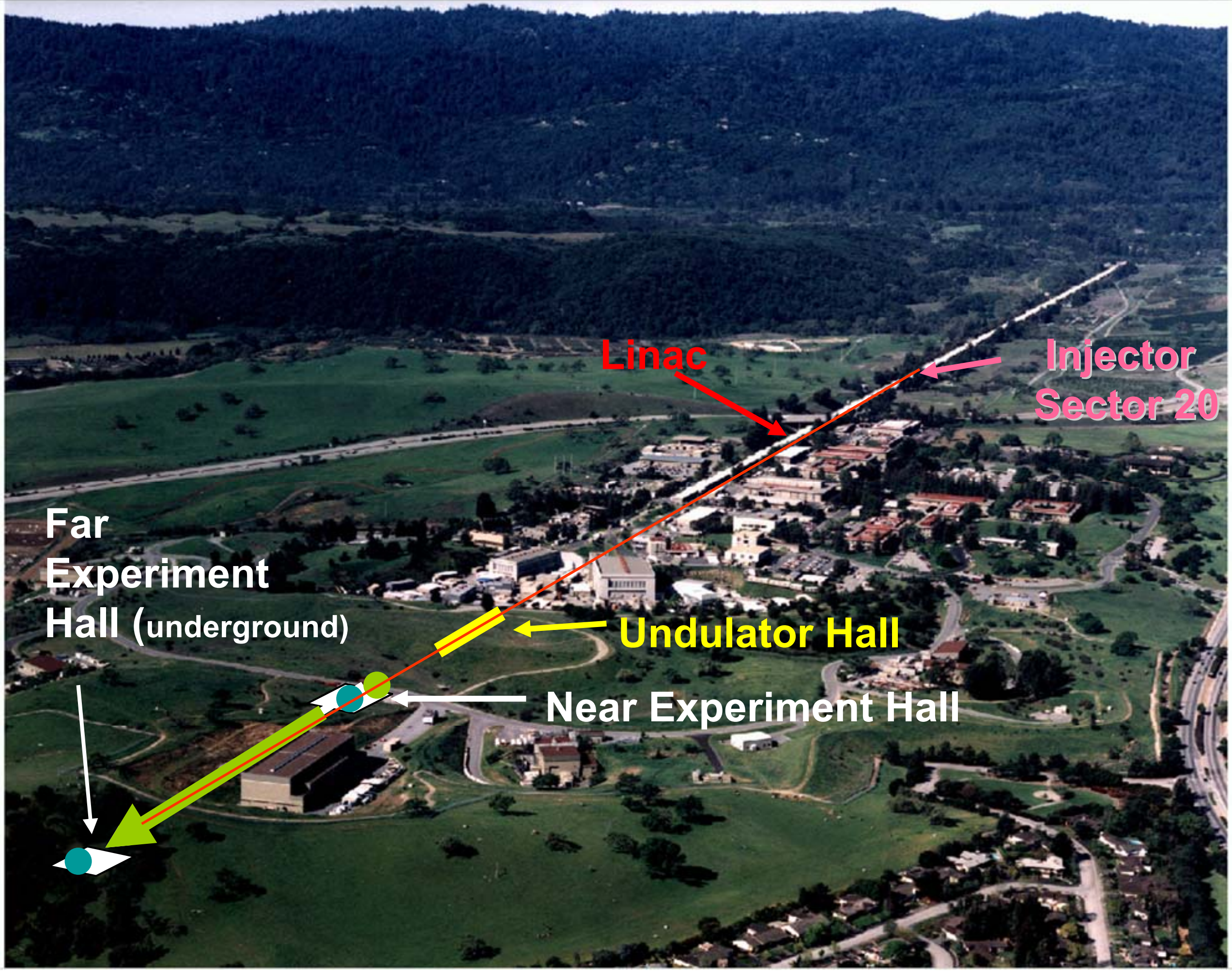
LCLS Injector Commissioning Results

David H. Dowell
Stanford Linear Accelerator Center
(on Behalf of the LCLS Commissioning Team)

- *Description of LCLS and Its Injector*
- *Electron Beam Measurements*
- *Unexpected Physics*
- *Summary of Results*

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

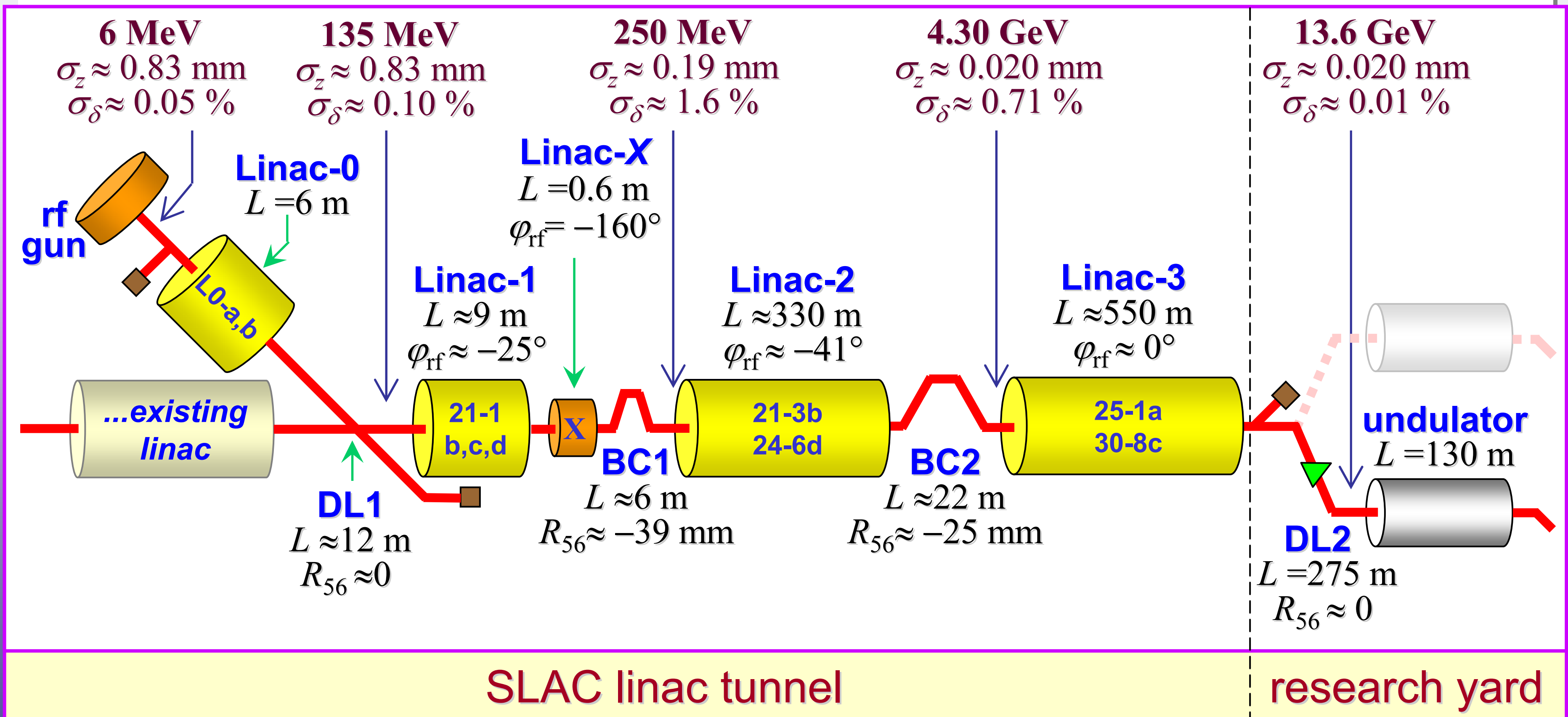


LCLS Design Parameters

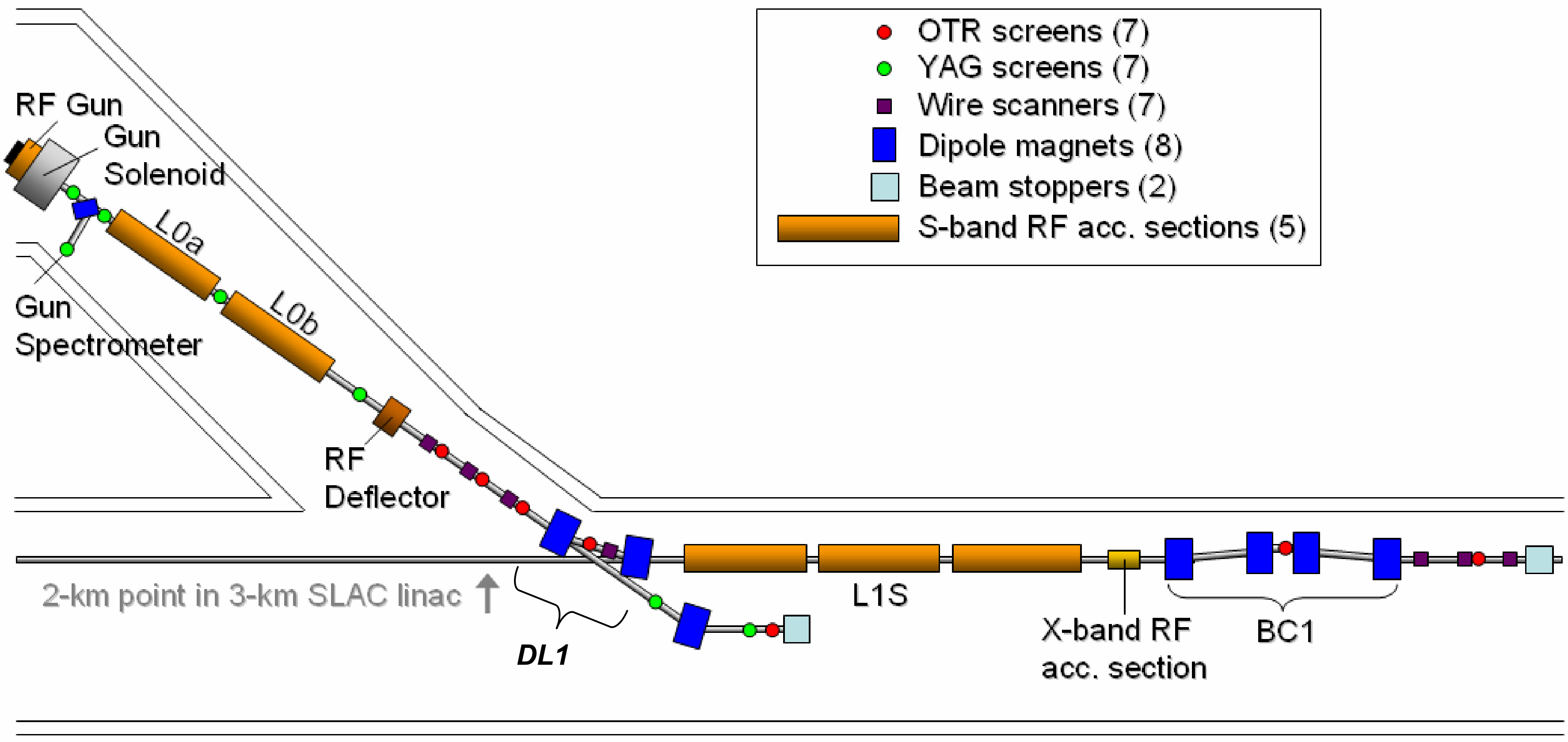
Fundamental FEL Wavelength	1.5	15	Å
Electron Beam Energy	13.6	4.3	GeV
Normalized Slice Emittance (rms)	1.2	1.2	mm-mrad
Peak Current	3.4	3.4	kA
Energy Spread (slice rms)	0.01	0.03	%
Bunch/Pulse Length (FWHM)	≤ 200	≤ 200	fs
Saturation Length	87	25	m
FEL Fundamental Power @ Saturation	8	17	GW
FEL Photons 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

LCLS Accelerator & Compressor Systems



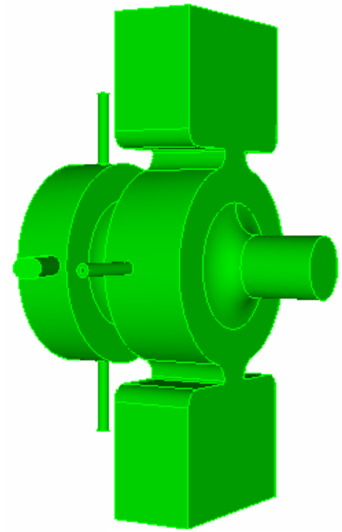
Injector and Bunch Compressor 1 Commissioned from April to September 2007 ~5 Months

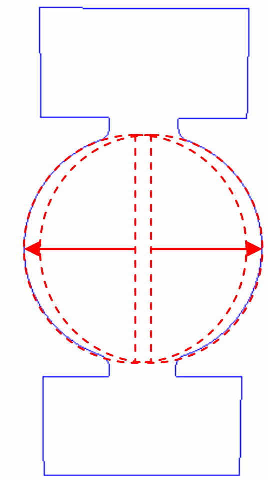


David H. Dowell et al.
dowell@slac.stanford.edu

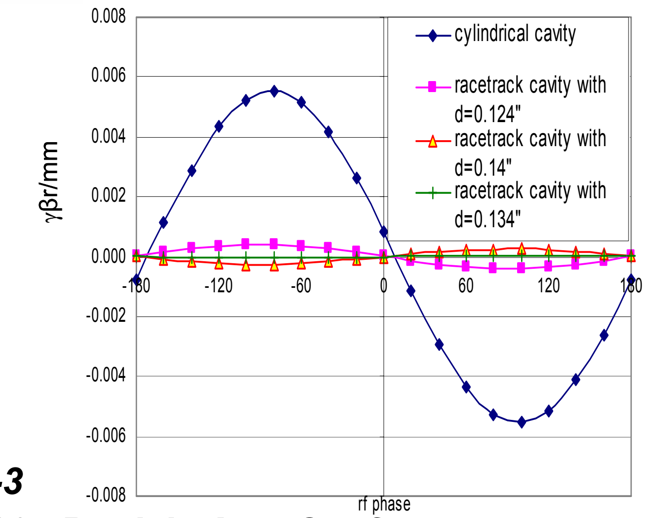
3D RF Design of Gun

- *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*





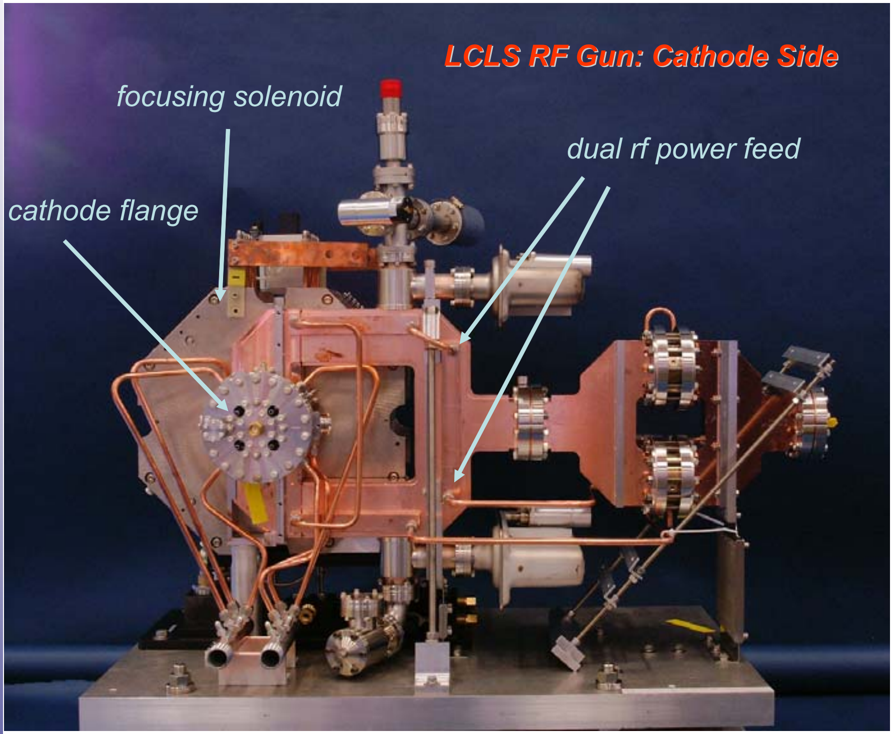
RF Parameters	
f_π (GHz)	2.855987
Q0	13960
β	2.1
Mode Sep. Δf (MHz)	15
E0:E1	0.999:1

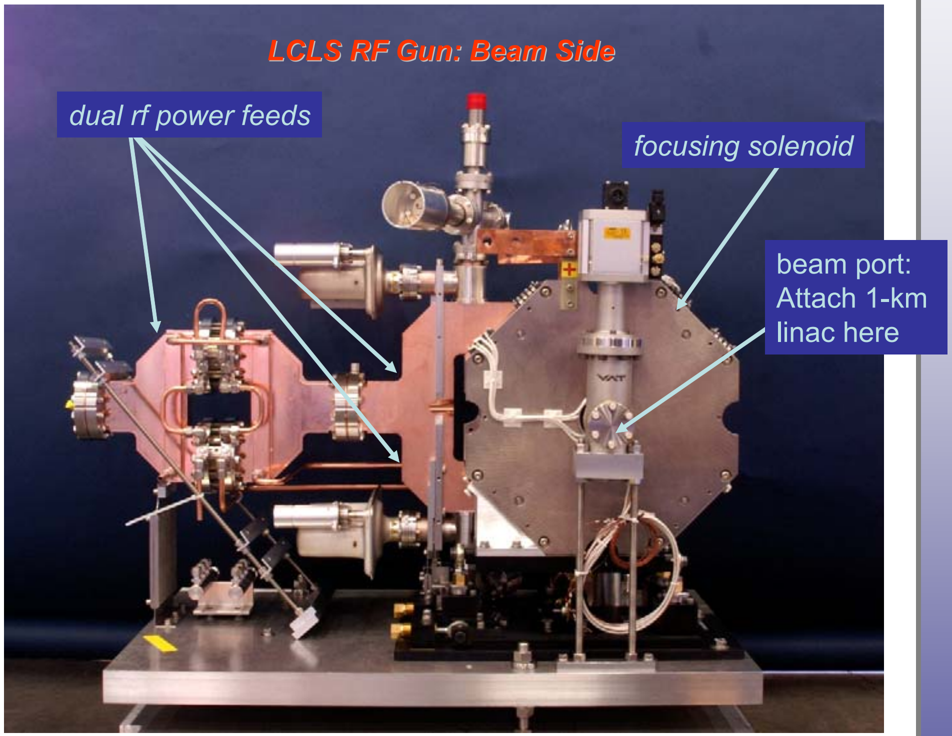


C. Limborg et al., "RF Design of the LCLS Gun", LCLS-TN-05-3
L. Xiao et al., "Dual feed rf gun design for the LCLS," Proc. 2005 Particle Acc. Conf.

Slide Compliments of Z. Li & L. Xiao

The LCLS RF Photocathode Gun & Solenoid Assembly

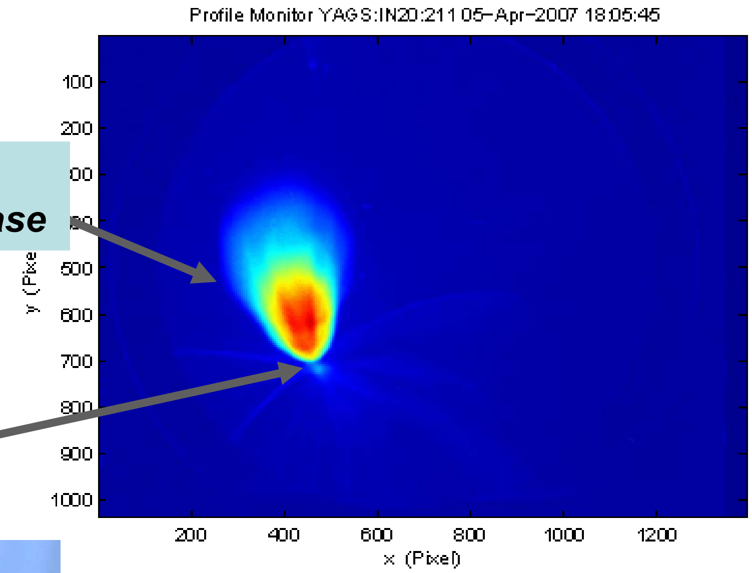


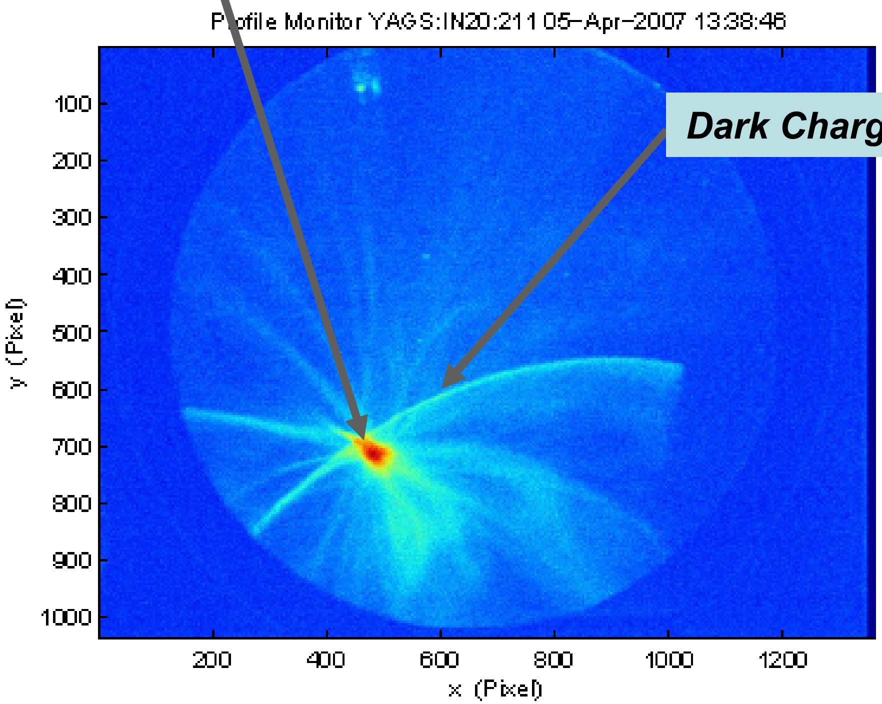


Images of First Photo-Electrons April 5, 2007

First Photo-Electrons!!!

Photo-Electrons: After adjusting laser-gun phase





Dark Charge

It Works!!!

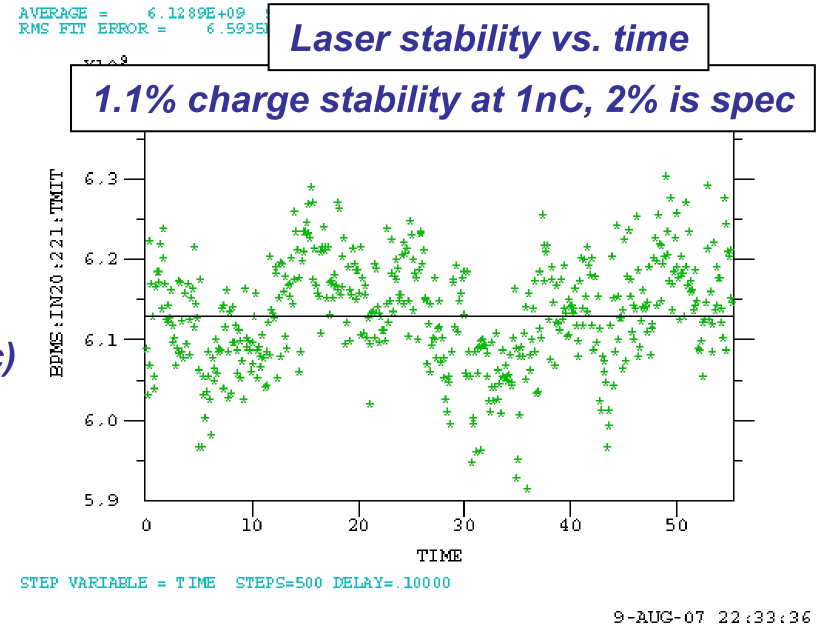
David H. Dowell et al.
dowell@slac.stanford.edu

Drive Laser Performance

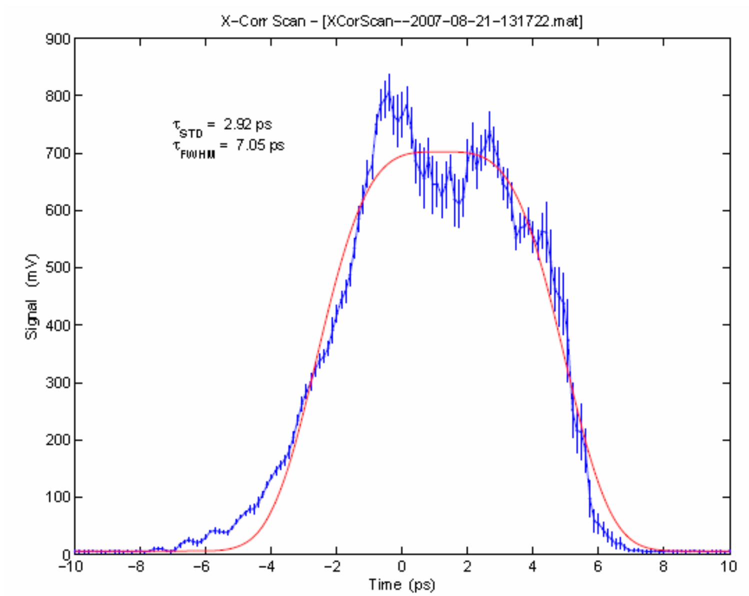
- •Laser reliability is very good: Up-time > 90%
  - •Excellent support from Thales & Femtolasers
- •Delivering > 400 microJoules to cathode (250 is spec)
- •Shaping needs work, but still producing good emittances
- •Excellent energy stability (1.1%)
- •Position stability on cathode, ~10-20 microns.

Laser stability vs. time

1.1% charge stability at 1nC, 2% is spec



X-Correlator Measurement of Laser Pulse



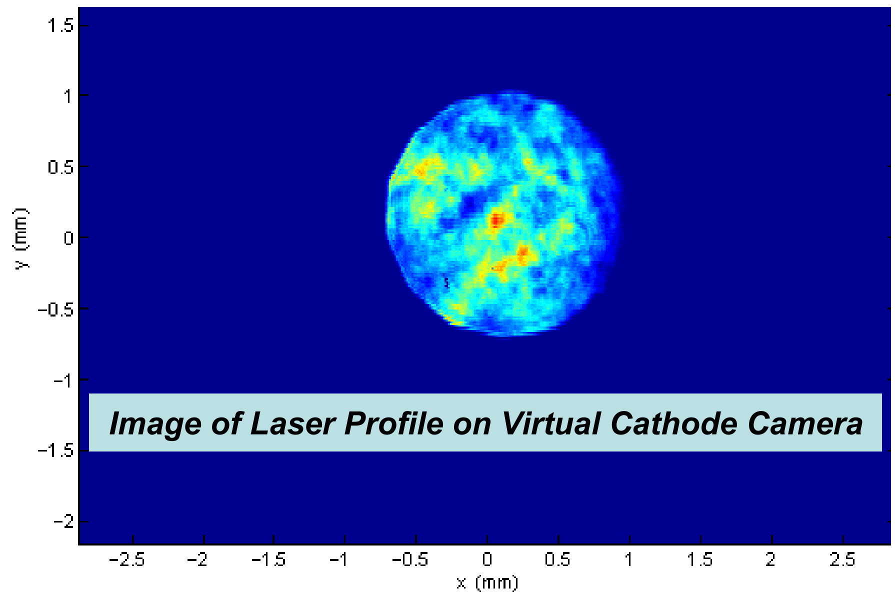
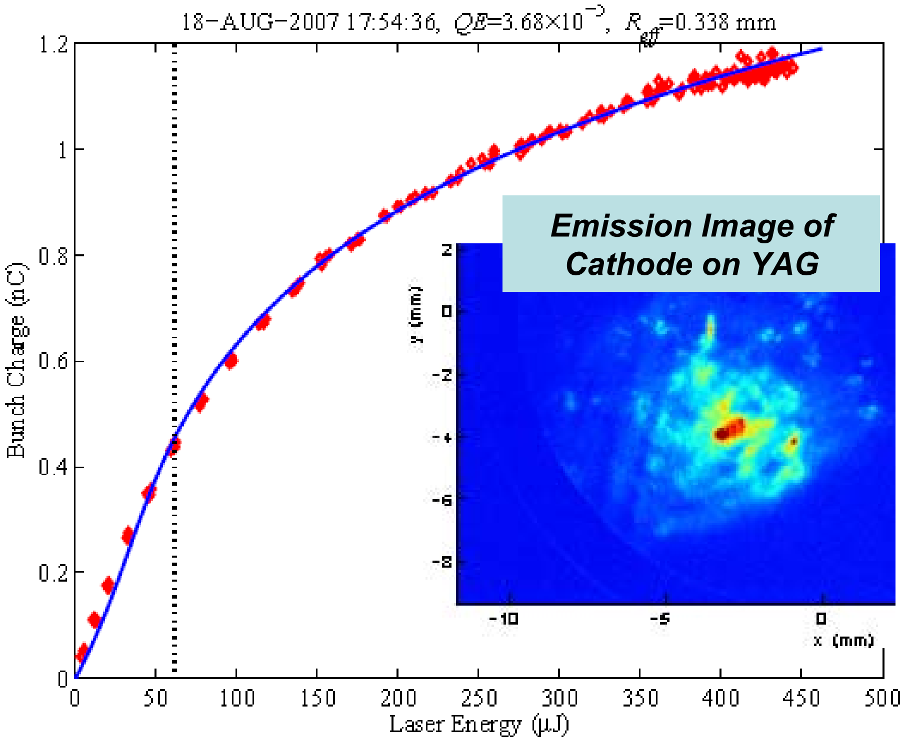
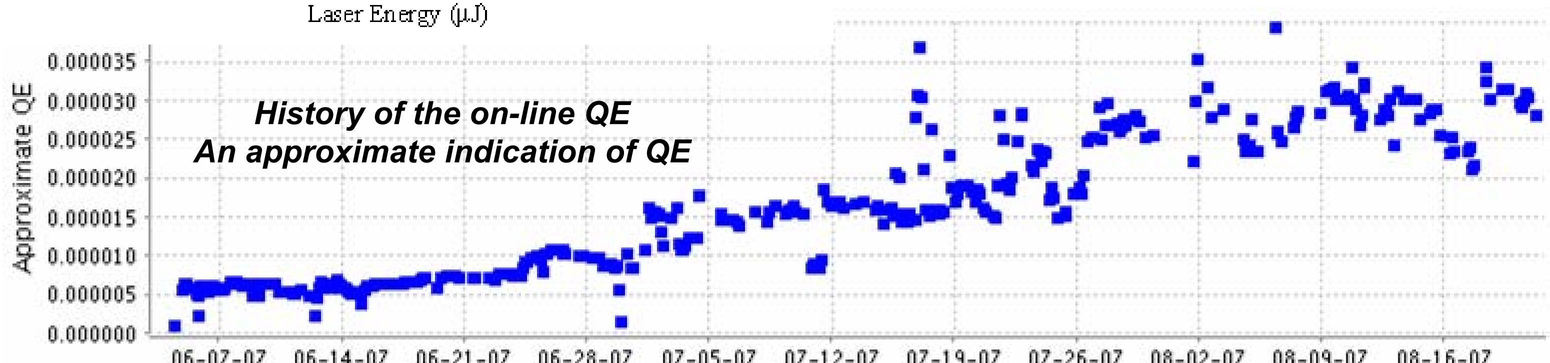


Image of Laser Profile on Virtual Cathode Camera

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 ~3x10^{-5}, 2 times lower than spec (6x10^{-5}).
- •QE-scans show emission is in the Space Charge Limited Regime at 1nC for a 1.3 mm dia. laser on the cathode.



David H. Dowell et al.
dowell@slac.stanford.edu

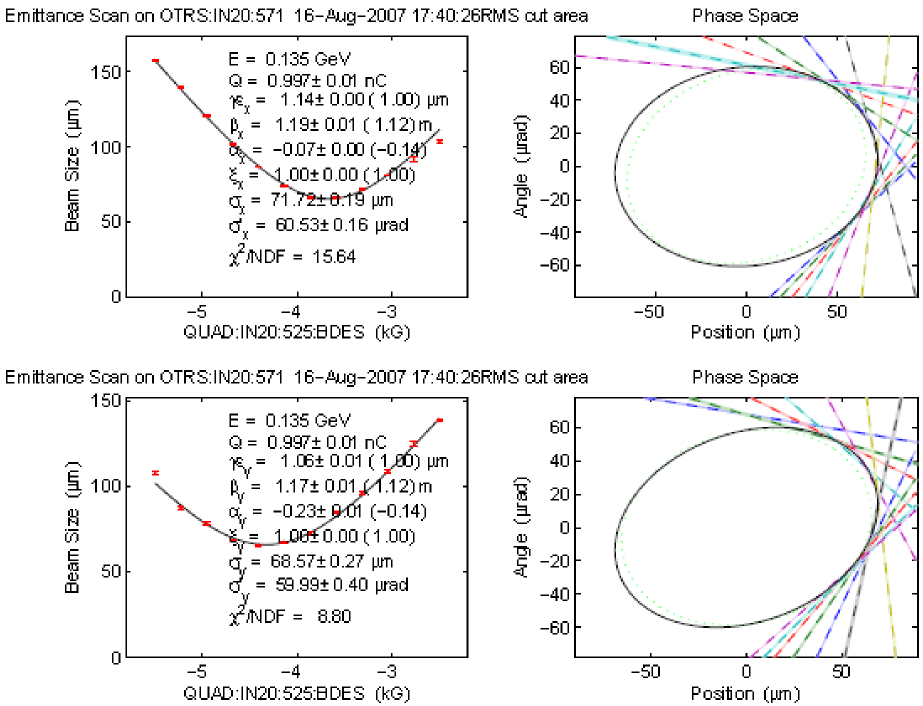
Projected & Slice Emittances at 1nC

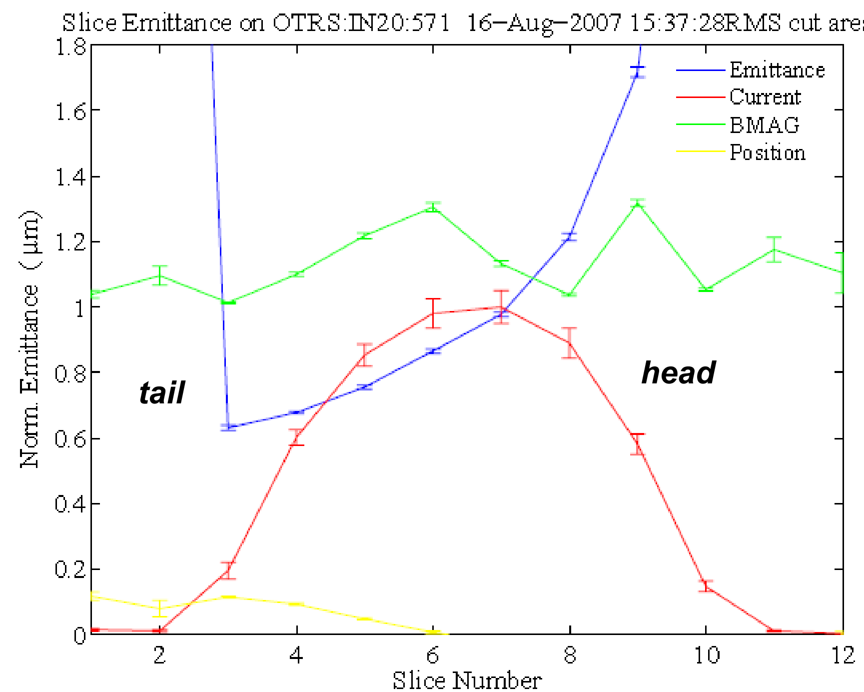
Projected Emittance (rms) at 1nC (95% of the beam):

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.





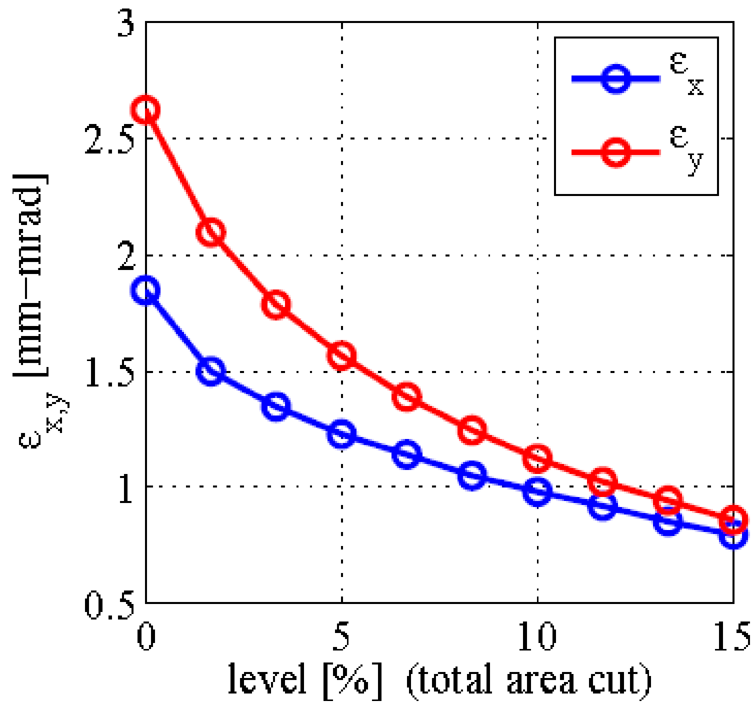
On-line analysis tools by H. Loos

David H. Dowell et al.
dowell@slac.stanford.edu

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

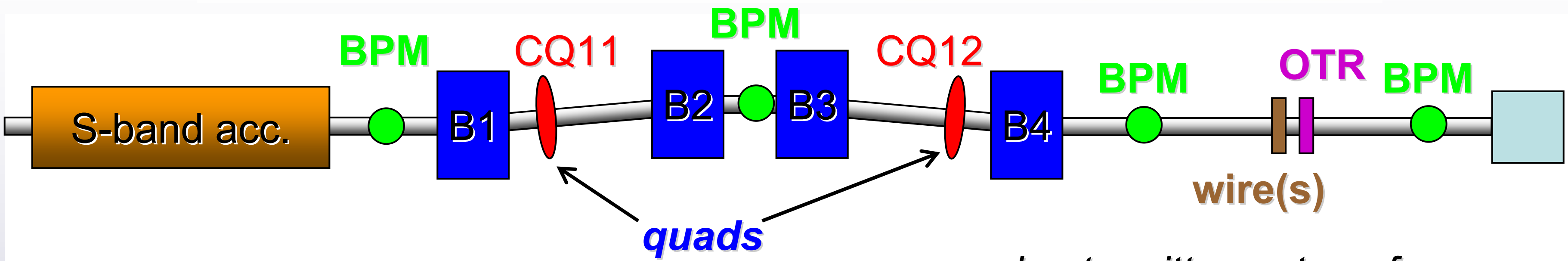


$\varepsilon_{thermal}$ = 0.6 micron / mm = 0.6 mrad (normalized divergence)

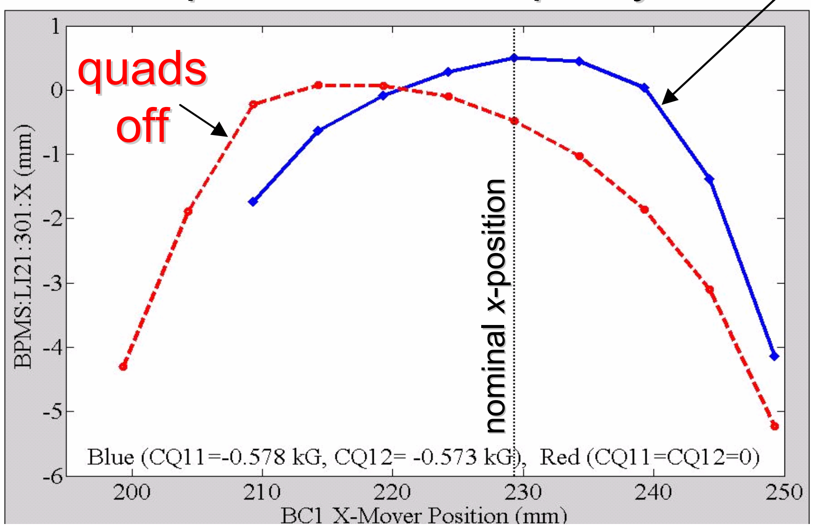
Simulations Courtesy C. Limborg-Deprey

David H. Dowell et al.
dowell@slac.stanford.edu

BC1 Chicane Emittance Growth

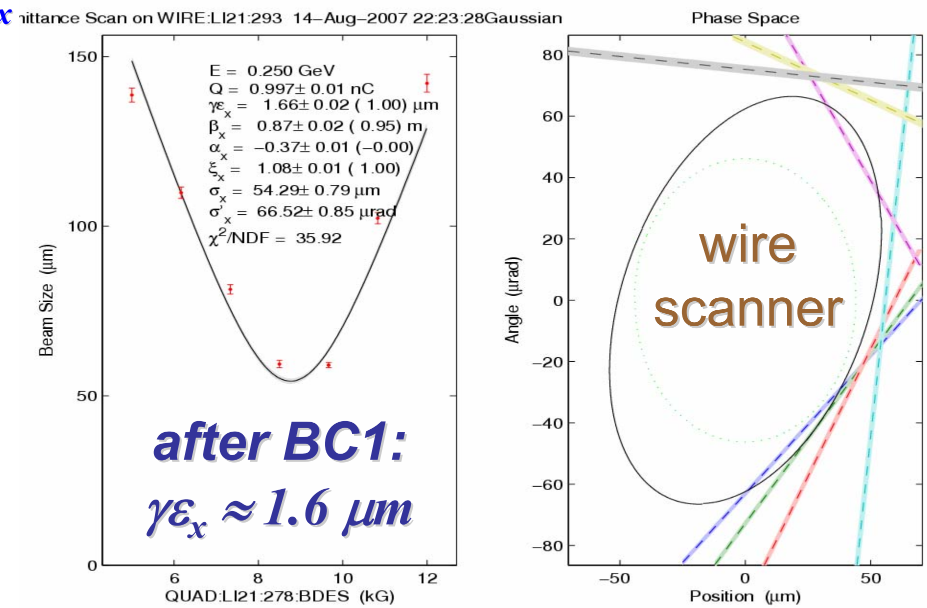


poor bend field quality



read BPMs while scanning BC1 mover

best emittance transfer

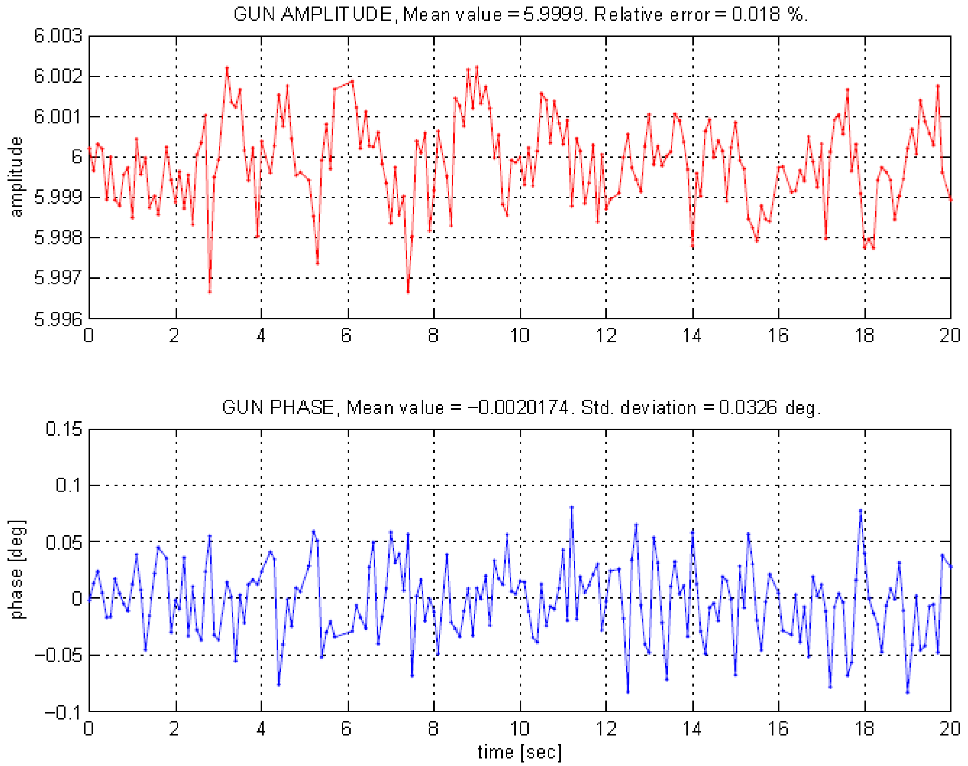


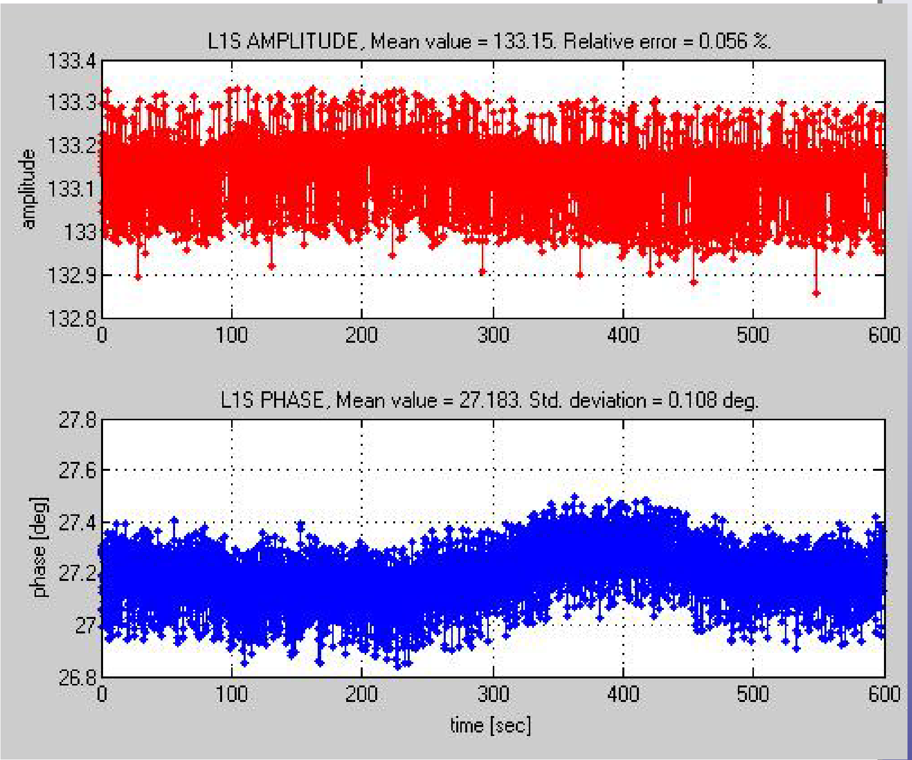
- **Best $\gamma\varepsilon_x$ after BC1 with nom. (& more) compression is 1.6 μm (& larger)**
- **Poor bend field quality (grad. + sext.) – $\Delta E/E$ scan shows 1st & 2nd-order η**
- **Screen image biased by COTR – wires vibrate – variable results (& in y)**
- **Bends will be upgraded in fall '07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

RF Phase & Amplitude Stability

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

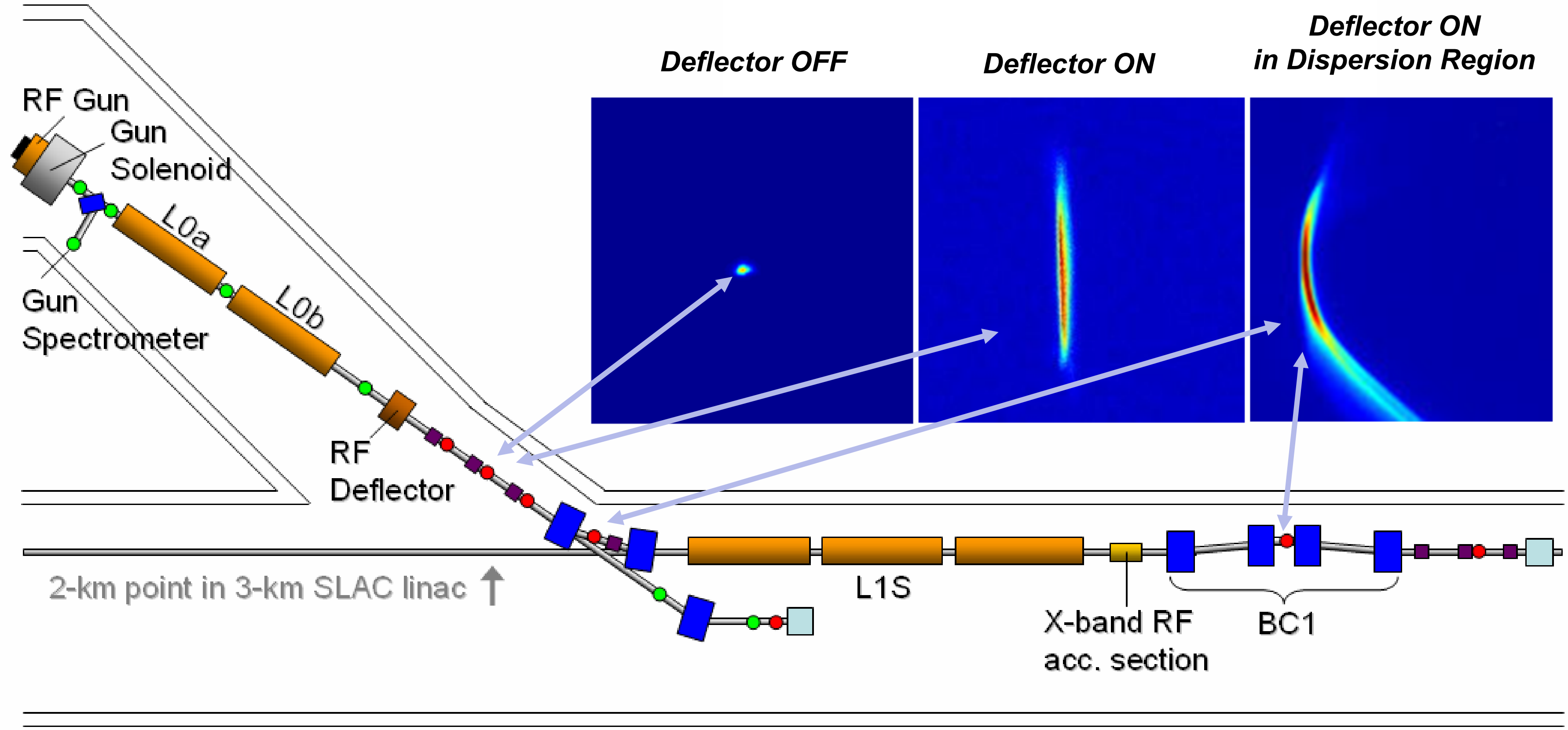
Linac:
rms amplitude error = 0.056%
rms phase error = 0.108 degS





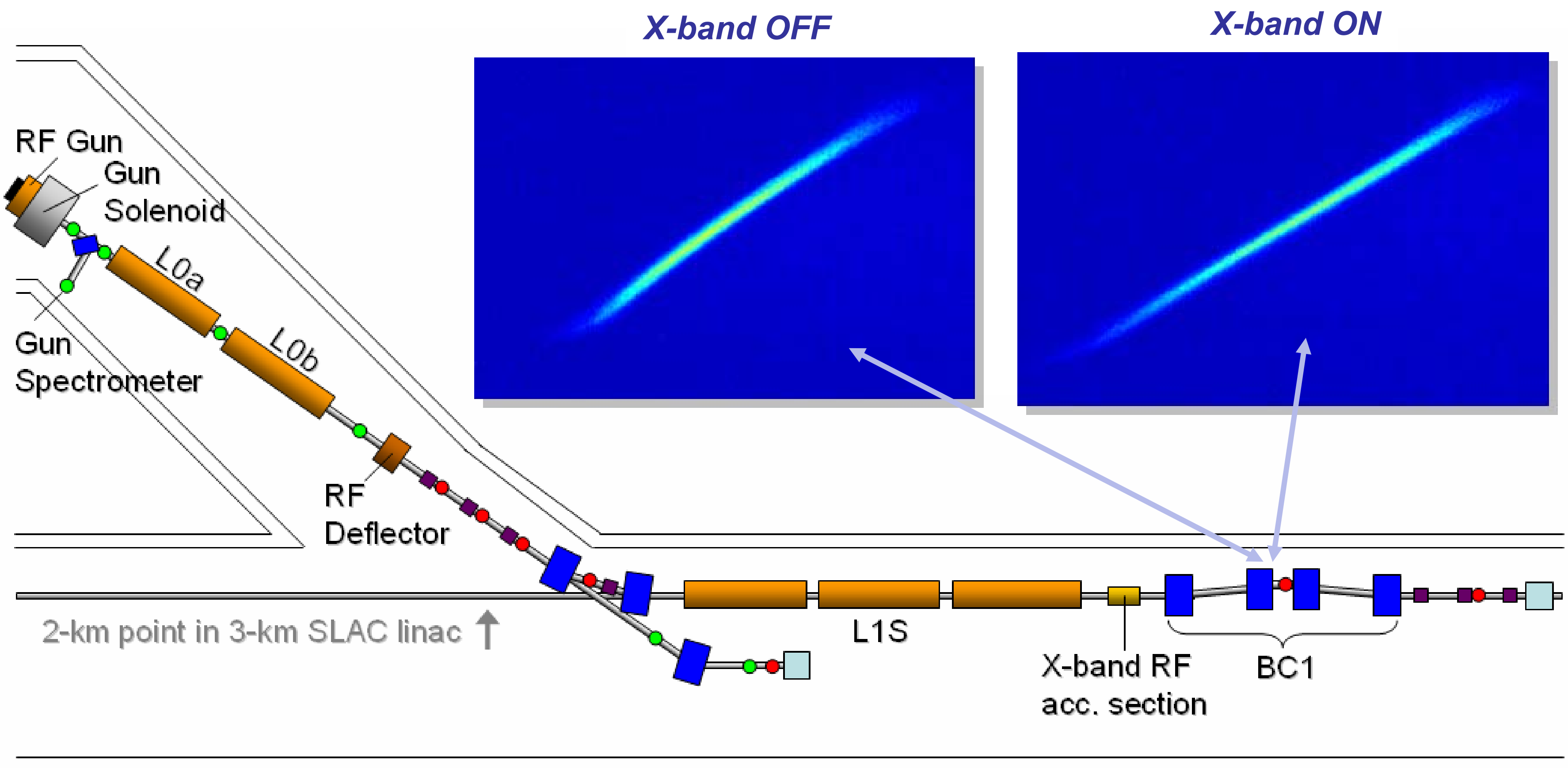
David H. Dowell et al.
dowell@slac.stanford.edu

Transverse Cavity (RF-Deflector) Measurements of Bunch Length



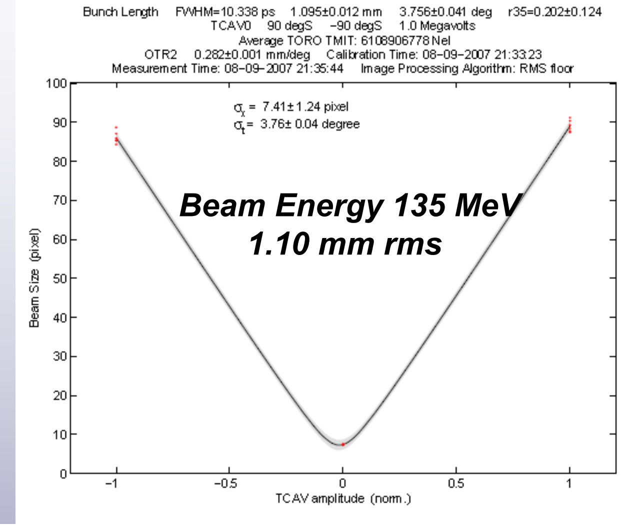
David H. Dowell et al.
dowell@slac.stanford.edu

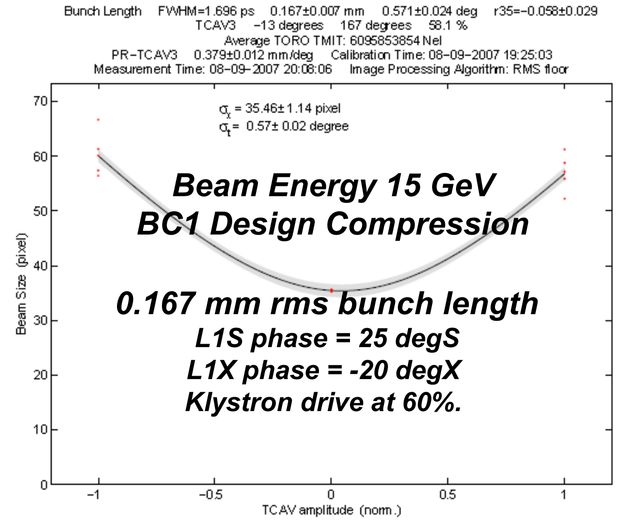
Linearization of Longitudinal Phase Space Measured Using the RF Deflector & OTR Screen in Center of BC1

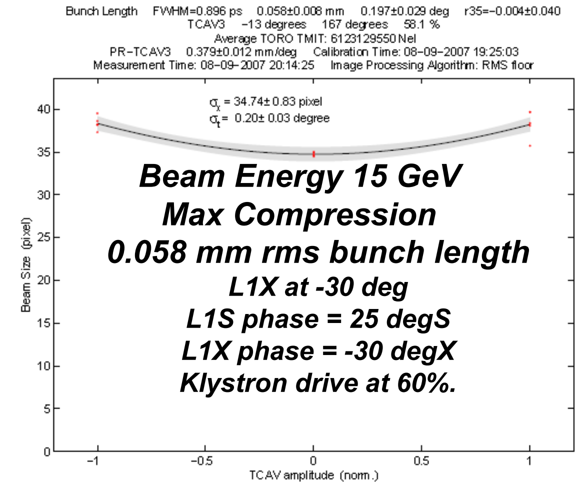


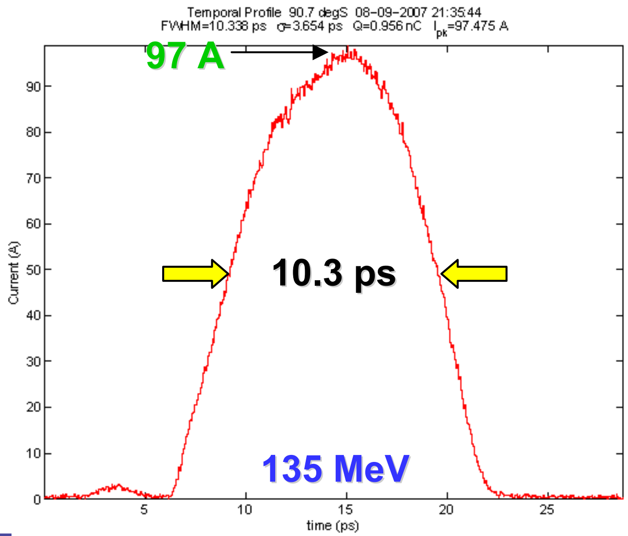
David H. Dowell et al.
dowell@slac.stanford.edu

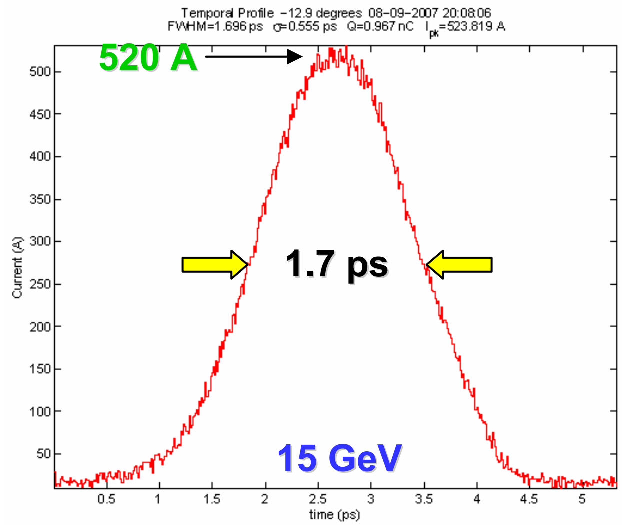
Bunch Length Measurements at 135 MeV & 15 GeV

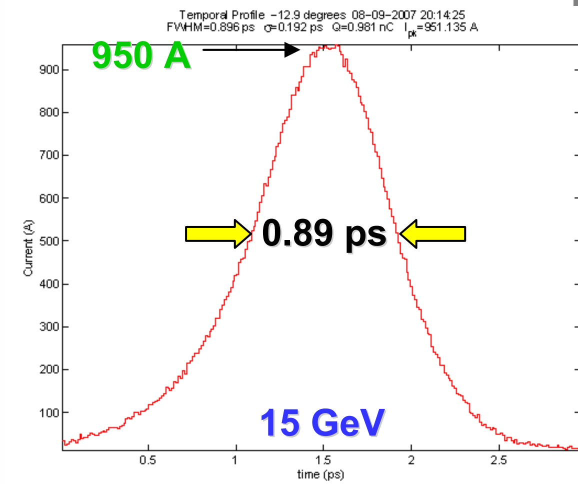










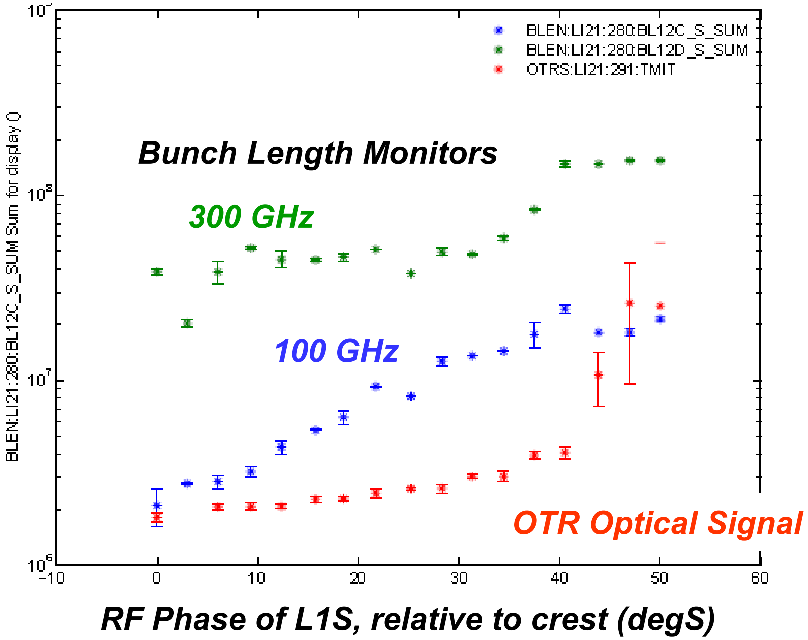


David H. Dowell et al.
dowell@slac.stanford.edu

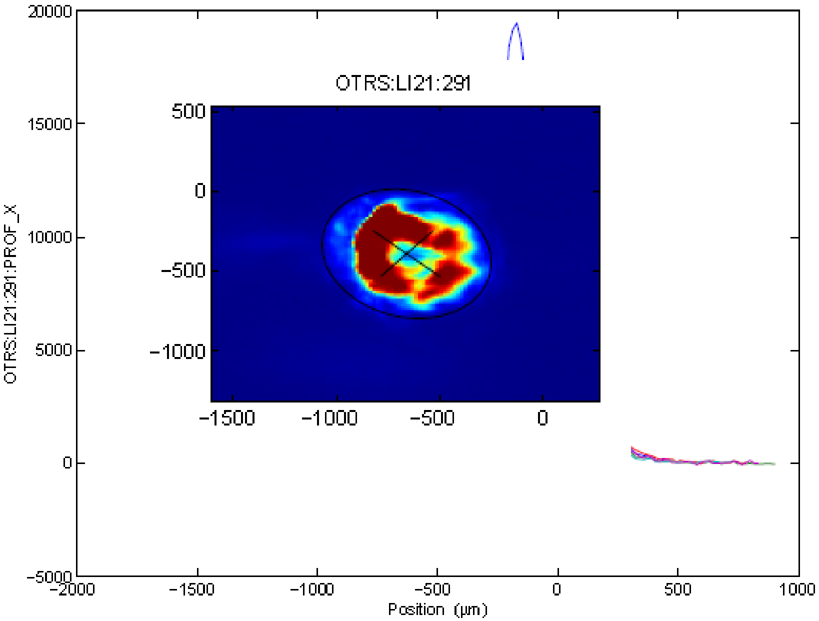
Unexpected Physics! Strong Optical Microbunching with BC1 Set to Maximum Compression

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!

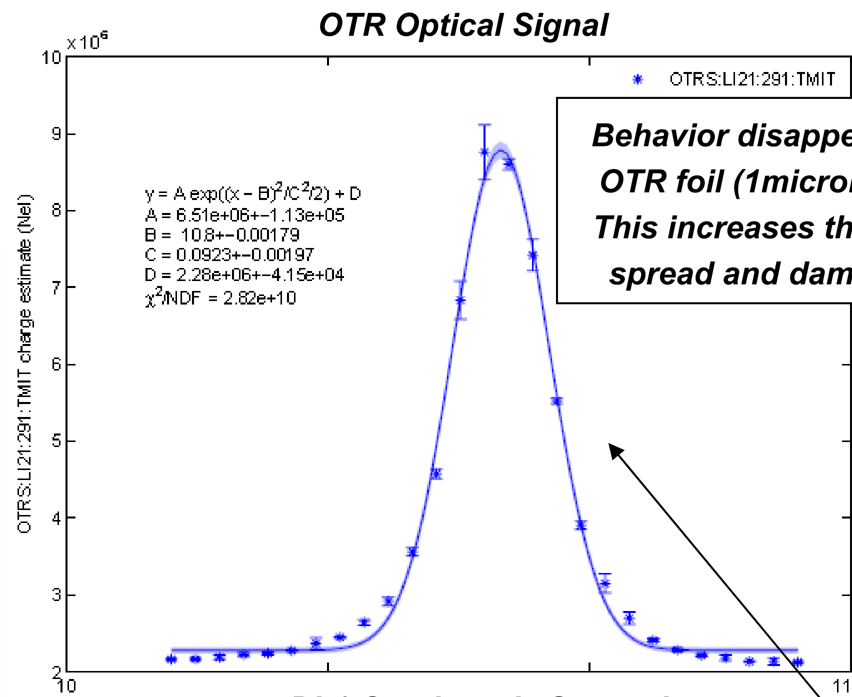


David H. Dowell et al.
dowell@slac.stanford.edu

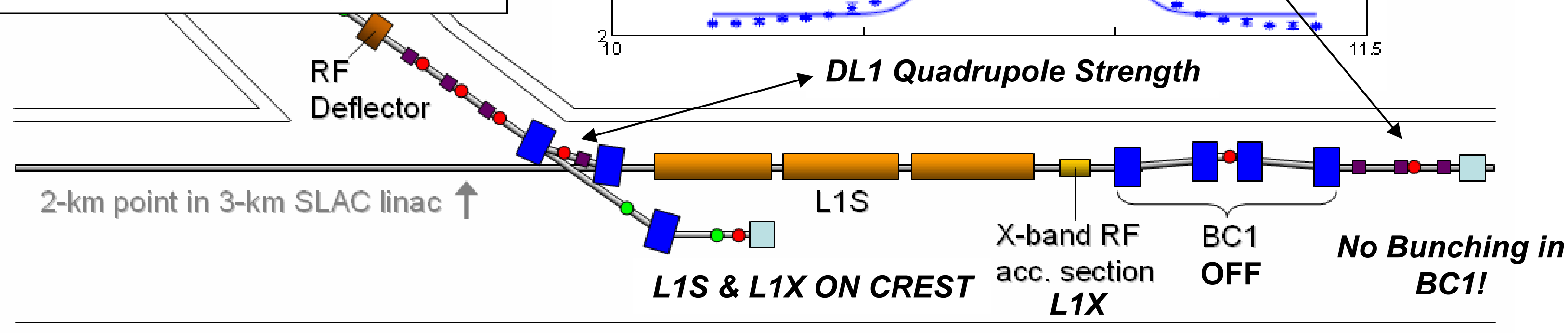
Unexpected Physics!
Coherent Optical Transition Radiation after DL1 Bend Even With No BC1 Compression

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 doubly-achromatic, its design value.



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



David H. Dowell et al.
dowell@slac.stanford.edu

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

David H. Dowell et al.
dowell@slac.stanford.edu

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!*

The LCLS Injector Commissioning Team:

R. Akre
J. Castro
Y. Ding
D. Dowell
P. Emma
J. Frisch
S. Gilevich
G. Hays
Ph. Hering
Z. Huang
R. Iverson
C. Limborg-Deprey
H. Loos
A. Miahnahri
J. Schmerge
J. Turner
J. Welch
W. White
J. Wu

Special Thanks
to the LCLS Injector Team
who allowed me to show their results.

And Our Visitors:

DESY
L. Froelich
T. Limberg
E. Prat
M. Roehrs
J. Roensch (PITZ)

Trieste
P. Craevich
G. Penco
M. Trovo

BESSY
T. Kamps

Soleil
M.-E. Couprie