Observation of Coherent OTR at LCLS

Unexpected Physics in Standard Beam Diagnostics

16 November 2007

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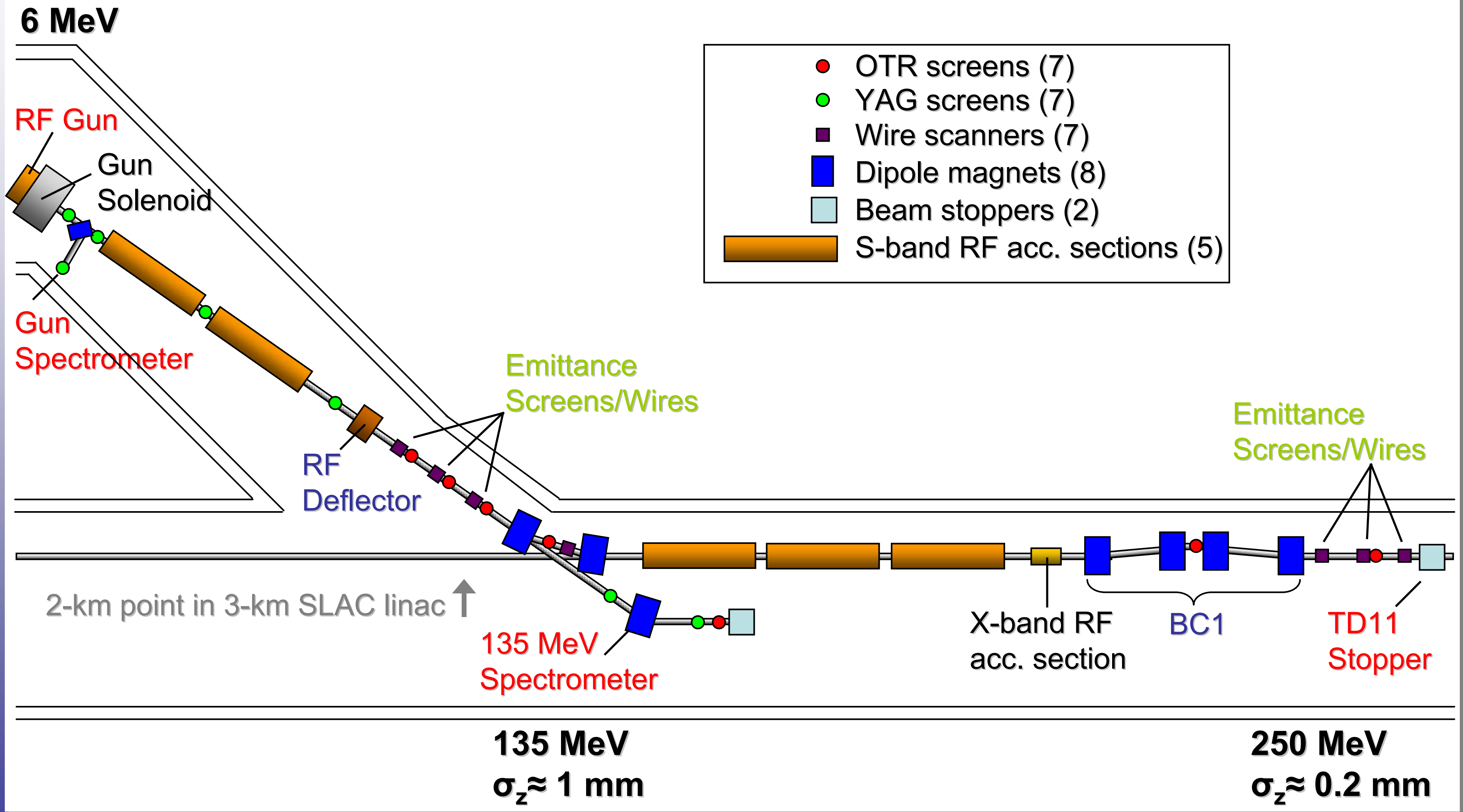
Theory Group Meeting

Outline

- Introduction into LCLS Injector
- Coherent OTR Observations
- Analysis and Interpretations
- Plans

LCLS Injector Layout



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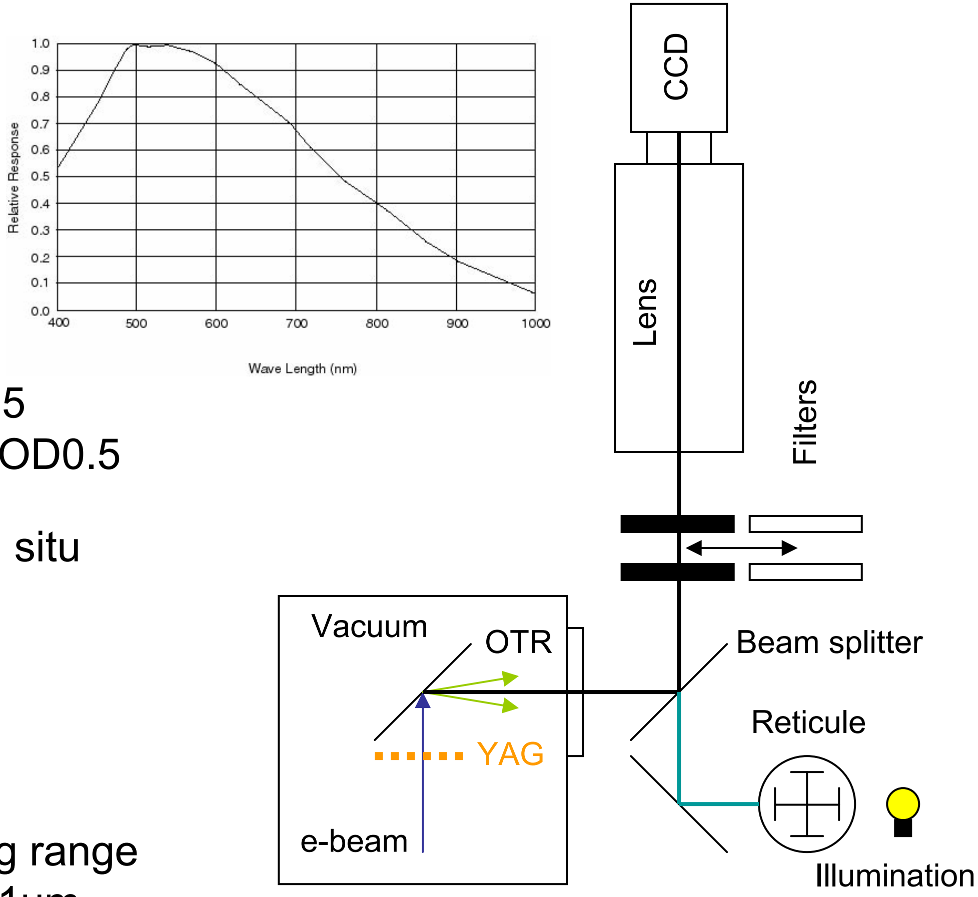
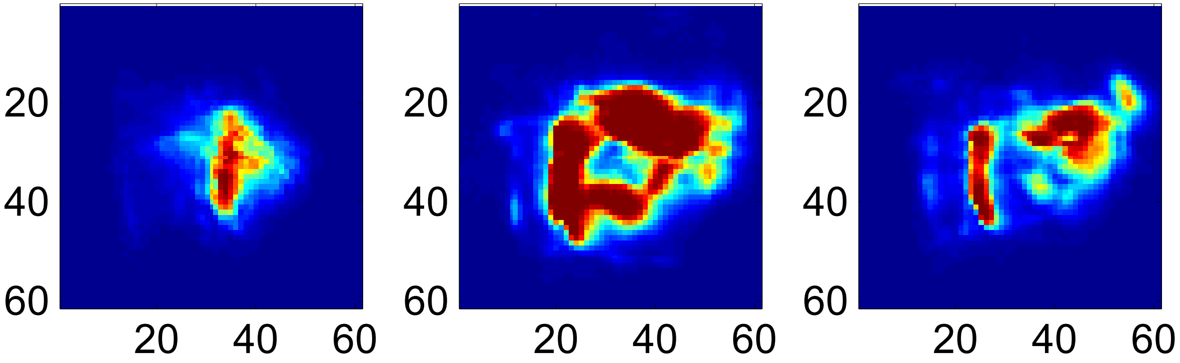
OTR Diagnostics

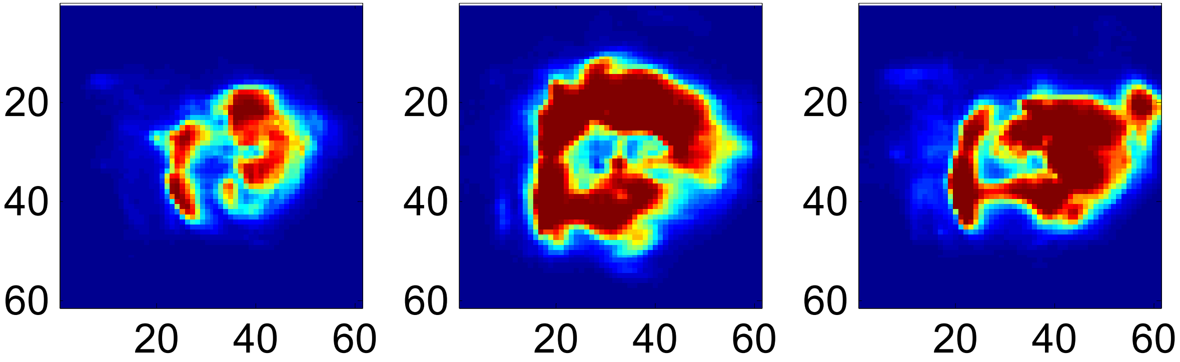
- OTR screen
  - Aluminum foil
  - Thickness 100um
  - Angle at 45 degrees to beam
- Imaging optics package
  - Telecentric lens, F2.8
  - 100 line pairs/mm
  - Typical magnification up to 1:2.5
  - Two neutral density filters with OD0.5 and OD1
  - Beam splitter and reticule for in situ calibration
- CCD camera
  - Megapixel CCD
  - Digital with 12bit depth
  - Pixel size 4.65µm
  - Linear response within digitizing range
  - Sensitive between 350nm and 1um



COTR Observations I: Fluctuating Shapes



OTR12, downstream of BC1



Shot to shot samples, 300pC, max compression w/ L1S & L1X

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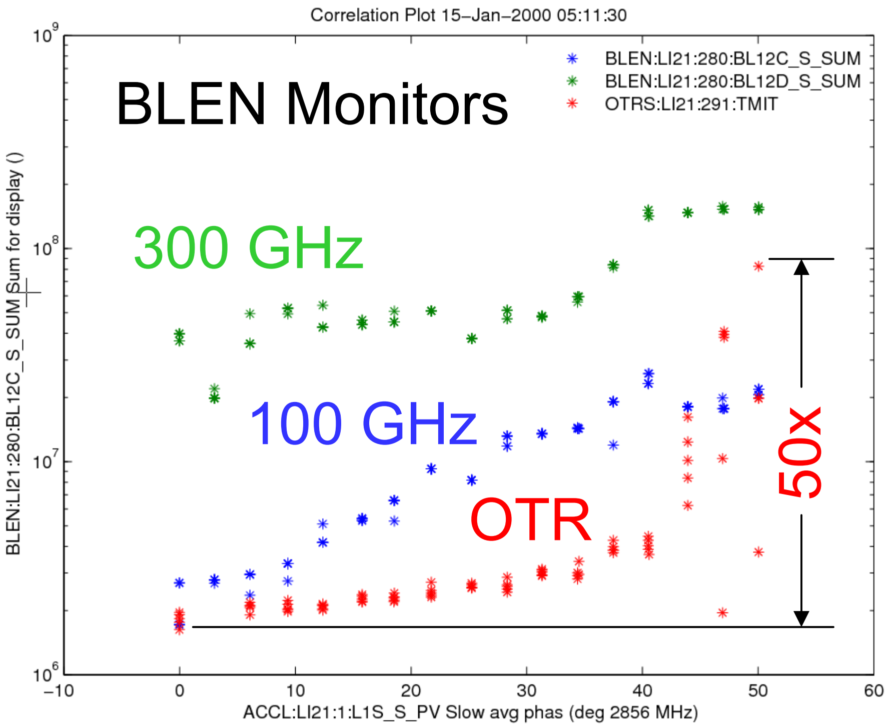
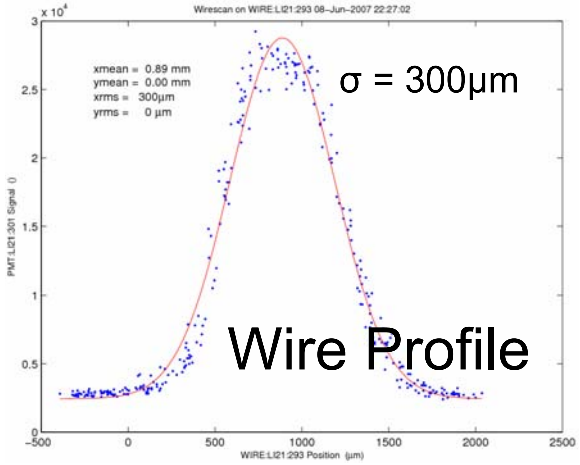
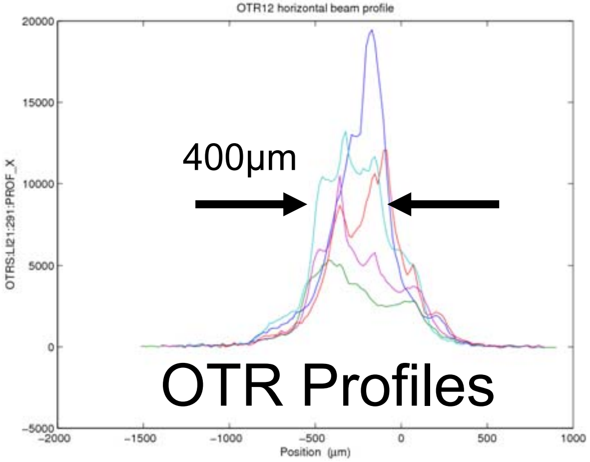
COTR Observations II: Bunch Compression



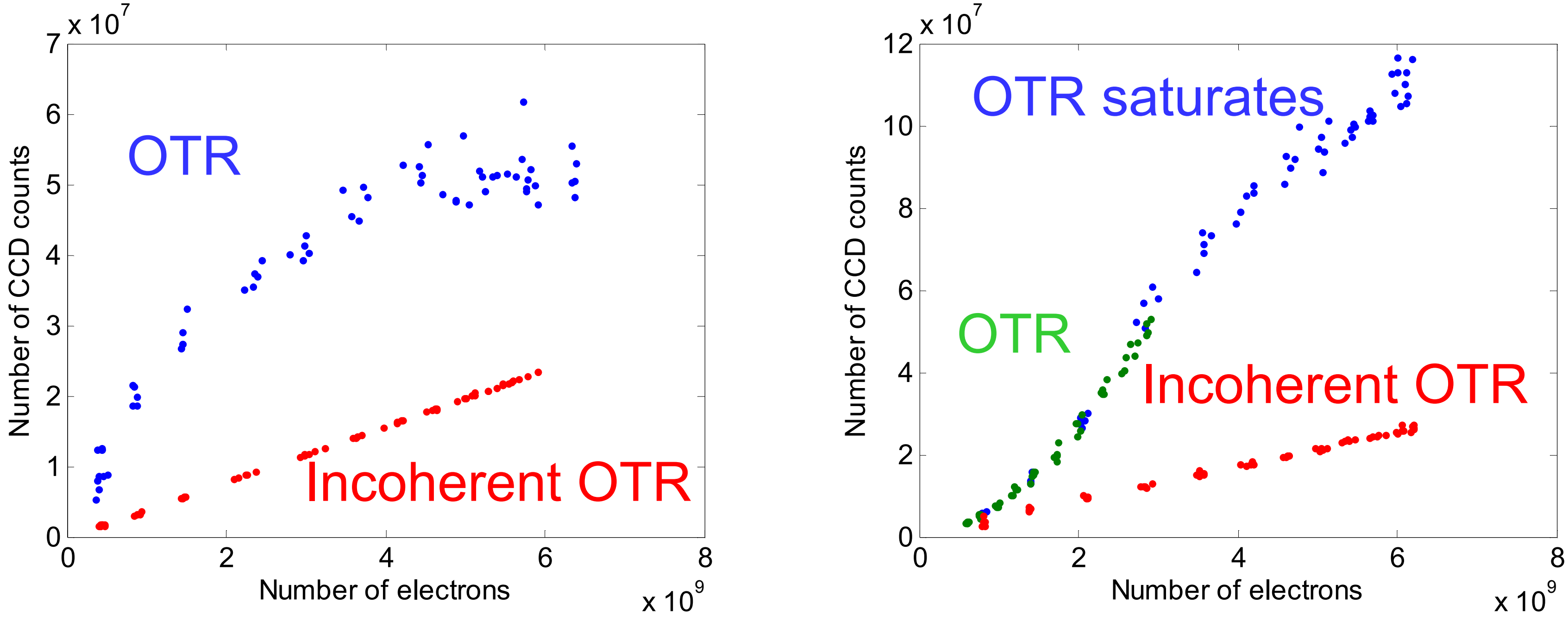
L1S Phase





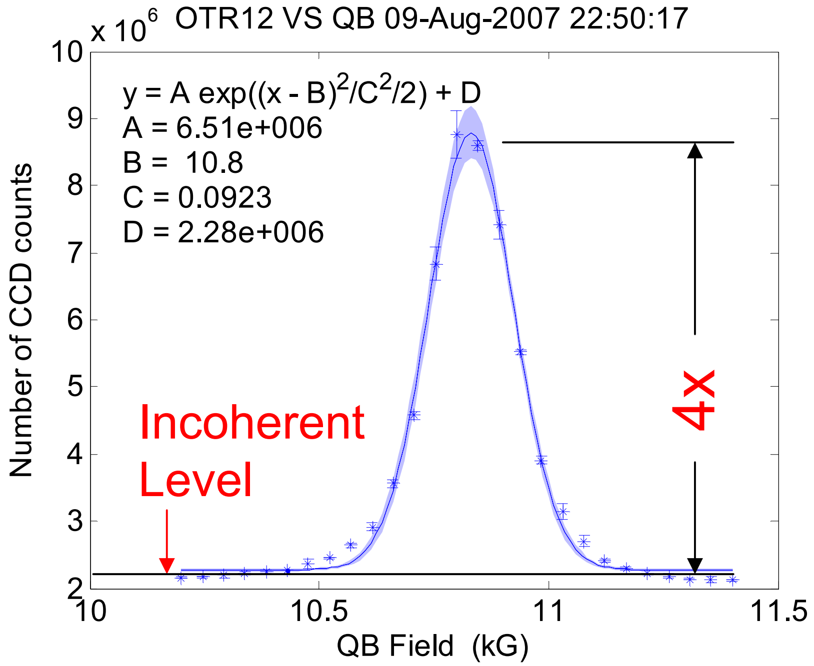
350pC, max compression

COTR Observations III: Charge Dependency



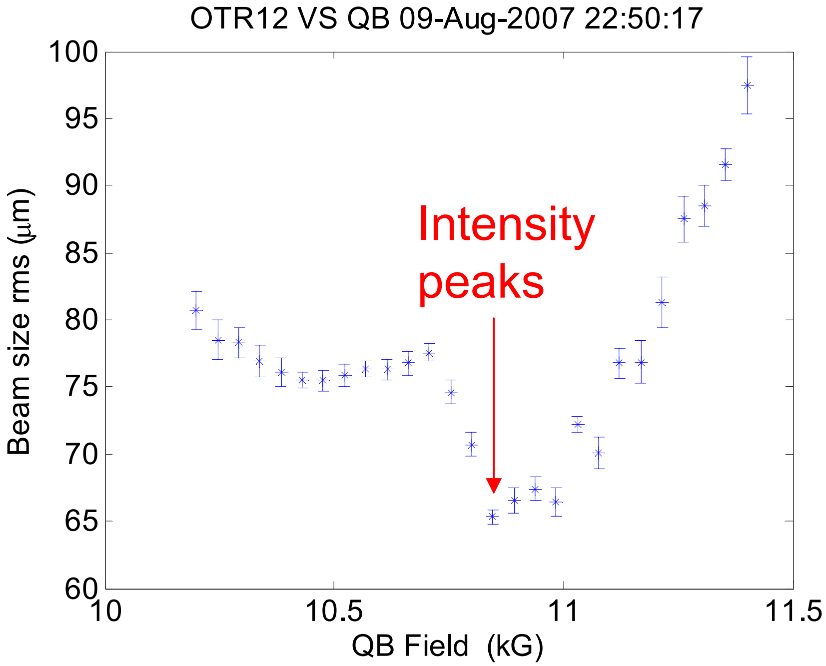
nom. compression w/ L1S & L1X

COTR Observations IV: Micro-Bunching



Incoherent Level

4x



Intensity peaks

1 nC, no compression, BC1 off, scan quad in DL1

COTR Observations Summary

- OTR light increases by orders of magnitude when bunch is compressed
- At high compression, transverse shape appears to fluctuate significantly
- At highest compression, ring shaped light distribution occurs
- OTR light has quadratic dependency on charge at lower charge
- Quadratic dependency saturates at high charge
- Uncompressed beam shows coherence and apparent size change after DL1 depending on R_{56}
- OTR is not a reliable diagnostic under certain conditions. Is expected to be worse for even shorter bunches after BC2

Optical Transition Radiation

- Transition radiation is scattering of virtual photons off boundary to generate real photons
- Source of radiation is Coulomb field
  - Temporal and spatial frequency components

$$E(\vec{k}) \propto \frac{\vec{k}_\perp}{k^2/\gamma^2 + k_\perp{}^2}$$

- Diffraction and imaging with optical system
  - Angular acceptance of system θ_0

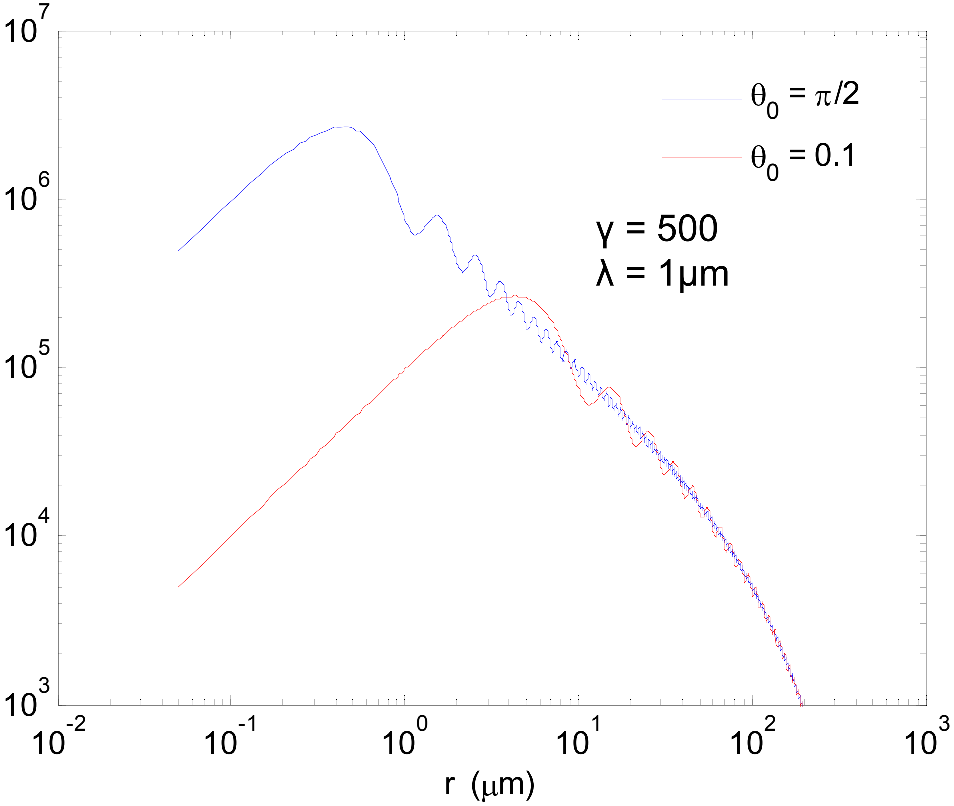
$$E(\vec{r}_\perp) \propto \int_0^{k\sin\theta_0} k_\perp dk_\perp J_1(k_\perp r_\perp) \frac{k_\perp}{k^2/\gamma^2 + k_\perp{}^2}$$

- Effective source distribution

$$E(\vec{r}_\perp) \propto \frac{\vec{e}_\perp}{r_\perp}\left[1 - J_0(r_\perp k \sin\theta_0)\right] \frac{r_\perp k}{\gamma} K_1\left(\frac{r_\perp k}{\gamma}\right)$$

- Camera Image Calculation
  - Lens images field distribution from target to CCD
  - CCD measures field intensity
- Incoherent light
  - Convolute source *intensity* with beam distribution
- Coherent light
  - Convolute source *field* with beam distribution

Diffraction Limited Source Distribution



COTR from Electron Bunch

- Source field spectral distribution

$$\tilde{E}(\vec{\kappa}) = \frac{iq}{2\pi^2 v}\frac{\vec{\kappa}}{(k/\gamma)^2 + \kappa^2}$$

- Field on screen is convolution of source field with lens diffraction pattern

$$\vec{E}_S(\vec{r}) = \int_0^{kd/z_L} d^2\kappa e^{i\vec{\kappa}\vec{r}}\tilde{E}(\vec{\kappa})$$

- Field of N radiating particles

$$\tilde{E}_N(\vec{\kappa}) = \sum_j e^{ikz_j + i\vec{\kappa}\vec{r}_j}\tilde{E}(\vec{\kappa})$$

- Radiation intensity for frequency k

$$\begin{aligned} S(\vec{r}) \propto \left|E_N(\vec{r})\right|^2 = {} & N\int d^2r'dz\rho(\vec{r}\,'-\vec{r},z)\left|E(\vec{r}\,')\right|^2 \\ & + N(N-1)\left|\int d^2r'dze^{ikz}\rho(\vec{r}\,'-\vec{r},z)E(\vec{r}\,')\right|^2 \end{aligned}$$

Coherent OTR Imaging

- Intensity of coherent part for fully coherent beam
- $$\vec{E}_N(\vec{r}) = \int_0^{kd/z_L} d^2\kappa\, e^{i\vec{\kappa}\vec{r}} \rho(\vec{\kappa}) \frac{iq}{2\pi^2 v} \frac{\vec{\kappa}}{(k/\gamma)^2 + \kappa^2}$$
- Assume Gaussian charge distribution
- $$\rho(\vec{\kappa}) = e^{-\kappa^2\sigma^2/2}$$
- If σ > γ/k, beam larger than source size

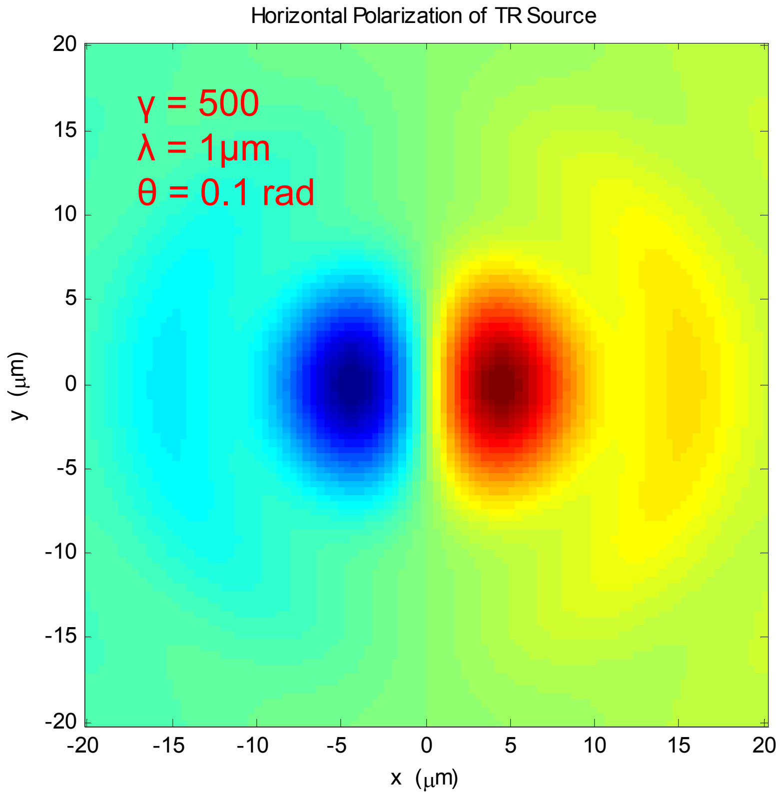
$$\vec{E}_N(\vec{r}) = \int_0^{kd/z_L} d^2\kappa\, e^{i\vec{\kappa}\vec{r}} \rho(\vec{\kappa}) \frac{q}{2\pi^2 v} \frac{\gamma^2}{k^2} i\vec{\kappa}$$

- This gives the field as the gradient of the charge distribution

$$\vec{E}_N(\vec{r}) = \frac{q}{2\pi^2 v} \frac{\gamma^2}{k^2} \vec{\nabla}\rho(\vec{r})$$

- Beam size « γλ
  - Image is OTR source distribution
- Beam size » γλ
  - Image is gradient of beam distribution

Horizontal Polarization Component of Source



Convolution of Source with Beam

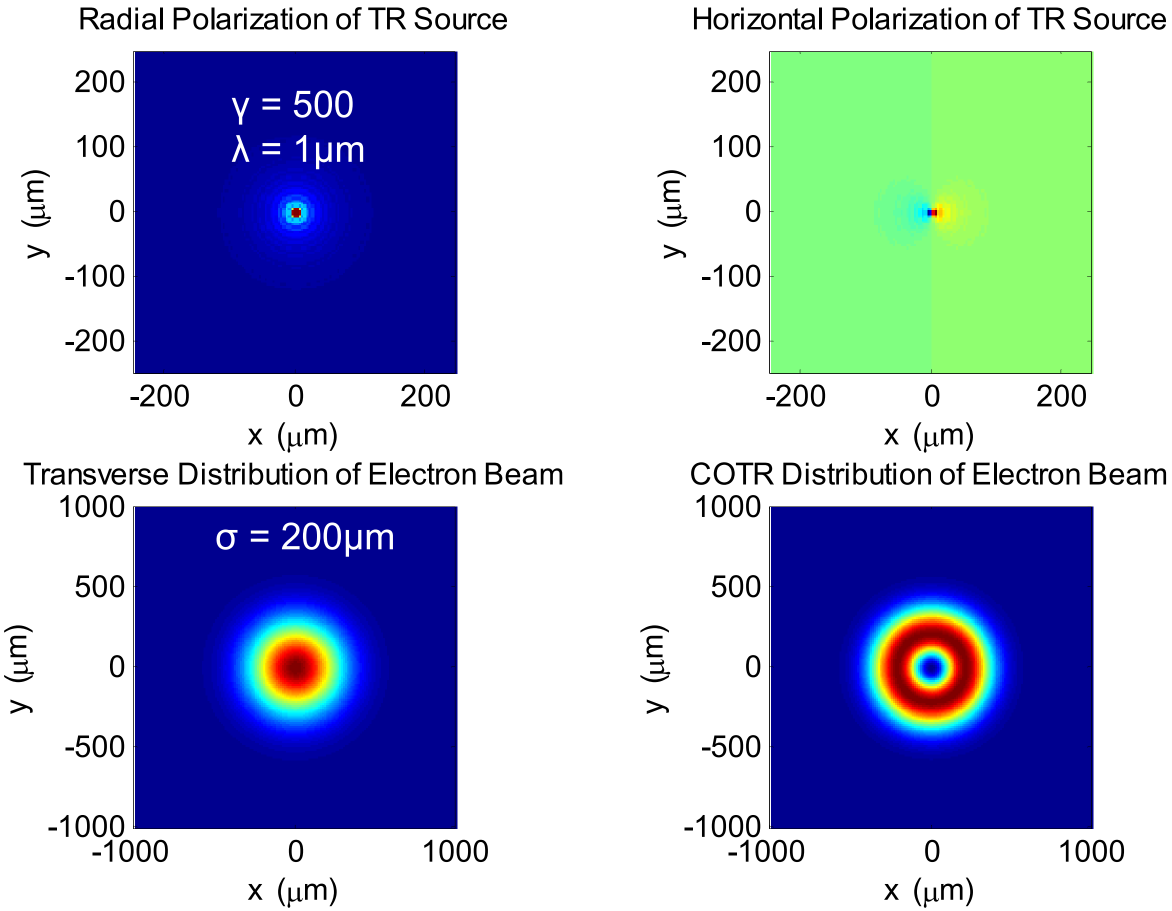
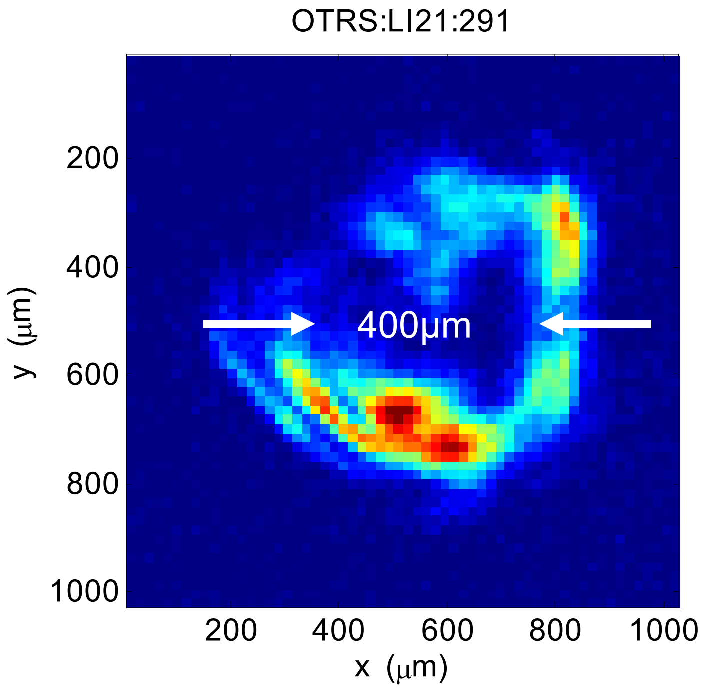
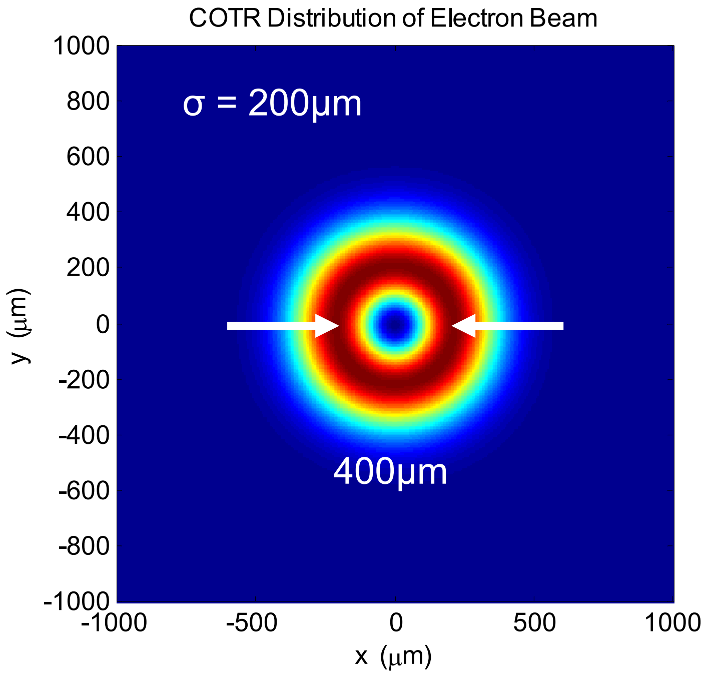


Image on OTR12

- Measured image
- Light intensity 30x above incoherent level

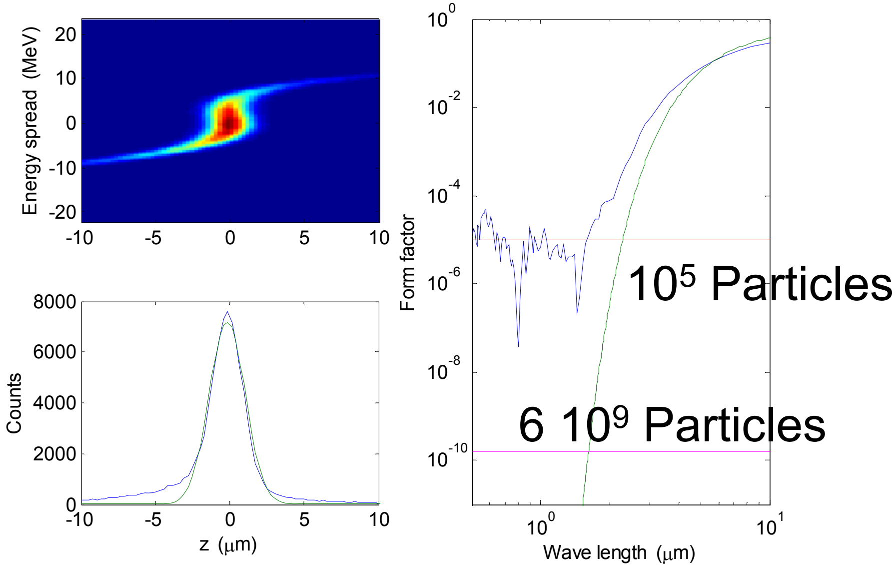


- Simulation
- Source acts like gradient operator
- Creates doughnut shape



Max. Compressed Bunch Form Factor

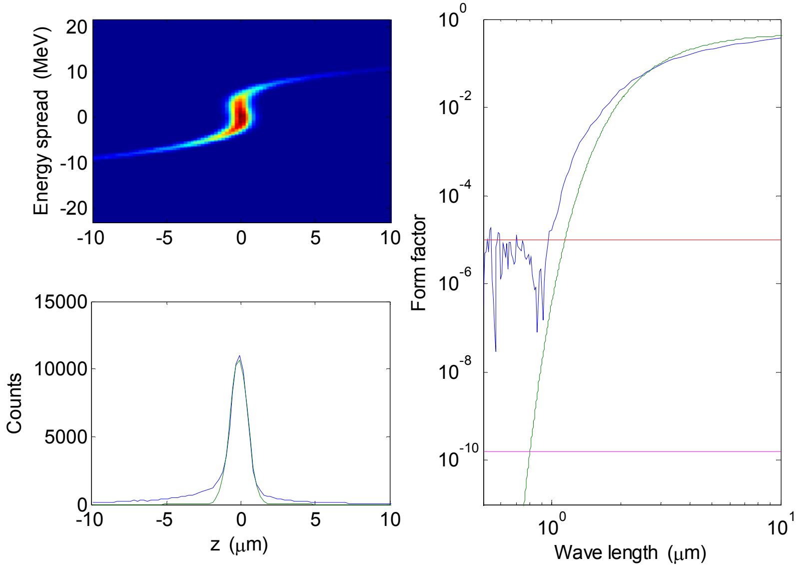
Initial 6keV, 0.8mm



10^5 Particles

6 10^9 Particles

Initial 3keV, 0.8mm



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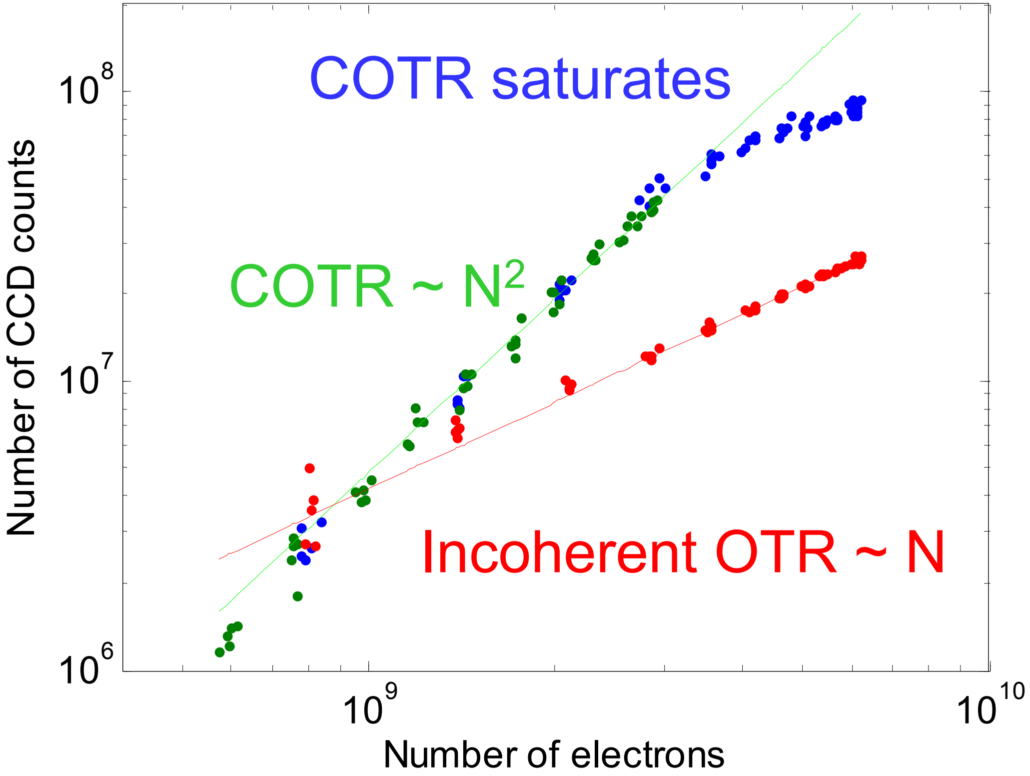
Observed Intensity Estimation

- Observed factor 30 enhancement
- Fully coherent 2 10^9 enhancement
- Beam size effect 2 10^3 suppression
- Long. form factor $10^4 – 10^?$ suppression
- $10^4 \cdot 10^3 \cdot 10^2 = 10^9$

COTR Charge Dependency

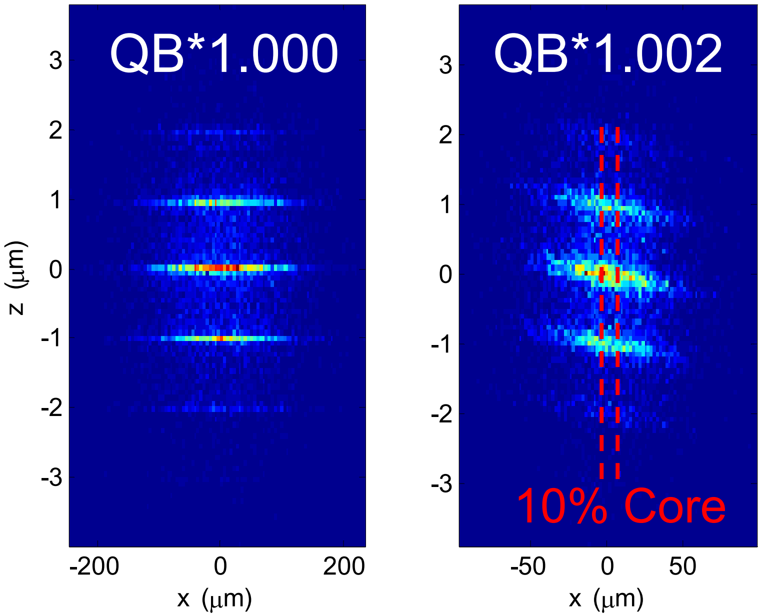


Quadratic dependency for small charge

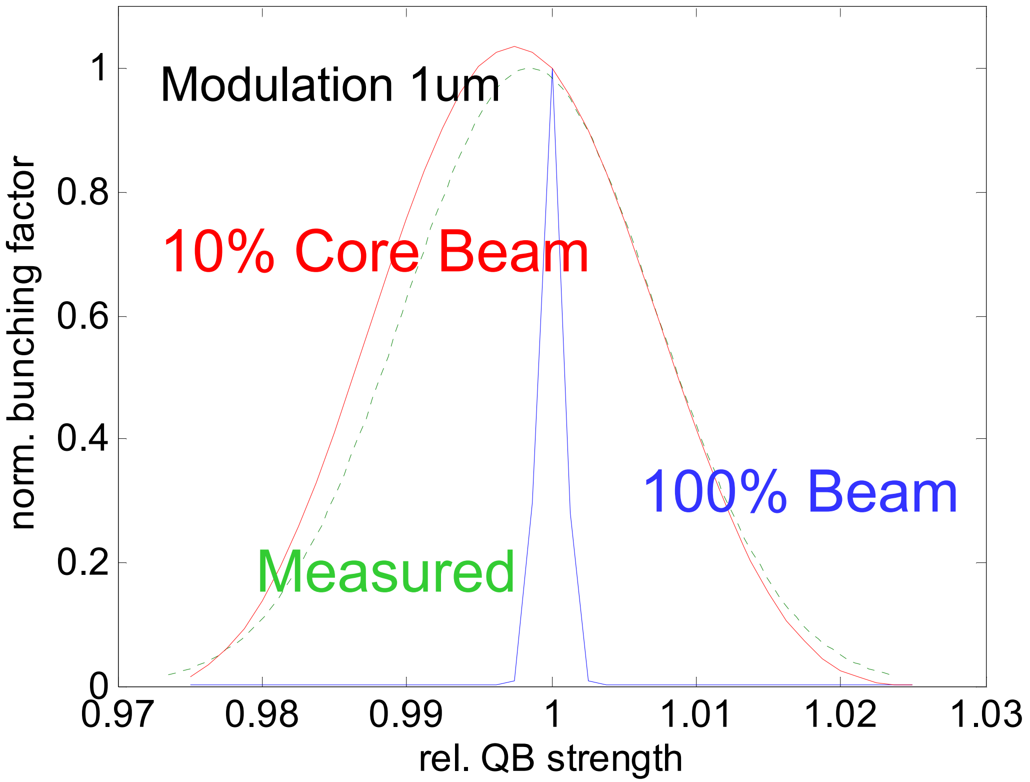
Micro-Bunching Simulation

- Start w/ energy modulation in injector
- R56 of DL1 generates temporal modulation
- Simulation
  - Modulate beam at 1um
  - x-z tilt on OTR12
  - Calculate reduction in modulation when QB changes
  - Neglect energy spread
  - Use full beam and transverse core of beam

Phase space x-z



Bunching Factor vs. QB



Issues

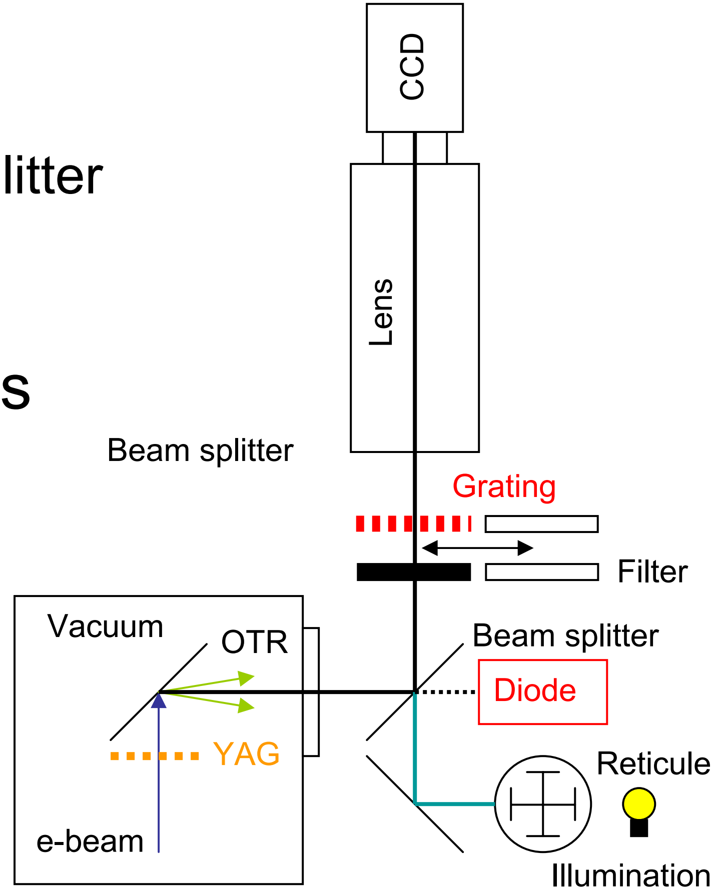
- In most cases, coherent effect only visible in increase in light output
- No significant change in beam shape noticable
- COTR from fully transverse coherent beam should give ring structure
- COTR from small coherent transverse fraction of beam should give spike
- Needs many coherent small parts of beam radiating at different wavelengths to explain still Gaussian beam shapes

Future Plans

- Measure spectrum of coherence light
  - Grating for spectrally resolved OTR profiles at visible wavelengths
  - UV and IR diode with filters for range beyond visible
  - Color CCD?
- Measure polarization of COTR
  - Polarization dependence of transverse distribution can indicate transverse coherence
  - Add radial to linear polarization transformer?

Transmission Grating Spectrometer

- Modifications of present setup
  - Add grating in one of the filter slots
  - Use transmitted light through beam splitter
- Grating diffraction in first order
  - $x_S = x_0 - L_G \lambda / d$
- Transmission grating in front of lens
  - Distance foil – grating: $L_G = 130\text{mm}$
  - Grating frequency: $g = 1/d = 100/\text{mm}$
  - Max wavelength: $\lambda = 800\text{nm}$
- Spectral resolution
  - $\Delta\lambda = d\lambda/dx_S \, 3\sigma = 3\sigma/gL_G$
  - $\Delta\lambda = 100\text{nm}$ ($\sigma = 300\text{um}$)
  - $\Delta\lambda = 20\text{nm}$ ($\sigma = 60\text{um}$)



LCLS Commissioning Team

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- Paul Emma
- Joe Frisch
- Cecile Limborg-Deprey
- Jim Turner
- Jim Welch
- Juhao Wu