# Observation of Coherent Optical Transition Radiation in the LCLS Linac

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# Coherent Optical Transition Radiation

- Each electron emits transition radiation with a broad spectrum, with a phase that depends on the electron's arrival time.
- In a typical beam, the arrival times of the electrons are random at optical wavelengths, so the energies emitted by the electrons sum: $P \sim N_e$
- If the electron beam is modulated at optical frequencies, the electric field sums coherently $P \sim N_e^2$
- Since $N_e \sim 10^9$ even a small modulation amplitude can generate a large coherent effect
- The high longitudinal brightness of beams for X-ray FELs can support optical wavelength modulation.
- Modulation will affect ANY prompt emission: OTR, ODR,Cerenkov, etc.
  - Makes beam diagnostics difficult
  - Interesting physics


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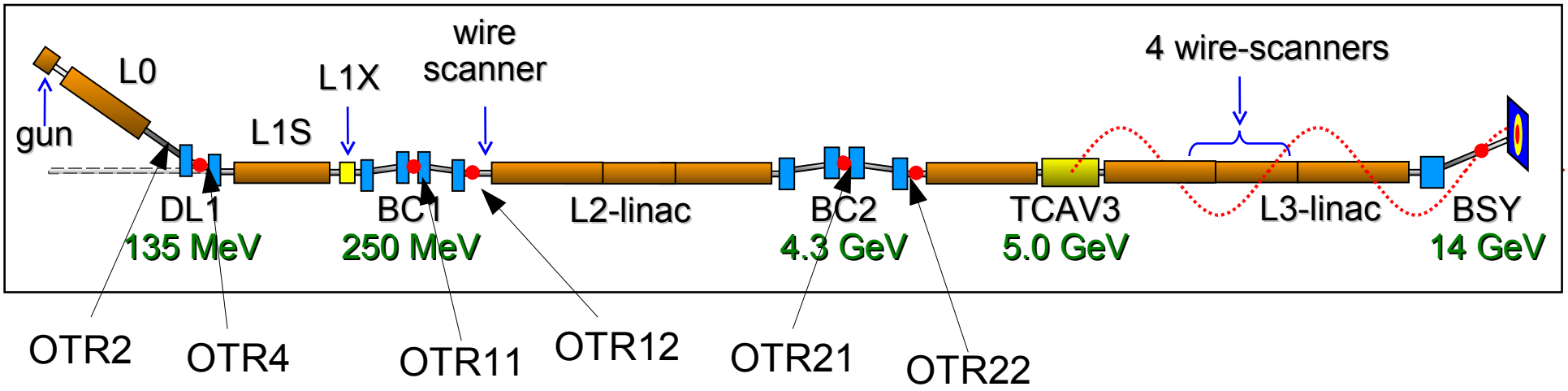
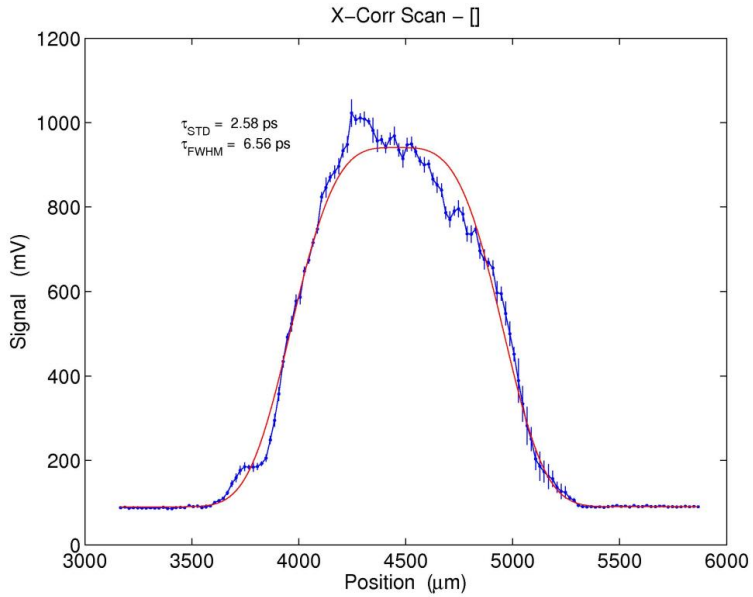
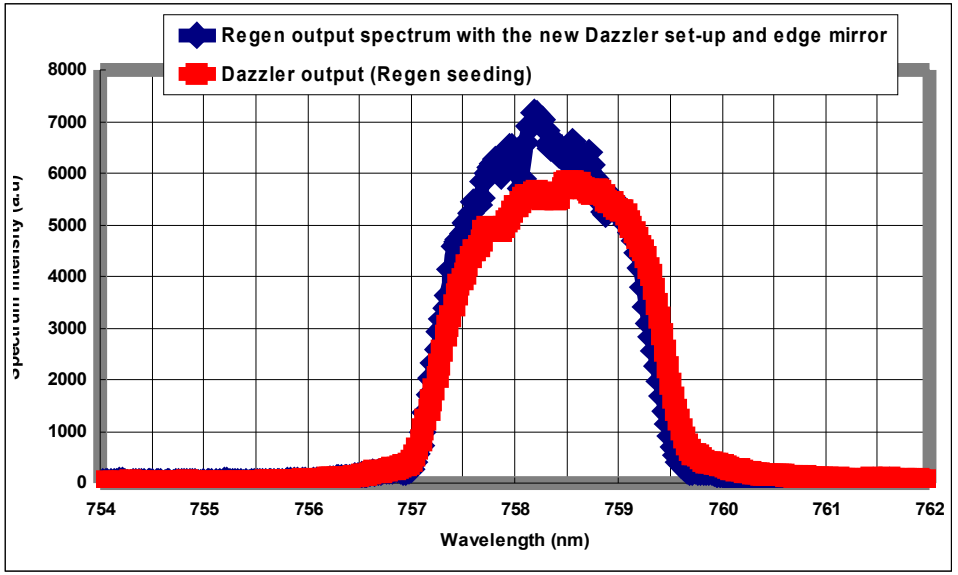
# The LCLS Accelerator




- Energy: 4.3 to 14 GeV,
- Charge: 20pC to 1nC. Typical operation is 250pC
- Peak Current
  - Gun to 250 MeV: 30A
  - After BC1: 300A
  - After BC2: 2500A
- Slice energy spread <5KeV (measurement limit) before compression.
- Emittance ~ 1 micron RMS normalized

# Laser System




- Frequency Tripled Ti:Sapphire Laser
- Bandwidth 3nm at 760nm. UV bandwidth is ~0.7nm
- Limits modulation wavelength to > ~100 microns
  - Laser modulation cannot produce optical bunching without compression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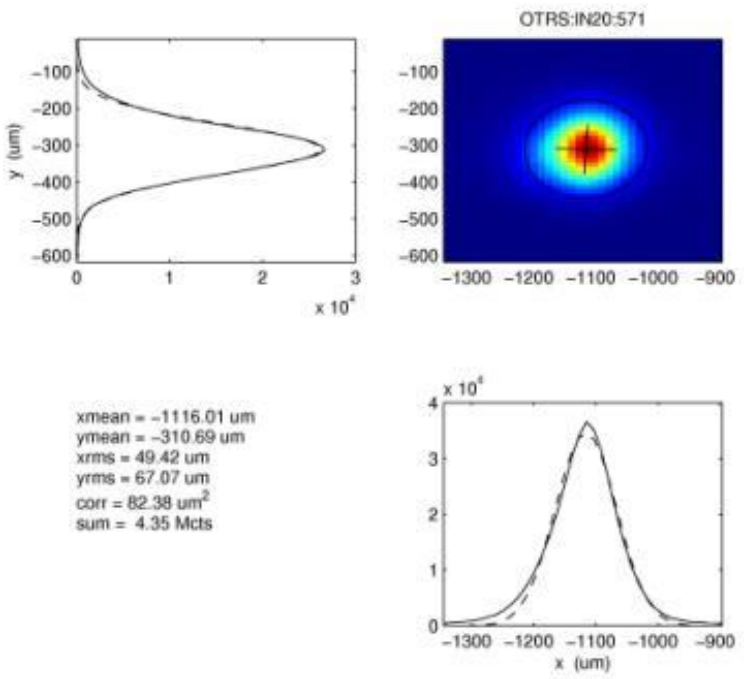
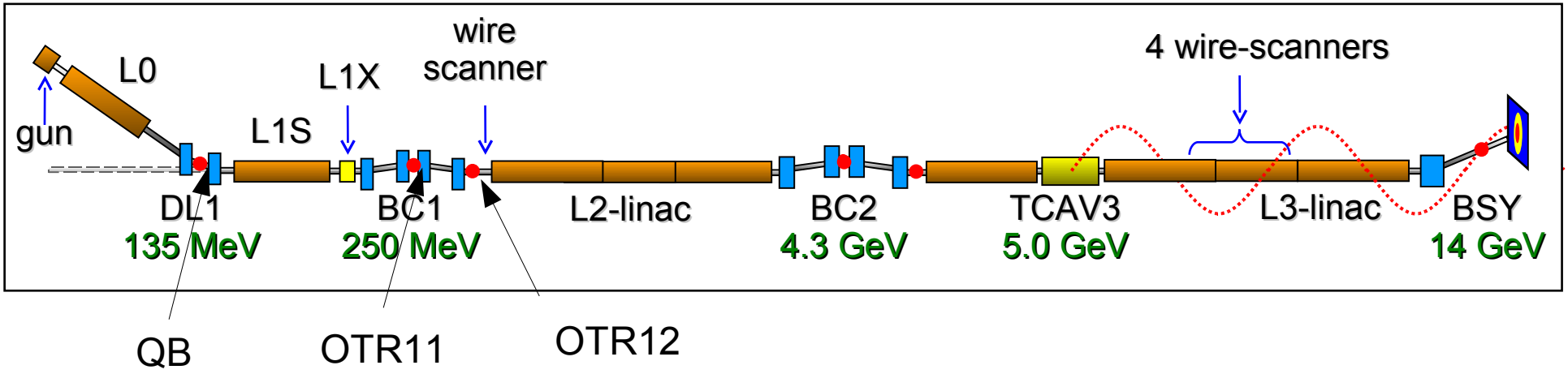
# LCLS OTR Monitors

- Radiators
  - 1 micron Al foil increases beam emittance ~5X, but does not cause significant beam loss.
  - Foil at 45 degrees to camera and beam – limited depth of field
- Camera
  - 12 bit, 1392 X 1040.
  - BW or color
- Filters
  - Neutral Density
  - Diffraction grating for spectrum

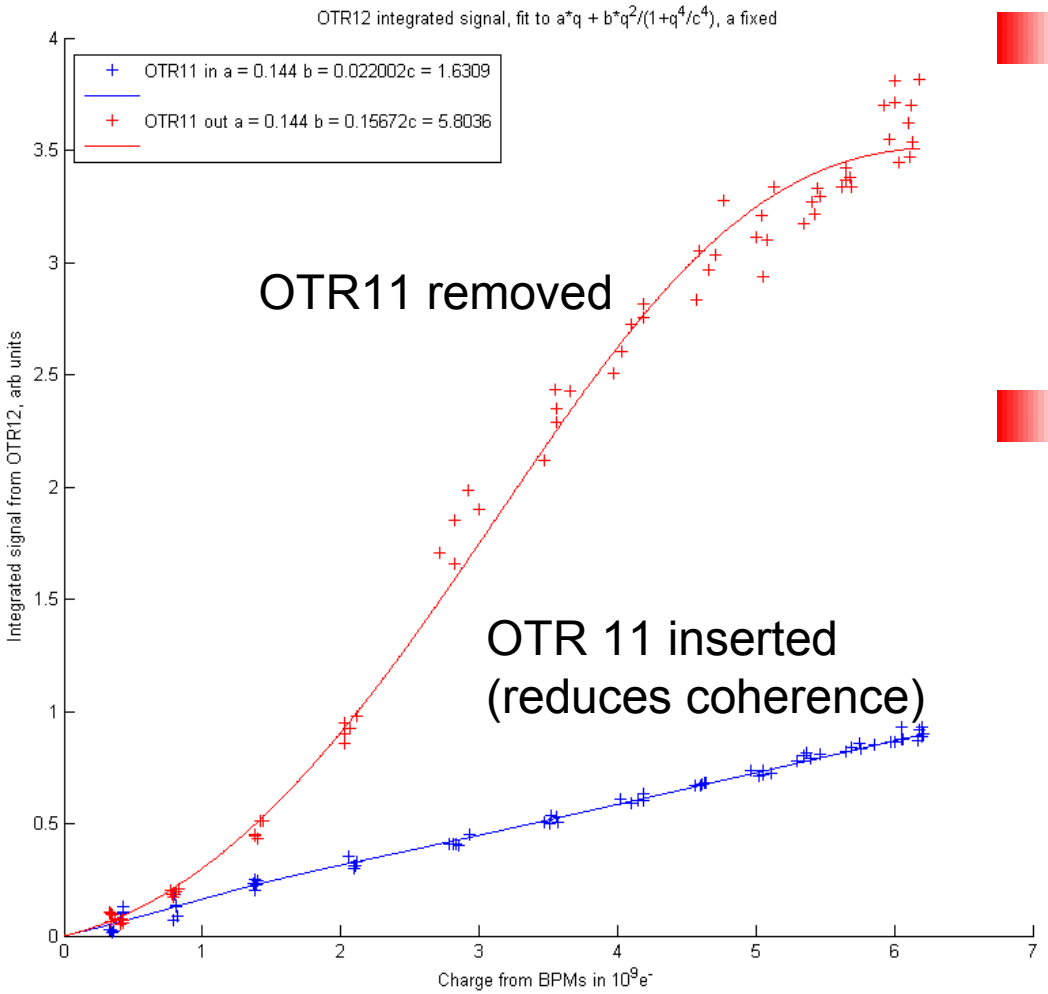


# Coherent OTR without compression



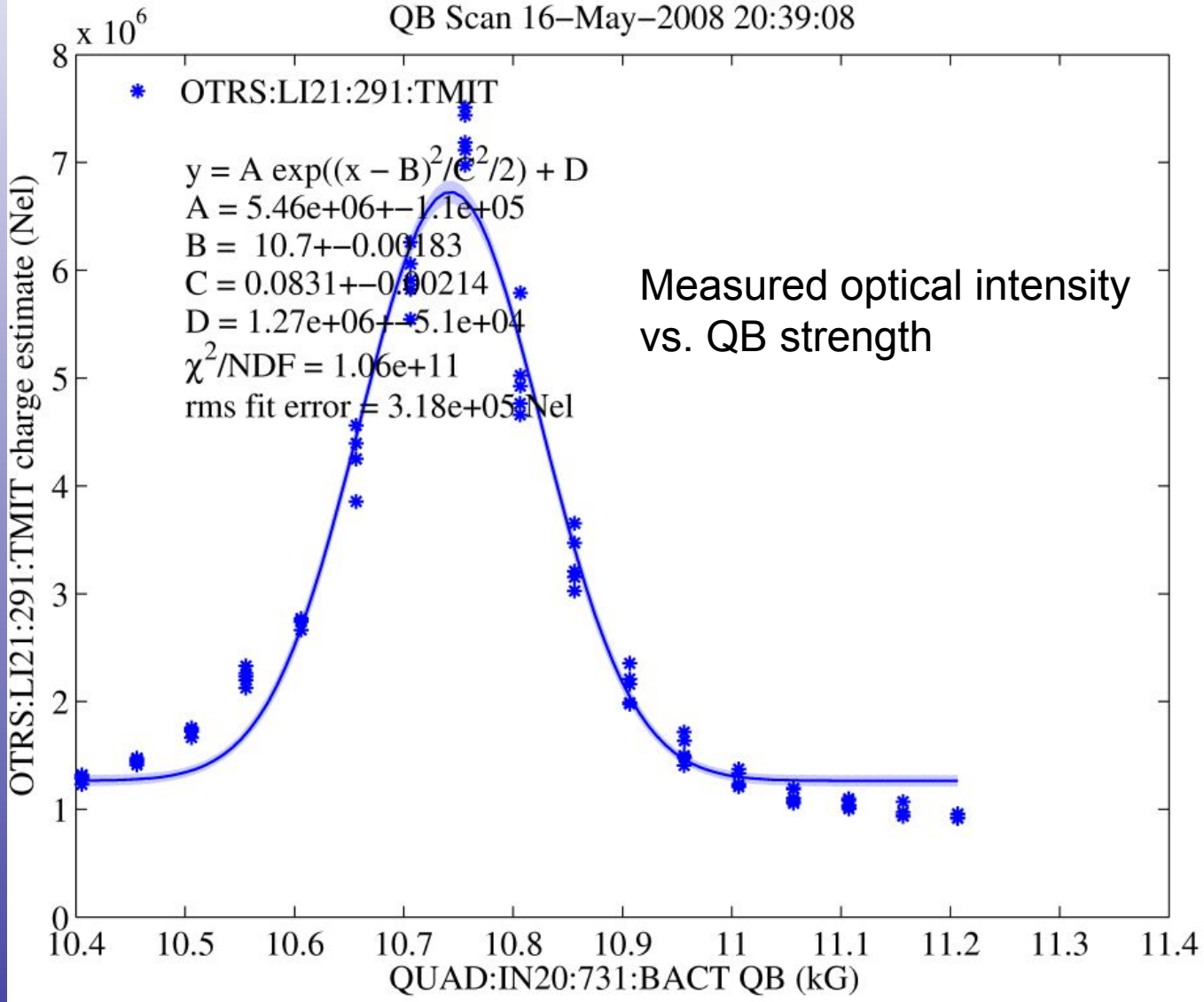

- Bunch compressor BC1 OFF (Beam line straight)
- Injector RF on crest
- Scan quad “QB”, dispersion matching quad in first bend
- Theory: Shot noise current -> energy modulation, $R_{56}$ in bend -> current modulation.

# Integrated Optical signal at OTR12 vs Charge

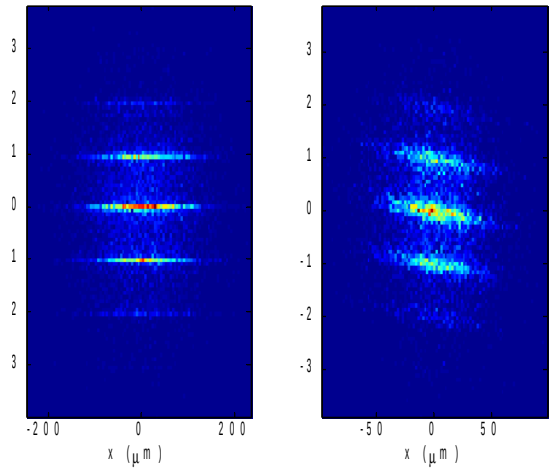



- Optical signal vs charge
  - Linear term
  - $Q^2$ term, attenuated above some frequency
- $P = aq+bq^2/(1+q^4/c^4)$
  - Empirical

# Coherent OTR with QB scan (no compression)




Measured optical intensity vs. QB strength



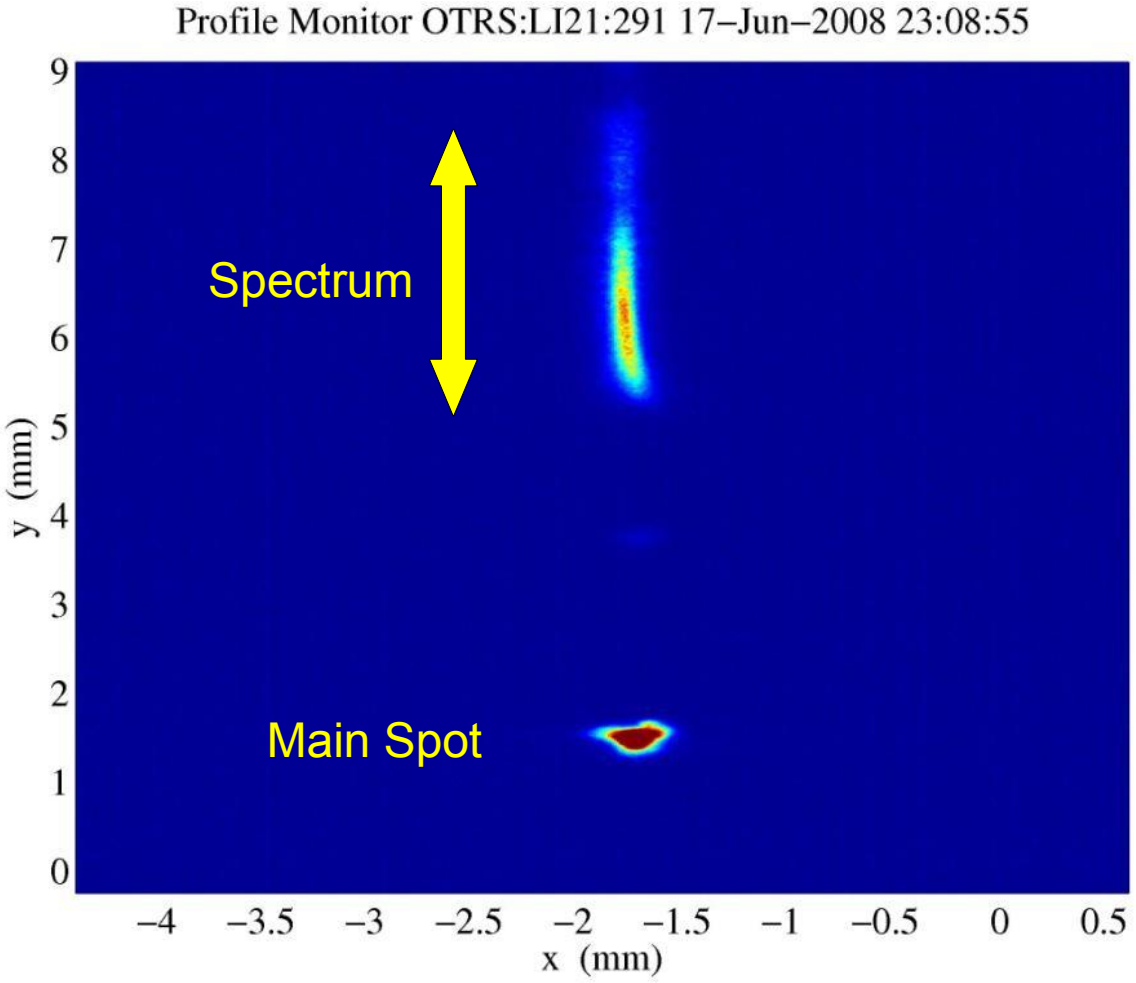

Simulation

Changing QB “tilts” microbunching wavefronts.

Theory predicts 2X narrower curve – still under study

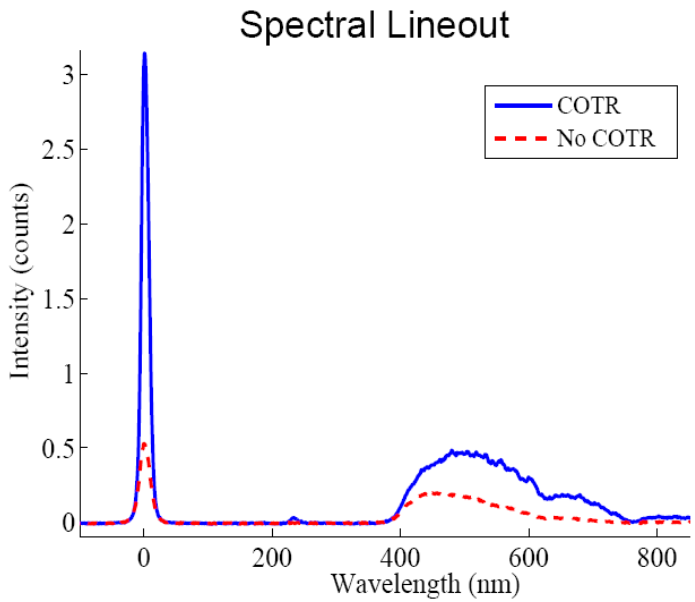
# Spectral Analysis

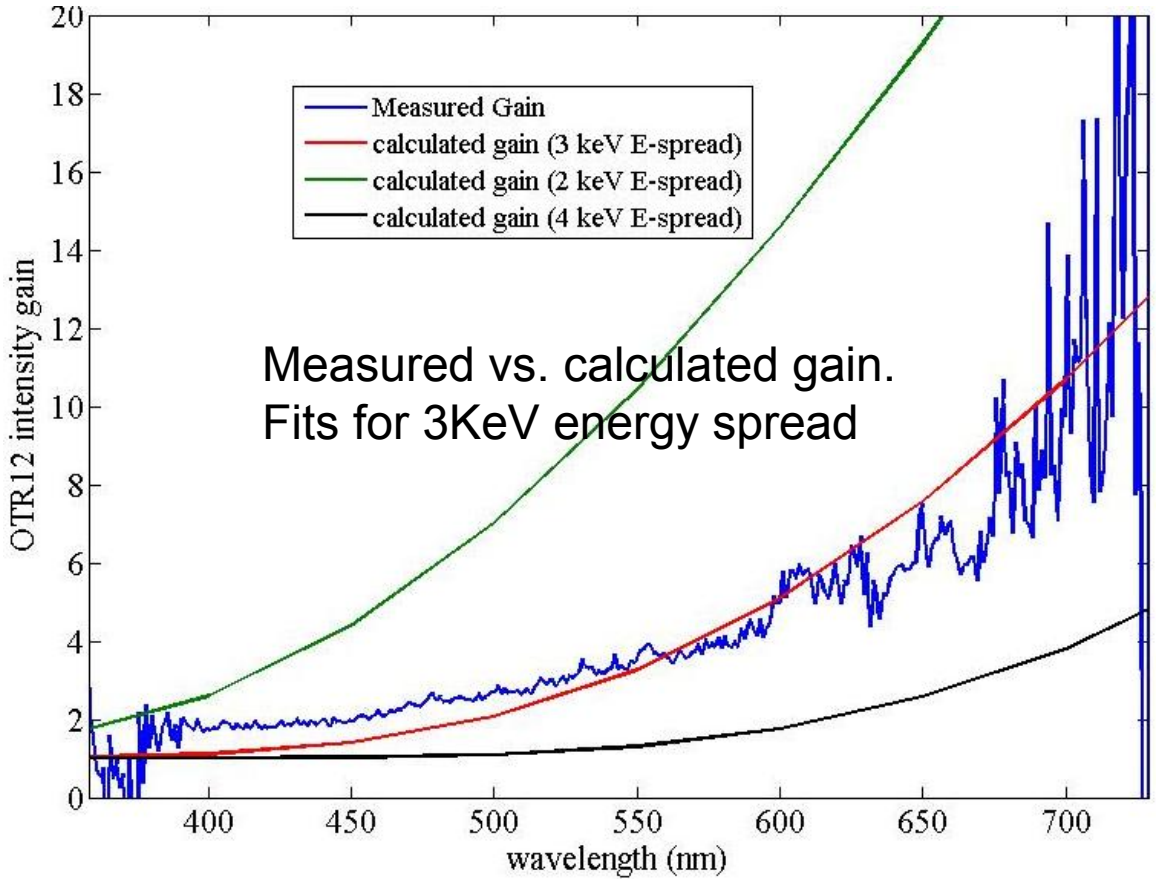
- Installed diffraction grating in OTR12
- Gives low resolution spectrum from 400nm to 800nm.
- No absolute intensity calibration, but can compare with incoherent radiation.



# Uncompressed COTR spectrum

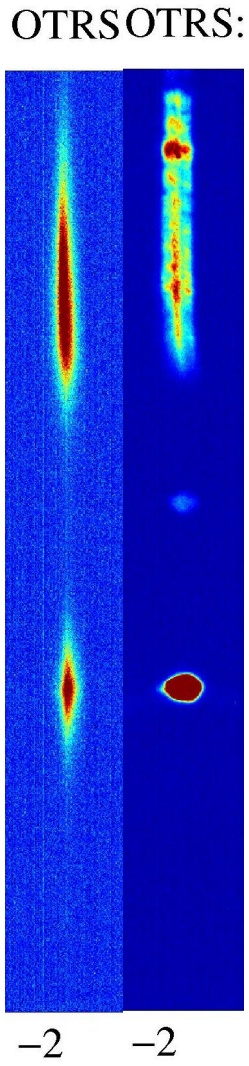
- Spectrum on and off peak of "QB" curve vs. theory
  - Simulation: I=40A, Emittance = 1 micron, 2.5KeV energy spread.




Measured vs. calculated gain.
Fits for 3KeV energy spread

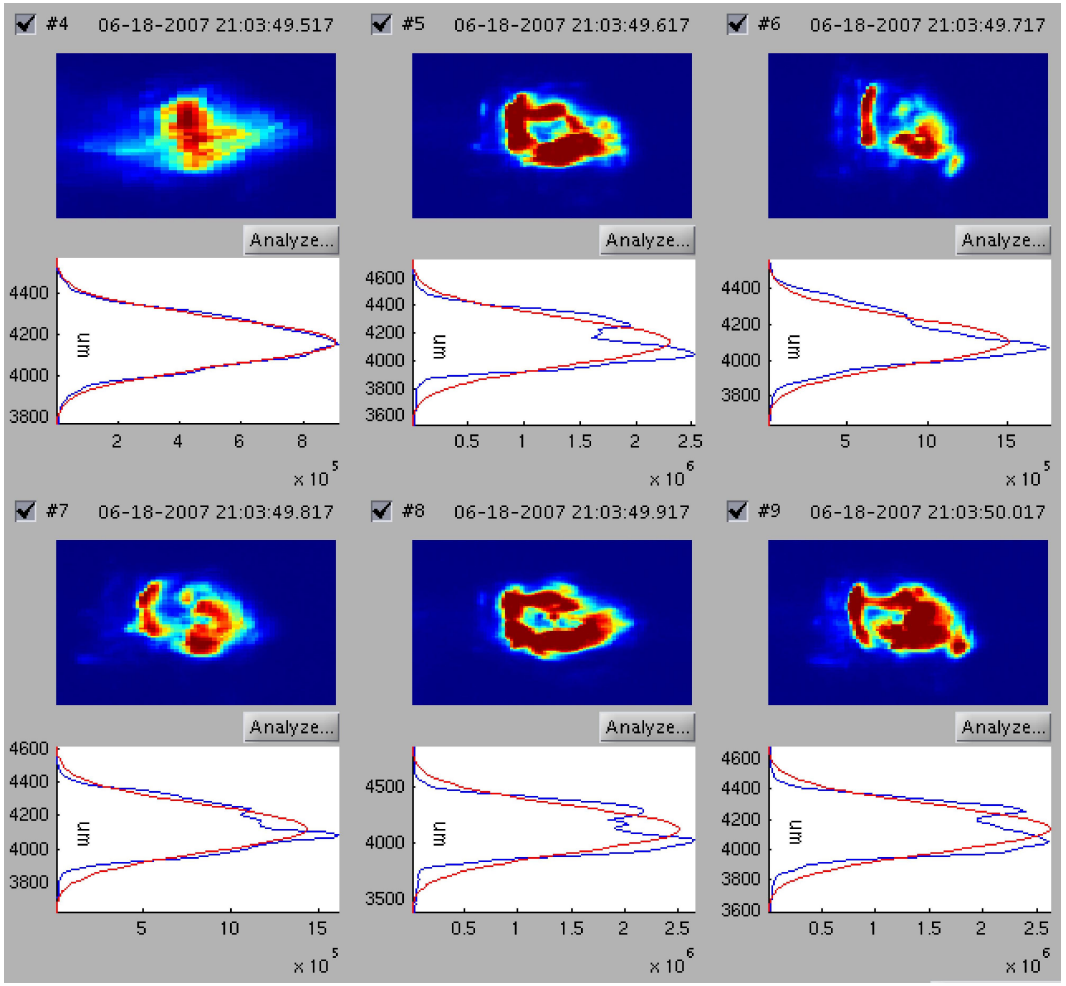
# COTR with compression in BC1 (250MeV)




- Image on OTR12 (after BC1) with OTR11 inserted and removed
- OTR11 increases incoherent energy spread, reducing high frequency modulation
  - Angular spread in BC1 mixes different energies after compression
- Coherent light image attenuated X64 relative to incoherent signal
- Coherent enhancement 10X-100X depending on operating conditions

# COTR "Rings" at high compression (BC1)

- Frequently observe "rings" with strong COTR
- Note this is near field, NOT far field
- OTR electric field is radially polarized
- Coherent emission proportional to spatial derivative of current profile





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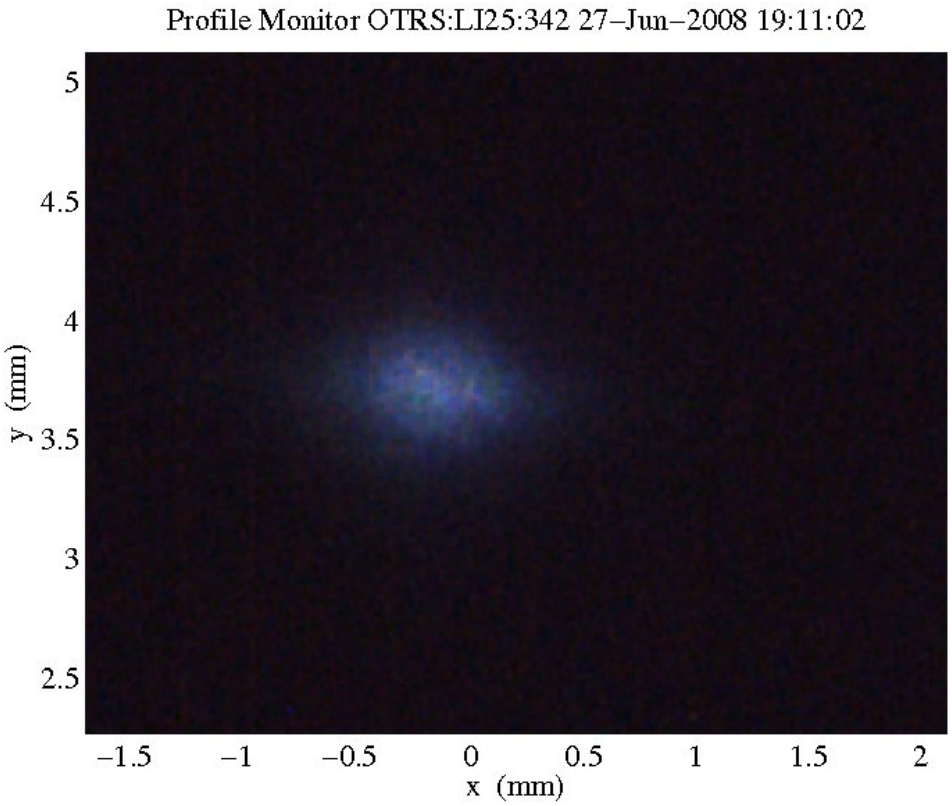
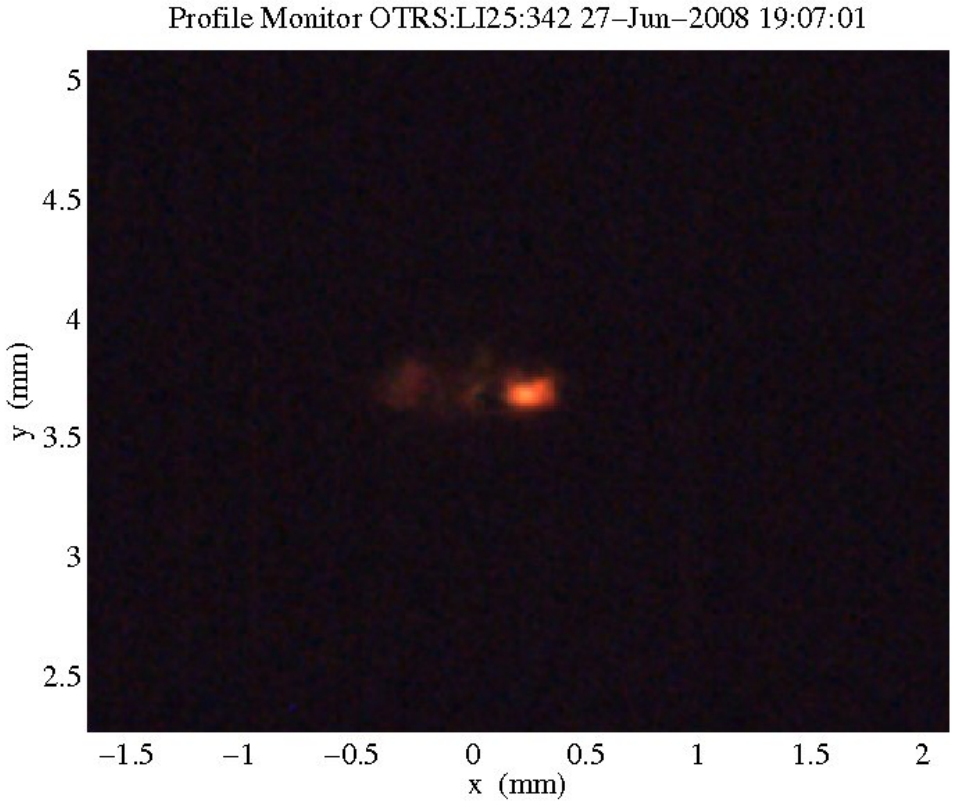
# COTR after BC2 on OTR22

Approximately true color images. Note longer wavelength of coherent signal

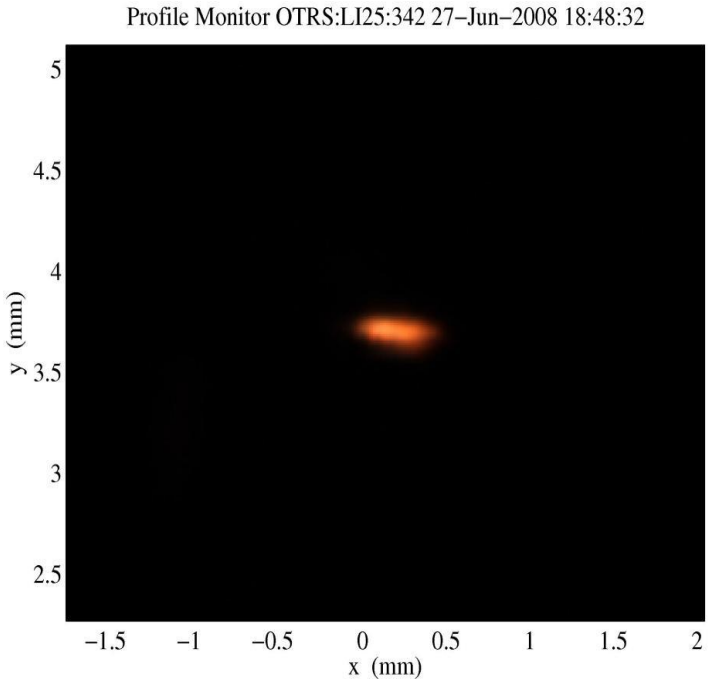
OTR11, OTR21 inserted, no coherence

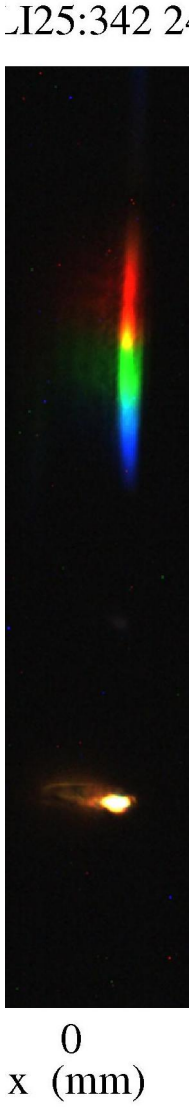


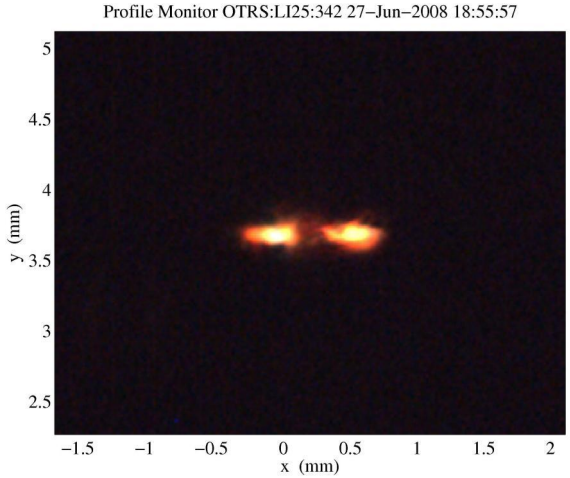

Normal operating conditions
X10,000 optical attenuation

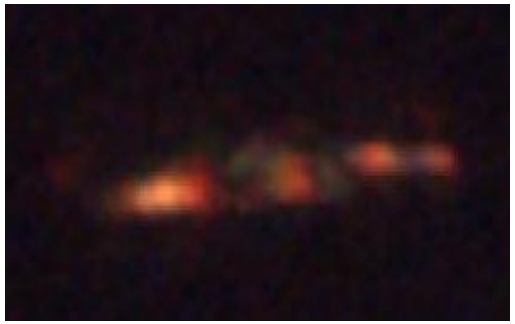


# COTR with maximum compression after BC2



Near maximum compression
Approximately $10^5$ X incoherent signal

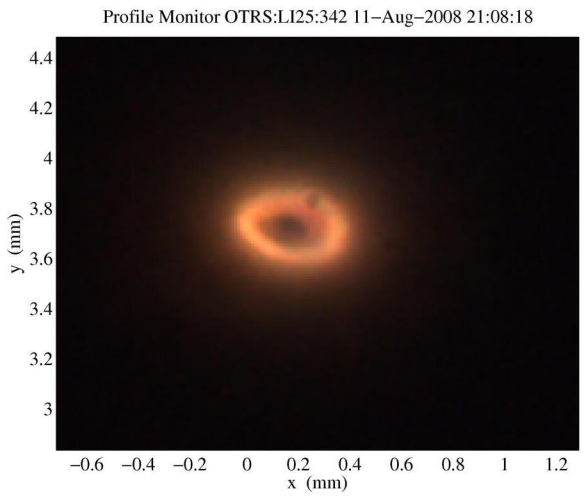
spectrum broad but variable

At full compression, CSR breakup + COTR produces various shapes

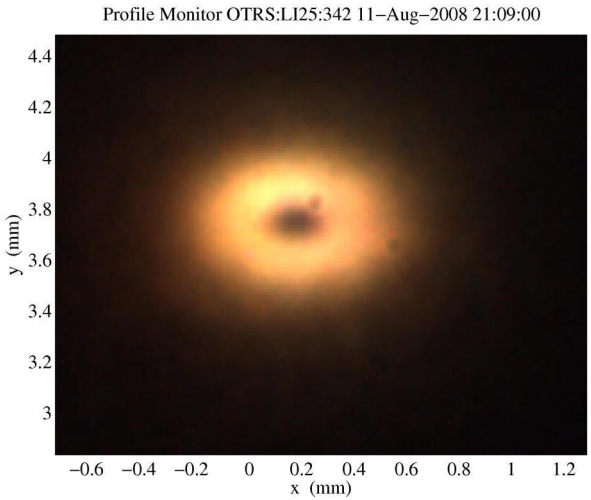
# Upstream foil INCREASES COTR after BC2

Measured at 150pc, but effect seen at higher currents as well.
Foil inserted before first bend increases COTR see after second bunch compressor

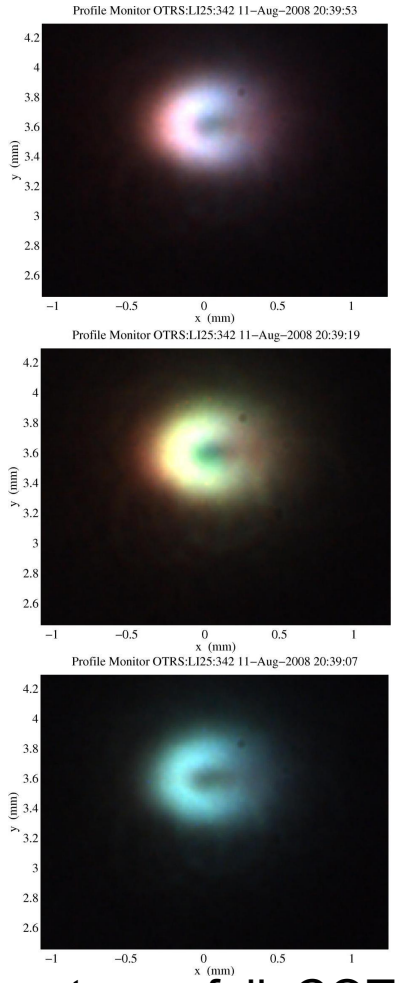
Effect seen for under and over compressed beams.




Upstream foil removed




Upstream foil inserted
~2.5X integrated intensity

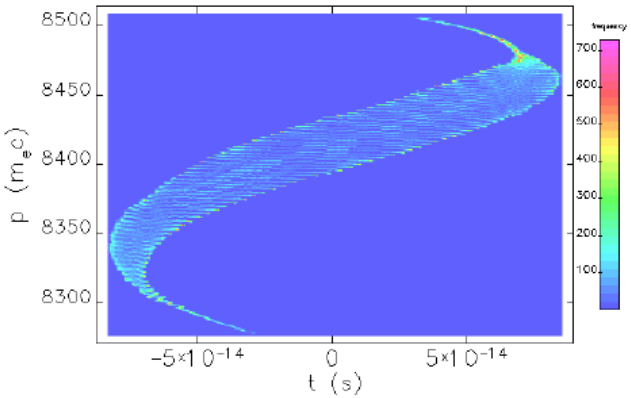


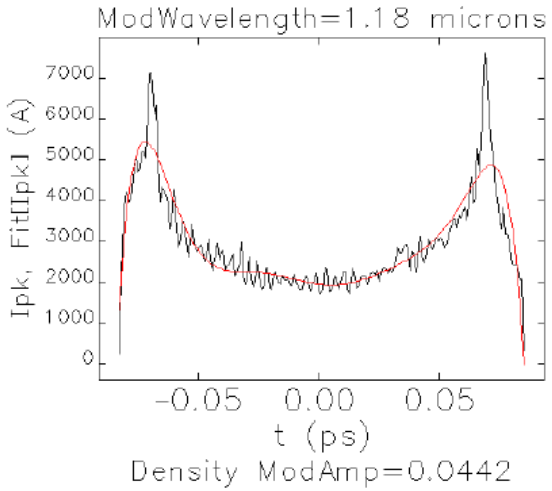

With upstream foil, COTR wavelength varies

# Upstream foil smooths modulation, produces sharper beam "horns" in bunch compressor

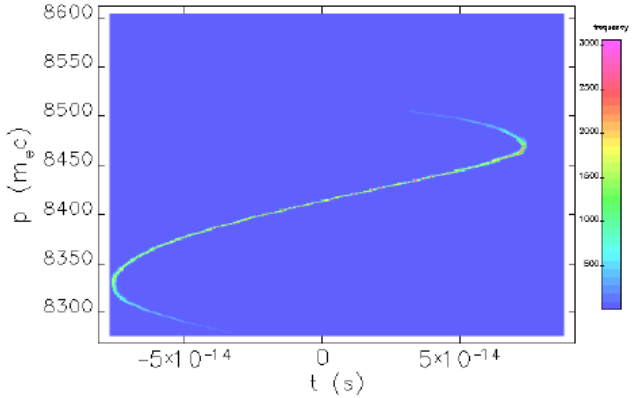
**Simulation results at OTR22**, using 2% density modulation at OTR2 with modulation wavelength of 40 um.

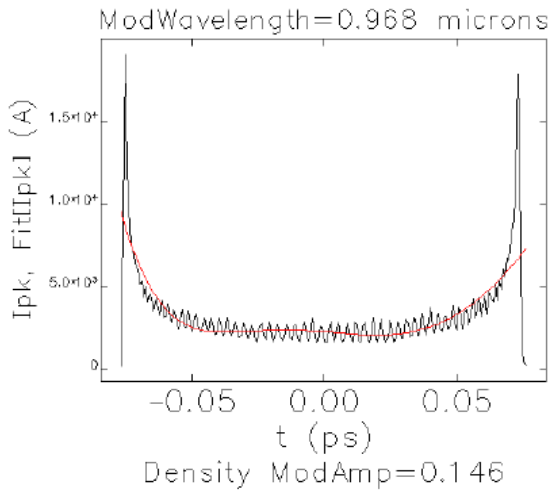
Without Foils in



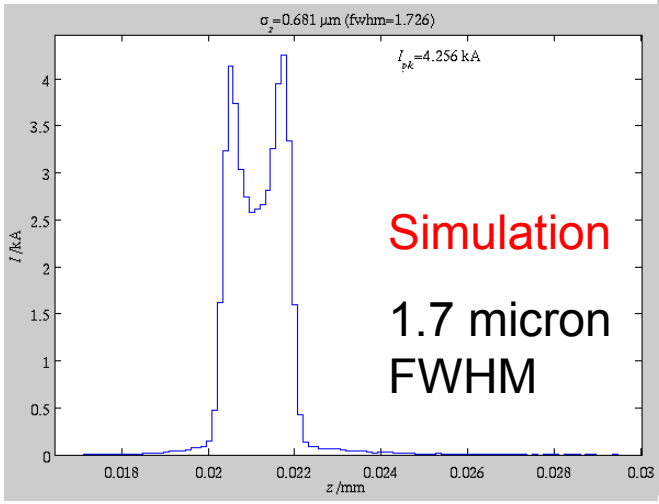



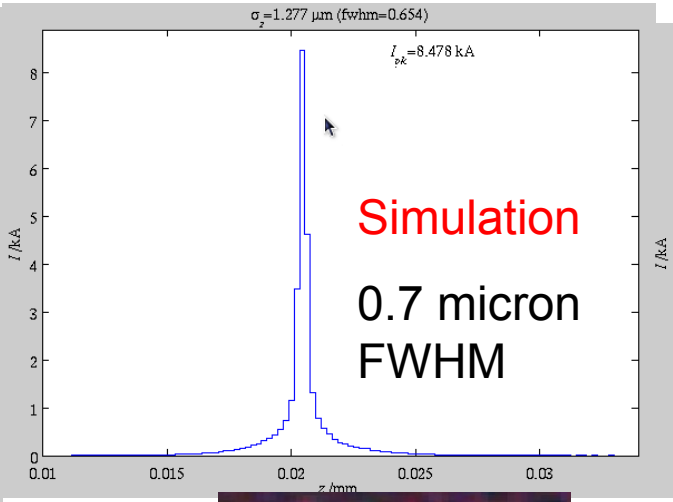

Put OTR2 foil in

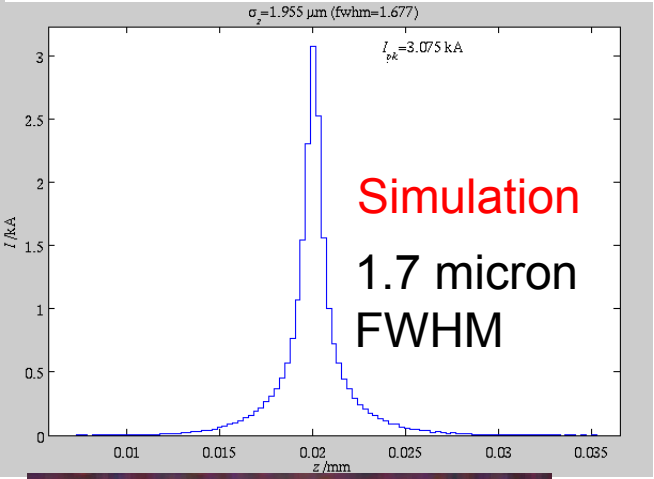


# Ultra-short bunch COTR



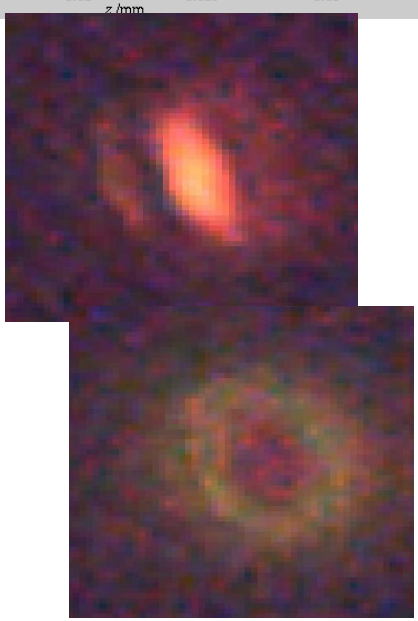



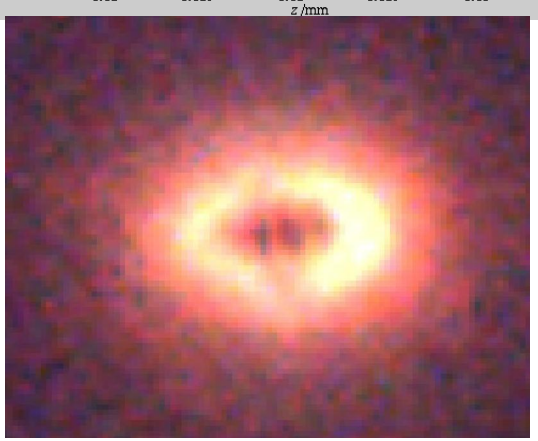




Simulation indicates that 20pC bunch can be compressed to < 2 micron FWHM

Measured beam emittance (wire scanners) 0.3 to 0.5 microns at full compression

No direct bunch length diagnostic for <2 micron bunches, but strong radiation at 2 micron wavelength observed





Strong (~$10^5$ X incoherent) COTR observed)

# COTR – what we think we know

- 3 related effects
  - Microbunching: shot noise density modulations produce energy modulation (through space charge). Energy modulation produces amplified density modulation through $R_{56}$.
  - Compression: Bunch compressors shift modulation to shorter wavelengths.
  - Beam spikes: Simulations indicate that bunch shape can have sub-micron features which can radiate coherently.
- Simulations can reproduce the observed qualitative effects.

# COTR - Physics

- The OTR stations in the LCLS were designed as beam diagnostics, not experimental stations.
  - Compact but inflexible design.
- Beamline space exists for a COTR experiment
  - Measure spectrum, divergence angle, etc
  - Calibrated power measurement.
- Potentially very interesting electron beam and OTR physics
- But – main goal of LCLS is producing X-rays.
  - Limited time for experiments.

# OTR Diagnostics

- LCLS experience is that OTR cannot be used for beam diagnostics after the first bend
  - Even uncompressed beam COTR causes large beam size distortion.
  - Compressed COTR is so strong (>$10^4$ X incoherent) that spatial filters and frequency selection are unlikely to completely eliminate coherent signal.
- LCLS laser heater (scheduled for installation this year) will increase incoherent energy spread of beam
  - Should dramatically reduce COTR : Will it be enough?
- Future high brightness accelerators will also likely see strong COTR effects