LCLS Injector Commissioning Results

David H. Dowell
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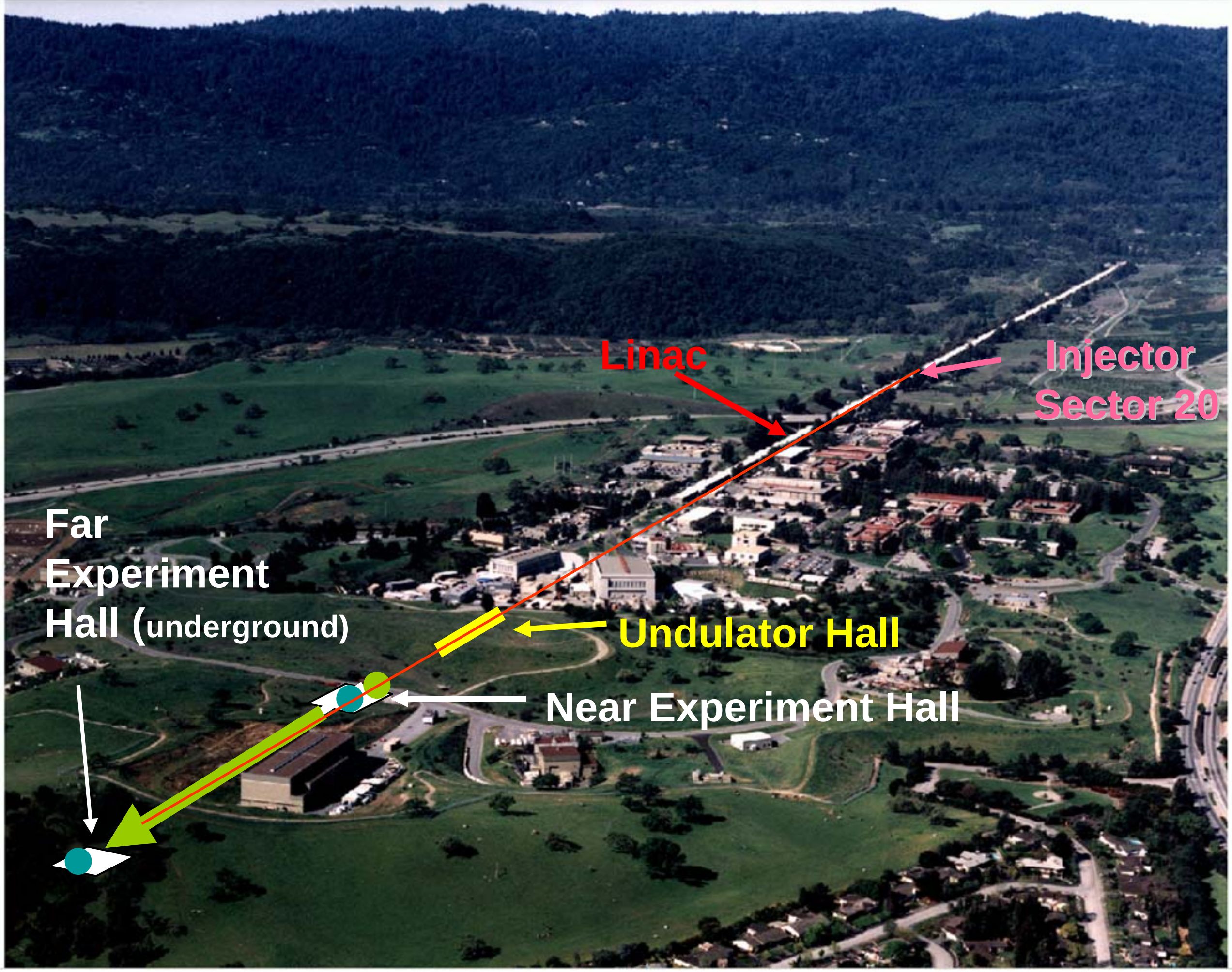
(on Behalf of the LCLS Commissioning Team)

- *Description of LCLS and Its Injector*
- *Commissioning Milestones*
- *The Drive Laser & Cathode*
- *Electron Beam Measurements*
- *Unexpected Physics*
- *Summary of Results and Conclusions*

The LCLS will use the last 1/3 of the SLAC linac to create an x-ray FEL



LCLS Design Parameters

Fundamental FEL Wavelength	1.5	15	Å
Electron Beam Energy	13.6	4.3	GeV
Normalized Slice Emittance (rms)	1.2	1.2	mm-mrad
Peak Current	3.4	3.4	kA
Energy Spread (slice rms)	0.01	0.03	%
Bunch/Pulse Length (FWHM)	≤ 200	≤ 200	fs
Saturation Length	87	25	m
FEL Fundamental Power @ Saturation	8	17	GW
FEL Photons per Pulse	1	29	10^{12}
Peak Brightness @ Undulator Exit	0.8	0.06	10^{33} *

* photons/sec/mm^2/mrad^2/ 0.1%-BW

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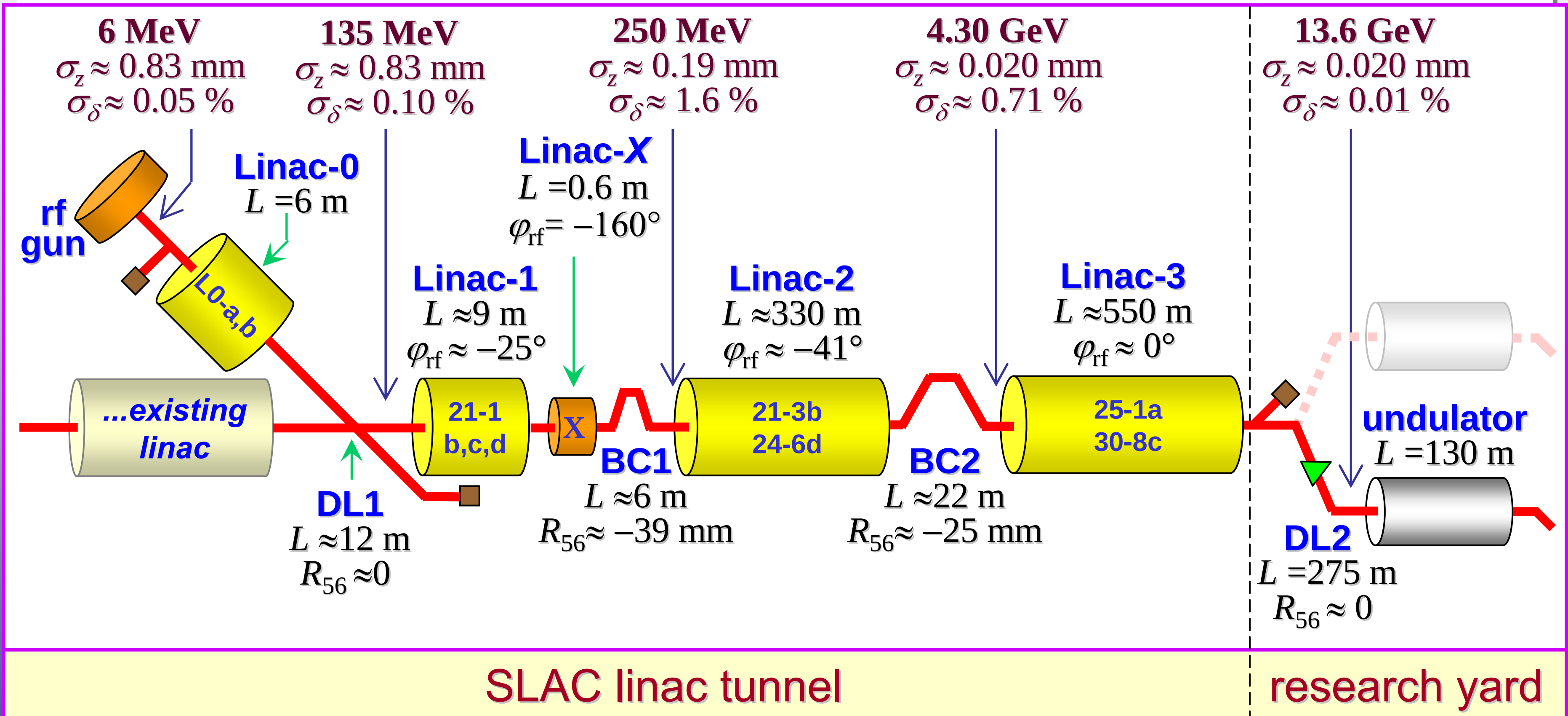
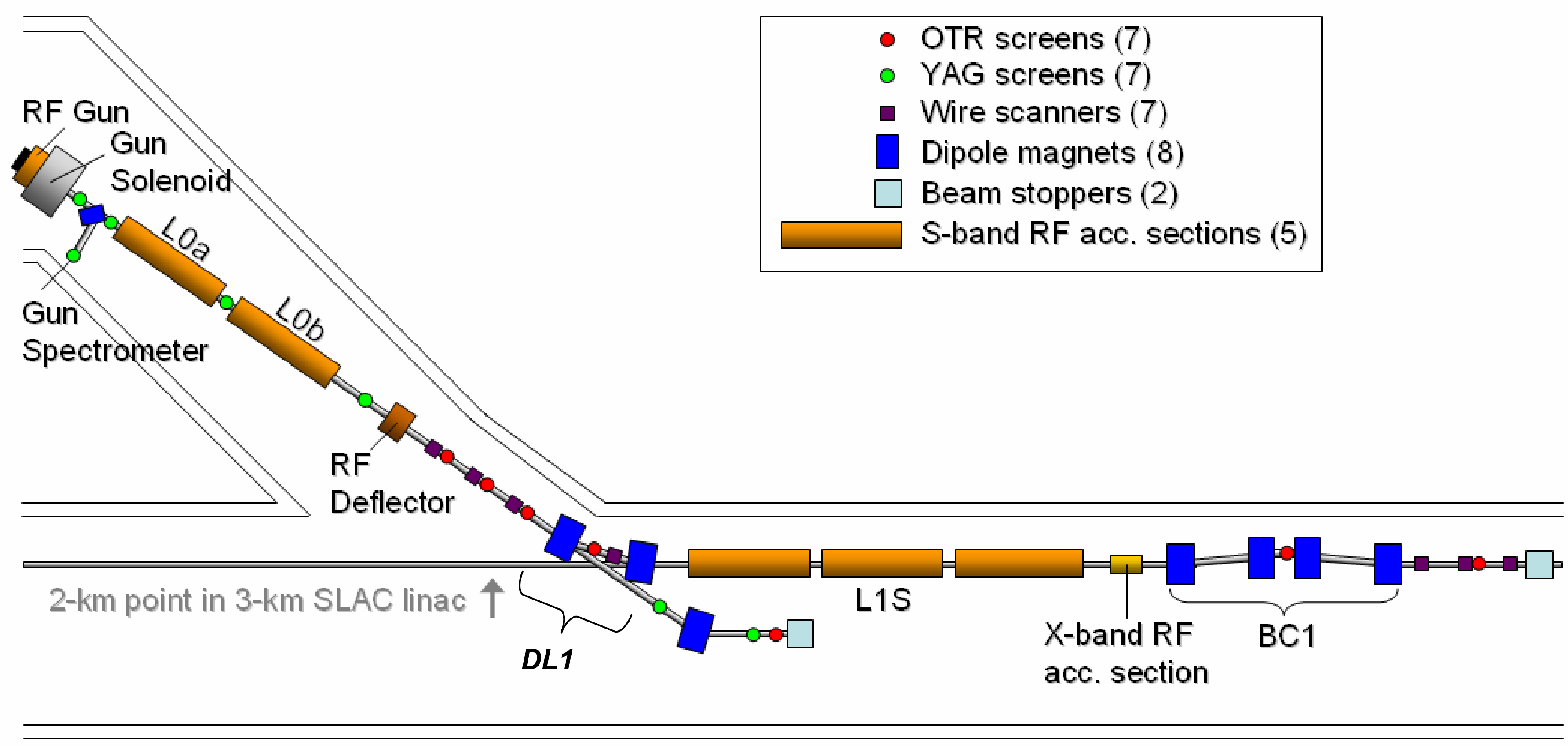
LCLS Accelerator & Compressor Systems



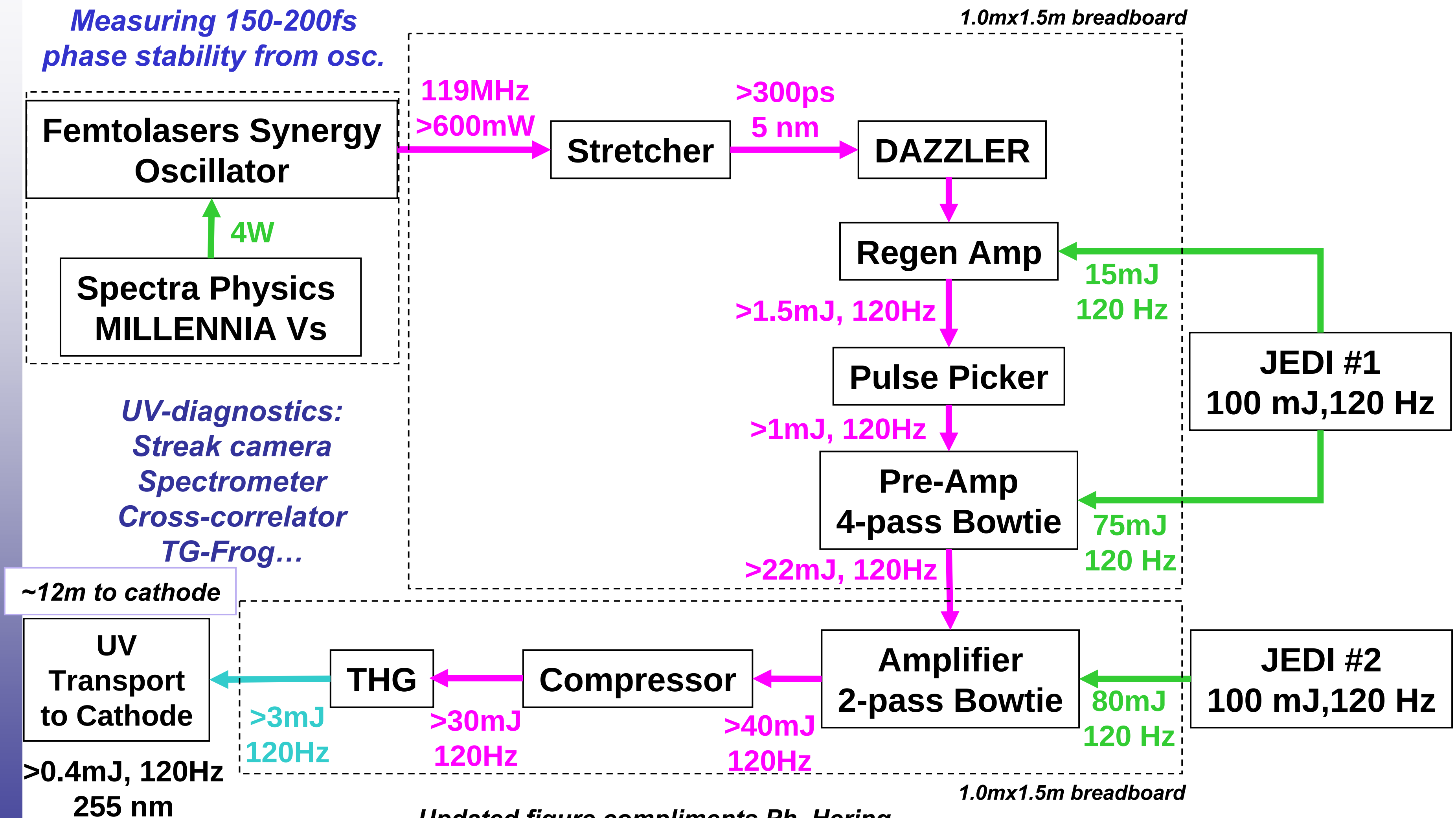
Injector and Bunch Compressor 1 Commissioned from April to September 2007 ~5 Months



Commissioning Milestones

- Spring 2006: Civil construction of buildings/shielding completed
- Summer 2006: Drive Laser Installed
- Oct-Nov 1006: Gun1 high power conditioning in Klystron Lab
- Fall 2006-Spring 2007: Drive laser commissioned, optics installed
- Spring 2007: Injector & BC1 beamline installed
- March 16, 2007: RF gun installed & RF processing started
- April 5, 2007: First Photo-electrons
- April 9, 2007: E-beam to 135 MeV
- April 16, 2007: E-beam to 250 MeV & compressed in BC1
- June 24, 2007: E-Beam to 15 GeV (200pC)
- July 24, 2007: E-Beam studies at 1 nC
- July 26, 2007: E-Beam at 1nC to 15 GeV
- August 8, 2007: Compressed 1 nC e-beam to 15 GeV
- August 2007: Injector Meets LCLS Requirements

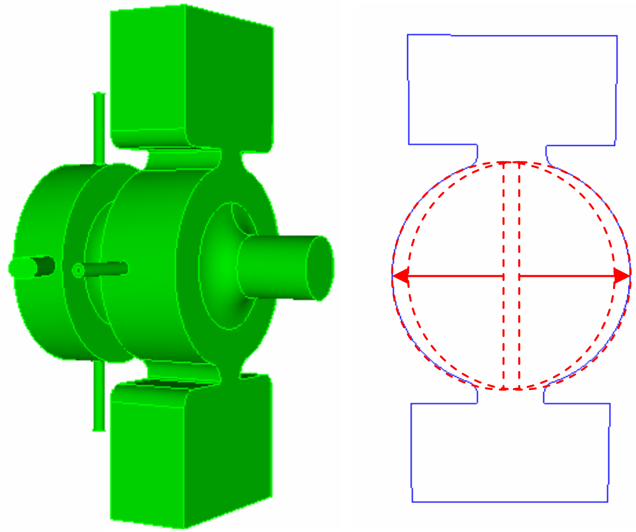
Thales Drive Laser System



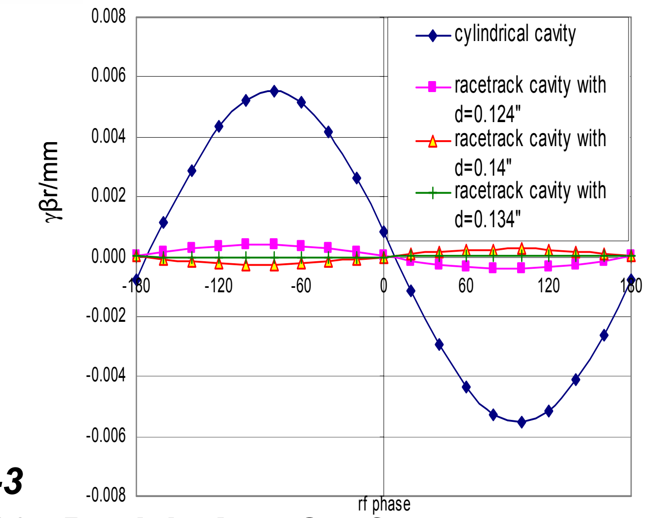
Updated figure compliments Ph. Hering

3D RF Design of Gun

- *Z-coupling:*
  - *reduces pulsed heating*
  - *increases vacuum pumping*
- *Racetrack to minimize quadrupole fields*
- *Deformation tuning to eliminate field emission from tuners*
- *Iris reshaped, reduces field 10% below cathode*
- *Increased 0-π mode separation to 15MHz*
- *All 3D features included in modeling:*
  - *laser port and pickup probes*
  - *3D fields used in Parmela simulation*



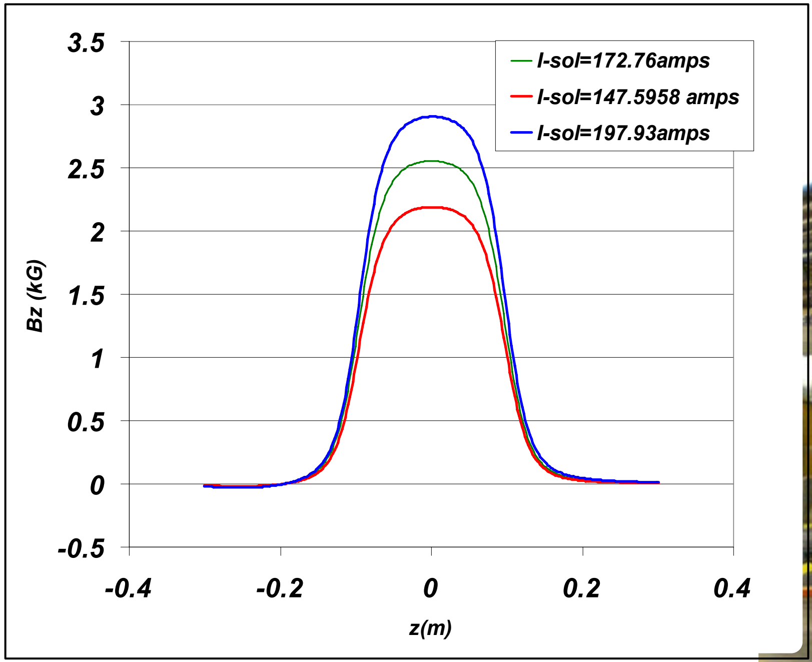
RF Parameters	
f_{π} (GHz)	2.855987
Q0	13960
β	2.1
Mode Sep. Δf (MHz)	15
E0:E1	0.999:1

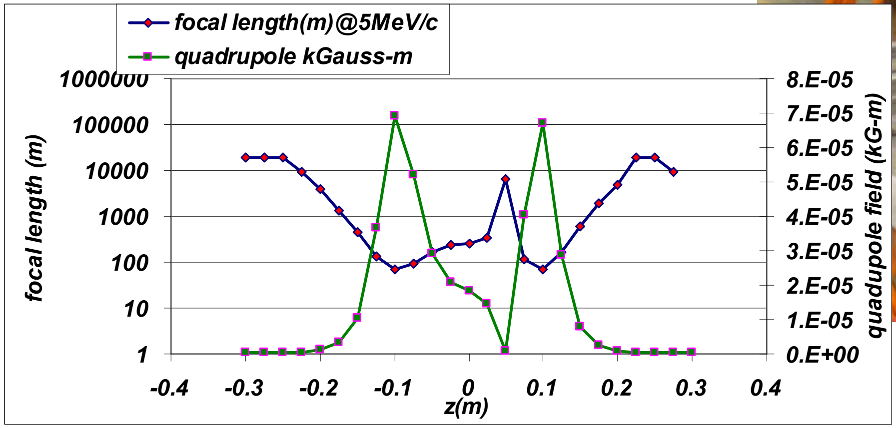


C. Limborg et al., "RF Design of the LCLS Gun", LCLS-TN-05-3
L. Xiao et al., "Dual feed rf gun design for the LCLS," Proc. 2005 Particle Acc. Conf.

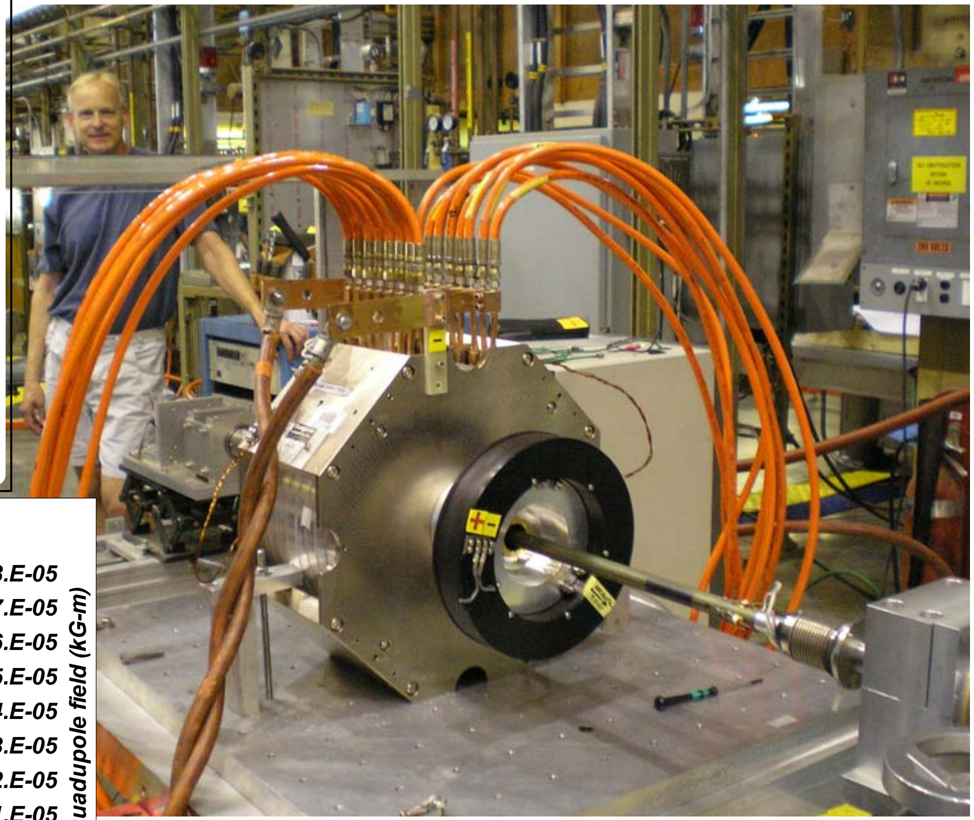
Slide Compliments of Z. Li & L. Xiao

Magnetic Multipole Characterization of the Gun Solenoid





Gun Solenoid on Magnetic Meas. Test Stand



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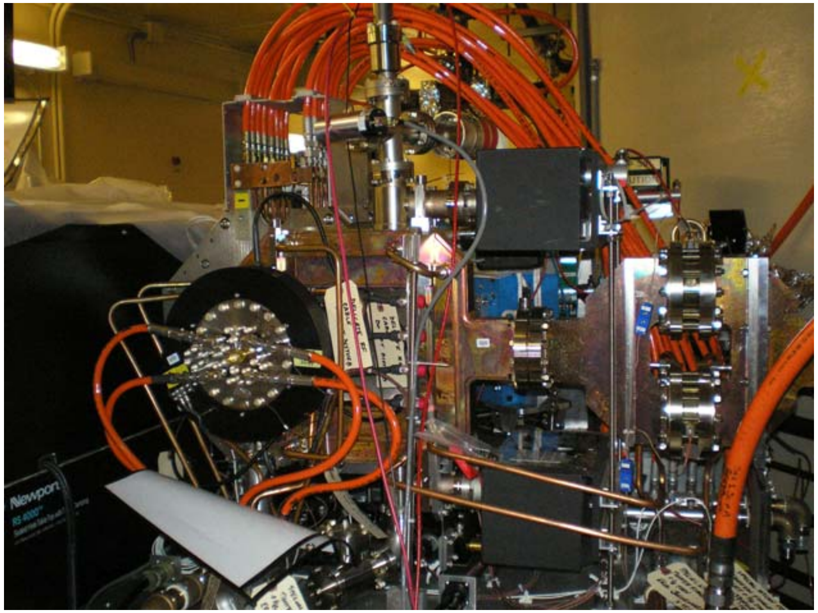
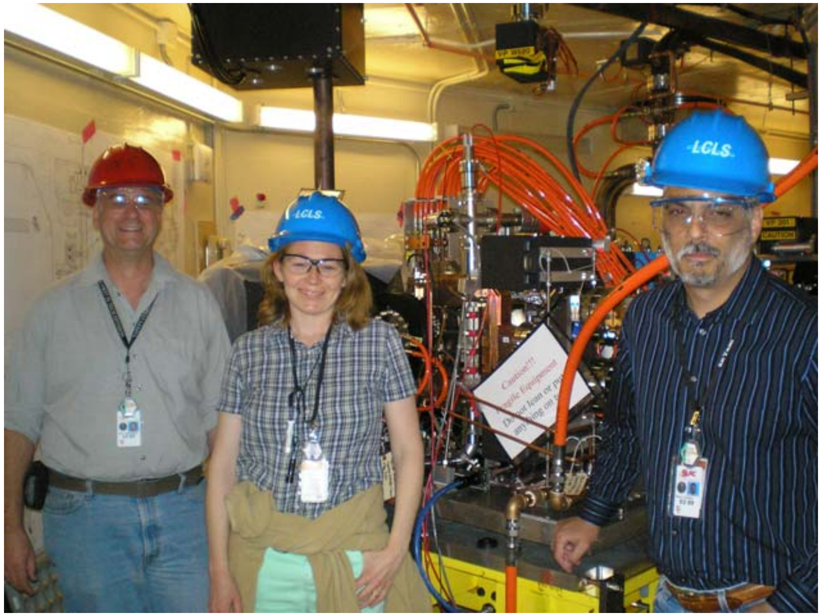
March 16: Gun-Solenoid Assembly Installed at Sector 20!



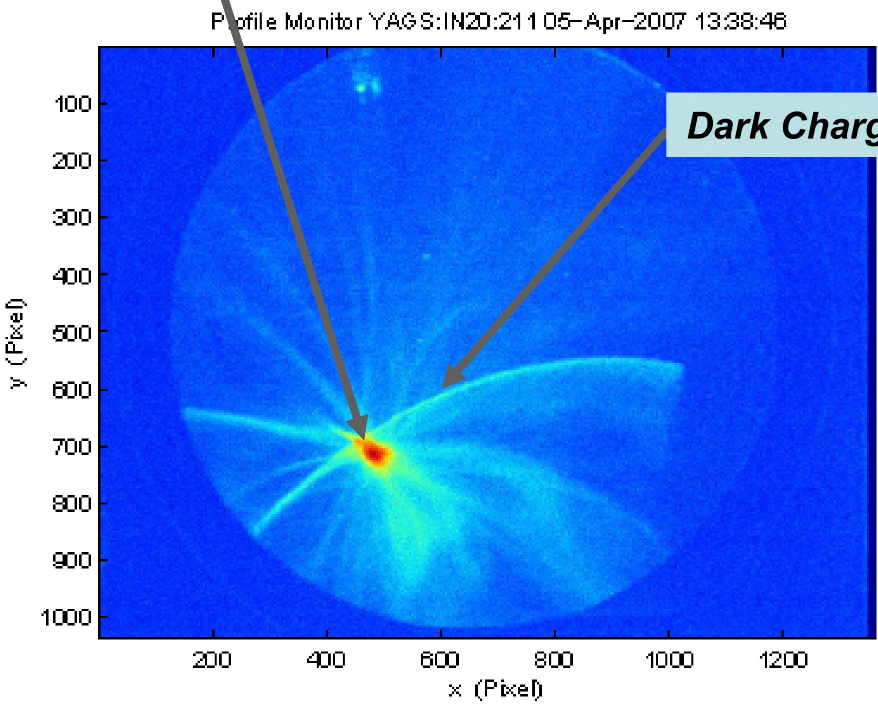


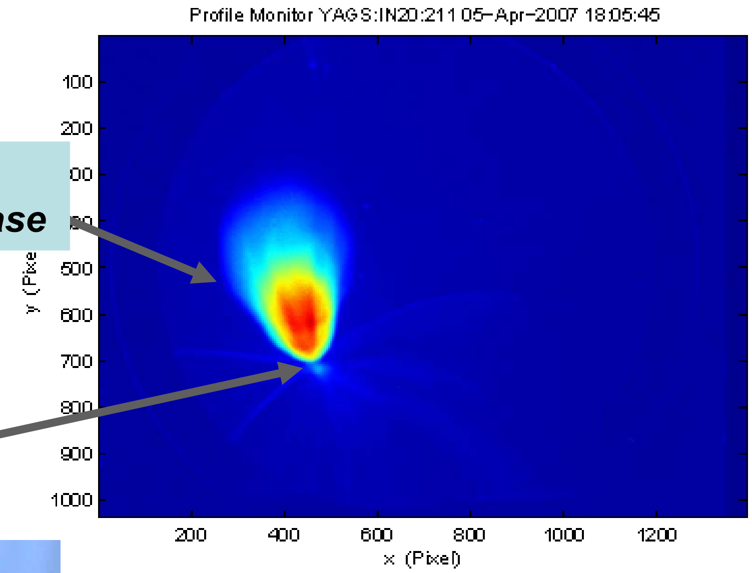
Images of First Photo-Electrons April 5, 2007

First Photo-Electrons!!!

Photo-Electrons: After adjusting laser-gun phase

Dark Charge





It Works!!!

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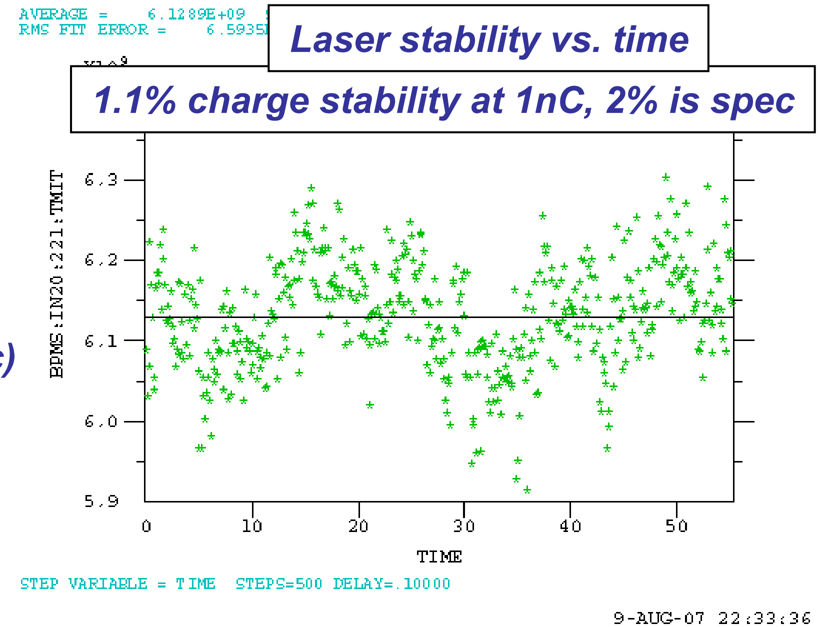
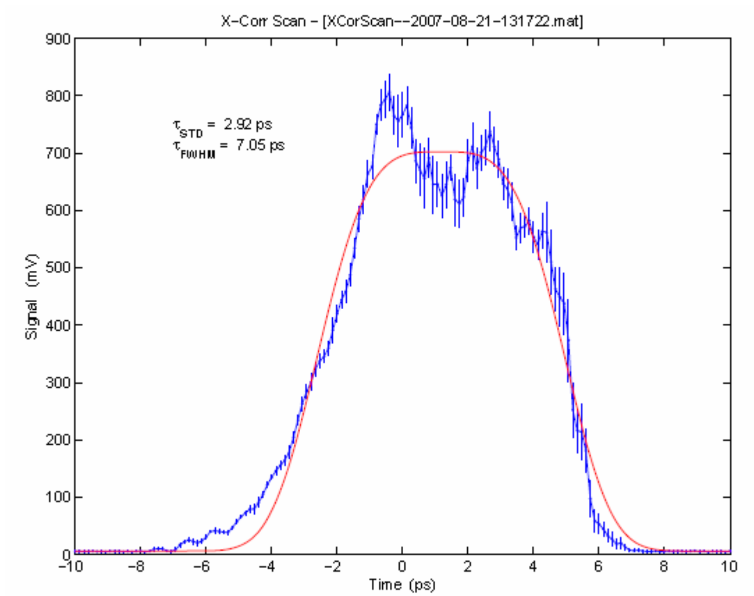
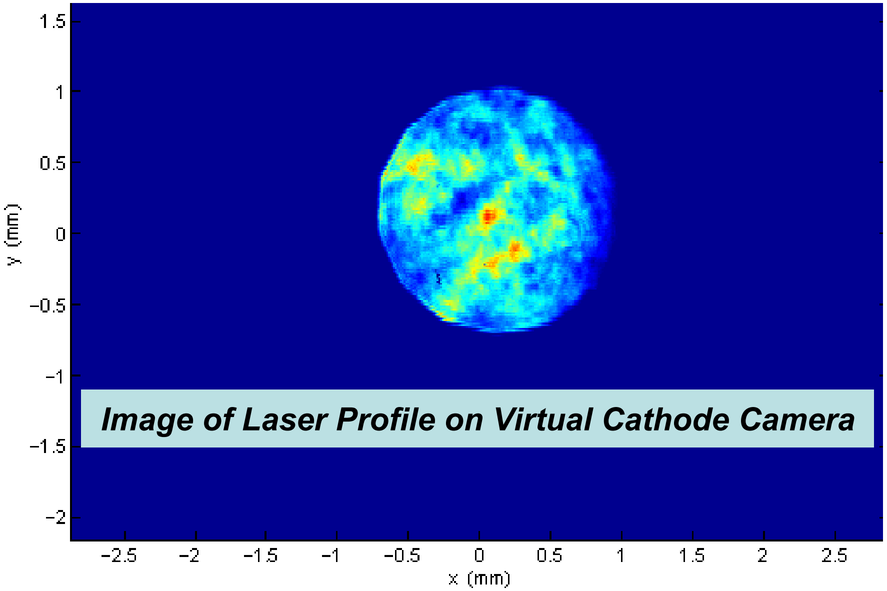
Drive Laser Performance

- Laser reliability is very good: Up-time > 90%
    - Excellent support from Thales & Femtolasers
- Delivering > 400 microJoules to cathode (250 is spec)
- Shaping needs work, but still producing good emittances
- Excellent energy stability (1.1%)
- Position stability on cathode, ~10-20 microns.



X-Correlator Measurement of Laser Pulse





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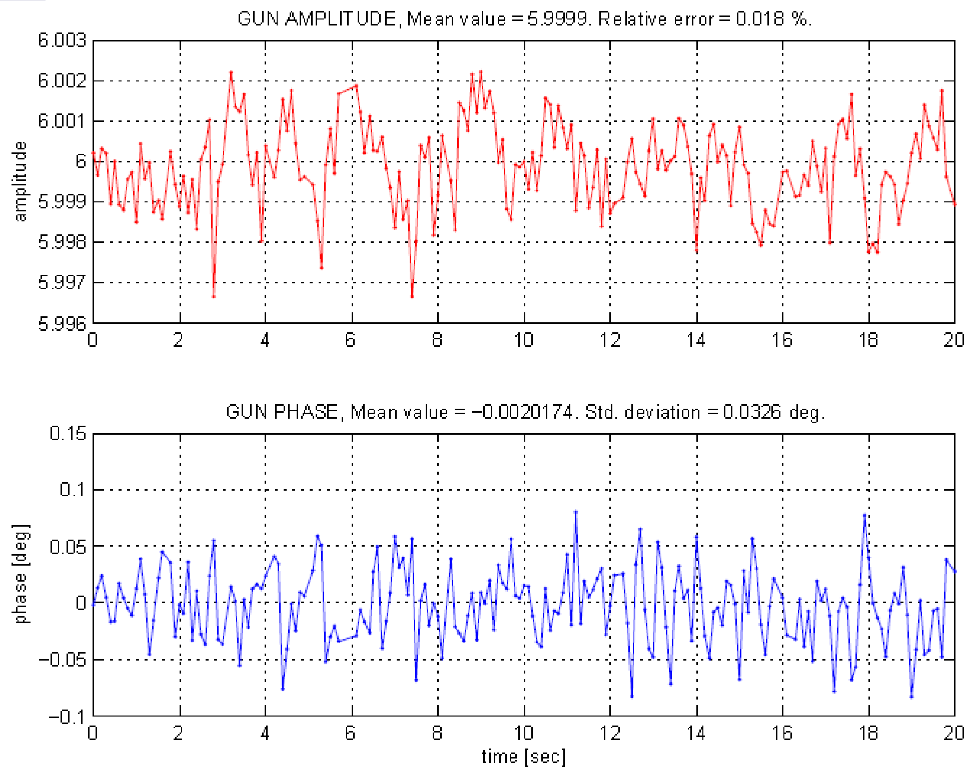
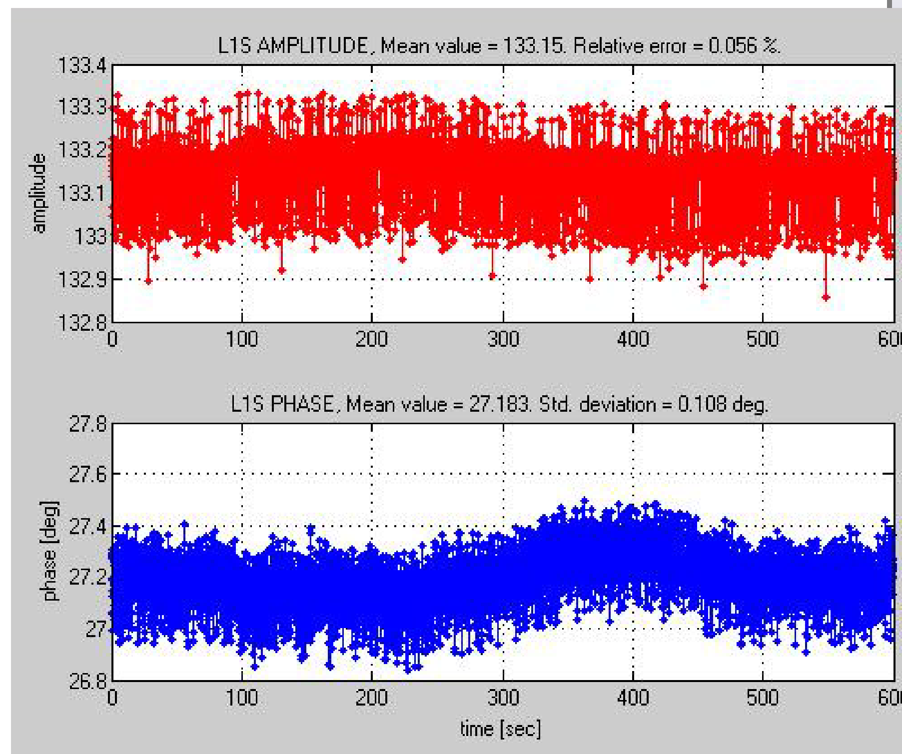
RF Phase & Amplitude Stability

Gun:
rms amplitude error = 0.018%
rms phase error = 0.032 degS

Linac:
rms amplitude error = 0.056%
rms phase error = 0.108 degS





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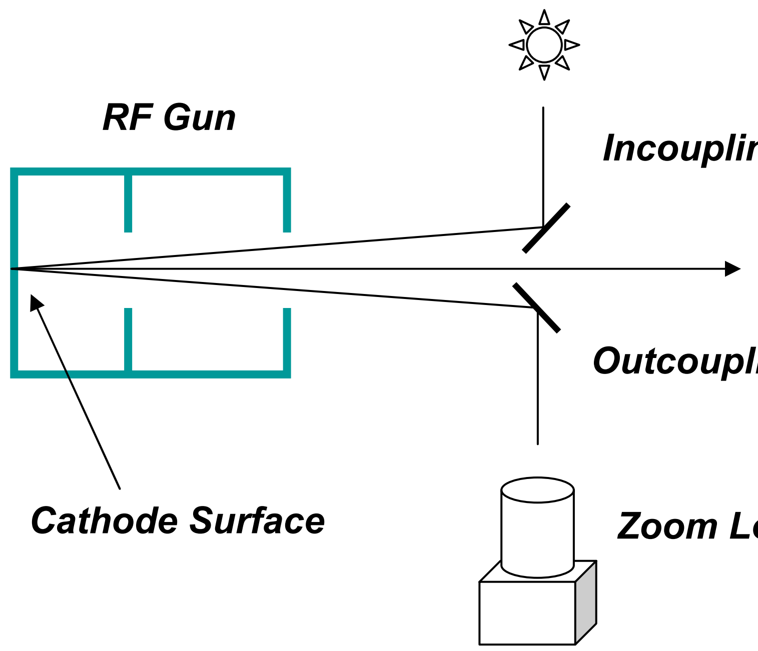
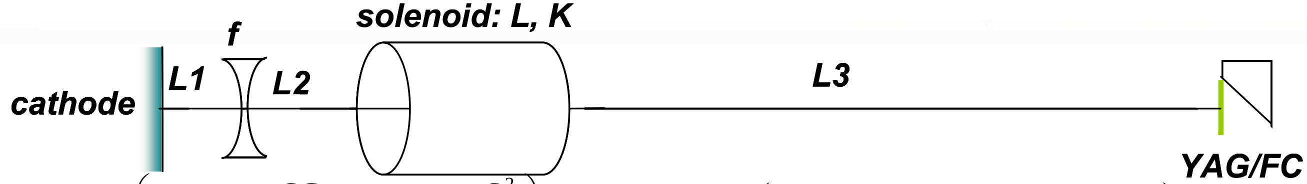
Viewing the Cathode and Laser Mirror Surfaces



- *Changing the zoom allows imaging of the mirrors and cathode surfaces*

Imaging Cathode Emission on YAG at 5-10 pC

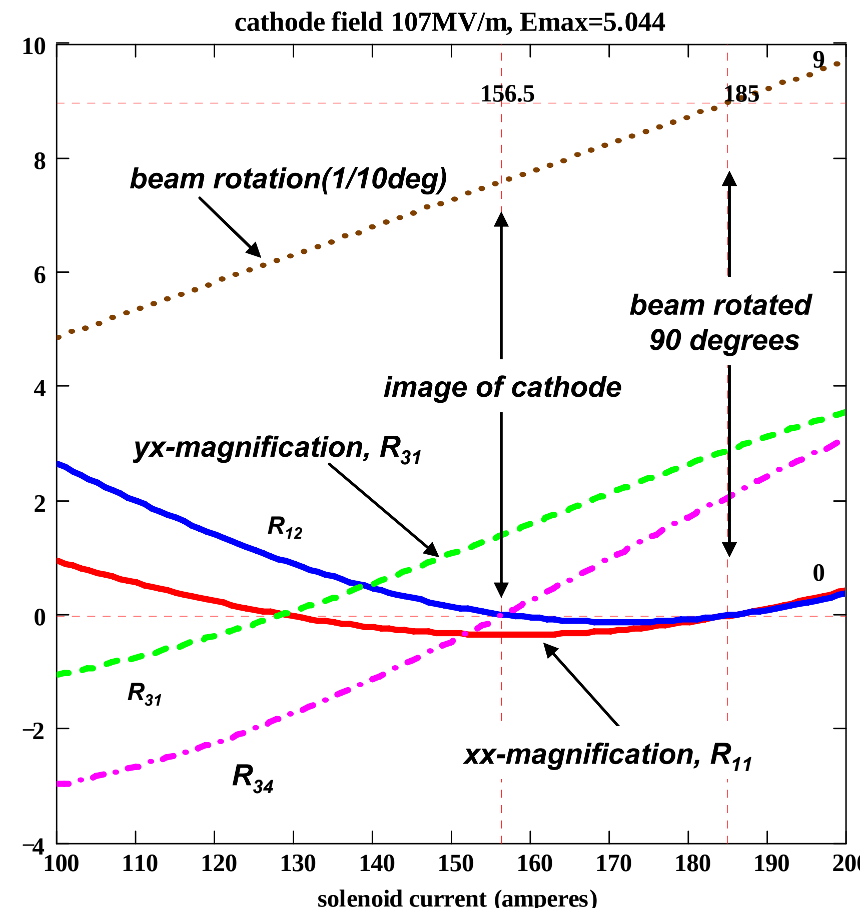


$$R_{YAG}=\begin{pmatrix}1 & L_3 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 1 & L_3\\ 0 & 0 & 0 & 1\end{pmatrix}\begin{pmatrix}C^2 & \frac{SC}{K} & SC & \frac{S^2}{K}\\ -KSC & C^2 & -KS^2 & SC\\ -SC & \frac{-S^2}{K} & C^2 & \frac{SC}{K}\\ KS^2 & -SC & -KSC & C^2\end{pmatrix}\begin{pmatrix}1 & L_2 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 1 & L_2\\ 0 & 0 & 0 & 1\end{pmatrix}\begin{pmatrix}1 & 0 & 0 & 0\\ \frac{E_0\sin\phi_{exit}}{mc^2} & 1 & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & \frac{E_0\sin\phi_{exit}}{mc^2} & 1\end{pmatrix}\begin{pmatrix}1 & L_1 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 1 & L_1\\ 0 & 0 & 0 & 1\end{pmatrix}$$

$$K(B_{solenoid},p_{beam})=\frac{B_{solenoid}(kG)}{2\cdot 0.033356\ p_{beam}(MeV/c)}(m^{-1})$$

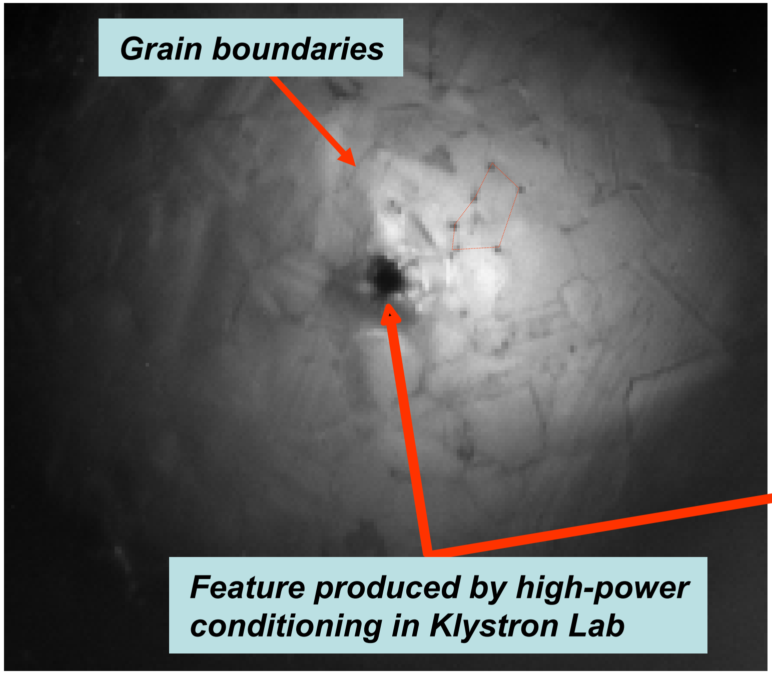
$$S=\sin(KL_{solenoid}) \qquad C=\cos(KL_{solenoid})$$

See: D. H. Dowell, E. Jongewaard, C. Limborg-Deprey, J. Schmerge and A. Vlieks, "Measurement and Analysis of Field Emission Electrons in the LCLS Gun," Proceedings of PAC2007.

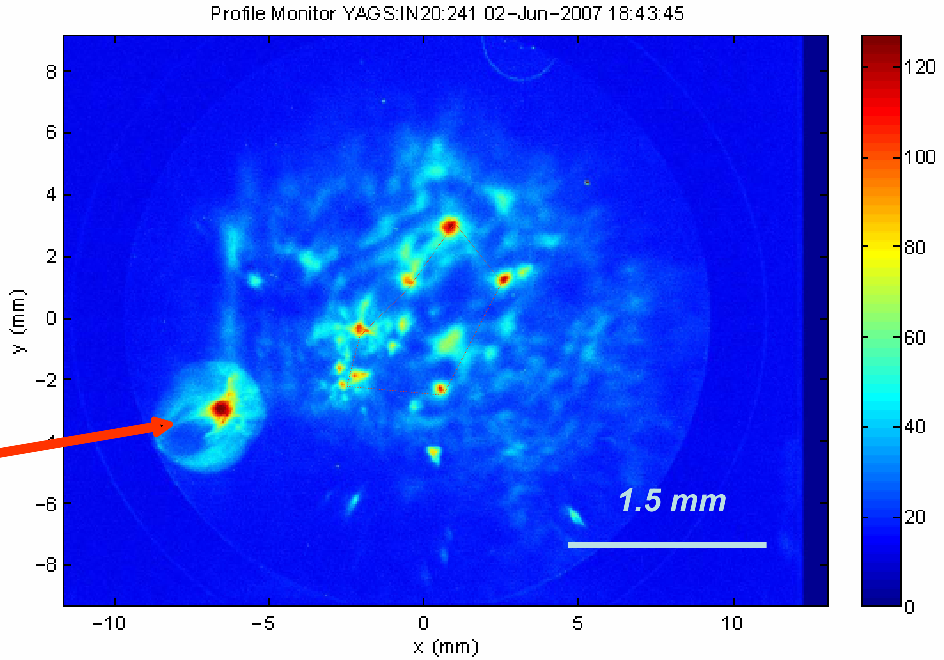


Cathode Uniformity:
Comparison of White Light & Electron Emission Images

June 6, 2007
White light cathode image



June 2, 2007
Electron beam image of cathode @ ~9pC



- *Emission is very non-uniform on the 10-micron scale*
- *Perform ~weekly inspection of the cathode surface*

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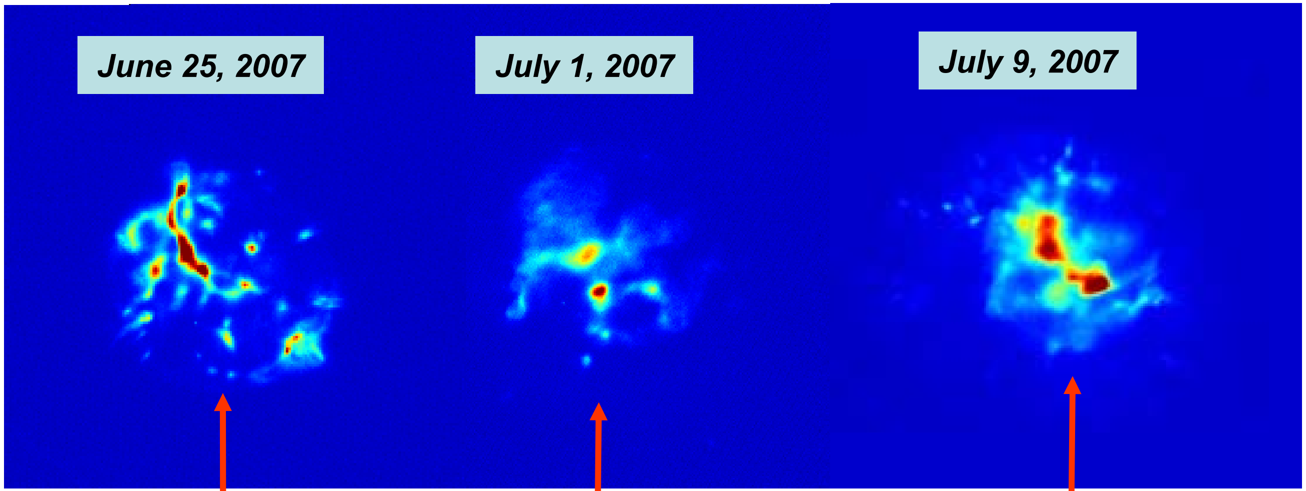
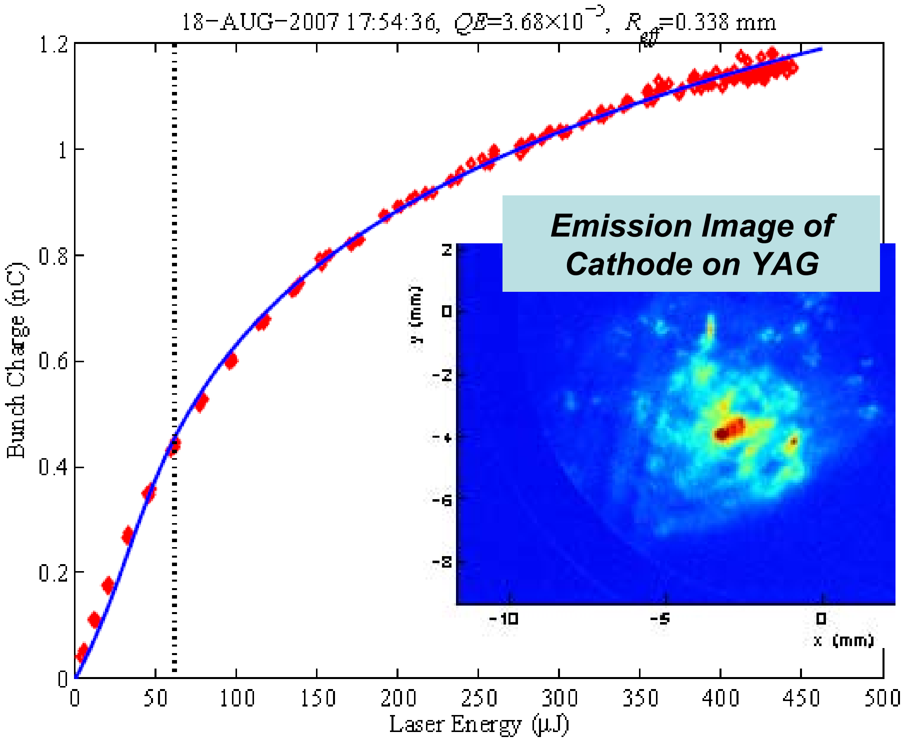
Drive Laser Processes the Cathode Surface Improving QE & Uniformity



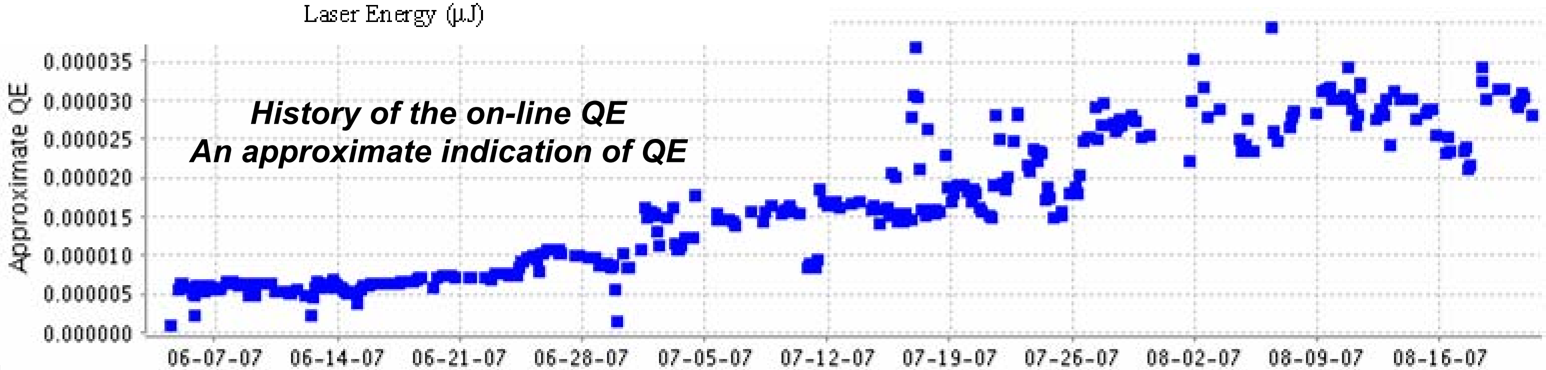
-Laser iris at 2mm dia.

-Laser iris completely open for these images

Cathode QE and Uniformity



- QE has been increasing due to constant exposure to the UV laser and by actively Laser Cleaning the cathode.
- QE is now ~3×10^{-5}, 2 times lower than spec (6×10^{-5}).
- QE-scans show emission is in the Space Charge Limited Regime at 1nC for a 1.3 mm dia. laser on the cathode.



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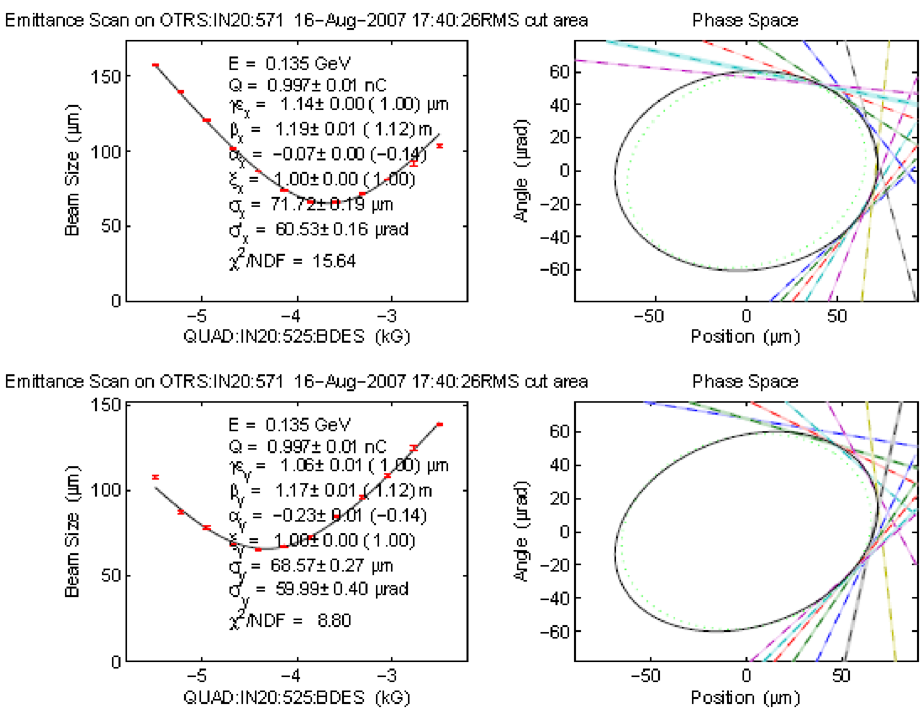
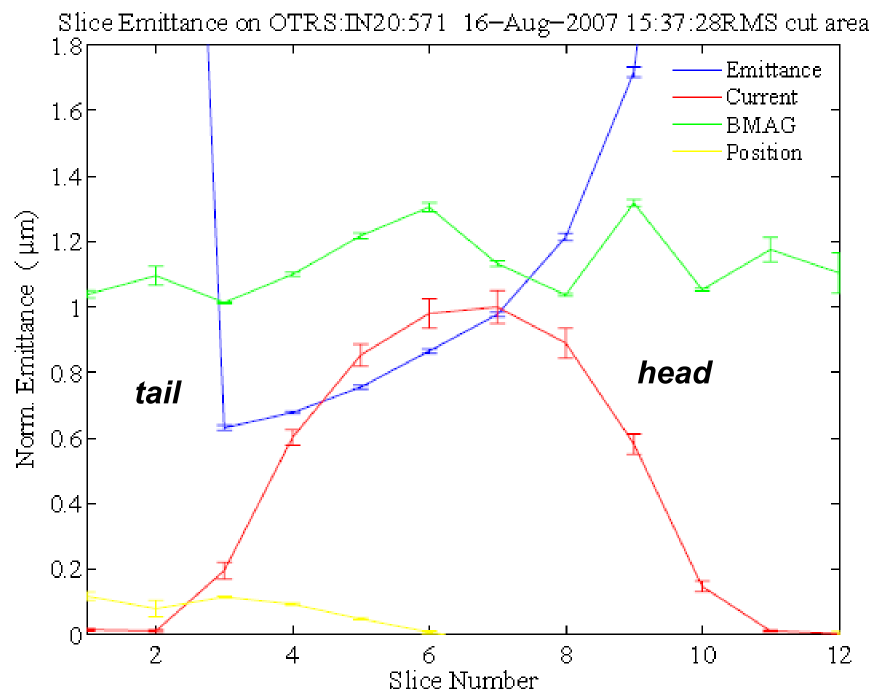
Projected & Slice Emittances at 1nC

Projected Emittance (rms) at 1nC (95% of the beam):
ε_x = 1.14 microns
ε_y = 1.06 microns

Slice Emittance, Current & Matching:
Slices 3 to 7 (tail) are all below 1 micron.
Head slices (8-10) are > 1 micron.
Peak Current is 100 amps.





On-line analysis tools by H. Loos

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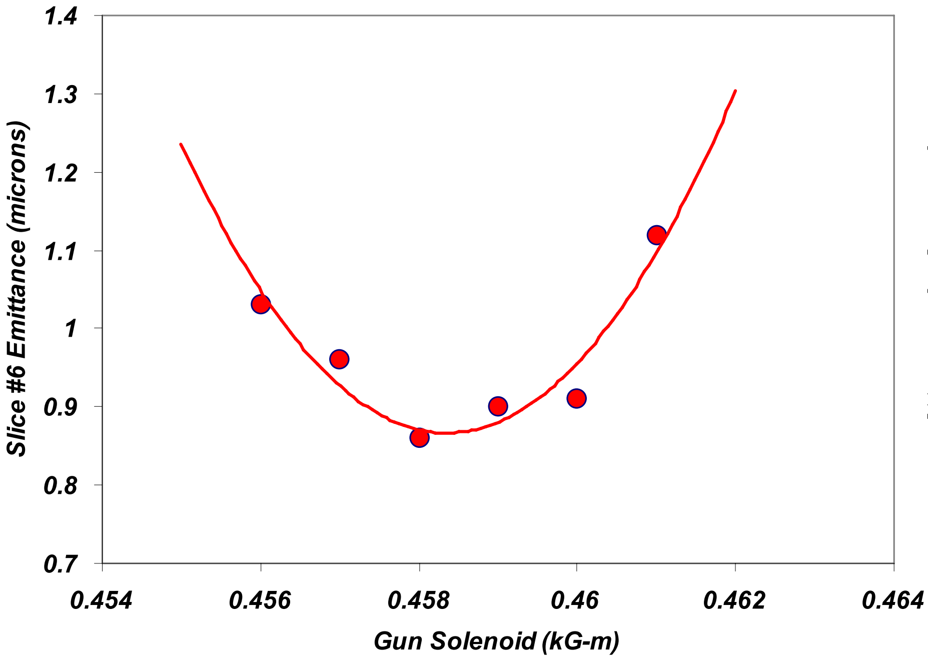
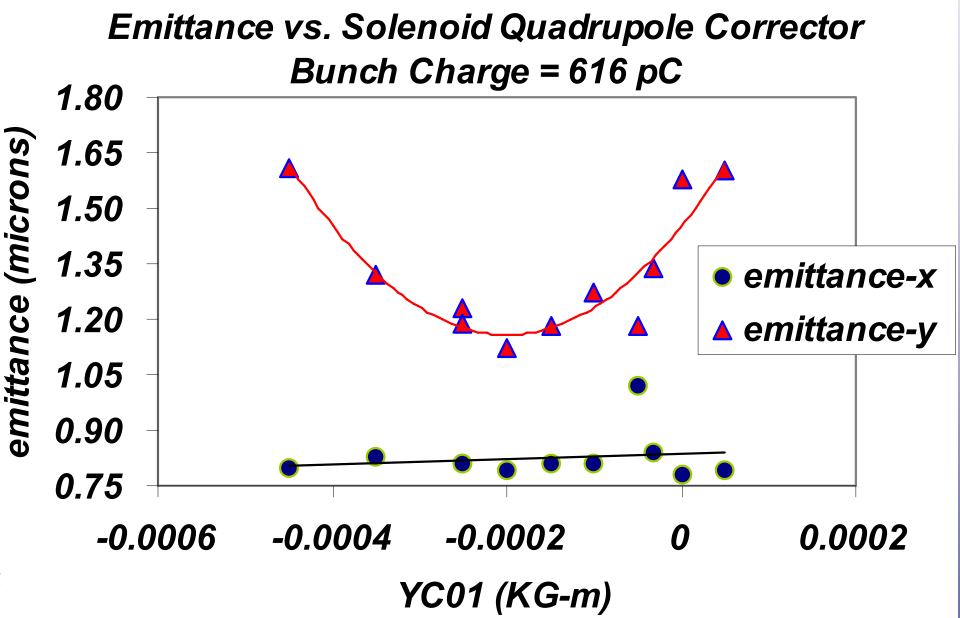
Examples of Emittance Optimization





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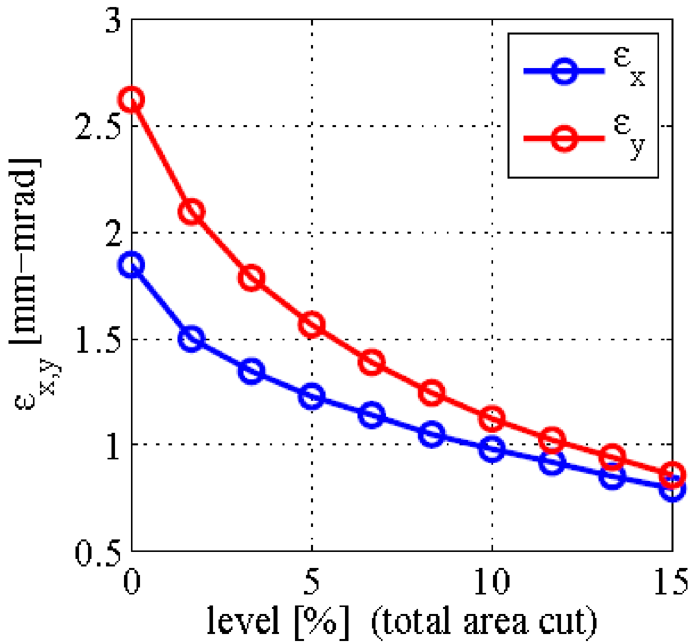
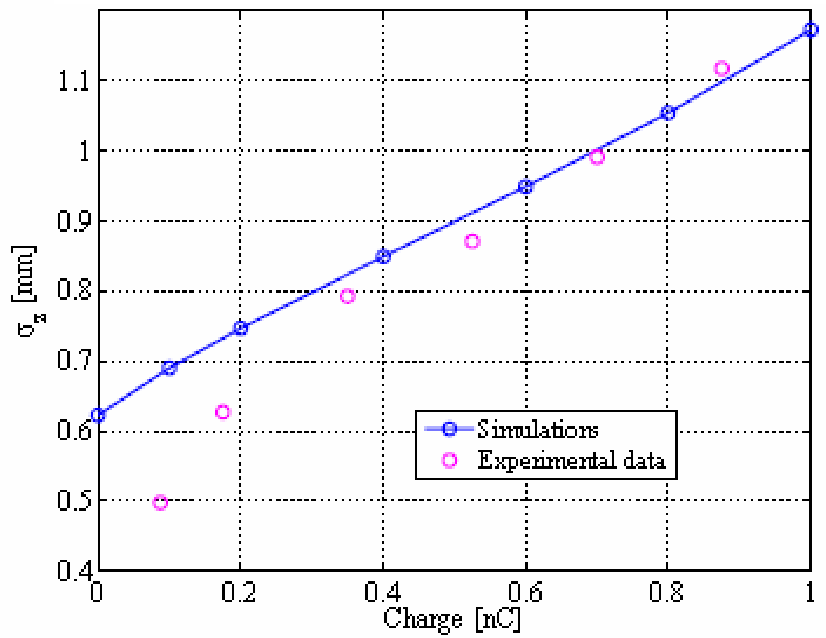
Comparison with Simulations

Measured emittance depends upon truncation of tails.
Experimental analysis truncates 5% of the base area of the images.
Therefore emittances are for 95% of the beam agreeing with similar analysis of simulations.

Simulated Quadrupole Scan



Comparison of Simulation (Parmela) with Measured Bunch Length vs. Charge



$\varepsilon_{thermal}$ = 0.6 micron / mm = 0.6 mrad (normalized divergence)

Simulations Courtesy C. Limborg-Deprey

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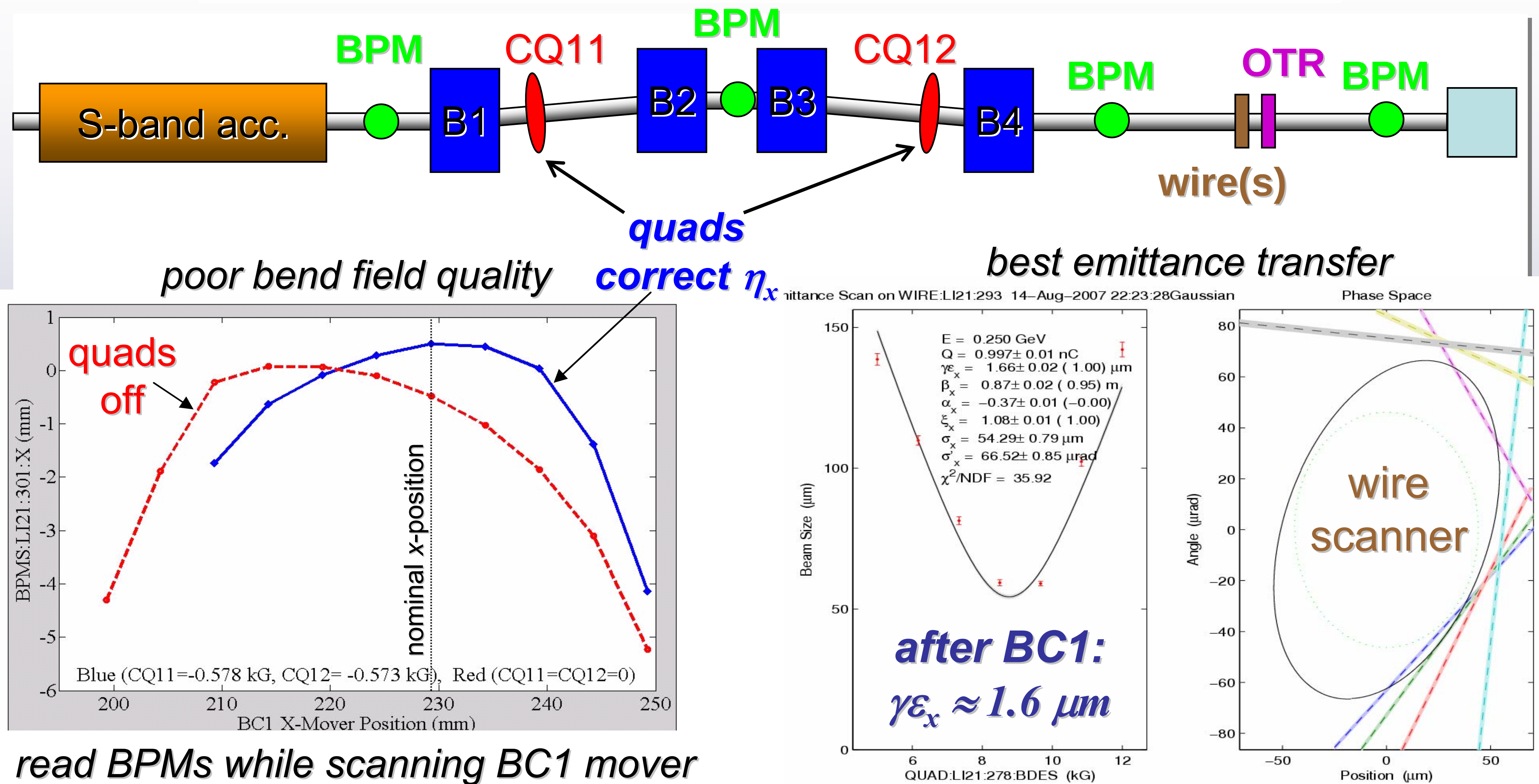
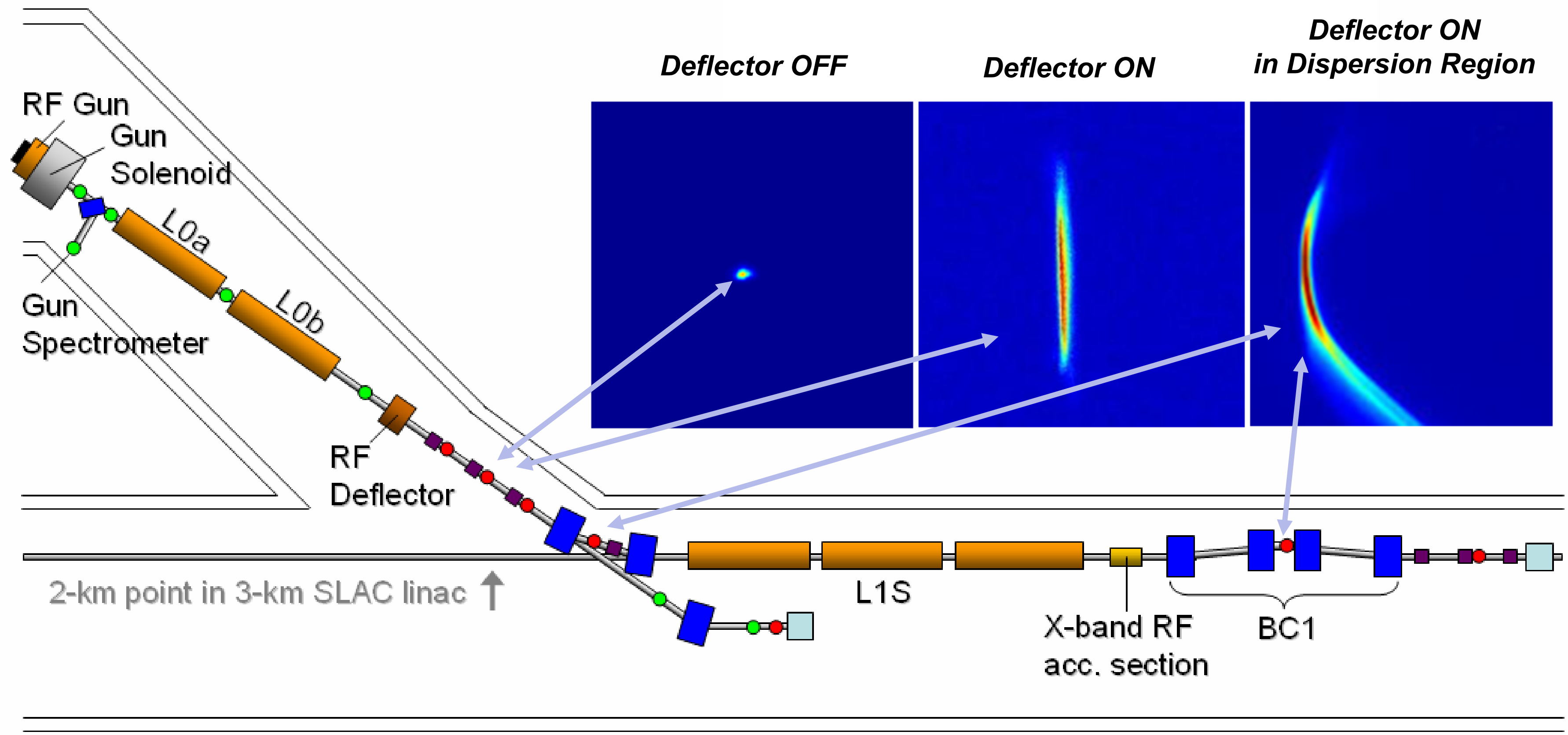
BC1 Chicane Emittance Growth



- ***Best $\gamma\varepsilon_x$ after BC1 with nom. (& more) compression is 1.6 μm (& larger)***
- ***Poor bend field quality (grad. + sext.) – $\Delta E/E$ scan shows 1st & 2nd-order η***
- ***Screen image biased by COTR – wires vibrate – variable results (& in y)***
- ***Bends will be upgraded in fall '07 + proper chirp set (now >2% → 1.6%)***

Transverse Cavity (RF-Deflector) Measurements of Bunch Length



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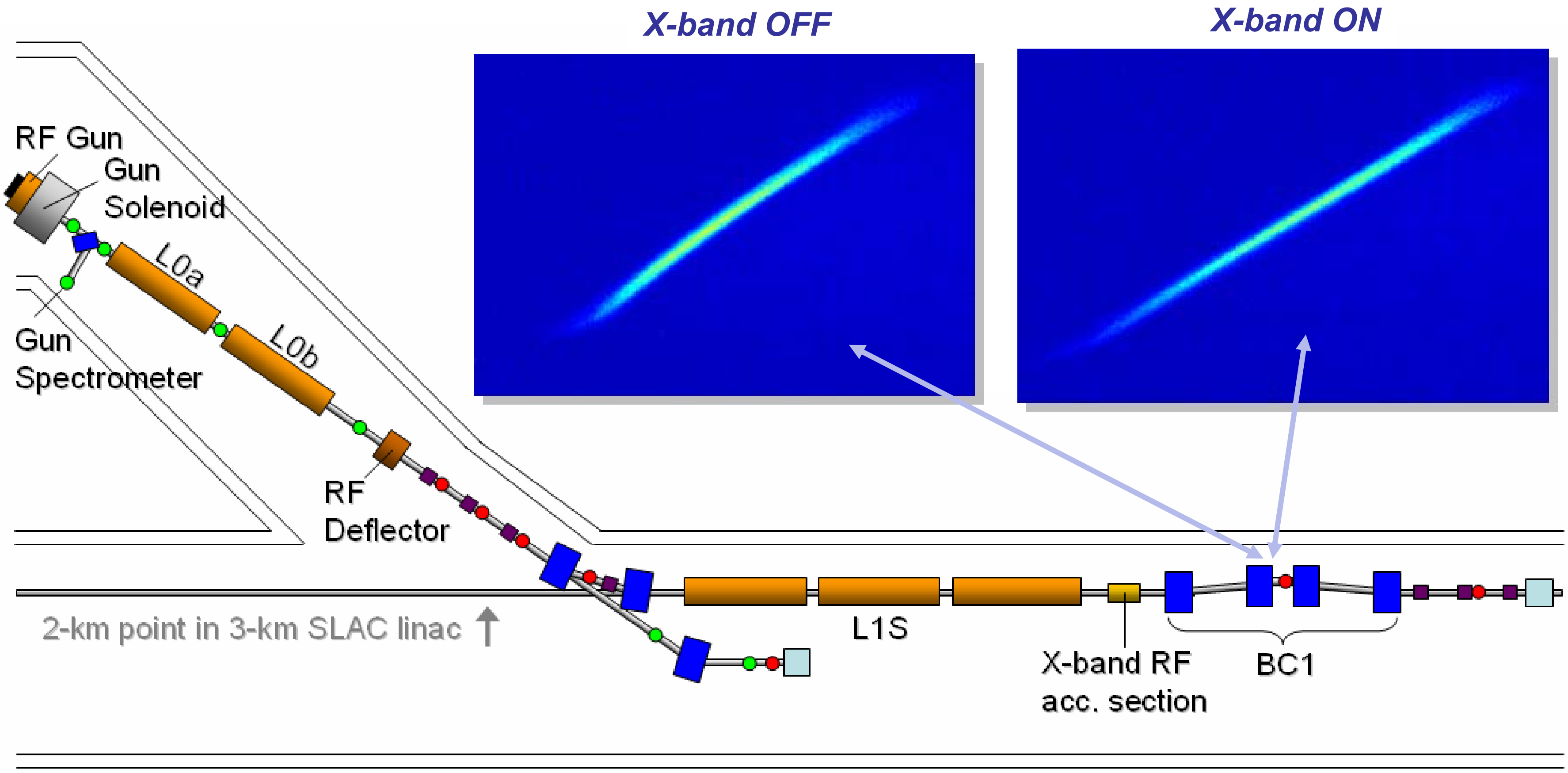
Linearization of Longitudinal Phase Space Measured Using the RF Deflector & OTR Screen in Center of BC1



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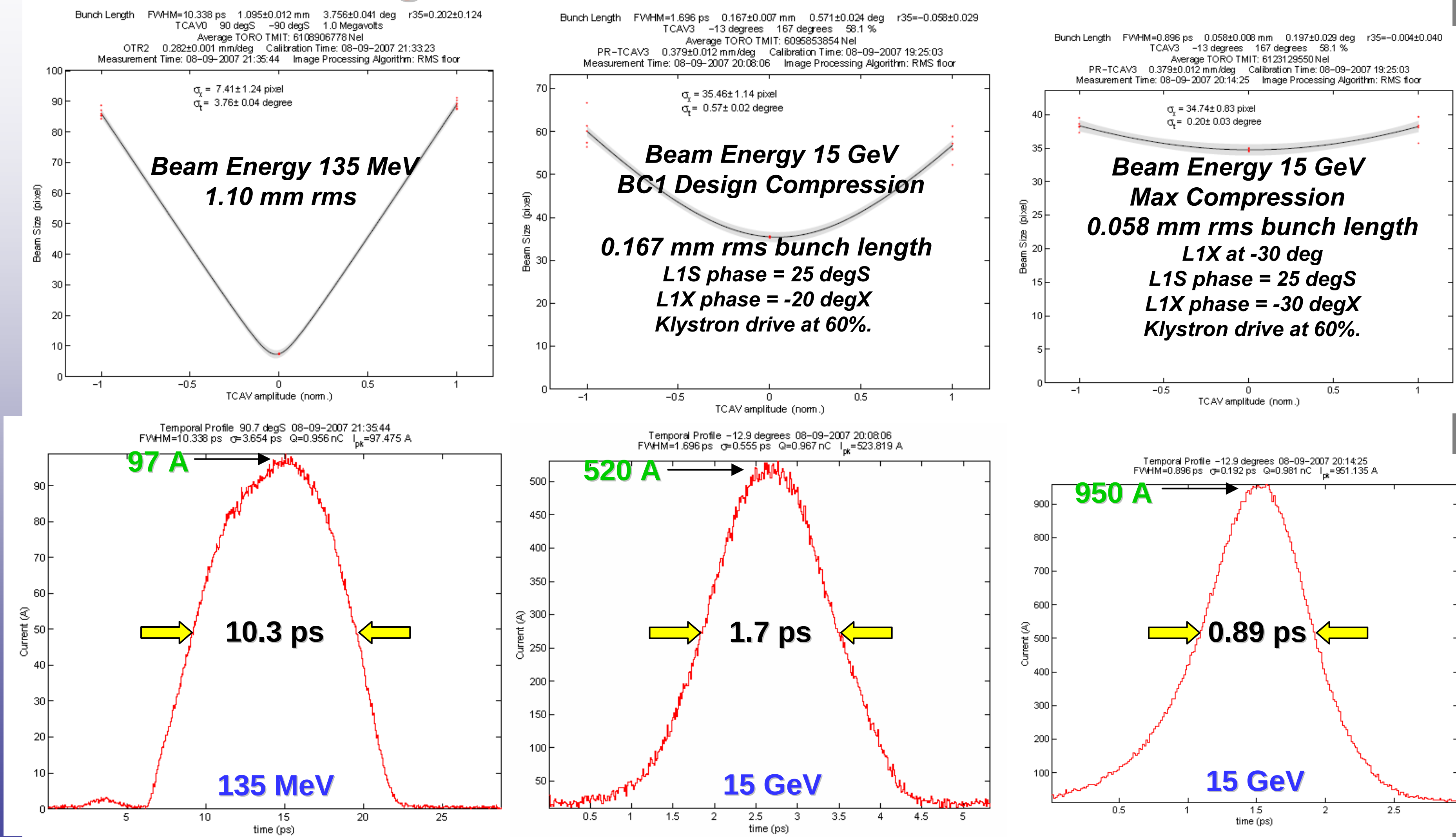
Bunch Length Measurements at 135 MeV & 15 GeV



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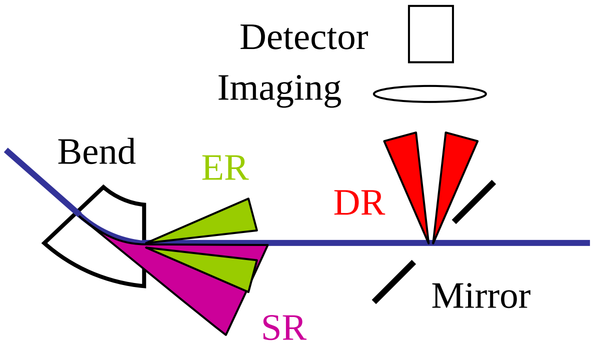
BC1 Edge Radiation Bunch Length Monitor

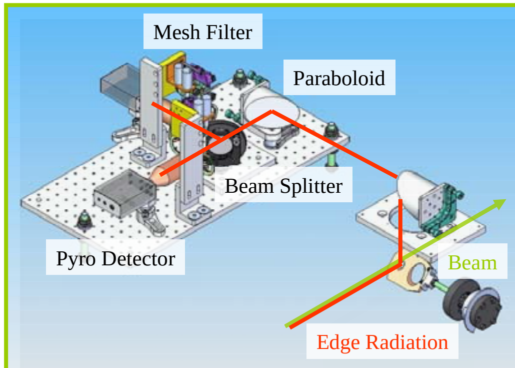
Coherent Radiation Sources from Bend



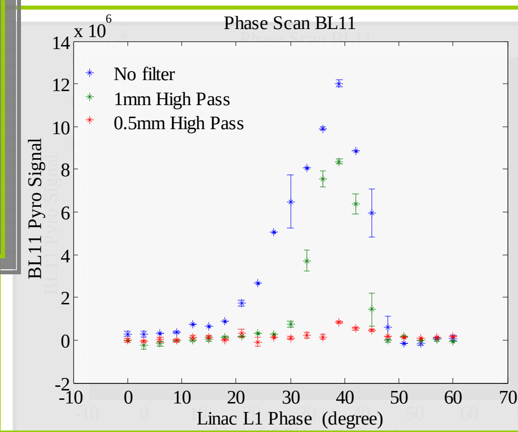
ER dominates at λ ~ 1mm

Bunch length after BC1: 60 – 200 µm
Wavelength range to determine bunch length: 0.3 – 1 mm
Measure integrated coherent power and use frequency filters

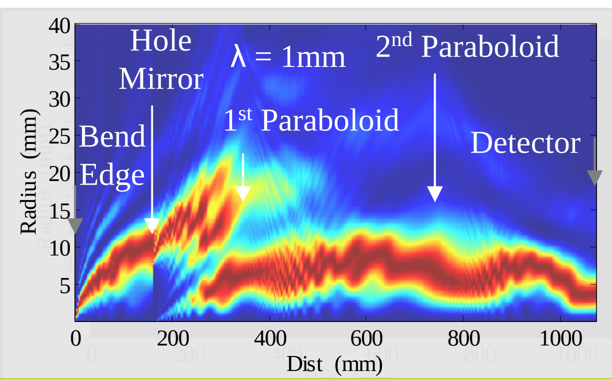
Measurement Layout



First Signals from Pyro



Edge Radiation Simulation



Slide and data compliments H. Loos

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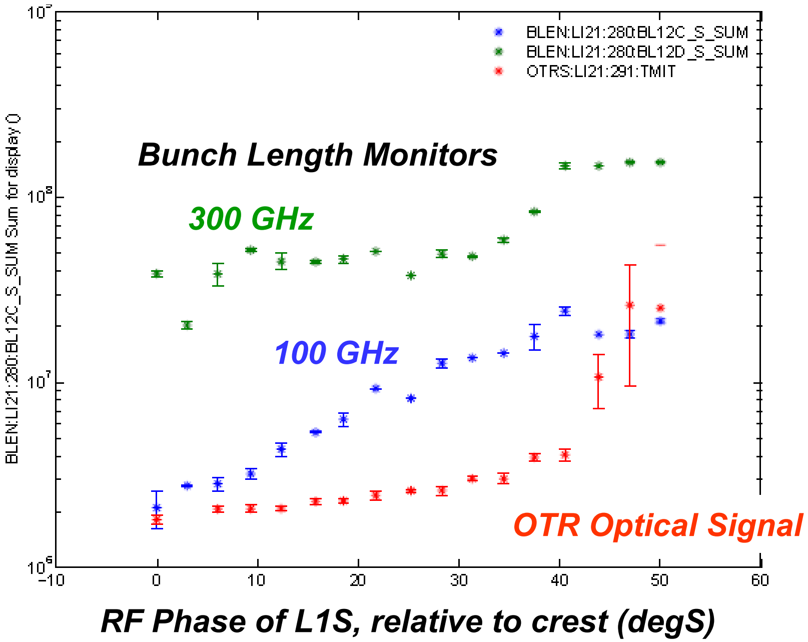
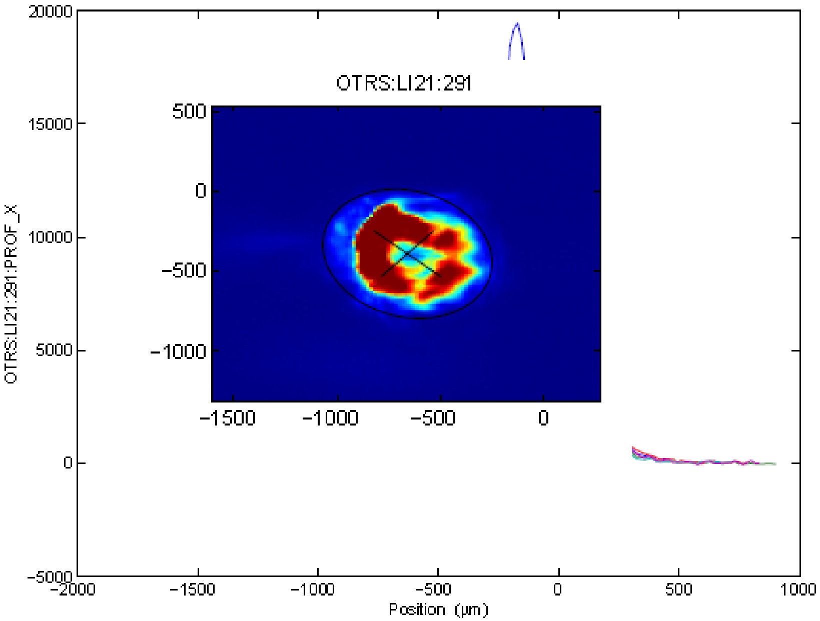
Unexpected Physics! Strong Optical Microbunching with BC1 Set to Maximum Compression

Generation of COTR in the Visible Spectrum Indicates Microbunching & Interferes with Using OTR Profiles for Emittance Measurements.

Comparison of Bunch Length Monitor & OTR Signals



OTR Images Fluctuate from Shot-to-Shot & Can Even Produce "Ring-Like" Shapes!



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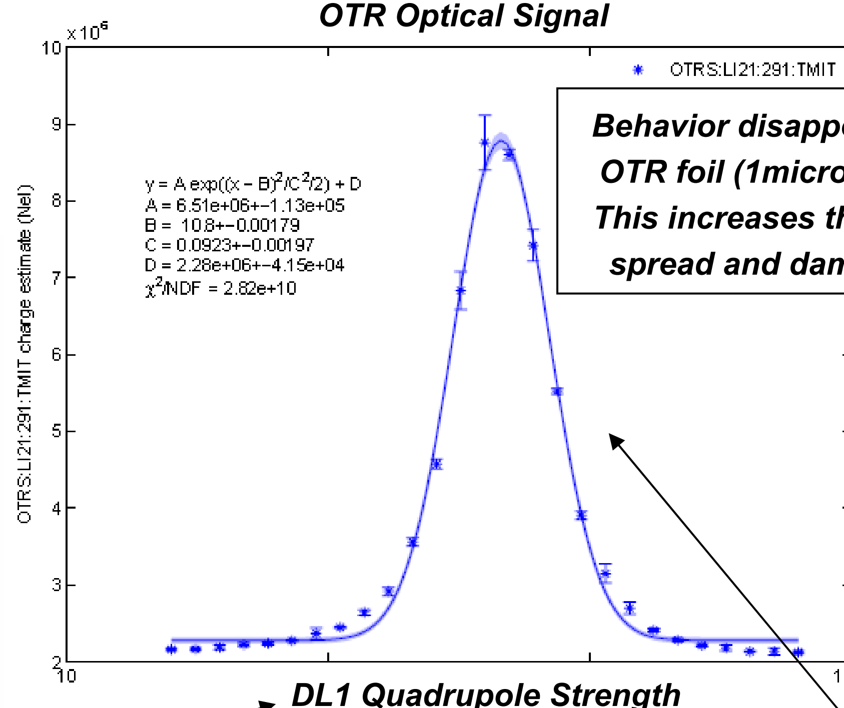
Unexpected Physics!
Coherent Optical Transition Radiation after DL1 Bend Even With No BC1 Compression

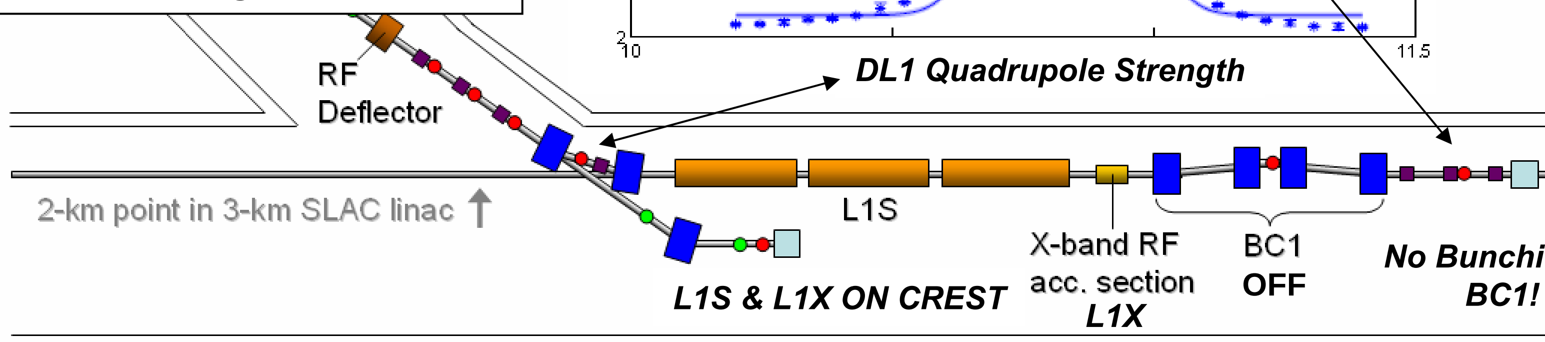
Evidence for Optical Microbunching:

Optical Signal from OTR screen with BC1 OFF is strongly dependent upon bend quad. Signal largest when quad is adjusted to make bend dispersionless, its design value.

OTR Optical Signal



Behavior disappears when upstream OTR foil (1micron thick) is inserted: This increases the correlated energy spread and damps microbunching



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Problems / Issues

- Low cathode quantum efficiency
  - Improving with time & laser cleaning
- Drive laser oscillator loses lock to the RF reference
  - New oscillator to be installed during fall 2007 (Compliments of Femtolasers)
- BC1 dipoles have marginal field quality
  - Problem aggravated by longer bunch from gun than expected: 1.05mm instead of 0.84mm (rms)
  - Will be shimmed and re-measured during Fall 2007
- Crucial diagnostics not functioning
  - Faraday cup
  - On-axis alignment laser
  - Gun-to-Linac charge toroid
- Significant wake fields in x-band structure
- Difficult to maintain good emittance
  - Day-to-day emittance varies from 1.1 to 1.5 microns for projected
- OTR diagnostics plagued by COTR
  - Also starting to see small 'holes' in 1 micron Al foils
  - Digital cameras lose trigger and video synch
- Wire scanners vibrate

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Comparison of Required and Demonstrated Beam Properties

Parameter	Sym	dsgn	meas.	unit
Final e^- energy	γmc^2	15	15	GeV
Bunch charge	Q	1000	1000	pC
Init. bunch length (fwhm)	Δt_0	10	10	ps
Fin. bunch length (fwhm)	Δt_f	2.3	1.5	ps
Initial peak current	I_{pk0}	100	100	A
Projected norm emittance	$\gamma\varepsilon_{x,y}$	1.2	1.1 to 1.3	μm
Slice norm. emittance	$\gamma\varepsilon^s_{x,y}$	1.0	0.8 to 1.0	μm
Single bunch rep. rate	f	120	10-30	Hz
RF gun field at cathode	$E_{cathode}$	120	115	MV/m
Laser energy on cathode	U_l	250	450	μJ
Laser wavelength	λ_l	255	255	nm
Laser diameter on cathode	2R	1.5	1.3	mm
Cathode material	-	Cu	Cu	
Cathode quantum eff.	QE	6	3	10^{-5}
Commissioning duration	-	8	5	mo

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Summary of Accomplishments

- *Achieved emittance goal of 1.2 micron projected, Less than 1 micron / slice at 1nC!*
- *Peak current 100 amps out of gun, 500 amps after compressing in BC1*
- *Less than 1.5% charge jitter*
- *Accelerated compressed bunches to 15 GeV*
- *Greater than 90% system up-time*
  - *Operated continuously (24/7) April 5 to Aug 24, 2007*
- *First Observation of Coherent Optical Transition Radiation during beam transport and compression*
- *The Injector Meets LCLS Requirements!*

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And Our Visitors:

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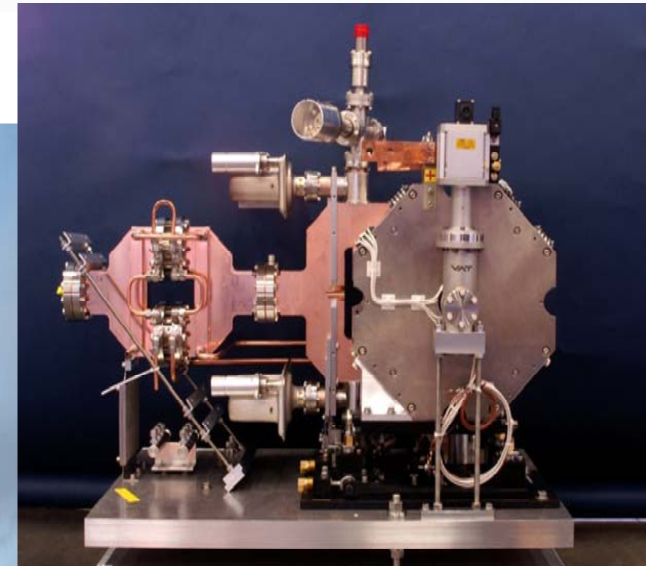
Pie(π)–of-Gold Emittance at the end of the Rainbow



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Thanks for a Great Gun!!

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