COTR Resistant Profile Monitor

International Free Electron Laser Conference 2015

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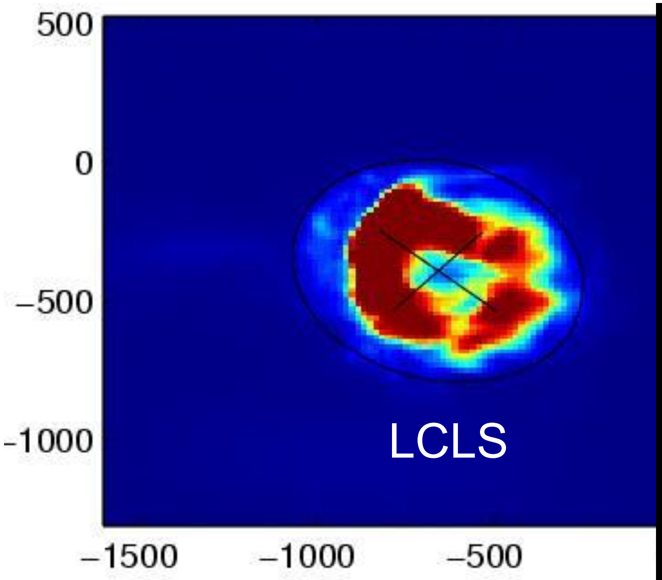
Outline

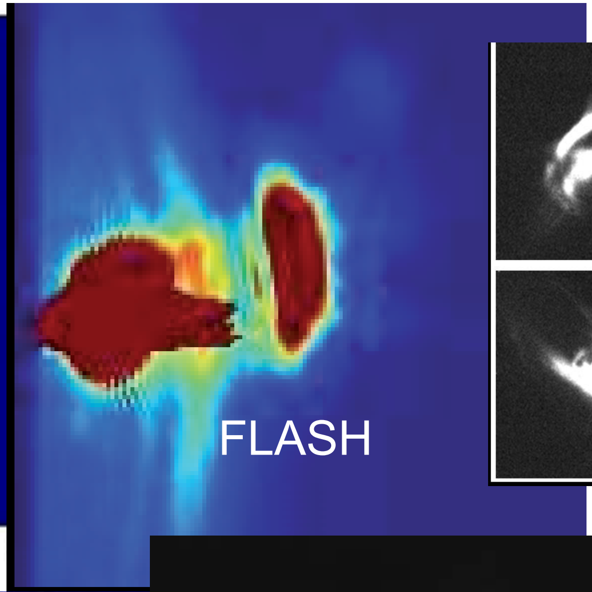
- Overview
- COTR
- Mitigation methods
  - Beam manipulation
  - OTR filtering
  - Scintillating crystals
  - PSI profile monitor
- Summary

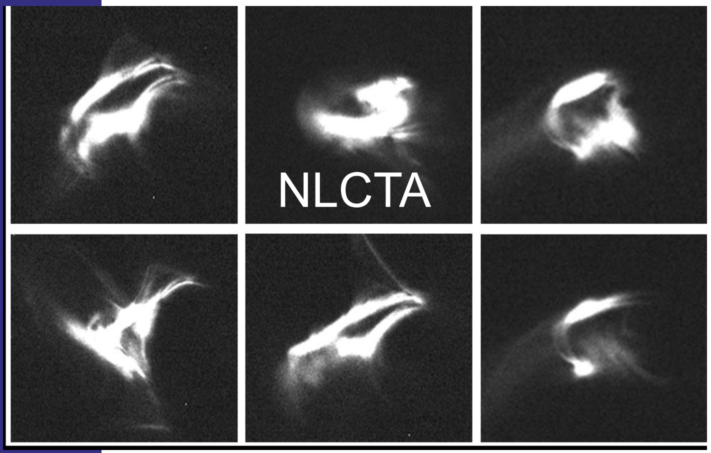
Overview

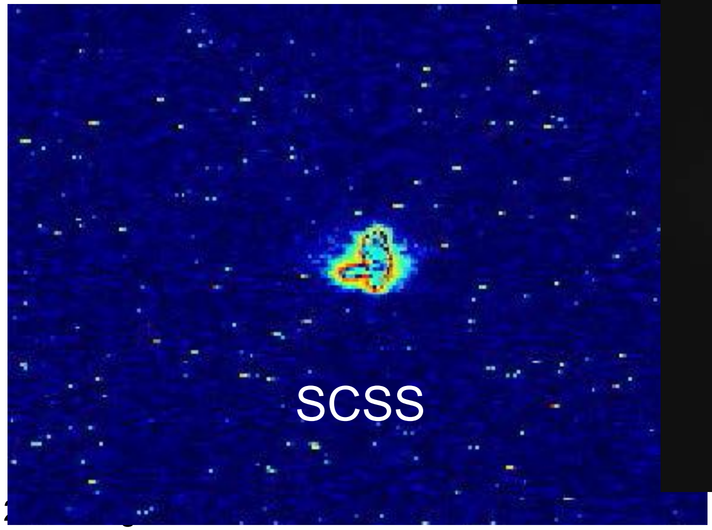
- Accelerators for X-FELs need high brightness beam
  - multi GeV
  - sub-micron emittance
  - 10^{-4} energy spread
  - sub 100 fs bunch duration
  - sub 100 μm beam size
- Need 2-D beam images (slice emittance, z-δ phase space)
- Choice of scintillator or OTR
- Initial choice OTR for XFELs (no saturation, resolution issues)
- High brightness also stimulates visible beam coherence
- Coherent OTR (COTR) makes OTR screens unusable

COTR Observations



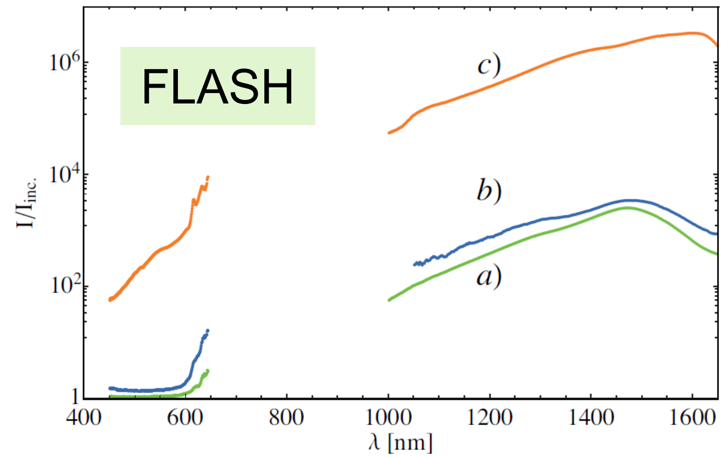




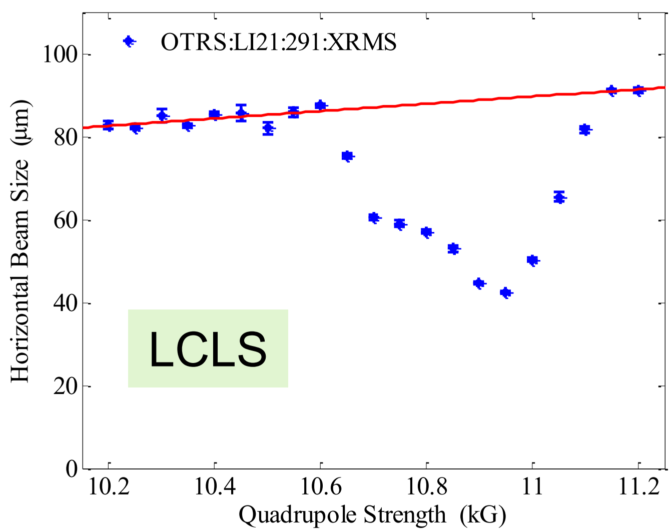


COTR Effects

- Driven by
  - longitudinal space charge instability
  - current spikes in ultrashort bunches
- Intensity enhancement
  - OTR ~ N electrons independent
  - COTR intensity ~ $N^2|f(\lambda)|^2$
- Apparent beam size changes
  - Core or fraction of bunch radiates coherently
- Shape changes
  - Doughnuts
  - Entire transverse beam extent radiates coherently



Wesch & Schmidt DIPAC11 WEOA01



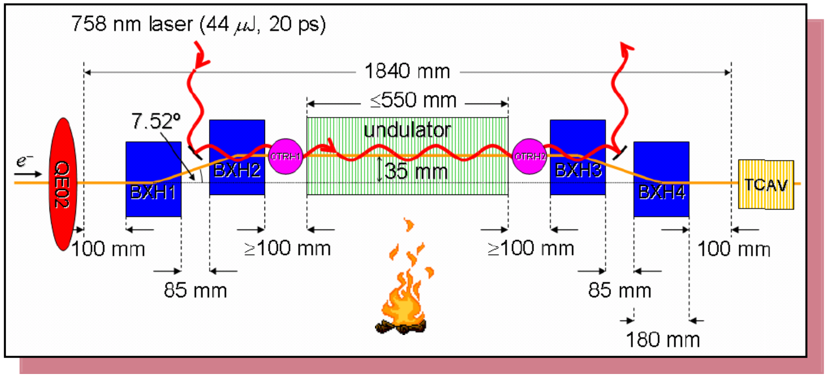
Mitigation Schemes

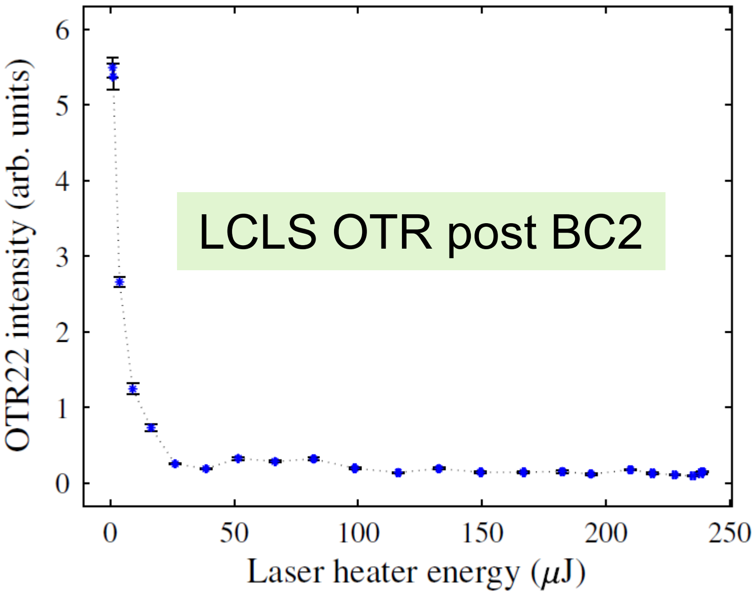
- Beam manipulation
  - Change particle distribution to suppress COTR generation
- OTR filtering
  - Selective OTR observation to suppress COTR fraction
- Scintillating crystals
  - Avoid OTR and use radiation process based on energy loss in a material

- All schemes need to suppress COTR to a level much less than the intensity of the desired radiation
  - This may require many orders of magnitude

Laser Heater

- LSC instability sensitive to slice energy spread
- Increase it with laser heater
- Should suppress COTR
- Suppression observed x100
- Still x6 above incoherent OTR

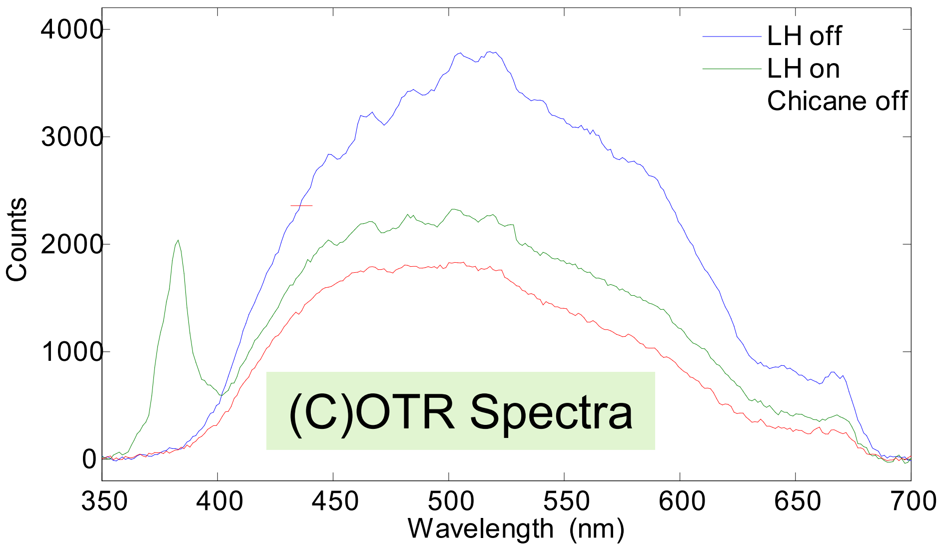




Huang et al. PRSTAB 13, 020703 (2010)

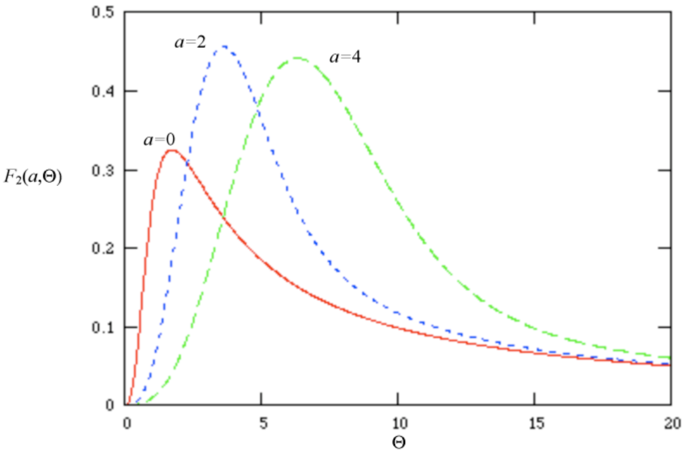
COTR Induced by Laser Heater

- LCLS laser heater chicane
  - Introduces small 8 mm R_{56}
  - Creates x2 COTR
  - Emittance underestimated by 25%
- LH on still has COTR
  - 20% enhancement still underestimates emittance

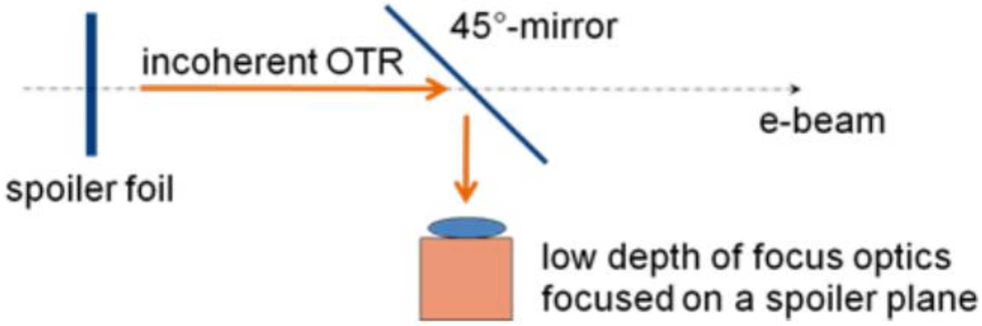


Divergence Spoiler

- Thick spoiler foil adds beam divergence
- Back side of foil generates OTR
- Beam divergence broadens OTR far-field
- Effectively narrows OTR source size
- Limits ability of electrons to interfere



- Related effect on COTR observed at LCLS

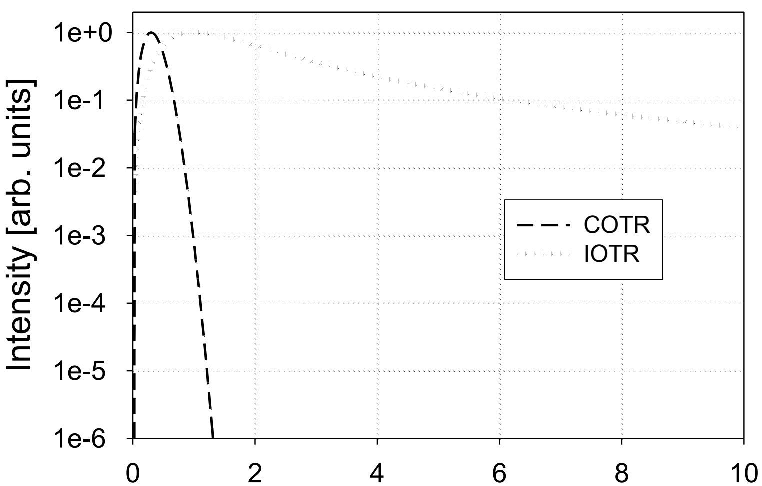


Murokh et al. PAC09 TH6REP021

Spatial COTR Suppression

- Fully transverse coherent COTR emitted by entire transverse bunch extent
- Can significantly narrow far-field distribution
- Spatial filter in Fourier plane of imaging system can block COTR entirely

250 MeV, Far field Intensities

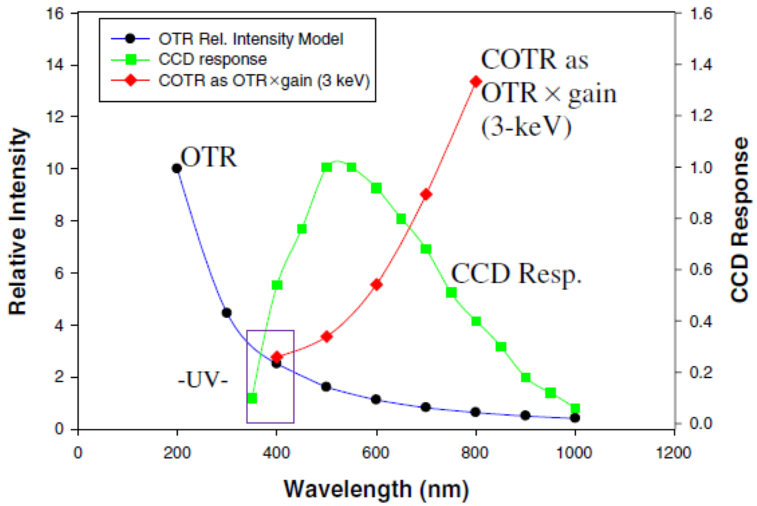


- Applicability limited where only small transverse fractions of beam radiate coherently
- Main application to scintillators

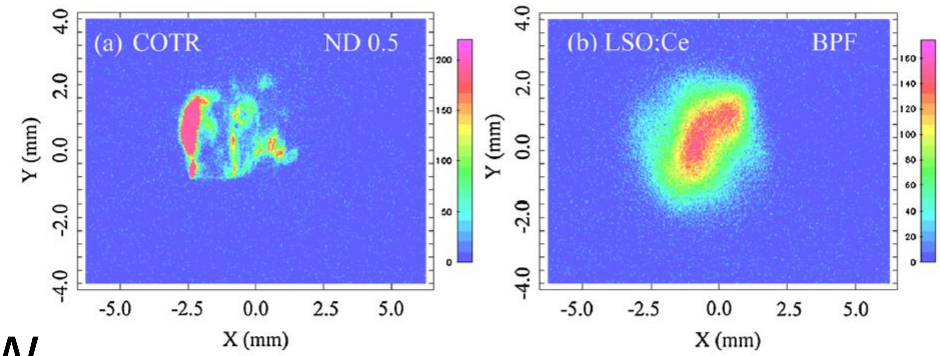
Fiorito PAC09 TU3GRI02

Spectral COTR Suppression

- COTR more intense at longer wavelengths
- Use narrow blue band-pass filter to block COTR in favor of OTR
- Can work where LCS gain is 1 for blue wavelengths



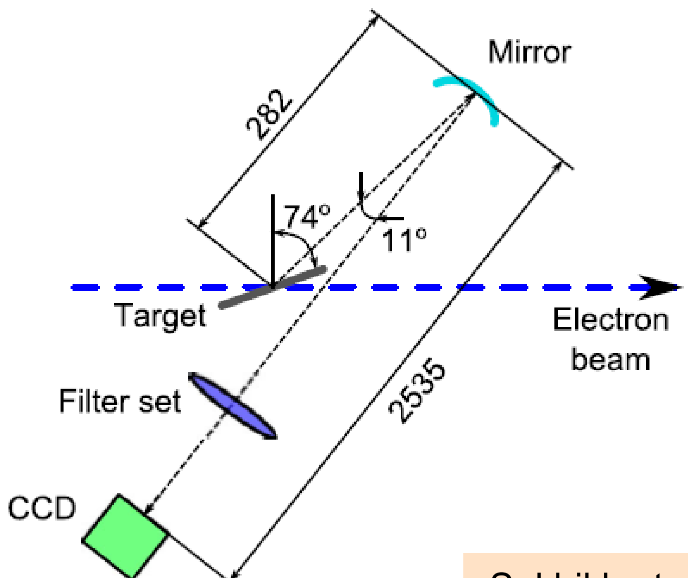
- No benefit in situations with COTR across entire visible spectrum
- Useful to narrow CCD acceptance to scintillator BW

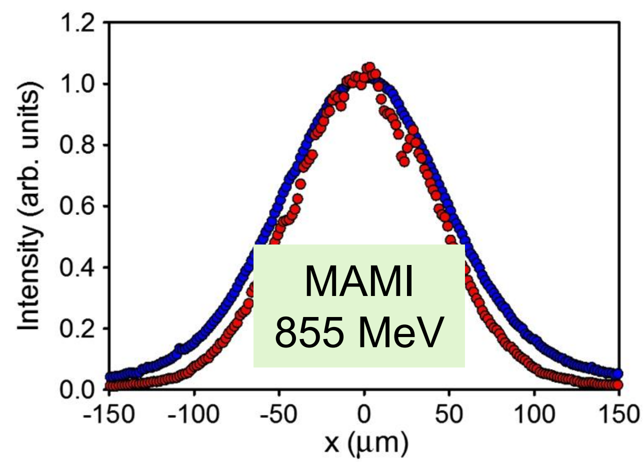


Lumpkin et al. PRSTAB 12, 080702 (2009)

EUV OTR Detection

- OTR generation at 20 nm
- Grazing incidence Mo-target for optimum reflectivity
- Spherical Mo/Si multilayer mirror
- Vacuum setup necessary
- EUV beam size somewhat smaller than visible OTR

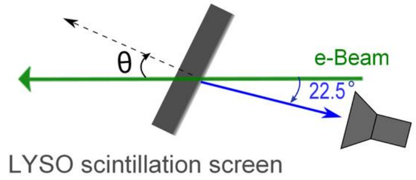


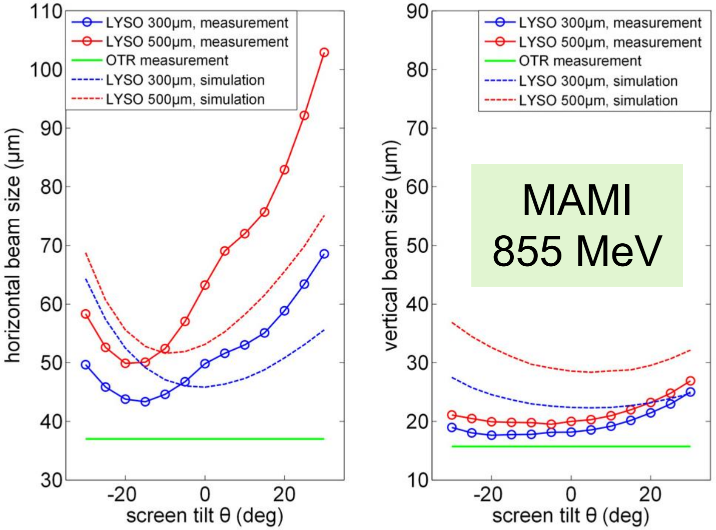


Sukhikh et al. PRSTAB 17, 112805 (2014)

Scintillators

- Based on electron beam bremsstrahlung energy loss
- Intensity proportional to charge density
- (C)OTR generation at crystal surfaces
- OTR x1000 weaker than fluorescence
- Issues
  - Resolution from finite crystal thickness
  - Saturation from high charge density
  - Avoid additional in-path viewing mirror as additional COTR source
- Investigations on optimum crystal tilt
- 15 µm beam size close to OTR measurement demonstrated
- Recently 7 µm shown (Naito IBIC14 TUPD08)





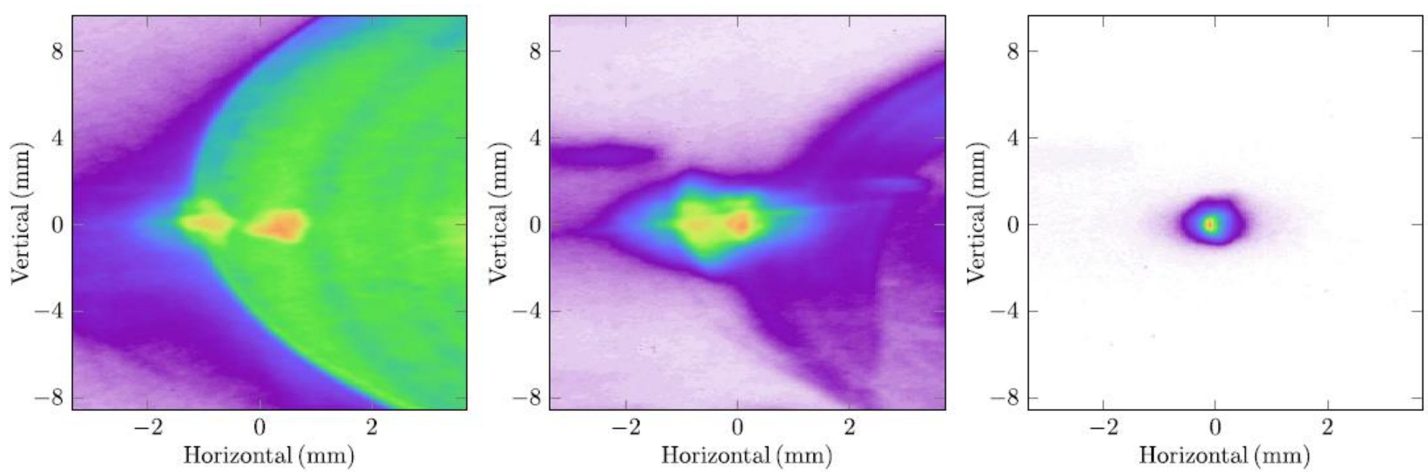
Yan et al. DIPAC11 TUPD59

Spatial COTR Separation

- Nearly isotropic fluorescence emission
- Blocking direct path of COTR towards camera leaves plenty of solid angle of scintillator light to reach camera.
- Blocking can be done by either pointing the camera away from the direct COTR path or by masking out the COTR cone
- Demonstrated at SACLA and LCLS

Temporal COTR Separation

- OTR emission instantaneous
- Fluorescence with ~100 ns lifetime
- Uses expensive gated CCD (intensified CCD)
- Delay CCD trigger by some 10 ns < lifetime
- Only detect fluorescence while COTR is blocked

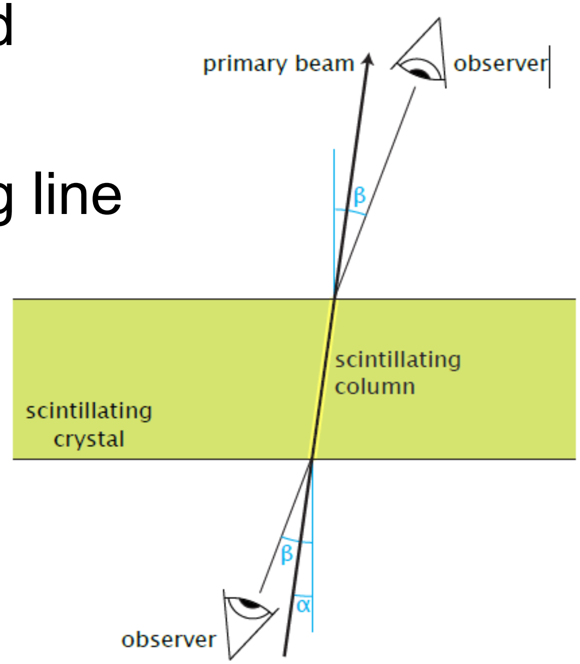


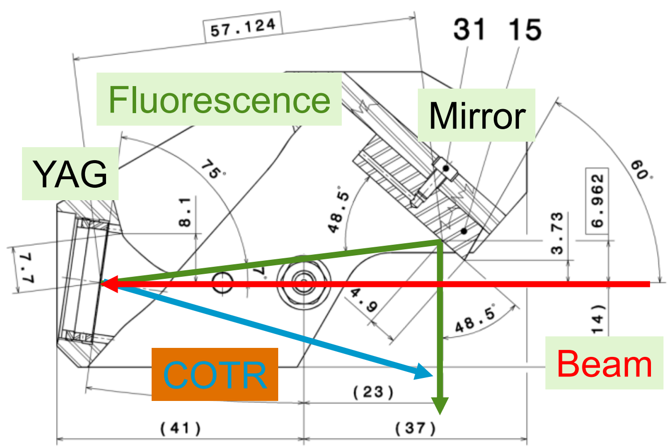
(a) OTR screen, no time delay. (b) LuAG screen, no time delay. (c) LuAG screen, time delay.

Behrens et al. PRSTAB 15, 062801 (2012)

SwissFEL Profile Monitor

- Combine optimized viewing geometry and spatial COTR suppression
- Optimum viewing angle where scintillating line source appears as point source
  $\beta = -\arcsin(n \sin \alpha)$
- COTR emitted at opposing angle 2α
- Off-axis mirror directs light to CCD perpendicular to beam

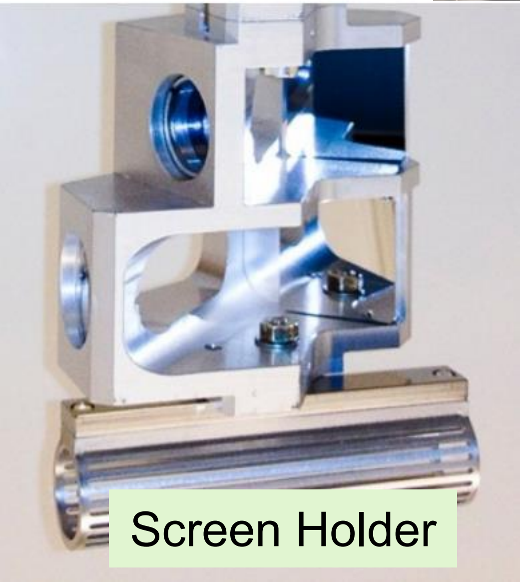




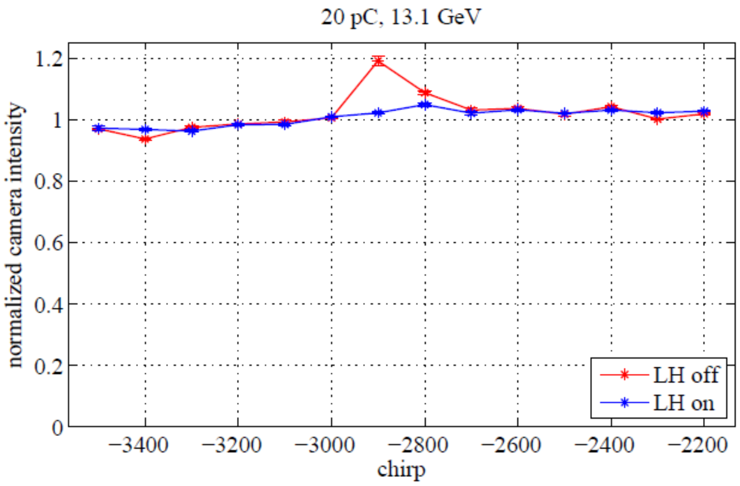
Courtesy R. Ischebeck

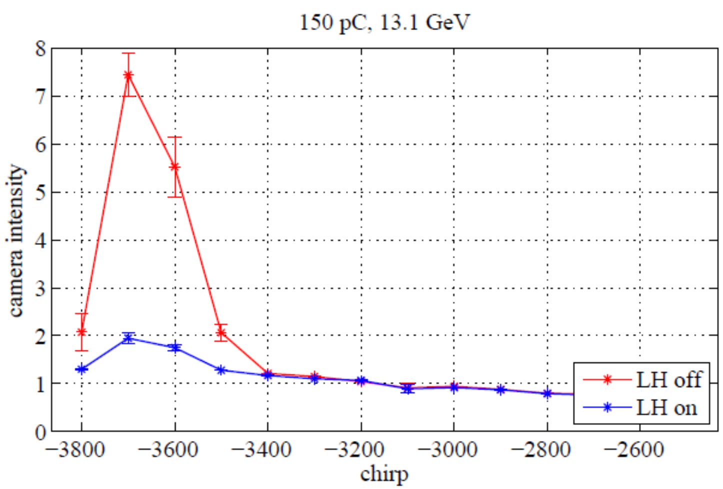
LCLS Installation

- Area upstream of undulators with prior 10^5 COTR enhancement
- Camera tilted to account for tilted crystal (Scheimpflug principle)
- Use 30 μm thick crystal to limit beam losses and enable 10 Hz operation



COTR Suppression Results



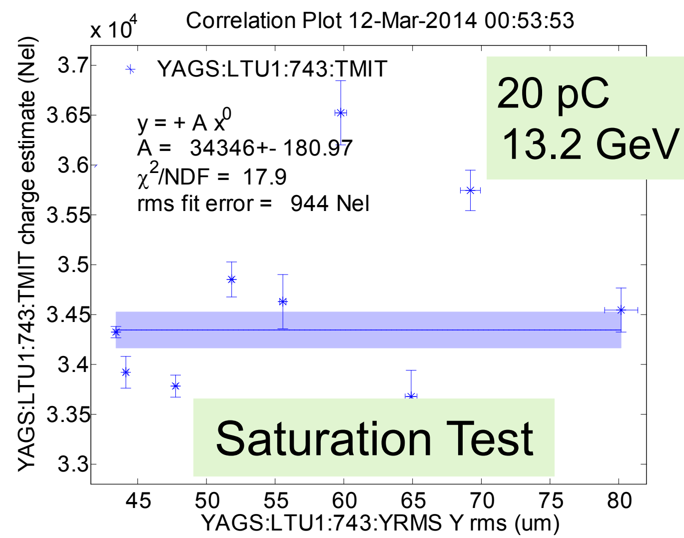


- Low charge and high charge
- With and without laser heater
- Scan RF phase (chirp in MeV) to change bunch length
- 20 pC
  - Small increase at peak compression w/o LH
  - Disappears completely with LH
- 150 pC
  - Still COTR enhancement of x7 at full compression, but much reduced with LH on
  - Nearly flat intensity over normal operating range

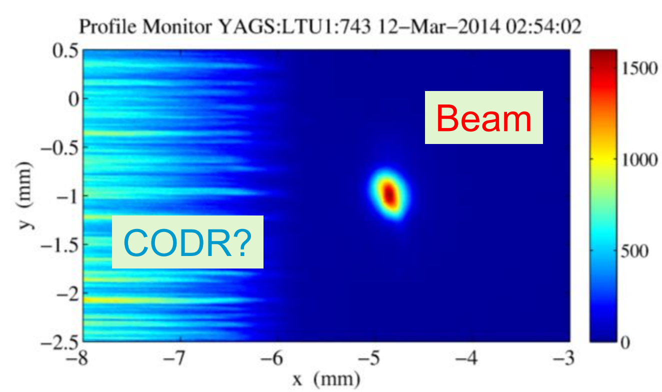
Ischebeck et al. IBIC14 TUCYB3

Commissioning Results

- YAG saturation test
  - Scan quadrupole to vary beam size
  - No saturation at 20 pC
  - Some indication at 180 pC

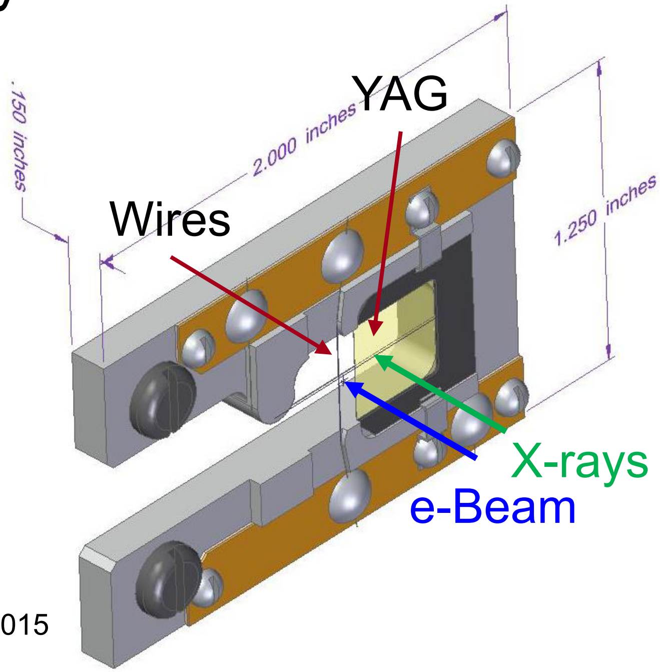


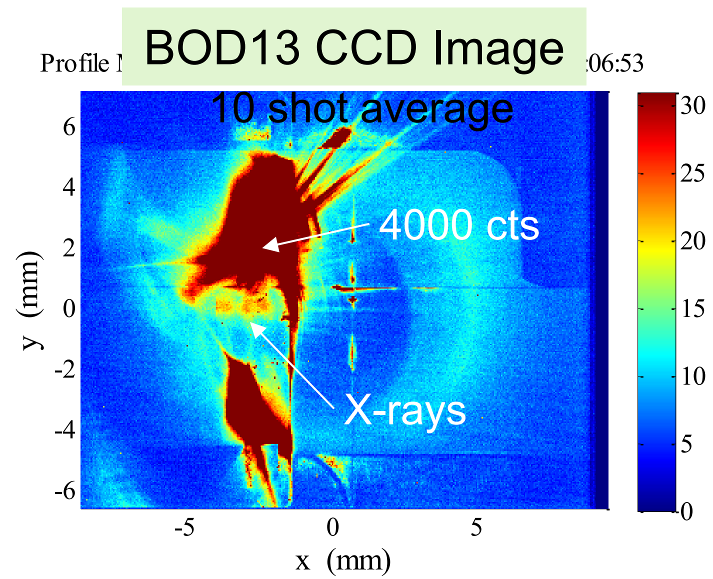
- Spurious radiation
  - Coherent ODR from chamfered off-axis mirror
  - Presently replaced with knife-edge version



Still COTR?

- LCLS x-ray/electron beam diagnostics for SXRSS
- Electrons pass by 20 μm thick YAG crystal within few mm
- Upstream annular mirror provides beam pass through and blocks specular reflections from crystal within central 50 mrad
- Very strong CODR emission from crystal observed
- Possibly excitation from UV micro-bunching





Summary

- Standard OTR screens unusable for high brightness accelerators due to COTR effect from uBI in many locations
- Mitigation schemes for OTR screens
  - not successful in fully suppressing COTR
  - option remains to move to much shorted detection wavelengths
- Scintillator screens
  - Reemerged as viable alternative to OTR
  - Demonstrated sub 10 μm resolution
  - Sufficient COTR suppression demonstrated by temporal and spatial separation
- Scintillator screens using spatial COTR separation schemes are used or planned for several X-ray projects operating or under construction

Thank you for your attention!