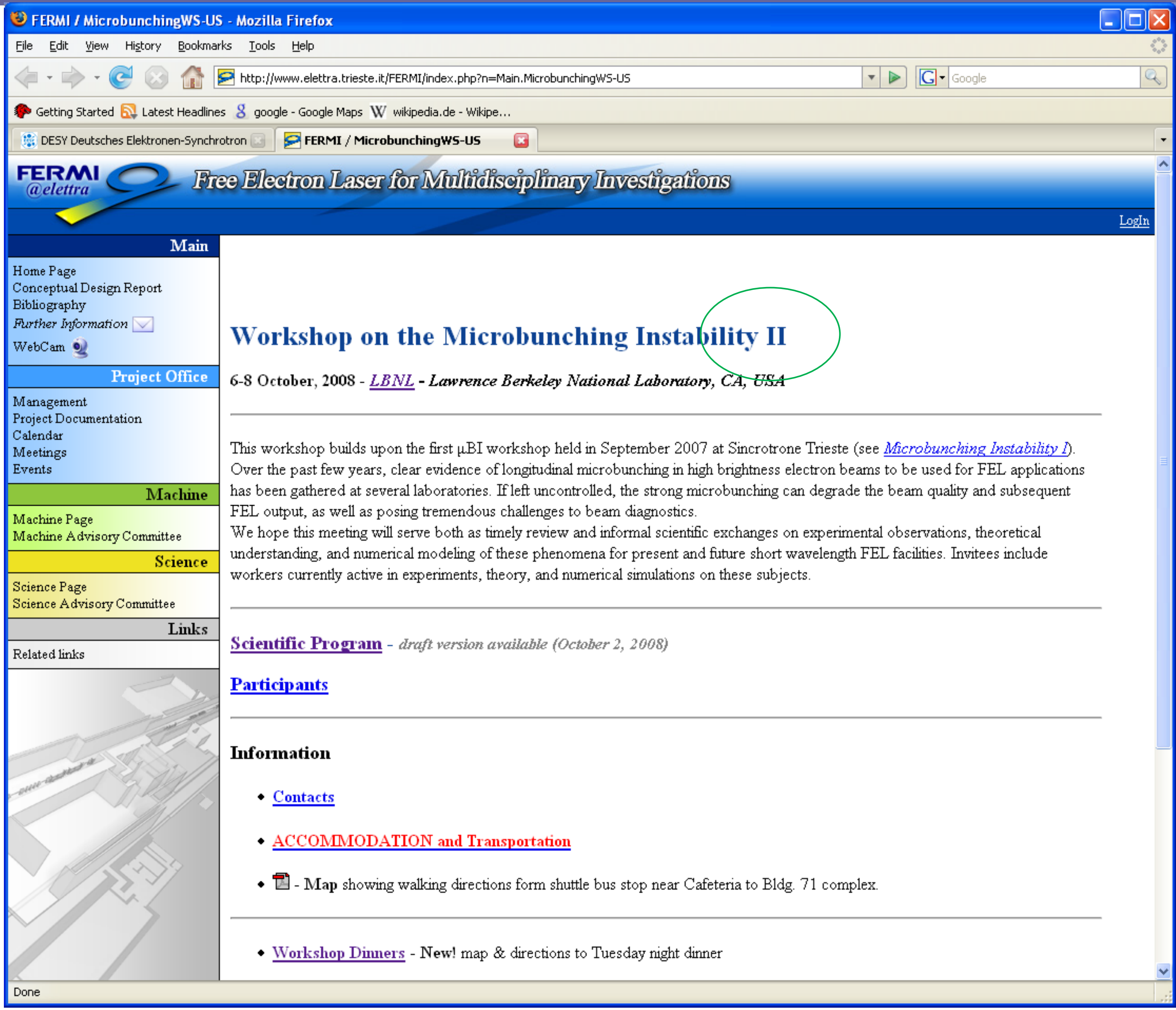
XFEL
X-Ray Free-Electron Laser

DESY

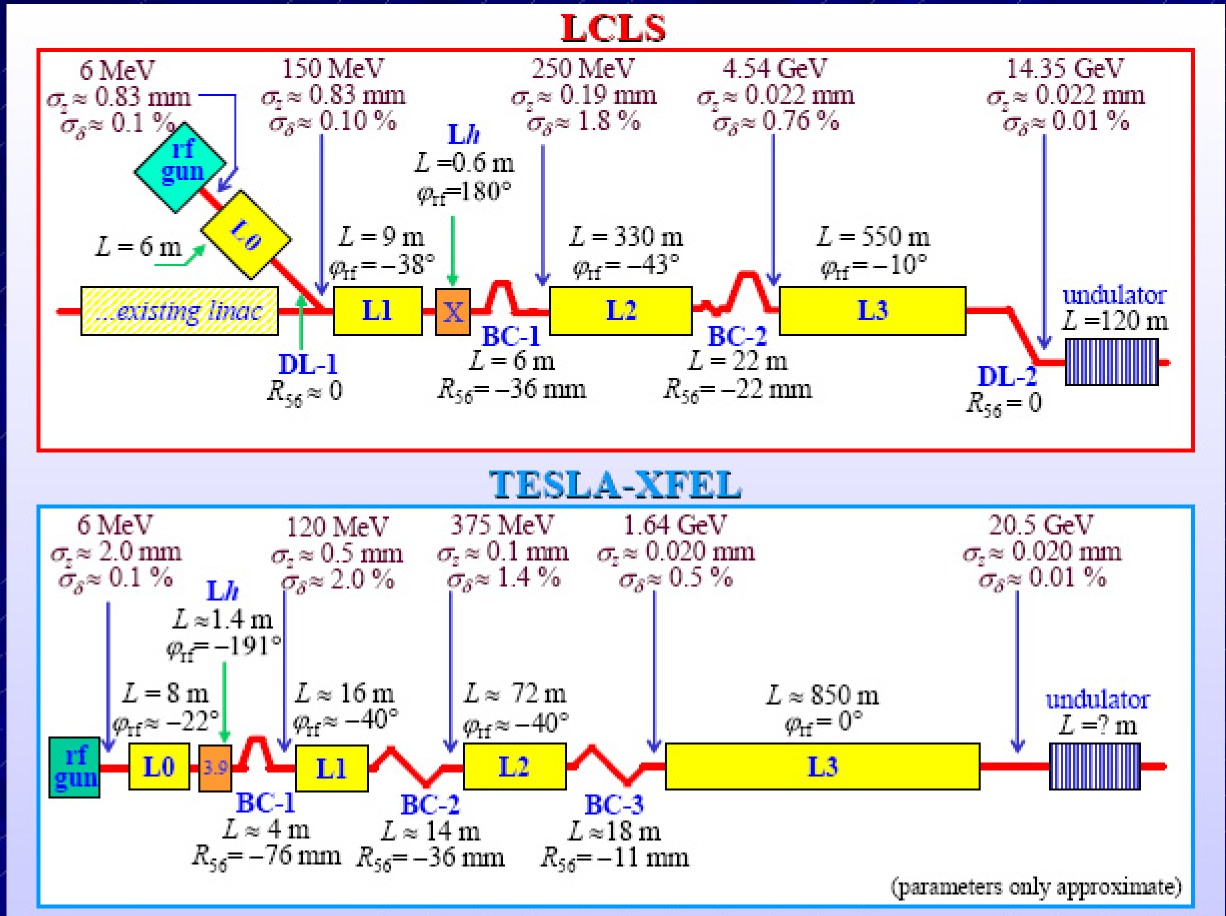
# LCLS Status and Micro-Bunching Workshop at LBNL

Torsten Limberg

# Workshop Home Page



# The Zeuthen Benchmarking Scenarios




Graphics: P. Emma

DESY-XFEL Benchmarking lattice: N. Golubeva, J.-P. Carneiro, Y. Kim

# E. Schneidmiller: Gain Curve for TTF-2 and Consequences

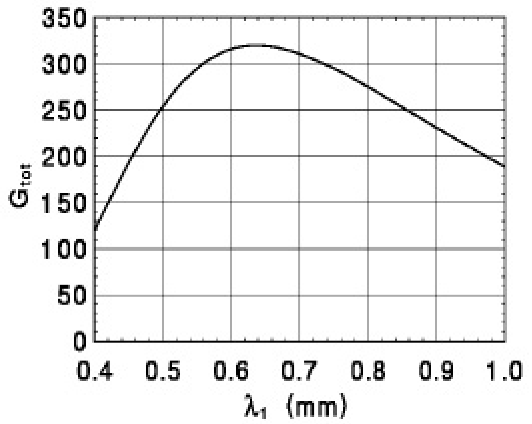



Figure 1: Total gain versus initial modulation wavelength

What happens next?
Assume initial modulation at the "optimal" wavelength to be 10-3. This results in 30 % density modulation at a wavelength of 10µm after BC2.

Consequences:
- Emittance growth in last dipole(s) of BC2
- LSC in BC2 to undulator section. For a final energy of 1 GeV the impedance is |Z|/Z0 = 200. That means about 4 MeV energy modulation (±2sigma). Also, local energy spread is growing.

Conclusion: for reliable operation of the facility one should keep initial modulations well below 10-3 level. Or suppress amplification.

What should we do?
Full S2E required (incl. plasma oscillations at low energy, CSR in BCs, other wake fields). Studies of noise sources in the gun. Laser pulse should be as smooth as possible. One might even refuse the concept of flat-top pulse with small rise/fall time (which is good for projected emittance, but not necessarily for central slices).

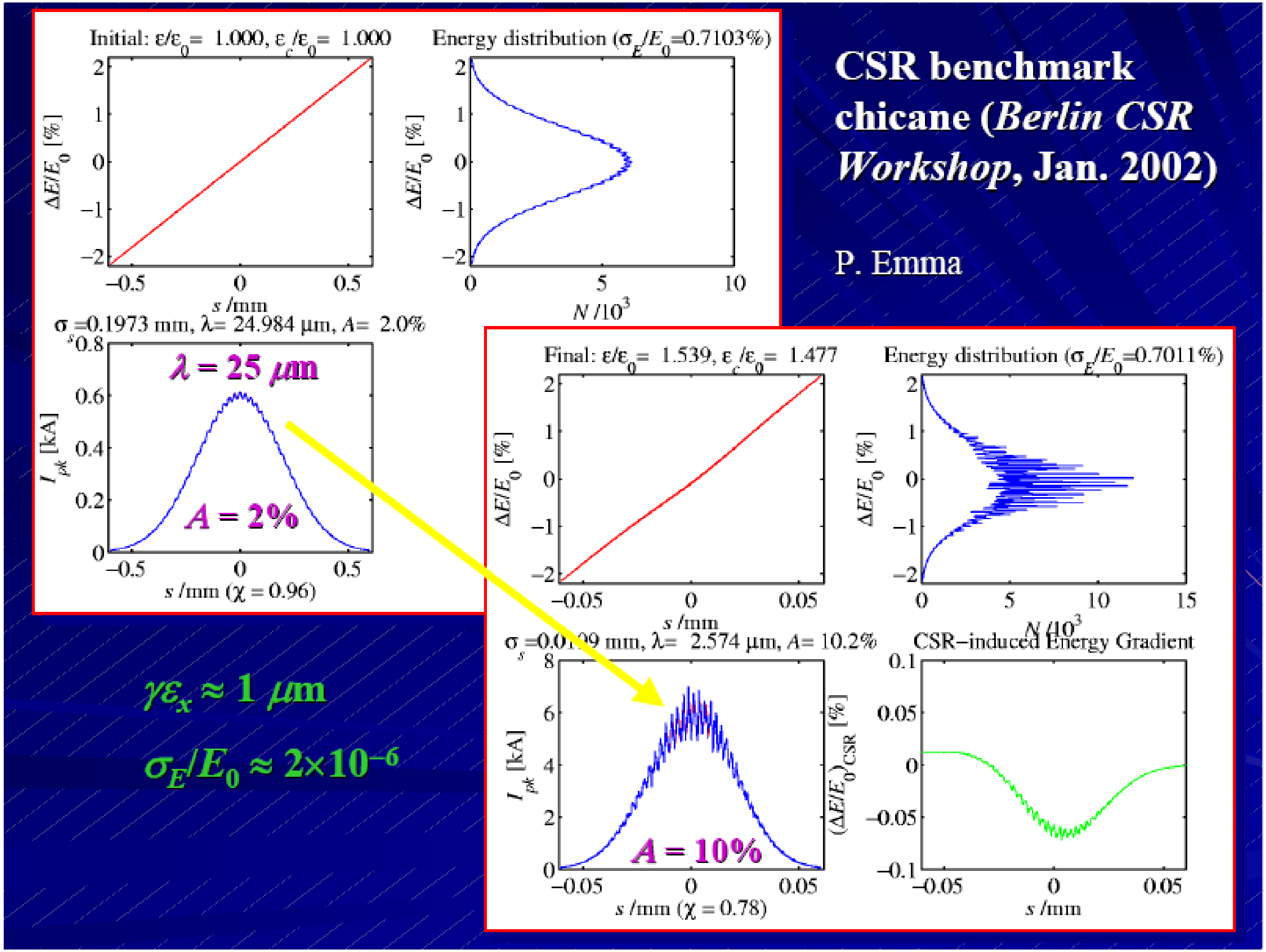
## "Emergency knob"

- Maximum gain is very sensitive to the local energy spread. Instability in TTF2 linac could be strongly suppressed if the initial energy spread would be 15-20 keV.
- LCLS: A super-conducting wiggler (at 4.5 GeV) is going to be used to control energy spread. This method does not work at relatively low energies.
- We suggest another method: FEL type modulation of the beam in optical wavelength range by a laser pulse in an undulator. Then the beam goes through the bunch compressor where these coherent energy modulations are quickly dissipated, leading to the e□ective "heating" of the beam. Similar mechanism takes place in storage ring FELs.

A numerical example for TTF2 (possibly for DESY-XFEL):

The undulator with ten periods, a period length 3 cm, and a peak field 0.49 T is located in front of

BC1. A fraction of power in the second harmonic ($\lambda$ = 0.52μm) of the Nd:YLF laser is outcoupled from the photoinjector laser system and is transported to the undulator. For a transverse size of the laser beam 0.5 mm (Rayleigh length is 1.5 m) and a power of 300 kW, the amplitude of energy modulation will be about 20 keV (rms energy spread is smaller by $\sqrt{2}$).

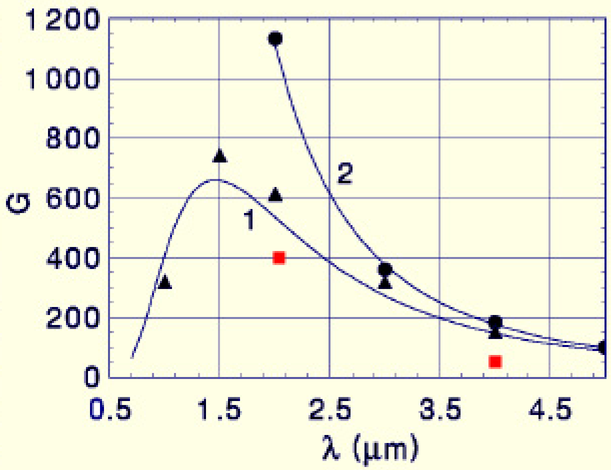

CSR benchmark chicane (*Berlin CSR Workshop*, Jan. 2002)
P. Emma
Initial: ε/ε0 = 1.000, εc/ε0 = 1.000
Energy distribution (σE/E0=0.7103%)
ΔE/E0 [%]
s /mm
N /10^3
σs=0.1973 mm, λ= 24.984 μm, A= 2.0%
λ = 25 μm
A = 2%
Ipk [kA]
s /mm (χ = 0.96)
Final: ε/ε0 = 1.539, εc/ε0 = 1.477
Energy distribution (σE/E0=0.7011%)
σs=0.0109 mm, λ= 2.574 μm, A= 10.2%
CSR−induced Energy Gradient
A = 10%
s /mm (χ = 0.78)
(ΔE/E0)CSR [%]
$\gamma\varepsilon_x \approx 1\ \mu m$
$\sigma_E/E_0 \approx 2\times10^{-6}$

# More Gain Calculations Zeuthen 2003



## CSR-induced instability – Gain curve

start with: $I(t) = I_o(t) \times (1 + m \times \cos(2\pi c/\lambda \times t))$

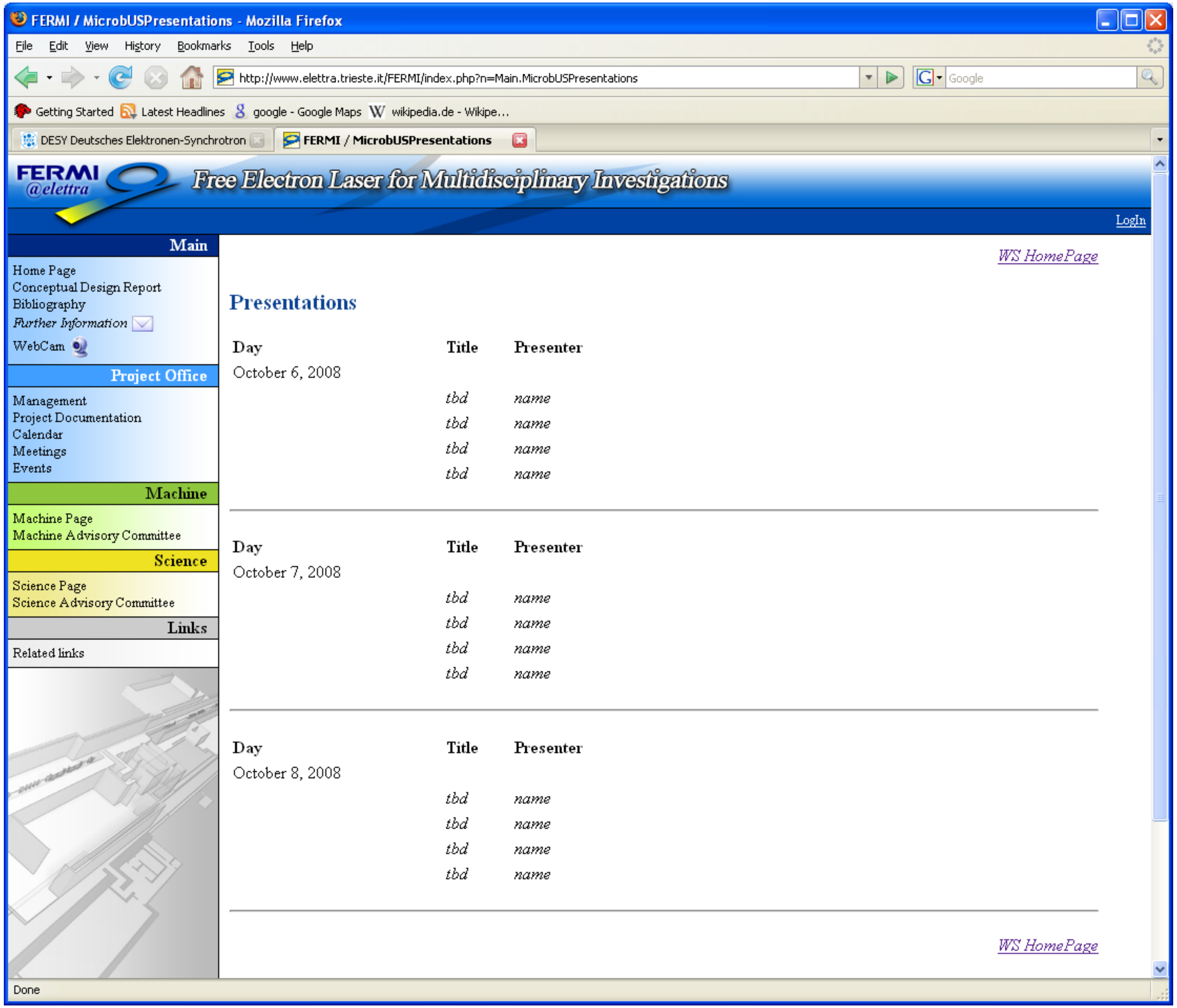



1: cold beam $< \delta^2 >^{1/2} = 0$

2: beam with $< \delta^2 >^{1/2} = 2 \times 10^{-5}$

- triangles and squares: M. Dolhus 1D-code
- red squares: TraFiC[4]

# Back to LBNL Workshop: 'Presentations' Page



# Talk Layout



- Tour Through the Workshop Program
- The LCLS COTR Problems and its Laser Heater
- LCLS Status

# Microbunching Workshop II – LBNL, 6-8 October, 2008

**Semi-Final Program Schedule *[last updated 2 October 2008]***
**Monday, 6 October**

**Introduction 9:00 – 9:20**

- 9:00-9:05 Welcome, S. Gourlay, LBNL AFRD Head
- 9:05–9:20 Workshop Goals + Facilty Info. "Nuts & Bolts", W. Fawley, LBNL

- **Session I - Observations of Microbunching 9:20-12:30 *Chairman: M. Cornacchia***
- 9:20-9:50 *Microbunching Observations at LCLS -- Z. Huang, SLAC*
- 9:50-10:20 *Microbunching Observations at FLASH -- B. Schmidt, DESY*
- 10:20-10:50 *Investigation of Microbunching Instability at the SCSS test accelerator -- K. Togawa,* SPRING-8
- 10:50-11:40 Discussion & Coffee Service
- 11:40-12:10 *Studies of fragmentation in electron beam energy spectra at SDL –- T. Shaftan, BNL*
- *Laser pulse shaping and beam structures at SDL -- S. Seletskiy, BNL*
- 12:10-12:40 *COTR and SASE from Compressed Beams -- A. Lumpkin, FNAL*

# Program…



## Session II - Theory and Simulation 14:00 - 18:00

***Chairs: A. Zholents (pre-break) & G.Stupakov (post-break)***

- 14:00-14:30 *Overview and Recent Progress in uBI Theory and Simulation* S. DiMitri, Trieste

**14:30-15:45 Contributed talks on uBI Theory and Simulation:**

- *Modeling uBI Growth in the SPARX Configurations,* C. Vaccarezza, INFN/Roma
- *Nonlinear Correction to the Gain of the Microbunching Instability Seeded by Shot Noise,* M. Venturini, LBNL
- *Large-Scale Simulation of Microbunching Instability in the Berkeley FEL Linac Studies,* J. Qiang, LBNL
- *A Vlasov-Maxwell Solver to Study Microbunching Instability in the FERMI@ELETTRA First Bunch Compressor System,* G. Bassi, Daresbury; J. Ellison, UNM; K. Heinemann

**16:45-17:20 Contributed Talks on uBI Simulation + Modeling Existing Experiments:**

- *Wisconsin FEL Bunch Compressor Modeling,* R. Bosch, U. Wis.
- *Accelerator Design Concepts and Simulation Issues Relevant to the Microbunching Instability,* Y. Kim, PSI
- *Unrecognized Singularity in the Field of a 1-D Evolving Bunch*, R. Warnock, SLAC
- *LSC Microbunching from Shot Noise and Comparison with LCLS Results,* D. Ratner

# Program…



***Session III - Cathode, Laser, & Injector Physics Relevant to uBI Initialization & Growth***
***9:00 - 12:30 Chairperson T. Limberg***

- 9:00-9:30 *Cathode Emission Physics and Origins of Non-uniformity* – K. Jensen, NRL
- 9:30-10:00 *Laser Photocathode Physics & Observations Relevant to μBI* -- D. Dowell, SLAC
- 10:00-10:30 *Post-cathode Dynamical Evolution of E-beam Non-Uniformities* -- P. Piot, NIU/Fermilab

- 11:15-12:30 **Contributed talks on uBI Initialization & Growth in Cathode/Injector Regions**:
- *Possible Sources of Non-Uniform Emission ,no, Velocity Bunching!,* M. Ferrario, INFN/Frascati
- *3D Study of Effects from Inhomogeneities upon the Minimum Achievable Emittance,*
  M. Quattromini, NEA/Frascati
- *Microbunching Instability in Velocity Bunching,* D. Xiang, SLAC
- *Simulation of Propagation of Cathode Region Modulations in the FERMI Injector,*
- *G.* Penco & P. Craievitch, Sincrotrone Trieste

# Program…

***Session IV - Diagnostics & Control 13:30-17:45 Chairpersons, D. Dowell (pre-break) & M. Ferrario (post-break)***

- 13:30-14:15 *Current state-of-art in OTR physics & diag. setup –* R. Fiorito, U Md., & A. Lumpkin, FNAL
- 14:15-14:40 *LCLS OTR setup and COTR studies –* H. Loos, SLAC
- 14:40-15:05 *COTR observations at FLASH –* B. Beutner, PSI

- *LCLS Laser Heater plans –* P. Emma, SLAC
- *FERMI Laser Heater plans –* S. Spampinati, Sincrotrone Trieste

- 16:00-17:15 **Contributed talks on Diagnostics and Control:**
- *E-beam High-Frequency Content on the Bunch Length Measurement and*
- *Longitudinal Feedback,* J. Wu, SLAC
- *Two Stage, Single Shot IR CTR Spectrometer,* S. Wesch, DESY
- *Compressing Electron Bunches with Solenoids,* A. Zholents, LBNL
- *COTR Mitigation with a Tilted OTR Foil,* G. Stupakov, SLAC
- 17:15-17:45 Discussion

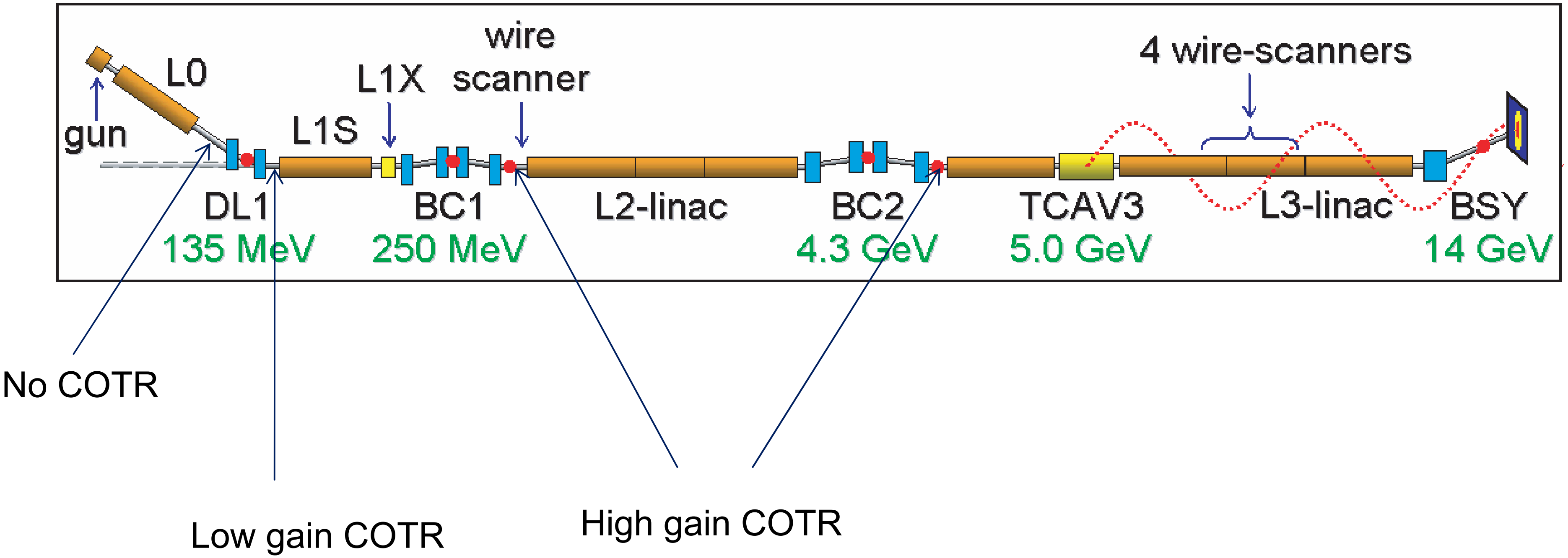
# Program…

- ***Near-Term Future Plans at Different Labs***

- 9:00-10:20 Plans @ different labs including expt. verification/benchmarking of uBI theory &
- simulation, followed by open general discussion
- *DESY FLASH & XFEL plans* – T. Limberg
- *FERMI Plans -- Injector microbunching characterization using a low energy deflecting cavity*
- *BNL plans* – S. Seletskiy
- *Frascati Plans* - M. Ferrario
- *ANL/FNAL Plans*, A. Lumpkin
- *Shanghai plans for uBI expt. studies*– Z. Huang, SLAC, speaking for D. Wong, Shanghai
- *Microbunching Experimental Plans at the Upcoming PSI 250 MeV injector* –
  Y. Kim, PSI
- *Daresbury Plans* --- P. Williams

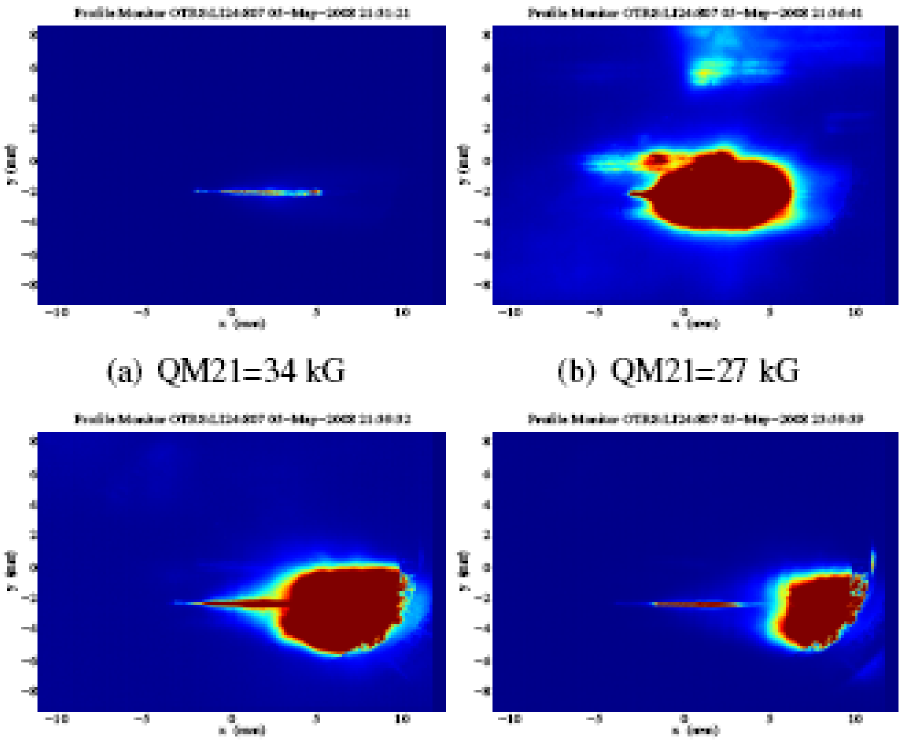
# The LCLS COTR Problem

OTR Screens downstream of 'dogleg' not usable with design machine parameters



# Scanning the Dogleg Quad





(a) QM21=34 kG (b) QM21=27 kG

(c) QM21=23 kG (d) QM21=21 kG

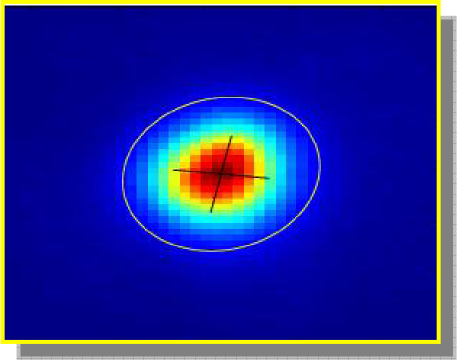
Figure 6: Optical radiation pattern observed on OTR21 near the beginning of the third dipole in BC2 vs. pre-BC2 quadrupole strength (QM21).

# *The LCLS* Laser-Heater

**P. Emma,** for The *LCLS* Commissioning Team

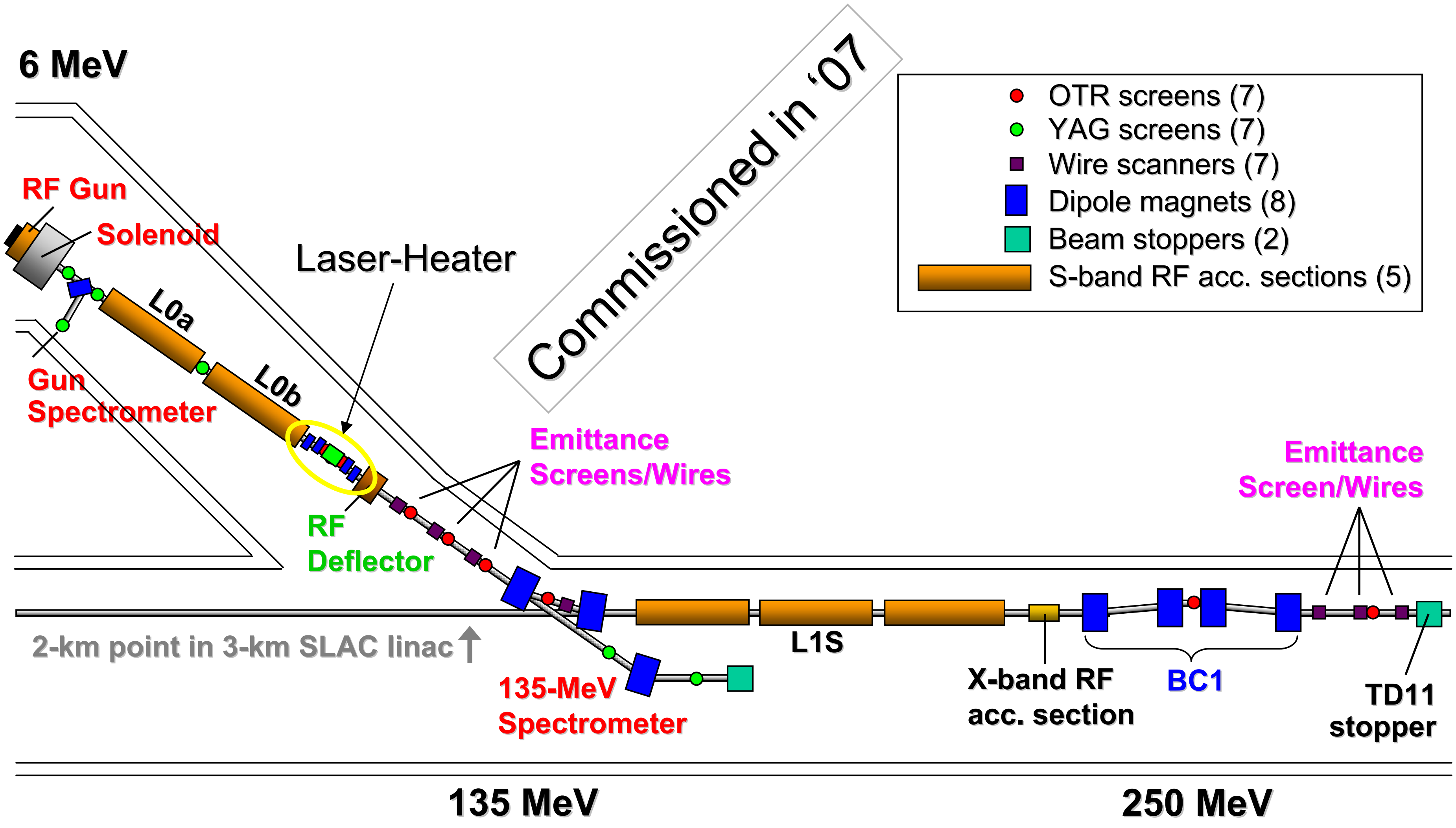
*LBNL $\mu$-BI Meeting*

Oct. 7, 2008

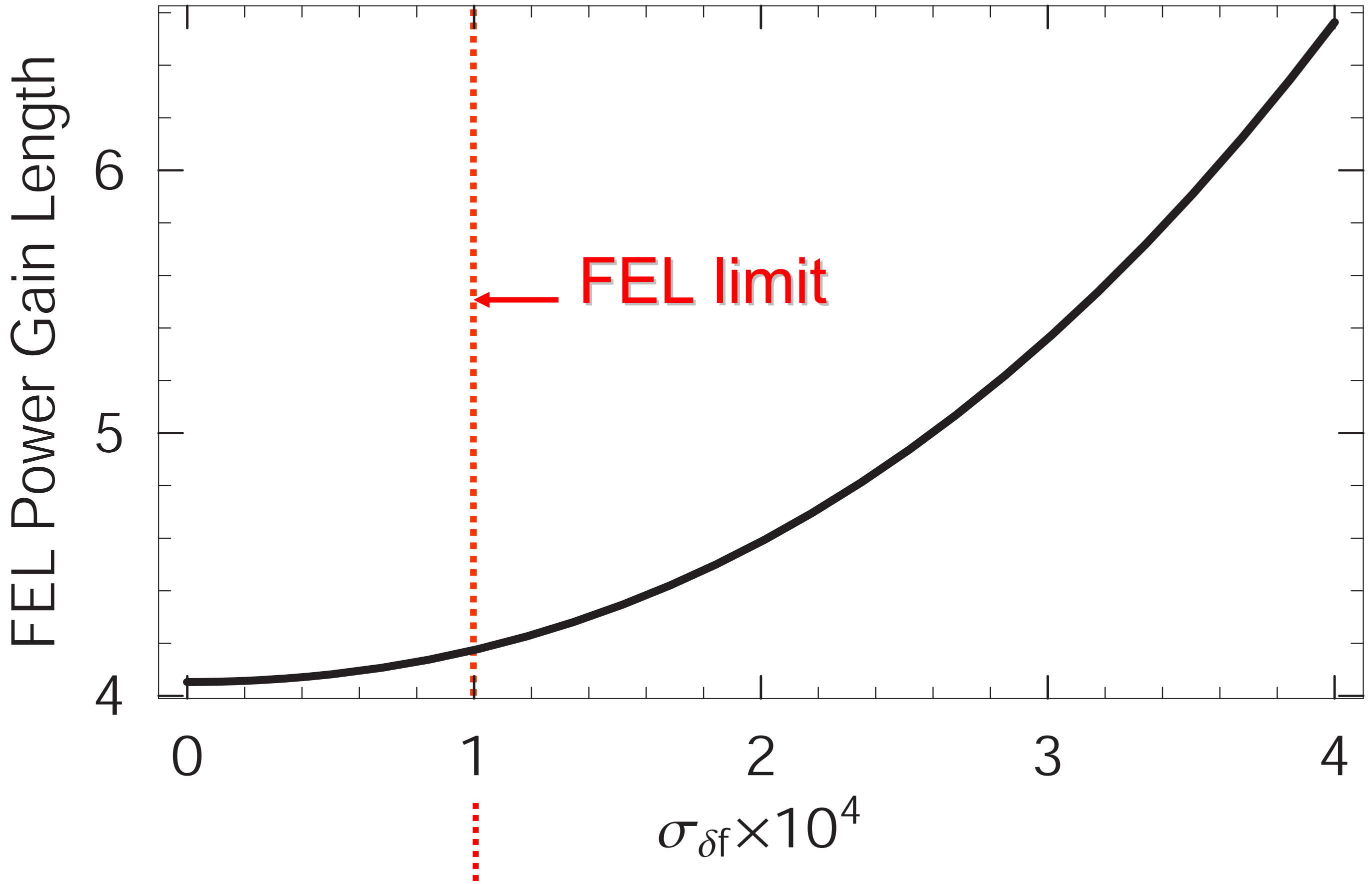



- Layout and Design
- Status of Installation
- Commissioning Issues
- Experiments?

# LCLS Injector Layout



# LCLS Slice Energy Spread Tolerance

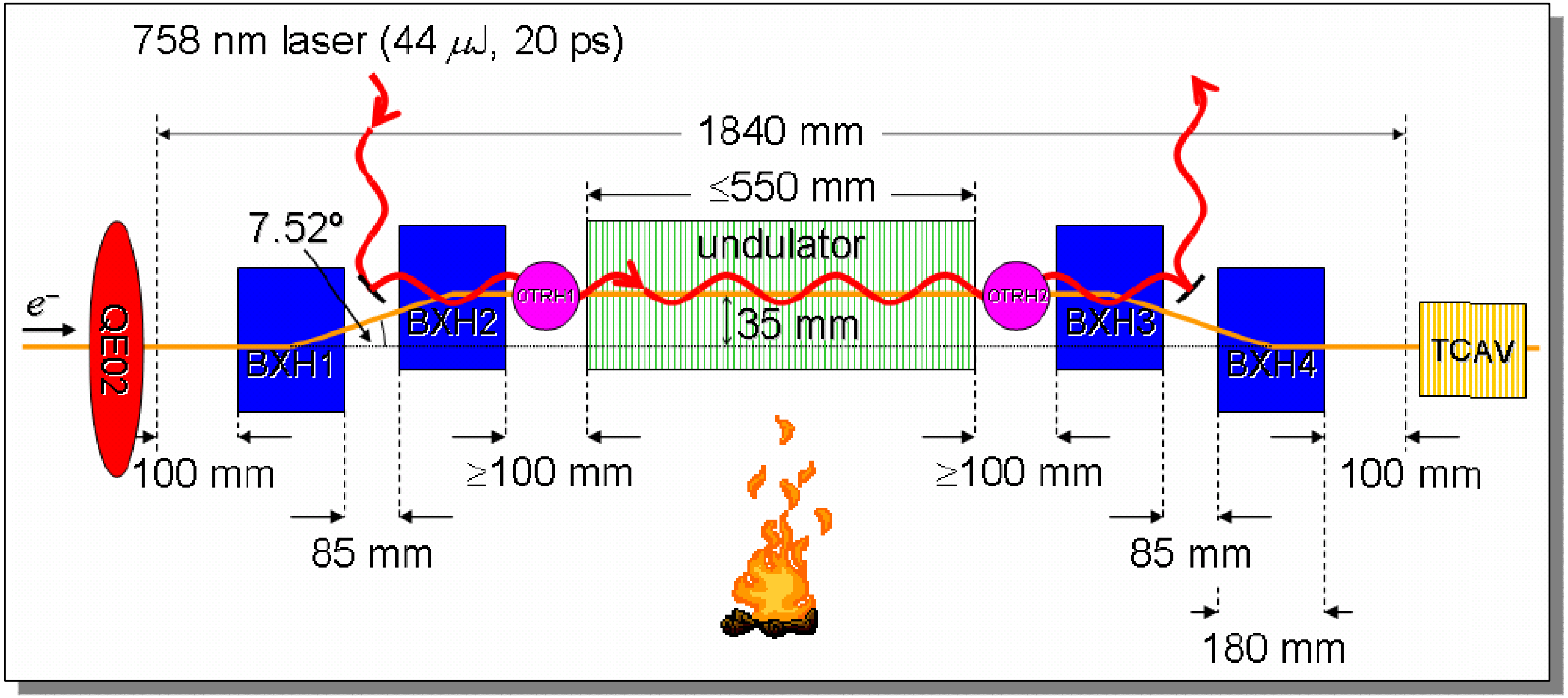



~40 keV at 1 nC operating point

Z. Huang et al., http://prst-ab.aps.org/abstract/PRSTAB/v7/i7/e074401

# The *LCLS* Laser Heater (135 MeV)

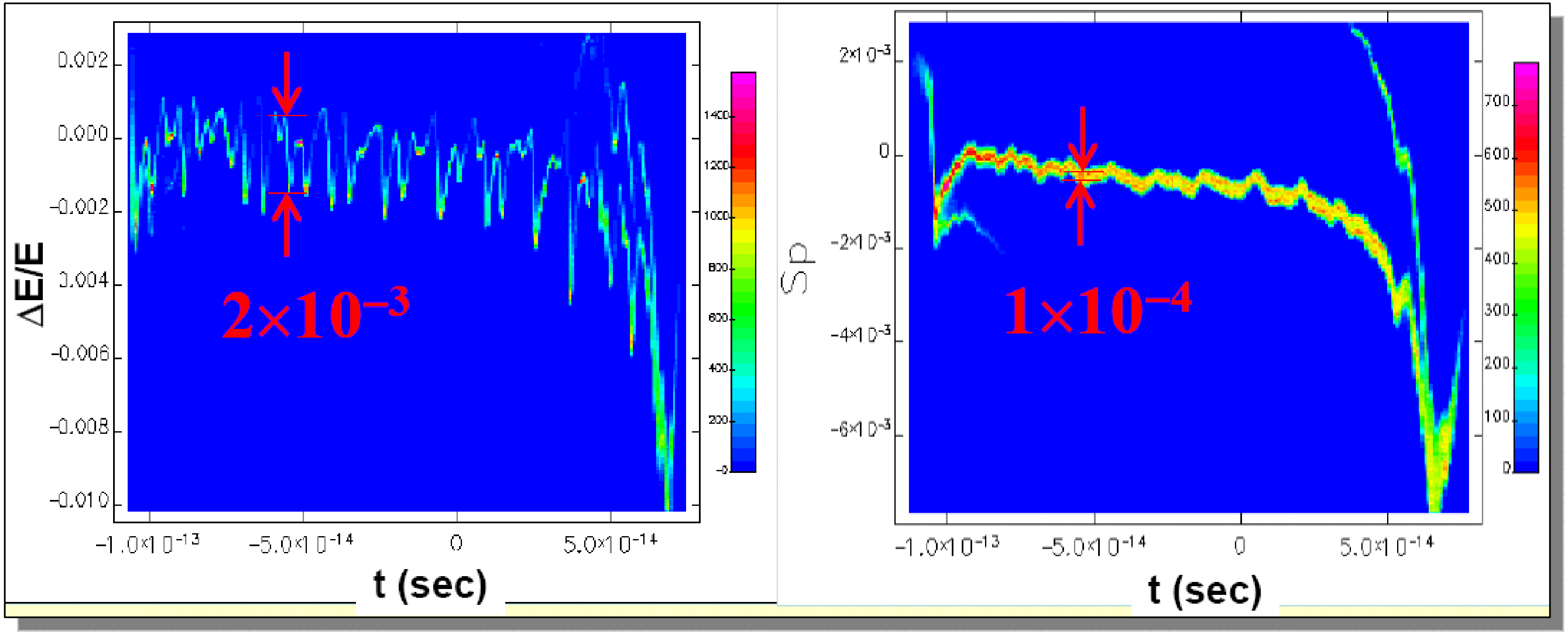





suggested by Saldin *et al.*

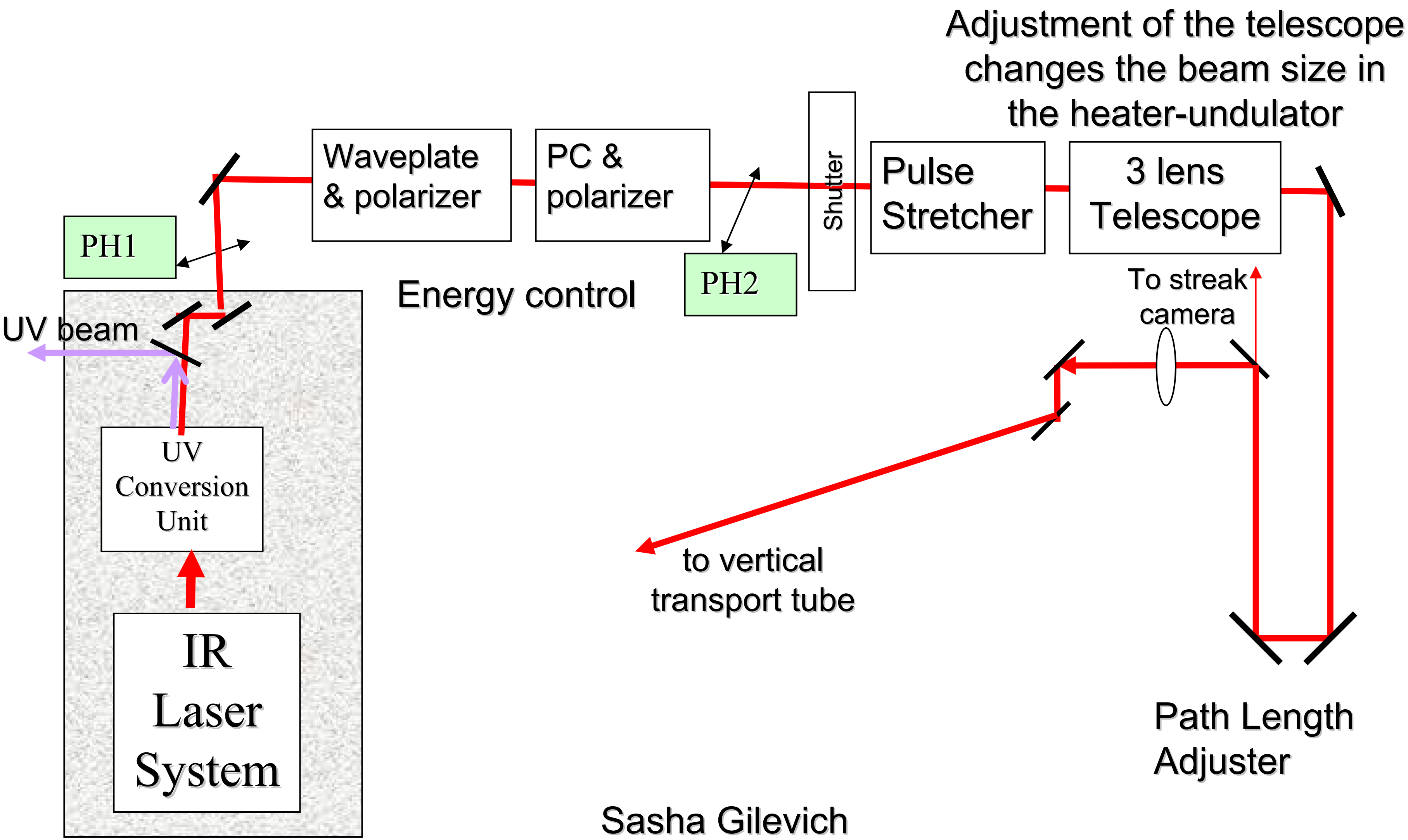
| parameter | symbol | Value | range | unit |
|---|---|---|---|---|
| electron energy | $E$ | 135 | 120 – 180 | MeV |
| FWHM electron bunch length (duration) | $\Delta\tau_e$ | 10 | 5 – 15 | ps |
| rms transverse electron beam size | $\sigma_{x,y}$ | 0.2 | 0.16 – 0.25 | mm |
| bunch charge | $Q$ | 1 | 0.2 - 1 | nC |
| transverse emittance | $\gamma\varepsilon_{x,y}$ | 1.2 | 0.8 – 2 | $\mu$m |
| rms uncorr. energy spread (before heater) | $\sigma_E$ | ~3 | - | keV |
| Laser wavelength | $\lambda_L$ | 758 | 750 - 770 | nm |
| Undulator period | $\lambda_u$ | 5.4[§] | - | cm |
| Undulator parameter | $K$ | 1.385[§] | 1.047 – 2.229 | - |
| Undulator minimum gap | $G$ | 34[§] | 25 - 100 | mm |
| Number of undulator periods | $N_u$ | 9 | - | - |
| Chicane magnet eff. length (approx.) | $L_B$ | 18 | - | cm |
| Bend angle of each chicane magnet | $\theta_B$ | 7.52 | 0 - 7.52* | deg |
| Beam offset in chicane center | $\|\eta_x\|$ | 35 | 0 - 35 | mm |
| Laser beam waist rms size (Gaussian mode) | $\sigma_{L-x,y}$ | 0.18 | 0.16 – 0.3 | mm |
| Laser beam Rayleigh range | $L_R$ | 50 | 42 - 1600 | cm |
| Laser pulse energy (nominal/high-setting) | $u_L$ | 44/400 | 0 - 400 | $\mu$J |
| Laser power (nominal/high-setting) | $P_L$ | 2.2/19 | 0 - 20 | MW |
| Laser pulse duration (FWHM) | $\Delta\tau_L$ | 20 | 10 - 20 | ps |
| rms energy spread generated (nom./high) | $\sigma_{E\text{-}max}$ | 45/130 | 0 - 130 | keV |
| Required spatial overlap of laser and *e*-beam | $\|\Delta x\| = \|\Delta y\|$ | <0.2 | - | mm |

Example of longitudinal phase space at 14 GeV with 8% initial modulation at 150-μm modulation



# Layout of the Laser Heater Optical System in the Laser Lab

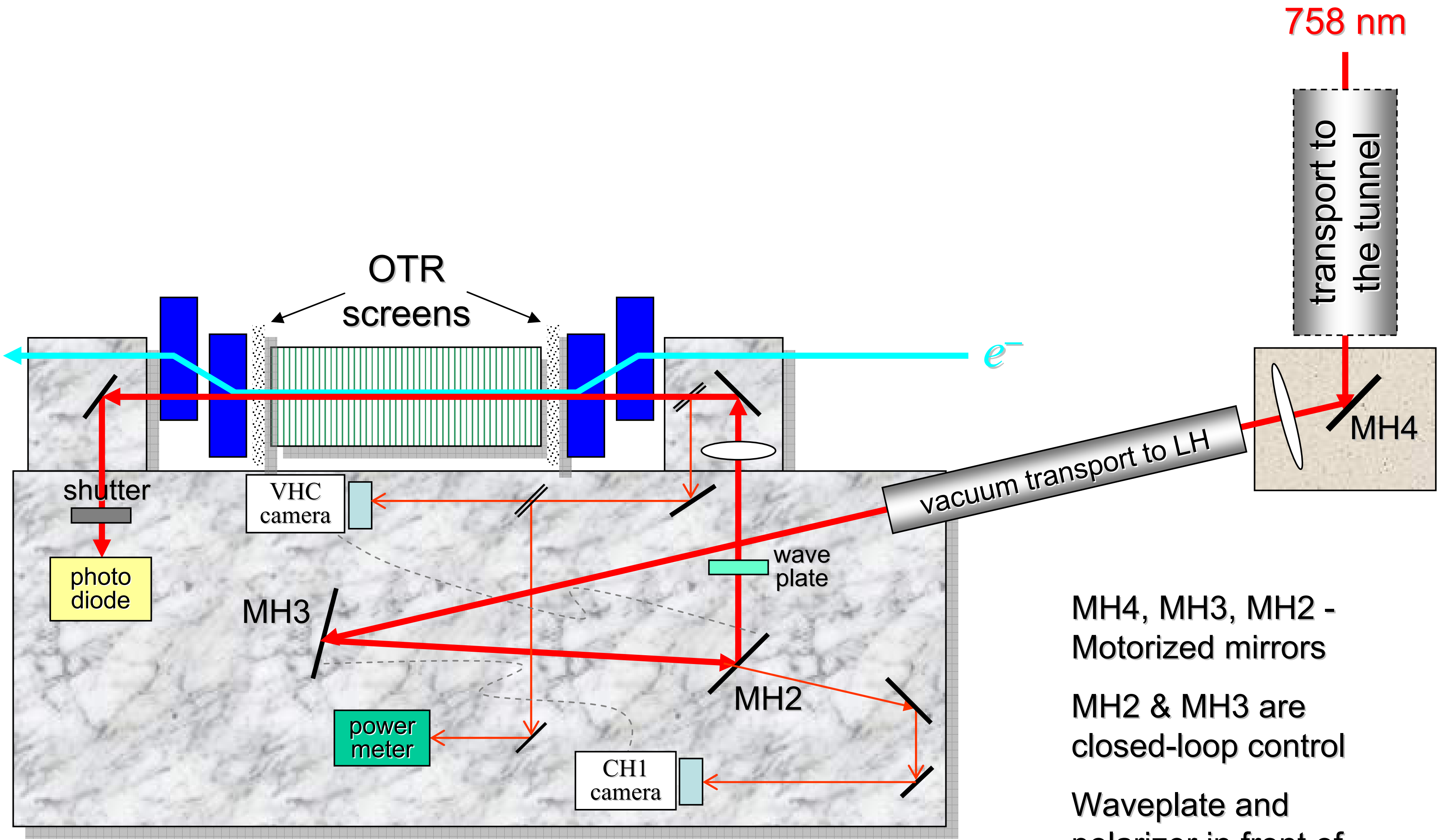





Sasha Gilevich

# Layout of the Laser Heater Optical System in the Injector Vault





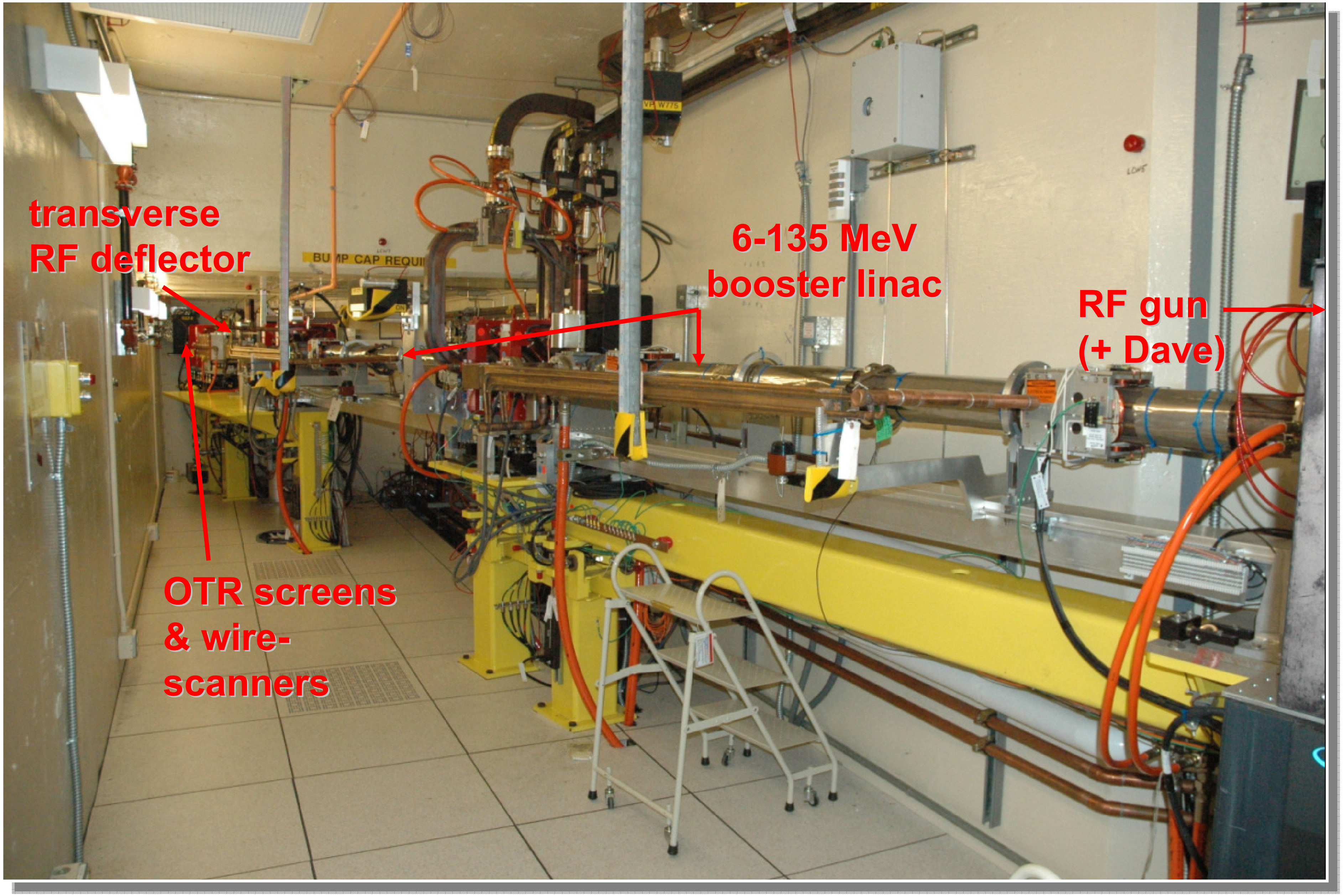

MH4, MH3, MH2 - Motorized mirrors

MH2 & MH3 are closed-loop control

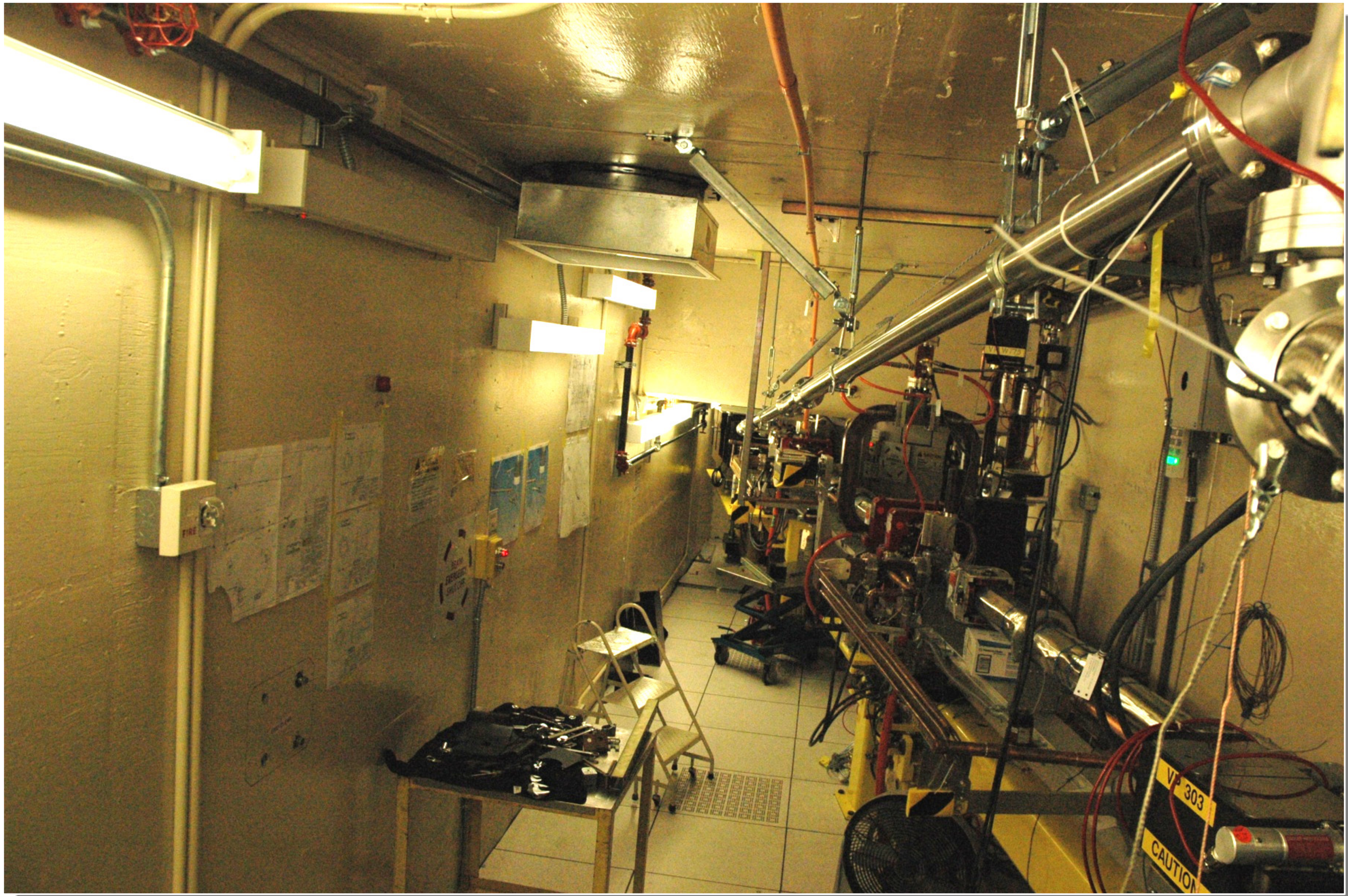
Waveplate and polarizer in front of both cameras

Sasha Gilevich

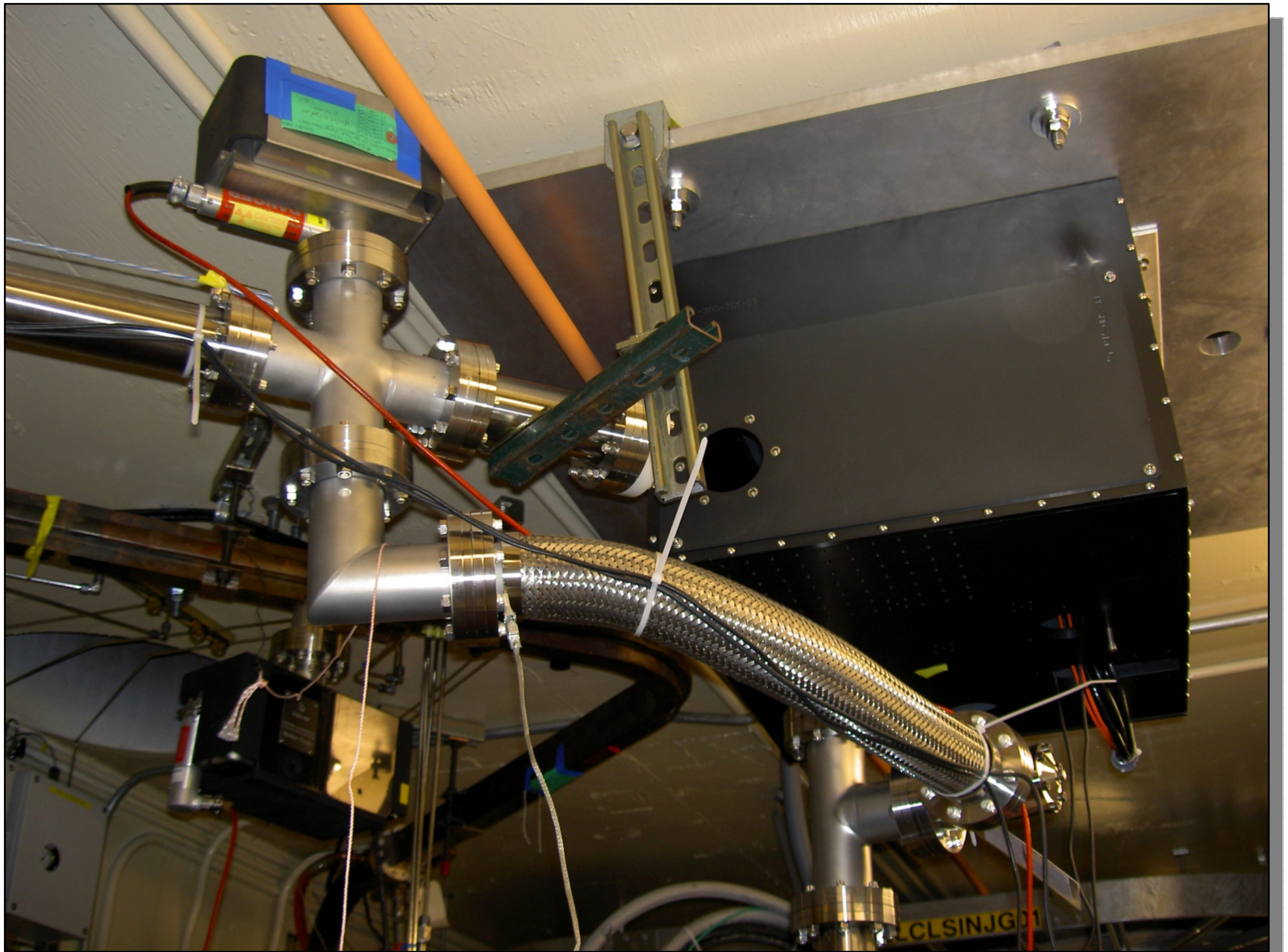
# Injector Vault (Oct. '07)



# Injector Vault (Oct. '08)



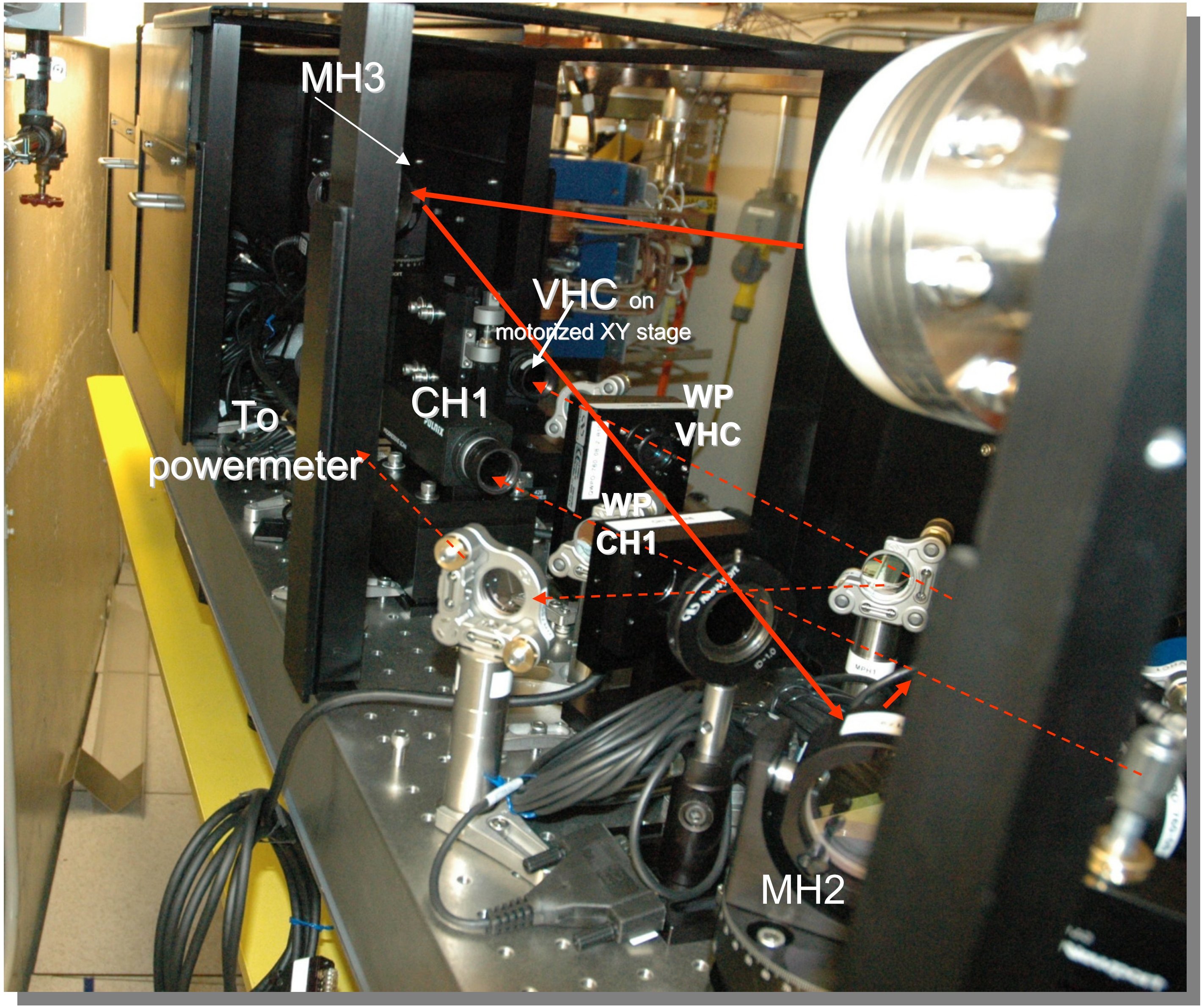
# IR & UV Laser Vertical Transport in Vault



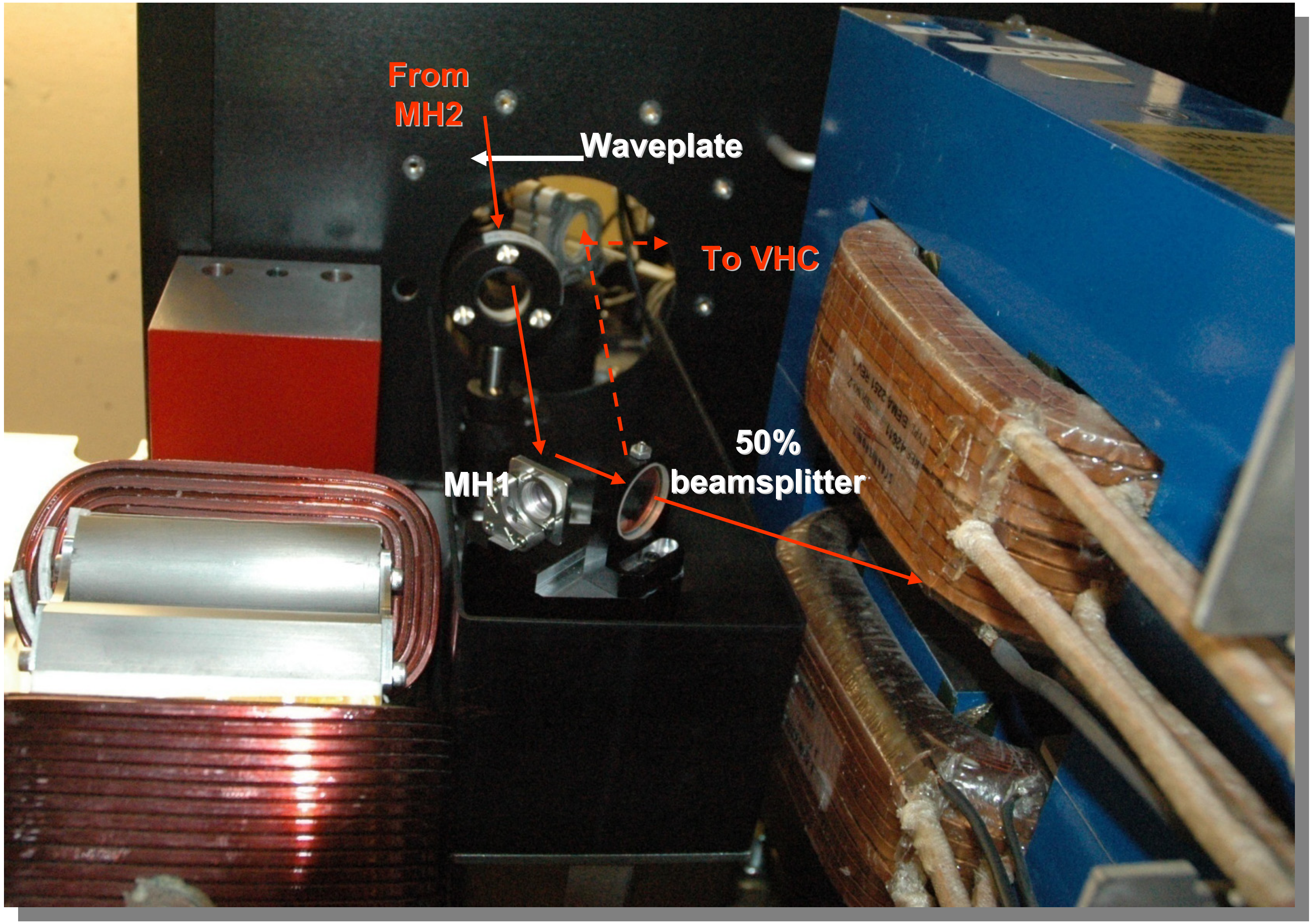
# Laser Table in the Injector Vault

# Laser Heater Table in the Vault

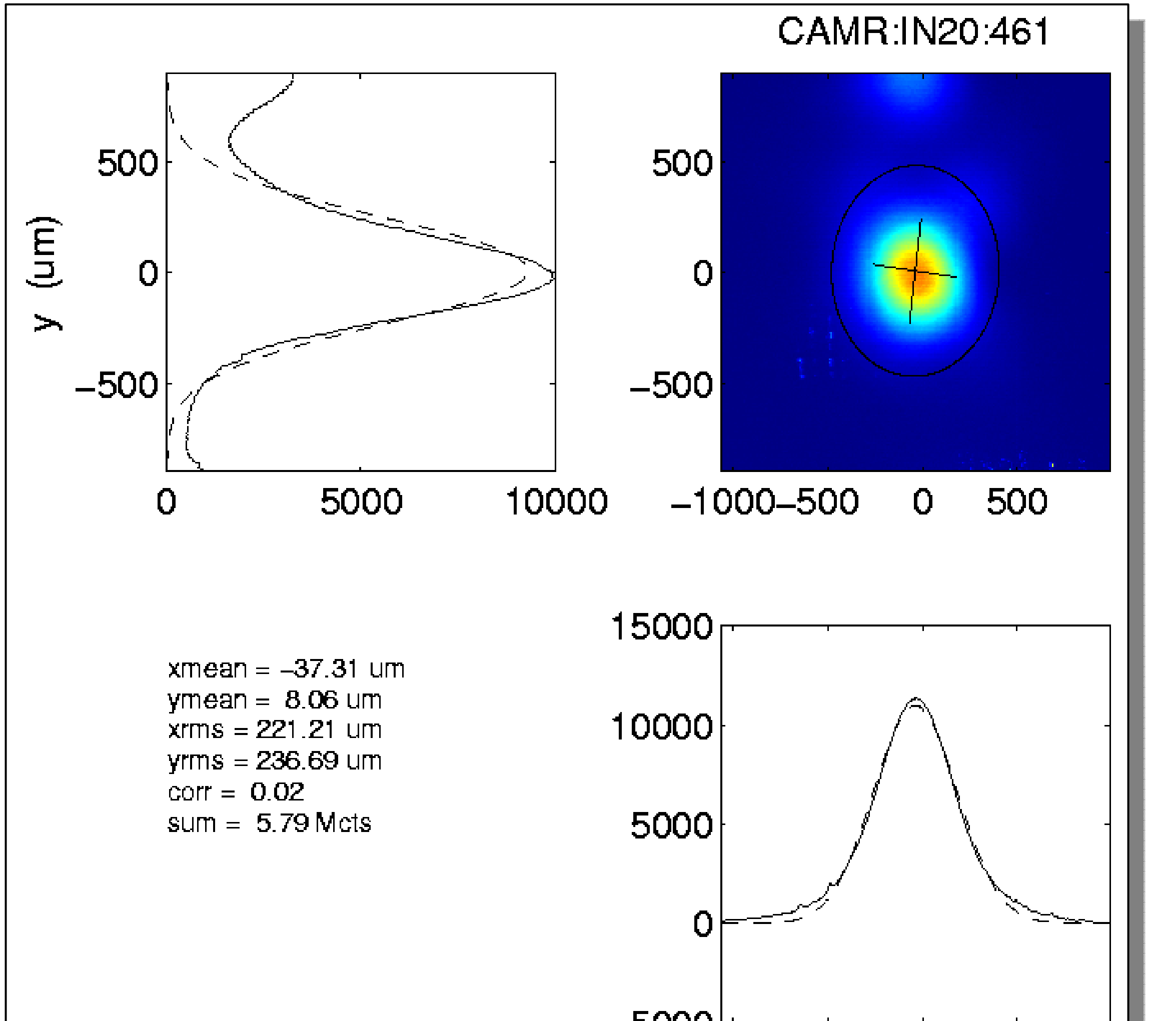




# Laser Heater Table in the Vault

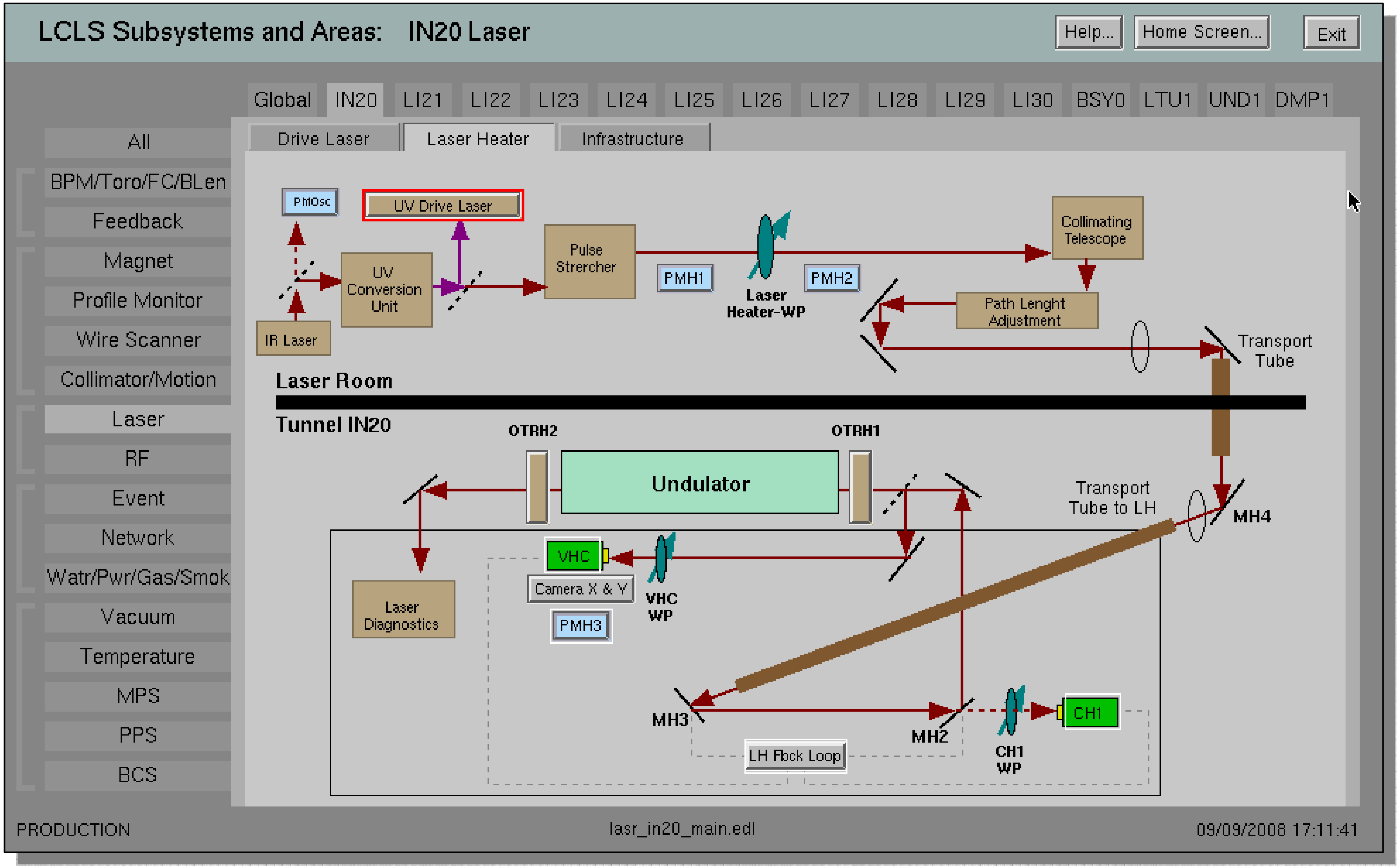


# IR Beam at Center of "Undulator"




~Sep. 30, 2008

# Laser Heater Controls Panel

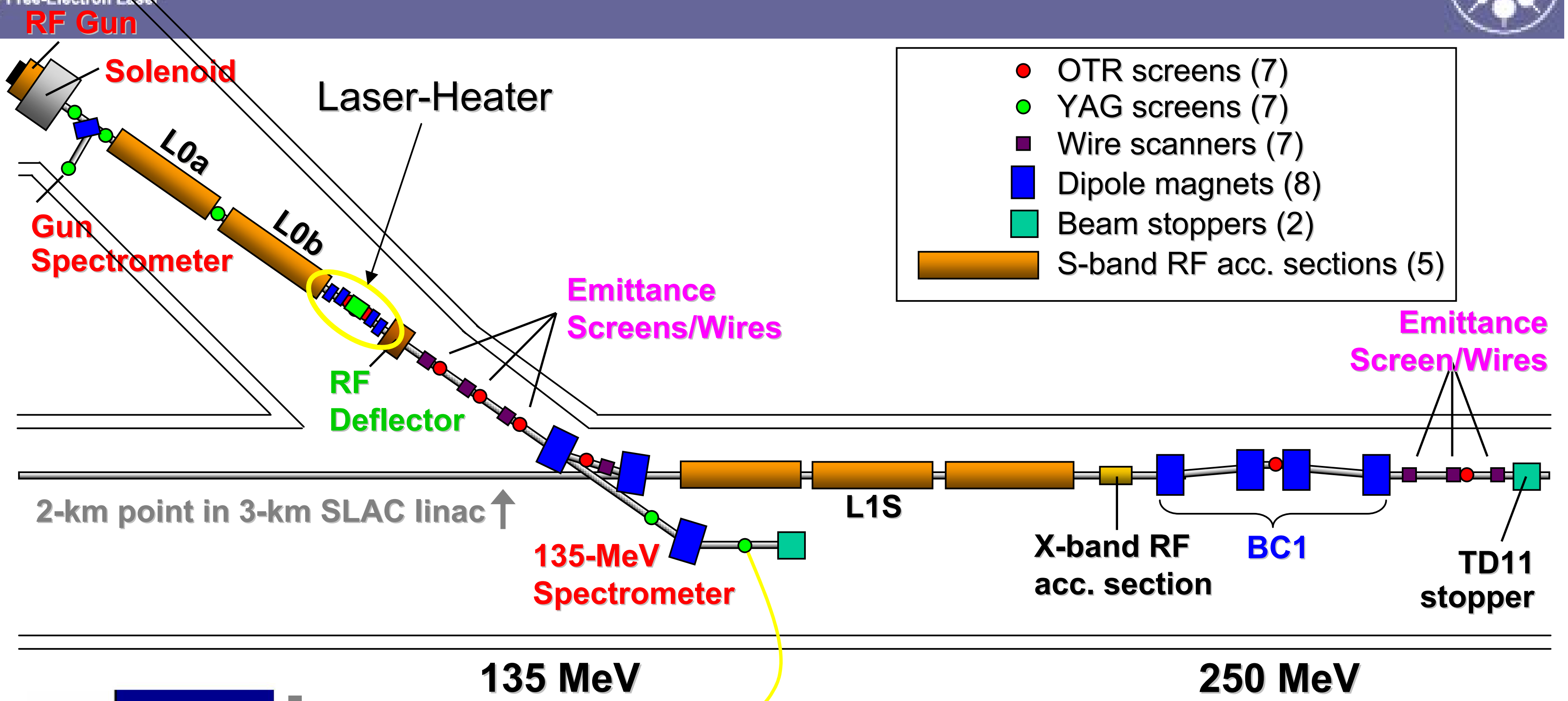


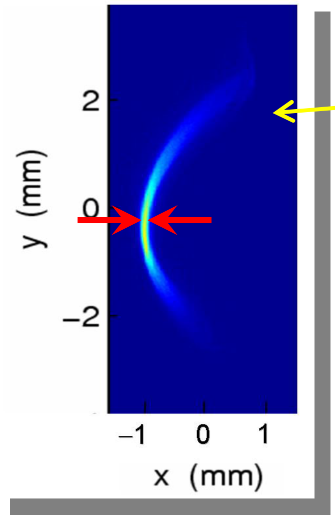

Matt Boyes

# Damping of COTR? (1 nC, 40 keV rms heating)

- **BC1:**
  - **COTR suppression for: $2\pi\sigma_E/E_0 R_{56} >> \lambda$**
  - **$2\pi$(40 keV)/(250 MeV)$\times$(39 mm) = 39 μm >> 1 μm**
- **BC2:**
  - **COTR suppression for: $2\pi\sigma_E/E_0 C_1 R_{56} >> \lambda$**
  - **$2\pi$(40 keV)/(4.3 GeV)$\times$4.5(25 mm) = 7 μm >> 1 μm**

similar numbers at 250 pC with $\sigma_E$ = 20 keV



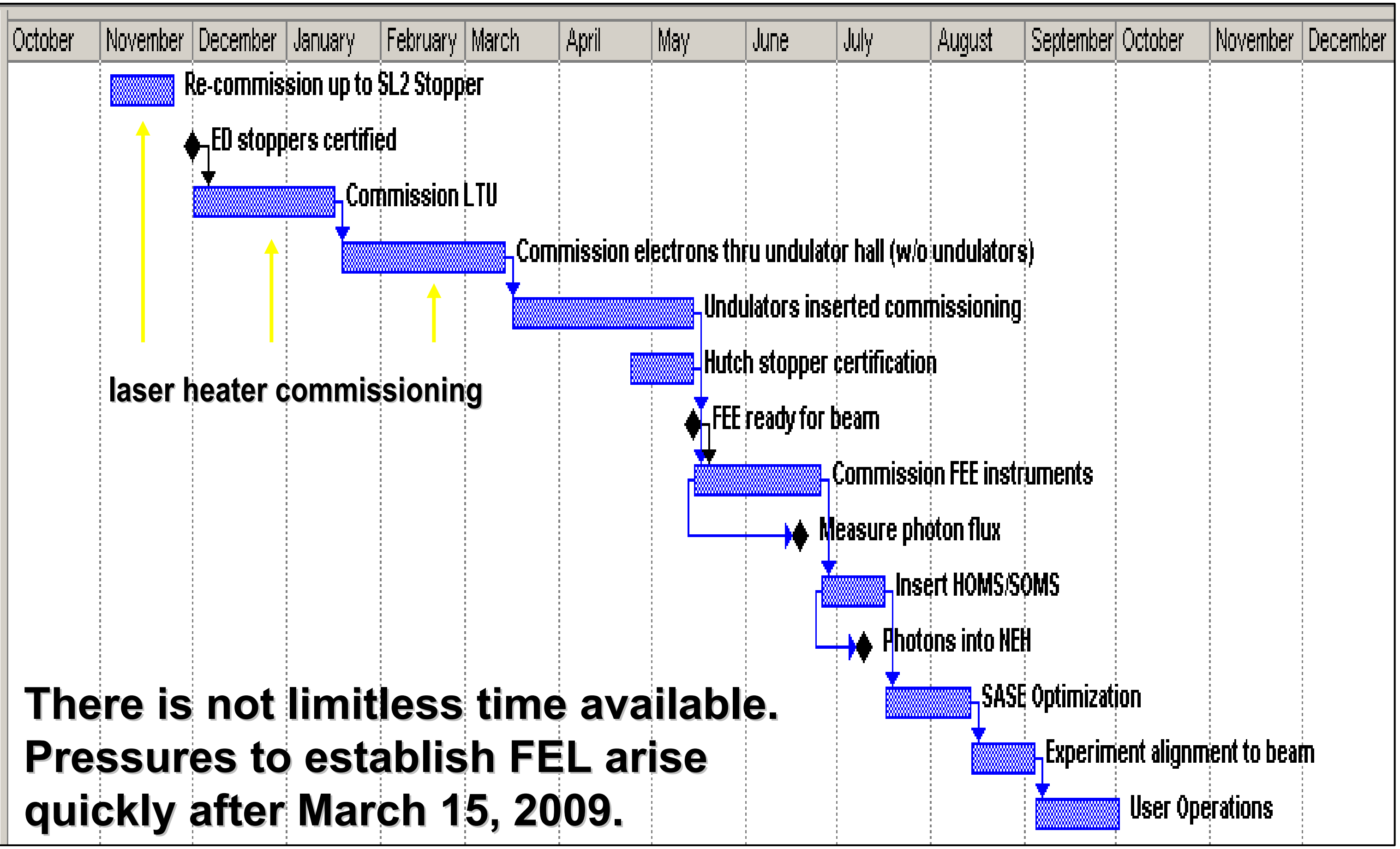

RF Deflector (LOLA) + special lattice configuration in spectrometer allows fine measurement of time-sliced energy spread (to <6 keV)

$\sigma_E \leq 6$ **keV rms** (40 $\mu$m)

# Laser Heater Commissioning Schedule

- All laser-heater systems will be ready by Nov. 3, 2008, **except** the LH-undulator (magnet vendor was late)
- LH-undulator will be installed in Dec. or Jan.
- FEL begins commissioning in March (must have LH ready)
- Ideas for reasonably well thought out experiments are welcome

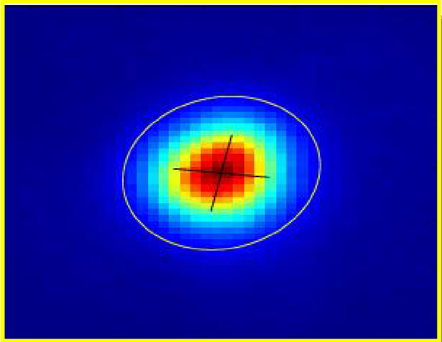
| | Start | Finish |
|---|---|---|
| 1 | Tue 11/4/08 | Mon 11/24/08 |
| 2 | Mon 12/1/08 | Mon 12/1/08 |
| 3 | Mon 12/1/08 | Fri 1/16/09 |
| 4 | Mon 1/19/09 | Fri 3/13/09 |
| 5 | Mon 3/16/09 | Thu 5/14/09 |
| 6 | Fri 4/24/09 | Thu 5/14/09 |
| 7 | Thu 5/14/09 | Thu 5/14/09 |
| 8 | Fri 5/15/09 | Thu 6/25/09 |
| 9 | Thu 6/18/09 | Thu 6/18/09 |
| 10 | Fri 6/26/09 | Thu 7/16/09 |
| 11 | Thu 7/9/09 | Thu 7/9/09 |
| 12 | Fri 7/17/09 | Thu 8/13/09 |
| 13 | Fri 8/14/09 | Thu 9/3/09 |
| 14 | Fri 9/4/09 | Thu 10/1/09 |




**There is not limitless time available. Pressures to establish FEL arise quickly after March 15, 2009.**

# *LCLS* Commissioning Status

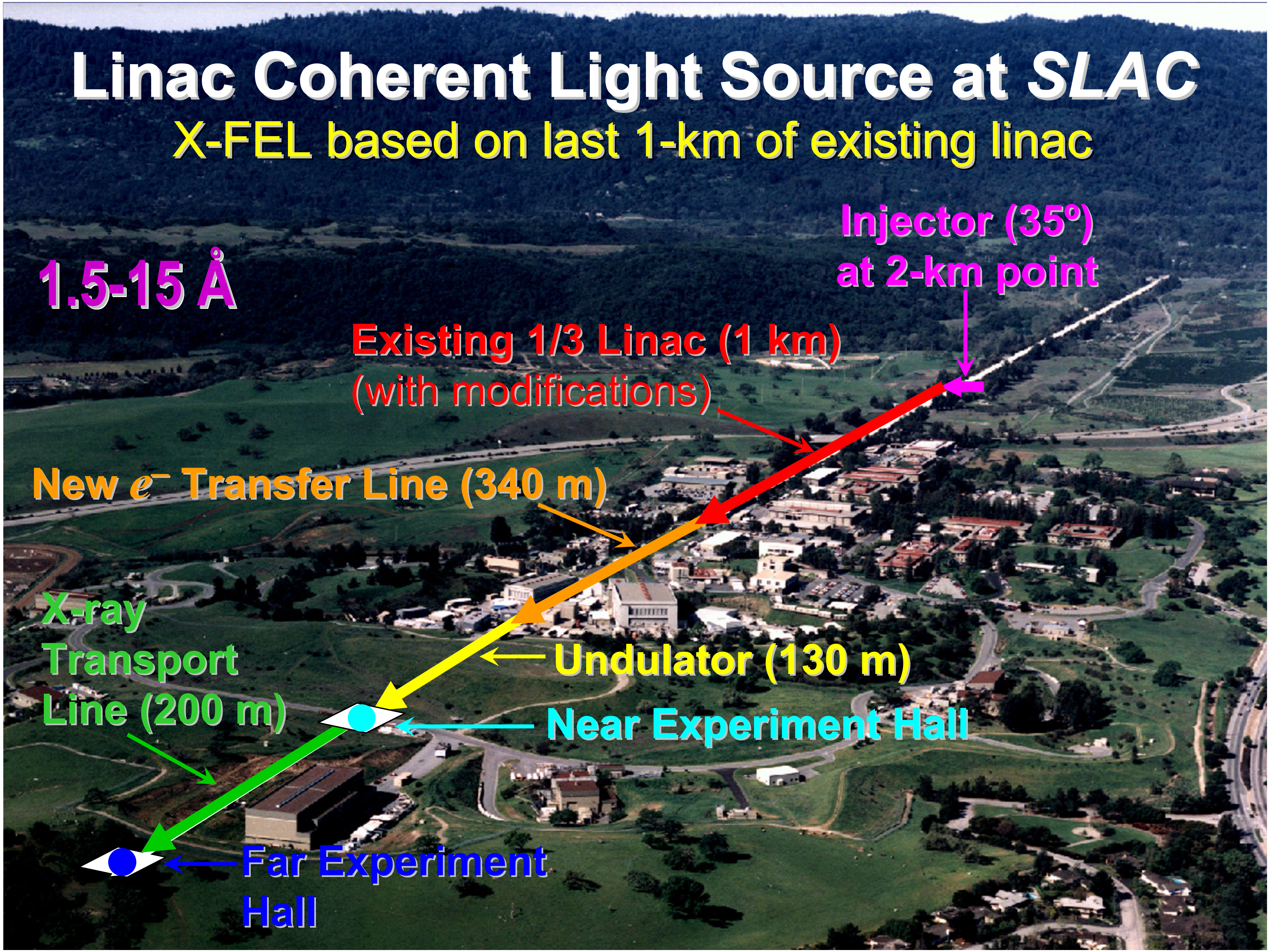
P. Emma, for **The *LCLS* Commissioning Team**



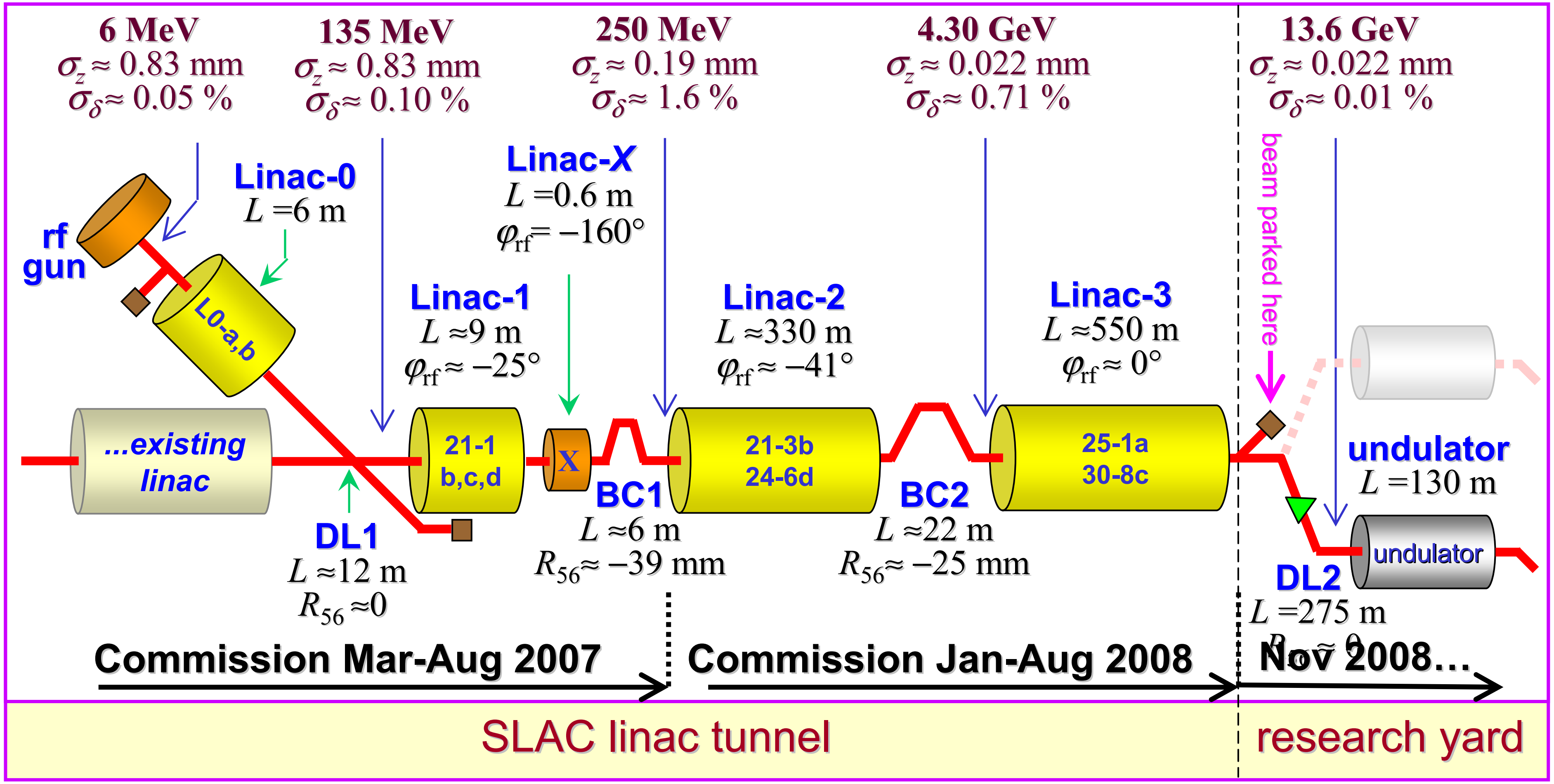
***LCLS SAC Meeting***

**October 20, 2008**


- Machine Performance
- Estimated FEL Power
- Present Stability
- Ultra-Short Pulse Possibilities


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

# *LCLS* Accelerator Layout



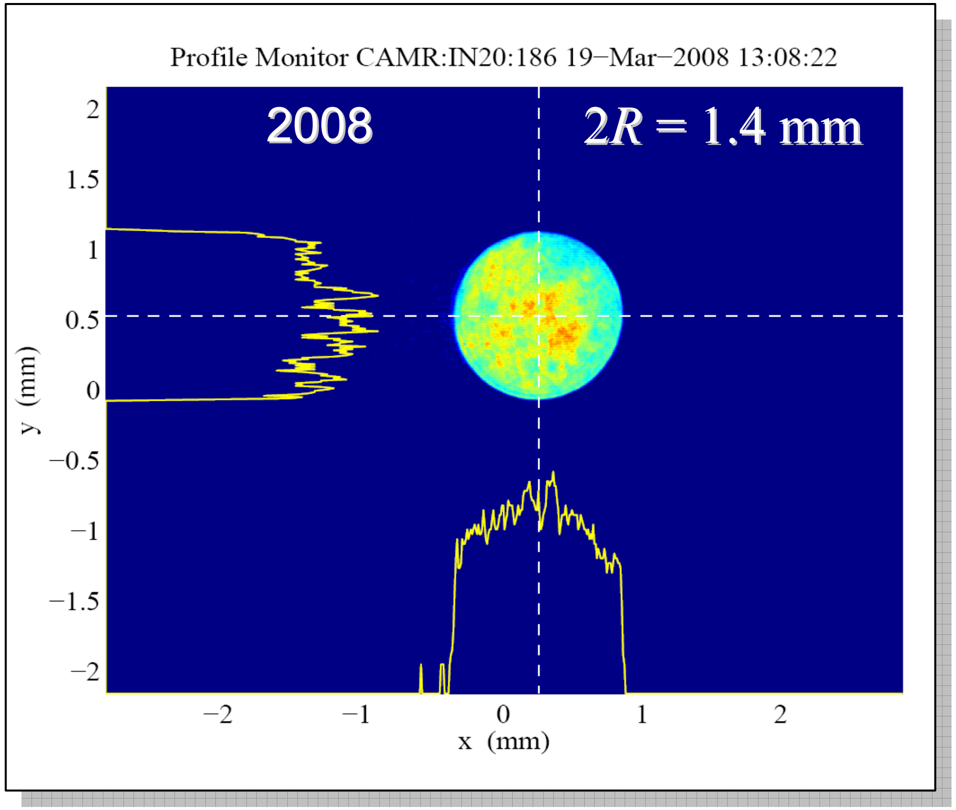

X-rays in spring 2009

# Phase-II Commissioning Highlights (2008)

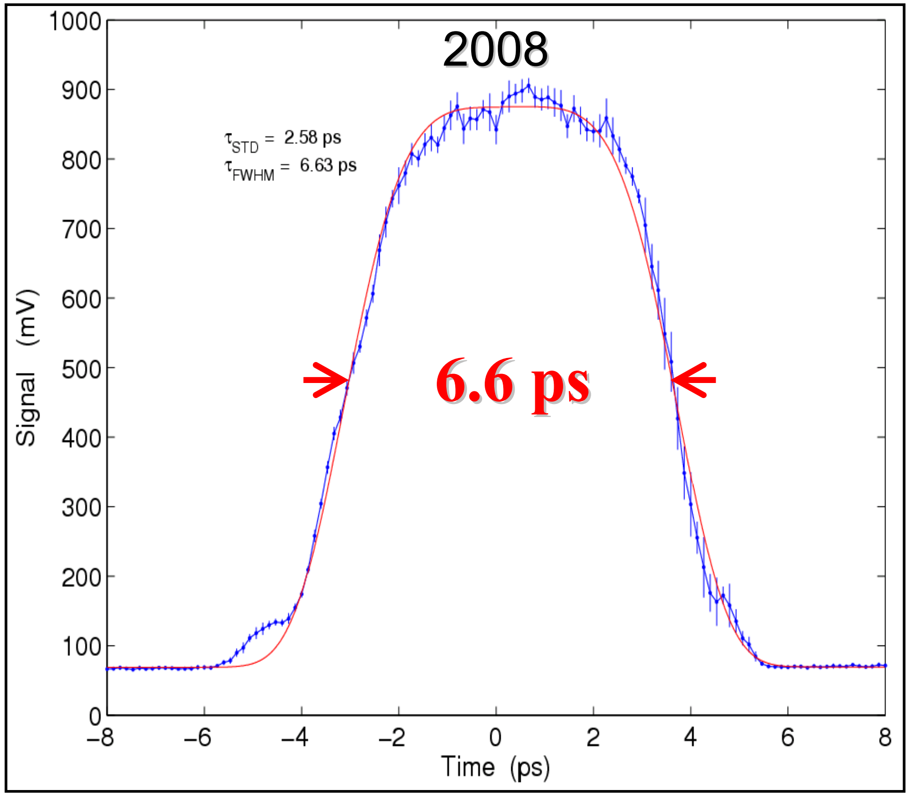


- *Injector Commissioning*: Apr-Aug, 2007 (**DONE**)
- *Phase-II Commissioning*: Dec-Aug, 2008 (**DONE**)
- Great drive-laser uptime (**99%**) and good performance
- Projected emittances **0.7-1.6 $\mu$m** at 0.25 nC, 10 GeV
- Routine 30-Hz $e^-$ to 14 GeV (~24/7 with ~90% up-time)
- Bunch compression fully demonstrated down to 1-2 $\mu$m
- Many beam & RF feedback systems running well
- Electron bunch appears bright enough to drive **1.5-Å** FEL
- 20-pC bunch with 0.14-$\mu$m emittance (& ~10 fs length?)

# Laser Spatial and Temporal Shaping in 2008




Spatial shape on cathode using iris




Temporal shape (6.6 ps FWHM)

**99% Drive Laser up time!**

**S. Gilevich, G. Hays, P. Hering, A. Miahnahri, W. White**

XFEL X-Ray Free-Electron Laser

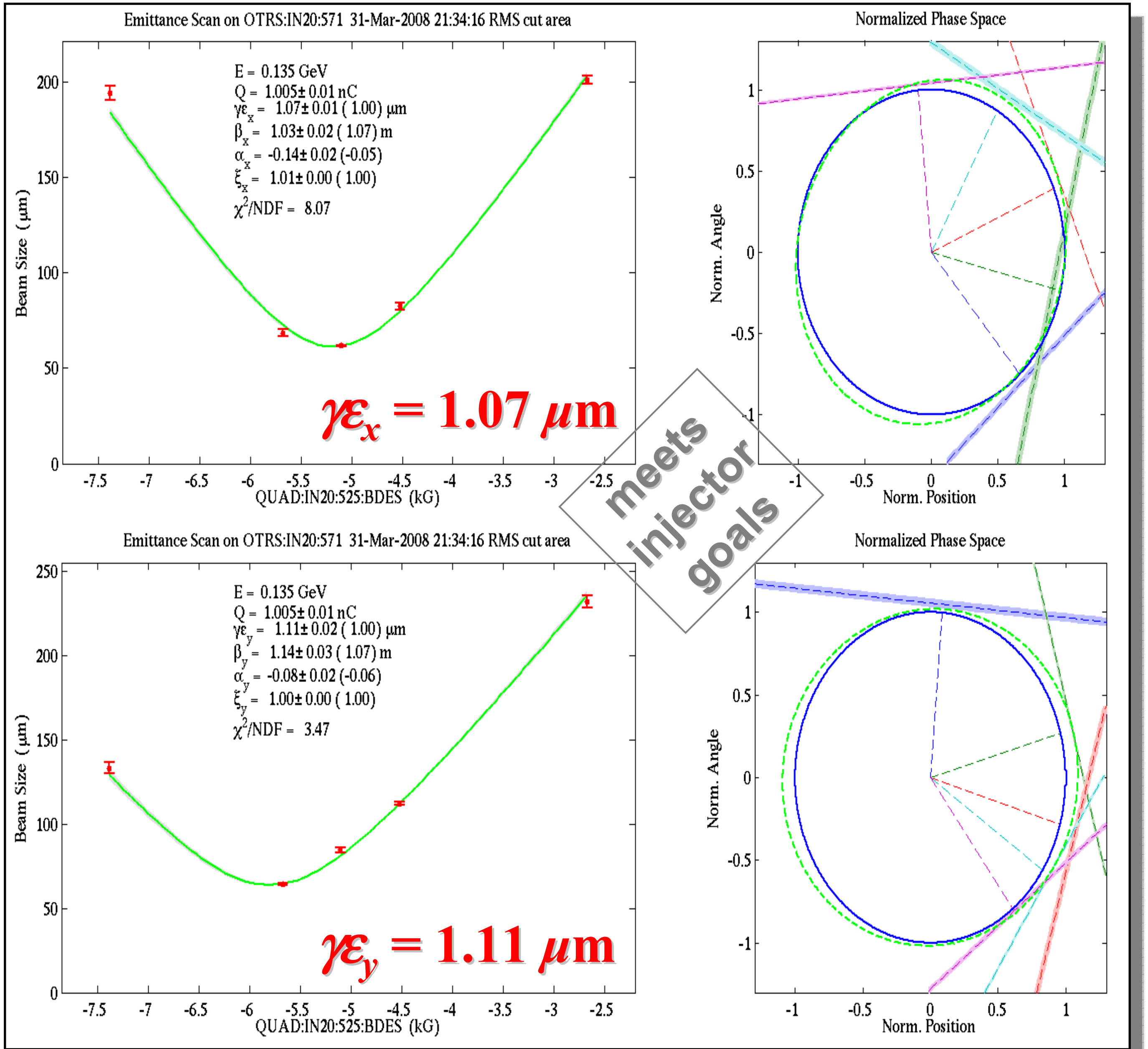
## Design and Typical Measured Parameters (Aug. 2008)

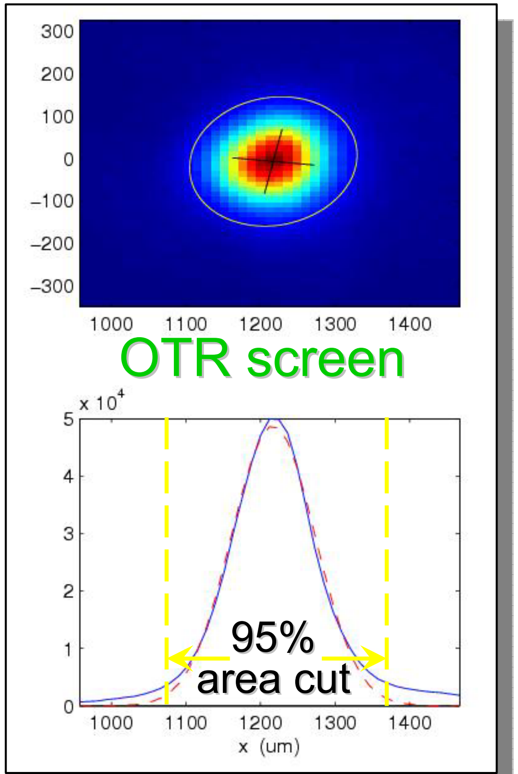
| Parameter | symbol | design | measured | unit |
|---|---|---|---|---|
| Final linac $e^-$ energy | $\gamma mc^2$ | 13.6 | 13.6 | MeV |
| Bunch charge | $Q$ | 1 | 0.25 | nC |
| Initial bunch length (rms) | $\sigma_{z0}$ | 0.9 | 0.75 | mm |
| Final bunch length (rms) | $\sigma_{zf}$ | 20 | 8-10 | $\mu$m |
| *Projected* emittance (injector) | $\gamma\varepsilon_{x,y}$ | 1.2 | 0.7-1.0 | $\mu$m |
| *Slice* emittance (injector) | $\gamma\varepsilon^{s}_{x,y}$ | 1.0 | 0.6 | $\mu$m |
| *Projected* emittance (linac end) | $\gamma\varepsilon^{L}_{x,y}$ | 1.5 | 0.7-1.6 | $\mu$m |
| Single bunch repetition rate | $f$ | 120 | 30 | Hz |
| RF gun field at cathode | $E_g$ | 120 | 115 | MV/m |
| Laser energy on cathode | $u_l$ | 250 | 20-150 | $\mu$J |
| Laser diameter on cathode | $2R$ | 1.5 | 1.2 | mm |
| Cathode quantum efficiency | $QE$ | 6 | 0.7-7 | $10^{-5}$ |

XFEL X-Ray Free-Electron Laser

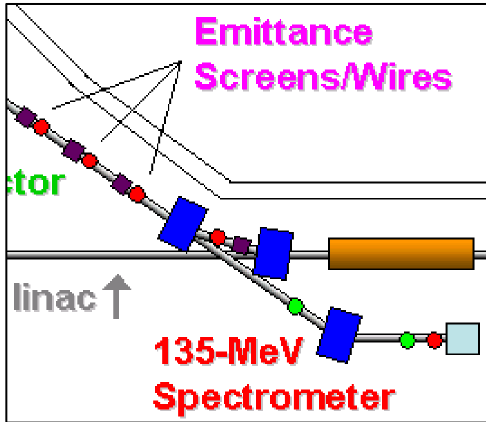
# Projected Emittance <1.2 $\mu$m at 1 nC (135 MeV)

DESY

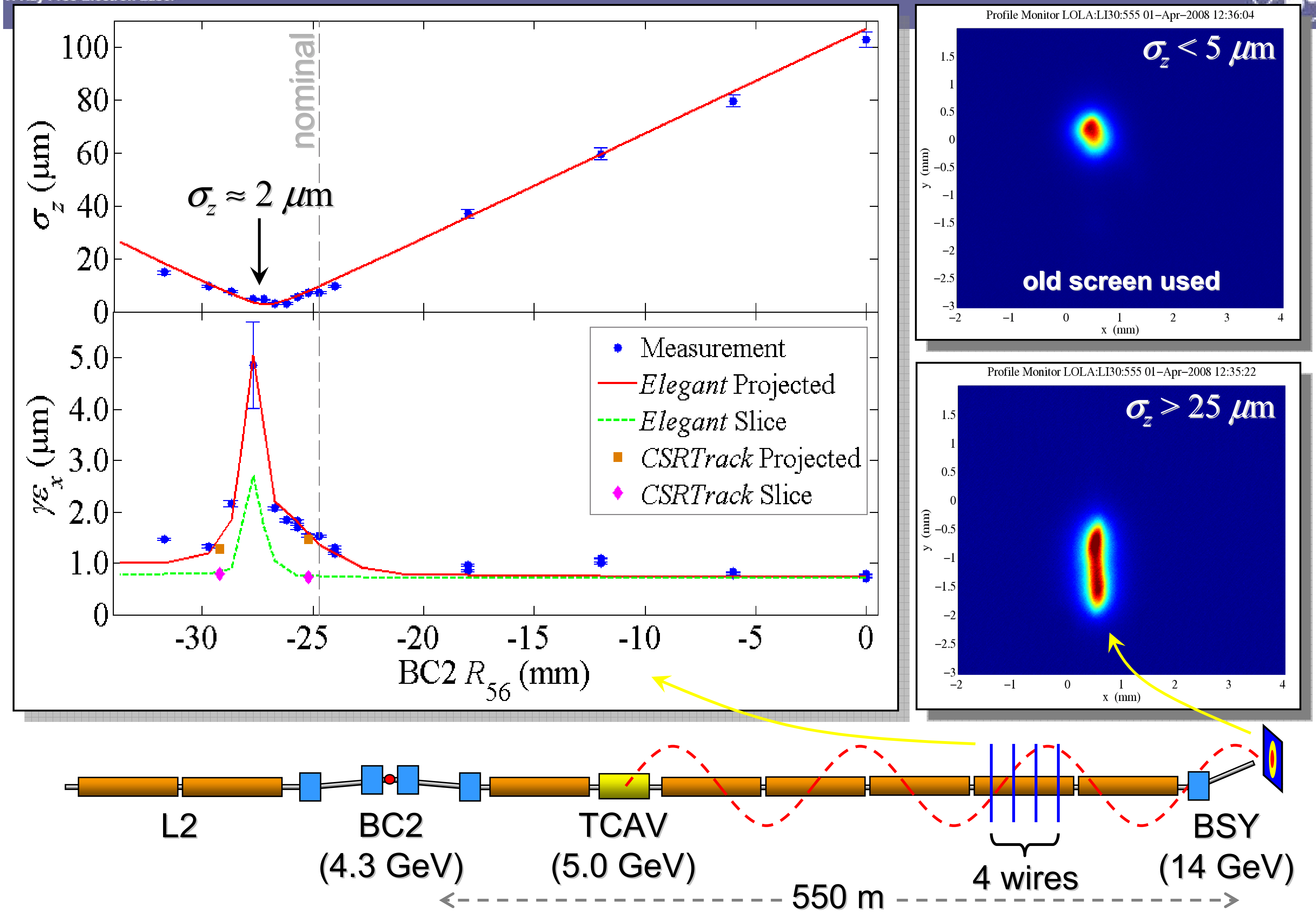



Gaussian overlay not used



# Bunch Compression & CSR Measured after BC2 (0.25 nC)



# Laser & Electron-Based Feedback Systems

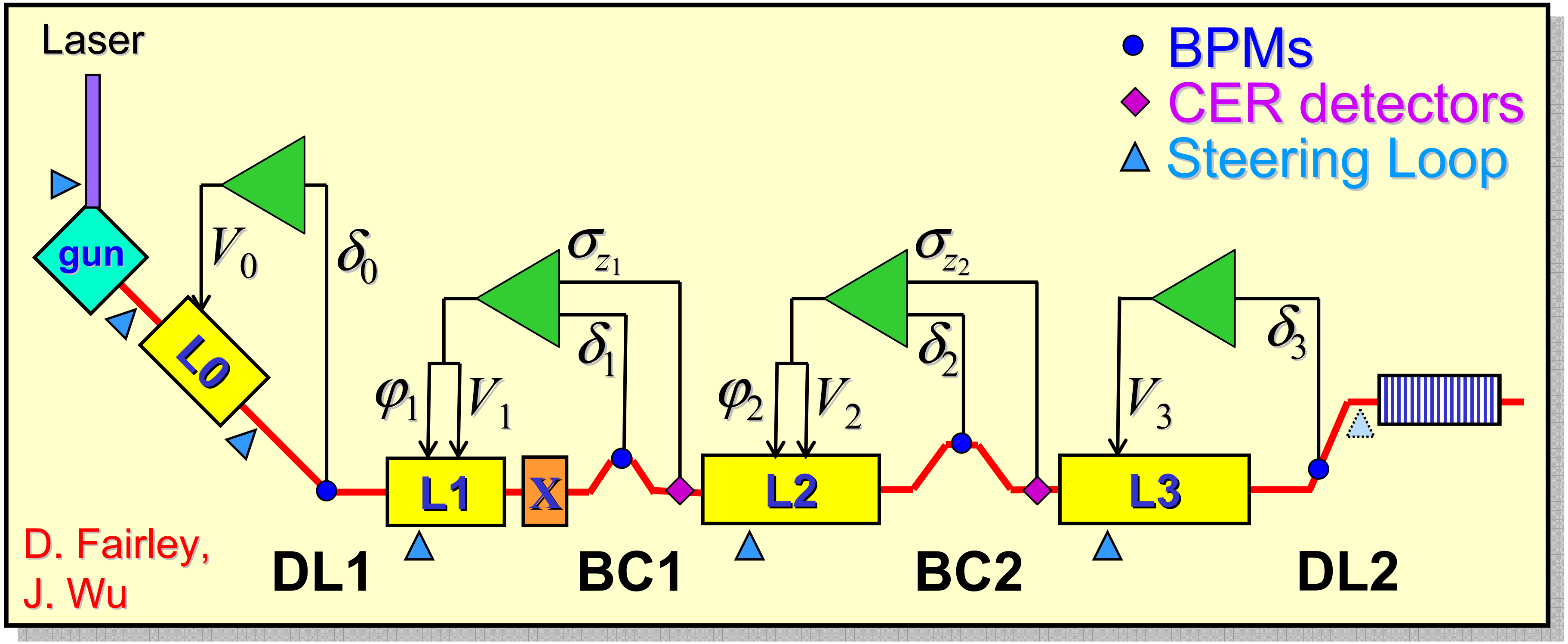


**Transverse Loops Stabilize:**

- Laser spot on cathode
- Gun launch angle
- Injector trajectory
- X-band cavity position
- Linac trajectory (2)
- Undulator traj. (future)

**Longitudinal Loops Stabilize:**

- DL1 energy
- BC1 energy
- BC1 bunch length
- BC2 energy
- BC2 bunch length
- Final energy



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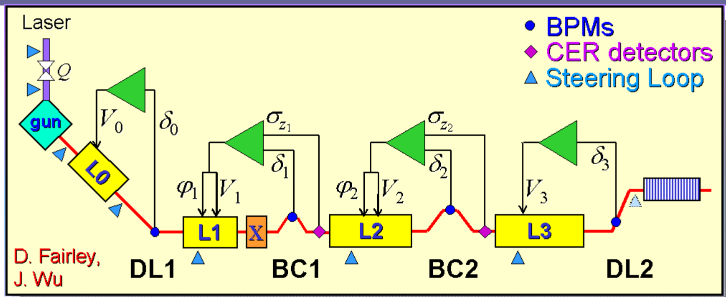
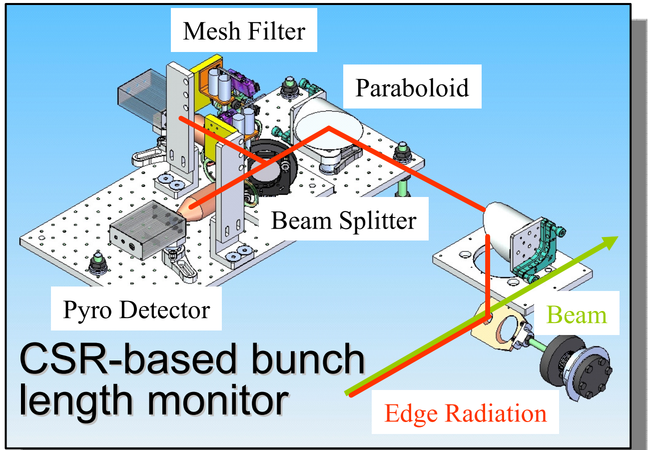
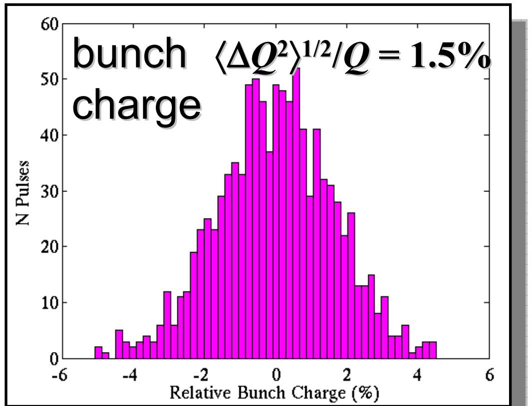
# Bunch Length & Energy Feedback Systems

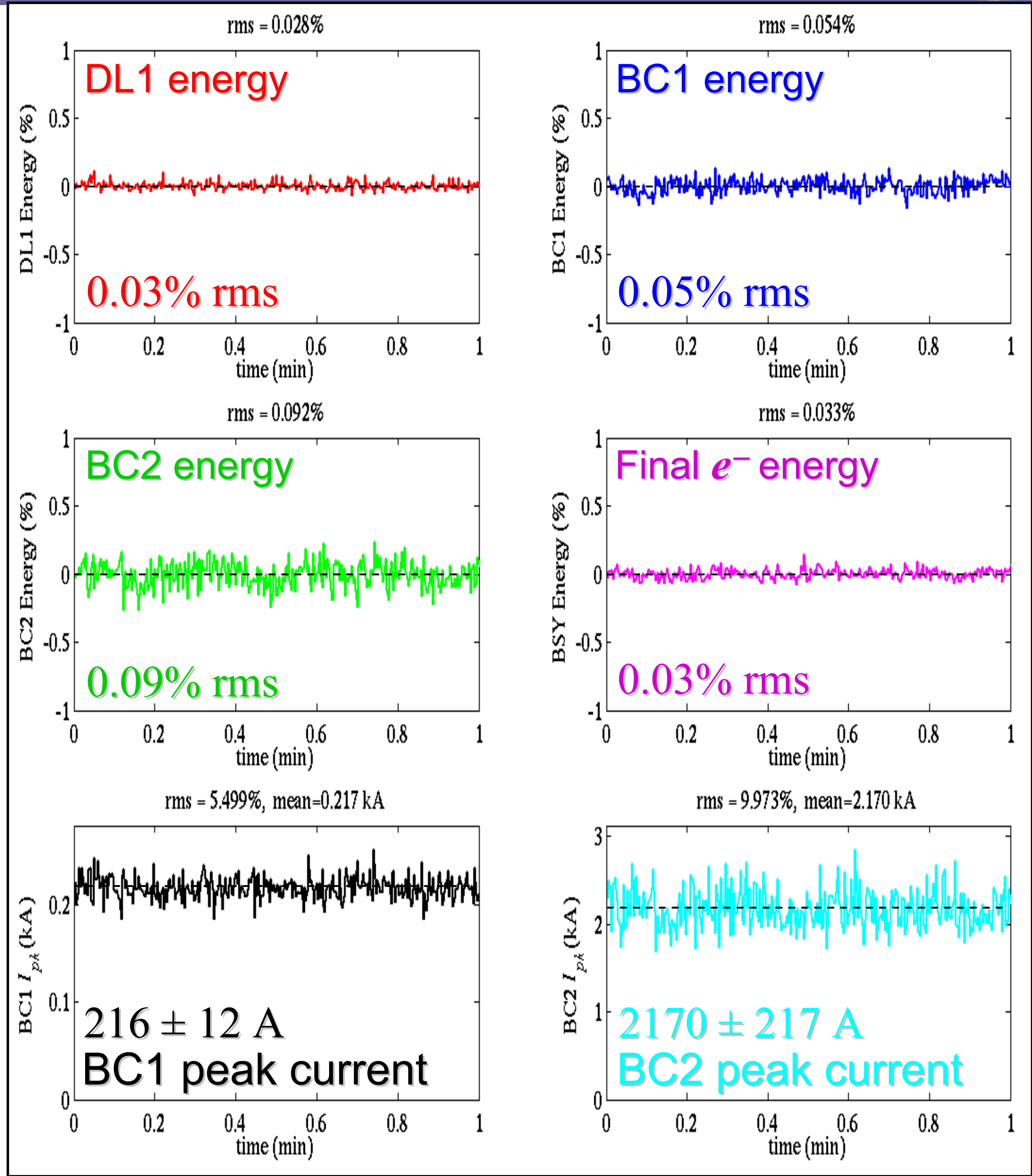
DESY




Charge feedback: $Q = 0.25$ nC

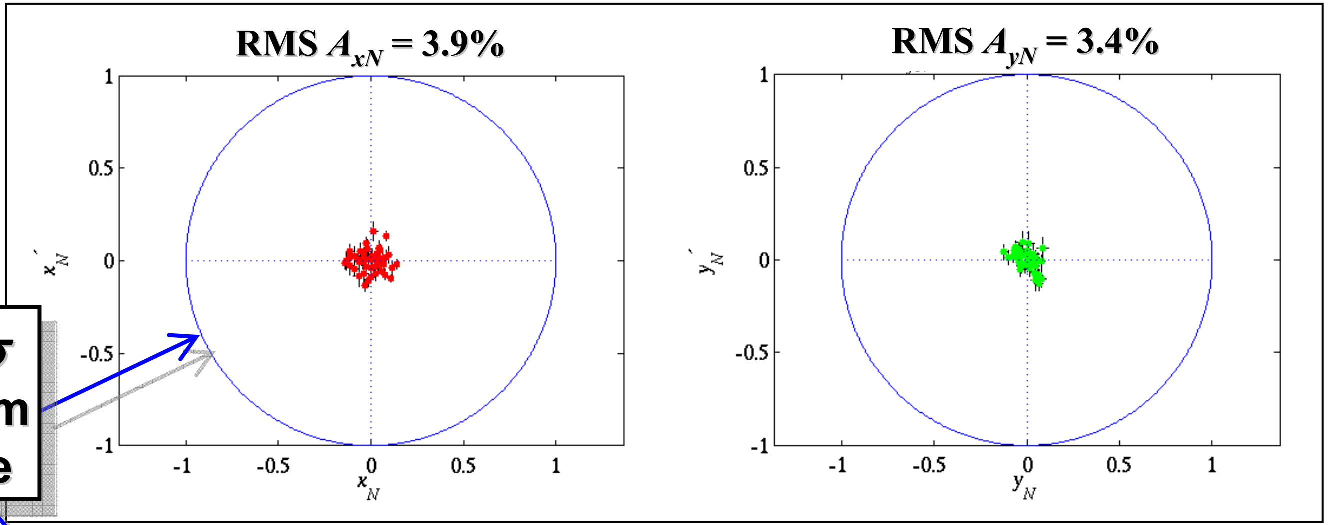


# Normalized phase space centroid jitter after BC1

(~4% of rms beam size)



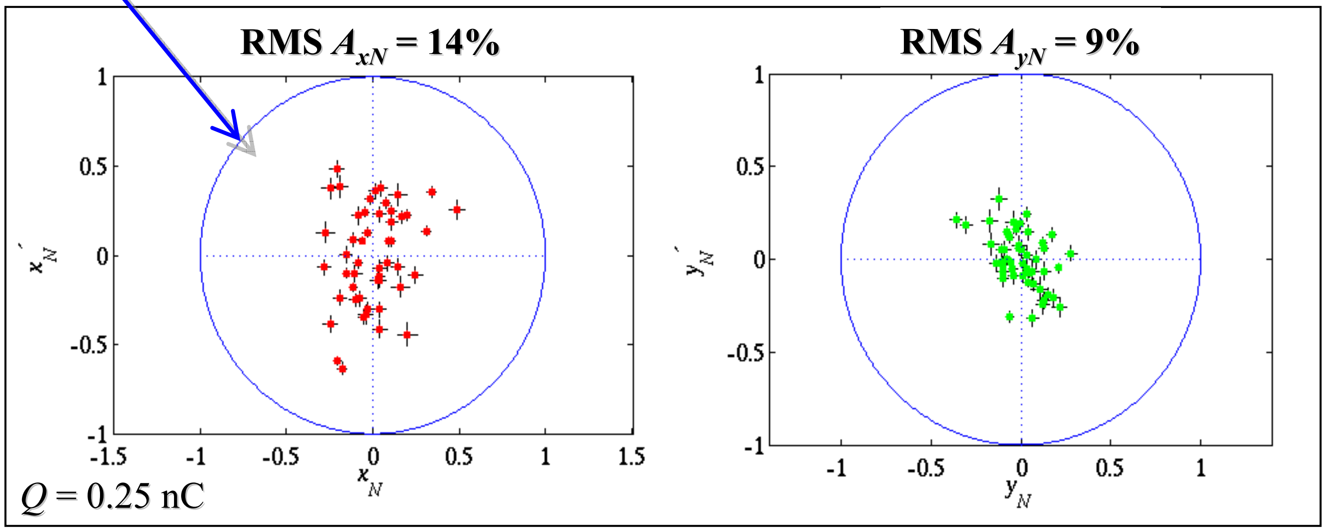



**1-$\sigma$ beam size**

**Stability is not so far from our goal (~10%)**

**D. Ratner**

## … near end of linac (10-15% of rms beam size)



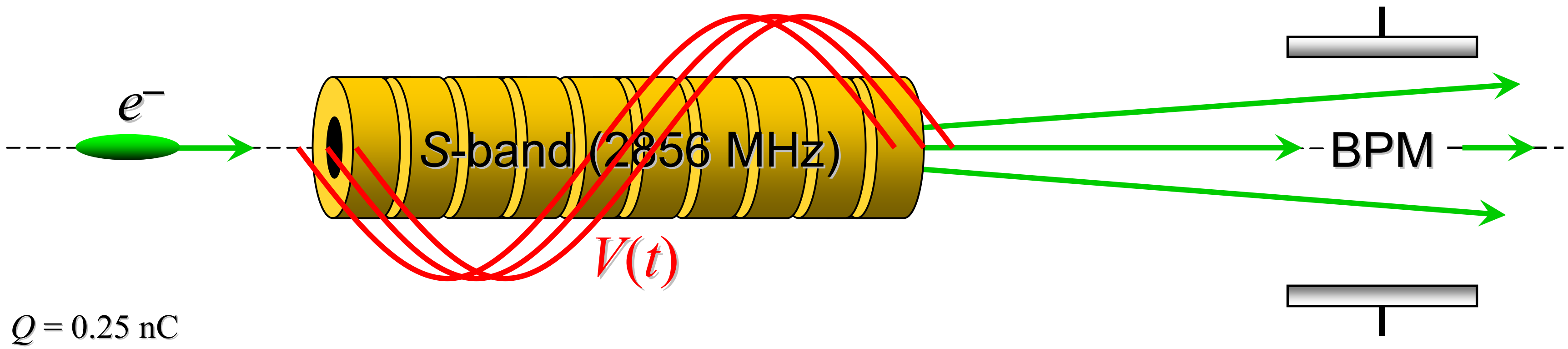

Thanks to **Controls** group for new BPM electronics!

**$\Delta E/E$ jitter ≈ 0.03%**

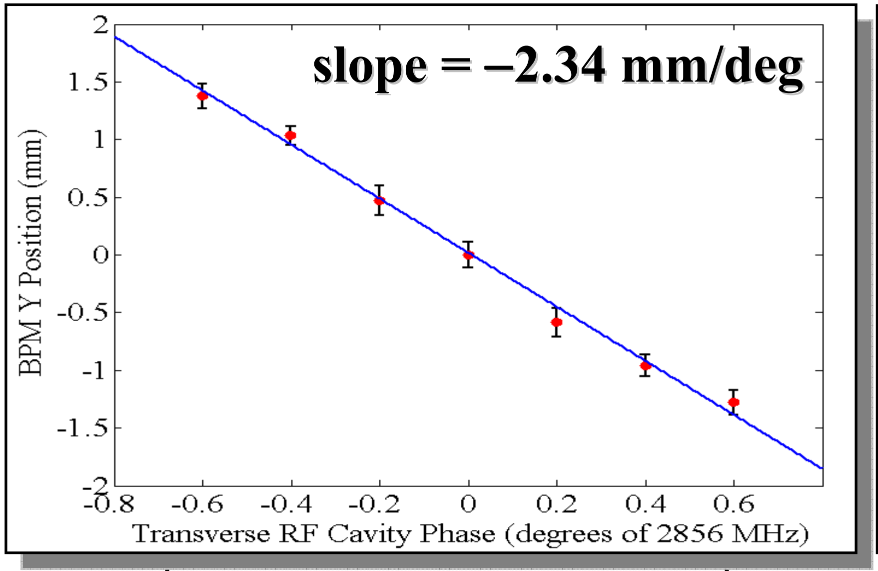
**$\Delta Q/Q$ jitter ≈ 1.5%**

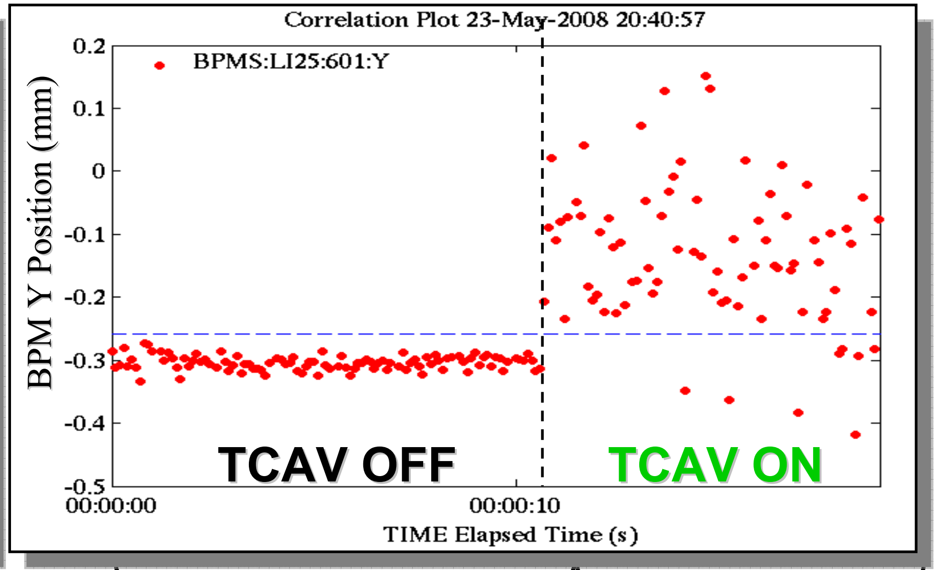
# Measuring Bunch Arrival Time Jitter






$Q$ = 0.25 nC



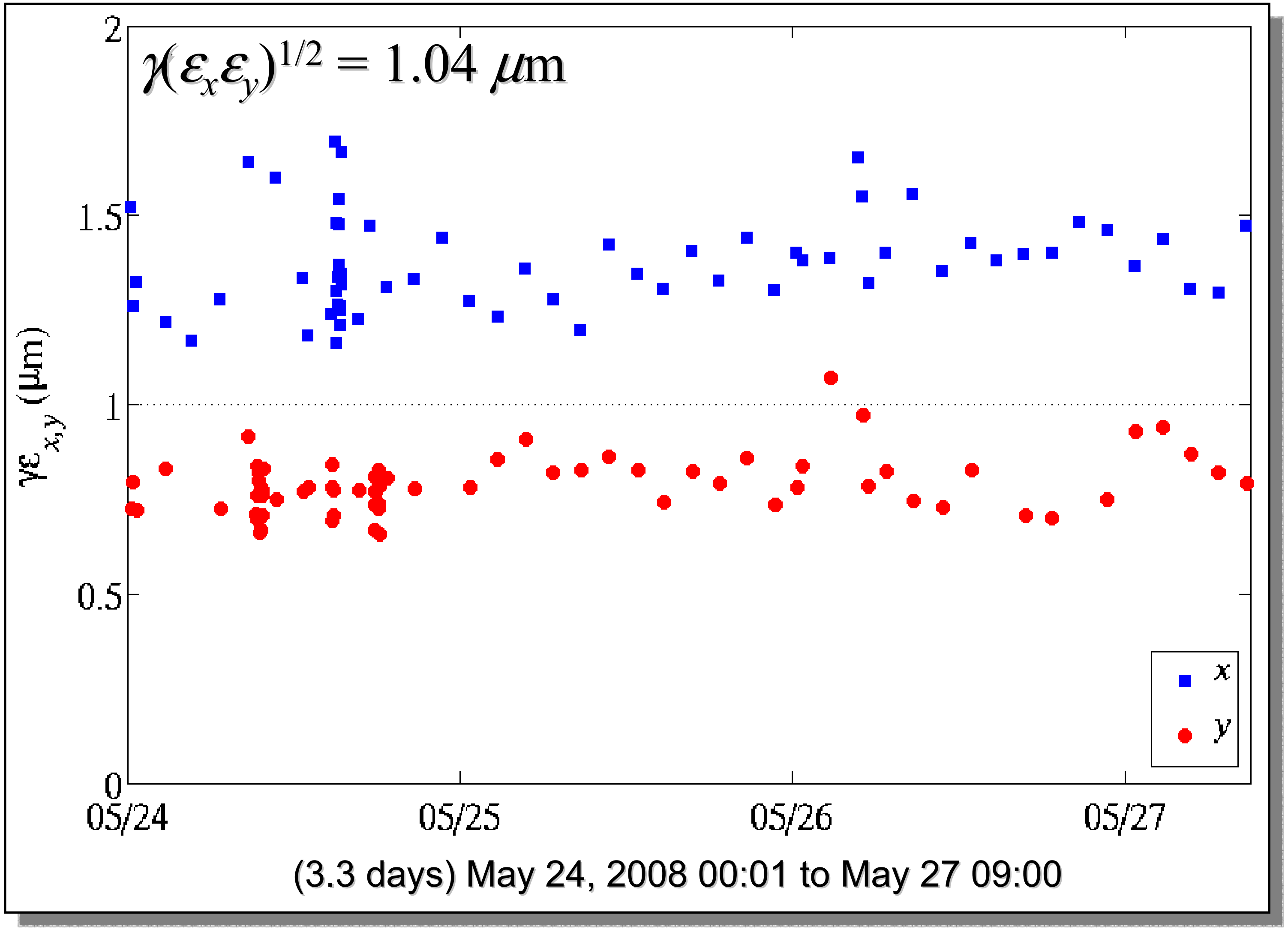

$\Delta t \approx \pm 0.6$ ps

9 $\mu$m rms

110 $\mu$m rms

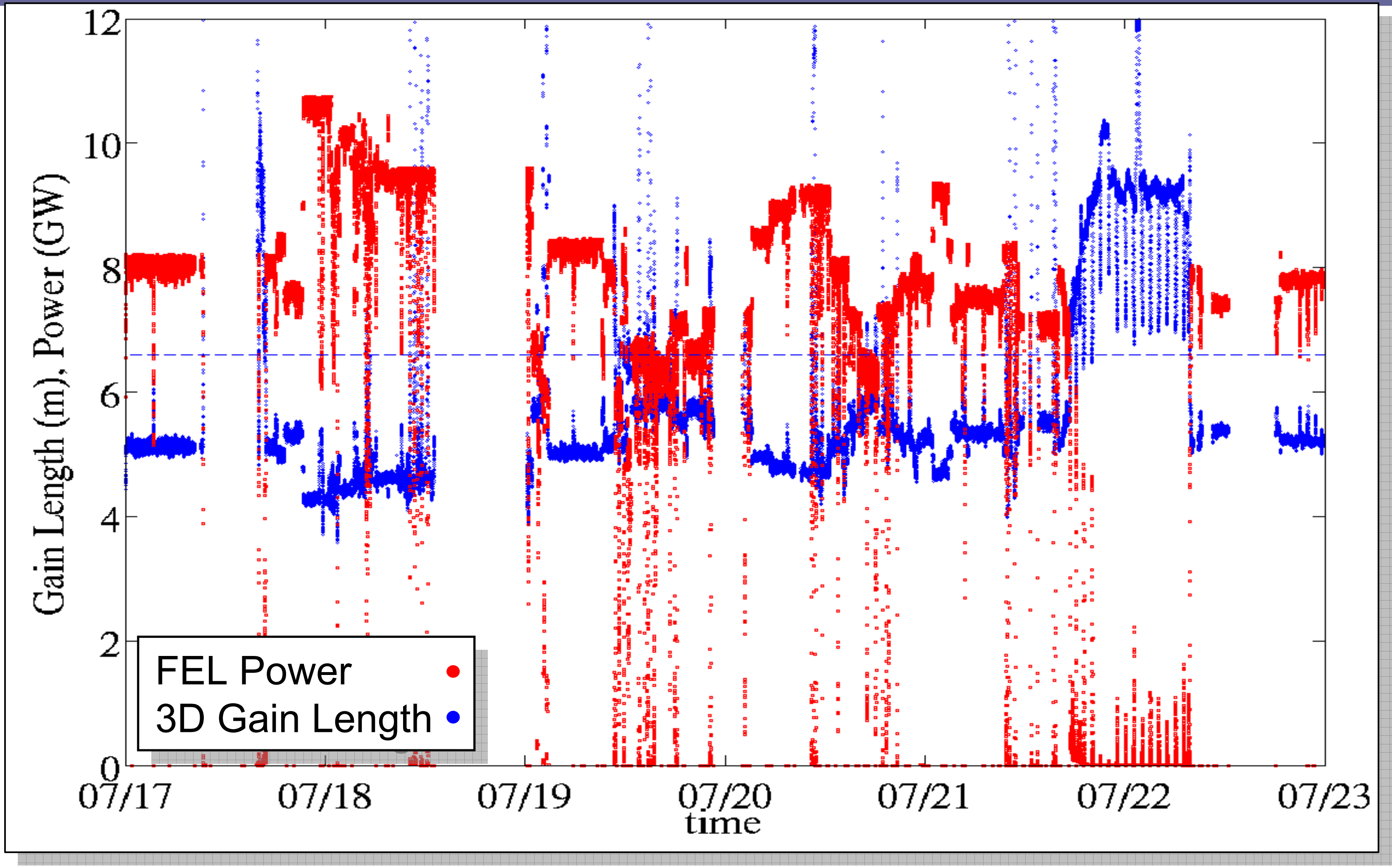
Timing Jitter (w.r.t. RF) = (110 $\mu$m)/(2.34 mm/deg) = 0.047 deg ⇒ **46 fsec rms**

# Emittance Near End of Linac Over Long Weekend




long weekend run at 0.25 nC with no tuning

# Beam Appears Bright Enough for FEL Saturation at 0.15 nm




Calculation based on measured end-of-linac ***projected*** emittance values, measured peak current, and design undulator parameters (assuming undulator alignment and ≤0.01% rms slice energy spread – not yet measurable)

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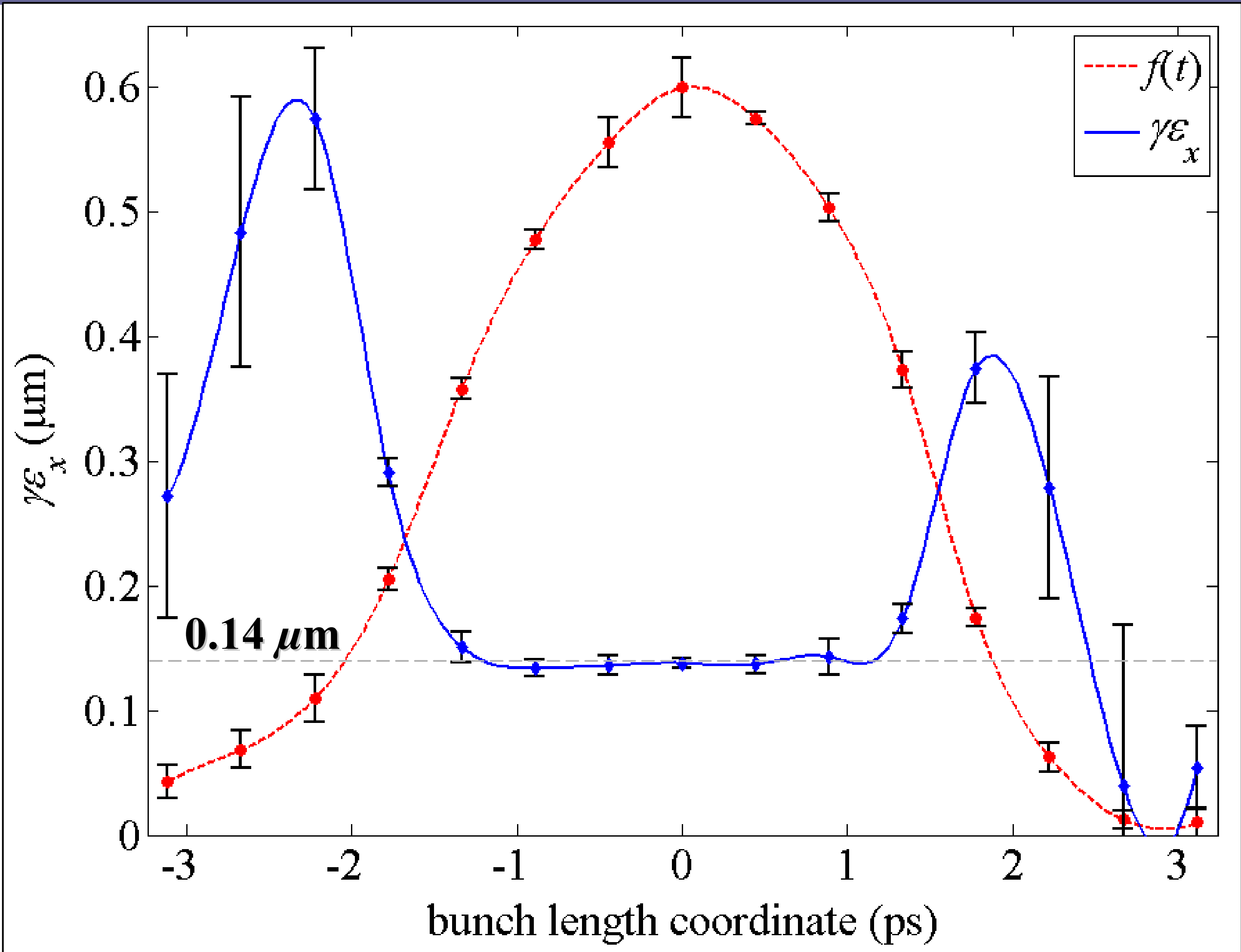
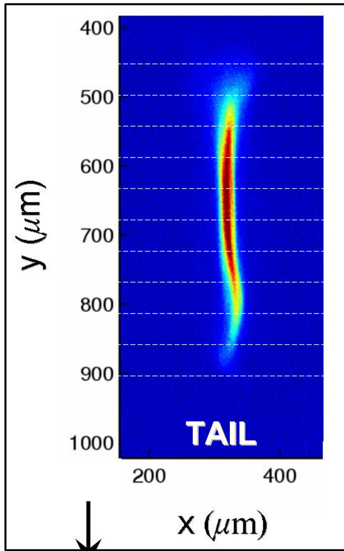
# Time-sliced *x*-Emittance at Very Low Charge

DESY




(not same data)

**20 pC, 135 MeV, 0.6-mm spot diameter, 400 *μ*m rms bunch length (5 A)**

Also measured at 0.6 *μ*m at 250 pC & 1.2-mm laser spot diameter (40 A)

# Measurements and Simulations for 20-pC Bunch at 14 GeV

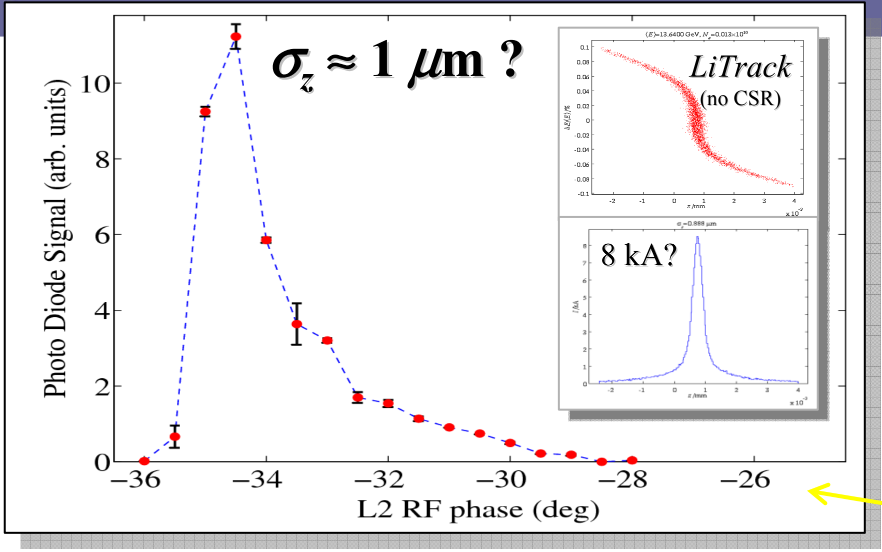
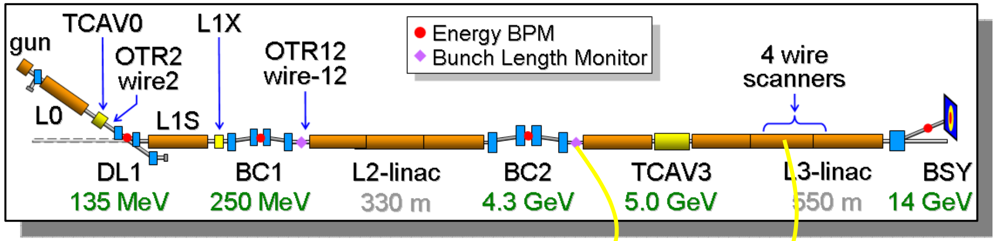
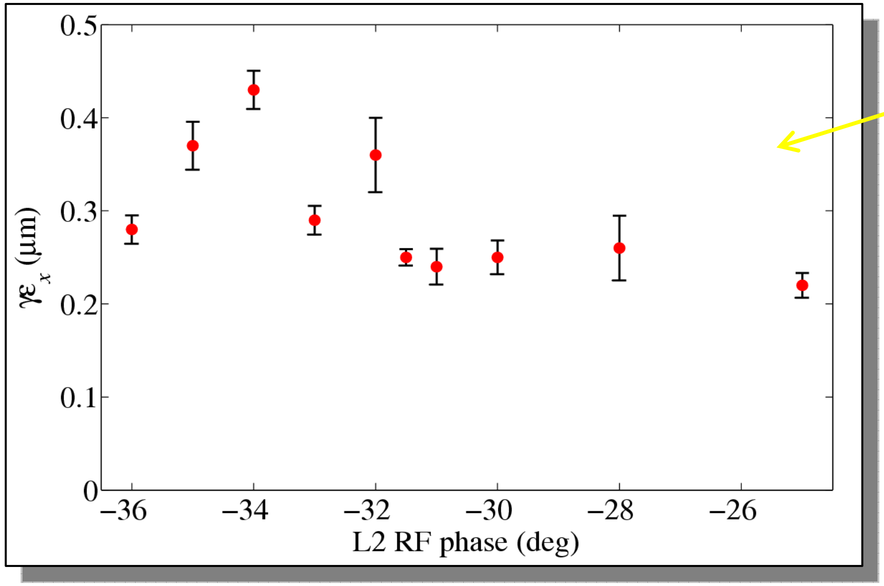


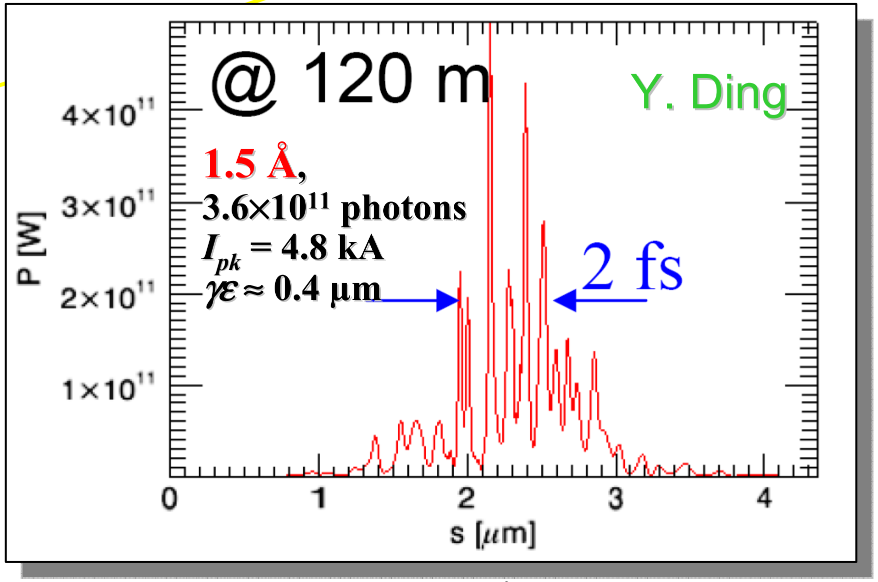

**Photo-diode signal** on OTR screen after BC2 shows minimum compression at L2-linac phase of -34.5 deg.



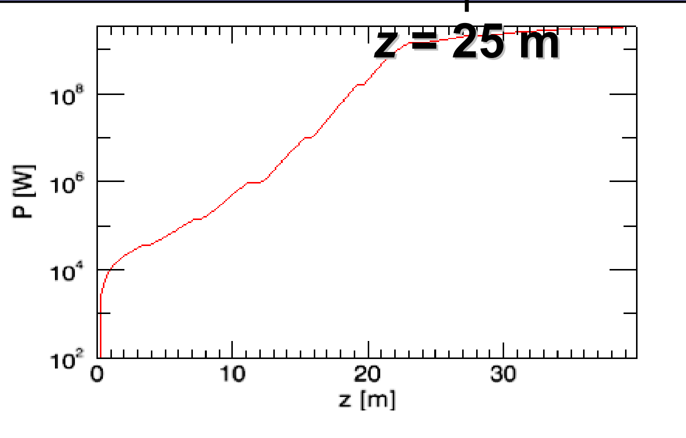

Horizontal projected emittance **measured** at 10 GeV, after BC2, using 4 wire-scanners.

SIMULATED FEL PULSE

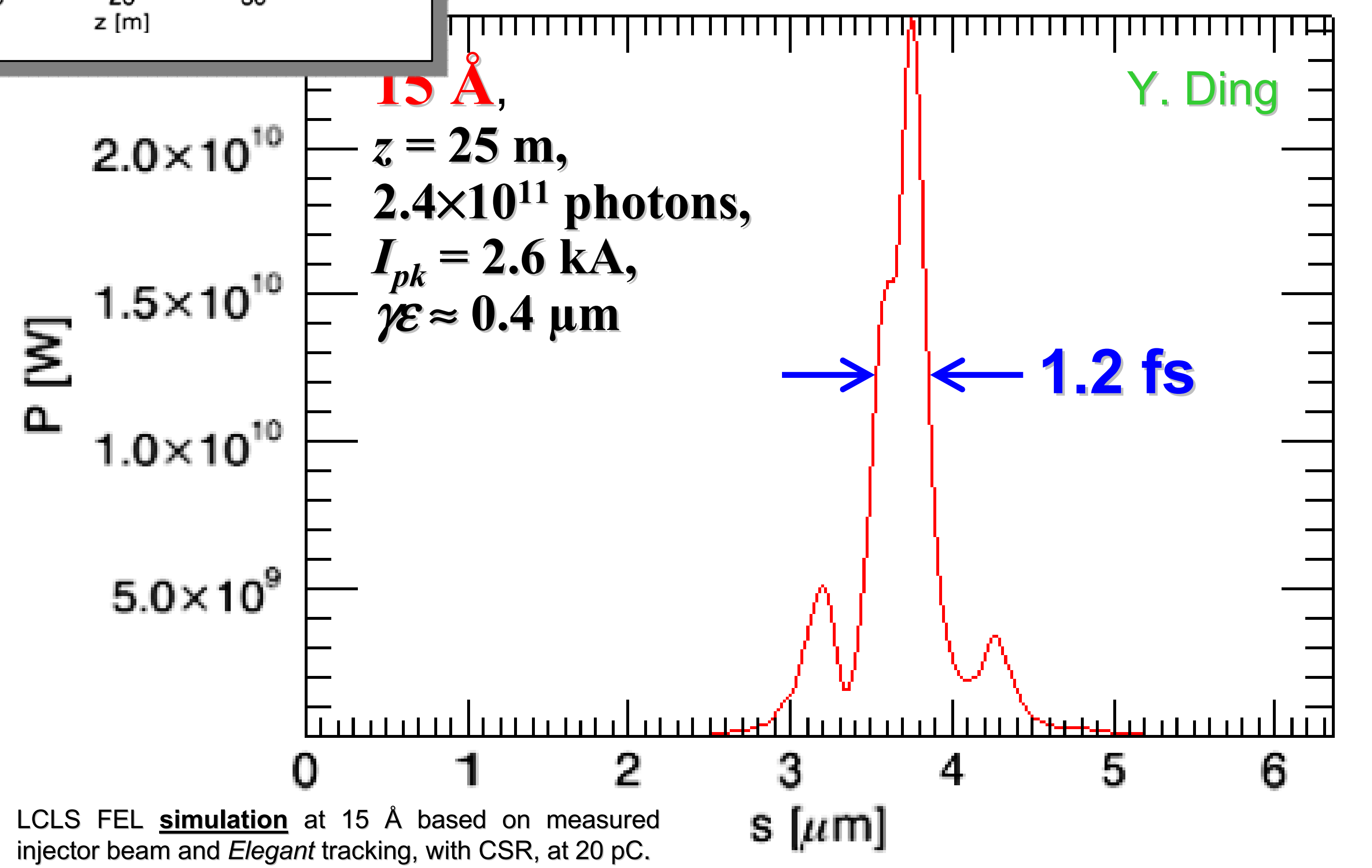



LCLS FEL **simulation** at 1.5 Å based on measured injector beam and *Elegant* tracking, with CSR, at 20 pC.

# Simulated 20-pC Bunch at 4.3 GeV: *Approaching a Single Longitudinally Coherent Spike*

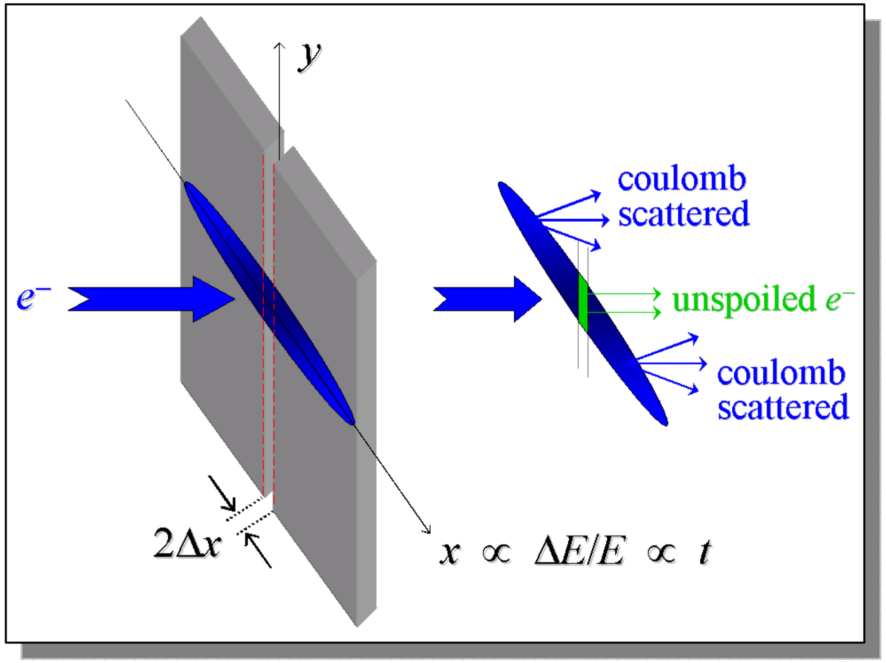


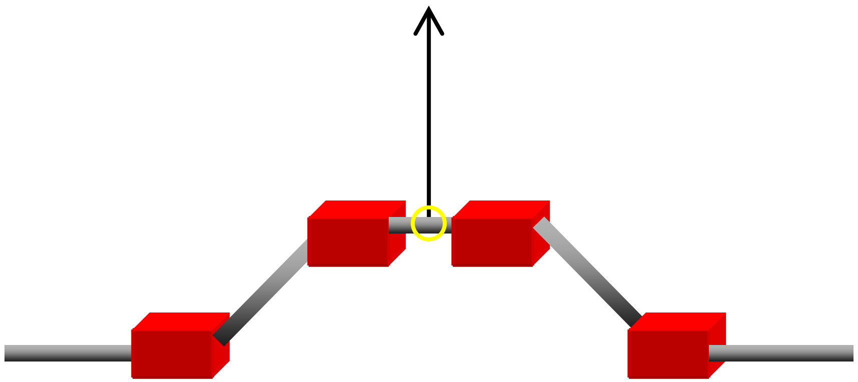

(power profile at *z* = 25 m varies from shot to shot due to noisy startup)



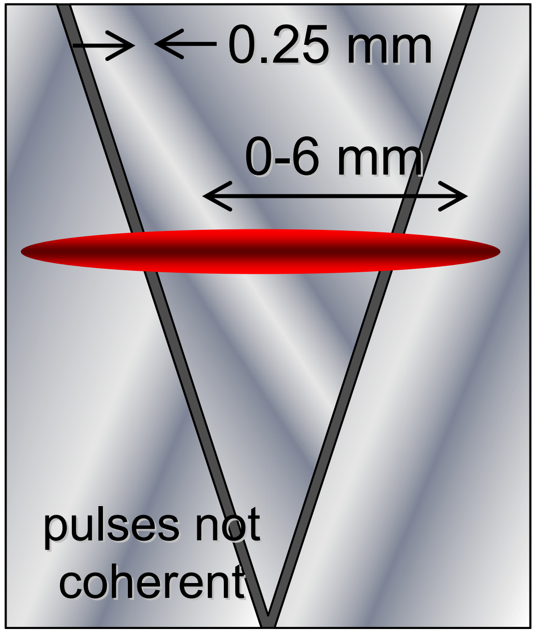

LCLS FEL **simulation** at 15 Å based on measured injector beam and *Elegant* tracking, with CSR, at 20 pC.

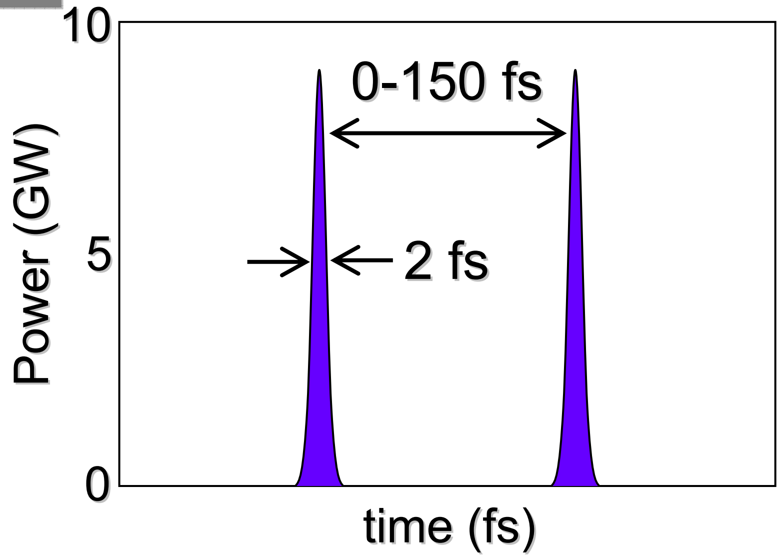
# 2-Pulse Production with 2 slots



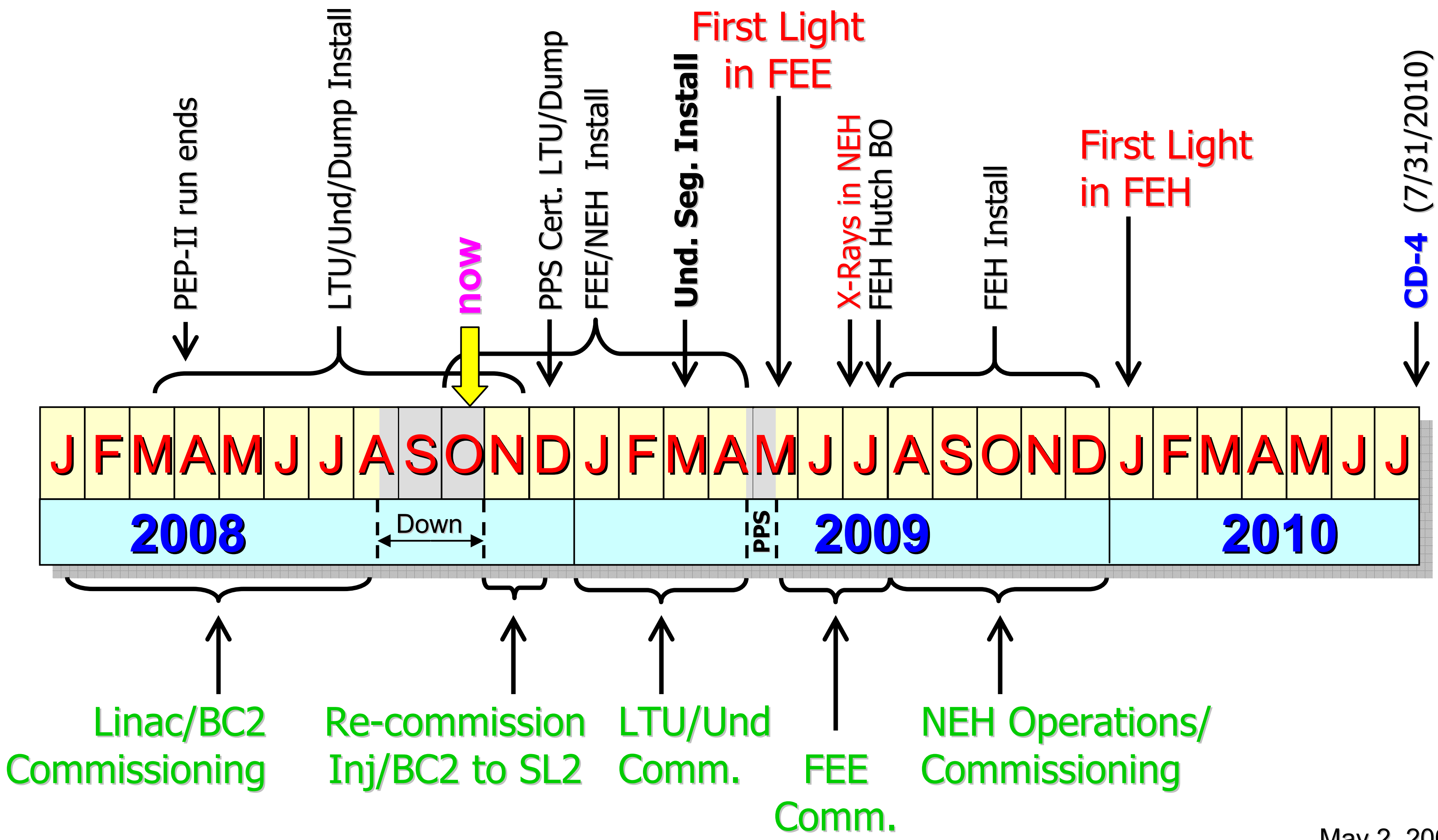



LCLS BC2 bunch compressor chicane



# *LCLS* Installation and Commissioning Time-Line




May 2, 2008