENT PROCESS IN THE E-BEAM

/Correct theory of the collective response for EC/

Formula for drag force have derived in my Soviet Doctoral Thesis (1978):

- $$\vec{F}(t) = -\frac{Z^2 e^2}{2\pi^2} \int d^3k \, \frac{\vec{k}}{k^2} \left\{ \frac{\mathrm{Im}\, \varepsilon_{\vec{k}}(\vec{k}\vec{v})}{\left|\varepsilon_{\vec{k}}(\vec{k}\vec{v})\right|^2} + i \sum_s \left[\frac{\exp(-i(\omega - \vec{k}\vec{v})t)}{(\omega - \vec{k}\vec{v})\, \partial \varepsilon_{\vec{k}}(\omega)/\partial \omega} \right]_{\omega=\omega_s} \right\}$$

The second term is the contribution of the transient field excited by an ion. Now, imagine that electron plasma is unstable. Then what?...

CEC: EC ENHENCEMENT BY A MW INSTABILITY

AS COULOMB LOG BIFURCATION

Electric field ignited by an ion in a homogeneous co-moving electron beam:

$$\vec{E}(\vec{r},t) = -\frac{Ze}{2\pi^2}\int d^3k\,\frac{\vec{k}}{k^2}\left\{\frac{\operatorname{Im}\varepsilon_{\vec{k}}\left(\vec{k}\vec{v}\right)}{\left|\varepsilon_{\vec{k}}\left(\vec{k}\vec{v}\right)\right|^2} + i\sum_s\left[\frac{\exp\left(-i\left(\omega-\vec{k}\vec{v}\right)t\right)}{\left(\omega-\vec{k}\vec{v}\right)\partial\varepsilon_{\vec{k}}(\omega)/\partial\omega}\right]_{\omega=\omega_s}\right\}\exp\left(i\vec{k}(\vec{r}-\vec{v}t)\right)$$

- *At* $Im\omega_s > 0$,

the transient (second) part grows along the cooling section

$$\vec{E}(\vec{r},t) \Rightarrow -\frac{Ze}{2\pi^2}\int d^3k\,\frac{i\vec{k}}{k^2}\sum_s\left[\frac{\exp\left(-i\left(\omega-\vec{k}\vec{v}\right)t\right)}{\left(\omega-\vec{k}\vec{v}\right)\partial\varepsilon_{\vec{k}}(\omega)/\partial\omega}\right]\exp\left(i\vec{k}(\vec{r}-\vec{v}t)\right)_{\omega=\omega_s}$$

…that maybe bad…-but could’nt be even used to build the **microwave** *stochastic cooling*?! (1980)

GOING FOR THE MW INSTABILITY SPECIES

- There are several possible ways to organize the MWI process in electron beam
- So the electron beam (basically fco-moving the ion beam) could serve in the all three duties: picup station, amplifier, and kicker

UNDERSTANDING THE LIMITATIONS

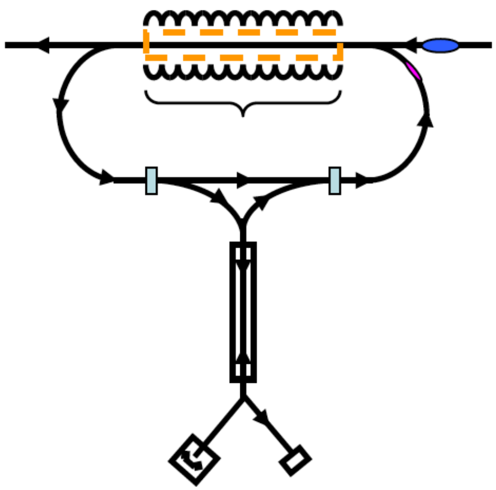
ELECTRON COOLING: PPP

-PAST & PRESENT-

Cooling of low energy beams
Relativistic cooling of p-bar
Magnetized cooling
Fast cooling
Super-deep cooling
Cooling of positrons (theory)

-PERSPECTIVES-

Cooling of positrons
Matched cooling
ERL based HEEC
Circulator-cooler ring



SUPER-PERSPECTIVE:

-COHERENT EC-

ON RISE

Revived by V.Litvinenko !

Thank you for your interest and attention!

Discussions

- How to simplify the description of CeC for easier understanding by general public?

Use Stochastic cooling to popularize CeC

-High freq

-initial force: Debye radius may exceed beam size

(pick up, larger than that in SC ---size of chamber)

-electron as information carrier

-Ratner's description: imprint signal, amplify,

phase condition for decelerating of ion

Discussions (con'd)

- How conventional eCooling, CeC and stochastic cooling compare to each other? What are the disengages or advantages of each scheme? Requirements for quality for e-beam? What are the requirement for accelerators for these schemes?

CeC—energy spread of e-beam, freq for microbunches, orders magnitude faster in cooling rate, not determined by bandwidth, but by saturation, average current lower than conventional e-cooling beam

e-beam is information carrier

instability of plasma: limited by space charge effect

Analogy with stochastic cooling: CeC and optical stochastic cooling is fundamentally different from the stochastic cooling in signal pickup

Importance of Low Noise and High Beam Quality

- Source of initial noise or modulation in beam

  Laser noise characterization
  - FEL community has studied this a lot, Six ICFA workshop on uBI
  - It's well known that initial noise in laser can be strongly amplified
  - Source of noise on a laser (have good diagnostics to identify modulations)
    - ripple in EOM
    - multiple mode
    - nonlinear amplification

  Need to study e-beam dynamics out of cathode

- On macro aspect, RF field velocity gradient or longitudinal space charge induced correlated field gradient, may hurt the feedback from e-beam to ion beam

- Need excellent diagnostics

• Tenability of the CeC?

For stochastic cooling, the cooling rate is (taking mixing and noise into account)

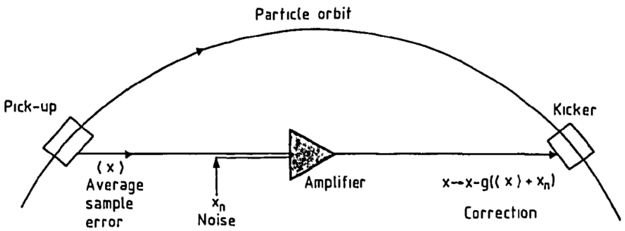


Fig. 9 Cooling loop including system noise. The noise is represented as an equivalent sample error $x_n(t)$ as observed at the pick-up.

$$\boxed{\frac{1}{\tau} = \frac{2W}{N}\left[2g - g^2\ (1+U)\right],}$$

Cooling remains possible despite very poor signal-to-noise ratios (1/U « 1). All we have to do is to choose g small enough (g ~ g0 = 1/(1 + U) s: 1/U), which unavoidably means slow cooling (x £ NU/2W). In other words, we have to be patient and give the system a chance to distil a signal out of the noise. (D. Mohl)

Tuning knobs in CeC:
-beam current
 (but avoid saturation)
-strength of chicane
-focusing strength

Importance of PoP Experiment

- Is experimental demonstration of CeC at RHIC is necessary for the progress of CeC?

  Are simulations sufficient as proof of principle?

Is it necessary? ---depend on cooling rate you suggest, if not high cooling rate then it's out of interest

Experimental verification is very important. Numerical characterization of noise is very limited, hard to sort out numerical signal from physical signal

- Experimental demo is absolutely needed for any future CeC
- Beam quality is most important, understanding and control noise is critical
- Experiment is necessary to test the predictive power of our simulation codes
- Theory and simulation can give guidance and insight, but are limited by their assumptions (especially about microbunching and noise amplification)

Gennady Stupakov's comments:

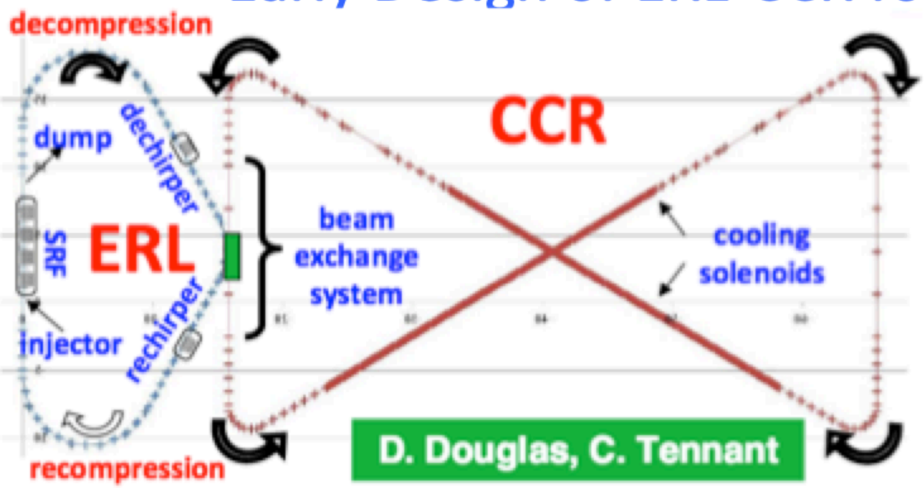
- Strongly support initiating CeC experiment and eventually reaching successful result
- Initial negative result—definite understanding of what's going on there
- Perception of accelerator community:
  - Overly complicated project and over-sold
  - Can only be done by experimental demonstration
  - Will be helpful for other approaches, generating quiet beam

Summary

- Understanding and control of beam quality and noise in beam is critically important for the success of CeC PoP and future projects
- The recent finding of noise effect on beam is important for deeper understanding and study for these topics
- PoP experiment is necessary to verify the theory and simulation for future CeC application with any type of amplifiers

Challenges in Numerical Simulation of Microbunching

Early Design of ERL-CCR for MEIC



(Tennant and Douglas, 2012)

Table 1: Relevant parameters for the CCR.

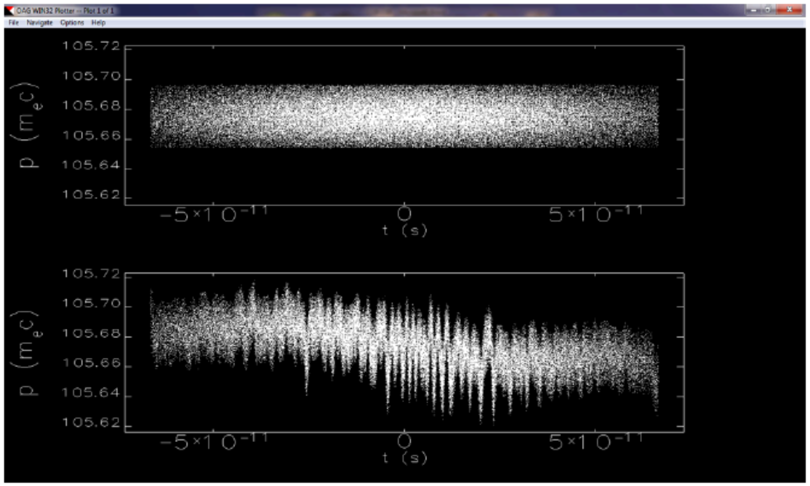
Parameter	Value
Beam energy (MeV)	54
Bunch charge (nC)	2
Repetition rate (MHz)	750
Relative energy spread	10^{-4}
RMS bunch length (ps)	33.33
Longitudinal emittance (keV-psec)	180
Transverse normalized emittance (mm-mrad)	3
Cooling solenoid field (kg)	20

Numerical Observation of Microbunching Instability

Bunch Longitudinal Phase Space Distribution

Elegant tracking results

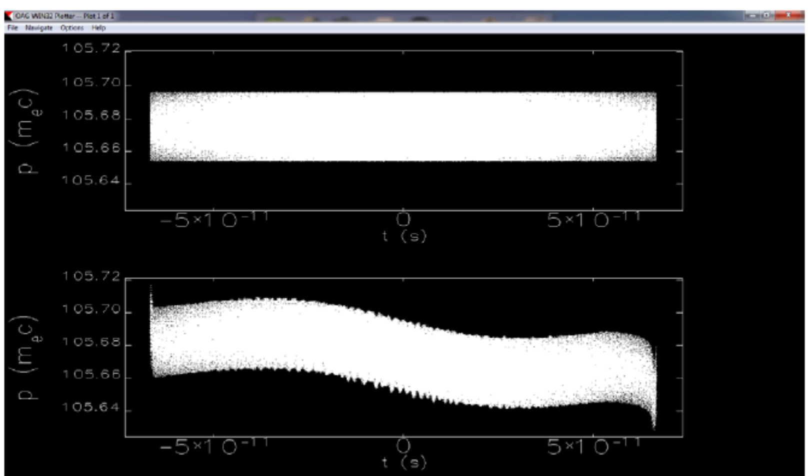
p



t

100K particles
Single turn
No quiet start

p



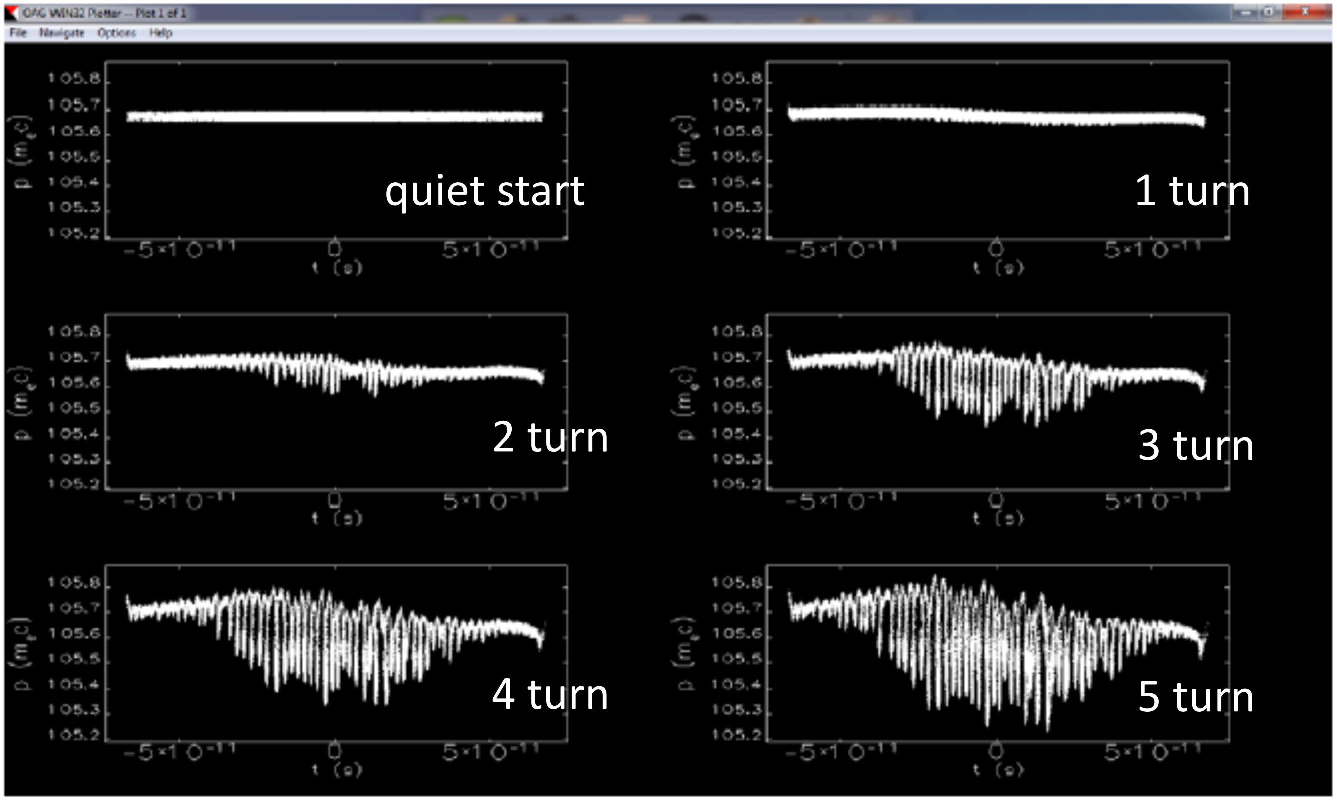
t

1000K particles
Single turn
With quiet start

(Tennant and Douglas, 2012)

(Nissen *et al.*, 2014)

Evolution of Longitudinal Phase Space



Elegant tracking Results

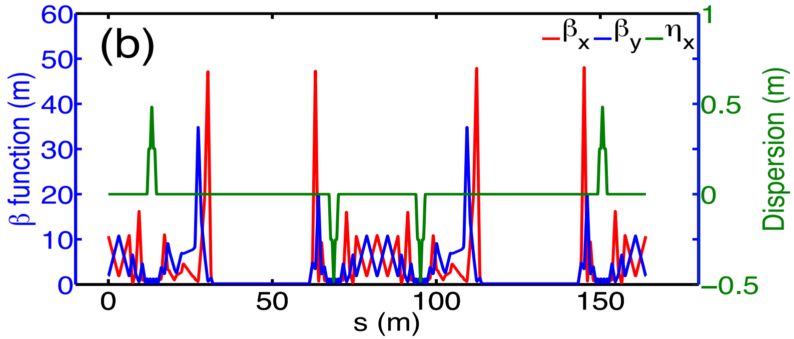
(100K particles)

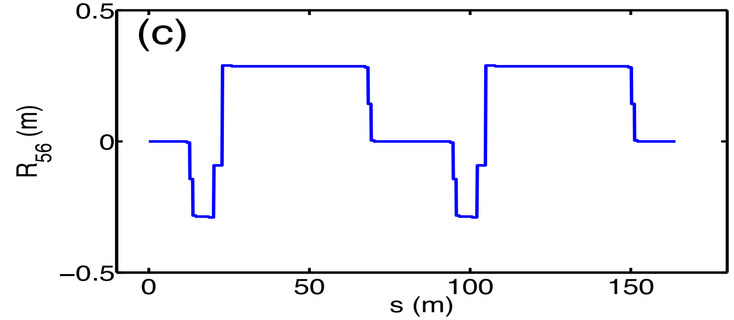
Table 2: Evolution of electron bunch parameters as a function of turns in the CCR.

	1 Turn	2 Turns	3 Turns	4 Turns	5 Turns
ε_x (mm-mrad)	2.9	3.1	3.8	4.5	5.1
ε_y (mm-mrad)	2.9	2.9	3.0	3.1	3.2
σ_t (ps)	29.33	29.31	29.28	29.24	29.19
$\sigma_{\Delta E/E}$ (%)	0.012	0.027	0.066	0.096	0.117

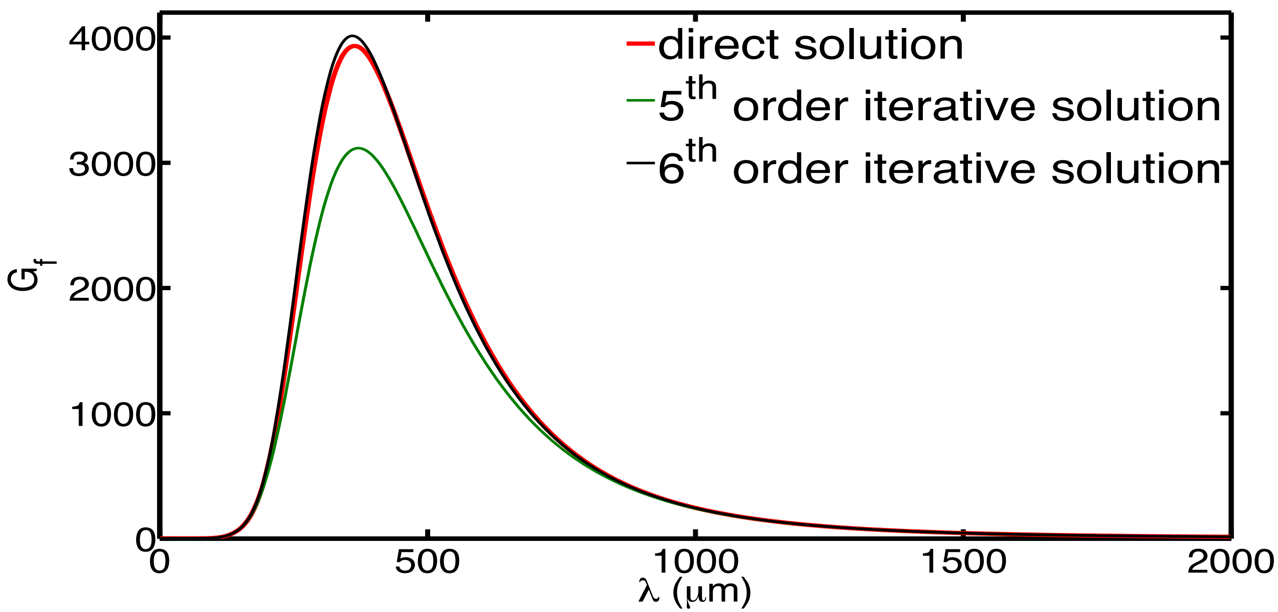
Microbunching Gain in CCR

- Lattice functions for CCR





- Staged microbunching gain spectrum for one pass through CCR

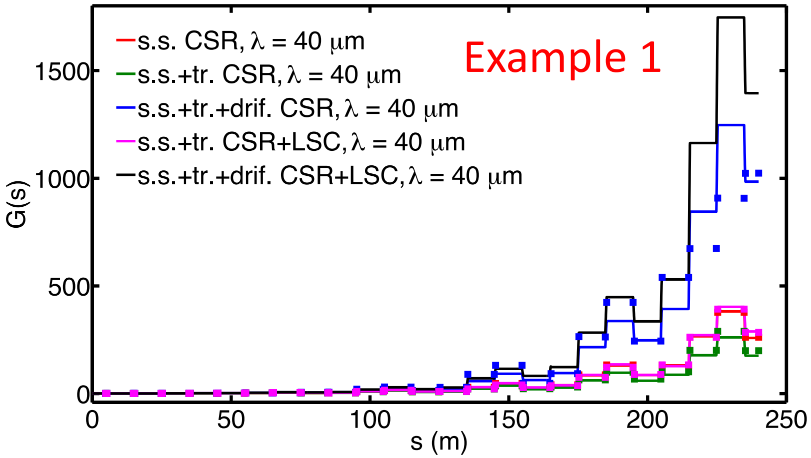


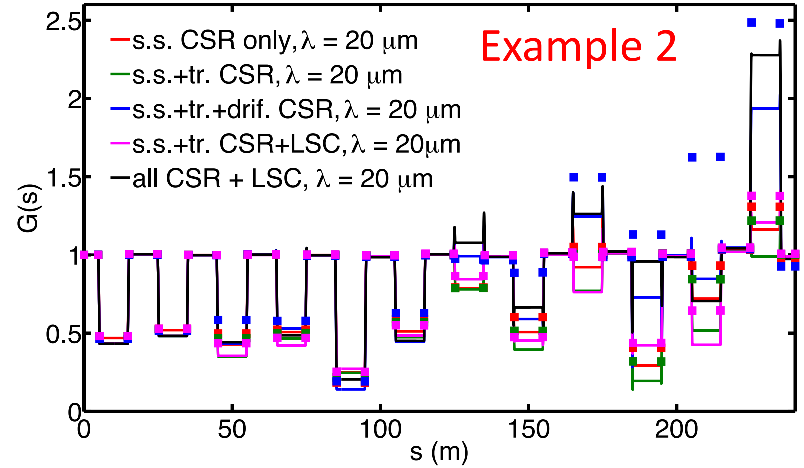
(C-Y Tsai *et al.*)

Microbunching Behavior for the Two Example Arcs

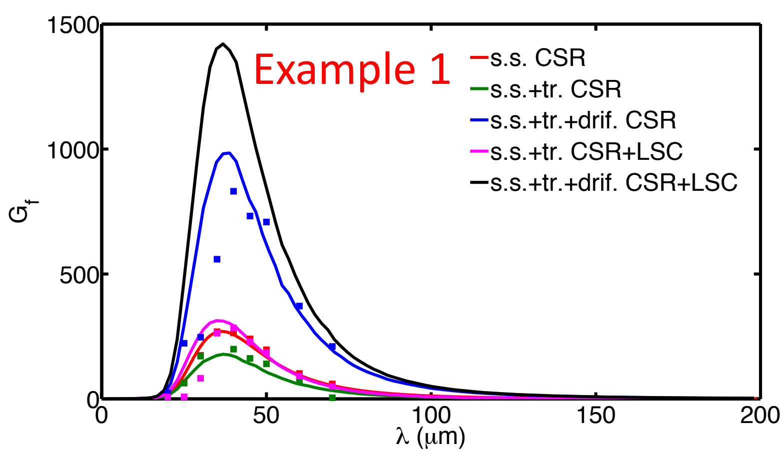
(C-Y Tsai *et al.*)

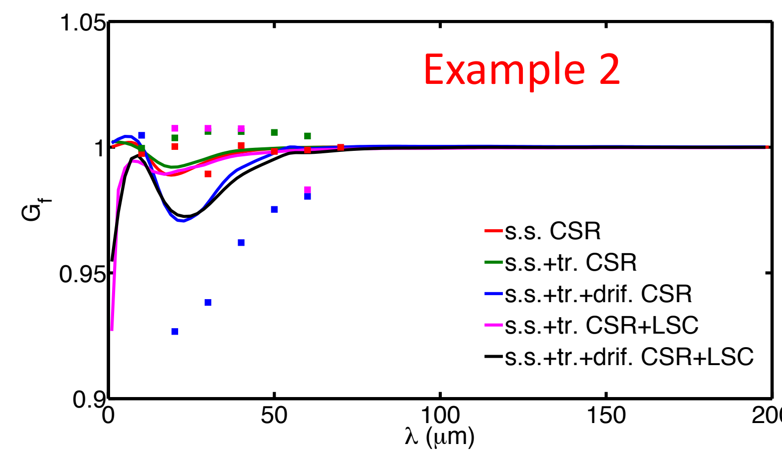
- Microbunching gain along the arc





- Microbunching gain spectrum at the end of the arc





Simulation parameters that generate convergent gain results

(C-Y Tsai *et al.*)

Name	**Value**	**Unit**
full(flattop) bunch duration	10 (6)	ps
full(flattop) bunch duration	300 (180)	ave. λ_m = 10 μm
total charges	3.46	nC
macroparticle number (total)	50×10^6	
macroparticle number (per bin)	2500	
CSR bin number	20000	
CSR bin number per wavelength	50	min. res. 0.1 μm
number of kicks within a dipole	400	
histogram bin number	2000	
clip number	600	
modulation wavelengths	2 ~ 70	μm
modulation amplitudes	0.05 ~ 2	%