Beam Diagnostics and Coherent Optical Radiation Induced by the Microbunching Instability

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OUTLINE

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 Mechanisms

- **Microbunching of an electron beam, or a z-dependent density modulation with a period λ, 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)**

Microbunching Instability

- **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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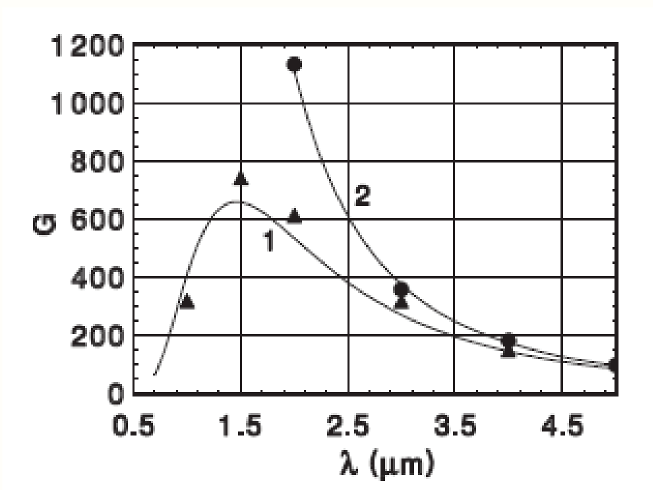
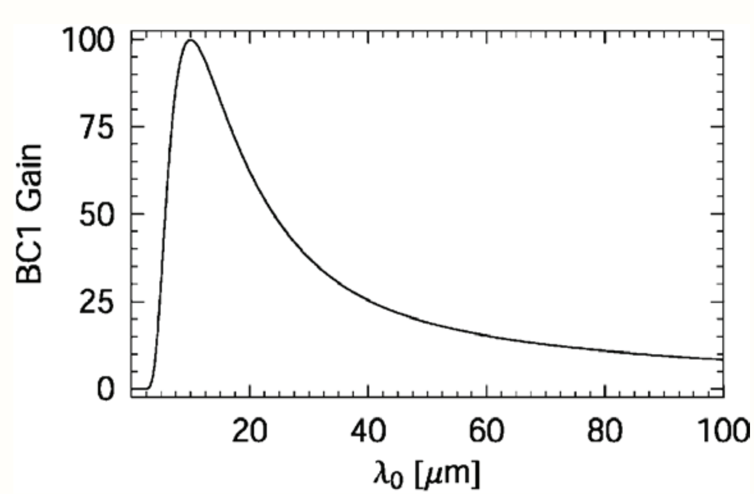
NIM Phys.Res.A 490,1 (2002)

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)



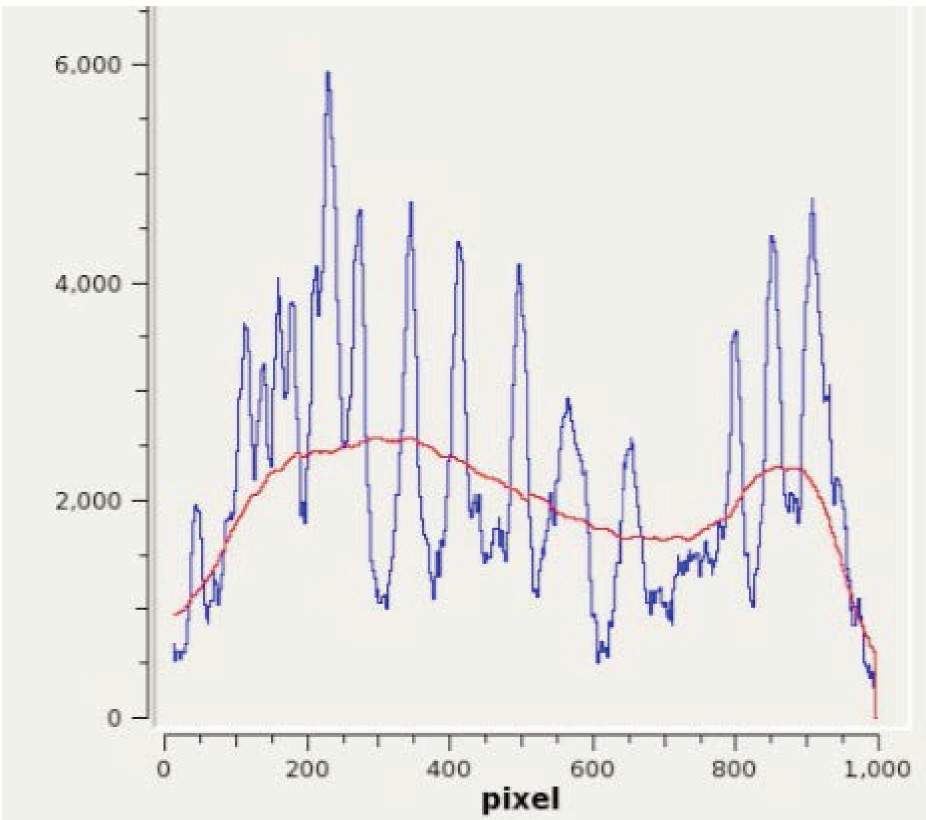


Diagnostics for µBI

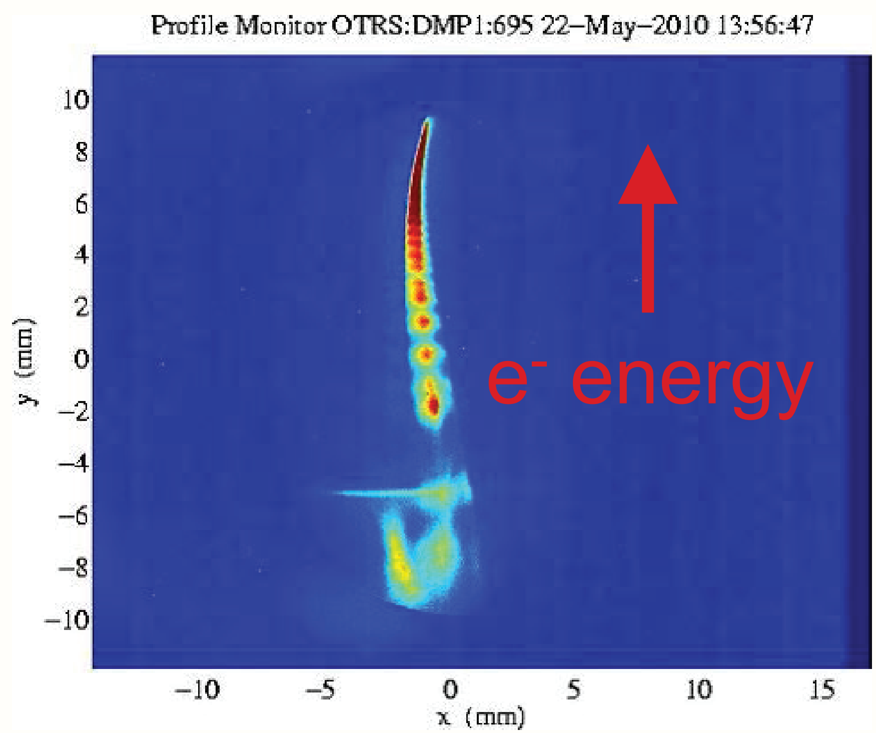
- Beam bunch length monitors for tuning compression: CTR, CSR, CER, CDR, streak camera, deflector cavity
- OTR Beam profile screens for COTR imaging: spatial structure, intensity fluctuations, enhancement
- Optical spectrometers, COTR NIR vs OTR bluish
- FIR spectrometers (mostly FLASH/DESY work).
- Deflecting mode cavites 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

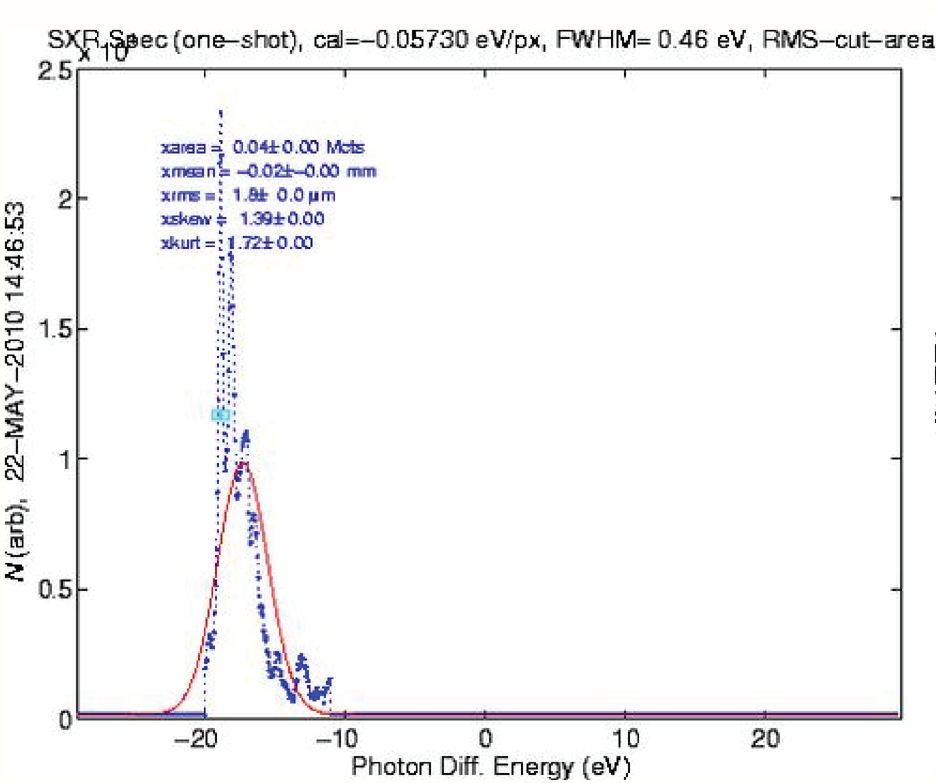
J. Welch et al., FEL10

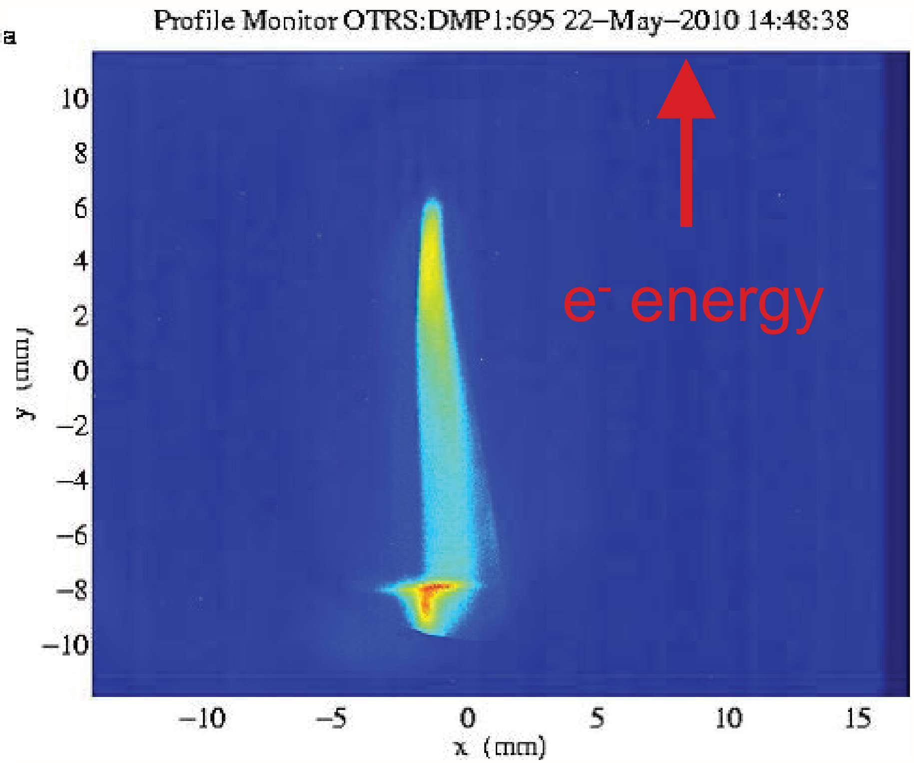
Microbunching Instability at LCLS

Fermilab

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

Laser Heater ON – No Instability

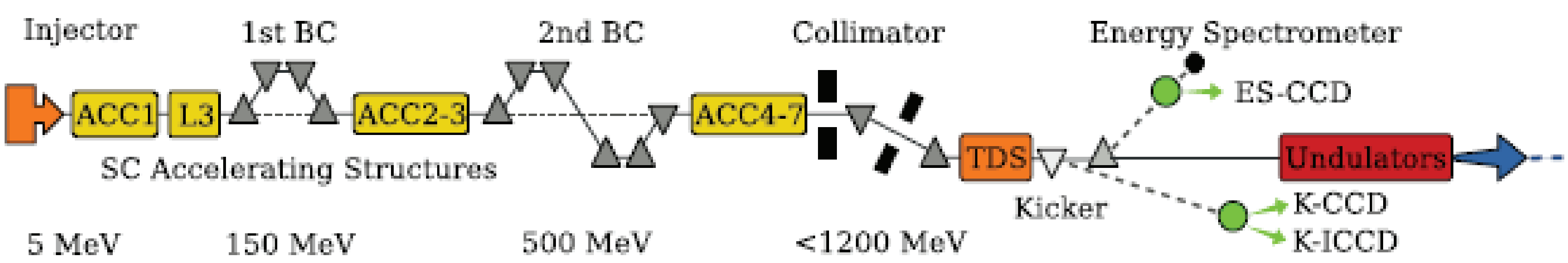


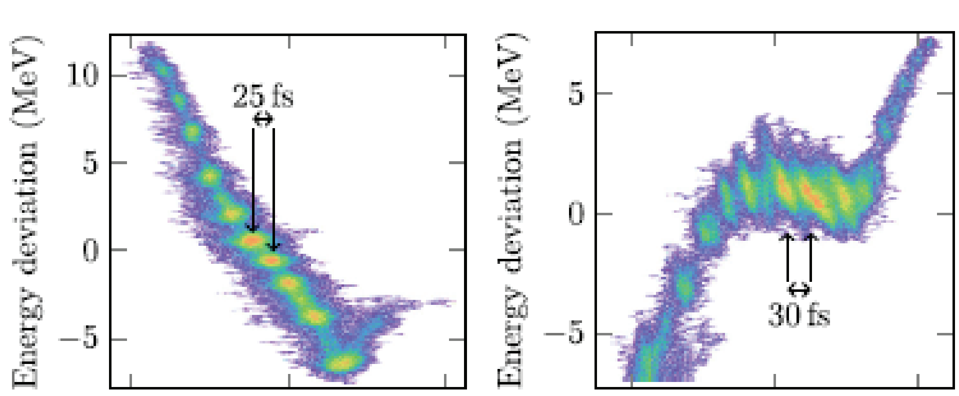


J. Welch et al., FEL10

FLASH/DESY E/t

- **Longitudinal phase space shows μBI structures**

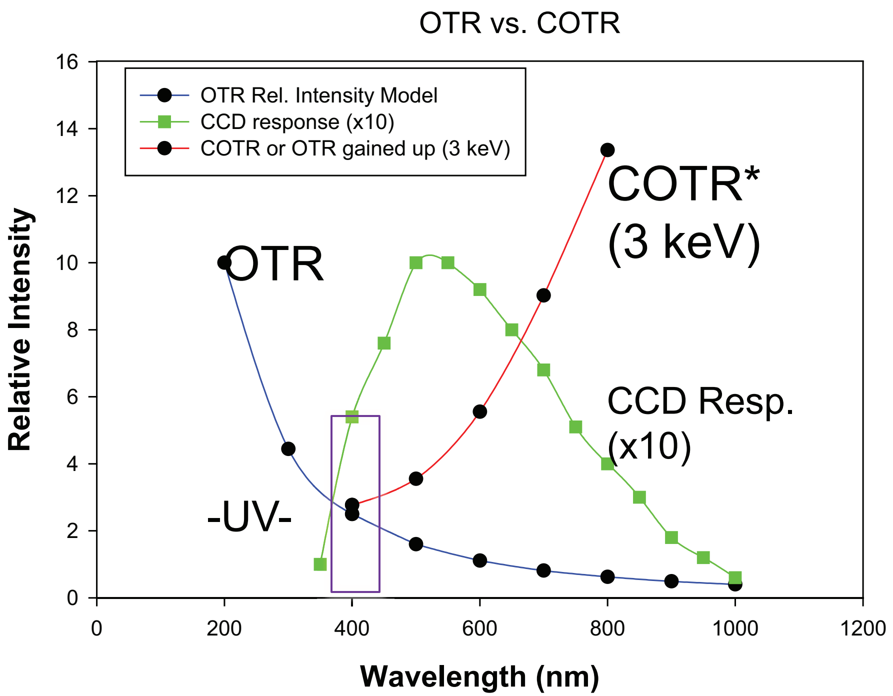


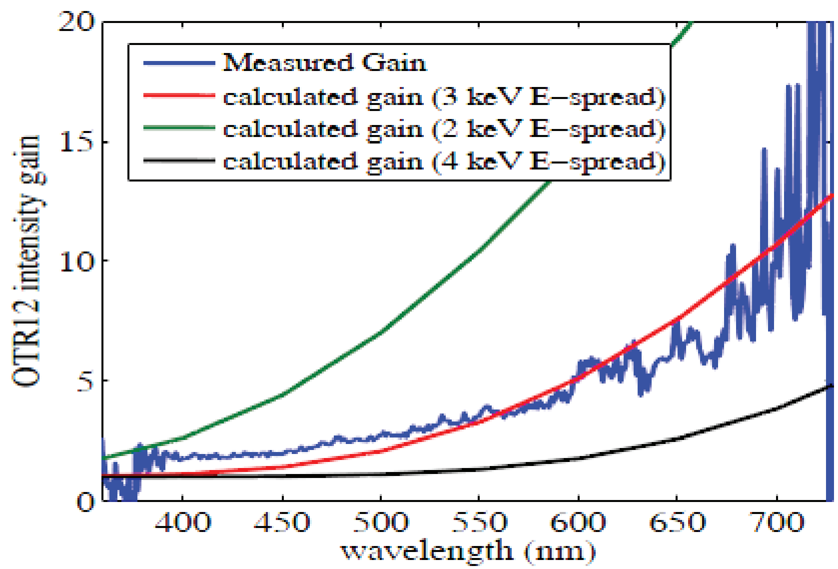


C. Behrens et al. PRST-AB **15,** 062801 (2012)

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.

$$\langle |b_e(k)|^2 \rangle \approx \frac{4}{3N}\left[\frac{I_0(z_0)}{\gamma_0 I_A}\frac{R_{56}L_d}{\sigma_{z_0}^2}\right]^2 \times \frac{\exp\left[-k^2R_{56}^2\sigma_{z0}^2 - k^2(R_2^2+\theta_y^2R_{34}^2)\sigma_{x0'}^2\right]}{\left[1+\gamma_0^2(R_1^2+\theta_y^2R_{33}^2)\right]^2}$$

$$\frac{dW}{d\omega} = \int_{-\theta_m/2}^{\theta_m/2} d\theta_x \int_{-\theta_m/2}^{\theta_m/2} d\theta_y \times \left(\frac{d^2W}{d\omega d\Omega}\right)_1 \left[N + N^2|b_e(k)|^2\right].$$

Summary of COTR tests

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

plus FERMI, BNL results

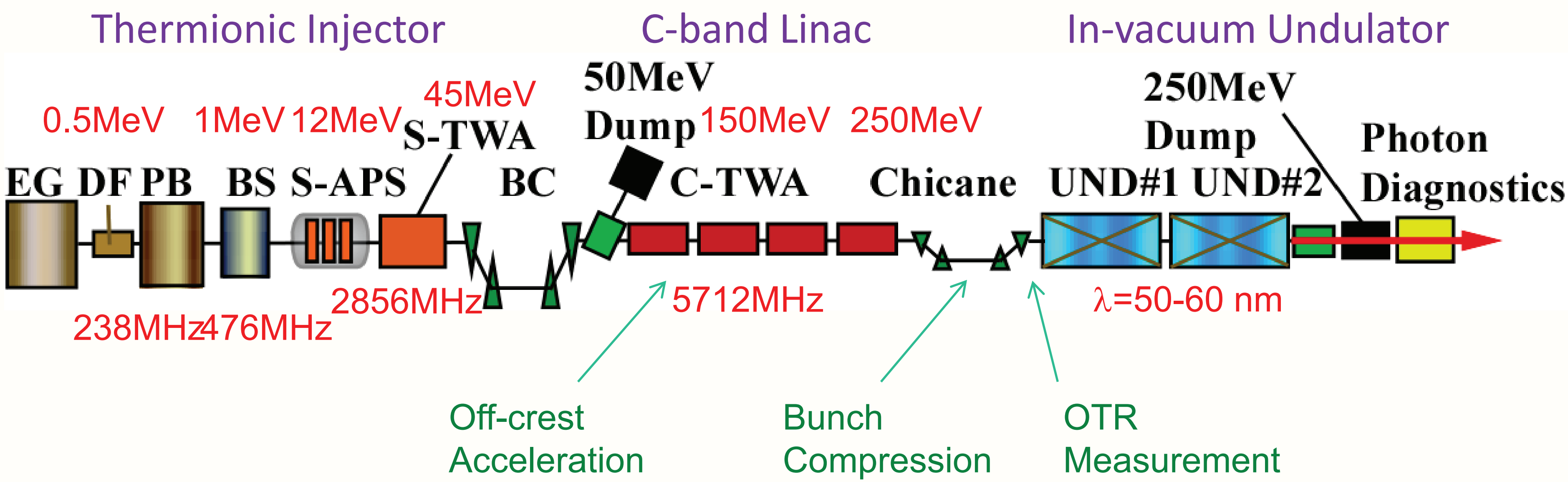
SCSS Test Accelerator

Specifications of Bunch Compressor and Dark Current Suppression Chicane at Test Accelerator

	Bending Angle (θ)	Momentum Compaction (R_{56})	Dispersion (η)	Beam Energy	Peak Current
BC	5.73 deg.	-20 mm	110 mm	45 MeV	300 A
Chicane	5.73 deg.	-28 mm	150 mm	250 MeV	300 A

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

COTR Generation Experiments at the SCSS Test Accelerator

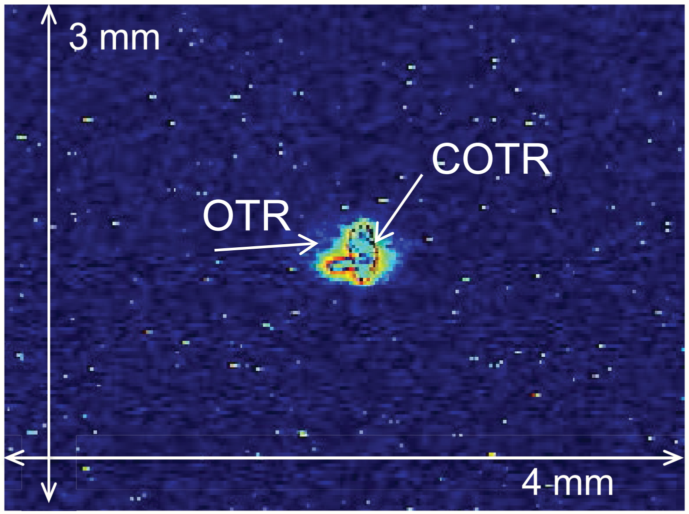


- The acceleration phase of the C-band main linac shifts to the bunching side to give an energy chirp.
- Chicane works as the second bunch compressor to compress the bunch more.
- Intensity of the OTR light was measured at the exit of the chicane.

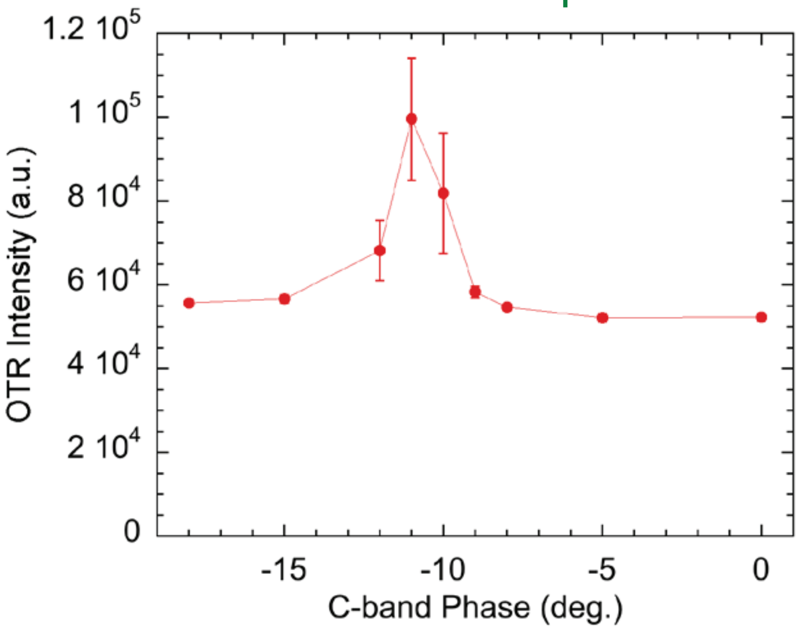
Courtesy of K. Togawa

COTR Generation Experiments at the SCSS Test Accelerator

COTR Image



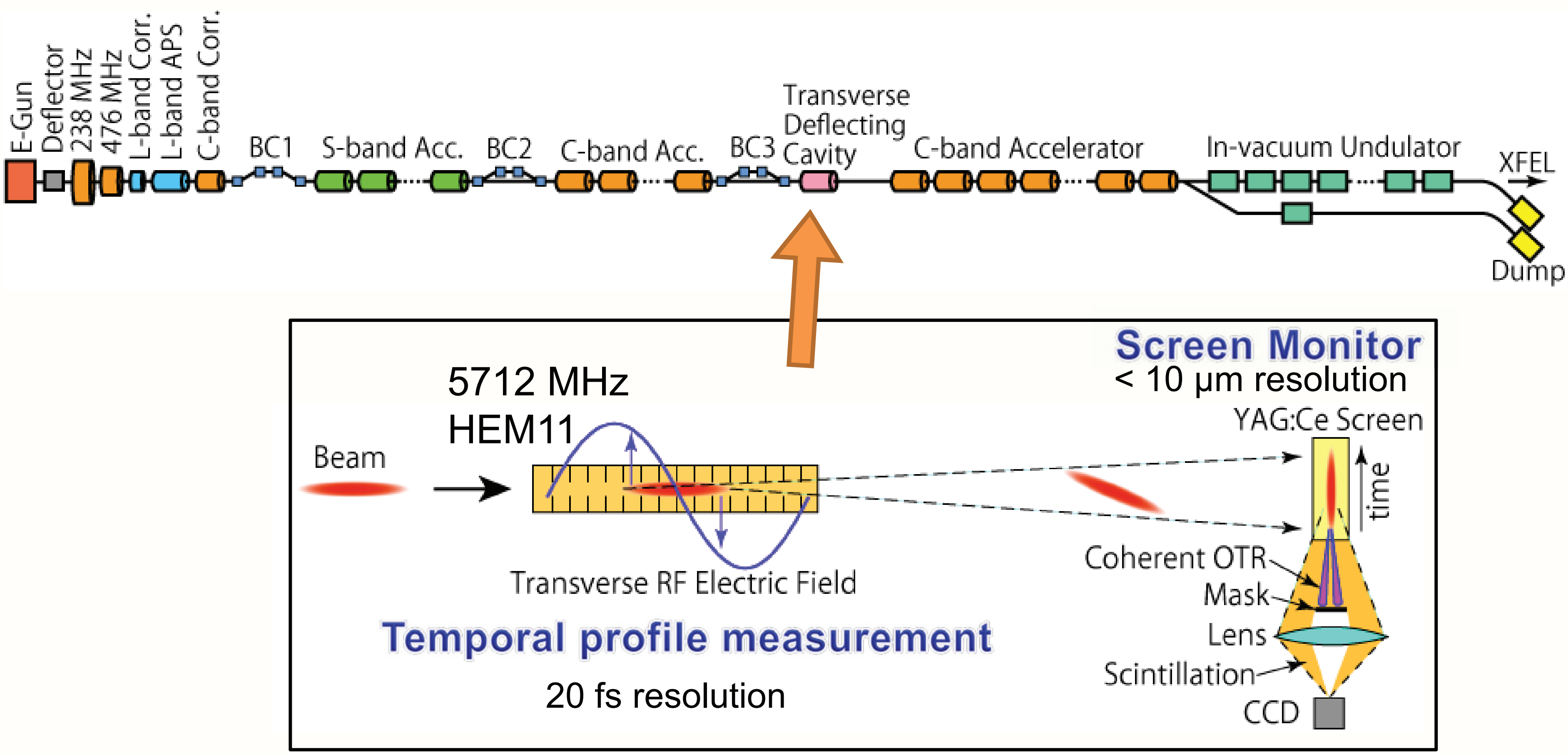
C-band Phase Dependence



- 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

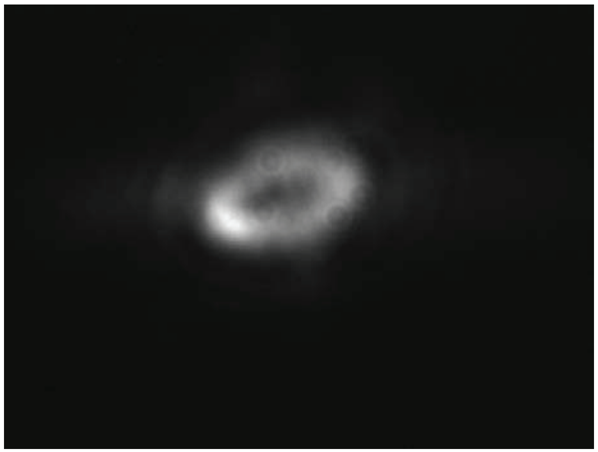


4th Microbunching Instability WS, Univ. of Maryland April 11-13, 2012

Courtesy of the SACLA Team

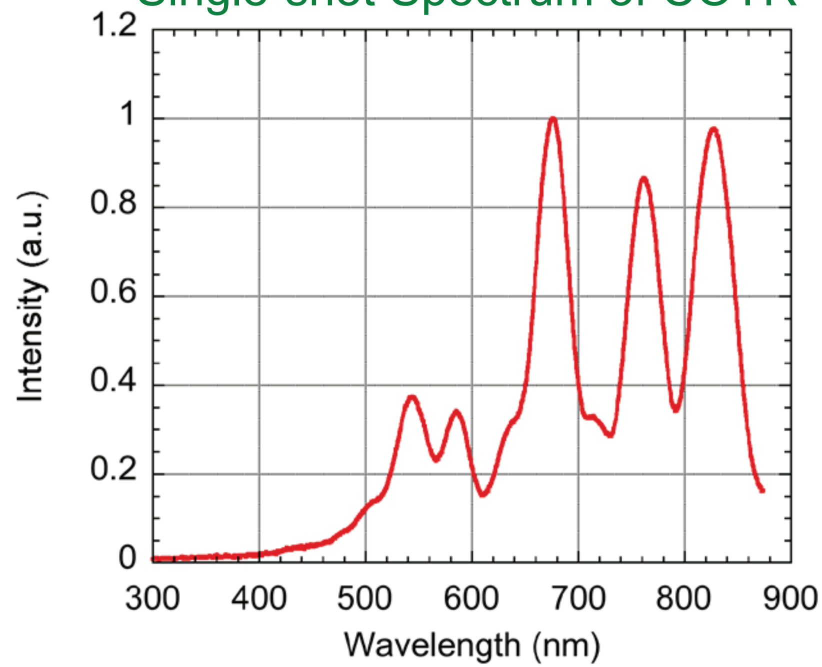
Spectrum of the COTR at the SACLA

Near Field Image of COTR



The Gain factor of the intensity is ~6x10^3.

Single-shot Spectrum of COTR

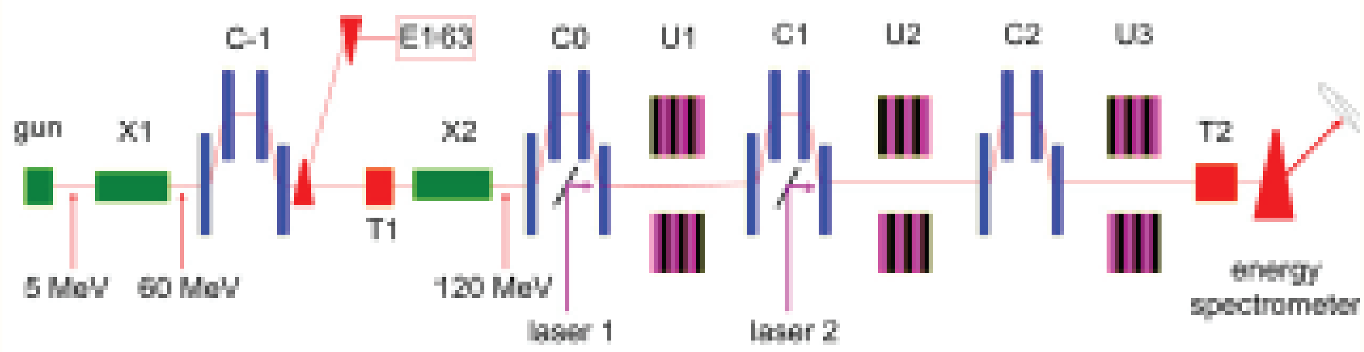


- Measured after the 3rd (final) bunch compressor (1.4 GeV).
- Vacuum Window : Quartz Grass
- Transport Mirror : Aluminum
- Spectrometer : Grism
- Longest wavelength is limited by the range of spectrometer.
- Some spikes were observed. This is an evidence of microbunch.

S. Matsubara

NLCTA Results

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



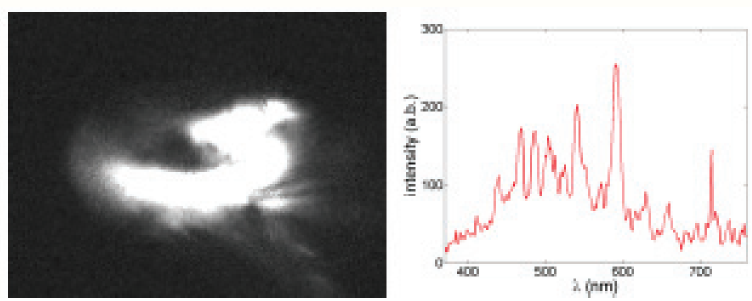


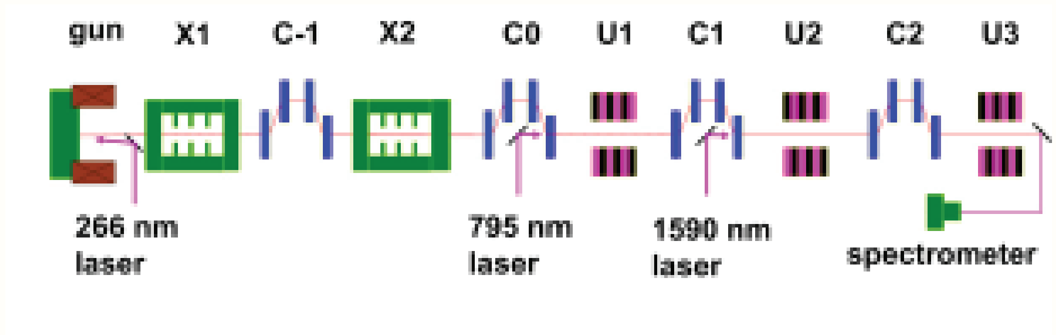
Figure 2: Typical COTR image (left) and wavelength spectrum (right).

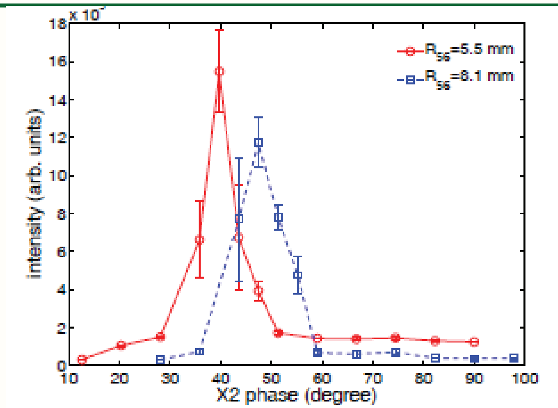
Dunning et al., PAC11

NLCTA Results: X-band

Fermilab

- **Microbunching also revealed in coherent optical undulator radiation (COUR) studies at NLCTA.**





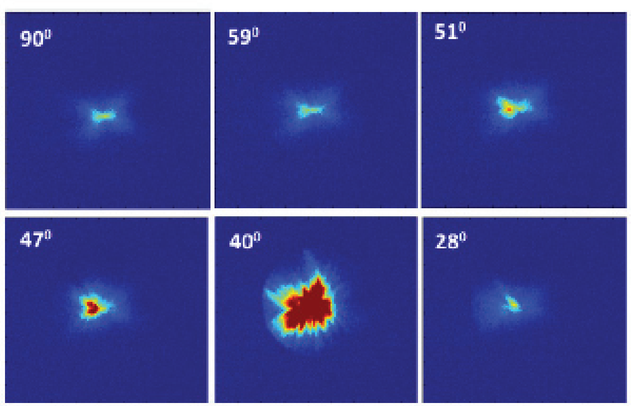
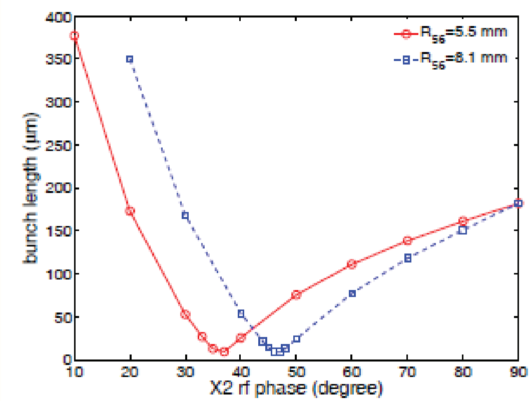


Figure 2: Radiation intensity for various rf phase in X2 measured with an OTR screen downstream of undulator U1.



Weathersby et al., PAC11

SUMMARY

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- Microbunching instability in electron beams worldwide.
  - Initially photocathode generated beams in L-band, S-band accelerators. Q= 200-400 pC per micropulse. Now at X band.
  - 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.

Acknowledgements

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