First Lasing of the *LCLS* X-Ray FEL at 1.5 Å

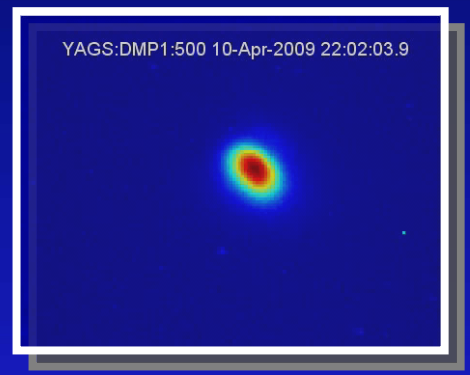
PAC09 Vancouver

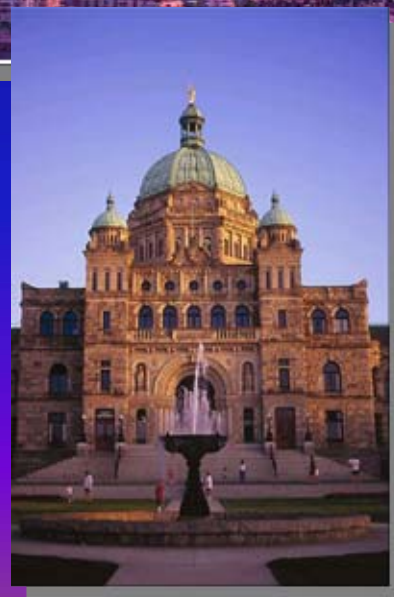
May 4-8, 2009

Paul Emma, **for the *LCLS* Commissioning Team**

SLAC ***National Accelerator Laboratory***

Argonne NATIONAL LABORATORY



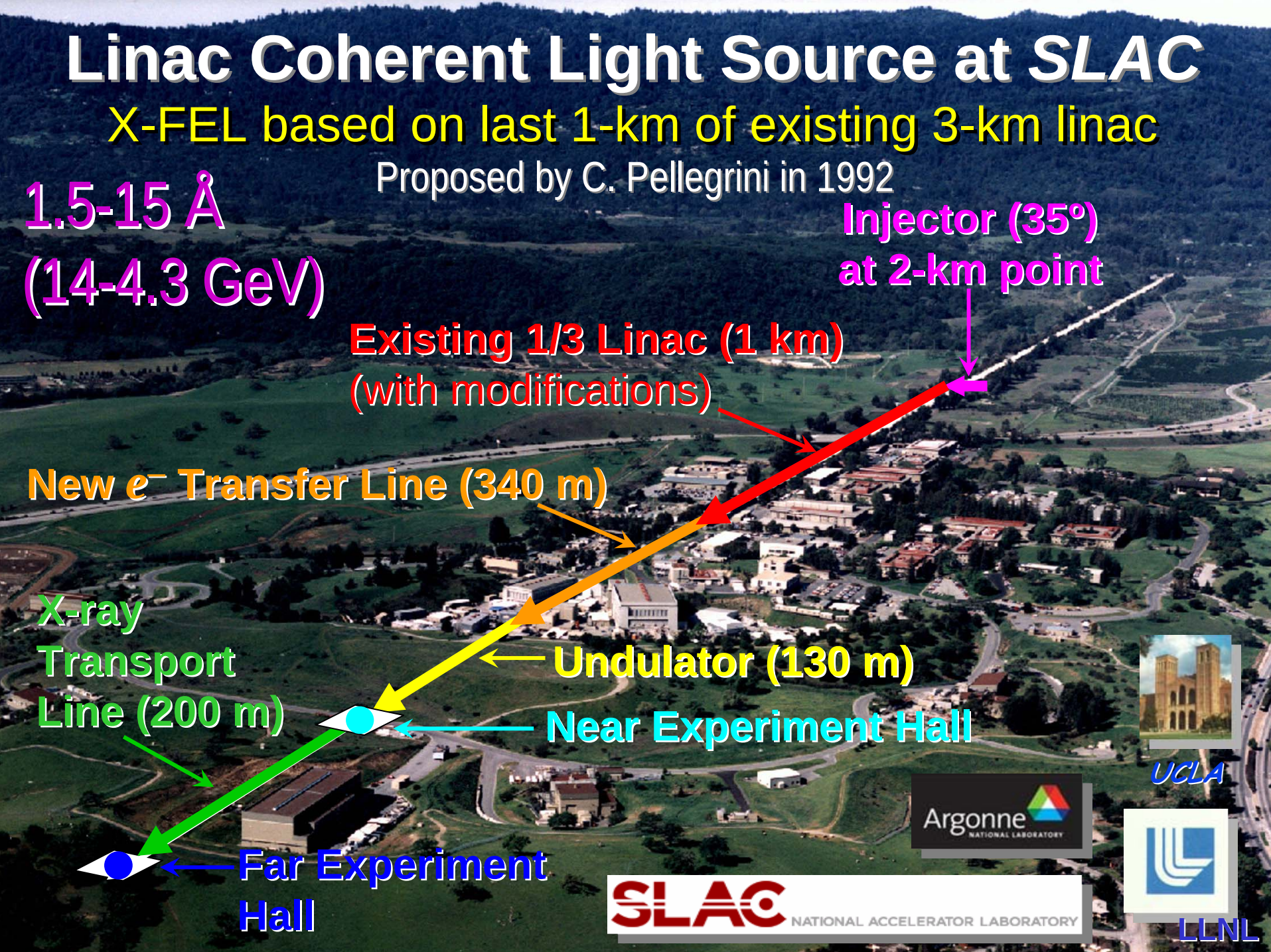


Planned/Proposed Hard X-ray FELs

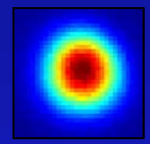
- *Euro X-FEL* at DESY (0.1-6 nm)
- *SCSS* at Spring8 in Japan (0.1-3.6 nm)
- *PSI-FEL* in Switzerland (0.1-7 nm)
- *LCLS* at SLAC in USA (0.15-1.5 nm)

…and many soft x-ray FELs taking shape around the globe

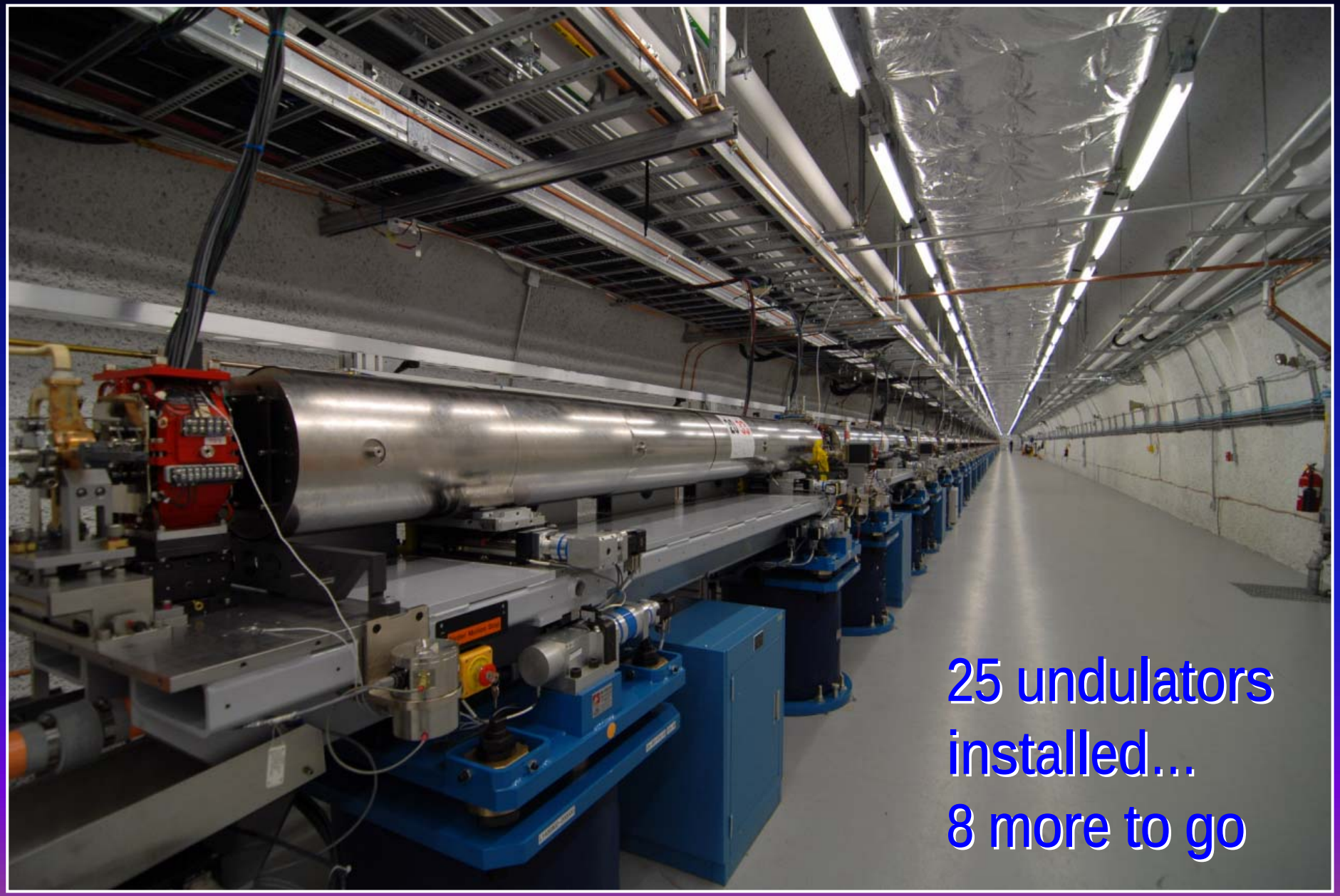
This talk will concentrate on *LCLS*, with first lasing and FEL saturation at 1.5 Å…


Linac Coherent Light Source at SLAC
X-FEL based on last 1-km of existing 3-km linac
Proposed by C. Pellegrini in 1992
1.5-15 Å
(14-4.3 GeV)
Injector (35°)
at 2-km point
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
UCLA
Argonne
NATIONAL LABORATORY
SLAC
NATIONAL ACCELERATOR LABORATORY
LLNL

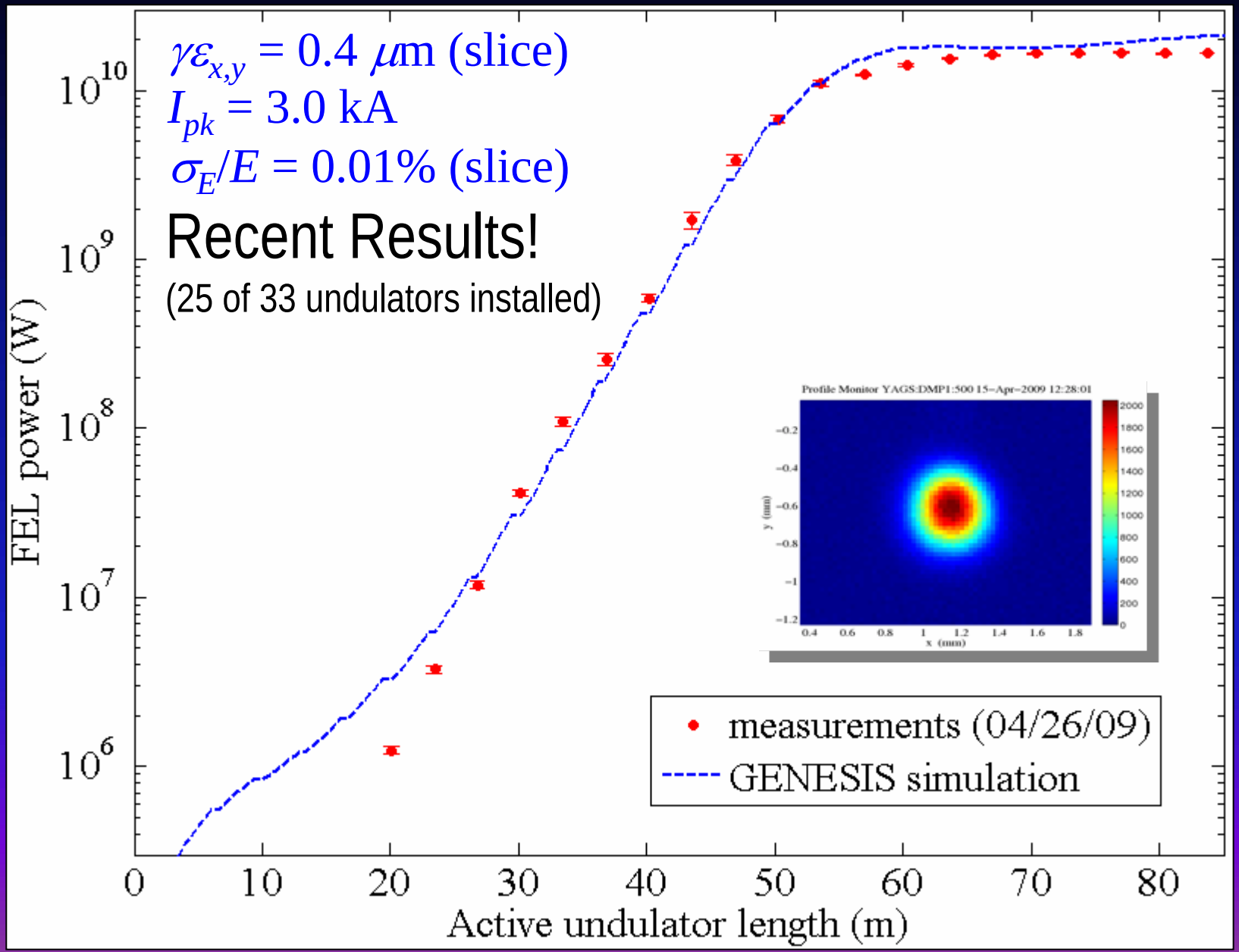
Commissioning Status of *LCLS*

- Laser, gun, & injector commissioned: 2007
- Linac & bunch compressors commissioned: 2008
- First beam through undulator beamline: Dec. 2008
- 21 undulator magnets installed & ready: April 7, 2009
- First lasing at 1.5 Å: April 10, 2009 (first try!) 
- 1.5 Å FEL saturation observed: April 14, 2009 (after BBA)
- X-ray diagnostics hall is not ready until early June
- Temporary (makeshift) x-ray diagnostics used up to now
- User operations start in Sep. 2009

84 meters of FEL Undulator Installed

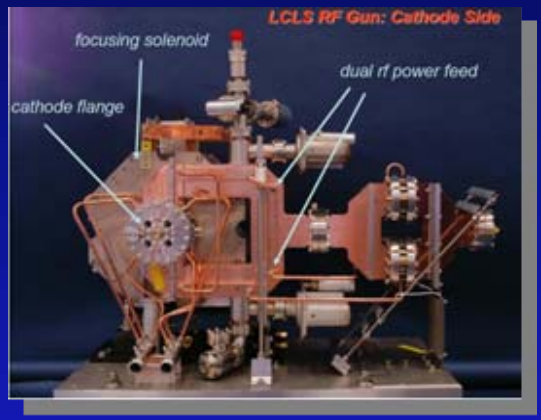


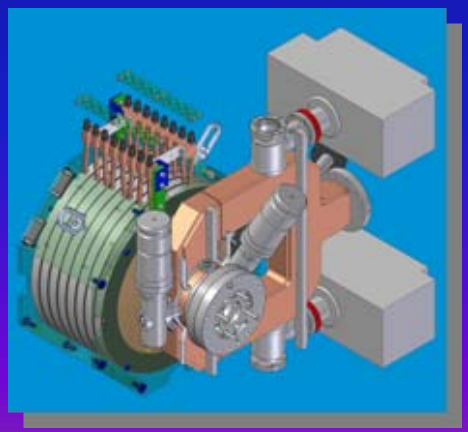
Undulator Gain Length Measurement at 1.5 Å: 3.3 m



Injector Transverse Projected Emittance <0.5 μm

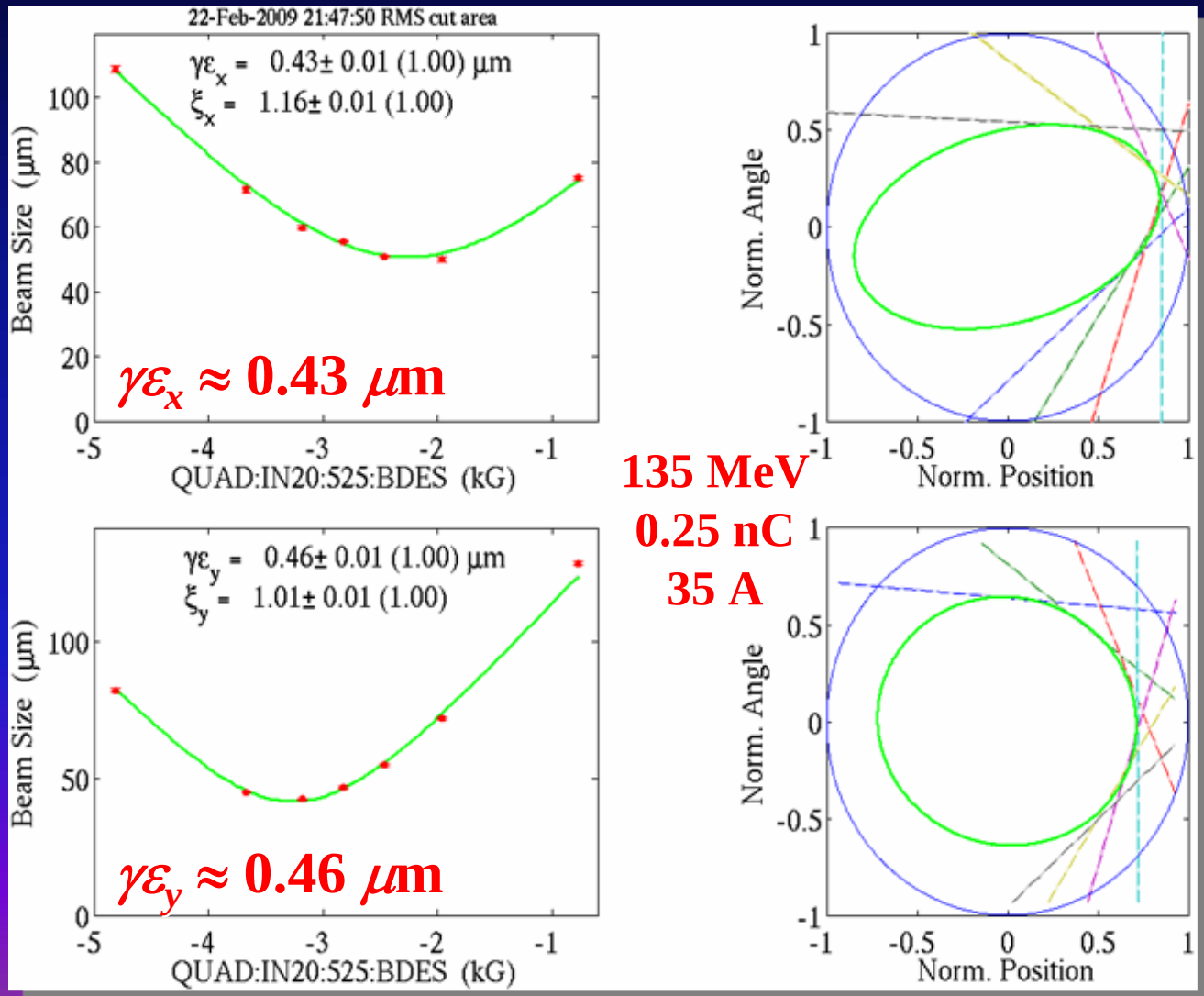
Exceptional beam quality from S-band Cu-cath. RF gun…



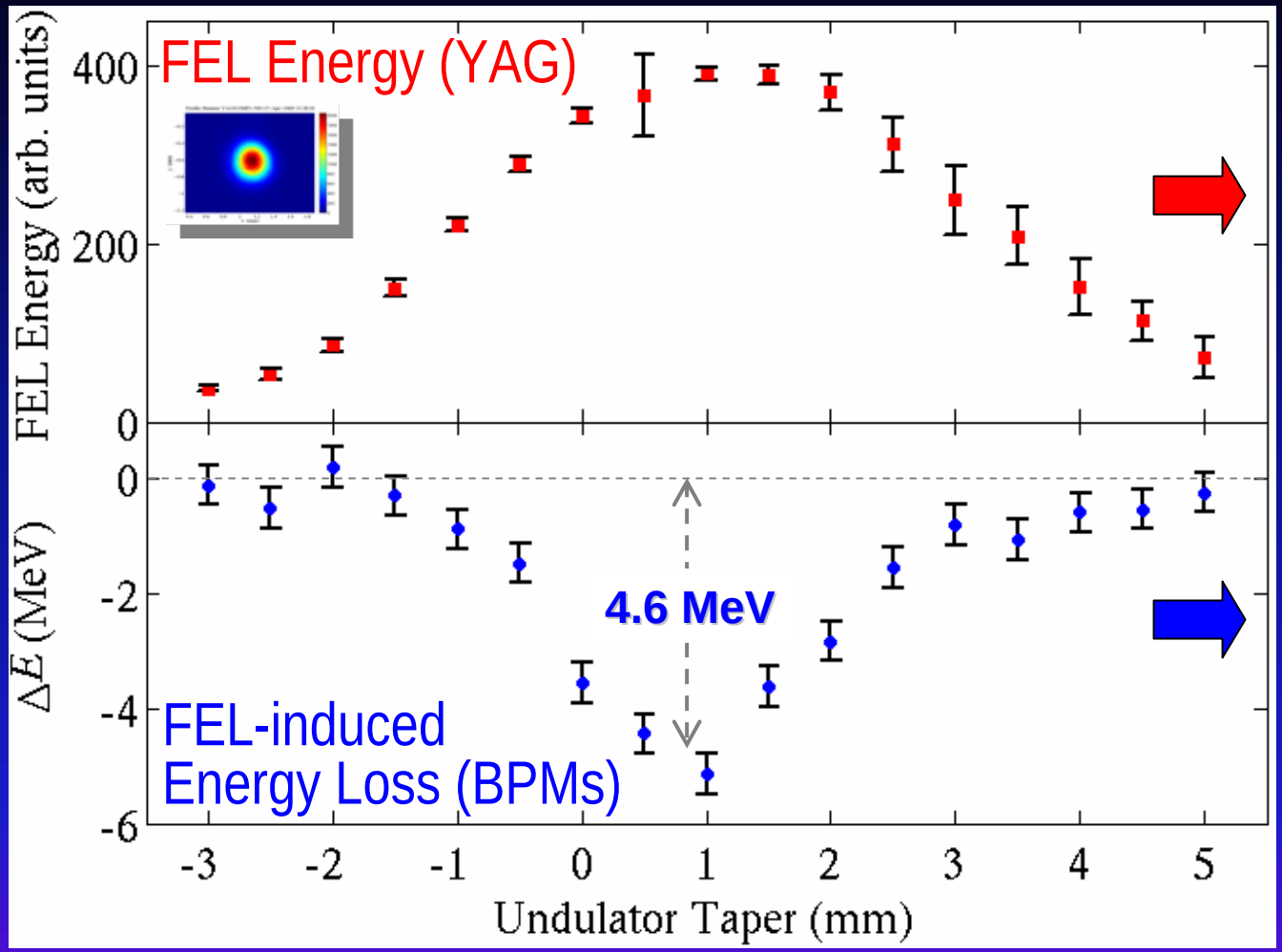


D. Dowell

Time-sliced emittance: 0.3-0.4 μm



Undulator 'Taper Scan' Shows 1.1 mJ per X-ray Pulse



1.5 Å

Pixel sum of x-ray YAG screen CCD camera vs undulator *K*-taper

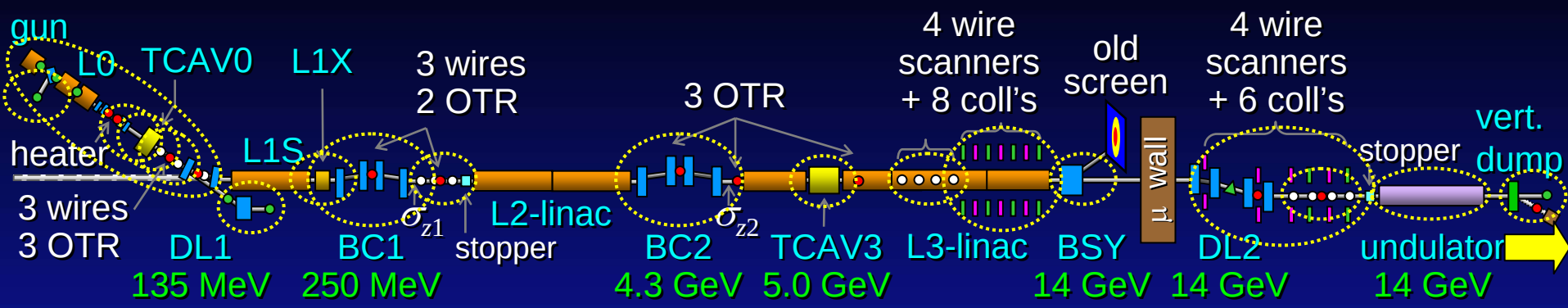
4.6 MeV at 0.25 nC = 1.1 mJ or **0.8×10^{12}** photons/pulse (15 GW at 75-fs FWHM pulse length)

Dumpline BPMs

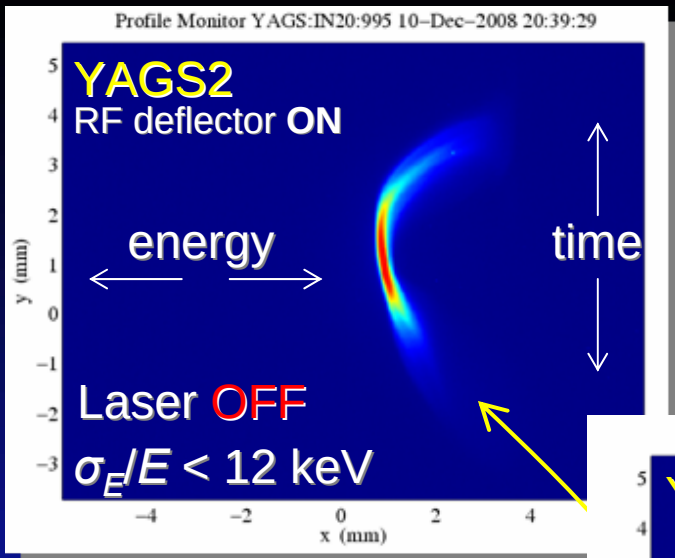
Dog-Leg BPMs

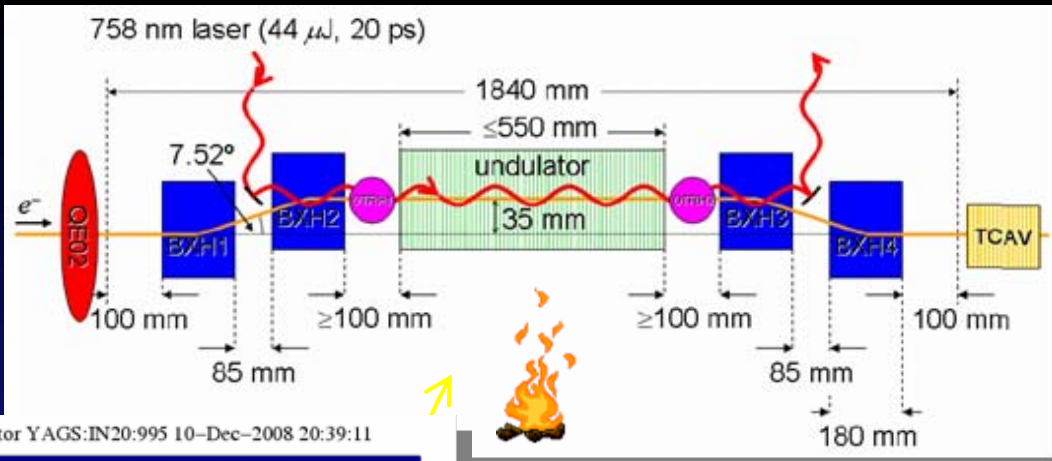
Vary the FEL power and record the e^- energy loss

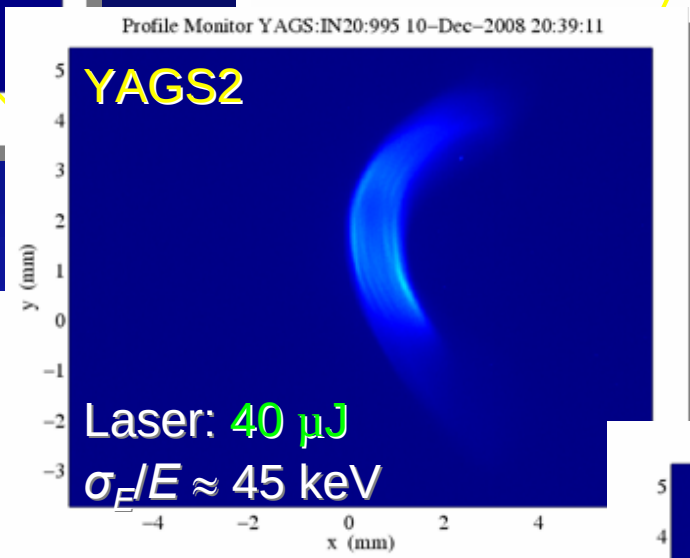
LCLS Machine Layout



- Accelerator is last 1-km of SLAC linac (14 GeV)
- RF photocathode gun and off-axis injector
- Two bunch compressors + 'laser heater'
- Two transverse RF deflectors for time-resolved beam measurements
- X-band (12 GHz) compression linearizer
- 4 emittance diagnostic stations + 4 spectrometers
- Primary and secondary collimation sections
- Fixed gap, planar, 132-m undulator at 14 GeV + 1-μm res. RF BPMs
- Near and Far Experimental Halls + 500 m of x-ray transport



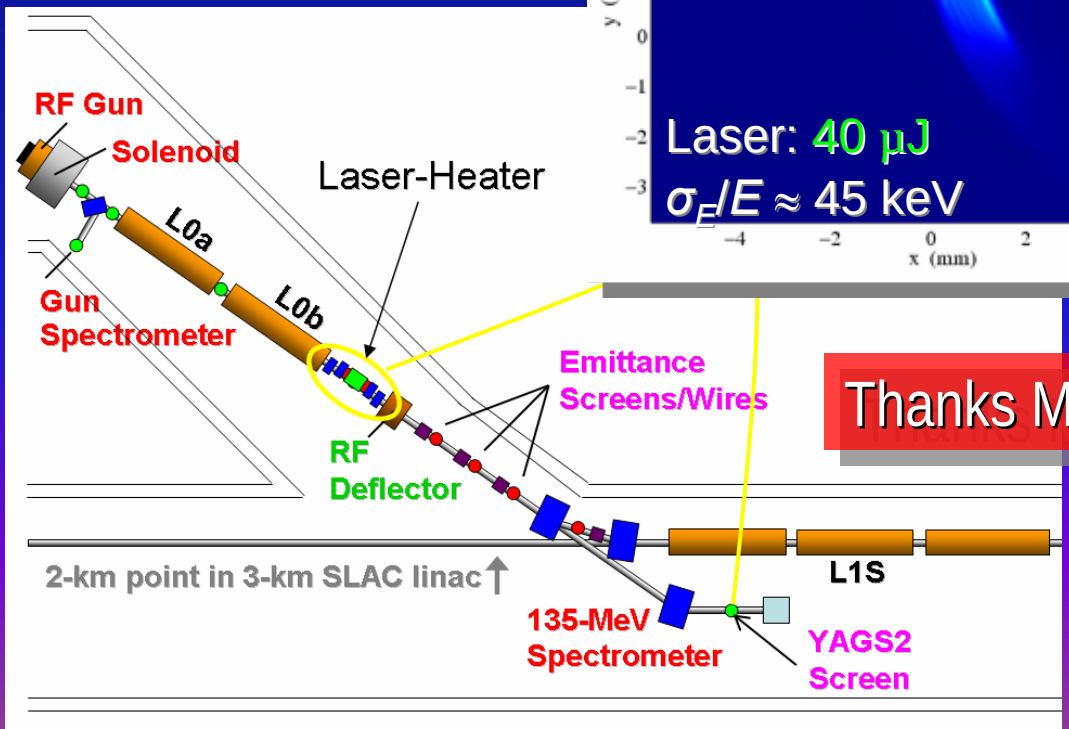




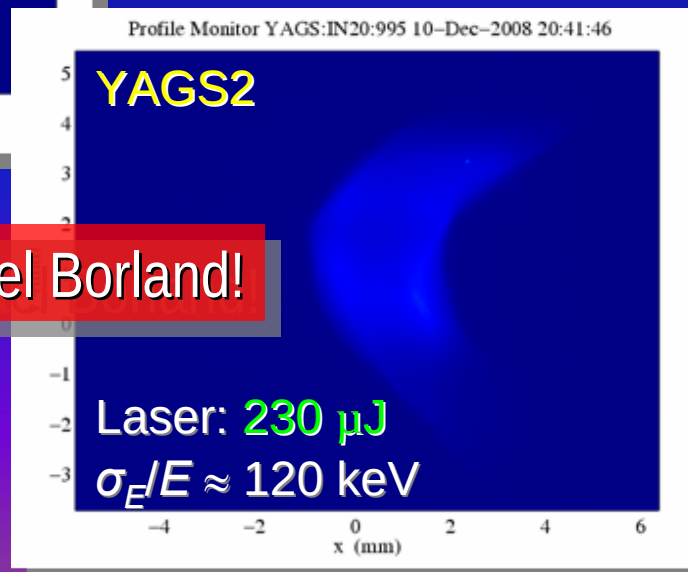
adds Landau damping

Laser Heater Working Well

see WE5RFP041

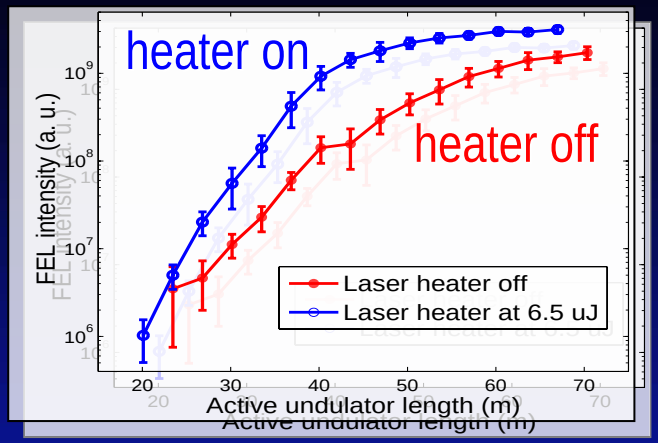


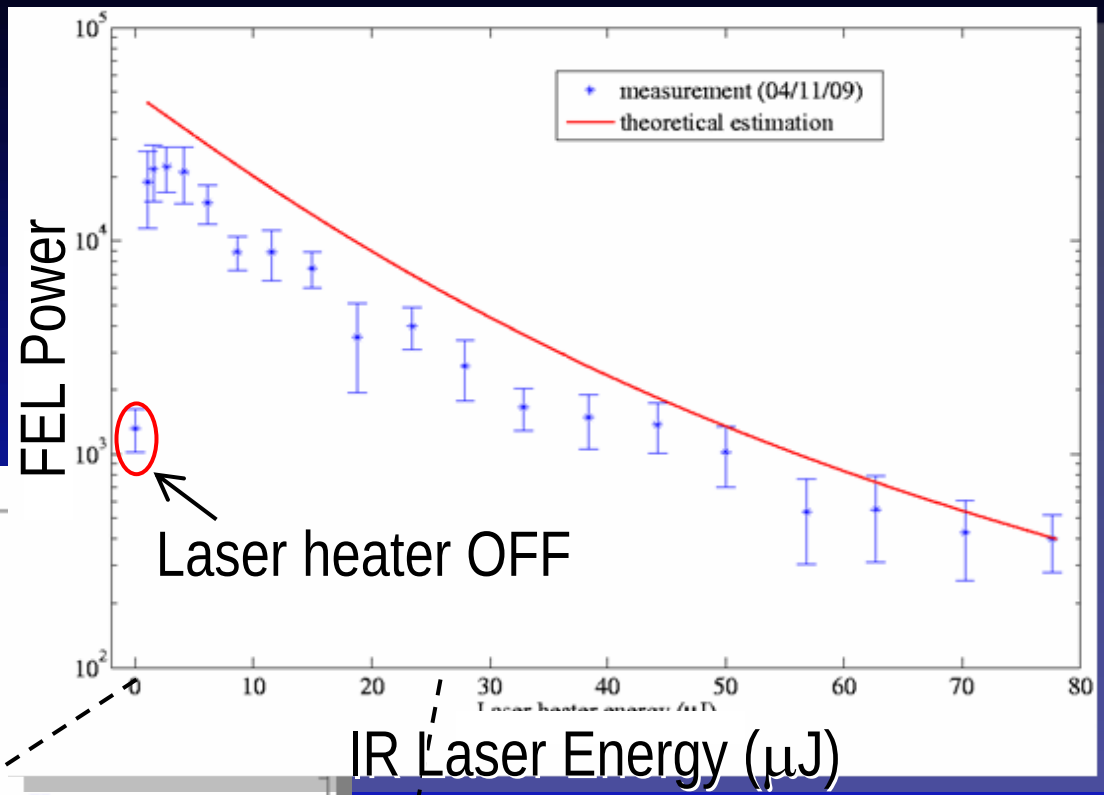
Thanks Michael Borland!

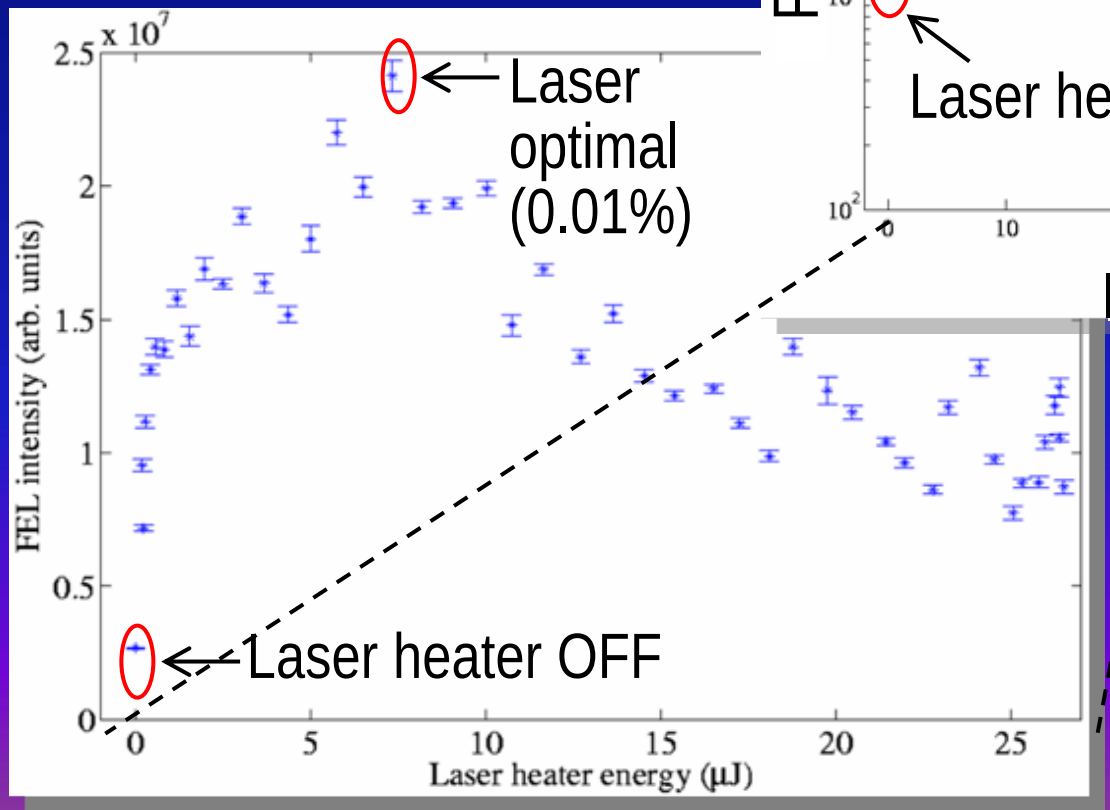


Laser Heater Improves FEL Power

FEL Gain:



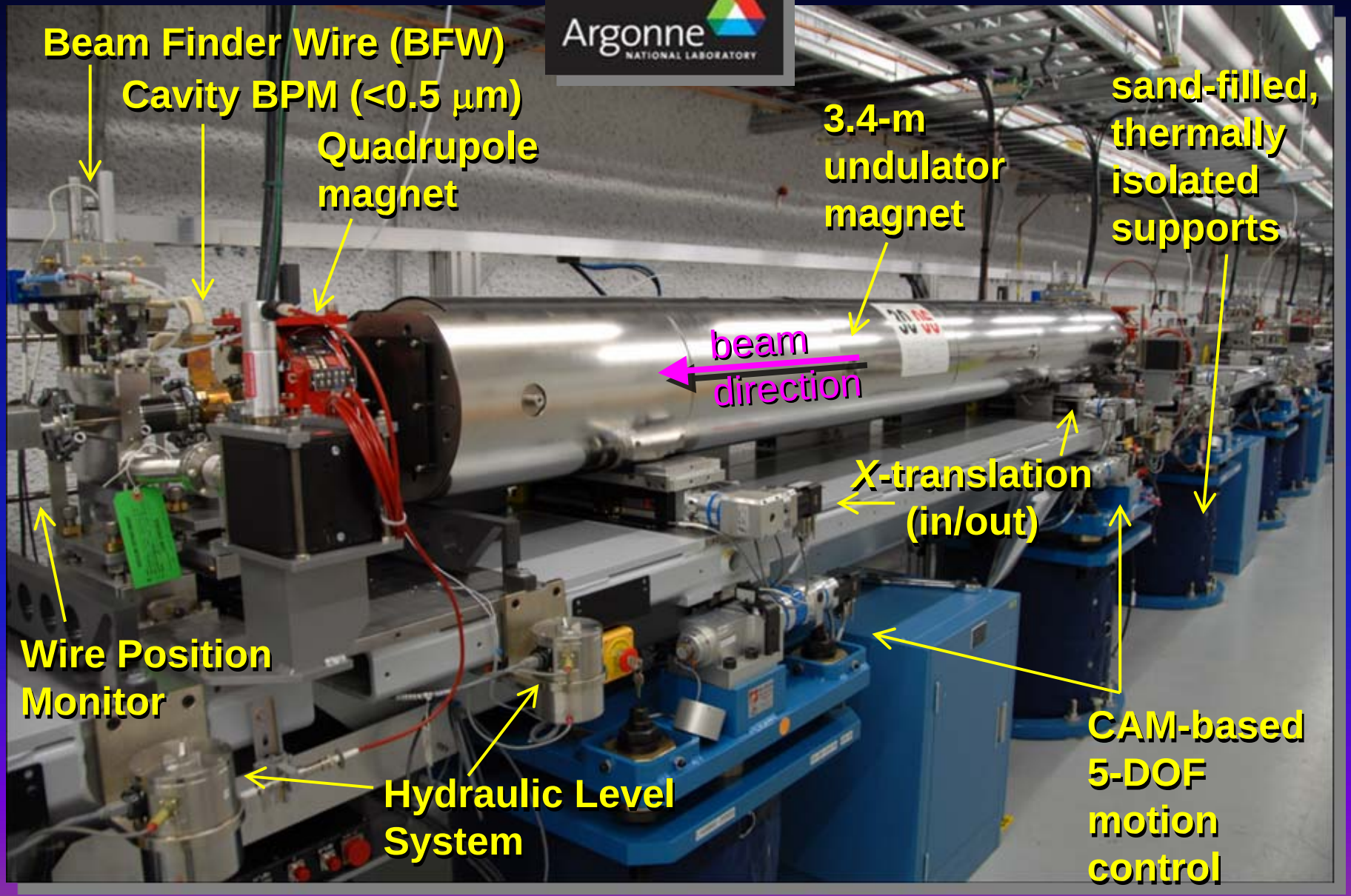




12 undulators inserted
(FEL not saturated here)

preliminary

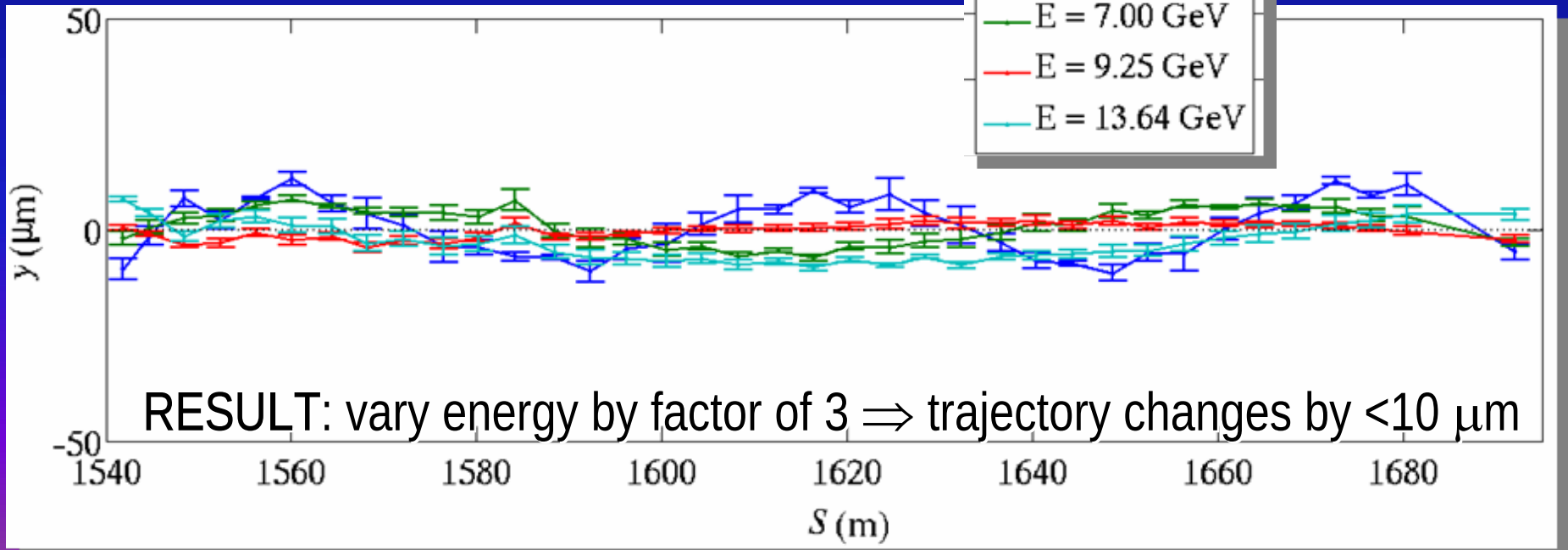
Undulator Girder with 5-DOF Motion Control + IN/OUT



Beam-Based Undulator Alignment

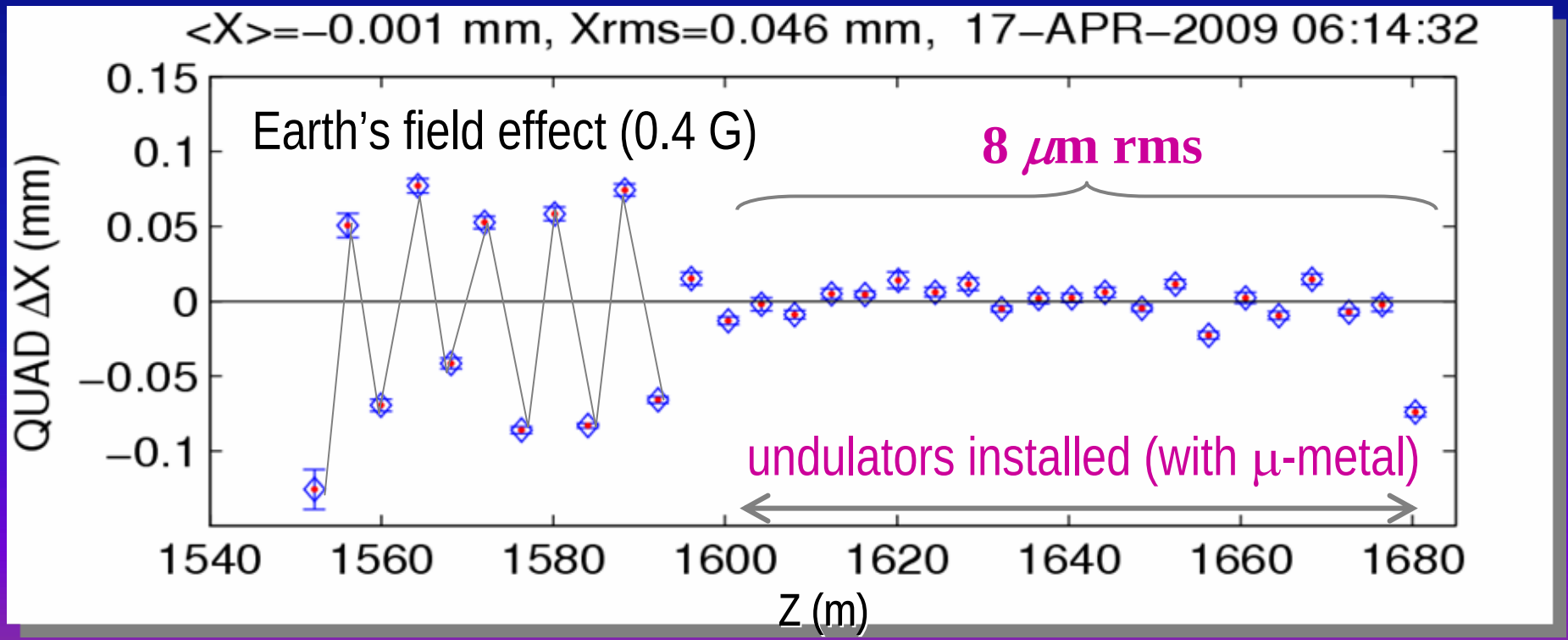
- Measure undulator trajectory at 4 energies (4.3, 7.0, 9.2, & 13.6 GeV)
- Scale all linac & upstream transport line magnets each time
- Do not change **anything** in the undulator
- Calculate… (*Matlab* GUI)
- Move quads and adjust BPM offsets for dispersion free trajectory
- Iterate…

H. Loos



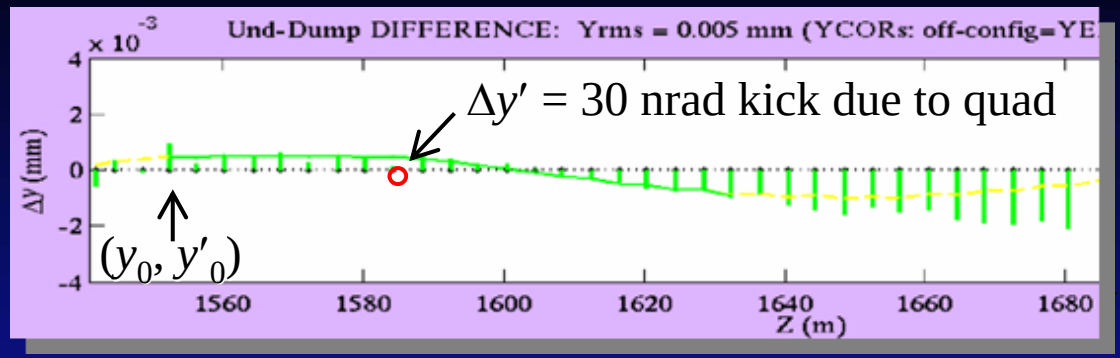
Undulator Quadrupole Alignment after BBA

- Vary each quadrupole magnet gradient by 30% sequentially
- Record kick angle using both upstream & downstream BPMs, adjusting for incoming jitter
- Calculate quadrupole magnet transverse offsets

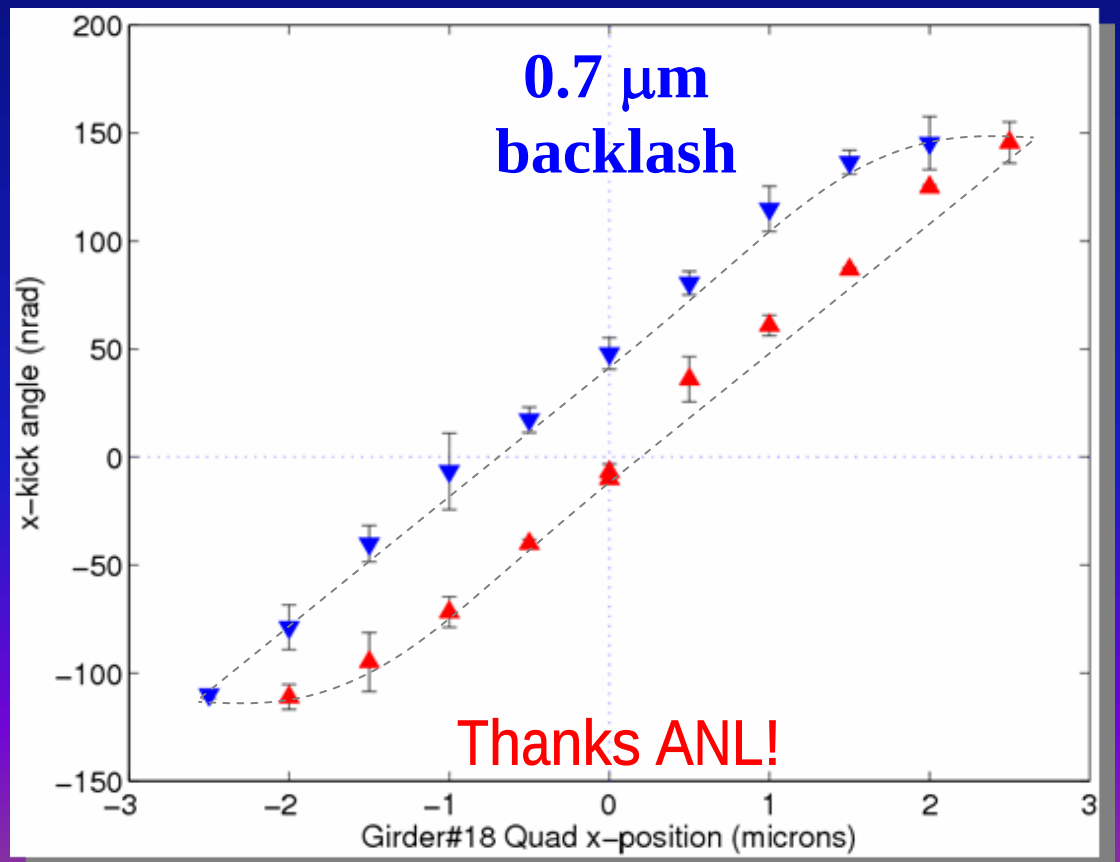


<1 μm Undulator Quadrupole Remote Position Control

3-parameter fit to 20 BPMs along undulator (y_0, y'_0, and $\Delta y'$)



±4 μm



<0.5 μm res.
S. Smith
TU3GRC05

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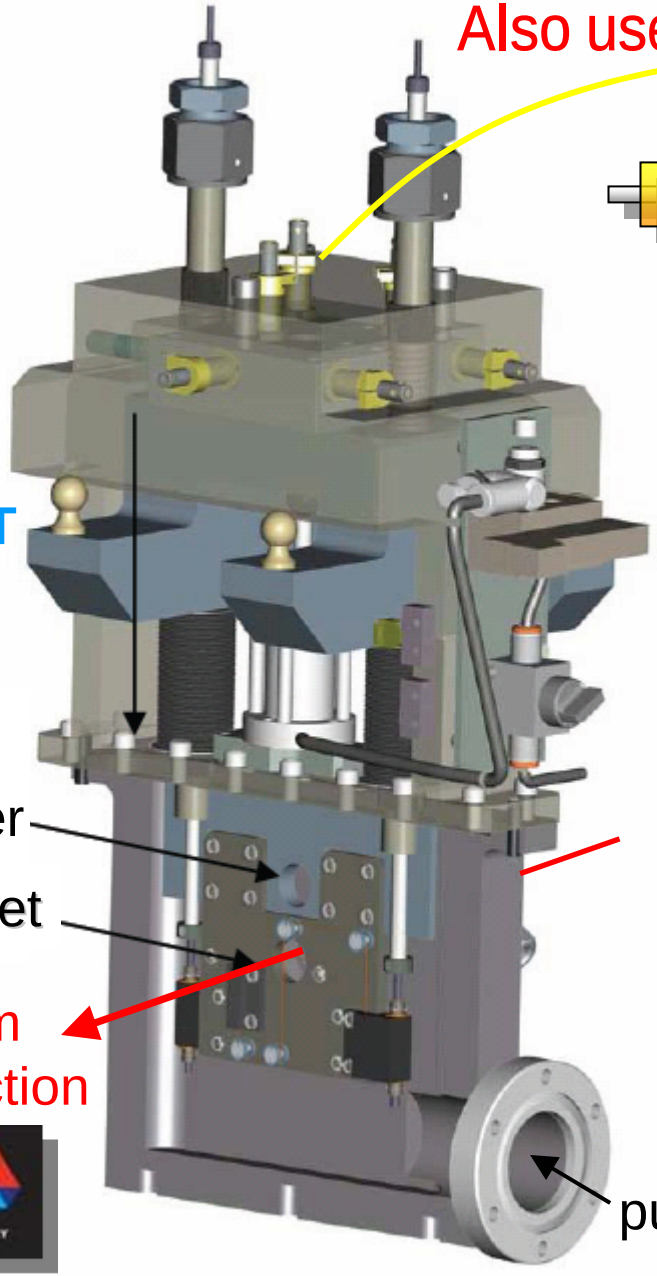
Beam Finder Wire – Aligns 'Loose' End of Undulator

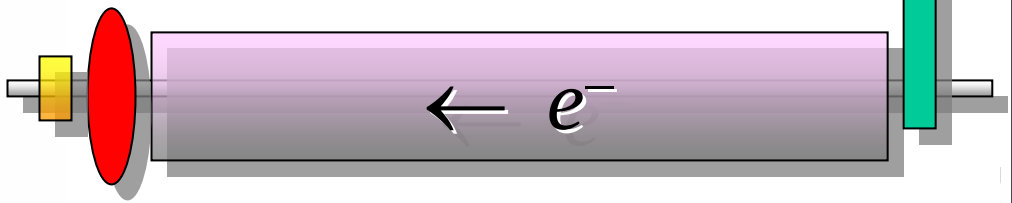
BFW

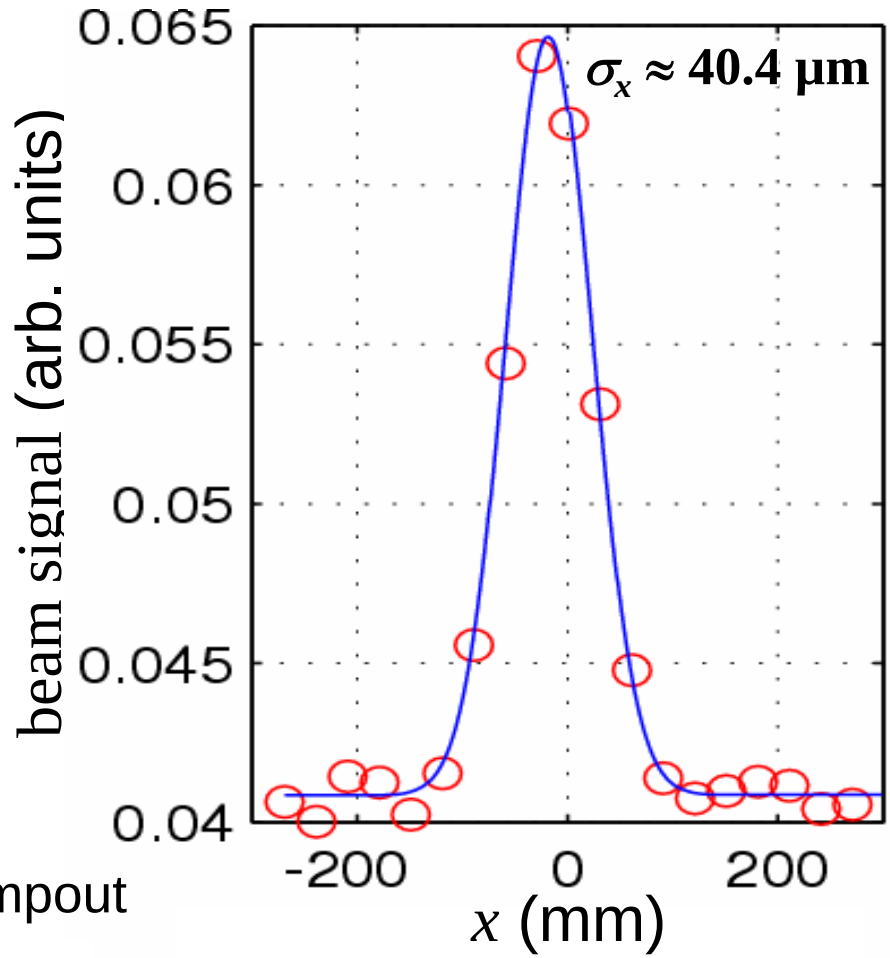
wire IN

wire OUT



Also used to measure emittance in undulator





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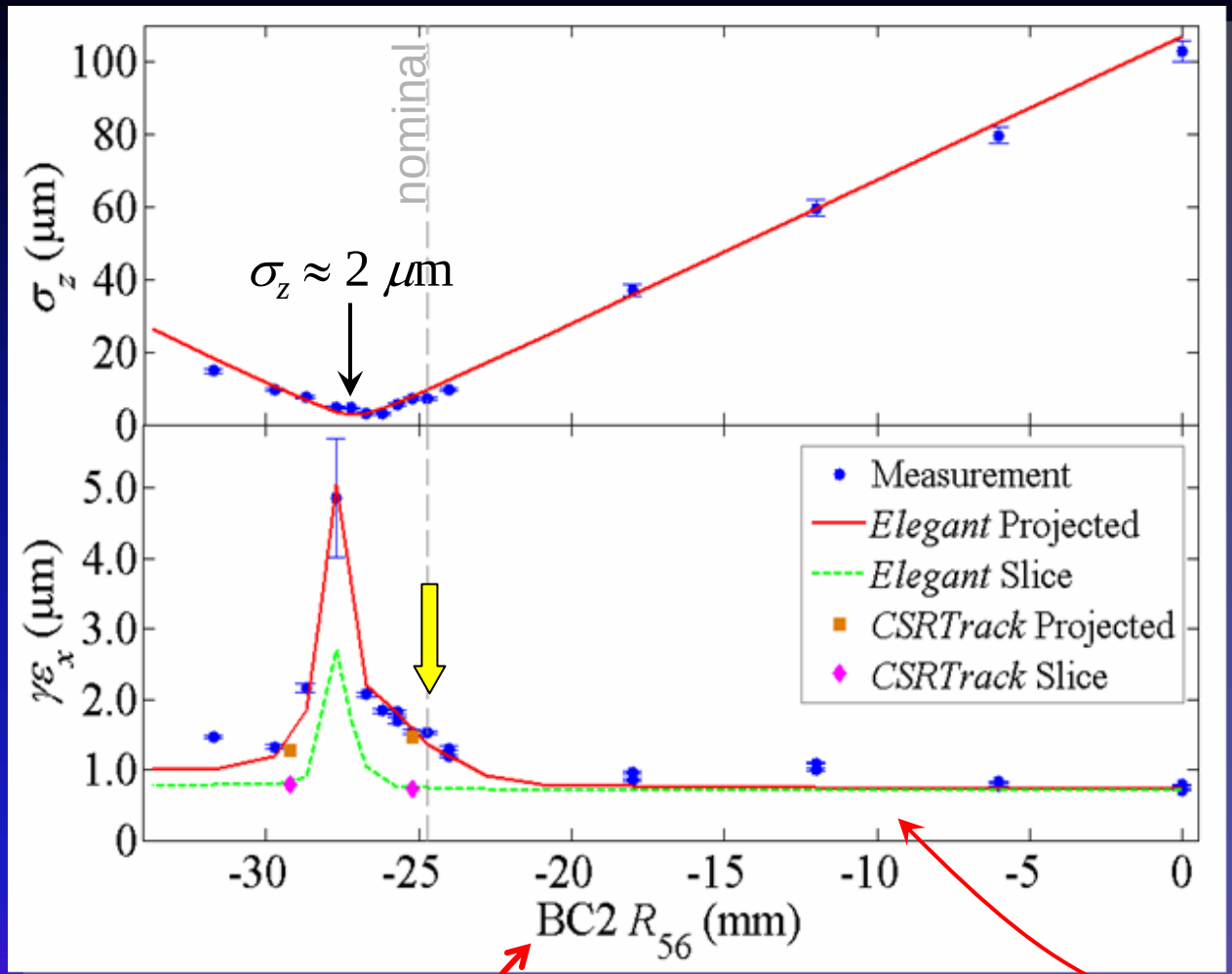
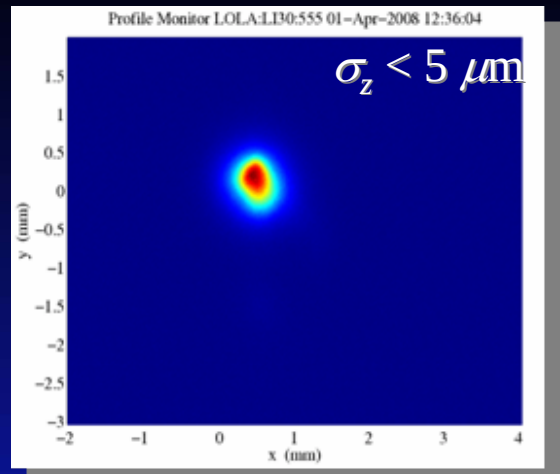
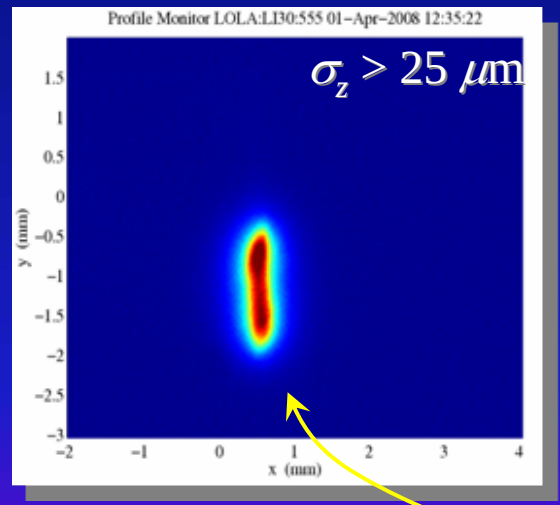
Bunch Compression & CSR Measured after BC2 (0.25 nC)

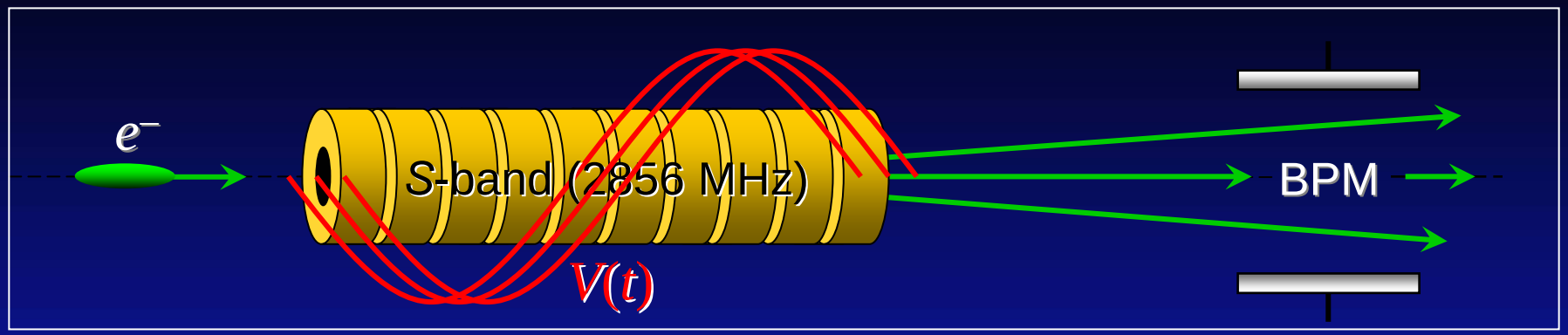


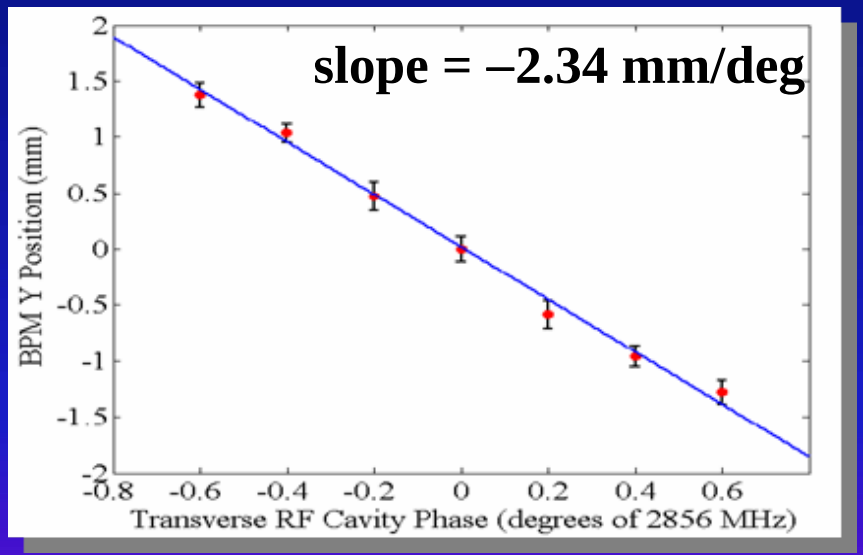


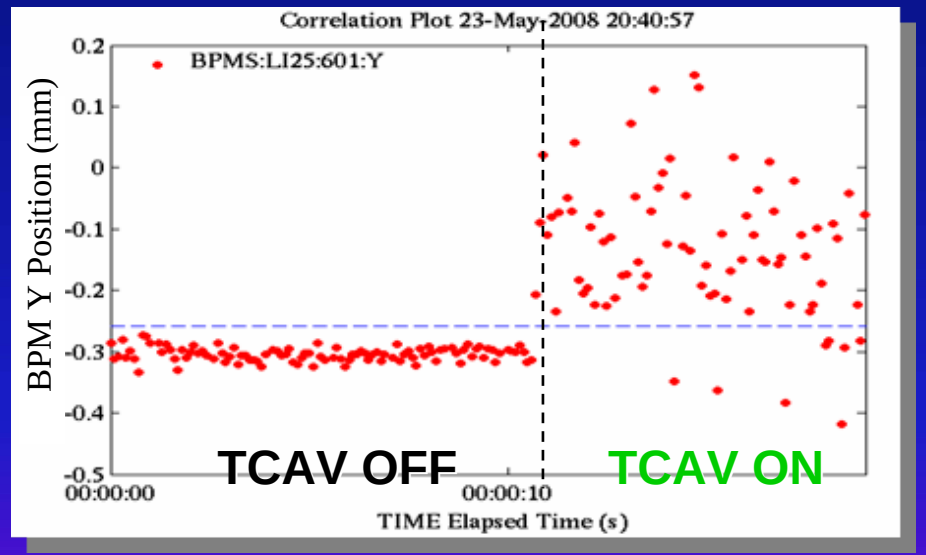


in PRSTAB

Measuring Bunch Arrival Time Jitter with an RF Deflector







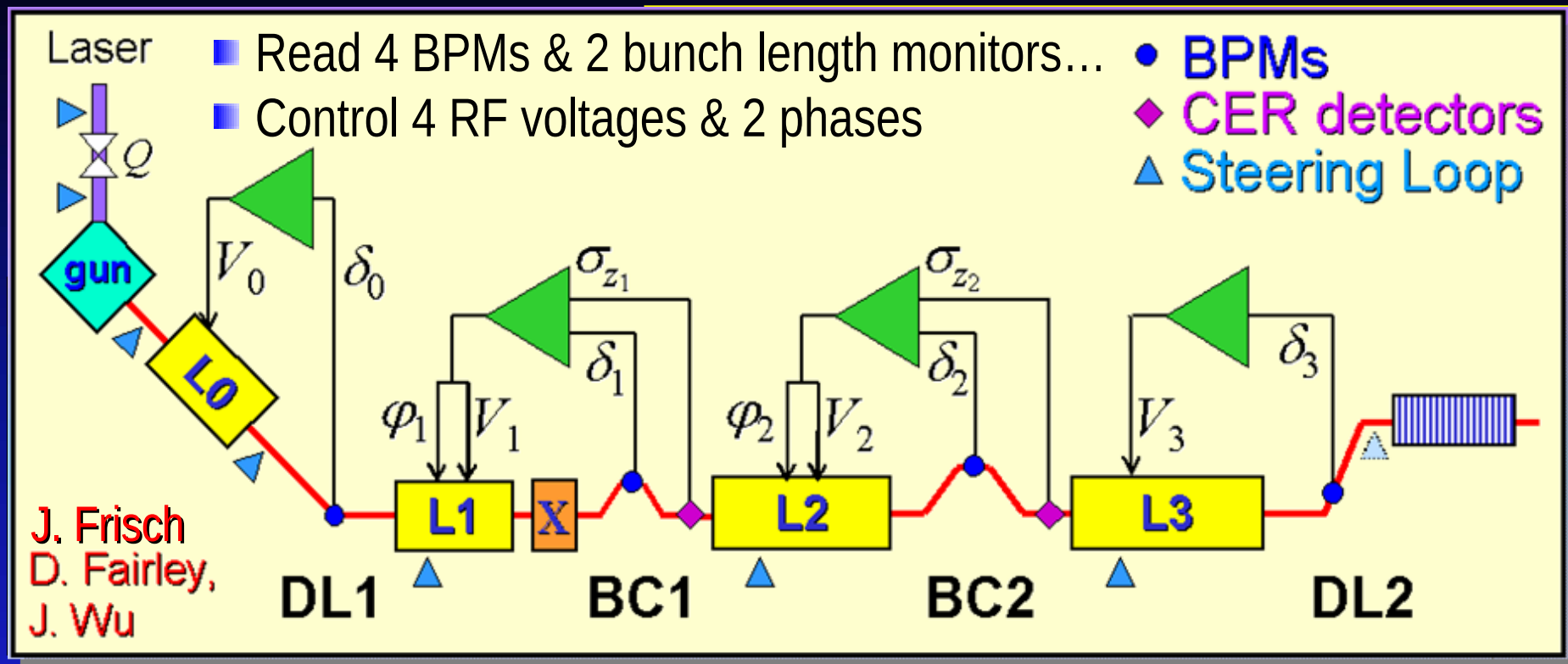
$\Delta t \approx \pm 0.6$ ps

9 μm rms

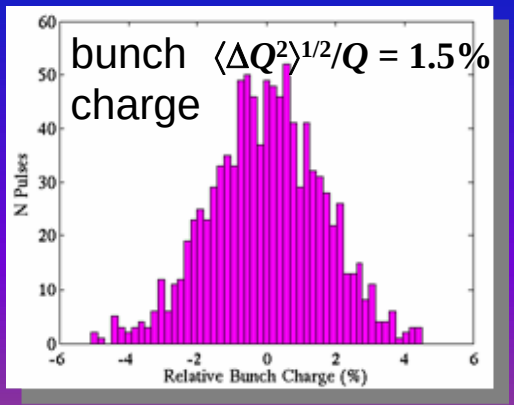
110 μm rms

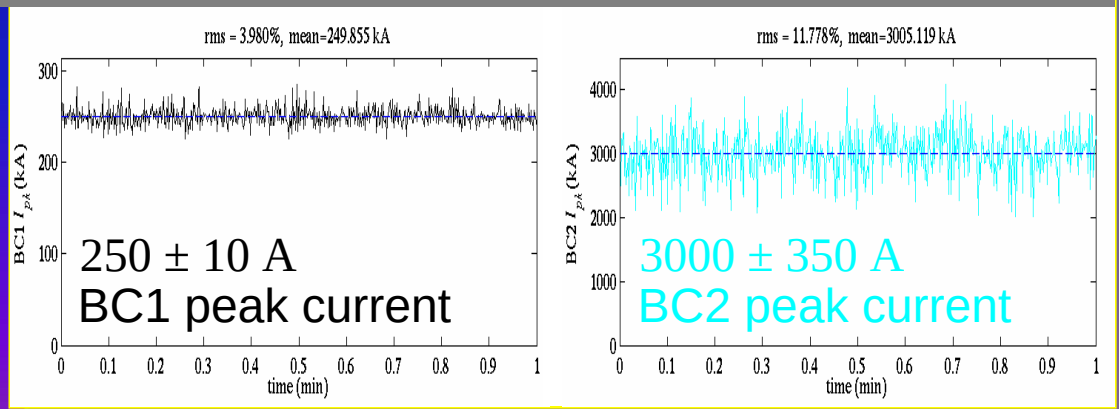
Timing Jitter = (110 μm)/(2.34 mm/deg) = 0.047 deg $\Rightarrow$ **46 fsec rms**

Feedback Systems - Bunch Length & Energy (6×6)



Charge feedback: $Q = 0.25$ nC



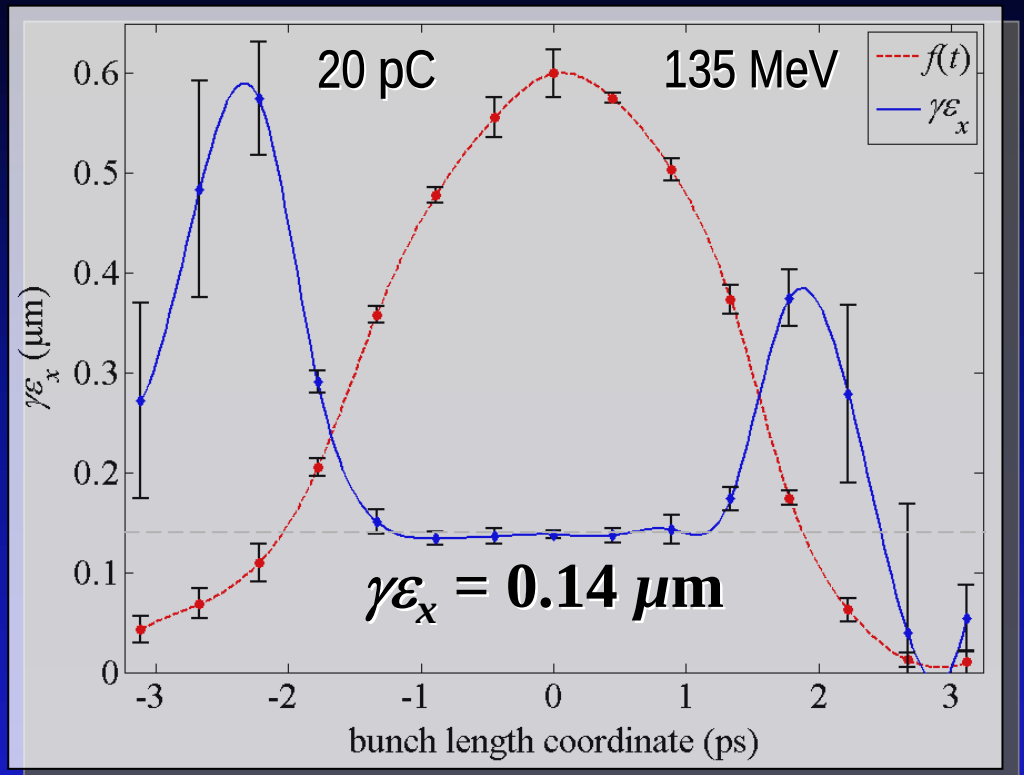


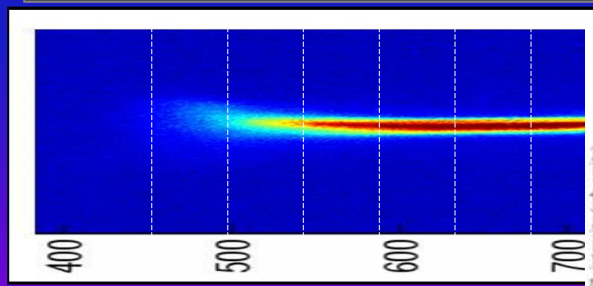
H. Loos, TU3GRI01

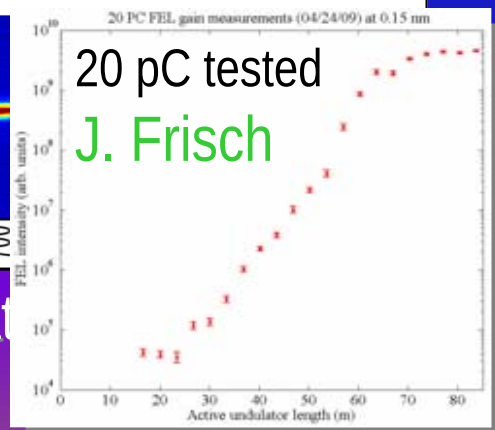
J. Wu, WE5RFP046

Measurements and Simulations for 20-pC Bunch at 14 GeV

MEASURED SLICE EMITTANCE



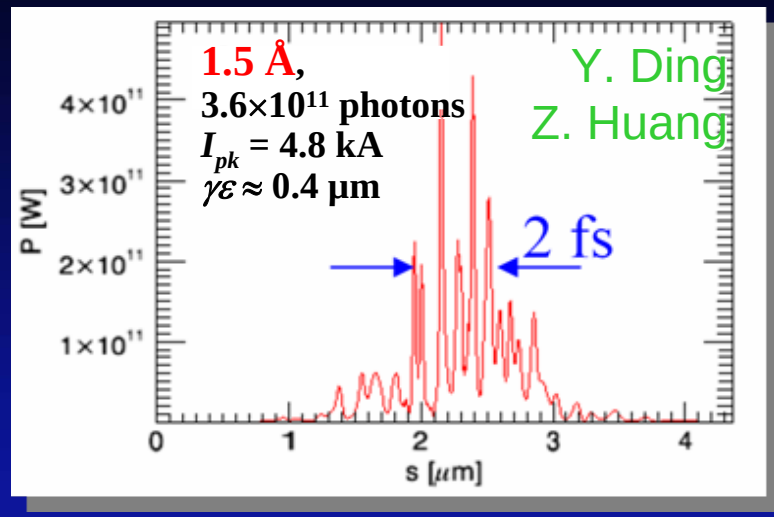




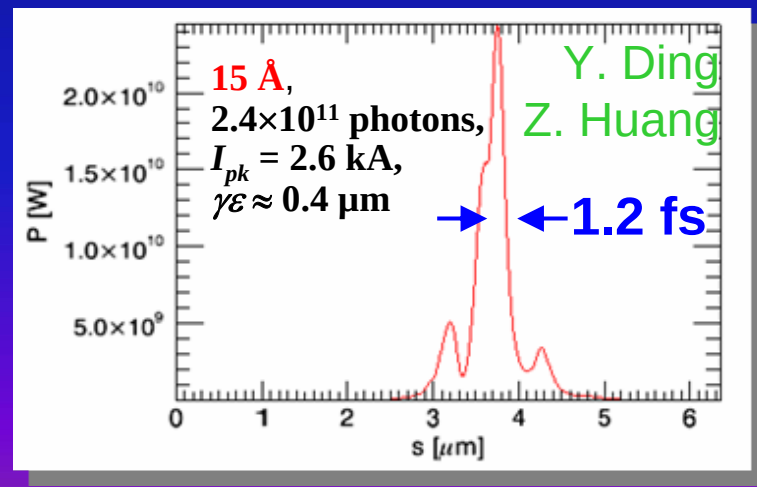
← time-slicing at

Y. Ding, WE5RFP040

SIMULATED FEL PULSES



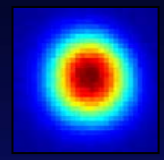
Simulation at 1.5 Å based on measured injector & linac beam & *Elegant* tracking, with CSR, at 20 pC.



Simulation at 15 Å based on measured injector & linac beam & *Elegant* tracking, with CSR & 20 pC.

Commissioning Time-Line

- Commissioning
- Project Milestones
- Installation Periods



First FEL Light

Injecrtor Install

First e^- from gun

BC2 Install

PEP-II ends

LTU/Und Sys Install

First e^- to dump

FEE/NEH Install

Install Undulators

PAC'09

First Light in FEE

X-Rays in NEH

First Users

First Light in FEH

Project complete

J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J

Down | 2007 | Down | 2008 | Down | 2009 | Down | 2010

Injector

Linac/BC2

Linac

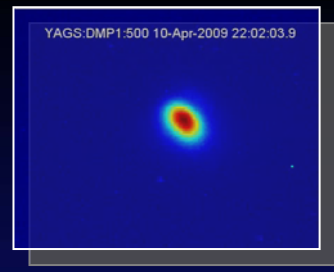
LTU/Und

FEL/FEE

NEH

FEH

Acknowledgements



Thanks to…

- The extraordinary commissioning **team** at ***SLAC***!
- The operations, metrology, engineering, controls, installation, and RF groups at ***SLAC***
- The tremendous undulator and cavity-BPM team at ***ANL*** – GREAT JOB!
- **John Galayda** (project director) for his leadership and confidence in the team
- And many of **you**, who have contributed your ideas, comments, codes, and many years of experience toward the design and operation of this revolutionary new light source – 17 yrs later