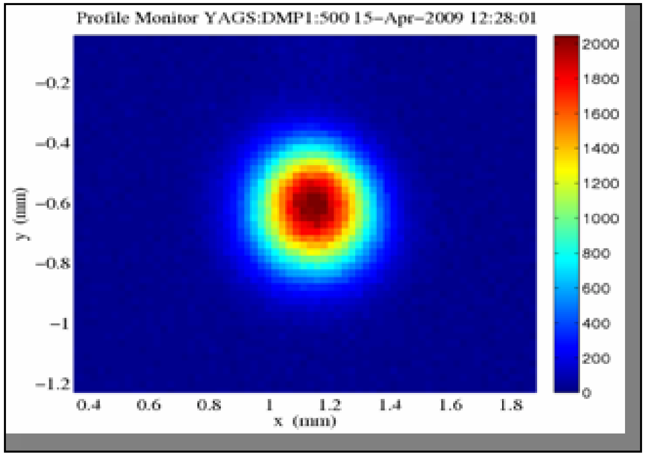
The LCLS: Where we are and where we are going

J. B. Hastings for the LCLS

May 18, 2010



SLAC National Accelerator Laboratory

Acknowledgements

Thanks to…

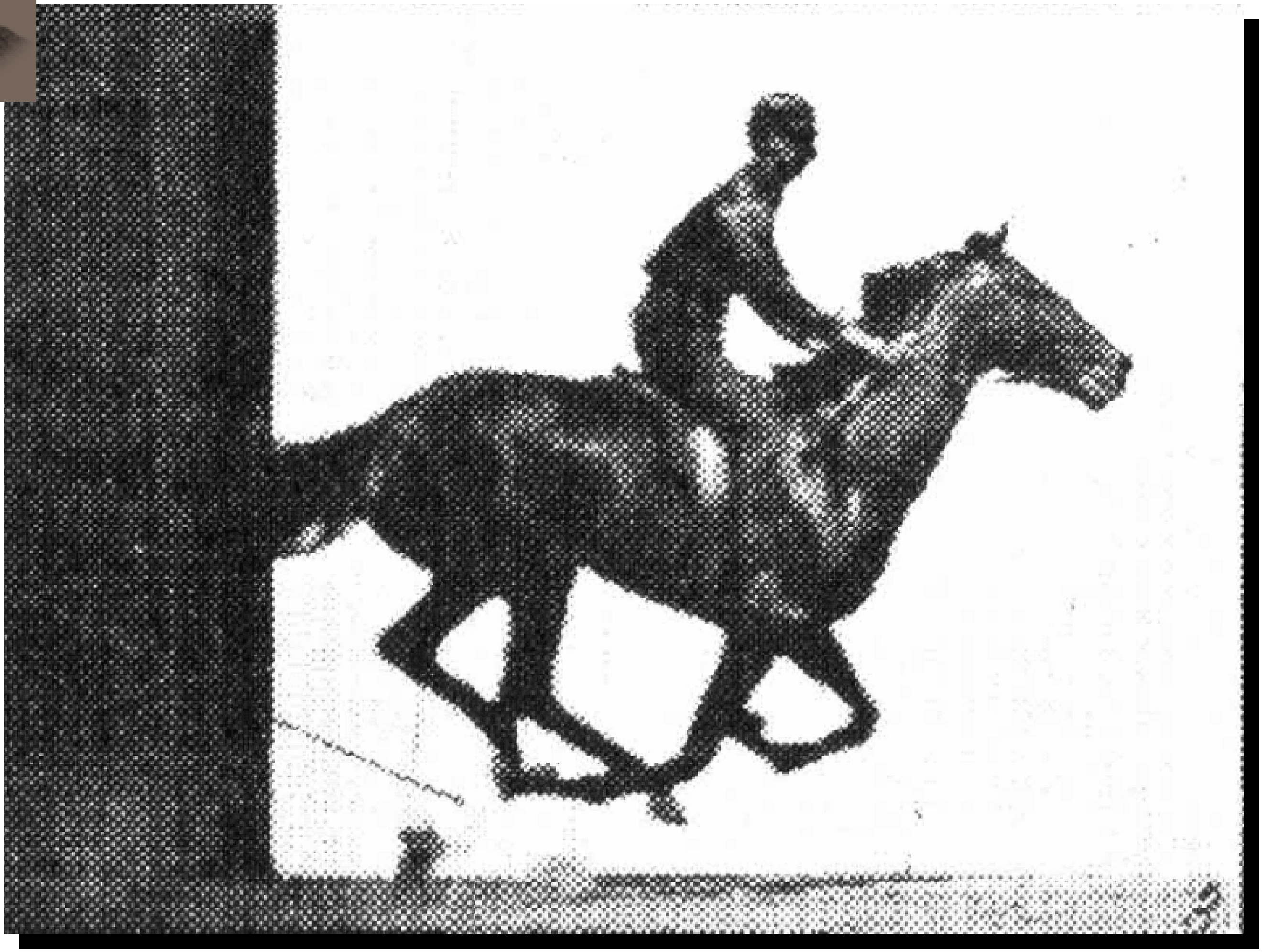
- The extraordinary commissioning **team** at ***SLAC***!
- The operations, metrology, engineering, controls, installation, and RF groups at ***SLAC***
- The tremendous undulator and cavity-BPM team at ***ANL*** – GREAT JOB!
- **John Galayda** (project director) for his leadership and confidence in the team
- And to the many **people**, 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

Finally ***Paul Emma***

1878: E. Muybridge at Stanford

E. Muybridge

Tracing motion of animals by spark photography



E. Muybridge, *Animals in Motion*, ed. by L. S. Brown (Dover Pub. Co., New York 1957).

The Vision…

John Madey, 1971

JOURNAL OF APPLIED PHYSICS VOLUME 42, NUMBER 5 APRIL 1971

Stimulated Emission of Bremsstrahlung in a Periodic Magnetic Field

John M. J. Madey

Physics Department, Stanford University, Stanford, California 94305

(Received 20 February 1970; in final form 21 August 1970)

The Weizsäcker–Williams method is used to calculate the gain due to the induced emission of radiation into a single electromagnetic mode parallel to the motion of a relativistic electron through a periodic transverse dc magnetic field. Finite gain is available from the far-infrared through the visible region raising the possibility of continuously tunable amplifiers and oscillators at these frequencies with the further possibility of partially coherent radiation sources in the ultraviolet and x-ray regions to beyond 10 keV. Several numerical examples are considered.

"…possibility of partially coherent radiation sources in the … x-ray regions to beyond 10 keV."

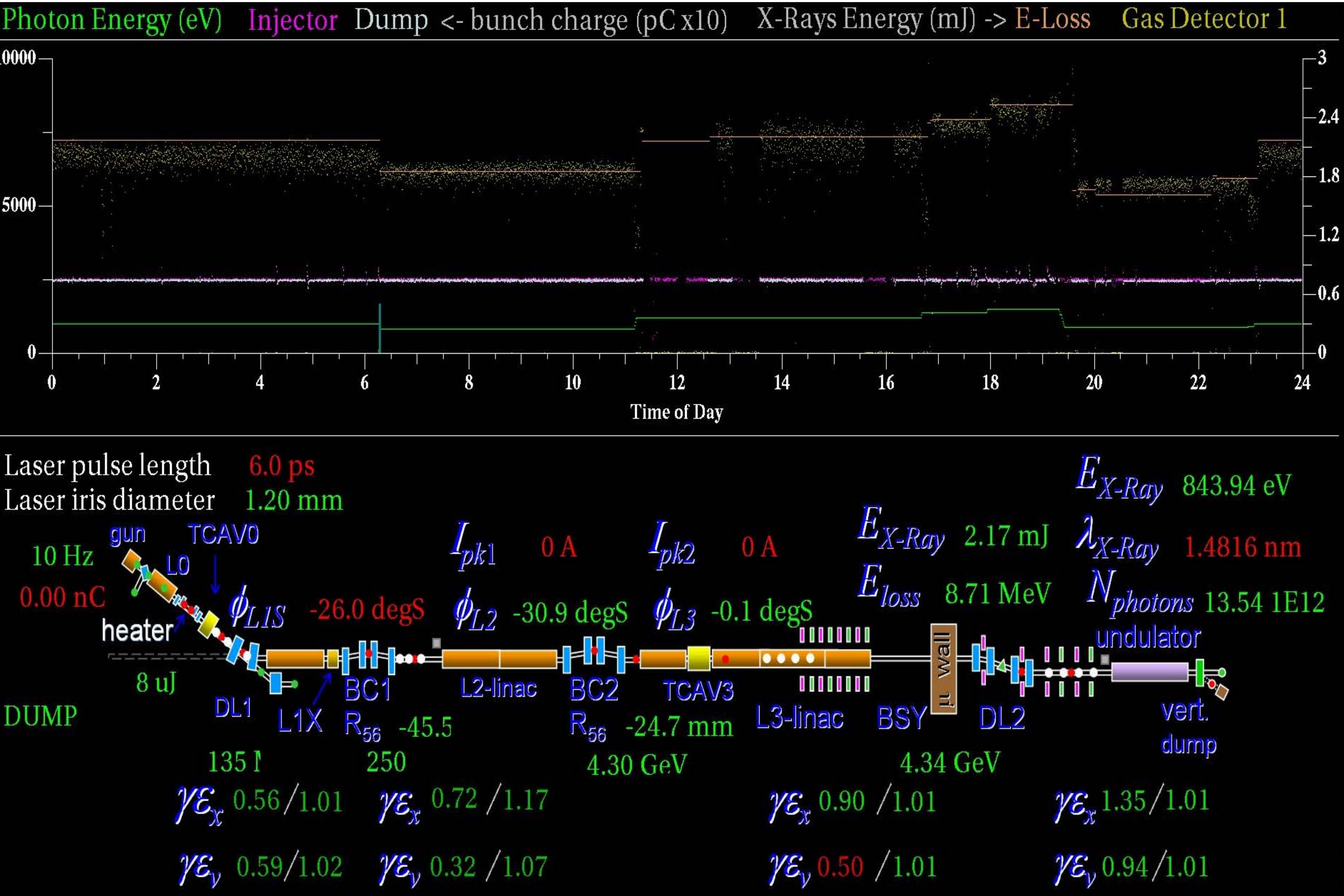
Hard X-ray FELs

- *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…

Good Up-Time and Performance (24-hr plot)



X-ray FEL requires extremely bright e^- beam

- Power grows exponentially with undulator distance, *z*

$$\mathbf{P} \propto \exp\left(\frac{\mathbf{z}}{\mathbf{L_G}}\right)$$

…but only if time-sliced **energy spread << 0.1%** and the transverse **emittance is ~λ_1/4π** (<1 μm)

time-sliced emittance

…power gain length: $$L_G \propto \left(\frac{\varepsilon}{I}\right)^{1/3}$$

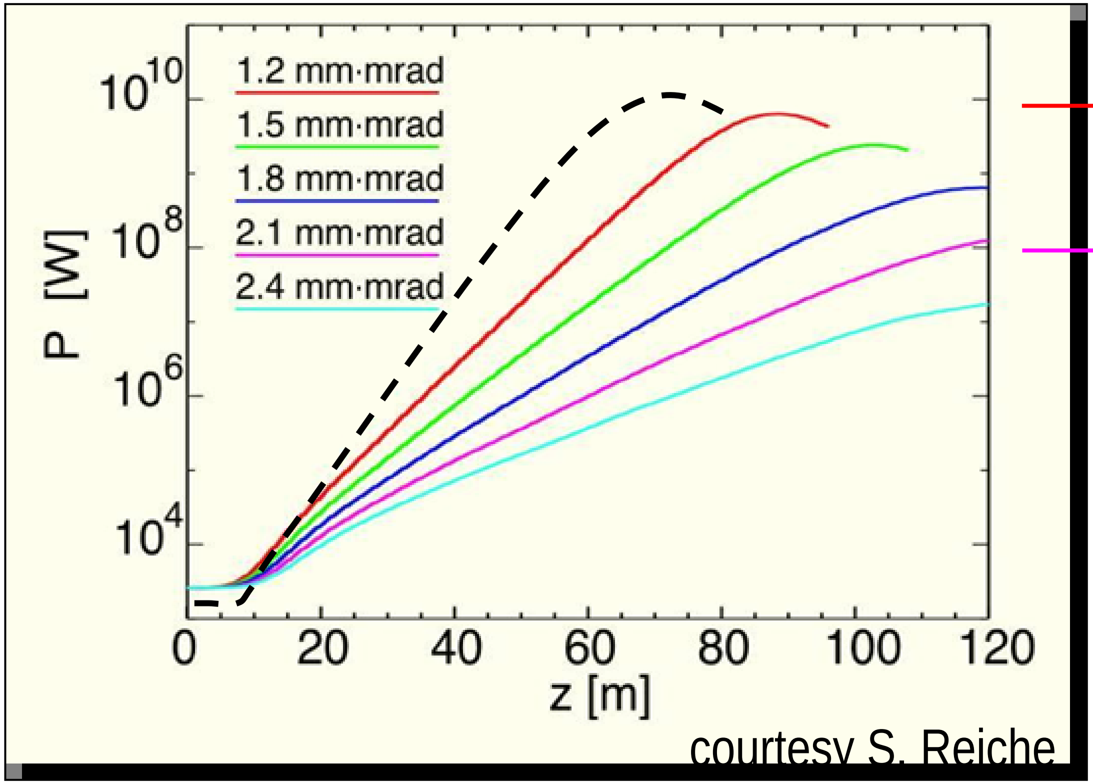
local peak current

- FEL power reaches ***saturation* at ~20L_G**
- SASE performance depends **exponentially** on *e*- beam quality (emittance & peak current) **!**

Z. Huang

Paul Emma has shown this slide many times over the years…

LCLS requires very bright electron beam (emittance)…



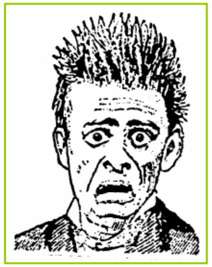
ε_N = 1.2 μm → ***P* ≈ 10 GW**

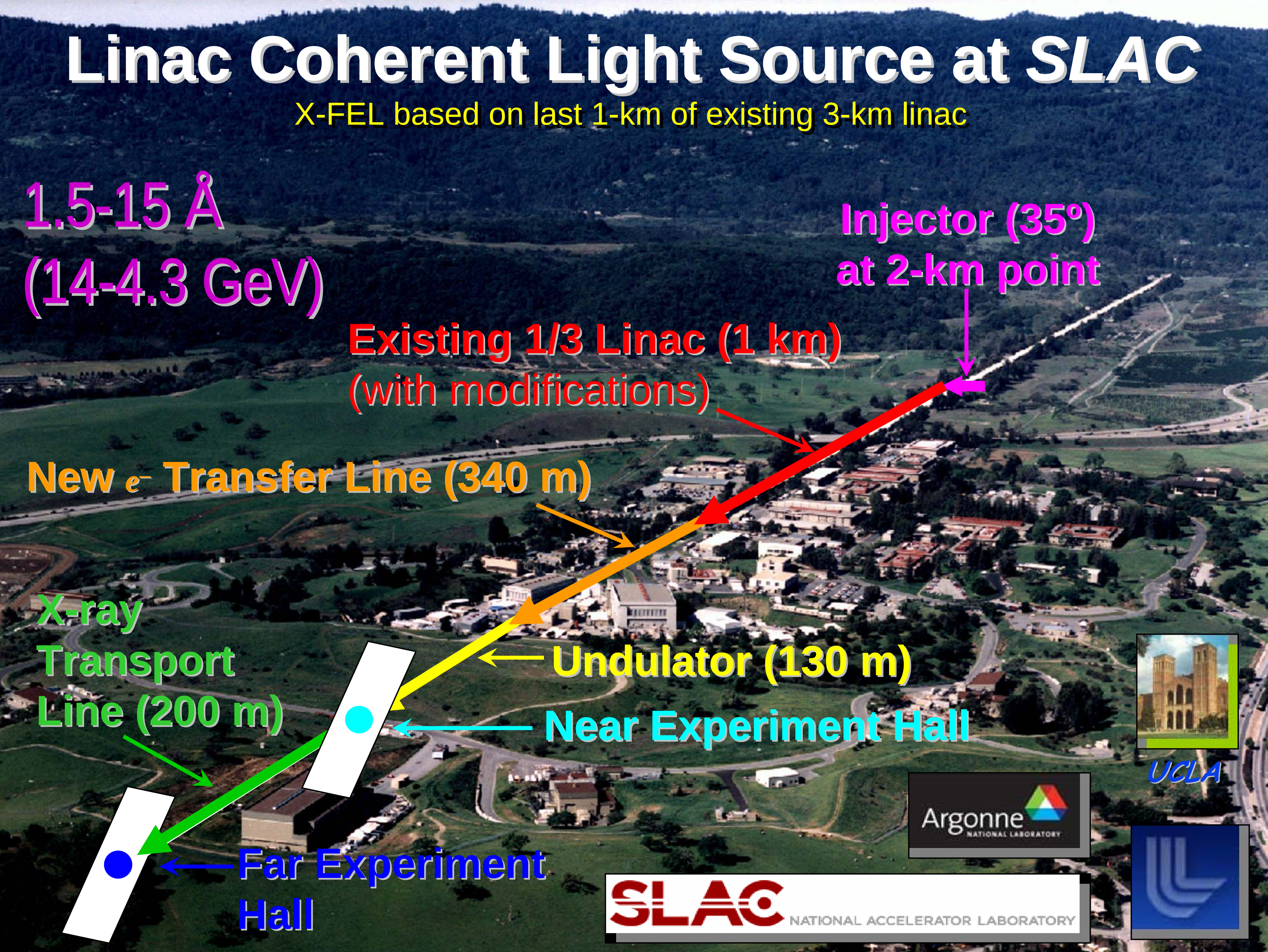
ε_N = 2.0 μm → ***P* ≈ 0.1 GW**

Finally, these worries have been relieved

SASE FEL is not forgiving — instead of mild luminosity loss, power nearly switches **OFF**

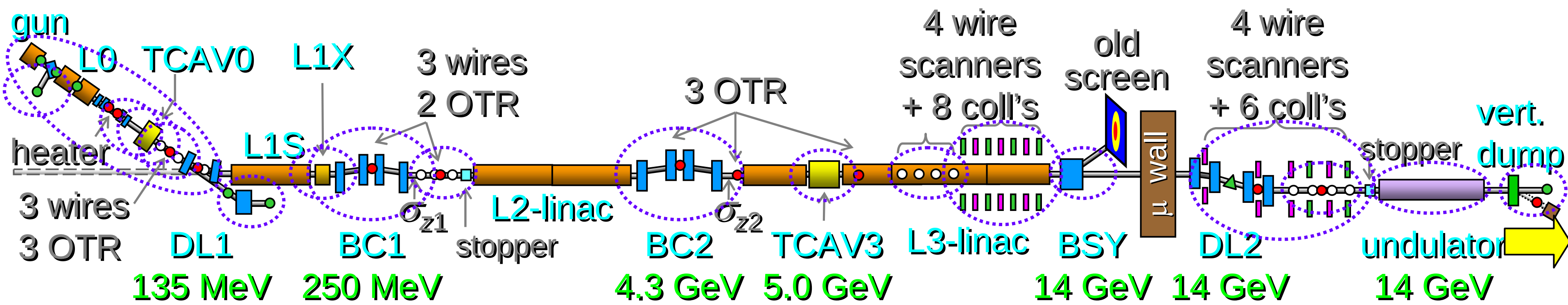
electron beam ***must*** meet brightness requirements





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
Far Experiment
Hall
UCLA
Argonne
NATIONAL LABORATORY
SLAC
NATIONAL ACCELERATOR LABORATORY

LCLS Machine Layout

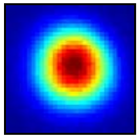


- Accelerator is last 1-km of SLAC linac (14 GeV)
- RF photocathode gun and off-axis injector
- Two bunch compressors + 'laser heater'
- Two transverse RF deflectors for time-resolved beam measurements
- X-band (12 GHz) compression linearizer
- 4 emittance diagnostic stations + 4 spectrometers
- Primary 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

Commissioning of the *LCLS*

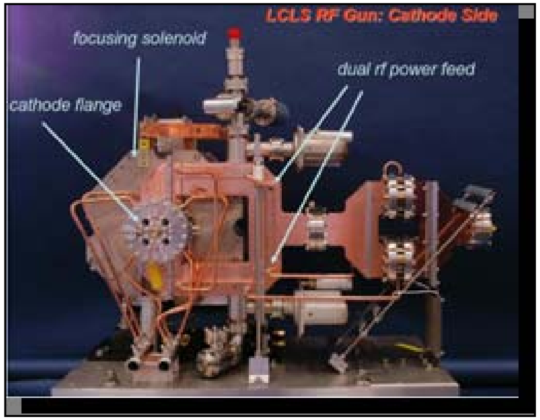
- Laser, gun, & injector commissioned: 2007
- Linac & bunch compressors commissioned: 2008
- First beam through undulator beamline: Dec. 13, 2008

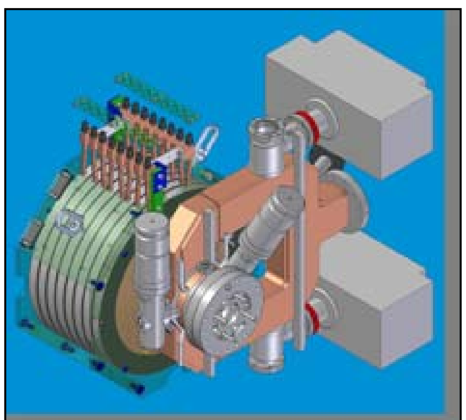
2 shots!

- 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)
- First user run: AMO Oct.-Dec. 2009
- Second user run: AMO;SXR May-Sept. 2009

Injector Transverse Projected Emittance <0.5 μm

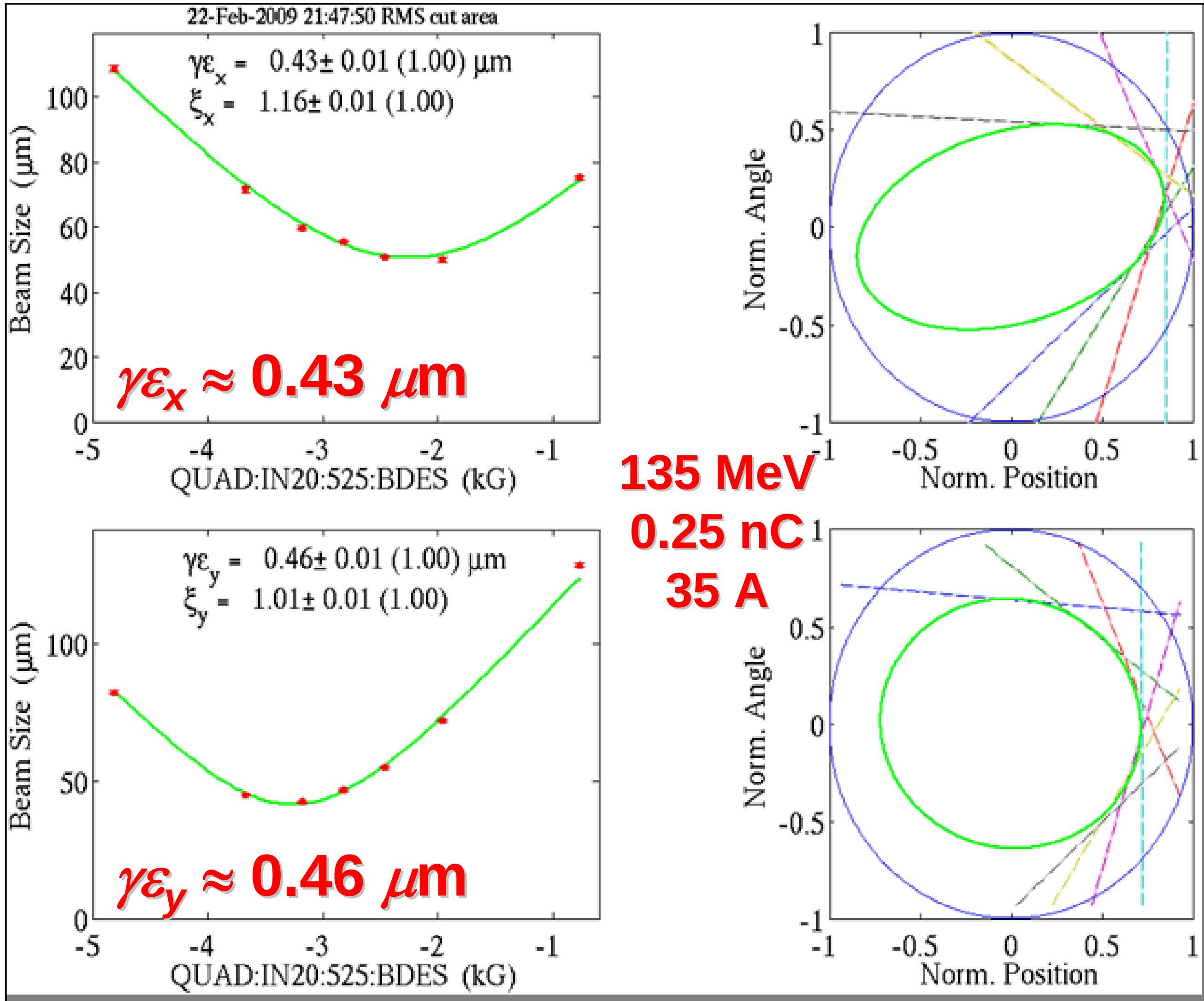
Exceptional beam quality from S-band Cu-cath. RF gun…





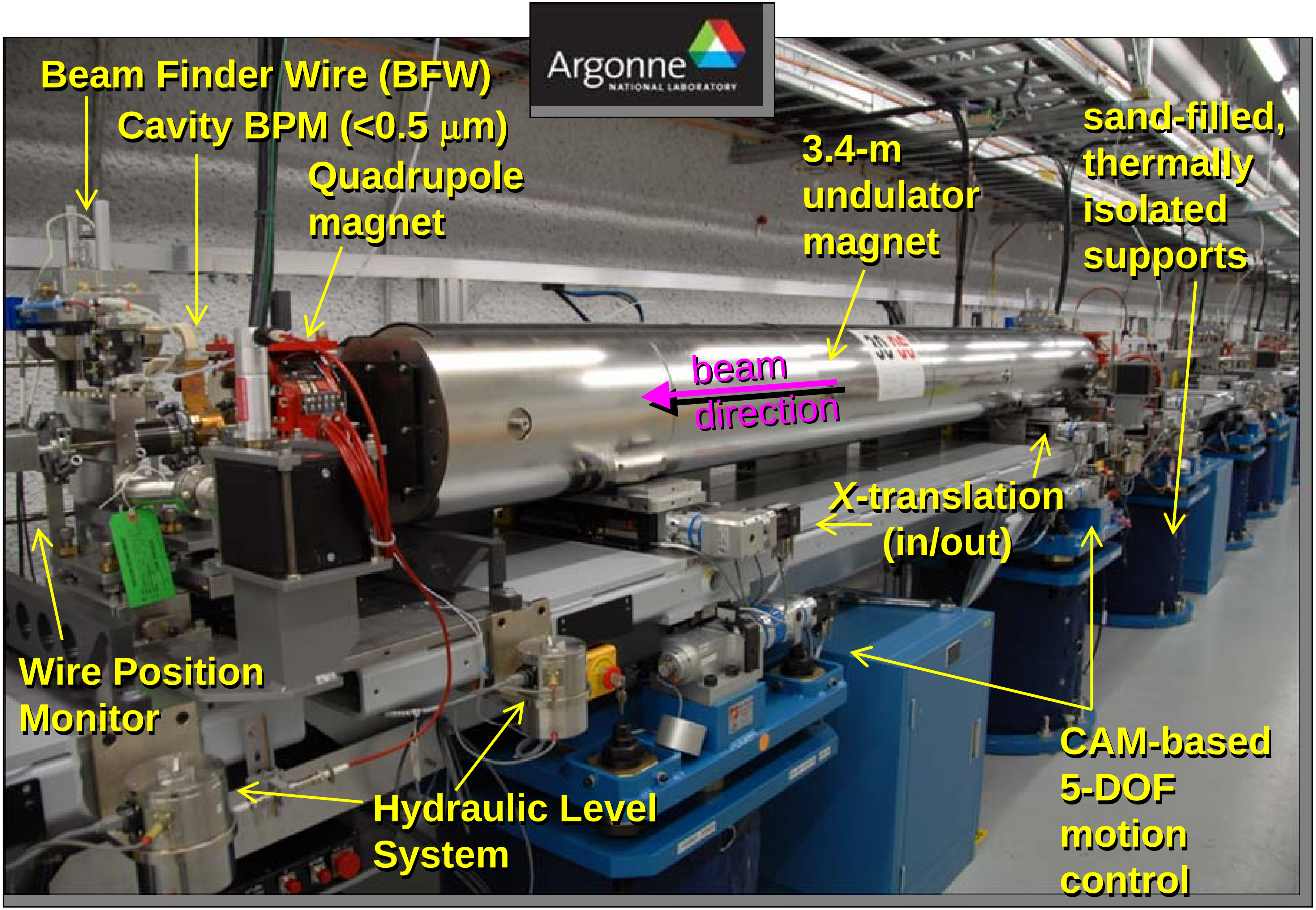
D. Dowell

Time-sliced emittance: 0.3-0.4 μm



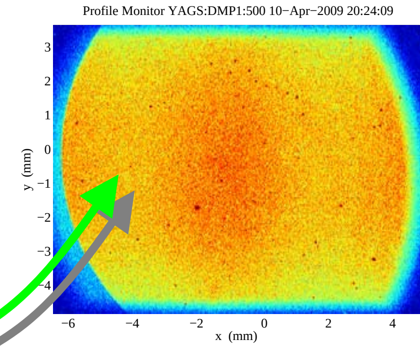
132 meters of FEL Undulator Installed

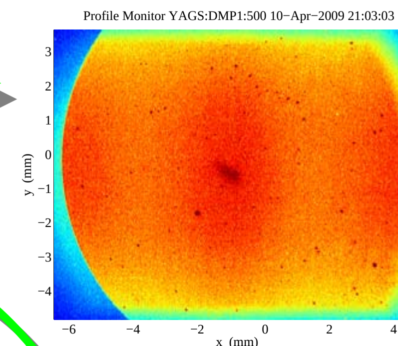
Undulator Girder with 5-DOF Motion Control + IN/OUT

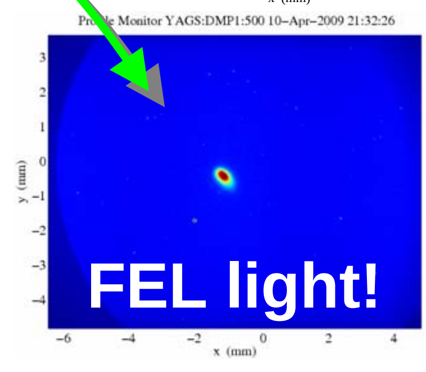


First Attempts at FEL Lasing – April 10, 2009…

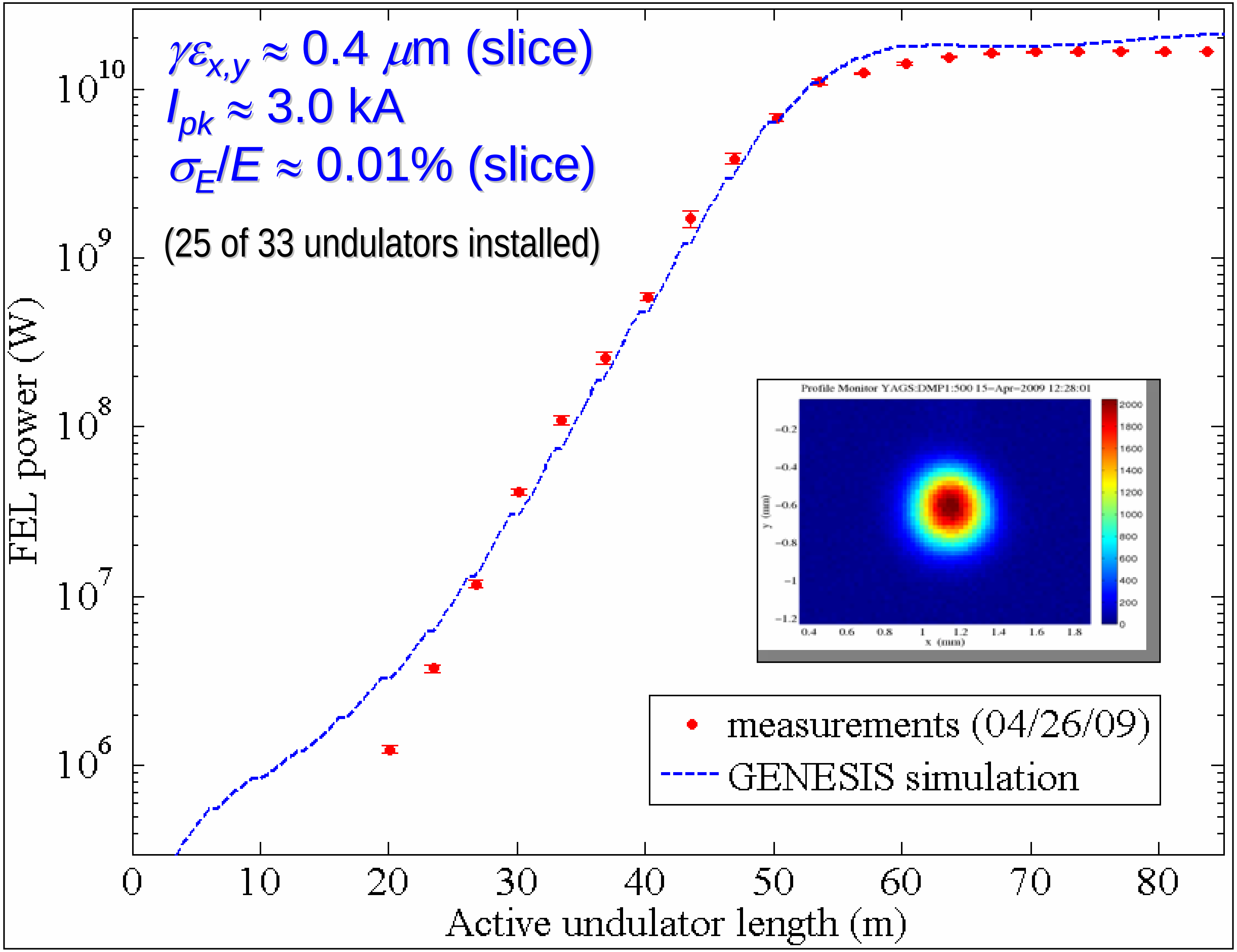
- 21 undulator magnets installed (slots 13-33)
- Reduce peak current to 500 A (normally 3000 A)
- Use beam screen installed 50 meters past undulator (FEE diagnostics not ready until late June)
- Insert one undulator magnet at a time. Correct orbit, check field integrals, & spontaneous radiation pattern
- After 10 undulators inserted, we begin to see a smaller spot at center of screen (still 500 A)
- So we insert 12 undulators and then slowly raise the peak current back to 3 kA…





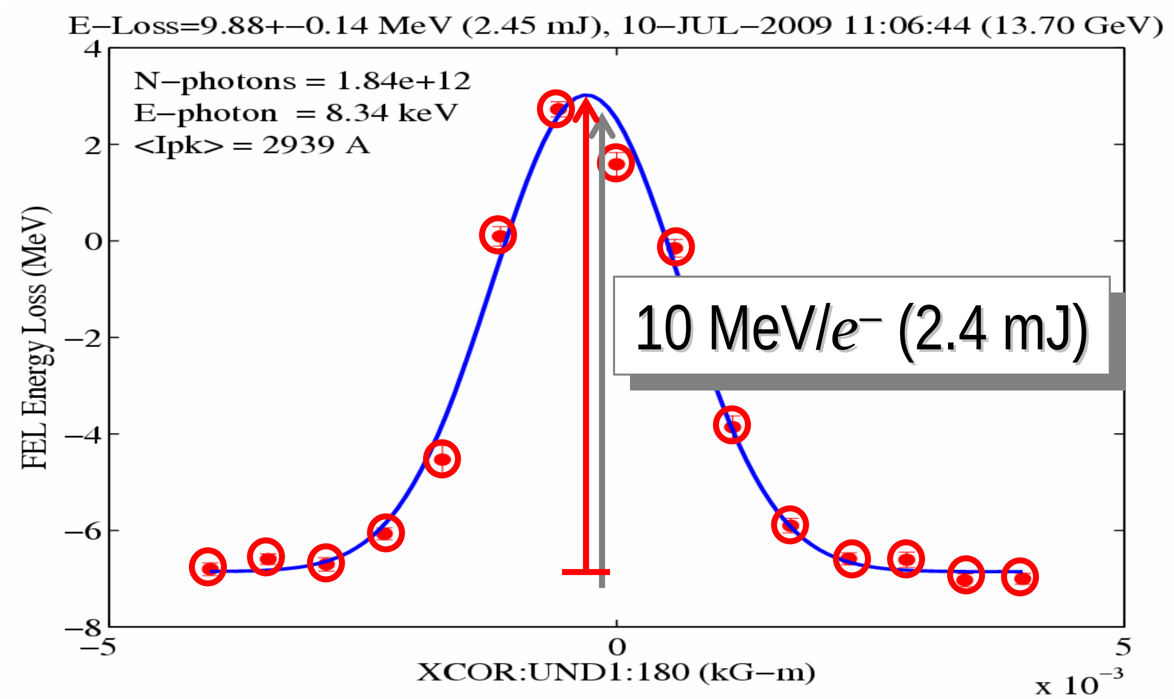


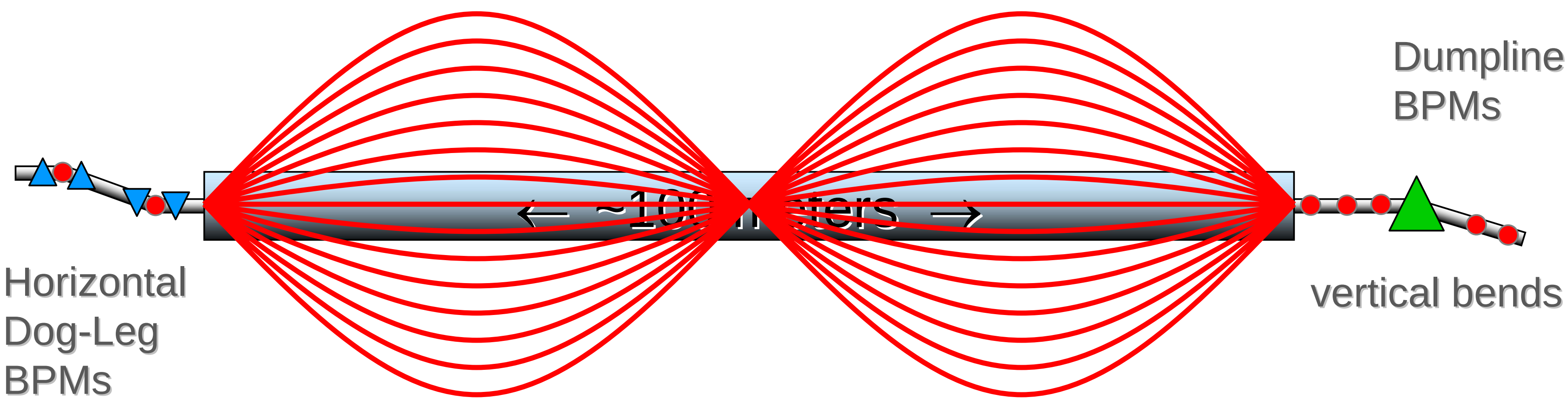
Undulator Gain Length Measurement at 1.5 Å: 3.3 m



FEL e^- Energy-Loss Shows >2 mJ per X-ray Pulse

1.5 Å

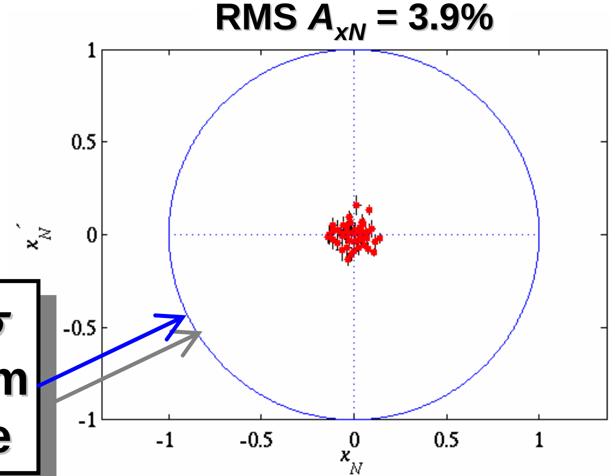




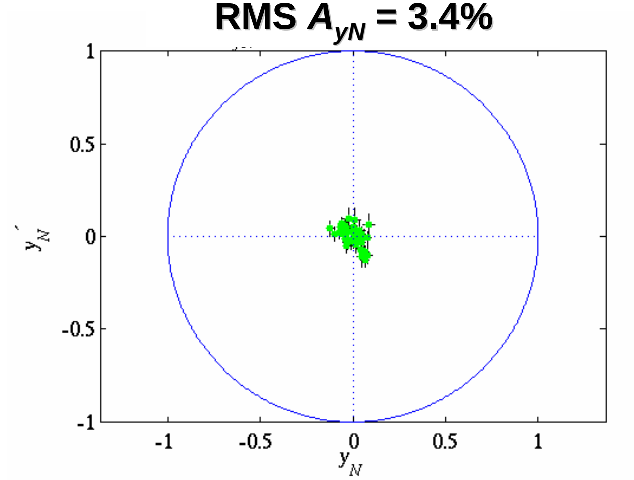
vary FEL power with oscillations & record e^- energy loss

Transverse Electron Jitter (position & angle)

Normalized phase space centroid jitter after BC1 (~4% of rms beam size)



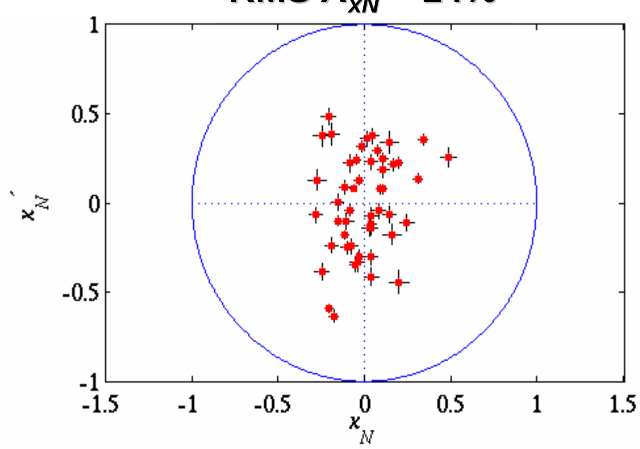
1-σ beam size

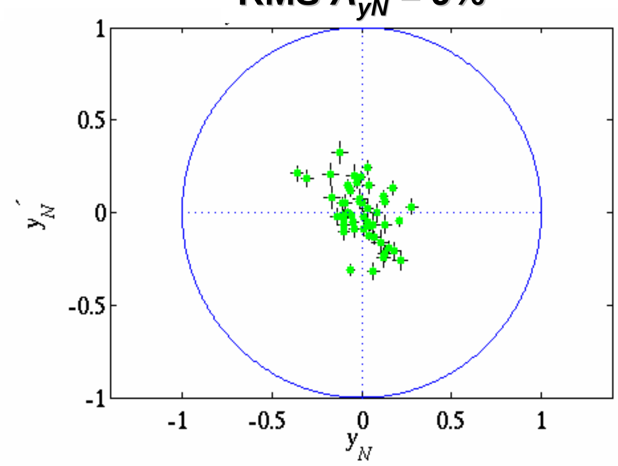


Stability is not so far off of our goals (~10%)

D. Ratner

… near end of linac (~12% of rms beam size, but sometimes larger)



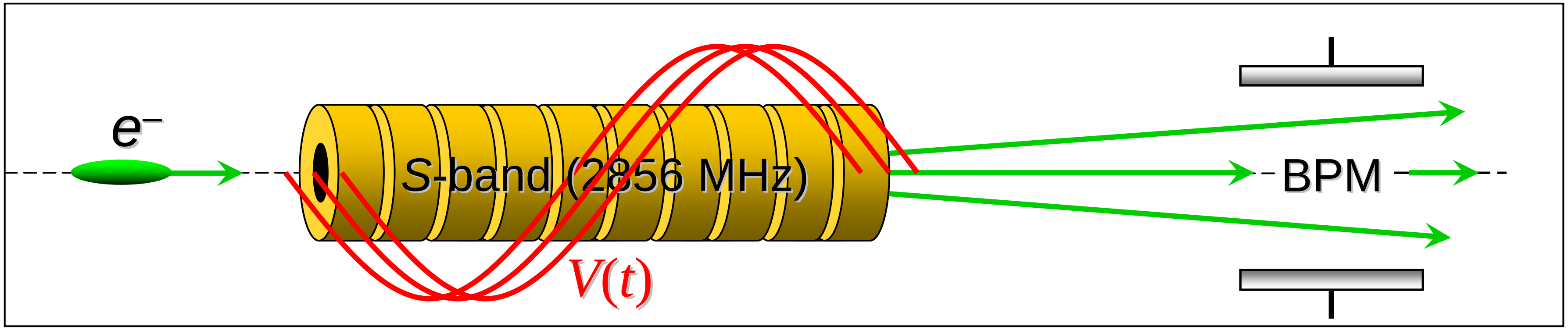


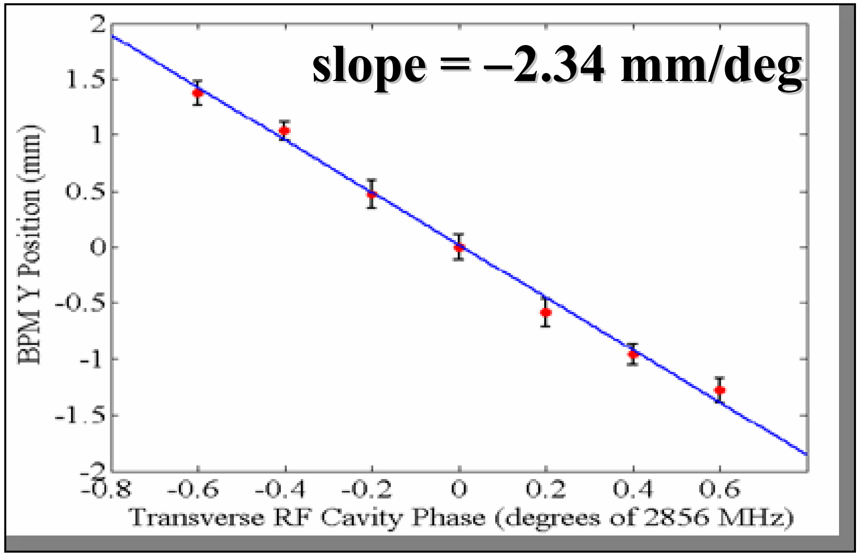
Thanks to **Controls** group for new BPM electronics!

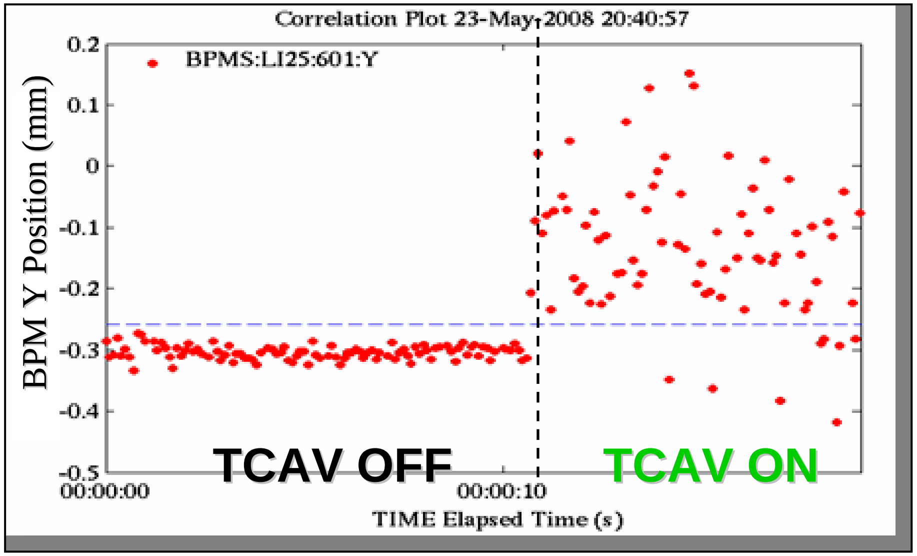
$\Delta E/E$ jitter ≈ 0.03%
$\Delta Q/Q$ jitter ≈ 1.5%

Q = 0.25 nC

Measuring Bunch Arrival Time Jitter with an RF Deflector







$\Delta t \approx \pm 0.6$ ps

9 μm rms

110 μm rms

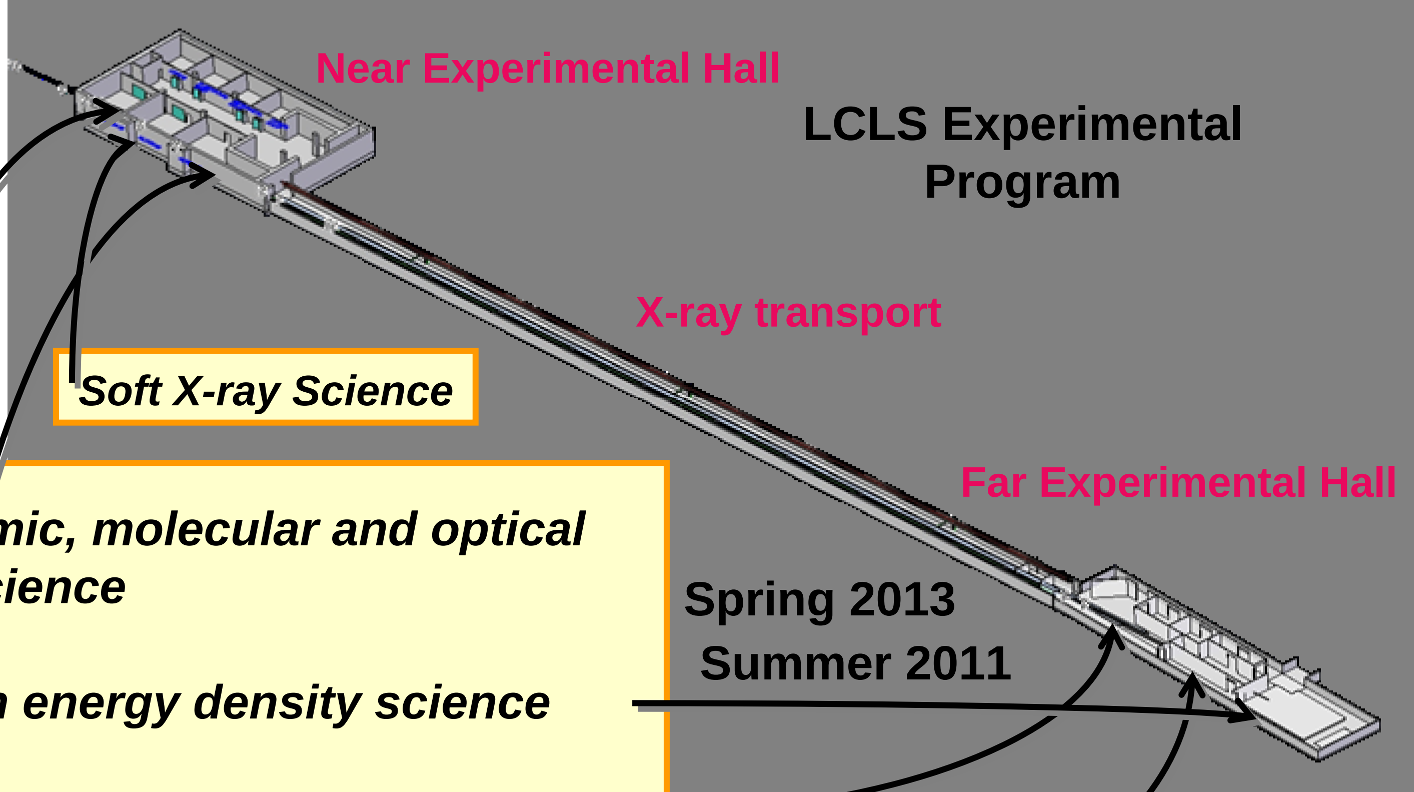
Timing Jitter = (110 μm)/(2.34 mm/deg) = 0.047 deg $\Rightarrow$ **46 fsec rms**

Photon beam characteristics

- FELs
  - Short pulse fs to as
  - ‘Full’ transverse coherence
  - High peak power
  - High field strengths
  - Unmatched peak brilliance

$$P_{sat} \cong \rho E_{GeV} I_{Amp} \quad \sim GWs$$

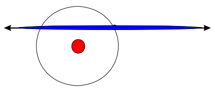
LCLS Experimental Program

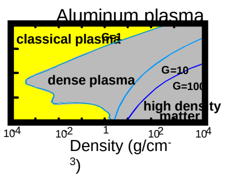


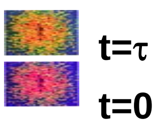
Summer 2010
Oct. 2009
Spring 2010

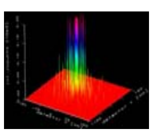
Soft X-ray Science

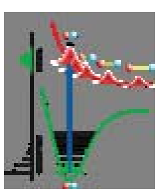
Spring 2013
Summer 2011
Sprin









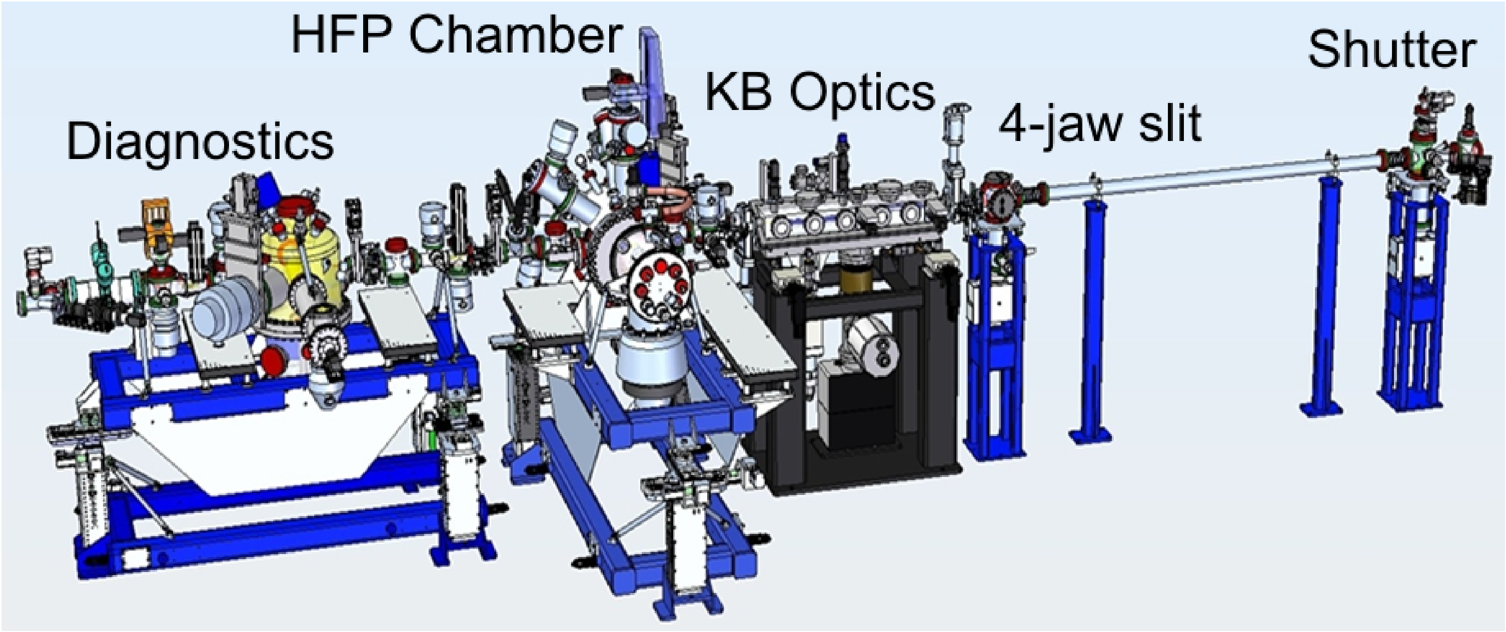


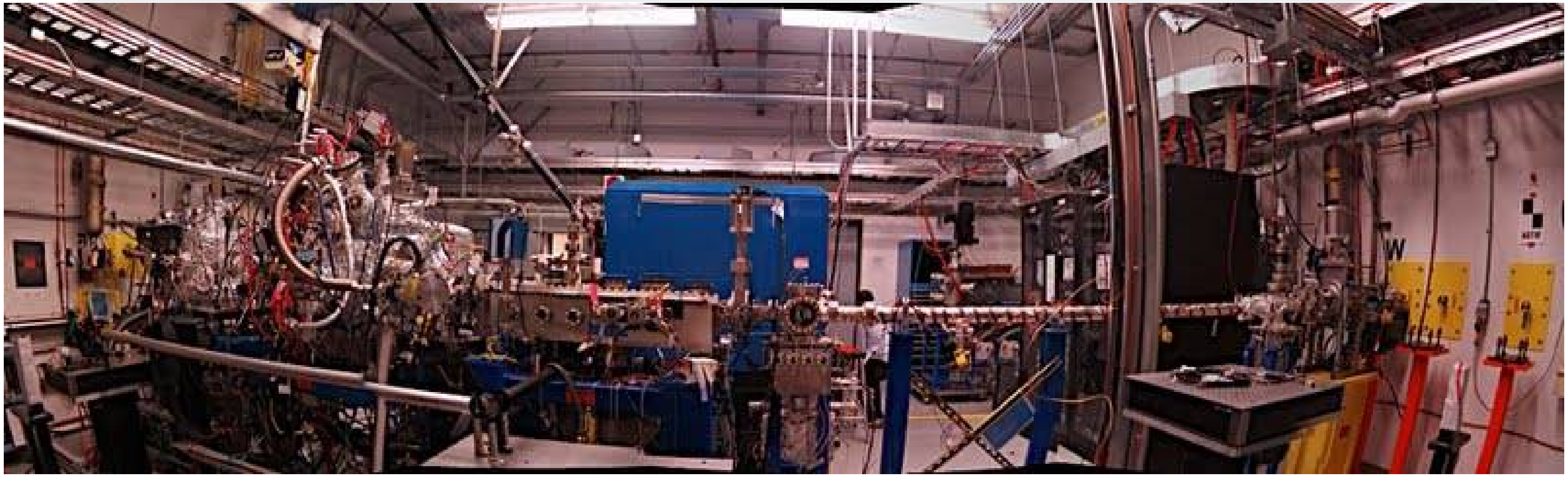
- ***Atomic, molecular and optical science***
- ***High energy density science***
- ***Coherent-scattering studies of nanoscale fluctuations***
- ***Nano-particle and single molecule (non-periodic) imaging***
- ***Diffraction studies of stimulated dynamics (pump-probe)***

Instrument Suite Complete 2013

John Bozek
William Schlotter
David Fritz
Sébastien Boutet
Aymeric Robert
Hae Ja Lee

Atomic Molecular Optical (AMO) Science Instrument





The AMO instrument is 4 distinct vacuum chambers with different functions

CH_4 clusters to explore the physics relevant to protein imaging

H. Thomas
K. Hoffmann
N. Kandadai
A. Helal
B. Erk
J. Keto
T. Ditmire

Uppsala University, Uppsala, Sweden
B. Iwan
N. Timneanu
J. Andreasson
M. Seibert
J. Hajdu (also Stanford)

Institut für Optik und Atomare Physik, Technische Universität Berlin
S. Schorb
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D. Rupp
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G. Doumy
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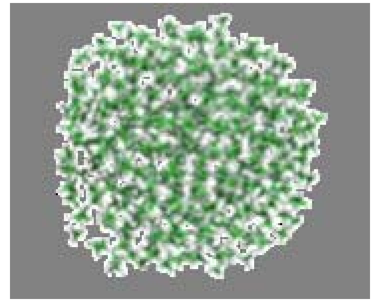
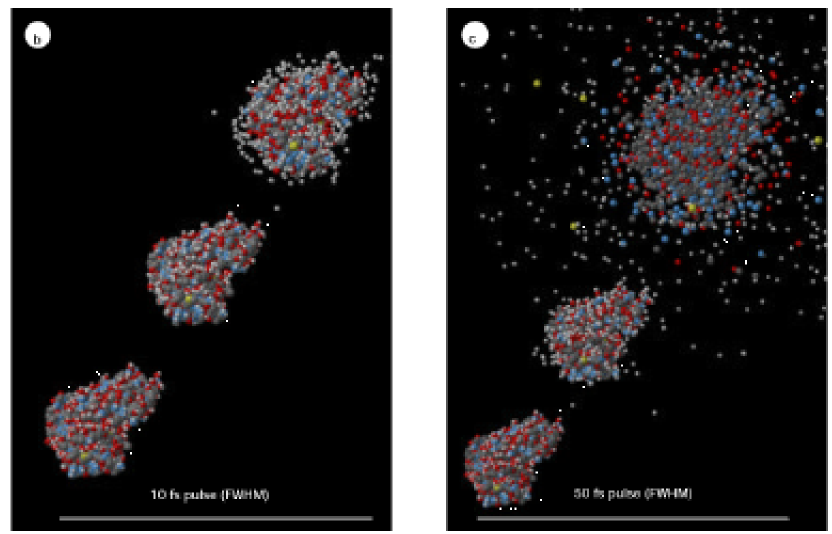
LCLS, Stanford Linear Accelerator Center
C. Bostedt
J. Bozek

Department of Physics, Western Michigan University
M. Hoener
B. Murphy (formerly at UT)
N. Berrah



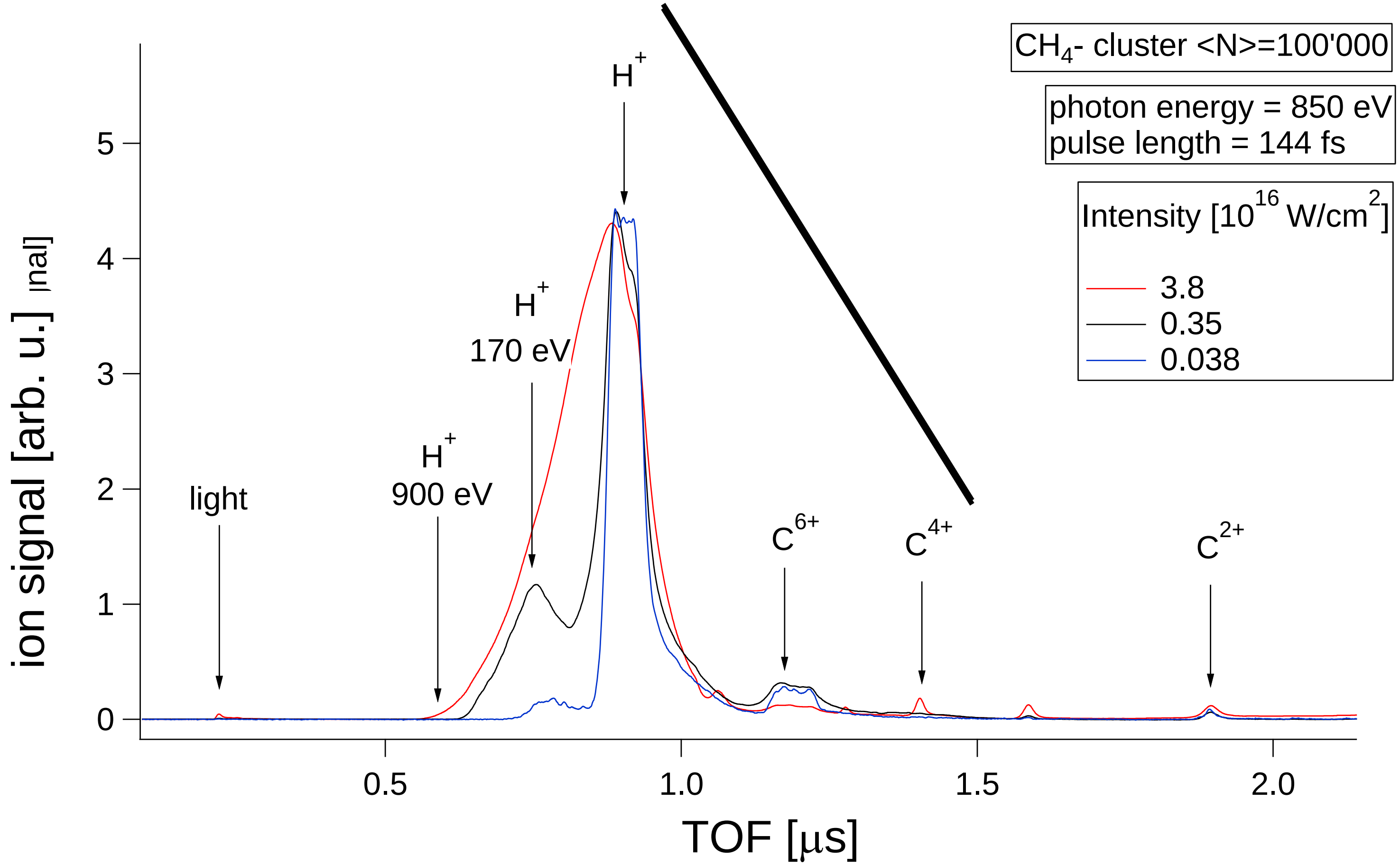
Methane cluster



Well known simulation of exploding protein molecule in an XFEL pulse

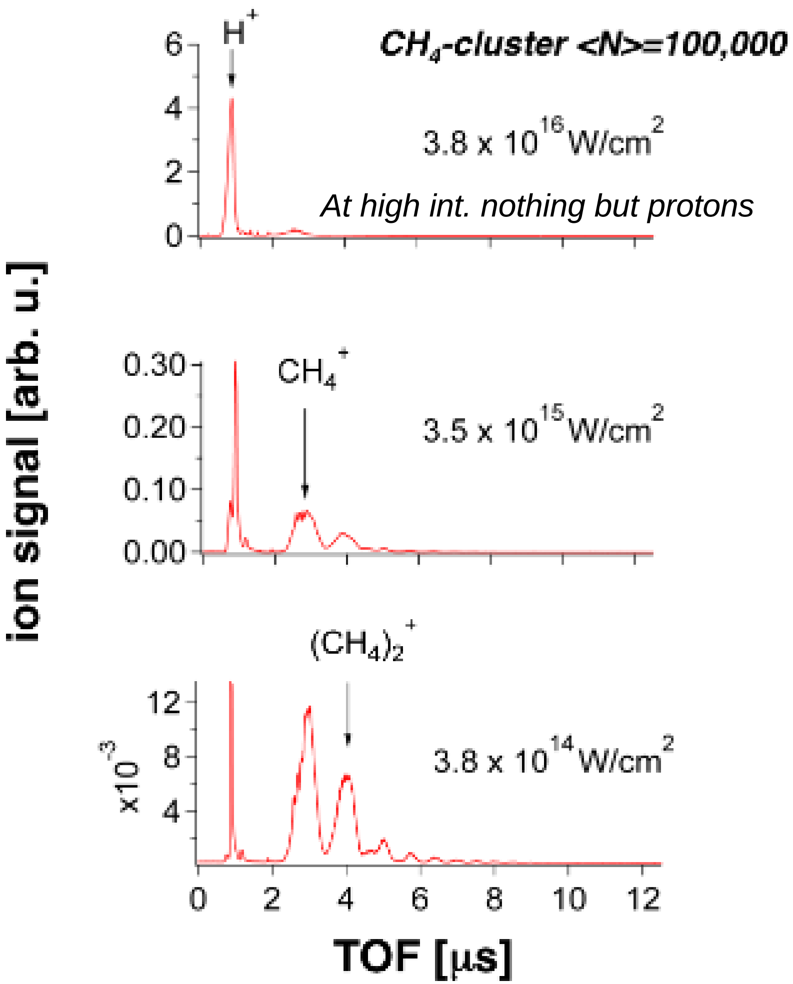
Irradiation of methane clusters yielded surprising results

Exploding methane clusters of 100,000 molecules with hν = 850 eV: strong proton peak appears but carbon ions are mysteriously absent

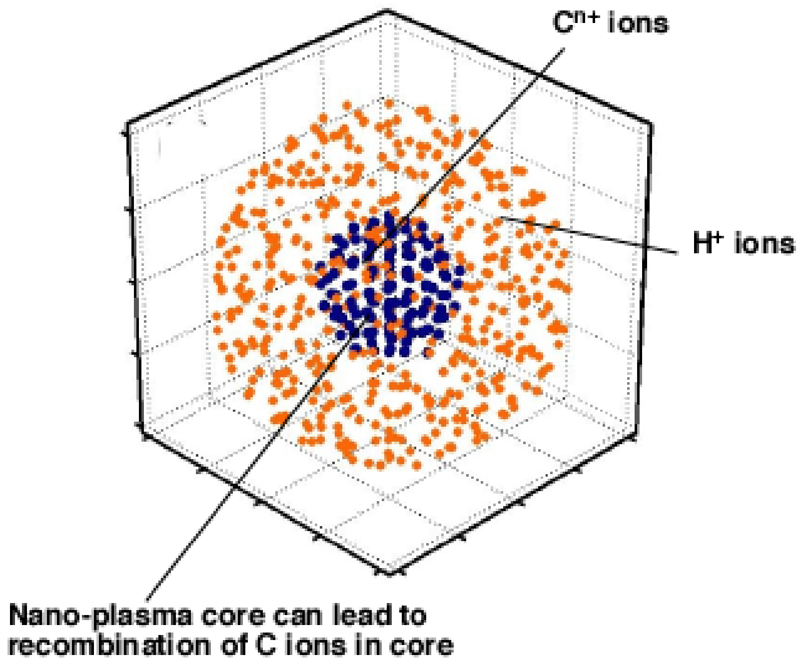


Possible explanation: recombination of the carbon ions in a

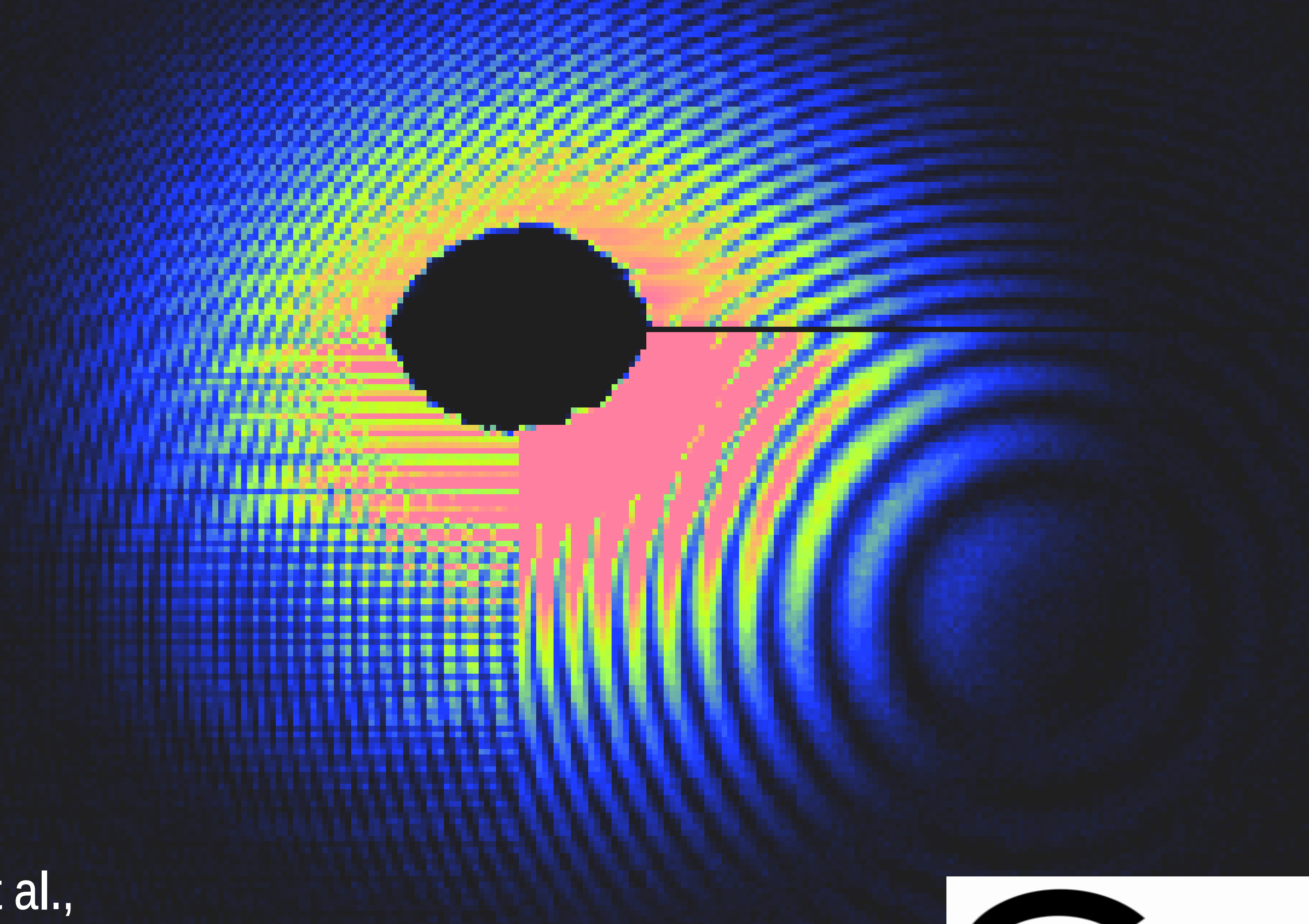
Ion TOF traces from Methane clusters vs intensity (850 eV photons)



Particle simulation of an exploding Methane cluster



Dynamics in Clusters



LCLS / SLAC
Christoph Bostedt (PI), John Bozek, et al.

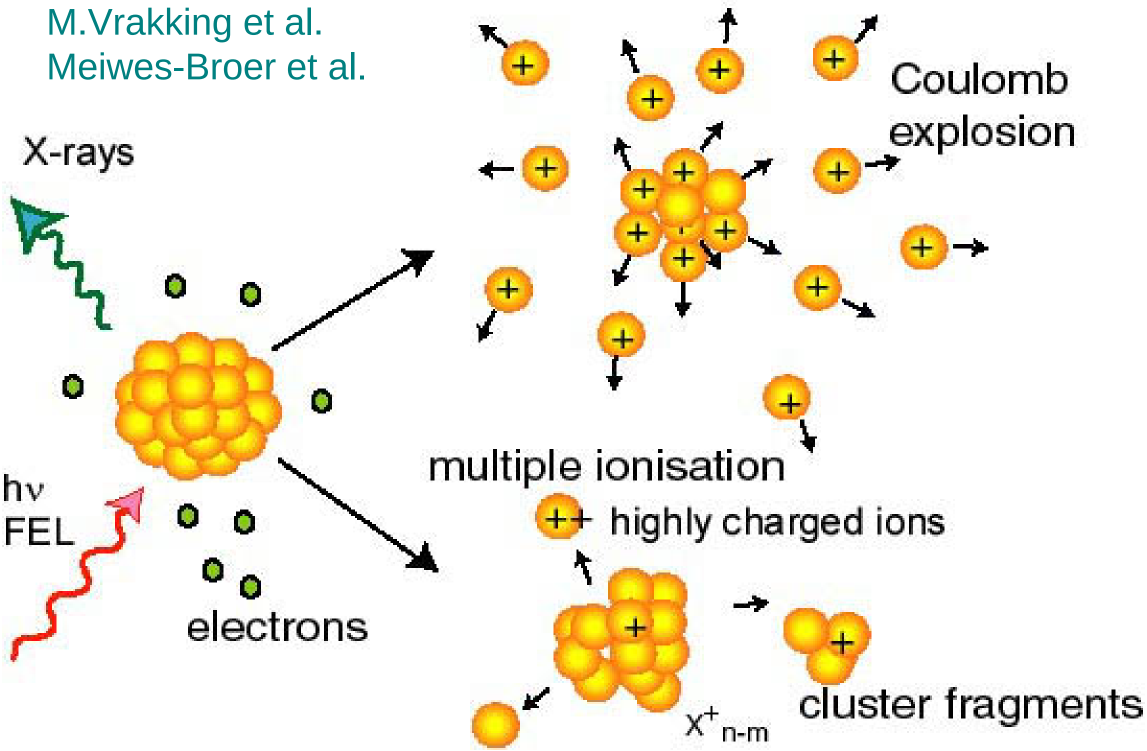
TU-Berlin
Marcus Adolph,
Daniela Rupp,
Sebastian Schorb,
Tais Gorkover,
Thomas Möller

Max-Planck ASG
Sascha Epp,
Lutz Foucar,
Robert Hartmann,
Daniel Rolles,
Artem Rudenko, et al.,

Project leaders: I. Schlichting, L. Strüder, J. Ullrich

Non-linear cluster ionization

Infrared
T. Ditmire et al.
M.Vrakking et al.
Meiwes-Broer et al.

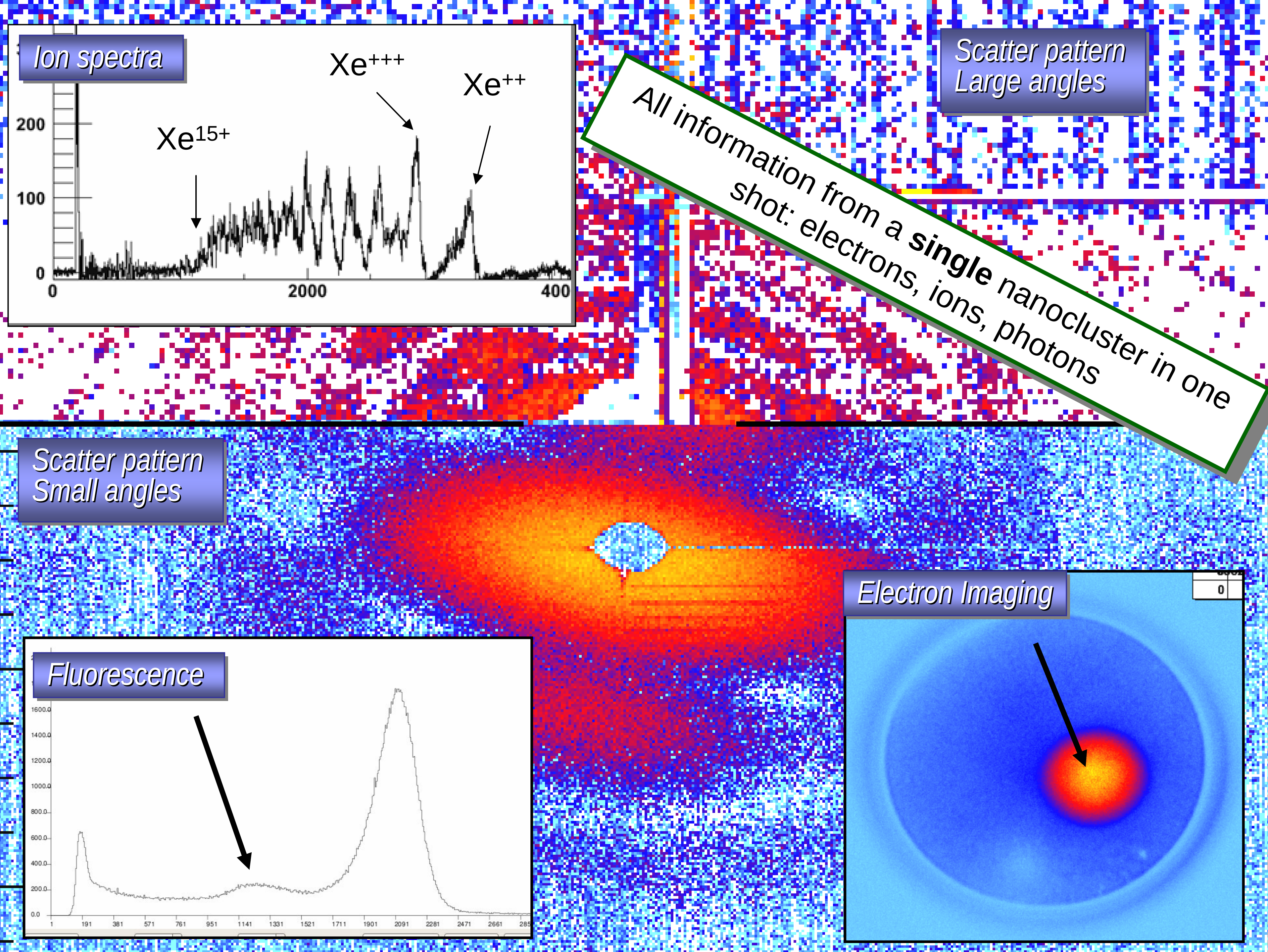


Clusters as "nanolab"
bulk density
no energy dissipation
intr- vs. interatomc effects

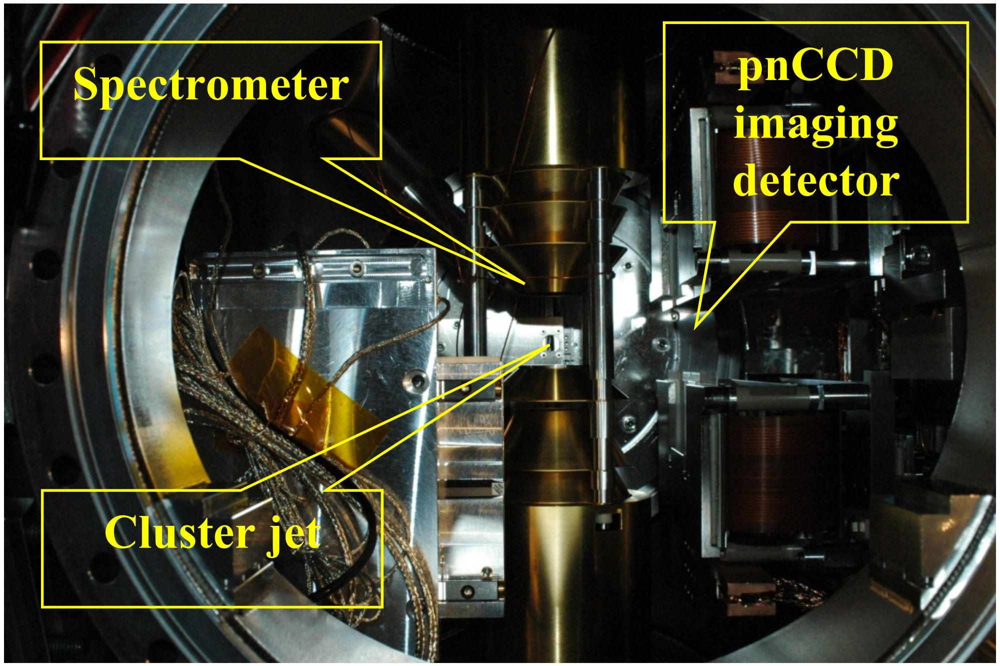
Driving questions:
mechanism of absorption and ionization
are non-linear / multi-photo processes observed?
time scale of electron emission and of ion motion

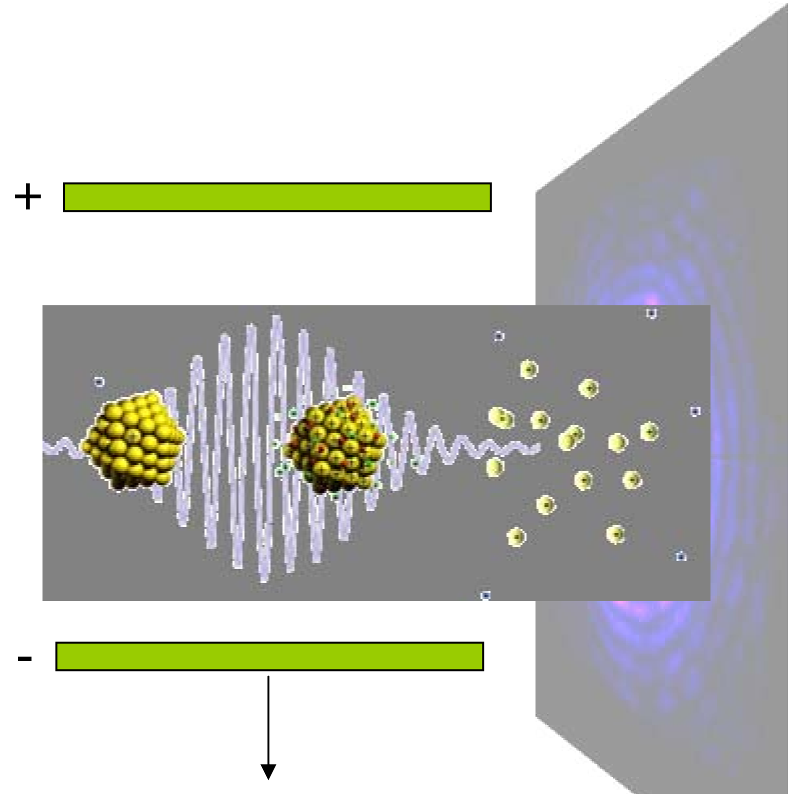
λ= 100nm (2002) 13 nm (2005) 1 nm (now)

Cluster physics yields insight into the fundamental questions on light – matter interaction


Ion spectra
Xe+++
Xe++
Xe15+
200
100
0
0
2000
400
Scatter pattern
Large angles
All information from a single nanocluster in one shot: electrons, ions, photons
Scatter pattern
Small angles
Electron Imaging
0
Fluorescence
1600.0
1400.0
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
1
191
381
571
761
951
1141
1331
1521
1711
1901
2091
2281
2471
2661

CAMP-Chamber





simultaneous detection of ions, electrons and scattered light

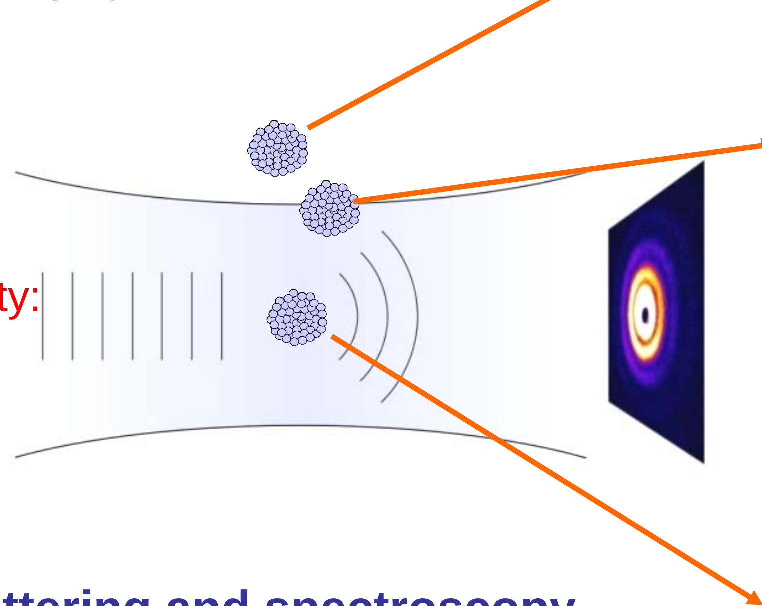
L. Strüder et al.
Nucl. Instr. Meth. A 610, 483 (2010)

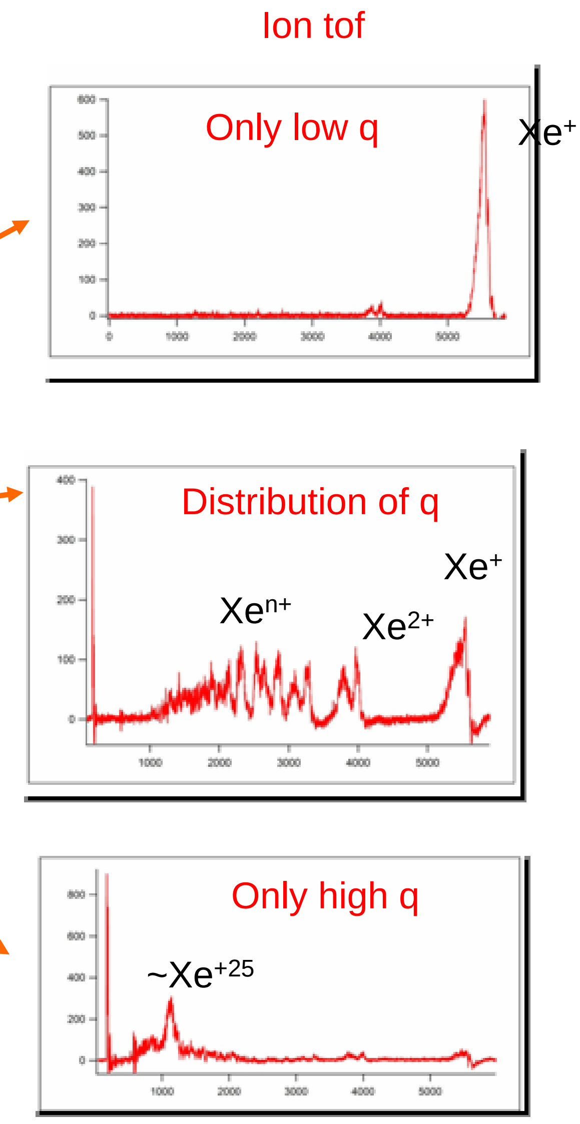
Single shot recording

Singe cluster ionisation vs scattering

- Correlation between scattering intensity and ionization dynamics
- Scattering yields information about cluster size and position in focus; electron dynamics
- Single shot – single particle information about explosion (ion) dynamics

From scattering intensity:
"position in focus"



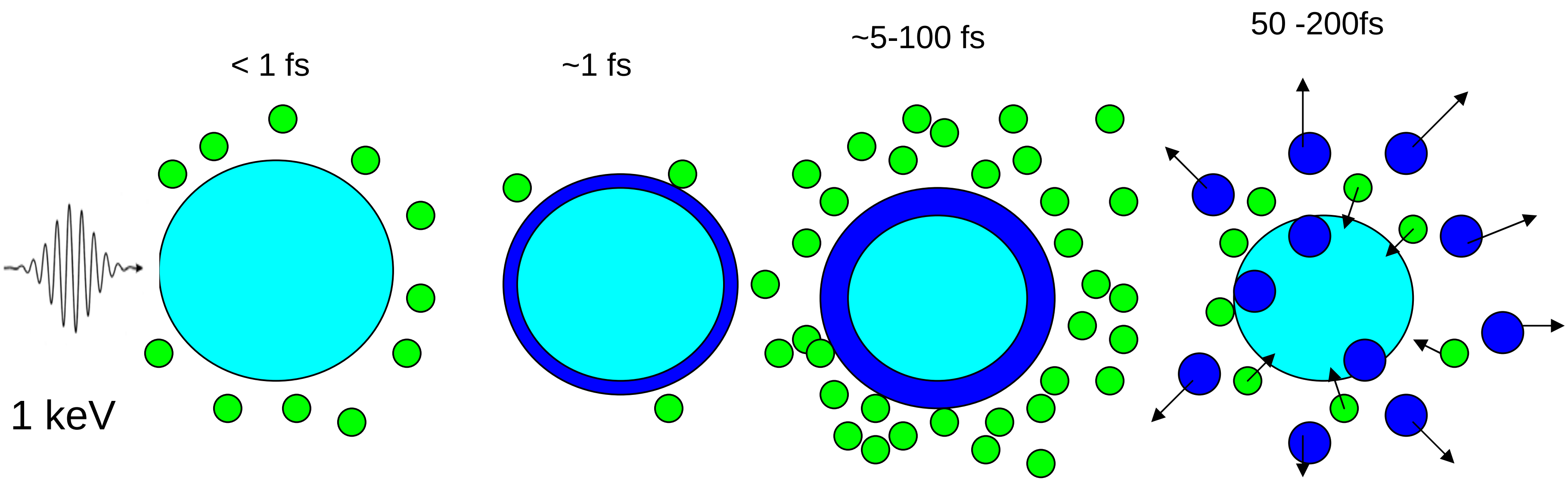


Combination of scattering and spectroscopy yields unique insight into ionization dynamics, i.e., light – matter interaction with a single nanoparticle

Conclusions on cluster ionization so far

Intense X-ray ionisation and expansion of large clusters

20 nm radius, 800.000 Xe atoms

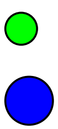


30000 electrons removed

surface layer positivly charged

many electrons removed by collisional autoionisation

explosion of surface monolayer
free ions charge up to Xe^{25+}
electrons move to cluster center

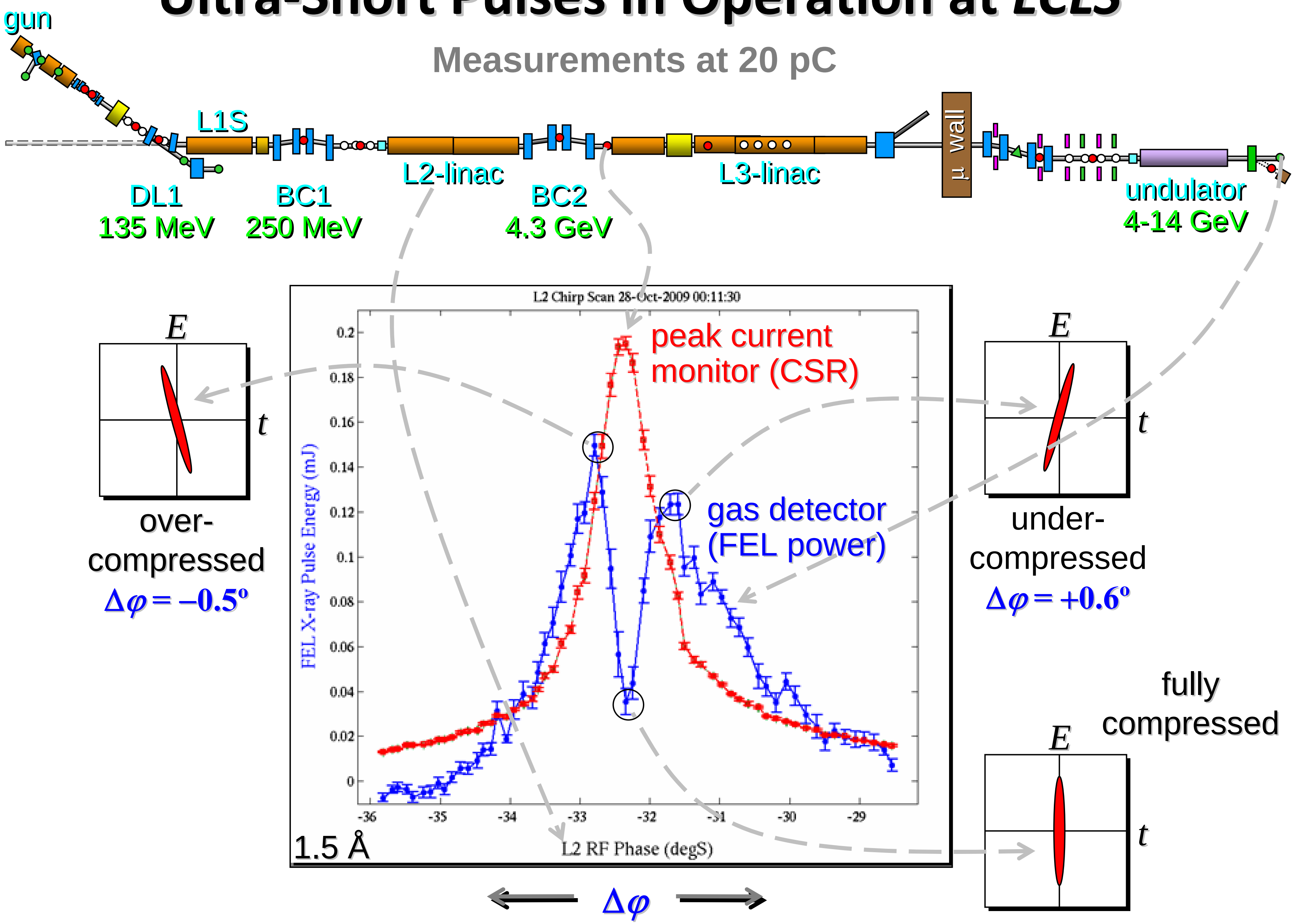


What is the fate of the hot cluster core?
90 % of the all atoms !

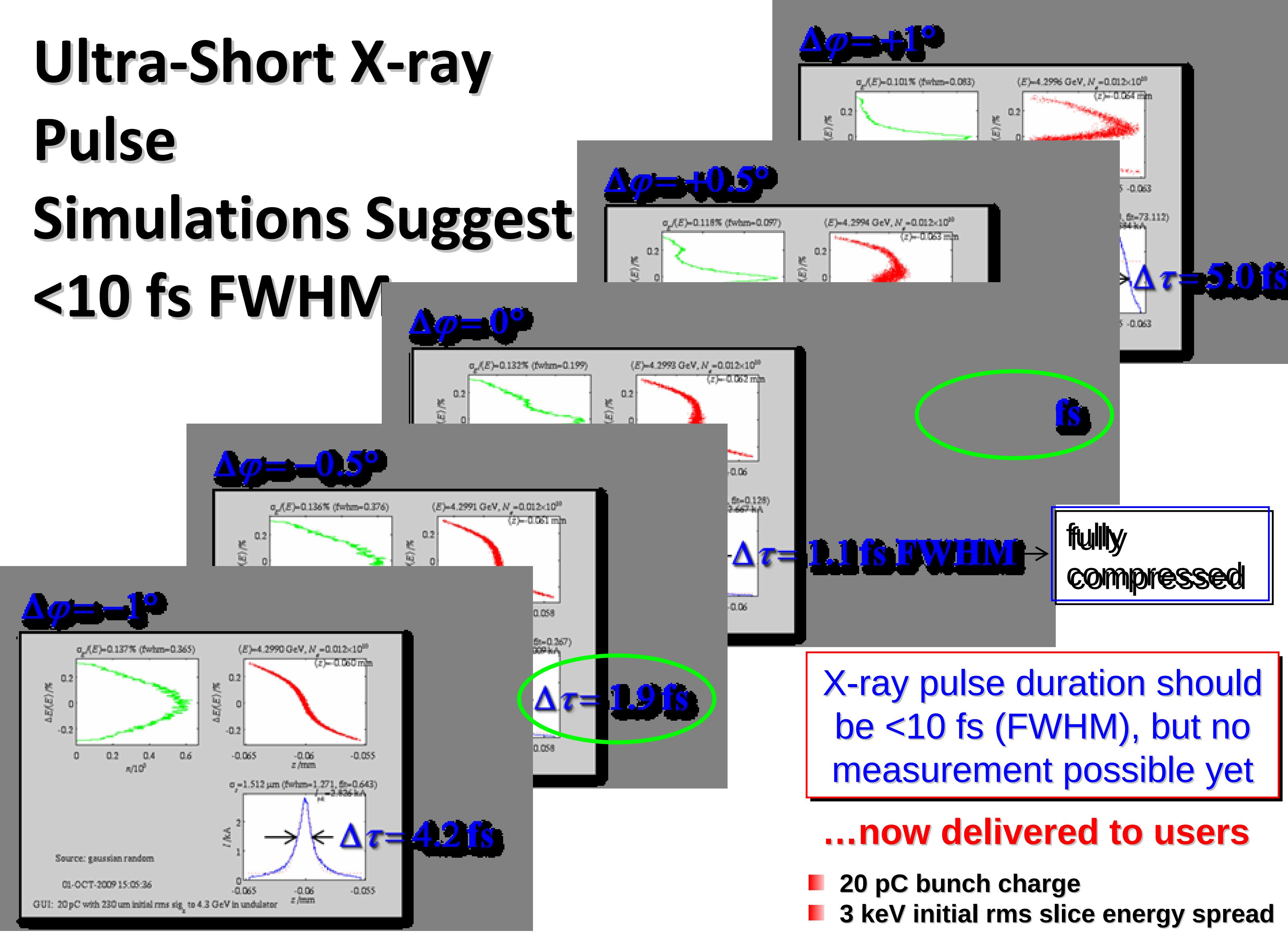
Deviates from current understanding of short-wavelength laser – matter interaction
Challenge for theory

Ultra-Short Pulses in Operation at *LCLS*

Measurements at 20 pC



Ultra-Short X-ray Pulse Simulations Suggest <10 fs FWHM



X-ray pulse duration should be <10 fs (FWHM), but no measurement possible yet

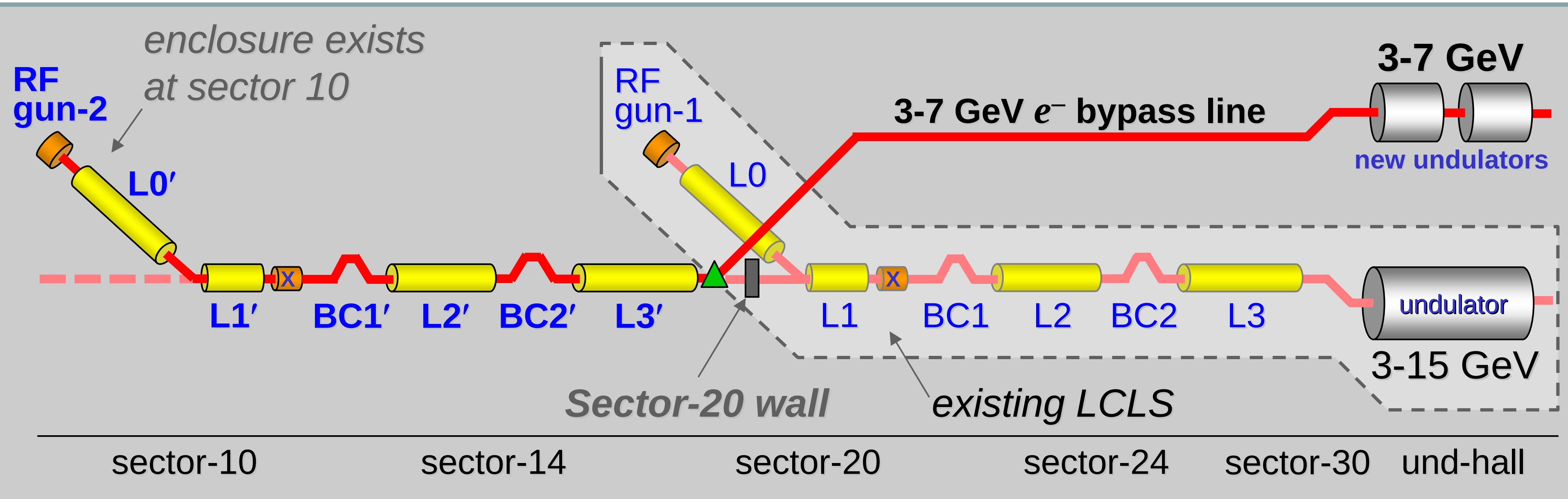
…now delivered to users

- 20 pC bunch charge
- 3 keV initial rms slice energy spread
- 0.23-mm initial rms bunch length

LCLS-II Requirements

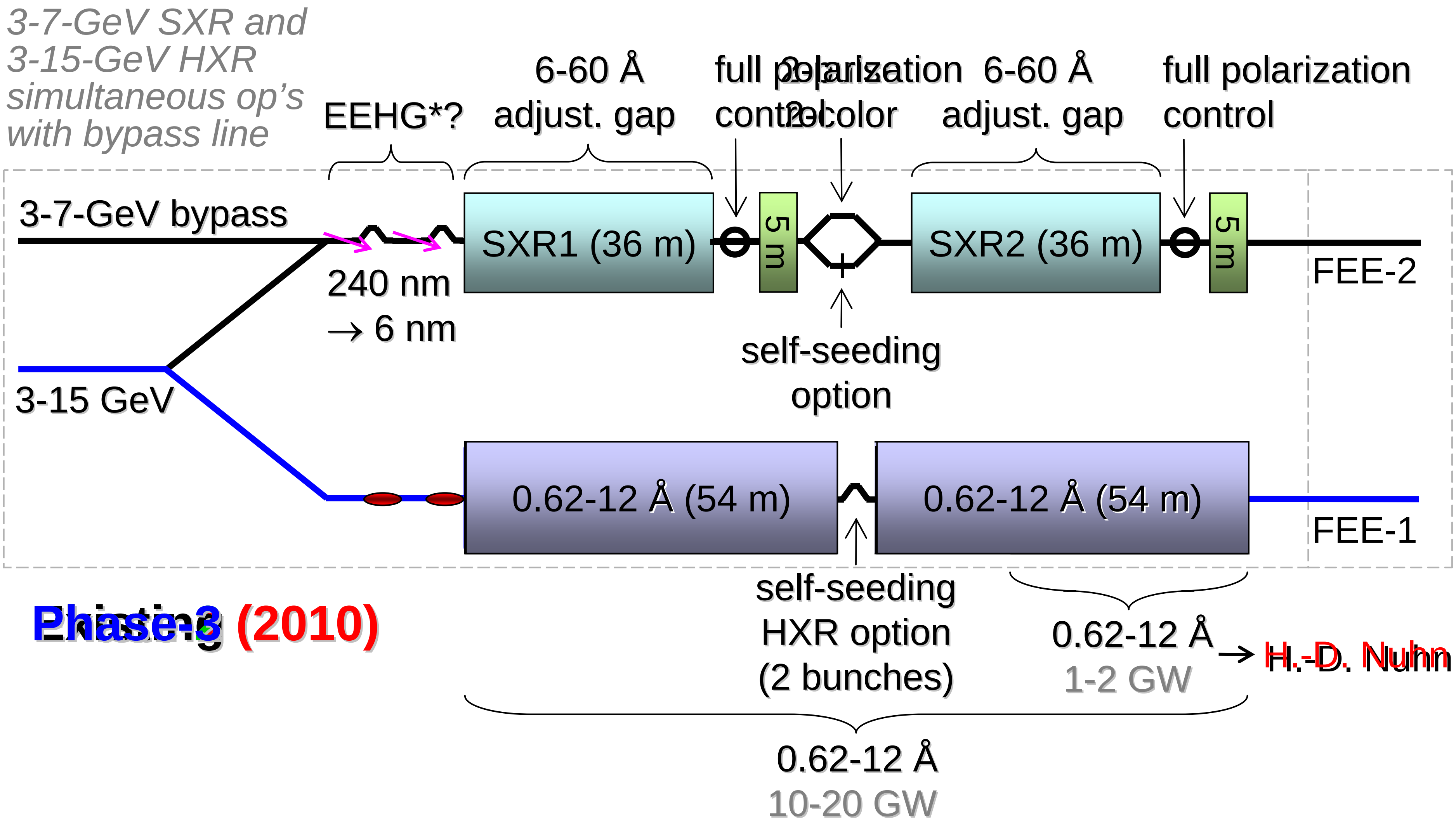
- Build new soft x-ray line from 200 to 2000+ eV
- Extend hard x-rays out to ~20 keV
- Include seeding options for narrow BW
- Incorporate 2-pulse, 2-color schemes
- Provide polarization control
- Take advantage of 3-km **SLAC** linac to provide separate sources for independent FELs
- Explore multi-bunch operations
- Find ways to increase capacity (user access)!

LCLS-II: New Injector & Accelerator



- Use 2nd km of SLAC linac (sector-10 to 20) – greater flexibility
- 3-7 GeV energy (no SLED) allows *possible* 360-Hz beam rate
- 2nd injector, linac, & bypass line allows 2+ independent FELs serving 2 experiments simultaneously with flexible parameters
- Combining beams allows x-ray pump/probe with decoupled wavelengths, pulse width, energy, and timing
- Preserves possibility of 22-30 GeV (and still 1 more km left!)

Phased Enhancement Plan for *LCLS-II* FELs

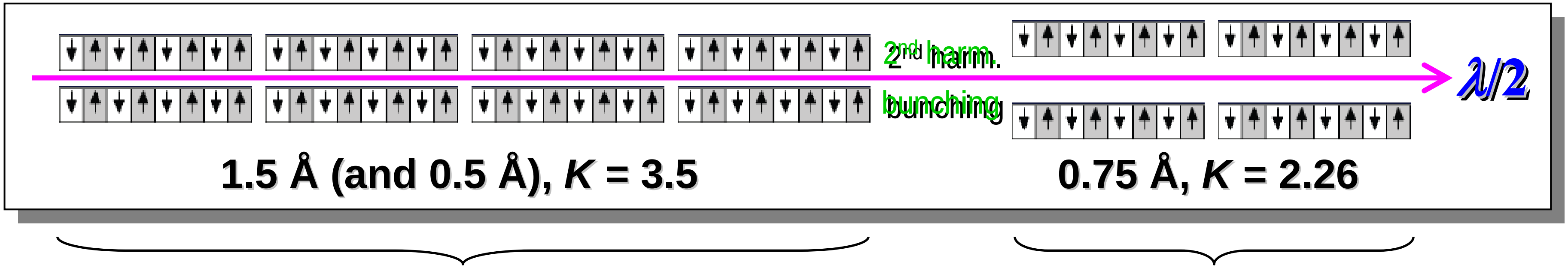


No civil construction. Uses existing beam energy and quailty.

* G. Stupakov, Phys. Rev. Lett. **102**, 074801 (2009)

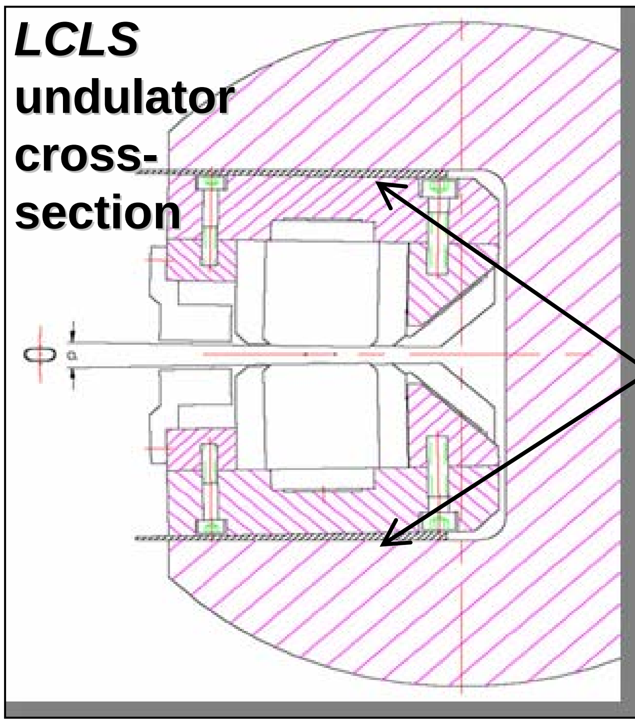
Fast Path to Producing FEL 2nd Harmonic

16 keV = 0.75 Å (up to 20 keV at 15 GeV)

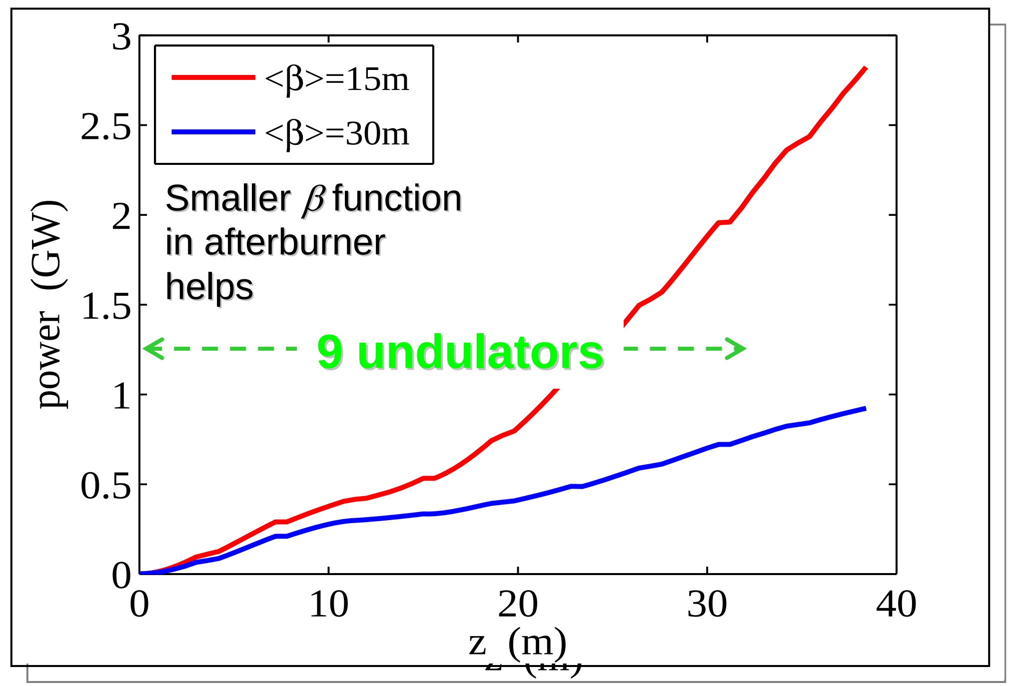


existing *LCLS* undulator

2nd harmonic after-burner



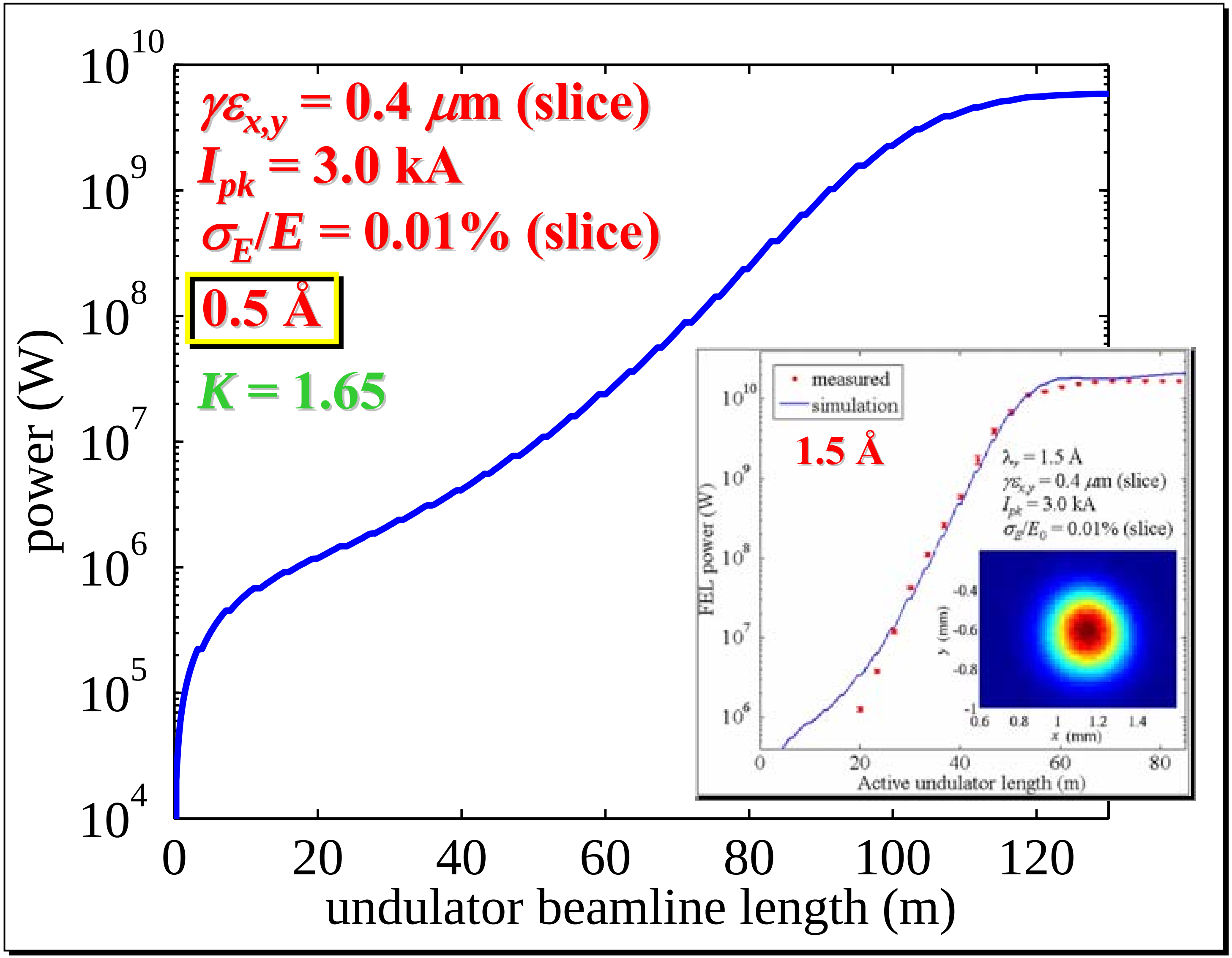
Replace shims for last 8-10 undulators (of 33)



Z. Huang, S. Reiche

LCLS Beam Supports 25-keV (0.5 Å) FEL at 14 GeV

increase undulator gap further



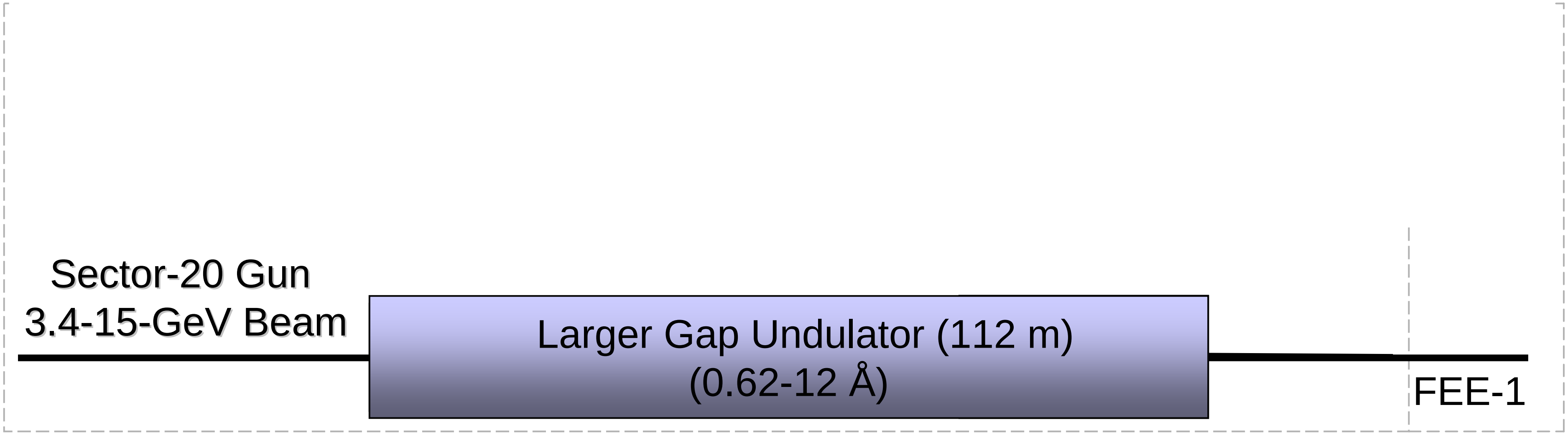
Same beam quality and energy as now

The next 6 slides will graphically outline 6 *LCLS-II* operating modes…

(thanks to H.-D. Nuhn)

1. Hard X-ray SASE
2. Soft X-ray SASE
3. Soft X-ray Self Seeding
4. Two-pulse, two-color soft x-rays (one e^{-} bunch)
5. Two-pulse, two-color soft x-rays (two e^{-} bunches)
6. Seeded soft x-ray FEL ('Echo')
7. Self Seeding of hard x-rays (two e^{-} bunches)

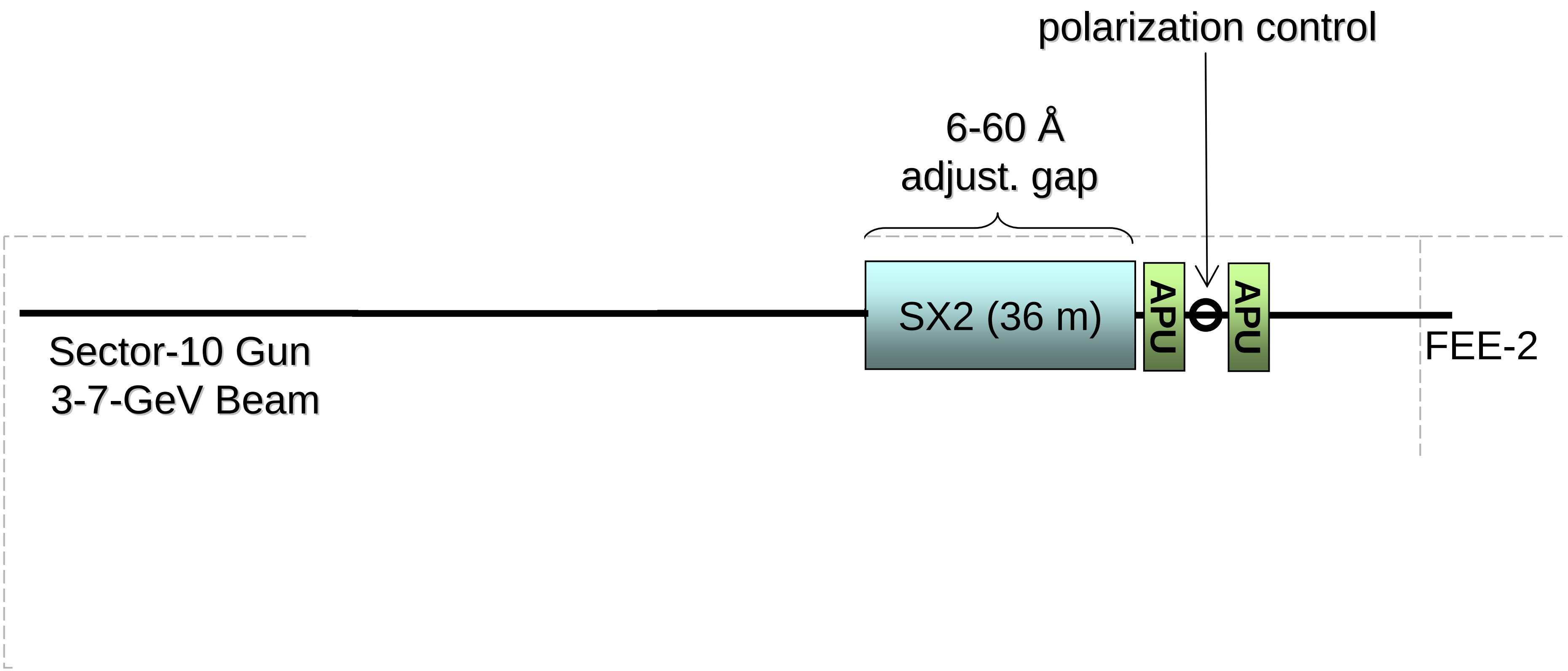
1. *LCLS-II:* Hard X-Ray SASE



- 2nd harmonic after-burner in 2010 (0.62-12 Å, 1-2 GW)
- Open all 33 undulator gaps for *LCLS-II* (0.62-12 Å, 10-20 GW)
- Or (?) replace all with variable gap (0.62-25 Å, >20 GW)

Z. Huang, S. Reiche, FEL'04, 201, (2004).

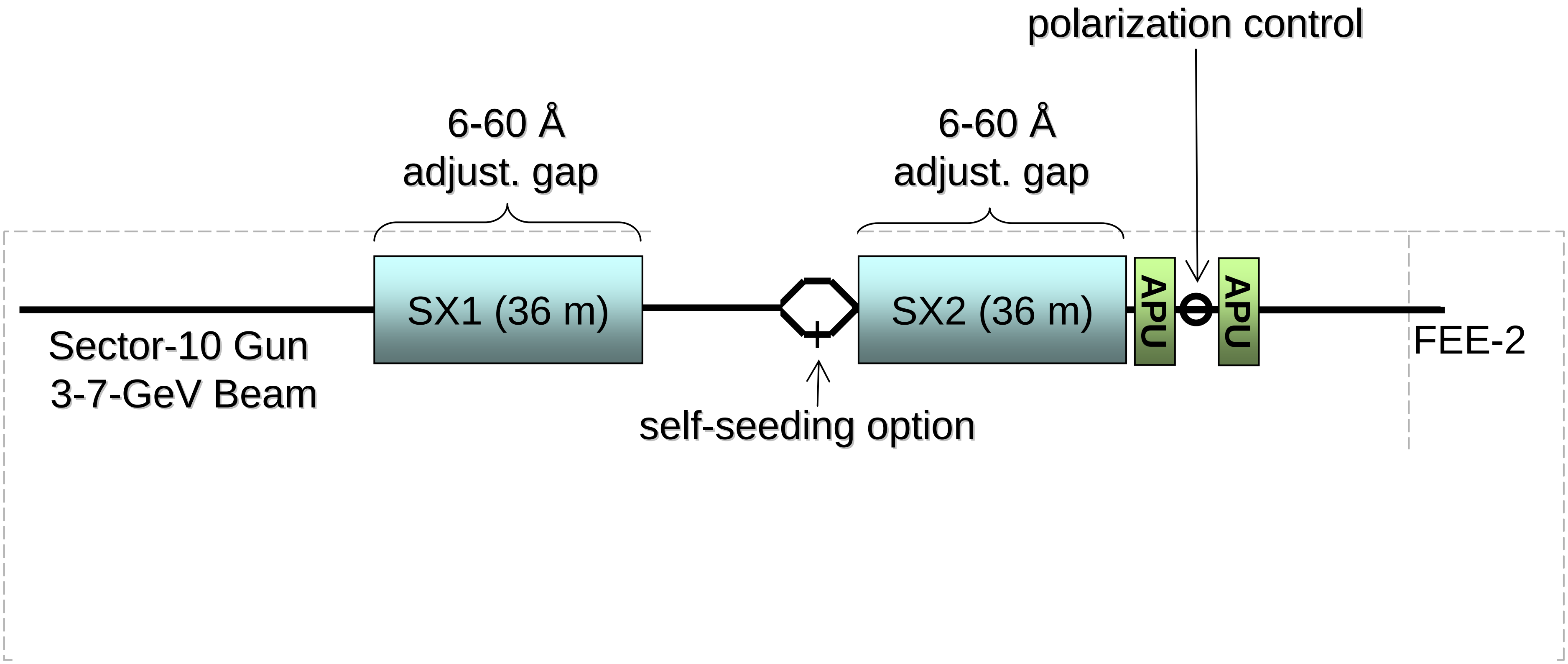
2. *LCLS-II:* SX2 (or SX1) SASE



- Simple use of new soft x-ray line: SASE from SX2 (or SX1)
- Full polarization control (fast at 80% or slow at ~100%)

Y. Ding, Z. Huang, Phys. Rev. ST-AB **11**, 030702

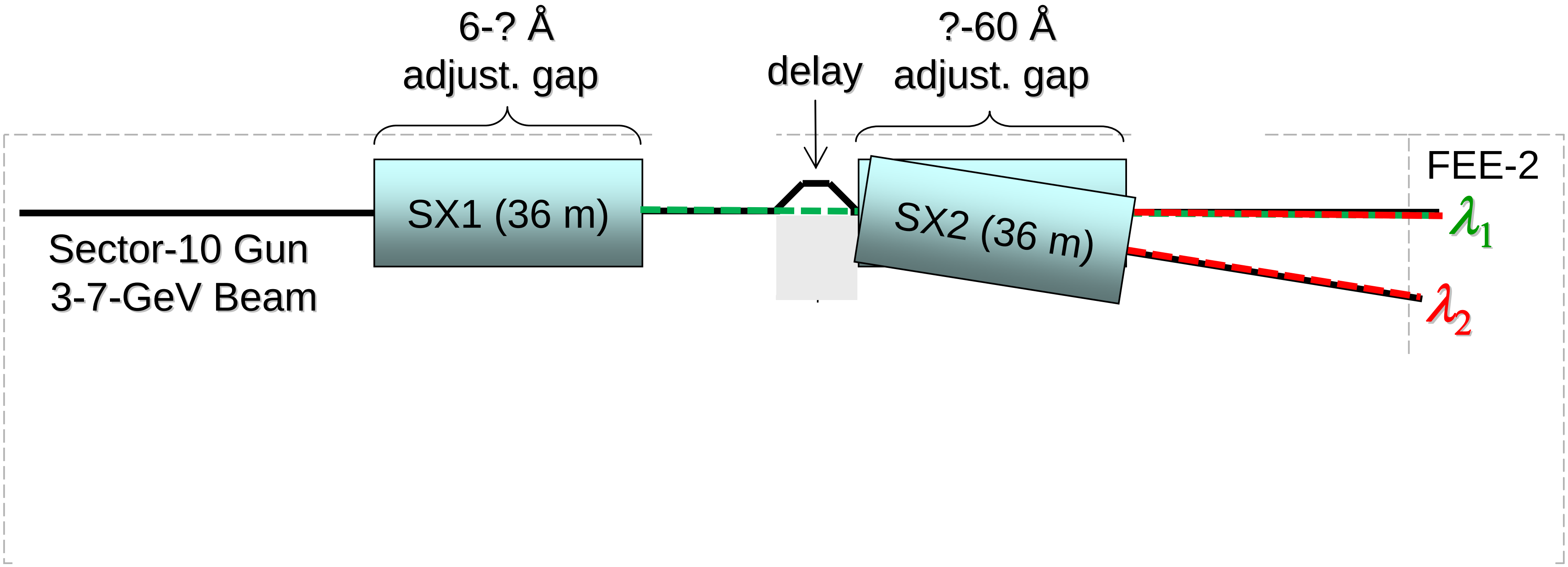
3. *LCLS-II:* Soft X-Ray Self-Seeding



- SX1 pulse passes monochromator and seeds SX2 pulse
- Narrow bandwidth pulse to <10^{-4} FWHM (6-60 Å)
- Can also use chirped bunch to generate short pulse (<50 fs)

J. Feldhaus *et al.*, Opt. Commun. **140**, 341 (1997).

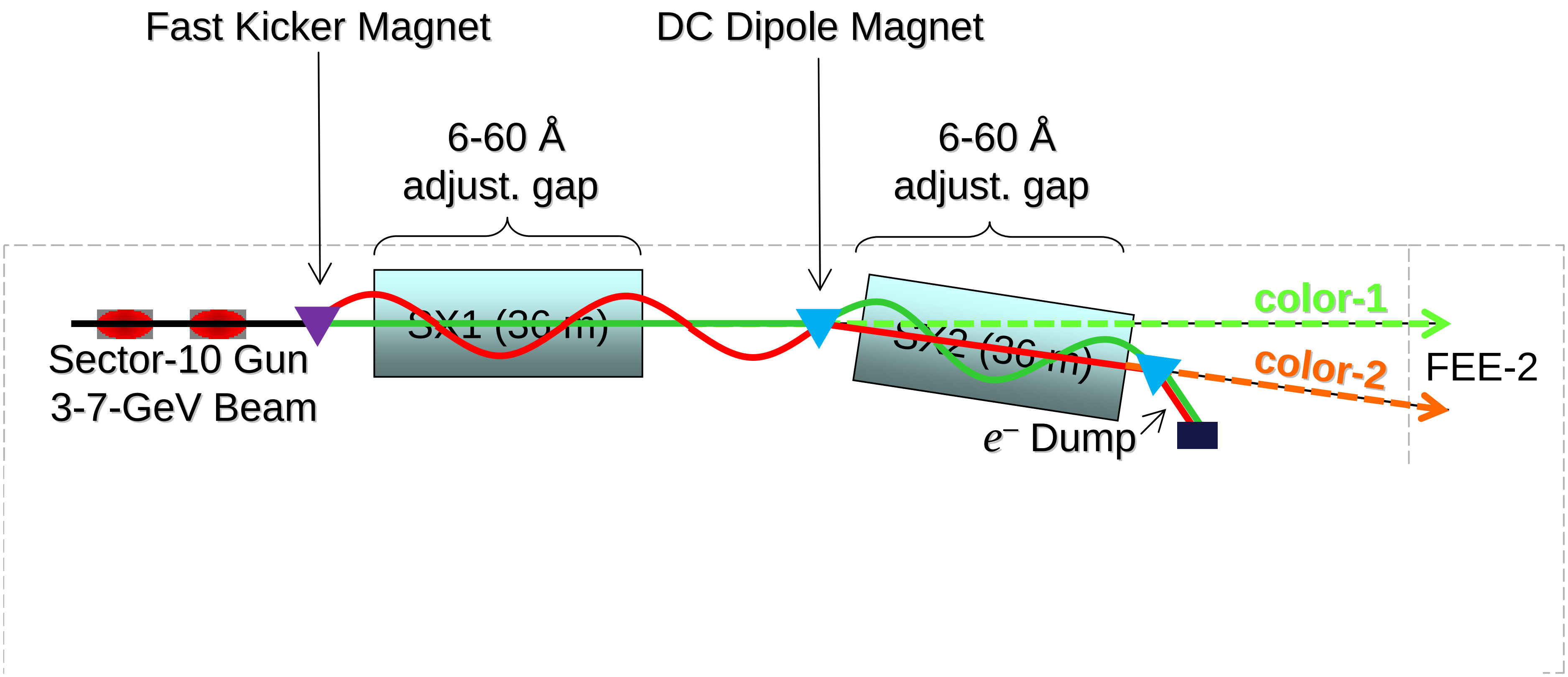
4. *LCLS-II:* SX1 & 2 SASE, *One*-Bunch, Two-Color



- One e^- bunch produces 2 SXR pulses (0-15 ps separation) for pump probe
- Deliver both pulses to one experiment or split them to two
- SX2 pulse color (λ_2) must be longer wavelength than SX1 (λ_1)

Angled SX2 suggested by J. Hastings and P. Heimann

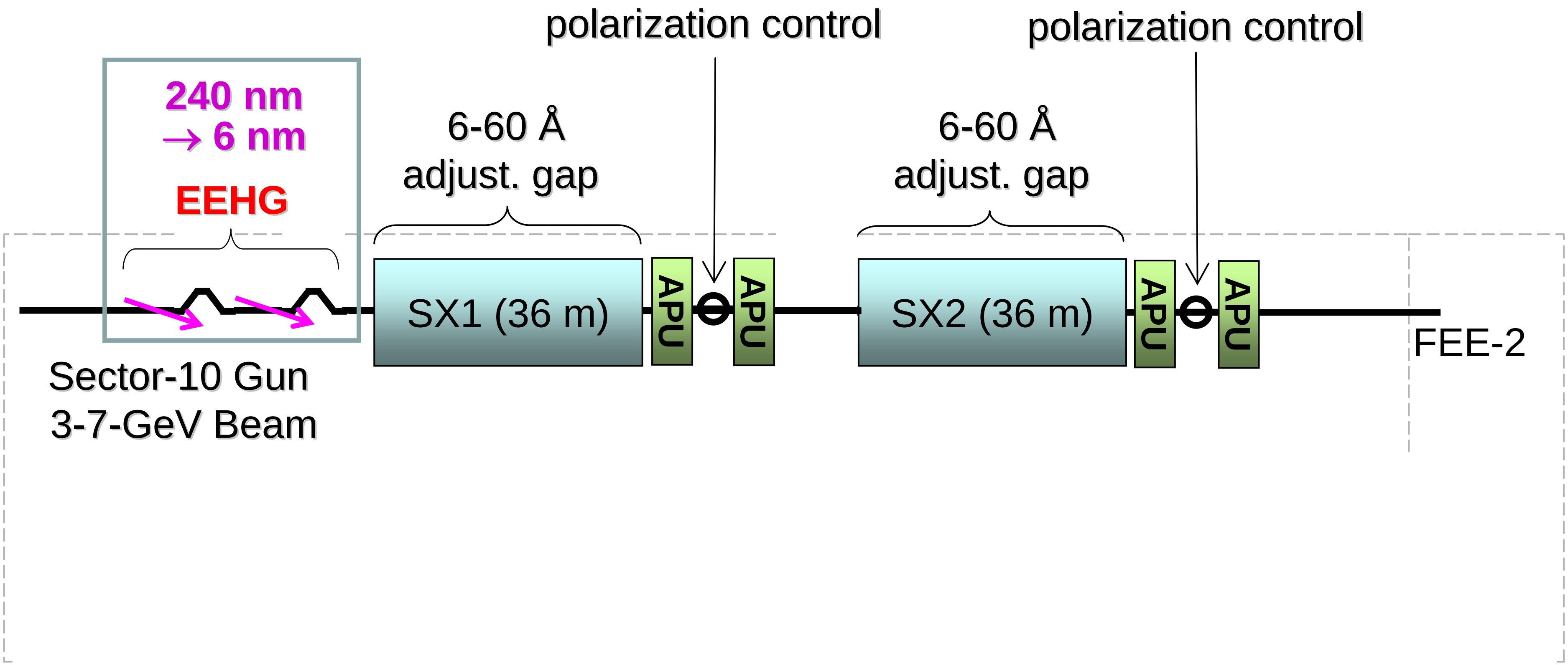
5. *LCLS-II:* SX1 & 2 SASE, *Two*-Bunch, Two-Color



- Two e^- bunches 10-100 ns apart (no pump probe here)
- One fast kicker & one DC – each bunch lases in just one FEL
- Allows 2 SXR experiments simultaneously (*user doubler*)
- Two colors can be any value (6-60 Å)

Suggested by J. Frisch and independently by R. Brinkmann *et al.*

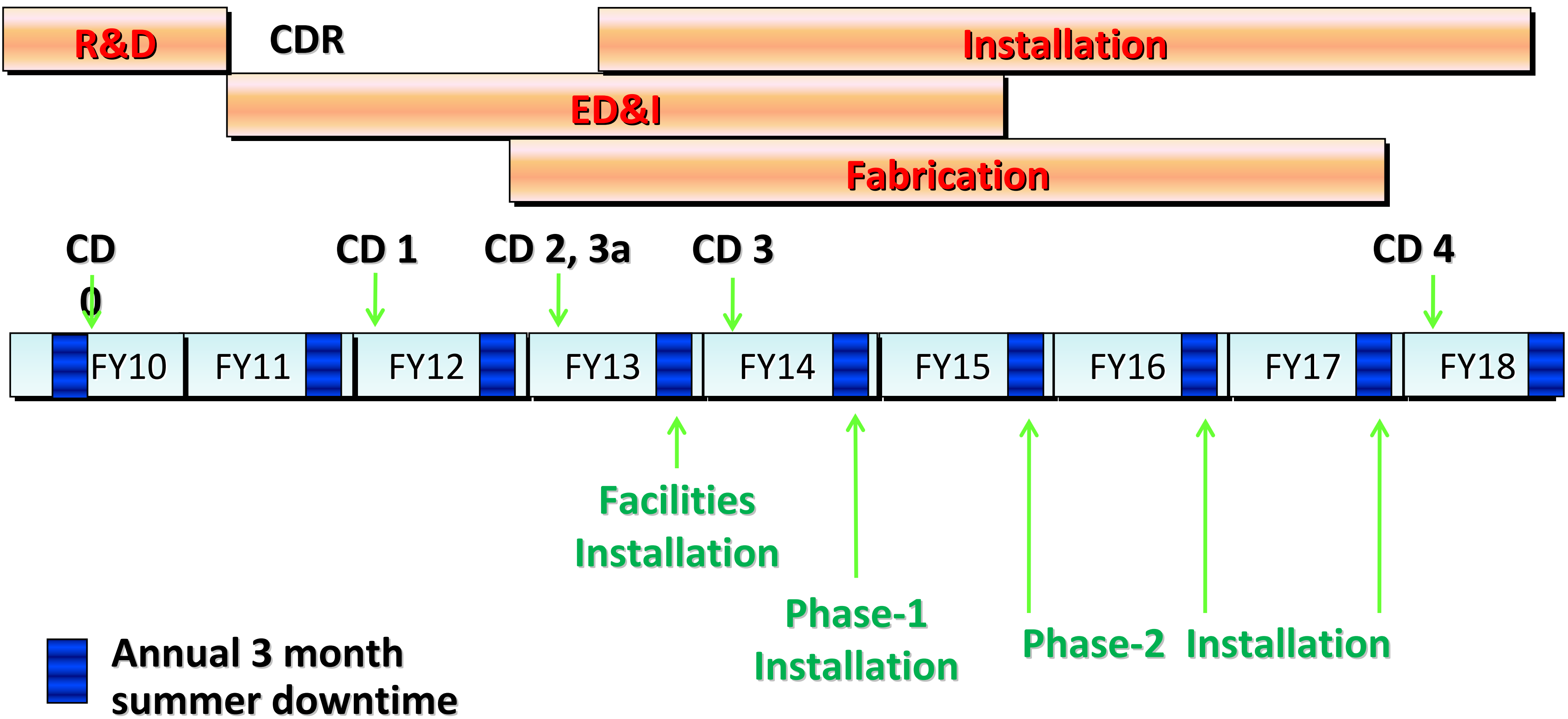
6. *LCLS-II:* Echo Seeding of SX1 or SX2



- External seeding (~30-60 Å) using Echo-Enhanced Harmonic Generation (EEHG*) – not in *LCLS-II* baseline at present
- Allows narrow BW and longitudinal coherence
- Under study now at NLCTA (SLAC)

* G. Stupakov, Phys. Rev. Lett. **102**, 074801 (2009)

LCLS-II Timeline, Compatible with Operations



LCLS-II Accelerator Summary

Soft X-Rays:

- 2-pulse, 2-color, variable delay (6-60 Å) using 1 e^- bunch or 2
- Self-seeding for narrow bandwidth (~10^{-4} at 6-60 Å)
- Full polarization control in SASE and self-seeded modes (fast & slow)
- 3-7 GeV bypass line allows simultaneous soft and hard x-ray operations in two separate beamlines with completely independent parameters
- Single femtosecond near-transform limited spike in low-charge mode

Hard X-Rays:

- Harder x-rays (0.62 Å) by modifying all undulators
- Few femtosecond pulses possible in low-charge mode
- Full polarization control
- Self-seeding with 2 electron bunches and short chicane (4 m)
- And… 22-30 GeV still possible using both 1-km linacs (+ 3rd km still open)

Photon Beam Distribution