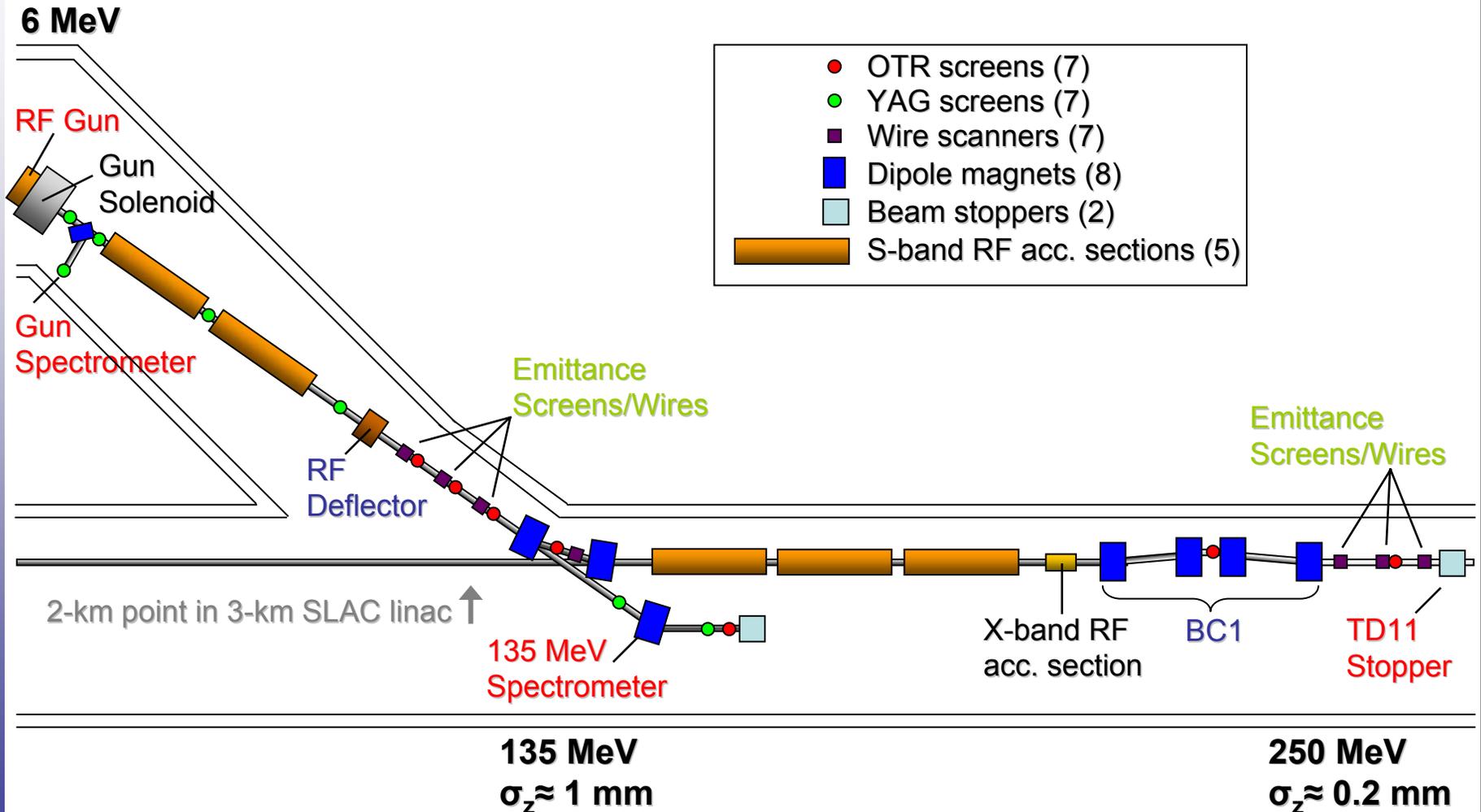


# Imaging of Micro Bunched Electron Beams with COTR

# Outline

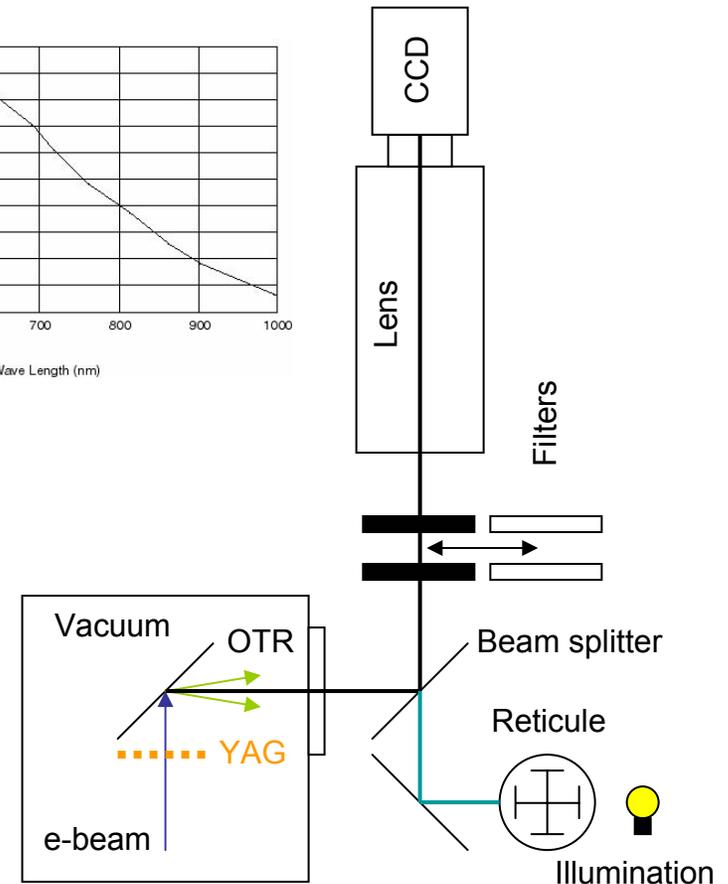
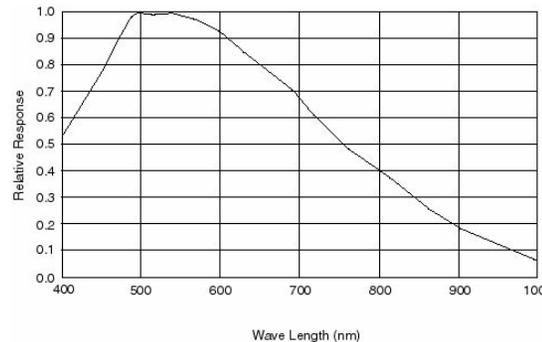
- Introduction
- Coherent OTR Observations
- Analysis

# LCLS Injector Layout

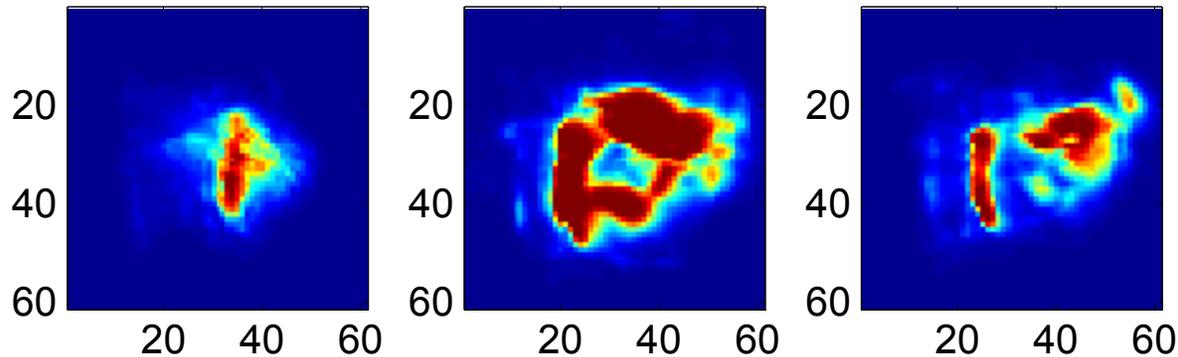


# OTR Diagnostics

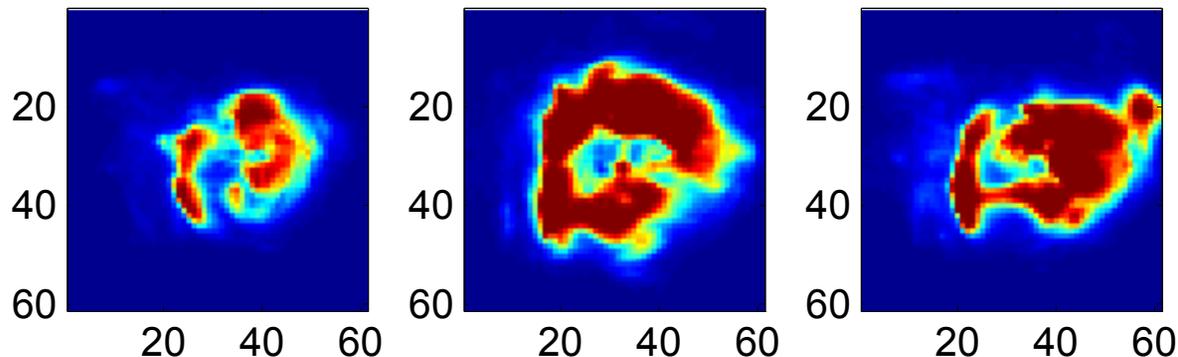
- OTR screen
  - Aluminum foil
  - Thickness 1 $\mu$ m
  - Angle at 45 degrees to beam
- Imaging optics package
  - Telecentric lens, F2.8
  - 100 line pairs/mm
  - Typical magnification up to 1:2.5
  - Two neutral density filters with OD0.5 and OD1
  - Beam splitter and reticule for in situ calibration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



# COTR Observations of Doughnut-like Shapes



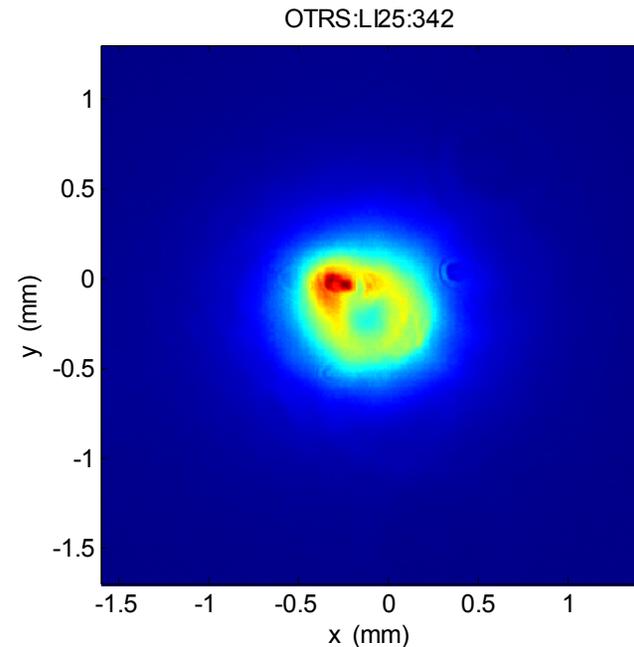
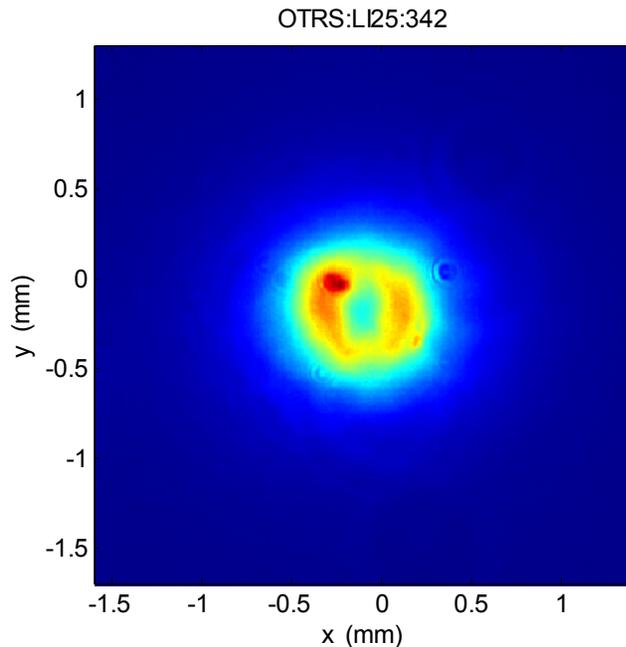
OTR12, downstream of BC1



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

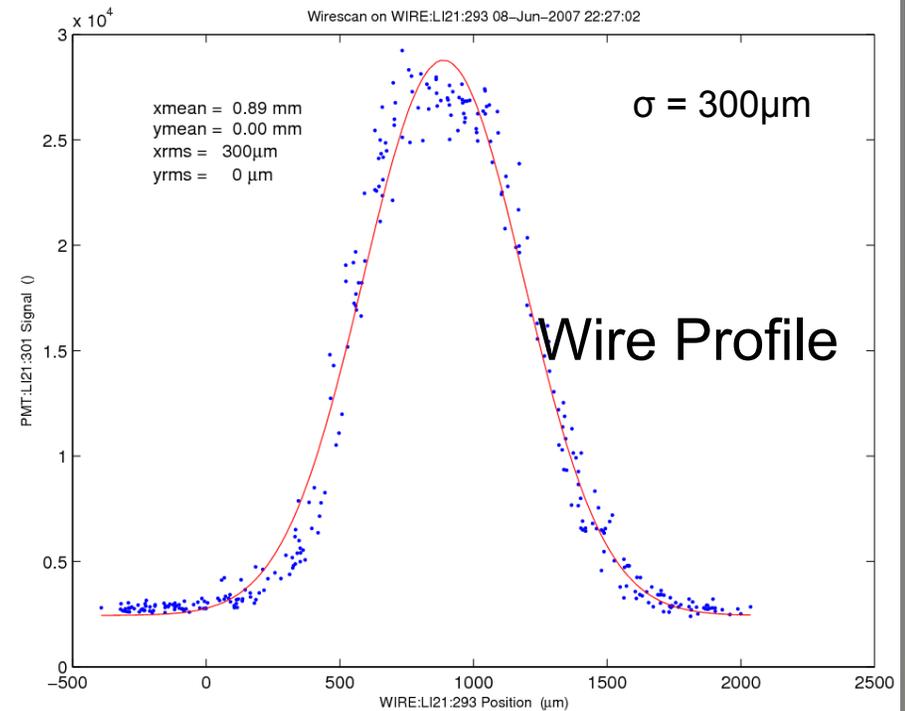
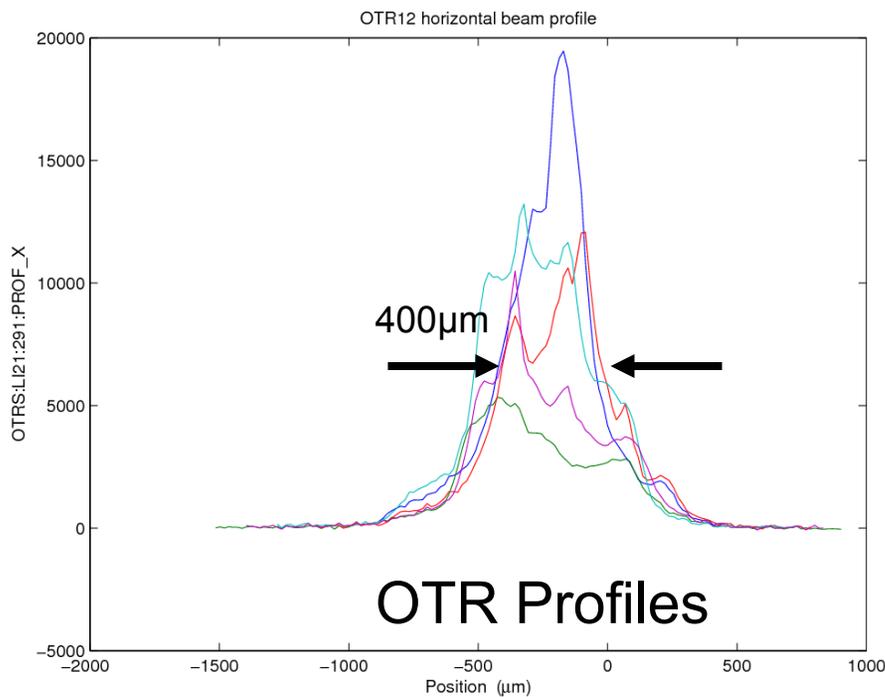
# More Observations

OTR22, downstream of BC2



Near max compression w/ 400MeV Chirp in L2, ?pC

# Comparison with Wire Profile



# 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

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

- Diffraction and imaging with optical system
  - Angular acceptance of system  $\theta_0$

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

- Effective source distribution

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

- Camera Image Calculation

- Lens images field distribution from target to CCD
- CCD measures field intensity

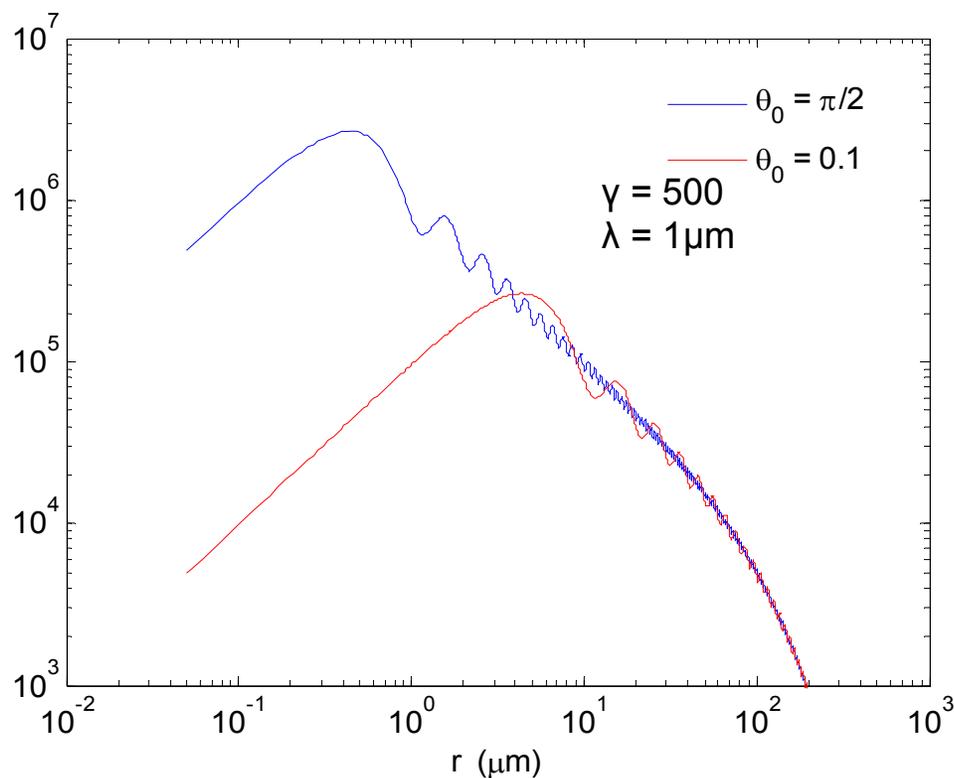
- Incoherent light

- 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

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

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

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

- Field of N radiating particles

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

- Radiation intensity for frequency k

$$S(\mathbf{r}) \propto |E_N(\mathbf{r})|^2 = N \int d^2 r' dz \rho(\mathbf{r}' - \mathbf{r}, z) |E(\mathbf{r}')|^2 + N(N-1) \left| \int d^2 r' dz e^{ikz} \rho(\mathbf{r}' - \mathbf{r}, z) E(\mathbf{r}') \right|^2$$

# Coherent OTR Imaging

- Intensity of coherent part for fully coherent beam

$$E_N(\vec{r}) = \int_0^{kd/z_L} d^2k e^{i\vec{k}\vec{r}} \rho(\vec{k}) \frac{iq}{2\pi^2 v} \frac{k}{(k/\gamma)^2 + \kappa^2}$$

- Assume Gaussian charge distribution

$$\rho(\vec{k}) = e^{-\kappa^2 \sigma^2 / 2}$$

- If  $\sigma > \gamma/k$ , beam larger than source size

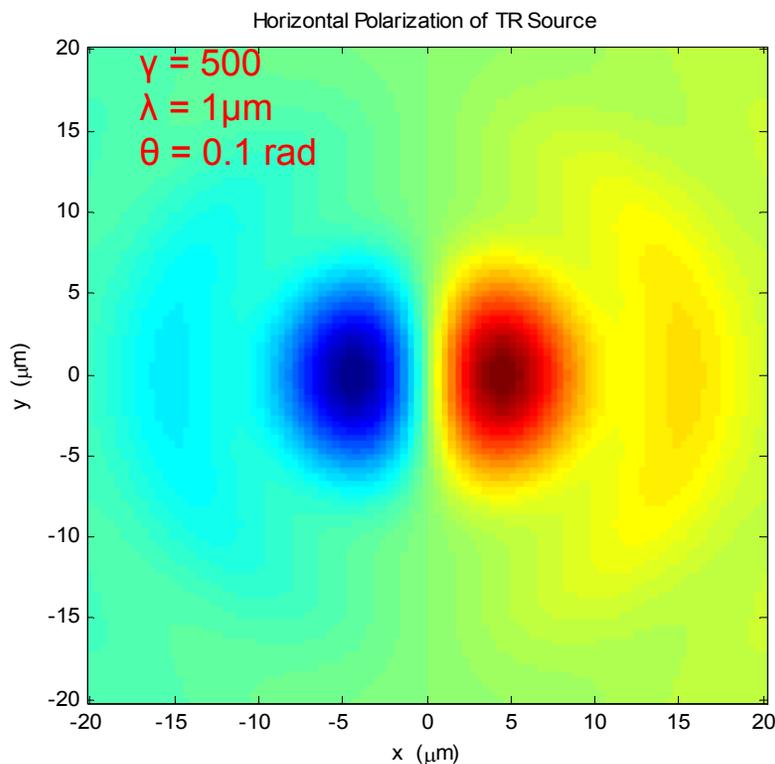
$$E_N(\vec{r}) = \int_0^{kd/z_L} d^2k e^{i\vec{k}\vec{r}} \rho(\vec{k}) \frac{q}{2\pi^2 v} \frac{\gamma^2}{k^2} i\vec{k}$$

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

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

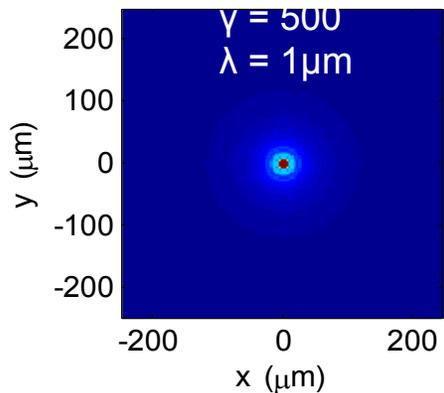
- Beam size  $\ll \gamma\lambda$ 
  - Image is OTR source distribution
- Beam size  $\gg \gamma\lambda$ 
  - Image is gradient of beam distribution

# Horizontal Polarization Component of Source

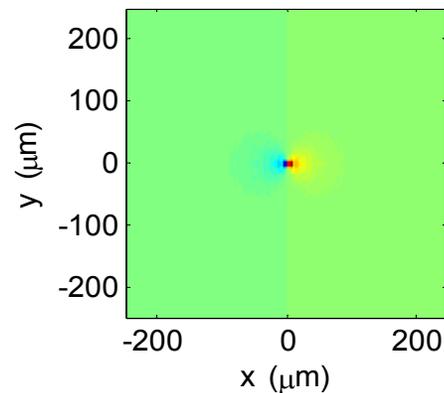


# Convolution of Source with Beam

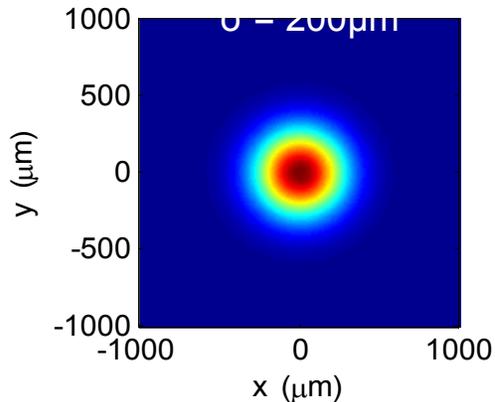
Radial Polarization of TR Source



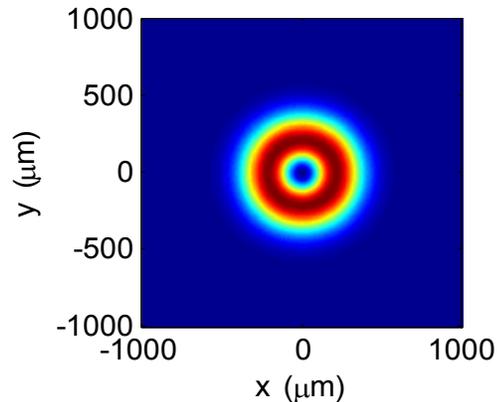
Horizontal Polarization of TR Source



Transverse Distribution of Electron Beam

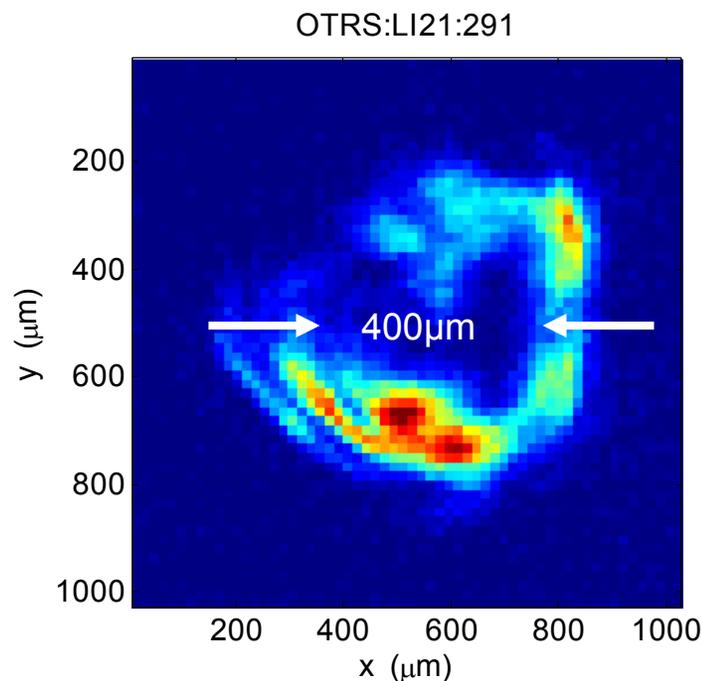


COTR Distribution of Electron Beam

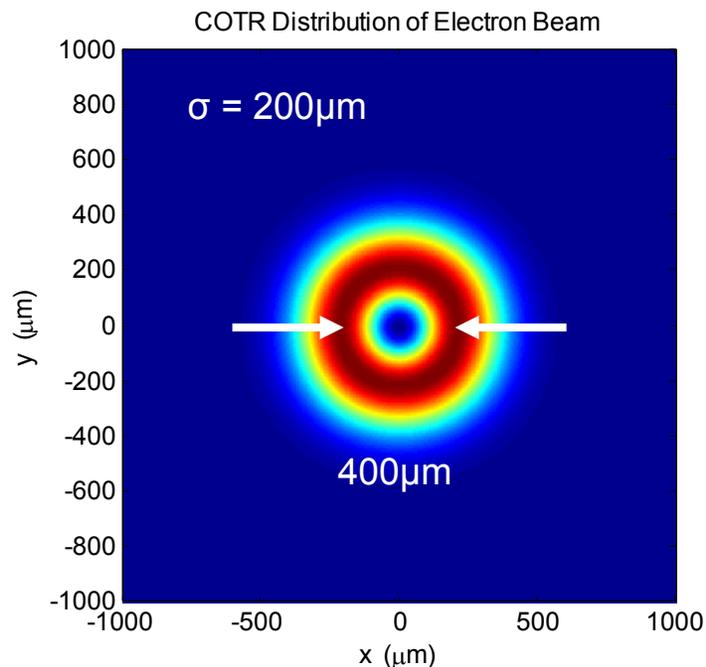


# Image on OTR12

- Measured image
- Light intensity 30x above incoherent level



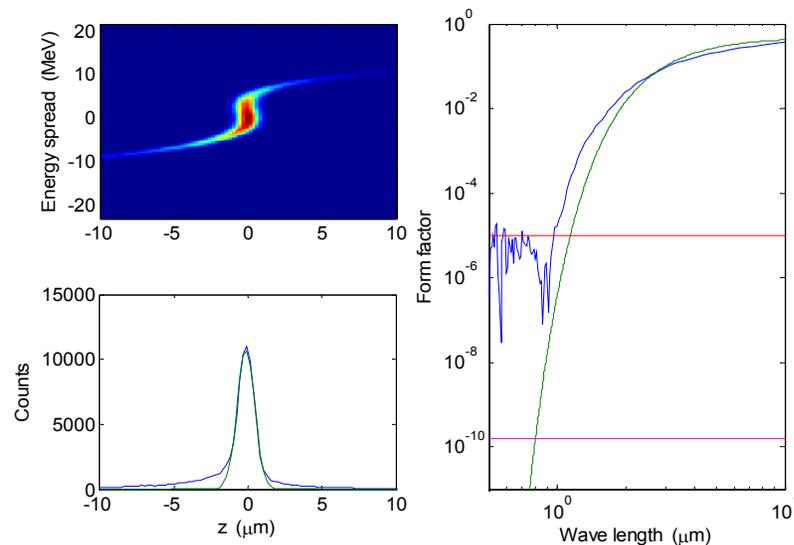
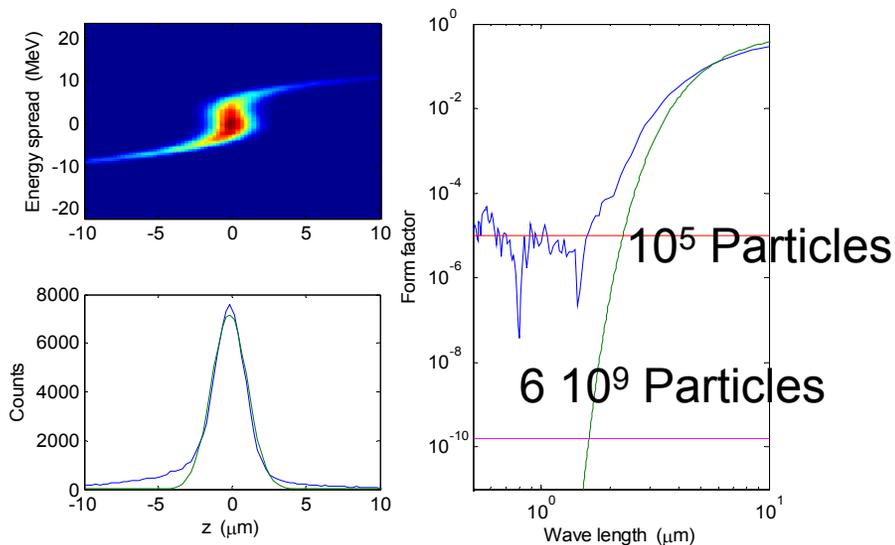
- Simulation
- Source acts like gradient operator
- Creates dark spots



# Max. Compressed Bunch Form Factor

Initial 6keV, 0.8mm

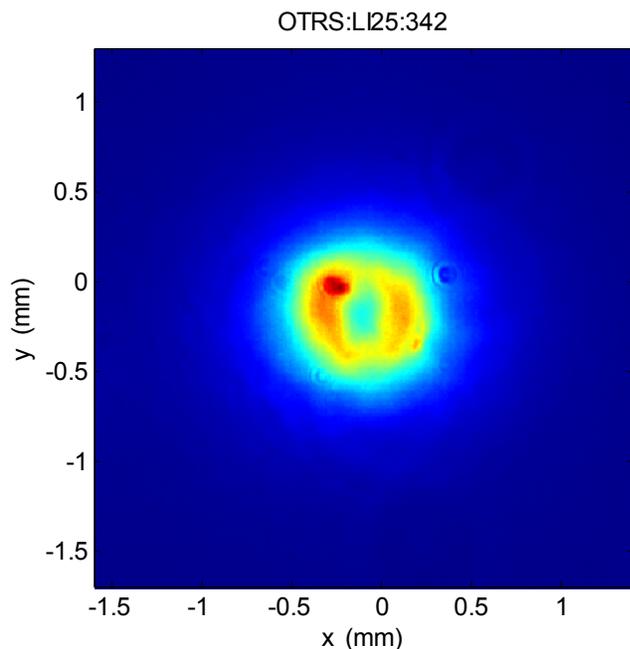
Initial 3keV, 0.8mm



## Observed Intensity Estimation

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

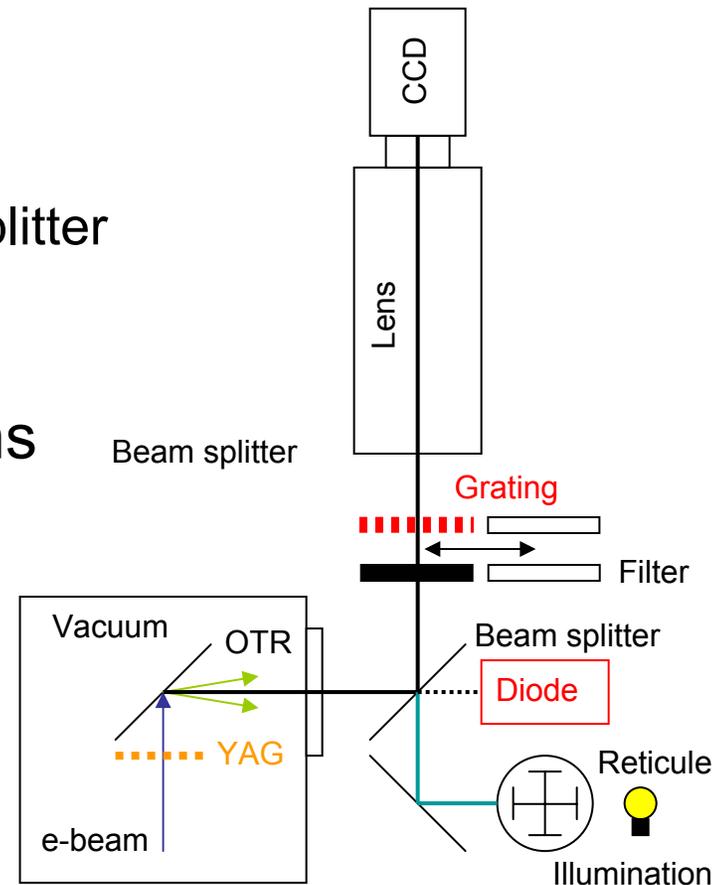
# Doughnut Shape on OTR22



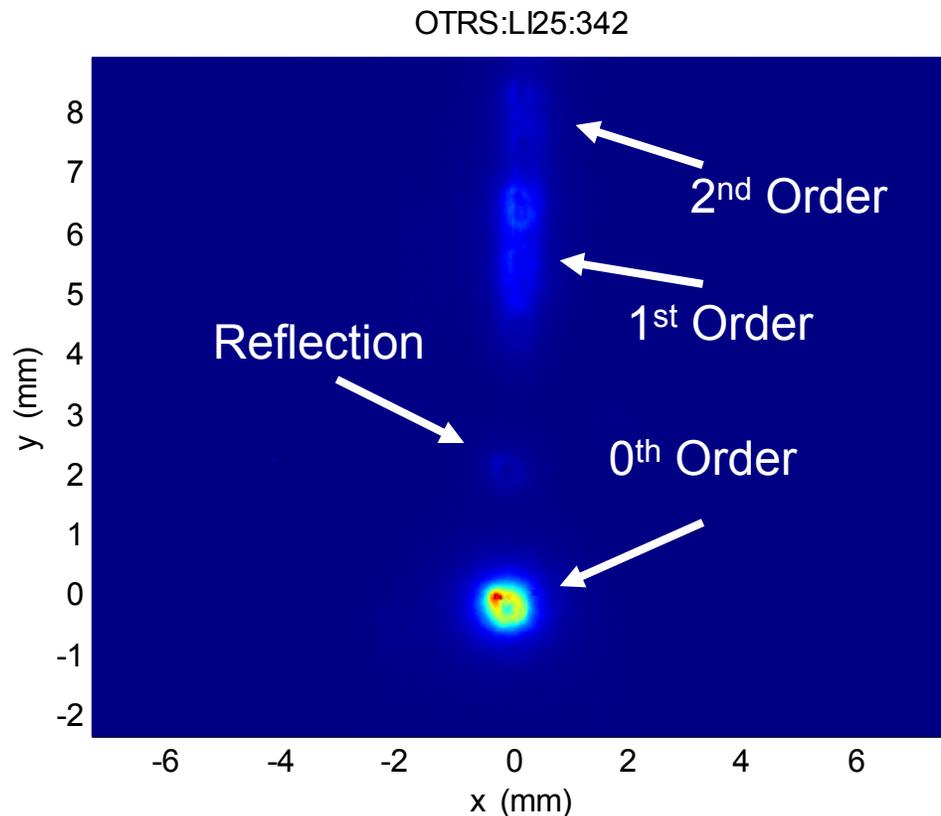
- Pixel count 18e6
- Attenuation 300
- N electrons 6.25E9
- Incoherent efficiency  
0.06 cts/electron
- Coherent  
enhancement 150

# 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
  - $\Delta\lambda = d\lambda/dx_S \ 3\sigma = 3\sigma/gL_G$
  - $\Delta\lambda = 100\text{nm}$  ( $\sigma = 300\mu\text{m}$ )
  - $\Delta\lambda = 20\text{nm}$  ( $\sigma = 60\mu\text{m}$ )

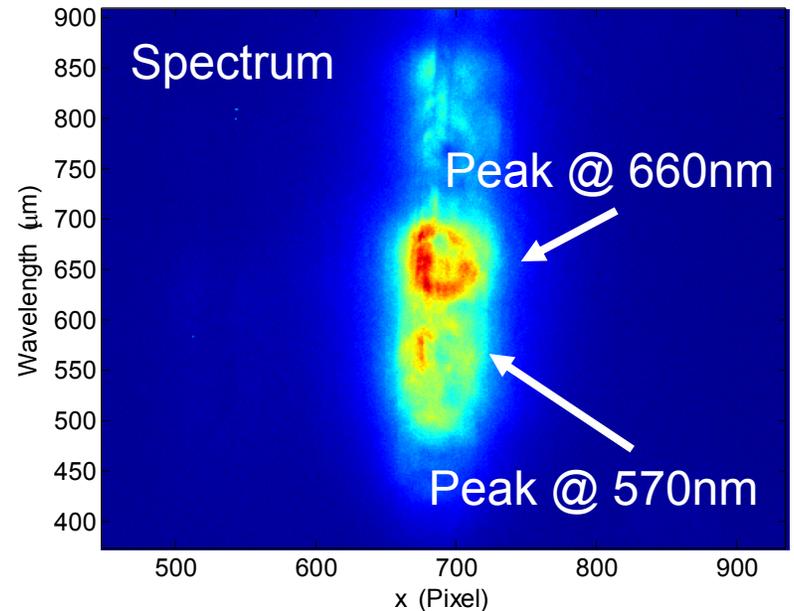
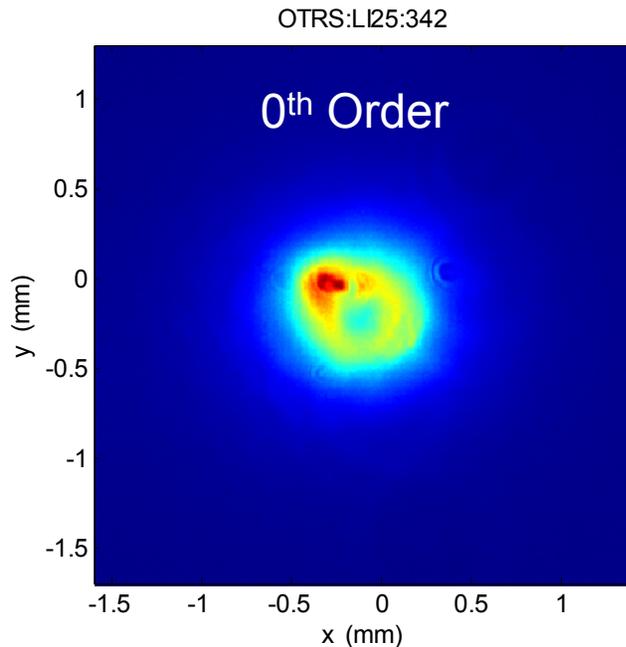


# COTR Image with Transmission Grating



# COTR Spectrum

Reproduction of doughnut shape in spectrum indicates strong coherent spectral spikes



## Future Experiments

- Add radial-axial polarization converter in front of lens
- Removes cancellation effect of radially polarized field
- COTR electric field on CCD will be proportional to coherence distribution
- Doughnut should change into Gaussian distribution for transversely coherent Gaussian beam shape