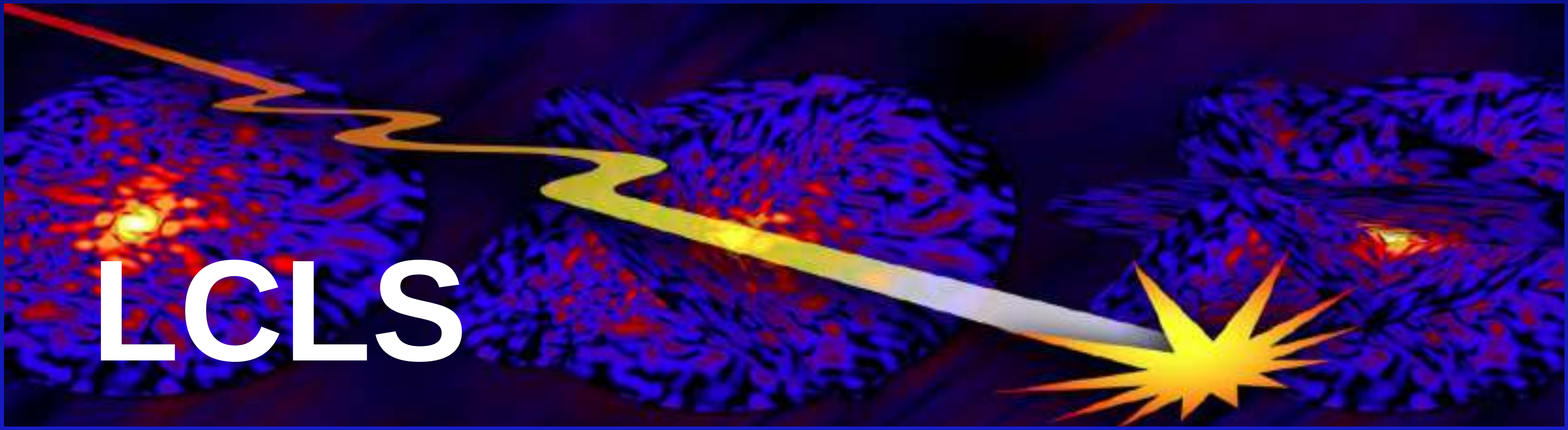
Hard X-ray Free Electron Lasers Really Work: Present Status and Future Potential

J. B. Hastings
for the LCLS team
SLAC *National Accelerator Laboratory*, Oct. 11, 2010



Workshop on Evolution and Control of Complexity:
Key Experiments Using Sources of Hard X-rays

Argonne NATIONAL LABORATORY
DESY
SLAC NATIONAL ACCELERATOR LABORATORY

The challenge:
Maximize the number of photons/electron/unit time

The solution:
Free Electron Lasers

The *LCLS* Proposal… 1992

C. Pellegrini, *"A 4 to 0.1 nm FEL based on the SLAC linac"*, in Workshop on 4th Generation Light Sources, M. Cornacchia and H. Winick, (Eds), pp. 364-375, 1992. SSRL-Report-92/02.

"…one is forced to have high gain, *i.e.* to use electron beams with large peak current, and at the same time small emittance and energy spread. **The road to an X-ray FEL requires the development of electron beams with unprecedented characteristics.**"

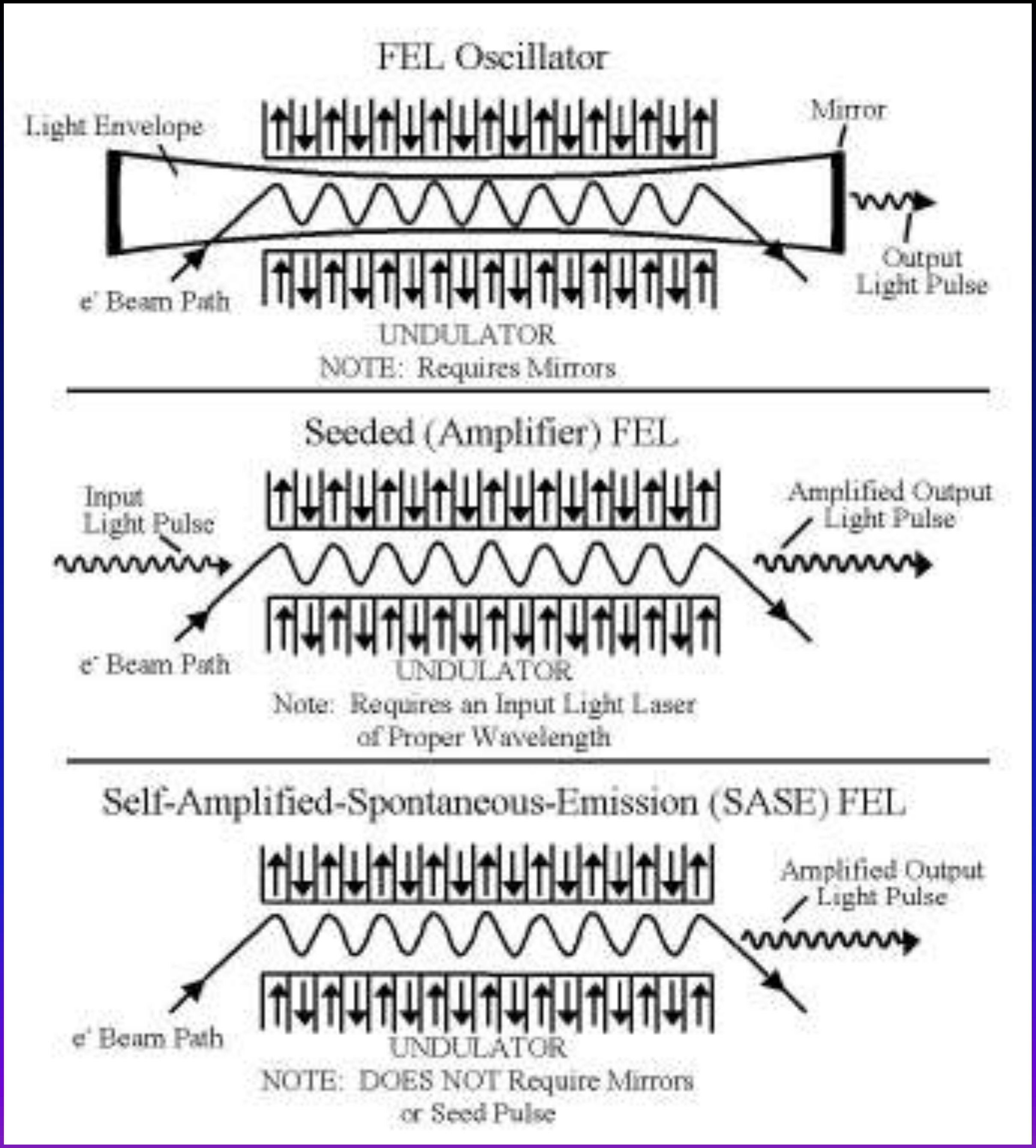
Photon beam characteristics

- Short pulses: fs to as
- 'Full' transverse coherence
- High field strengths
- High peak power
- Unmatched peak brilliance

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

‘Hard’

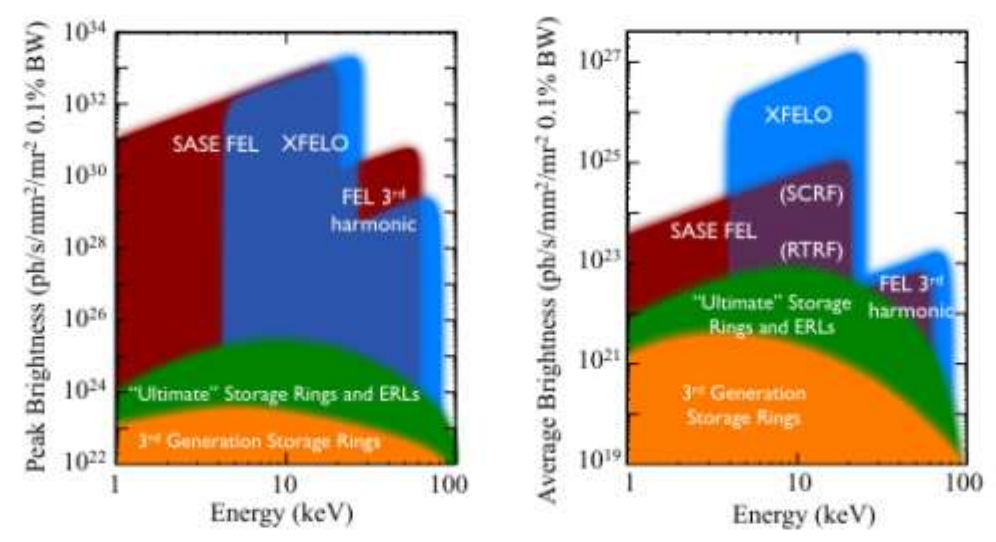
‘Easy’



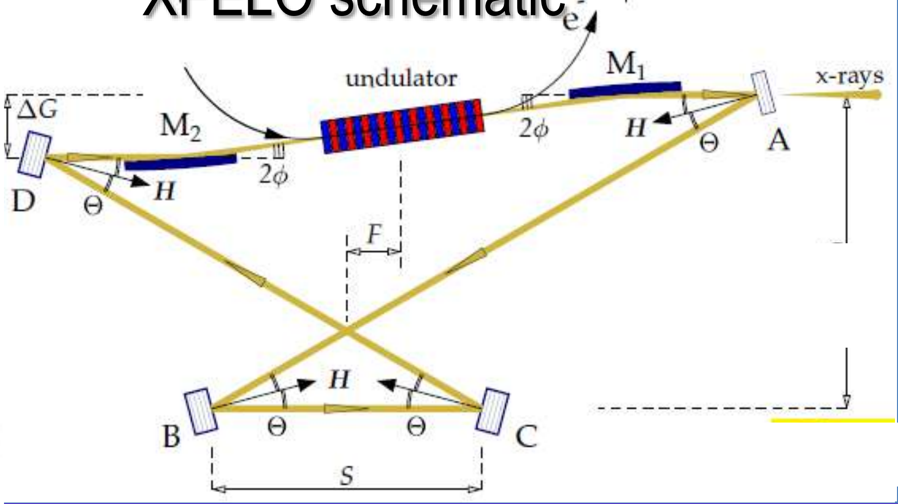
Kwang-Je Kim and Zhirong Huang, unpublished

X-ray FEL oscillator (XFELO) opens a new avenue for the future hard x-ray science*

- Fully coherent, tunable hard x-rays, ~ 1 meV bandwidth, 10^9 photons/pulse, 1 MHz rep rate
- XFELO will dramatically improve techniques developed in the 3rd generation light sources and will create new opportunities complementary to SASE



XFELO schematic

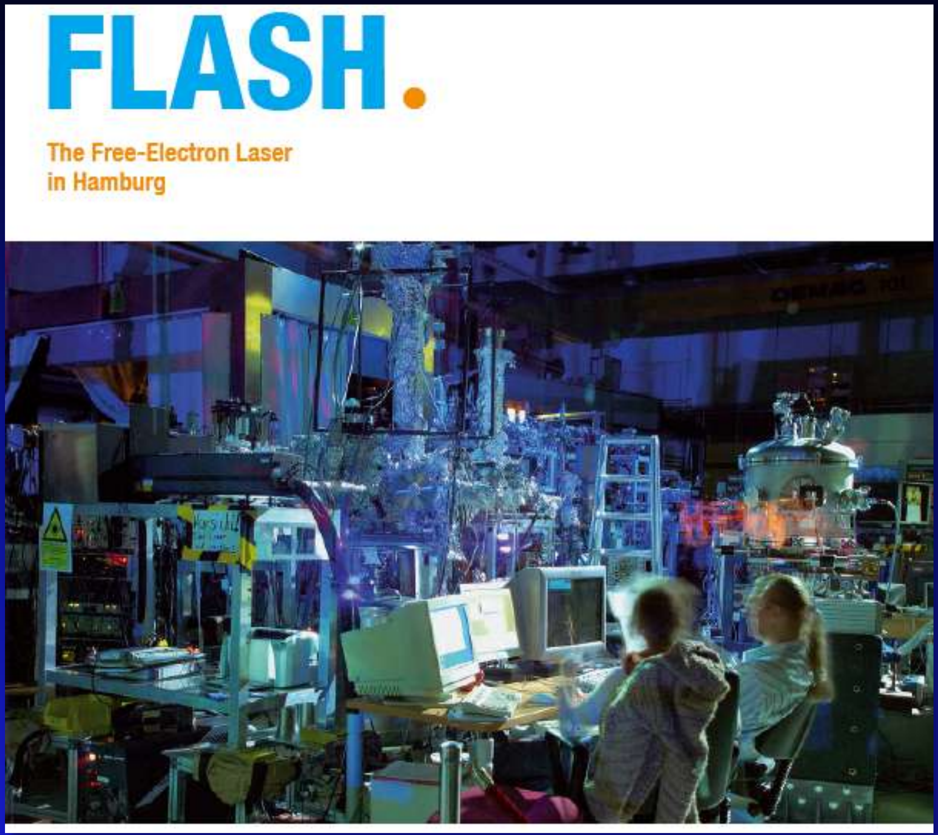


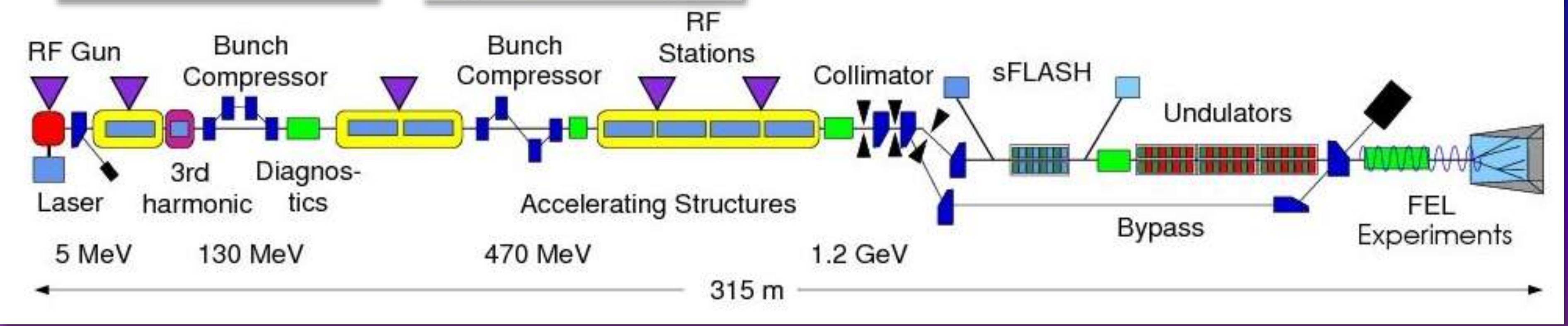
* talk by K.-J. Kim at this WS (Focus Panel 6)

Uses diamond crystals with a high Bragg reflectivity

The *FLASH* FEL at DESY (Hamburg, Germany)

- 10 years of FEL operation (100 - 6 nm)
- Development of FEL science & technology
- Many experienced people now at ***LCLS***





Planned/Proposed Hard X-ray FELs (~1 Å)

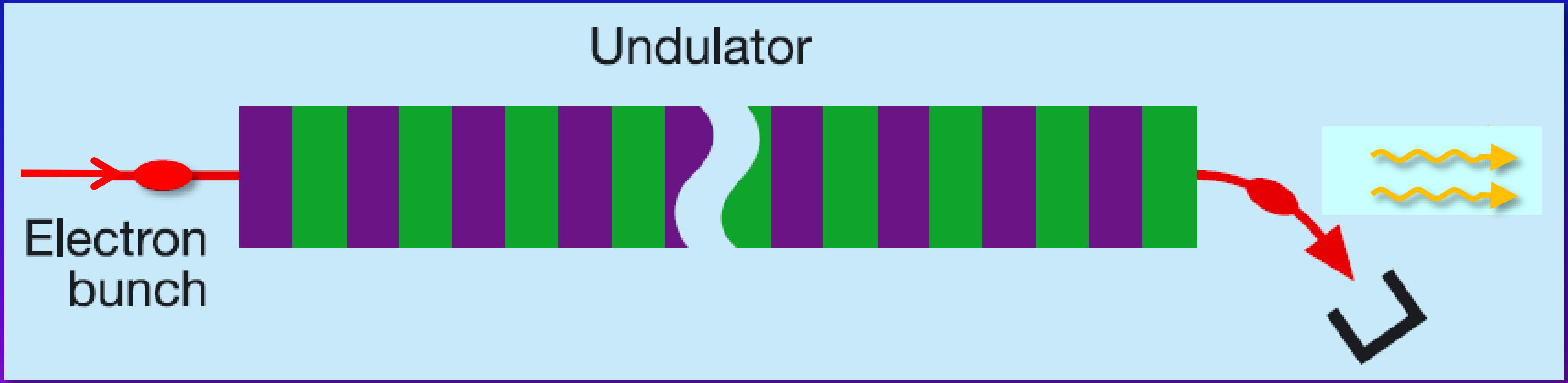
- ***SCSS*** at SPring-8 in Japan (0.1-3.6 nm) — **2011**
- ***European X-FEL*** at DESY (0.1-6 nm) — **2015**
- ***Swiss-FEL*** at PSI (0.1-7 nm) — **2016**
- ***LCLS*** at SLAC (0.12-2.5 nm) — **now** (2009)
- ***LCLS-II*** at SLAC (0.06 – 6 nm) — **2017**

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

The *Linac Coherent Light Source* (*LCLS*), with 25-1.2 Å FEL light is now leading the way forward…

What is a SASE* Free-Electron Laser (FEL)?

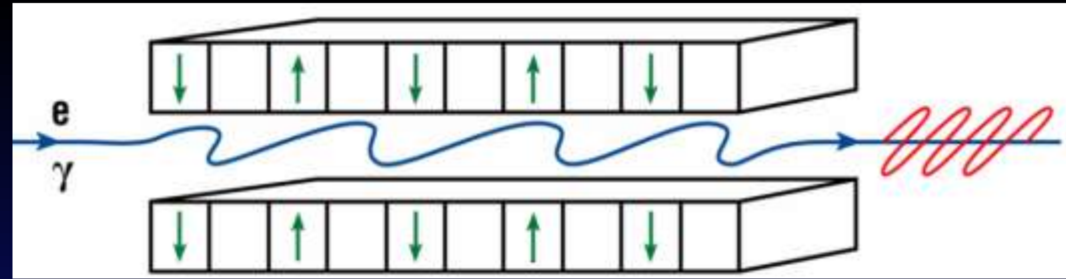
- *Need a very bright, high-energy, bunched electron beam → linear accelerator provides **MUCH** brighter beam than a ring*
- *Electron bunch is injected into a long undulator → an array of periodic alternating dipole magnets*
- *Stimulated emission is resonantly amplified by interaction of radiation with electron bunch*



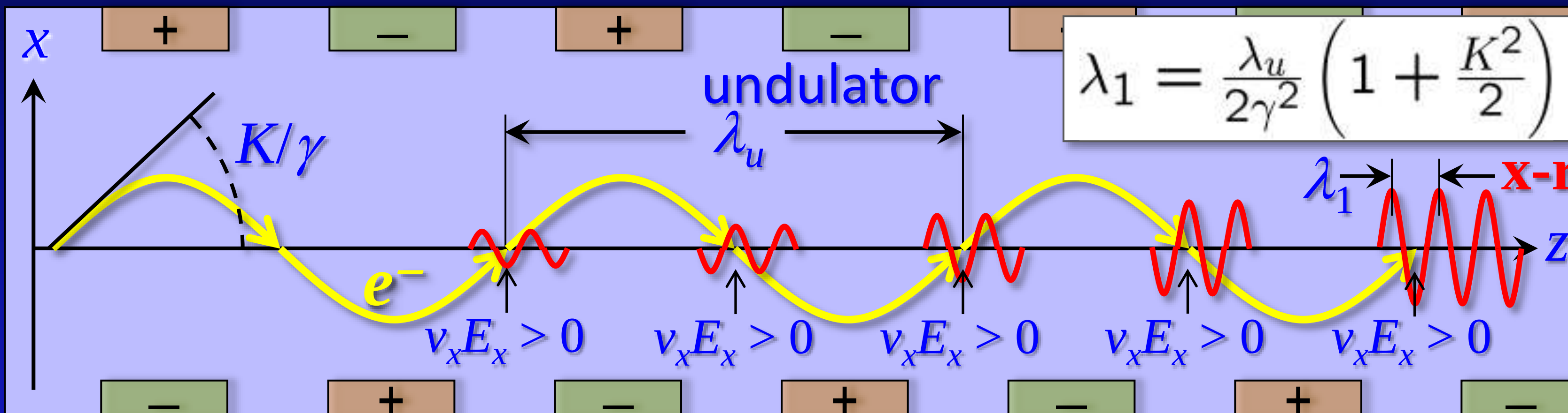
** Self-Amplified Spontaneous Emission*

Resonant Interaction of Field with Electrons

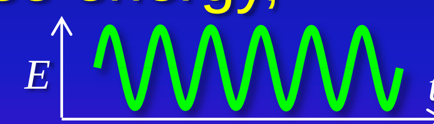
Z. Huang



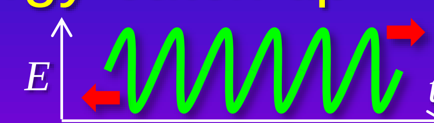
- Electrons **slip** behind EM wave by λ_1 per undulator period (λ_u)



- Due to sustained interaction, some electrons lose energy, while others gain ➔ energy modulation at $\lambda_1 \Rightarrow$

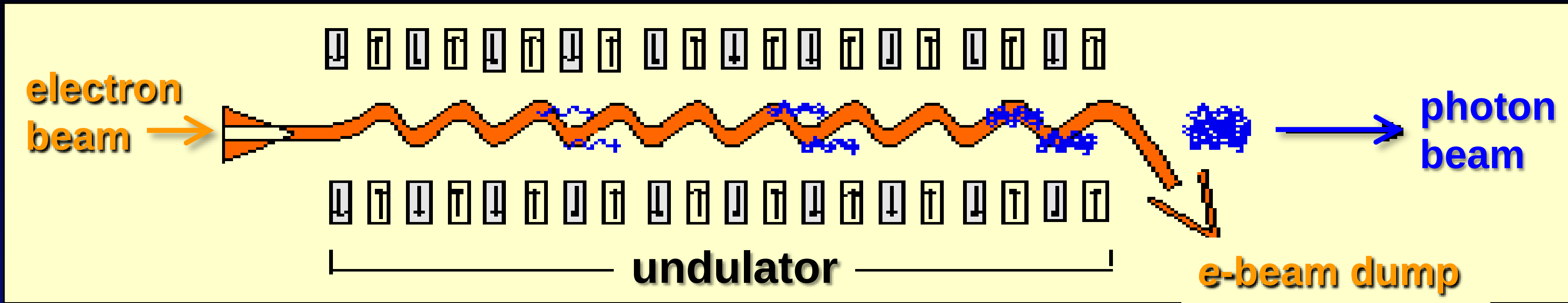


- e^- losing energy slow down, and e^- gaining energy catch up ➔ density modulation at λ_1 (microbunching) $\Rightarrow$



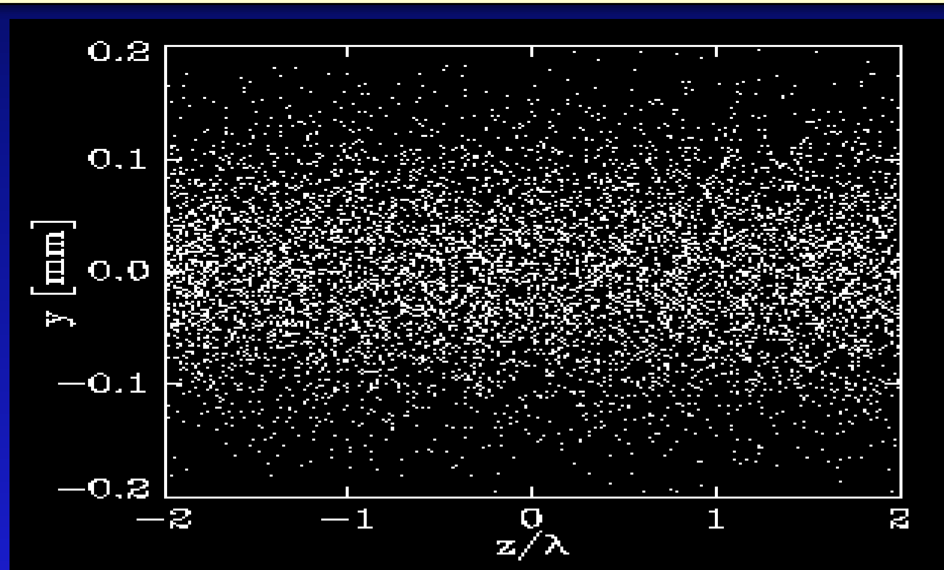
- Micro-bunched beam radiates coherently at λ_1, enhancing the process ➔ **exponential growth of radiation power**

FEL Micro-Bunching Along Undulator



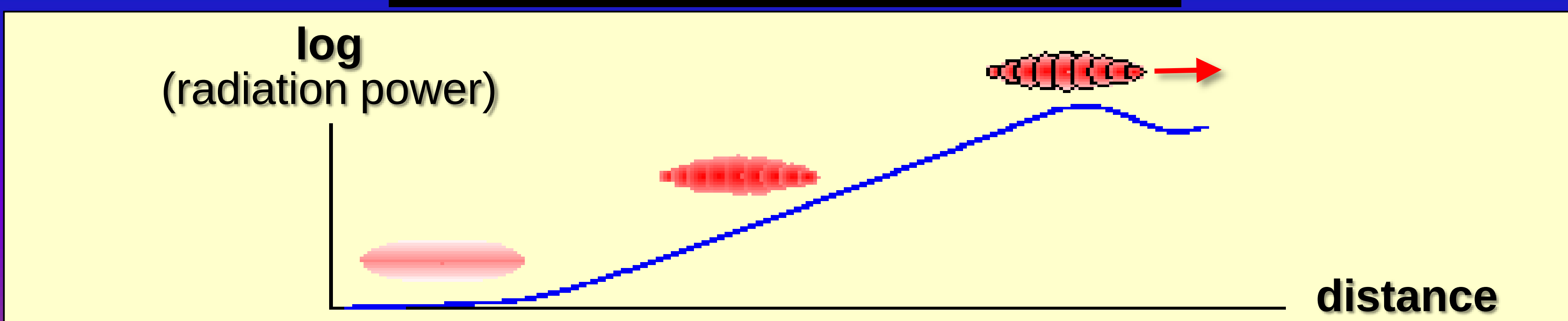
SASE* FEL starts up from noise

* Self-Amplified Spontaneous Emission

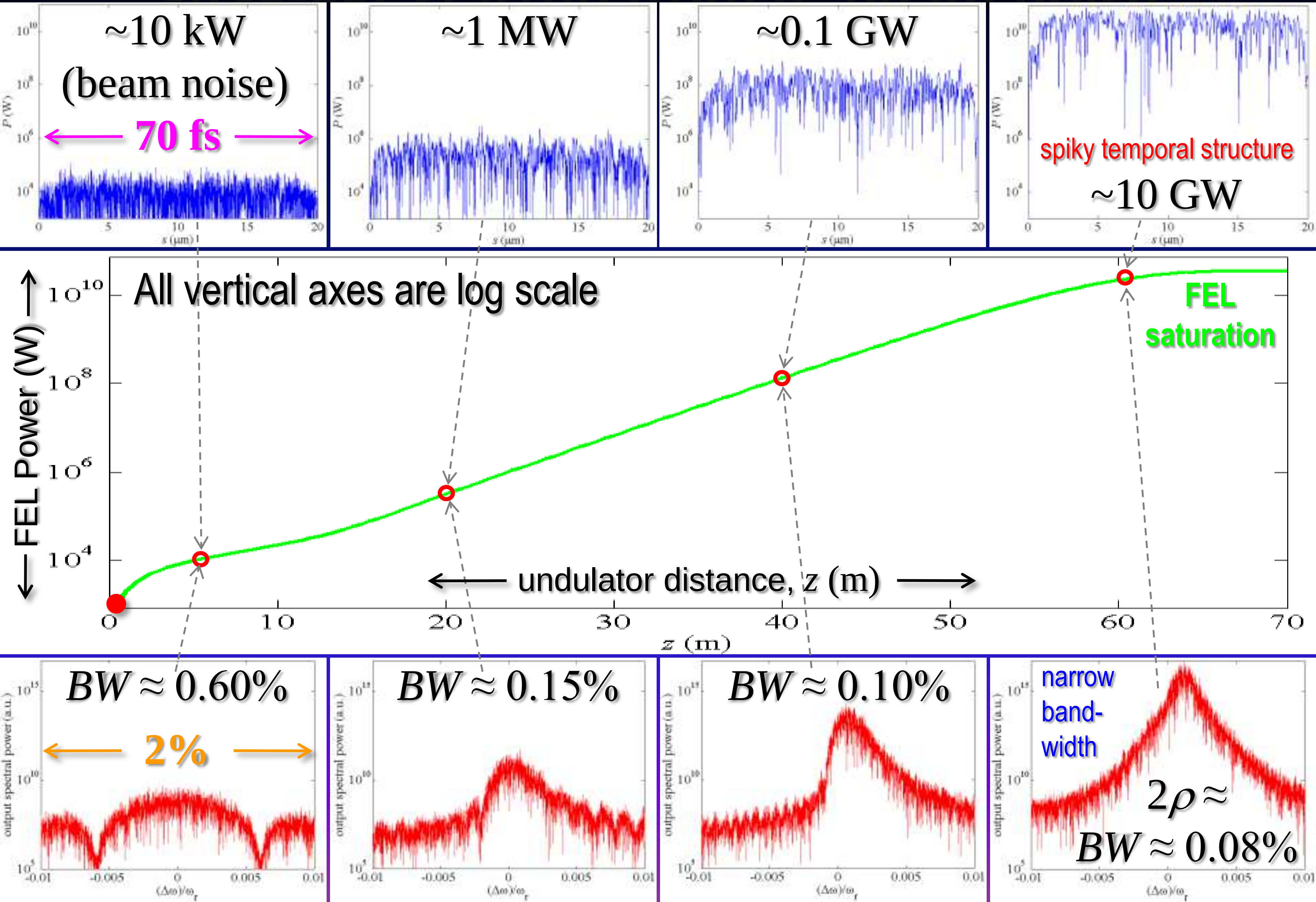


Electrons form micro-bunches at the radiation wavelength (~1.5 Å)

S. Reiche

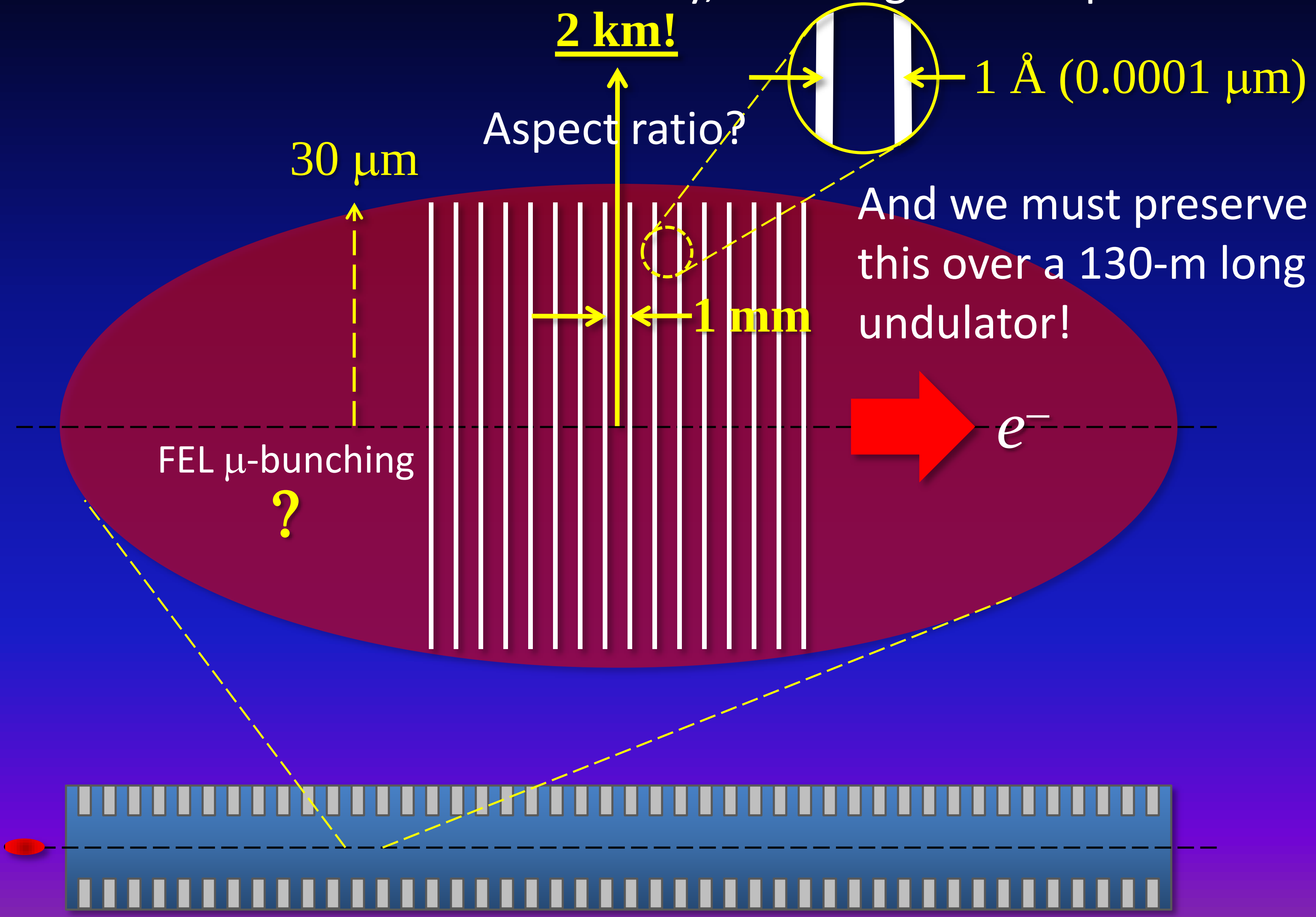


SASE-FEL startup from e^- beam noise



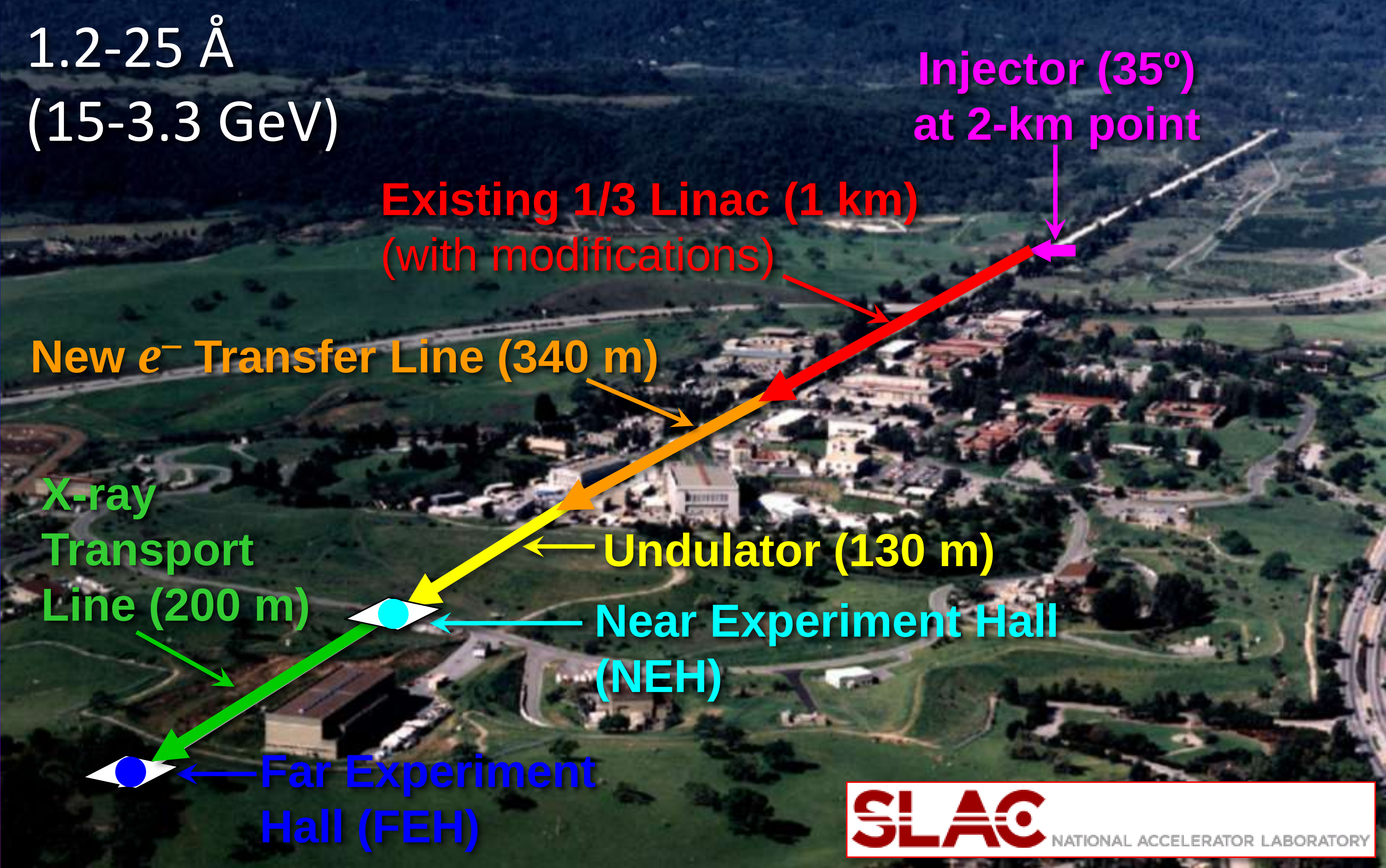
Must Preserve 1-Å Micro-Bunching Over Long Undulator!

Now let's draw this more accurately, choosing a 1-mm period…



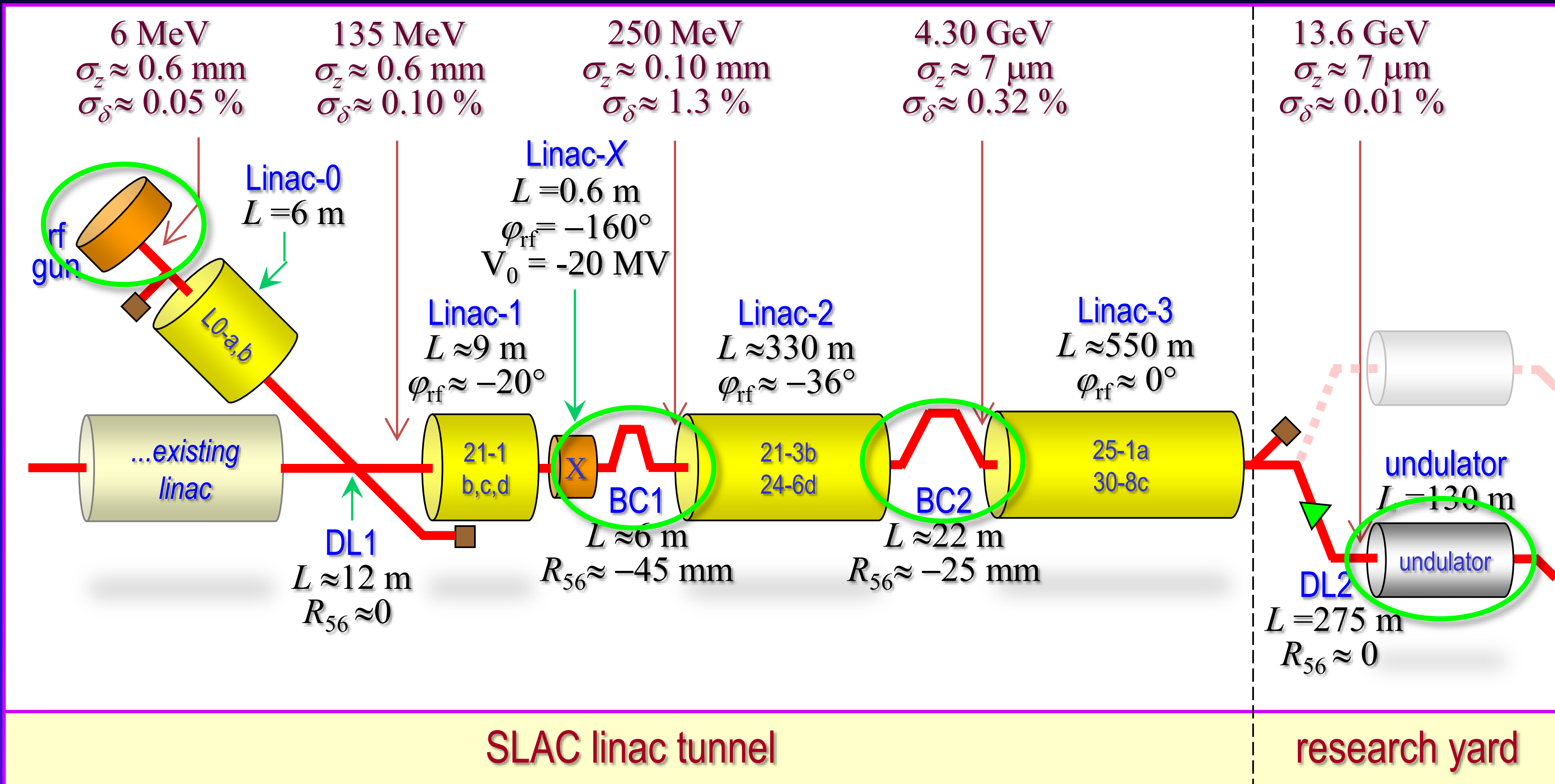
Linac Coherent Light Source at *SLAC*

X-FEL based on last 1-km of existing 3-km linac



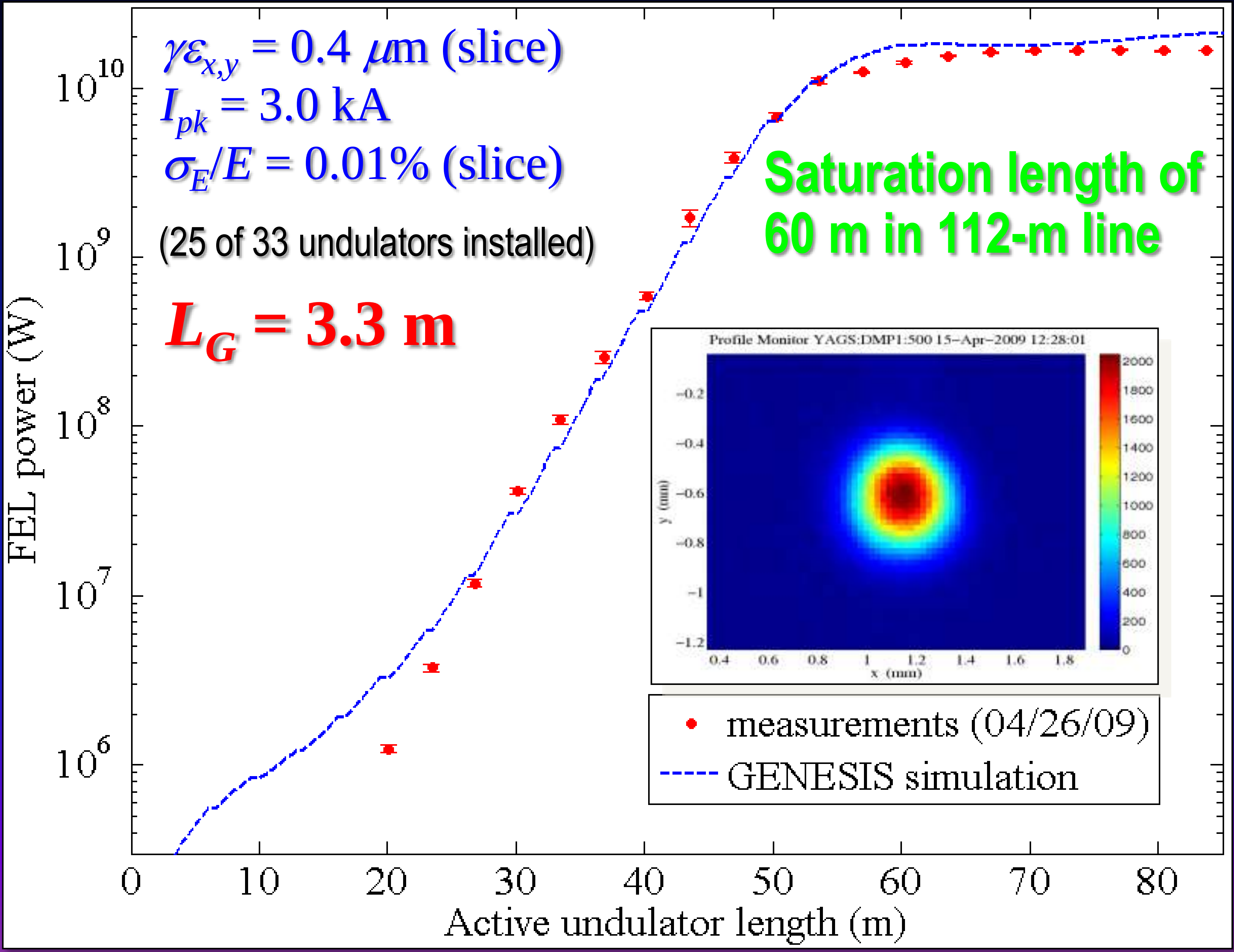
LCLS Accelerator Required for SASE X-Ray FEL

Entire machine is >2000 m long



Most of accelerator existed (1960's), but new electron source, new bunch compressors, and new undulator were added

Undulator Gain Length Measurement at 1.5 Å

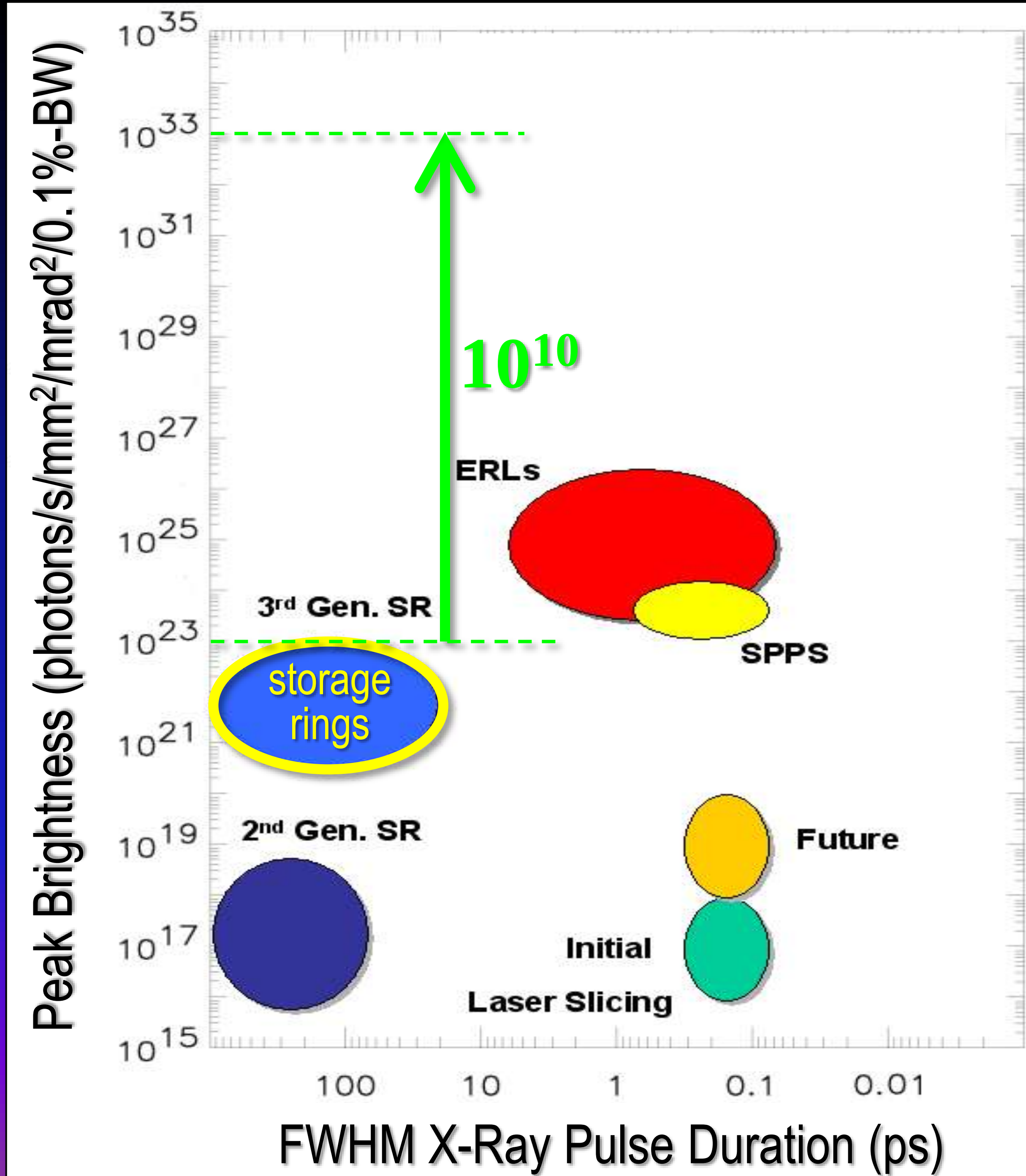


LCLS Parameter Changes - Some Fast, Some Not

- **Machine Pulse Rate** (1, 10, 30, 60 Hz, & one-shot)* changed in seconds with one button push.
- **Wavelength** (25 - 1.2 Å) changed in 5-60 minutes.
- **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 – for soft x-rays) easily changed in 1 minute (closed loop control).
- **Peak FEL Power** (0 - 40 GW) set by pulse length (increases with peak current – see next slide).
- **Ultra-Short Pulse Length** (<10 fs FWHM?) 20 pC - requires 1-2 hours to establish (starting from nominal 250-pC conditions).

* 120 Hz in Oct. 2010, with laser and most RF systems already at 120 Hz or tested there

Light Sources at ~1 Å



Free-Electron Lasers **(FEL) represent a major technical advance with very high peak brightness coherent x-rays and sub-100-fsec pulses at Angstrom wavelengths**

H.-D. Nuhn, H. Winnick

LCLS Operations statistics to date

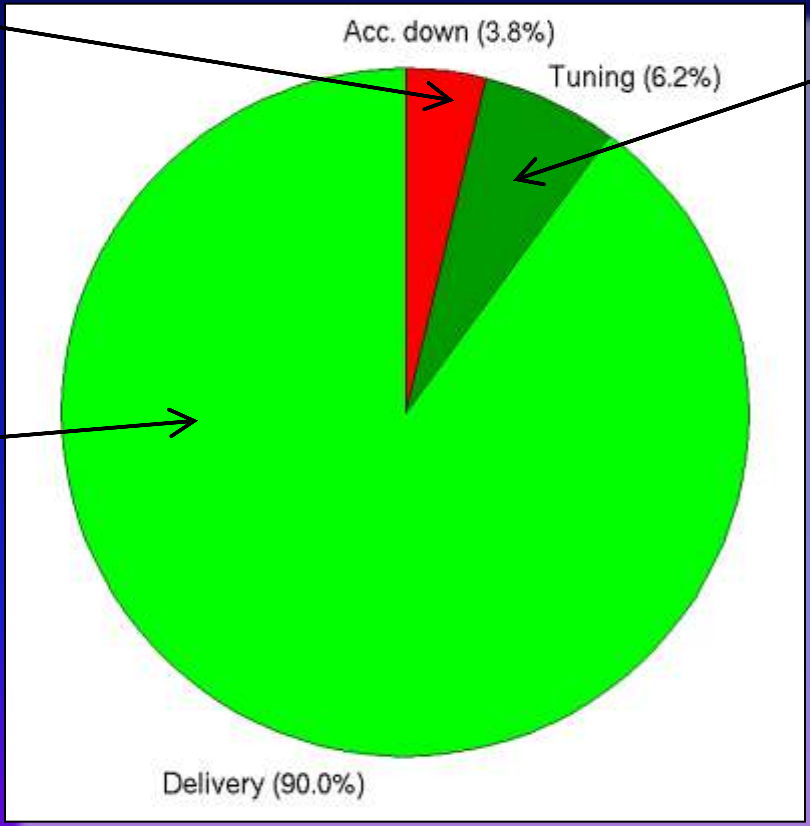
- First experiment run Oct-Dec 2009
  - AMO instrument only
  - 28 proposals received, 10 experiments scheduled & run
- 2nd experiment run May-Sept 2010
  - AMO, SXR instruments
  - 62 proposals received, 21 scheduled & run
- 3rd experiment run Oct 2010 - March 2011
  - AMO, SXR, XPP instruments
  - 107 proposals received, 25 scheduled

LCLS Machine Up-Time vs. Scheduled Time

Oct. 1 – Nov. 9, 2009

2.6% of "Acc. down" due to weekend of Oct. 24-26

90% up-time, *excluding* "tuning" time



Most of "tuning" time (~4%) used for user-requested *ultra-short pulse* setup

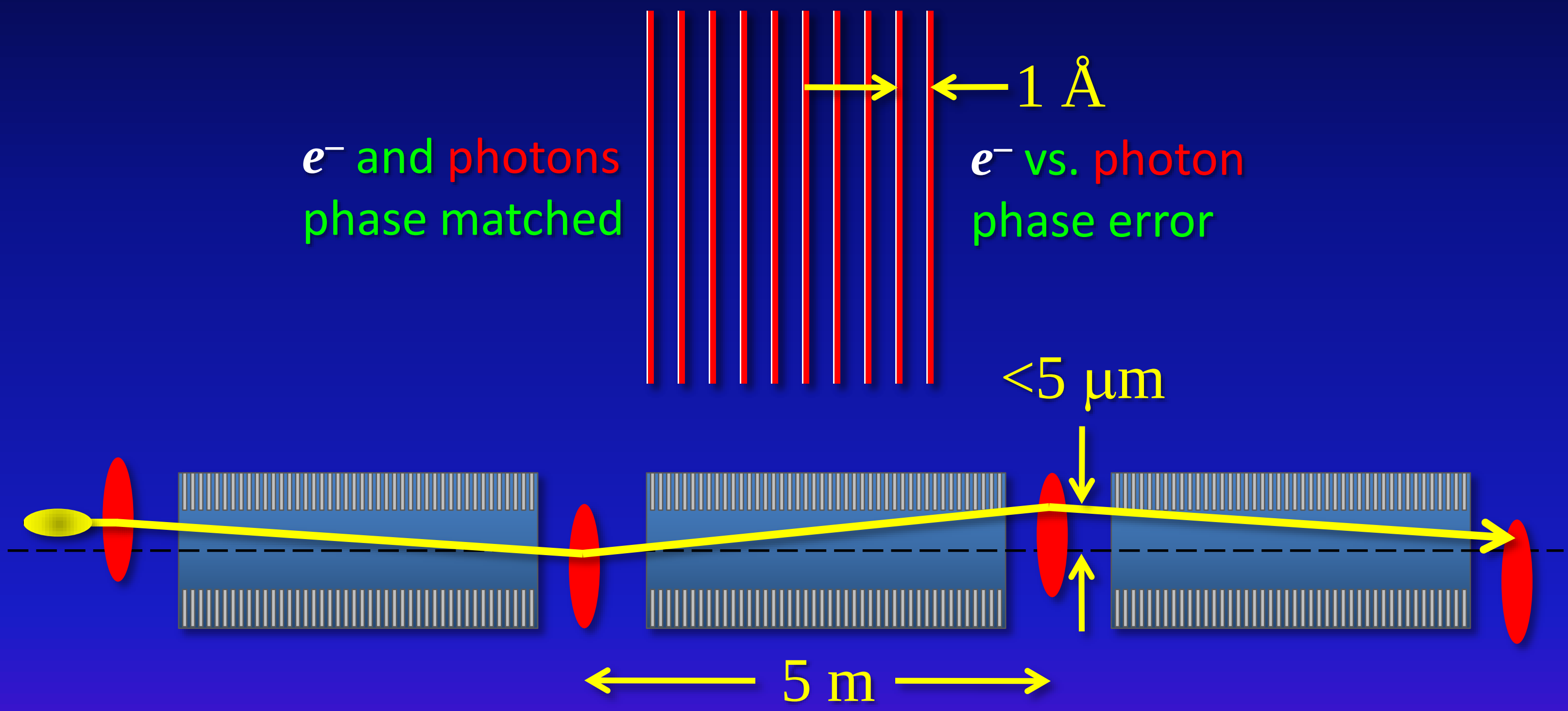
96% up-time, *including* "tuning" time

"Scheduled time" = 100%

(not including time when users or hutch was not ready)

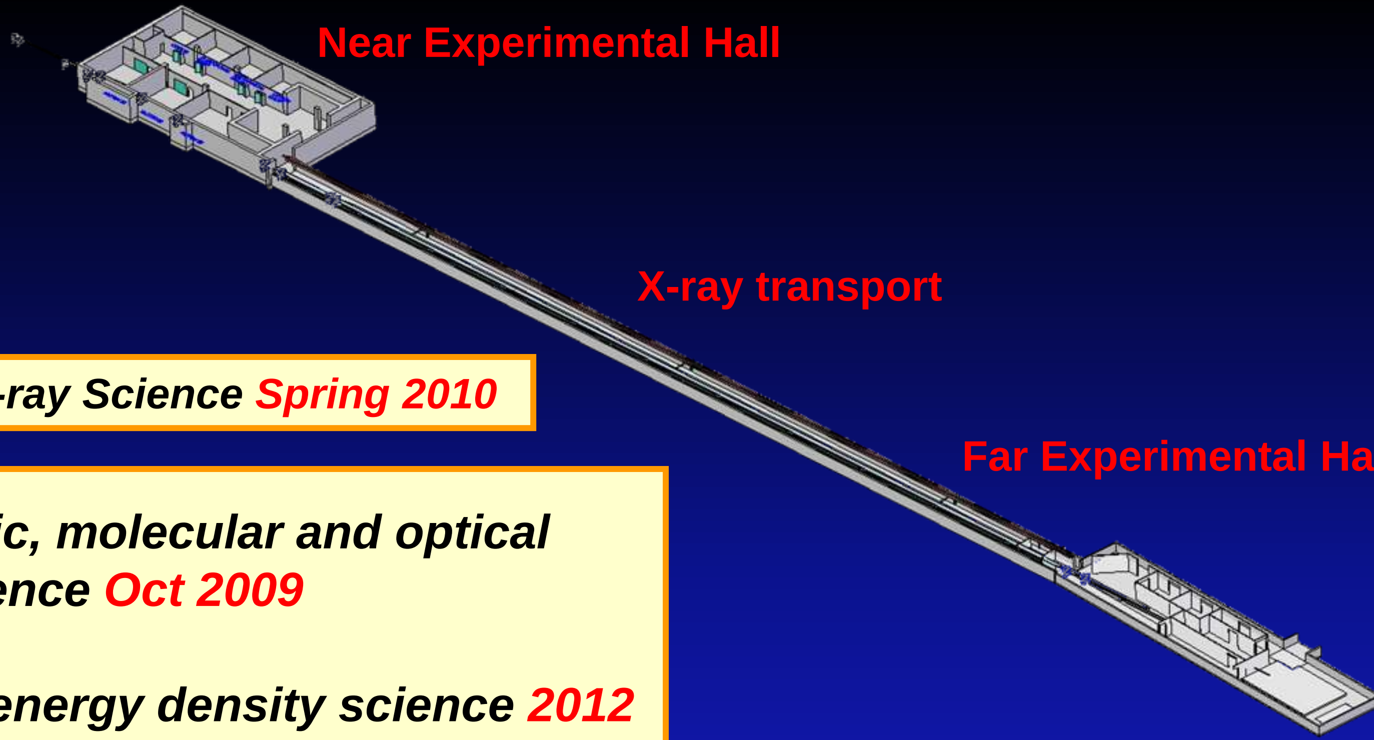
Must have a 5-μm straight trajectory over a gain length!

Get additional e^-/photon slippage (phase error) with imperfect trajectory

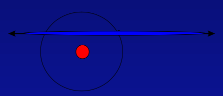


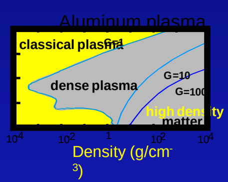
Trajectory straightness requirements are frighteningly tight !

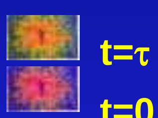
Producing a sufficiently straight undulator trajectory requires an empirical beam-based alignment method

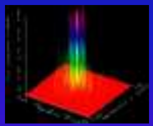


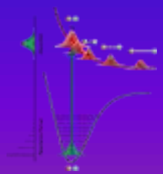
Soft X-ray Science ***Spring 2010***









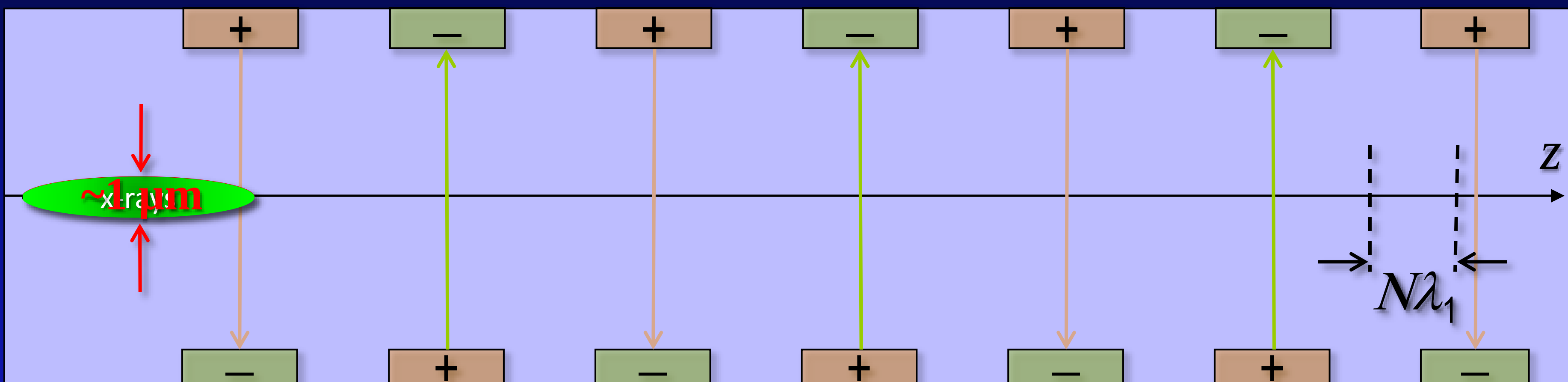


- ***Atomic, molecular and optical science Oct 2009***
- ***High energy density science 2012***
- ***Coherent-scattering studies of nanoscale fluctuations Fall 2011***
- ***Nano-particle and single molecule imaging Spring 2011***
- ***Diffraction studies of stimulated dynamics (pump-probe) Oct 2010***

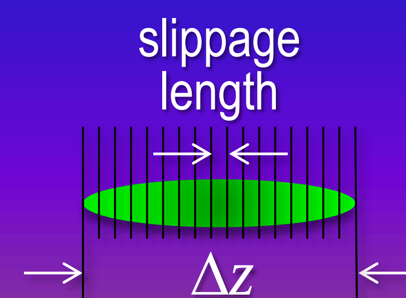
LCLS Experimental Program

Slippage and coherence length

Light overtakes e^- beam by one radiation wavelength λ_1 per undulator period (interaction length = undulator length)



- Slippage length = $\lambda_1 \times N$ undulator periods:
  (at 1.5 Å, *LCLS* slippage is: $l_s \approx$ 1.5 fs << 100-fs pulse length)
- Each part of optical pulse is amplified by those electrons within a slippage length (an FEL slice)
- Coherence length is slippage over ~$2L_G$ ($l_c << l_s$)
- $M_L \approx \Delta z / l_c$ independent radiation sources (modes)



Why a Linac-Based Free-Electron Laser* ?

- "Recent" advances in high-brightness RF photocathode guns
- Longitudinal emittance from linac is ~10^3 smaller than ring
- Bunch length can be <100 fs and with small energy spread
- Experience from linear collider operation and study (***SLC***, *TESLA*, *JLC*, *NLC*, *CLIC*)
- The last 1-km of the *SLAC* linac is available
- FEL produces unprecedented brightness and fsec pulses

Use **SASE**** (Self-Amplified Spontaneous Emission) ⇒ *no mirrors or seed-lasers at 1-Å wavelengths*

* Motz 1950; Phillips 1960; Madey 1970

** Kondratenko, Saldin 1980; Bonifacio, Pellegrini 1984

- - SASE and FEL principle - seeding - XFELO- LCLS examples - list of first experiments

LCLS X-ray Operations plan

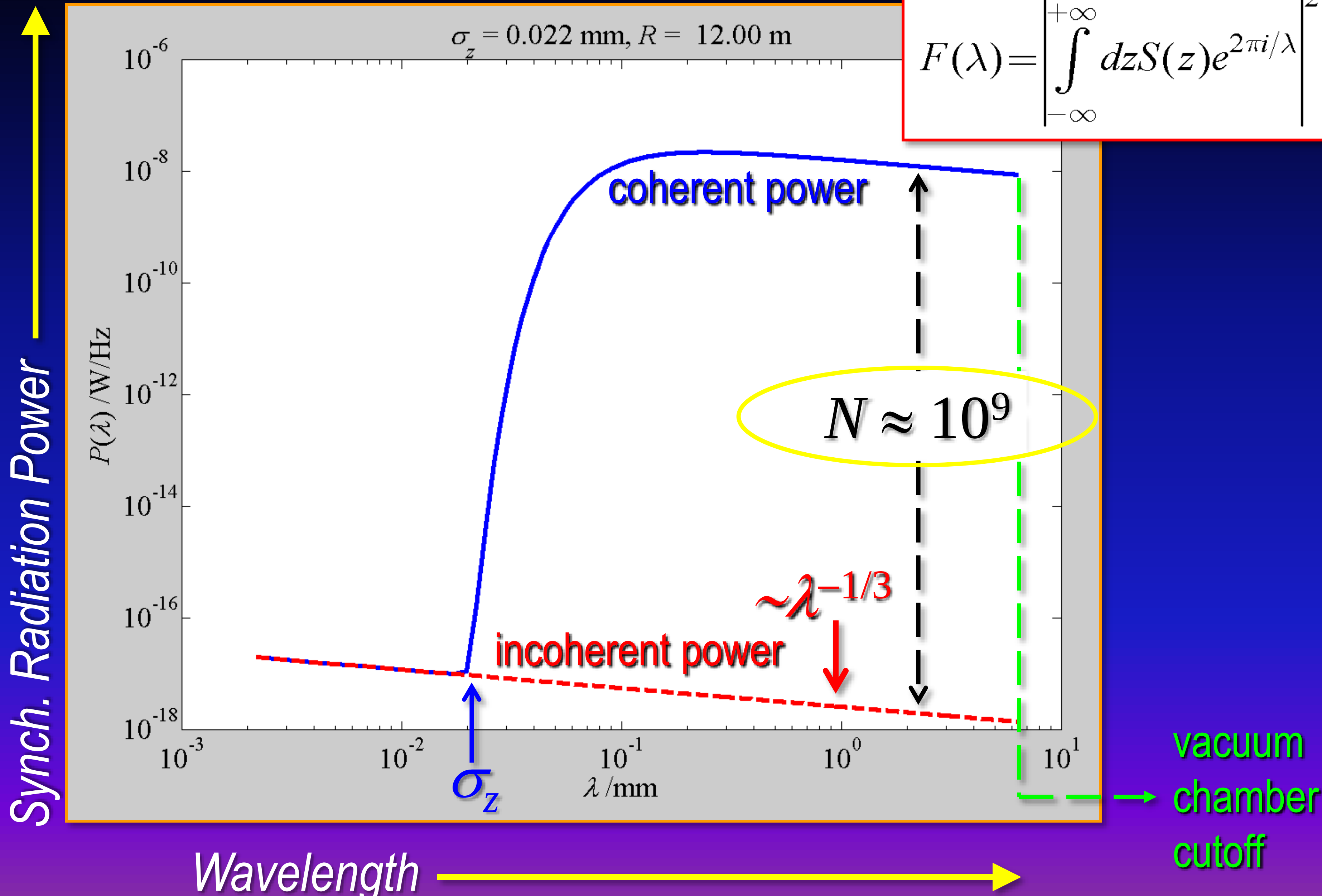
- Sept-Dec 2009, with 1 instrument (AMO)
- May-Sept 2010, with 2 instruments (AMO, SXR)
- Oct 2010-Mar 2011, with 3 instruments (AMO, SXR, XPP)
- May-Sept 2011, with 4 instruments (AMO, SXR, XPP, CXI)
- Add XCS in Oct 2011, MEC in 2012

- Steady-state X-ray operations at >4000 hrs/year
- Scheduled in blocks of about 6 months, with periodic brief interruptions for machine studies
- Typical experiment lasts for about 1 week

Coherent Synchrotron Radiation in Bends

$$P(\lambda) = P_0 N \{1 + NF(\lambda)\}$$

$$F(\lambda) = \left| \int_{-\infty}^{+\infty} dz S(z) e^{2\pi i/\lambda} \right|^2$$



Electron Beam Requirements for SASE FEL

$$\varepsilon_N < \gamma \frac{\lambda_r}{4\pi}$$

radiation wavelength (*e.g.*, 1 Å)

transverse emittance: ε_N < 1 μm at 1 Å, 15 GeV

(volume occupied in phase space)

$$\sigma_\delta < \rho \approx \frac{1}{4}\left(\frac{1}{2\pi^2}\frac{I_{pk}}{I_A}\frac{\lambda_u^2}{\beta\varepsilon_N}\left(\frac{K}{\gamma}\right)^2\right)^{1/3}$$

FEL parameter; peak current; undulator period; beta function; undulator 'field' = $0.93 \cdot B\lambda_u$

relative energy spread: <0.04% at I_{pk} = 3 kA, $K \approx 3$, $\lambda_u \approx 3$ cm, …

$$L_g \approx \frac{\lambda_u}{4\pi\sqrt{3}\rho}$$

FEL gain length: $18L_G \approx$ 100 m for $\varepsilon_N \approx$ 1.5 μm

- Need high peak current, low emittance, and small energy spread so that the x-ray radiation power grows exponentially with undulator distance, z
  $P(z) = P_0 \cdot \exp(z/L_G)$
- FEL power reaches *saturation* at $\sim 18L_G$
- SASE performance depends *exponentially* on e^- beam quality ! (challenge)

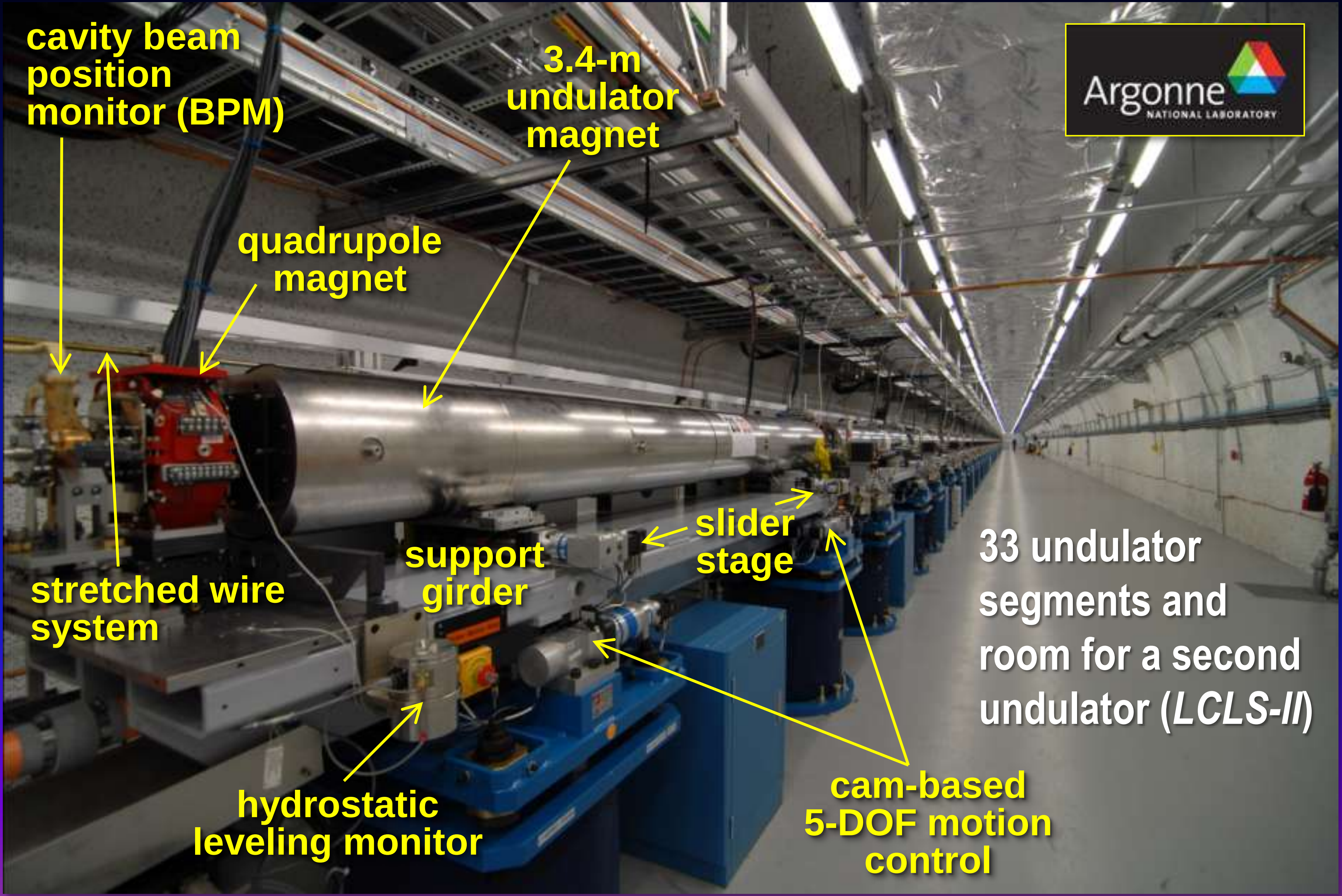
Remarks of Prof. J. Etchemendy, Stanford University Provost, at the LCLS Groundbreaking, Oct. 20, 2006.

Quoting from Tom Hankins and Robert Silverstein in ***Instruments and the Imagination***

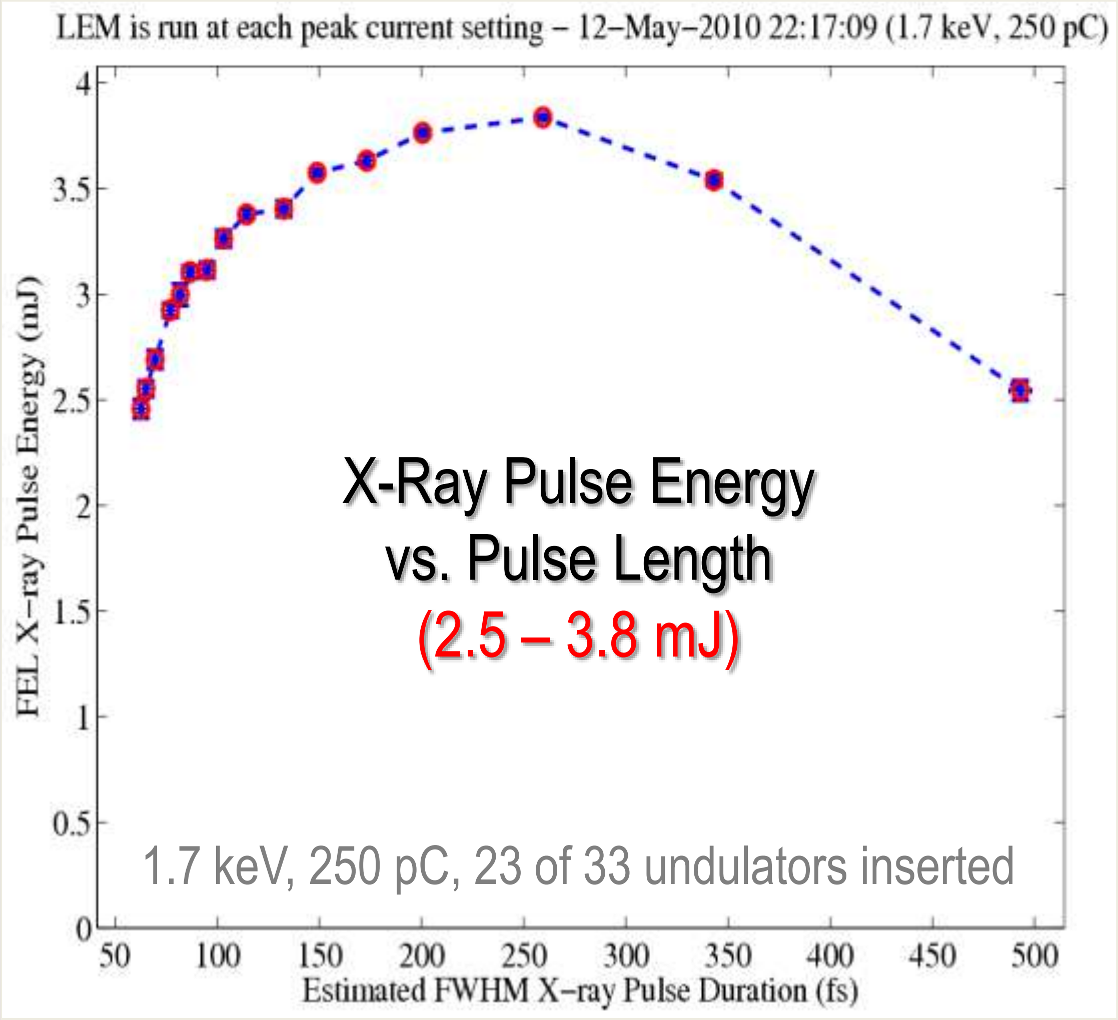
“Instruments have a life of their own. They do not merely follow theory; often they determine theory, because instruments determine what is possible, and what is possible determines to a large extent what can be thought.”

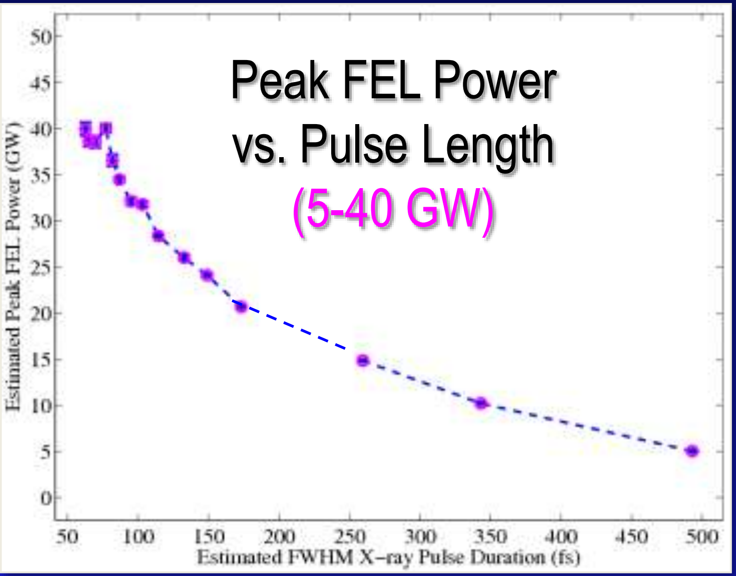
The telescope, the microscope; the chronograph, the photograph: all gave rise to a blossoming of theoretical understanding not possible before their invention.

132-m Long Undulator with 5-DOF Motion Control Girders + IN/OUT



Pulse Length Easily Adjusted (500-60 fs)*





* for soft x-rays (0.5-2 keV)

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