Noise in Intense Electron Bunches

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Bunch compression

Electron beam

OTR screen

Mirror system

Lens and filters

Photodiode

0 – 6 μm
Introduction. Coherent Electron Cooling

Noise:
Shot noise → $\sqrt{2}$ reduction
Above shot → may become not effective

Goal:
Determine how much noise we have and how to suppress it

Similar method but with undulators – Optical stochastic cooling – already done
### Introduction. EIC vs FAST parameters

<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></td>
</tr>
<tr>
<td>Drift section (amplifier)</td>
<td>80 m</td>
<td>100 m</td>
<td>100 m</td>
<td></td>
</tr>
</tbody>
</table>

### Diagram

- Photo-cathode Gun
- CC1
- CC2
- Chicane
- ILC-Type Cryomodule
- Three OTR stations
- Dipole
- To IOTA

- Current experiments
- Planned experiments

- 18 meters
- 80 meters
Introduction. Microbunching instability

Initial distribution: \( \rho(z) = \rho_{\text{smooth}}(z) + \frac{1}{2\pi} \int_{-\infty}^{\infty} \rho_{\text{modulation}}(k)e^{ikz} \, dk \)

Each term in modulation spectrum is increased by gain

Without deliberate modulation is random

Need a physical mechanism that depends on longitudinal distribution

Final distribution: \( \rho(z) = \rho_{\text{smooth}}(z) + \frac{1}{2\pi} \int_{-\infty}^{\infty} G(k)\rho_{\text{modulation}}(k)e^{ikz} \, dk \)

Final \( \rho_m(k) \to \rho_m(\lambda) \)

Microbunching instability produced by longitudinally modulated photocathode laser
Experimental scheme. Transition Radiation

\[ \frac{d^2 I}{d\Omega d\lambda} = \frac{Z_0 q^2 c}{\pi \lambda^2} \frac{\beta^2 \sin^2 \theta}{(1 - \beta^2 \cos^2 \theta)^2} \left( N + N(N - 1) \int \rho(z) \exp \left( \frac{2\pi i z}{\lambda} \right) dz \right)^2 f(\sigma_x) f(\sigma_y) \]

For interesting parameters is small for microbunching instability

Incoherent term
N – number of particles

Coherent term
Dependence on longitudinal distribution

S. Kladov, A. Lumpkin, J. Ruan, R. Thurman-Keup, A. Saewert et al. Noise in Electron Bunches. X121 OTR results. Bunch compression

**Spectrum “bricks”**

\[
\frac{d^2 I}{d\Omega d\lambda} = \frac{z_0 q^2 c}{\pi \lambda^2} \frac{\beta^2 \sin^2 \theta}{(1-\beta^2 \cos^2 \theta)^2} \left( N + N(N-1) \left| \int \rho(z) \exp \left( \frac{2\pi iz}{\lambda} \right) dz \right|^2 f_1(\sigma_x) f_2(\sigma_y) \right)
\]

Micro-bunches are displaced randomly:

\[
\frac{N(N-1)}{N_b} \left| \int \rho_{1\text{norm}}(z) \exp \left( \frac{2\pi iz}{\lambda} \right) dz \right|^2
\]

Micro-bunches are ordered:

\[
\frac{N(N-1)}{N_b} \left[ \sum_{n=1}^{N_b} \exp \left( \frac{2\pi in t_0}{\lambda} \right) \right]^2 \left| \int \rho_{1\text{norm}}(z) \exp \left( \frac{2\pi iz}{\lambda} \right) dz \right|^2
\]
Theory conclusion. Signs of COTR. Experimental scheme. Methods

\[
\frac{d^2I}{d\Omega d\lambda} = \frac{2q^2c}{\pi \lambda^2} \frac{\beta^2 \sin^2 \theta}{(1 - \beta^2 \cos^2 \theta)^2} \left( N + N(N-1) \int f \rho(z) \exp \left( \frac{2\pi iz}{\lambda} \right) dz \right)^2 f(\sigma_x)f(\sigma_y)
\]

- Nonlinear dependence on beam charge
- Dependence on beam length
- Larger signal fluctuations for COTR

Two measurement methods to compare results:
Photodiode and CMOS camera
Background. Similar studies in the past

APS, Argonne National Laboratory

OTR images for uncompressed and compressed beams

LCLS, SLAC

OTR intensity (10^6 Counts)

\[
\sigma = 0.096 \text{ kG}
\]

OTR power increase at specific chicane parameters

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Background. Similar studies in the past

LCLS

OTR angular distribution

COTR fluctuations – each wavelength is produced randomly

FLASH, DESY

Amplification factors of coherent spectral intensity with respect to the incoherent level

Relative fluctuations histograms

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Noise in Electron Bunches. X121 OTR results. Bunch compression
Signal and its evaluation. Bunch compression

Usual signal on the scope (voltmeter) at the end of the amplifier circuit of the photodiode and its evaluation

Longitudinal beam profile for different CC2 phases. Streak camera. “200phase” – on crest
Bunch compression. Main result

Beam length dependence on CC2 phase

OTR signal dependence on CC2 phase (bunch compression). 1570nm filter
Wavelength + compression dependence

- Total charge is conserved
- Beam is always steered well

\[
\frac{d^2 I}{d\Omega d\lambda} \approx \frac{1}{\lambda^2} \left( N + N(N - 1) \left| \int \rho(z) \exp \left( \frac{2\pi i z}{\lambda} \right) dz \right|^2 \right)
\]

20 times increase!
**frequency dependence. Gain plot**

\[ \frac{d^2I}{d\Omega d\lambda} = \frac{Z_0 q^2 c}{\pi^2 (1-\beta^2 \cos^2 \theta)^2} \left( N + N(N-1) \int f(\rho(z)) \exp \left( \frac{2 \pi i z}{\lambda} \right) dz \right)^2 f(\sigma_x) f(\sigma_y) \]

\[
\frac{\text{compressed}}{\text{uncompressed}} = \frac{\text{OTR} + \text{COTR}}{\text{OTR}}
\]

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

Q=0.9nC. Compressed/uncompressed ratios for 6 points in wavelength
Filter two-spots correction

What we want the filter do – integrate over dashed area

What the filter does in practice – also integrates wrong area

\[ I = \int_{\lambda_1}^{\lambda_2} dI(\lambda) f(\lambda) d\lambda + \int_{\lambda_3}^{\lambda_4} dI(\lambda) f(\lambda) d\lambda \]

\( w_1, w_2 \) – wrong area
\( c_1, c_2 \) – correct area

\( q(\lambda) \) - photodiode quantum efficiency
\( f(\lambda) \) - filter transmission rate

We know the 1st term: \( \int_{\lambda_1}^{\lambda_2} dI(\lambda) f(\lambda) d\lambda \)

\[ \left. \frac{dI}{d\lambda} \right|_{\lambda=1570\text{nm}} \approx I_{\text{measured}} - \int_{\lambda_1}^{\lambda_2} \frac{dI}{d\lambda} \bigg|_{\lambda=770\text{nm}} q(\lambda) f(\lambda) d\lambda \]

OTR energy per 100-nm BW dependence on wavelength for different bunch lengths
Charge + compression dependence

OTR energy per 100-nm BW dependence on CC2 phase for different charges
(complementary plot)

OTR energy per 100-nm BW dependence on beam charge for different CC2 phases

Nonlinear charge dependence
New data. Fluctuations

OTR signal dependence on CC2 phase (bunch compression).

1570nm filter

Relative signal fluctuations for 1.3nC

Signal histogram at 1424nm, 1.3nC, compressed

Larger fluctuations in microbunching area
New data. Gain verification

Old (August) data. Q=0.9nC. Good compression

New data. Q = 0.63 nC. Worse compression

New data. Q = 1.3 nC. Worse compression
Test with CMOS camera

770 nm:
21% increase found on CMOS camera (0.6 nC) instead of 80% from the photodiode (0.9 nC)

Using the charge dependence fit:
~70% on CMOS vs 80% on PD

Signal is not visible by eye in 960nm.
OTR power conclusions

What signifies the Coherent Optical Transition Radiation (COTR):

• Dependence on beam longitudinal distribution, Large signal increase for some parameters (~20 times)
• Nonlinear (higher than linear) dependence on charge
• Larger relative fluctuations in COTR area

Future steps:

What can be done now:

• More measurements (CMOS camera, streak camera)
• New filters (> 1700nm)
• Calibrate the streak camera; CMOS camera
• Energy spectra without and with compression (might see energy modulation)

What can be done during the next runs:

• IRIS right after the vacuum window for the angular distribution measurements
• Manual generation of microbunching, including the transverse one
• Microbunching gain simulations for FAST
Thank you! Questions time.
Strange peak investigation (additional slide)