Highlights of the CeC Workshop

Rui Li

JLEIC R&D Meeting

8-15-2019
Workshop Program

ICFA mini-workshop CeC 2019

Coherent Electron Cooling – Theory, Simulations and Experiment
July 24-26, 2019, at the Center for Frontiers in Nuclear Science
Department of Physics and Astronomy, Stony Brook University,
Stony Brook, NY 11794, USA

Organized by Center for Accelerator Science and Education

Workshop chair
Vladimir N Litvinenko

Workshop program chair
Gang Wang

Local organizing committee chair
Yichao Jing

http://case.physics.stonybrook.edu/index.php/ICFA_workshop_CeC
- **Goal of the workshop** is in depth discussion of progress and challenges in the Coherent Electron Cooling theory, simulations and experiment.
- **Workshop format:** In contrast with conference style workshops, this will be a real workshop with full length discussion sessions. Few invited presentations are designed to stimulate discussions.
- **Logistics:** Workshop is by invitation only — send expression of interest to Vladimir Litvinenko vladimir.litvinenko@stonybrook.edu and Gang Wang gawang@bnl.gov.
- There will be no workshop fees and no offered support — all participants will be responsible for their travel and living expenses.

- **Wednesday, July 24**
  - **Session 1:** Convener – Rui Li (JLab)/ Local session chair - Sergei Seletskiy
  - 9:00 Thomas Roser, *Why strong hadron cooling is needed?*
  - 9:30 Yaroslav S Derbenev, *How Coherent electron Cooling was conceived?*
  - 10:00 Discussion lead by the convener - coffee break at 10:30
  - 12:00 – 14:00 Lunch break
  - **Session 2:** Convener – Yue Hao (MSU)
  - 14:00 Vladimir N Litvinenko, *Variety of CeC systems*
  - 14:15 Gang Wang, *CeC theory*
  - 15:00 – 17:00 Discussion lead by the convener - coffee break at 15:30

- **Thursday, July 25**
  - **Session 3:** CeC. Convener – David Bruhwiler (RadiaSoft)
  - 9:00 Jun Ma, *CeC simulations*
  - 9:30 Yichao Jing, *Beam dynamics in CeC accelerator*
  - 10:00 Discussion lead by the convener - coffee break at 10:30
  - 12:00 – 14:00 Lunch break
  - **Session 3:** CeC. Convener – Dmitry Kayran (BNL)
  - 14:00 Igor Pinayev, *CeC experiment – physics*
  - 14:30 Jean Clifford Brutus, *CeC experiment – engineering*
  - 15:00 – 17:00 Discussion lead by the convener - coffee break at 15:30

- **Friday, July 26**
  - **Session 4:** CeC. Convener –Vladimir Litvinenko (SBU)
  - 9:00 Short discussion of possible collaborations
  - 9:15 – 12:00 **Summaries** - coffee break at 11 am
  - Rui Li, *CeC & Hadron cooling*
  - Yue Hao, *CeC theory*
  - David Bruhwiler, *CeC simulations*
  - Dmitry Kayran, *CeC experiment*
  - 12:00 Close up
Outline

• Workshop program
• Status of the CeC Project
• Session I: Motivation of CeC
• Session II and III: CeC theory and simulations
• Session IV: CeC experiment
What is Coherent electron Cooling

• Short answer – stochastic cooling of hadron beams with bandwidth at optical wave frequencies: 1 – 1000 THz

• Longer answer

\[ \gamma_e = \gamma_h \]
The goal of the experiment is to demonstrate longitudinal cooling of a single Au\(^{+79}\) bunch in the Relativistic Heavy Ion Collider.

The circulating hadron beam imprints its distribution on the electron bunch in the modulator section. The longitudinal charge modulation is amplified in the free-electron laser structure comprising three helical permanent magnet wigglers with \(a_w=0.5\). The electrical field accelerates and/or decelerates hadrons in the kicker section.

### Required electron beam parameters
- Normalized emittance < 5 mm mrad
- Relative energy spread \(\sigma_E/E < 10^{-3}\)
- Bunch charge 500 pC – 1.5 nC
- Repetition rate 1 Hz – 78 kHz
- R.m.s. bunch length 10-50 psec
- Peak current > 75 A
- Kinetic energy 14.5 MeV
- IR FEL wavelength 30 microns

### Hadron beam parameters
- Energy 27 GeV/u
- Intensity \(10^9\) hadrons/bunch (12 nC)
- R.m.s. bunch length 5 nsec
- Revolution frequency 78 kHz
Puzzle of the CeC Run 18

Search for ion’s imprint

\[ R = \frac{I_{\text{overlap}} - I_{\text{separated}}}{I_{\text{separated}}} \times \% \]

Expected and measured relative change in the FEL signal with overlapping and separated beams. Each point corresponds to 16 or more cycles of 20 FEL power measurements for overlapped and separated beams. Data analysis indicate RMS error of 2%.

Top plot: electron beam current through the CeC ~ 110 µA or 1.4 nC per bunch at 78 kHz. Bottom plots: evolution of the bunch lengths for interacting (blue trace) and witness bunches (orange and green traces).

Heating of ion beam was occurring only with a perfect overlap of the beams and high FEL gain. Reducing the FEL gain eliminated the heating.

We have not observed growth of the FEL power due to the interactions with hadrons because of the beam instability due to PCI and/or overbunching.
PCA based CeC System

Required electron beam parameters
- Normalized emittance < 5 mm mrad
- Relative energy spread $\sigma_E/E < 10^{-3}$
- Bunch charge 0.5 – 1.5 nC
- Repetition rate 1 Hz – 78 kHz
- R.m.s. bunch length 10 – 25 psec
- Peak current 50-100 A
- Kinetic energy 14.5 MeV

- Mechanical design of new CeC system is completed
- We procured and commissioned new laser system with controllable pulse structure
- All new vacuum chambers with beam diagnostics are built
- All supports are built and installed
- All solenoids are designed, manufactured, delivered and undergo magnetic measurements
- Assembly of the plasma-cascade based CeC can be completed during this year’s RHIC shut-down
What can be tested experimentally?

Cooling test requires serious modification of the RHIC lattice & superconducting magnets +$20$-$30\text{M}$ OR
Building new CeC system at another hadron storage ring

RHIC Runs 20-22

Cooling test requires serious modification of the RHIC lattice & superconducting magnets +$20$-$30\text{M}$ OR
Building new CeC system at another hadron storage ring
Session I: Motivation of CeC

• Why strong hadron cooling is needed?  
  Thomas Roser

• How coherent electron cooling was conceived?  
  Yaroslav S Derbenev

• Discussions
Why strong hadron cooling is need? (T.Roser)

Luminosity of Storage Ring Colliders

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

- 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

\[ \mathcal{L} = \frac{N^2}{4\pi \sigma^2} = \frac{N^2}{4\pi \beta^* \varepsilon^n} \]

- 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 \((N/\varepsilon)\).
- This results in the same luminosity.
- Now reduce \(\beta^*\), which is possible because of the smaller emittance, to get increased luminosity.
- This requires large crossing angle to avoid parasitic collisions and crab cavities.

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 – beam-beam

\[ \xi_{1;x,y} = \frac{N_2 r_0 \beta_{1;x,y}^*}{2\pi \gamma \sigma_{2;x,y} (\sigma_{2;x} + \sigma_{2;y})} = \frac{N_2 r_0}{4\pi \varepsilon\pi} \]

(for equal round beams)

\[ \xi_{1;x,y} = \frac{N_2 r_0 \beta_{1;x,y}^*}{2\pi \gamma \sigma_{2;x,y} \sigma_{2;x}} \]

(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.
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 \( \sim 10 \, \text{cm} \), \( \varepsilon^\text{rms} \sim 0.2 \, \mu\text{m} \), \( \beta^* \sim 10 \, \text{cm} \) gives \( \sim x10 \) luminosity increase \( \sim 5 \times 10^{33} \, \text{cm}^{-2} \, \text{s}^{-1} \)!
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 $1 \times 10^{28}$ cm$^{-2}$s$^{-1}$ at RHIC

- For proton-proton collisions (total cross section ~ 60 mb) maximum luminosity is about $1 \times 10^{34}$ 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 coherent electron cooling was conceived?
(Ya. Slava)

**Electron Cooling:**

*The thermostat of a relativistic engineer*

- Do not renounce from prison and money bag...
- Landau liked to call me ‘The relativistic engineer’. I am very proud of that. *Gersh Budker*
- Kinetic equation (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...)
- EC and IBS: similar equations...

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**EC as plasmas relaxation**

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

\[
\frac{dT}{dt} = - \frac{8\sqrt{2\pi}}{3} \frac{\eta}{m} \frac{n_e^2 Z^2 e^4 L}{m M} \left( \frac{T}{M} + \frac{T_e}{m} \right)^{3/2}
\]

**Drag force of a fast ion**

- \( \vec{F}(\vec{u}) = -\frac{4n_e Z^2 \kappa \vec{e} L}{mv^3} \) for \( v \gg v_{ei} \)
- \( L(\nu) = \frac{\kappa}{Ze^2} \) for \( \tau_{eff} = \min \left( \frac{1}{\omega_p}, \frac{1}{\gamma \beta c} \right) \)
- Magnetized cooling: \( \tau_c \ll \omega_p \)
  
  \( \vec{F}(\vec{u}) = -\frac{4n_e Z^2 \kappa \vec{e} L}{mv^3} \) for \( v \gg \frac{\Delta \nu_{ce}}{\gamma} \)

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**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 Debye 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:

$$ \vec{F} = -\frac{Z^2e^2}{2\pi^2} \int d^3 k \frac{k}{k^2} \frac{\text{Im} \varepsilon_k(k\vec{v})}{|\varepsilon_k(k\vec{v})|^2} $$

- 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...

CEC: EC ENHANCEMENT BY A MW INSTABILITY

AS COULOMB LOG BIFURCATION

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

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

- At Im$$\omega_s > 0$$, the transient (second) part grows along the cooling section

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

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

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):

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

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

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

- COHERENT EC-ON RISE
  - Revived by V.Litvinenko!
Discussions

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

• Tunability of the CeC?

• Is experimental demonstration of CeC at RHIC is necessary for the progress of CeC?
  
  Are simulations sufficient as proof of principle?
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
Session II and III: CeC Theory and Simulations

The role of theoretical tools

- Make predictions for an ideal/simplified system:
  - Validate numerical simulations;
  - Improve our understandings of the physical processes involved in CeC and if possible, obtain scaling laws;
- Theoretical tools are often inadequate for accurate prediction of a realistic CeC system (requires numerical simulation).

Tool and algorithm

- The SPACE code is a parallel, relativistic, three-dimensional electromagnetic PIC code. Used in simulations of modulator, kicker, and PCA.
- The GENESIS code is a three-dimensional, time-dependent code developed for high-gain FEL simulations. Used in simulations of FEL amplifier.
- Use single ion in modulator simulations
- Extract modulation signal from shot noise.
Modulator: Theory and Simulation

- Warm uniform electron beam with k-2 velocity distribution (uniform e-distribution)

\[
f_0(\vec{v}) = \frac{1}{\pi^2 \beta_x \beta_y \beta_z} \left( 1 + \frac{v_x^2}{\beta_x^2} + \frac{v_y^2}{\beta_y^2} + \frac{v_z^2}{\beta_z^2} \right)^{-2}
\]


- Density modulation:

\[
\tilde{n}_i(x,t) = \frac{Z_i}{\pi^2 a_x a_y a_z} \int_0^{\infty} \tau \sin \tau \cdot d\tau
\]

\[
\left[ \frac{x^2}{a_x} + \left( \frac{v_{0,x}}{\beta_x} \tau \right)^2 + \left( \frac{y}{a_y} + \frac{v_{0,y}}{\beta_y} \tau \right)^2 + \left( \frac{z}{a_z} + \frac{v_{0,z}}{\beta_z} \tau \right)^2 \right]^{-2}
\]

- Energy modulation

It reduces to the previously derived cold beam result at the corresponding limits:

\[
\bar{\beta} = 0 \quad v_{0,z} = 0 \quad L_{\text{mod}} \ll \beta_0 \gamma_0 c / \omega_p
\]

\[
\left\langle \frac{\delta E}{E} \right\rangle \approx -2Z_i \frac{r_e}{\gamma^2} \frac{L_{\text{mod}}}{\gamma} \left[ \frac{z_i}{z_i} - \frac{z_i}{\sqrt{z_i^2 + a^2 / \gamma^2}} \right].
\]

- Benchmark with simulation (SPACE)

- Benchmarked with theory for uniform warm beam

(imprint in e-beam) (energy modulation)
Modulator: Simulation (SPACE code)

Imprint in a Gaussian e-beam

- Gaussian beam in a continuous focusing field

(a) Ion at center  
(b) Ion 0.5σ off center  
(c) Ion 1.0σ off center  
(d) Ion 1.5σ off center  
(e) Ion 2.0σ off center  
(f) Transverse density

Continuous imprint along the modulator

- Gaussian beam in a quadrupole beam line

(a) Longitudinal density  
(b) Longitudinal velocity  
(c) Transverse density  
(d) Transverse velocity
FEL Amplifier: Theory

Analytical Prediction for FEL Amplifier

- For the CeC PoP parameters, the FEL amplifier works in the diffraction dominated regime

\[ \eta_a = \frac{l_{ID}}{2k_o \sigma_z^2} = 6.6 \gg 1 \quad l_{ID} = \frac{1}{2\sqrt{3} \rho k_o} = 0.15m \quad \sigma_z, \text{rel} = 0.235 \text{mm} \]

and hence we can’t rely on 1-D theory to predict the performance of the amplifier.

- There are formulae to make corrections to the 1-D gain length for the general case developed by Ming Xie,

\[ l_{ID} = l_{1D} (1 + A_{3D}) = 0.363 m \]

and using this number we get (for 40A peak current and 5 mm.mrad emittance)

\[ G = \frac{1}{3} \delta w \exp \left( \frac{l_{sat}}{2l_{1D}} \right) = 74.6 \]

\[ \delta_w = \sqrt{\frac{3}{k_o l_{1D}}} = 0.0073 \]

Bunching factor (at entrance of FEL)

\[ \lambda_{opt} = 30 l_D \]

Bunching factor (at exit of FEL)

\[ G_{sat} = \frac{1}{3} \delta_w \exp \left( \frac{l_{sat}}{2l_{1D}} \right) = 330 \]

Approximate Gain= 210

Effects due to multi-subsections

- Our undulator consists of 3 sub-sections and more than 80% of radiation power is lost in the 44cm gap between two successive sub-sections.

Effects due to Longitudinal Space Charge

- Longitudinal space charge has more pronounced effects on the FEL gain than what to be expected from theory.
Kicker: Theory and Simulation

Analytical Tools for Kicker

- Dynamic equation in Kicker is very similar to that in the modulator except the initial modulation in 6D phase space dominates the process. For 1D FEL output with the certain assumptions for the transverse distribution, the following analytical formula for density modulation can be derived:

\[
\hat{n}(k_z, t) = -Z_0 \hat{N}_{drive}(k_z) e^{ik_z t} e^{-\frac{(\lambda t)^2}{\sigma^2}} \left[ \cos(\omega t) + \frac{\lambda t}{\omega} \sin(\omega t) \right]
\]

Used electron distribution within 4 slices where maximum gain occurs

Energy kick to ions in the kicker

- V\textsubscript{z}=0 cooling time=0 s
- V\textsubscript{z}=\textasciitilde9\texttimes10^4 m/s cooling time=3.9 s
- V\textsubscript{z}=\textasciitilde9\texttimes10^4 m/s cooling time=5.2 s

widening of wave packet

(a) Ions at different locations
(b) Ion with reference energy
(c) Ion with lower energy
(d) Ion with higher energy
Ion Dynamics: Theory and Simulation

Single-Pass Kick Received by an ion in FEL-based CeC section

Energy kicks from CeC is \( \Delta E_i = \Delta E_{\text{coh.}} + \Delta E_{\text{inc.}} \).

Coherent kick induced by the ion itself

\[ \Delta E_{\text{coh.}} = -Z_e e E_j \sin(k_z D \cdot \delta_i) \]

Incoherent kick induced by the neighbor ions (using the Gaussian profile as obtained by quadratic expansion of FEL eigenvalues)

\[ \Delta E_{\text{inc.}} = -Z_e e E_j \sum_{i \neq j} \exp \left( -\frac{(z_i - z_j)^2}{2 \sigma_{\text{rms}}^2} \right) \sin \left( k_z D \delta_i + k_z (z_i - z_j) \right) \]

- \( z_i \): longitudinal location of the \( i \)-th ion;
- \( \sigma_{\text{rms}} \): RMS width of the wave-packet;
- \( D : R_{\text{L}} \).

Since there is no correlation between any successive incoherent kicks, one can use a random kick to represent the incoherent kicks.

\[ \Delta E_{\text{inc.}} = -Z_e e E_j \sin(k_z D \cdot \delta_i) + \sqrt{\langle \Delta E_{\text{inc.}}^2 \rangle} \cdot X_{j,N} \]

For a random number uniformly distributed between -1 and 1

Simulation tools for predicting the influences of CeC to a circulating ion beam II

- Assuming the ion density does not vary significantly over the width of the wave-packet

\[ \langle \Delta E_{\text{inc.}}^2 \rangle = \frac{Z_e e E_j^2}{2} \int_{-\infty}^{\infty} \rho_{\text{ion}}(z) e^{\frac{(z-z_i)^2}{2 \sigma_{\text{rms}}^2}} dz \approx \frac{Z_e e E_j^2}{2} \sqrt{\pi} \rho_{\text{ion}}(z) \sigma_{\text{rms}} \]

- The one-turn energy kick due to CeC is

\[ \Delta E_{j,N} = -Z_e e E_j \sin(k_z D \cdot \delta_i) + Z_e e E_j \sqrt{\frac{3}{2} \sqrt{\pi} \rho_{\text{ion}}(z_j)} \sigma_{\text{rms}} \cdot X_{j,N} + \Delta E'_{j,N} \]

Diffusive kick induced by neighbor electrons, i.e. electrons’ shot noise

\[ \Delta E'_{j,N} = e E_j \sqrt{\frac{3}{2} \sqrt{\pi} \rho_{\text{ion}}(z_j)} \sigma_{\text{rms}} \cdot Y_{j,N} \]

Applying Single-pass Kick to Predict Ion Beam Evolution with Cooling

1. Macro-particle tracking
2. Solving Fokker-Planck equation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge number, ( Z_e )</td>
<td>70</td>
</tr>
<tr>
<td>FEL wavelength, ( \lambda )</td>
<td>80</td>
</tr>
<tr>
<td>Peak current, ( I_{\text{p}} )</td>
<td>1.165 \times 10^{-4}</td>
</tr>
<tr>
<td>Coherent kick amp., ( g_c )</td>
<td>4.657 \times 10^{-4}</td>
</tr>
<tr>
<td>Coherent kick length, ( L_{\text{coh}} )</td>
<td>1.165 \times 10^{-4}</td>
</tr>
<tr>
<td>Coherent kick at bunch centre, ( J_{\text{coh}}(0) )</td>
<td>1.0 \times 10^{-4}</td>
</tr>
</tbody>
</table>

Sin cooling
Linear cooling

Overall Structure of CeC Prediction

A. Prediction of the single pass kicks received by an ion in the cooling section

Kicks due to CeC
\( dx', dy', dE \)

B. Long term prediction for circulating ions
Plasma Cascade Amplifier

Plasma-Cascade Instability

Longitudinal plasma oscillation with periodically varying plasma frequency
\[ \frac{d^2 \hat{n}}{dt^2} + \omega_0^2(t) \hat{n} = 0; \]
\[ \hat{\sigma} = \frac{2}{\omega_0^2} \int_{-T/2}^{T/2} \hat{n}(t) \hat{n}(t + T) \, dt; \]
Stability condition
\[ \left| \frac{\hat{n}(t)}{\hat{n}(0)} \right| = \frac{1}{1 + k \hat{\sigma}}. \]

Betatron motion in a FODO cell
\[ y'' + K_y(s)y = 0, \]
\[ M = \begin{pmatrix} 1 & \frac{1}{2} & 0 & \frac{1}{2} \\ 0 & 1 & \frac{1}{2} & \frac{1}{2} \\ 0 & 0 & 1 & \frac{1}{2} \\ 0 & 0 & 0 & 1 \end{pmatrix}, \]
\[ X_1 = L_1/2f_1, \]
\[ X_2 = L_1/2f_2. \]

Estimate Cooling Force for PCA-based CeC: Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy, γ</td>
<td>28.5</td>
</tr>
<tr>
<td>Electron beam peak current, A</td>
<td>100</td>
</tr>
<tr>
<td>Bunch length, ns</td>
<td>0.015</td>
</tr>
<tr>
<td>Bunch charge, nC</td>
<td>1.5</td>
</tr>
<tr>
<td>Modulator length, m</td>
<td>3</td>
</tr>
<tr>
<td>Amplifier length, m</td>
<td>8 (4 sections)</td>
</tr>
<tr>
<td>Beam width at modulator, mm</td>
<td>0.94</td>
</tr>
<tr>
<td>Amplifier gain (Cold, infinitely wide), $g_{amp}$</td>
<td>200</td>
</tr>
<tr>
<td>RMS energy spread</td>
<td>1e-4</td>
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<tr>
<td>KV envelope norm. emittance, μm</td>
<td>8</td>
</tr>
<tr>
<td>Minimal beam width at PCA, mm</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Estimate Cooling Force for PCA-based CeC: Line density perturbation

Line density perturbation at the exit of the modulator:
\[ \hat{\rho}_0(z) = \frac{Z e^2}{4 \pi a_0^2} \int_{-\infty}^{\infty} \hat{\phi}(k_z) dk_z \]
\[ = \frac{Z e^2}{4 \pi a_0^2} \int_{-\infty}^{\infty} \frac{r \sin \tau}{a_z + \beta_z \tau} \hat{\phi}(k_z). \]

Line density perturbation at the exit of the Plasma-Cascade Amplifier:
\[ \hat{\rho}_z(k_z) = g_{amp}R_{amp}(k_z) \exp(-|k_z| \beta_z \frac{\Gamma_{amps}}{\gamma C}) \hat{\rho}_0(k_z). \]
Plasma Cascade Amplifier: Theory

Estimate Cooling Force for PCA-based CeC: Longitudinal Electric Field in the Kicker Section

The electric potential induced by the line density perturbation is determined by the following equations:

\[
\psi(r,z) = \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial \psi}{\partial r} (r,z) \right) + \frac{\partial^2}{\partial z^2} \psi(r,z) = \frac{1}{e_0} \rho_e(z) f_1(r)
\]

If we take the transverse distribution of the electrons as:

\[ f_1(r) = \frac{1}{\pi a^2} H(a - r) \]

The electric field can be solved as:

\[ E_z(r,z) = -\frac{\partial \psi}{\partial z} = \frac{1}{2\pi a} \int \hat{E}_z(r,k_z)e^{ik_z z}dk_z \]

For easy implementation into ion tracking code, we use the fitting formula:

\[ E_{z,\text{fit}}(z) = E_0 \cdot \left( 1 + \frac{z}{l_0} \right)^{-\frac{1}{2}} \]

Longitudinal location in lab frame (mm)  
Longitudinal electric field (V/m)  
\( l_0 = 124 W / m \)  
\( E_0 = 3.75 \mu m \)

Tolerance of PCA-based CeC on the noise of electron beam

\[
\Delta Y_{J,N} = -g_T \frac{D \cdot \delta_{J,N}}{\alpha_T} \left[ 1 + \frac{D \cdot \delta_{J,N}}{\alpha_T^2} \right]^{-3/2} + g_T \sqrt{\frac{3\pi}{8} \rho_{\text{mat}}(z,J,N)} \sigma_T \cdot Y_{J,N} + R_{\text{tot}} \sqrt{\frac{3\pi}{8} \rho_T(z,J,N)} \sigma_T \cdot Y_{J,N}
\]

Open Questions

- Theoretical 3-D model possible?
- Gain more insight in how PCA scheme react on longitudinal/transverse noises, together with simulation? Benchmark with the existing CEC @ RHIC experiment results?
Plasma Cascade Amplifier (Simulation)

**PCA for CeC**
- KV distribution
- Energy $\gamma = 28.5$, R.M.S. energy spread $\delta E/E = 2e^{-4}$
- Peak current 100 A
- Normalized envelope emittance 8 mm mrad, beam waist $a_0 = 2e^{-4}$ m
- Cell length 2 m

**Evolution of 2.5e+13 Hz signal**
(a) Entrance of PCA  
(b) At waist of 1st cell  
(c) Before waist of 2nd cell  
(d) After waist of 2nd cell  
(e) End of 3rd cell  
(f) Exit of PCA

- Electron at transverse edge fall behind the Central electrons, as they experience stronger solenoid field

- Start-to-end simulations of FEL based CeC has been performed, with detailed study of modulator section.
- Amplification of density modulation in the PCA has been demonstrated in numerical simulations.
- Preliminary start-to-end simulations of PCA based CeC has been conducted for center and off-center ions.
Density modulation for center ion

(a) Ion always there

(b) Ion always there

(c) Ion always there
Density modulation for center ion

(d) Ion moved at 1.2 m

(e) Ion moved at 1.2 m

(f) Ion moved at 1.2 m
Start-to-end Simulation of Beam Dynamics

Electron Linear Accelerator Simulation

Common section with RHIC

- Start to end electron beam dynamics simulation from photocathode to the common section
  - Each element is modeled with real geometry with measured fields
  - Lattice matching design (Dogleg and Common section)
- Collective effects
  - Space Charge effect (ASTRA/GPT/IMPACT-T/PARMELA)
  - Chromatic aberration and Coherent Synchrotron Radiation effect (ELEGANT)
- Demonstrate required electron beam can be generated using simulation
  - peak electron current (50 - 100A), slice Emittance < 5 micro, Energy spread~0.1%
  - Flat top longitudinal distribution
Comparison of measurements and simulations (long.)

To check beam's longitudinal distribution, we need to propagate beam to YAG in dogleg where dispersion function will couple energy variation to horizontal displacement. In addition, we vary the linac’s phase to compare the bunch pattern on dogleg YAG with simulation.

Multi-pacting (cont’d)

In simulation, we found different levels of multi-pacting are correspondent to SEY electrons trapped at different locations. When the cavity voltage increases, the multipacting zone is moving from corner of the cavity to the end of the cavity, causing less trouble in raising the voltage further.

By applying an abrupt strong RF power (max FPC insertion) to the cavity (pulsed thus not affecting vacuum), the multipacting is not fast enough to catch up with the RF power. Thus we were able to “jump” over MP zones. As soon as the RF voltage reaches to a level where we believe is safe, a tool developed by LLRF group will switch the RF pulse to CW for continuing operation.

Wakefields

By reducing solenoid strengths, we were able to generate a smooth transition in beam envelope in LEBT and the microbunching structure (in the frequency region of interest ~ 10 THz is greatly reduced.

Red curves show the frequency spectrum at the end of 704 MHz cavity for relaxed lattice. The low frequency structures represent the compressed electron bunch. Sharp spikes are numerical structures which are related to mesh size and integration time steps.

10 different types of wakes (cavities, bellows, BPMs, PMs, etc...) from after gun to after linac were simulated in ABCI/ECHO. Cross-checking was performed and calculated wakes were imported into IMPACT-T.
Concerns & Present Limitations

- Initial beam distribution in modulator is idealized
  – be careful about claiming "end to end" modeling
  – see comments (above) from Rui Li

- Micron-scale 3D beam structures
  – must be created, amplified and controlled
    - initial beam microstructures must be understood
    - 3D ES plasma dynamics must be understood (multiple approaches)
    - effects of e- beam energy structure must be understood
      – total $\Delta E/E$, slice $\Delta E/E$, interaction with dipoles
    - shot noise must be understood (and included, like SASE FEL)
    - numerical noise must be understood (and minimized)
    - does dipole dynamics disrupt micron-scale structures in other ways?
      – see next slide
  – timing with individual hadrons is critical
    - $R_{se}$ techniques $\Rightarrow$ e- beam energy must be well-controlled
      – very small $\Delta E$ of electrons will shift structure locations wrt hadrons

- Comments:
  - Rui Li: start-to-end modeling should be coupled into modulator
  - Vladimir Litvinenko: this may be computationally intractable

- Comments:
  - David Bruhwiler: To date, all modulator simulations reduce numerical noise (as much as possible) and ignore shot noise. I believe shot noise should be included.
  - Vladimir Litvinenko: Shot noise is understood

Summary

- BNL/Stony Brook team presented very good results
  - detailed simulations of accelerator
    - multiple codes, with benchmarking
    - quantitative comparison with experimental diagnostics
    - discovery of plasma cascade instability (PCI)
  - idealized simulations of FEL and PCI based CeC configurations

- Needs for future work have been identified
  - solutions still need to be developed

- Role of simulations on the road to EIC success
  - identify physics and engineering concerns
    - explore non-ideal issues to help establish requirements
  - support experimental demonstrations and EIC design
    - experimental demonstrations are essential

- External collaboration & alternate efforts are important
Session IV: CeC Experiment

CEC demonstration at BNL
Two possible signal amplification systems have been considered:
1) based on FEL amplification (studied during 2016-2018)
   a) three helical undulators with phase shifters and matching quadrupoles have been installed in common (cooling) section
2) based on plasma cascade amplification (planned)
   a) 7 strong focusing solenoids to be installed in cooling section

Accelerator System Commissioning
- The accelerator for CeC experiment consists of a 113 MHz SRF gun with a photocathode, two 500 MHz copper cavities, a 704 MHz SRF accelerator cavity, various focusing/corrector magnets and beam instrumentation.
- All elements of the experiment have been successfully commissioned during run 18 and provide beam quality required for CeC such as bunch charge, emittance, energy, energy spread, peak current and etc.
- Methods for energy and emittance measurement, trajectory correction, RF phasing, synchronization and characterization of the produced light were implemented.

Required electron beam parameters
- Normalized emittance < 5 mm mrad
- Relative energy spread $\sigma_E/E < 10^{-3}$
- Bunch charge 500 pC – 1.5 nC
- Repetition rate 1 Hz – 78 kHz
- R.m.s. bunch length 10-50 psec
- Peak current > 75 A
- Kinetic energy 14.5 MeV
- IR FEL wavelength 30 microns

Demonstrated electron beam parameters
- Normalized emittance 3 – 4 mm mrad
- Relative energy spread $\sigma_E/E < 3 \times 10^{-4}$
- Bunch charge 0.03 – 10.7 nC
- Repetition rate 1 Hz – 78 kHz
- R.m.s. bunch length 10 – 500 psec
- Kinetic energy 14.5 MeV

Electrons effects to ions has been observed
Top plot: electron beam current through the CeC ~ 110 μA or 1.4 nC per bunch at 78 kHz.
Bottom plots: evolution of the bunch lengths for interacting (blue trace) and witness bunches (orange and green traces).

Ions effect to electrons was not observed
Search for ion’s imprint

Expected and measured relative change in the FEL signal with overlapping and separated beams. Each point corresponds to 18 or more cycles of 20 FEL power measurements for overlapped and separated beams. Data analysis indicate RMS error of 2%.

Heating of ion beam was occurring only with a perfect overlap of the beams and high FEL gain. Reducing the FEL gain eliminated the heating.

Plans for PCA based CeC
- Shutdown jobs
  - Install new elements into the common section
  - Add IR diagnostics: two sets – one after DX magnet, another at low power dump
- Run 20
  - Establish electron beam operation in the background mode in parallel with RHIC operation
  - Optimize electron beam parameters
  - Establish high-current operation and demonstrate interaction with hadrons circulating in RHIC
- Demonstrate longitudinal cooling during Run 21
- Perform cooling experiments including transverse and/or 3D cooling during Run 22
LEBT 1.76 MeV e-beam

- PCI gain
- PCI @ 0.36 THz
- PCI @ 0.48 THz
- PCI @ 0.6 THz

PCI gain vs. s, m

- $a_x(s)$, mm
- $a_y(s)$, mm

113 MHz 1.25 MV SRF photo-gun with Photo-Cathode storage and exchange system

Profile monitor 4
- 704 MHz SRF linac
- 3 quads

FFT, a.u.

(a) 27 psec, 200 kV
(b) 54 psec, 100 kV
(c) Normalized density vs. t, psec
CeC PCA Beam Line

1. New water coated solenoids
2. Dipole gap modification
3. New Stands
4. New Profile Monitor
5. New BPM housing and buttons
6. 6 pairs of corrector magnets
7. New Y vacuum chamber for dipole
8. New NBO coated beam line vacuum chambers
9. New stand supports for magnets
10. New RF shielded boxes
11. New coaxial transitions to RHIC
12. New beam line supports
13. Water manifold for solenoids

Noise studies

PUZZLE: growth of the FEL power due to the interactions with hadrons has not been observed.

- Current understanding the problem: the beam instability due to Plasma Cascade Instability and/or overbunching.
- The development of the PCI was experimentally confirmed in the dedicated studies and methods for it suppression were developed.
- As a result of proper bunching cavities settings and solenoids in LEBT optimization the noise level sufficient for CEC demonstration using PCA has been achieved.

Conclusions (physics)

- Accelerator delivered the beam with parameters suitable for the CeC PoP experiment:
  - Electron normalized emittance as low as 0.3 mm mrad was measured
  - Relative energy spread 3x10^{-4} was demonstrated
- Two new methods for measuring beam trajectory vs. solenoid axis (position and angle) and energy utilizing solenoid were developed.
- We were unable to demonstrate the imprint of the hadrons on the electron beam due to the discovered plasma cascade instability and/or overbunching.
- The development of the PCI was experimentally confirmed in the dedicated studies and methods for it suppression were developed.
- The PCA based CeC system will be tested during Runs 20-22.
Comments and recommendation from general discussion:

Good Laser, good accelerator, and excellent diagnostics are the key. Any possible improvement in any of these systems should be considered.

Longitudinal beam quality is critical:
- Explore option to use deflecting cavity for longitudinal phase space tuning and slice emittance characterization.

Ion-electrons energy matching is critical:
- Magnetic measurements of dipoles after modification is recommended.
- Check if RHIC recombination signal could be used for better matching energies.

Consider to install set of quadrupoles in the common section for better matching beam envelopes.

Benchmarking ions heating observations during run 2018 with simulation is recommended.

In general potential heating mechanisms should not be overlooked.
Advantages and Disadvantages

- The best studied and fully explored scheme
- Experimentally demonstrated both as instability and amplifier
- 3D FEL theory and simulation are very advanced
- Can operate at relatively low electron beam peak currents
- Allows – in principle – economic option without separating electron and hadron beams

- When compared with micro-bunching amplifier, it has relatively lower bandwidth ~ few % of the FEL frequency
- FEL saturates at lower gain than micro-bunching amplifier
- Semi-periodic structure of the modulation limits the range where cooling occurs

CeC with High gain FEL amplifier
Advantages and Disadvantages

- Very broad band amplifier, can operate at significant gain without saturation
- Plasma-cascade micro-bunching instability was experimentally demonstrated
- Has good theoretical model and is extensively studied in 3D numerical simulations
- Cool hadrons with all energy deviation (no anti-cooling)
- Does not require (full) separation of electron and hadron beams

- Micro-bunching amplifier was not demonstrated
- Requires better quality electron beam than FEL amplifier
- Can operate for medium hadron energies (up to hundreds of GeV, such as US EIC), but can not be extended to LHC energies
- Less studied than FEL-based CeC

Plasma-Cascade Microbunching amplifier
Advantages and Disadvantages

- Very broad band amplifier
- Micro-bunching instability was experimentally demonstrated
- Can operate at significant gain without saturation and can be extended to LHC energies
- Ratner’s original scheme is - in principle - insensitive to longitudinal space charge effects in the electron beam

- Micro-bunching amplifier was not demonstrated
- Less studied – especially numerically in 3D - than other CeC schemes
- Requires electron beam with low energy spread
- Definitely require separation of electron and hadron beams

Multi-Chicane Microbunching amplifier