I. Introduction
   - Longitudinal space charge (LSC) instability

II. Diagnostics options for microbunching instability (µBI)
    (Including Diagnostics with optical transition radiation (OTR) and characterization of microbunching using coherent OTR (COTR))

III. Recent Results: Photocathode (PC) rf guns, Thermionic cathode (TC) DC guns, and TC rf gun source, L-band to X-band linacs. µBI-5 in Pohang, Korea, May 2013.

IV. Summary
Introduction

• The generation of the ultrabright beams required by modern free-electron lasers (FELs) has generally relied on chicane-based bunch compressions that often result in the microbunching instability.

• Following compression, spectral enhancements extend even into the visible wavelengths through the longitudinal space charge impedances.

• Optical transition radiation (OTR) screens have been extensively used for transverse electron beam size measurements for the bright beams, but the presence of longitudinal microstructures (microbunching) in the electron beam or the leading edge spikes can result in strong, localized coherent enhancements (COTR) that mask the actual beam profile.

• It should be kept in mind that the modulation is even stronger in the several micron period regime where it impacts the effective energy spread and can reduce FEL gain.
Microbunching of an electron beam, or a z-dependent density modulation with a period \( \lambda \), can be generated by several mechanisms:

- The LSC-induced microbunching (LSCIM) starts from noise fluctuations in the charge distribution which causes an energy modulation that converts to density modulation following Chicane compression. This is a broadband case. (our topic).
- The laser-induced microbunching (LIM) occurs at the laser resonant wavelength (and harmonics) as the e-beam co-propagates through the wiggler with the laser beam followed by Chicane compression. This is narrow-band. (Oct. 2011 WS)
- In self-amplified spontaneous emission or (SASE) induced microbunching (SIM) the electron beam is also bunched at resonant wavelength and harmonics. This is narrow band.

A microbunched beam will radiate coherently. (COTR)
• A microbunching instability driven by LSC, CSR, and linac wakefield effects predicted in bright beams.

Klystron instability of a relativistic electron beam in a bunch compressor

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Suppression of microbunching instability in the linac coherent light source

Z. Huang,1,* M. Borland,2 P. Emma,1 J. Wu,1 C. Limborg,1 G. Stupakov,1 and J. Welch1 PRST-AB 7, 074401 (2004)
Diagnostics for μBI

• Beam bunch length monitors for tuning compression: CTR, CSR, CER, CDR, streak camera, deflector cavity
• OTR Beam profile screens for COTR imaging: spatial structure, intensity fluctuations, enhancement
• Optical spectrometers, COTR NIR vs OTR bluish
• FIR spectrometers (mostly FLASH/DESY work).
• Deflecting mode cavities or streak cameras need fs resolution to see longitudinal structure directly: (Issue)
• Energy spectrometer, need high resolution to see modulation (Issue)
• FEL spectral effects
• Apply to TC gun beams?
Microbunching Instability at LCLS

Laser Heater Off

SXR Spectrometer

Dump YAG Screen

J. Welch et al., FEL10
Laser-induced energy modulation used to suppress µBI at LCLS in x-ray FEL, but COTR interferences still exist.

Laser Heater ON – No Instability

J. Welch et al., FEL10
• Longitudinal phase space shows µBI structures

C. Behrens et al. PRST-AB 15, 062801 (2012)
LCLS COTR Case: BC1

- Estimate OTR spectral effect in LCLS OTR12 case.

*3-keV curve based on D. Ratner et al., FEL08 Equations and figure above from that article.
## Summary of COTR tests

<table>
<thead>
<tr>
<th>Facility</th>
<th>Gun</th>
<th>Linac, Energy</th>
<th>Chicanes</th>
<th>COTR Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCLS</td>
<td>PC, S-band</td>
<td>S-band, 250, 14 GeV</td>
<td>two</td>
<td>very strong, x10^4</td>
</tr>
<tr>
<td>APS</td>
<td>PC, S-band, rf TC, S-band</td>
<td>S-band, 150, 325</td>
<td>one alpha, one</td>
<td>x10-100 localized x4 integral</td>
</tr>
<tr>
<td>DESY</td>
<td>PC, L-band</td>
<td>SCRF, L-band, 1.2 GeV, linearizer</td>
<td>two</td>
<td>x 10-100 localized</td>
</tr>
<tr>
<td>SACLA</td>
<td>TC, DC gated</td>
<td>S-band, C-band, 1 GeV</td>
<td>three</td>
<td>&gt;10^3 after 3 compressions</td>
</tr>
<tr>
<td>SCSS</td>
<td>TC, DC gated</td>
<td>S-band, C-band, 250 MeV</td>
<td>two</td>
<td>x2, Observable after two comp.</td>
</tr>
<tr>
<td>NLCTA</td>
<td>PC, S-band</td>
<td>X-band, 120 MeV</td>
<td>two of four</td>
<td>x20 after two</td>
</tr>
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</table>

plus FERMI, BNL results
## Specifications of Bunch Compressor and Dark Current Suppression Chicane at Test Accelerator

<table>
<thead>
<tr>
<th></th>
<th>Bending Angle (θ)</th>
<th>Momentum Compaction (R&lt;sub&gt;56&lt;/sub&gt;)</th>
<th>Dispersion (η)</th>
<th>Beam Energy</th>
<th>Peak Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC</td>
<td>5.73 deg.</td>
<td>-20 mm</td>
<td>110 mm</td>
<td>45 MeV</td>
<td>300 A</td>
</tr>
<tr>
<td>Chicane</td>
<td>5.73 deg.</td>
<td>-28 mm</td>
<td>150 mm</td>
<td>250 MeV</td>
<td>300 A</td>
</tr>
</tbody>
</table>
The acceleration phase of the C-band main linac shifts to the bunching side to give an energy chirp.

Chicane works as the second bunch compressor to compress the bunch more.

Intensity of the OTR light was measured at the exit of the chicane.
• At the phase around -10 deg., COTR generated.
• The gain factor of the intensity is ~2.
• The COTR disappeared at the deeper phase.

K. Togawa Talk, µBI-13
Temporal Profile Measurement at SACLA under COTR

5712 MHz
HEM11

Screen Monitor
< 10 μm resolution
YAG:Ce Screen

Transverse RF Electric Field

Temporal profile measurement
20 fs resolution

4th Microbunching Instability WS, Univ. of Maryland April 11-13, 2012

Courtesy of the SACLA Team
The Gain factor of the intensity is $\sim 6 \times 10^3$.

- Measured after the 3\textsuperscript{rd} (final) bunch compressor (1.4 GeV).
- Vacuum Window : Quartz Grass
- Transport Mirror : Aluminum
- Spectrometer : Grism
- Longest wavelength is limited by the range of spectrometer.
- Some spikes were observed. This is an evidence of microbunch.

S. Matsubara
• Observe COTR on X-band linac after two chicane compressions. S-band Photoinjector.

Figure 2: Typical COTR image (left) and wavelength spectrum (right).

Dunning et al., PAC11
- Microbunching also revealed in coherent optical undulator radiation (COUR) studies at NLCTA.

Weathersby et al., PAC11

Figure 2: Radiation intensity for various rf phase in X2 measured with an OTR screen downstream of undulator U1.
• **Microbunching instability in electron beams worldwide.**
  - Now TC generated beams at SCSS and SACLA exhibit µBI
  - Preliminary COTR results with rf TC gun beam at ANL
  - Energy modulation due to LSCIM can be measured directly.
    • Benchmark codes on microbunching fractions, TC beams.
• Mitigation techniques for diagnostics have been demonstrated for moderate to extensive COTR.
• Intrinsic suppression of µBI by laser beam heating, reversible beam heating, and dispersive elements.
• Future tests planned at Fermilab; High Q/µpulse.
• Compression factors critical in a general phenomenon.
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