LCLS Accelerator R+D issues: Beam Transverse Profile Measurement

LCLS Commissioning Team

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Spring 8 3-way collaboration

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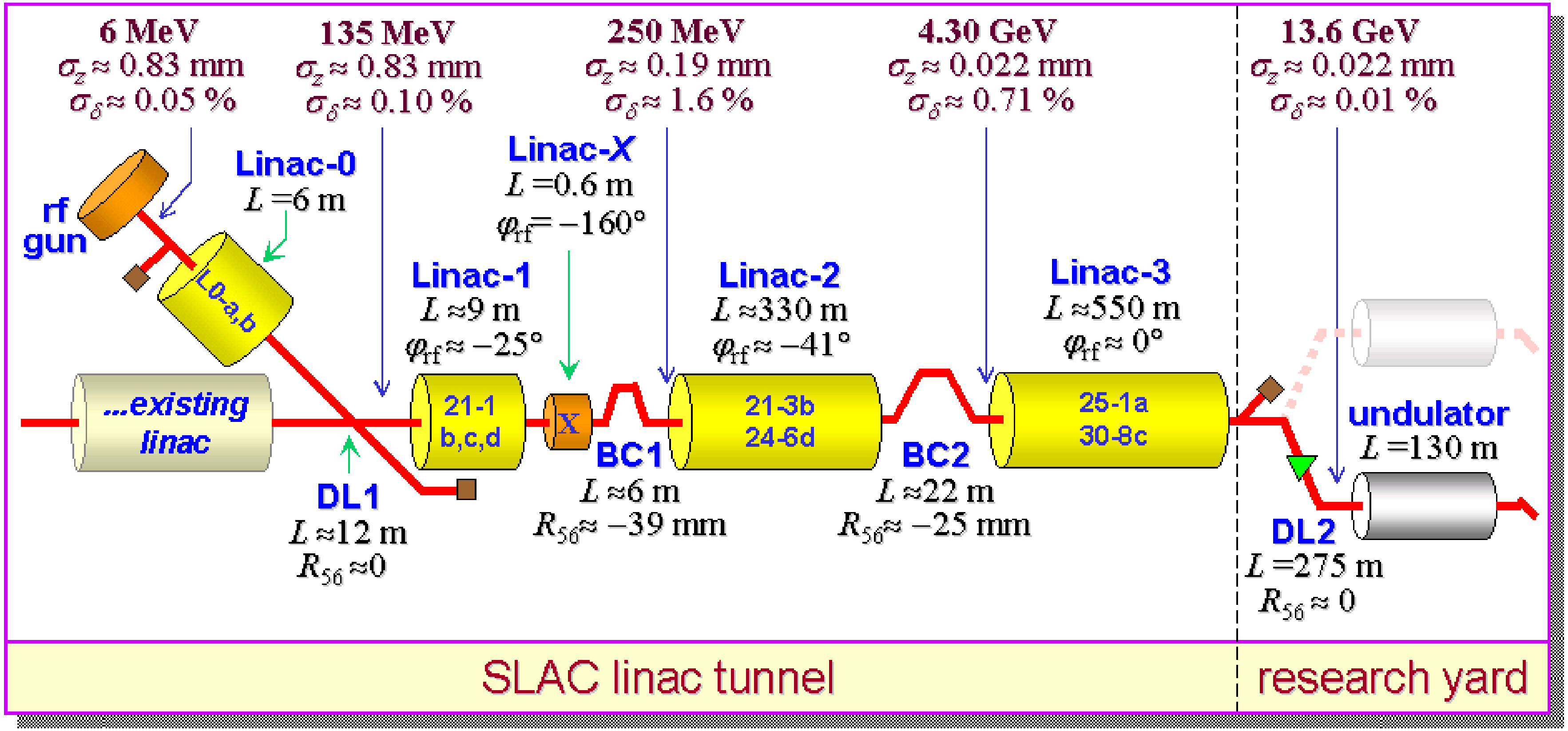
LCLS Accelerator Schematic



6 MeV
$\sigma_z \approx 0.83$ mm
$\sigma_\delta \approx 0.05$ %

135 MeV
$\sigma_z \approx 0.83$ mm
$\sigma_\delta \approx 0.10$ %

250 MeV
$\sigma_z \approx 0.19$ mm
$\sigma_\delta \approx 1.6$ %

4.30 GeV
$\sigma_z \approx 0.022$ mm
$\sigma_\delta \approx 0.71$ %

13.6 GeV
$\sigma_z \approx 0.022$ mm
$\sigma_\delta \approx 0.01$ %

rf gun

Linac-0
$L = 6$ m

L0-a,b

Linac-X
$L = 0.6$ m
$\varphi_{\rm rf} = -160°$

Linac-1
$L \approx 9$ m
$\varphi_{\rm rf} \approx -25°$

Linac-2
$L \approx 330$ m
$\varphi_{\rm rf} \approx -41°$

Linac-3
$L \approx 550$ m
$\varphi_{\rm rf} \approx 0°$

...existing linac

21-1 b,c,d

X

21-3b 24-6d

25-1a 30-8c

undulator
$L = 130$ m

DL1
$L \approx 12$ m
$R_{56} \approx 0$

BC1
$L \approx 6$ m
$R_{56} \approx -39$ mm

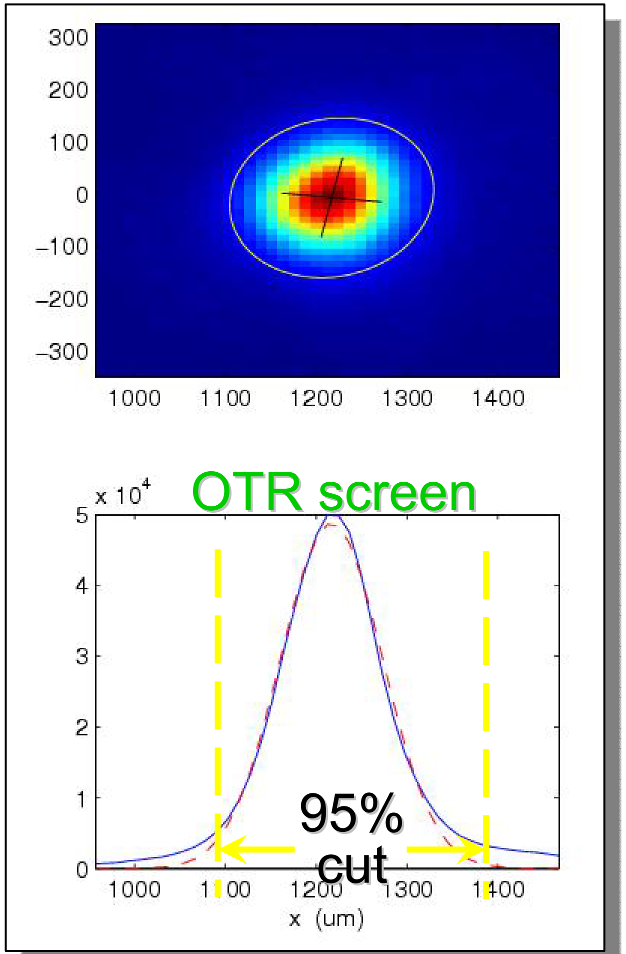
BC2
$L \approx 22$ m
$R_{56} \approx -25$ mm

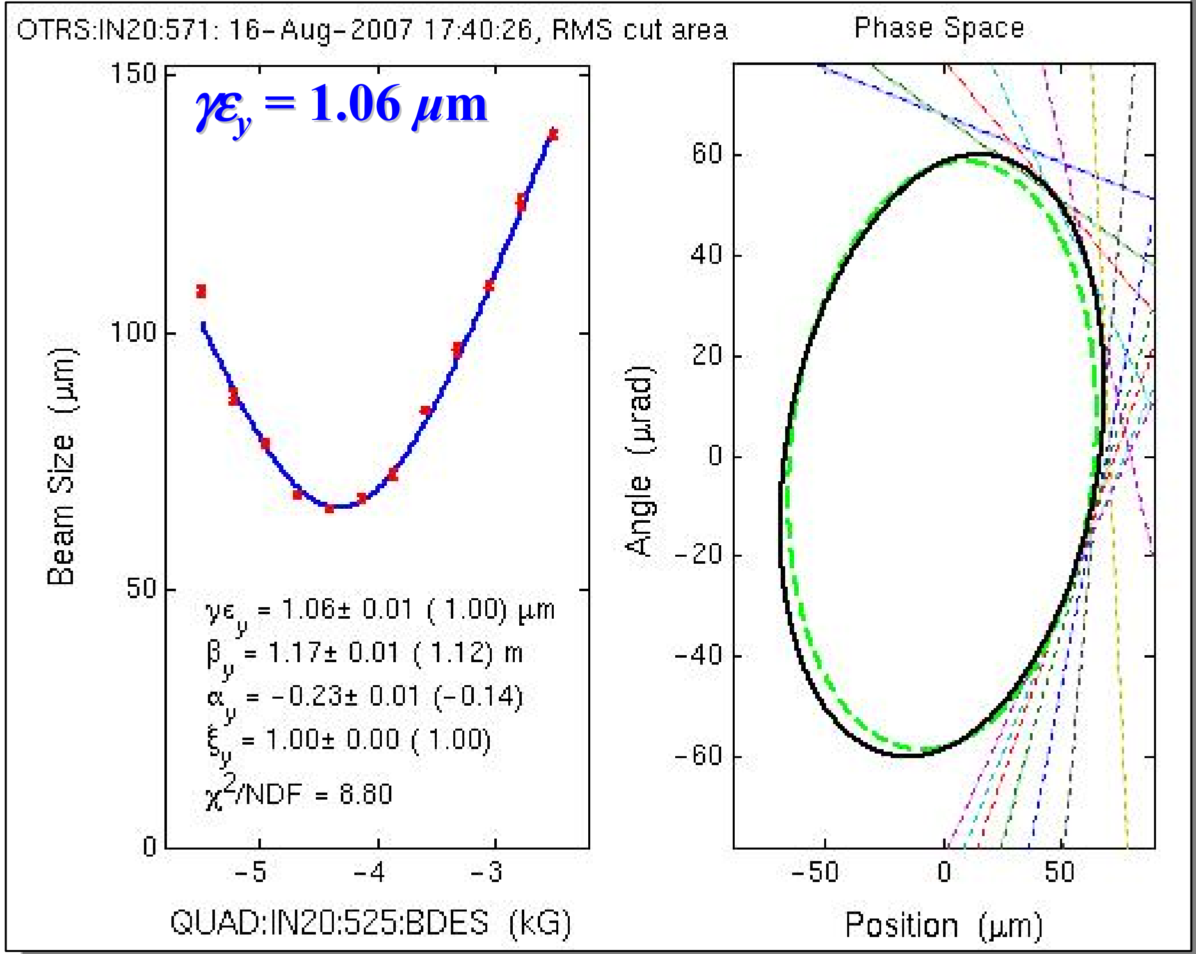
DL2
$L = 275$ m
$R_{56} \approx 0$

SLAC linac tunnel

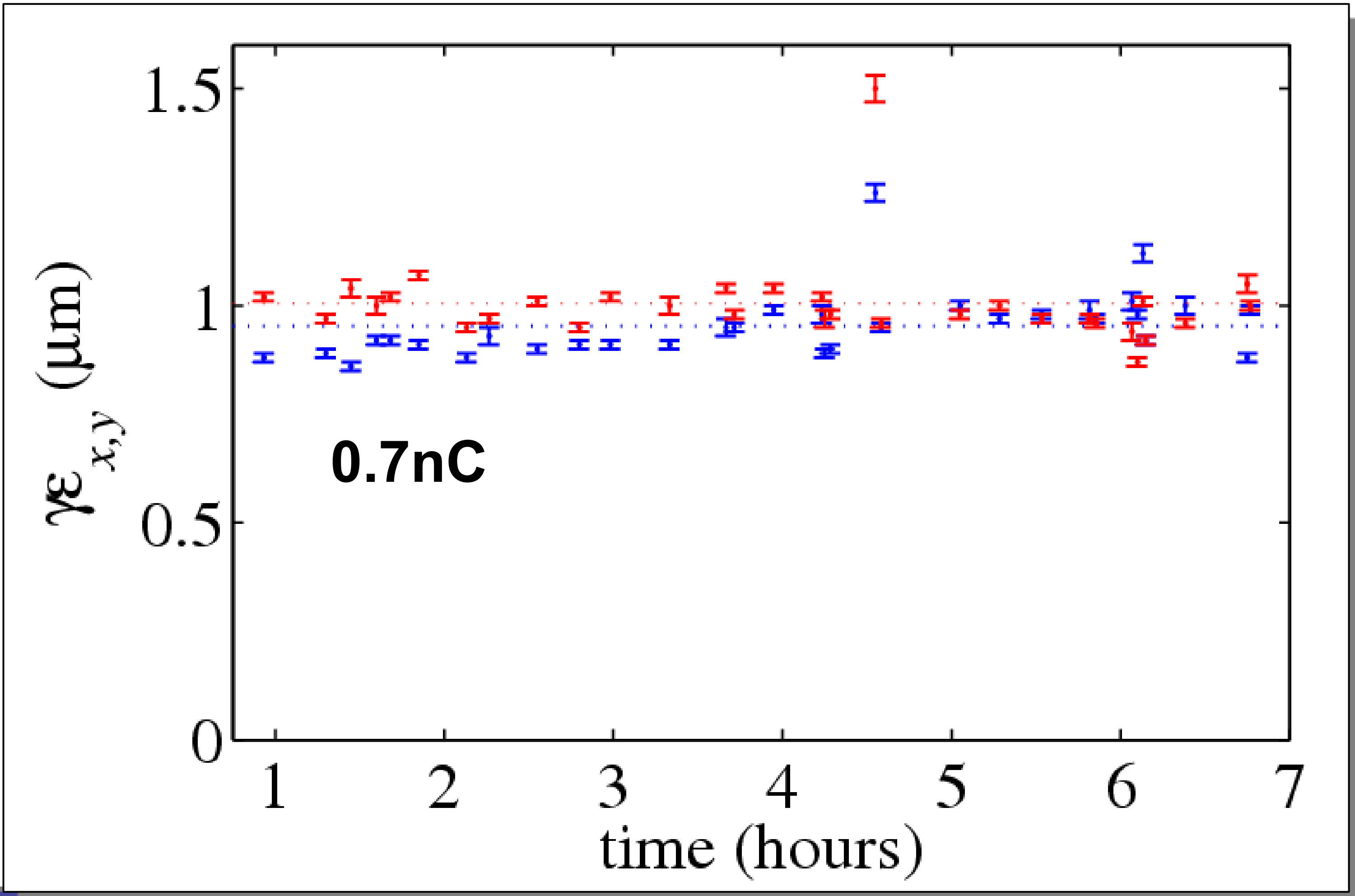
research yard

Emittance measurement at 1nC

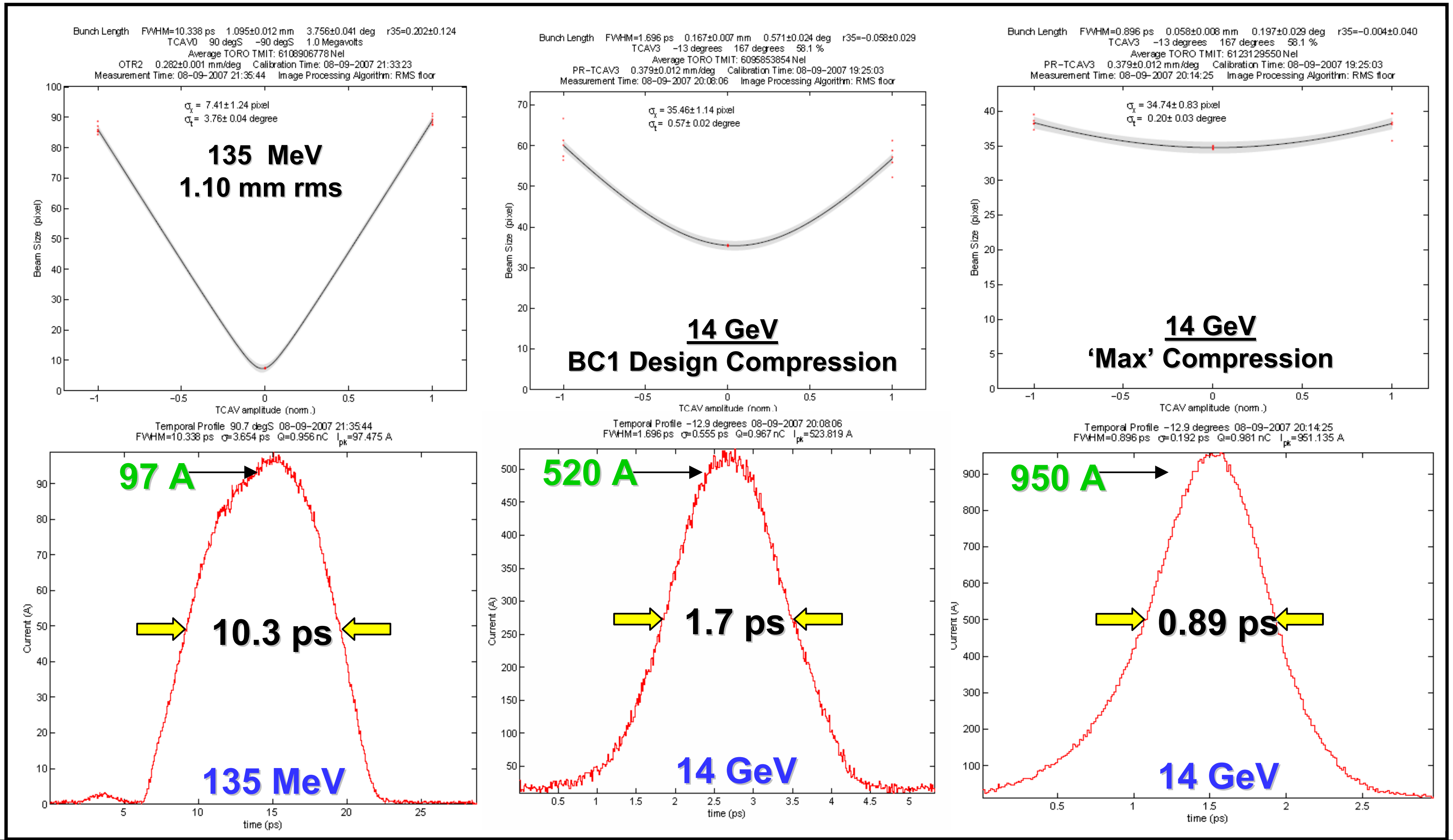




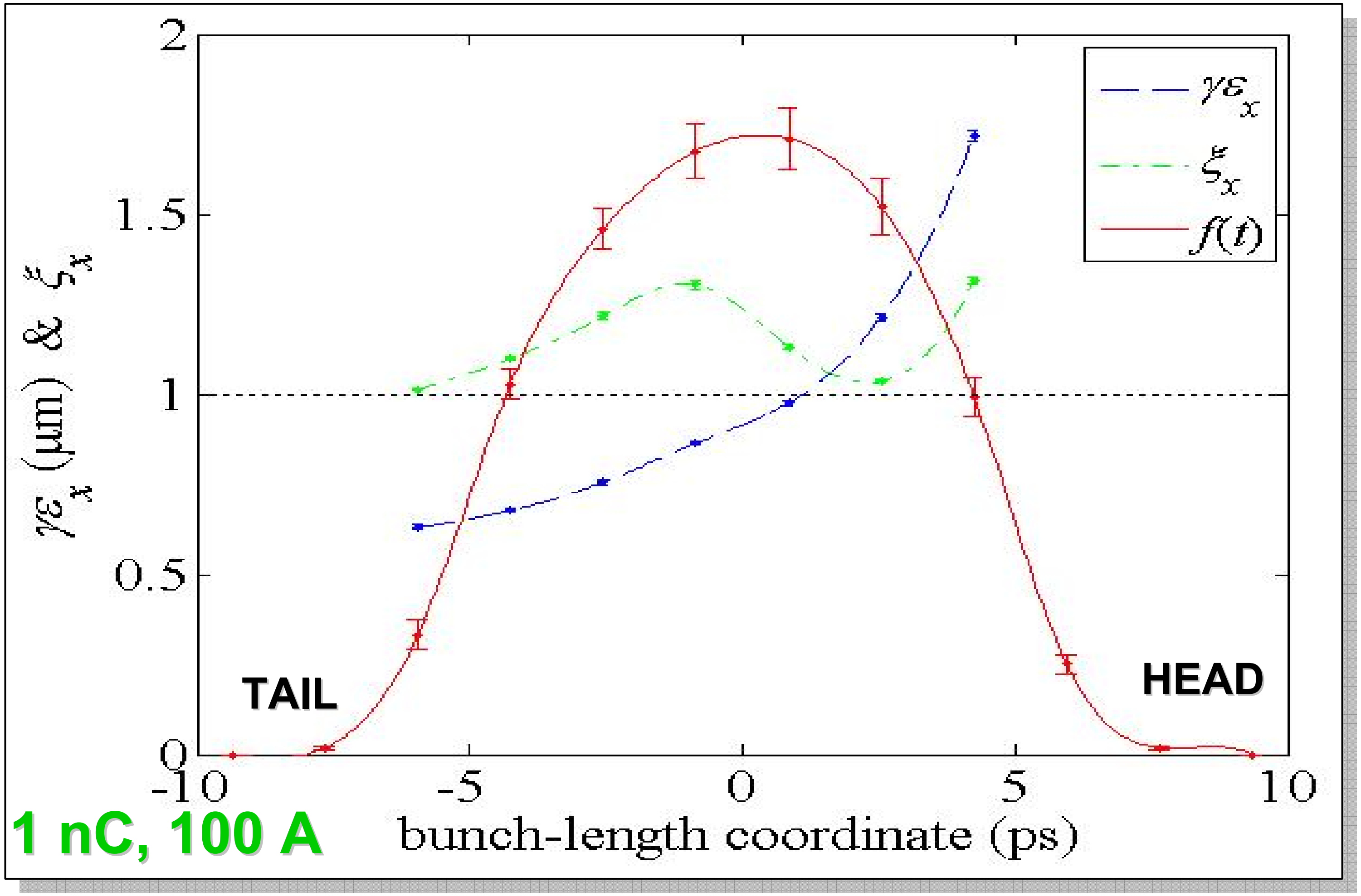
Stable Operation



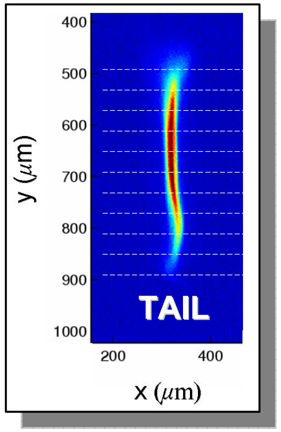
Bunch Compression (TCAV)



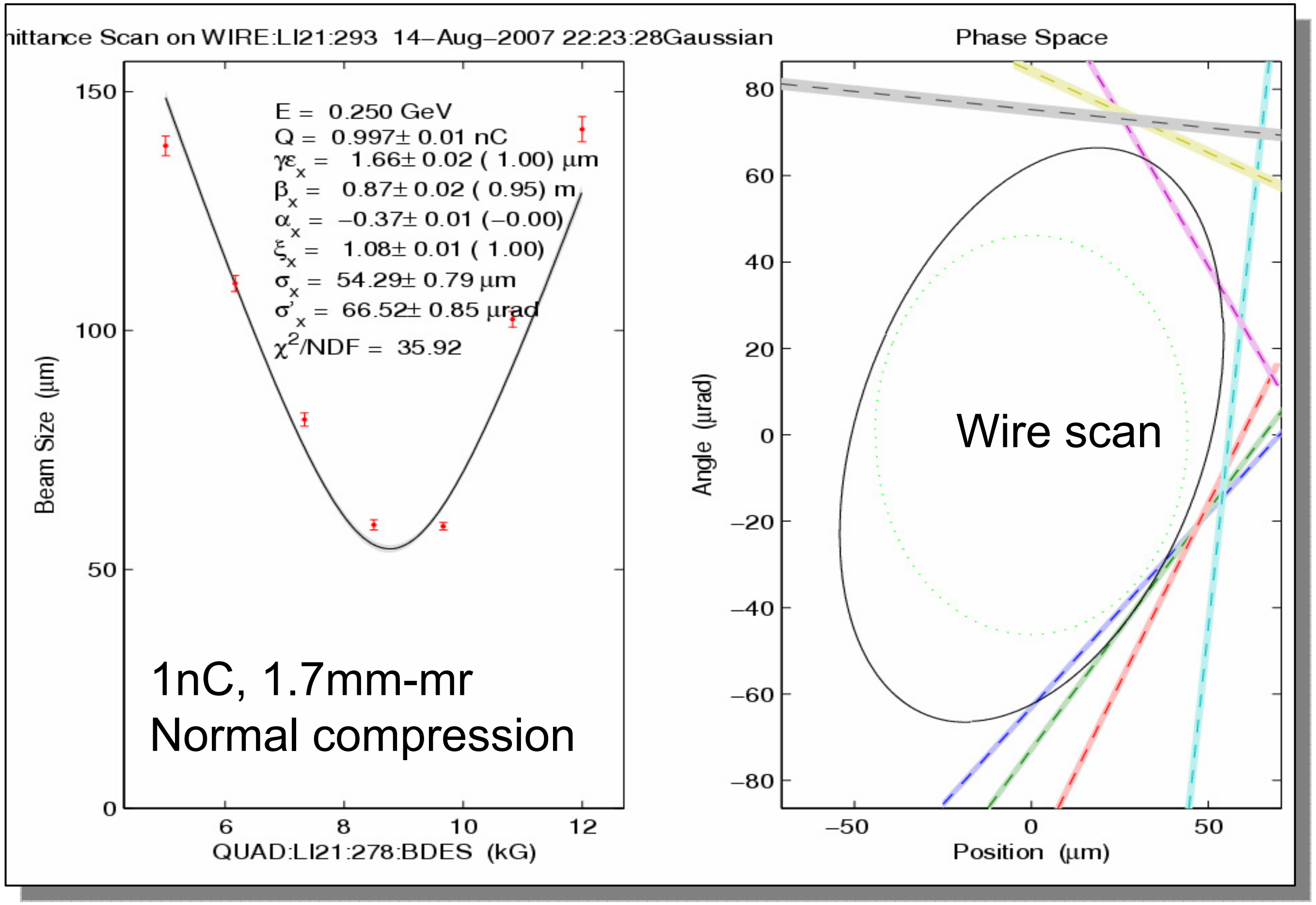
Slice Emittance with TCAV



1 nC, 100 A



Emittance worse after BC1



1nC, 1.7mm-mr
Normal compression

Wire scan

Steering in X-band, structure, poor field quality in compressor bends

Accelerator R+D topics

- Various LCLS Specific issues including beam steering from the X-band RF, not of great general interest
- Run uncovered some issues that ARE of general interest.
- Diagnostics for high brightness beams are much more difficult that we had anticipated.
- Will concentrate on the issues for beam transverse profile monitors

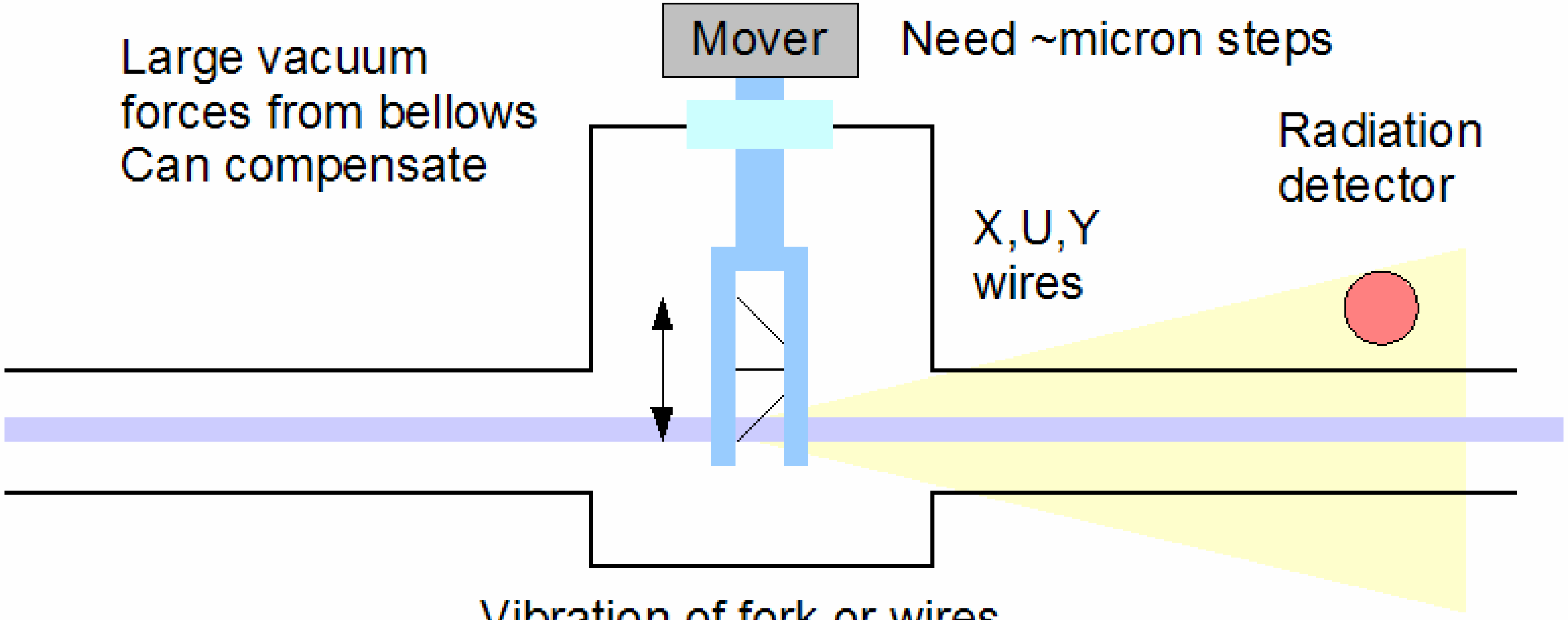
What makes diagnostics difficult?

- High brightness beams typically have small spot sizes in diagnostic regions.
- High longitudinal brightness beams can produce a host of coherent effects that confuse diagnostics.
- Accelerators with high brightness beams typically need very good beam control – and therefore accurate diagnostics
- **Can’t use primitive tools to diagnose advanced machines**

Profile Monitor Options

- **Wire Scanner**: Scan wire through beam, measure secondary radiation
  - Direct calibration. Good dynamic range. Good linearity. Insensitive to longitudinal structure. Can read individual bunches in a train
  - Slightly invasive
  - Slow. Integrated profile only. Vibration problems
- **Fluorescent Screens**: Use scintillator material in beam
  - Single shot image. Good sensitivity.
  - Invasive. Saturation for high charge densities. Material degradation over time. Powders have poor spatial resolution
- **OTRs**: Metal foil in beam produces visible radiation at the beam “reflection” angle.
  - Good linearity. Good resolution. Prompt optical output, can be sued with streak cameras.
  - Degrades emittance but beam continues to propagate.
  - Poor depth of field for most installations. Coherent effects – discussed at length later.
- **Other**: Laser wire, X-ray OTR or SLM, etc.
  - Tend to be **Experiments**, not **Diagnostics**

Wire Scanners



Mover

Need ~micron steps

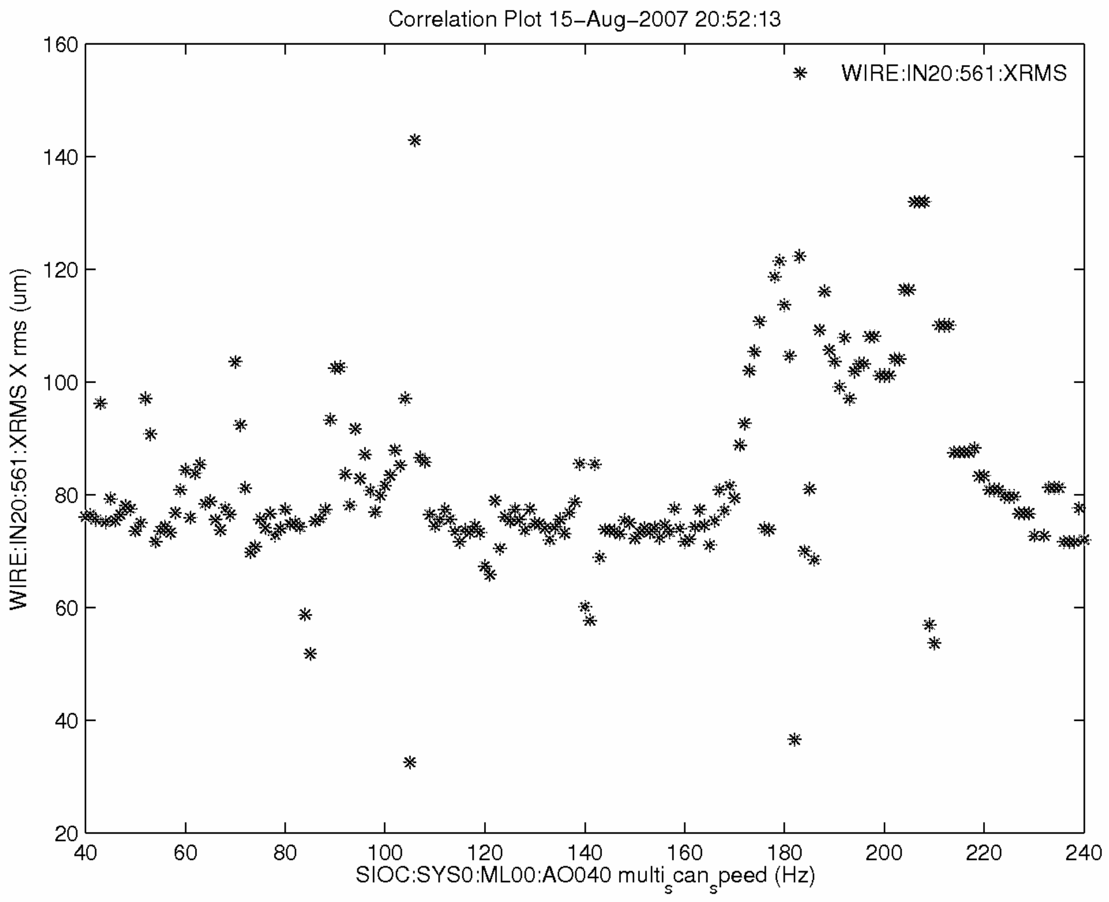
Large vacuum
forces from bellows
Can compensate

Radiation
detector

X,U,Y
wires

Vibration of fork or wires
can distort measurement

Wire Scanner Vibration

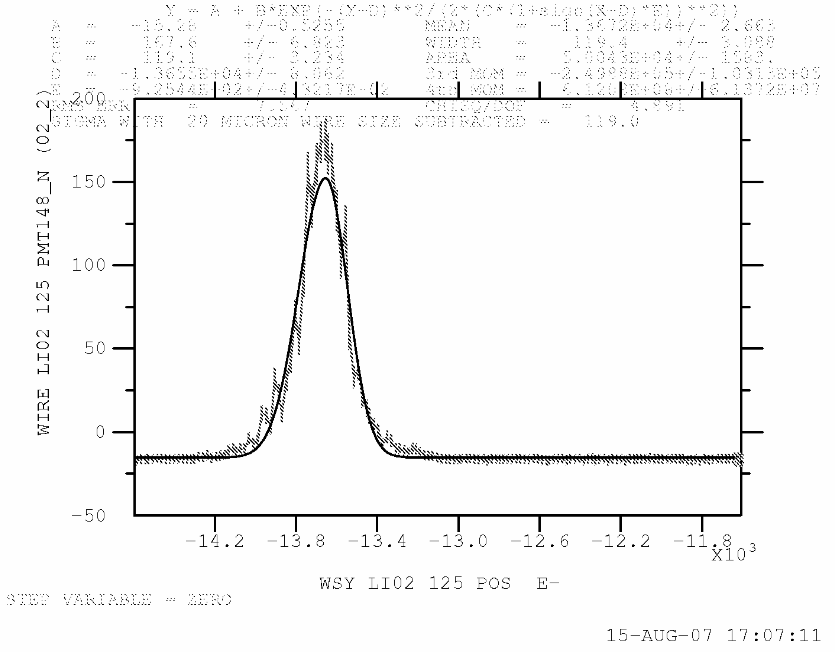


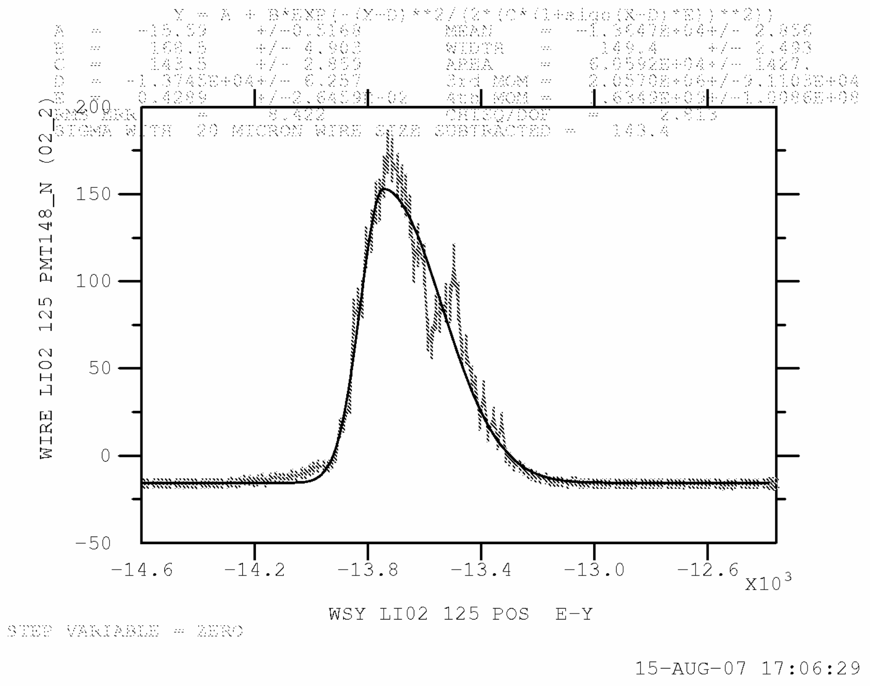
Measured beam size
Vs. Motor Steps / second
Range is 40-140 microns

With slow scanning, size was reproducible to 5 microns.

Wire Scanner Vibration is not a new problem.

Scan from old SLC wires (1980s)





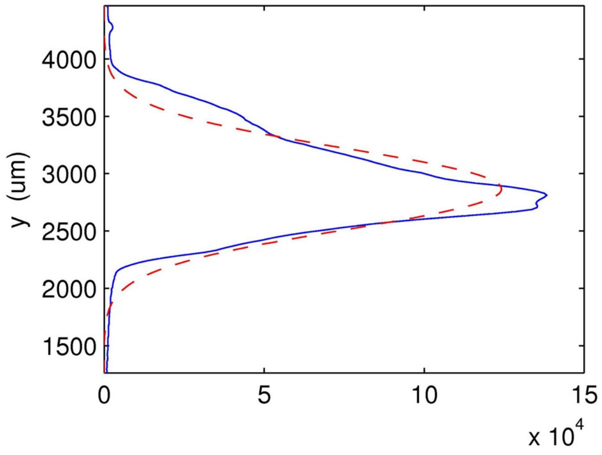
LI02 wire scanner, 20um/step
119 micron width

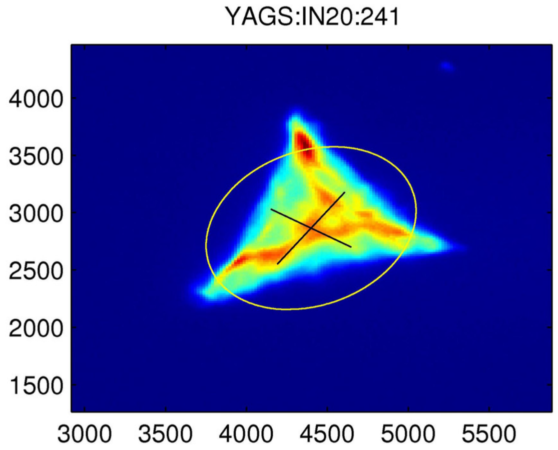
LI02 wire scanner, 15um/step
149 micron width

Wire Scanner Vibration Fixes

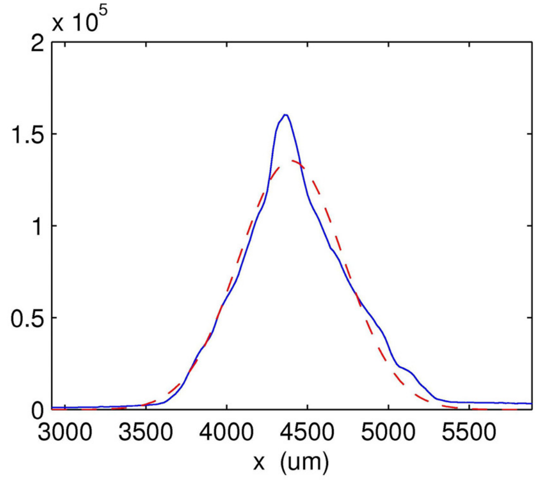
- Increase lowest resonance frequency above step frequency
  - Make structure stiffer or smaller: Resonant frequency only goes as square root of stiffness.
- Increase step frequency above low order mechanical resonances
  - Gear reducers – should work, but reduce maximum speed
- Non-stepping driver: DC servo motor, micro-stepping, direct piezoelectric drive.
  - More complexity, problems with radiation and long cables.
- Move beam not wire
  - Works if you understand the optics, but makes wire scan invasive.
- Wire scanners can be made to work – but don't ignore the engineering issues: Easy to get it wrong.

Why we need screens: A wire-scanner like measurement would not have shown this!



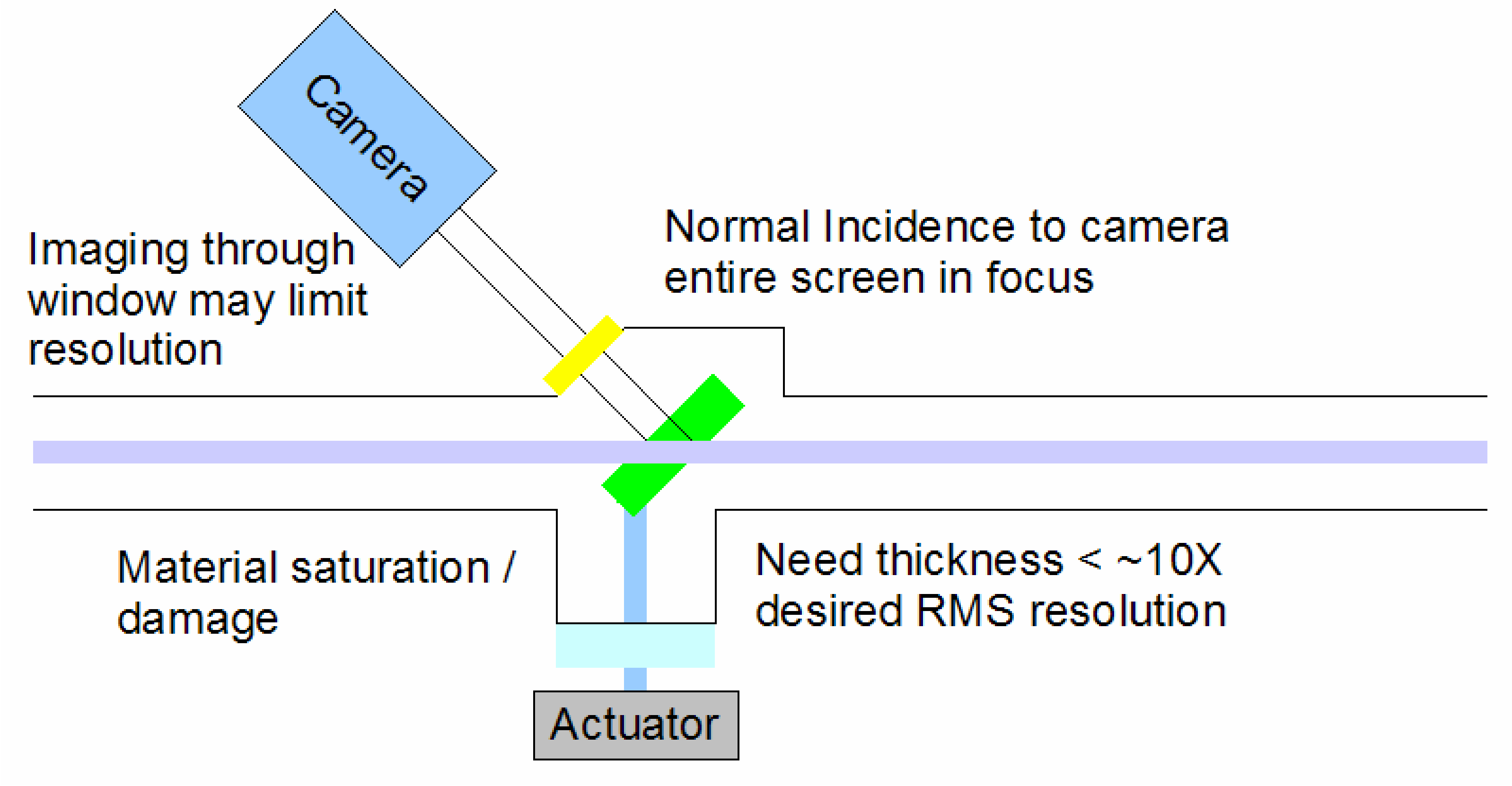


xmean = 4399.70 um
ymean = 2865.32 um
xrms = 324.56 um
yrms = 354.96 um
corr = 24674.79 um^2
sum = 110.32 Mcts



Pathological beam shape that would
Not be apparent on wires

Fluorescent Screen



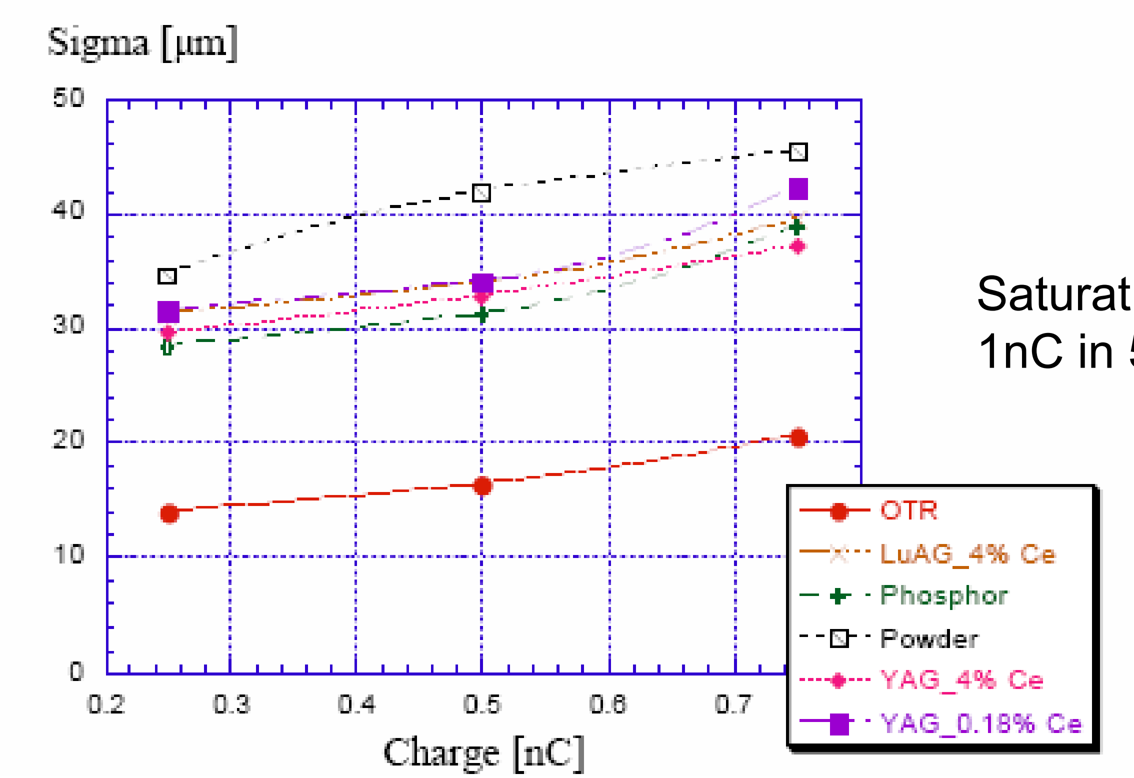
Imaging through window may limit resolution

Normal Incidence to camera entire screen in focus

Material saturation / damage

Need thickness < ~10X desired RMS resolution

Screen Saturation



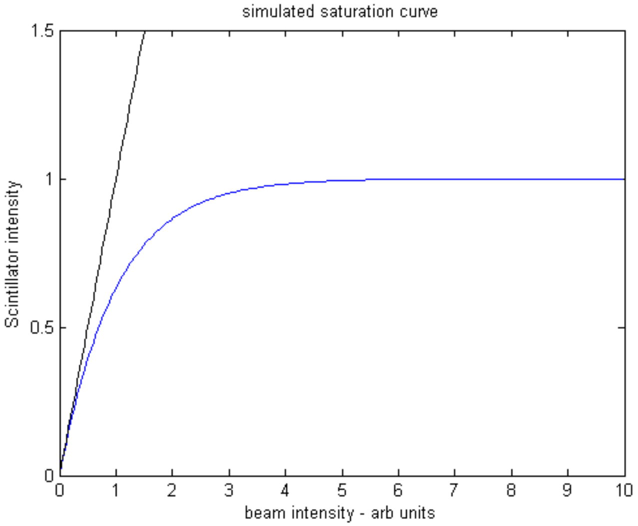
Does good data on saturation exist?

Saturation estimated at 0.04pC/um^2
1nC in 50um spot is 10X this density

A. Murokh et al, PAC2001

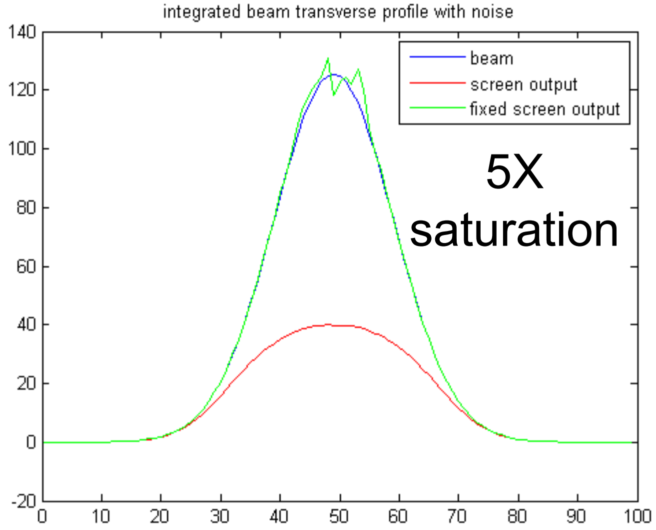
Can we fix saturation in software?

- Expect saturation to have the form $y=1-e^{-x}$ with x the beam intensity, y the fluorescence intensity.

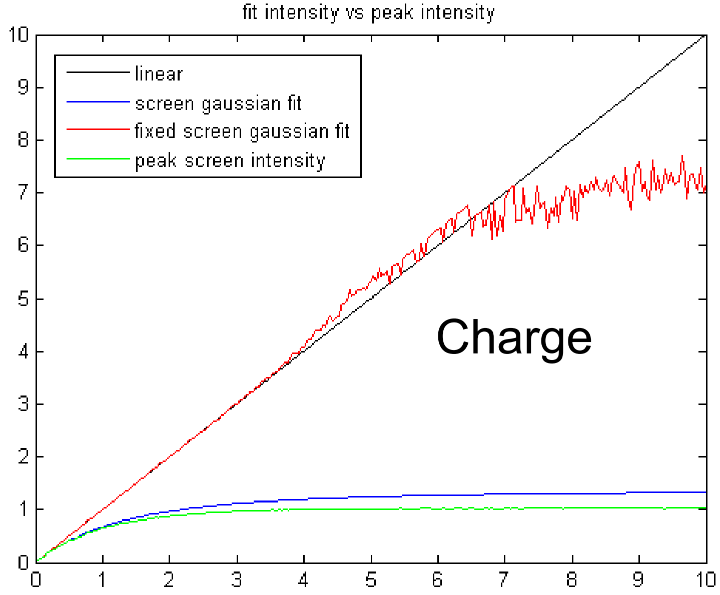


- Can in principal fix with $y_f=-\ln(1-y)$
- Of course this will amplify noise for high saturation levels

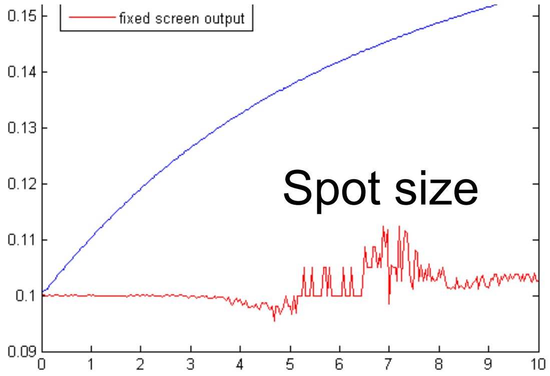
Simulated Gaussian Beam Spots – Saturation Correction



5X saturation



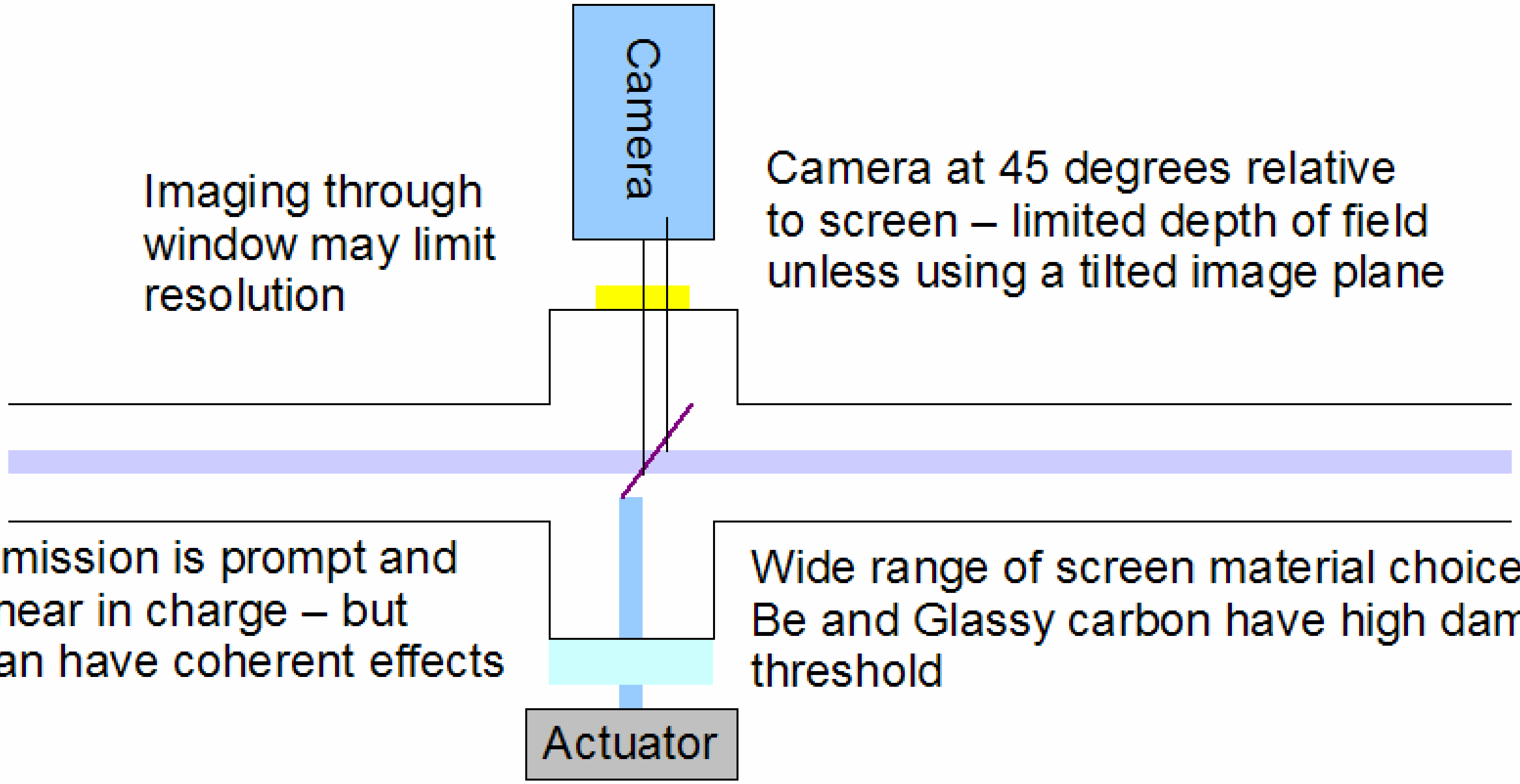
Charge



Spot size

Can probably make a reasonable correction for a factor of ~5 above saturation. (simulation assumes 100:1 signal / noise, 1000:1 dynamic range for camera

Optical Transition Radiation



Imaging through window may limit resolution

Camera at 45 degrees relative to screen – limited depth of field unless using a tilted image plane

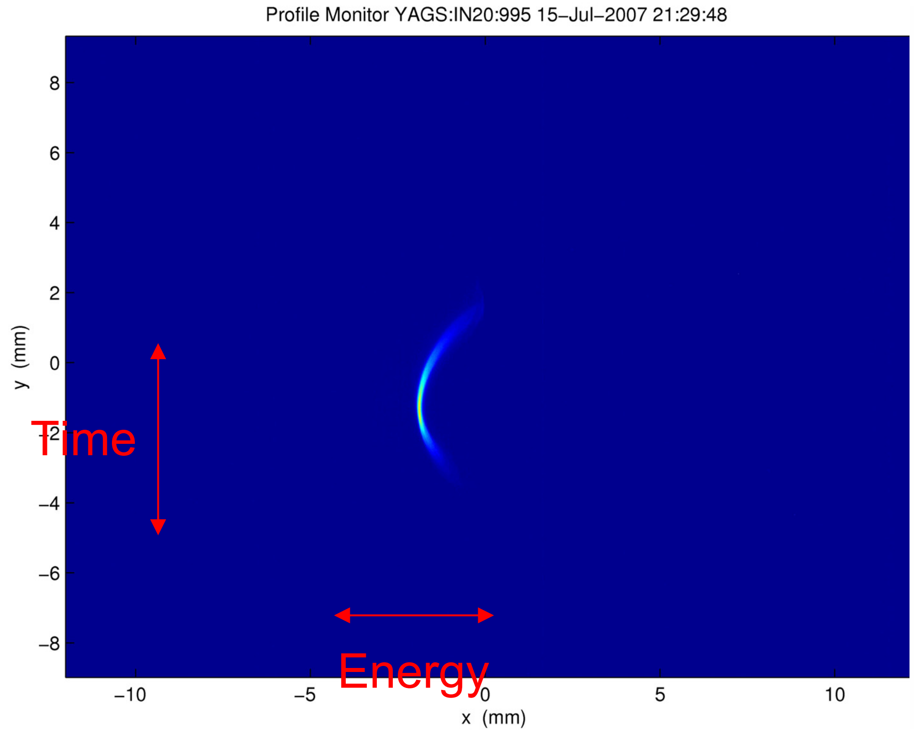
Emission is prompt and linear in charge – but can have coherent effects

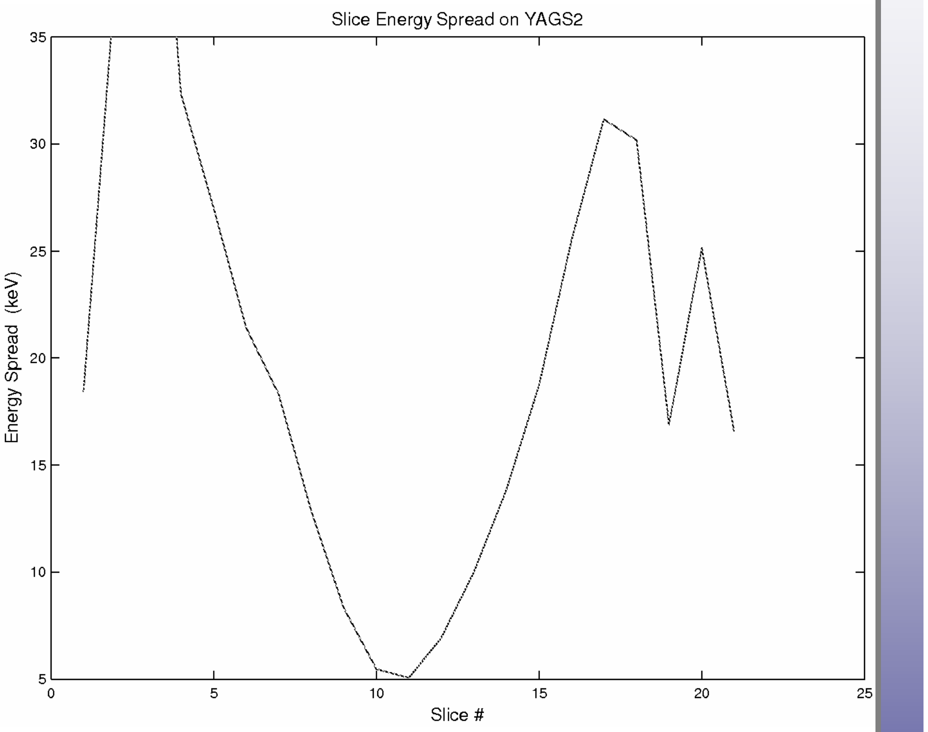
Wide range of screen material choices
Be and Glassy carbon have high damage threshold

OTR Emission

- Each electron emits ~ α (1/137) photons from ~DC to $\gamma\omega_p$ in the forward direction, and DC to ω_p in the "Reflected" direction .where ω_p is the plasma frequency ~100nm (20eV) for typical metals.
- Emission is prompt
  - For CW beam, each electron emits incoherently, power scales as N_e
  - For wavelengths long compared to the bunch length, electrons will radiate coherently, power scales as N_e^2
  - For 1nC beam, for wavelengths >> bunch length, coherent effects can increase output power by $>10^9$
- If there is modulation on the electron beam at optical frequencies, this will produce additional coherent emission.
  - With a typical 1mm pulse length, 1nC, we have $\sim 10^6$ electrons in an optical wavelength.
  - Density modulation of $\sim 10^{-3}$ at optical wavelengths will substantially increase emission.
- Longitudinal coherence causes longitudinal structure to distort transverse profiles.

LCLS Energy Spread 157pC

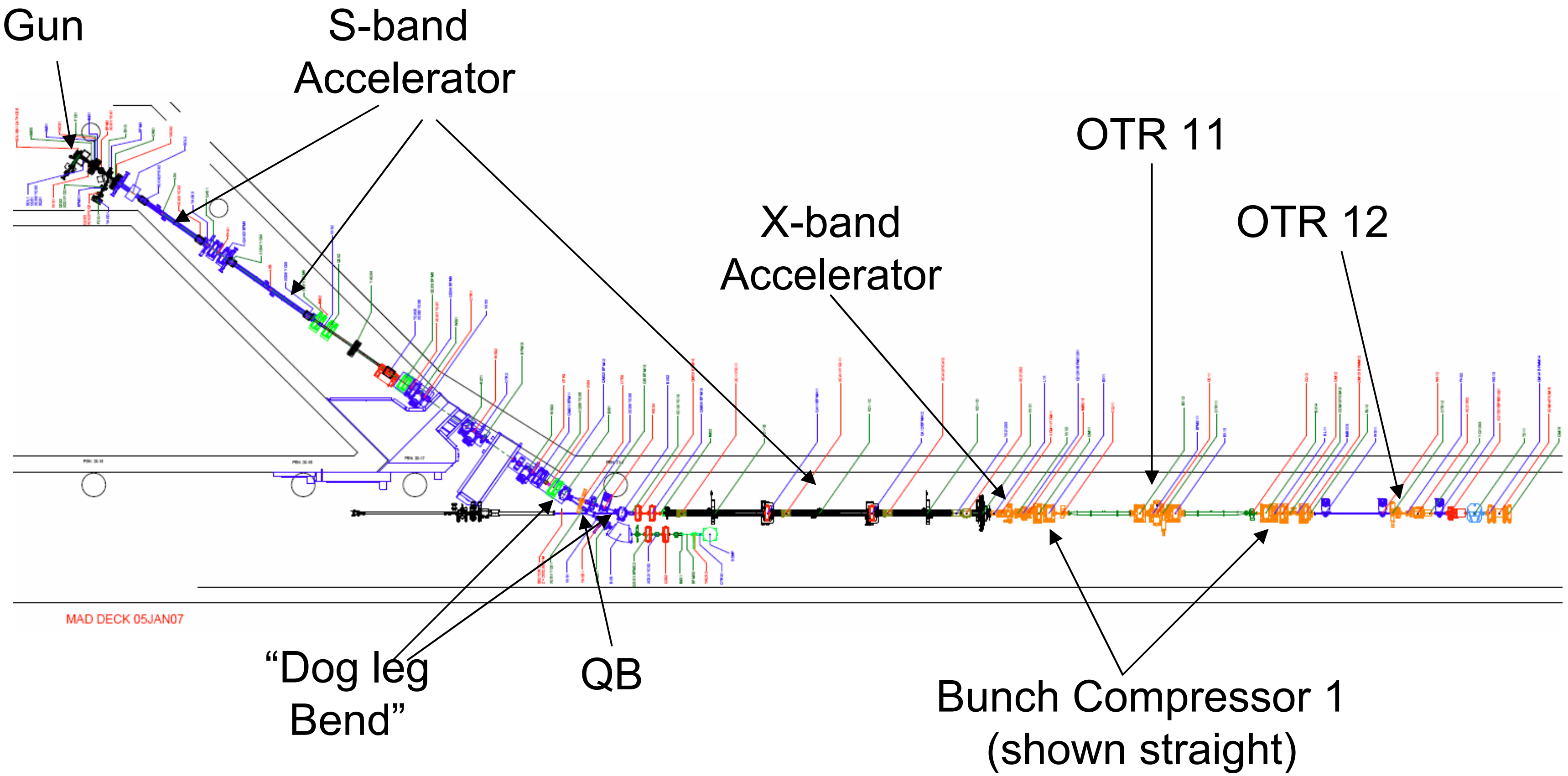




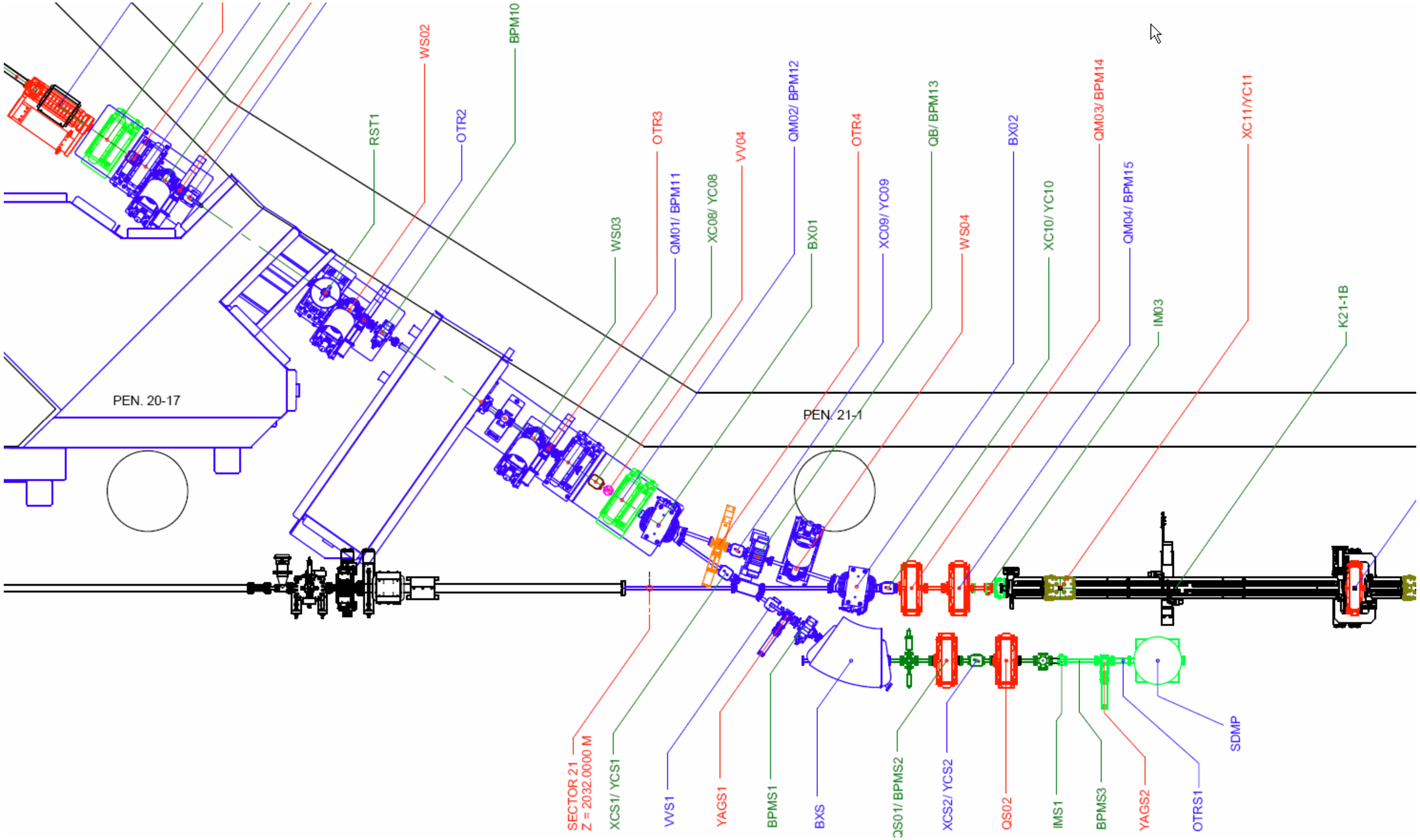
Transverse cavity on, minimum energy spread at spectrometer (135MeV) is ~5KV

Small energy spread allows preservation and amplification of short wavelength current modulation

LCLS Injector



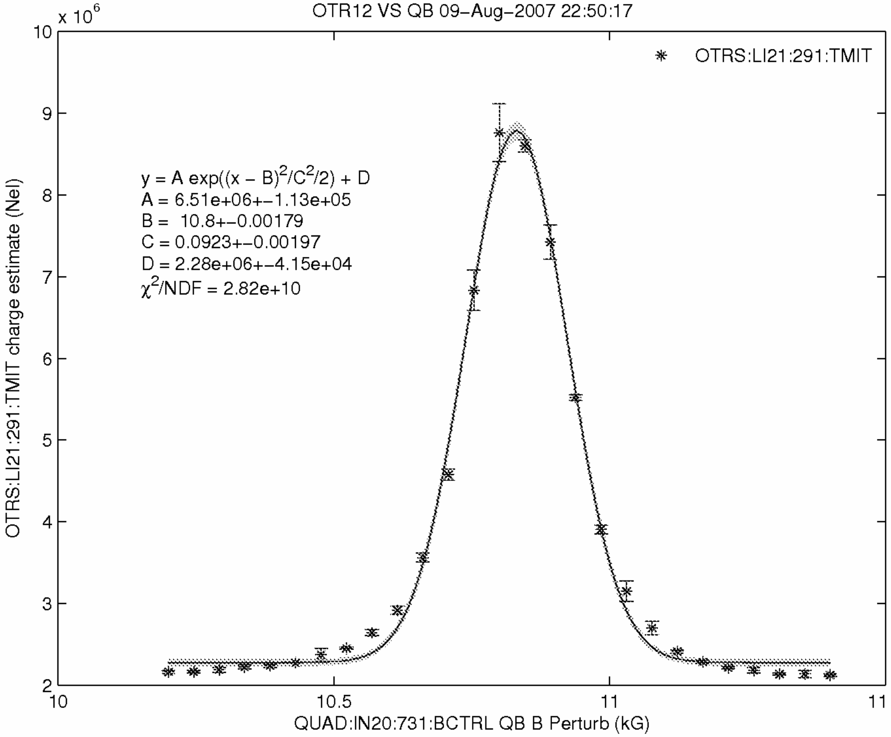
LCLS Injector, DL1

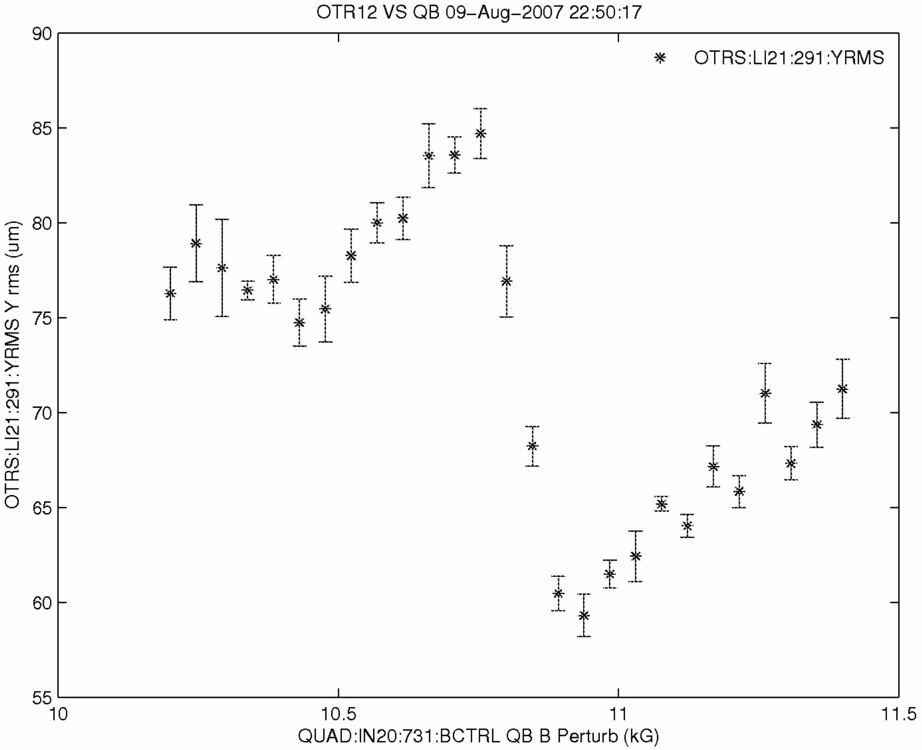


Coherent OTR effects in LCLS

- In “Dog leg 1”, the first bend, we can adjust the residual dispersion with quad “QB”.
- Look at images on OTR screen after dog leg
- Bunch compressor magnets ON
- RF on crest (no compression)

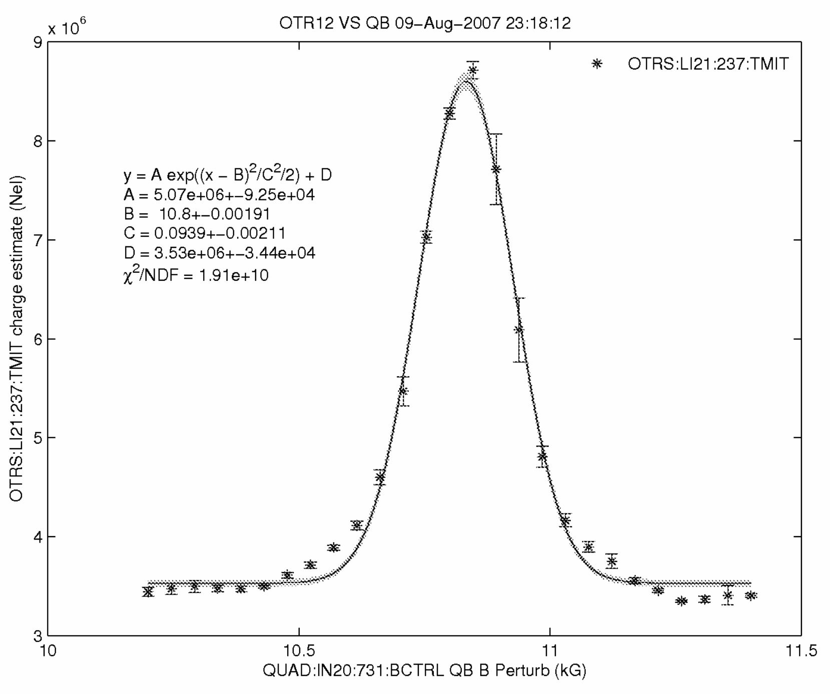
Beam size distortions in OTR12



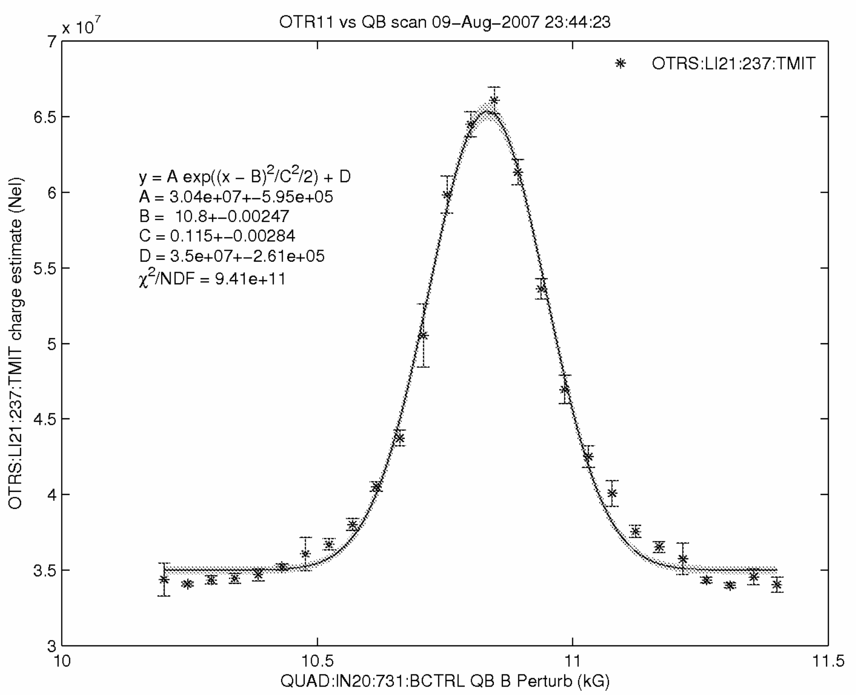


OTR12 sum signal as QB is varied. BC1 off, L1X, L1S on crest. Y beam size Varies with observed intensity

Effect is in the OTR, not the camera – vary optical attenuation

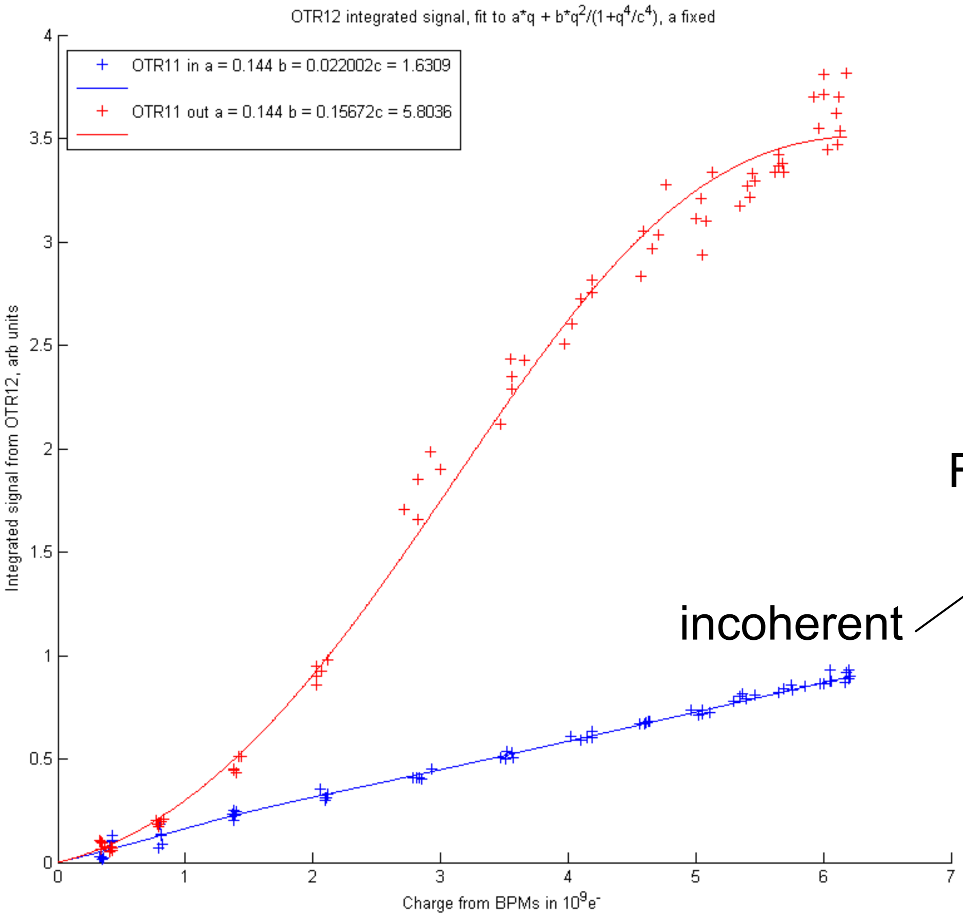


OTR11 integrated signal, Vary QB
Filter 2 in. Width 0.094 +/- .002
Amplification 2.43



OTR11 integrated signal, Vary QB
No filter. Width 0.115 +/- .003
Amplification 1.86

OTR12 signal with OTR11 in or out



L1S, L1X on crest
BC1 off, Filter 1+2

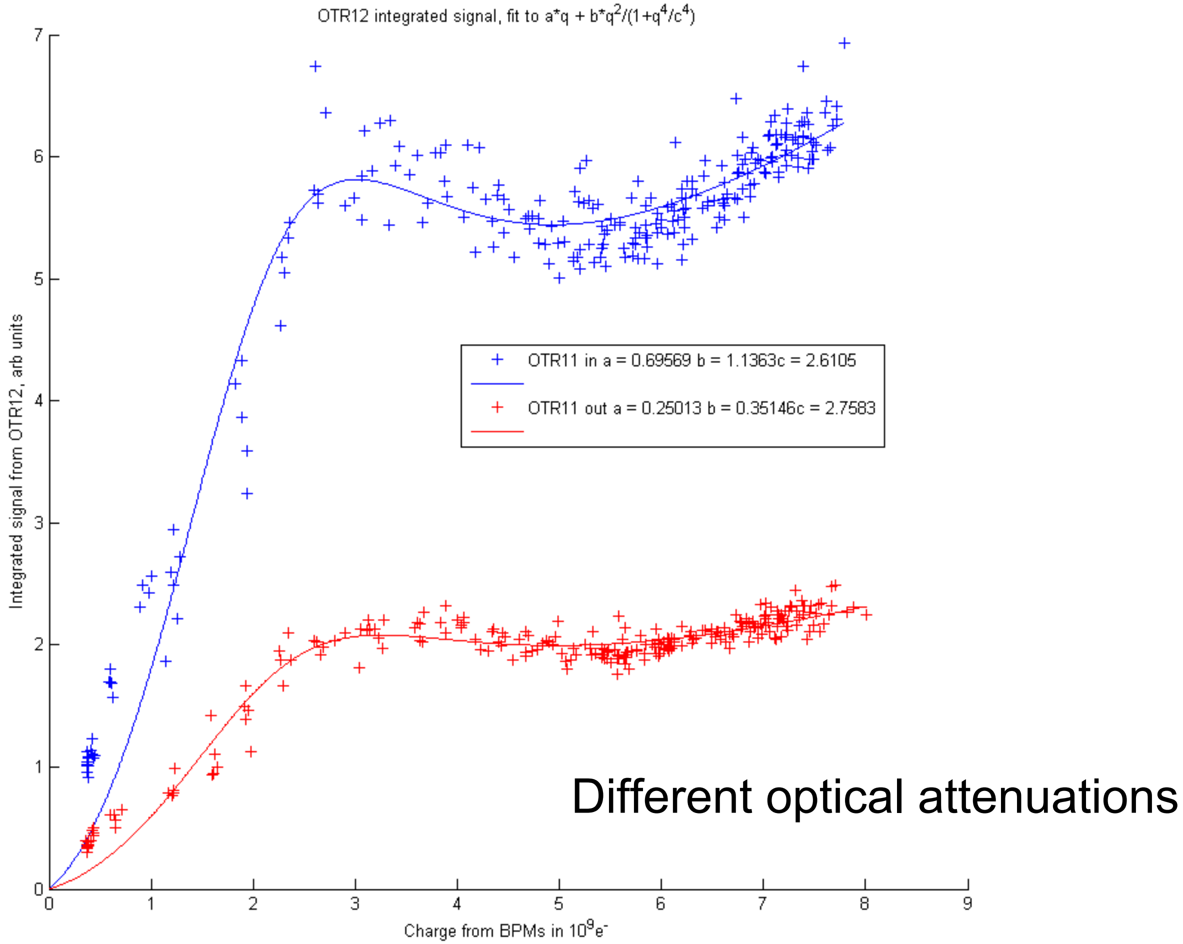
Fit to A*q + B*q^2/(1+q^4/c^4)

incoherent

Coherent

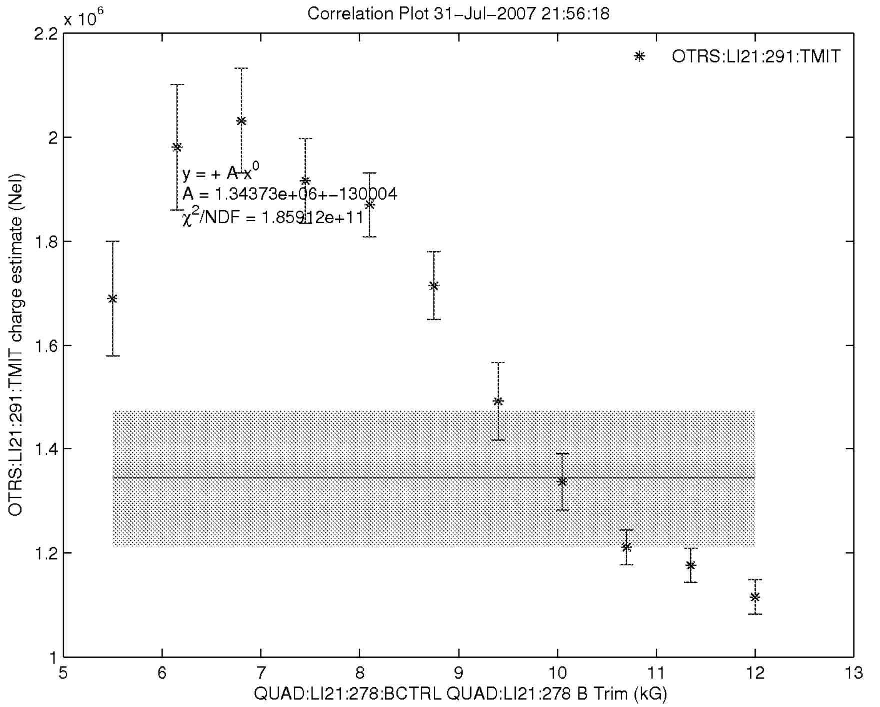
Modulation decreased (space charge?) for higher currents (VERY APPROXIMATE)

OTR12 effect is OTR, not camera

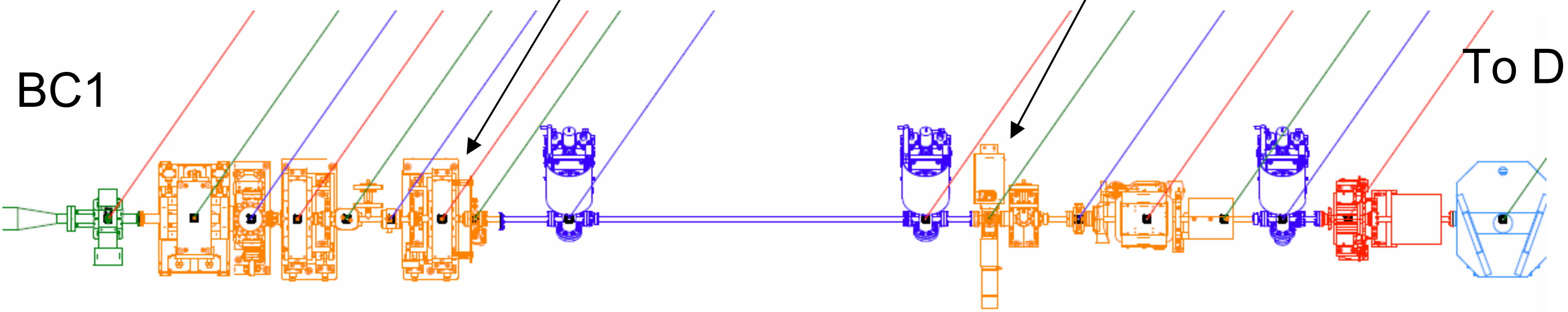


Different optical attenuations

OTR12 Sum vs. QM 13



Can have significant effects
From other quads.



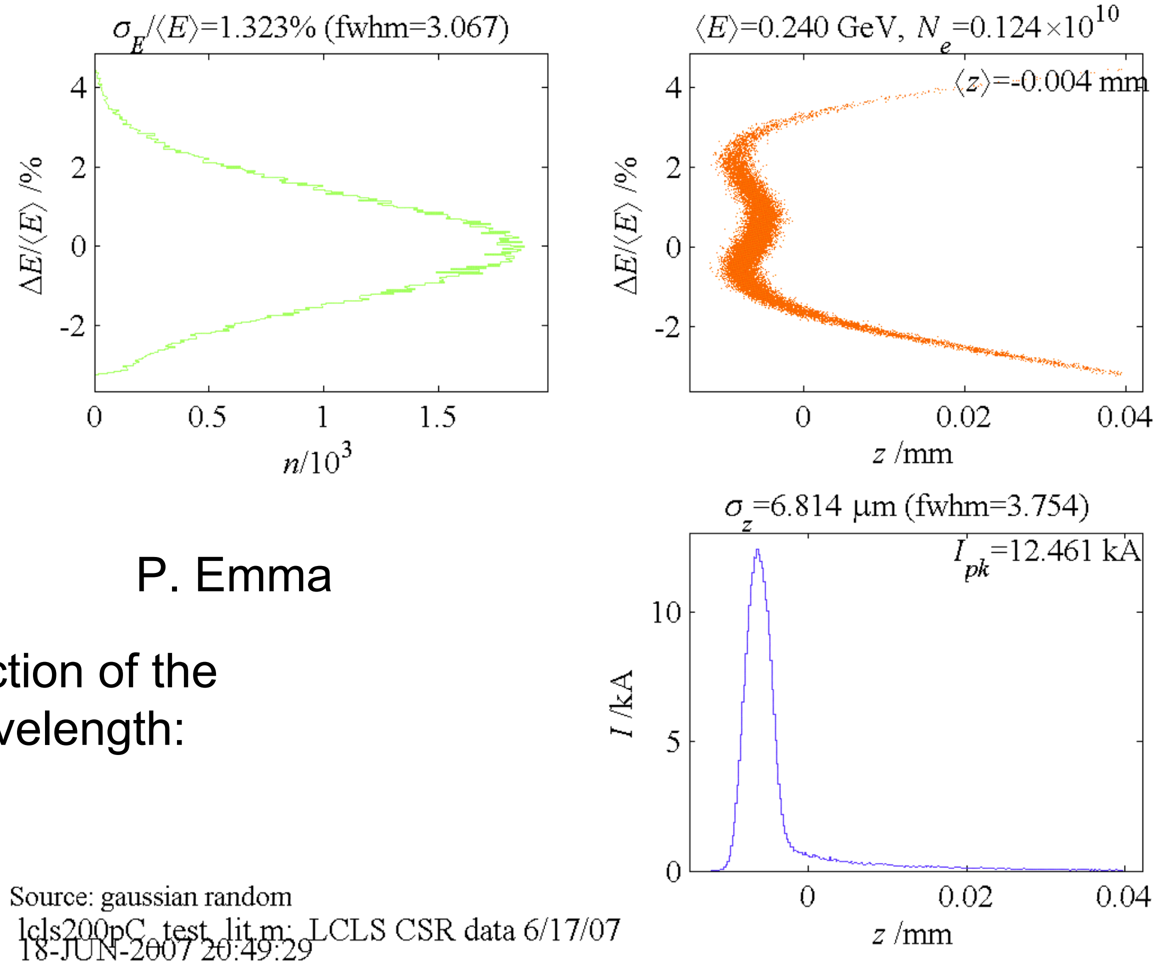
OTR12

QM 13

From BC1

To Dump

Effects at high compression: Litrack simulation, 200pc, maximum compression 12 fs, FWHM

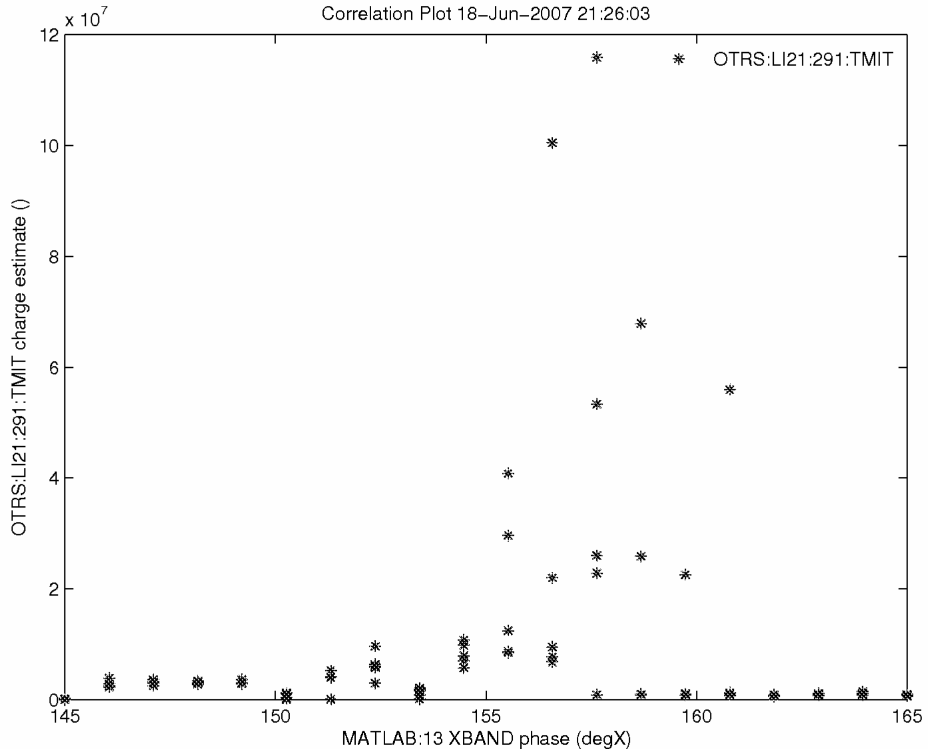


Source: gaussian random
lcls200pC_test_lit.m; LCLS CSR data 6/17/07
18-JUN-2007 20:49:29

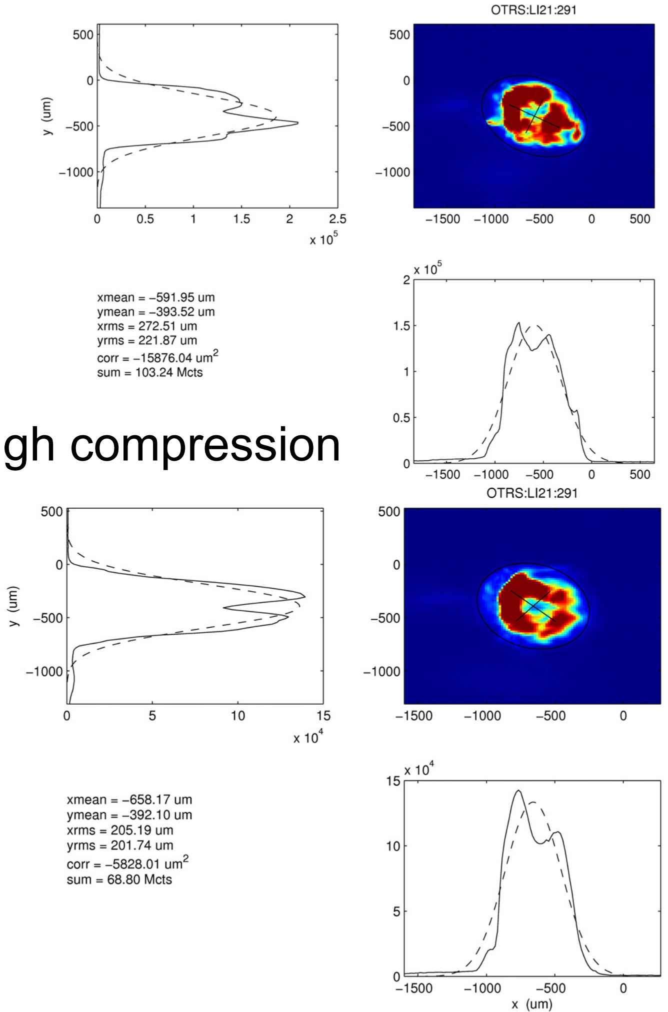
P. Emma

Might expect significant fraction of the beam within one optical wavelength: Strong coherent effects

OTR12 optical signal vs. Phase 200pc.



Typical signal non-compressed 3 MCounts, Maximum at compression >100MCounts and saturated.

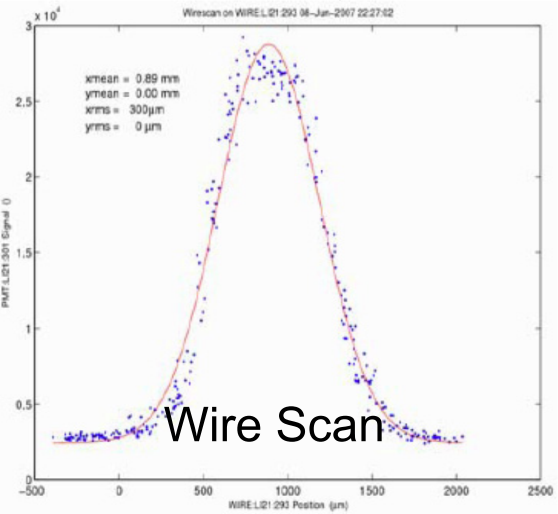


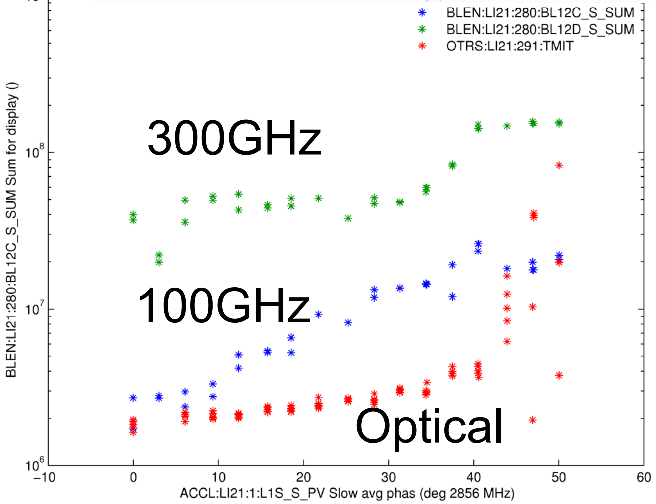
```
xmean = −591.95 um
ymean = −393.52 um
xrms = 272.51 um
yrms = 221.87 um
corr = −15876.04 um^2
sum = 103.24 Mcts
```

High compression

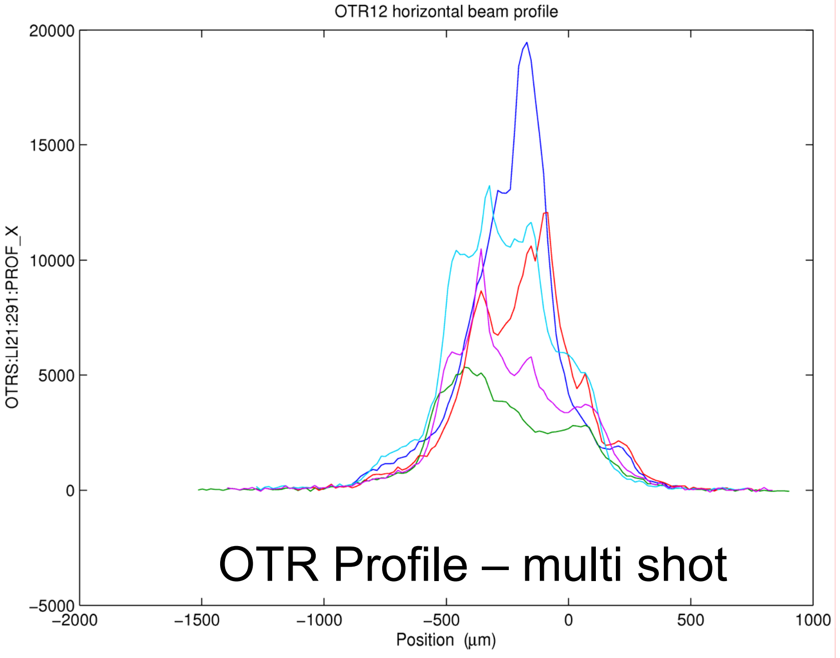
```
xmean = −658.17 um
ymean = −392.10 um
xrms = 205.19 um
yrms = 201.74 um
corr = −5828.01 um^2
sum = 68.80 Mcts
```

100GHz, 300GHz and Optical signals



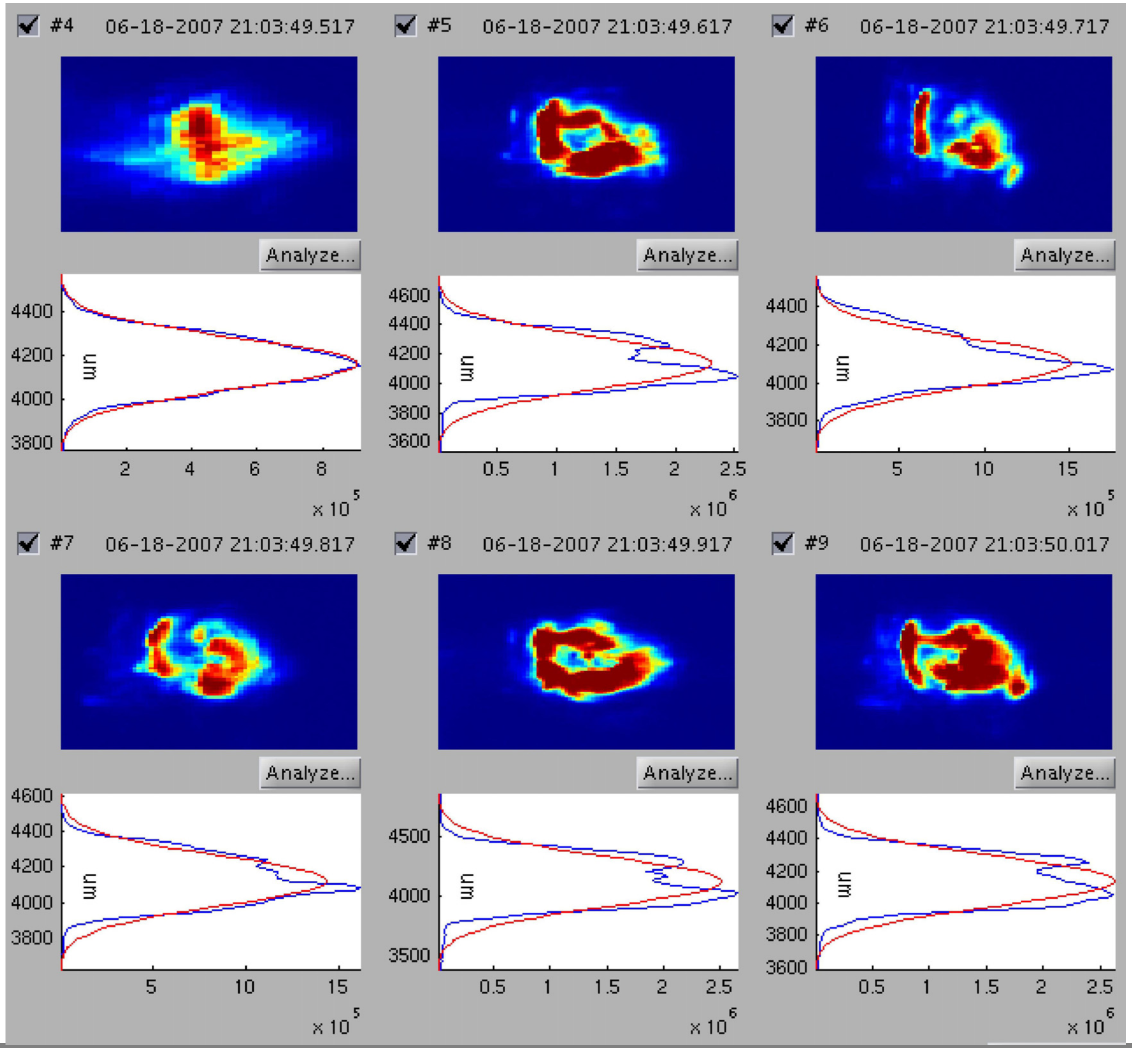


Bunch length diodes show maximum compression at same phase as maximum OTR. OTR produces unstable transverse beam measurements

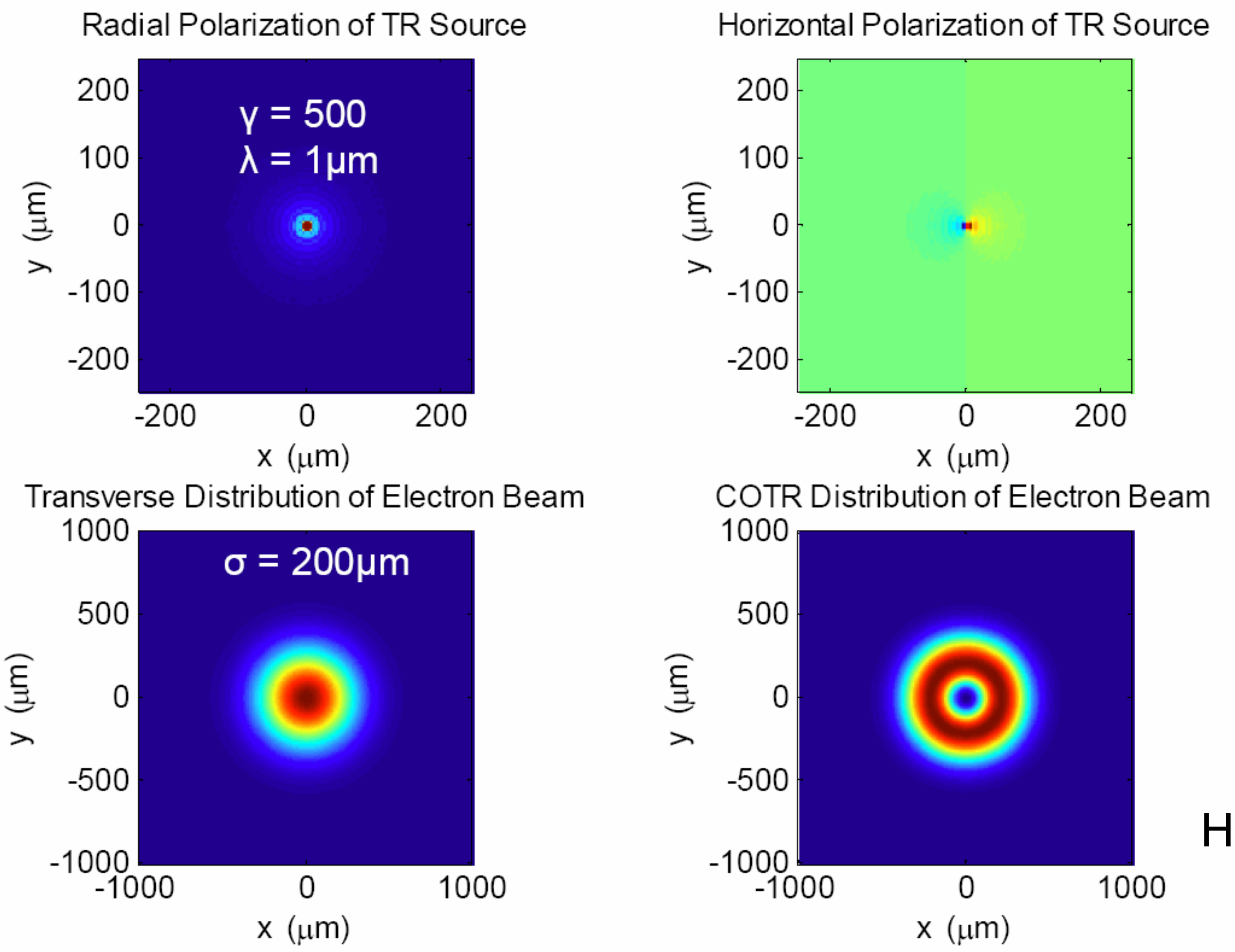


OTR12 projections (COTR? CSR breakup?)

More COTR images with high compression



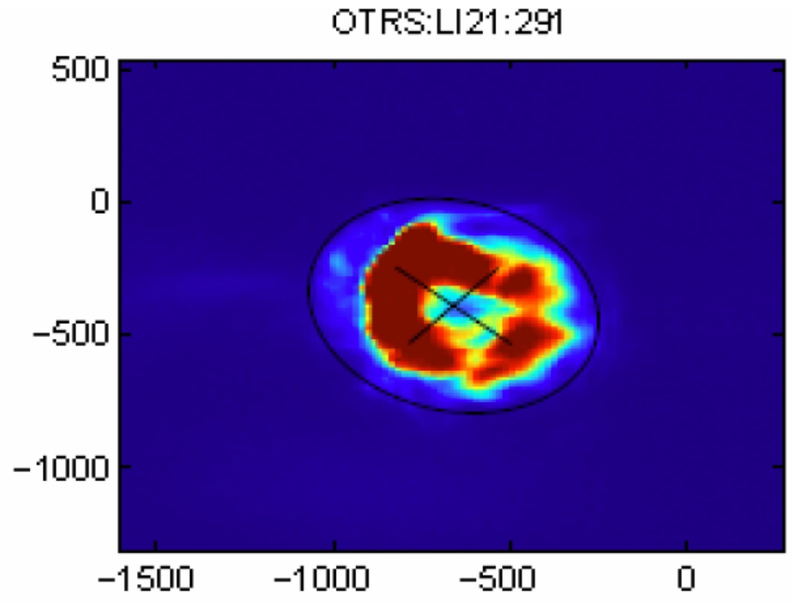
Why Doughnuts?

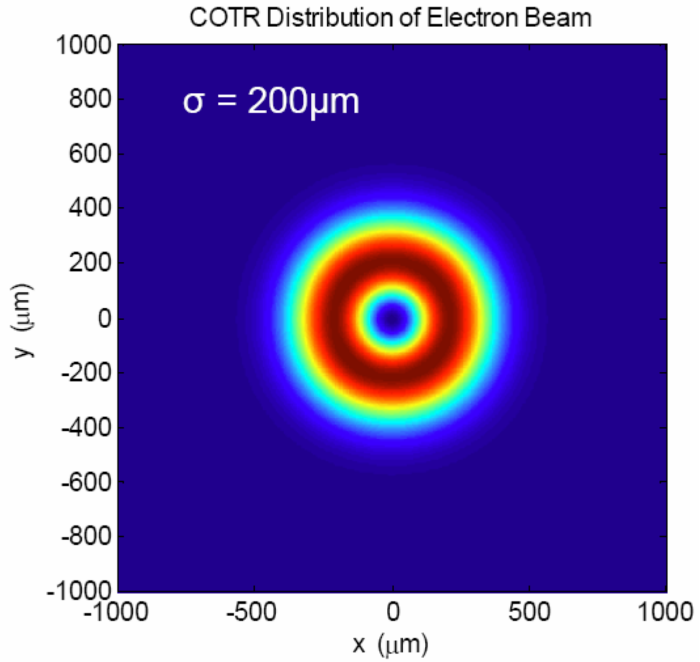


H. Loos

COTR Doughnuts

- Radial polarization acts like gradient operator
- For Gaussian beam gives doughnut

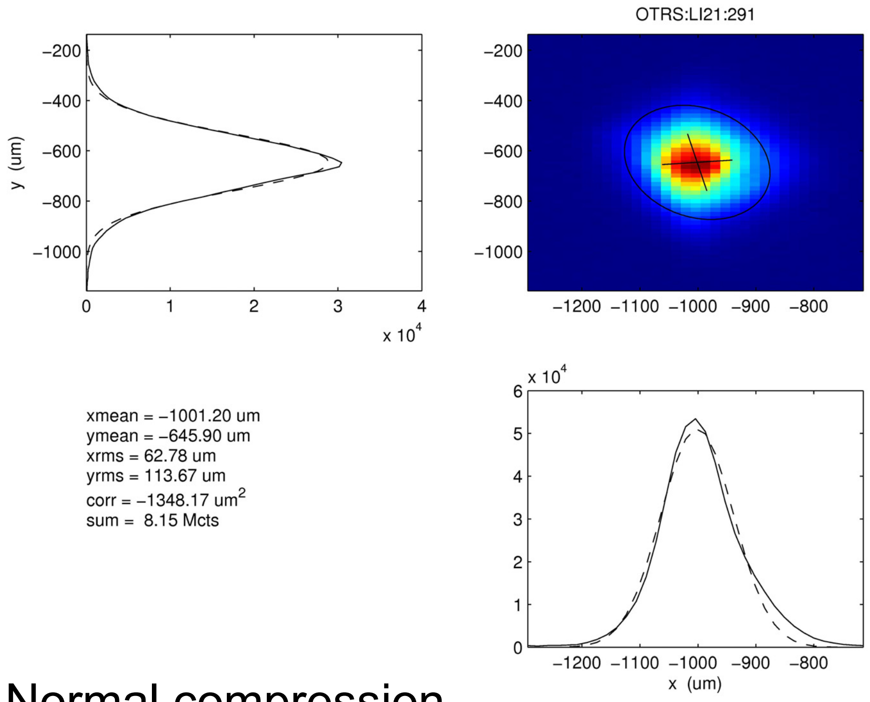

OTRS:LI21:291


COTR Distribution of Electron Beam

H. Loos

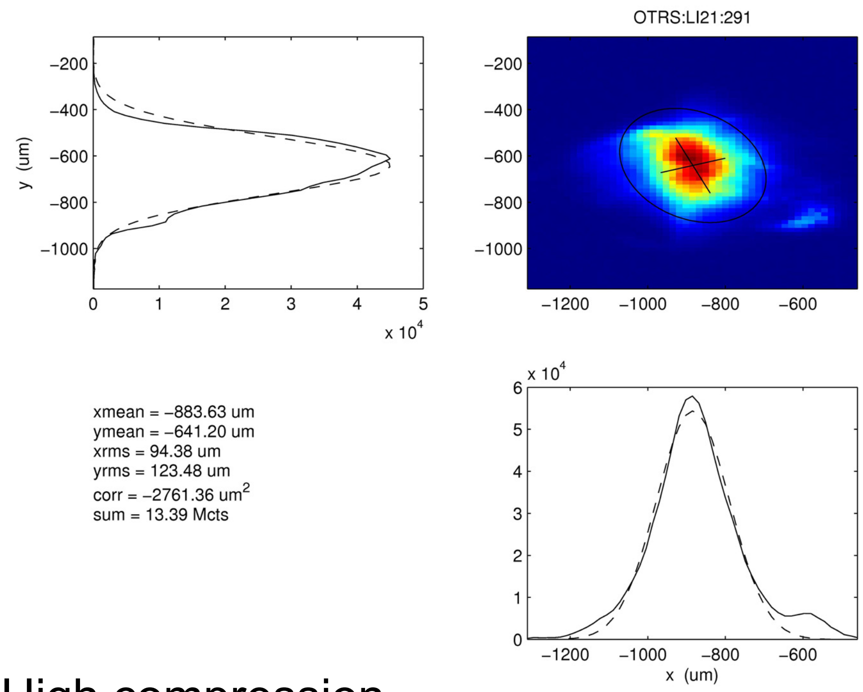
OTR12 images, 200pC

COTR not always dramatic



xmean = −1001.20 um
ymean = −645.90 um
xrms = 62.78 um
yrms = 113.67 um
corr = −1348.17 um^2
sum = 8.15 Mcts

Normal compression
Sum Signal 8.15 Mcounts

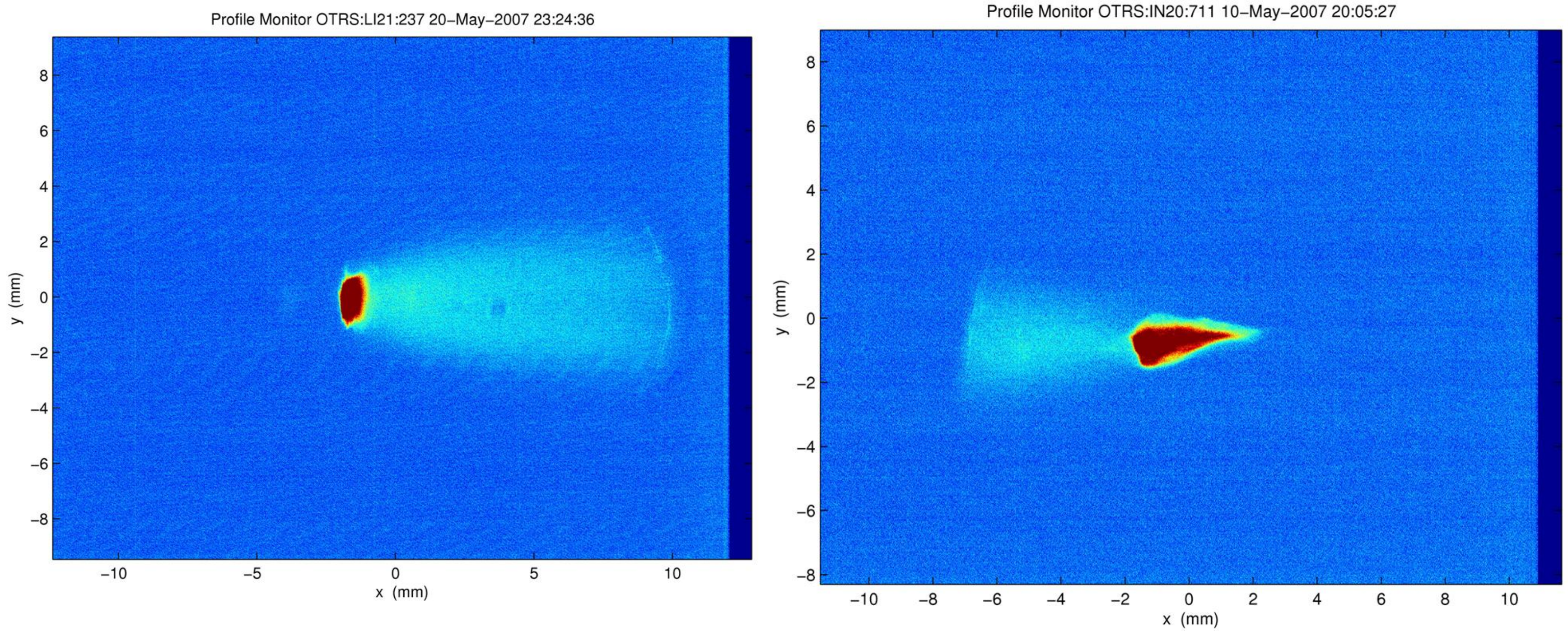


xmean = −883.63 um
ymean = −641.20 um
xrms = 94.38 um
yrms = 123.48 um
corr = −2761.36 um^2
sum = 13.39 Mcts

High compression
Sum Signal 13.39 Mcounts

Other OTR effects – Synchrotron radiation OTR11

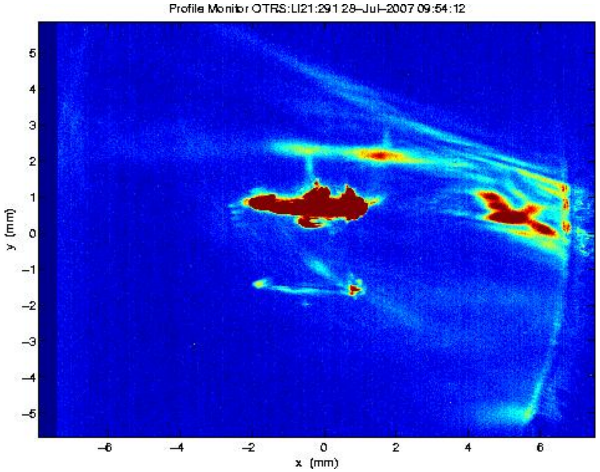
OTR beam exists at “reflection” angle – so foil will also reflect SR
Can add optical vertical polarizer to suppress synchrotron light.

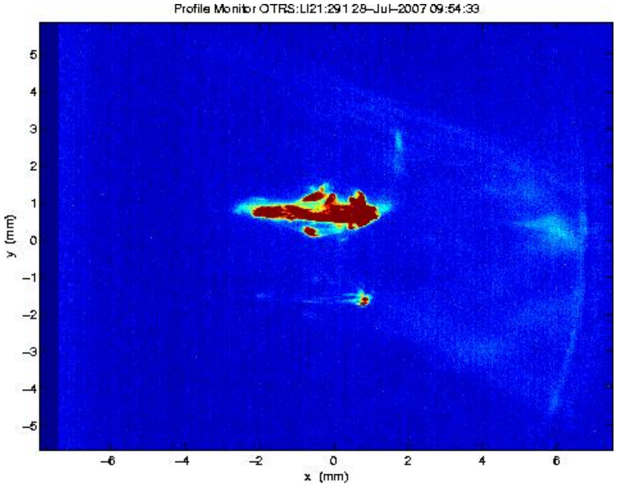


OTR11 (in BC1)

OTR4 in DL1

Gallery of Beam Breakup / coherent Effects. All at same (extreme compression, 1nC) settings


Profile Monitor OTRS:LI21:291 28–Jul–2007 09:54:12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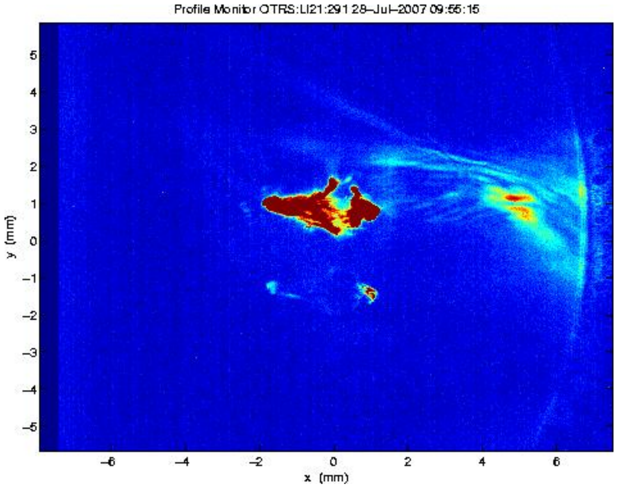
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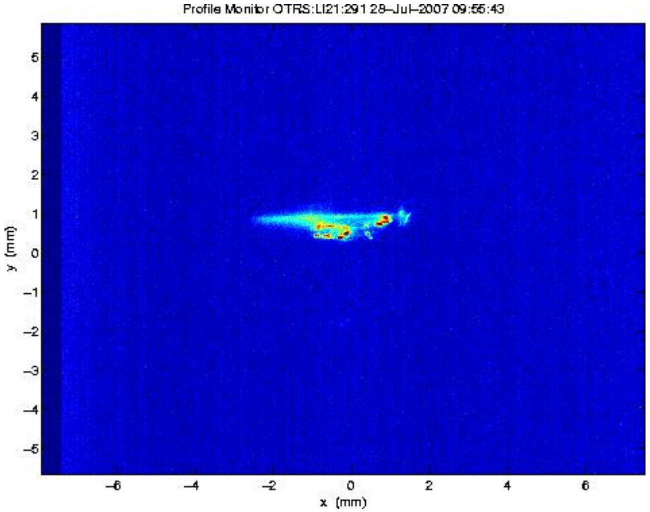
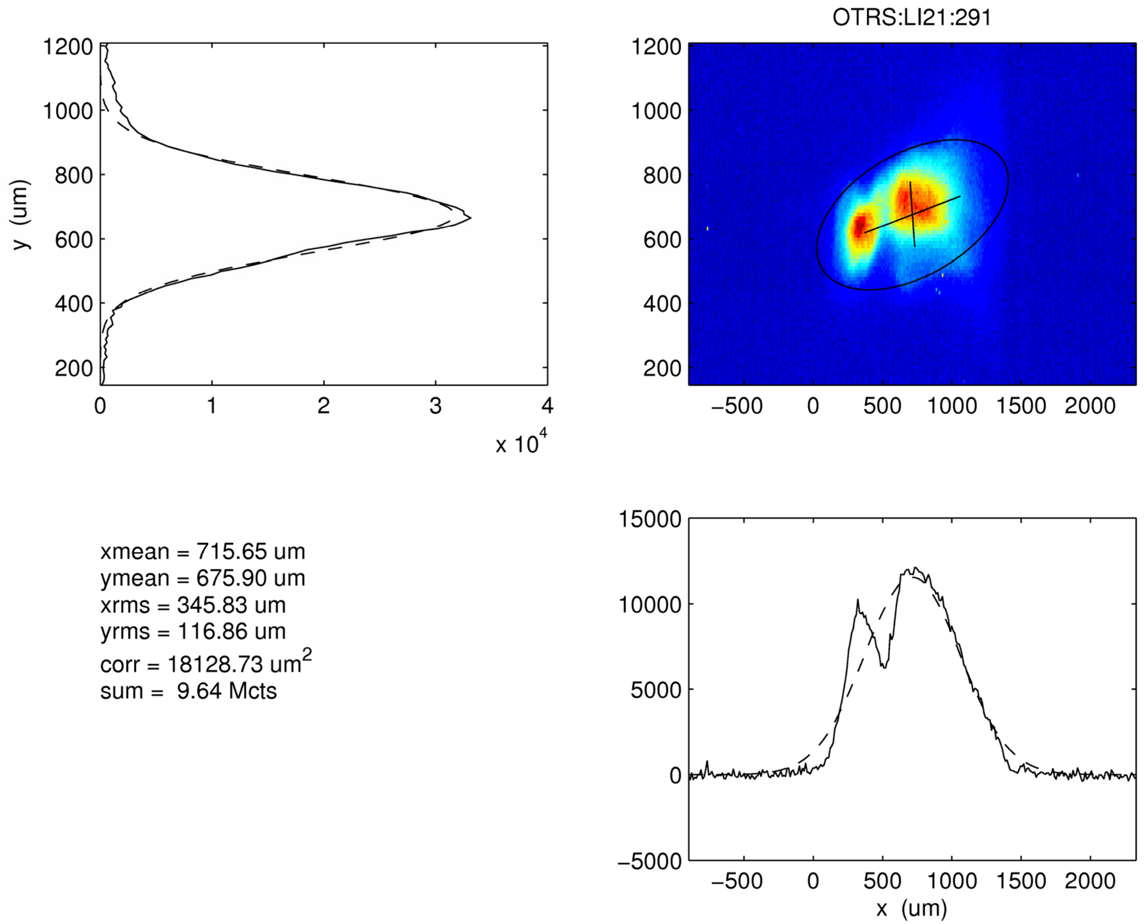

Profile Monitor OTRS:LI21:291 28–Jul–2007 09:55:43

Uses for COTR

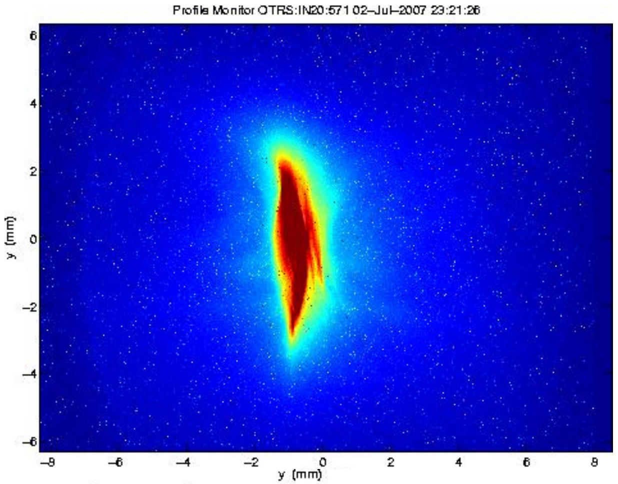
- With maximum bunching in BC2, it may be possible to generate a substantial amount of very broadband (DC-light), power in a few femtosecond pulse, synchronized with the LCLS beam.
- Is this useful as an experimental source, optical trigger, etc?
- If we modulate the beam at optical wavelengths (laser / undulator), can detect optical modulation downstream on any OTR. Measure propagation of high freuqency structure.

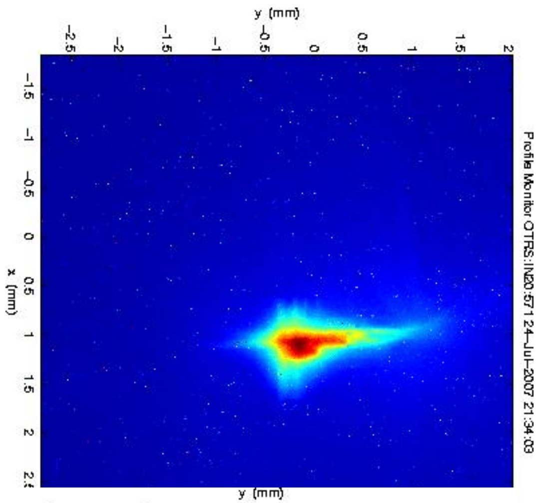
Physics?, Nope, wire scanner in beam

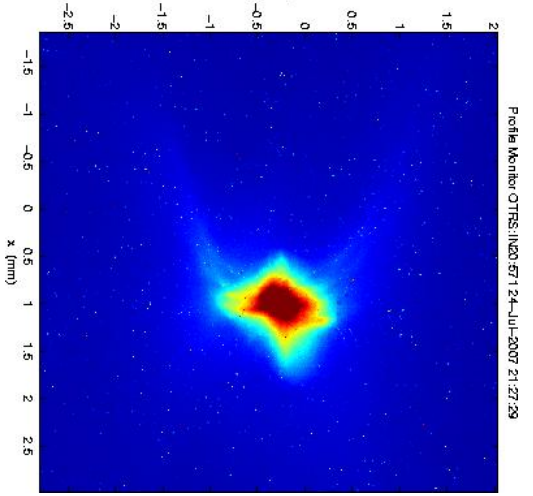


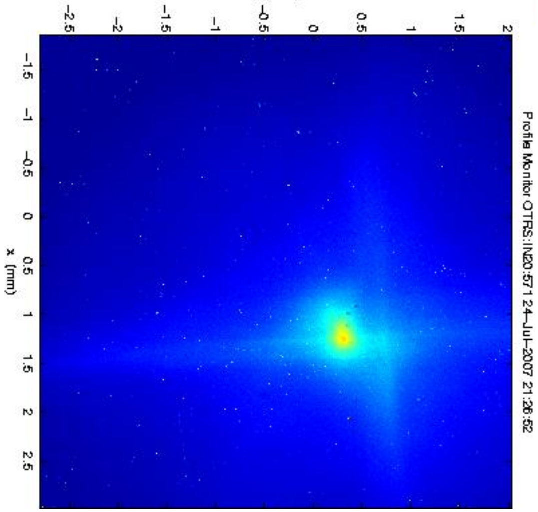
xmean = 715.65 um
ymean = 675.90 um
xrms = 345.83 um
yrms = 116.86 um
corr = 18128.73 um^2
sum = 9.64 Mcts

Gun Bursts, Explosive Emission (not COTR)









COTR Implications For Other Diagnostics

- Coherent effects will distort measurements from any “prompt” light emission:
  - ODR, Cherenkov, Synchrotron, etc.
- Coherent effects could distort fluorescent screen measurements
  - Coherent OTR or Cherenkov in the UV could excite fluorescence.
  - Directly excitation of fluorescence from the coherent high frequency components in the electric field.
  - COTR can be brighter than scintillation, need gated camera to separate.
- Thermal measurements may be OK
  - Coherent emission could add to ionization energy loss.
  - In principal I^2R heating depends on bunch length and could become significant compared with ionization energy loss
  - Probably not a problem for our beam parameters, but needs study
  - Not clear how to image a high resolution thermal source.

OTR / Profile monitor Questions

- What is the spectrum of the OTR under different beam conditions
- What is the total OTR optical power when we see strong COTR
- Understand longitudinally coherent, spatially incoherent OTR

What to do for Beam Imaging

- OTR operating in near UV
  - Will work if we don't have beam modulation at short wavelengths.
  - Can go as far as ~200nm without exotic windows, cameras.
  - But – will problem be worse after BC2?
  - Calculations do not rule out coherence at wavelengths as short as 100nm in the LCLS.
- X-ray imaging
  - Short wavelengths immune to coherent effects
  - X-ray generation forward directed. Difficult to set up optics.
  - More like an "experiment" than a diagnostic.
- Wire scanners
  - Work with good engineering
  - Mult-shot profiles only.
- Laser Heater
  - The LCLS plans to use an inverse FEL to increase the energy spread of the beam to reduce CSR
  - Should dramatically reduce COTR problems
  - Don't like to rely on this – nice to be able to diagnose the beam without the heater.