Instrumentation for Linac-based X-Ray FELs

Henrik Loos

12th Beam Instrumentation Workshop
May 1-4, 2006

Outline

- XFEL introduction
- LCLS overview
- Electron beam diagnostics
  - Transverse Beam Properties
  - Longitudinal Beam Properties
- Photon beam diagnostics

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X-Ray FEL Features

- ~1Å photon wavelength or ~10keV photon energy
- Uses SASE principle to amplify and saturate spontaneous radiation in ~100m of undulator
- Requires
  - Multi GeV beam energy
  - kA peak beam current
  - Micron beam emittance to match photon beam phase space

$$\lambda_R = \frac{\lambda_U}{2\gamma^2}\left(1 + K_{rms}^2\right)$$

$$\varepsilon \approx \frac{\lambda}{4\pi}$$

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X-Ray FEL Parameters

Electron Beam		LCLS	XFEL	SCSS
Energy	GeV	4.3-13.6	10-20	6.1
Peak Current	kA	3.4	5	3
Bunch Charge	nC	0.2-1	1	1
Norm. Slice Emittance	µm	1.2	1.4	0.85
Bunch Length	fs	70	80	80
Slice Energy Spread	MeV	1.4	2.5	0.25

Photon Beam		LCLS	XFEL	SCSS
Saturation Length	m	60-100	40-170	80
Photon Energy	keV	0.8-8	0.2-12.4	12
Peak Power	GW	4-8	22-135	3

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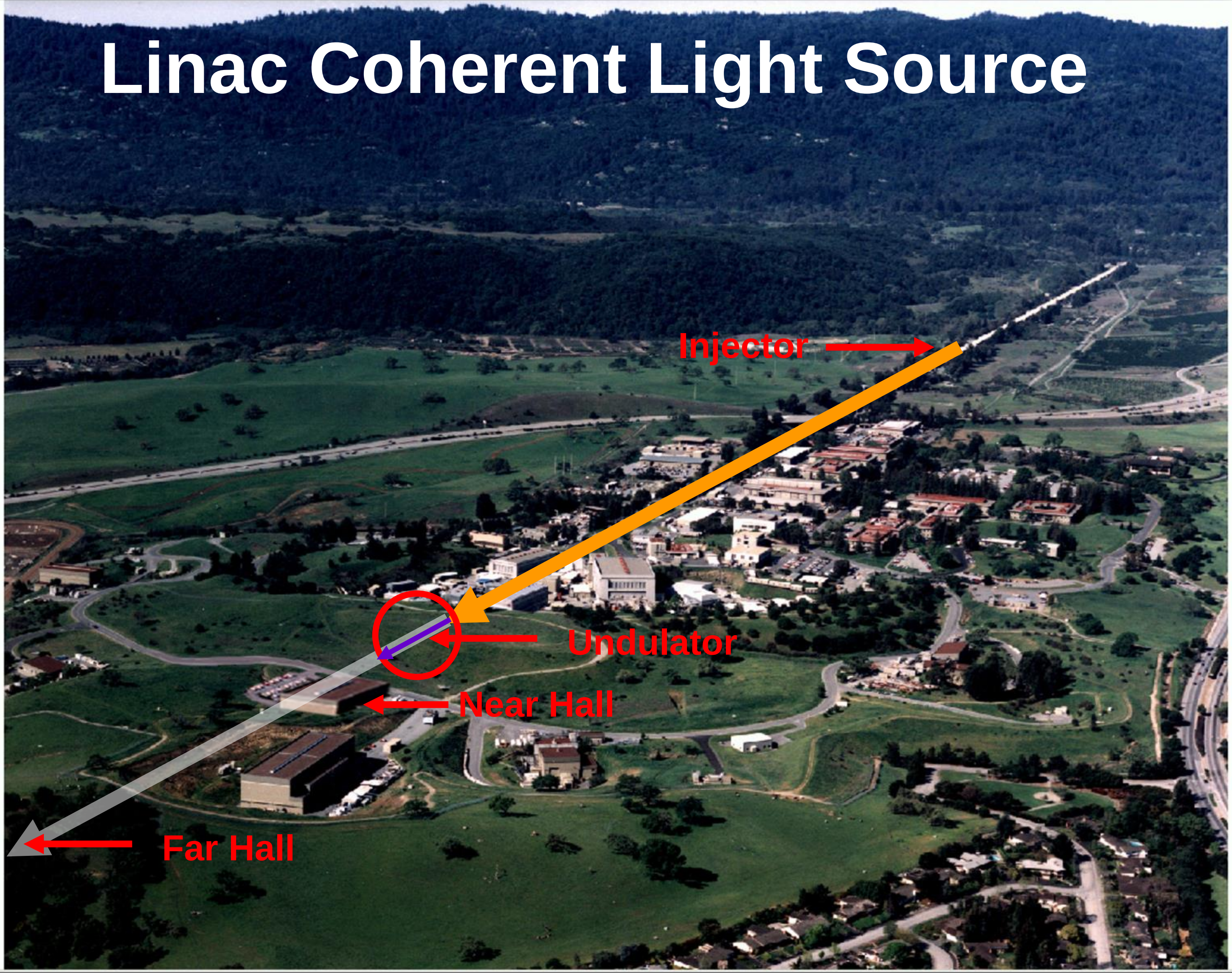
Linac Coherent Light Source



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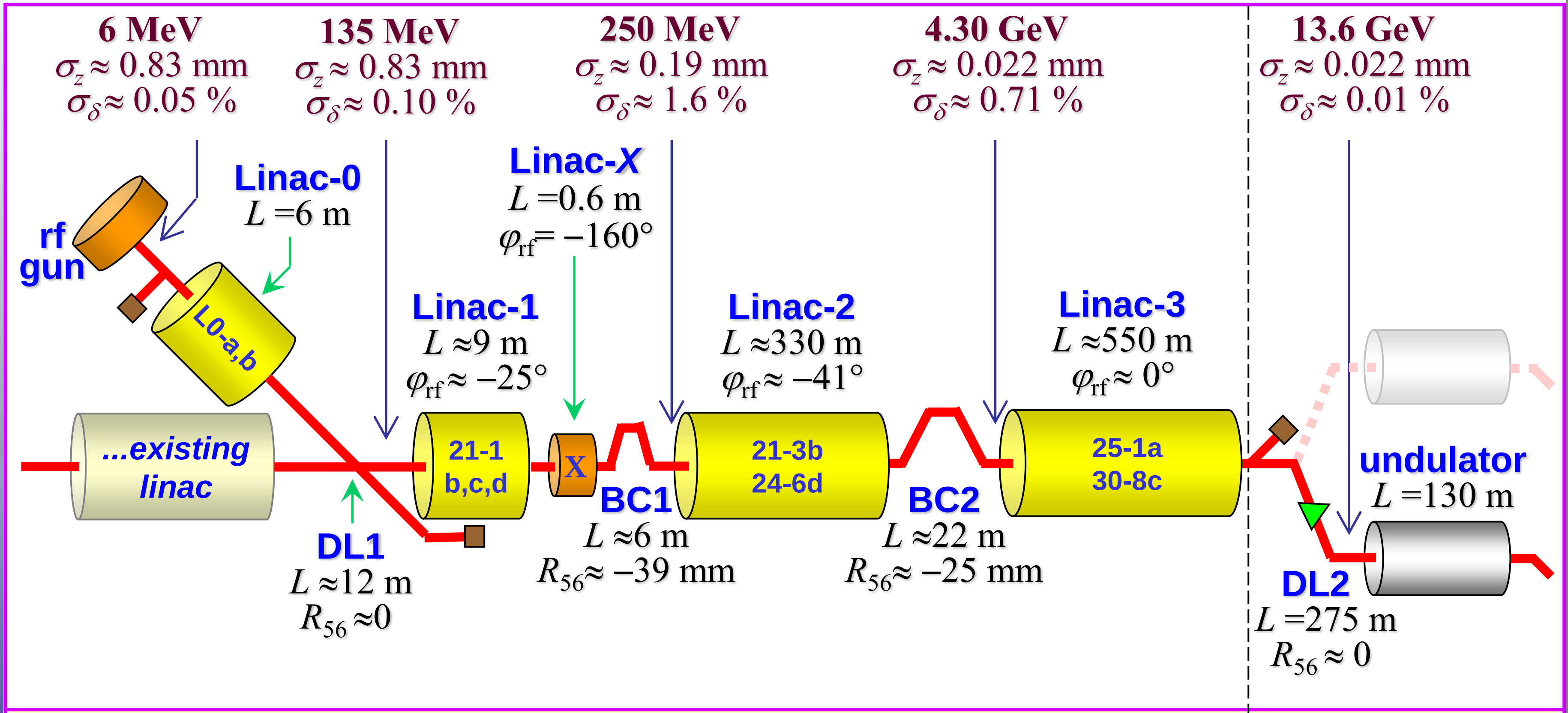
LCLS Accelerator Layout



Courtesy P. Emma

LCLS Diagnostics Tasks

- Charge
  - Toroids (Gun, Inj, BC, Und)
  - Faraday cups (Gun & Inj)
- Trajectory & energy
  - Stripline BPMs (Gun, Inj, Linac)
  - Cavity BPMs (Und)
  - Profile monitors (Inj), compare position with alignment laser
- Transverse emittance & energy spread
  - Wire scanners
  - YAG screen (Gun, Inj)
  - OTR screens (Inj, Linac)
- Bunch length
  - Cherenkov radiators + streak camera (Gun)
  - Transverse cavity + OTR (Inj, Linac)
  - Coherent radiation power (BC)
- Slice measurements
  - Horizontal emittance
    - T-cavity + quad + OTR
  - Vertical Emittance
    - OTR in dispersive beam line + quad
  - Energy spread
    - T-cavity + OTR in dispersive beam line

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Diagnostics Requirements

Parameter	Method	Unit	Resolution
Current	Toroid, FC	%	2
Position	Stripline BPM	µm	5 - 20
	Cavity BPM	µm	1
Beam Size	Wire Scanner	µm	5
	YAG	µm	15 – 30
	OTR	µm	5 – 30
Bunch Length	Streak Camera	fs	300
	Transverse Cavity	Slices	10
	BLM	%	5

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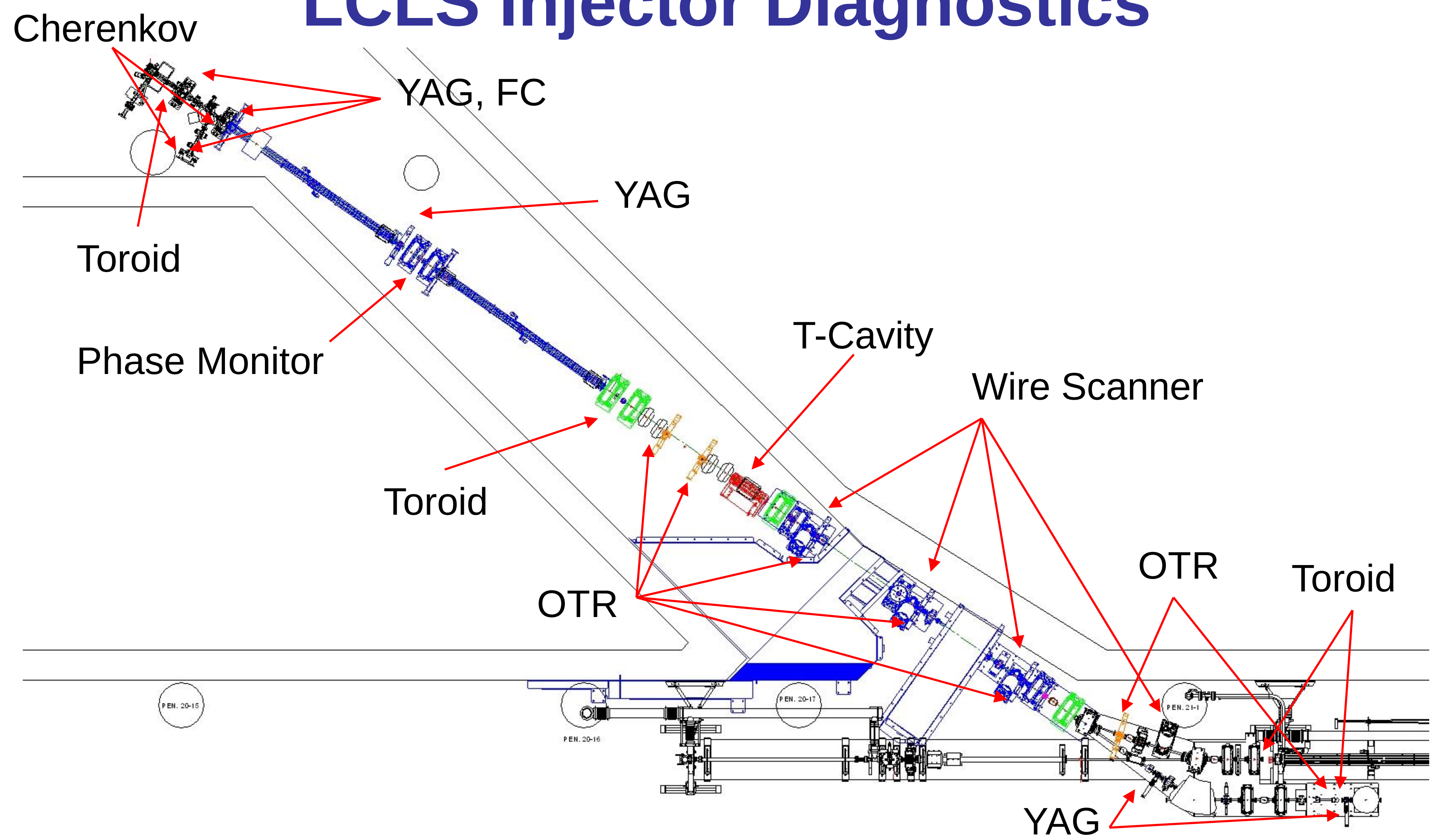
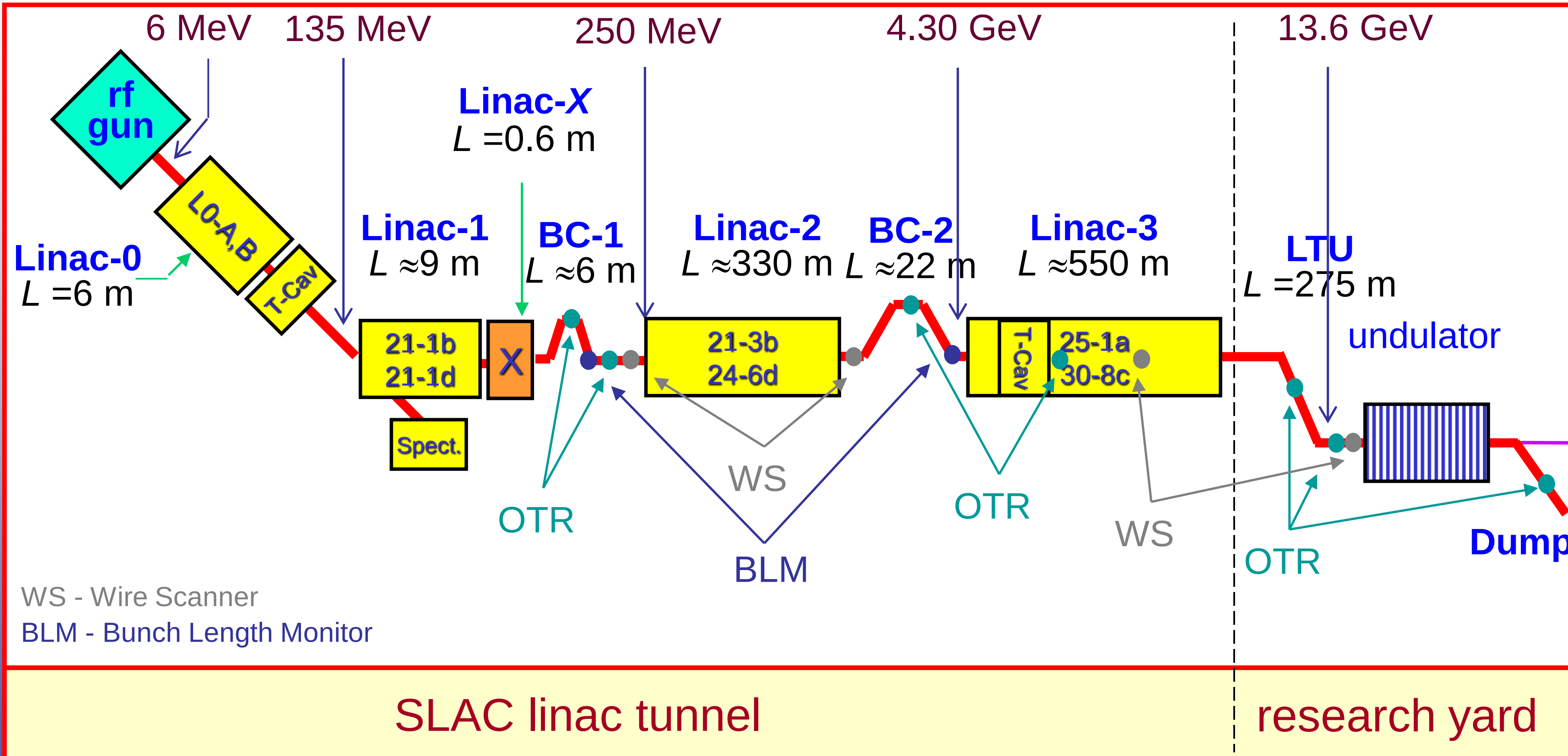
LCLS Injector Diagnostics



LCLS Linac Diagnostics



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Beam Profile Monitors (YAG & OTR)

- YAG requirements
  - Use 100µm thick crystals to meet resolution
  - GTF measurements show feasibility
- OTR requirements
  - Optimize yield to enable beam profile measurement at 0.2nC

OTR yield for 100mrad angular acceptance

Energy (MeV)	QE (%), 450-650 nm	QE (%), 400-750 nm
135	0.44	0.75
4300	0.98	1.68
13500	1.17	1.99

  - Provide sufficient depth of field for imaging of 45° foil
    - Simulation shows 1mm DOF for f/# of 5 within 20µm resolution
  - Match direction of reflection with axis of dispersion or T-CAV deflection
  - Foil is aluminum to optimize TR yield and 1µm thick to minimize radiation

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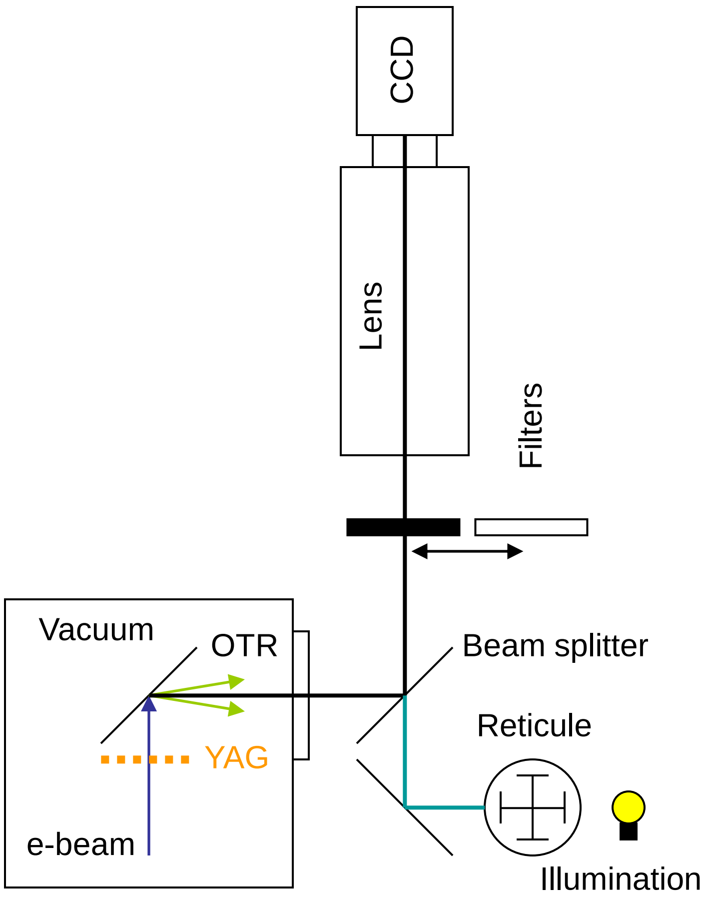
Optics Layout

- Used for all standard YAG/OTR screens
- Telecentric lens
  - 55mm focal length
  - >100 line pairs/mm
  - Magnification up to 1:1
- Stack of 2 insertable neutral density filters
- Beam splitter and reticule for in situ calibration
- Megapixel CCD with 12bit and 4.6µm pixel
- Radiation shielding required in main linac tunnel



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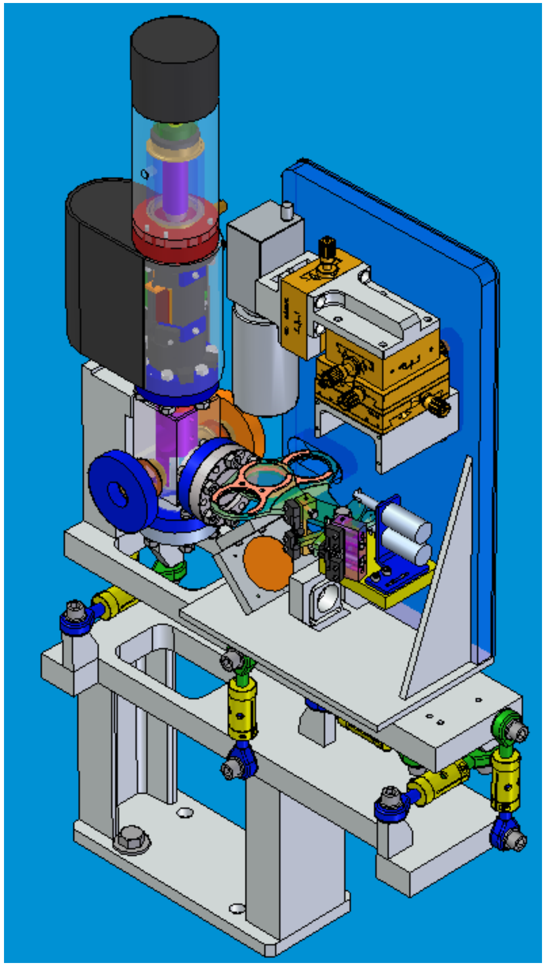
OTR/YAG Optics Design



Courtesy V. Srinivasan

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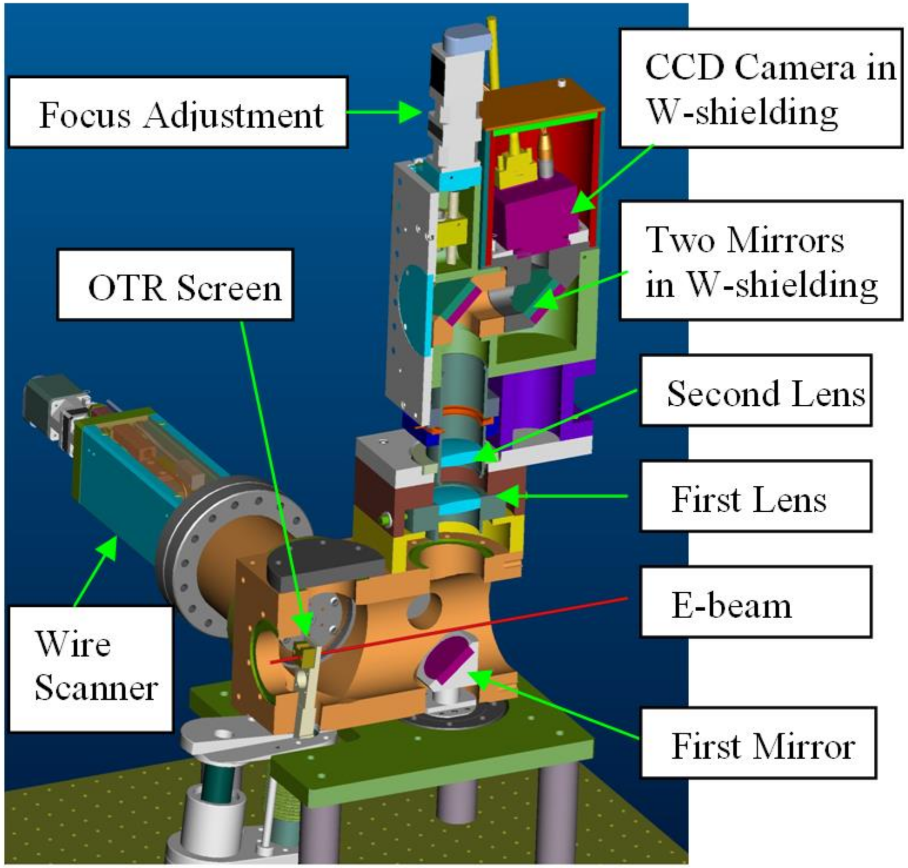
OTR Imager with Tilted Geometry

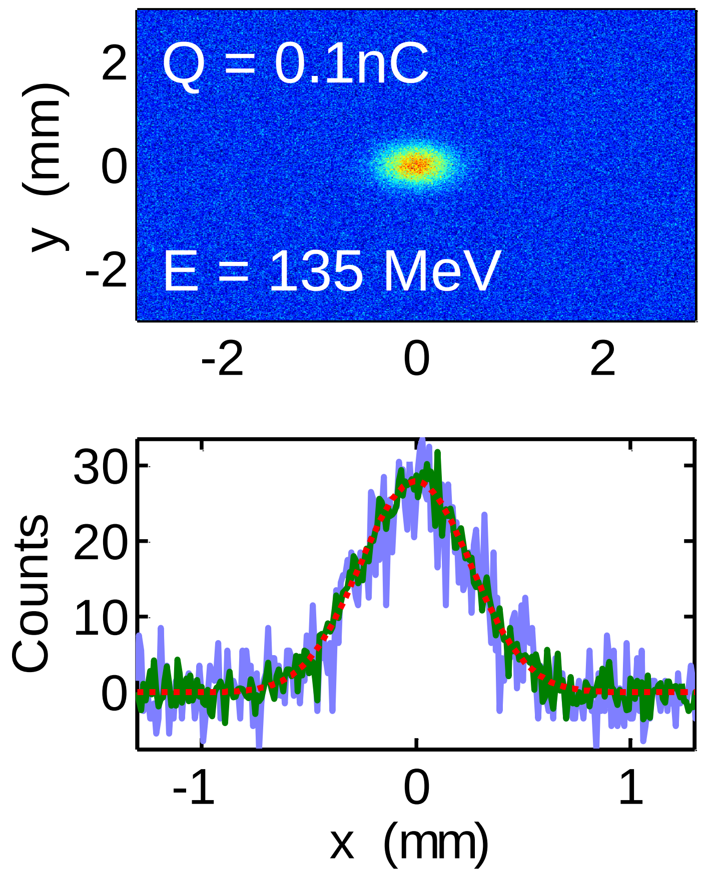
- Need wide field of view in focus for measurements in spectrometer beam line
- Tilt OTR screen and CCD by 5 degrees in 1:1 imaging
- 10um resolution



B.X. Wang et al. PAC05

Simulation of OTR Beam Size Measurement

- Simulation of CCD image
  - Include 0.5% TR yield, photon shot noise, and typical CCD parameters for quantum efficiency, read out noise, pixel size, digitizer gain
- Calculation of beam size
  - Generate beam profile with 10σ bounding box
  - Compare rms width of profile with original Gaussian beam size
- Simulation agrees well with OTR measurement at GTF
- Error of 5% in beam size for beam of 0.1nC, 260µm at 10µm resolution



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Longitudinal Diagnostics

- Gun region
  - Cherenkov radiator & streak camera
- Bunch length and slice emittance
  - Transverse cavity
- Longitudinal feedback loop
  - Integrated power from coherent radiation

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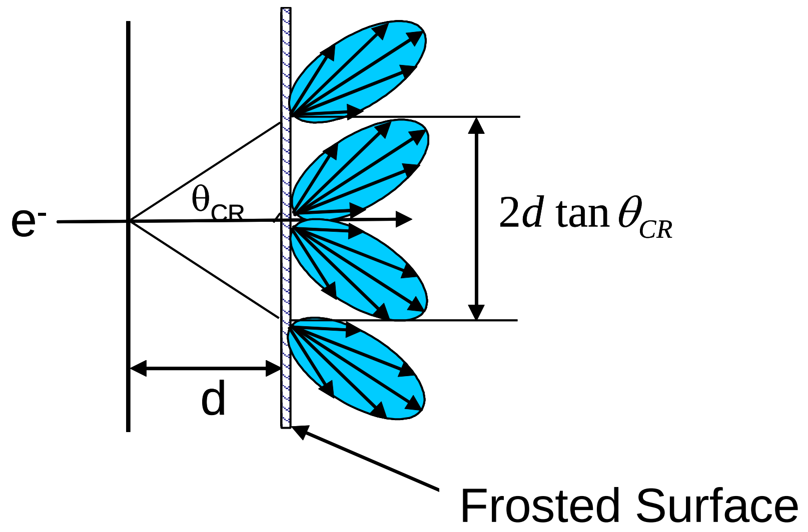
Cherenkov Radiators

- Located in gun region for temporal diagnostics of 6 MeV beam from gun
- Convert electron beam time structure into light pulse for streak camera measurement
- Cherenkov light suitable at low beam energies
- Design requirements
  - Match time resolution of radiator to streak camera (Hamamatsu FESCA-200, < 300fs)
  - Generate and transport a sufficient # of photons for 200pC beam to streak camera in laser room (10m away)

Cherenkov Radiator Design

- Fused silica
  - $n = 1.458$, $\theta_{CR} = 46.7°$
  - Total internal reflection
  - Frosting of back surface
  - $N_{\Phi} = 7.5$/e/mm/50nm @400nm
- Temporal and spatial resolution
  - Thickness of 100µm
  - $\Delta t = 375$fs
  - $\Delta x = 190$µm



Courtesy D. Dowell

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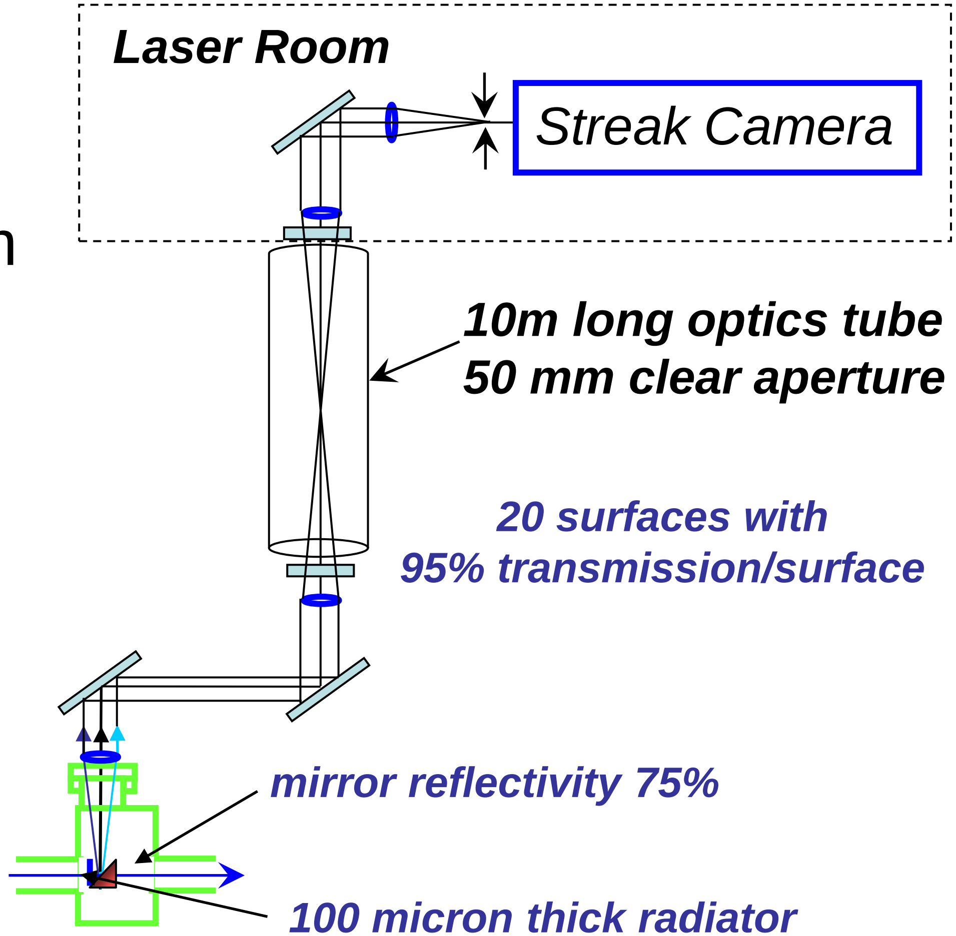
Optical Transport Layout

- 1:1 relay imaging from radiator to streak camera
- Assume 1% efficiency from frosting to scatter into 100mrad
- 6% acceptance through tube for source of 5mm x 100mrad
- $1.5 \cdot 10^5$ photons on slit of streak camera for 200 pC



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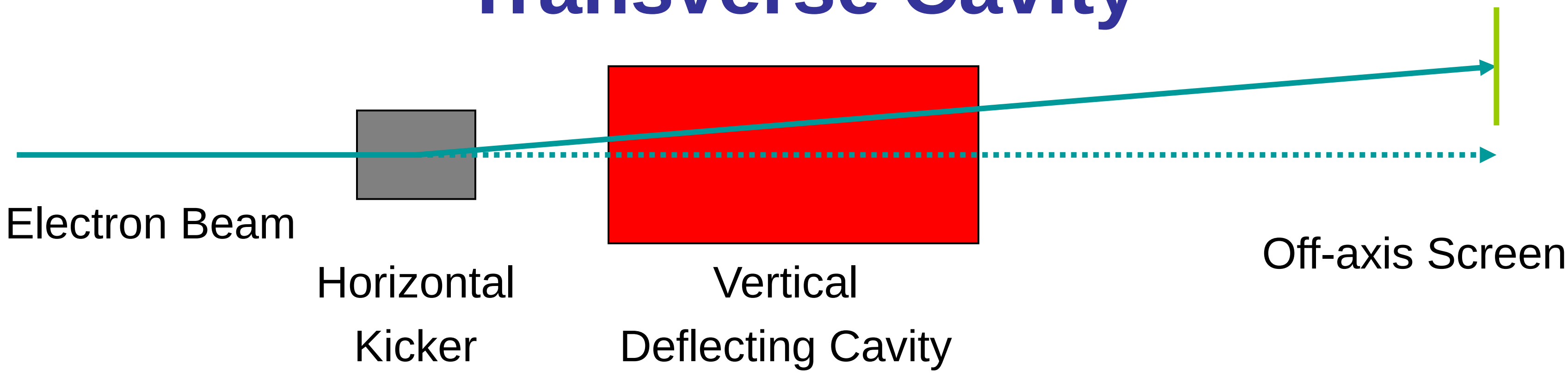
Transverse Cavity



- Translates longitudinal into transverse beam profile when operating at RF zero crossing
- Parasitic operation with kicker and off-axis screen
- Single shot absolute bunch length measurement
- Temporal resolution limited by unstreaked spot size

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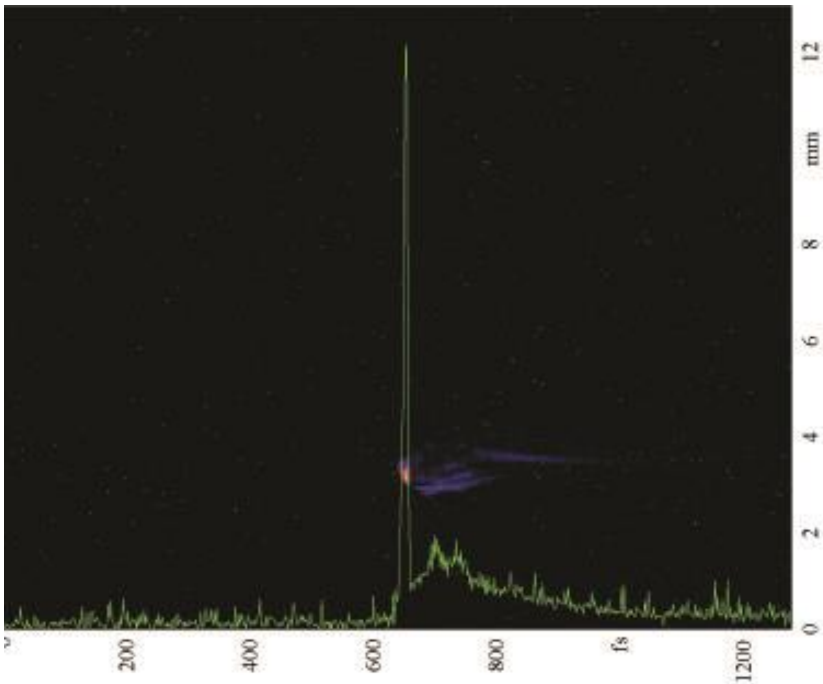
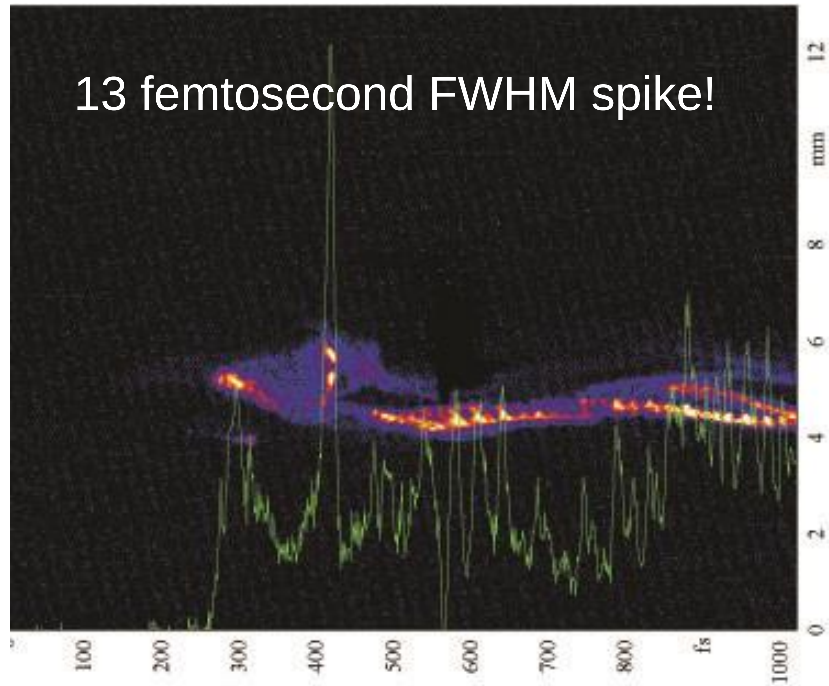
Transverse Cavity Measurement at TTF

Beam without and with BC 3 (second bunch compressor)





1 picosecond

1 picosecond

Scans at high power ~16MW

Courtesy J. Frisch

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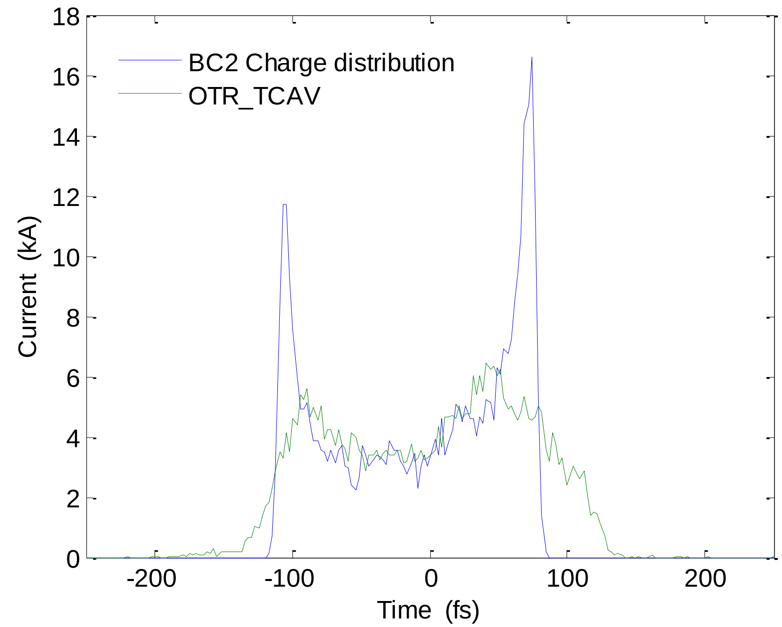
TCAV in LCLS after BC2

- Short 70fs bunch length requires full RF power for cavity
- Parasitic measurement with beam optics optimized for SASE
- Resolution 20fs sufficient for length measurement



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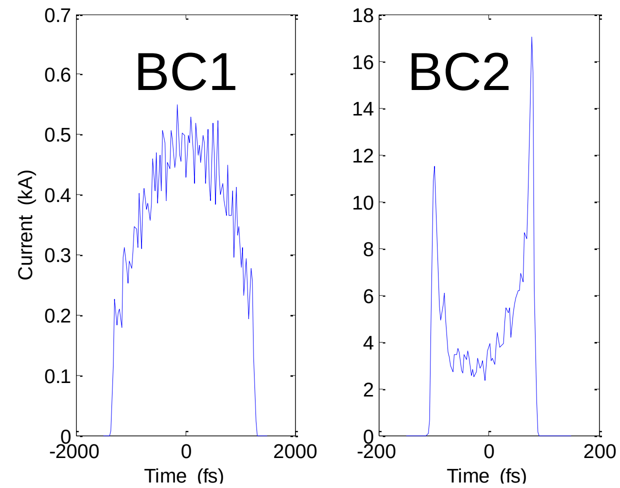
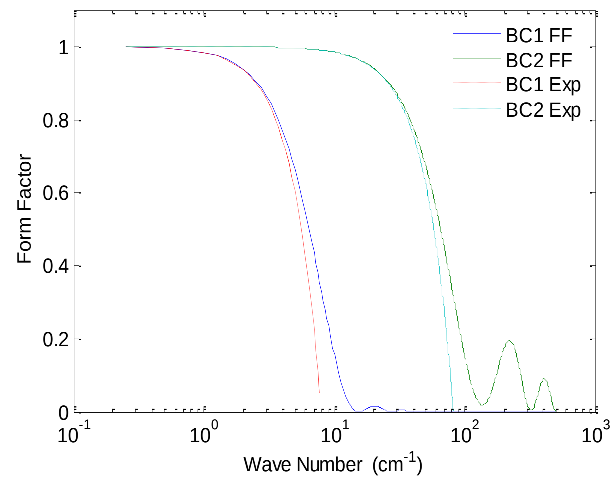
Bunch Length Monitor

- Relative bunch length measurement used for longitudinal feedback
- Non-intercepting, calibrated with interceptive TCAV measurement
- Based on integrated power from coherent radiation source (C*R)

$$W = N_e^2 \int d\omega \frac{dW_1(\omega)}{d\omega} f(\omega), \quad f(\omega) = \left| \int n(t) e^{i\omega t} d\omega \right|^2$$

- Single electron radiation spectrum $W_1(\omega)$ depends on radiation source
- Bunch length determined by long wavelengths $\lambda \gg 2\pi\sigma_{rms}$
- BC1: 1cm – 1mm
- BC2: 1mm - .1mm





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Radiation Sources

- Wide range of bunch lengths from 25um to 300um
- Diode detectors work well below 300GHz
- Pyroelectric detectors work well above 300GHz
- Long bunches
  - Couple radiation from ceramic gap in beam pipe into waveguides with different diode detectors
- Short bunches
  - Extract coherent radiation from bend magnet with hole mirror and send to a pyroelectric detector

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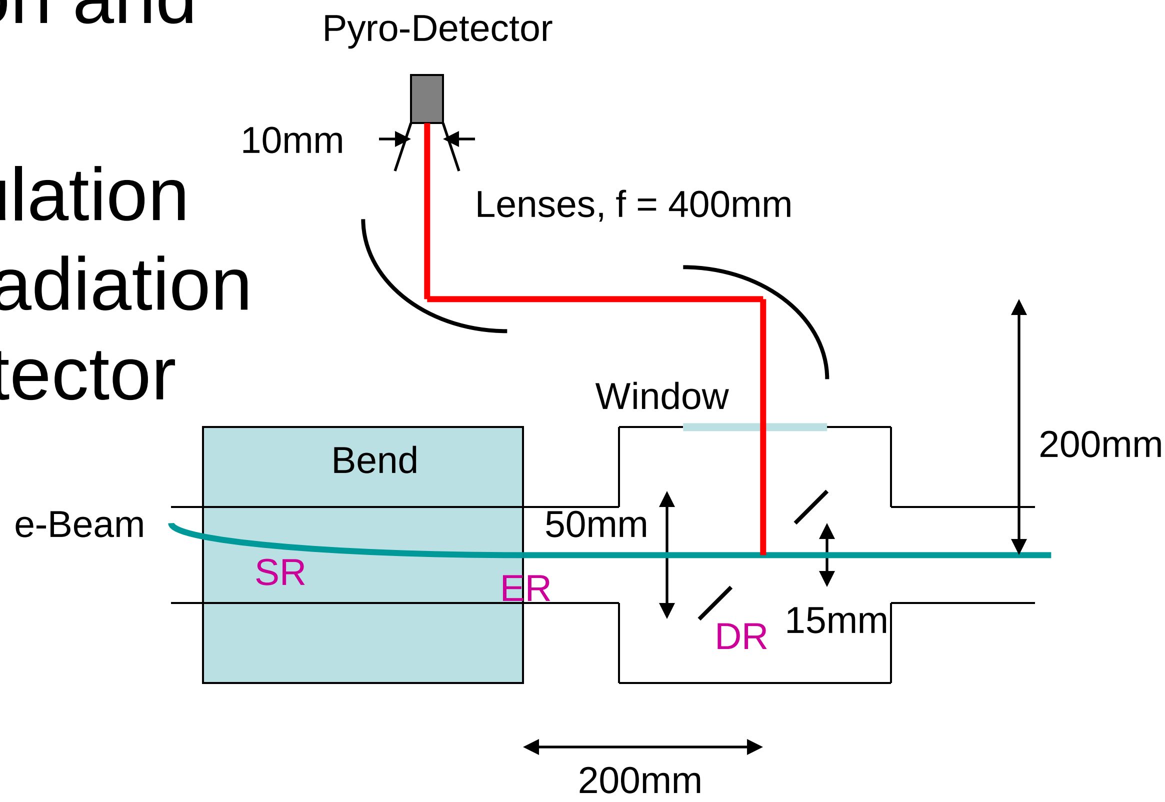
CER Detector Layout

- Edge rad. dominates over synchrotron and diffraction
- Near field calculation necessary for radiation spectrum at detector



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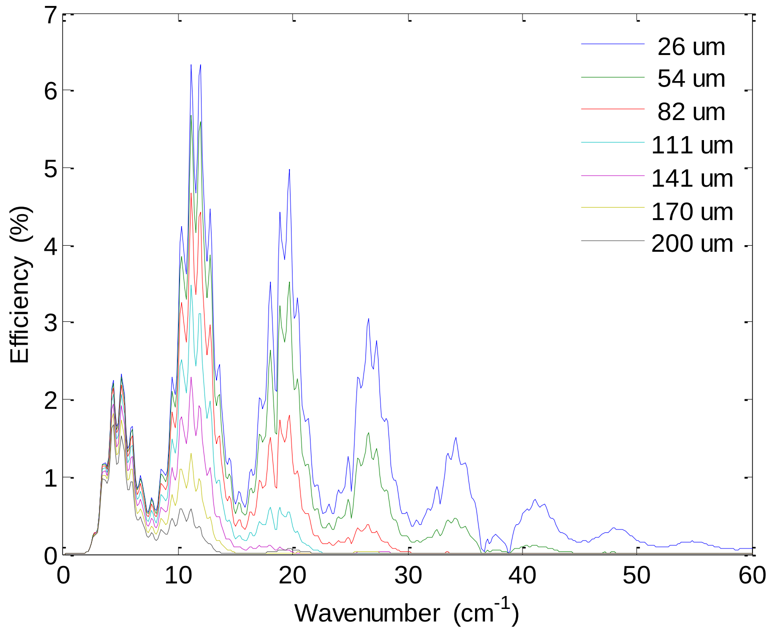
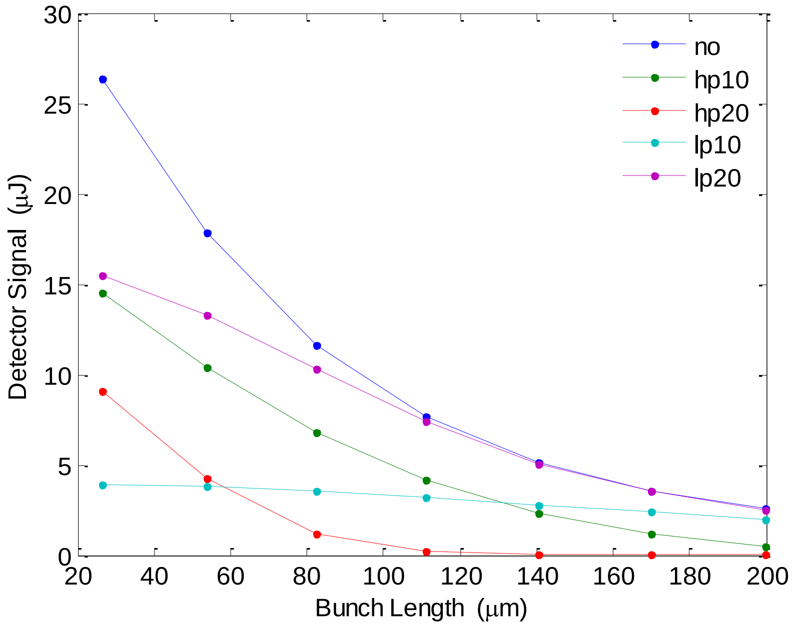
Bunch Length Sensitivity of Detector Signal

- Detection efficiency includes diffraction, vacuum window, water absorption, pyroelectric detector response, and bunch form factor.
- Introduce high and low pass filters at 10cm^{-1} and 20cm^{-1}.





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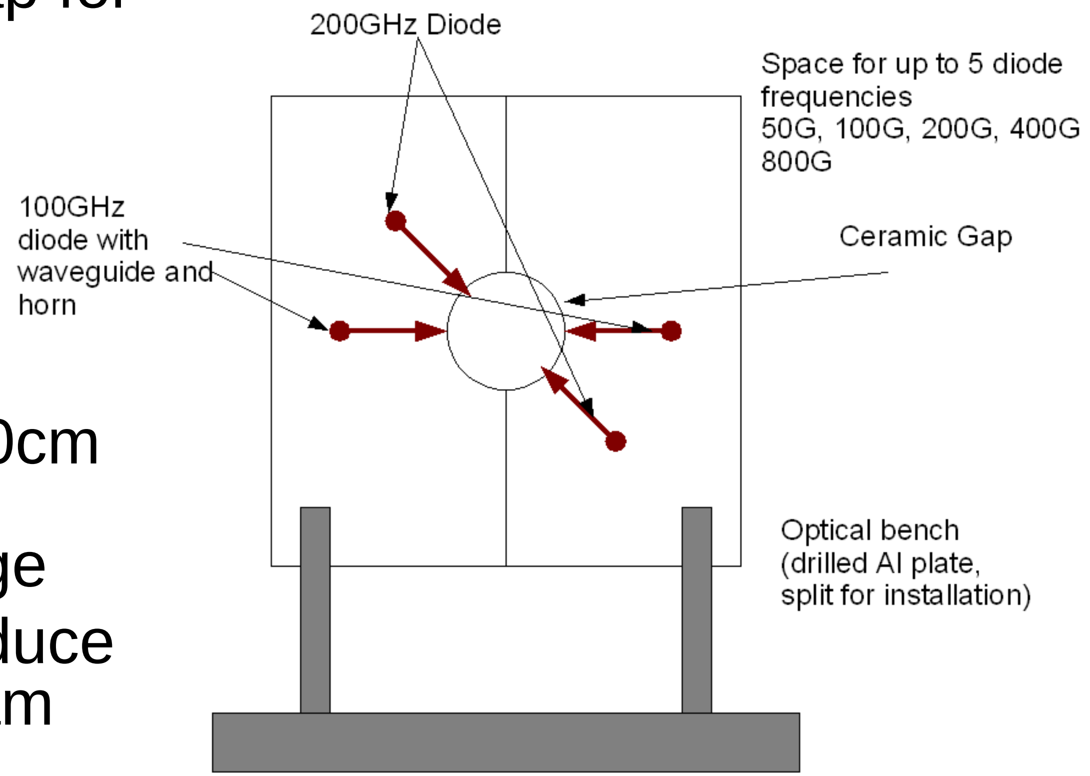
Gap Radiation Detector

- Expect 2uJ radiation energy from 2cm gap for 1nC, 200um bunch
  (Calculation J. Wu)
- Energy density of $1.6 nJ/mm^2$
- Diode sensitivity $\sim 0.1 pJ/mm^2$
- Disperse pulse in 20cm waveguide to keep diodes in linear range
- Diodes paired to reduce dependence on beam position



Courtesy S. Smith

Photon Beam Diagnostics

- Measure spontaneous radiation for undulator commissioning
- Measure FEL photon beam for SASE commissioning
- Nondestructive measurements of beam properties for user operation

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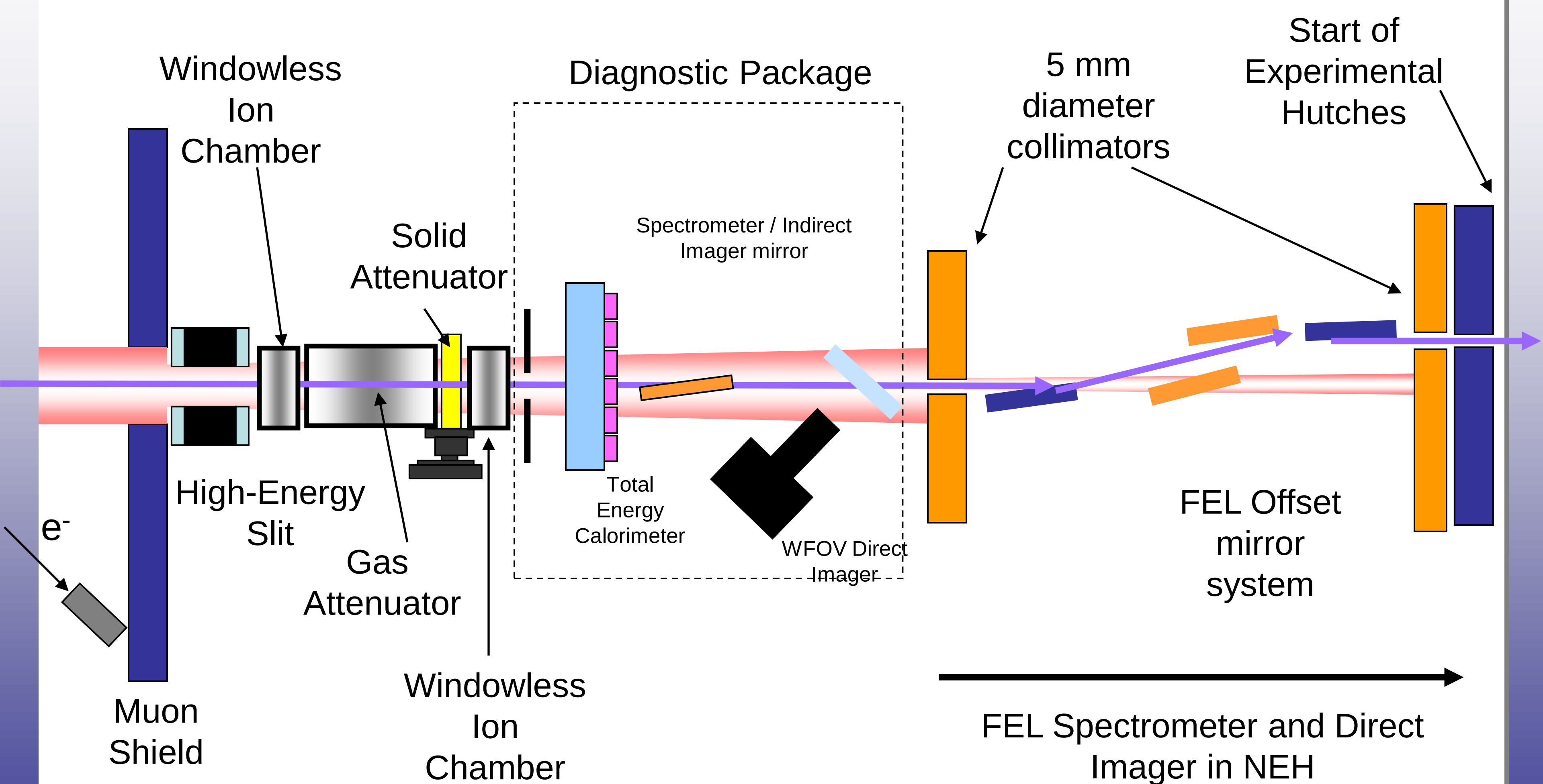
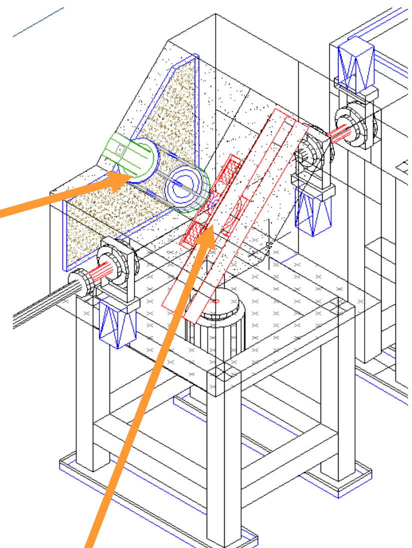
LCLS FEE Schematic



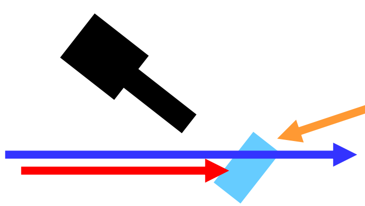
Courtesy R. Bionta

Wide Field of View Direct Imager

Single shot measurement of *f(x,y), x, y ,u*

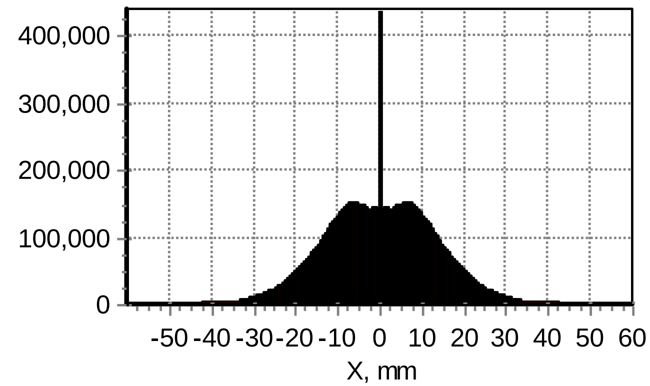


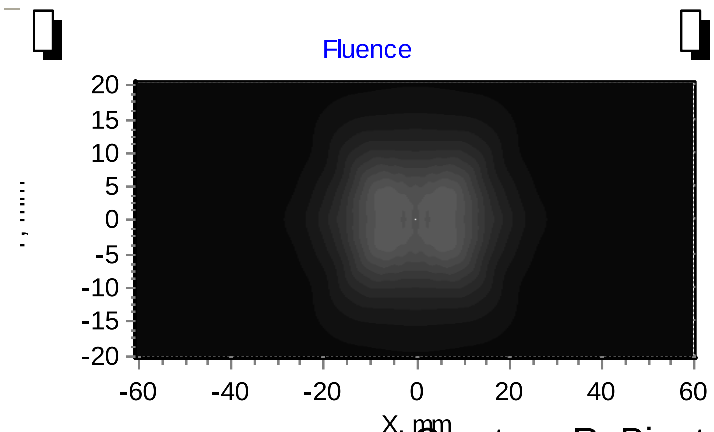
Camera



Scintillators

Photoelectrons generated by 0.01% FEL





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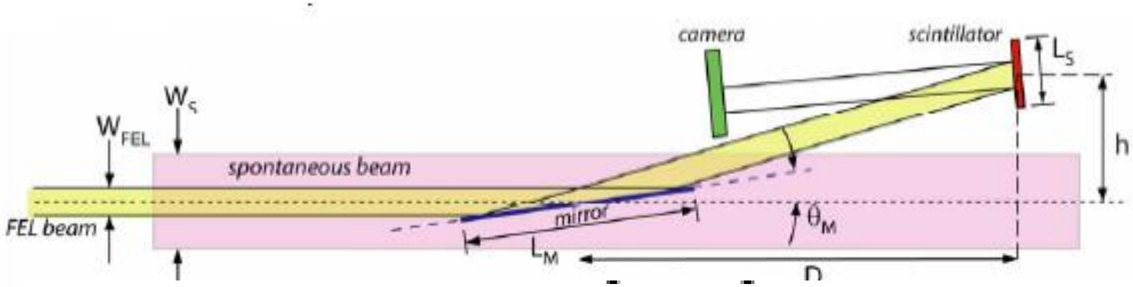
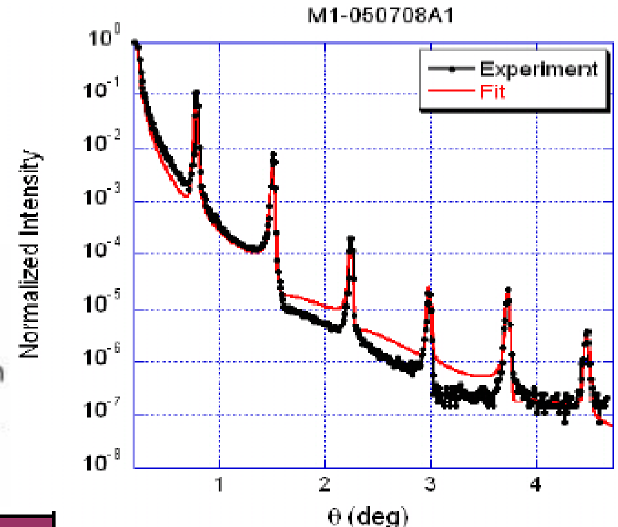
Indirect Imager

Single shot measurement of *f(x,y), x, y, u*
Multi shot measurement of λ

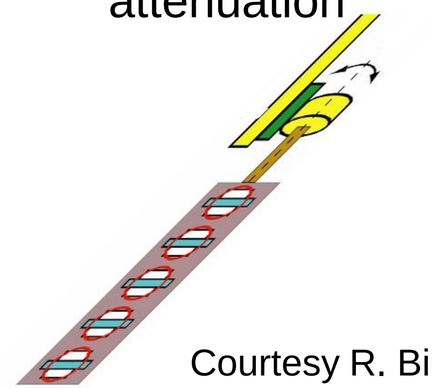


Material Pairs	N	d	Γ	Primary Energy
B_4C/SiC	150	60 Å	0.7	8.261 keV
B_4C/SiC	35	100 Å	0.75	8.261 keV
Be/SiC	40	110 Å	0.75	0.8261 keV
B_4C/SiC	750	20 Å	0.55	24.78 keV
B_4C/SiC	450	20 Å	0.55	24.78 keV
B_4C/SiC	150	70 Å	0.45	24.78 keV
B_4C/SiC	50	100 Å	0.754	2.478 keV

B4C/SiC Test Multilayers Fabricated



Angle selects energy and attenuation



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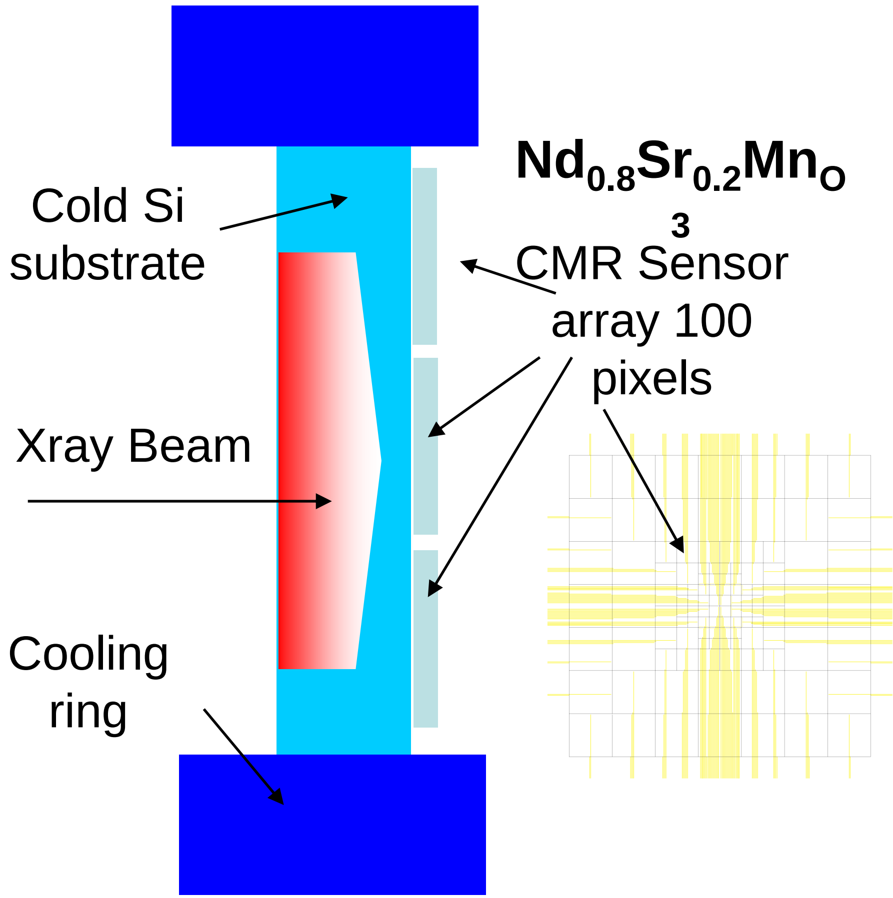
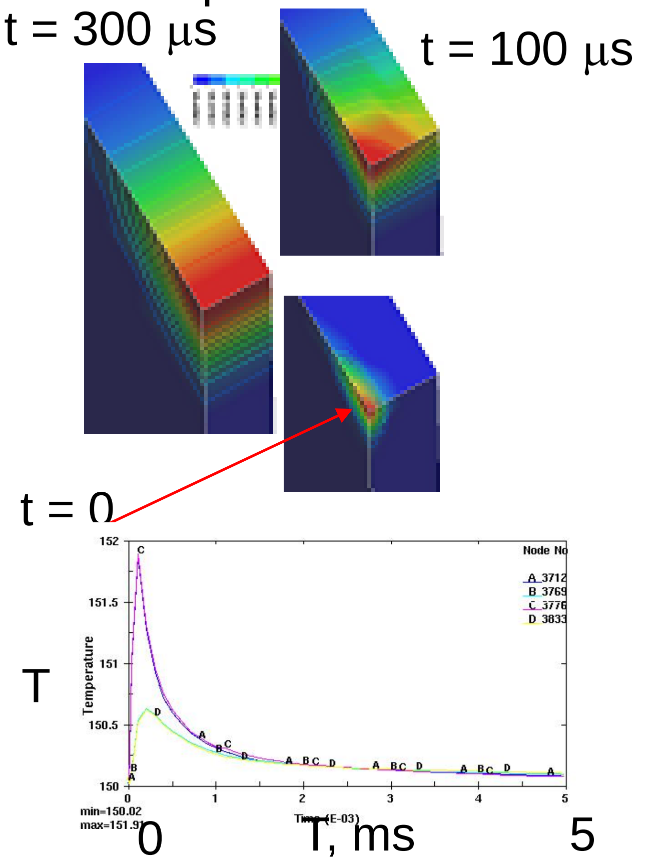
Total Energy Calorimeter

Single shot measurement of *f(x,y), x, y, u*



Thermal diffusion calculations performed



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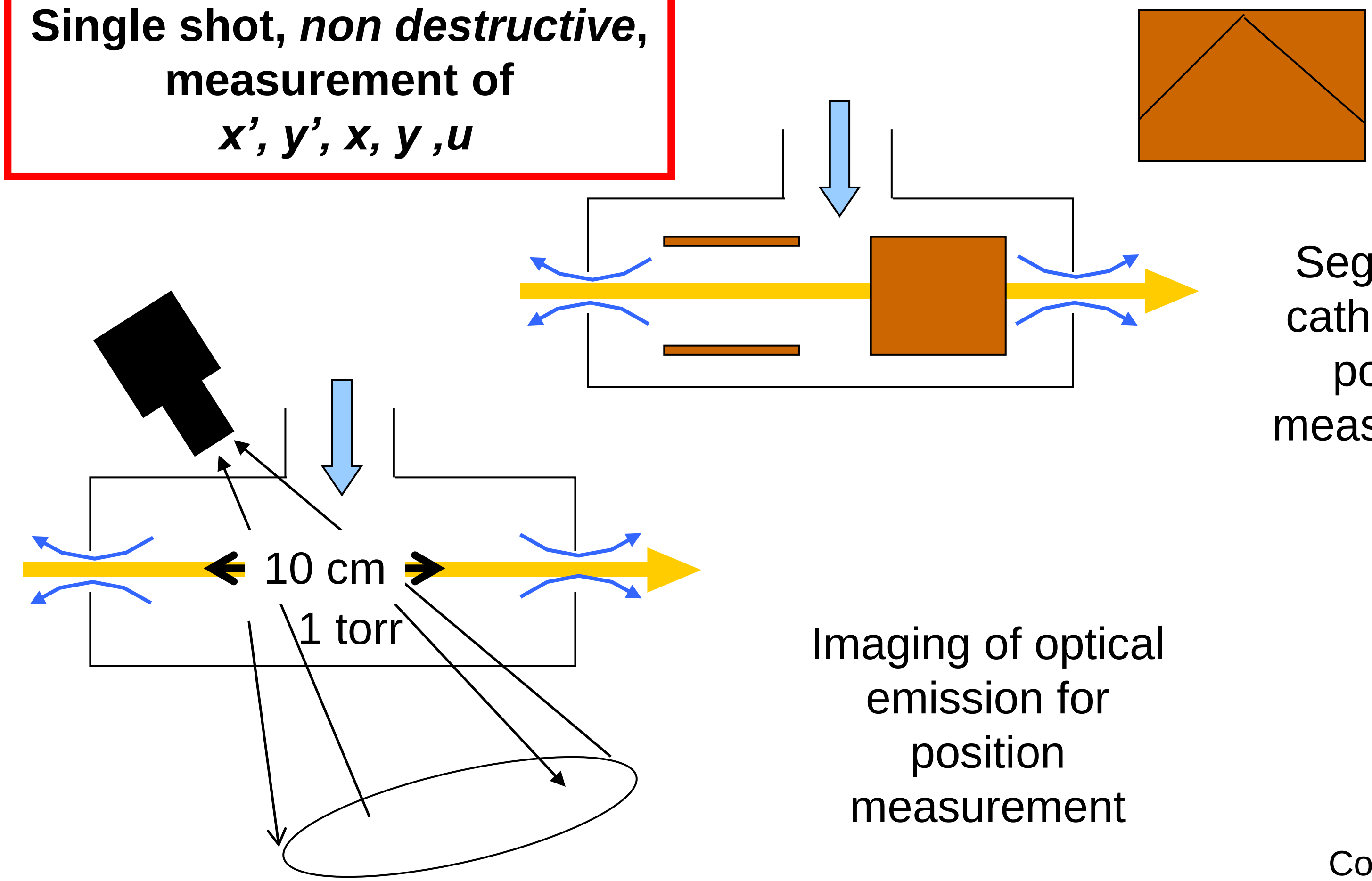
Ion Chamber

Single shot, *non destructive*, measurement of *x’, y’, x, y ,u*



Segmented cathodes for position measurement

Imaging of optical emission for position measurement

Courtesy R. Bionta

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Summary

- Electron beam diagnostics based on proven methods
- Photon beam diagnostics needs development of new techniques which are difficult to test due to the lack of a photon source comparable to an X-FEL

Acknowledgements

- Thanks to many colleges from the LCLS collaboration

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