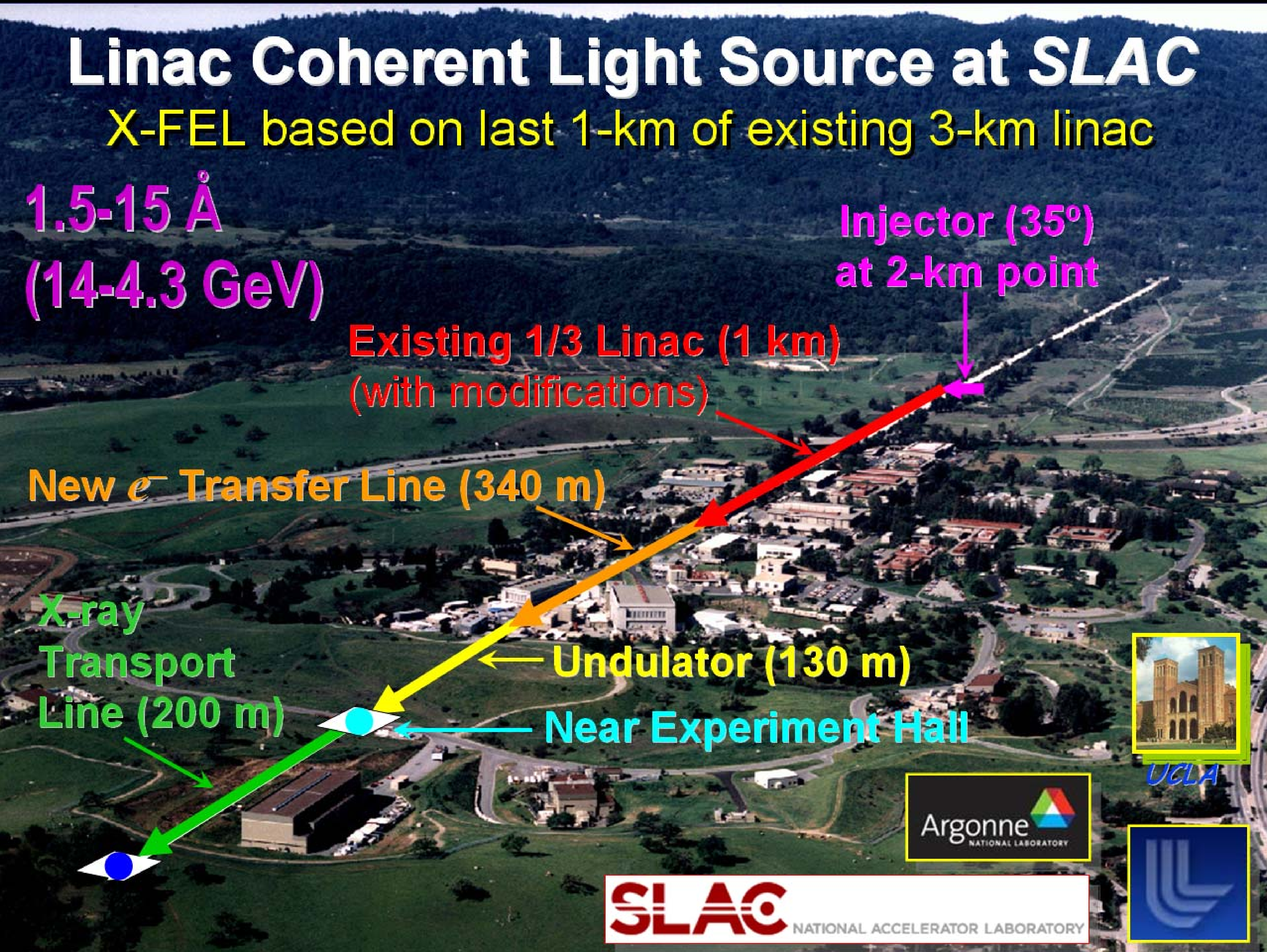
LCLS – The World's First X-Ray Free-Electron Laser

John N. Galayda
Representing the
LCLS Collaboration

May 24, 2010

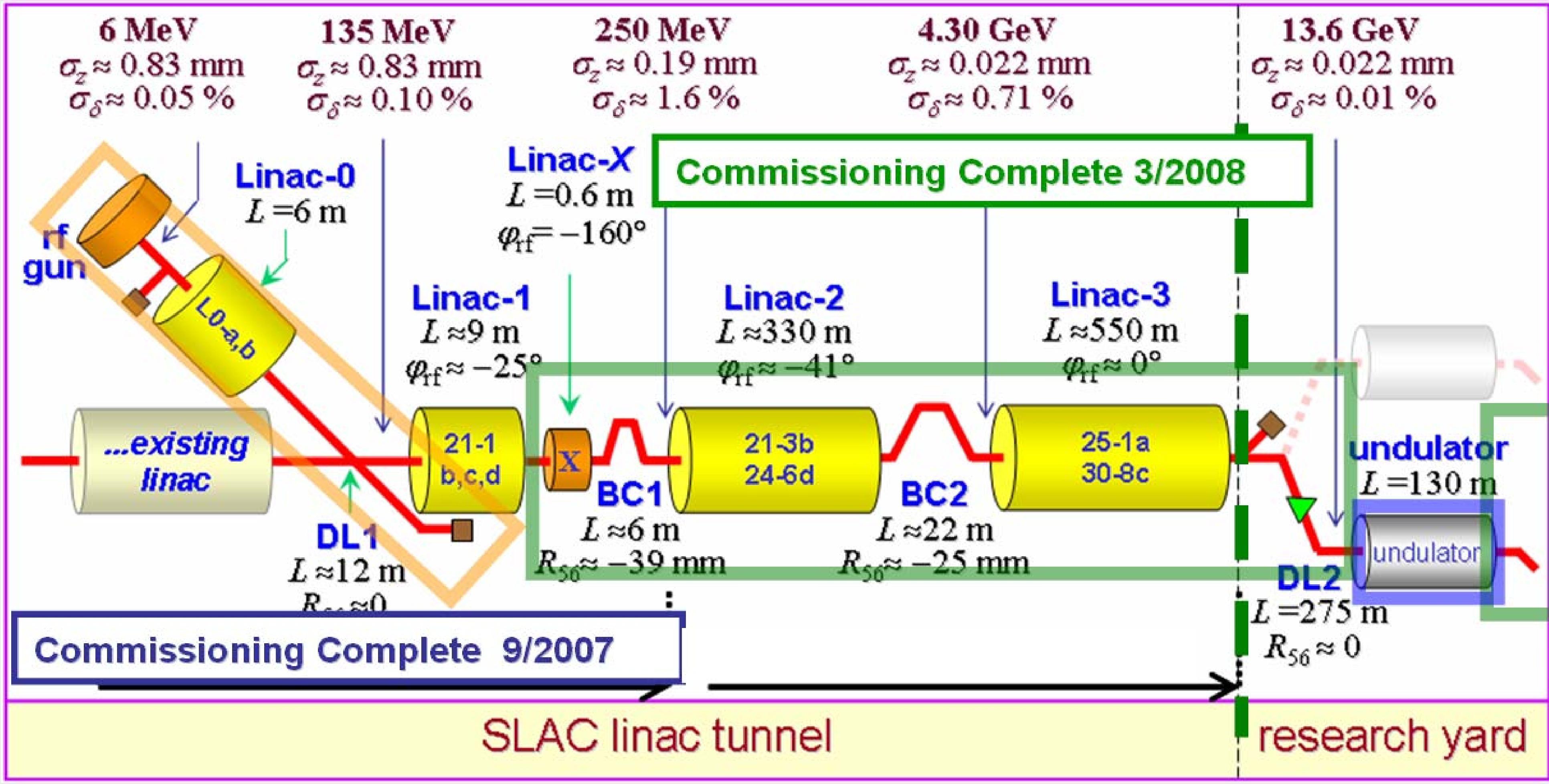
UCLA


Linac Coherent Light Source at SLAC
X-FEL based on last 1-km of existing 3-km linac
1.5-15 Å
(14-4.3 GeV)
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)
Undulator (130 m)
Near Experiment Hall
UCLA
Argonne
NATIONAL LABORATORY
SLAC
NATIONAL ACCELERATOR LABORATORY

LCLS Injector

LCLS Linac

LCLS Undulator Systems
First Electrons 12/2008
First Lasing 4/2009



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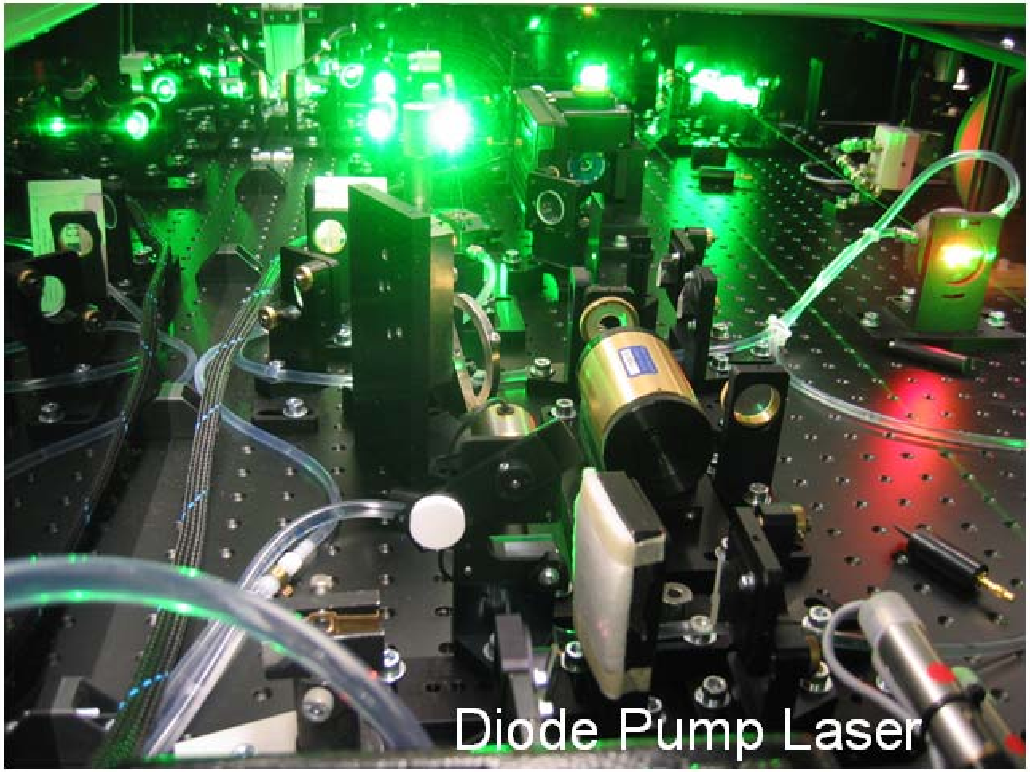
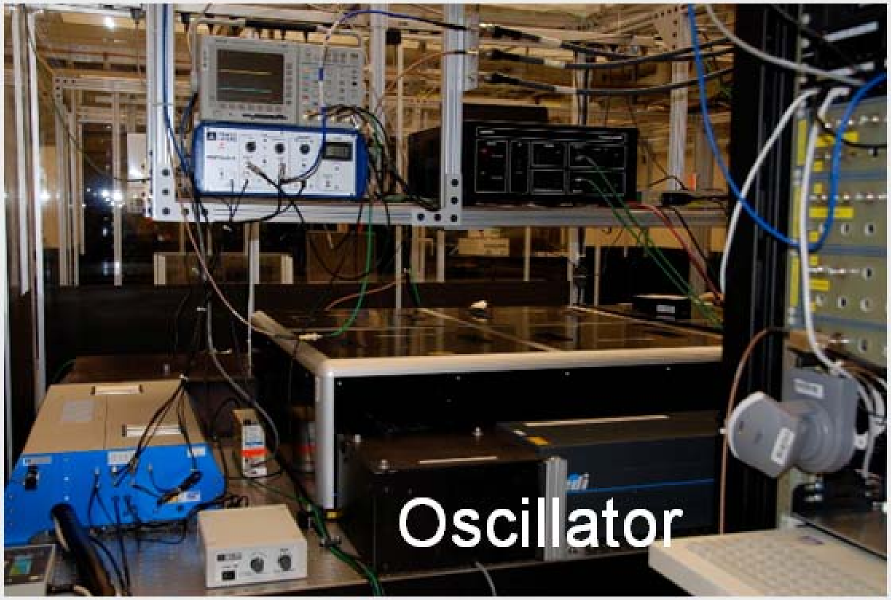
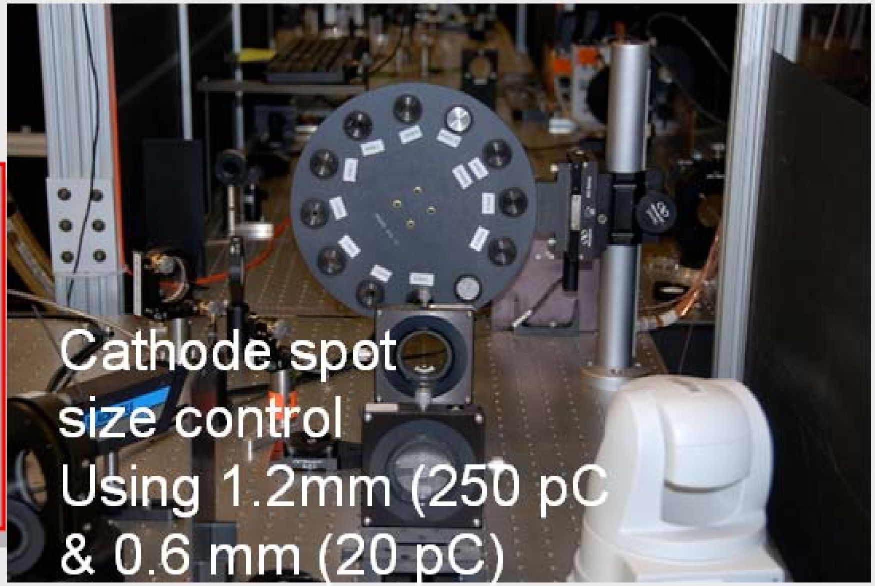
1.2 Photocathode Laser





Laser Performance

- Reliability has been excellent: >99%
- High power laser now a backup
- Simpler laser for 0.25 nC running
- 3 psec gaussian(temporal) works well



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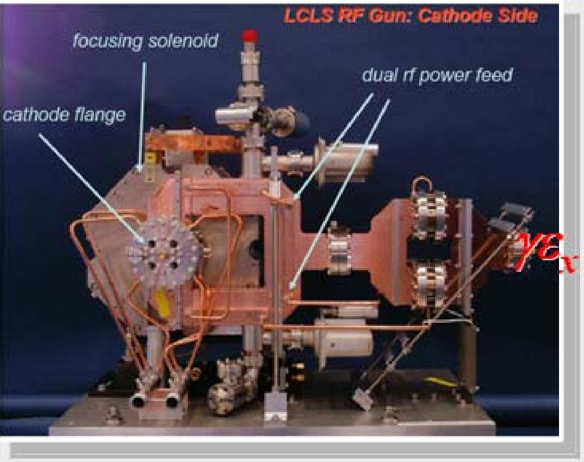
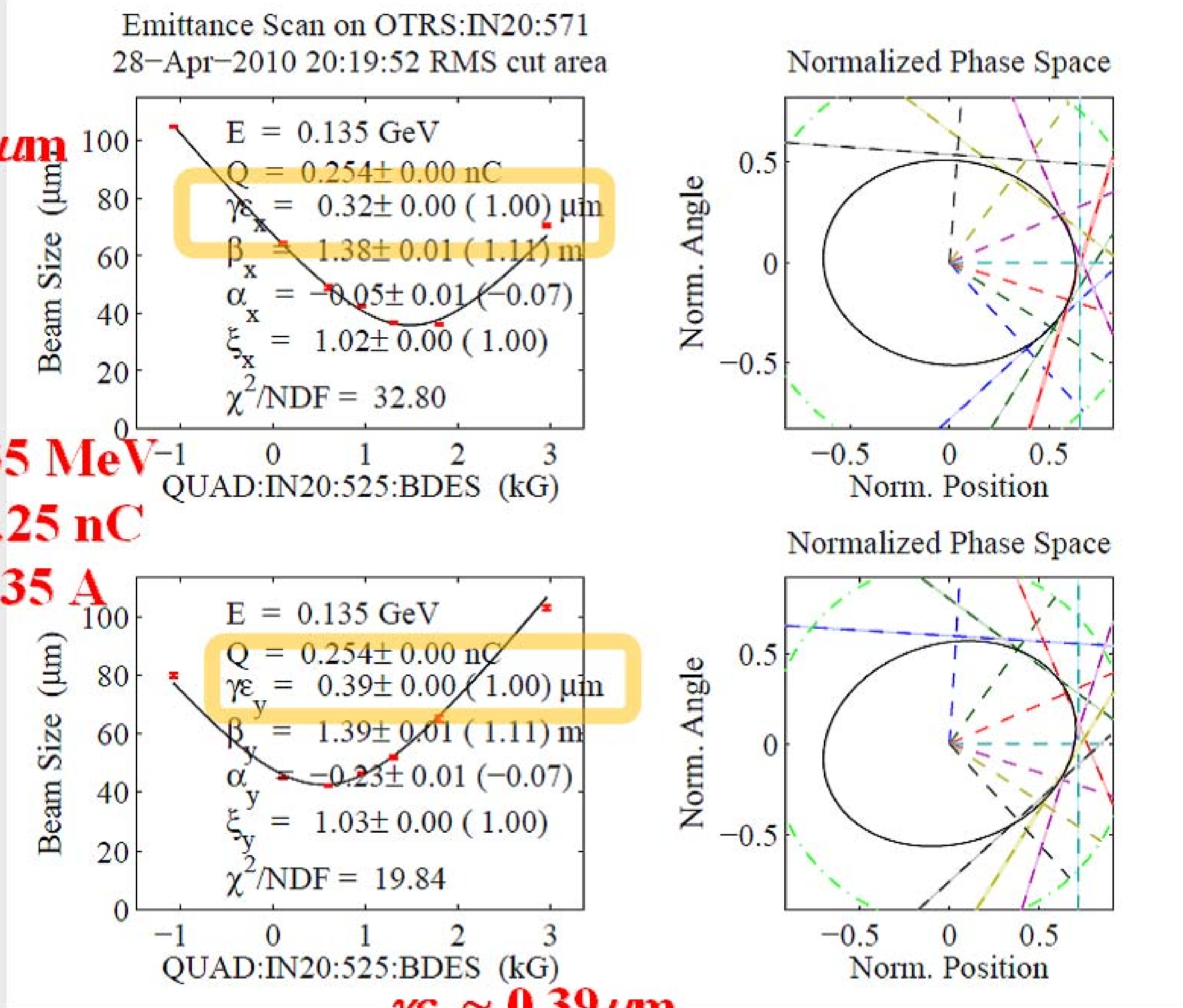
26 April 2010 Gun Brightness



$\gamma\varepsilon_x \approx 0.32\ \mu m$



135 MeV
0.25 nC
35 A

$\gamma\varepsilon_y \approx 0.39\,\mu m$

TUPE064 **Simulations of IonMigration in the LCLS RFGun and Injector** – *A. Brachmann (SLAC)*

TUPE065 **Surface Characterization of the LCLS RF Gun Cathode** – *A. Brachmann (SLAC)*

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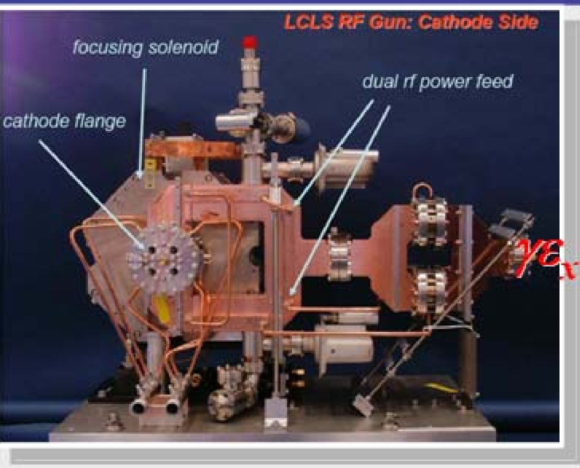
26 April 2010 Gun Brightness



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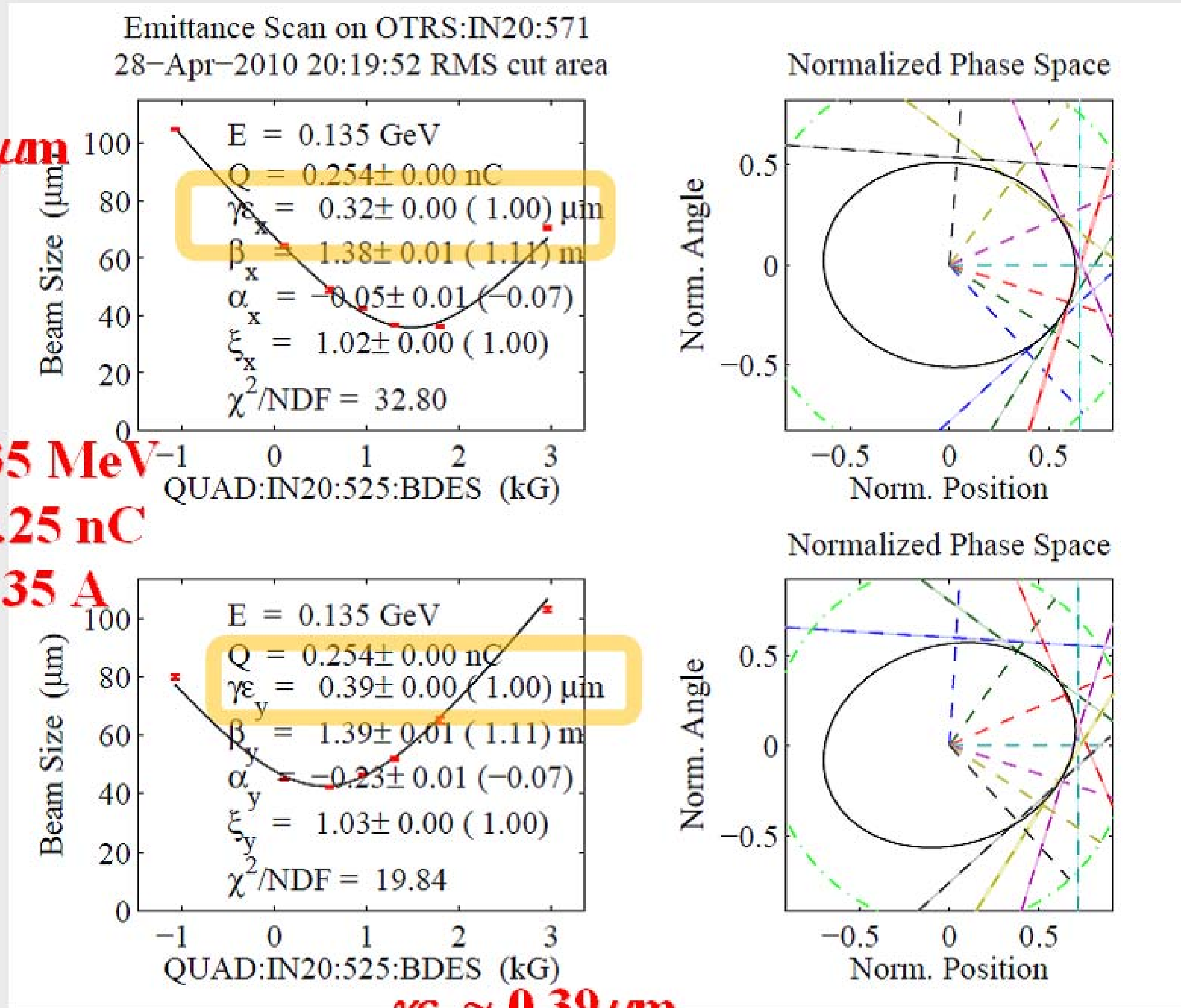

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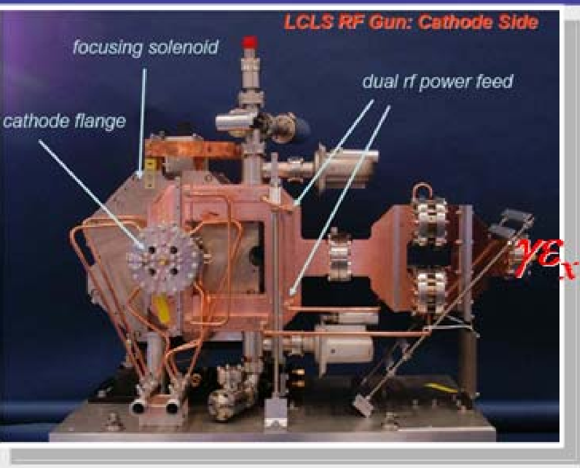
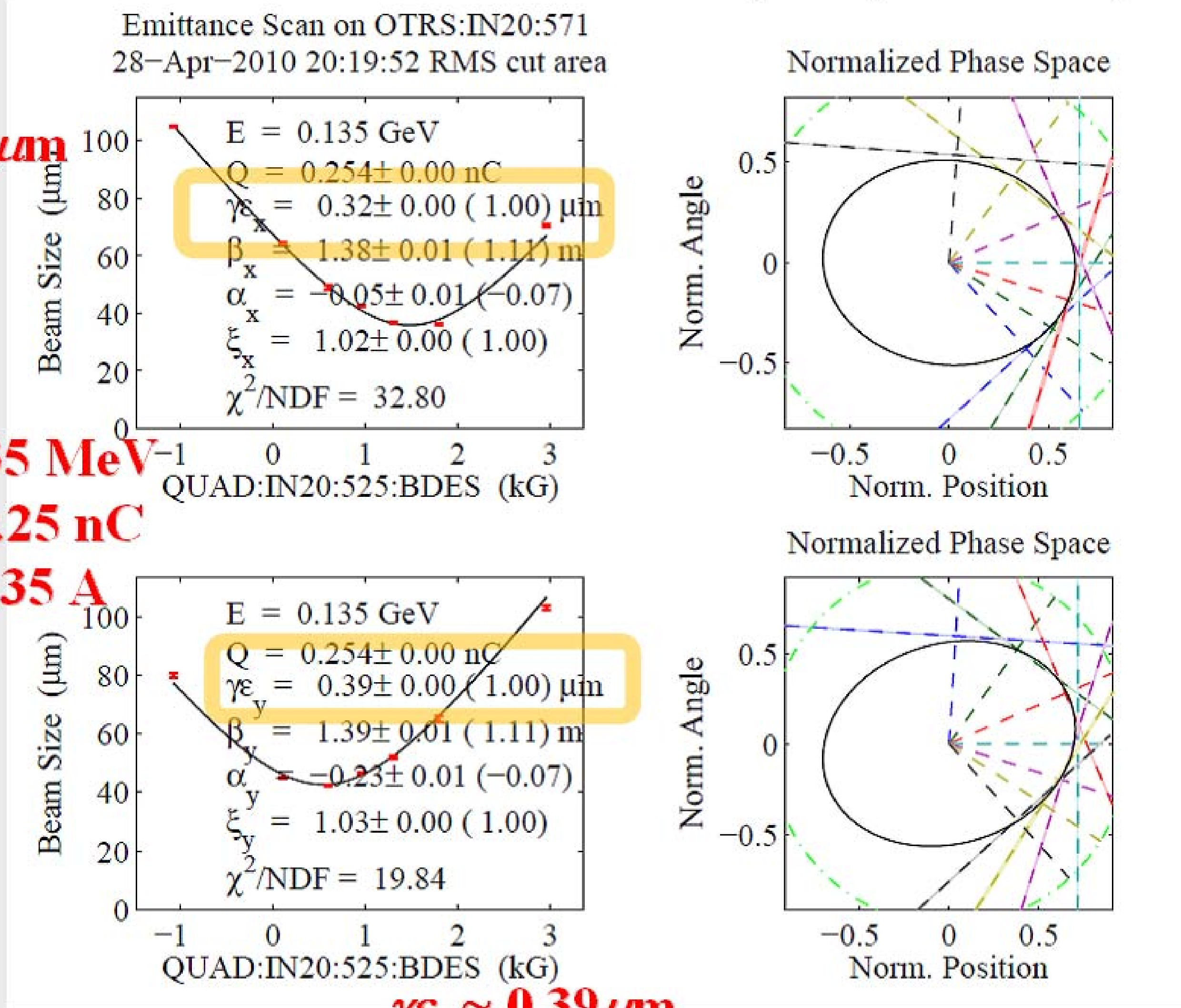


- Time-sliced emittance: <0.4 μm (0.25 nC)



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– A. Brachmann (SLAC)

TUPE065 **Surface Characterization of the LCLS RF Gun Cathode –**
A. Brachmann (SLAC)

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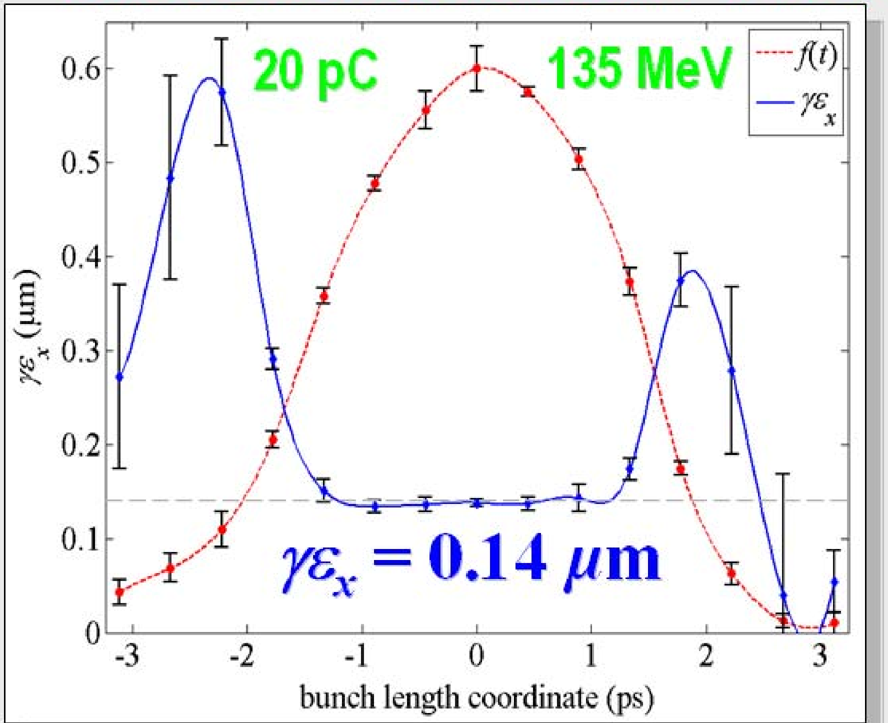
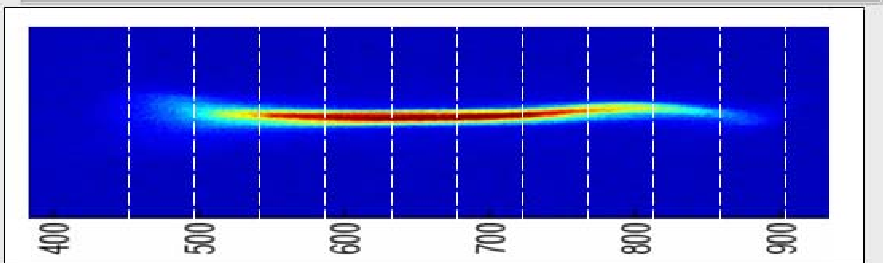
Low Charge, Low Emittance, Short X-ray Pulses

<10 fs FWHM?

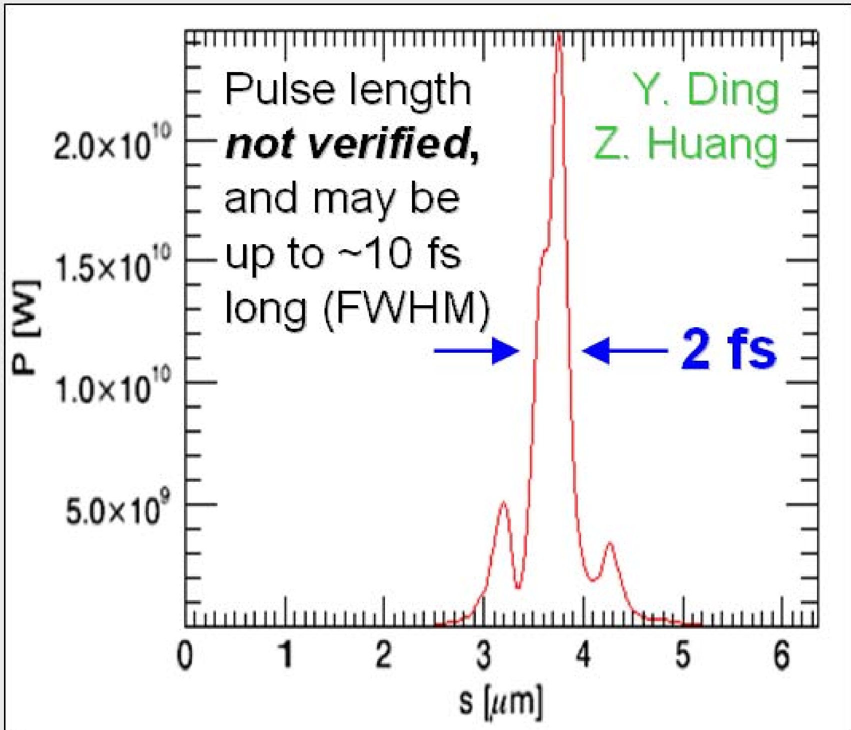
MEASURED SLICE EMITTANCE





time-slicing at 20 pC

Y. Ding et al., PRL 102, 254801 (2009)



Simulation at 15 Å based on measured injector & linac beams (2.4×10^{11} photons, I_{pk} = 2.6 kA, $\gamma\varepsilon \approx 0.4$ μm).

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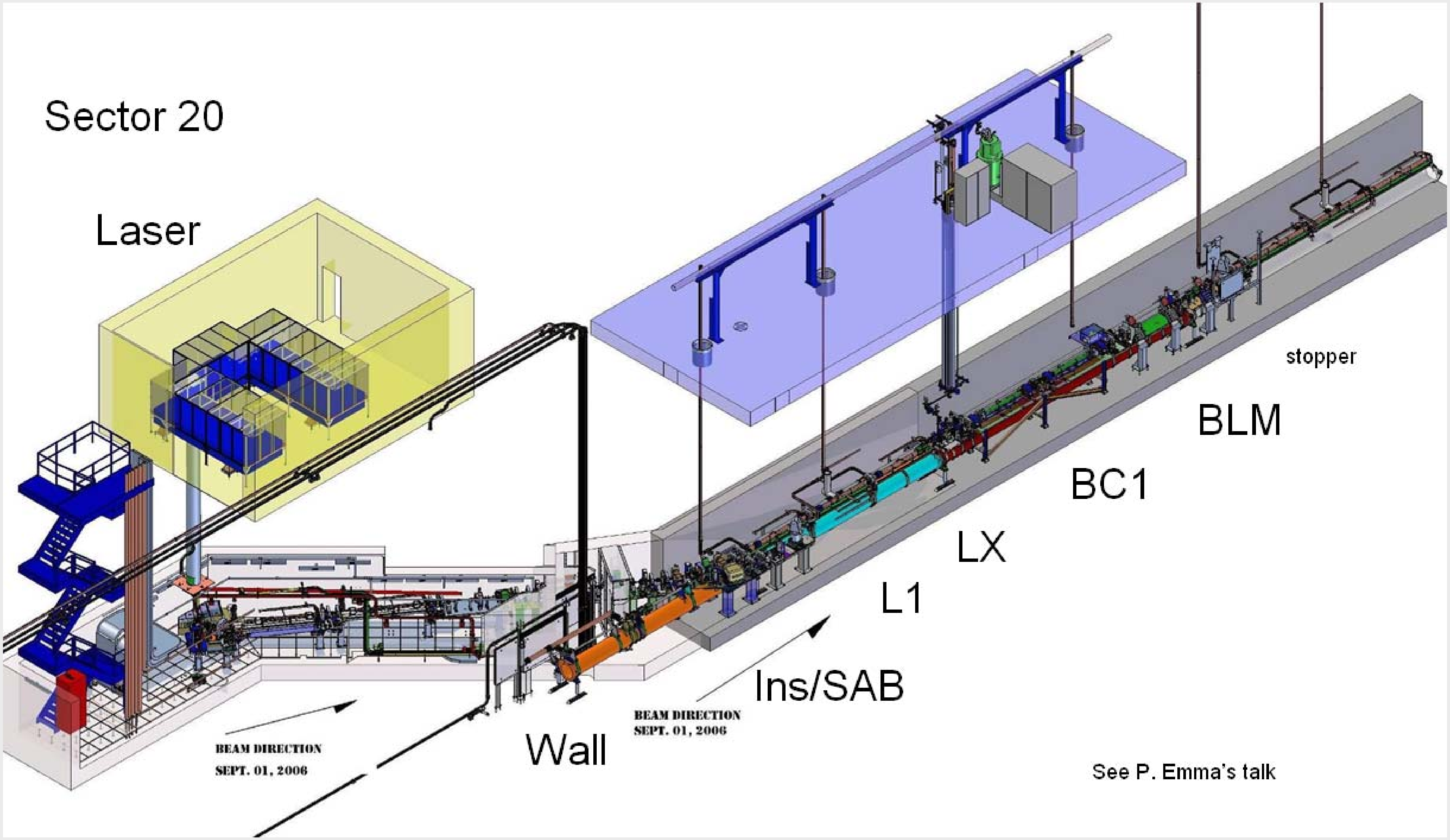
Injector, Bunch Compressor 1



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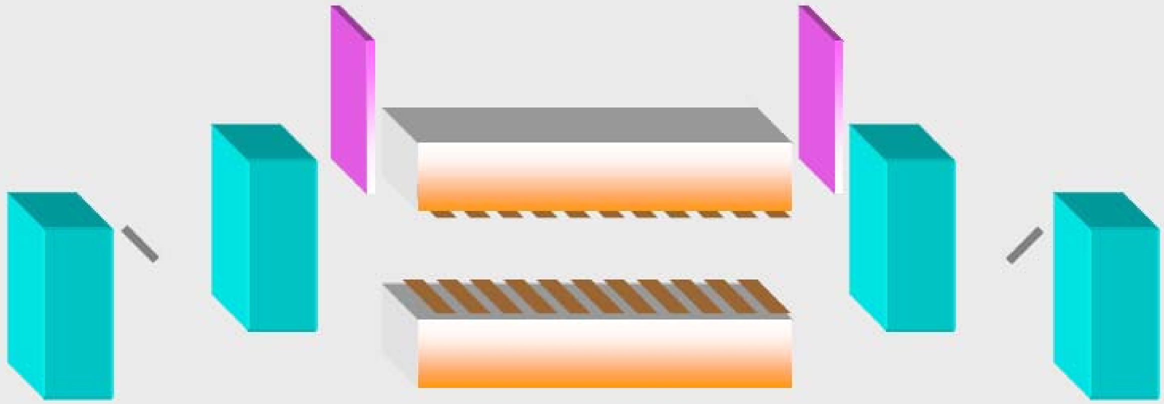
Example: Physics Applications



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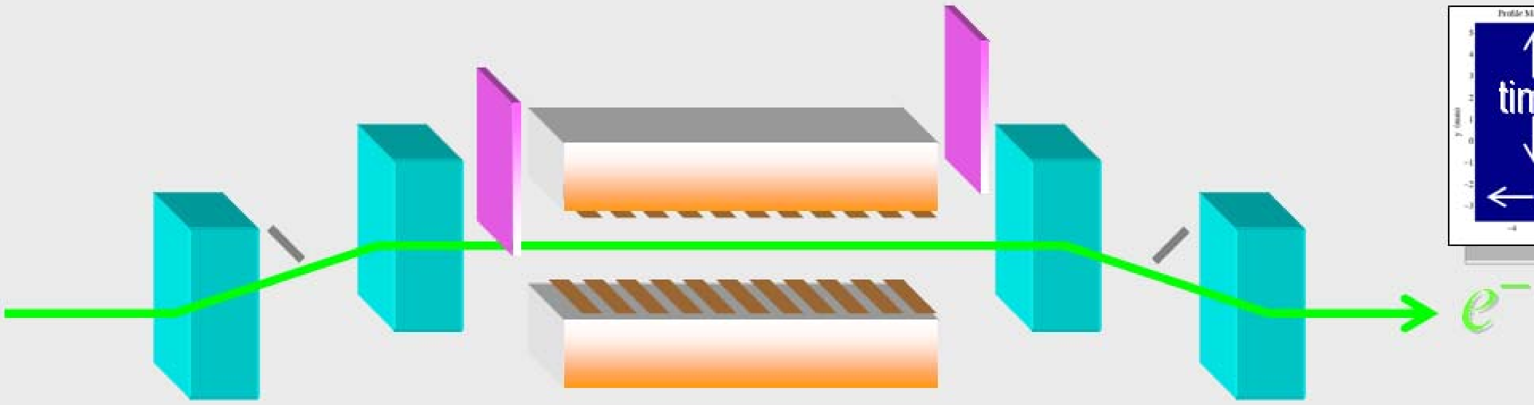

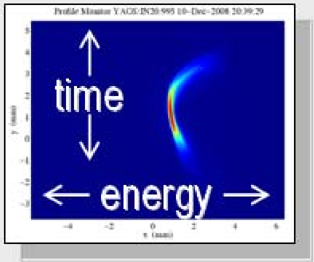

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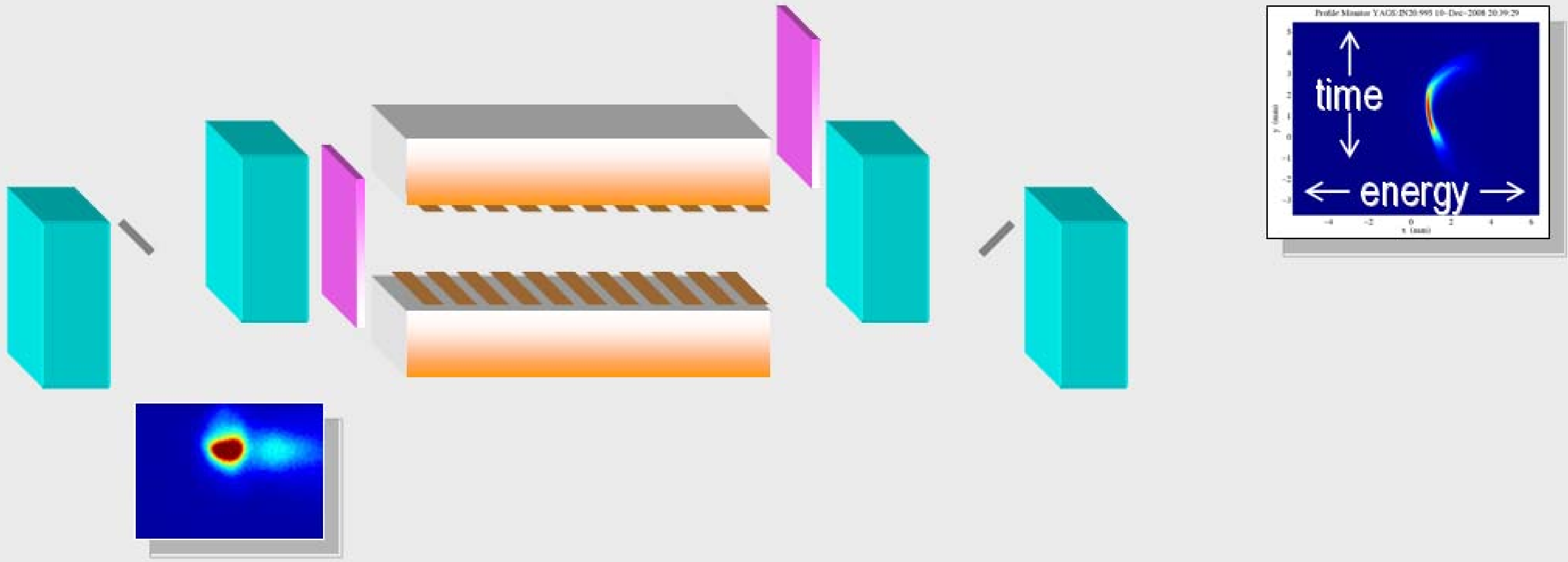

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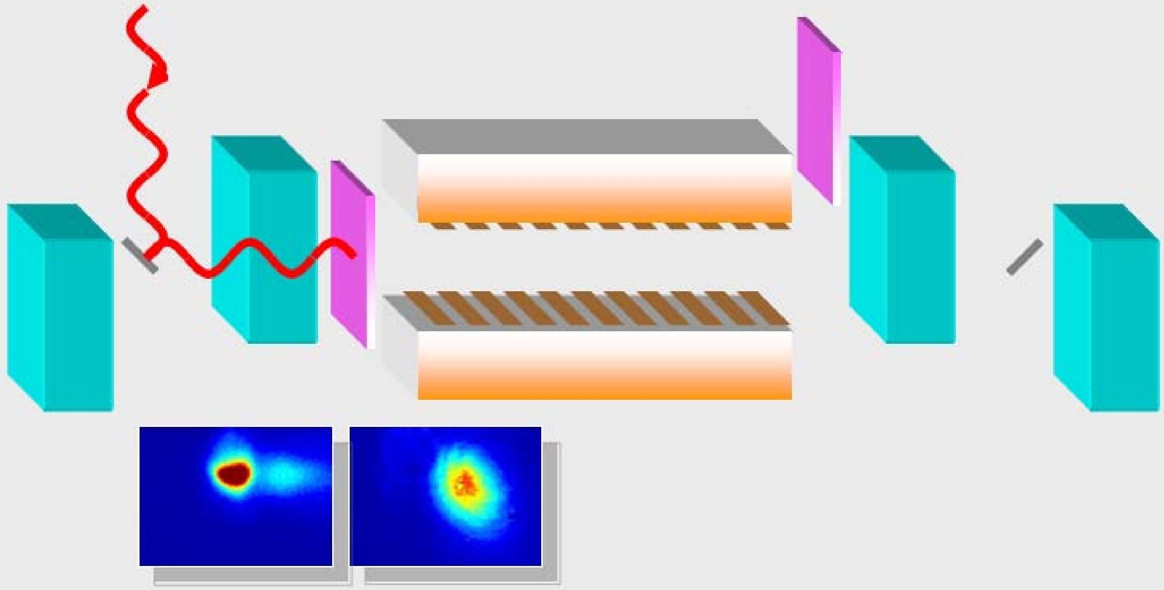

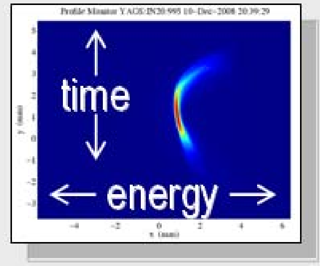

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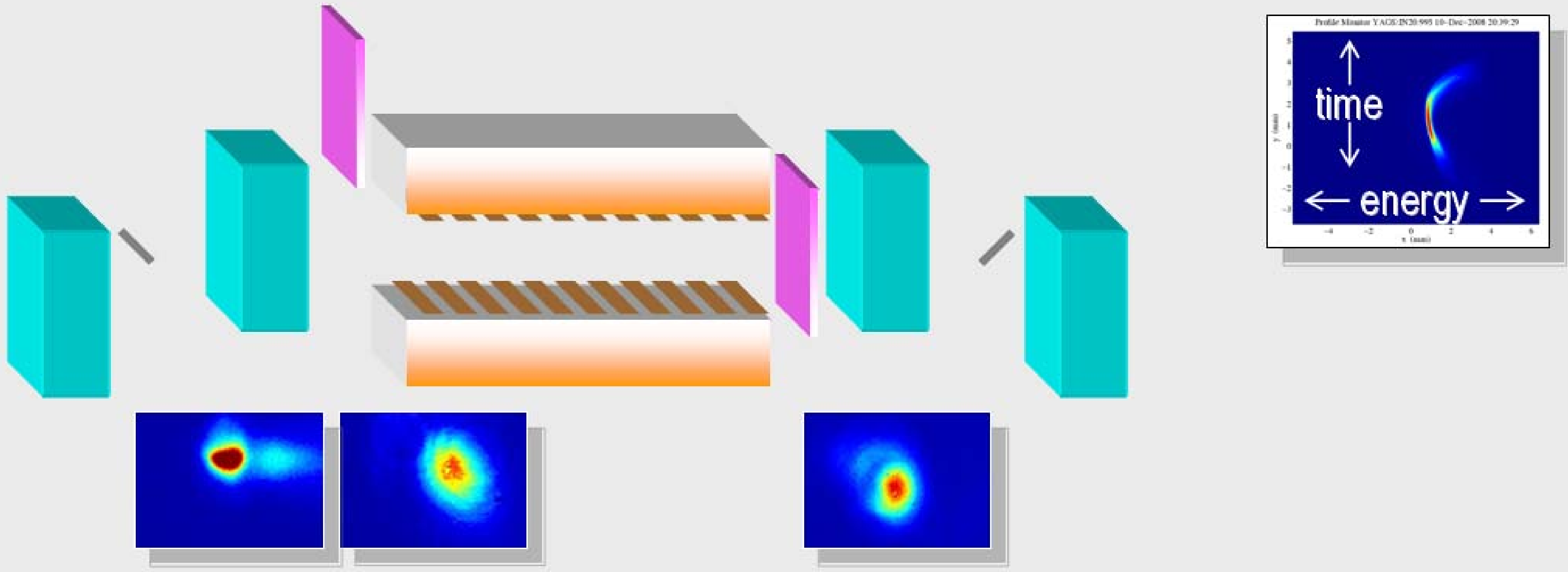

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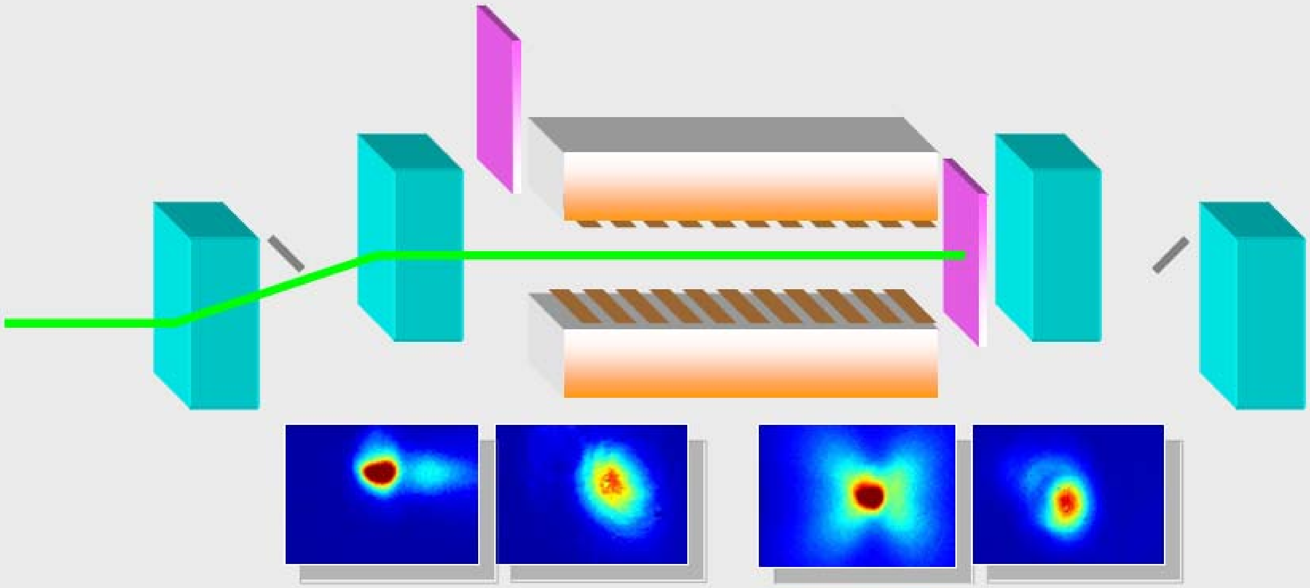

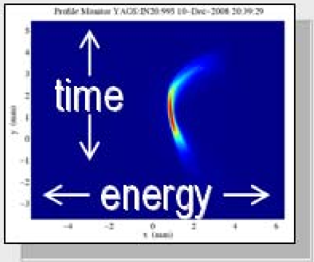

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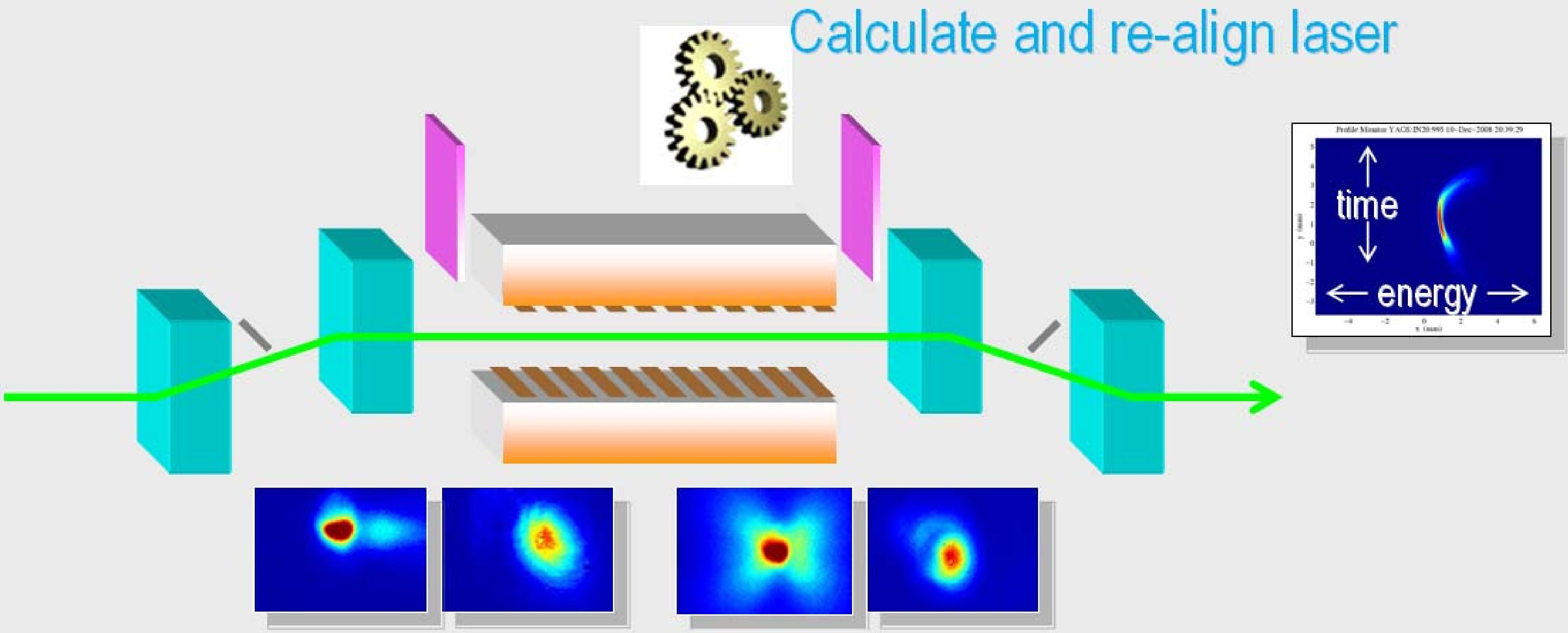

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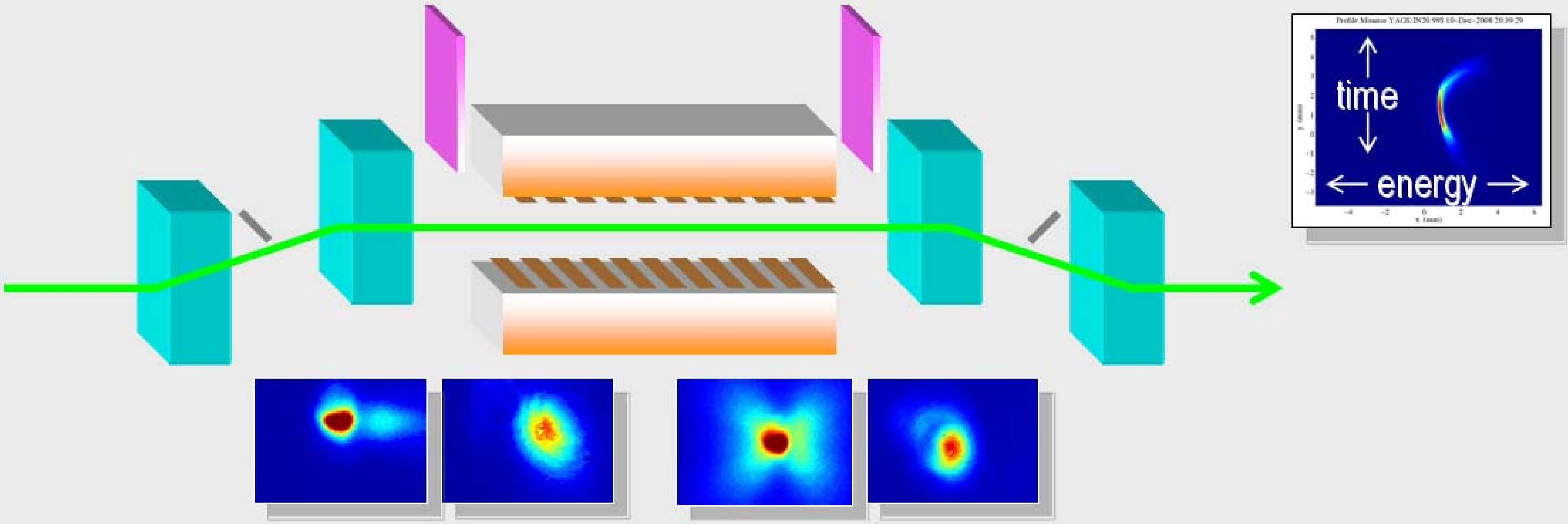

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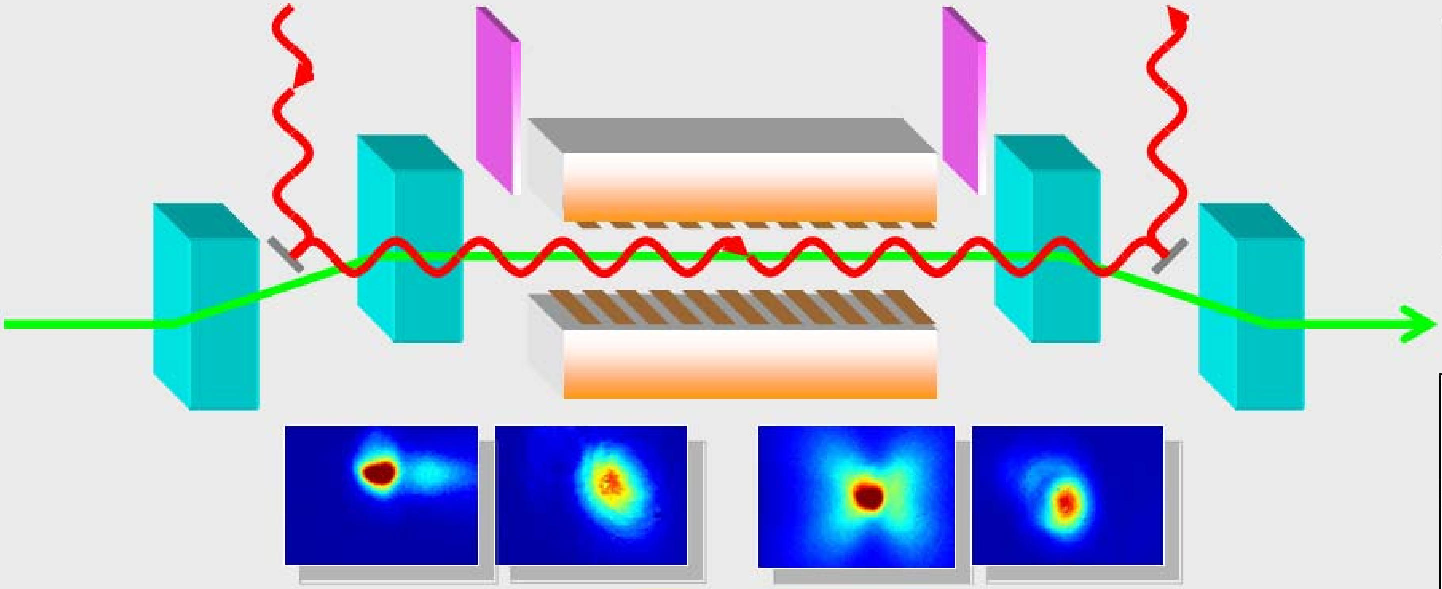
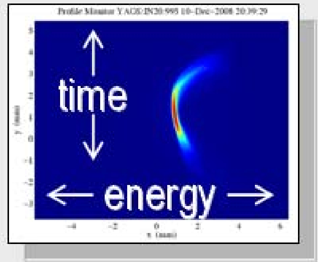
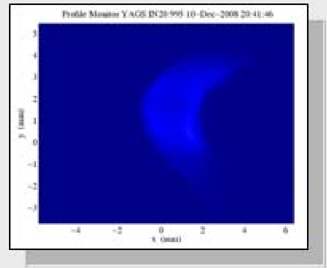
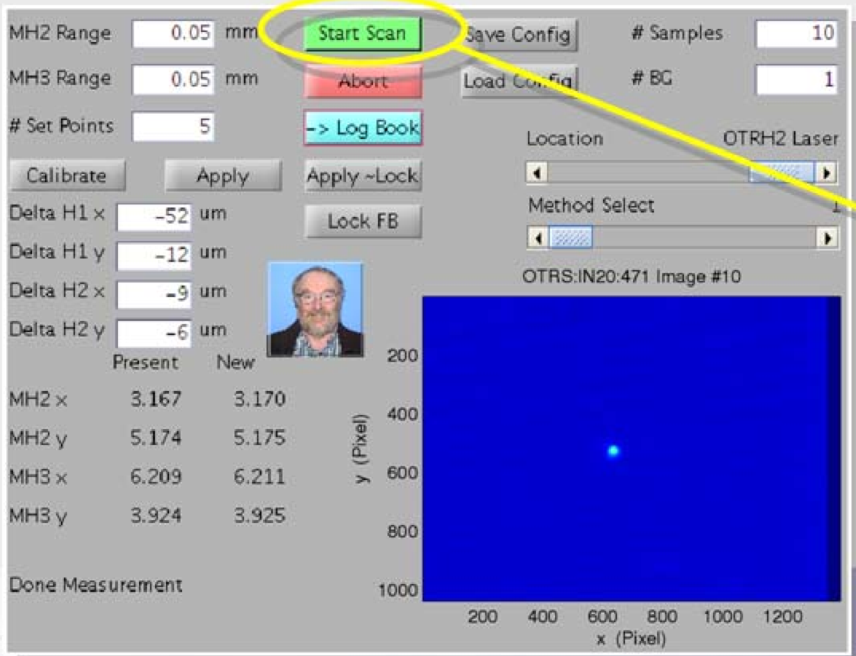






good heating



One

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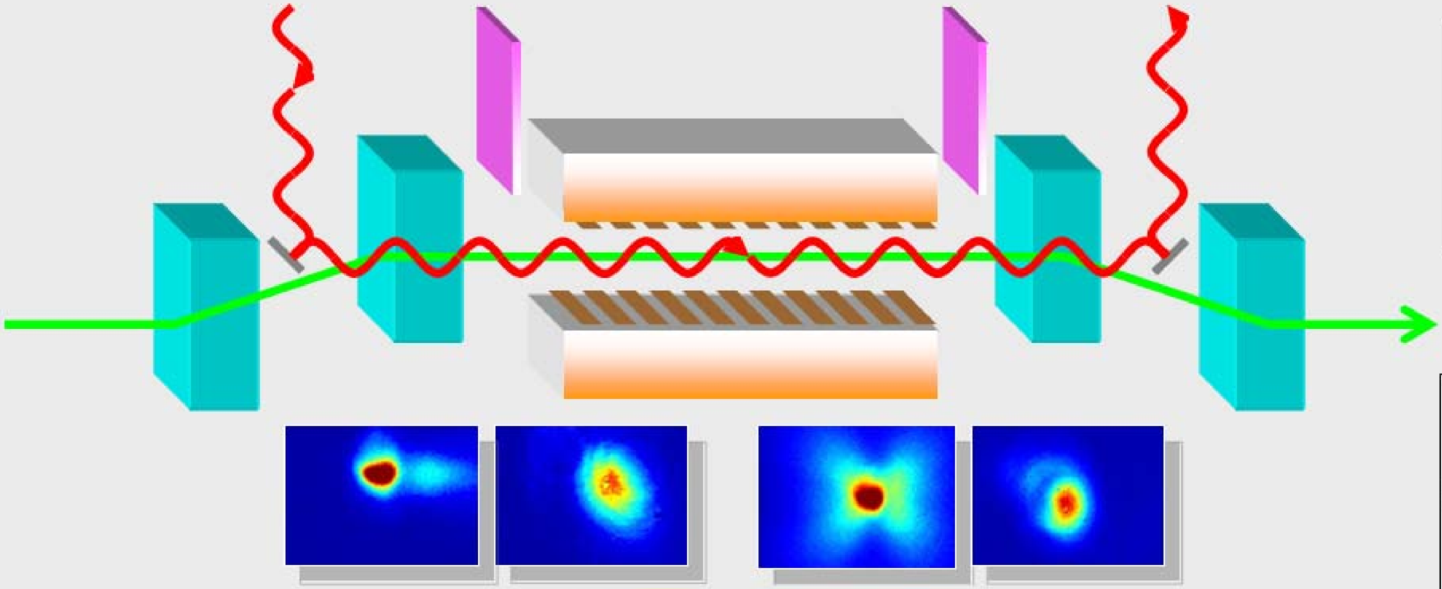
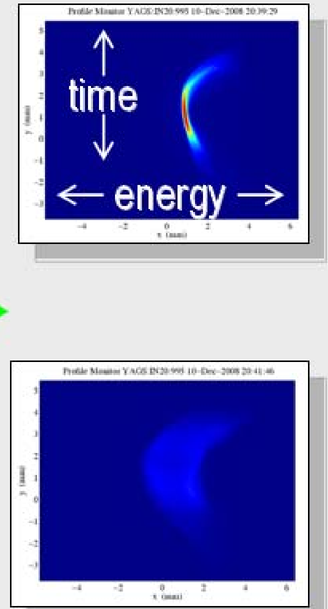
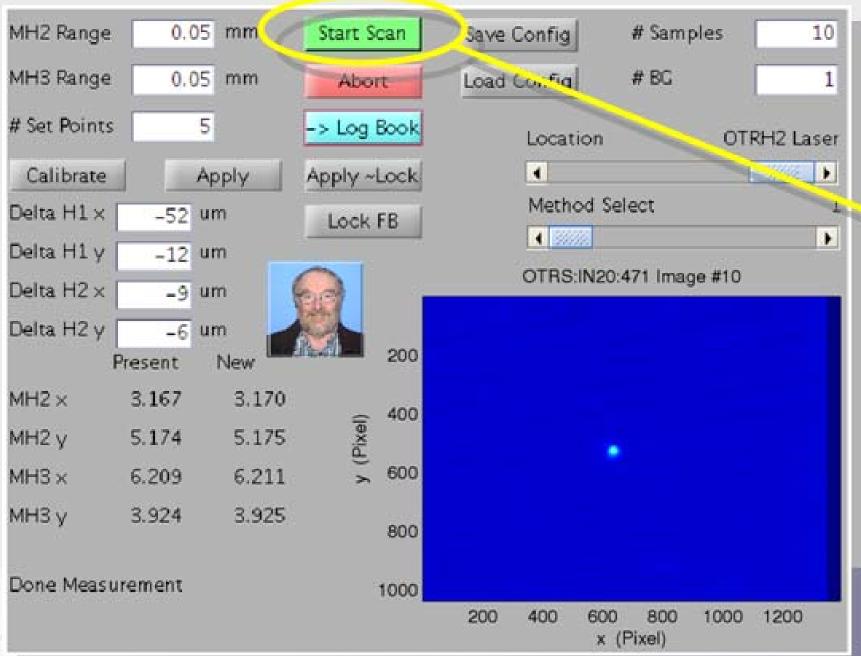




good heating



One button click (~1 minute)

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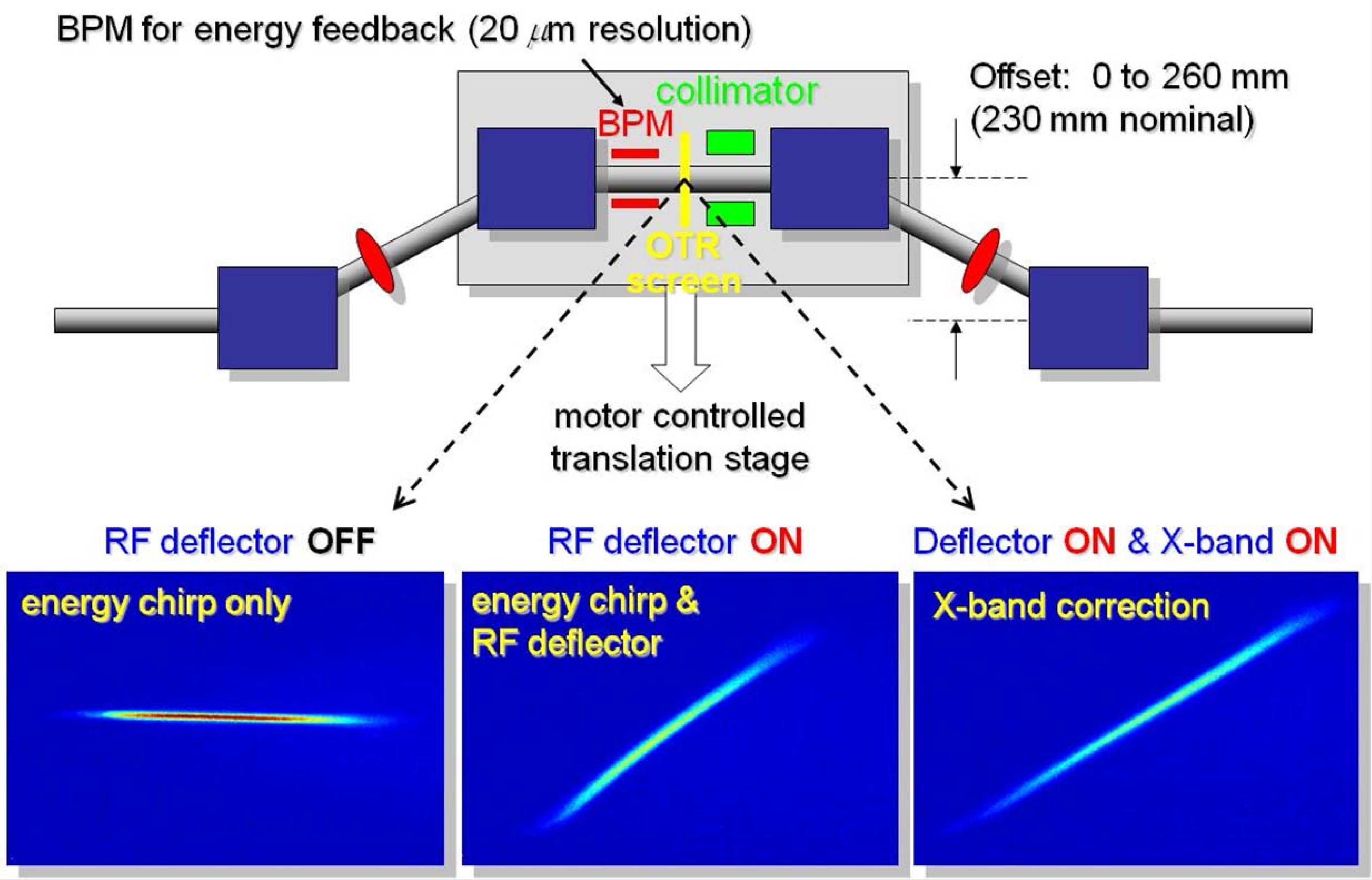
Bunch Compressor 1



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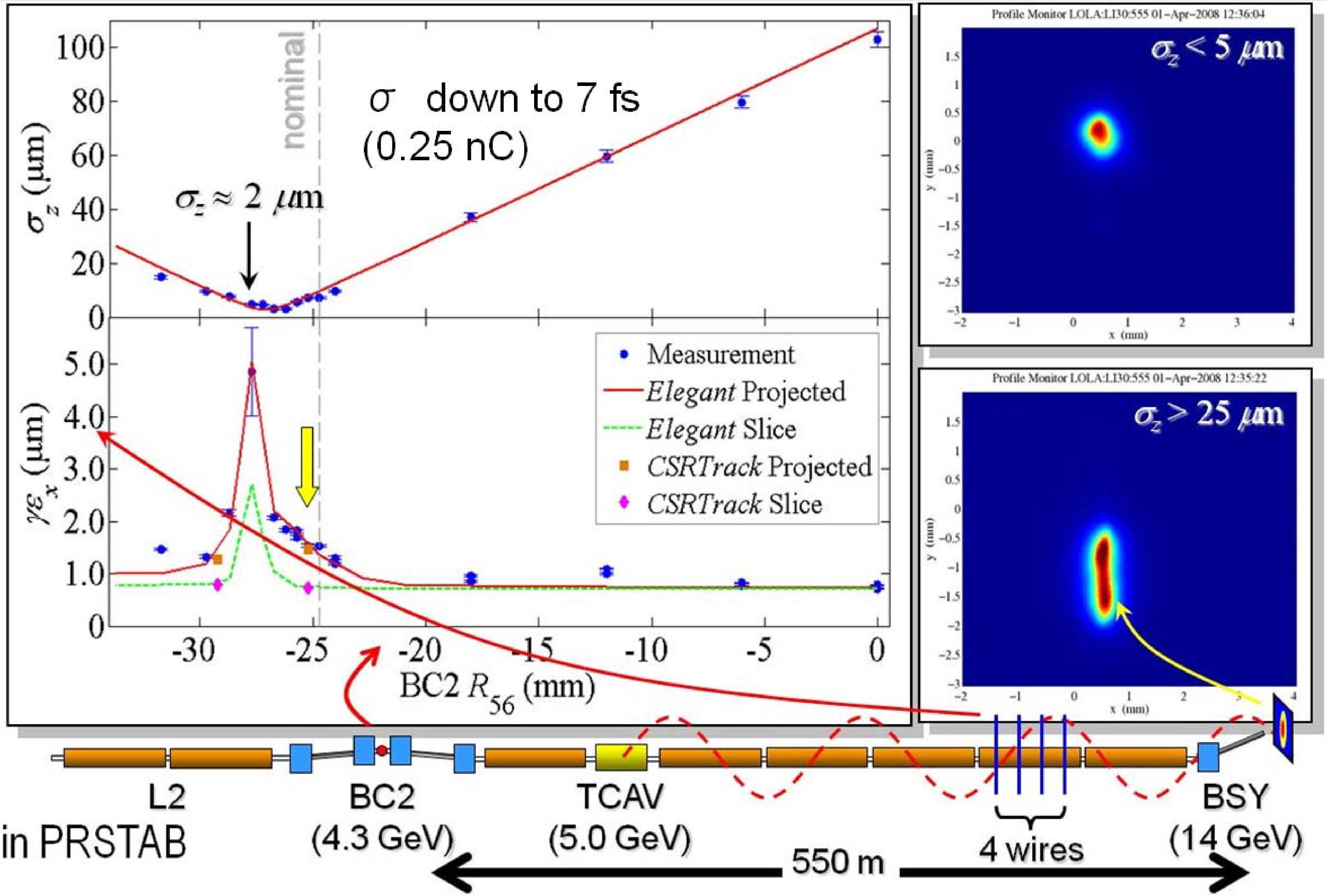
Bunch Compressor 2



in PRSTAB

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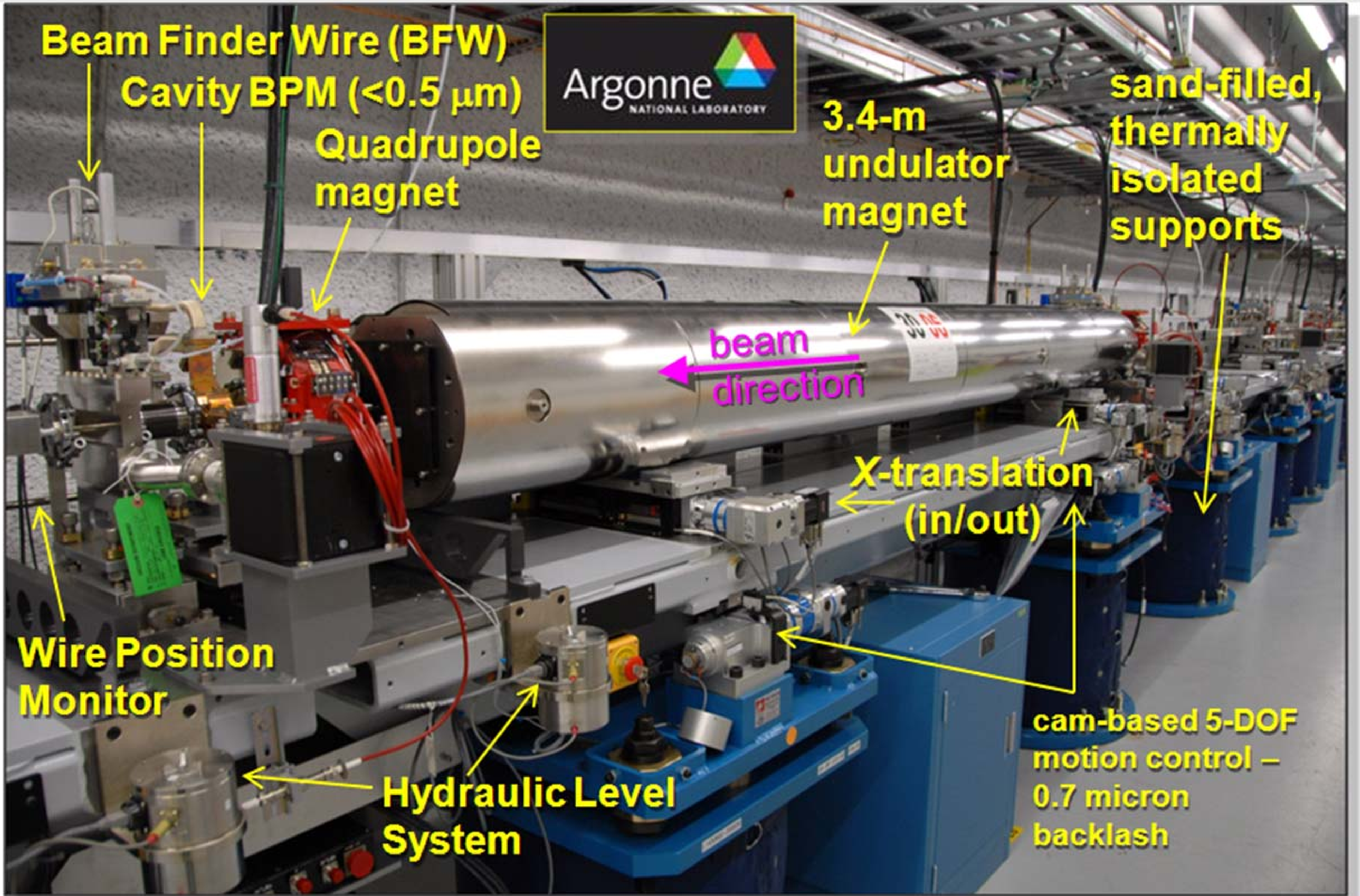
Undulator System Fully Functional



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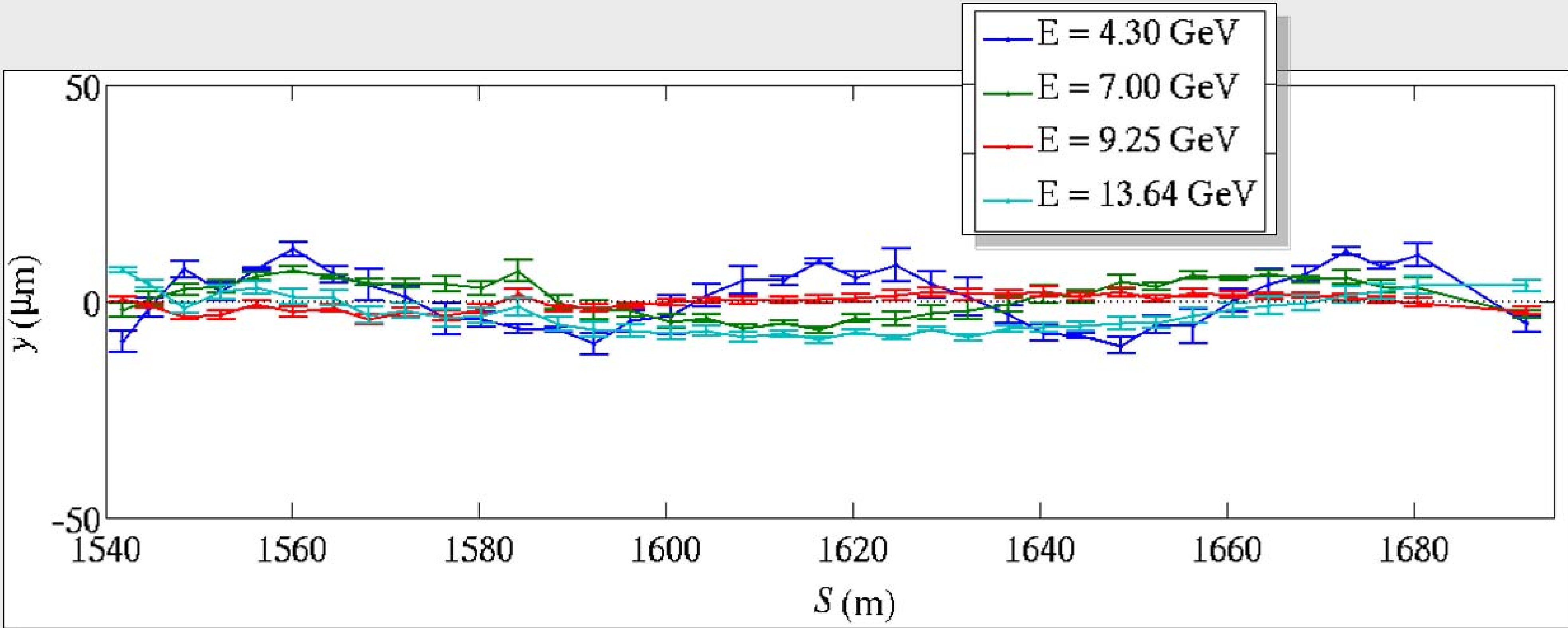
Beam-Based Undulator Alignment

- Measure undulator trajectory at 4 energies (4.3, 7.0, 9.2, & 13.6 GeV)
- Repeated ~ 2 week intervals
- Taut wire system & water level may permit increased interval
  - Not used this way yet
- Taut wire has excellent sensitivity, fewer transient response issues



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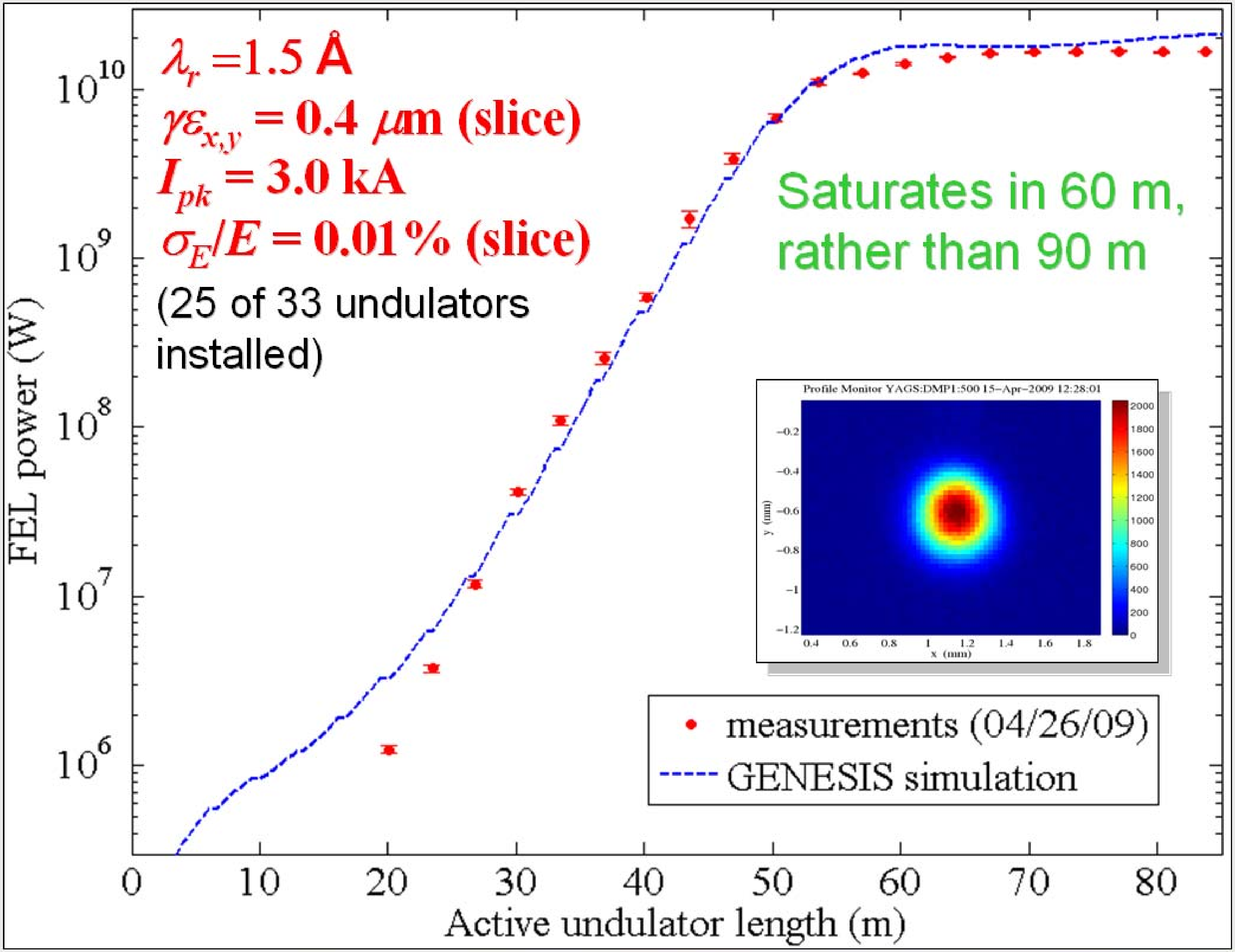
Beam Brightness Pays Big Dividends



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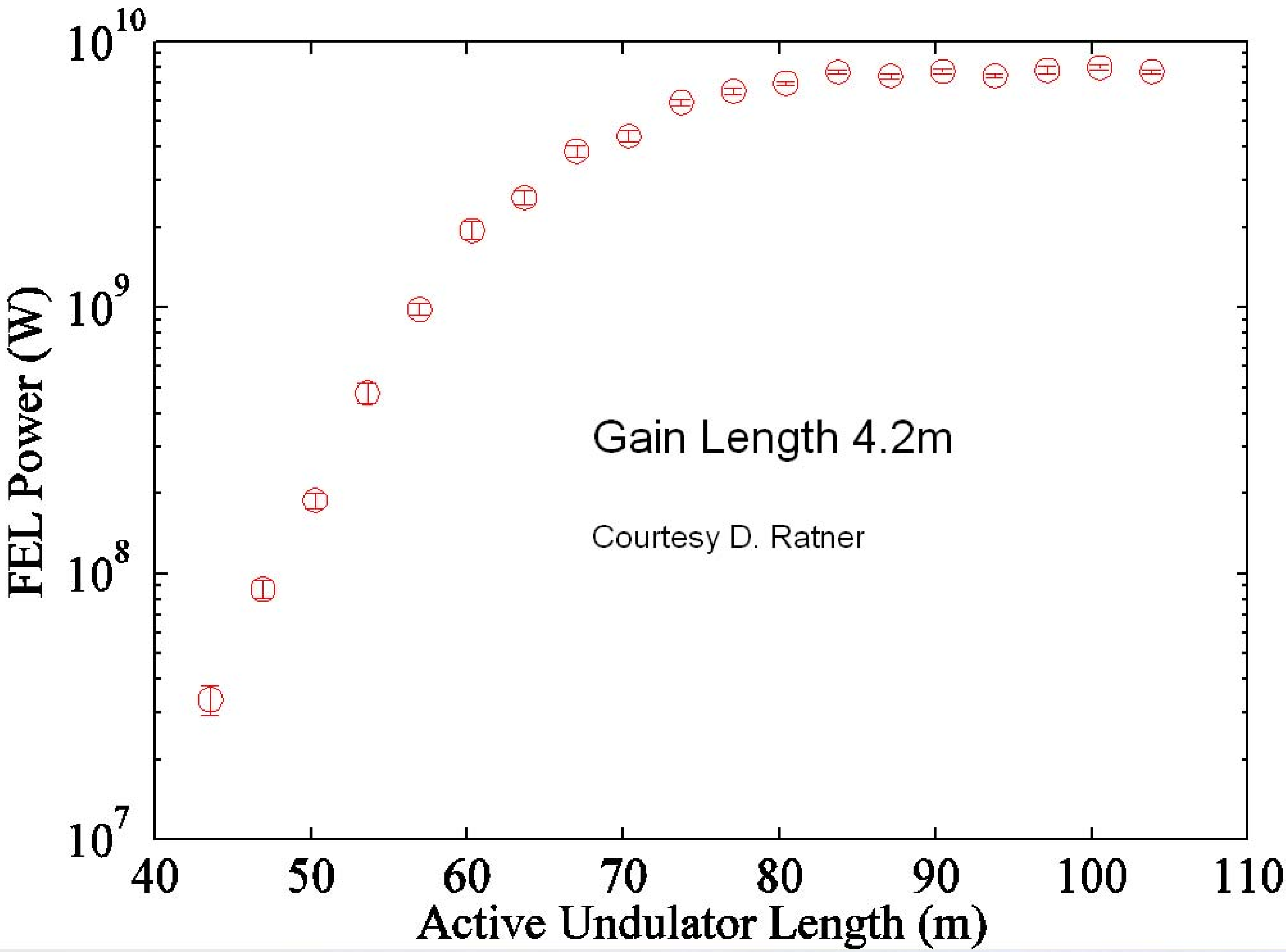
Saturation @ 10 keV (15.1 GeV)



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Beam Dump Used to Measure Energy Loss of Electron Beam

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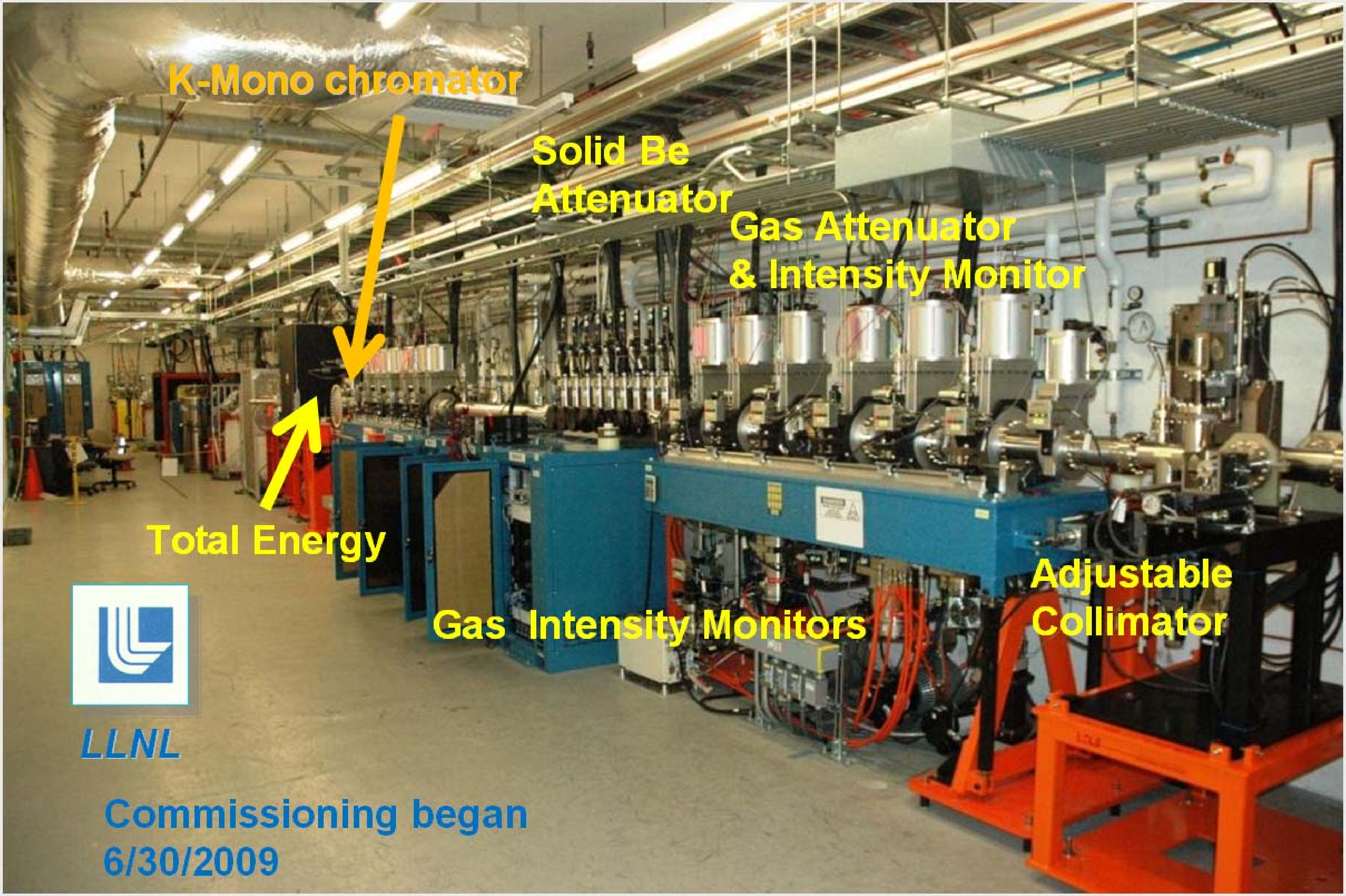
Front End – Calorimeter & Gas Intensity moniror



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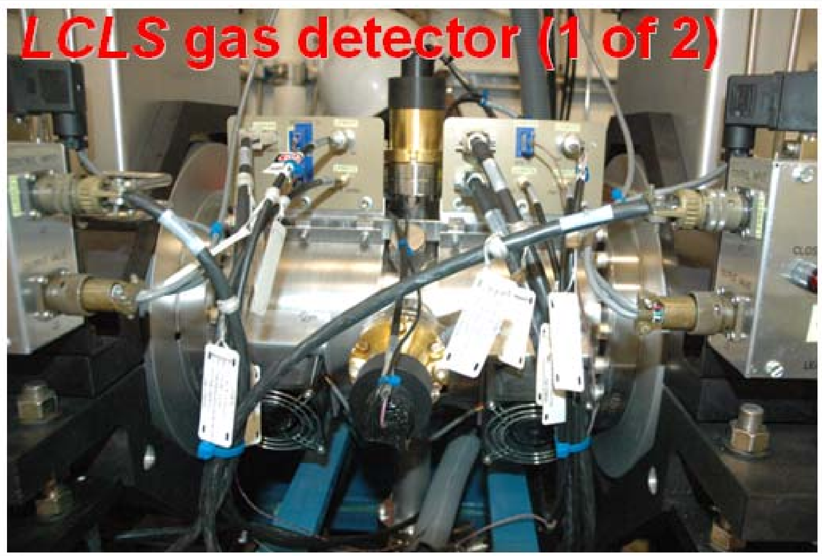
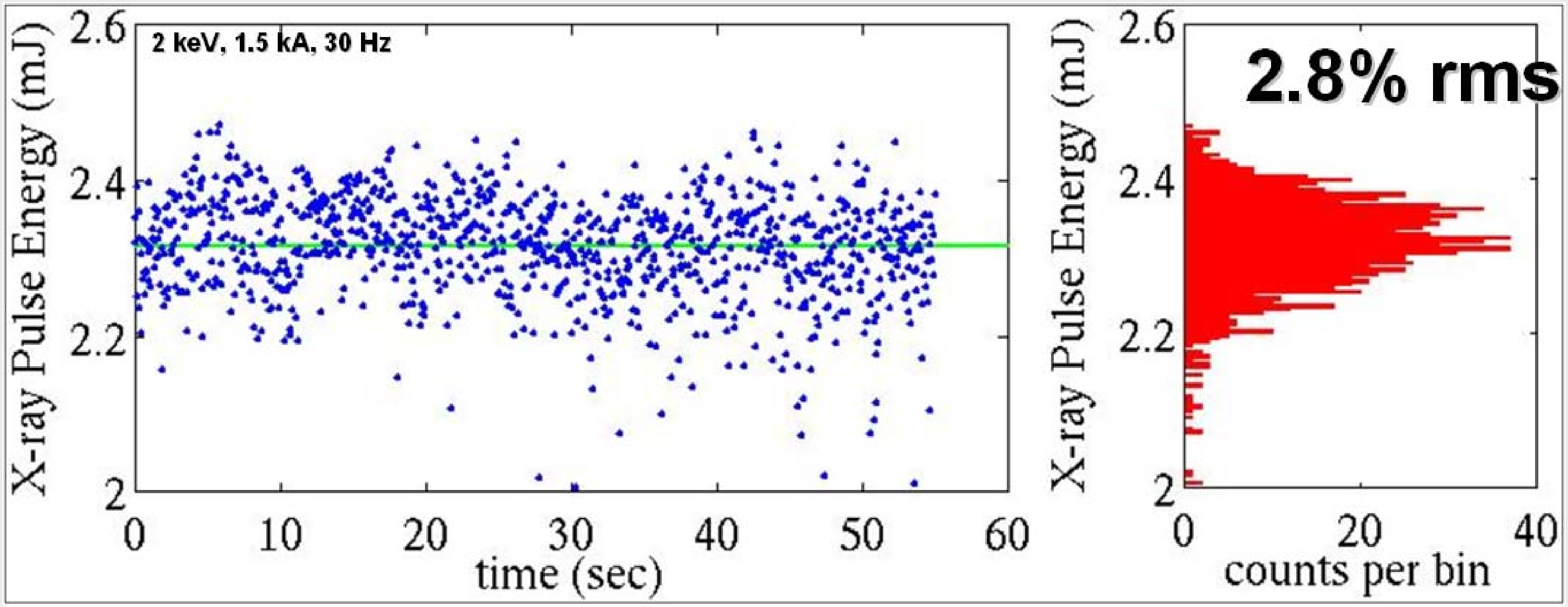
FEL Stability <3% Using "Gas Detectors"



0.02-1 Torr N_2 gas + solenoid & 2 PMTs
Tracking of detectors → <2% intrinsic noise

Non-invasive measure of FEL X-ray pulse energy on each shot (sychronous with other data)



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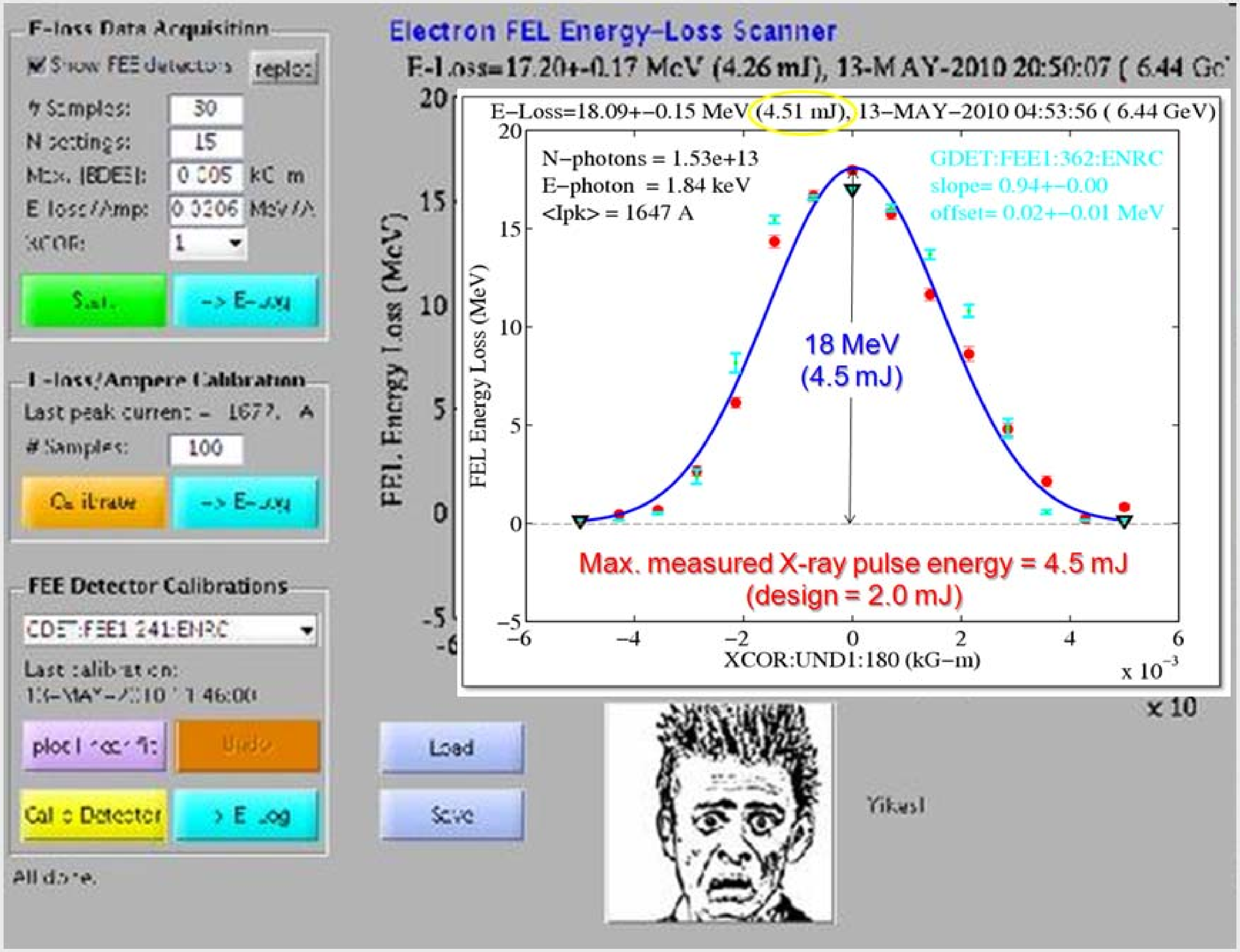
Recent Max. X-Ray Pulse Energy

4.5 mJ @ 1.84 keV



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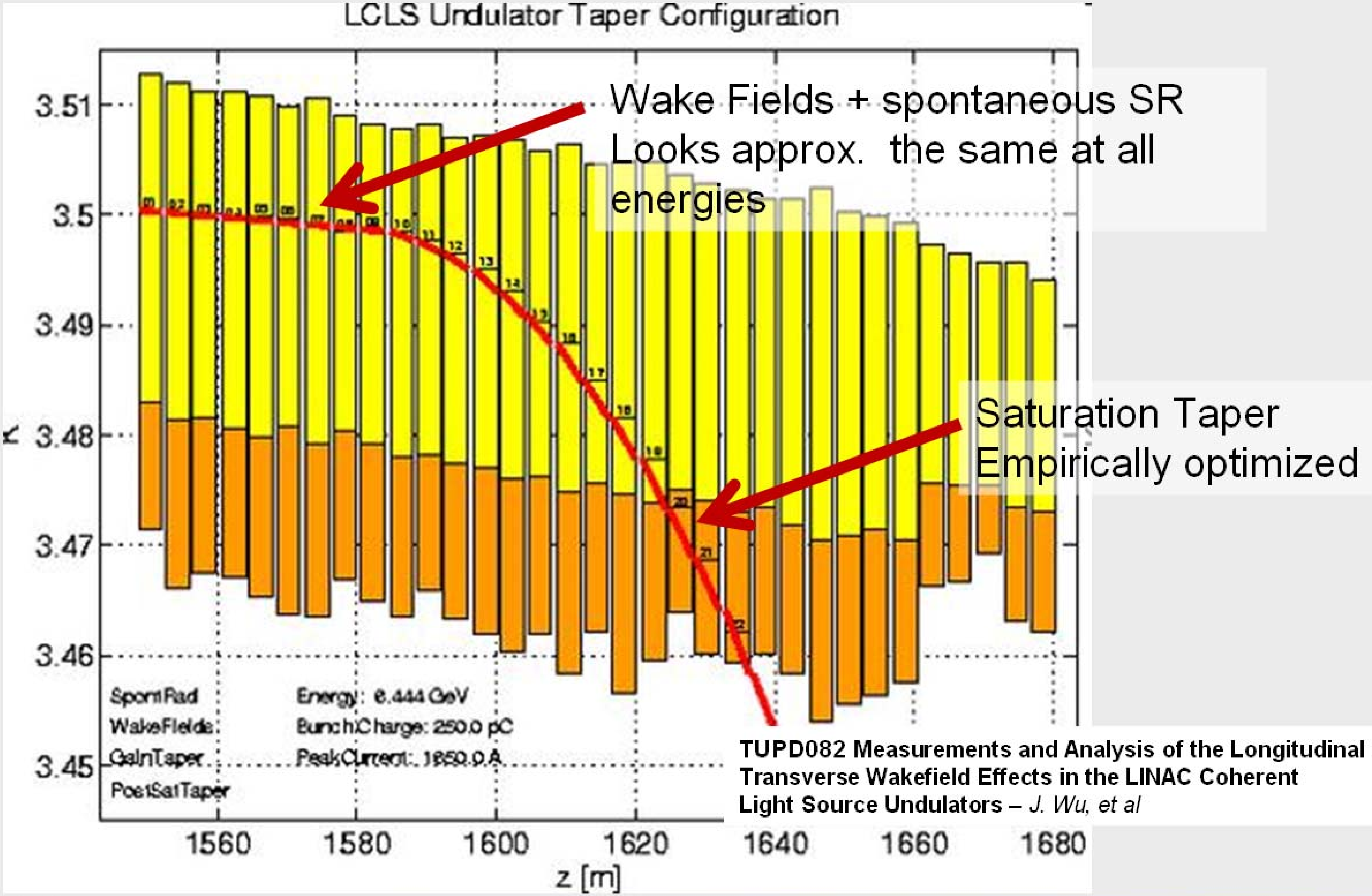
Wake Fields, Taper



TUPD082 Measurements and Analysis of the Longitudinal and Transverse Wakefield Effects in the LINAC Coherent Light Source Undulators – *J. Wu, et al*

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Parameter Changes and Time Required

- **Repetition Rate** (1, 10, 30, 60 Hz, & one-shot) changed instantly (one button push) – 120 Hz in Oct. 2010†
- **Photon Energy** (500 - 2000 eV)* changed in 5-30 minutes (achieved wavelength as short as 1.2 Å)
- **Pulse Energy** (0 - 4 mJ) easily lowered, but may take 1-2 hrs to achieve >2.5 mJ (depends on wavelength, etc).
- **Pulse Length** (60 - 500 fs FWHM) easily changed in 1 minute (closed loop control with bunch length monitor after BC2) - (60 - 100 fs range for hard x-rays).
- **Peak FEL Power** (0 - 40 GW) set by pulse length (increases with peak current – see next slide).
- **Ultra-Short Pulse Length** (<10 fs FWHM) requires 1-2 hrs to establish, starting from nominal 250-pC conditions.

† Laser & injector RF are already at 120 Hz, and most linac RF already tested at 120 Hz
* Up to 10 keV achieved, but no hard x-ray users yet

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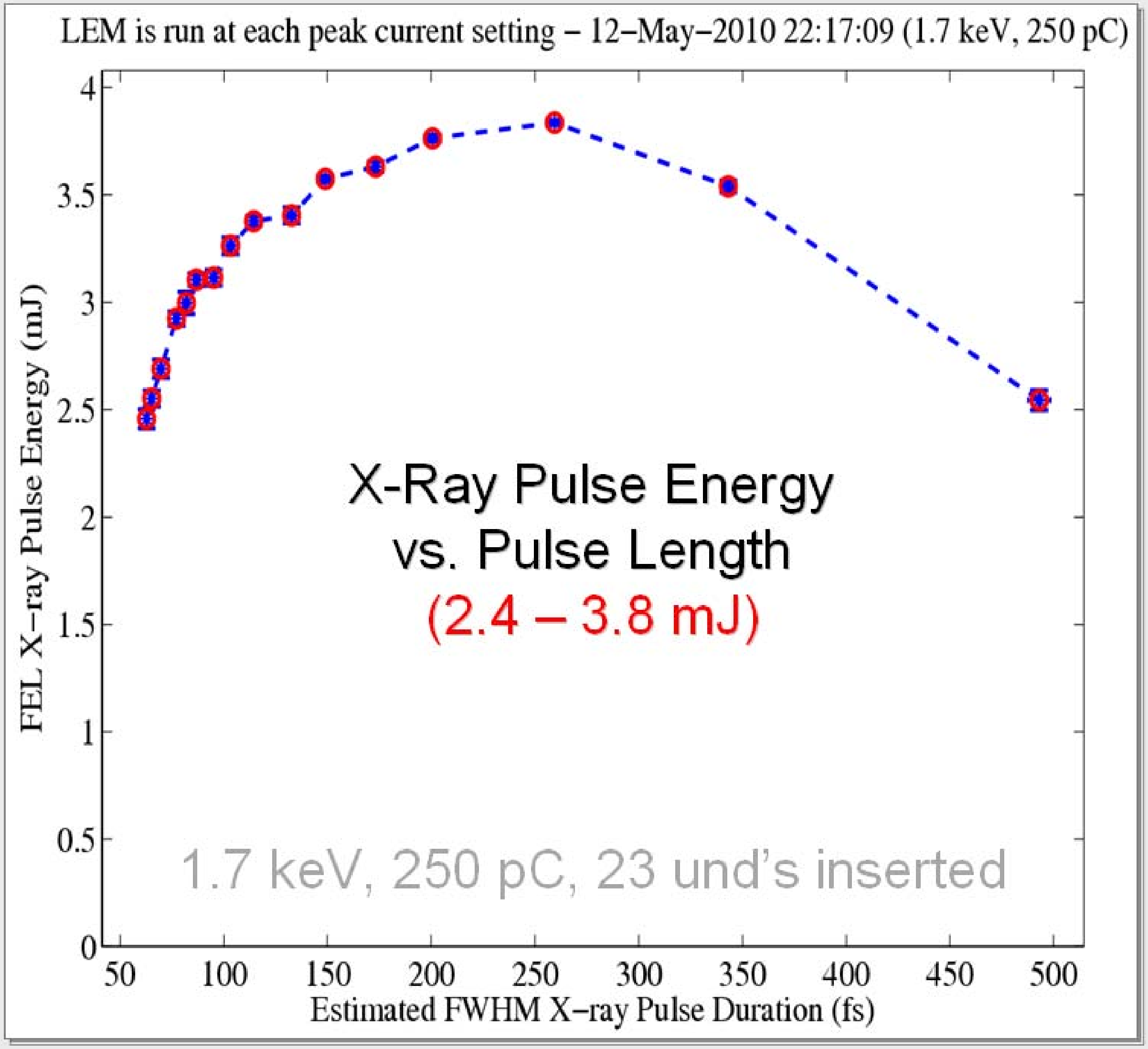
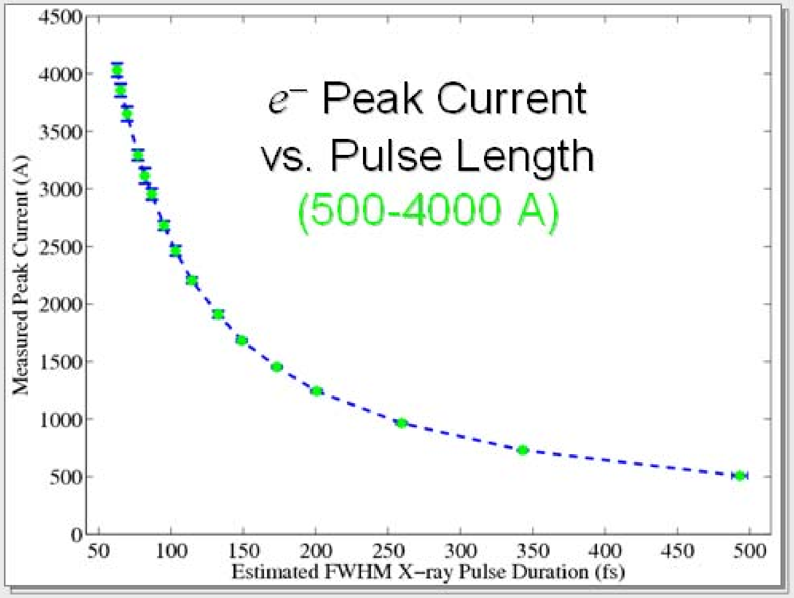
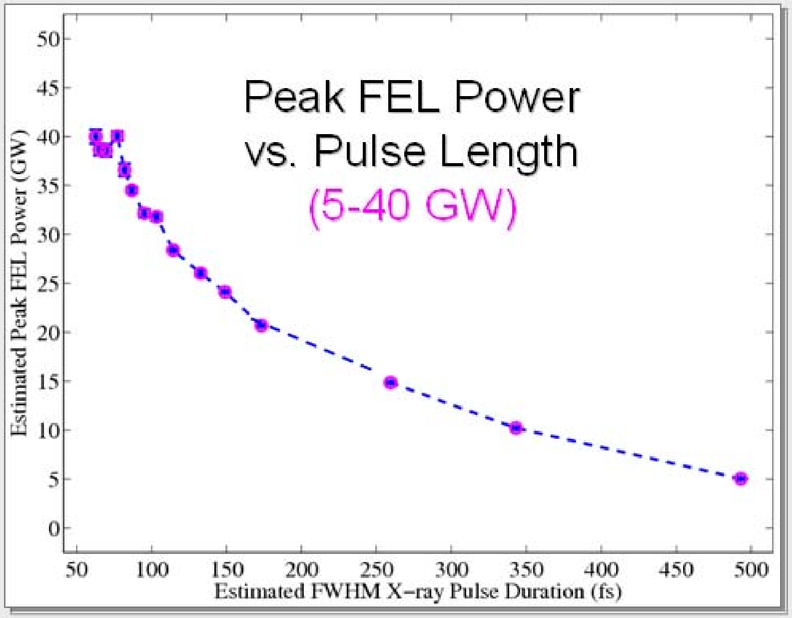
Pulse Length Easily Adjusted (500-60 fs)







e^- bunch length is quickly adjustable (<1 min) from 60 to 500 fs (hard x-rays: 60 to 100 fs)

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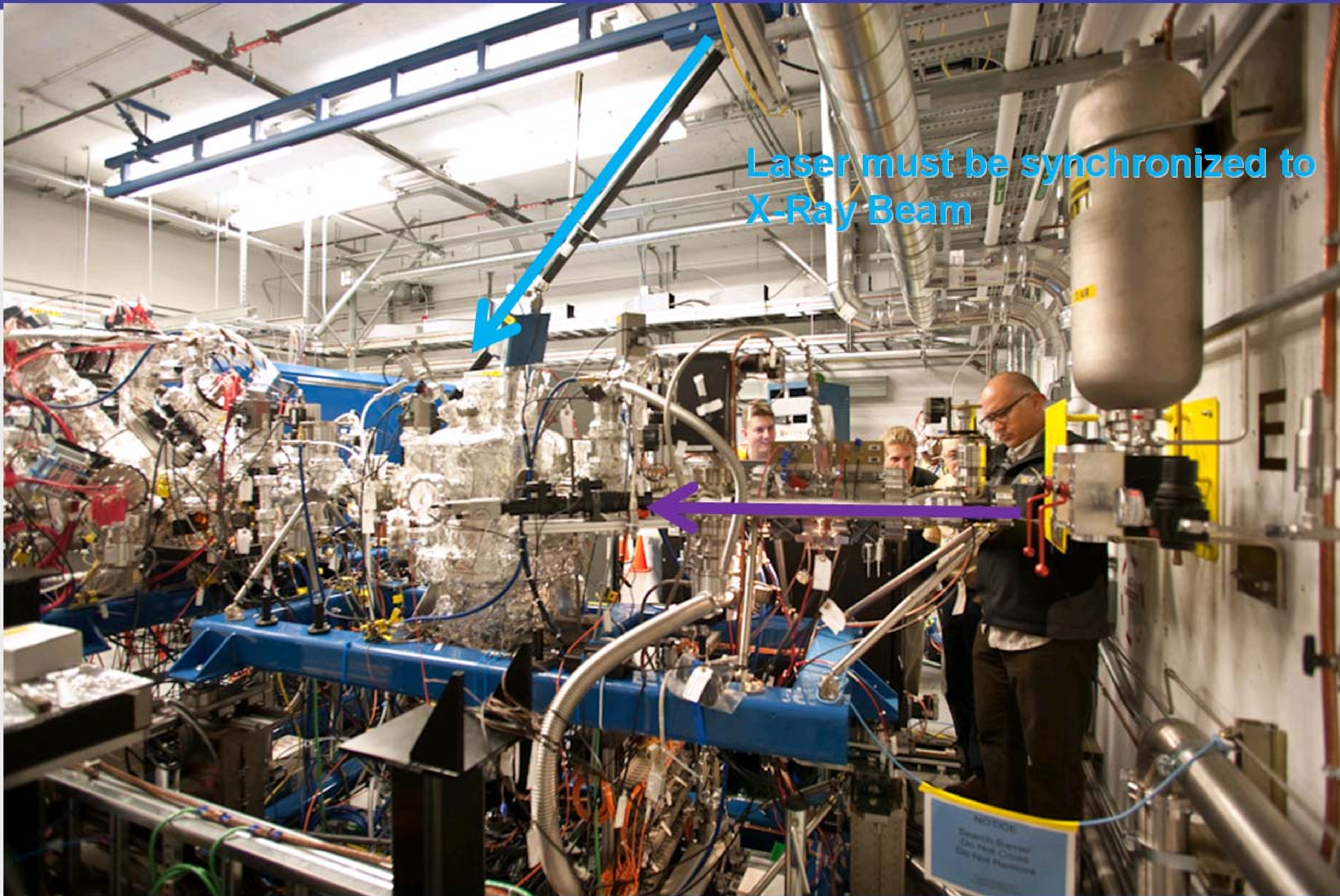
AMO Instrument



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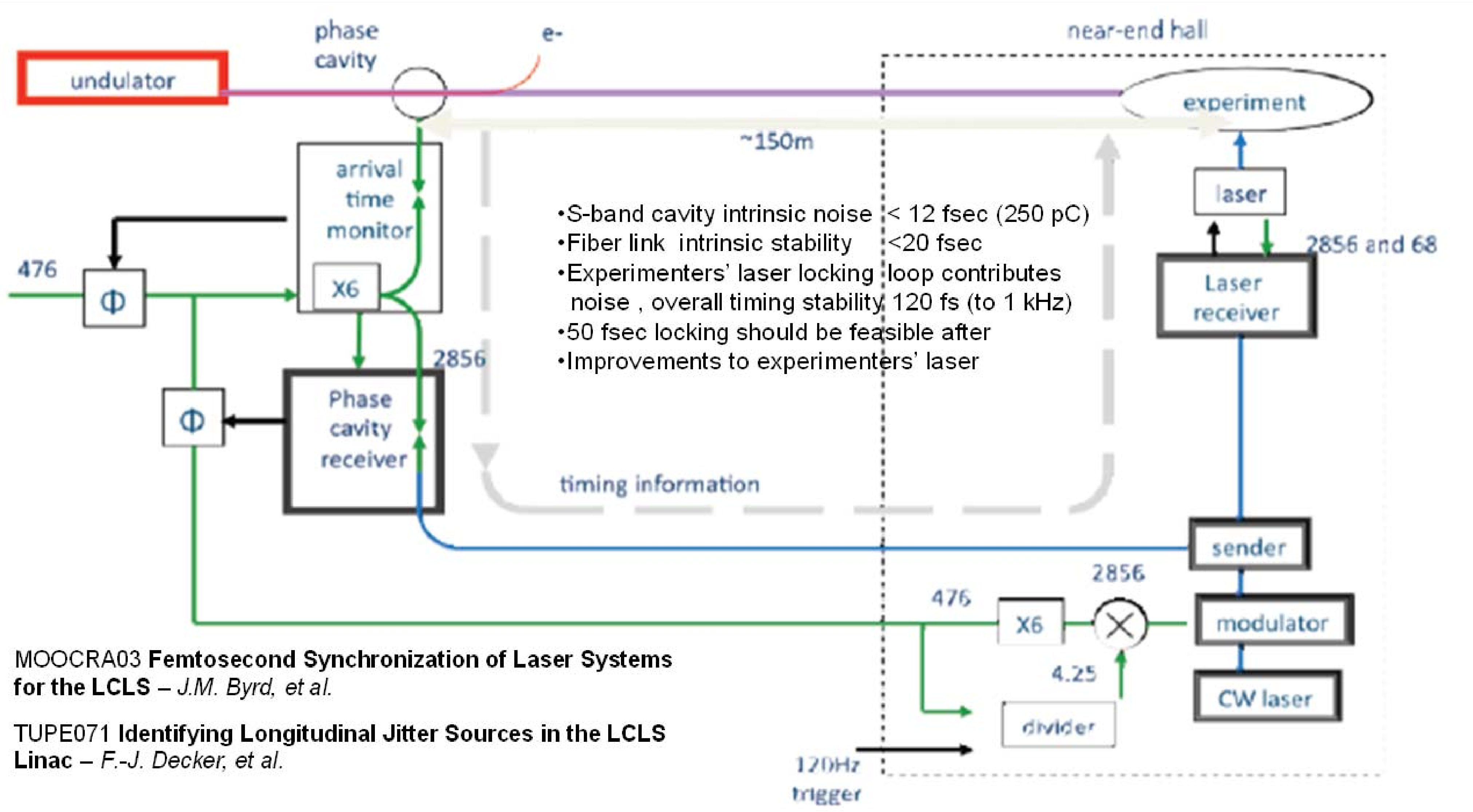
Synchronization of x-rays to Experimenters' Laser



- S-band cavity intrinsic noise < 12 fsec (250 pC)
- Fiber link intrinsic stability <20 fsec
- Experimenters' laser locking loop contributes noise , overall timing stability 120 fs (to 1 kHz)
- 50 fsec locking should be feasible after
- Improvements to experimenters' laser

MOOCRA03 **Femtosecond Synchronization of Laser Systems for the LCLS** – *J.M. Byrd, et al.*

TUPE071 **Identifying Longitudinal Jitter Sources in the LCLS Linac** – *F.-J. Decker, et al.*

TUPE067 **Operational X-ray Diagnostics for the LCLS** – *J.C. Frisch,, et al.*

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parameter	design	hard	soft	unit
electrons				
charge per bunch	1	0.25	0.25	nC
single bunch rep. rate	120	60	60	Hz
final linac e^- energy	13.6	13.6	3.3-6.7	GeV
slice† emittance (inj.)	1.2	0.4	0.4	µm
final *proj.*† emittance	1.5	0.5-1.2	0.5-1.6	µm
final peak current	3.4	2.5-4.0	0.5-4.0	kA
timing stability (rms)	120	50	50	fs
peak current stability (rms)	12	8-12	5-10	%
x-rays				
FEL gain length	4.4	3.5	~1.5	m
radiation wavelength	1.5	1.5 (1.2)	6-22	Å
photons per pulse	2.0	1.0-2.3	10-20	10^{12}
energy in x-ray pulse	1.5	1.5-3.5	1-4.5	mJ
peak x-ray power	10	15-40	5-40	GW
pulse length (fwhm)	200	60-100	60-500	fs
bandwidth (fwhm)	0.1	0.2-0.5	0.2-1.0	%
peak brightness (est.)	8	20	0.3	10^{32} *
wavelength stability (rms)	0.2	0.1	0.2	%
power stability (rms)	20	5-12	3-10	%

† "*slice*" refers to femtosecond-scale time slices and "*proj.*" to the full time-projected (*i.e.*, integrated) emittance of the bunch.

* Brightness is photons per phase space volume, or photons/sec/mm^2/mrad^2 per 0.1% spectral bandwidth.

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Closing Comments

- LCLS producing good x-ray output
- Pulse-to-pulse stability OK
- Timing stability good for ultrafast science
- Lots of interested experimenters
- First results of experiments published soon
- Thanks to SLAC, ANL, LLNL, also LBNL
  - For really beautiful work
- Thanks to Paul Emma and LCLS commissioning team

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MOOCRA03 **Femtosecond Synchronization of Laser Systems for the LCLS** – *J.M. Byrd, L.R. Doolittle, G. Huang, J.W. Staples, R.B.Wilcox (LBNL) J. Arthur, J.C. Frisch,W.E.White (SLAC)*

TUPEA060 **A Compact X-band Linac for an X-ray FEL** – *K.L.F. Bane, C. Adolphsen, Z. Huang, Z. Li, C.D. Nantista, F. Wang,b F. Zhou (SLAC)*

TUPEA061 **LLRF System Upgrade for the SLAC Linac** – *B. Hong, R. Akre, V. Pacak (SLAC)*

TUPD082 **Measurements and Analysis of the Longitudinal and Transverse Wakefield Effects in the LINAC Coherent Light Source Undulators** – *J. Wu, K.L.F. Bane, A. Brachmann, A. Chao, F.-J. Decker, Y.T. Ding, D. Dowell, S.A. Edstrom, P. Emma, J.C. Frisch, A. Gilevich, G.R. Hays, P. Hering, Z. Huang, R.H. Iverson, H. Loos, A. Miahnahri, H.-D. Nuhn, D.F. Ratner, G.V. Stupakov, J.L. Turner, J.J. Welch, W.E. White, D. Xiang (SLAC)*

TUPE065 **Surface Characterization of the LCLS RF Gun Cathode** – *A. Brachmann (SLAC)*

TUPE066 **Femtosecond Operation of the LCLS for User Experiments** – *J.C. Frisch, C. Bostedt, J.D. Bozek, A. Brachmann, R.N. Coffee, F.-J. Decker, Y.T. Ding, D. Dowell, P. Emma, A. Gilevich, G. Haller, G.R. Hays, P. Hering, B.L. Hill, Z. Huang, R.H. Iverson, E.P. Kanter, B. Kraessig, H. Loos, A. Miahnahri, H.-D. Nuhn, A. Perazzo, M. Petree, D.F. Ratner, T.J. Smith, S.H. Southworth, J.L. Turner, J.J. Welch, W.E. White, J.Wu, L. Young (SLAC) R.B.Wilcox (LBNL)*

TUPE067 **Operational X-ray Diagnostics for the LCLS** – *J.C. Frisch, J. Arthur, P. Emma, G. Haller, S.A. Lewis, H. Loos, M. Messerschmidt, M. Petree, T.J. Smith, P. Stefan, H. Tompkins, J.L. Turner, J.J. Welch (SLAC) R.M. Bionta, S. Friedrich, S.P. Hau-Riege (LLNL)*

TUPE070 **Second and Third Harmonic Measurements at the Linac Coherent Light Source** – *D.F. Ratner, F.-J. Decker, Y.T. Ding, P. Emma, J.C. Frisch, Z. Huang, R.H. Iverson, H. Loos, M. Messerschmidt, H.-D. Nuhn, T.J. Smith, J.L. Turner, J.J.Welch, J.Wu (SLAC) R.M. Bionta (LLNL)*

TUPE071 **Identifying Longitudinal Jitter Sources in the LCLS Linac** – *F.-J. Decker, R. Akre, A. Brachmann, J. Craft, Y.T. Ding, D. Dowell, P. Emma, J.C. Frisch, Z. Huang, R.H. Iverson, A. Krasnykh, H. Loos, H.-D. Nuhn, D.F. Ratner, T.J. Smith, J.L. Turner, J.J. Welch, G.R. White, J. Wu (SLAC)*

WEPD057 **Linac Energy Management for LCLS** – *P. Chu, R.H. Iverson, P. Krejcik, D. Rogind, G.R. White,M.Woodley (SLAC)*

TUPE064 **Simulations of IonMigration in the LCLS RFGun and Injector** – *A. Brachmann (SLAC)*

TUZMH02 **Feedback Requirements for SASE FELs** – *H. Loos (SLAC)*

WEXRA02 **Echo-Enhanced Harmonic Generation** – *G. Stupakov (SLAC)*