The Chilling Recount of an Unexpected Discovery:
First Observations of the Plasma-Cascade Instability
in the Coherent Electron Cooling Experiment

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August 1, 2019

Electron Ion Collider – eRHIC
1 Project Overview
2 Accelerator Performance
3 Experiment with FEL-based System and Unexpected Result
4 Plasma-Cascade Instability
5 Future Plans and Conclusions
What is Coherent electron Cooling?

**Short answer:** stochastic cooling of hadron beams with bandwidth at optical wave frequencies: 1-1000 THz.

**Long answer:**

![Diagram of coherent electron cooling process]

1. **Imprint by hadrons**
   - Hadrons
   - Electrons
   - Modulator: $2R_D$
   - $V_h$

2. **Amplification**
   - CeC central section
   - Electron-beam density amplifier and time-of-flight dispersion section for hadrons
   - $\gamma_e = \gamma_h$

3. **Momentum correction**
   - Kicker
   - $E < E_0$
   - $E > E_0$
   - $E_z$

---

**References:**

Vladimir N. Litvinenko¹ and Yaroslav S. Derbenev²

¹Brookhaven National Laboratory, Upton, Long Island, New York, USA
²Thomas Jefferson National Accelerator Facility, Newport News, Virginia, USA

(Received 24 September 2008; published 16 March 2009)
CeC Proof of Principle Experiment

**Goal:** demonstrate longitudinal cooling of a single Au$^{+79}$ bunch in the Relativistic Heavy Ion Collider.

**Common Section with RHIC**

<table>
<thead>
<tr>
<th>Component</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kicker</td>
<td></td>
</tr>
<tr>
<td>FEL Amplifier</td>
<td></td>
</tr>
<tr>
<td>Modulator</td>
<td></td>
</tr>
<tr>
<td>Dogleg</td>
<td></td>
</tr>
<tr>
<td>13.5 MV SRF linac</td>
<td></td>
</tr>
<tr>
<td>Low Energy Transport Beamline</td>
<td></td>
</tr>
<tr>
<td>Bunching RF cavities</td>
<td></td>
</tr>
<tr>
<td>1.25 MV SRF Photogun</td>
<td></td>
</tr>
</tbody>
</table>

**Required e-beam parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalized emittance, mm-mrad</td>
<td>&lt;5</td>
</tr>
<tr>
<td>Relative energy spread $\sigma_E/E$</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>Bunch charge, nC</td>
<td>0.5-1.5</td>
</tr>
<tr>
<td>Pulse repetition rate, kHz</td>
<td>78</td>
</tr>
<tr>
<td>RMS bunch length, ps</td>
<td>10-50</td>
</tr>
<tr>
<td>Peak current, A</td>
<td>&gt;75</td>
</tr>
<tr>
<td>Kinetic energy, MeV</td>
<td>14.5</td>
</tr>
<tr>
<td>FEL wavelength, $\mu$m</td>
<td>30</td>
</tr>
</tbody>
</table>

**CeC Accelerator**

**Hadron beam parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy, GeV/u</td>
<td>27</td>
</tr>
<tr>
<td>Intensity, hadron/bunch</td>
<td>$10^9$</td>
</tr>
<tr>
<td>RMS bunch length, ns</td>
<td>5</td>
</tr>
<tr>
<td>Revolution frequency, kHz</td>
<td>78</td>
</tr>
</tbody>
</table>

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113 MHz SRF gun with CsK$_2$Sb photocathode. Cathode operation—weeks.

- 532 nm drive laser.
- Two 500 MHz copper cavities for ballistic compression to the required peak current.
- 704 MHz SRF accelerator cavity.

**Demonstrated e-beam parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalized emittance, mm-mrad</td>
<td>3-4</td>
</tr>
<tr>
<td>Relative energy spread $\sigma_E/E$</td>
<td>$3 \times 10^{-4}$</td>
</tr>
<tr>
<td>Bunch charge, nC</td>
<td>0.03-10.7</td>
</tr>
<tr>
<td>Pulse repetition rate, kHz</td>
<td>78</td>
</tr>
<tr>
<td>RMS bunch length, ps</td>
<td>10-500</td>
</tr>
<tr>
<td>Kinetic energy, MeV</td>
<td>14.5</td>
</tr>
</tbody>
</table>
113 MHz SRF gun with warm CsK$_2$Sb photocathode

Operating temperature, K: 4
CW voltage, MV: 1.25
Maximal charge, nC: 10.7

Normalized emittance for a 600 pC, 400 ps e-beam

- Projected emittance, mm-mrad: 0.57
- Slice emittance, mm-mrad: 0.35
Achieved parameters of the $e^-$ beam.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design</th>
<th>Status</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Species in RHIC (GeV/u)</td>
<td>$Au^{+79}$ 40</td>
<td>$Au^{+79}$ 26.5</td>
<td>to match e-beam</td>
</tr>
<tr>
<td>Electron energy (MeV)</td>
<td>21.95</td>
<td>14.56</td>
<td>linac quench</td>
</tr>
<tr>
<td>Charge per e-bunch (nC)</td>
<td>0.5-5</td>
<td>0.1-10.7</td>
<td>✓</td>
</tr>
<tr>
<td>Peak current (A)</td>
<td>100</td>
<td>50-100</td>
<td>✓</td>
</tr>
<tr>
<td>Bunch duration (psec)</td>
<td>10-50</td>
<td>12</td>
<td>✓</td>
</tr>
<tr>
<td>Normalized emittance ($\mu m$)</td>
<td>&lt;5</td>
<td>3-5</td>
<td>✓</td>
</tr>
<tr>
<td>Energy spread, RMS (%)</td>
<td>0.1</td>
<td>0.1</td>
<td>✓</td>
</tr>
<tr>
<td>FEL wavelength ($\mu m$)</td>
<td>13</td>
<td>31</td>
<td>new IR diagnostics</td>
</tr>
<tr>
<td>Repetition rate (kHz)</td>
<td>78.18</td>
<td>78.18</td>
<td>✓</td>
</tr>
<tr>
<td>CW beam ($\mu A$)</td>
<td>&lt;400</td>
<td>150</td>
<td>✓</td>
</tr>
</tbody>
</table>
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.

\[
R = \frac{I_{\text{overlap}} - I_{\text{separated}}}{I_{\text{separated}}}
\]
Bunch spectra have demonstrated a broadband PCI gain peaking at $\sim 0.4$ THz in an uncompressed beam.

Bunched beam spectrum has a peak at 10 THz.

The measurements were confirmed through simulations done by SPACE and Impact-T.
Plasma-Cascade Instability

longitudinal plasma oscillation with periodically varying plasma frequency:

\[ \ddot{n}'' + \omega_p^2(s) \dot{n} = 0 \]

\[ \hat{a}'' - k_{sc}^2 \hat{a} - k_{\beta}^2 \hat{a}^{-3} = 0, \quad \ddot{n}'' + 2k_{sc}^2 \hat{a}^{-2} \dot{n} = 0. \]

\[ \hat{a} = \frac{a}{a_0}, \quad \hat{s} = \frac{s}{l} \in \{-1, 1\} \]

\[ k_{sc} = \sqrt{\frac{2}{\beta^3 \gamma^3 I_0} \frac{l^2}{I_a a_0^2}}, \quad k_{\beta} = \frac{\varepsilon l}{a_0^2} \]
Goal of 2019

Demonstrate generation of electron beam with parameters satisfying or exceeding requirements for the CeC demonstration experiment.

- As a result of optimization we were able to achieve the IR signal only factor two above shot noise level.
- The optimized set-up has rather flat response of the noise on the variation of the solenoid current leaving sufficient headroom for optimizing other beam parameters.
PCI applications $\rightarrow$ ACeC

Changing CeC amplifier: FEL $\rightarrow$ PCA

- Mechanical design of the new CeC system is completed.
- New laser system is procured and commissioned.
- All new vacuum chambers with beam diagnostics are built and installed.
- All solenoids are designed, manufactured, delivered and underwent magnetic measurements.
- Assembly of the ACeC can be completed during this year.
Conclusions

- Accelerator delivered the beam with parameters suitable for the CeC PoP experiment:
  - Normalized emittance as low as 0.35 mm-mrad for a 600 pC bunch was measured.
  - Relative energy spread $3 \times 10^{-4}$ was demonstrated.
- We were unable to demonstrate the imprint of the hadrons on the electron beam due to the discovered Plasma-Cascade Instability.
- The development of the PCI was experimentally confirmed in the dedicated studies, and methods for its suppression were developed.
- The PCA-based CeC system will be tested during Runs 20-22.
Thank you for your attention!
Plasma-Cascade Instability (PCI)

Plasma-Cascade Instability

Longitudinal plasma oscillation with periodically varying plasma frequency:

\[ \ddot{n}'' + \omega_p^2(s)\dot{n} = 0 \]

\[ \hat{a}'' - k_{sc}^2 \hat{a}^{-1} - k_\beta^2 \hat{a}^{-3} = 0, \quad \hat{n}'' + 2k_{sc}^2 \hat{a}^{-2} \dot{n} = 0. \]

\[ \hat{a} = \frac{a}{a_0}, \quad \hat{s} = \frac{s}{l} \in \{-1, 1\} \]

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\[ \hat{a}'' - k_{sc}^2 \hat{a}^{-1} - k_\beta^2 \hat{a}^{-3} = 0, \quad \hat{n}'' + 2k_{sc}^2 \hat{a}^{-2} \dot{n} = 0. \]

FODO

Betatron motion in a FODO cell:

\[ y'' + K_y(s)y = 0 \]

\[ M = \begin{bmatrix} 1 & 0 & 1 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 1 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 + \frac{L_1}{f_2} - \frac{L_1}{f_1} - \frac{L_1^2}{f_1 f_2} & \frac{2L_1}{2f_2} & 
\frac{1}{f_2} - \frac{1}{f_1} & \frac{L_1}{f_1 f_2} & \frac{L_1^2}{4f_1^2 f_2} & 1 + \frac{L_1}{f_2} - \frac{L_1}{f_1} - \frac{L_1^2}{f_1 f_2} \end{bmatrix} \]
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
What is cooling and why do we need it?

**Luminosity** characterizes the ability of a particle accelerator to produce the required number of interactions:

\[
\frac{dN}{dt} = \sigma \cdot L
\]  

\[
L = \frac{N_1 \times N_2 \times \text{frequency}}{\text{Overlap Area}} = \frac{N_1 \times N_2 \times f_{\text{coll}}}{4\pi \beta^* \varepsilon} \times h\left(\frac{\sigma_s}{\beta^*}\right)
\]

We want to have a large charge per bunch, high collision frequency and small spot size!

**Cooling:**

reduces beam phase space volume, emittance and momentum spread in order to improve beam quality.
CeC scheme is based on electrostatic interactions between electrons and hadrons that are amplified either in a high-gain FEL or by other means.

The electron and hadron beams co-propagate in a vacuum along a straight line in the modulator and kicker with the same velocity:

\[ \gamma = \frac{E_e}{m_e c^2} = \frac{E_h}{m_h c^2} \]
Coherent electron Cooling (CeC): Kicker

When the hadron and electron beams are recombined, hadrons are exposed to the longitudinal electric field.

With a proper delay section, a hadron with central energy $E_0$ arrives at the kicker on top of the electron density peak—zero electric field.

Hadrons with higher energy are decelerated, and ones with lower energy are pulled forward.
### Coherent electron Cooling: Proof of Principle

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gun energy, MeV</td>
<td>1.25</td>
</tr>
<tr>
<td>Beam charge, nC</td>
<td>1-5</td>
</tr>
<tr>
<td>Final beam energy, MeV</td>
<td>14.6</td>
</tr>
<tr>
<td>Normalized emittance, mm-mrad</td>
<td>&lt;5</td>
</tr>
<tr>
<td>Energy spread</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>Pulse repetition rate, kHz</td>
<td>78</td>
</tr>
</tbody>
</table>

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![Diagram of Coherent electron Cooling system](image-url)

**Note:**
- IR diagnostics
- CeC "kicker" 4 quads
- CeC FEL amplifier 3 helical wigglers
- CeC modulator 4 quads
- High power beam dump 1 dipole, 2 quads
- Low power beam dump
- Common section with RHIC
- 1.25 MV SRF photo-gun and cathode manipulation system
Coherent electron Cooling: Proof of Principle

- $e^-$ beam is generated by 113 MHz SRF gun with CsK$_2$Sb photocathode driven by a 532 nm laser.

- Two 500 MHz copper cavities provide energy chirp and beam is compressed to desired peak current.

- After the compression beam is accelerated by a 704 MHz SRF cavity and merged into CeC PoP structure with three helical undulators.
**Coherent electron Cooling: Proof of Principle**

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SRF photoinjectors—challenging, but rewarding creations

Pros:
- Good vacuum inside Nb cavity at 2K/4K
- Relatively high accelerating gradients
- CW operation

Cons/Questions:
- Are high-QE cathodes compatible with SRF?
- Can high-QE cathodes survive in an SRF cavity?
- How to keep cathodes at room temperature without causing multipacting (MP)?
- How to get to operational voltage without causing MP and killing cathode?
- Dark current?

It is expensive and challenging—hence, there are very few operational SRF guns!
### Overview of existing SRF photoinjectors

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CeC PoP</th>
<th>FZD¹</th>
<th>HZB²</th>
<th>NPS³</th>
<th>UW⁴</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity type</td>
<td>QWR*</td>
<td>Elliptical</td>
<td>Elliptical</td>
<td>QWR</td>
<td>QWR</td>
</tr>
<tr>
<td>Number of cells</td>
<td>1</td>
<td>3.5</td>
<td>1.4</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>RF frequency, MHz</td>
<td>113</td>
<td>1300</td>
<td>1300</td>
<td>500</td>
<td>200</td>
</tr>
<tr>
<td>LiHe Temperature, K</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Beam energy, MeV</td>
<td>1.25-1.5</td>
<td>3.3</td>
<td>1.8</td>
<td>0.47</td>
<td>1.1</td>
</tr>
<tr>
<td>Charge per bunch, nC</td>
<td>10.7</td>
<td>0.3</td>
<td>0.006</td>
<td>0.078</td>
<td>0.1</td>
</tr>
<tr>
<td>Beam current, μA</td>
<td>150</td>
<td>18</td>
<td>0.005</td>
<td>&lt;0.0001</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Dark current, nA</td>
<td>&lt;1</td>
<td>120</td>
<td>-</td>
<td>&lt;20, 000</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>$E_{cath}$, MV/m</td>
<td>10-20</td>
<td>5</td>
<td>7</td>
<td>6.5</td>
<td>12</td>
</tr>
<tr>
<td>Photocathode</td>
<td>CsK₂Sb</td>
<td>Cs₂Te</td>
<td>Pb</td>
<td>Ni</td>
<td>Cu</td>
</tr>
</tbody>
</table>

*QWR—Quarter Wave Resonator


CeC PoP SRF gun with warm CsK$_2$Sb photocathode

- Quarter-wave cavity.
- 4 K operating temperature.
- 4 kW CW solid state power amplifier.
- CsK$_2$Sb cathode is at room temperature.
- Up to three cathodes can be stored in garage for quick exchange.
- Design gradient 22.5 MV/m.
The gun can generate electron bunches with charge per bunch exceeding 10 nC (saturated the diagnostics).

During the first years of operation the gun was affected by multipacting.
Definition of multipacting
Definition of multipacting
Definition of multipacting

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Definition of multipacting
MP Simulations: Affected Areas & Influence of B-Field

CST Particle Studio

ACE3P (Track3P)

- 28 kV
- 40 kV

Graphs showing the comparison of enhancement counter with and without the magnetic field for different gun voltages.

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Multipacting Well Studied and Understood Now

\[ \begin{align*}
    V_1, I_1 & \\
    V_2, I_2 & \rightarrow I_3
\end{align*} \]

\[ \begin{align*}
    dV_c &= \frac{1}{2\tau} (|V_0| - |V_c|) - f_0 \delta V_{mp} e N_e(t) \frac{e N_e(t)}{2 Q_0 |V_c|} \omega_0 R_{sh}, \\
    dN_e &= \alpha(|V_c|) N_e.
\end{align*} \]

1 : k

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PHYSICAL REVIEW ACCELERATORS AND BEAMS 21, 082001 (2018)

Mitigation of multipacting in 113 MHz superconducting rf photoinjector

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2Collider-Accelerator Department, Brookhaven National Laboratory, Upton, New York 11973, USA

(Received 28 February 2018; published 13 August 2018)
Example of Cavity Turn On Attempt with Strong MP

- Lengthen period between attempts from $\sim 20$ min to $\sim 40$ min $\Rightarrow 5^{th}$ attempt $=$ successful turn on.
- Cathode QE not impacted by turn on attempts as MP related vacuum activity is kept minimal.

- Four repeated attempts to turn on result in getting stuck at 22 kV MP barrier.
- Attempts last only 20 ms, controlled by LLRF MP trap code.
- Prevents significant energy deposition $\Rightarrow$ vacuum activity which would kill cathode QE.
Challenges of the beam dynamics simulations in the gun

- Traditional simulations tools (PARMELA, GPT, ASTRA, BMAD, IMPACT-T) have a difficulty to properly simulate beam dynamics inside the SRF gun.
- There is no problem to perform simulations outside of the gun, but the challenge is in grasping the details of the environment in the cathode vicinity.
- **Goal**: utilize Particle In Cell (PIC) codes dedicated to such problems, and use the resulting distribution in the start-to-end simulations.
The equations of motion used for the simulations:

\[
\frac{d\vec{r}}{dt} = \frac{\vec{p}}{m\gamma}, \quad \frac{d\vec{p}}{dt} = q \left( \vec{E} + \frac{\vec{p}}{m\gamma} \times \vec{B} \right).
\]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CST PS</th>
<th>Pic3P</th>
<th>GPT</th>
<th>IMPACT-T</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Equations solved</strong></td>
<td>Maxwell</td>
<td>Maxwell</td>
<td>Poisson</td>
<td>Poisson</td>
</tr>
<tr>
<td>Wakefields</td>
<td>✓</td>
<td>✓</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Space charge</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Retardation effects</td>
<td>✓</td>
<td>✓</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Image charge</td>
<td>Real geometry</td>
<td>Real geometry</td>
<td>Flat wall</td>
<td>Flat wall</td>
</tr>
<tr>
<td><strong>Field distribution</strong></td>
<td>CST MWS</td>
<td>Omega3P</td>
<td>SUPERFISH (map)</td>
<td>SUPERFISH ((E_z))</td>
</tr>
<tr>
<td>Transverse particle distribution</td>
<td>Area/Circular</td>
<td>Uniform</td>
<td>Uniform</td>
<td>Uniform</td>
</tr>
<tr>
<td>Longitudinal particle distribution</td>
<td>Truncated Gaussian</td>
<td>Uniform</td>
<td>Uniform</td>
<td>Uniform</td>
</tr>
<tr>
<td><strong>Performance</strong></td>
<td>Intel Core i7 (8 CPU)</td>
<td>NERSC</td>
<td>Intel Core i7 (8 CPU)</td>
<td>Intel Core i7 (8 CPU)</td>
</tr>
<tr>
<td>Duration</td>
<td>1 week</td>
<td>1 day</td>
<td>1 day</td>
<td>5 hours</td>
</tr>
</tbody>
</table>

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Comparison with the experiment

- Turn off the bunching cavities
- Scan LEBT 1 solenoid at a fixed value of the gun solenoid
- Measure the RMS beam size at YAG 1.
Emittance, $\varepsilon$:

measure of the area $A$ occupied by a beam in phase space.

\[
\varepsilon = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2}, \text{ with }
\]

\[
\langle x^2 \rangle = \sigma_x^2 = \frac{1}{N} \sum_{i=1}^{N} (x_i - \langle x \rangle)^2,
\]

\[
\langle x'^2 \rangle = \sigma_{x'}^2 = \frac{1}{N} \sum_{i=1}^{N} (x'_i - \langle x' \rangle)^2,
\]

\[
\langle xx' \rangle = \sigma_{xx'} = \frac{1}{N} \sum_{i=1}^{N} (x_i - \langle x \rangle)(x'_i - \langle x' \rangle).
\]

Normalized emittance, $\varepsilon_n$:

\[
\varepsilon_n = \varepsilon \gamma \beta,
\]

with relativistic parameters $\beta$ and $\gamma$ defined by the energy of the beam.
Slice emittance & Emittance compensation

- Slices have different emittance and ellipse orientation;
- Variation in the ellipse orientation leads to a high projected emittance;
- Projected emittance can be reduced by the alignment of the slices.
How to measure emittance

Matrix of a solenoid:

\[
F = \begin{pmatrix} 1 & 0 \\ 1/f_{\text{sol}} & 1 \end{pmatrix}, \quad 1/f_{\text{sol}} = \int \left( \frac{eB_s}{2pc} \right)^2 ds
\]

Solenoid+drift:

\[
M = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 1/f_{\text{sol}} & 1 \end{pmatrix} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix}
\]

Beam matrix:

\[
\Sigma_{\text{beam}} = \begin{pmatrix} \sigma_x^2 & \sigma_{xx'} \\ \sigma_{xx'} & \sigma_{x'}^2 \end{pmatrix}
\]

\[
\sigma_b^2 = m_{11}^2 \sigma_x^2 + 2m_{11}m_{12}\sigma_{xx'} + m_{12}^2 \sigma_{x'}^2
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\[
\sigma_b^2 = \varepsilon(m_{11}^2\beta_0 - 2m_{11}m_{12}\alpha_0 + m_{12}^2 \frac{1 + \alpha_0^2}{\beta_0})
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How to measure emittance

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How to measure emittance

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How to measure emittance

**Matrix of a solenoid:**

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\[ \sigma_b^2 = m_{11}^2 \sigma_x^2 + 2m_{11}m_{12}\sigma_{xx'} + m_{12}^2 \sigma_{x'}^2 \]

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How to measure emittance

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\[ \sigma_b^2 = \varepsilon(m_{11}^2\beta_0 - 2m_{11}m_{12}\alpha_0 + m_{12}^2 \frac{1 + \alpha_0^2}{\beta_0}) \]
Emittance measurements

For a 100 pC e-beam we can achieve a core slice emittance as low as 0.15 mm-mrad.

The best normalized RMS emittance achieved for 600 pC was 0.57 mm-mrad with core slice emittance of 0.35 mm-mrad.
Emittance Measurements

- $\varepsilon_x$ @ YAG1 with LEBT1
- $\varepsilon_y$ @ YAG1 with LEBT1
- $\varepsilon_x$ @ YAG2 with LEBT3
- $\varepsilon_y$ @ YAG2 with LEBT3
- $\varepsilon_{\text{min}}$ @ YAG1 with LEBT1 manual
- $\varepsilon_{\text{min}}$ @ YAG2 with LEBT3 manual
- $\varepsilon_{\text{min}}$ @ YAG1 with Gun Sol manual

Normalized RMS emittance (mm-mrad) vs. Charge (pC)

Irina Petrushina (SBU)
What did we learn about our photoinjector?

- We have demonstrated the record parameters for the SRF CW gun both in charge per bunch and transverse emittance.
- Photocathode at room temperature have high QE.
- Low frequency of the gun allows to generate electron beam close to conditions in a DC gun and fully utilize available field gradient.
- Good vacuum inside SRF gun provides long lifetime for the cathode.
- Multipacting is no longer a challenge.
Achieved parameters of the $e^-$ beam.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design</th>
<th>Status</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Species in RHIC (GeV/u)</td>
<td>$Au^{+79}$ 40</td>
<td>$Au^{+79}$ 26.5</td>
<td>to match e-beam</td>
</tr>
<tr>
<td>Electron energy (MeV)</td>
<td>21.95</td>
<td>14.56</td>
<td>linac quench</td>
</tr>
<tr>
<td>Charge per e-bunch (nC)</td>
<td>0.5-5</td>
<td>0.1-10.7</td>
<td>✓</td>
</tr>
<tr>
<td>Peak current (A)</td>
<td>100</td>
<td>50-100</td>
<td>✓</td>
</tr>
<tr>
<td>Bunch duration (psec)</td>
<td>10-50</td>
<td>12</td>
<td>✓</td>
</tr>
<tr>
<td>Normalized emittance ($\mu m$)</td>
<td>&lt;5</td>
<td>3-5</td>
<td>✓</td>
</tr>
<tr>
<td>Energy spread, RMS (%)</td>
<td>0.1</td>
<td>0.1</td>
<td>✓</td>
</tr>
<tr>
<td>FEL wavelength ($\mu m$)</td>
<td>13</td>
<td>31</td>
<td>new IR diagnostics</td>
</tr>
<tr>
<td>Repetition rate (kHz)</td>
<td>78.18</td>
<td>78.18</td>
<td>✓</td>
</tr>
<tr>
<td>CW beam ($\mu A$)</td>
<td>&lt;400</td>
<td>150</td>
<td>✓</td>
</tr>
</tbody>
</table>
Plan for the CeC PoP demonstration experiment:

1. Establish the required transverse overlap of the electron and ion beams.
2. Synchronize the electron and ion beams to achieve longitudinal overlap.
3. Confirm the interaction of the beams in the modulator by measuring the FEL power.
4. Adjust the energy of the electron beam to match the ion beam energy based on the FEL signal.
5. Establish interaction between the bunches and observe the ion beam evolution in time to test the CeC.
Confirm interaction of the beams in the modulator section is a significant increase in the FEL power.

\[ R = \frac{I_{\text{overlap}} - I_{\text{separated}}}{I_{\text{separated}}} \]
Confirm interaction of the beams in the modulator

Indicator of the ion and electron beam interactions in the modulator section is a significant increase in the FEL power.

$$R = \frac{I_{overlap} - I_{separated}}{I_{separated}}$$
Possible reasons to investigate

1. Energy difference between the ion and electron beams was larger than 3%.
2. Transverse overlap between the bunches was reduced and therefore was insufficient for the interaction.
3. FEL was operating in saturation.
4. High initial noise level in the electron beam was present.
Possible reasons to investigate

1. Energy difference between the ion and electron beams was larger than 3%.

The measurements of the energy were repeated independently:

- Energy of the electron beam was reported as requested for the experiment with a ±1% relative error;
- Energy measurement of the ion beam in RHIC was performed with a ±0.1% accuracy;
- The energy difference between the beams could not be larger than ±1%;
- The ion imprint experiment was performed in a wide (±2.5%) range of energies.
Possible reasons to investigate

1. Energy difference between the ion and electron beams was larger than 3%.
2. Transverse overlap between the bunches was reduced and therefore was insufficient for the interaction.
3. FEL was operating in saturation.
4. High initial noise level in the electron beam was present.
Possible reasons to investigate: slice emittance

2 Transverse overlap between the bunches was reduced and therefore was insufficient for the interaction.

- Operate the 704 MHz cavity \( \sim 15^\circ \) off-crest;
- Propagate the beam with the introduced energy spread through the main dipole;
- Observe the desired longitudinal beam profile.

To measure the slice emittance, utilize the quadrupole located at the point of zero dispersion, and perform a quadrupole scan for various phases of the linac.
Possible reasons to investigate: slice emittance

- For every quadrupole setting, record the corresponding beam profile.
- Slice all of the profiles.
- For each slice plot square of the RMS beam size as a function of the quadrupole strength.
- Fit the data to calculate the emittance.

The slice emittance in the central part of the beam doesn’t show any variations which could have led to a reduction of the ion imprint.
Possible reasons to investigate

1. Energy difference between the ion and electron beams was larger than 3%.

2. Transverse overlap between the bunches was reduced and therefore was insufficient for the interaction.

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4. High initial noise level in the electron beam was present:
   - Modulation in e-beam induced by structures in the drive laser pulse.
   - Longitudinal instability driven by wake fields induced by components of vacuum chambers and RF cavities
   - Instability in dogleg driven by coherent synchrotron radiation in dogleg.
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Wakefields

Wake potential in the elements of the laser cross and buncher assembly.

- The simulations showed a good agreement between the two codes.
- Wake fields were calculated for every element of the CeC beam line.
- The highest amplitude of the wake field was observed at the transition between the two bunching cavities.
IMPACT-T simulations performed by Dr. Yichao Jing showed that introduction of the wake fields into the simulation didn’t result in a significant change of the beam dynamics in the system.

RMS beam size in the LEBT section with and without wake fields.

Longitudinal phase space at the exit of the 5-cell cavity.
Possible reasons to investigate

1. Energy difference between the ion and electron beams was larger than 3%.

2. Transverse overlap between the bunches was reduced and therefore was insufficient for the interaction.

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?
First observations of PCI

Time profiles showing the dependence of the time resolution on the linac voltage.

Dependence of the dipole radiation on focusing by LEBT 5 solenoid: 7800 bunches, 0.6 nC/bunch:

$I_{sol} = 3.625$ A

$I_{sol} = 3.675$ A

Pyroelectric detector signal (yellow)
ICTs signals are cyan and magenta

Pyroelectric detector signal (yellow)
ICTs signals are cyan and magenta
Time profiles of 1.75 MeV electron bunches with charge per bunch from 0.45 nC to 0.7 nC were measured.

Compared the spectra of measured bunch density modulation and PCI spectrum simulated by Dr. Jun Ma with SPACE.
Plasma-Cascade Instability (PCI)

Propagating beam experiences density modulation with period of \( T = \frac{2l}{\gamma v} \):

\[
n_0(s) = \frac{I}{ev} \frac{1}{\pi a^2(s)}
\]

**Cold beam model:**

\[
n(s, t) = n_0(s) (1 + \tilde{\eta}(s, t))
\]

\[
\frac{\partial n}{\partial t} + \nabla \cdot (n\vec{v}) = 0
\]

\[
\frac{d^2 \tilde{\eta}}{ds^2} + k_p^2(s) \tilde{\eta} = 0, \quad \text{with} \quad k_p^2(s) = \frac{4\pi e^2 n_0(s)}{\gamma \gamma_z^2(s) m v^2}
\]

\[
\frac{d^2 \hat{a}}{ds^2} - \frac{k_{sc}^2}{\hat{a}} - \frac{k_{\beta}^2}{\hat{a}^3} = 0, \quad \frac{d^2 \tilde{q}_k}{ds^2} + \frac{2k_{sc}^2}{\hat{a}^2} \tilde{q}_k = 0.
\]

\[
\hat{a} = \frac{a}{a_0}, \quad \hat{s} = \frac{s}{l}
\]

\[
k_{sc} = \sqrt{\frac{2}{\beta^3 \gamma^3}} \frac{I_0}{I_a} \frac{l^2}{a_0^2}, \quad k_{\beta} = \frac{\varepsilon l}{a_0^2}
\]
PCI suppression

Dr. Yichao Jing has shown through the IMPACT-T simulations that the PCI can be suppressed by the choice of lattice.

During the Run 2019 we were able to demonstrate the ability of having a quite beam.
Mechanical design of the new CeC system is completed.

New laser system is procured and commissioned.

All new vacuum chambers with beam diagnostics are built and installed.

All solenoids are designed, manufactured, delivered and underwent magnetic measurements.

Assembly of the ACeC can be completed during this year.
Conclusions

- Accelerator delivered the beam with parameters suitable for the CeC PoP experiment:
  - Electron normalized emittance as low as 0.35 mm-mrad was measured
- We were unable to demonstrate the imprint of the hadrons on the electron beam due to the discovered Plasma Cascade Instability
- PCI was experimentally confirmed in the dedicated studies and methods for its suppression were developed
- The PCI will be utilized for the advanced CeC system

V.N. Litvinenko et.al., *Coherent Electron Cooling Demonstration Experiment*, IPAC’11, San Sebastian, Spain, 2011;

S. Belomestnykh et.al., *SRF and RF systems for CeC PoP experiment*, NAPAC’13 Pasadena, CA, 2013;

I. Pinayev et.al., *First results of the SRF gun test for CeC PoP*, IPAC’16, Busan, Korea, 2016;

I. Pinayev et.al., *Commissioning of the CeC PoP accelerator*, NAPAC’16, Chicago, IL, 2016;

S. Belomestnykh et.al., *Commissioning of the 112 MHz SRF gun*, SRF2015, Canada, 2015;

I. Pinayev et.al., *Performance of CeC PoP Gun During Commissioning*, NAPAC’16, Chicago, IL, 2016;

H. Padamsee, *RF Superconductivity*, 2009;

IR Diagnostics during Run19

- Utilized high-sensitivity CCD camera for the dogleg profile monitor.
- YAG was removed from low-power dump profile monitor. Viewport was replaced with CVD diamond window. IR detector was installed. Mesh was installed to suppress THz radiation.

1" CVD diamond window covered with 1.4 mm x 1.4 mm metal mesh to suppress GHz radiation.
Baseline (shot noise level) measurements

The base line was measured for modestly (4-fold) compressed beam with 1.5 and 0.3 nC charges per bunch in relaxed LEBT lattice. Averaged over 4 long scans the lock-in amplifier MDM signal was 105 V/C (24 μW/A) with RMS error of 15 V/C (3 μW/A).

This value is at 40% level of synchrotron radiation that reaches the Cu mirror.
LEBT Optimization

As a result of optimization we were able to achieve the FIR signal only factor two above shot noise level. The optimized set-up has rather flat response of the noise on the variation of the solenoid current leaving sufficient headroom for optimizing other beam parameters.
Thorough investigation of multipacting in the 113 MHz photoinjector through the simulations and experiment.

Comprehensive study of beam dynamics in the photoinjector.

Beam dynamics simulations in the CeC accelerator.

Analysis of wake fields in the CeC beamline.

Participation in the CeC PoP commissioning.
Linac phase scan
Parameters of the beam.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Charge, nC</td>
<td>0.5</td>
</tr>
<tr>
<td>Initial Velocity, $\beta_z$</td>
<td>0.003</td>
</tr>
<tr>
<td>Type of radial Distribution</td>
<td>Uniform</td>
</tr>
<tr>
<td>Radius, mm</td>
<td>1.5</td>
</tr>
<tr>
<td>Type of Longitudinal Distribution</td>
<td>Flat Top</td>
</tr>
<tr>
<td>Duration of the flat top, ns</td>
<td>0.5</td>
</tr>
<tr>
<td>Rise/Drop time, ns</td>
<td>0.005</td>
</tr>
</tbody>
</table>
## Back-Up: Summary of the SRF guns

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Elliptical Cavity + NC cathodes</th>
<th>DC-SC</th>
<th>Quarter Wave SRF guns</th>
<th>Elliptical Cavity + SC cathodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam kinetic energy, $V_c$</td>
<td>$\text{MeV}$</td>
<td>$9.4$</td>
<td>$2$</td>
<td>$\leq 3.5$</td>
</tr>
<tr>
<td>Max bunch charge, $Q_{\text{max}}$</td>
<td>$\text{nC}$</td>
<td>$1 / 0.077$</td>
<td>$5 / 0.7$</td>
<td>$0.077$</td>
</tr>
<tr>
<td>Norm. trans. emittance, $\beta_{\text{nl}}$</td>
<td>$\text{mm mrad}$</td>
<td>$2.5 / 1$</td>
<td>$5 / 1.4$</td>
<td>$1$</td>
</tr>
<tr>
<td>Average beam current, $I_b$</td>
<td>$\text{mA}$</td>
<td>$1 / 0.5$</td>
<td>$50 / 500$</td>
<td>$100$</td>
</tr>
<tr>
<td>Peak current, $I_{\text{pk}}$</td>
<td>$\text{A}$</td>
<td>$67 / 20$</td>
<td>$166 / 70$&lt;sup&gt;(10)&lt;/sup&gt;</td>
<td>$4$</td>
</tr>
<tr>
<td>Photocathode</td>
<td></td>
<td>$\text{Cs}_2\text{Te}$</td>
<td>$\text{CsK}_2\text{Sb}$</td>
<td>$\text{CsK}_2\text{Sb}$</td>
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<tr>
<td>Quantum efficiency, Q.E.</td>
<td>$%$</td>
<td>$1$</td>
<td>$18$</td>
<td>$10$</td>
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<tr>
<td>Driving laser wavelength, $\lambda$</td>
<td>$\text{nm}$</td>
<td>$263$</td>
<td>$355$</td>
<td>$527$</td>
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<tr>
<td>Pulse duration (FWHM)</td>
<td>$\text{ps}$</td>
<td>$15 / 4$</td>
<td>$30 / 20$&lt;sup&gt;(10)&lt;/sup&gt;</td>
<td>$\leq 20$</td>
</tr>
<tr>
<td>Bunch repetition rate, $f_{\text{rep}}$</td>
<td>$\text{MHz}$</td>
<td>$0.5 / 13$</td>
<td>$10 / 704$</td>
<td>$\leq 1300$</td>
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<tr>
<td>Gun frequency, $f_0$</td>
<td>$\text{MHz}$</td>
<td>$1300$</td>
<td>$703.75$</td>
<td>$1300$</td>
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<tr>
<td>Operating temperature</td>
<td>$K$</td>
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<td>$2$</td>
<td>$2$</td>
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<tr>
<td>Dissipated power, $P_{\text{dis}}$</td>
<td>$W$</td>
<td>$26$</td>
<td>$4.2$</td>
<td>$12.1$&lt;sup&gt;(1)&lt;/sup&gt;</td>
</tr>
<tr>
<td>at the intrinsic $Q_0$ of</td>
<td></td>
<td>$@ 1 \times 10^{10}$</td>
<td>$@ 1 \times 10^{10}$</td>
<td>$@ 1 \times 10^{10}$</td>
</tr>
<tr>
<td>Active cavity length, $l_{\text{act}}$</td>
<td>$\text{cm}$</td>
<td>$50$</td>
<td>$9.5$</td>
<td>$17.1$</td>
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<tr>
<td>$R_{\text{shunt}} / Q_{\text{sh}}$ (from acc. def.)</td>
<td>$\Omega$</td>
<td>$334$</td>
<td>$96$</td>
<td>$95.2^b$</td>
</tr>
<tr>
<td>Transit time factor, $V_c / V_0$</td>
<td>$\text{TTF}$</td>
<td>$0.715$</td>
<td>$0.888$&lt;sup&gt;(3)&lt;/sup&gt;</td>
<td>$0.54$&lt;sup&gt;(1)&lt;/sup&gt;</td>
</tr>
<tr>
<td>Stored energy at $E_{\text{sh}}$, $U$</td>
<td>$J$</td>
<td>$32.4$</td>
<td>$8.4 / 9.5^a$</td>
<td>$14.8$&lt;sup&gt;(1)&lt;/sup&gt;</td>
</tr>
<tr>
<td>Electric cathode field $E_{\text{sh,c}}$</td>
<td>$\text{MV/m}$</td>
<td>$30$</td>
<td>$20$</td>
<td>$\geq 10$</td>
</tr>
<tr>
<td>Peak electric field, $E_{\text{sh}}$</td>
<td>$\text{MV/m}$</td>
<td>$50$</td>
<td>$35.7$</td>
<td>$\leq 50$</td>
</tr>
<tr>
<td>Peak magnetic flux, $B_{\text{sh}}$</td>
<td>$\text{mT}$</td>
<td>$110$</td>
<td>$74$</td>
<td>$116$</td>
</tr>
<tr>
<td>Peak magnetic field, $H_{\text{sh}}$</td>
<td>$\text{A/m}$</td>
<td>$87535$</td>
<td>$59000$</td>
<td>$\leq 92600$</td>
</tr>
</tbody>
</table>

Persons that provided the data via private communication:
- A. Arnold<sup>(1)</sup>
- I. Ben-Zvi<sup>(2)</sup>
- T. Kamps<sup>(4)</sup>
- J. Hao<sup>(5)</sup>
- J.W. Lewellen<sup>(7)</sup>
- B. Legg<sup>(6)</sup>
- A. Burnett<sup>(10)</sup>
- J. Sekutowicz<sup>(11)</sup>

- A. Arnold<sup>(1)</sup>
Existing cooling methods are not sufficient:

- Electrons and positrons have natural strong cooling mechanism: Synchrotron Radiation (\(\sim\) milliseconds)
- Synchrotron Radiation will not help to cool hadrons at the currently available energies
- Main limitation of electron cooling is its rapidly falling efficiency with the increase of the beam energy \(\tau \sim \gamma^{7/2}\)
- Stochastic cooling (for a fixed bandwidth) is limited by the fact that its cooling time directly proportional to linear density of the particles and modern proton beams are simply too dense.

Cooling rate in hours for various cooling methods.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>RHIC - CeC PoP (Au)</td>
<td>26</td>
<td>-</td>
<td>-</td>
<td>(~ 1)</td>
<td>10 sec - local, 30 min - bunch (~ 0.1)</td>
</tr>
<tr>
<td>eRHIC (p)</td>
<td>325</td>
<td>(~ 100)</td>
<td>(~ 100)</td>
<td>(~ 30)</td>
<td></td>
</tr>
<tr>
<td>LHC (p)</td>
<td>7000</td>
<td>(~ 1000)</td>
<td>13(energy)/26(transverse)</td>
<td>(\infty)</td>
<td>(~ 1)</td>
</tr>
</tbody>
</table>
Coherent electron Cooling (CeC) and eRHIC

High energy luminosity Electron-Ion Collider requires strong hadron cooling: < 1 min cooling time of 250 GeV protons

If CeC is successful and fully operational, eRHIC Linac/Ring configuration could reach $2 \cdot 10^{33}$ luminosity with 5 mA polarized electron current.
Each individual hadron attracts surrounding electrons and generates density modulation.

In about a quarter of the plasma period, each hadron is surrounded by a cloud of electrons.

$$\omega_p = \sqrt{\frac{4\pi n_e e^2}{\gamma m_e}}$$

In the co-moving frame, the longitudinal velocity spread is much smaller than that in the transverse direction.

Electron cloud is shaped as a very flat pancake-like shape.
An FEL is a resonant instability at the wavelength of:

$$\lambda_o = \lambda_w \frac{1 + \langle \bar{a}_w^2 \rangle}{2\gamma^2}, \quad \bar{a}_w = \frac{e\bar{A}_w}{mc^2}$$

If the longitudinal extent of an induced perturbation is considerably shorter than FEL wavelength, it will be amplified.

A periodic density modulation generates a periodic longitudinal field.
Fundamental RF power coupling and fine frequency tuning is accomplished via a coaxial beam pipe and the beam exit port.

With the travel of ±2 cm, the tuning range is ∼6 kHz. Rough tuning is accomplished manually via mechanical linkages outside the cryomodule.

The center conductor and RF windows are water-cooled. The outer conductor copper coated bellows are air-cooled.

The center conductor is gold-plated to reduce heat radiated into the SRF cavity.
The cathode stalk is a hollow center conductor of the coaxial line formed by the stalk and the cavity. The stalk is shorted at one end and is approximately half wavelength long. A quarter-wave step from the short creates an impedance transformer → reduces RF losses in the stalk from $\sim 65 \text{ W}$ to $\sim 25 \text{ W}$. The gold plating reduces radiation heat load from the stalk.
Cathode Recess

Vacuum Gauge location
Solenoid location
Front rounding
Cathode Recess

Cavity “nose”
Cathode puck

Cathode

Back rounding

$E_z$ (MV/m)

$z$ (cm)

$E_z$ (MV/m)

$z$ (cm)

Cathode puck

Irina Petrushina (SBU) August 1, 2019 77 / 97
Magnification ratio of the beam position at the YAG screen and the laser spot position.
In order to determine the electrical axis of the gun:

- change the beam rigidity \( \frac{p}{e} = B\rho \) by scanning the voltage of the gun
- measure the position of the beam center at the first profile monitor

The y-intercept gives the direction of the gun axis for an infinitely rigid beam:
horizontal angle of \(-11.1\pm0.1\) mrad, and vertical angle of \(+1.6\pm0.2\) mrad.
Multipacting Simulations

Calculate EM fields  Define SEY  Define Emitting Surface  Analyze Trajectories

CST Particle Studio  ACE3P (Track3P)

\[ N_e(t) = N_0 e^{\alpha t} \]

\[ EC = \delta_1 \times \delta_2 \times \ldots \times \delta_n \]
Multipacting Simulations

CST Particle Studio

\[ N_e(t) = N_0 e^{\alpha t} \]

ACE3P (Track3P)

\[ EC = \delta_1 \times \delta_2 \times \ldots \times \delta_n \]
Simulation results: not so consistent.

Beam energy vs. z in the gun. 
RMS beam size evolution in the gun.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CST PS</th>
<th>Pic3P</th>
<th>GPT</th>
<th>IMPACT-T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equations solved</td>
<td>Maxwell</td>
<td>Maxwell</td>
<td>Poisson</td>
<td>Poisson</td>
</tr>
<tr>
<td>Wakefields</td>
<td>✓</td>
<td>✓</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Space charge</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Retardation effects</td>
<td>✓</td>
<td>✓</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Image charge</td>
<td>Real geometry</td>
<td>Real geometry</td>
<td>Flat wall</td>
<td>Flat wall</td>
</tr>
</tbody>
</table>

Specifics of the algorithm
XY distribution at the gun exit

Pic3P

CST

GPT

IMPACT-T
XY distribution at the gun exit

Tetrahedral meshing in Pic3P.

Irina Petrushina (SBU)
XY distribution at the gun exit

Tetrahedral meshing in Pic3P.

Particle source in CST.
XZ distribution at the gun exit

Longitudinal distribution

- **Pic3P, GPT, IMPACT-T**: uniform with rise/drop time
- **CST**: truncated Gaussian.

**CST** and **Pic3P** are excluded from the race for the best initial particle distribution.
**Goal:** optimize the normalized RMS emittance at YAG 1 by appropriate choice of the gun and LEBT 1 solenoids.

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Radius of the laser spot, mm</td>
<td>0.25-2.5</td>
</tr>
<tr>
<td>Pulse length, ps</td>
<td>400</td>
</tr>
<tr>
<td>Bunch charge, pc</td>
<td>10-600</td>
</tr>
<tr>
<td>Gun Voltage, MV</td>
<td>1.25</td>
</tr>
<tr>
<td>Cathode recess, mm</td>
<td>0-12</td>
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Goal: optimize the normalized RMS emittance at YAG 1 by appropriate choice of the gun and LEBT 1 solenoids.

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<td>Cathode recess, mm</td>
<td>0-12</td>
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113 MHz Photoinjector: excellent performance!

- Gun energy: 1.25 MeV.
- Laser spot on cathode RMS size: 0.8mm (3.2 mm diameter).
- Bunch charge: 600 pC.
- Bunch length: 400 ps.
- Gun solenoid: 8.6 A.
- LEBT1 solenoid varied from -7 to -1 A (left) and 1 to 7 A (right).

Projected normalized emittance—0.57 mm-mrad.

Normalized core slice emittance—0.35 mm-mrad.
The simulation results of the LEBT scan provide a projected normalized RMS emittance of 0.23 mm-mrad, while the slice emittance demonstrated a uniform core with the slice emittance of about 0.13 mm-mrad.
The oscillation in the beam emittance after the gun solenoid is the result of the successful emittance compensation.
20% increase of the spot size caused an increase in the projected emittance by 32% (0.303 mm-mrad) with the slice emittance of about 0.15 mm-mrad on average.
This data set was obtained for a 0.4 ns 100 pC electron beam at 1.25 MV gun voltage, and 1.34 mm diameter of the laser spot at the cathode.
Wakefields

- The beam loses part of its energy to establish EM—wake—fields that remain after the passage of the beam.
- Theses wake fields affect trailing particles of the same beam or the following beam.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ABCI</th>
<th>ECHO 3D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry</td>
<td>Axially symmetric</td>
<td>Full 3D</td>
</tr>
<tr>
<td>Beam Duration (ps)</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Simulation Duration (ps)</td>
<td>500</td>
<td>500</td>
</tr>
</tbody>
</table>
Transverse overlap of the electron and ion beams

1. Utilize two quadrupole magnets at the beginning and the end of the common section: the first quadrupole of the modulator section and the last quadrupole of the kicker section.

2. When passing through the center of a quadrupole, the orbit of a charged particle beam doesn’t change.

3. Varying the transverse position of a beam, and then observing the effect of the varied field in the quadrupole, find the quadrupole center.

4. Performed for both, the electron and ion beams at the beginning and the end of the common section.
Longitudinal overlap of the electron and ion beams

1. Observe the signal from the BPM in the common section.
2. By adjusting the phase shift of the CeC RF system, align the signal from the electron bunch to the center of the ion bunch.
Personal Contribution

1. Thorough investigation of multipacting in the 113 NHz photoinjector through the simulations and experiment.
2. Comprehensive study of beam dynamics in the photoinjector.
3. Beam dynamics simulations in the CeC accelerator.
4. Analysis of wake fields in the CeC beamline.
5. Participation in the CeC PoP commissioning.