RMS Emittance Measurements Using Optical Transition Radiation Interferometry at the Jefferson Lab FEL

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Overview

- To apply Optical Transition Radiation Interferometry (OTRI) techniques to high current accelerators
- Investigate the ability of OTRI to measure complex beam distributions
- Further develop an all optical method of phase space mapping

First step: RMS emittance measurements
OTRI as an Emittance Diagnostic

Measure RMS beam size and RMS divergence at a waist condition to calculate the emittance

RMS emittance

\[ \tilde{\varepsilon}_x = \left( \frac{\left( x^2 \right)}{\left( x' \right)^2} - \left( xx' \right)^2 \right) \frac{1}{2} \]

At a beam waist

\[ \tilde{\varepsilon}_x = x_{rms} x'_{rms} \]

where: \( x_{rms} = \sqrt{\langle x^2 \rangle} \) and \( x'_{rms} = \sqrt{\langle x'^2 \rangle} \)
Two thin parallel metal foils

phase term

Vacuum coherence length

\[ \phi = \frac{L}{L_v} \]

\[ L_v = \left( \frac{\lambda}{\pi} \right) \left( \frac{1}{\gamma^{-2} + \theta^2} \right) \]

Spectral-angular distribution of two foil OTR

\[
\frac{dI_{\text{tot}}}{d\omega d\theta} = \frac{\alpha}{\pi} \frac{\theta^2}{(\gamma^{-2} + \theta^2)^2} \left| 1 - e^{-i\phi} \right|^2
\]
Effect of Beam Parameters on Fringe Visibility

Interference fringes are highly sensitive to:
1. Optical bandwidth
2. Energy spread
3. Divergence

We want divergence to dominate the fringe visibility effects

**Gaussian angular distribution function**

\[ P(\sigma, \theta) = \left( \frac{1}{2\sigma^2} \right)^{\frac{1}{2}} e^{-\frac{\theta^2}{2\sigma^2}} \]

**Normalized divergence**

\[ s = \gamma \sigma \]
Experimental Setup

**Interferometer location**

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**Experimental beam conditions**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy</td>
<td>115 MeV</td>
</tr>
<tr>
<td>Macro Pulse Width</td>
<td>100μs</td>
</tr>
<tr>
<td>Micro Pulse rep rate</td>
<td>2MHz</td>
</tr>
<tr>
<td>Charge per bunch</td>
<td>135 pC</td>
</tr>
<tr>
<td>Beam Current (Avg)</td>
<td>~150μA</td>
</tr>
</tbody>
</table>
Optical Arrangement

- Beam imaging camera
- Beam splitter
- Optical band-pass filter
- Angular distribution camera
- View ports
- Interferometer
- Electron beam Direction
Beam Size Measurements

Beam image profile is complex
Beam Size Measurement

<table>
<thead>
<tr>
<th>Waist</th>
<th>filter</th>
<th>$\sigma_1$ (μm)</th>
<th>$\sigma_2$ (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>650x10 nm</td>
<td>134.4 +/- 1.4</td>
<td>380.1 +/- 5.6</td>
</tr>
<tr>
<td>X</td>
<td>450x10 nm</td>
<td>144.9 +/- 2.6</td>
<td>390.7 +/- 16.9</td>
</tr>
<tr>
<td>Y</td>
<td>650x10 nm</td>
<td>56.4 +/- 0.59</td>
<td>410.7 +/- 11.0</td>
</tr>
<tr>
<td>Y</td>
<td>450x10 nm</td>
<td>49.4 +/- 1.0</td>
<td>380.5 +/- 14.8</td>
</tr>
</tbody>
</table>
Divergence Measurements

Simple Gaussian does not work

- Sector scan of far field image provides intensity profile
- Computer code used to fit intensity profile
Divergence Measurements

Two Gaussian fit works remarkable well

<table>
<thead>
<tr>
<th>Waist</th>
<th>Filter</th>
<th>( \theta_1 ) (mrad)</th>
<th>( \theta_2 ) (mrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>650x10 nm</td>
<td>0.54+/-0.01</td>
<td>2.3+/-0.1</td>
</tr>
<tr>
<td>Y</td>
<td>450x10 nm</td>
<td>0.55+/-0.01</td>
<td>2.4+/-0.08</td>
</tr>
<tr>
<td>X</td>
<td>650x10 nm</td>
<td>0.43+/-0.01</td>
<td>1.4+/-0.08</td>
</tr>
<tr>
<td>X</td>
<td>450x10 nm</td>
<td>0.45+/-0.01</td>
<td>1.3+/-0.07</td>
</tr>
</tbody>
</table>

Y waist \( \lambda = 650 \text{nm} \)

Calculated Fit:
- \( \sigma_1 = 0.54+/-0.01 \text{mrad} \)
- \( \sigma_2 = 2.3+/-0.08 \text{mrad} \)

Data:
- \( 1.3+/-0.07 \text{nm} \)
- \( 0.45+/-0.01 \text{nm} \)
- \( 650 \text{nm} \)

\( X \) and \( \theta_2 \) (mrad)
Emittance Measurements

<table>
<thead>
<tr>
<th>Waist</th>
<th>filter</th>
<th>Inner ( \sigma ) (mm-mrad)</th>
<th>Outer ( \sigma ) (mm-mrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>650x10 nm</td>
<td>13 +/- .4</td>
<td>117.2 +/- 7.7</td>
</tr>
<tr>
<td>X</td>
<td>450x10 nm</td>
<td>14.7 +/- .7</td>
<td>126.5 +/- 14.0</td>
</tr>
<tr>
<td>Y</td>
<td>650x10 nm</td>
<td>6.8 +/- .2</td>
<td>212.5 +/- 14.9</td>
</tr>
<tr>
<td>Y</td>
<td>450x10 nm</td>
<td>6.0 +/- .2</td>
<td>205.4 +/- 14.9</td>
</tr>
</tbody>
</table>

**Conclusion**

- OTRI has shown potential to measure multiple spatial and angular components within the beam
- Need to use a method to correspond spatial and angular data
Next Step: Optical Masking and Optical Phase Space Mapping

Measure position

Measure divergence and centroid shift

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