Physik Zentrum Bad Honnef

10-13 April 2012

WE Heraeus Seminar

Free-electron lasers: from fundamentals to applications

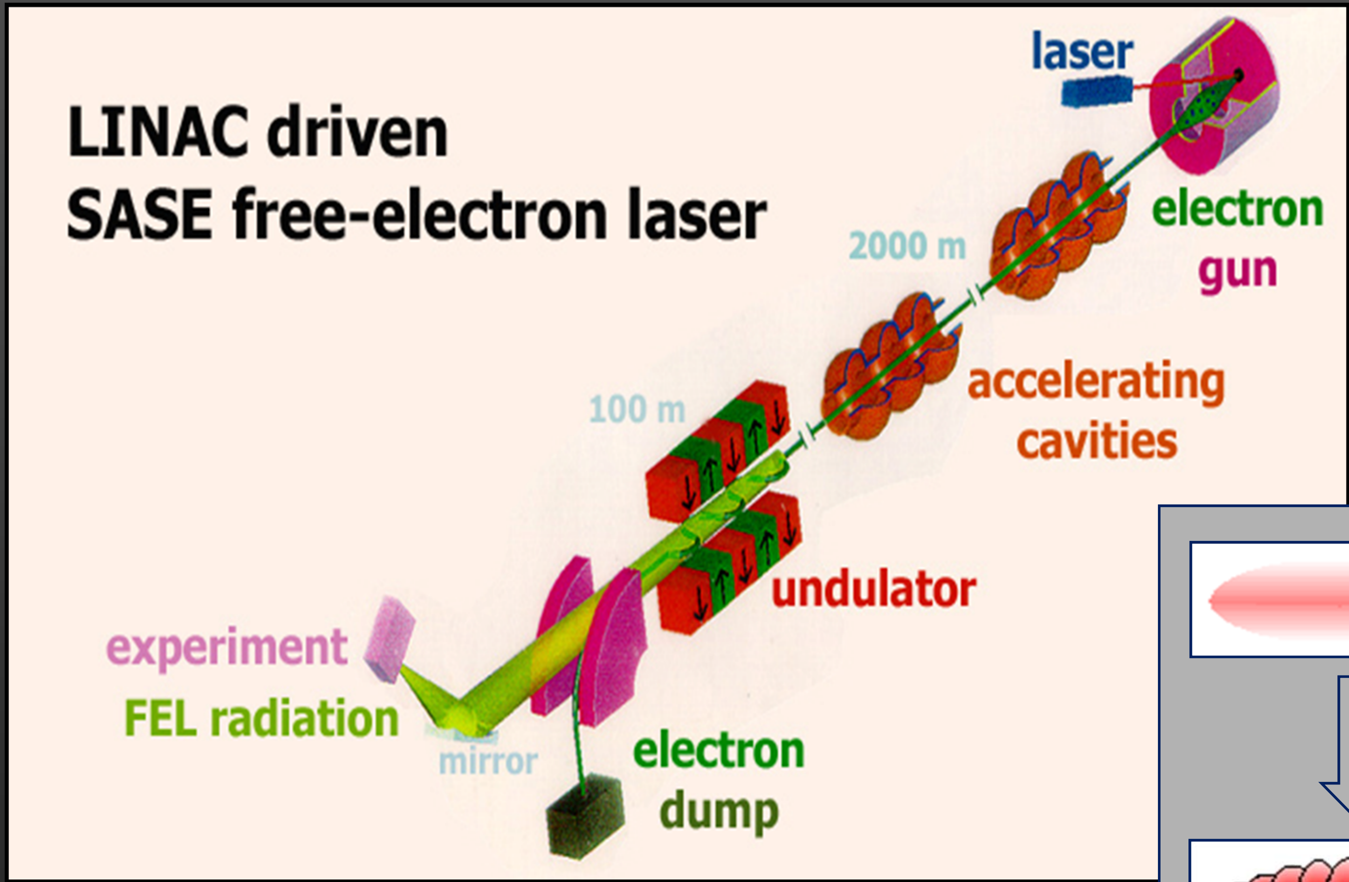
Overview X-ray FELs

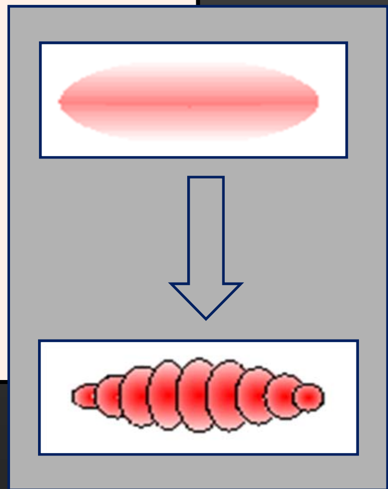
The Science/Facility Ping-Pong

Jochen R. Schneider

Deutsches Elektronen-Synchrotron DESY
Center for Free-Electron Laser Science CFEL

Single-Pass Free-Electron Lasers





challenging technology!

Fascination XFEL radiation

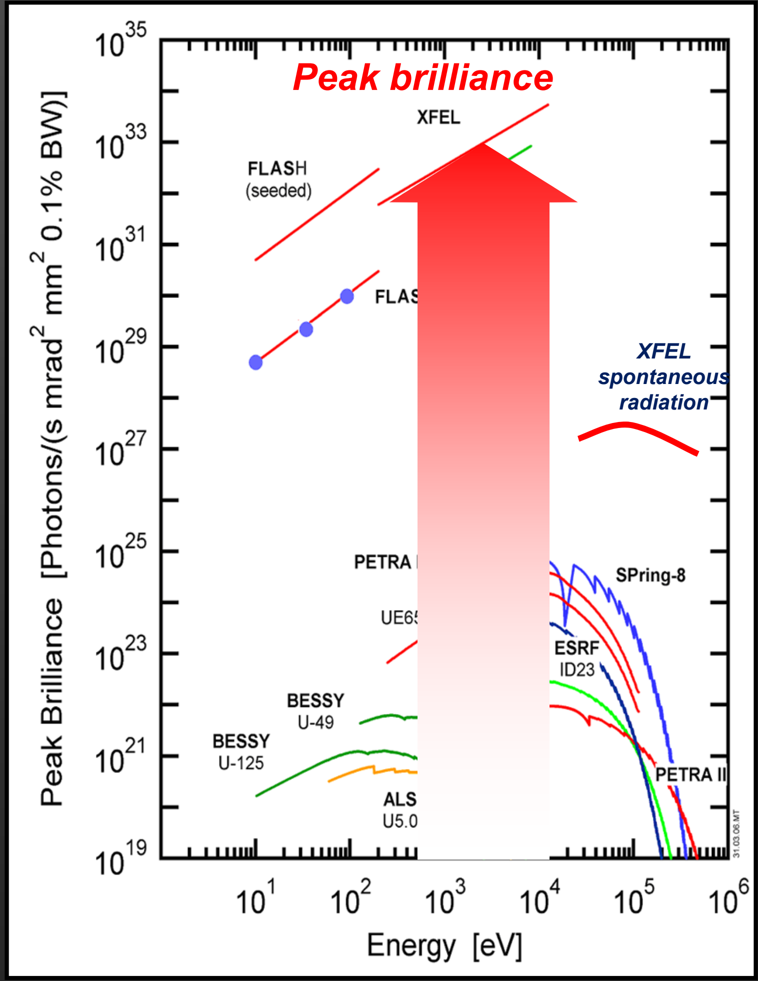
*Compared to 3rd generation storage ring based synchrotron radiation facilities, the **gain factors** are:*

- ***peak brilliance:*** *10^9 at the FEL line*
- ***average brilliance:*** *10^4 at FEL line (E-XFEL)*
- ***coherence:*** *10^9 at FEL line*

With an FEL one gets in a pulse of ~25 fs duration

~10^{13} photons,

i.e. as many as with a modern storage ring in 1 sec



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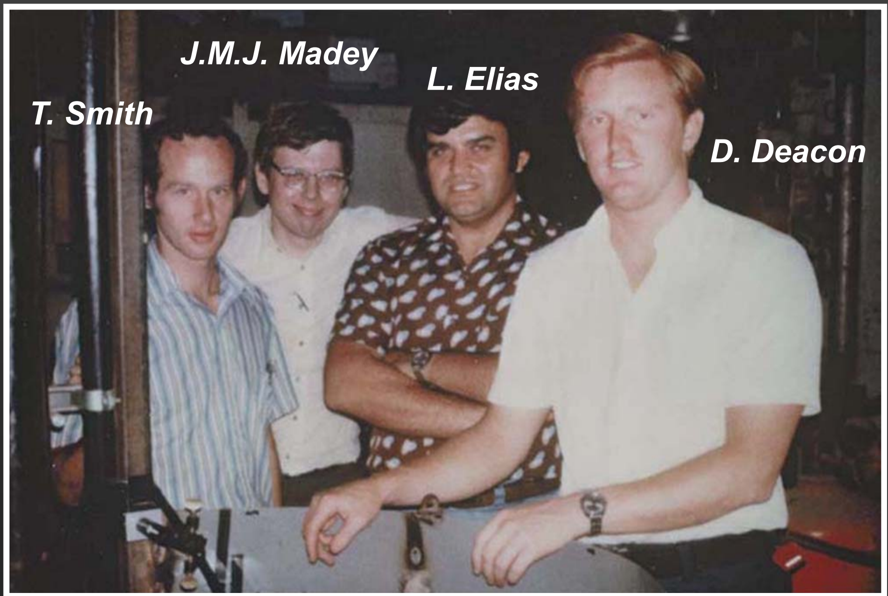
History

Invention of the Free Electron Laser

John M.J. Madey
madey@hawaai.edu

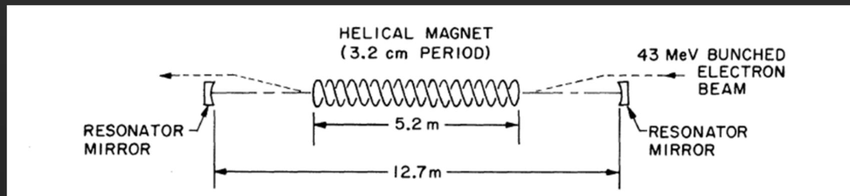
Review of Accelerator Science and Technology, Vol 3 (2010) 1-12
World Scientific Publishing Company
DOI: 10.1142/S1793626810000336



First Operation of a Free-Electron Laser

D.A.G. Deacon, L.R. Elias, J.M.J. Madey,
G.J. Ramian, H.A. Schwettman, and T.I. Smith
(Stanford University)

Phys. Rev. Lett. 38, 892 (1977)



Single-Pass (SASE) Free-Electron Lasers

Two seminal accelerator science papers:

A.M. Kondratenko, E.L. Saldin
"Generation of Coherent Radiation by a Relativistic Electron Beam in an Undulator"
Part. Accelerators 10, 207 (1980)

R. Bonifacio, C. Pellegrini, L.M. Narduci
"Collective Instabilities and High-Gain Regime in a Free-Electron Laser"
Opt. Communications 50, 373 (1984)

Workshops:

1986 ICFA workshop on low emittance e- - e+ beams (BNL)
J.B. Murphy and C. Pellegrini

1990 Workshops on prospects for a 0.1 nm free-electron laser (BNL)
R. Palmer, W. Willis, J.G. Gallardo

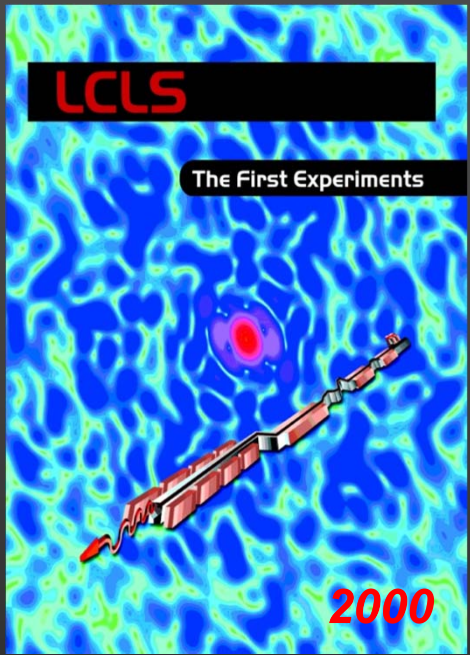
1992 Workshop on Forth Generation Light Sources (SLAC)
M. Cornacchio and H. Winnick

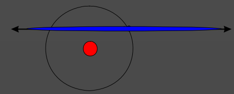
1992 Workshop on Scientific Applications of Short Wavelength Coherent Light Sources (SLAC)
W. Spicer, J. Arthur, H. Winnick

1994 Workshop on Scientific Applications of Coherent X-rays (SLAC)
J. Arthur, G. Materlik, H. Winnick

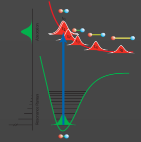
Scientific case for hard X-ray FELs

SLAC Report 611

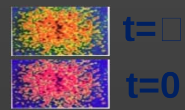




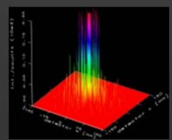
Atomic, molecular and optical sciences (AMO)



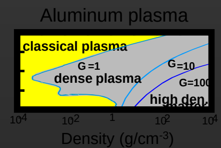
Diffraction studies of stimulated dynamics (pump-probe) - femtochemistry



Coherent-scattering studies of nanoscale fluctuations (XPCS)



Nano-particle and single molecule imaging



High energy density science (HEDS)

Updated scientific case for soft X-rays (2010):

Baseline Pre-conceptional Design for a „Next Generation Light Source"

Lawrence Berkeley National Laboratory, Berkeley, USA

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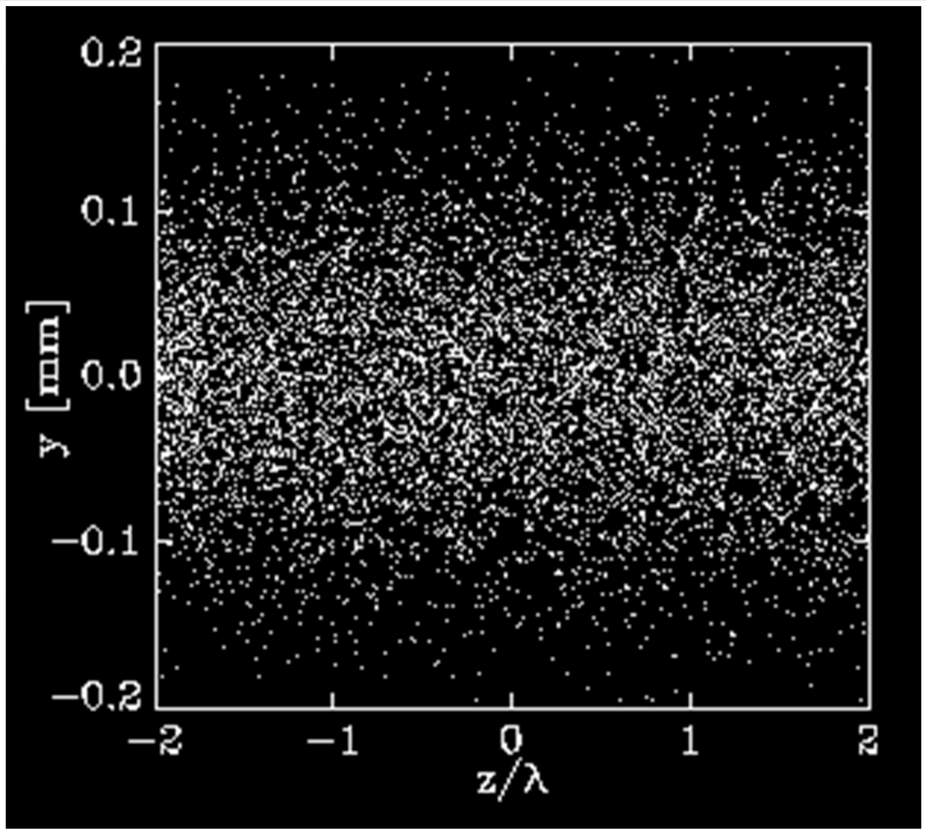
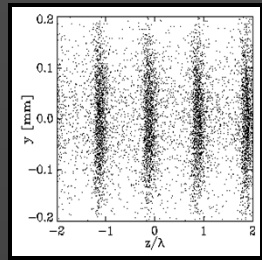
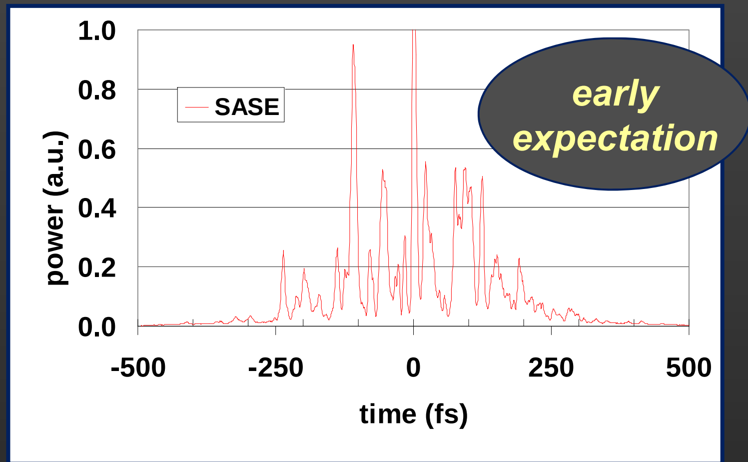
SASE electron bunch modulation



GENESIS **- simulation for FLASH parameters**
Courtesy - Sven Reiche (PSI)

full saturation





Temporal profile of a SASE radiation pulse, generated by an electron bunch of $\sigma_t \approx$ 250 fs

Improvements by seeding or reducing electron bunch length

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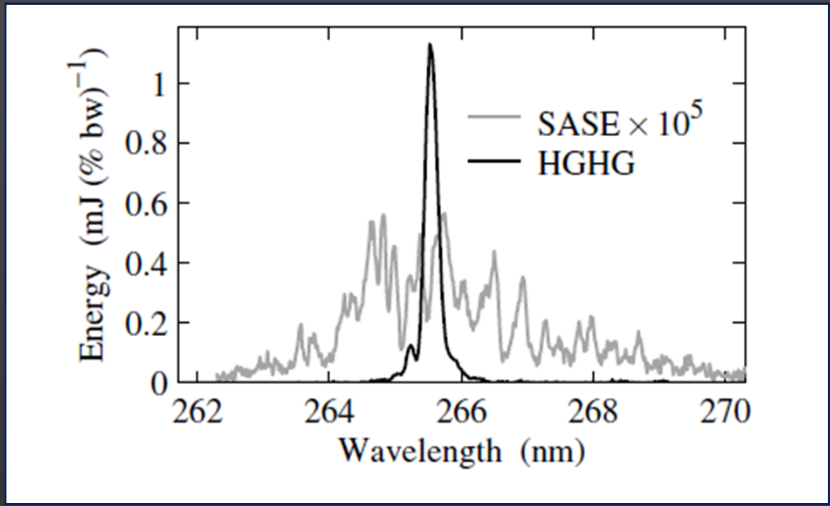
External vs. Self-Seeding for Soft X-rays

First Ultraviolett High-Gain Harmonic-Generation Free-Electron Laser

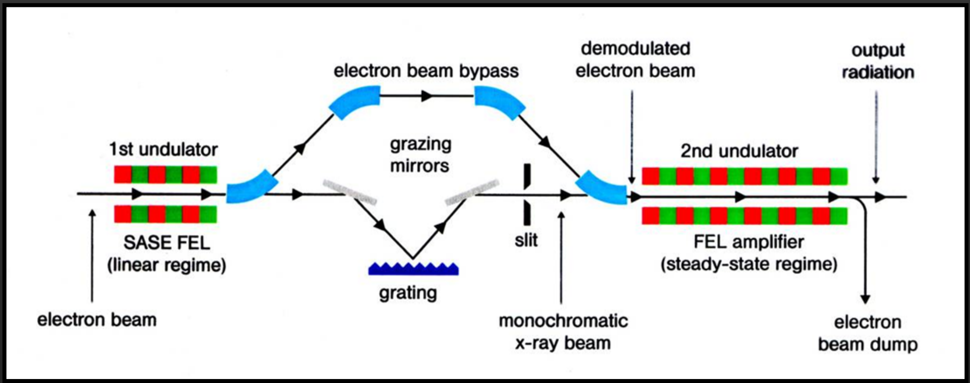
L. H. Yu et al. (NSLS at Brookhaven National Laboratory)

Phys. Rev. Lett. 91 (2003) 074801



Fermi@Elettra: 43 nm, 6th harmonic

Concept



Feldhaus J, Saldin E L, Schneider J R, Schneidmiller E A, and Yurkov M V

Opt. Communications 140, 341-352 (1997)

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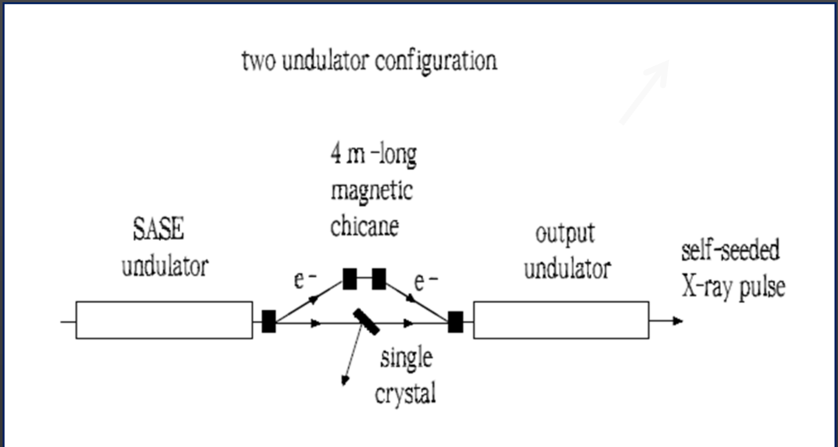
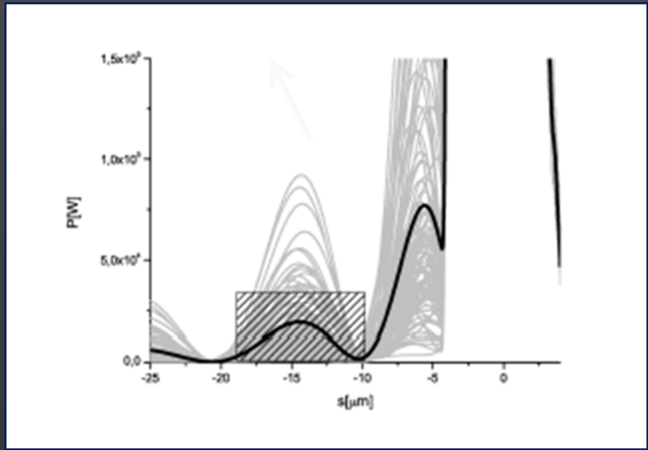
Self-Seeding for Hard X-rays

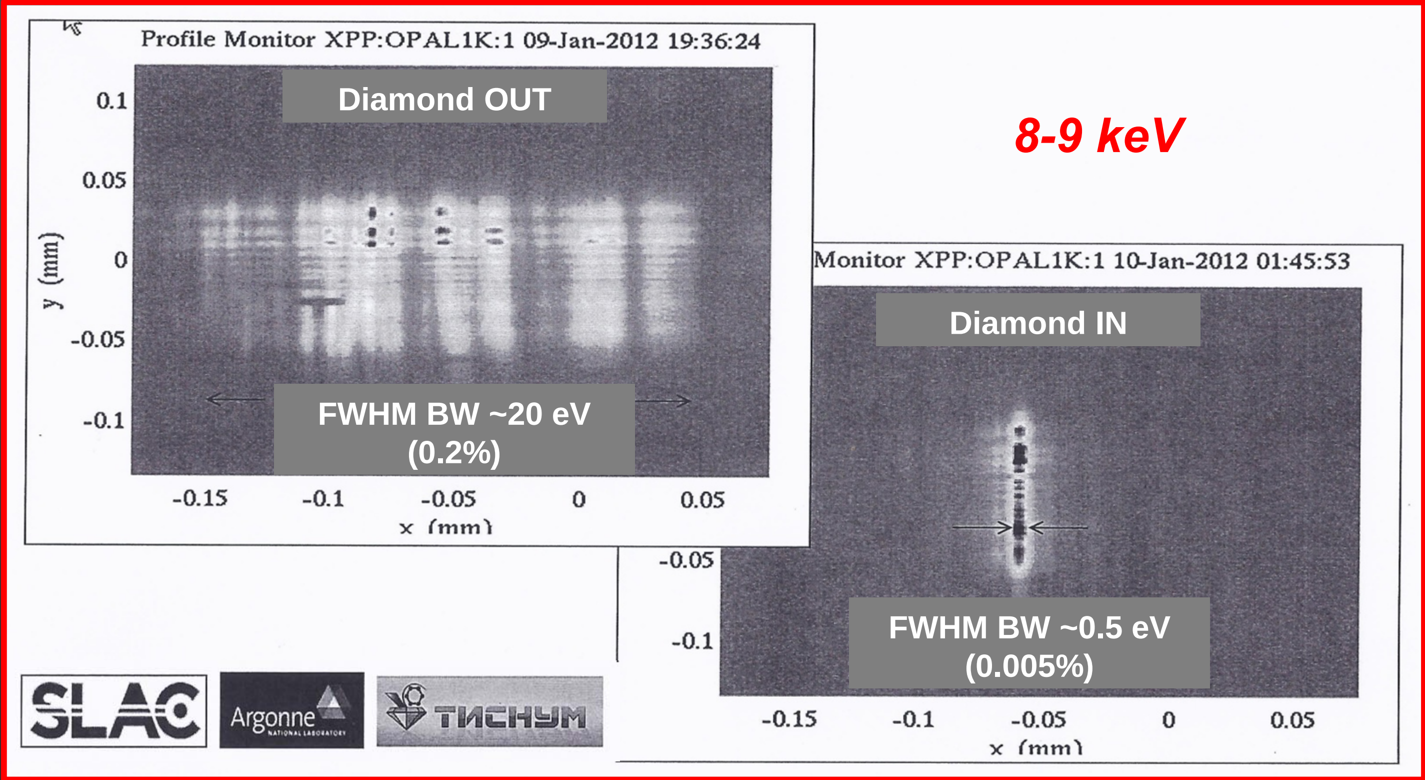
Gianluca Geloni, Vitali Kocharyan, and Evgeni Saldin

arXiv: 1109.511v1 [physics.acc-ph] 23 Sept 2011





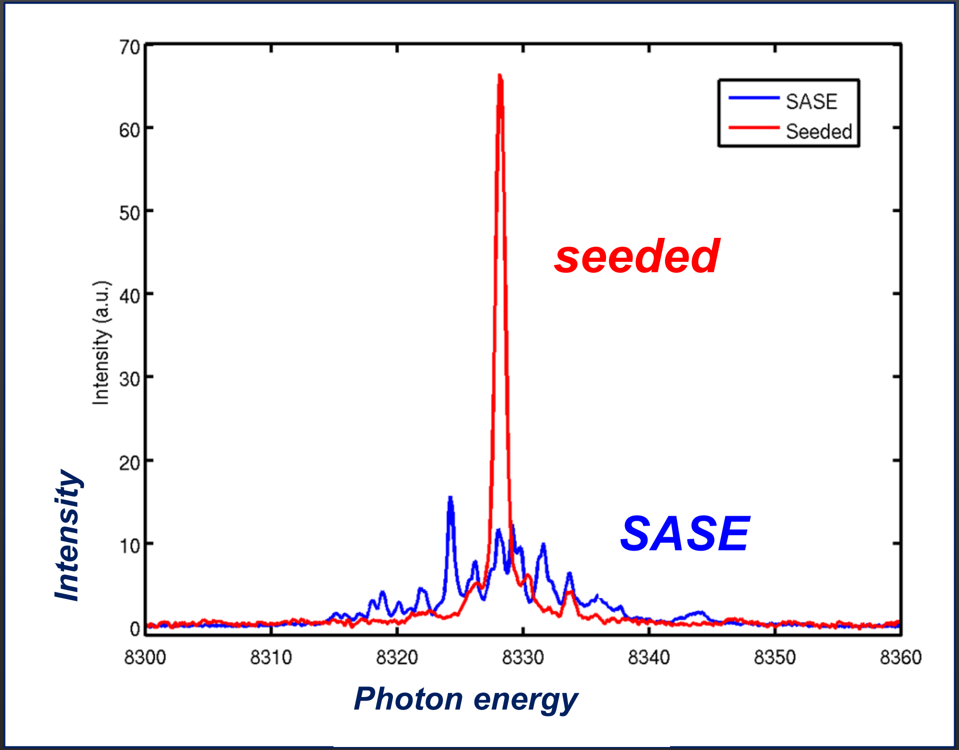
It works at LCLS (Jan. 2012)



XFEL radiation: From „laser-like“ to „very, very much laser-like“

Self-Seeding for Hard X-rays

It works at LCLS



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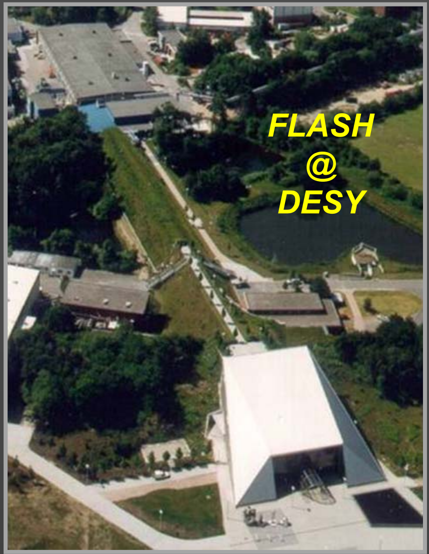
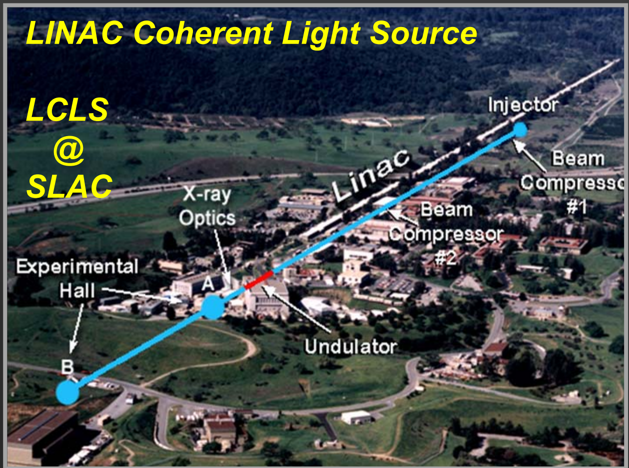


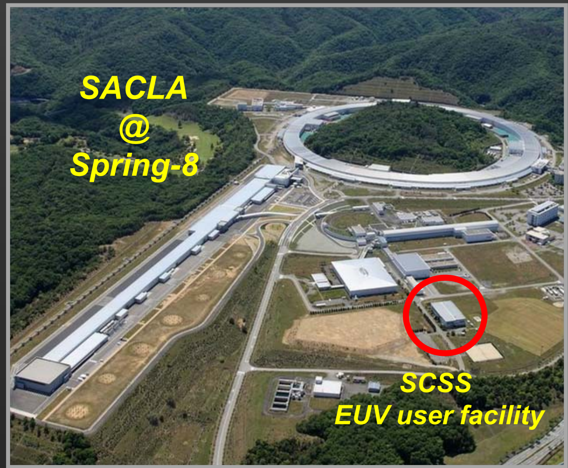
In Operation since
Aug 2005

Today:

Evolution of Science
with X-ray FELs
is
largely determined by
availability of facilities

Commissioning since
Summer 2011





In operation since

Oct 2009

Fall 2011

Operation expected
End of 2015

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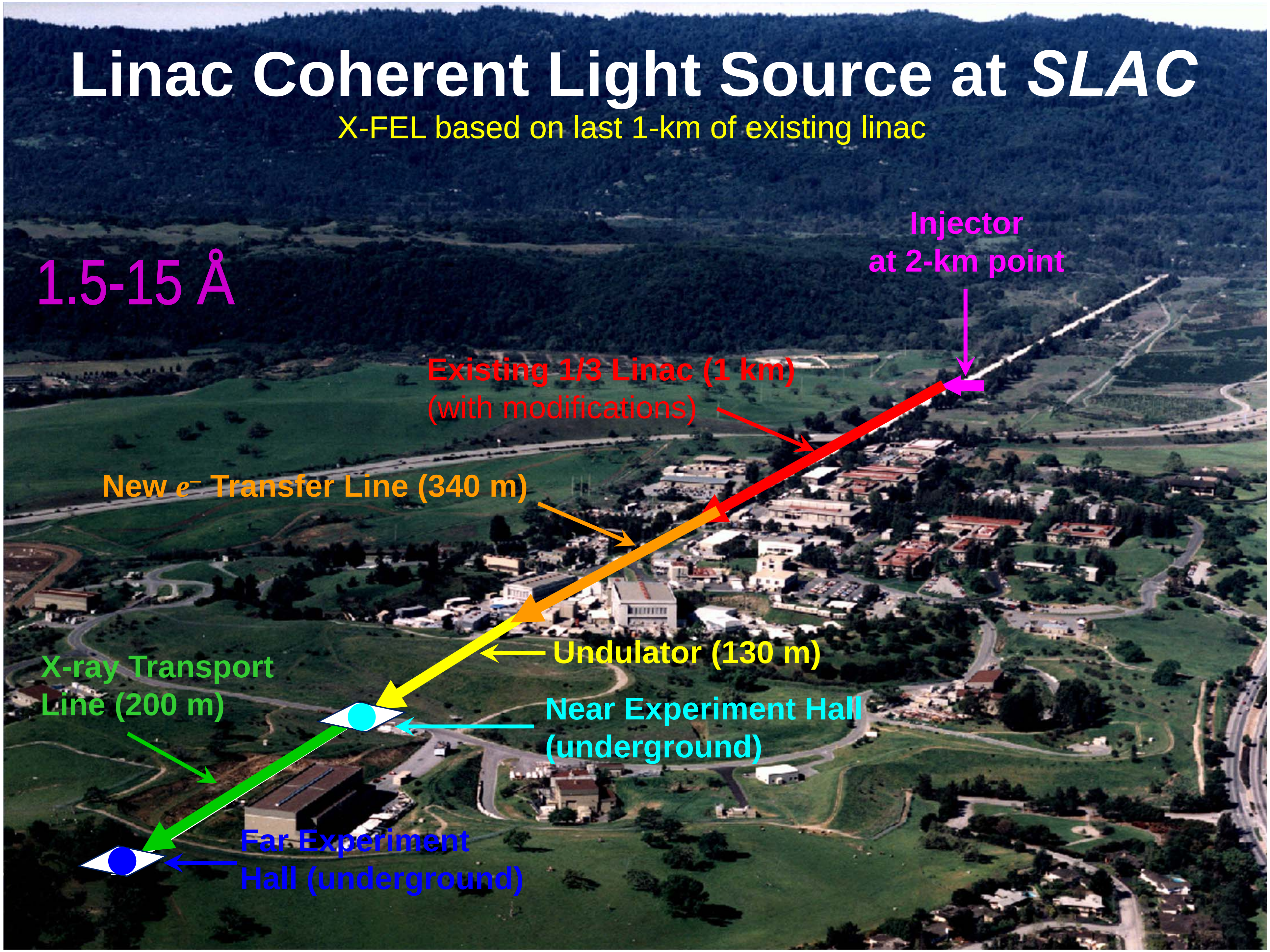
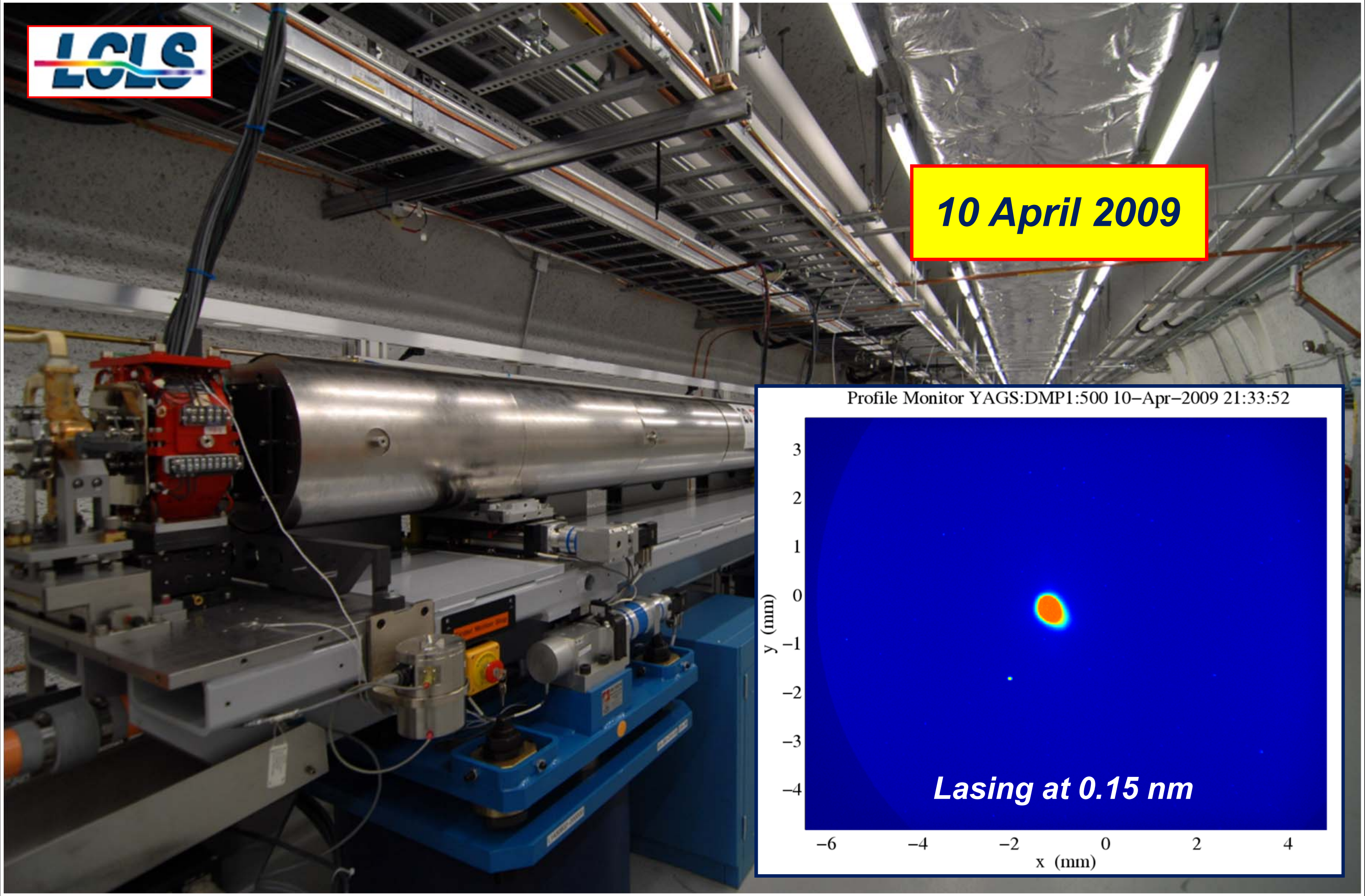

Linac Coherent Light Source at SLAC
X-FEL based on last 1-km of existing linac
1.5-15 Å
Injector
at 2-km point
Existing 1/3 Linac (1 km)
(with modifications)
New e^- Transfer Line (340 m)
Undulator (130 m)
X-ray Transport
Line (200 m)
Near Experiment Hall
(underground)
Far Experiment
Hall (underground)

LCLS – the Linac Coherent Light Source at SLAC



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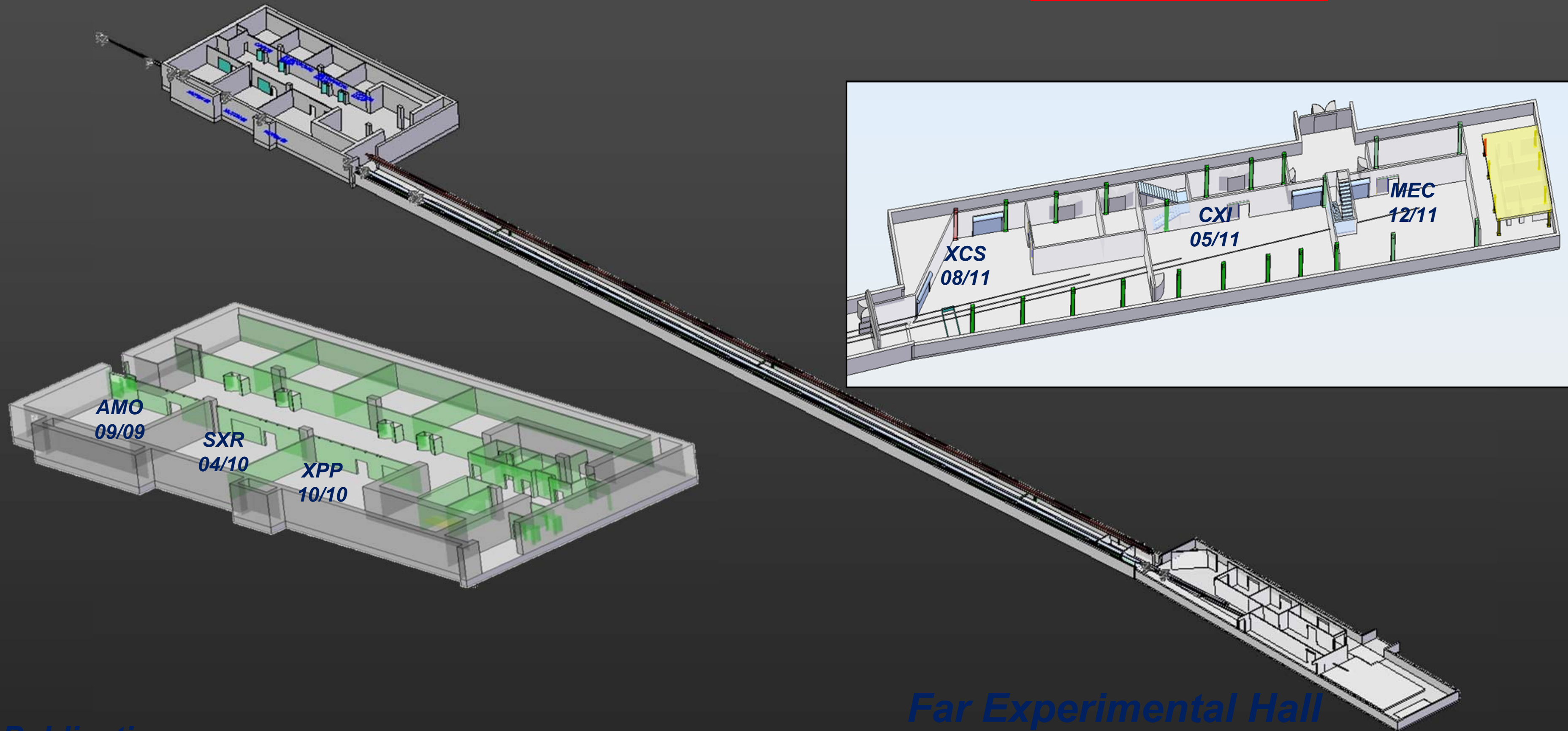
LCLS layout of experimental areas

Near Experimental Hall



Publications:

LCLS: ***https://slacportal.slac.edu/sites/lcls_public/Pages/Publications.aspx (38)***

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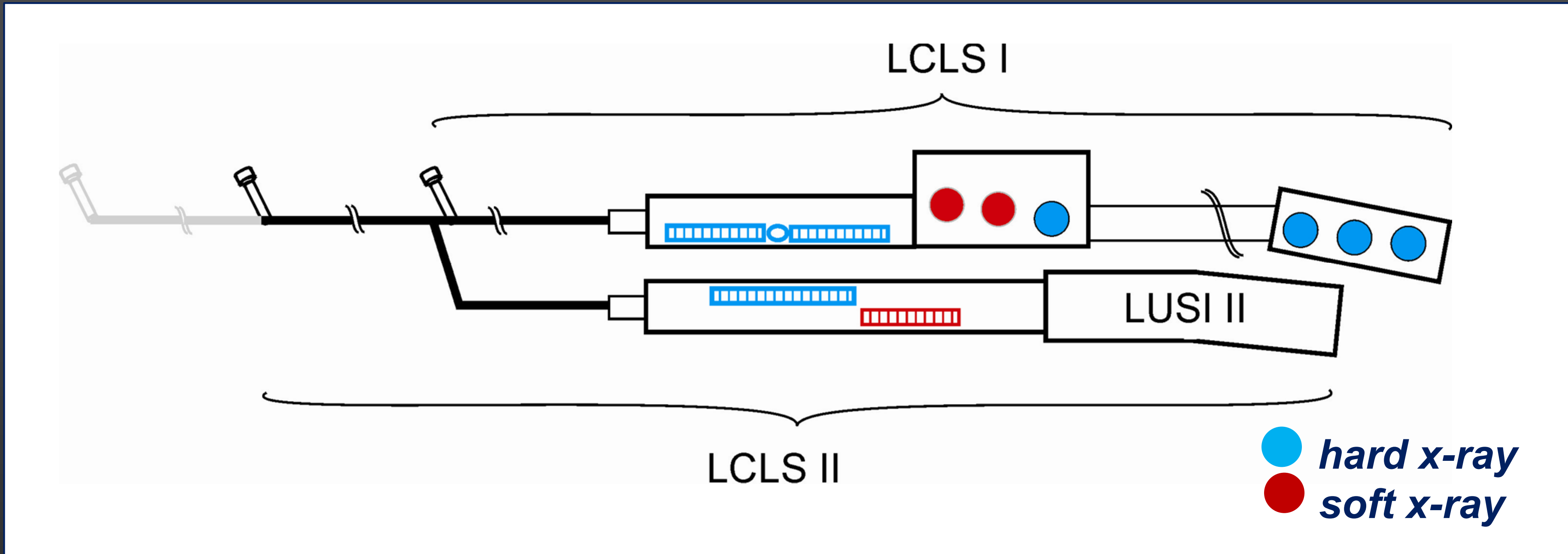
LCLS-II is part of long-term LCLS 2025 strategy

(courtesy Jo Stöhr)



Workshop focus is on LUSI II:

- ***science opportunities***
- ***enabling capabilities and capacities, e.g beam parameters and instrumentation***

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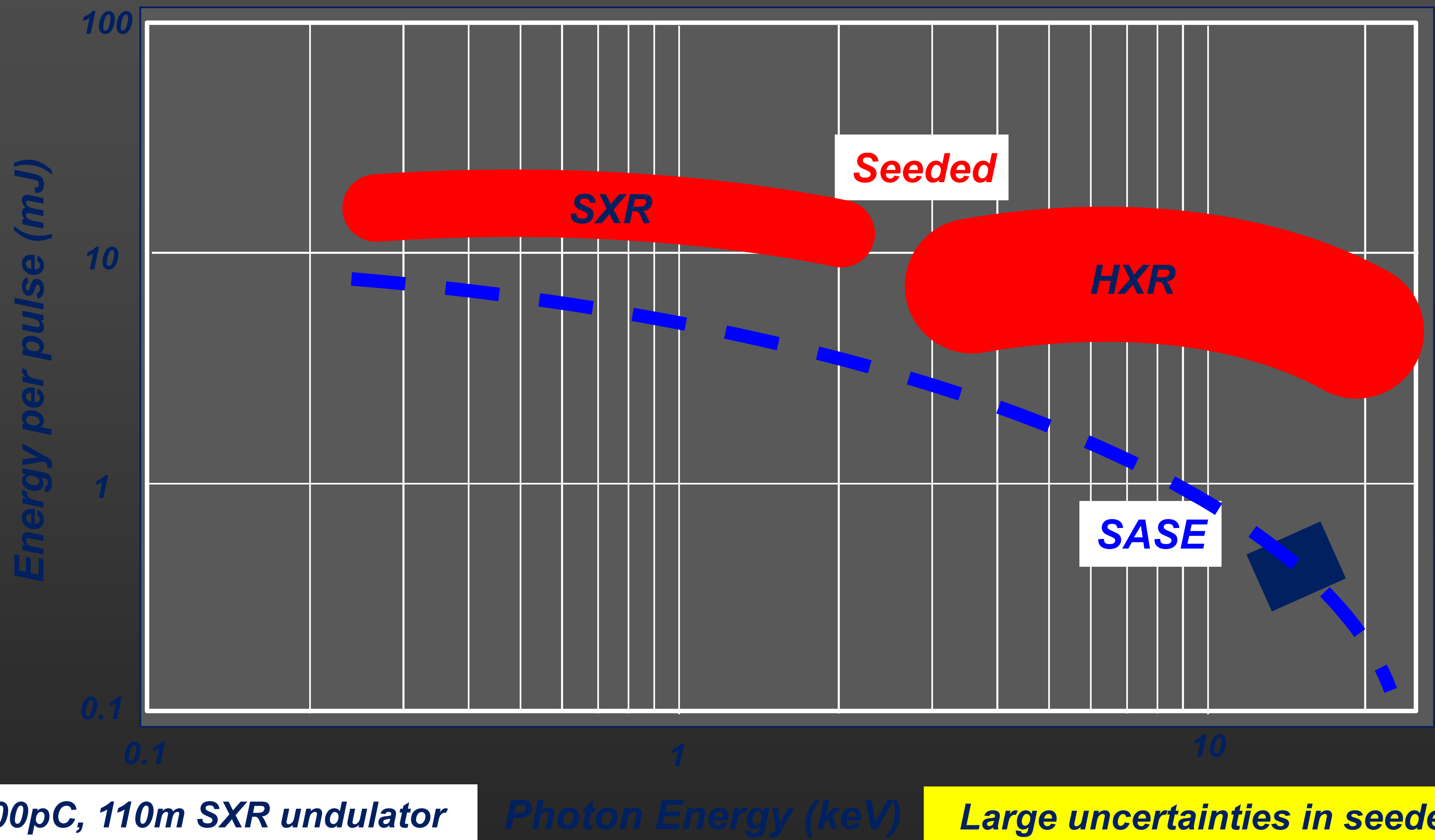
LCLS seeded source characteristics

(courtesy John Arthur)



100pC, 110m SXR undulator
50pC, 250m HXR undulator

Large uncertainties in seeded optimization and sensitivity

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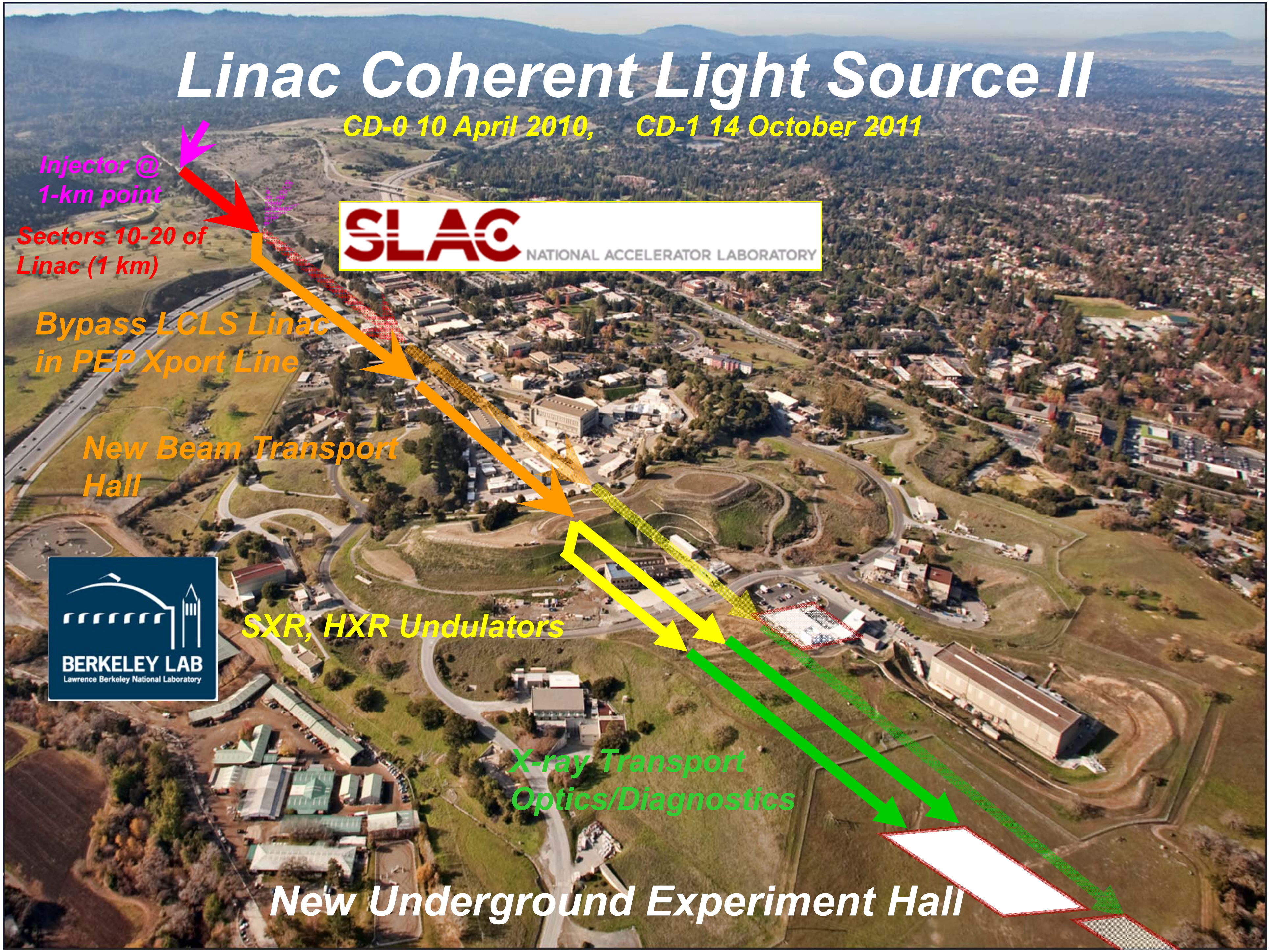
Linac Coherent Light Source II
CD-0 10 April 2010,
CD-1 14 October 2011
Injector @ 1-km point
Sectors 10-20 of Linac (1 km)
SLAC NATIONAL ACCELERATOR LABORATORY
Bypass LCLS Linac in PEP Xport Line
New Beam Transport Hall
BERKELEY LAB
Lawrence Berkeley National Laboratory
SXR, HXR Undulators
X-ray Transport Optics/Diagnostics
New Underground Experiment Hall

Spring-8 Angstrom Compact Free-Electron Laser

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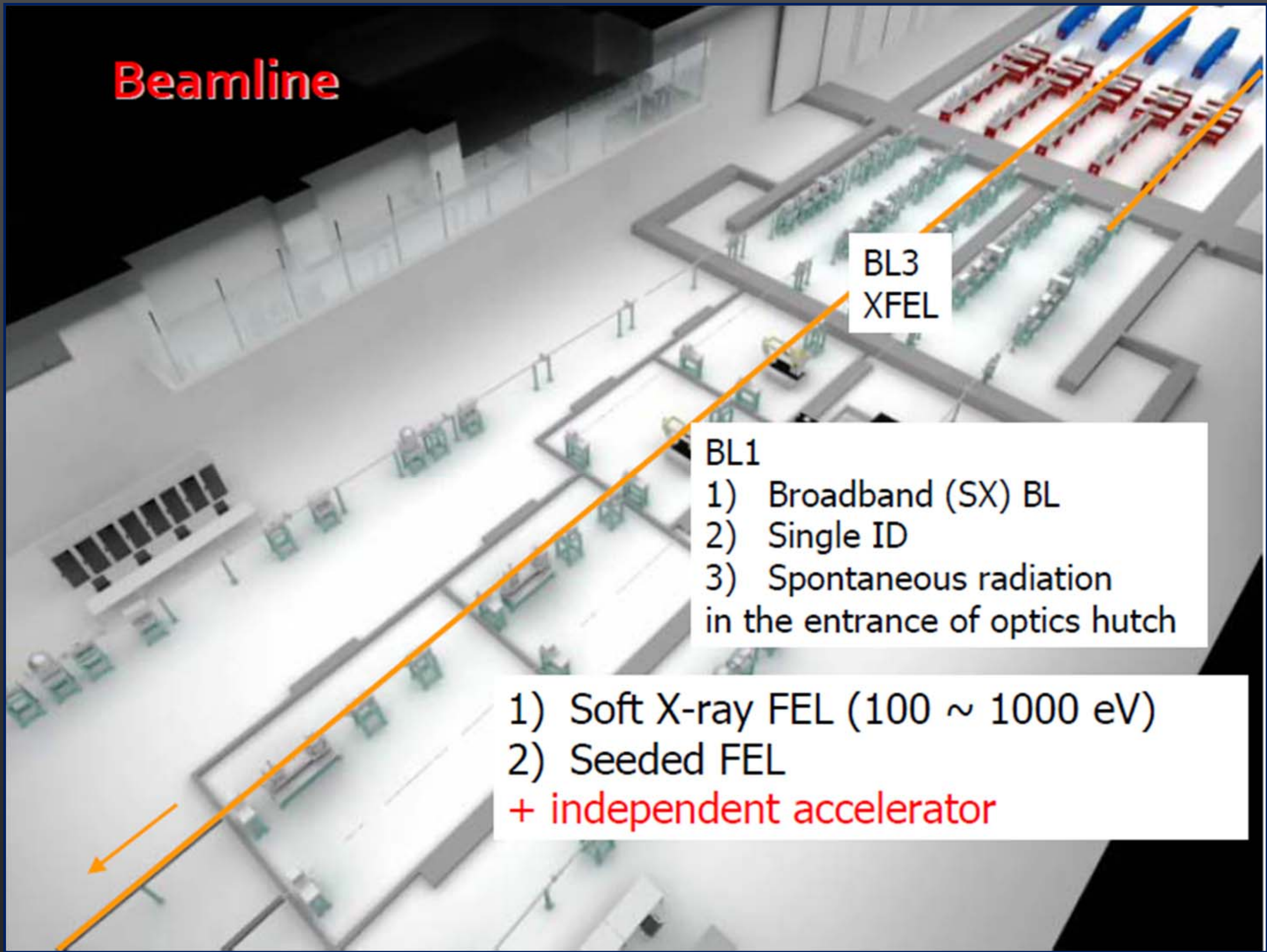
jochen.schneider@desy.de

Spring-8 Angstrom Compact Free-Electron Laser

(courtesy Makina Yabashi)



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European XFEL Facility (XFEL)

Technical Design Report published in July 2006

DESY started civil construction January 2009

Realization as European Facility in 2 steps

1. step: 3 radiators with 6 experimental stations (1150 M€ in 2011 prices)

2. step: Full facility (TDR) with 5 radiators and 10 experimental stations

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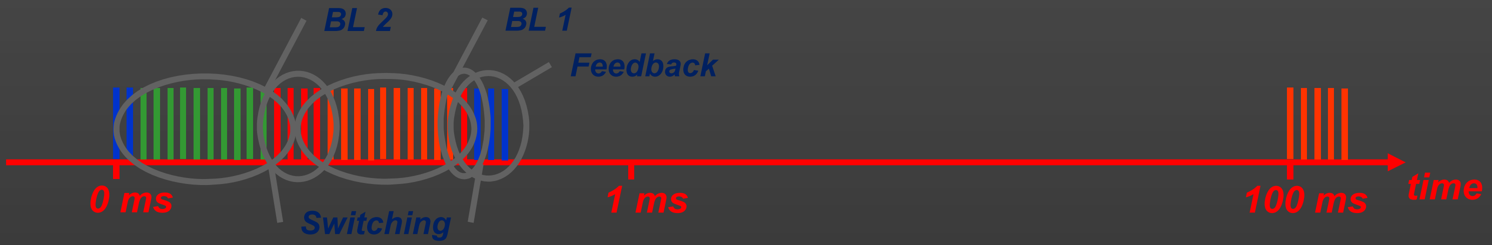
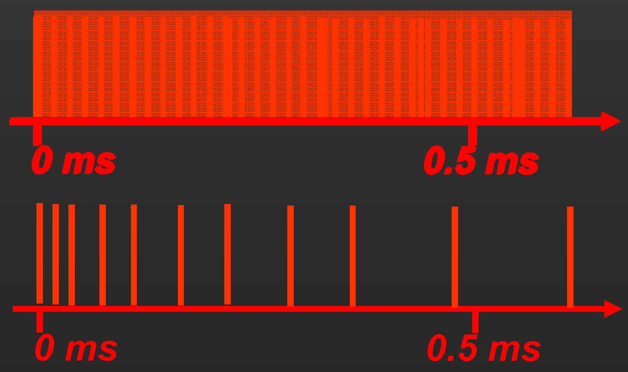
European XFEL: tunnel work

European XFEL time structure

– operate sc-accelerator in almost steady-state mode
– division of bunchtrain into functional portions :
  - intra-train feedback → stabilization (x, t, E)
  - two sub-trains going to two e^- beam lines
  - gaps for switching between beam lines



– time pattern for each beam line can be determined by experiment
  - single pulses
  - medium repetition rate (10 – 100 kHz)
  - high repetition rates (0.1 → 1 → 5 MHz)
  - special fills
    – logarithmic distribution
    – shorter distances (~700 ps – 200 ns)



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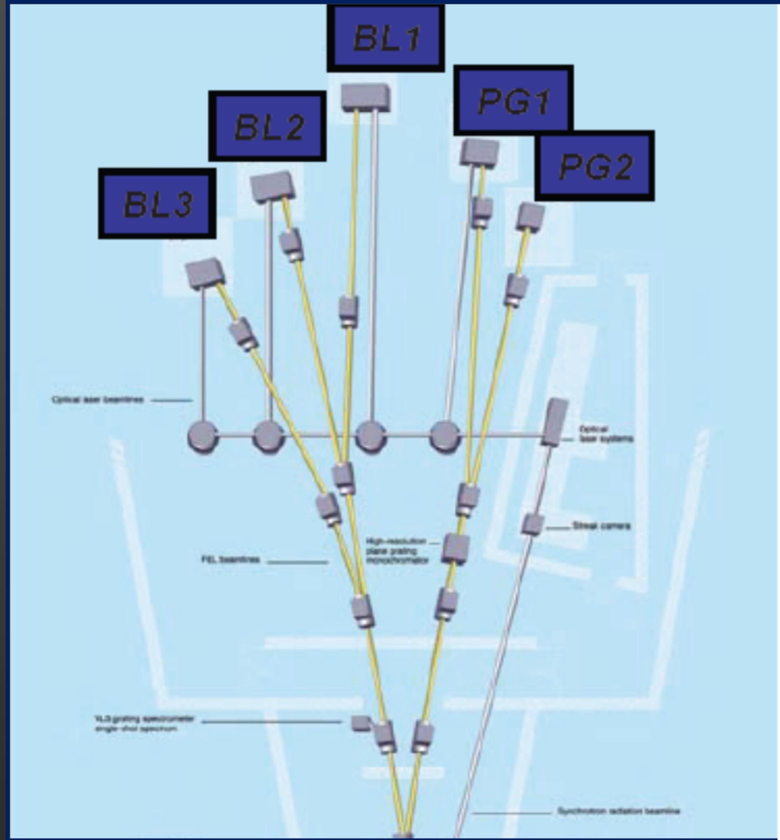
FLASH at DESY



- 5 VUV beamlines + 1 THz beamline
- focused and unfocused beamlines available
- plane grating monochromator (PG beamlines)

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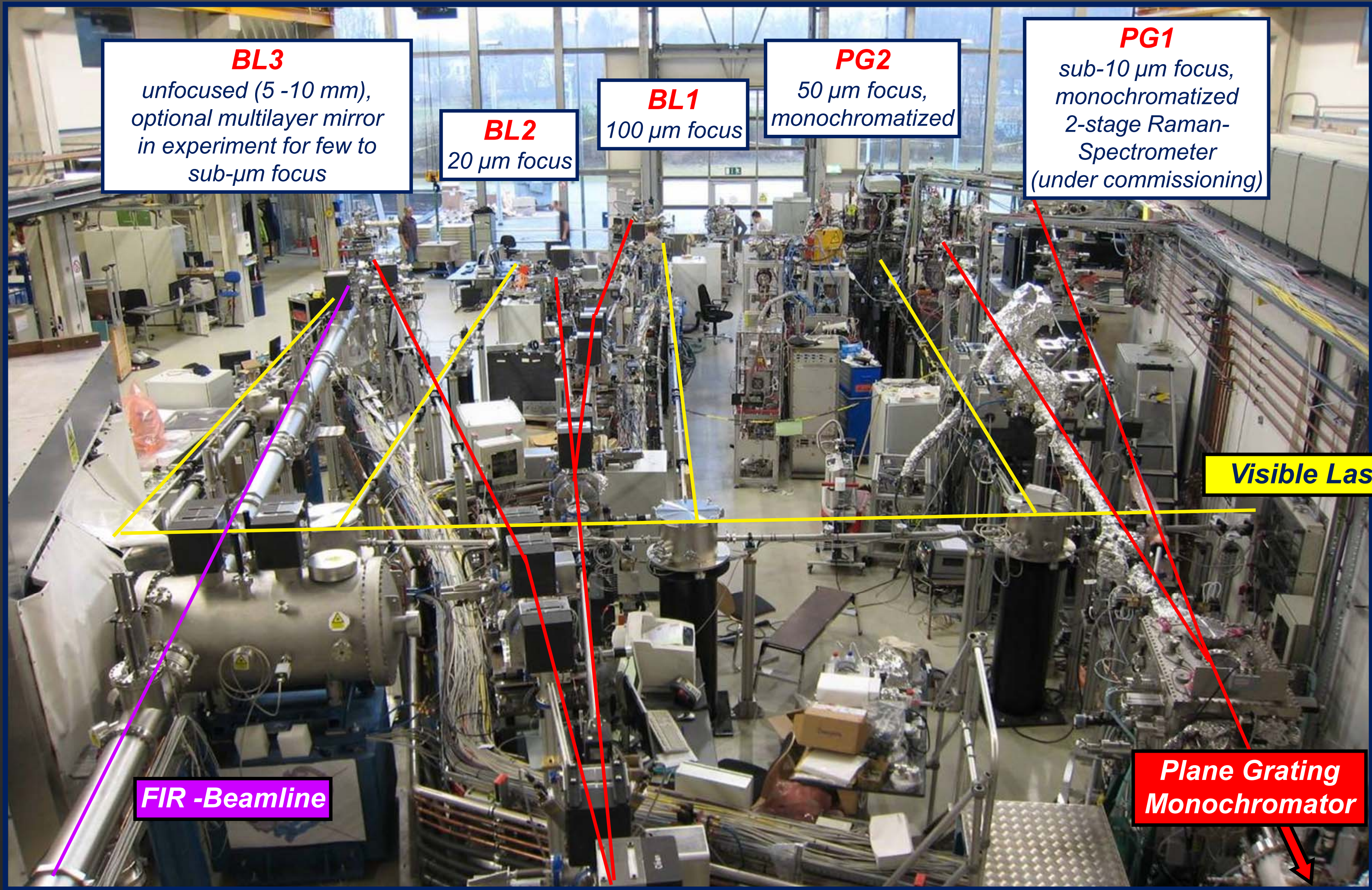
FLASH experimental hall



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Scientific papers from FLASH

Start of user operation: August 2005

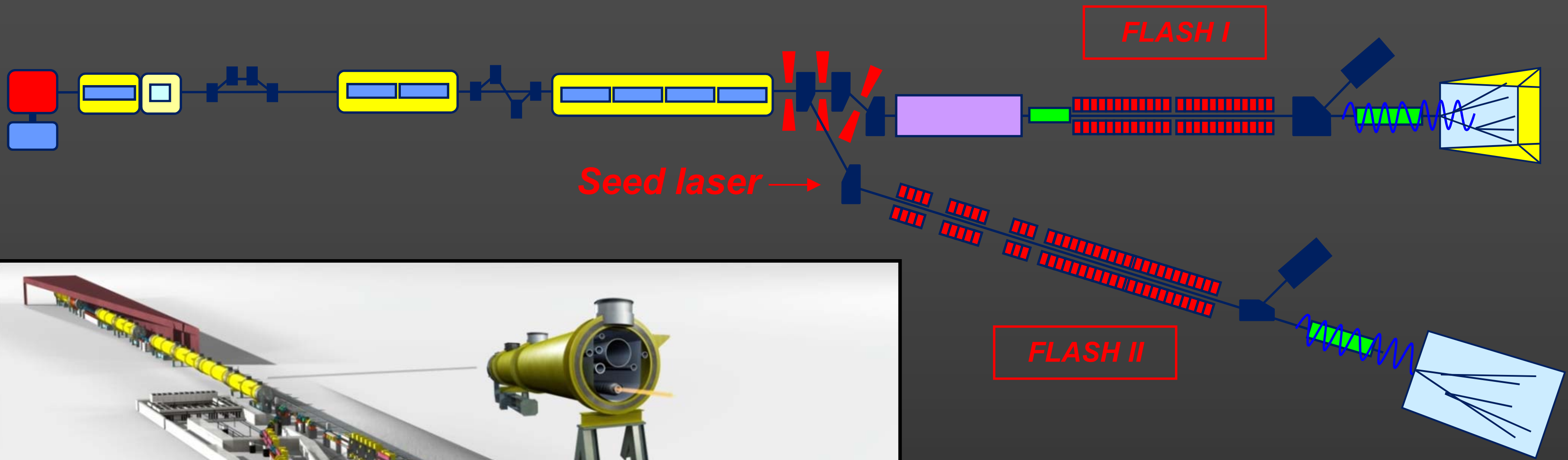
155 science papers have been published in refereed journals

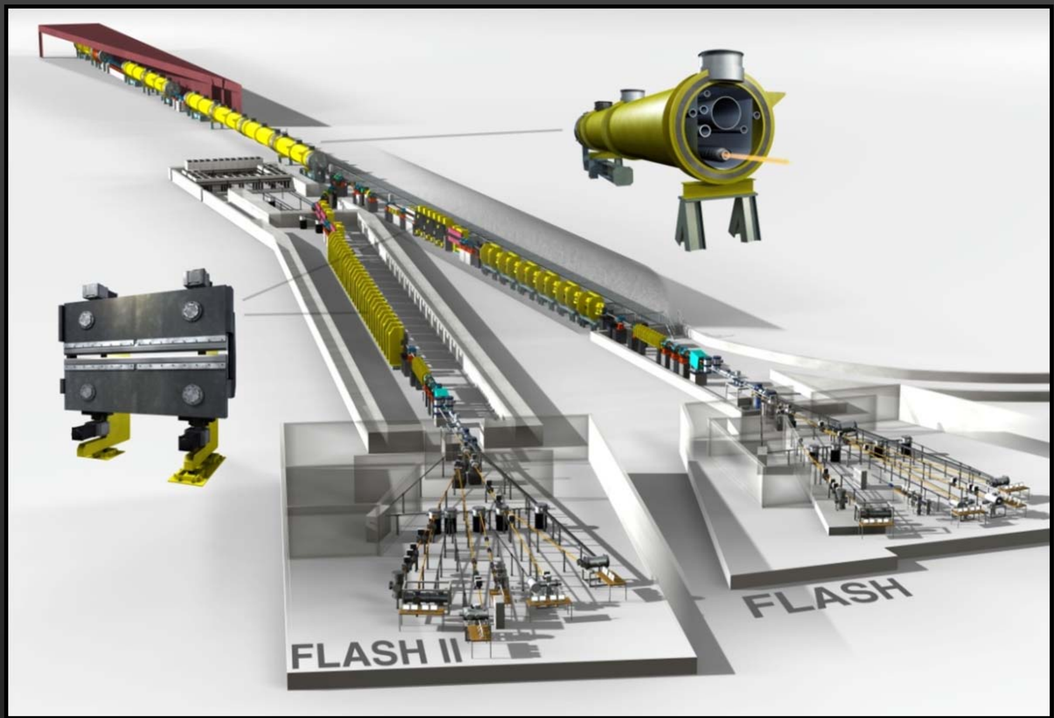
http://hasylab.desy.de/facilities/flash/publications/selected_publications/

- *Atoms, molecules*
- *Clusters*
- *High energy density,*
- *Radiation damage*
- *Single shot imaging*
- *Single shot nano-crystallography*
- *Condensed matter: spectroscopy, phase transitions*
- *Diagnostics*
- *Instrumentation*

In addition numerous papers on accelerator and FEL physics

Upgrade scenarios at FLASH *FLASH-II*





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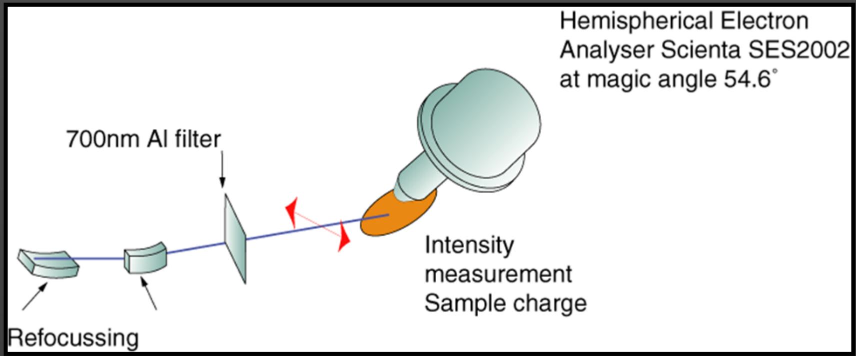
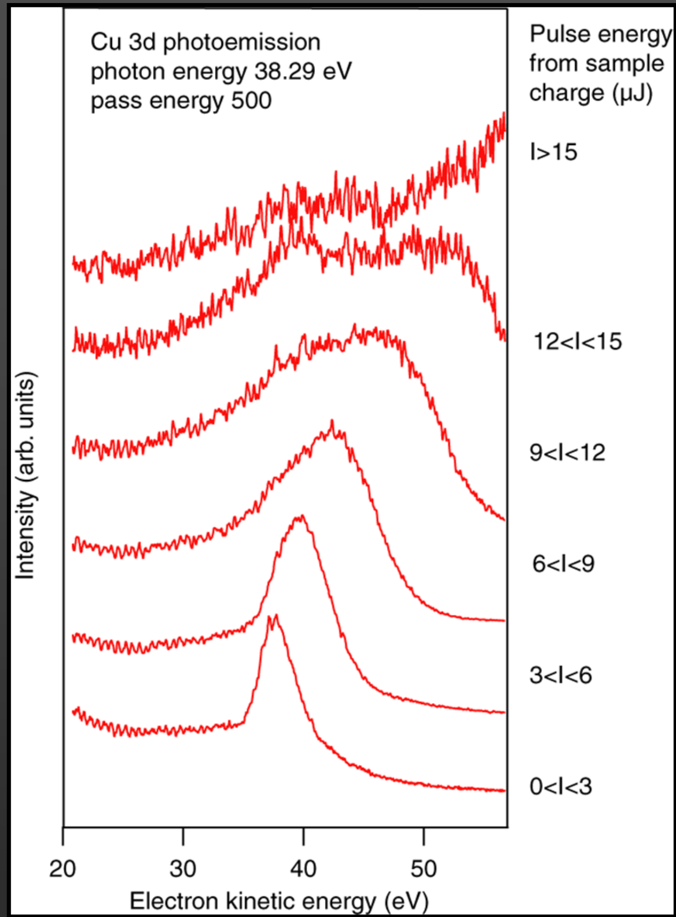
Single Shot Photoemission





Towards single shot time resolved pump–probe spectroscopy for non-reversible dynamics.

At high peak brilliance space charge limitations.

Cu subshell photoionization cross section at 38.29 eV:
3d: 9.934 Mb/atom 4s: 0.041 Mb/atom

A. Pietzsch, A. Föhlisch, M. Nagasono, W. Wurth

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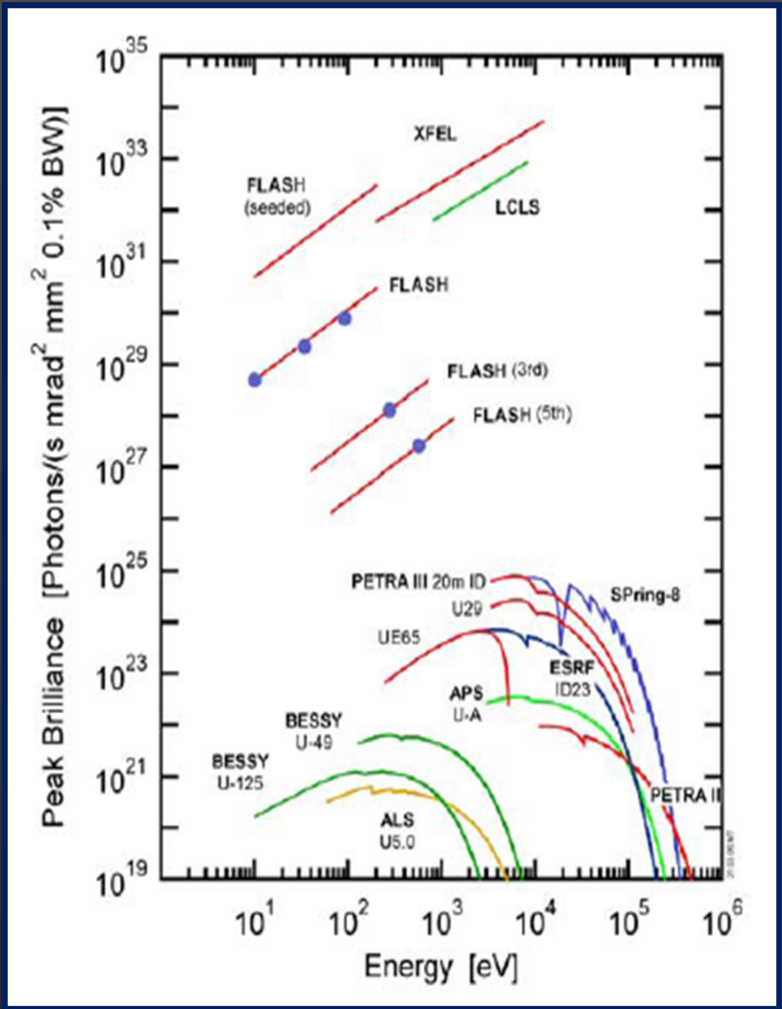
jochen.schneider@desy.de

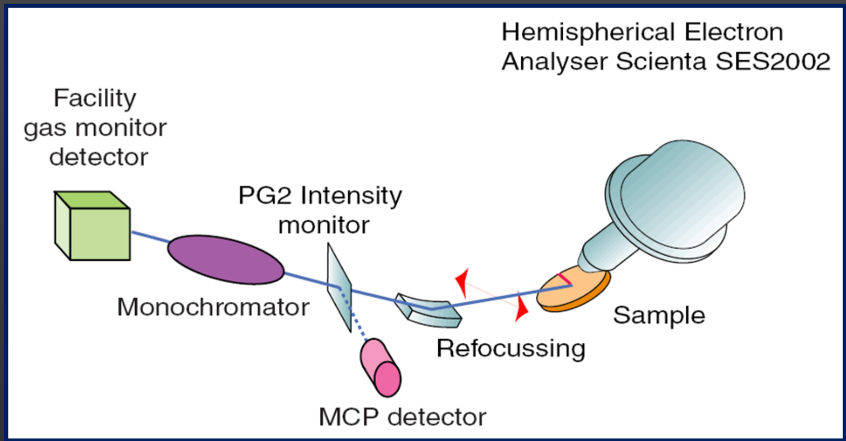


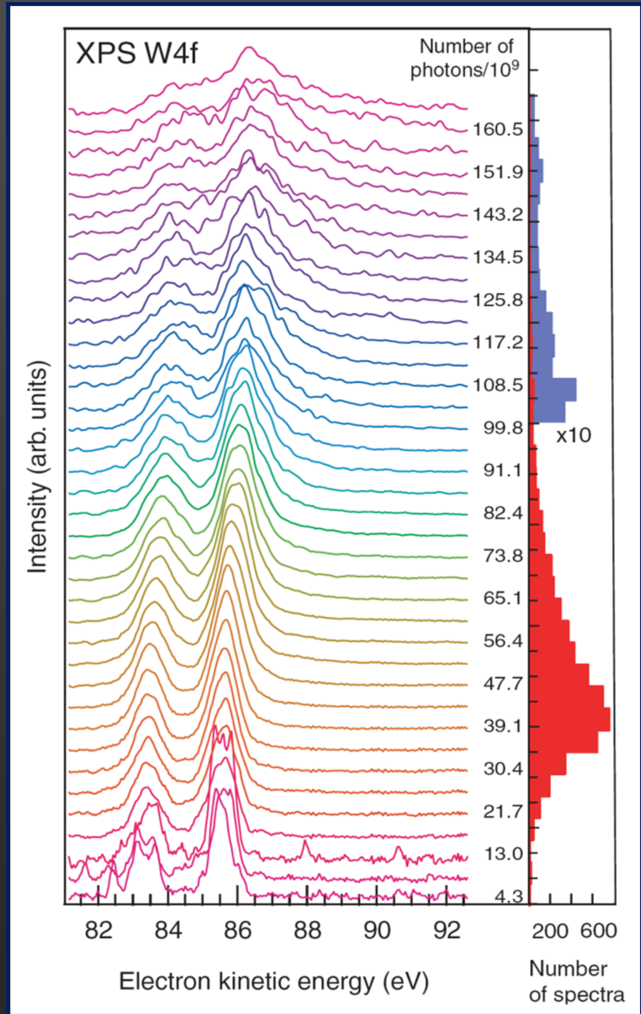
peak brilliance

Time resolved photoemission at FEL

Towards time-resolved single-shot photoemission

Exploring space charge limits

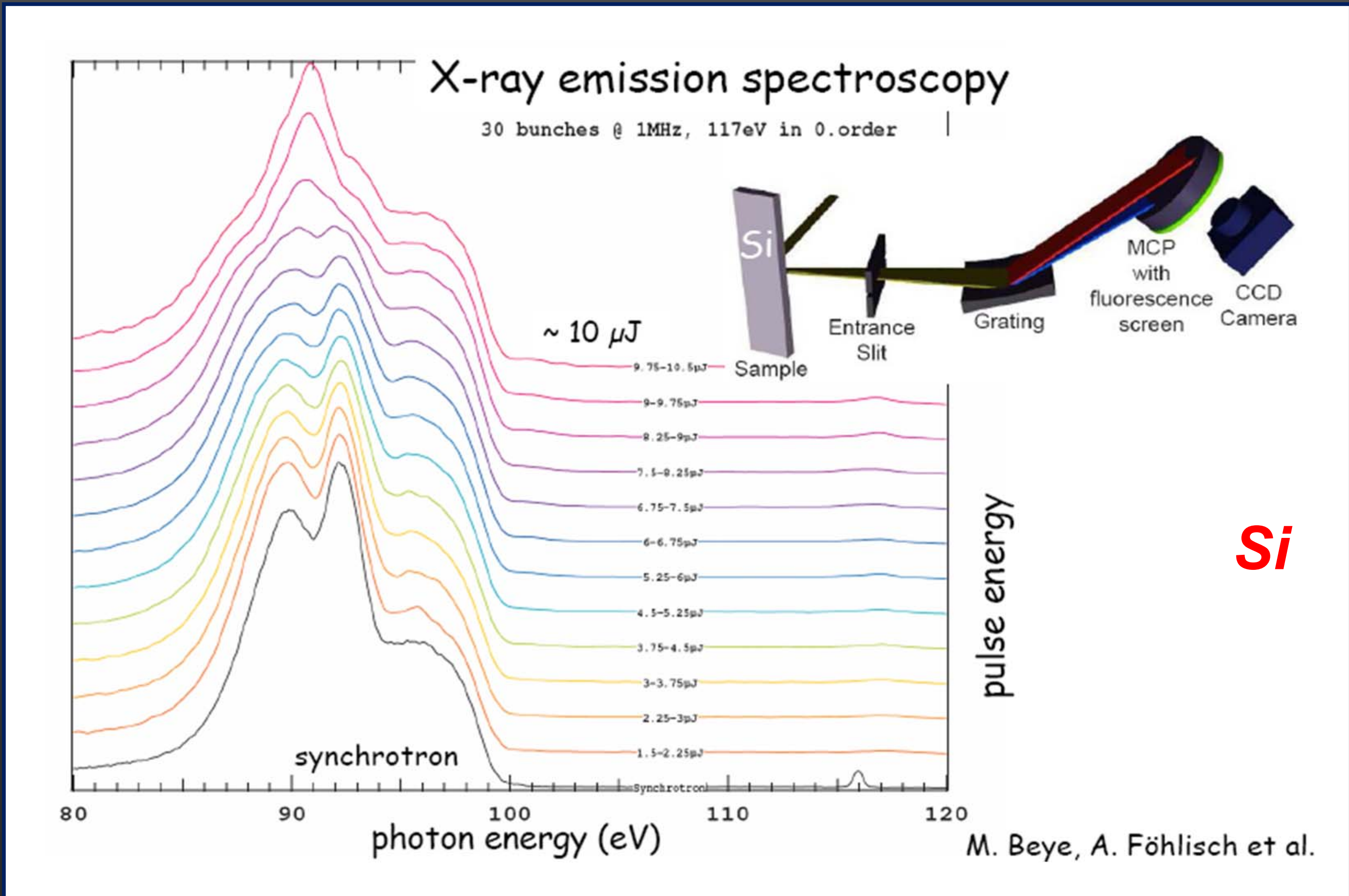




W 4f lines ;
FLASH 118.5 eV (3rd harmonic)
50 pulses/macrobunch

A. Pietzsch et al., New Journal of Physics 10 (2008) 033004

Photon-in / photon-out experiments

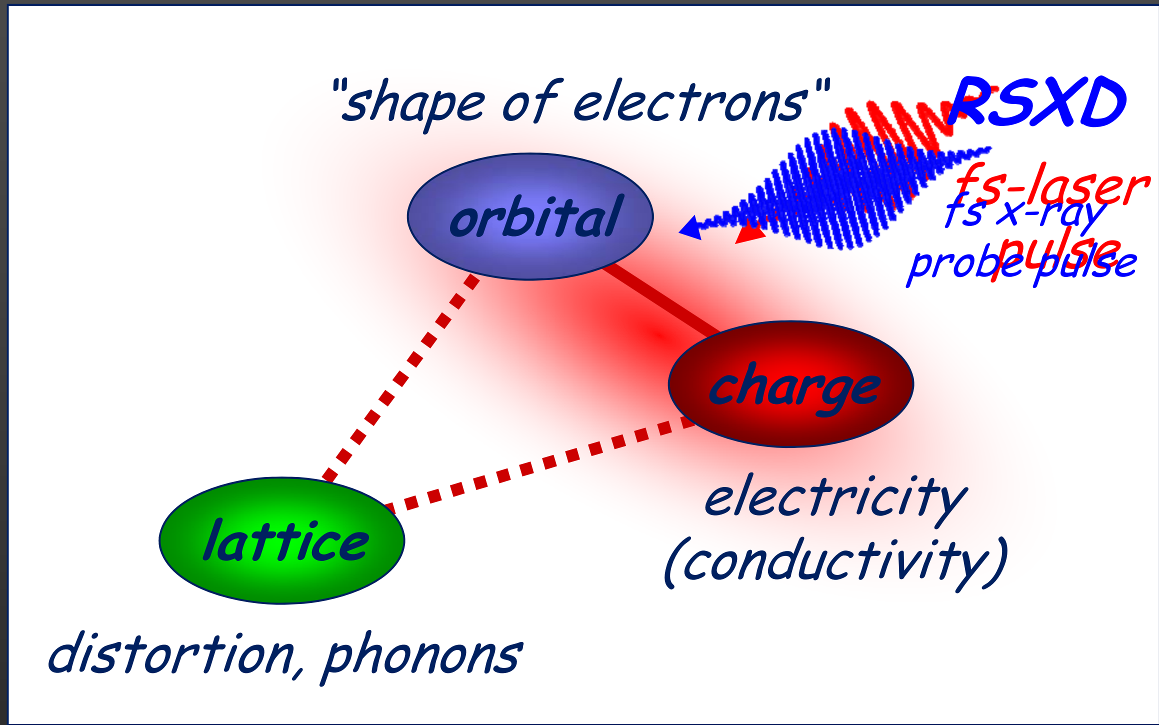


The physics of strongly correlated materials

interplay between different degrees of freedom

Verwey transition in Fe_3O_4 at 120K:

- insulator ↔ 'metal'
- charge order ↔ disorder
- orbital order ↔ disorder
- structural transition



- selective heating of the electronic degrees of freedom
- probe electronic order by resonant soft x-ray diffraction

courtesy N. Pontius

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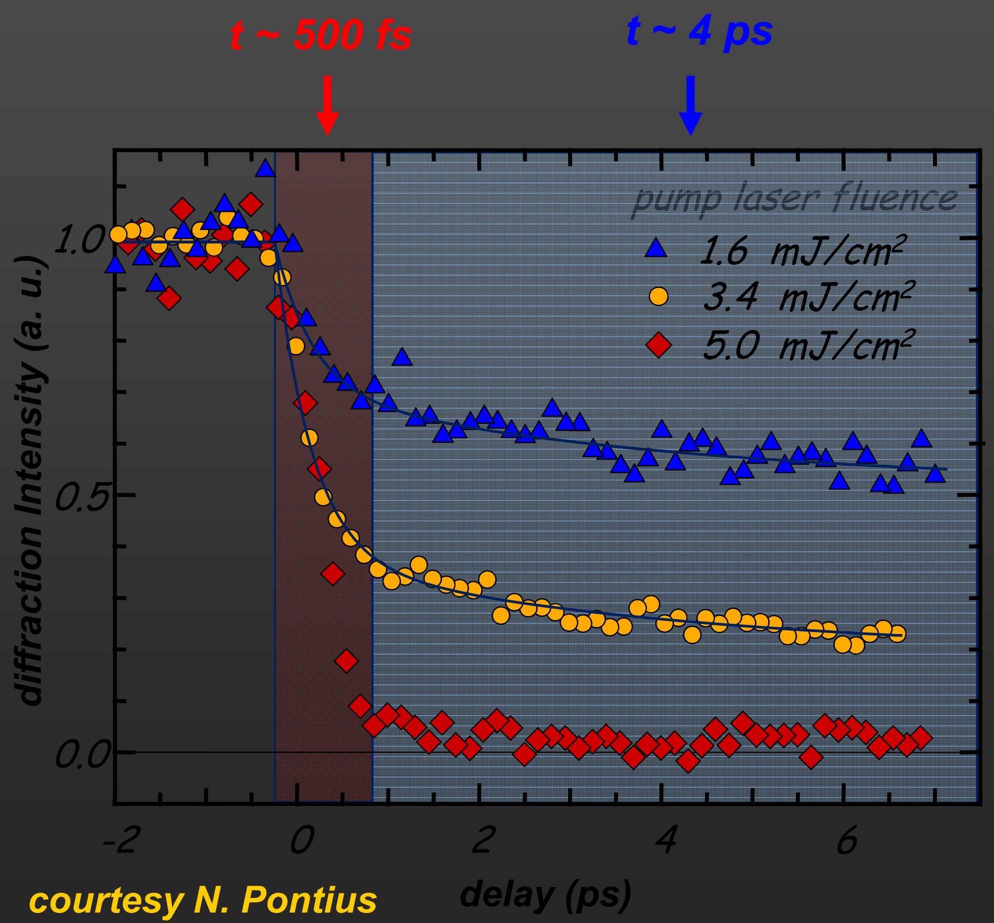
jochen.schneider@desy.de

Real time observation of femtosecond polaronic dynamics in magnetite

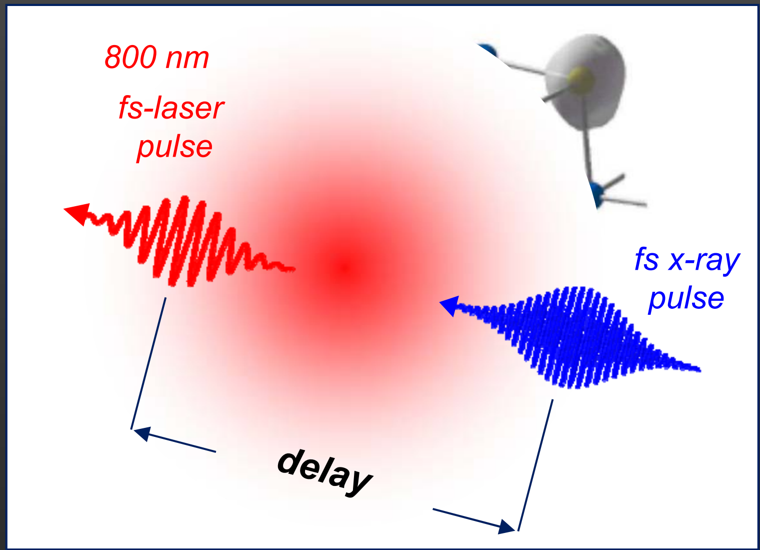
N. Pontius[1], T. Kachel[1], C. Schüßler-Langeheine[2], W. Schlotter[3], M. Beye[3], C. F. Chang[2], F. Sorgenfrei[3], A. Föhlisch[3], W. Wurth[3], P. Metcalf[4], I. Leonov[5], A. Yaresko[6], N. Stojanovic[7], H. A. Dürr[1]

first time-resolved RSXD at FLASH

oxygen edge at 529 eV



courtesy N. Pontius

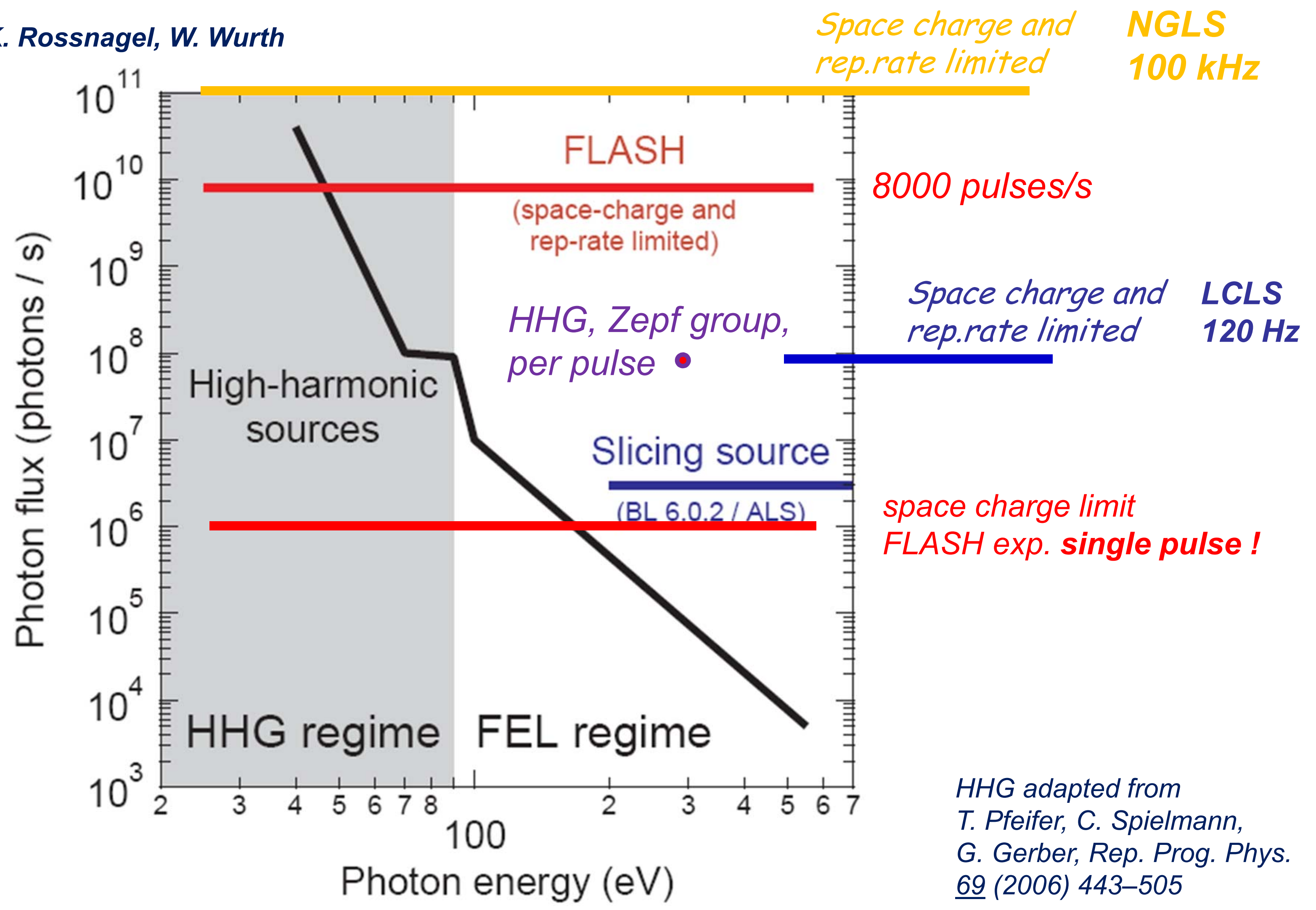


Quenching of electronic order :

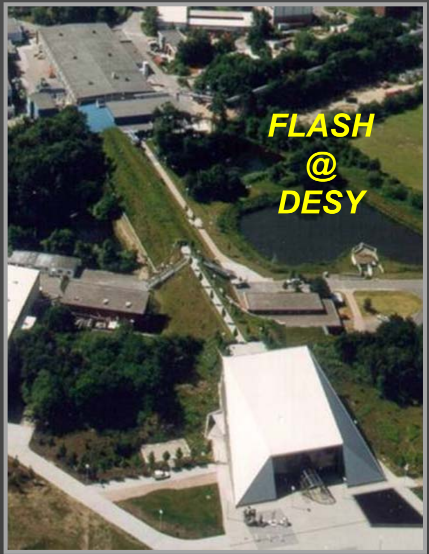
$\tau_{disorder} \sim 500$ fs

Comparing sources- example: core level photoemission

K. Rossnagel, W. Wurth



HHG adapted from T. Pfeifer, C. Spielmann, G. Gerber, Rep. Prog. Phys. 69 (2006) 443–505



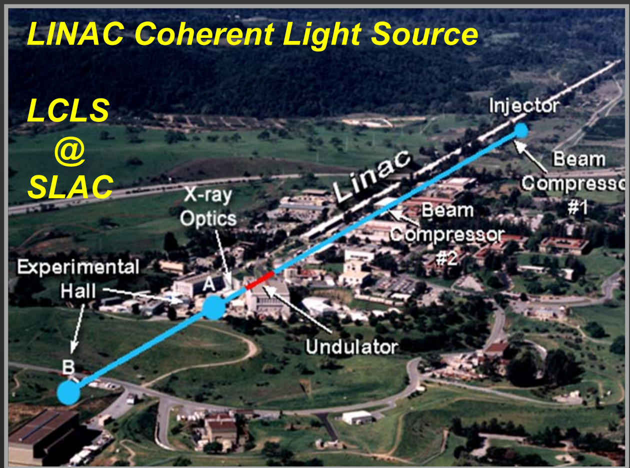
Today:

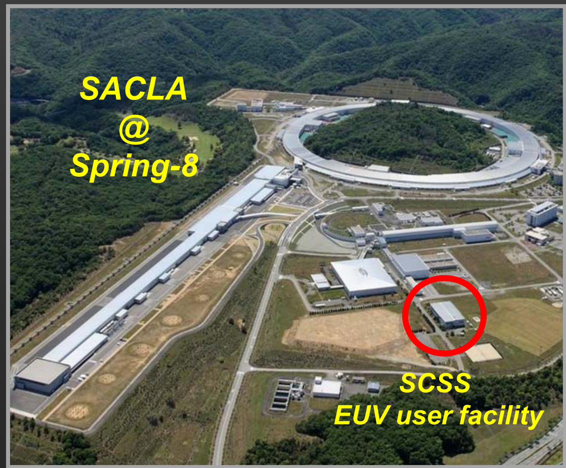
Things are moving fast

The right time to get involved

In Operation since
Aug 2005

Commissioning since
Summer 2011





In operation since
Oct 2009 *Fall 2011*

Operation expected
End of 2015