Beam Measurements at LCLS

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The LCLS

- 1.5 Angstrom FEL
- Accelerator:
  - 4.3 to13.6 GeV,
  - 250pC to 1nC
  - Design emittance ~1.2 micron normalized, slice
  - Current ~3.4 KA
  - 120 Hz, single pulse operation
- Status
  - ½ way through second run.
  - Beam to 13.6GeV
  - Undulator to be installed late ’08, X-rays in ‘09

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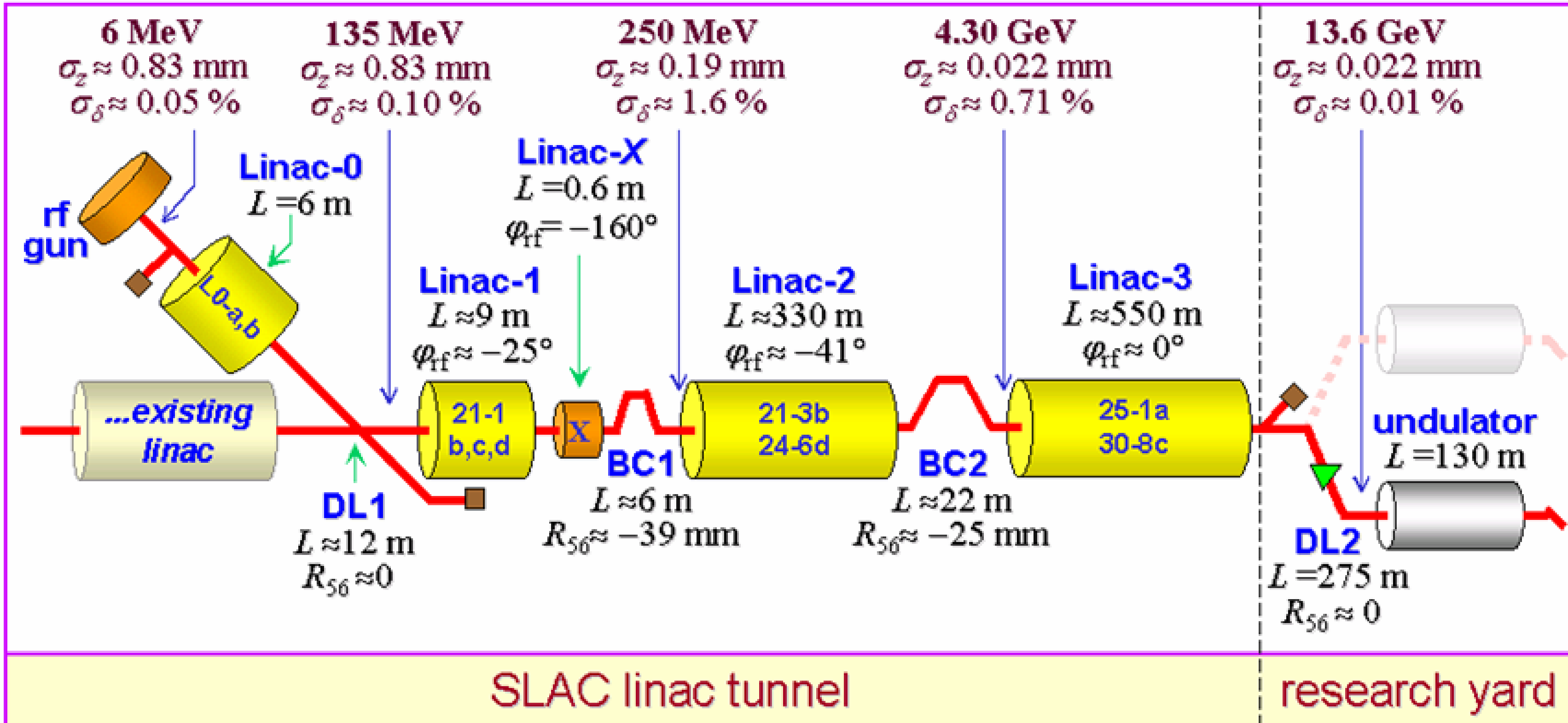
LCLS Accelerator Overview



Linac-2 and Linac-3 are only slightly modified from their configuration for SLC operations(1989-1998). The remainder of the machine is new, though It makes use of some SLC accelerator structures and magnets

Beam Diagnostics

- Position Measurements
  - BPMs
- Charge measurements
  - BPMs, Toroids, Faraday Cups.
- Beam loss
  - Ion chambers, PMTs
- Profile measurements
  - Fluorescent screens, Wire scanners or OTR screens
- Transverse measurements (emittance)
  - Use multiple profile monitors, or Quad scans
- Longitudinal measurements
  - Spectrometers, Millimeter wave bunch length monitors, Transverse Deflection Cavities

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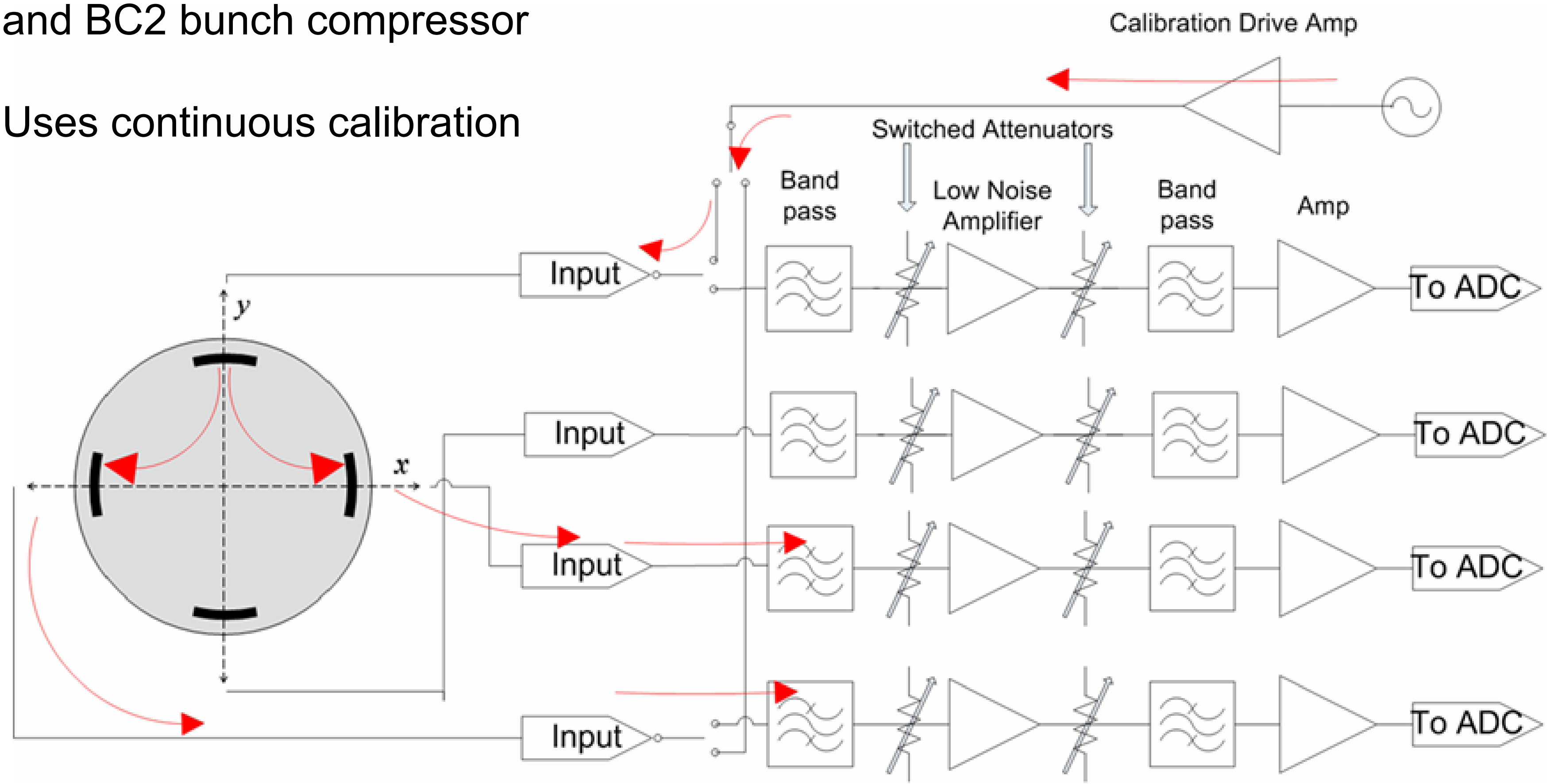
BPMS

New EPICS controlled BPMS installed in LCLS injector and BC2 bunch compressor

Uses continuous calibration



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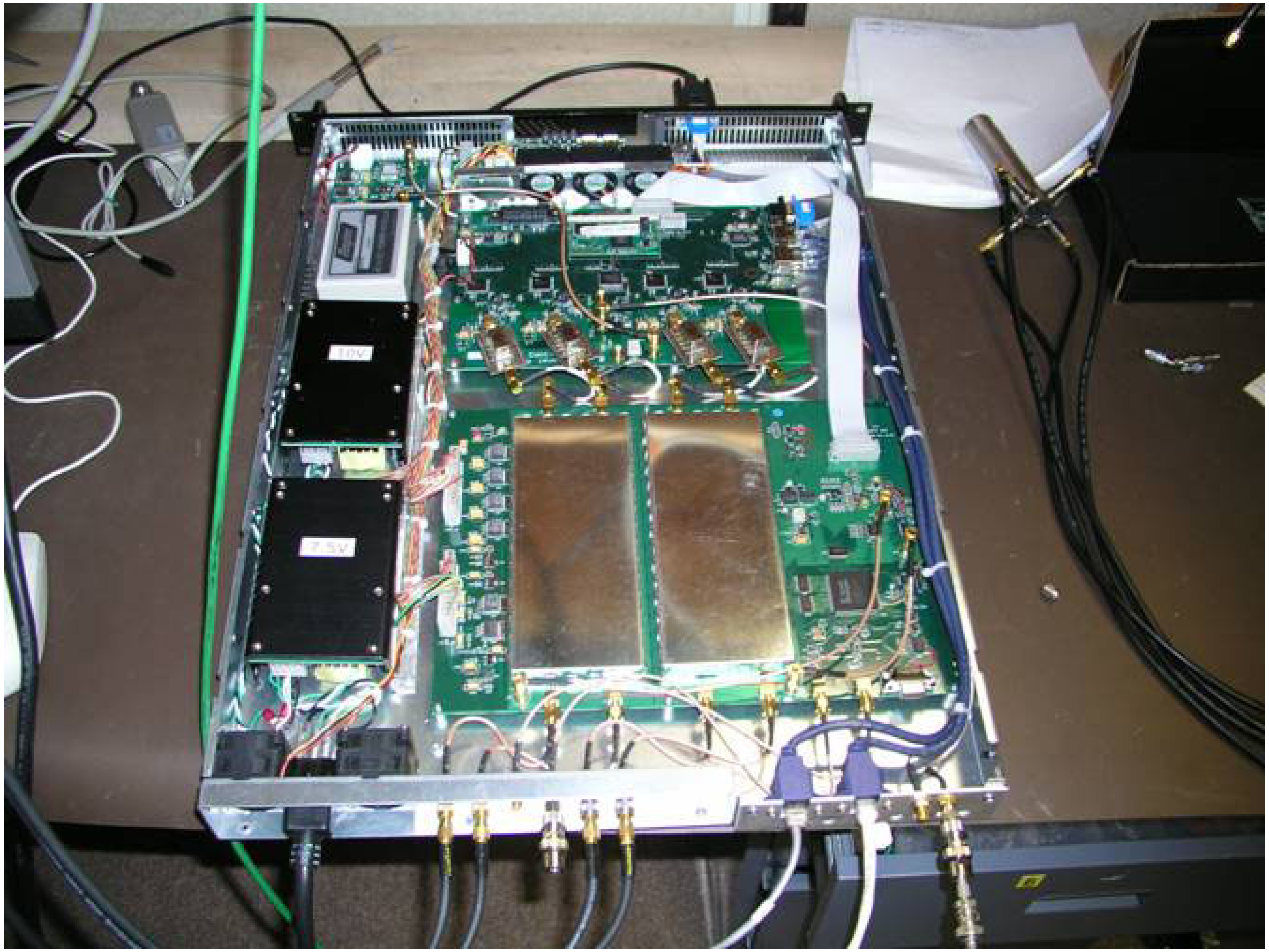
BPM Modules



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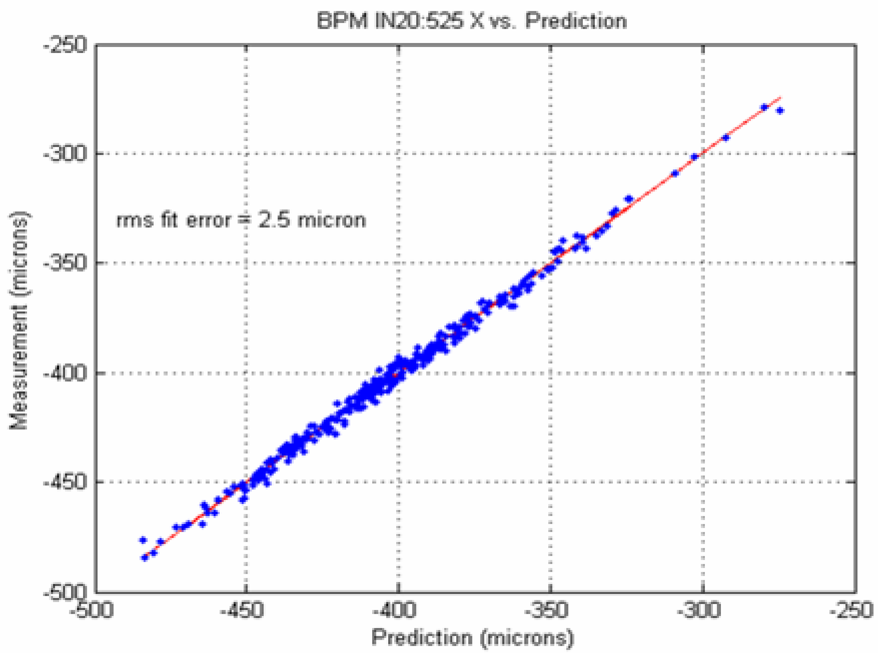
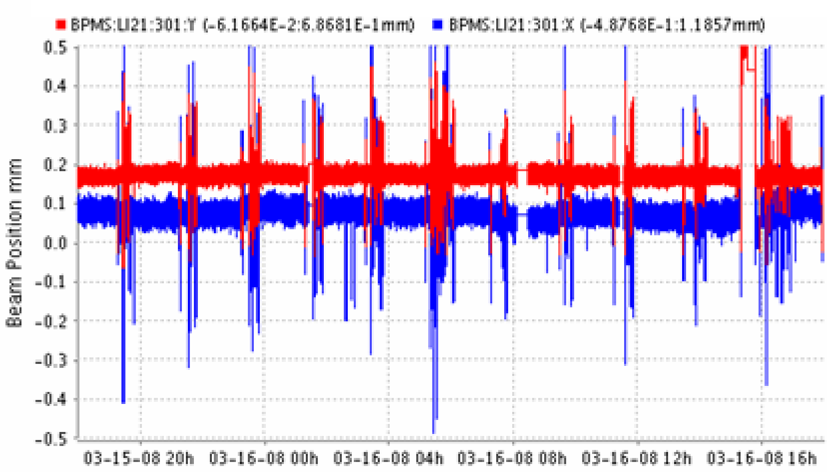
BPM Performance

Noise can be measured by performing a linear regression to predict one BPM reading based on the other BPMS.



Beam / BPM stability for 1 day at end of Injector. Approximately 15 um RMS, Beam size ~50um RMS at this location



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Charge Measurement

- BPMs provide a low noise relative charge measurement (7×10^{-4} RMS)
- Absolute calibration is done using toroids
  - New toroids for LCLS
  - Compared with SLC toroids (at 13.6 GeV)
  - Agree within 5%
- Gun Faraday cup charge measurement does not agree well (40%) with toroid measurements.
  - Not really a Faraday cup, more like a Faraday “plate”, but still surprising there is such a large error.

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Beam Loss Monitors

- Minimal beam loss in the accelerator under normal operating conditions.
- Single pulse intensity below the damage threshold (in the accelerator)
- High average power loss could produce activation, and damage electronics
- Loss measured with Ion Chambers (conventional and cable based “long” Ion Chambers)
- Beam rate limited / disabled when excessive average loss is seen.
- Under normal conditions, loss is below measurement limit of a few percent.

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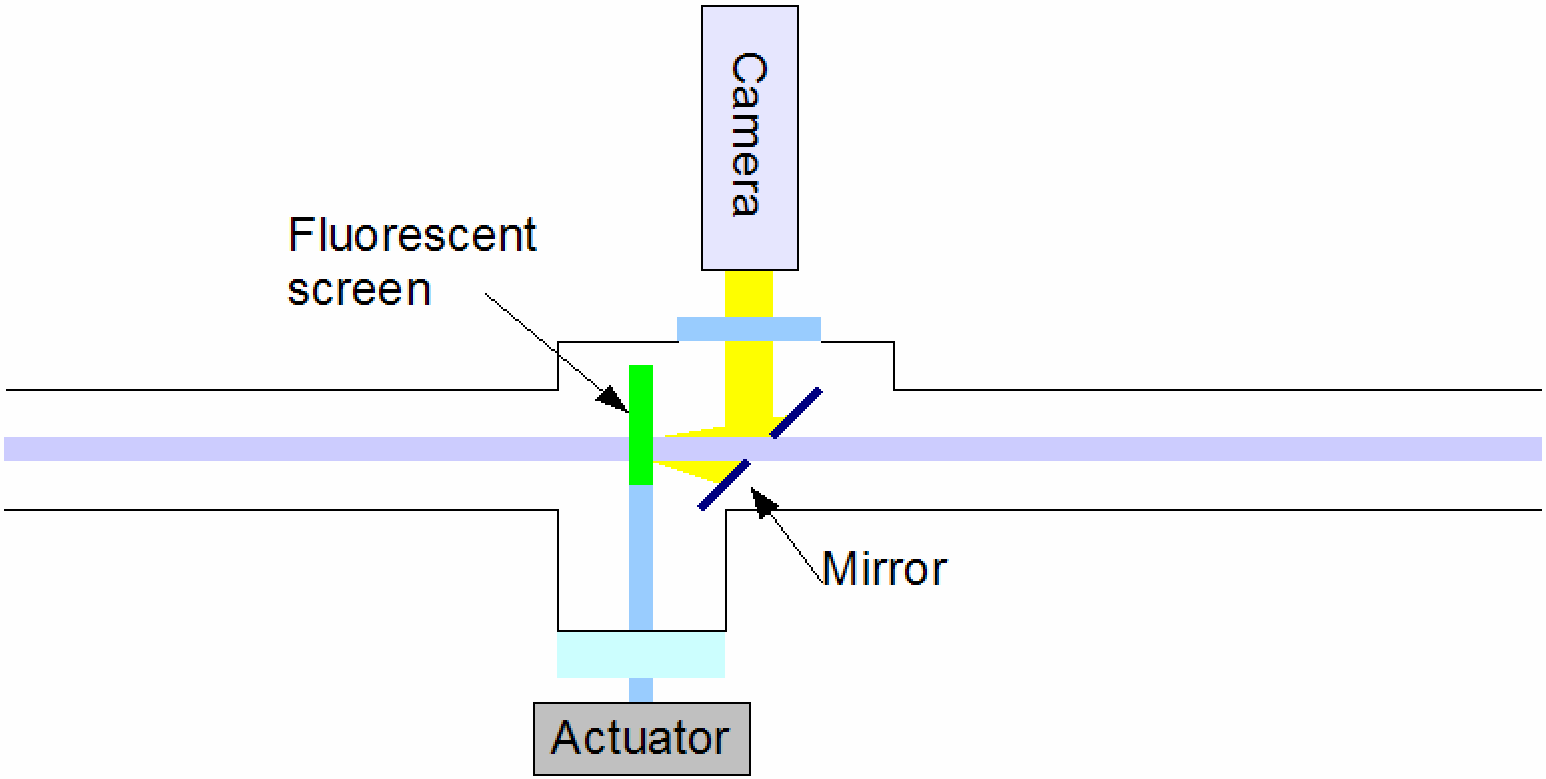
Beam Profile Measurements

- Fluorescent Screens
  - Good sensitivity
  - Saturate at high intensities (>0.04pC/um^2)
    - Typical LCLS 1nC, 50 micron spot is 10X this density
  - Used in LCLS at 135MeV and below
- Wire Scanners
  - Good resolution, Nearly non-invasive, work with high intensity beams
  - Slow, and integrated profile only
  - Mechanical vibration problems
  - Used in LCLS at 135MeV and above
- Optical Transition Radiation Monitor
  - Good resolution, work with high intensity beams
  - Coherent effects limit use in LCLS (discussed later in this talk)
  - Installed in LCLS at 135MeV and up, but only useable before first bunch compressor

Fluorescent Screens



- No depth of field problems for camera
- Thickness relative to beam limits resolution.

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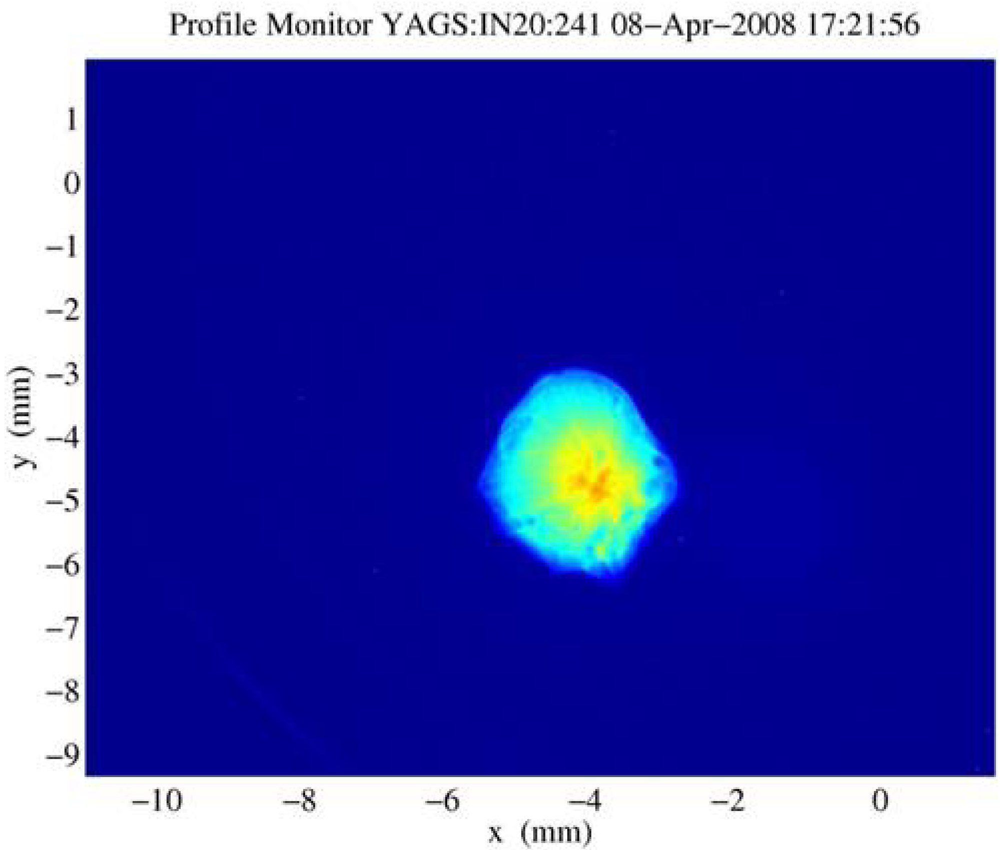
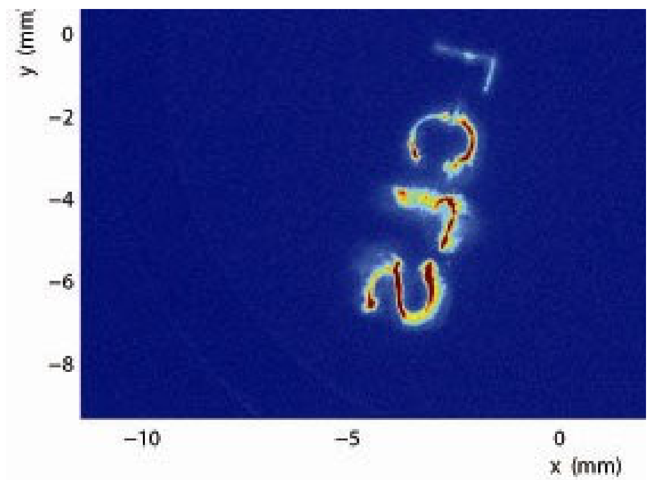
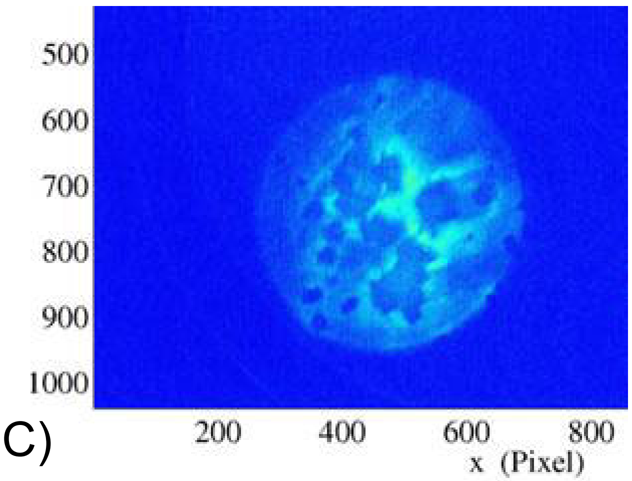
Sample Images from YAG screens







YAG image for 1nC beam at 6MeV

Also possible to image cathode at low charge (30pC)

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Wire Scanners

- Wire scanners use 20 micron tungsten wires.
- Stepper motor / leadscrew drive
- Scintillators downstream to detect scattered electrons.
- Direct drive gave 5 micron resolution, but with some vibration problems
- Addition of 10X gear ratio reduced vibration.

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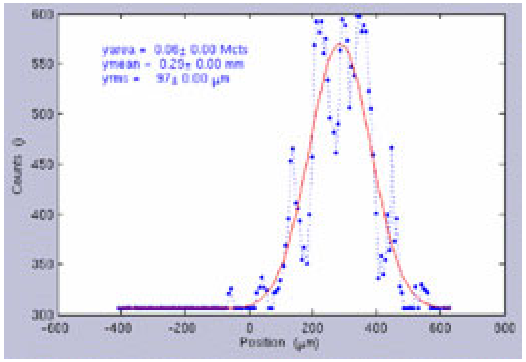
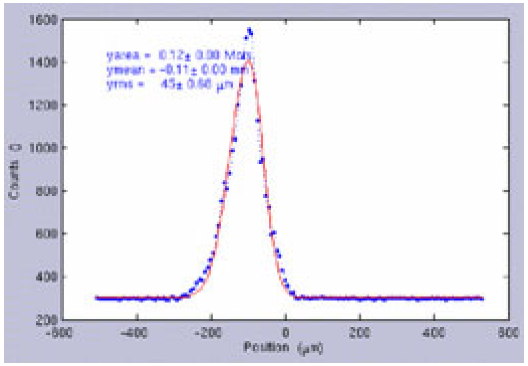
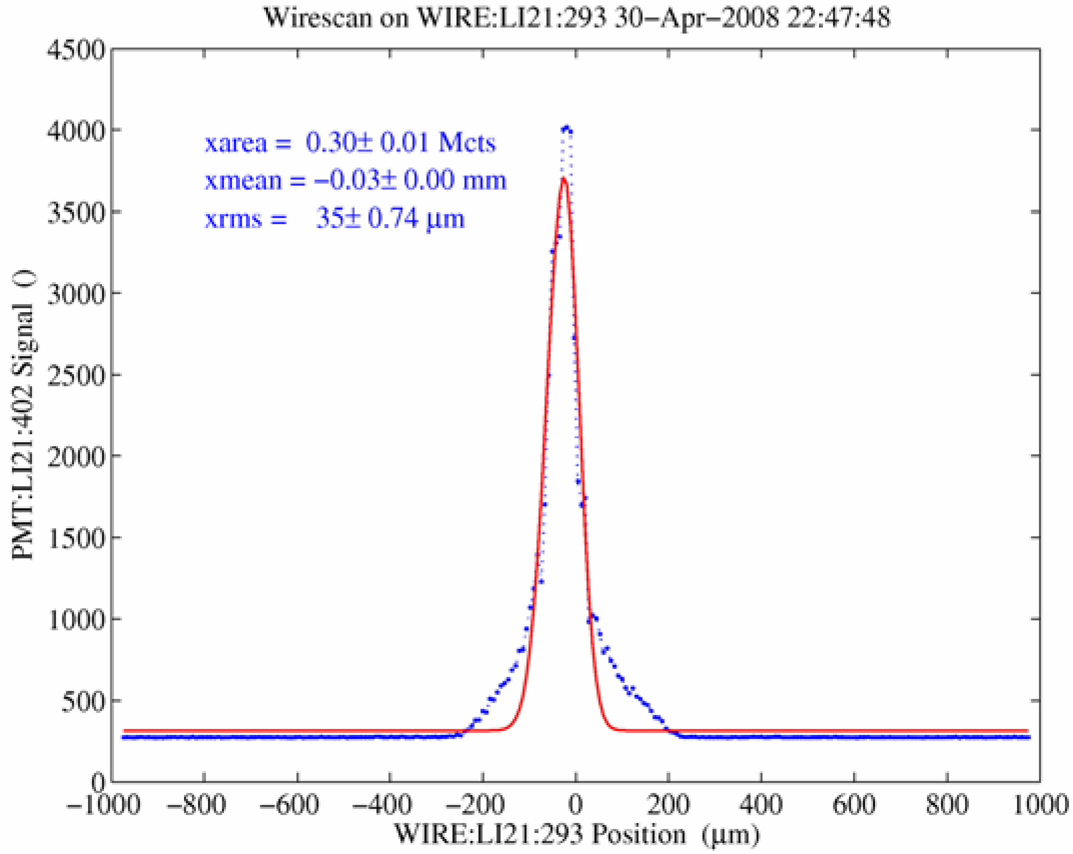
Wire Scans



Scan before addition of 10X reducer gear



Scan after addition of 10X reducer gear



Wire scan at 250MeV after first bunch compressor
Asymmetric Gaussian fit (LCLS standard)

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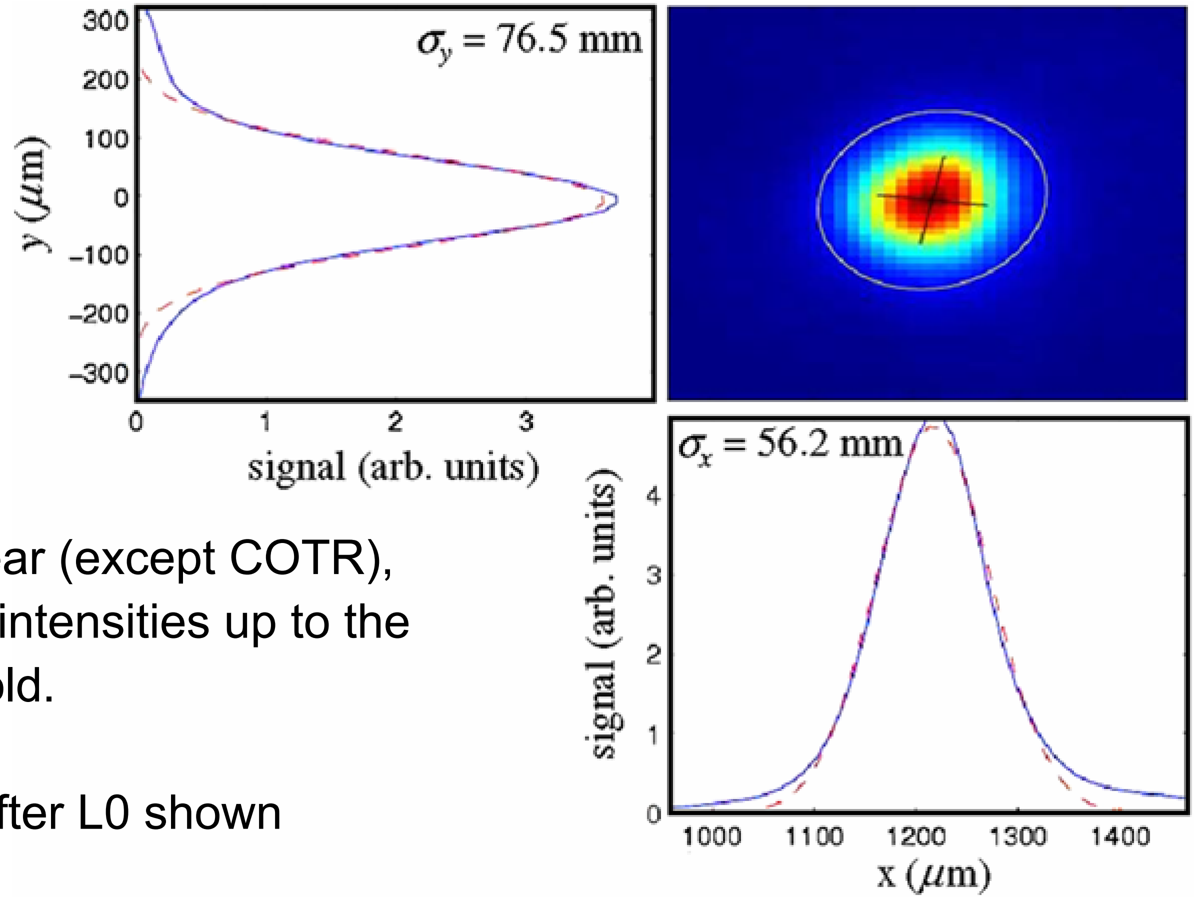
OTR Profile Monitors



OTR process is linear (except COTR), and can operate at intensities up to the foil damage threshold.

Beam at 135MeV after L0 shown

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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 $\sim10^6$ electrons in an optical wavelength.
  - Density modulation of $\sim10^{-3}$ at optical wavelengths will substantially increase emission.
- Longitudinal coherence causes longitudinal structure to distort transverse profiles.

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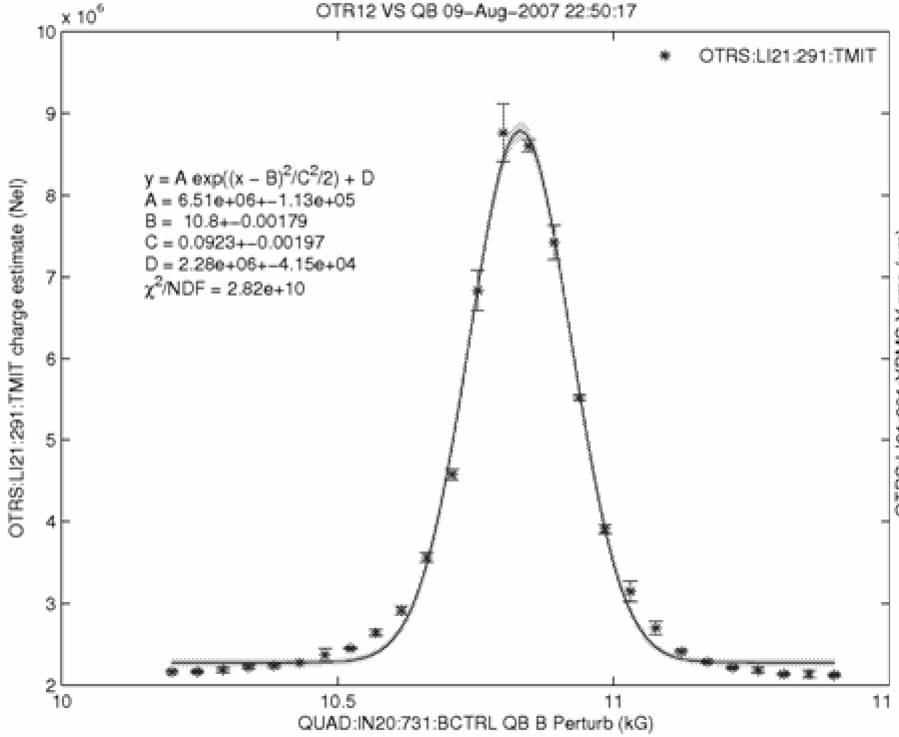
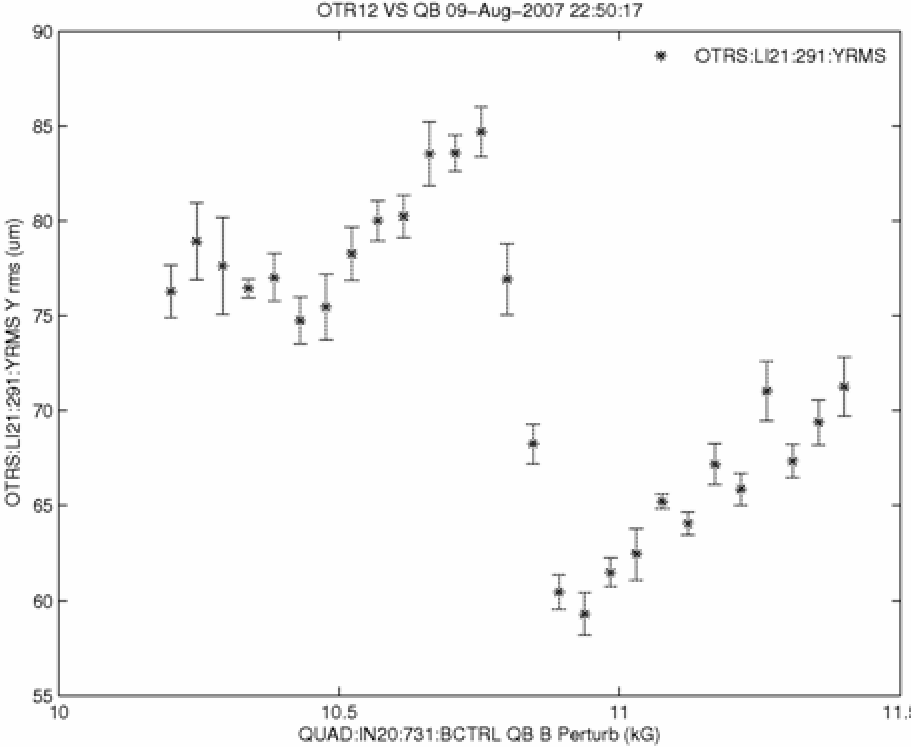
COTR: Beam size distortions in OTR12





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

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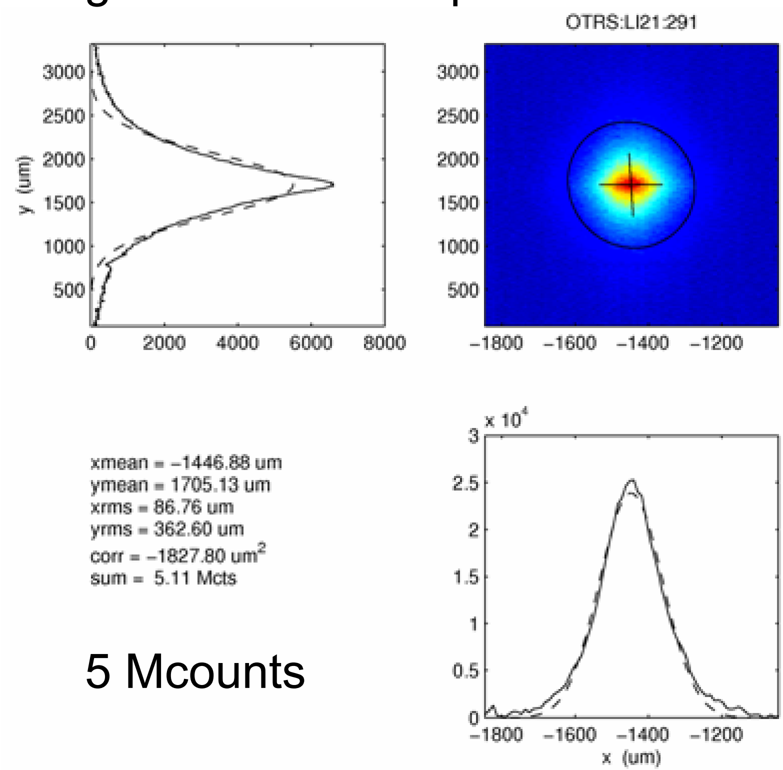
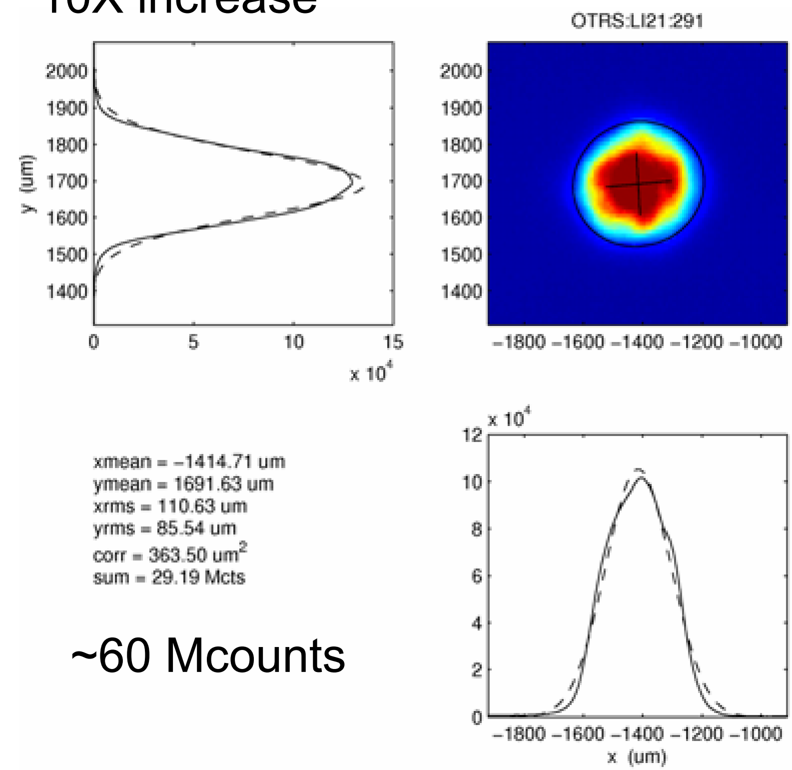
COTR for compressed beam

OTR after BC1, normal compression
250pC, upstream OTR foil inserted
In compressor Chicane to spoil
Longitudinal Phase space



5 Mcounts

With upstream foil removed, signal
Is saturated. Neutral density filters
Give approximately 60M counts
10X increase



~60 Mcounts

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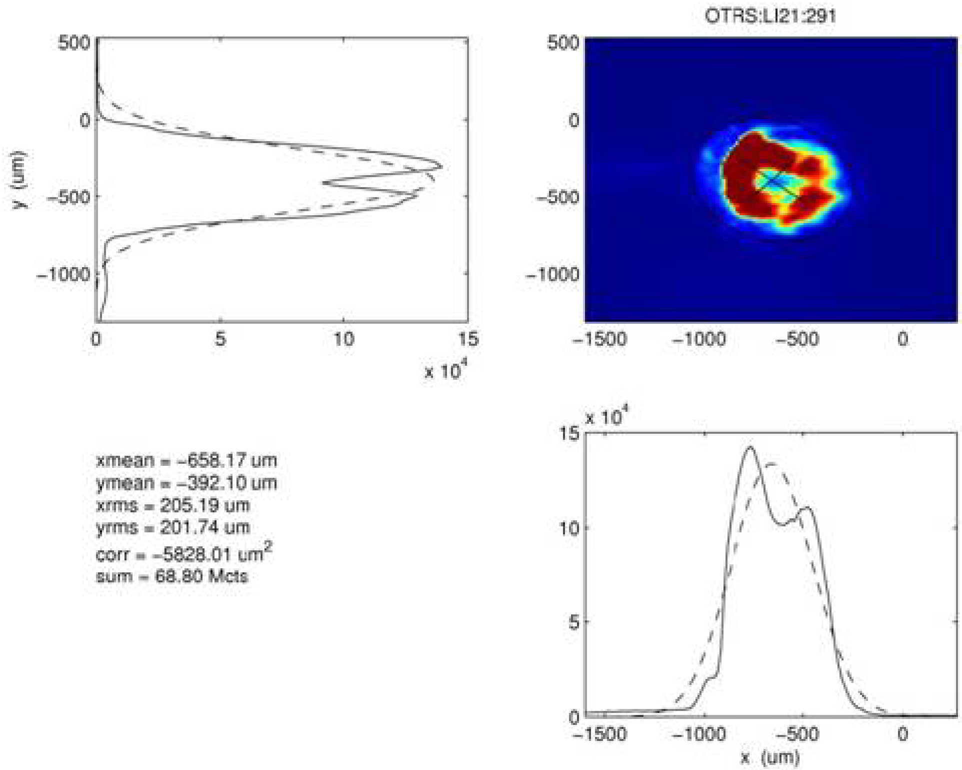
COTR at maximum BC1 compression

COTR with injector phases
set for maximum compression
In BC1. Integrated signal ~100X
Incoherent

The toroidal shape is expected
From the circular polarization of
The OTR light.

Interference produces a signal
Proportional to the spatial derivative
Of the source.



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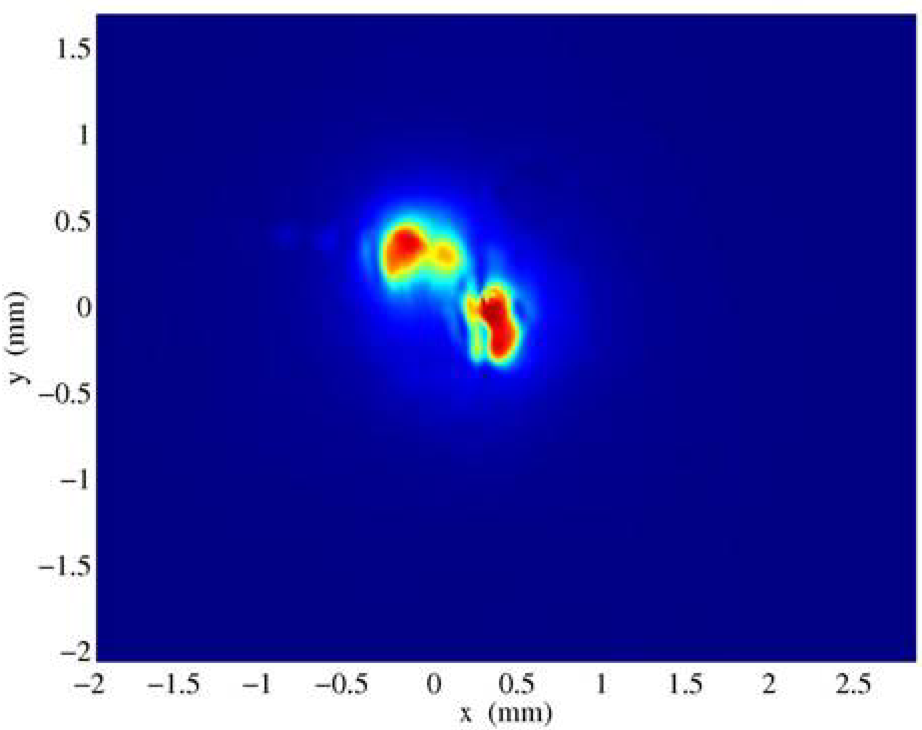
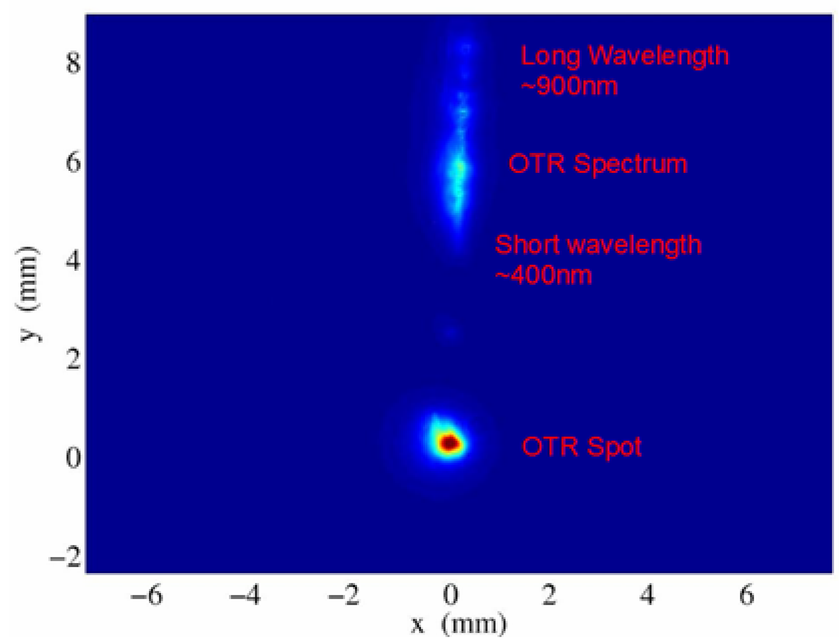
COTR after Second Bunch Compressor

At normal compression in BC2
Image is dramatically distorted.
Integrated intensity > 100X incoherent



Diffraction grating added to OTR System to measure approximate spectrum of COTR



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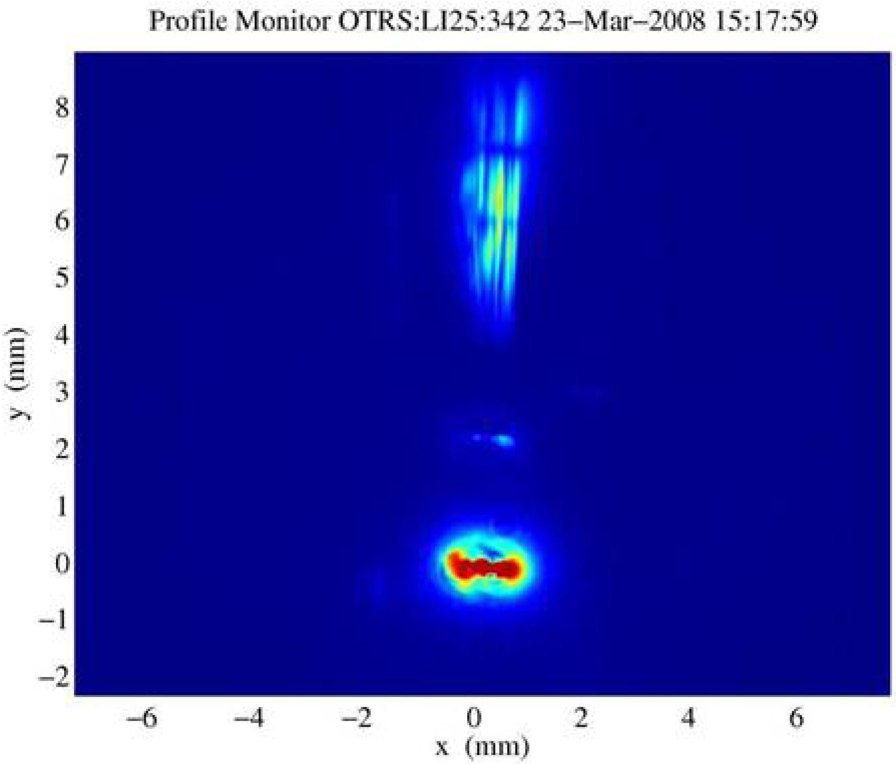
Maximum Compression in BC2

Camera is saturated even with X100 neutral density filter and diffraction grating.

Integrated signal > 1000X incoherent

Note complex optical spectrum, and interference artifacts



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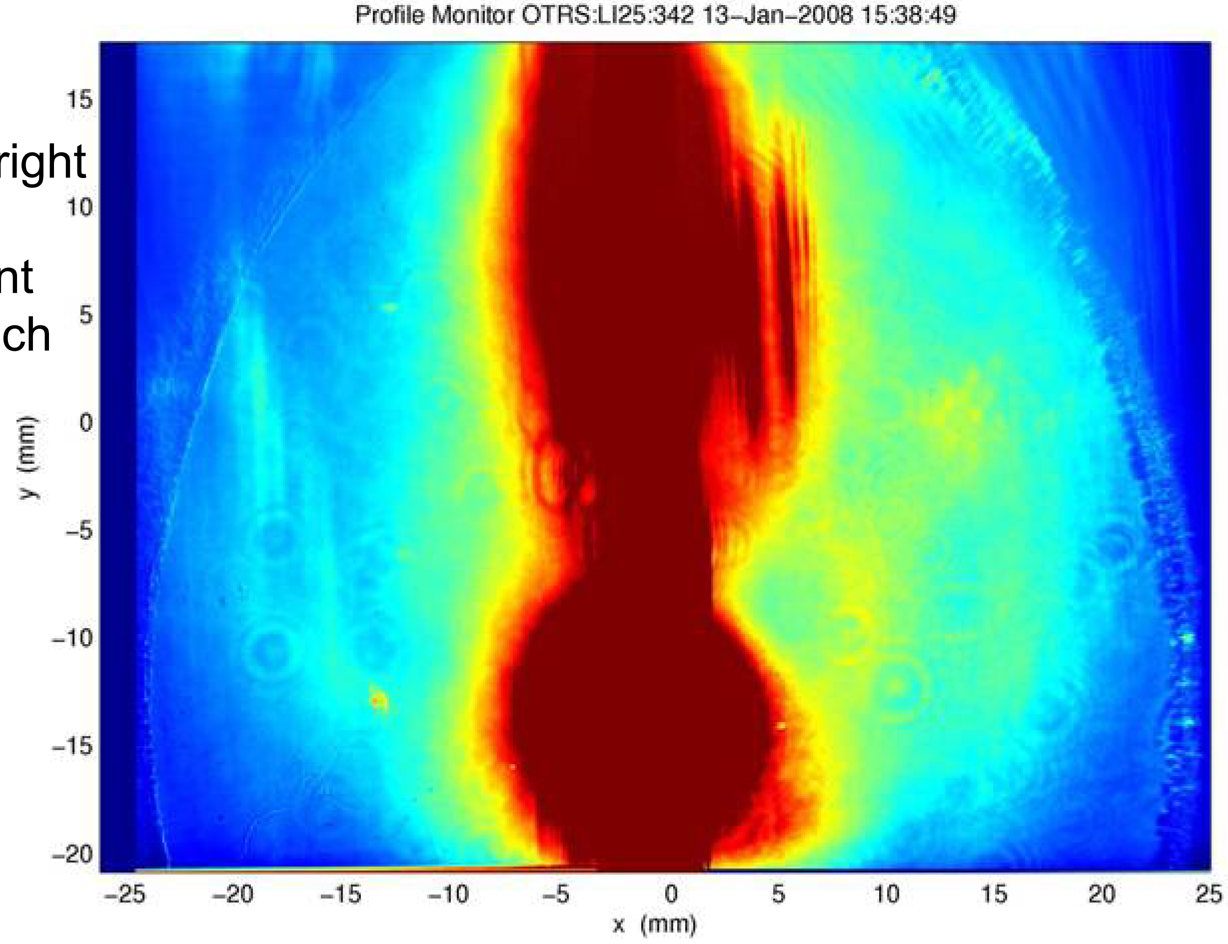
X-treme COTR

Occasional pulses very bright

Beam may have significant charge in sub-micron bunch

Note, both filters in.
Camera still saturated.



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What to do about COTR?

- Weak coherent effects distort beam shapes beyond 135MeV point
- Strong coherent effects make OTR unusable in the LCLS after first bunch compressor
- Coherent spectrum extends throughout visible.
- We will look for COTR at 200nm, but expect to find some there as well
- Future “laser heater” planned for installation in injector may eliminate COTR problem.
- Beam waist (~50um) after L0 is significant source of longitudinal impedance. Will try modifying optics to remove this waist.
- Interesting physics BUT for now:

  Can’t use OTR monitors in the LCLS
- Emittance measurements done using Wire Scanners

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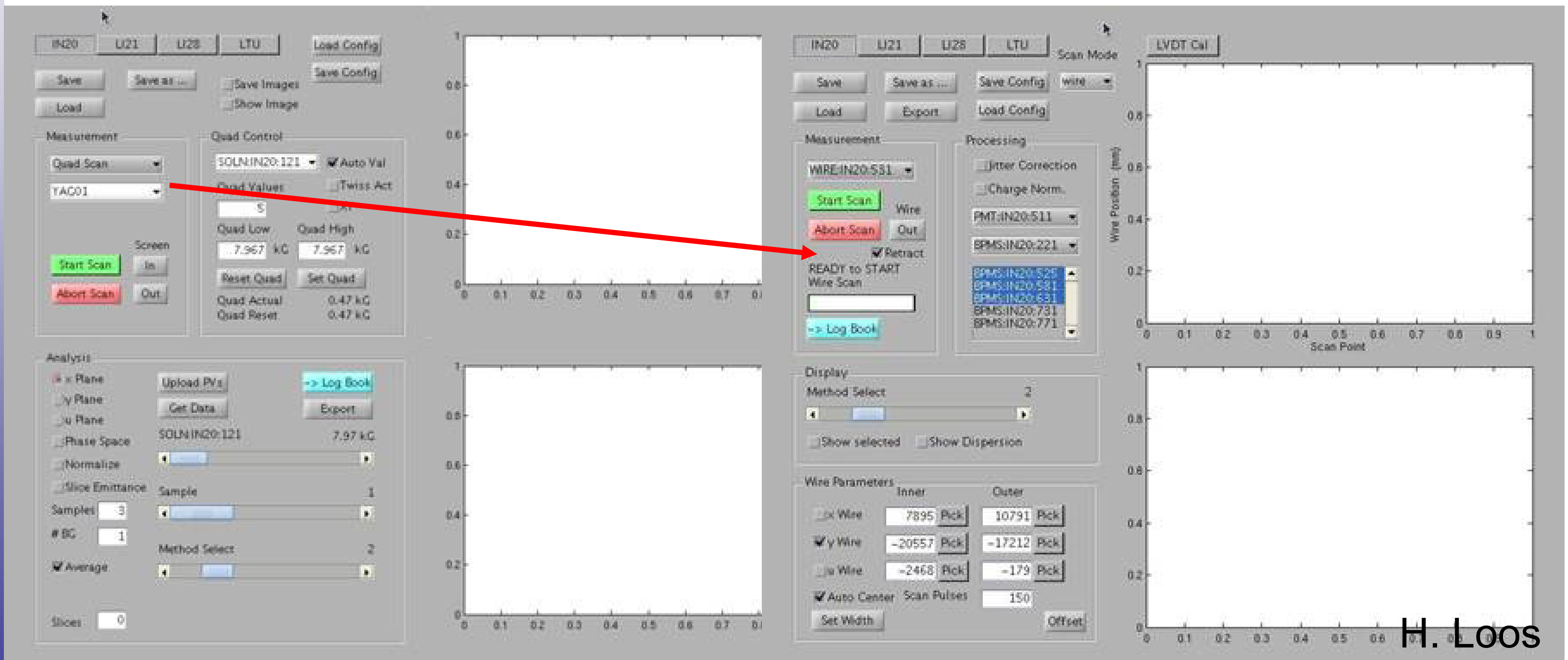
Emittance Measurements

- Quad scan: Measure beam profile near a waist for a range of quad strengths
- Multi-profile: Measure beam profile at several locations with known phase advances.
- Use wire scanners for profile measurements, except OTR can also be used before DL1.
- Emittance measurement also gives beam matching information.

Automated Emittance Software

Emittance Application

Wire scanner application



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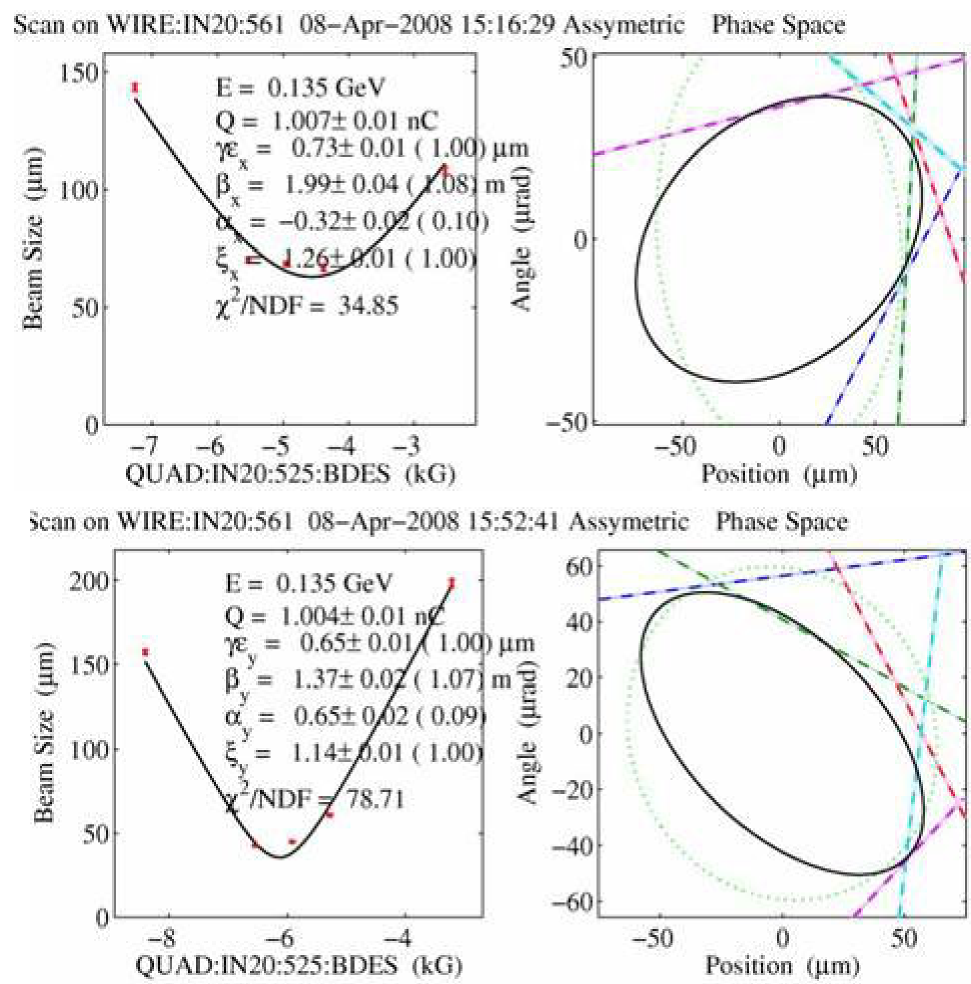
Emittance after Gun, L0 (135 MeV)

Emittance at 135 MeV, 1nC:
ex=0.73um, ey= 0.65um

Measurement based on asymmetric Gaussian fit to data

See similar emittances at 250pC.
(but bunch length is longer)



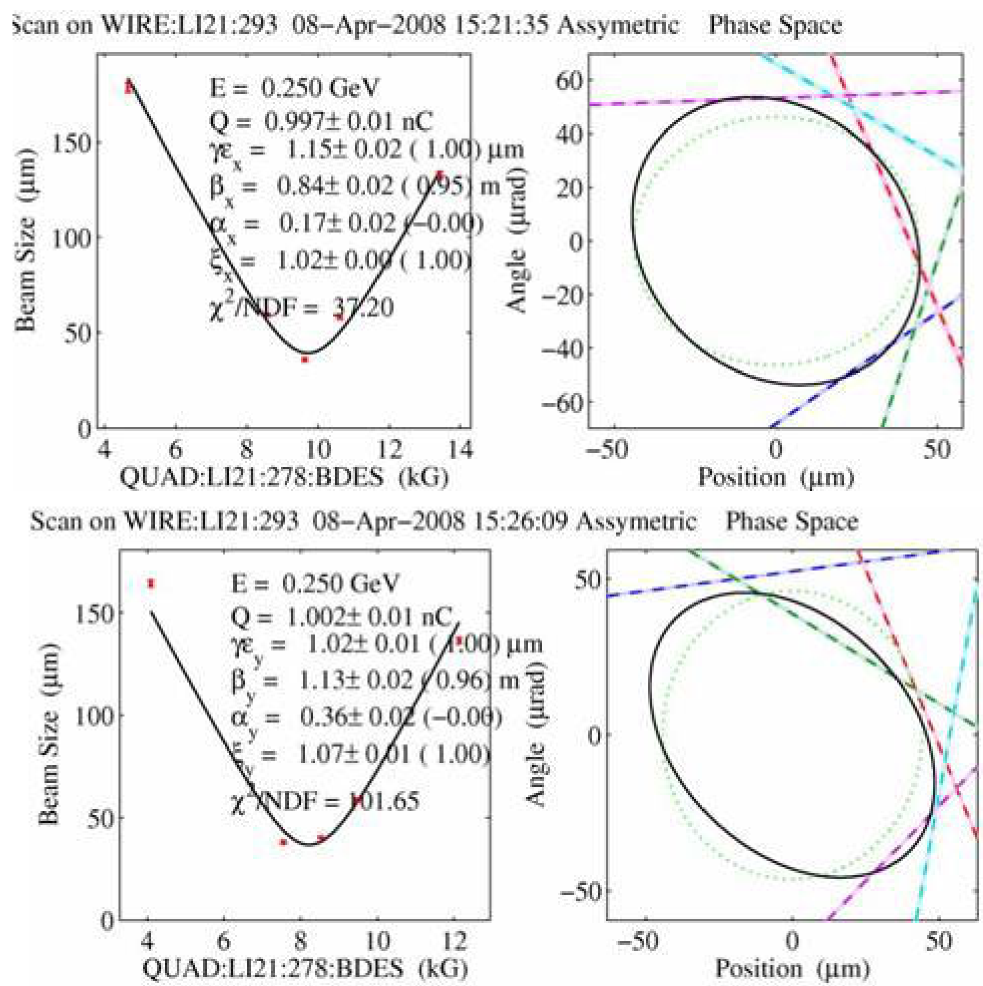
Emittance after first bunch compressor

After first bunch compressor, ex=1.15, ey=1.02 at 1nC
Set for normal compression
Asymmetric Gaussian fit method

Note that X emittances as low as 0.68 microns at 1nC have been measured.

At 250pC, typical ex = 0.8, ey = 0.7

Measurements variable, strongly dependant on steering in X-band section (L1x)



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Emittance in the L2, BC2, L3

- Unfortunately the beam diagnostics in the second bunch compressor are based on OTR, and are unusable.
- We have no beam profile measurements between the end of the injector (250MeV, after first compressor), and the end of L3, at 13GeV, 800Meters, and a bunch compressor downs stream!
- Wire scanners in the end of L3 are not fully commissioned so the emittance numbers are not reliable.

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Longitudinal Measurements - Energy

- Gun Spectrometer
  - 6 MeV, fluorescent screen
- Injector Spectrometer, or DL 1 bend.
  - 135 MeV, OTR screen
- Bunch Compressor 1
  - 250 MeV, OTR screen
- Bunch Compressor 2
  - 4.3 GeV, OTR screen – nearly unusable due to coherent effects
- End of linac-3
  - 13.6 GeV, Fluorescent screen (installed for SLC)

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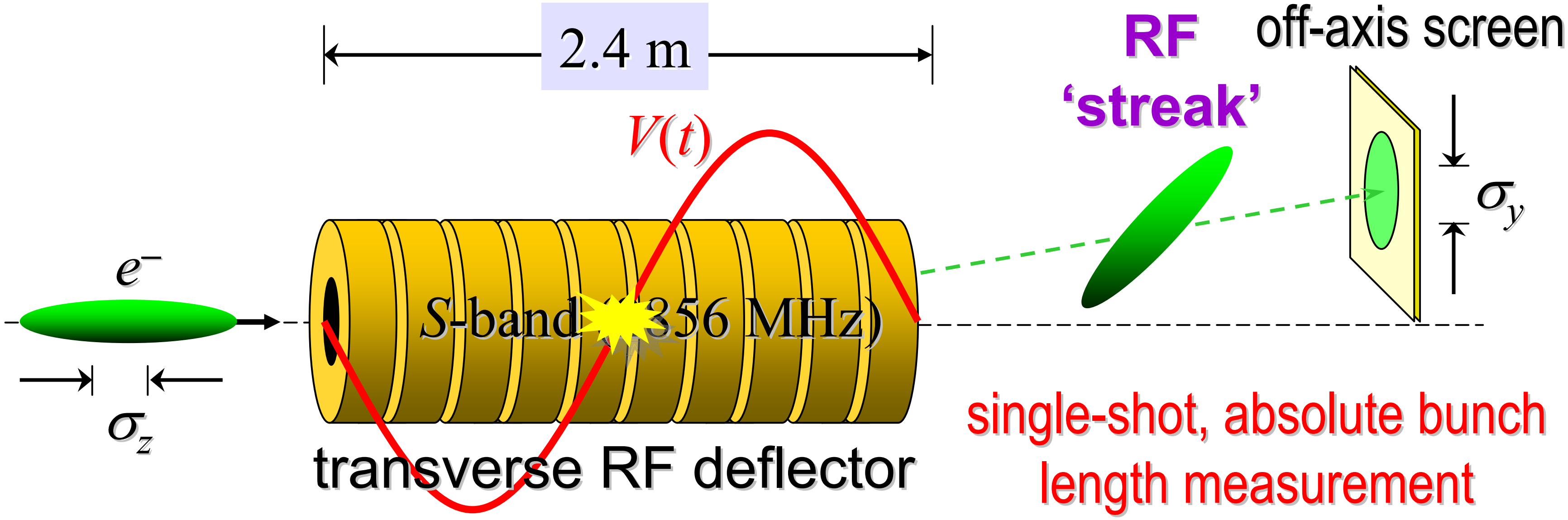
Temporal Measurements

- LCLS has 2 transverse deflection cavities
  - 135 MeV before DL1 bend
  - 4.3 GeV after BC2 compressor.
  - (would like a TCAV after BC1, space exists but no budget).



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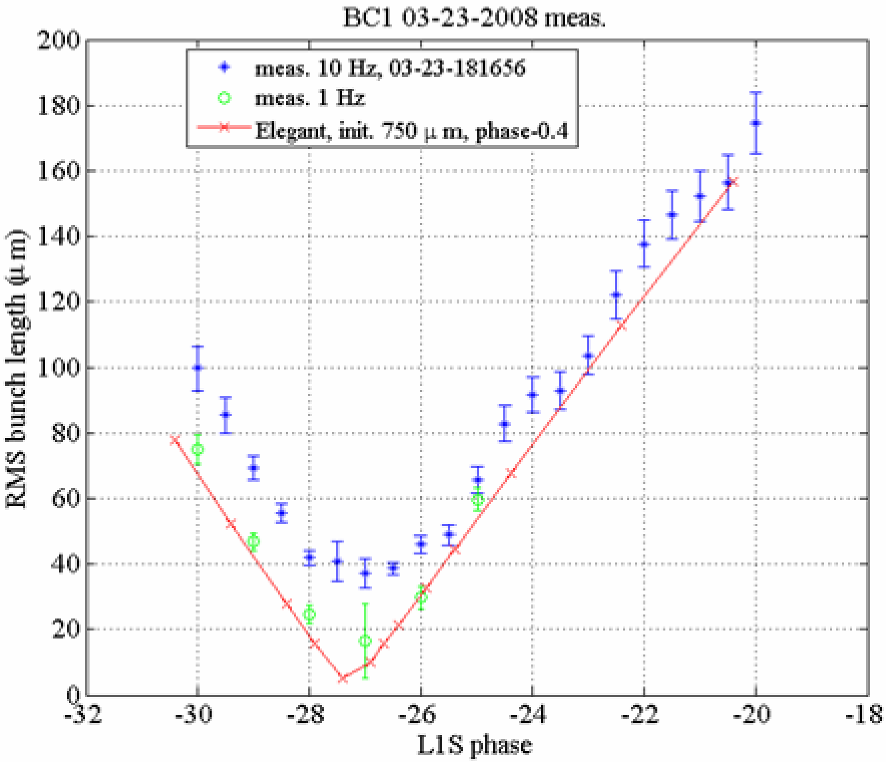
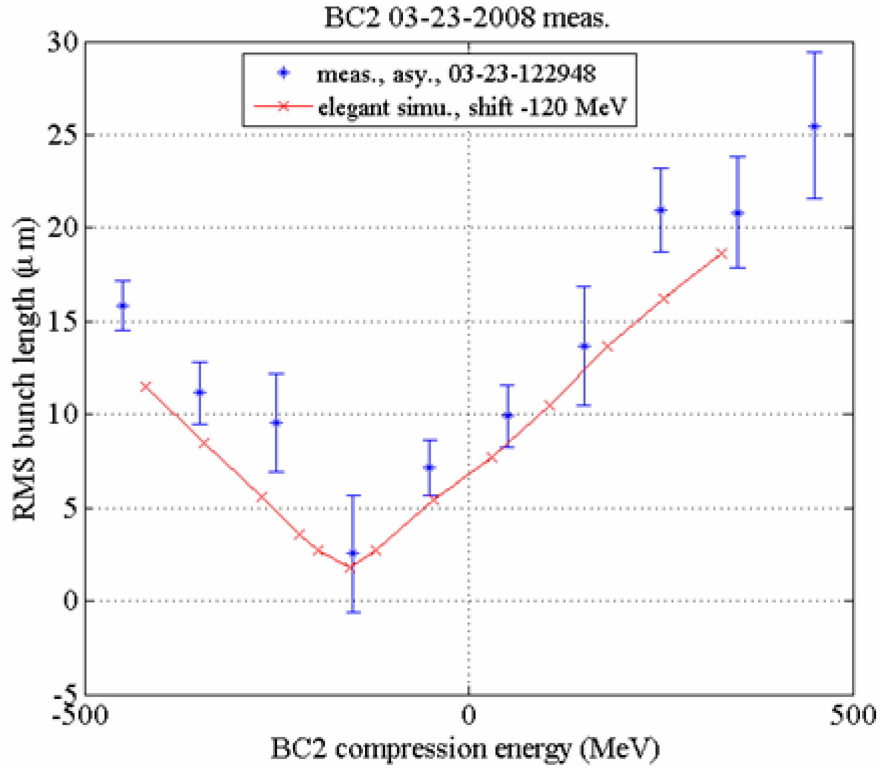
Bunch length after BC1 and BC2





Approximately 5 micron minimum bunch length observed, limited by TCAV / fluorescent screen resolution

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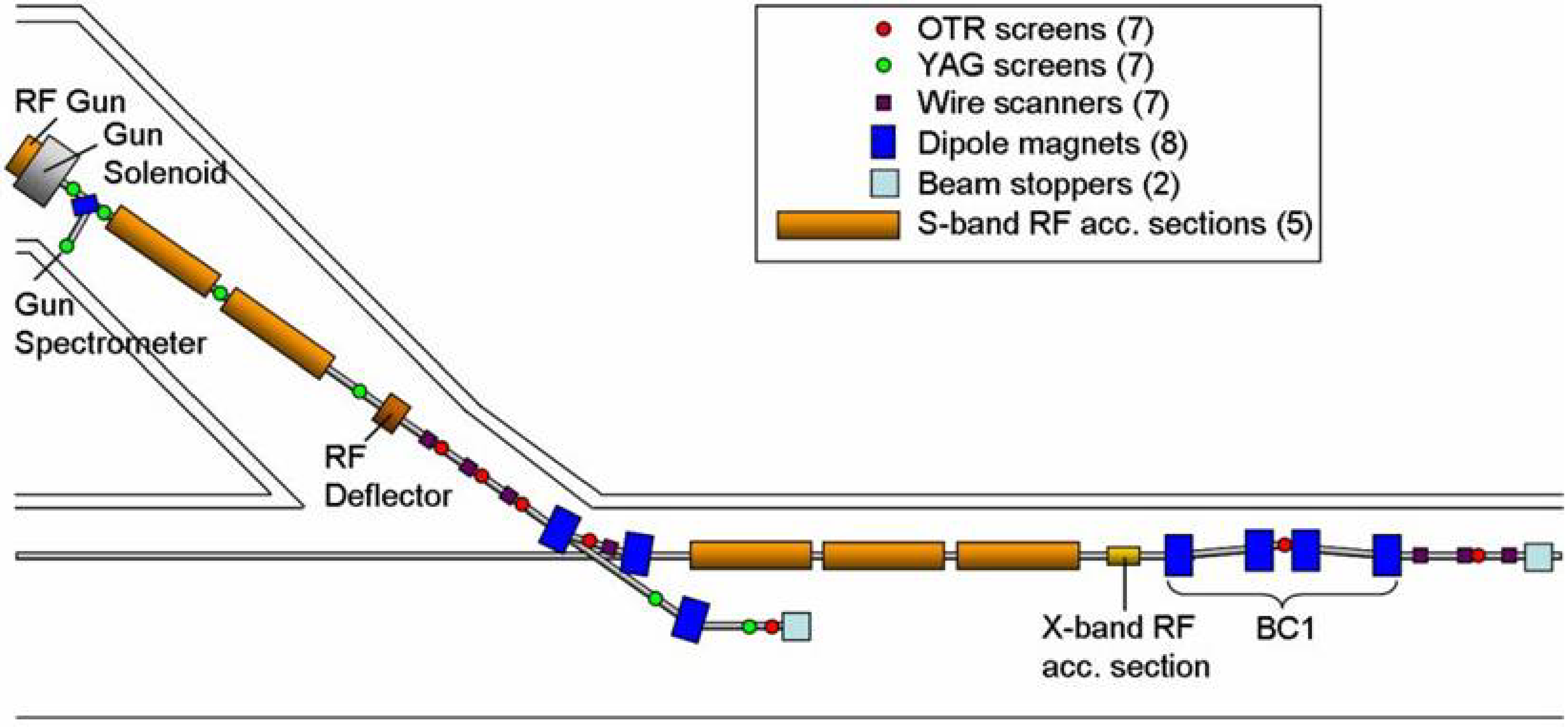
Energy vs. Time measurements

- The combination of transverse cavities and spectrometers provides a powerful tool for analyzing the longitudinal phase space of the beam.



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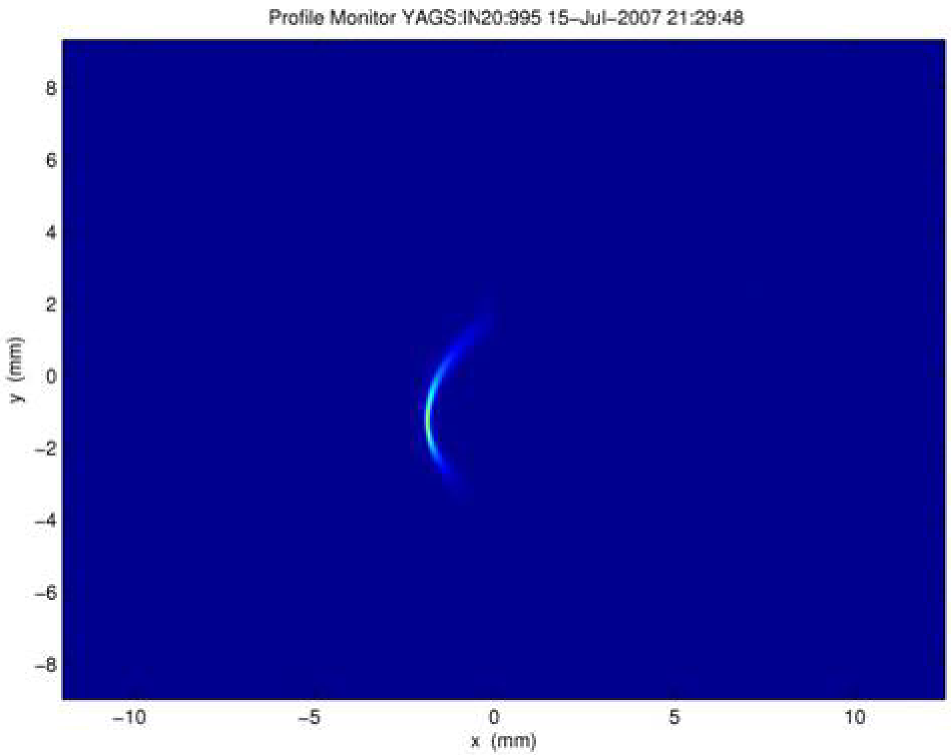
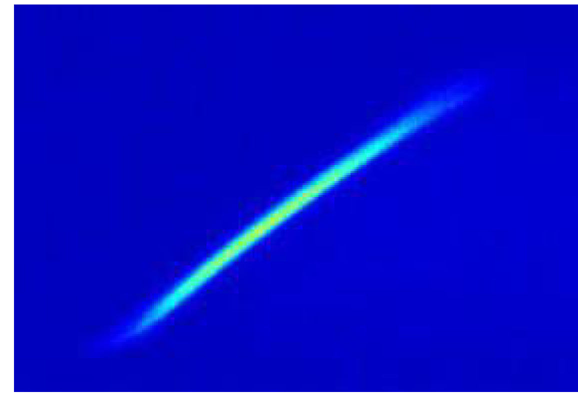
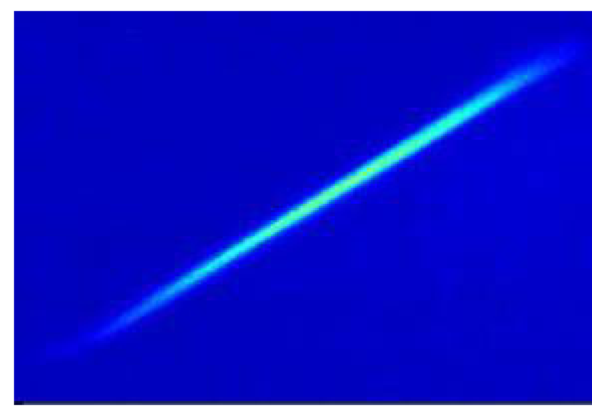
Energy vs. Time



Energy vs. time in DL1



Energy vs. time in BC1 without and with X-band



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Relative Bunch Length Measurement

- Need a non-invasive bunch length measurement.
- An electron bunch will radiate when is crosses an impedance change.
- Radiation will be coherent at wavelengths long compared to the electron bunch length.
- Monitoring the total radiated energy at wavelengths comparable to the bunch length will provide a RELATIVE measure of the bunch length for use in feedback.

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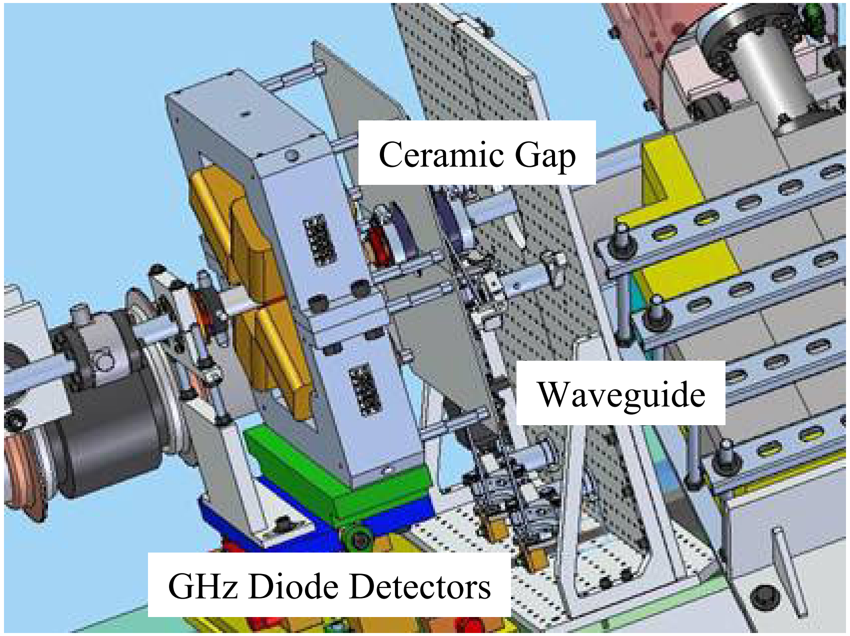
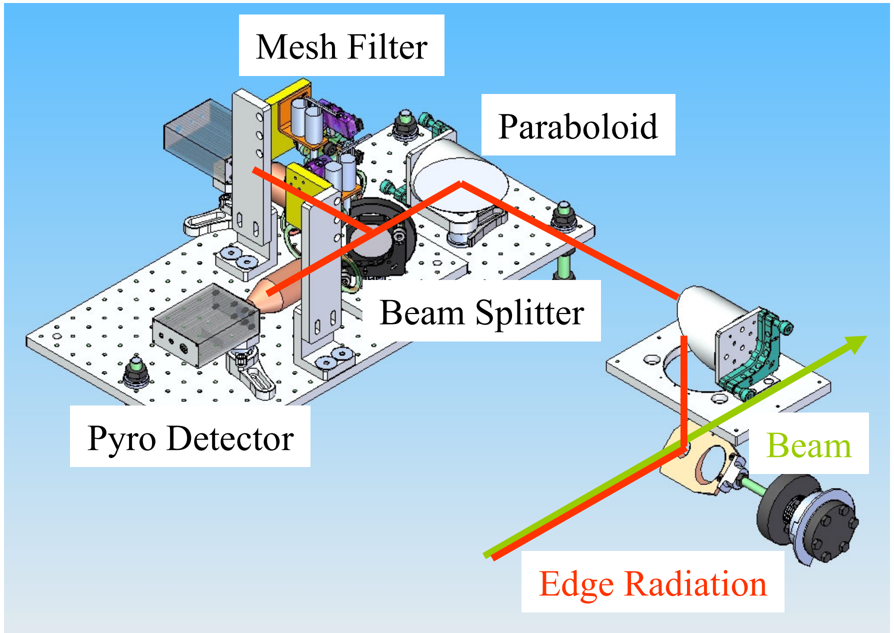
Relative Bunch Length Monitors

BL12 – Ceramic Gap

BL11 – Coherent Edge Radiation





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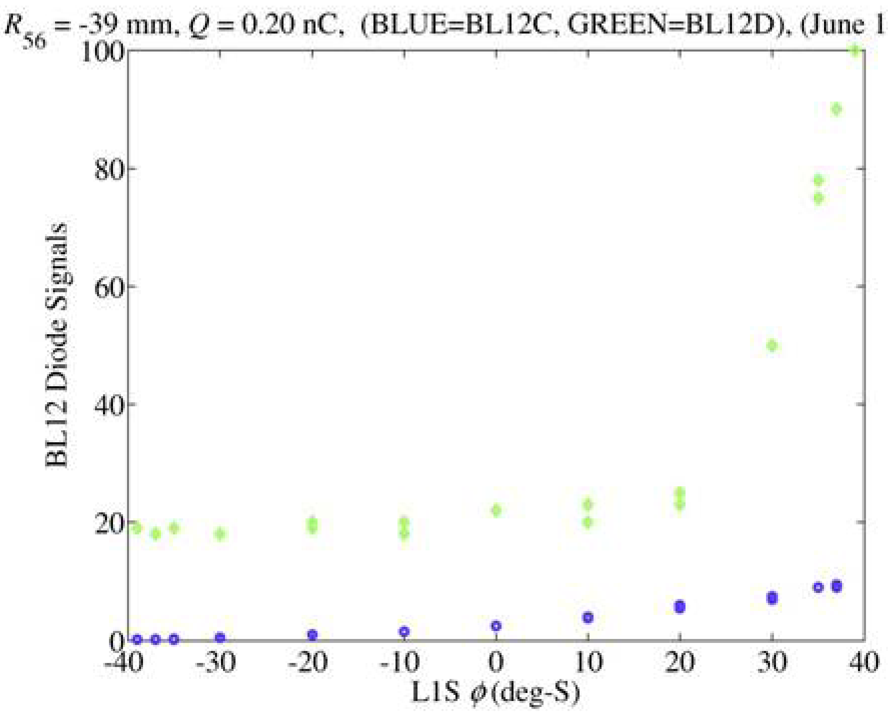
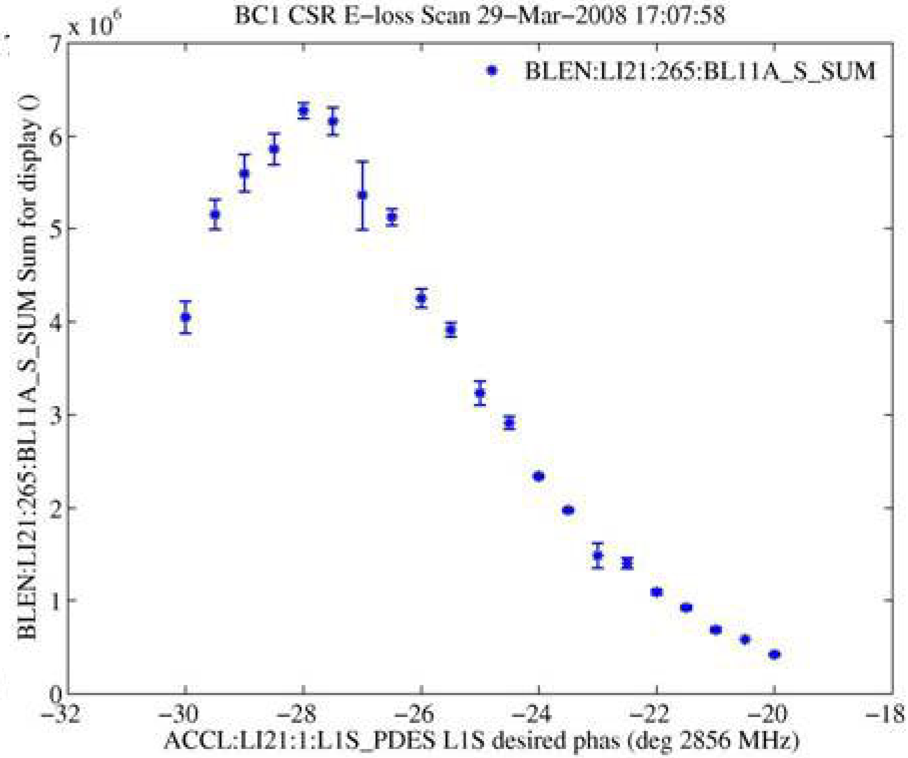
Bunch length monitor signals



Ceramic Gap bunch length monitor
100GHz and 300GHz diodes



Pyroelectric bunch length monitor
After BC1

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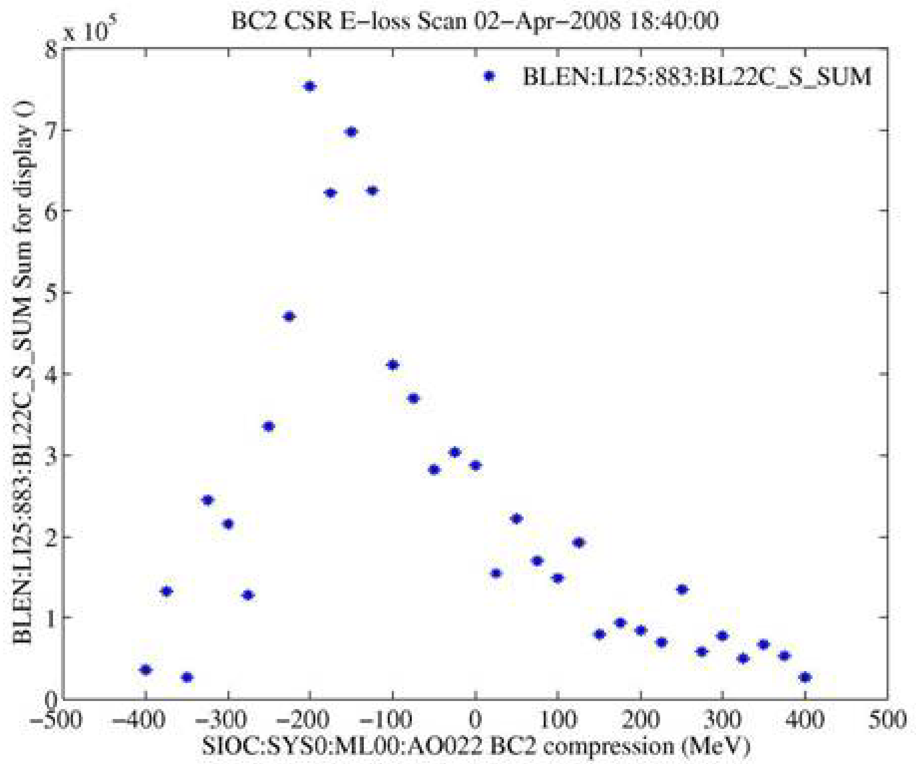
BC2 Bunch Length Monitor

Bunch length monitor signal for BC2 while compression is varied in L2.

BC2 bunch length monitor similar to BC1 monitor except no focusing optics is used, detector is positioned directly above Silicon vacuum window.



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Coherent Synchrotron Radiation

- The CSR instability causes increased energy spread and emittance when the beam is over-compressed.
- CSR will cause energy loss in the bunch compressor, resulting in a beam angle after the last compressor magnet.
- CSR will also increase the horizontal emittance.
- Measurements were done of the energy loss and emittance after BC1 and BC2

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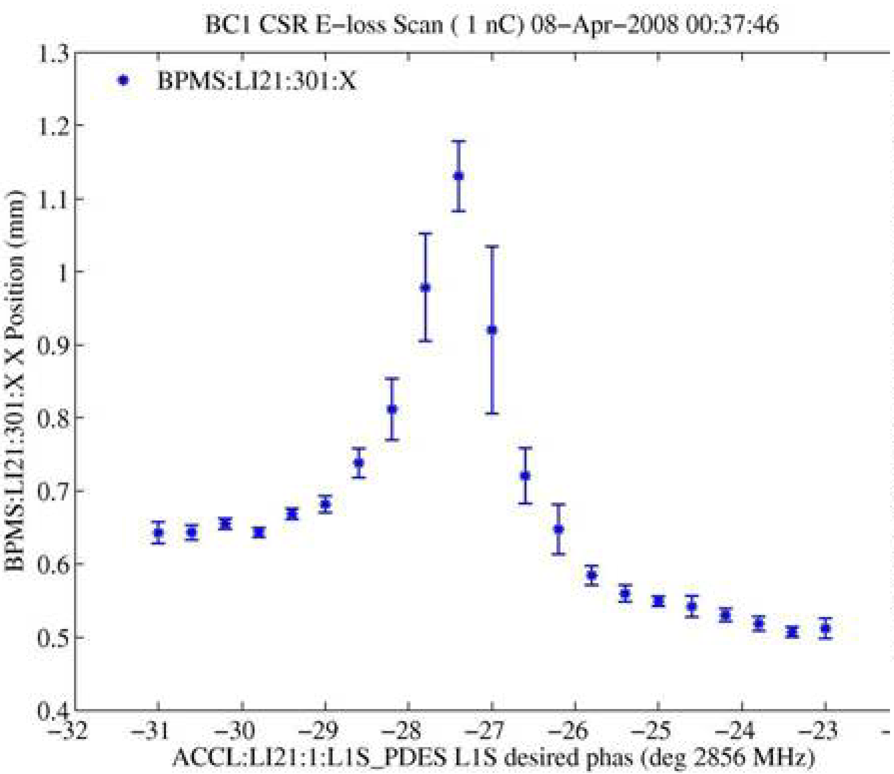
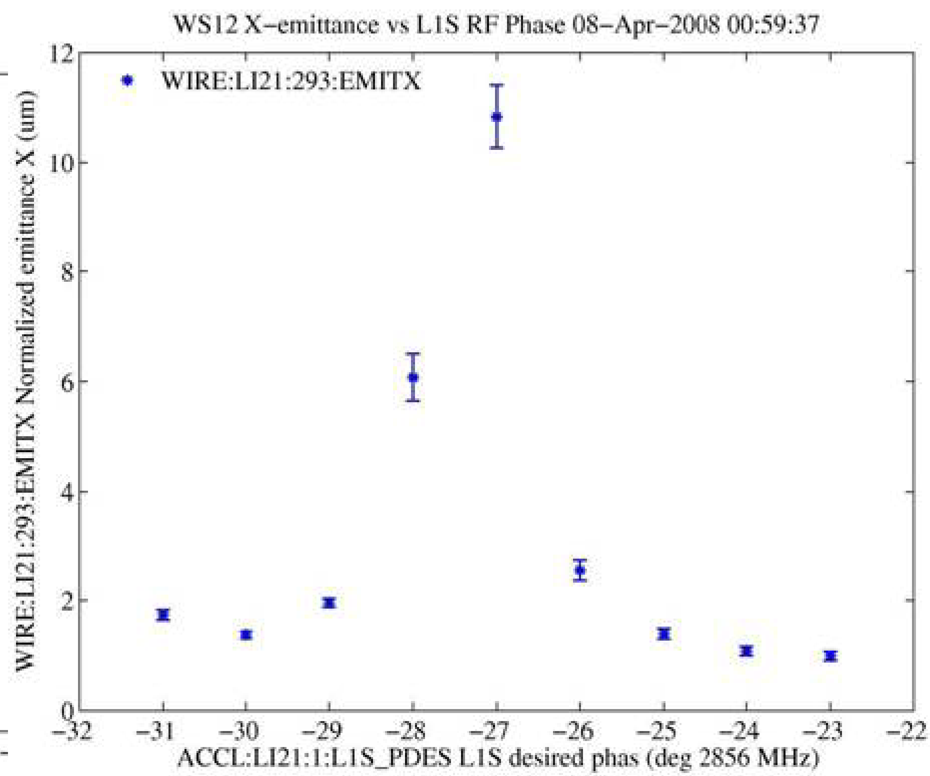
CSR in First Bunch Compressor

Energy loss due to CSR in BC1



Emittance increase due to CSR in BC1



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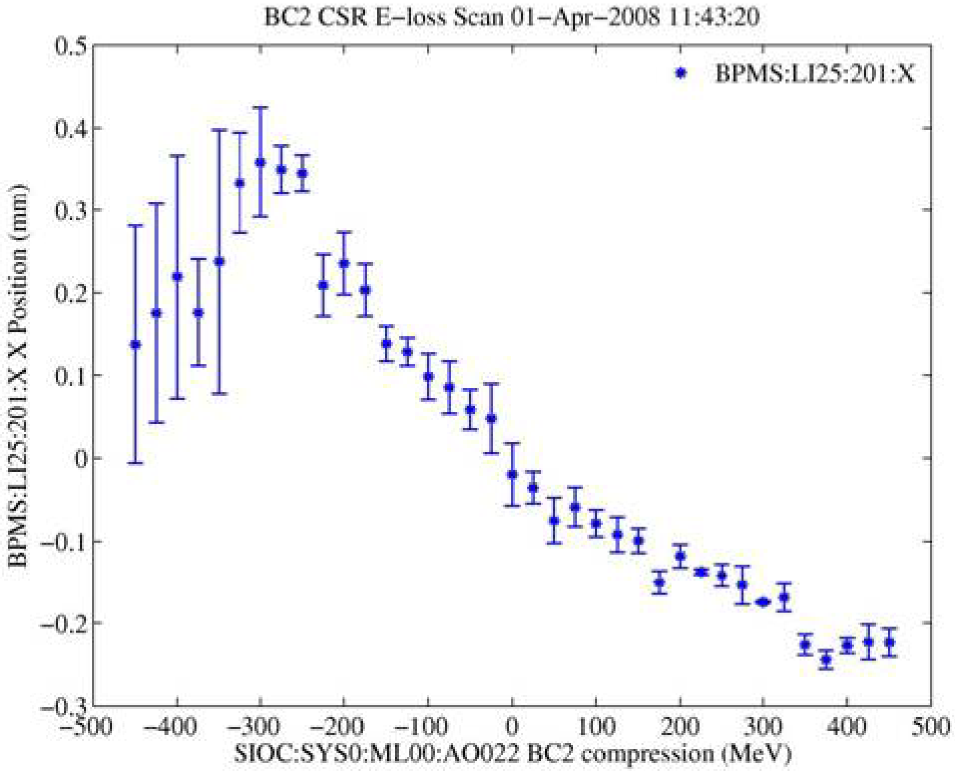
CSR energy loss in BC2



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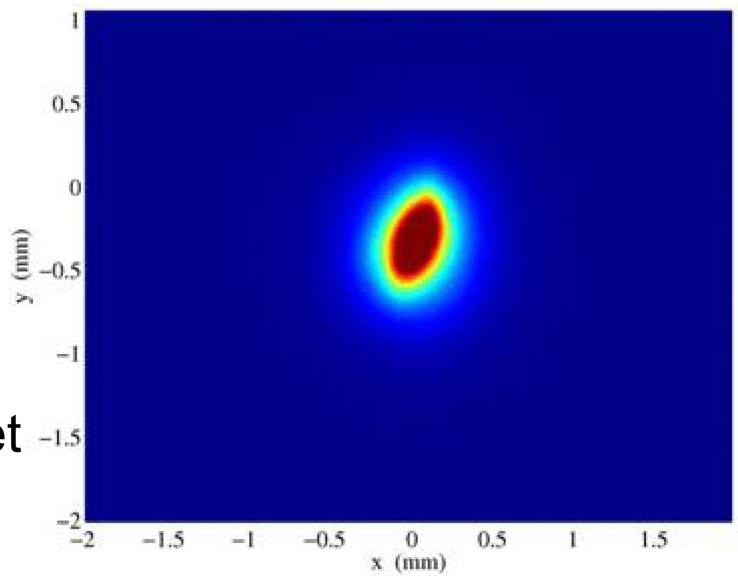
Status and Future Plans

- COTR makes many of our diagnostics unusable
- No profile measurement in the 900 Meters between BC1 and the end of Linac-3
- Several plans to mitigate COTR
  - Laser Heater
  - Optics change in injector
- Beam charge, bunch length, energy meet LCLS requirements
- Emittance at end of injector meets LCLS requirements
- Expect that with additional tuning the we can meet the emittance goals at the end of L3.



Beam at 13.6 GeV

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