LCLS Commissioning (Phase I)

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LCLS, SLAC

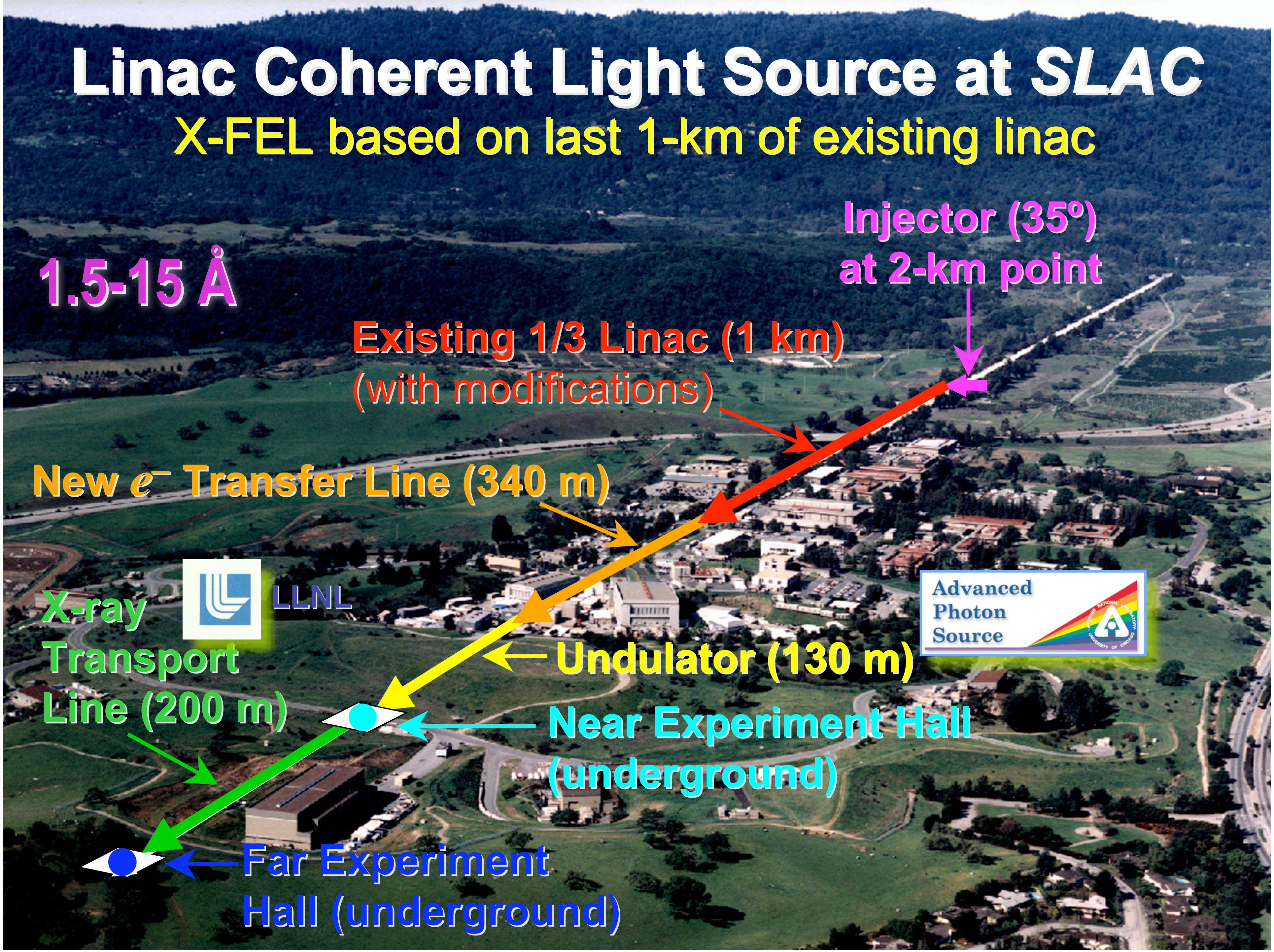
Sept.24th 2007

Outline

1. LCLS Project Overview
2. Injector Commissioning
   – Laser, Gun, Cathode, …
   – Electron Beam Measurements
   – Some interesting beam physics …
3. Comparison with simulations

PART 1:

LCLS Project


Linac Coherent Light Source at SLAC
X-FEL based on last 1-km of existing linac
1.5-15 Å
Injector (35º)
at 2-km point
Existing 1/3 Linac (1 km)
(with modifications)
New e⁻ Transfer Line (340 m)
X-ray
Transport
Line (200 m)
LLNL
Undulator (130 m)
Advanced
Photon
Source
Near Experiment Hall
(underground)
Far Experiment
Hall (underground)

3^{rd} vs 4^{th} Generation Light Sources


APS, USA


ESRF, Europe


Spring8,Japan

…

~ 15 years old

+ newer SLS, SPEAR3,SOLEIL…

	3^{rd} GLS	4^{th} GLS
Peak Brilliance	5.10^{23}	10^{33}
Coherent flux	10^{10} /s /0.01%	10^{13} / s/0.01%
Pulse Length	σ ~ 10ps	σ ~ 100 fs (*)

(*) or less with less flux

under construction


X-FEL,Germany

SCSS, Japan


LCLS, USA

4^{th} Generation Light Sources

Peak Brilliance 10 orders of magnitude > that of 3^{rd} GLS

2 from ↘ bunch length (10ps → 100fs)
2 from ↘ in horizontal emittance (3nm→ 0.03nm)
1 from smaller divergence (SASE)
2 from longer undulator (~ 100m)
3 from FEL gain (SASE)

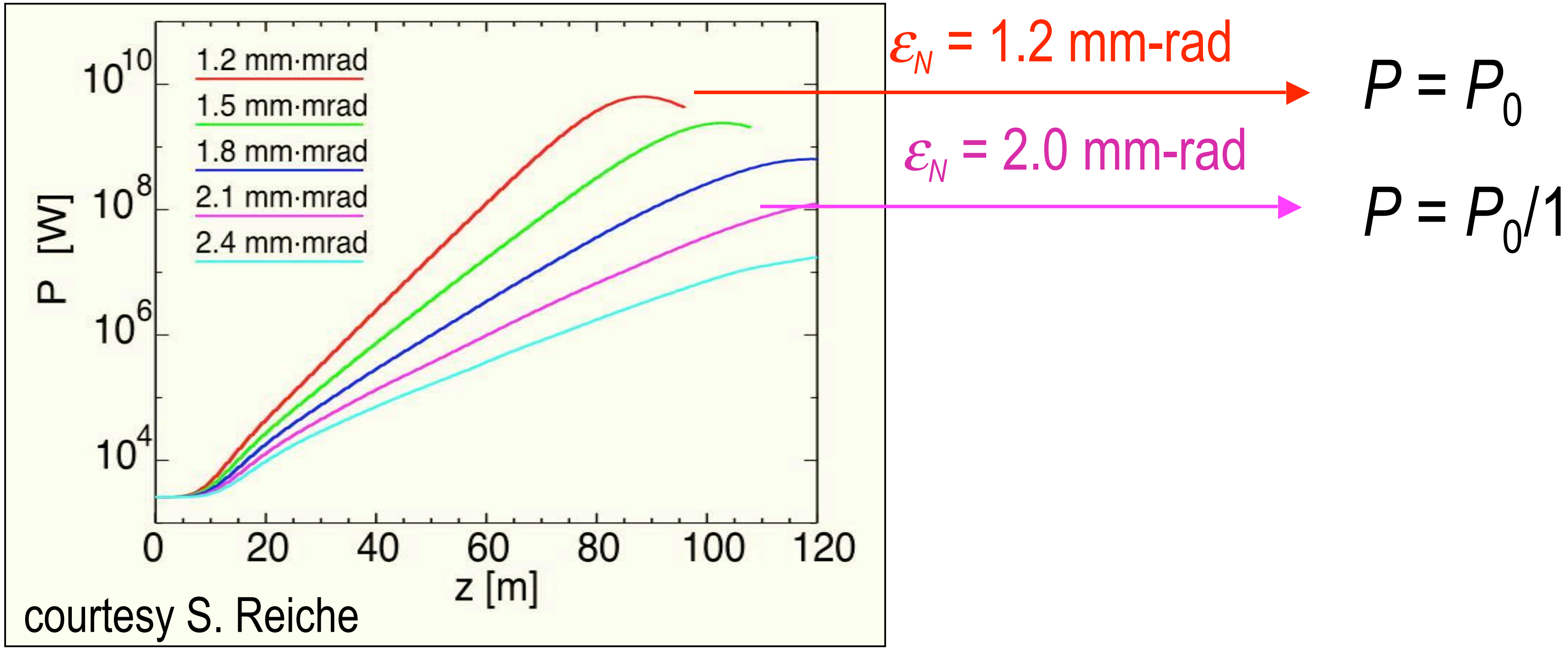
<u>But:</u> 3^{rd} GLS
High repetition rate & High average brilliance
Stability decoupled from that of injector

Nominal LCLS Parameters

Fundamental FEL Radiation Wavelength	**1.5**	**15**	Å
Electron Beam Energy	14.3	4.5	GeV
Normalized RMS Slice Emittance	1.2	1.2	mm-mrad
Peak Current	3.4	3.4	kA
Bunch/Pulse Length (FWHM)	230	230	fs
Relative Slice Energy Spread	<0.01	0.025	%
Saturation Length	87	25	m
FEL Fundamental Saturation Power	8	17	GW
FEL Photons per Pulse	1.1	29	10^{12}
Peak Brightness @ Undulator Exit	0.8	0.06	10^{33} *
Transverse Coherence	Full	Full	
RMS Slice X-Ray Bandwidth	0.06	0.24	%
RMS Projected X-Ray Bandwidth	0.13	0.47	%

*** photons/sec/mm²/mrad²/ 0.1%-BW**

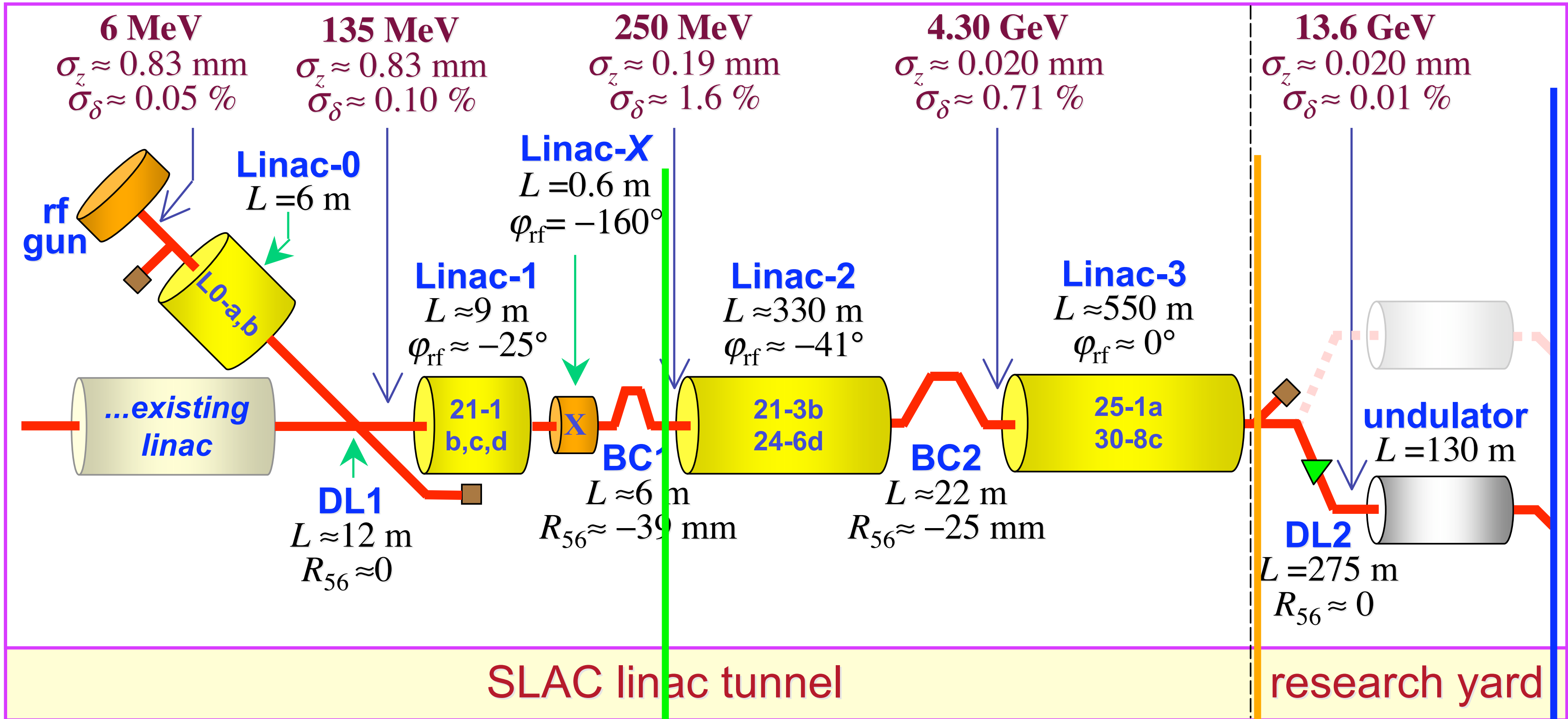
LCLS e-beam requirements



- Slice emittance $\varepsilon_{x/y,n} < 1.2$ mm-mrad
- Slice energy spread $\sigma_\delta < 10^{-4}$
- High Peak Current 3.4 kA (σ_τ ~ 150 fs)
- Stability dQ/Q < 2% rms (P ↘ 30 %)

Nominal LCLS Parameters

Single bunch, 1-nC charge, 1.2-μm *slice* emittance, 120-Hz repetition rate…

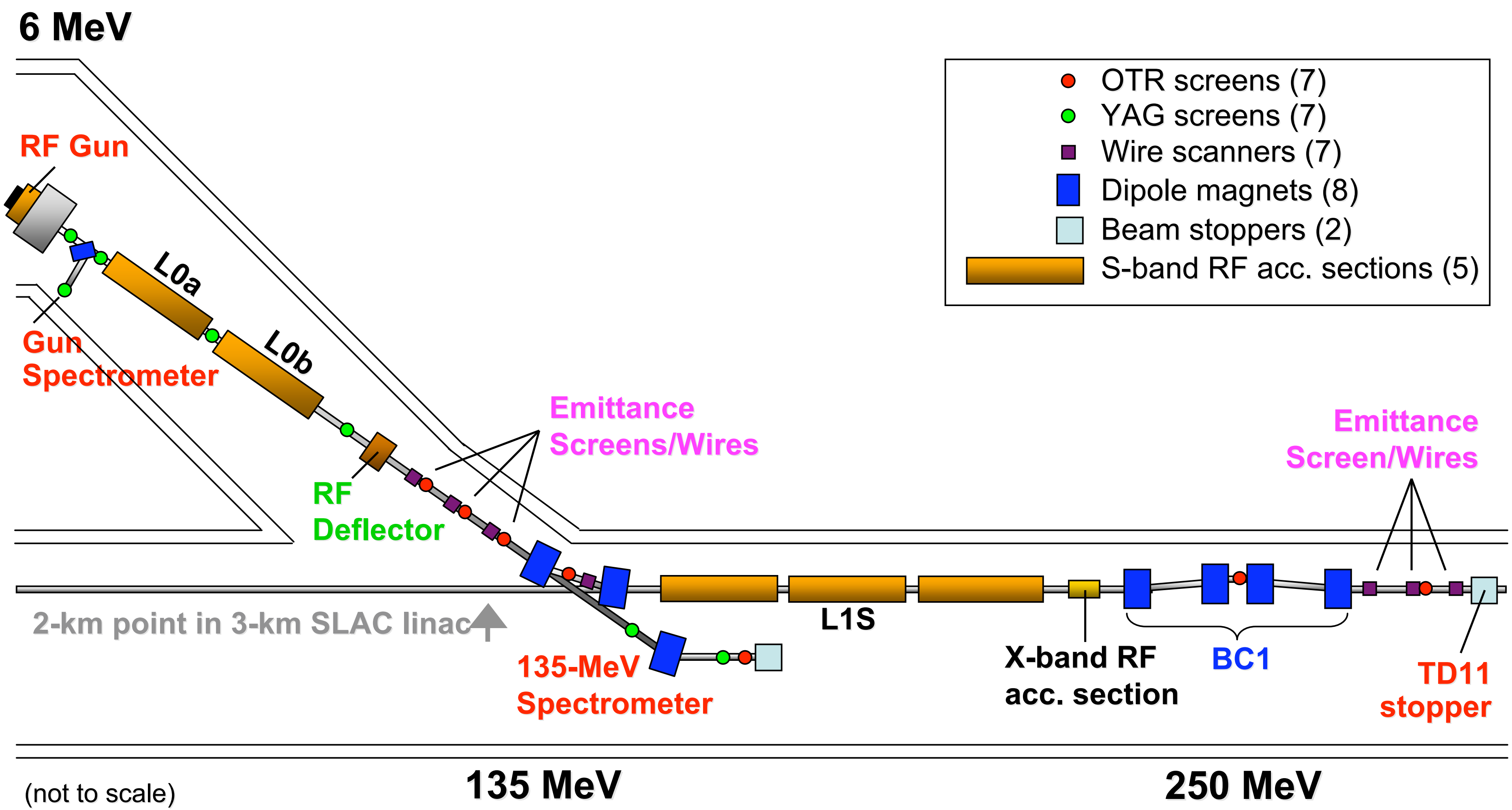


Installation	Summer 06	Fall 07	Year 08
Commissioning	April. -> Aug 07	Jan. 08	Spring 09

PART 2:

LCLS Injector Commissioning

Injector and 1st Bunch Compressor commissioning

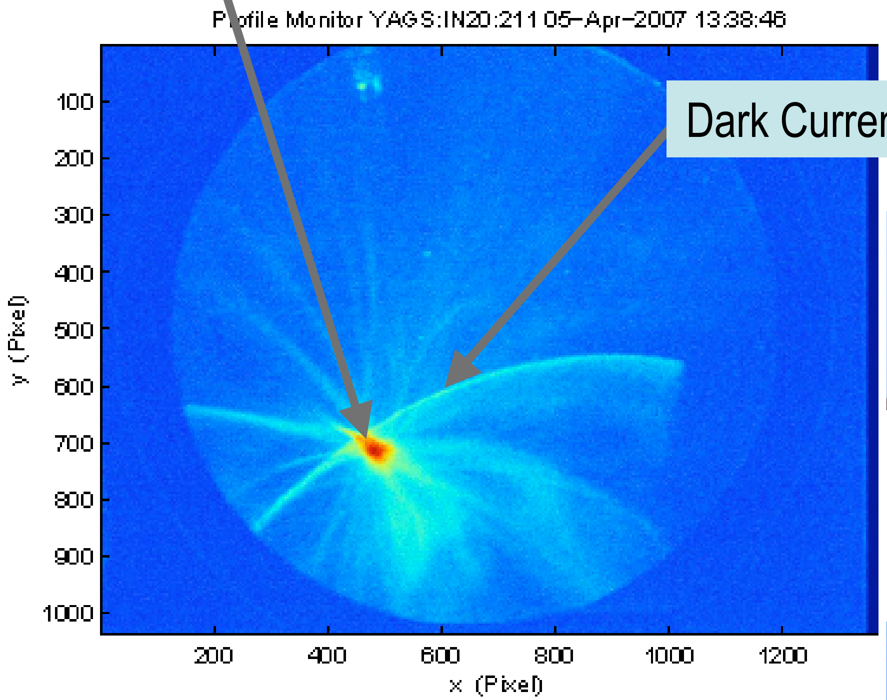


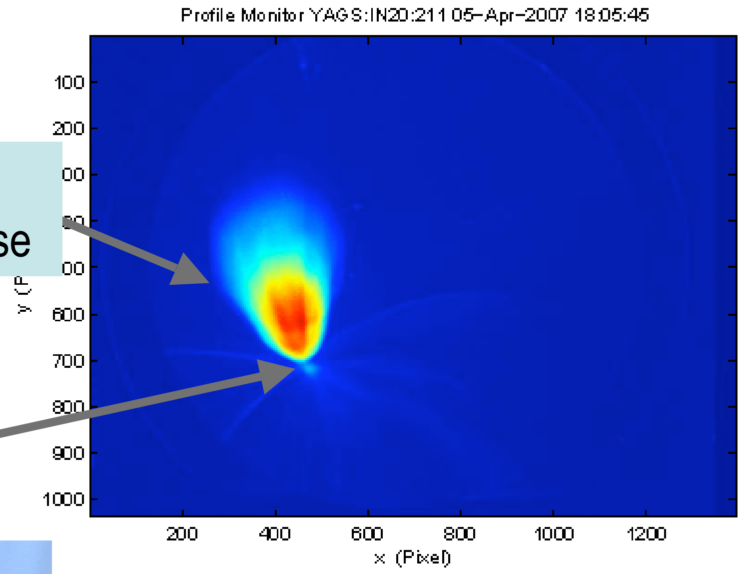
First Photo-Electrons, April 5, 2007

First Photo-Electrons!!!

Photo-Electrons:
After adjusting laser-gun phase

Dark Current

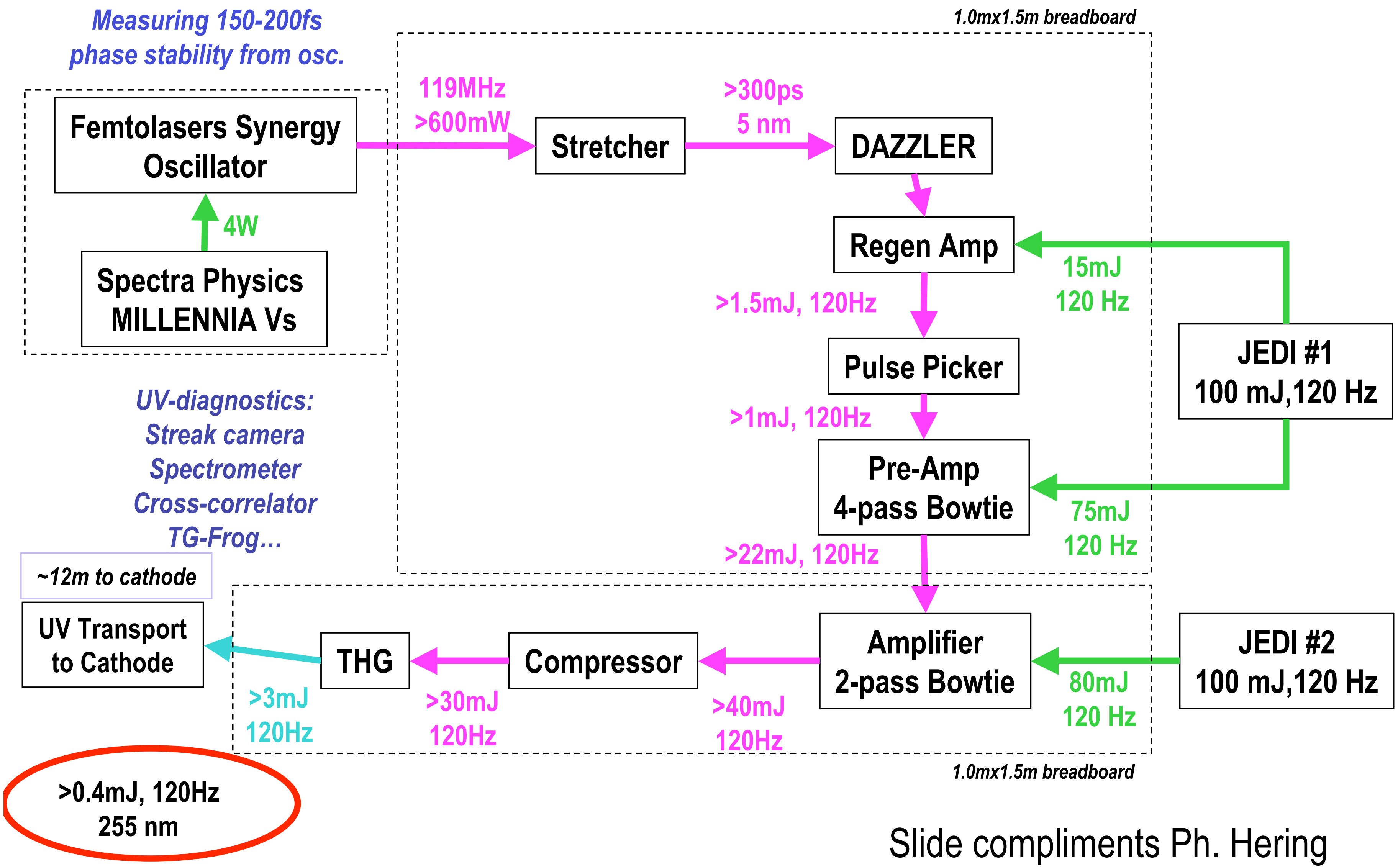




Commissioning Milestones

- Spring 2006: Civil construction of buildings/shielding completed
- Summer 2006: Drive Laser Installed
- Fall 2006: Drive laser commissioned & Gun1 high power conditioning in Klystron Lab
- 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

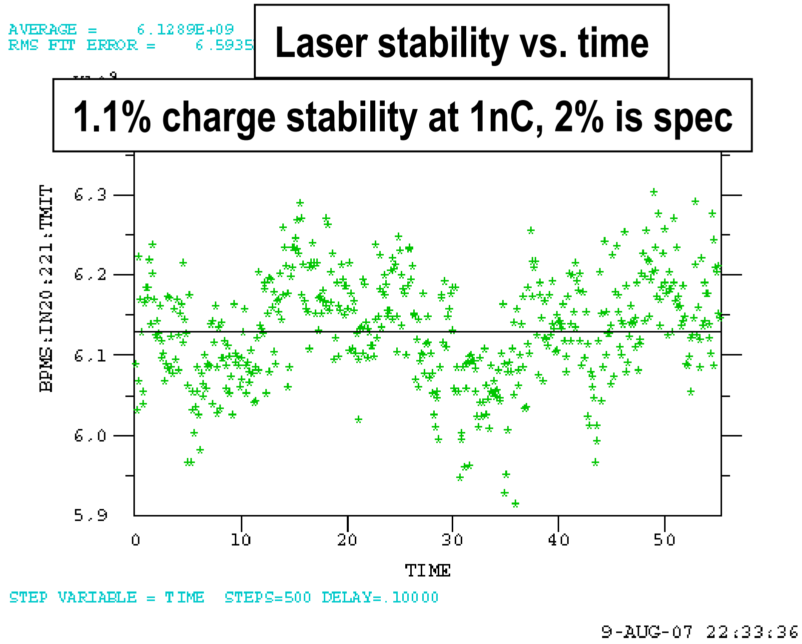
Thales Drive Laser System

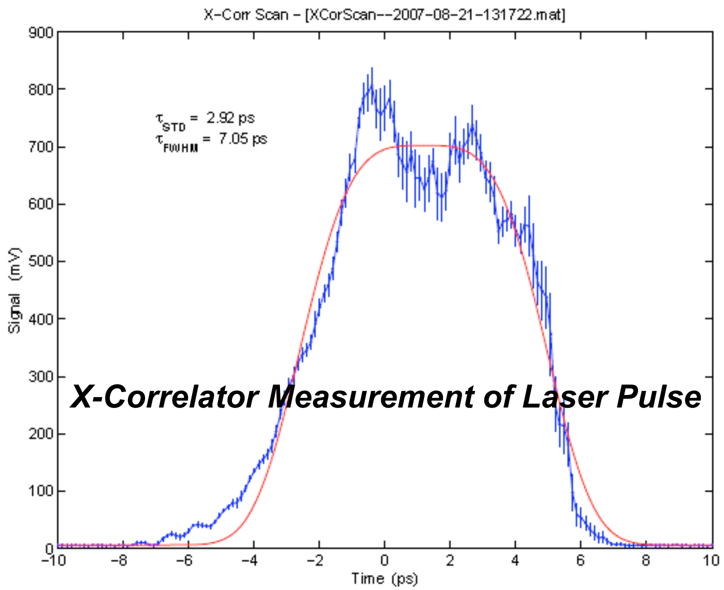


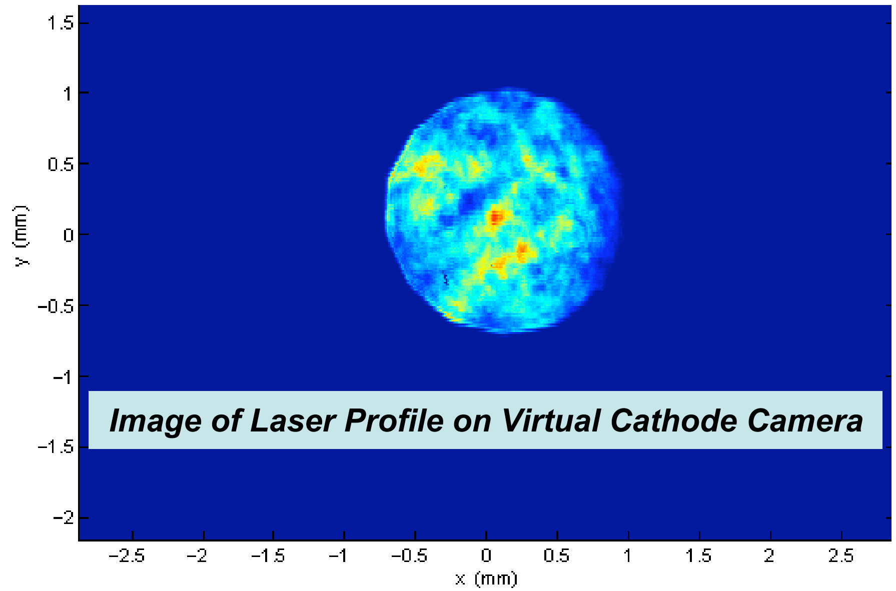
Slide compliments Ph. Hering

Drive Laser Performances

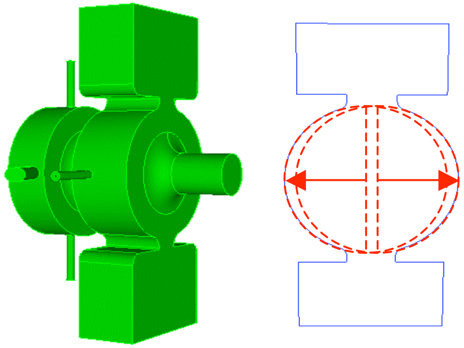
- Laser reliability is very good: Up-time > 90%
  - Excellent support from Thales & Femtolasers
- E ~ 400 µJ to cathode (250 µJ spec)
- Shaping needs work, but still producing good emittances
- Excellent energy stability (1.1%)
- Position stability on cathode, ~10-20 µm

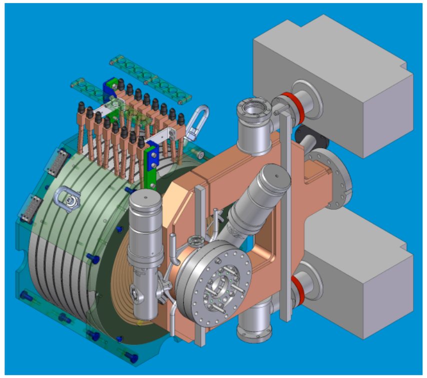


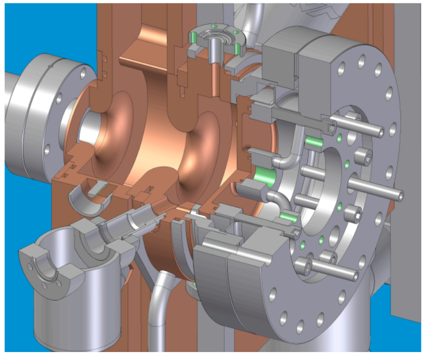




RF Gun: 1.6 cell S-Band







Modified from BNL/UCLA/SLAC design

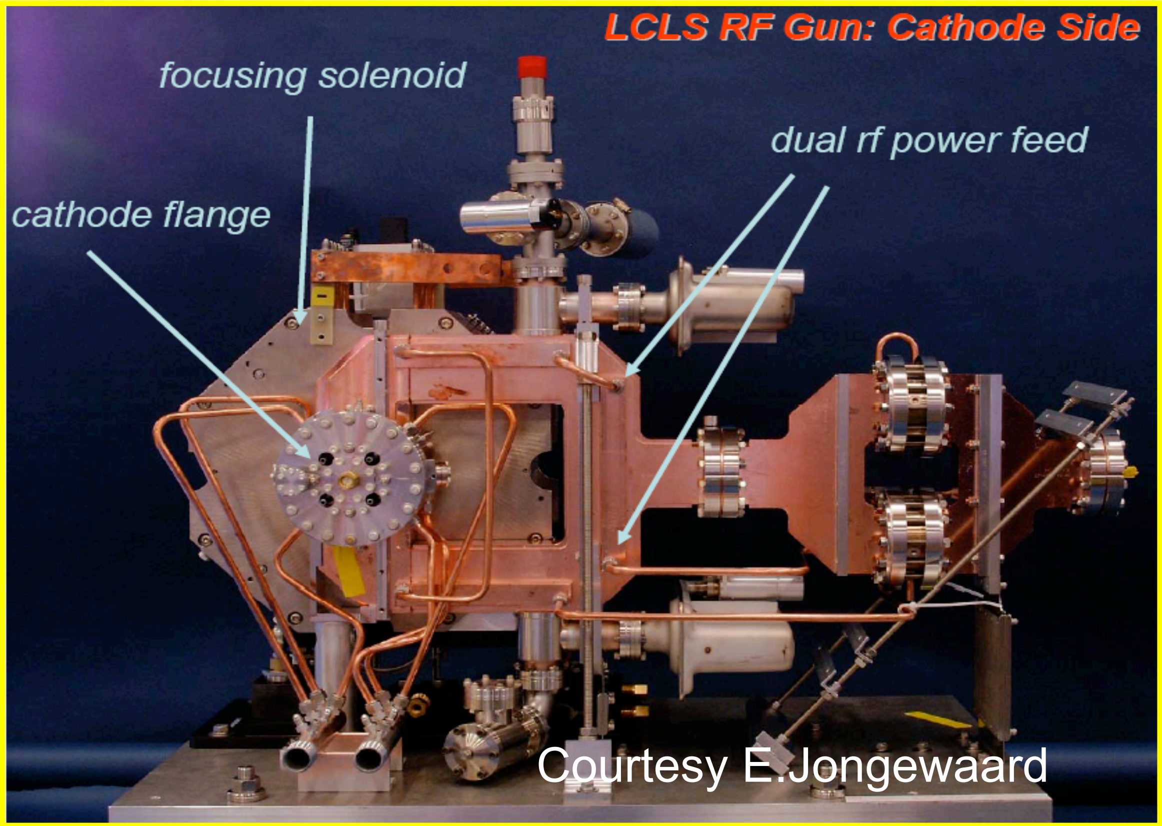
- Z-coupling:
  - reduces pulsed heating
  - increases vacuum pumping
- Racetrack to minimize quadrupole fields
- Deformation tuning to eliminate field emission from tuners
- Increased 0-π mode separation to 15MHz
- Iris reshaped, reduces field 10% below cathode

RF Parameters	
f_p (GHz)	***2.855987***
Q0	***13960***
β	***2.1***
Mode Sep. Δf (MHz)	***15***

RF Gun: Processing and Operation

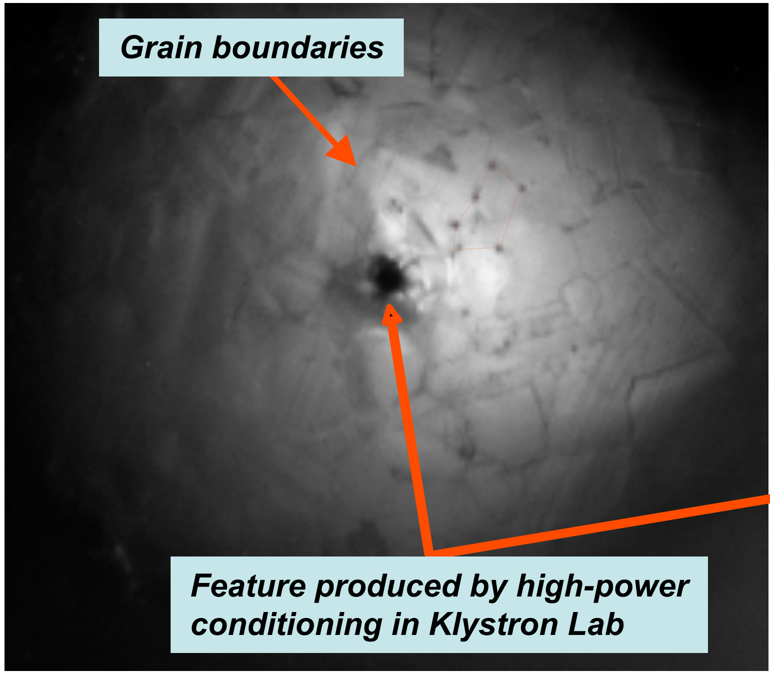
- Conditioning
  - 60Hz, 120 MV/m
  - 120Hz , 107 MV/m due to heating of probes
- Operation
  - 30 Hz, 110MV/m, 1 μs klystron pulse
  - 3.10^8 pulses

  (from April to Aug 07)

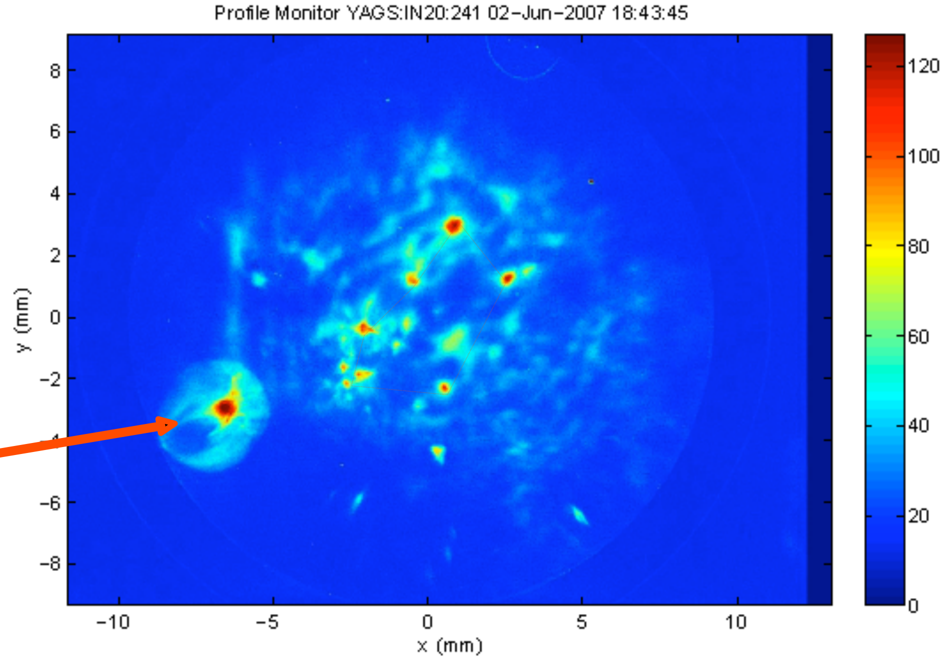


Cathode Non-Uniformity

June 6, 2007
White light cathode image



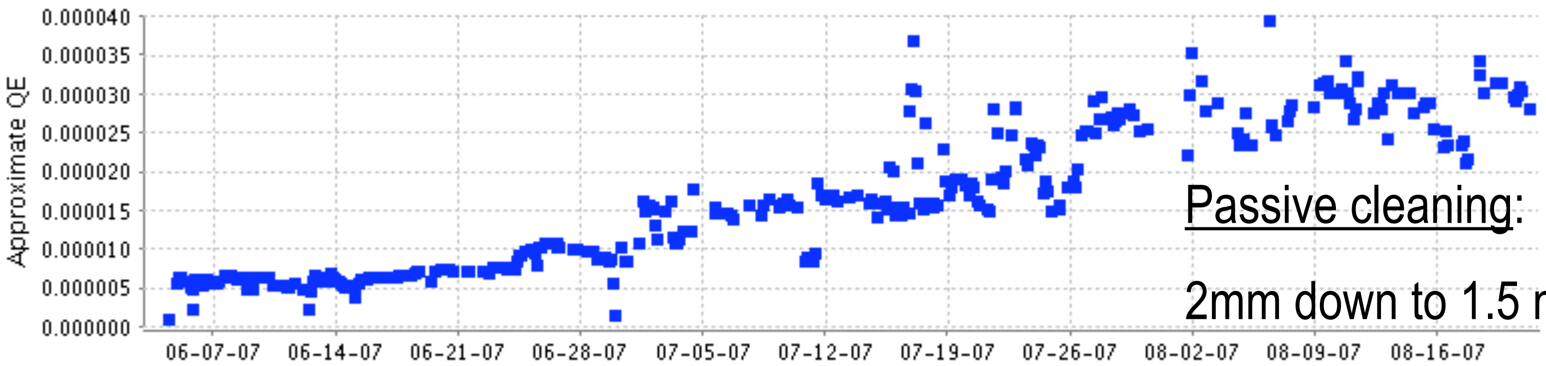
June 2, 2007
Electron beam image of cathode @ ~9pC



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

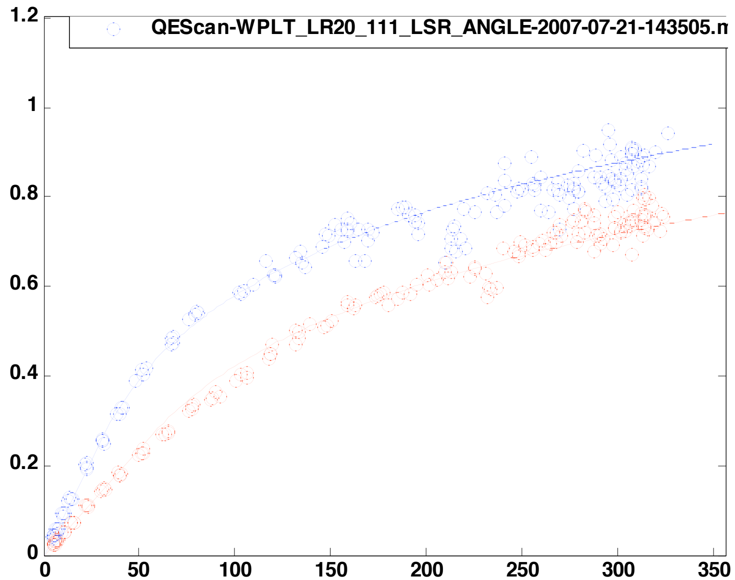
courtesy D.Dowell

Laser Cleaning: QE from 2.10^{-6} to 4.10^{-5}



Passive cleaning:

2mm down to 1.5 mm



Active cleaning:

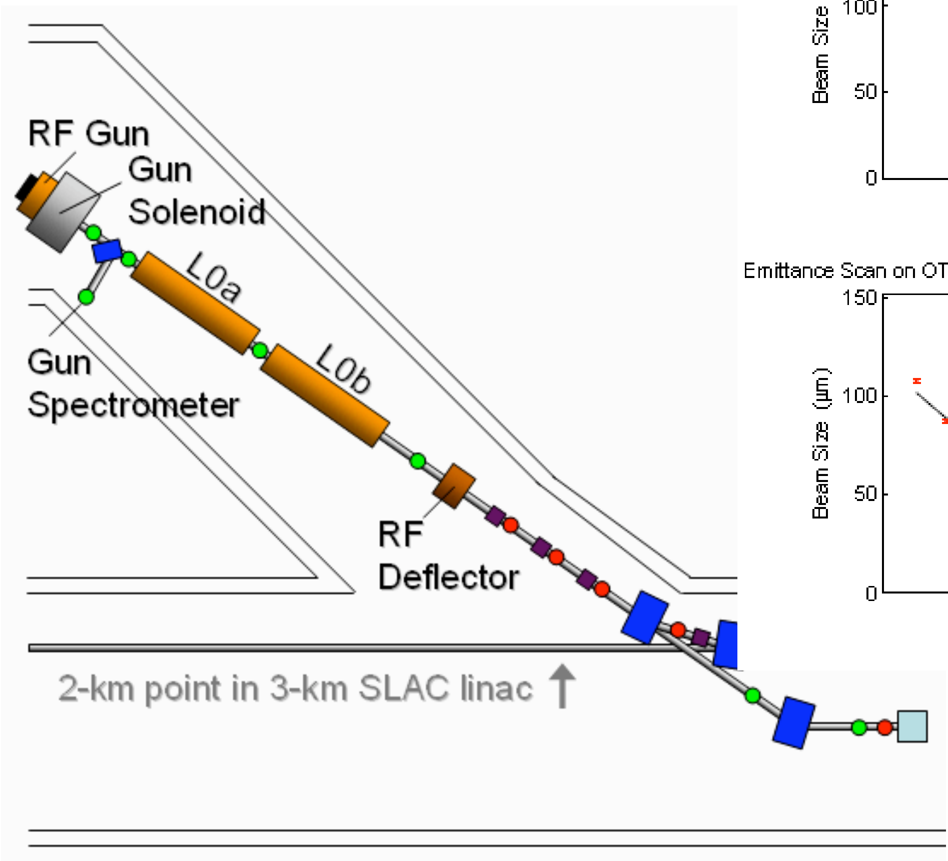
RF on 1MV and at 30 °

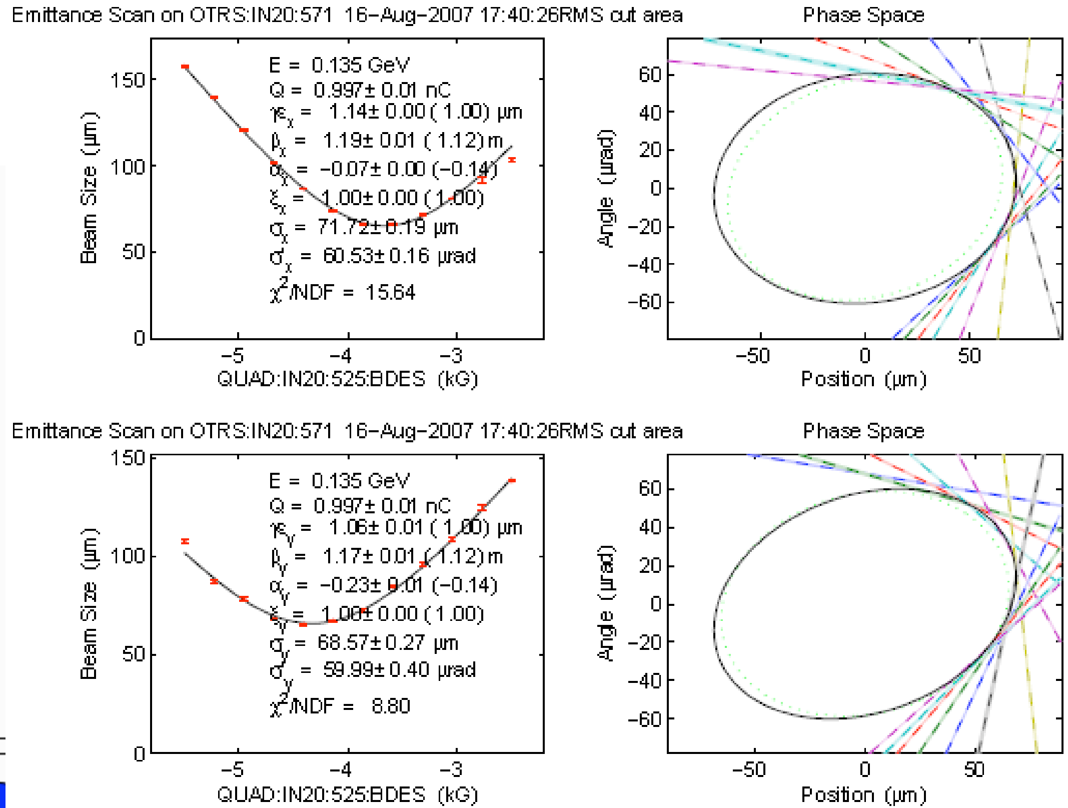
Laser 360 μJ per mm²

Operation in Space Charge Limited regime

Projected Emittances at 1nC

On-line analysis tools by H. Loos

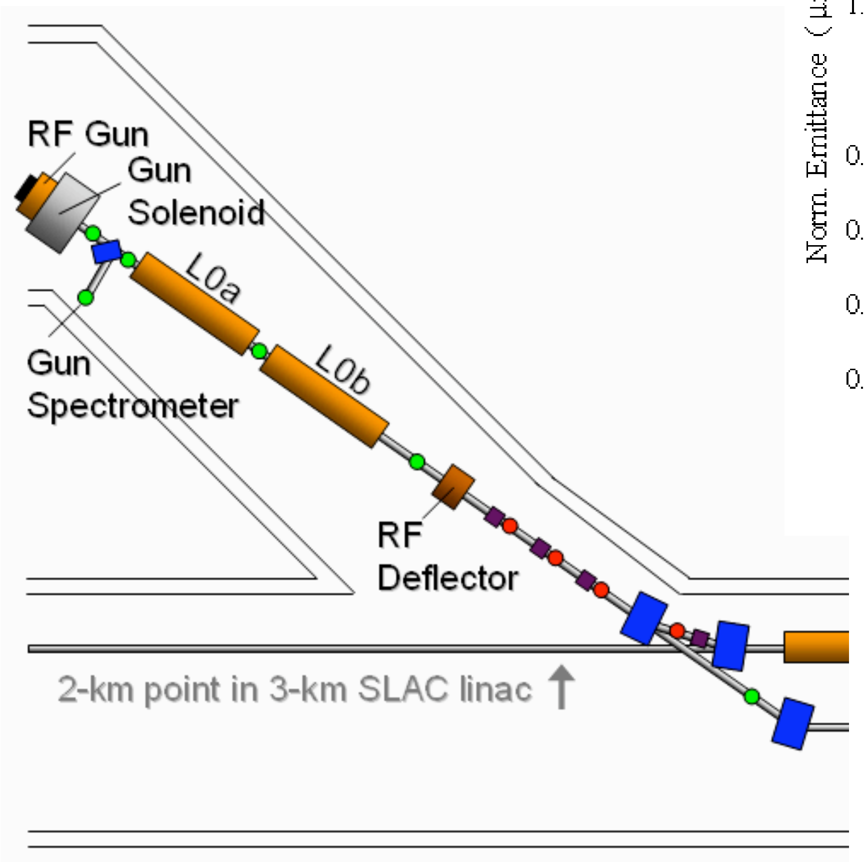


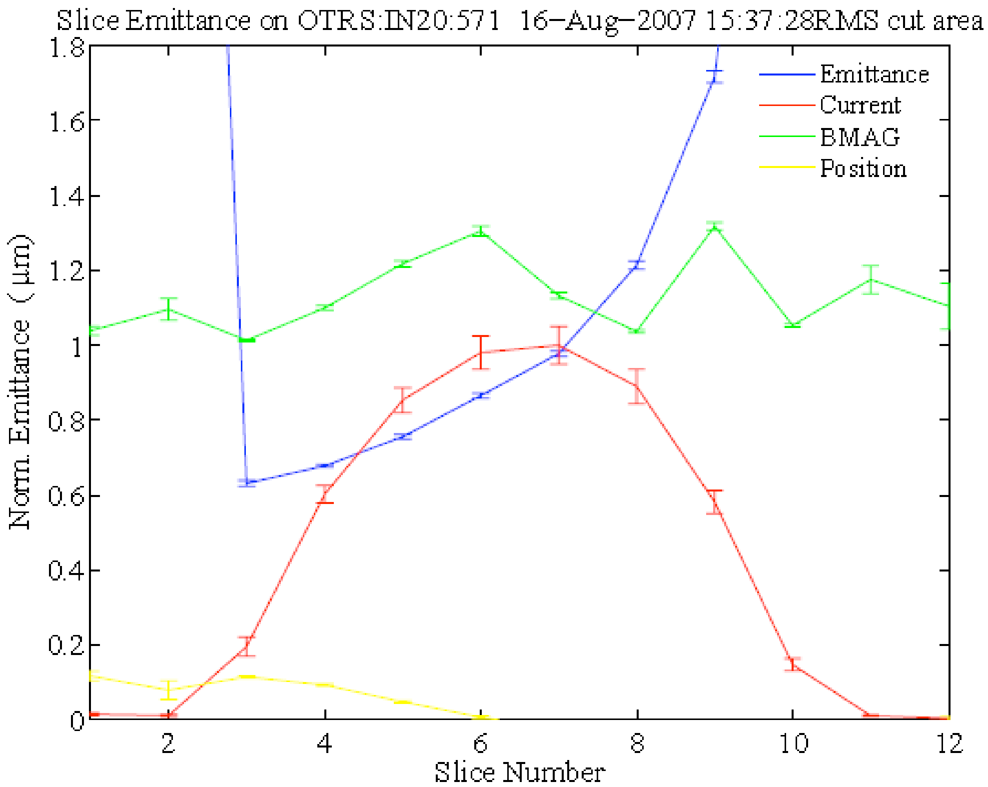


Projected Emittance (rms) at 1nC
(95% of the beam):
ε_x = 1.14 mm-mrad
ε_y = 1.06 mm-mrad

Slice Emittances at 1nC

On-line analysis tools by H. Loos

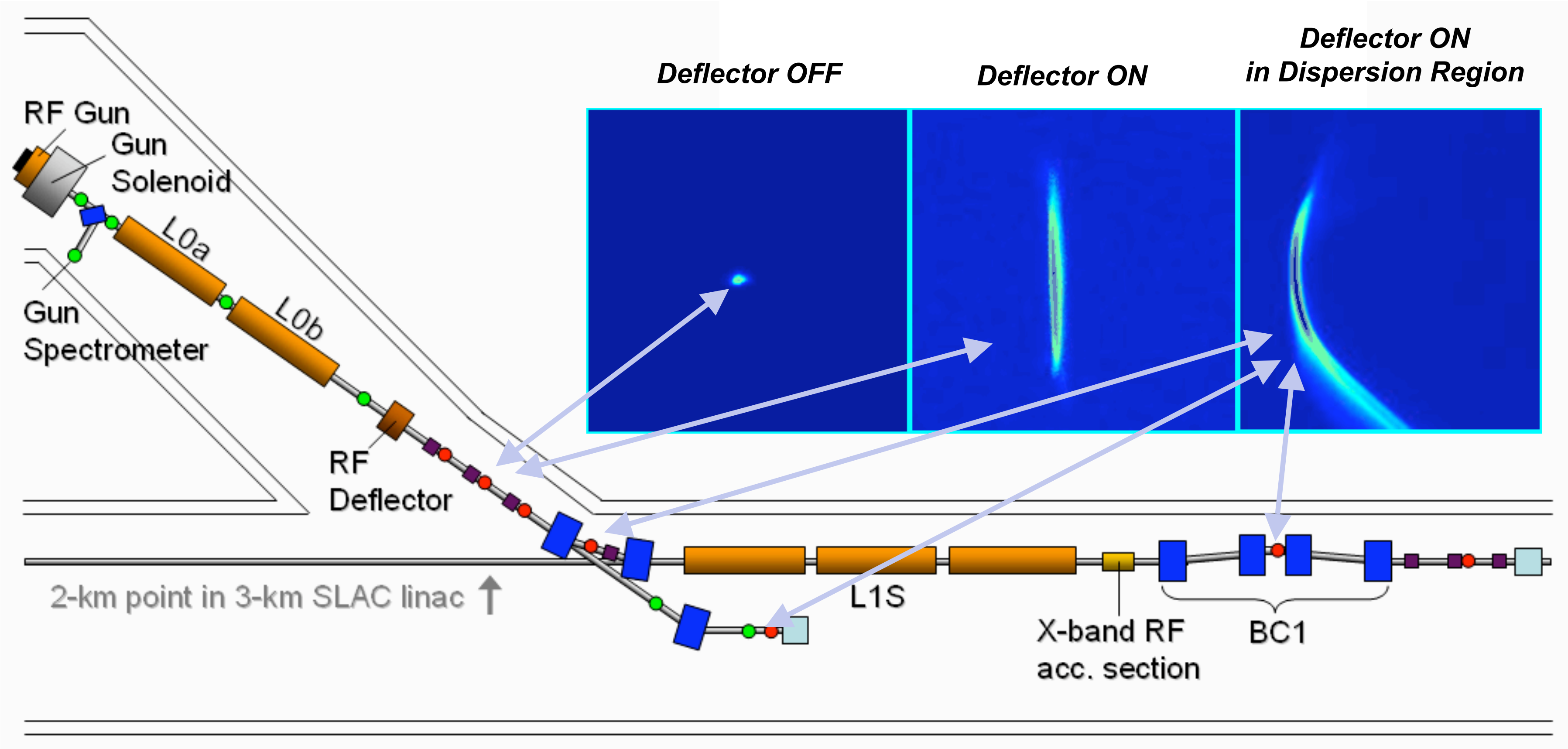




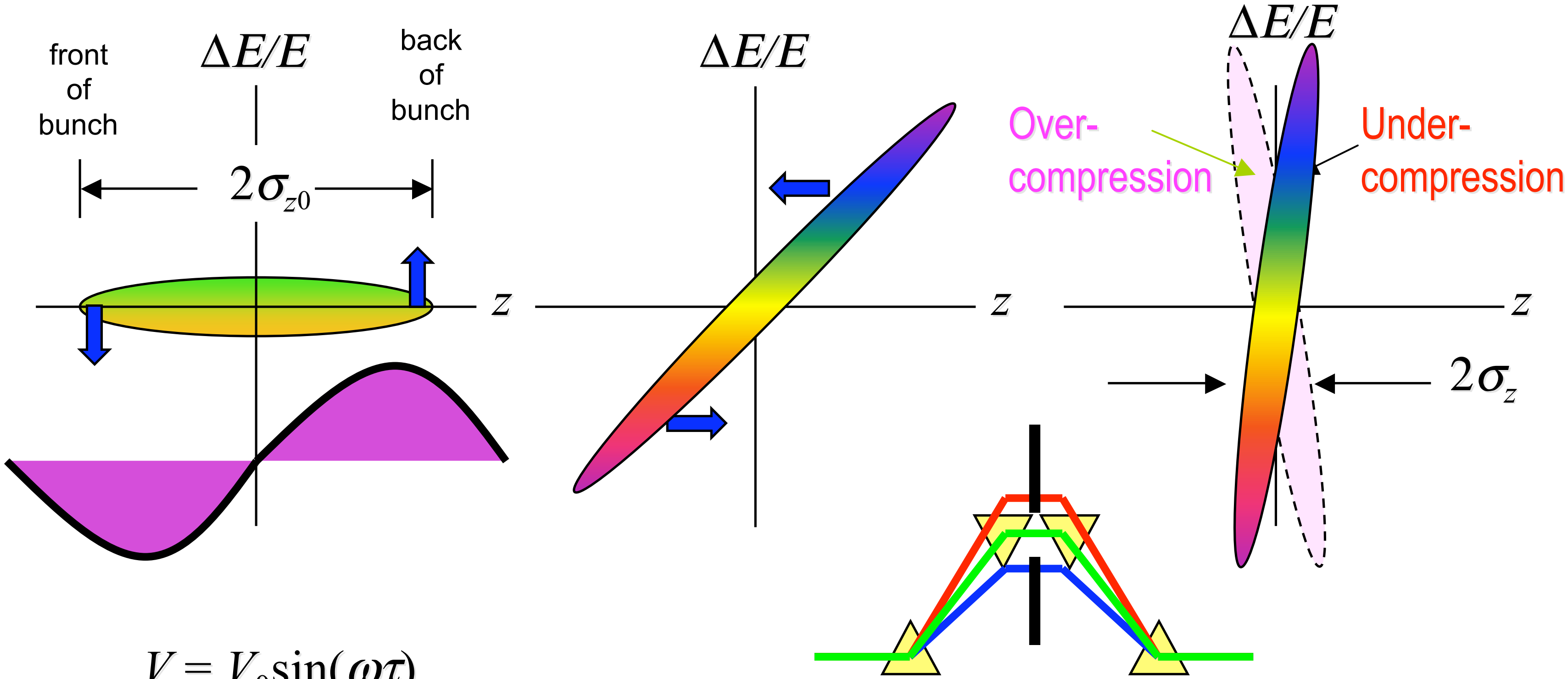
<u>Slice Emittance, Current & Matching</u>

Slices 3 to 7 (tail) are all below 1 mm-mrad
Head slices (8-10) are > 1 mm-mrad
Peak Current is 100 A

Transverse Cavity (RF-Deflector) Measurements of Bunch Length



Bunch Compression



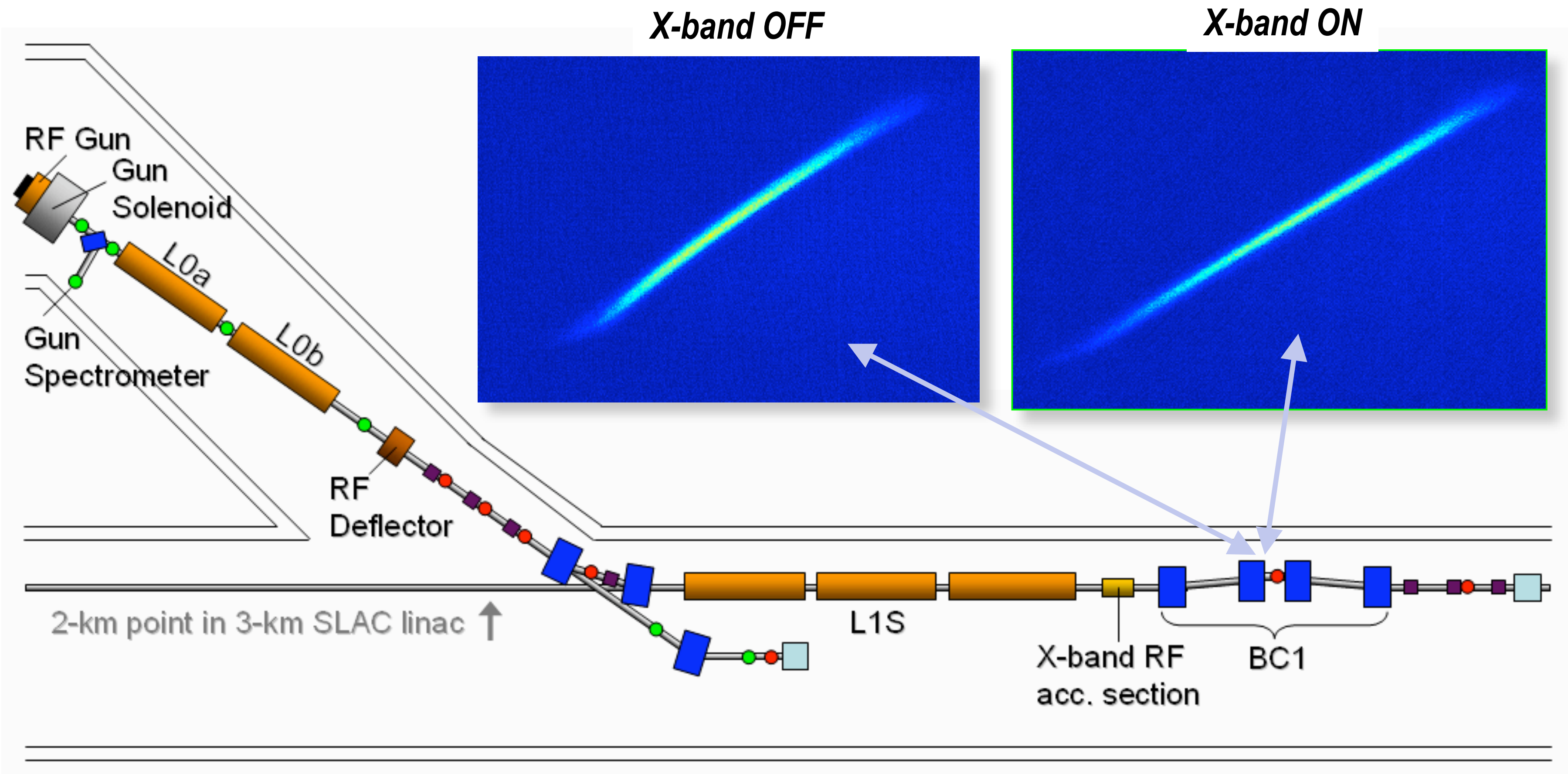
$V = V_0 \sin(\omega\tau)$

$\Delta z = R_{56} \Delta E/E$

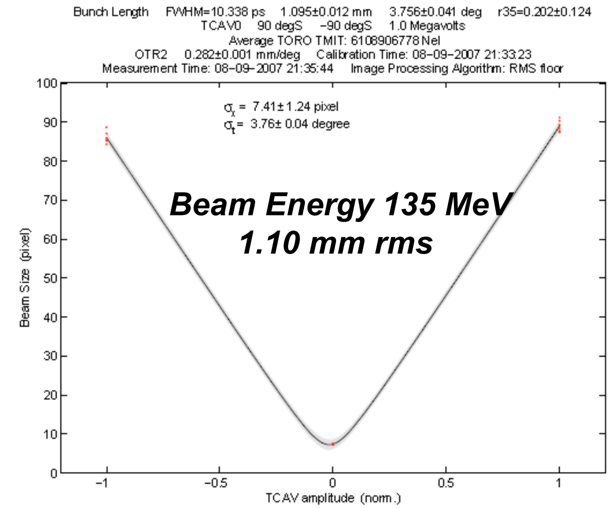
RF Accelerating Voltage

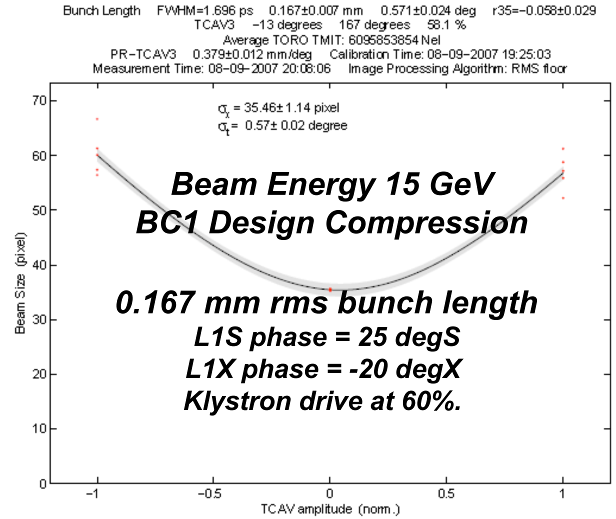
Path Length-Energy Dependent Beamline

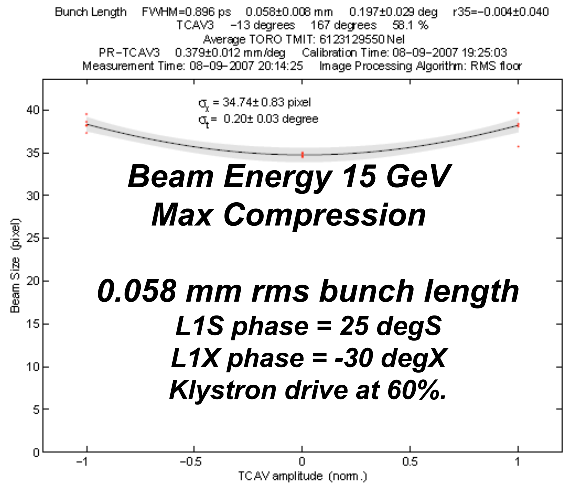
Linearization of Longitudinal Phase Space Measured Using RF Deflector & OTR Screen in Center of BC1

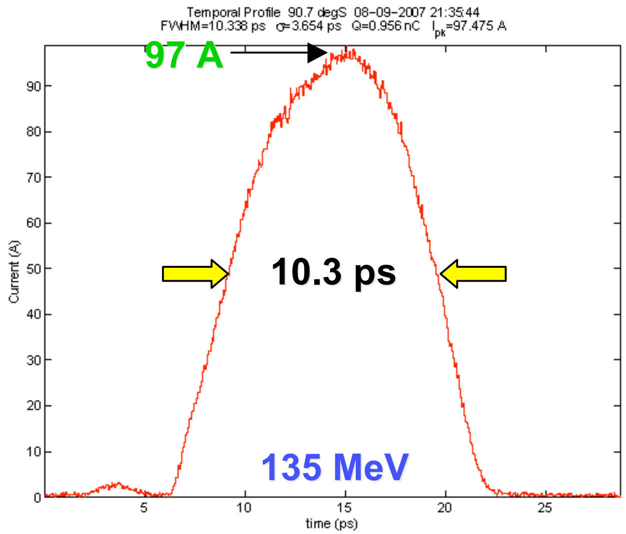


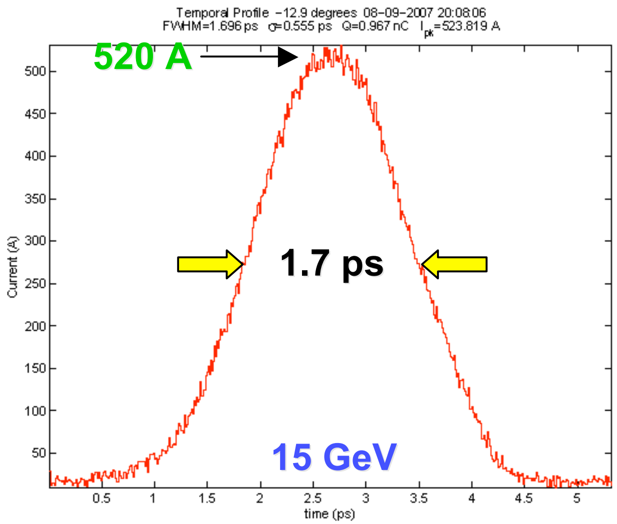
Bunch Length Measurements at 135MeV & 15GeV

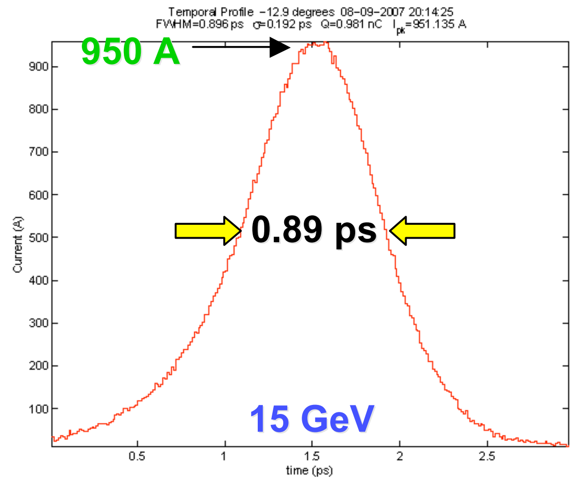








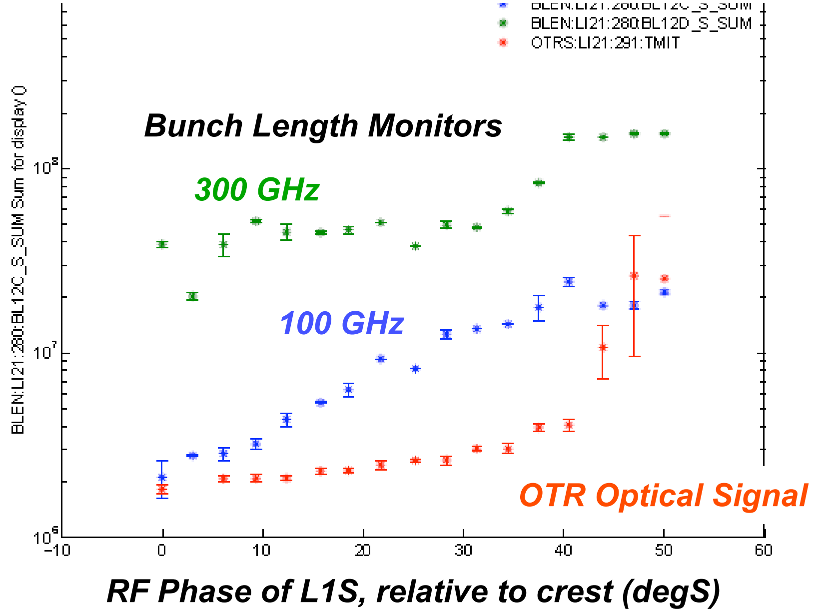




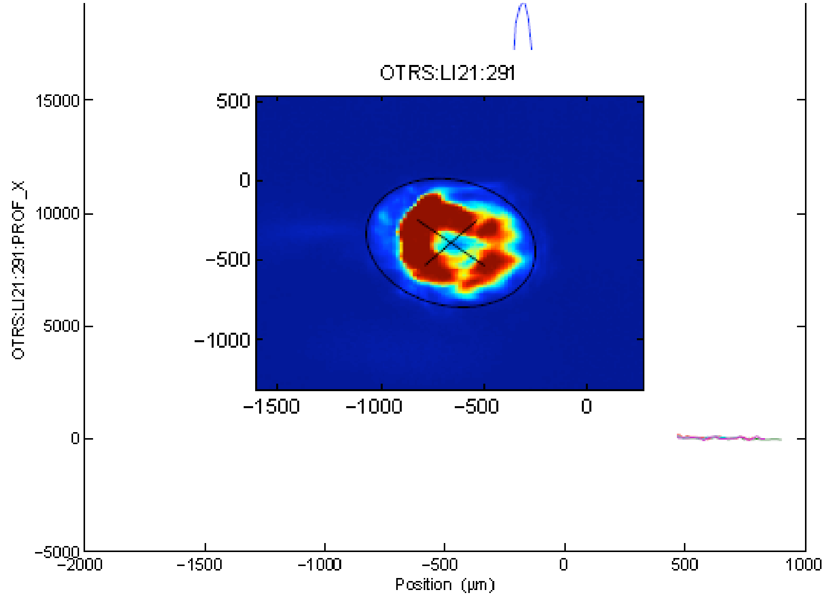
Strong Optical Microbunching with BC1 Set to Maximum Compression

- Generation of COTR in the Visible indicates Microbunching
- COTR Interferes with OTR Profiles for Emittance Measurements.

Comparison of Bunch Length Monitor & OTR Signals

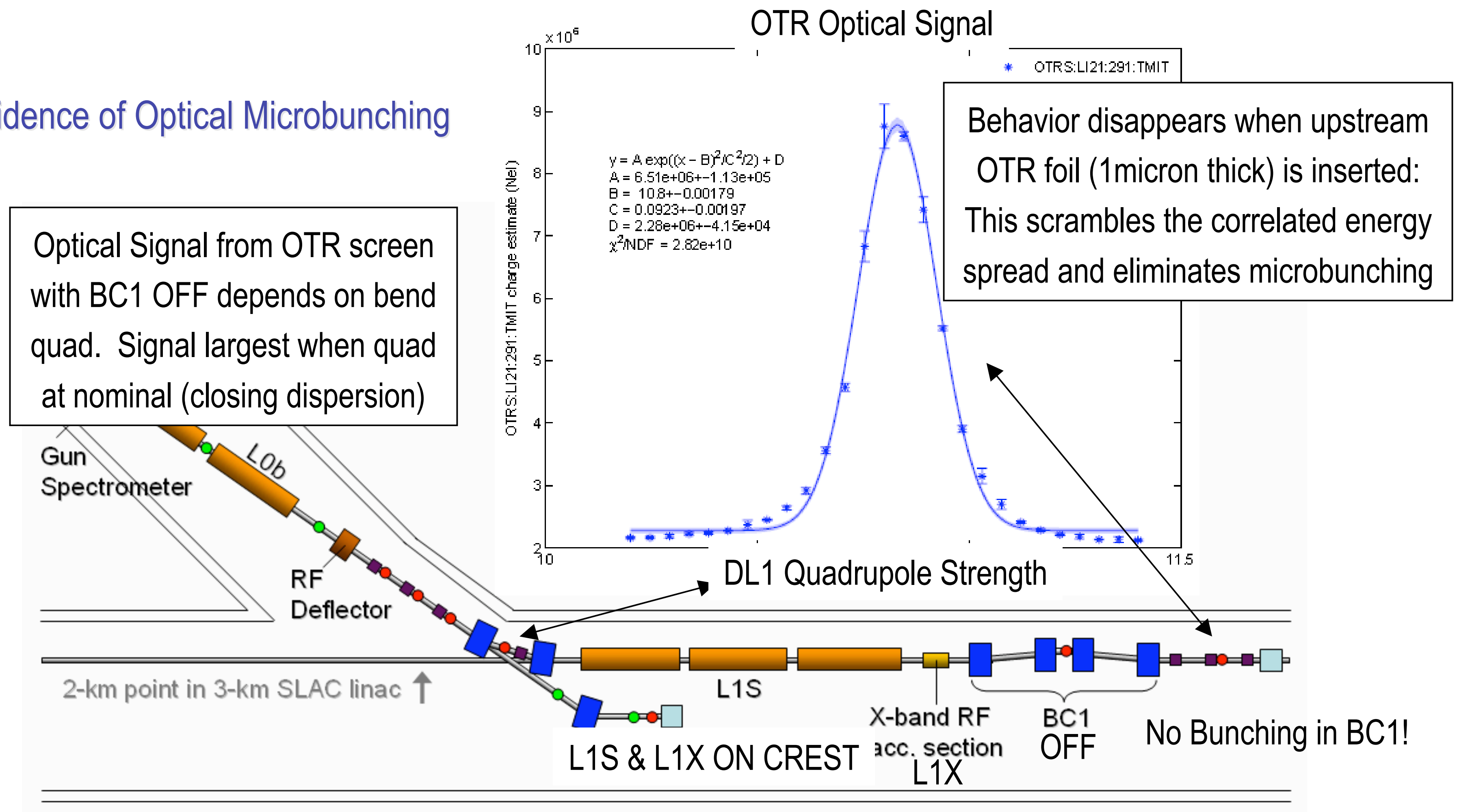


OTR Images Fluctuate from Shot-to-Shot & can produce "Ring-Like" Shapes!

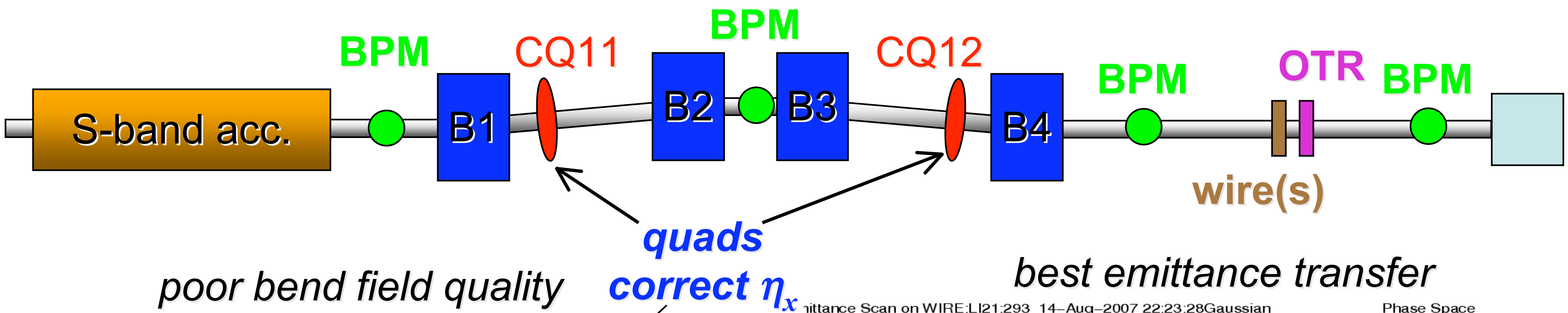


Coherent Optical Transition Radiation after DL1 Bend Even With No BC1 Compression

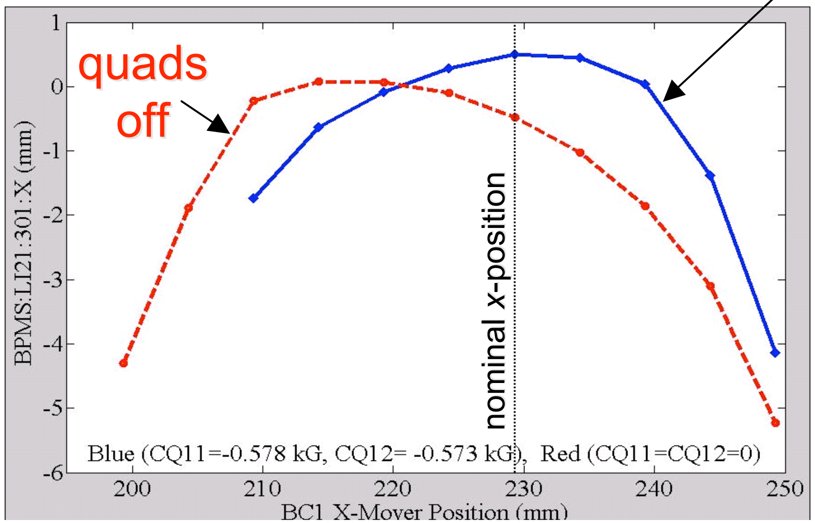
Evidence of Optical Microbunching



BC1 Chicane Emittance Growth

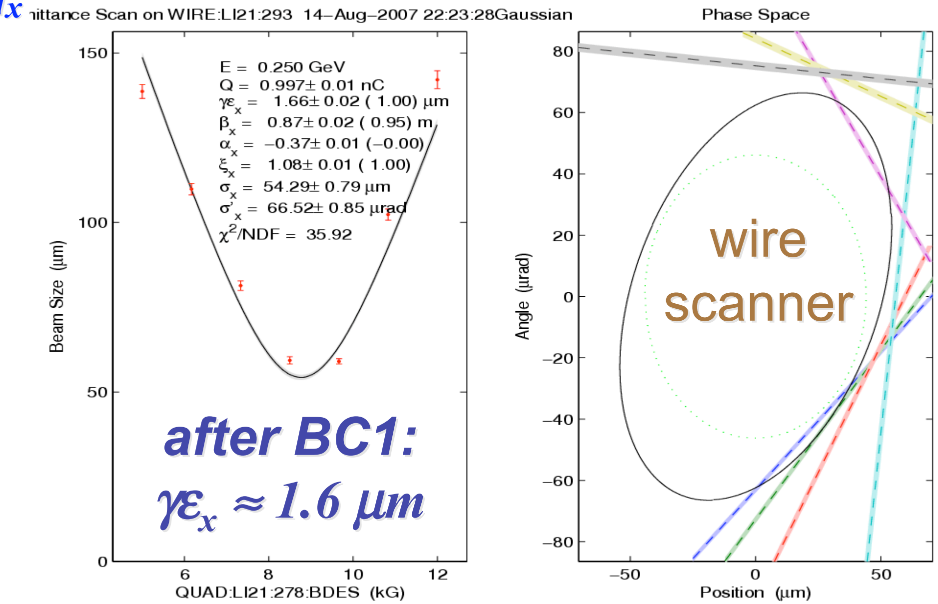


poor bend field quality



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%)

PART 3:

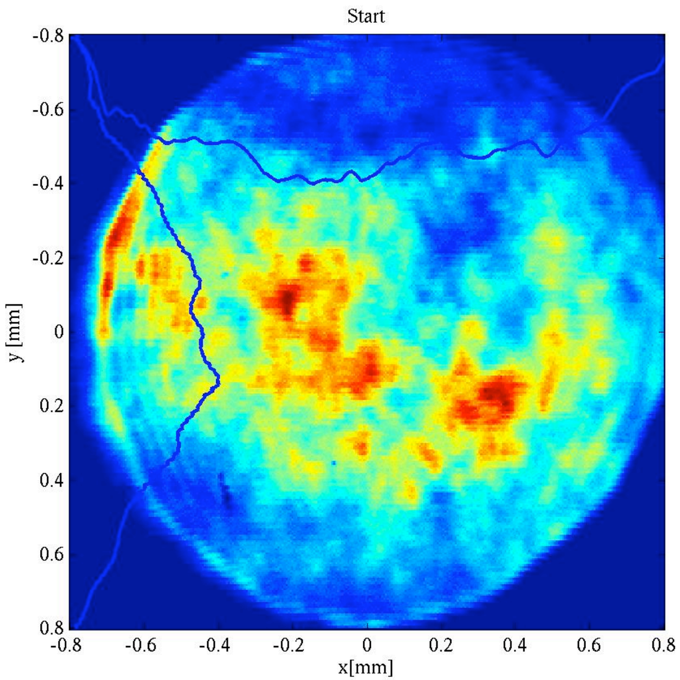
Simulations:

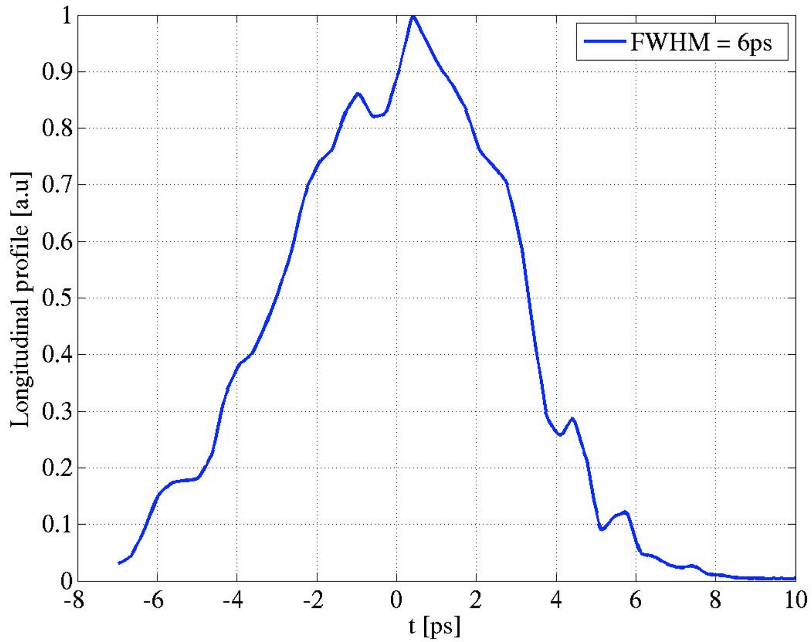
- effects of tails truncation in emittance computation
- comparison of emittance data along solenoid scan

Initial Distribution

Spatial distribution based on laser profile (transverse and longitudinal)

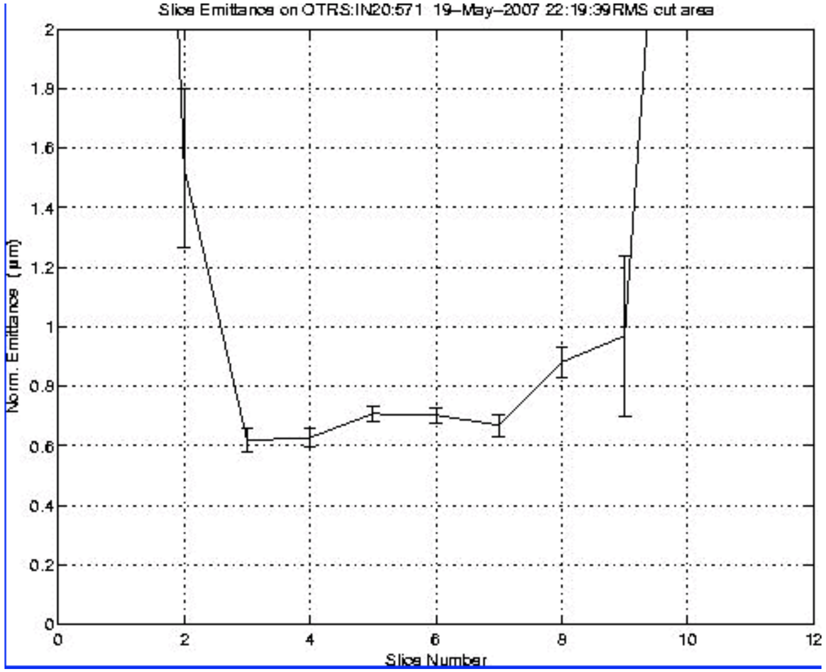
Quiet start routine based on Halton sequences



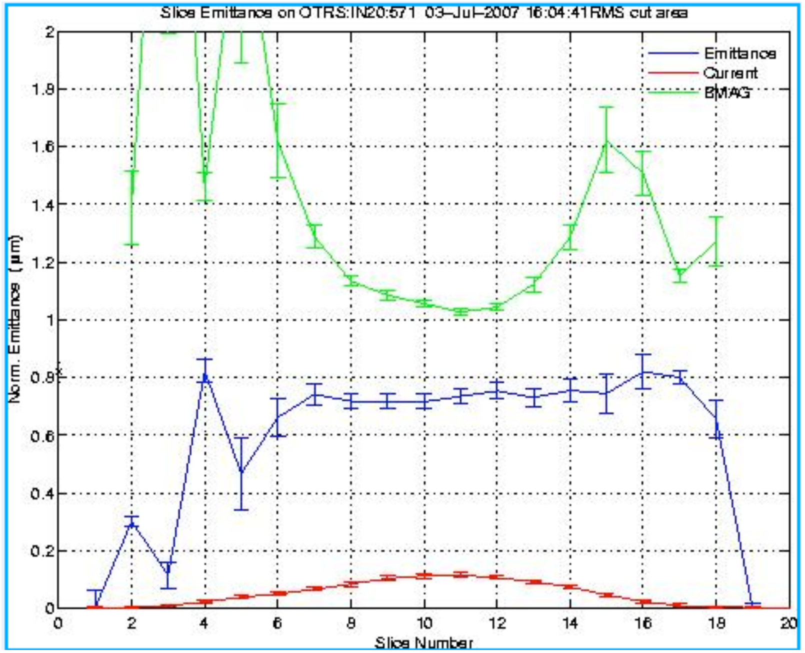


“Thermal” Emittance

Based on Measurements



At 30 pC ,May 19th

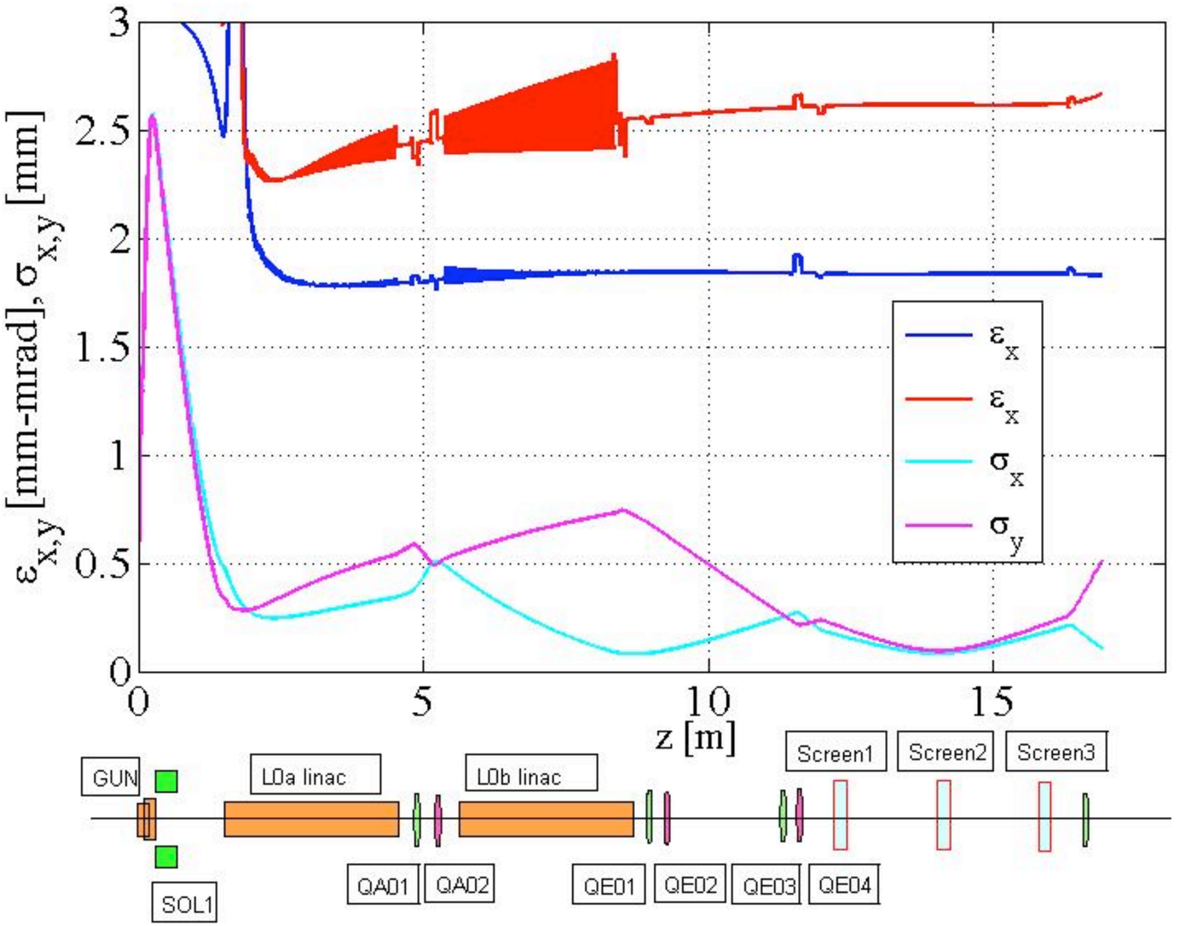


30pC, July 3rd , after “cleaning”

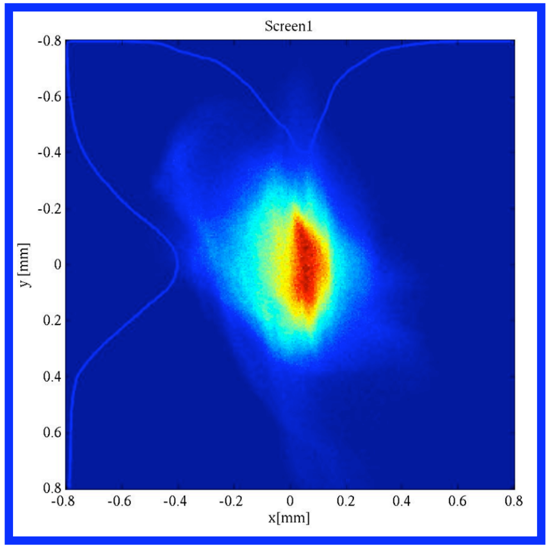
Simulations used 0.6mm-mrad per mm

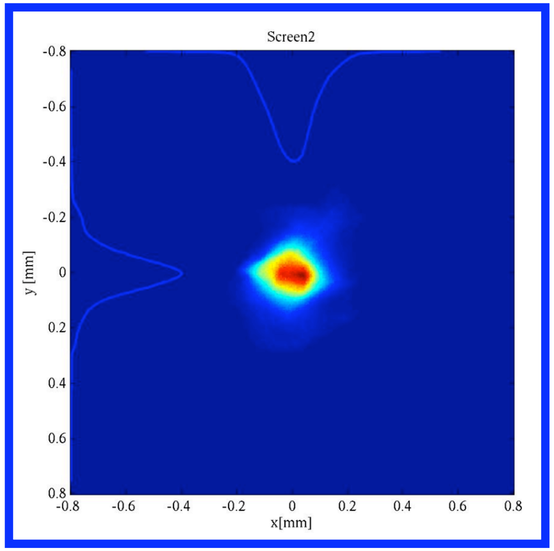
Beamline Matched

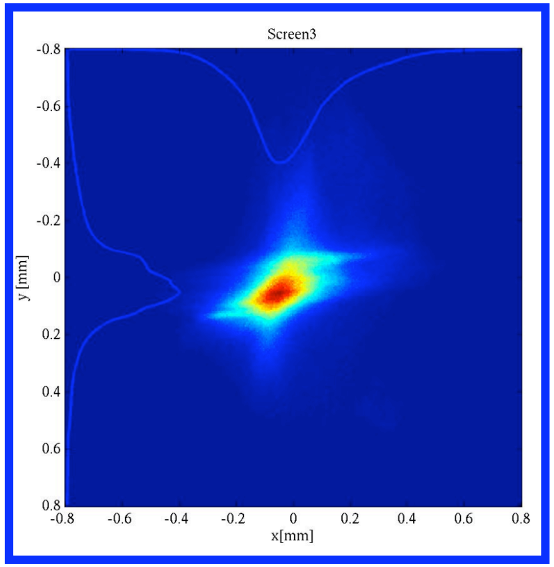
Simulations try to represent at best experimental conditions



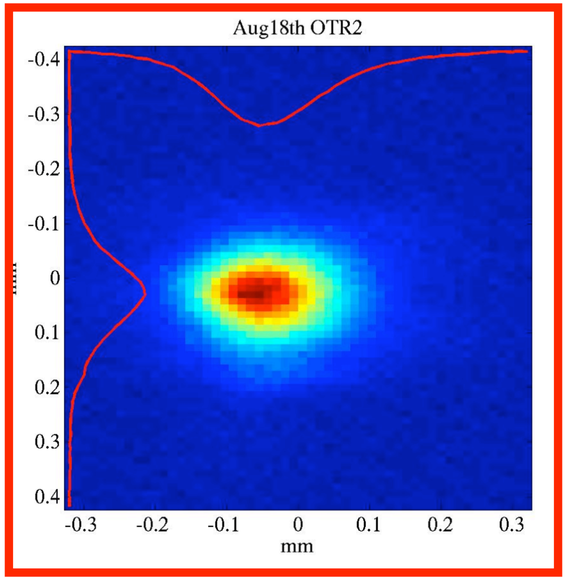
Transverse Tails





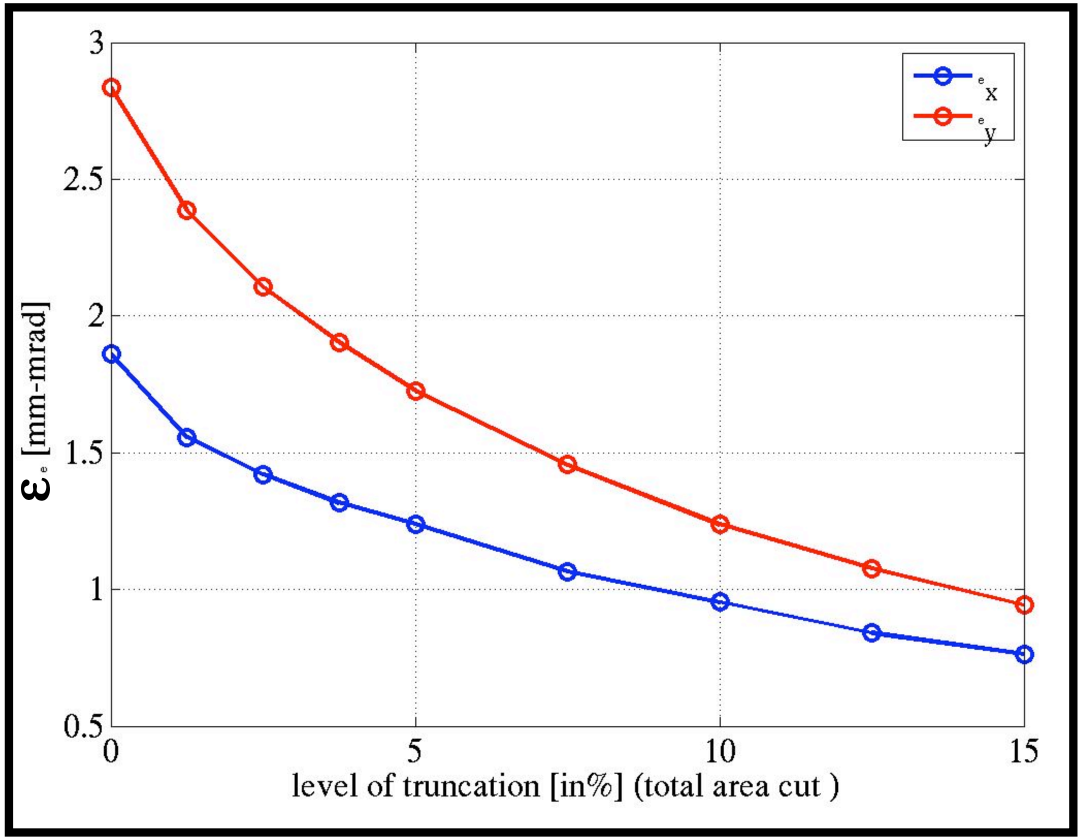


IMPACT simulations (4 Million particles)



OTR2 image: resolution of 12 μm

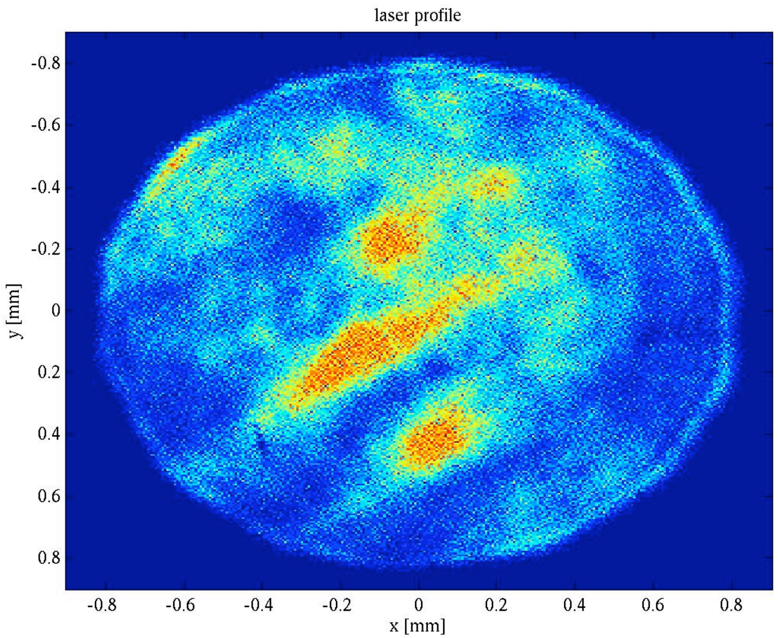
Emittance for various cut levels

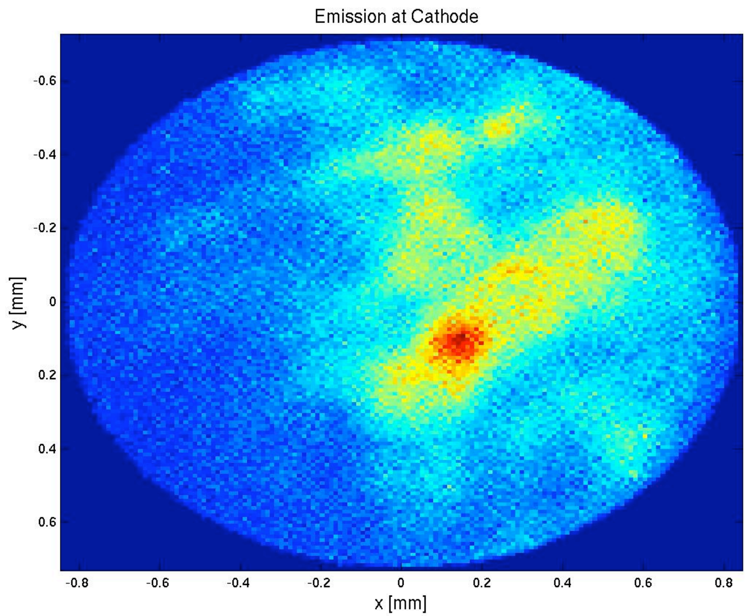


Measurements give ~ 1-1.5 mm-mrad using 5 % area cut on beam size (highly reproducible result at 1nC)

Simulations predict similar result at 7.5% cut level

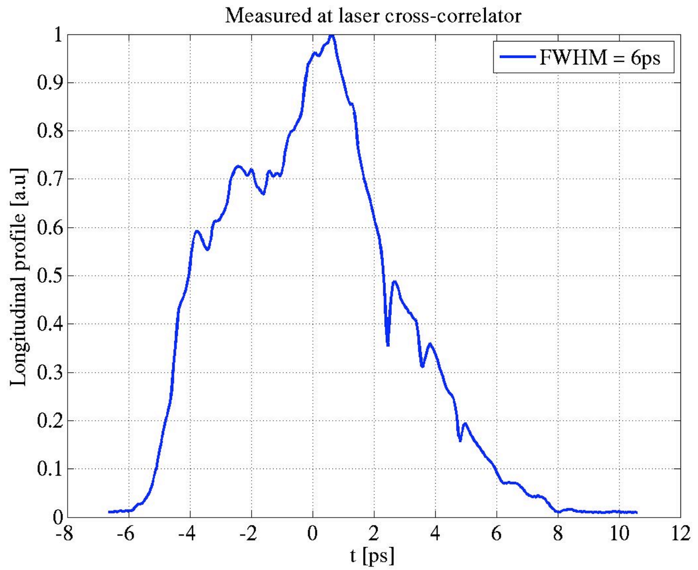
Emission distribution used in simulations

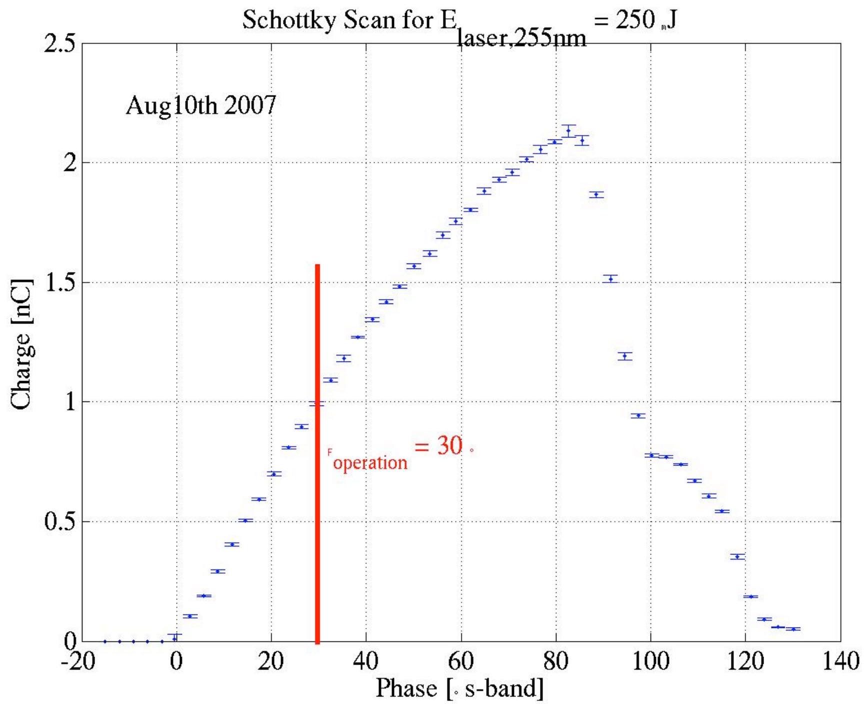




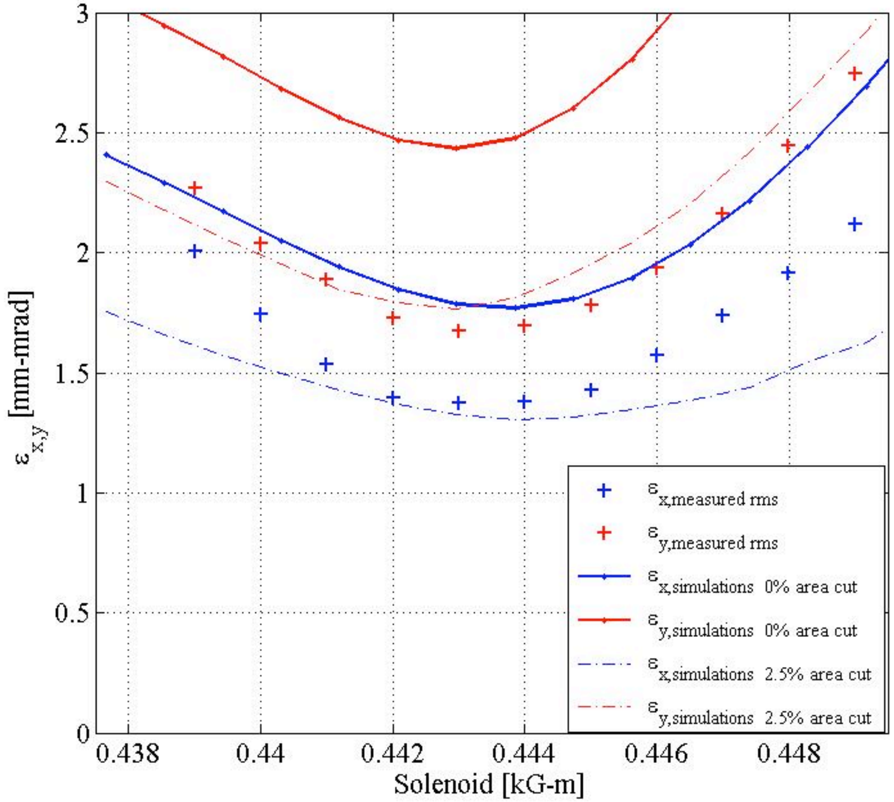
Emission distribution needed for accurate distribution

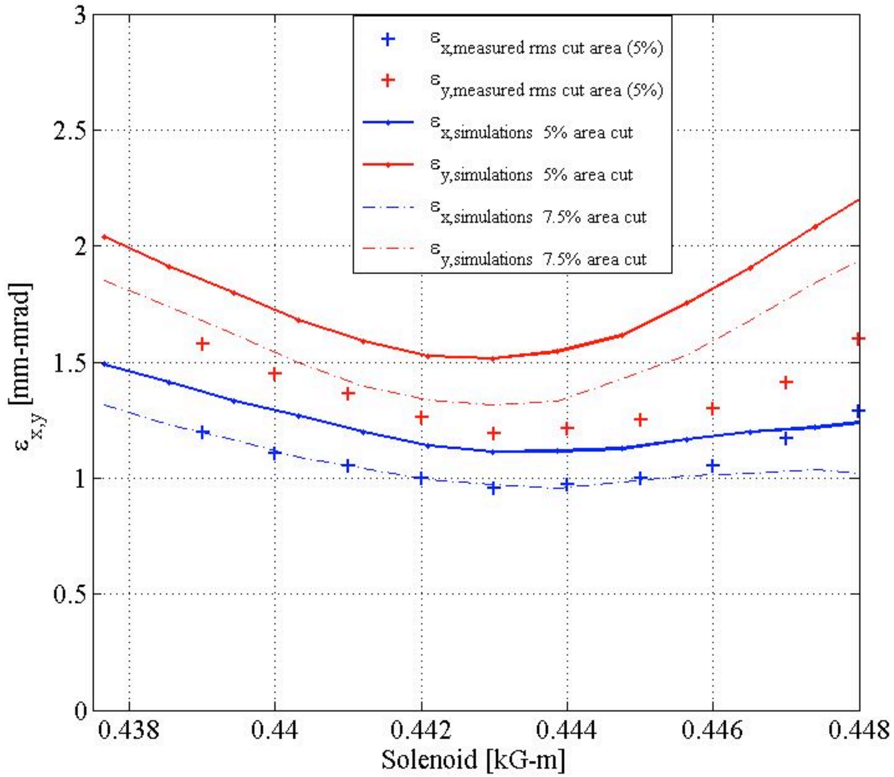
Longitudinal Profile



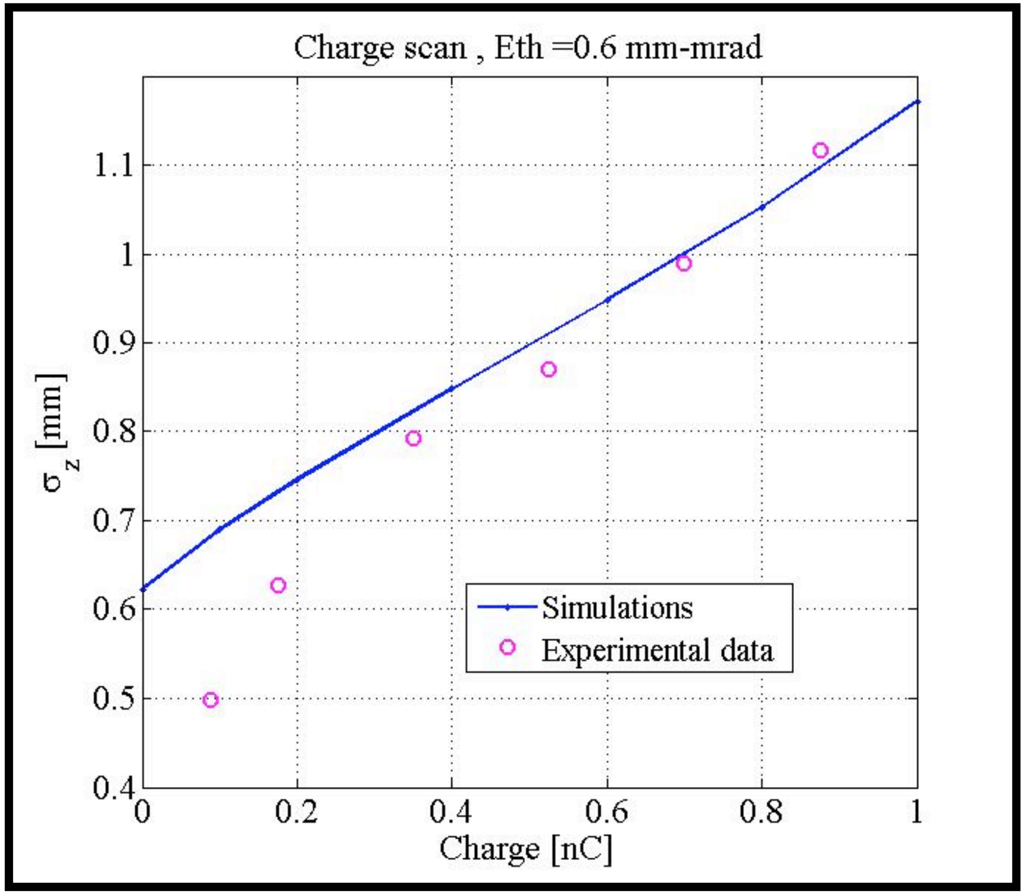


Solenoid Scan





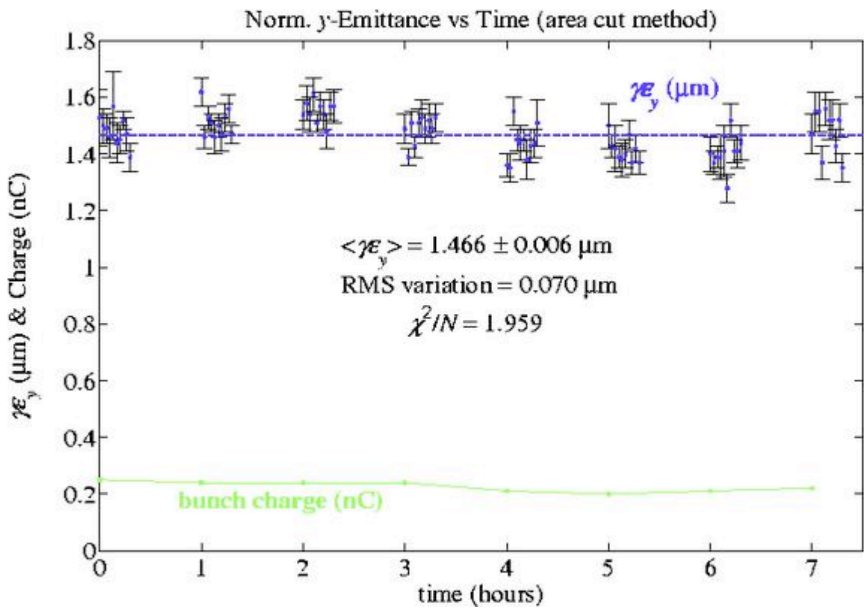
Bunch length

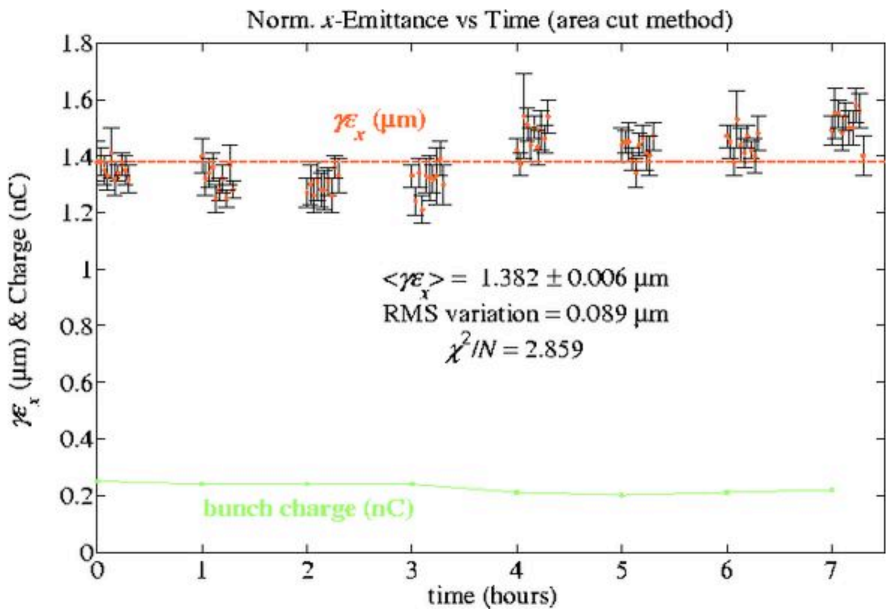


Laser Profile was 5ps FWHM

Emittance measurements

220 pC, projected emittance , in early commissioning





May 20th 2007 , from LCLS commissioning team

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, 0.9	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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- Merci pour votre attention