Noise in Intense Electron Bunches at FAST

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0 – 6 µm
Electron-Ion Collider

- **High luminosity**: \( L = 10^{33} \) to \( 10^{34} \text{ cm}^{-2}\text{sec}^{-1} \) - a factor 100 to 1000 beyond HERA

<table>
<thead>
<tr>
<th></th>
<th>Electrons</th>
<th>Protons</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beam energies</strong></td>
<td>2.5 - 18 GeV</td>
<td>41- 275 GeV</td>
</tr>
<tr>
<td>Center of mass energy range</td>
<td>( E_{\text{cm}} = 20-140 \text{ GeV} )</td>
<td></td>
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<tr>
<td><strong>Beam energies</strong></td>
<td>10 GeV</td>
<td>275 GeV</td>
</tr>
<tr>
<td>Center of mass energy</td>
<td>( E_{\text{cm}} = 105 \text{ GeV} )</td>
<td></td>
</tr>
<tr>
<td>number of bunches</td>
<td>( \text{nb} =1160 )</td>
<td></td>
</tr>
<tr>
<td>crossing angle</td>
<td>25 mrad</td>
<td></td>
</tr>
<tr>
<td>Bunch Charge</td>
<td>( 1.7 \cdot 10^{11} \text{e} )</td>
<td>( 0.7 \cdot 10^{11} \text{e} )</td>
</tr>
<tr>
<td>Total beam current</td>
<td>( 2.5 \text{ A} )</td>
<td>1 A</td>
</tr>
<tr>
<td>Beam emittance, horizontal</td>
<td>20 nm</td>
<td>9.5 nm</td>
</tr>
<tr>
<td>Beam emittance, vertical</td>
<td>1.2 nm</td>
<td><strong>1.5 nm</strong></td>
</tr>
<tr>
<td>( \beta )- function at IP, horizontal</td>
<td>43 cm</td>
<td>90 cm</td>
</tr>
<tr>
<td>( \beta )- function at IP, vertical</td>
<td>5 cm</td>
<td>4 cm</td>
</tr>
<tr>
<td>Beam-beam tuneshift, horizontal</td>
<td>0.073</td>
<td>0.014</td>
</tr>
<tr>
<td>Beam-beam tuneshift, vertical</td>
<td>0.1</td>
<td>0.007</td>
</tr>
<tr>
<td>Luminosity at ( E_{\text{cm}} = 105 \text{ GeV} )</td>
<td>( 1 \cdot 10^{34} \text{cm}^{-2}\text{sec}^{-1} )</td>
<td></td>
</tr>
</tbody>
</table>
Beam Cooling

Transverse momentum energy growth:

**Source:** longitudinal degree of freedom.

Coupling to transverse degree **processes**:

- Scattering (intra-beam, beam-beam, residual gas)
- Improper bending and/or focusing at injection
- Interaction with beam’s environment (e.g. wake fields)
- Space-charge effects
- Secondary and tertiary beams

Cooling is a reduction in the phase space occupied by the beam (for the same number of particles)

- The figure of merit – beam emittance

\[ e_{x,n} = \beta \gamma \left( \langle x^2 \rangle \langle \theta_x^2 \rangle - \langle x \theta_x \rangle^2 \right)^{1/2} \]

\[ \theta_x = \frac{p_x}{\beta \gamma Mc} \]

Necessary: \( \langle p_\perp \rangle \sim 10^{-4} \langle p_\parallel \rangle \)
Beam Cooling

- At 275 GeV, IBS times are: H/L = 1.5/4 hours
- IBS heating rate scales as $\lambda_{\perp} \sim \frac{1}{\gamma^{1.5}}$

Thus, the hadron cooling system must provide ~1-2 hour horizontal cooling time to prevent emittance blowup and conserve luminosity

- We are calling it Strong Hadron Cooling

Two basic methods employed for hadron cooling today:

**Electron cooling** – energy exchange
- Many low-energy proton/ion rings.
- Highest hadron beam energy to date - 8.9 GeV at Fermilab
- Cooling rate: $\lambda_{\perp} \sim \frac{1}{\gamma^{2.5}}$

**Stochastic cooling** (1984 Nobel Prize in Physics)
- CERN, Fermilab, GSI, RHIC, etc.
Optical Stochastic cooling

Concept:
Coherent electron cooling with microbunching amplification

- Type of stochastic cooling based on transit time between the modulator and the kicker
- Typical bandwidth of ~40 THz (conventional SC ~10 GHz)
- This is a longitudinal-only cooling scheme. Cooling in x and y requires coupling/sharing of cooling.
- Achievable cooling times of about 1 hour for 275 GeV protons
Electron beam noise

**Noise** = beam density fluctuations above (Poissonian) shot noise, $F = 1$

\[
F = \frac{\text{var}(N)}{\langle N \rangle}
\]

Fano factor

We would like to confirm that for the ERL electron bunches $F < 2$ at $\lambda \sim 3\mu m$

- IMPACT simulation (LBNL): energy spread, emittance, and bunch length matched well to GPT results
- Observed > 250 um modulation with noise amplitude 2x shot noise. It will not be amplified in the cooler.
- 250 um modulation will not affect the diffusion rate
- Current fluctuation through the linac and the merger is close to the shot noise level
**Beam spectrum ↔ Transition Radiation (TR) spectrum**

<table>
<thead>
<tr>
<th></th>
<th>FAST</th>
<th>EIC (100 GeV)</th>
<th>EIC (275 GeV)</th>
<th>Current experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron beam energy</td>
<td>50 – 300 MeV</td>
<td>50 MeV</td>
<td>137 MeV</td>
<td>32 MeV</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>0 – 3 nC</td>
<td>1 nC</td>
<td>1 nC</td>
<td>0.2 – 1.1 nC</td>
</tr>
<tr>
<td>Emittance (norm, rms)</td>
<td>~3 μm (at 1 nC)</td>
<td>2.8 μm</td>
<td>2.8 μm</td>
<td></td>
</tr>
<tr>
<td>Bunch length</td>
<td>0.3 – 20 mm</td>
<td>9 mm</td>
<td>8 mm</td>
<td>0.15-5 mm</td>
</tr>
<tr>
<td>Drift section (amplifier)</td>
<td>80 m</td>
<td>100 m</td>
<td>100 m</td>
<td></td>
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</table>

**Diagram:**
- **Photo-cathode Gun**
- **CC1**
- **CC2**
- **Chicane**
- **ILC-Type Cryomodule**
- **Three OTR stations**
- **Electron beam**
- **OTR screen**
- **Mirror system**
- **Lens and filters**
- **Photodiode**
- **100 nm**
- **80 meters**
- **18 meters**
- **Dipole**
- **To IOTA**
- **Current experiments**
- **Planned experiments**
Optical Transition Radiation. Its registration

- One particle

\[ \frac{dI}{d\omega d\Omega} = \frac{Z_0 e^2}{4\pi^3 |n \times \beta|^2} \left[ \frac{1}{1 - (\beta n)^2} \right] \]

- Beam size dependence is determined by the PD size \((\gamma \gg 1)\)

\[ \frac{dI}{d\omega d\Omega} \sim N \left( 1 - \exp \left( -\frac{a^2}{2\sigma^2} \right) \right) \]

- SiO2 (fused silica) glass vacuum window

- 2 Al parabolic mirrors
- 1 Al flat mirror
- 5 Silver flat mirrors

- FD10D photodiode

Vacuum window transmittance

Photodiode responsivity
Data Analysis Flow

Transitions:
- Vacuum window
- Flat and parabolic mirrors
- Filters
- PD responsivity

Pass OTR through the light channel (Theory and Experiment)

Compare voltage $U(\lambda)$ for a set of filters (set of single values)

Discrete Homogeneous Fredholm Integral Equation

$$\int T(n, \lambda) \frac{dI}{d\lambda} d\lambda = U(n)$$

System of integral equations

If filters are narrow-band:
- Integrals are easily evaluated $\rightarrow$ unique solution

In reality:
- Ambiguous, guessed solution
Noise in the system is $F = 1 \div 1.62$

OTR power Theory and Experiment comparison. Low noise

Predicted and Experimental $U(\lambda)$ comparison. 9 filters

Incoherent term

$$\frac{d^2 I}{d\omega d\Omega} = \frac{d^2 I_1}{d\omega d\Omega} \left[ N + N^2 \left| \int \rho(z) \exp \left( i \frac{w z}{c} \right) dz \right|^2 \right]$$

Coherent term

Shot-noise:

$$\int \rho(z) \exp \left( i \frac{w z}{c} \right) dz \approx \frac{1}{1.129 \sqrt{N}}$$

Beam size measurement error in work. Example

$35\%$ $\sigma$ error $\rightarrow$ $50\%$ $U$ error $\rightarrow$ $62\%$ $F$ error
Bunch compression

Beam length dependence on CC2 phase. Interesting region is circled red.

OTR energy per 100-nm BW dependence on wavelength for different bunch lengths.

Fano factor of $\langle F(\lambda) \rangle \sim 3$
Elevated noise

Additional OTR spectrum when the beam is compressed

\[ N \left| \int \rho(z) \exp \left(2\pi i \frac{z}{\lambda} \right) \, dz \right|^2 \]

- No COTR at < 0.9 \( \mu \text{m} \)
- Peak at 1.5-1.6 \( \mu \text{m} \)
- Peak at 0.9-1 \( \mu \text{m} \)

An attempt to fit the elevated noise picture

Is the largest only at 960nm
Simulations

- ImpactX
- Cross-checked with ASTRA

Uncompressed beam

Compressed beam

- No microbunching? Need more accuracy
- Gain plot (with initial distortion) shows the same

Beam length comparison + OTR peak

OTR peak on multiple filters. Peak ~31.4 (from symmetry)
Next steps

Data analysis:

• Fit the elevated noise automatically

• Fit the vacuum window transmission lower edge

Experiment:

• Perform the experiment with ultimate control of the beam size

• Create additional measurement stations in the high energy line

• Try other filters / neutral density filters to improve the data

Simulations

• Regular tracking:
  Beam length vs cc2 phase for the high energy channel

• Microbunching:
  Increase accuracy and compare with other tools like GPT

Noise in the system is $F = 1 \div 1.62$
Thank you! Questions time.
EIC features

- Large range of center-of-mass energies $E_{cm} = 29$ to $140$ GeV/u
- Polarized beams with flexible spin patterns
- Favorable condition for detector acceptance such as $p_T = 200$ MeV/c
- Large range of hadron species: protons, ..., Uranium
- Collisions of electrons with polarized protons and light ions ($^3$He, d, ...)

Possible discrepancy in beam length experiment vs simulation explanation