The Future of X-ray FELs

Hans-H. Braun
Paul Scherrer Institut

3rd International Particle Accelerator Conference
New Orleans
May 20-25, 2012

IPAC'12 talks on X-ray FELS

IPAC12 Conference Synoptic Table: May 21-25, 2012

Time	Monday, May 21 2012 – Hall B	Tuesday, May 22, 2012 – Room 209	Tuesday, May 22, 2012 – Room 218	Wednesday, May 23, 2012 – Room 209	Wednesday, May 23, 2012 – Room 218	Thursday, May 24, 2012 – Room 209	Thursday, May 24, 2012 – Room 218	Friday, May 25, 2012 – Room 209	Friday, May 25, 2012 – Room 218
	Chair: Victor Suller, CAMD, LSU	Chair: Thomas Roser, BNL	Chair: Bob Hettel, SLAC	Chair: Vladimir Shiltsev, FNAL	Chair: Kevin Jones, ORNL	Chair: Yu-Juian Chen, LLNL	Chair: Vladimir Litvinenko, BNL	Chair: Lia Merminga, TRIUMF	Chair: Andrew Hutton, Jlab
09:00 09:10	Welcome from the Chairs	Status of the J-Parc Facility, Shoji Nagamiya, JAEA/J-PARC	Progress Towards Ultimate Storage Ring Light Sources, Michael Borland, ANL	Project X: Research, Design, Development and Collaboration Efforts for an Ultra High Power Superconducting RF Linac, James Kerby, Fermilab	Recent Advances and New Techniques in Visualization of Ultra-short Relativistic Electron Beam Bunches, Dao Xiang, SLAC	Backgrounder: Producing Medical Isotopes using X-rays, Mark Sybe de Jong, CLS	Suppression of Head-Tail Instability Using a Broadband Feedback, Yong Ho Chin, KEK	Marrying Lasers and Beams, Luca Serafini, INFN Milano	Symplectic Tracking and Compensation of Dynamic Field Integrals in Complex Undulator Structures, Johannes Bahrd, HZB
09:20 09:30 09:40	The Future of X-ray Science, Joachim Stohr, SLAC	The Upgrade Plans for the LHC Injector Complex, Roland Garoby, CERN	Review of ERL Projects at KEK and Around the World, Norio Nakamura, KEK	Development of Electron Coolers in Novosibirsk, Vasily Parkhomchuk, BINP	Diagnostics for High Power Targets and Dumps, Edda Gschwendtner, CERN	Operation and Patient Treatments at CNAO Facility, Erminia Bressi, CNAO Foundation	Experimental Demonstration of Suppressing Coherent Synchrotron Radiation, Vitaly Yakimenko, BNL	Recent Developments in Lasers for use in Accelerators, Andreas Tünnermann, Friedrich Schiller Universität, Jena	Femtosecond Electron Guns for Ultrafast Electron Diffraction, Jinfeng Yang, Osaka University
09:50 10:00 10:10 10:20	First Two Years of LHC Operation, Steve Myers, CERN	Increasing the AGS Beam Polarization with 80 Tune Jumps, Vincent Schoefer, BNL	Overview of Present and Future Compton Photon Sources, Ying K. Wu, FEL/Duke University	Accelerator Physics and Technology for FRIB, Michael James Syphers, MSU	Protecting Accelerator Control Systems in the Face of Sophisticated Cyber Attacks, Steven M. Hartman, ORNL	Accelerator Systems for Heavy-Ion Inertial Fusion, Steven Lidia, LBNL	Beam and Spin Dynamics in an All-electric Ring for Proton EDM, Richard Michael Talman, CLASSE	Overview of Recent Progress on High Repetition Rate, High Brightness Electron Guns, Fernando Sannibale, LBNL	Review of Microwave Schottky Beam Diagnostics, Ralph James Pasquinelli, FNAL
10:30	Coffee Break 10:30-11:00								
	Chair: Stuart Henderson, FNAL	Chair: Oliver Brüning, CERN	Chair: Georg Hoffstaetter, U. Cornell	Chair: Katsunobu Oide, KEK	Chair: In Soo Ko, PAL	Chair: Akira Noda, U. Kyoto	Chair: Valeri Lebedev, FNAL	Hall B Chair: Jeff Corbett, SLAC	
11:00 11:10	Accelerator Driven Systems, Dirk Vandeplassche, SCK-CEN	Research and Development Toward a Future Muon Collider, Katsuya Yonehara, Fermilab	Proton Beam Acceleration with Circular Polarized Laser Pulses, Xueqing Yan, PKU/IHIP	CLIC Design and R&D Status, Steinar Stapnes, CERN	The SPring-8 Angstrom Compact Free Electron Laser (SACLA), Hitoshi Tanaka, RIKEN SPring-8 Centre	High field Magnet Development, Tatsushi Nakamoto KEK, Ibaraki)	Beam-beam Effects in Hadron Colliders: Theory and Experiment, Kazuhito Ohmi, KEK	The Future of X-ray FELs, Hans-Heinrich Braun, PSI	
11:20 11:30 11:40	State of the Art and Future Prospects in RF Superconductivity, Kenji Saito, KEK	Overview of Asymmetric Hadron Electron Colliders, Vadim Ptitsyn, BNL	Manufacture and Testing of Optical-scale Accelerator Structures from Silicon and Silica, Joel England, SLAC	Studies of Electron Cloud Beam Dynamics for Future Damping Rings at CesrTA, Gerald Dugan, CLASSE	Hard X-ray Self-Seeding at the LCLS FEL, Paul J. Emma, SLAC	Ultracompact Accelerator Technology for a Next-Generation X-ray Source, Fred V. Hartemann, LLNL	Influence of e-beam Parameters on Coherent Electron Cooling, Gang Wang, BNL	Accelerators for Intensity Frontier Research, Paul Derwent, FNAL	
11:50 12:00 12:10 12:20	Design and Simulation of IOTA - a Novel Concept of Integrable Optics Test Accelerator, Sergei Nagaitsev, Fermilab	Performance and Prospect of BEPCII, Qing Qin, IHEP Beijing	FFAG Experience and Future Prospects, Yoshiharu Mori, KURRI	Overview of Super B Factories, Maria Enrica Biagini, INFN/LNF	High Average Power UV Free Electron Lasers Experiments at JLAB, David Douglas, JLAB	Critical Technologies and Future Directions in High Intensity ISOL RIB Production, Pierre Gerard Bricault, TRIUMF	Collective Effects in the LHC and its Injector Complex, Elias Métral, CERN	Physics Results at the LHC and Implications for Future HEP Programmes, Rolf Heuer, CERN	
12:30	Lunch Break 12:30 - 2:00							Closing Remarks: Jeff Corbett, SLAC, IPAC'12 SPC Chair, Zhentang Zhao, SINAP, IPAC'13 OC Chair	

Time	Monday – Room 209	Monday – Room 218	Monday – Room 221	Tuesday – Room 209	Tuesday – Room 218	Tuesday – Room 221	Wednesday – Room 209	Wednesday – Room 218	Wednesday – Room 221	Thursday – Hall B
	Chair: Won Namkung, PAL/Paul Schmor, TRIUMF	Chair: Andrzej Wolski, U. Liverpool & Cockcroft/Joseph Bisognano, U. Wisconsin-Madison	Chair: Paolo Pierini, INFN Milan/Mats Lindroos, ESS	Chair: Vadim Ptitsyn, BNL/Byung Ho Choi, KAERI	Chair: Steve Gourlay, LBNL/Chan Joshi, UCL	Chair: Gianluigi Arduini, CERN/Caterina Biscari, INFN Frascati	Chair: Kay Wittenburg, DESY/Chuang Zhang, IHEP Beijing	Chair: David Sutter, U. Maryland/Alex Chao, SLAC	Special Session for Industry Chair: Alan M.M. Todd, AES	Awards Session Chair: Stan Schriber, IEEE
14:00	Cornell ERL Photoinjector Progress, Bruce Dunham, Classe	A Proton-driven Plasma Wakefield Accelerator Experiment with CERN SPS Bunches, Patric Muggli, MPI	The European XFEL LLRF System, Julien Branlard, DESY	3-Dimensional Modeling of Electron Clouds in Non-uniform Magnetic Fields, Seth Veitzer, Tech X	Timing and Synchronization for the APS Short Pulse X-Ray Project, Frank Lenkszus, ANL	Challenges of the FAIR Vacuum System, Andreas Kraemer, GSI	Injected Beam Imaging at SPEAR 3 with a Digital Optic Mask, Hao Zhang, UMD	New Results from the EMMA Experiment, Bruno Muratori, STFC/DL/ASTeC	Future Government-funded Accelerator Projects, Zhentang Zhao, SINAP	Student Poster Prizes presented by Jeff Corbett, SLAC, SPC Chair and Kay Wittenburg, DESY, SPC Member (10')
14:10 14:20 14:30	Instrumentation and Diagnostic for High Repetition Rate Linac driven FELs, Stefano De Santis, LBNL	First Results from the Electron Hose Instability Studies in FACET, Erik Adli, U. Oslo	Status and Plans for a Superconducting RF Accelerator Test Facility at Fermilab, Jerry Liebfritz, FNAL	Focusing Charged Particle Beams Using Multipole Magnets in a Beam Transport Line, Yosuke Yuri, JAEA/TARRI	Investigation of the Use of Silicon, Diamond and Liquid Helium Detectors for Beam Loss Measurements at 2 Kelvin, Christoph Kurfuerst, CERN	Development of HTS Magnets, Kichiji Hatanaka, RCNP	Inorganic Scintillators for Particle Beam Profile Diagnostics of Highly Brilliant and Highly Energetic Electron Beams, Gero Kube, DESY	Photocathode R&D at Cornell University, Luca Cultrera, CLASSE	Future Medical Accelerators, Kiyoshi Yasuoka, University of Tsukuba	Newly Elected IEEE-NPS Fellows Presenter TBD (10') IEEE/NPSS Particle Accelerator Science and Tech Awards Presenter TBD (10')
14:40 14:50	Fast Feedback Strategies for Longitudinal Beam Stabilization, Sven Pfeiffer, DESY	FACET First Beam Commissioning, Steven Yocky, SLAC	Superconducting Resonators Development for the FRIB and ReA Linacs at MSU, Alberto Facco, INFN/LNL	Tests of Low EmittanceTuning Techniques for SuperB at SLS and DAFNE, Simone Liuzzo, INFN/LNF	Five Years of Operation Experience at HIT, Andreas Peters, HIT	Development and Test of a Single-Aperture 11T Nb3Sn Demonstrator Dipole for LHC Upgrades, Alexander Zlobin, FNAL	Development of the Beam Halo Monitor in J-PARC 3-GeV RCS, Masahiro Yoshimoto, JAEA/J-PARC	An Update on a Superconducting Photonic Band Gap Structure Resonator Experiment, Evgenya Simakov, LANL	Future Security and Defense Accelerators, Peter Zielinski, DTRA	IEEE/NPSS PAST Student Thesis Presentation (20') Awarded by Ilan Ben-Zvi, BNL (5')
15:00 15:10	Thorium Energy Futures, Robert Cywinski, U. Huddersfield	Transverse-to-longitudinal Emittance-exchange with an Energy Chirped Beam, Jayakar Thangaraj, FNAL	Electron Linac Photo-fission Driver for the Rare Isotope Program at TRIUMF, Yu-Chiu Chao, TRIUMF	Summary of Fermilab's Recycler Electron Cooler Operation and Studies, Lionel Prost, FNAL	A European Proposal for the Compton Gamma-ray Source of ELI-NP, Cristina Vaccarezza, INFN-LNF	Experimental Verification of the CLIC Two-beam Scheme, Status and Outlook, Roberto Corsini, CERN	Construction Progress of the RHIC Electron Lenses, Wolfram Fischer, BNL	Measurement of the Slice Energy Spread of Electron Beam at SDUV FEL using the CHG-based Method, Chao Feng, SINAP	Future Advanced Accelerator Applications, Wim Leemans, LBNL	APS/DPB Outstanding Doctoral Thesis Research in Beam Physics Award Presenter TBD (20')
15:20 15:30	Perspectives of the HIE-ISOLDE Project at CERN, Yacine Kadi, CERN	Laser-induced CSR: Toward a Probe to Explore Wakefields in Storage Rings, Serge Bielawski, PhLAM/CERCLA	Status of Main Linac Cryomodule Development for Compact ERL Project, Kensei Umemori, KEK	Beam Commissioning and Operation of New Linac Injector for RIKEN RI-beam Factory, Kazunari Yamada, RIKEN	Commissioning of the PLS-II, Seunghwan Shin, PAL	Small-Beta Collimation at SuperKEKB to Stop Beam-Gas Scattered Particles and to Avoid Transverse Mode Coupling Instability, Hiroyuki Nakayama,	Tevatron End-of-Run Beam-Beam Experiments, Alexander Valishev, FNAL	Refraction Contrast Imaging via Laser-Compton X-ray Using Optical Storage Cavity, Kazuyuki Sakaue, RISE	Future Accelerator-based Material Processing, Wendy Ruth Flavell, UMAN	
15:40 15:50	High-power Coherent THz Sources and THz-TDS System, Masafumi Kumaki, RISE	An Alternative 1D Model for CSR with Chamber Shielding, Demin Zhou, KEK	A Multi-purpose X Band Accelerating Structure, Micha Dehler, PSI	H- and Proton Beam Loss Comparison at SNS Superconducting Linac, Andrei Shishlo, ORNL	Status of the FERMI@Elettra Project, Michele Svandrlik, ELETTRA	Experimental Measurements of e-Cloud Mitigation using Clearing Electrodes in the DAFNE Collider, David Alesini, INFN/LNF	Beam Tests of a High Pressure Gas-Filled Cavity for a Muon Collider, Thomas Schwarz, FNAL	Characterization of Undulator Radiation in Phase Space Using the Wigner Distribution Function, Ivan Bazarov, CLASSE	Future Accelerator-based Instruments, Oliver Kester, GSI	Special Invited Presentation Chair: Vincent Suller, LSU LIGO, the Laser Interferometer Gravity-wave Observatory (30') Rainer Weiss, MIT

Time	Mon						Tue						Wed						Thu					
16:00	Canal	Decatur	Poydras	Royal	Bourbon	-	Canal	Decatur	Poydras	Royal	Bourbon	-	Canal	Decatur	Poydras	Royal	Bourbon	-	Canal	Decatur	Poydras	Royal	Bourbon	-
	Collider	Hadron	SR and FEL	Instrument	Collider	-	Beam Dyn	Sources	SR and FEL	Collider	Beam Dyn	-	Tech	Tech	Sources	Beam Dyn	Sources	-	Tech	Tech	Hadron	Instrument	Hadron	-
	Beam Dyn	-	-	-	Instrument	-	-	-	-	-	SR and FEL	-	-	-	Instrument	-	Tech	-	-	-	-	Applications	Applications	-
17:50	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Tech	-
	Chairman's Reception						Industrial Reception						Women in Science and Engineering Reception						Banquet					

MC1: Circular/Linear	MC2: SR and FEL	MC3: Sources/Alternative	MC4: Hadron	Opening, Closing and Special
MC5: Dynamics	MC6: Instrumentation	MC7: Technology	MC8: Applications	

+ many good posters on the subject

Content

- Recent developments
- X-ray FEL* user community
- R&D issues
- Near future of X-ray FELs
- Mid term Future
- Long term future

*Definition used:

X-ray FEL is a FEL with smallest λ_{photon}<5 nm

Acknowledgements

Many thanks to

Paul Emma/LBNL
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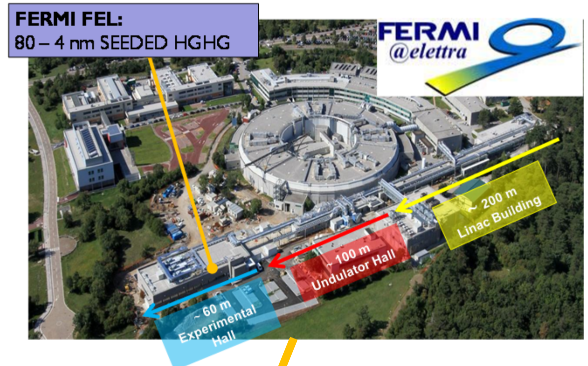
Subrata Nath/LANL
Jörg Rossbach/Univ. Hamburg
Siegfried Schreiber DESY
Michele Svandrlik/ELETTRA
Hitoshi Tanaka/Spring-8
Dong Wang/SINAP
and my colleagues at PSI

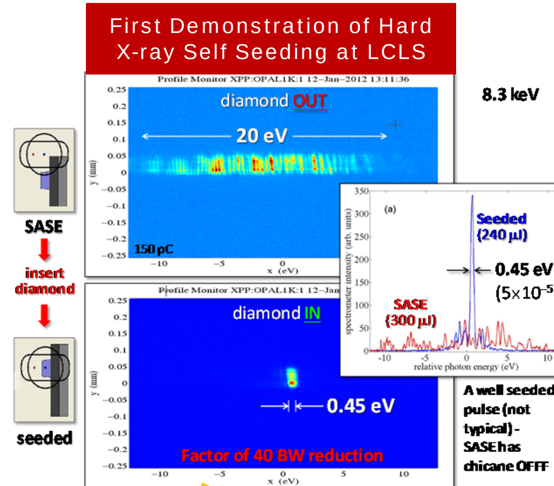
for providing information for this talk

The young history of X-ray FELs

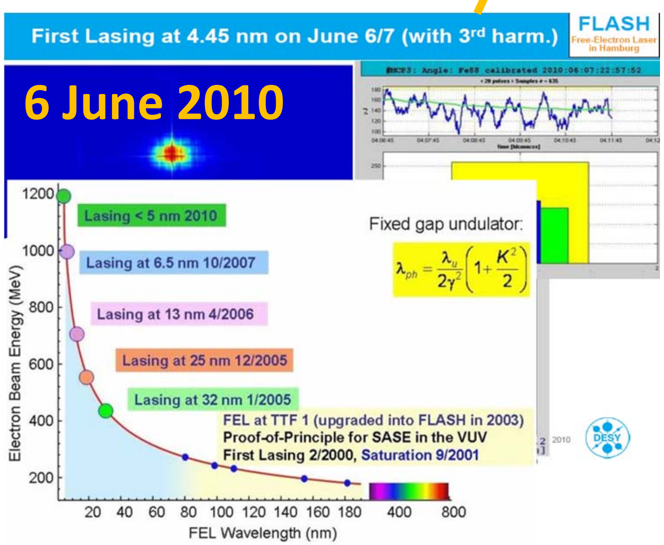
Paul Emma
WEYB02

Michele Svandrlik
TUOBB03





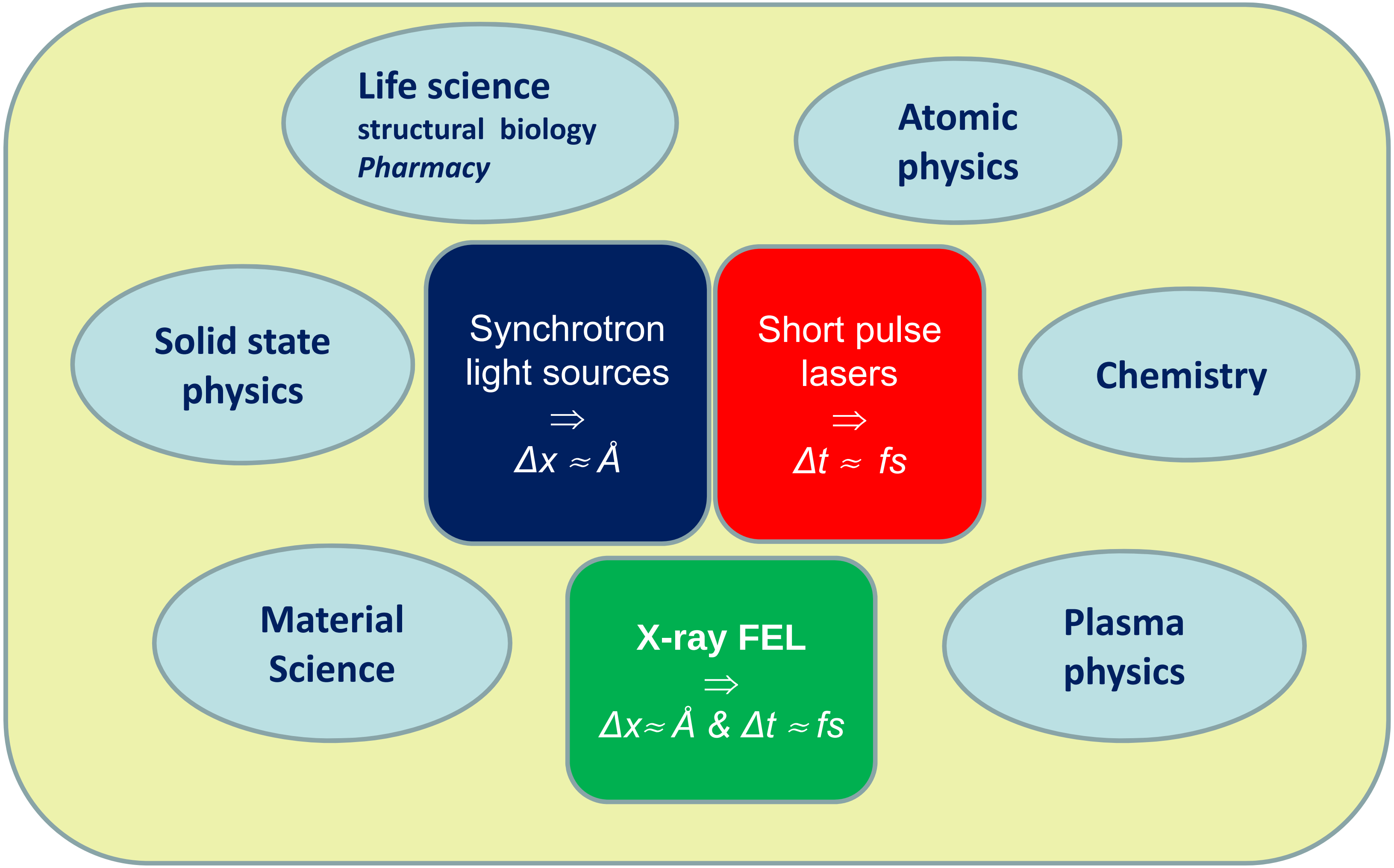
2009 2010 2011 2012

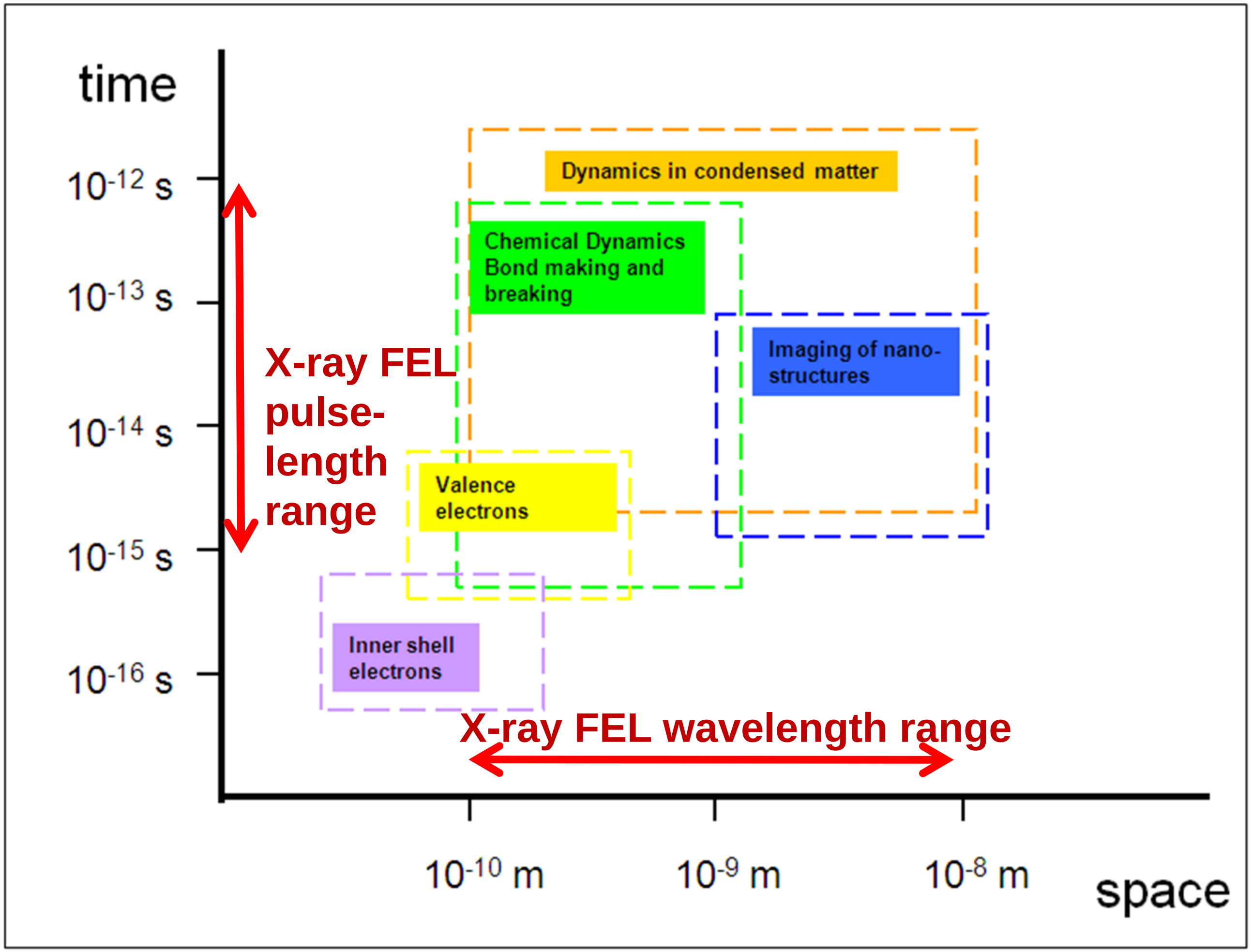


Hitoshi Tanaka
WEYB01

X-ray FEL users

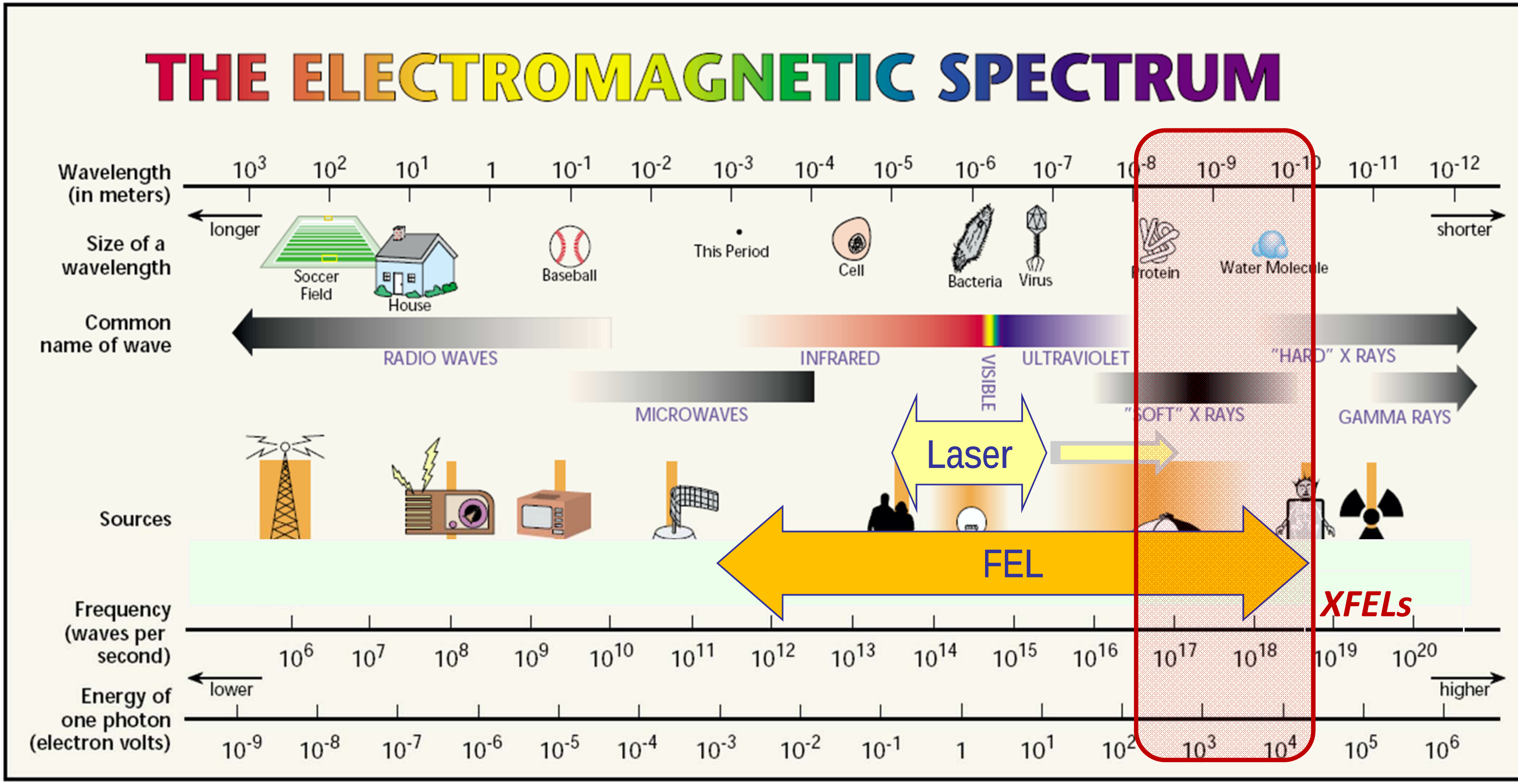
- who are they ?
- what instruments are they used to?





⇒ ***X-ray FEL allows for flash images on time scale of fastest chemical processes***

Spectral coverage of Lasers and FELs in the E.M. spectrum



$\Rightarrow$ *FELs have the monopoly for intense coherent X ray beam*

X-ray FELs vs. synchrotron

World map of SR storage rings

Worldwide >50 synchrotron for photon science
with ≈1000 user stations total

- wide range of applications in life science and material science
  attractive science portfolio of high brightness X-ray sources

Advantages X-FELs vs. synchrotron

+ orders of magnitude higher peak brightness
+ order of magnitude higher average brightness
+ orders of magnitude better time resolution
+ clean polarization and coherence

Difficulties X-FELs vs. SR storage rings

- much less integrated photon flux
- less beamlines/facility
- less stable beam conditions
- much higher cost per user station

vast scientific potential in uncharted territory

"New Science" session organized by Jochen Schneider/DESY
Every speaker was asked for a XFEL parameter-wishlist!

Monday, August 22

13:00 ~ 15:00	New Science
13:00	Multi-photon processes and two-color studies in atomic and molecular systems *M. Meyer, European XFEL GmbH*
13:30	Overview of Warm Dense Matter experiment at the FLASH and LCLS Free Electron Lasers *B. Nagler, SLAC*
14:00	Femtosecond protein X-ray nanocrystallography *H. N. Chapman, DESY*
14:30	XFEL interaction with correlated electron materials *H. A. Dürr, SLAC*

FEL 2011

FEL parameter wish list for

Research on Atoms and Molecules

Michael Meyer (European XFEL)

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i) Non-linear processes — > 10^{15} W/cm^2
- Direct processes — "short" pulses: < 10 fs
- Sequential processes — "long" pulses: 100 – 300 fs

Variable pulse duration & pulse energy

ii) Time-resolved experiments — "Synchronization"
- Pulse duration — < 10 fs (< 1 fs)
- Temporal stability — < 10 fs

iii) "Complete" experiment — Coincidence techniques
- repetition rate — > 1 kHz ("MHz")

iv) Soft X-ray regime "tunable" — C(1s) = 290 eV, N(1s) = 410eV, O(1s) = 560eV

v) linear / circular polarization — Dichroism

FEL 2011

FEL parameter wish list for

Matter in Extreme Conditions Research

Bob Nagler (SLAC-LCLS)

- Short pulse lengths:
  - isochoric heating with inertial confinement
  - beat hydrodynamic expansion (~10ps)
  - beat electron-ion equilibration time (~1ps)
  - beat inner shell recombination rate (1-100fs)
  - beat electron-electron equilibration time (sub fs)
- High Photon Flux
  - High energy deposition, to increase heated sample size and temperatures (10^{13}-10^{14} photons)
  - Photon hungry probe techniques (10^{13}-10^{14} photons in small bandwidth 10^{-4} - 10^{-6})
- Bandwidth
  - Thomson scattering probe: 10^{-4} - 10^{-6}
  - X-ray absorption near edge spectroscopy : 1%-5%
- Repetition rate
  - 10Hz, limited by optical laser, target refresh rate

FEL 2011

FEL parameter wish list for

Macromolecular Single-Shot Coherent Imaging

Henry N. Chapman (DESY-CFEL)

- The key metric is photon power. Ideally ~10 TW
  - This gives about 10^{20} W/cm^2 (with 1 micron focus, assuming beamline and focusing efficiency)
  - Only the first 10 to 30 fs of the pulse usefully contributes
- Wavelength range: 4 keV to 14 keV (to cover elemental edges from S to Se)
  - Also: 300-500 eV for water-window imaging of cells, viruses
  - Up to 30 keV for time-resolved imaging of nanoparticles
- Repetition rate: As high as possible
  - Need to match detector capabilities. 1 kHz repetition could be feasible
- Bandwidth: As high as possible
  - 1 to 10% bandwidth would allow structure determination with about 1% of the required pulses. i.e. structure determined in <1000 shots

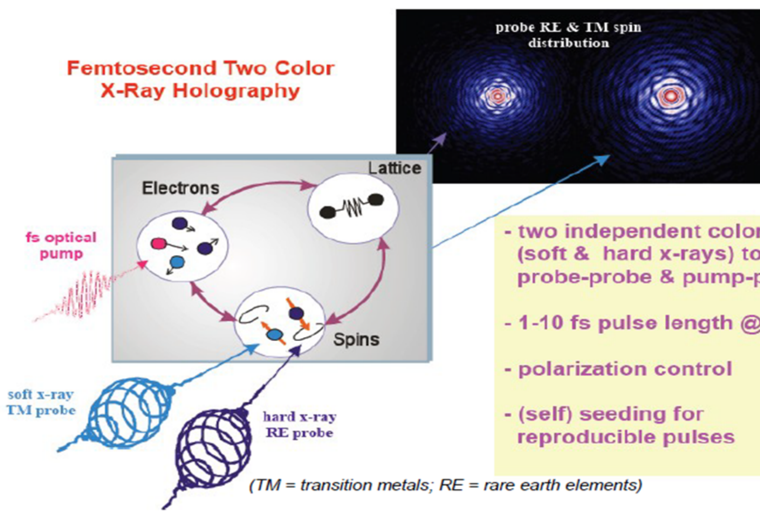
FEL 2011

FEL performance wish list for

Condensed Matter research

(especially correlated materials)

Hermann Dürr (SLAC-Pulse/SIMES)



- two independent colors (soft & hard x-rays) to probe-probe & pump-probe
- 1-10 fs pulse length @ 1mJ
- polarization control
- (self) seeding for reproducible pulses

(TM = transition metals; RE = rare earth elements)

X-ray FEL dream machine wish-list summary from FEL'11 "New Science" session

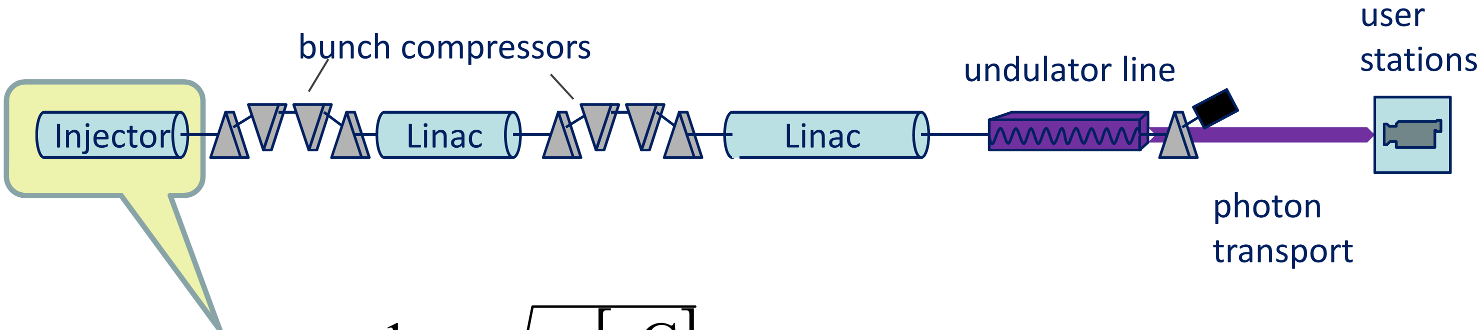
	Shortest Pulse length	Max Peak Power	rep. rate	Polarisation control	band width
Research on Atoms and Molecules	<10 fs	0.1 TW	> 1 kHz	yes	
Matter in extreme conditions	<1 fs	1 TW	10 Hz		10^{-3}-10^{-6}
Macromolecular Single-Shot Coherent Imaging	10-30 fs	10 TW	1 kHz		10^{-1}-10^{-2}
Condensed Matter Research	1-10 fs	1 TW		yes	two color
state of the art	1-100 fs	≈10 GW	LCLS 120 Hz FLASH 10x800	only at FERMI	SASE $2 \cdot 10^{-3}$ seeded $5 \cdot 10^{-5}$

⇒ *more power, shorter pulses, more pulses and more bandwidth control (chirp!)*

X-ray FEL R&D Issues

Generic X-ray FEL*

*number of BC and undulator lines may vary



$$\varepsilon_N < 1\mu\text{m}\sqrt{q_B[\text{nC}]}$$

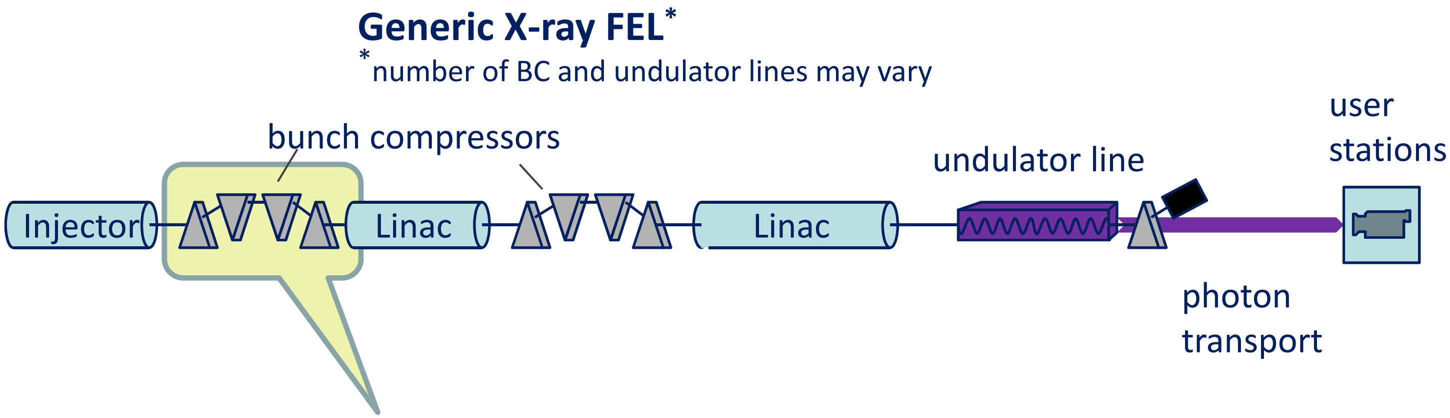
achieved with different injector technologies

LCLS:	S-band 1½ cell RF gun with Cu photo-cathode
PITZ:	L-band 1½ cell RF gun with Cs_2Te photo-cathode
SACLA:	Pulsed diode with thermionic CeB_6 cathode
SwissFEL:	S-band 2½ cell RF gun with Cu photo-cathode
…	

open issues

- low emittance for cw operation ⇒***Fernando Sannibale, FRBBA01***
- operational robustness
- lower emittance always welcome

X-ray FEL R&D Issues cont.



Theory of CSR and microbunching instability made enormous progress during last decade

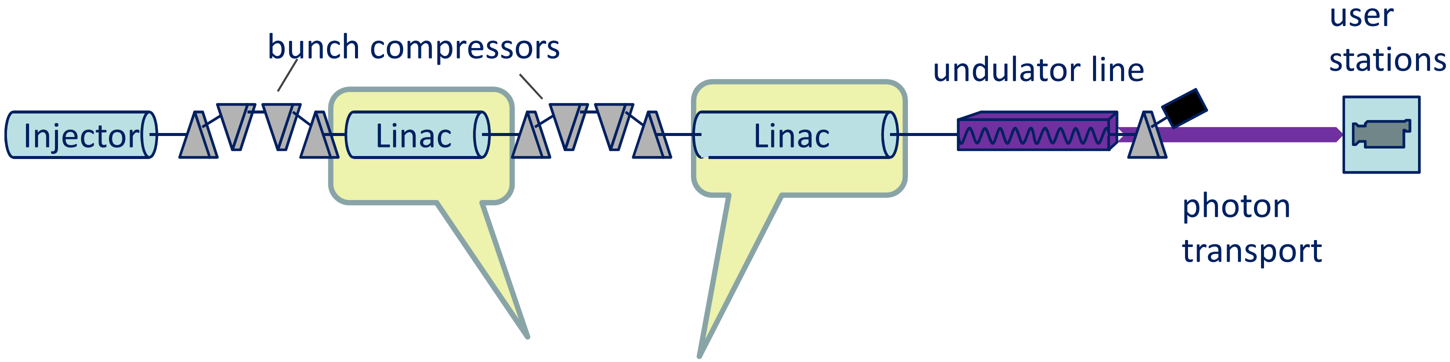
LCLS has set the standard for most projects:

- laser heater to cure microbunching instability
- harmonic cavity for flat current profile
- long, small angle bunch compressors to minimize CSR emittance growth

Arguably biggest issue today is phase and amplitude stability of upstream RF

X-ray FEL R&D Issues cont.

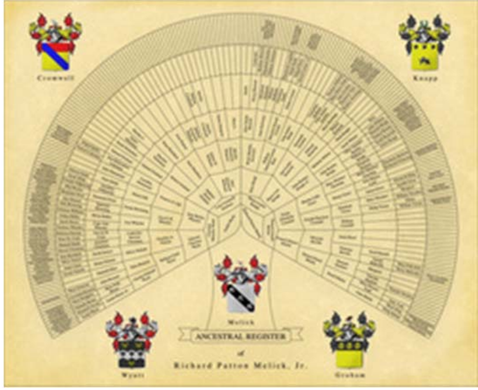
Generic X-ray FEL*
*number of BC and undulator lines may vary



Not a feasibility issue, but major factor for investment and operation cost

R&D topics
- A & φ stability
- Reliable and cost effective RF sources
- Low power consumption for reasonable accelerating fields

Genealogy of X-ray FELs



SLC - 50GeV Linear collider
1989-1998

LCLS

TESLA 500 GeV Linear collider
(preparation continues as ILC)

FLASH + FLASH II

European XFEL

JLC-C 500 GeV Linear Collider
R&D project (abandoned 2004)

SACLA

Present XFELs linac technology & parameters driven by particle physics ancestors
The LC Mantra of high gradient is not the key issues for X-ray FELs!

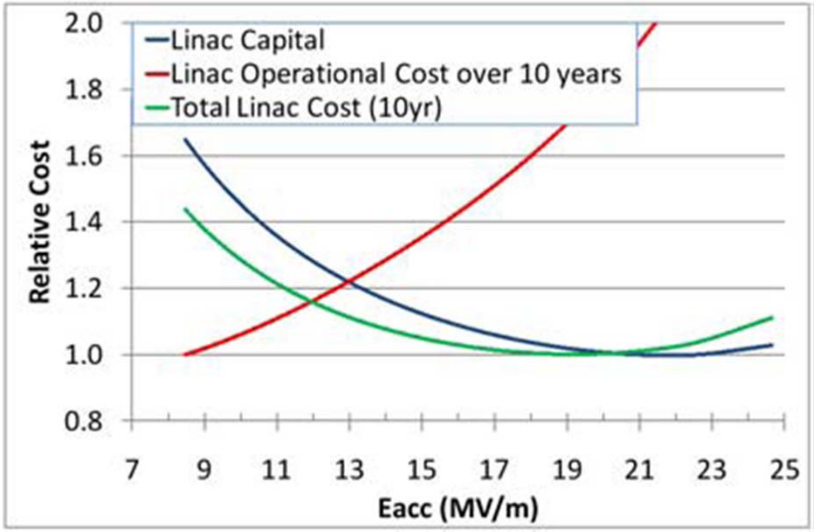
Make XFELs available for national labs and users
⇒ more economical solutions required without compromising scientific potential

Cost comparison linac technologies
or
Why doesn't everybody build s.c. & c.w.

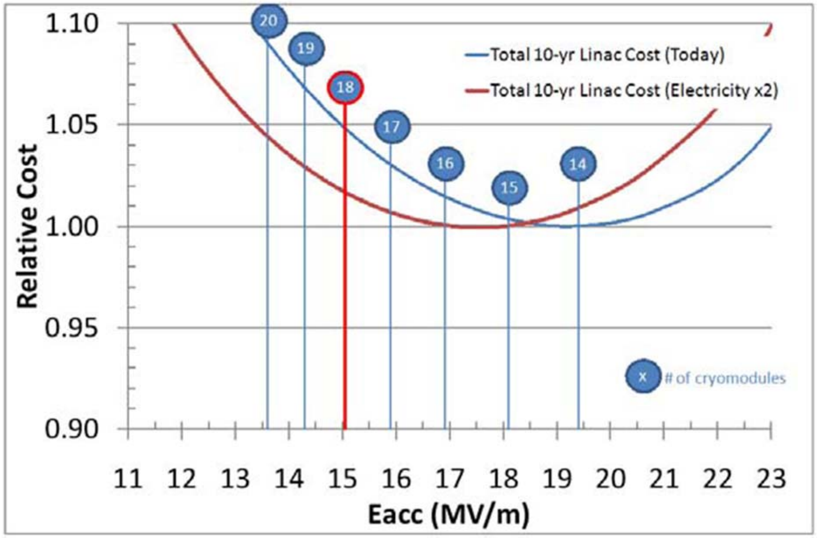
Technology	**Linac investment cost** w/o building	**Typical gradients** (excl. fill factor)	**Electric consumption**
Pulsed n.c. with SLED	$\lesssim$ 10 M€/GeV	20 MV/m (S-band) 30 MV/m (C-band)	≈ 0.5 MW/GeV
Pulsed superconducting	≈ 20 M€/GeV	24 MV/m	≈ 0.5 MW/GeV
c.w. superconducting	$\gtrsim$ 30 M€/GeV	15 MV/m	≈ 5.0 MW/GeV

Beware!
This is not exact science !

cost optimization s.c. linac in c.w. mode
from STFC-NLS design report



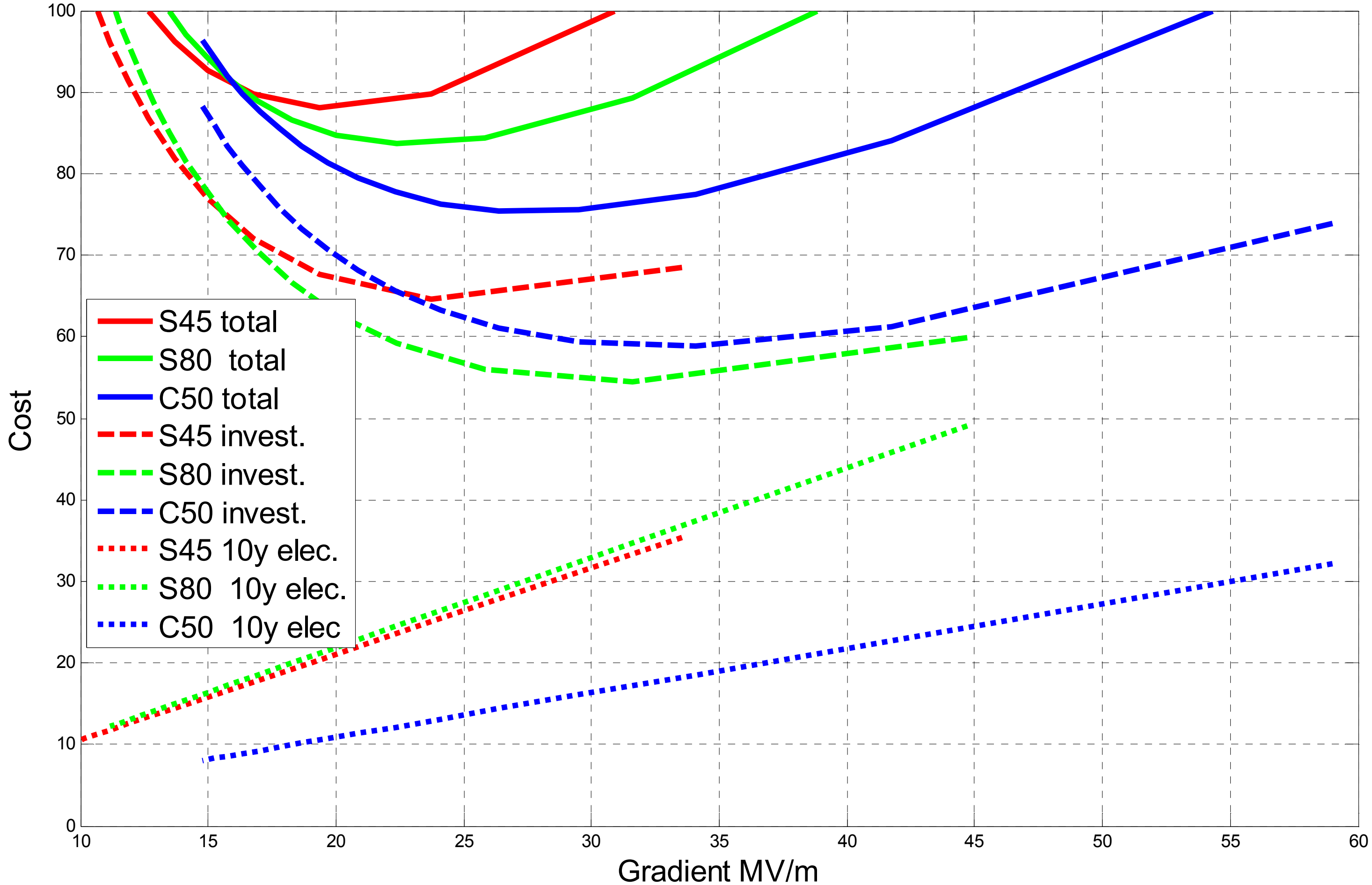
Relative total capital and
10-year operational linac costs



Effect of increased energy cost
on Eacc optimisation over 10 years

cost optimization pulsed n.c. linac for SwissFEL

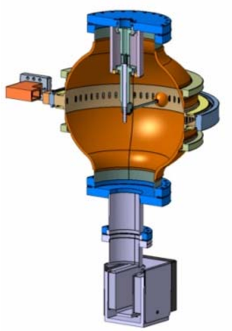
Cost vs. gradient for S-band with 45 MW klystron,
S-band with 80MW klystron
and C-band with 50 MW klystron

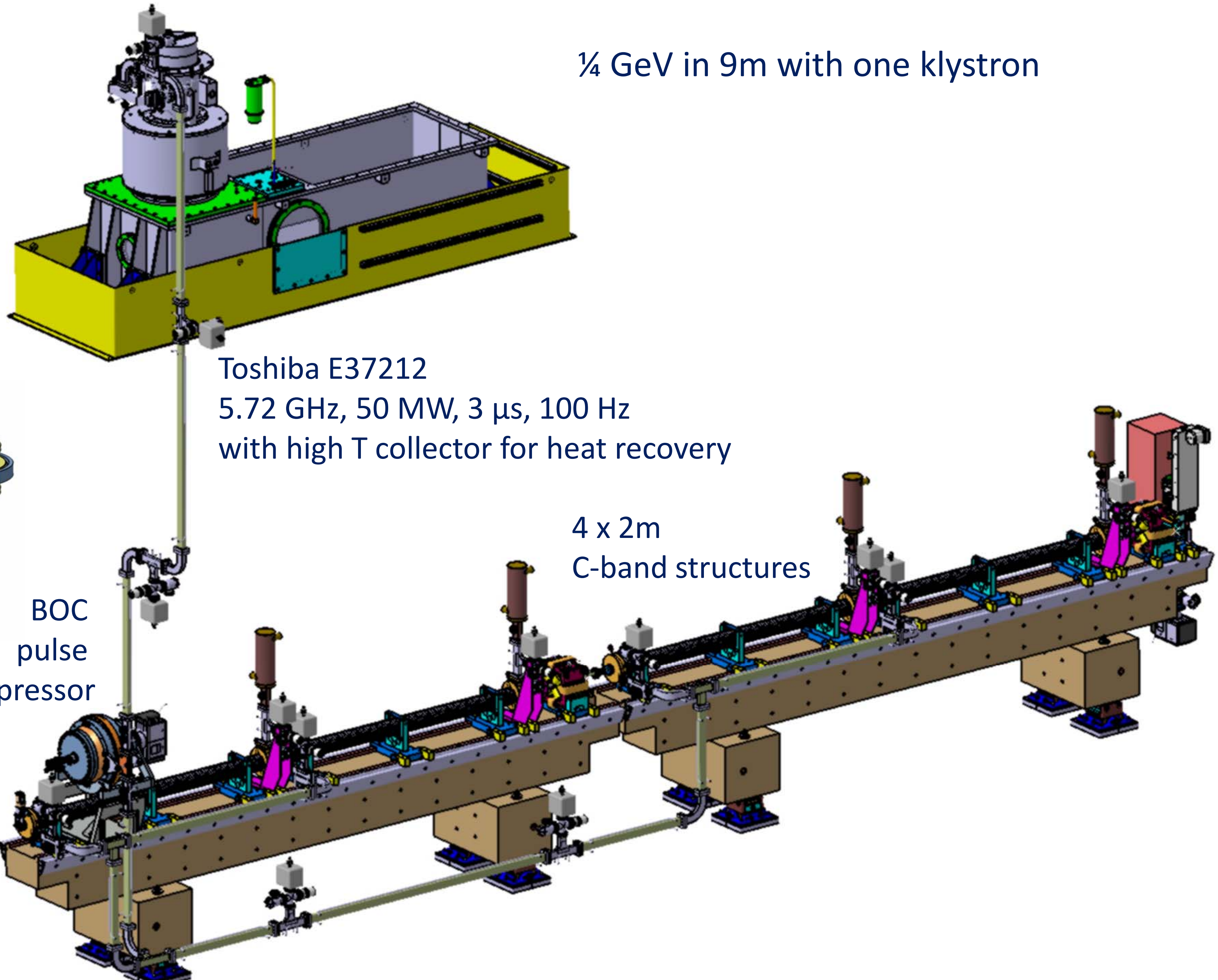


Advantage of C-band is in real-estate needs and electricity consumption

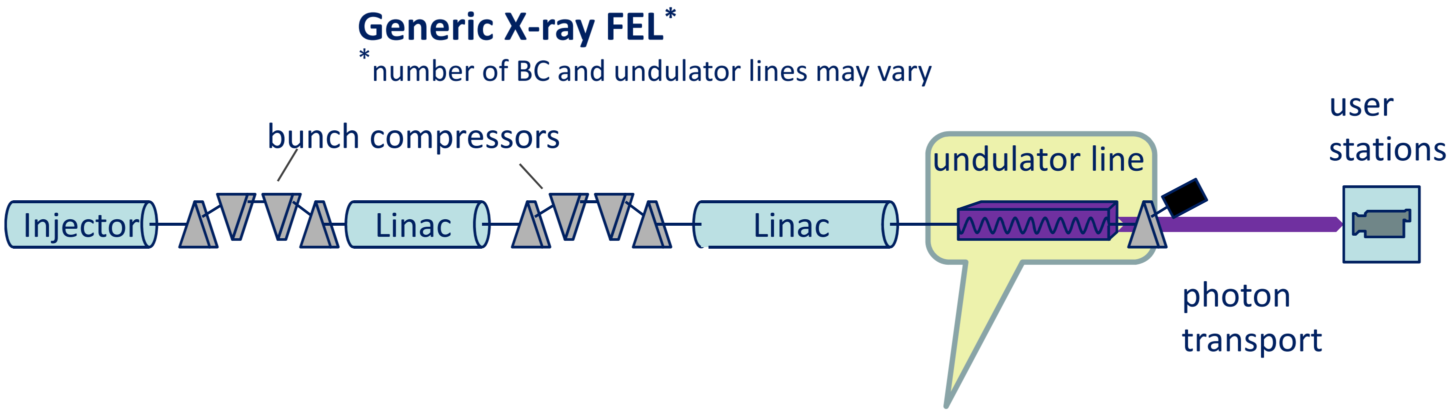
SwissFEL C-Band Linac Module

¼ GeV in 9m with one klystron





X-ray FEL R&D Issues cont.



In vacuum, variable gap undulators: for X-ray FELs pioneered by SACLA with λ_U=18 mm

Apple II undulators: for X-ray FELs pioneered by FERMI@ELETTRA

Open questions

- What is the smallest acceptable gap 4,3,2mm?
  Decisive question for design of compact X-ray FELs
  Tests at SACLA foreseen
- Shorter period PM undulators
- Improved PM materials
- Feasibility of short period sc undulators

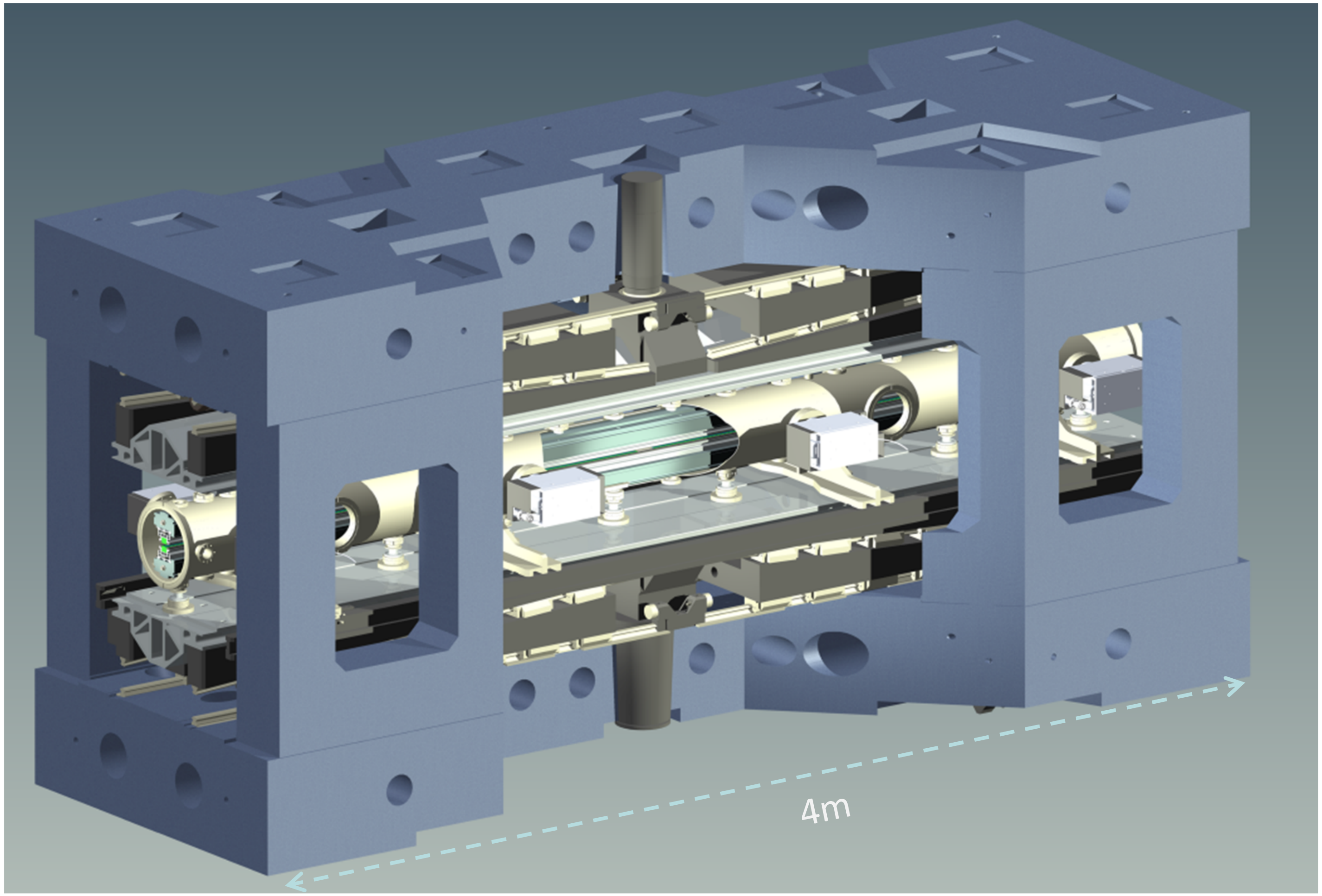
Excellent undulator technology reviews in proceedings of FEL'11

J. Bahrdt, " Pushing the Limits of Permanent Magnet Short Period Undulators"

S. Prestemon et al., "Development of Superconducting Undulators"

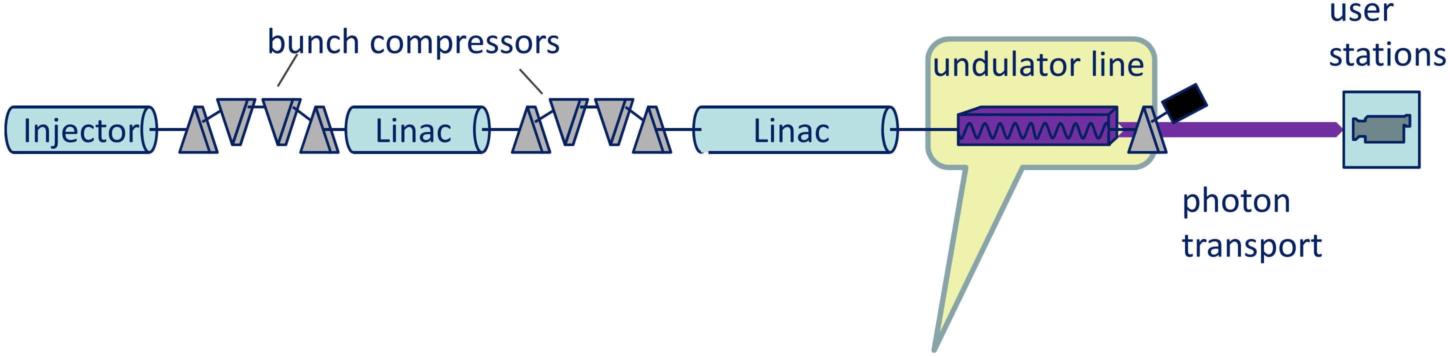
PAUL SCHERRER INSTITUT

U15 in-vacuum undulator for SwissFEL



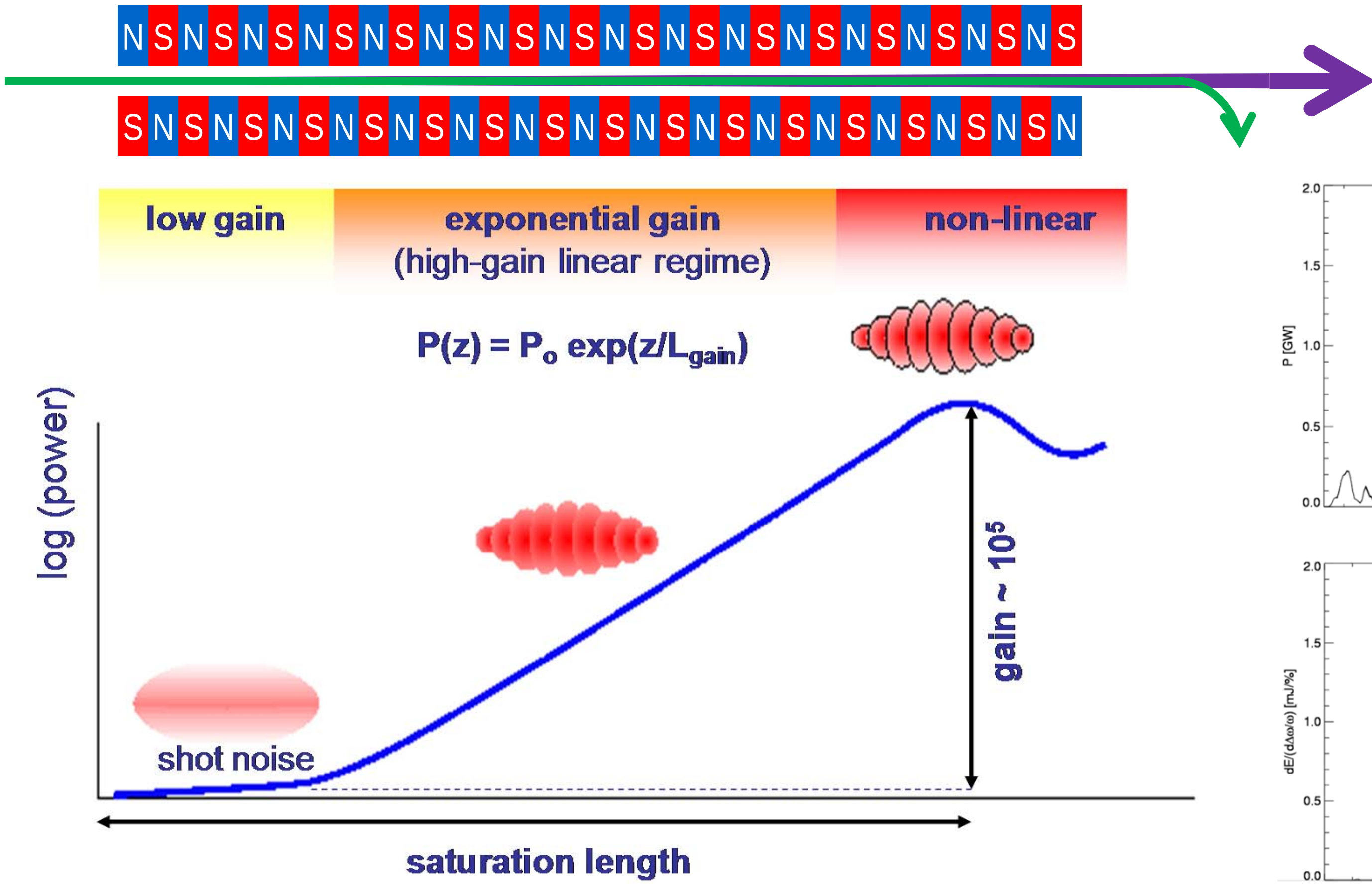
X-ray FEL R&D Issues cont.

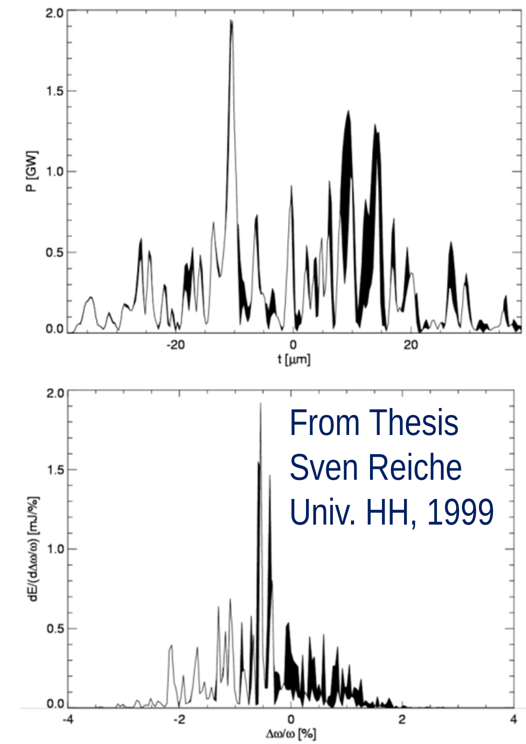
Generic X-ray FEL*
*number of BC and undulator lines may vary



SASE or Seeding ?

SASE principle

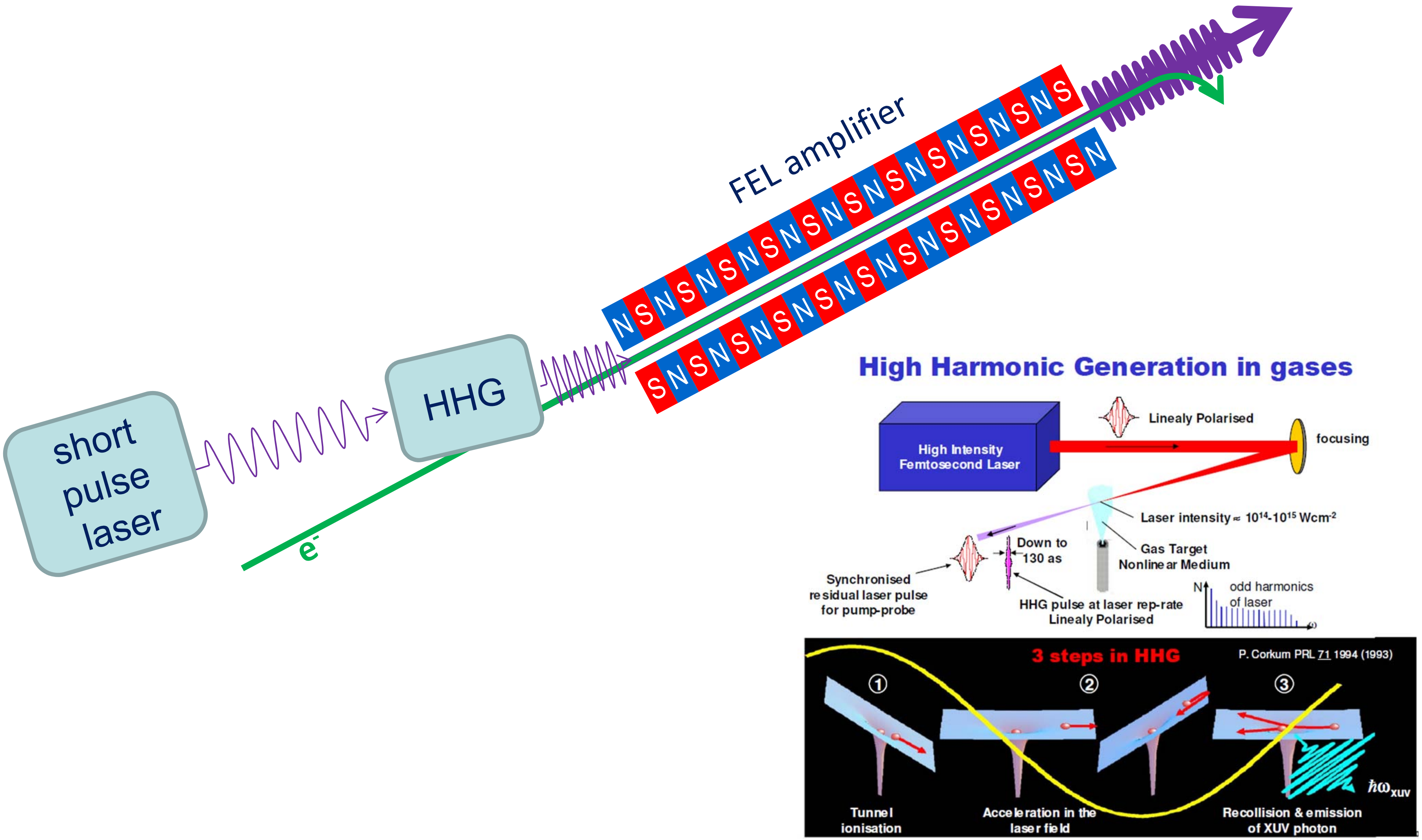




+ FEL amplifier without mirrors and without input signal ⇒ applicable for large wavelength range
Baseline operation mode for LCLS, SACLA and FLASH

- Individual time slices in the bunch radiate independently ⇒ spiky time structure, spectrum, intensity jitter by principle!

HHG seeding principle



HHG figure from http://www.newlightsource.org/events/presentations/open_meeting/Tisch.pdf

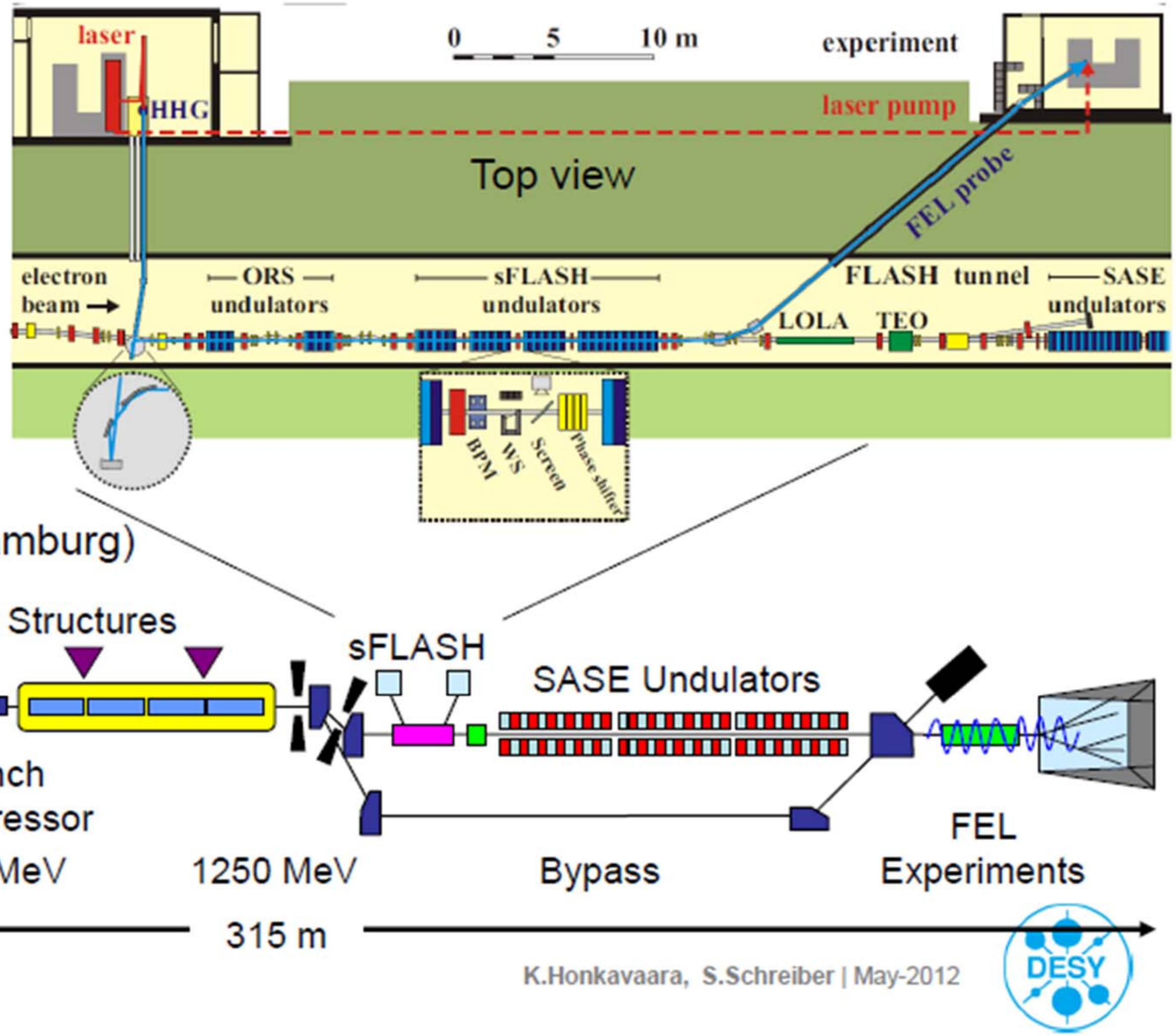
sFLASH seeding experiment at FLASH

- Experiment for direct HHG seeding in XUV range
- First seeding (38 nm) April-29, 2012

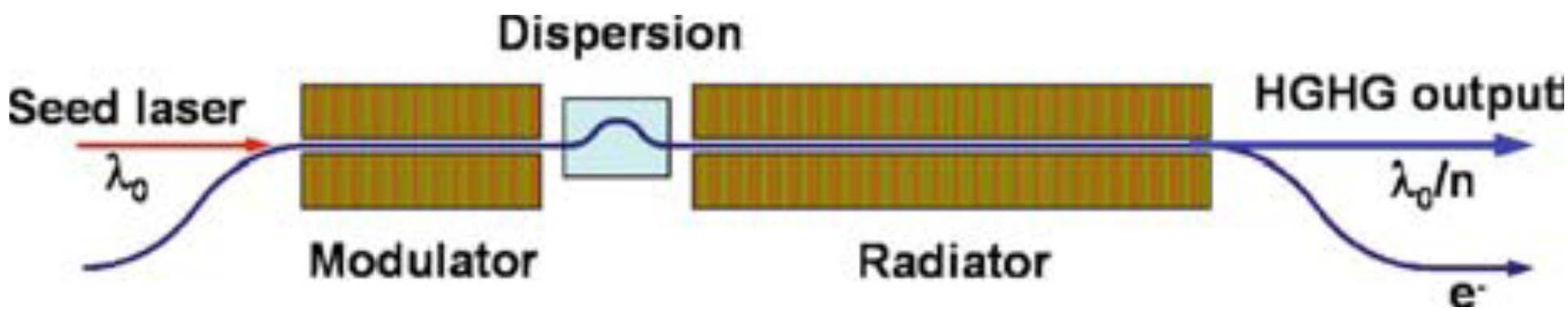
Courtesy
Katja Honkavara/DESY

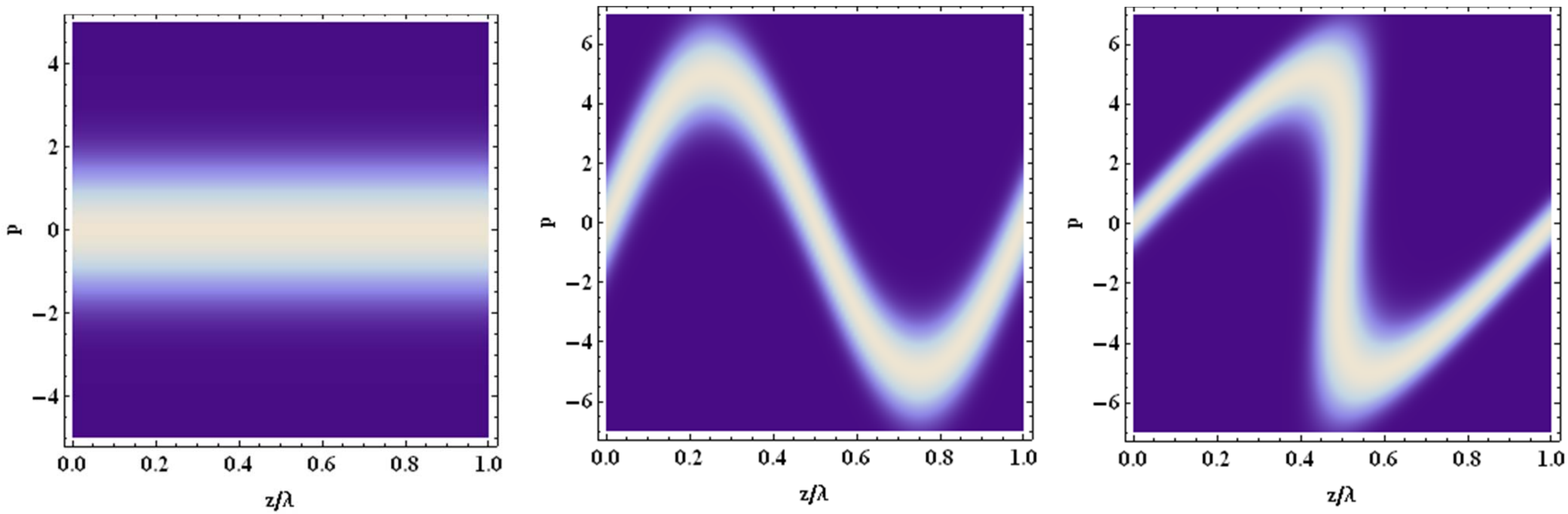
λ_{photon} =38nm
Record for HHG seeding!

FLASH FEL user facility (DESY ,Hamburg)



HGHG principle





L.H. Yu, PRA 44, 5178 (1991)

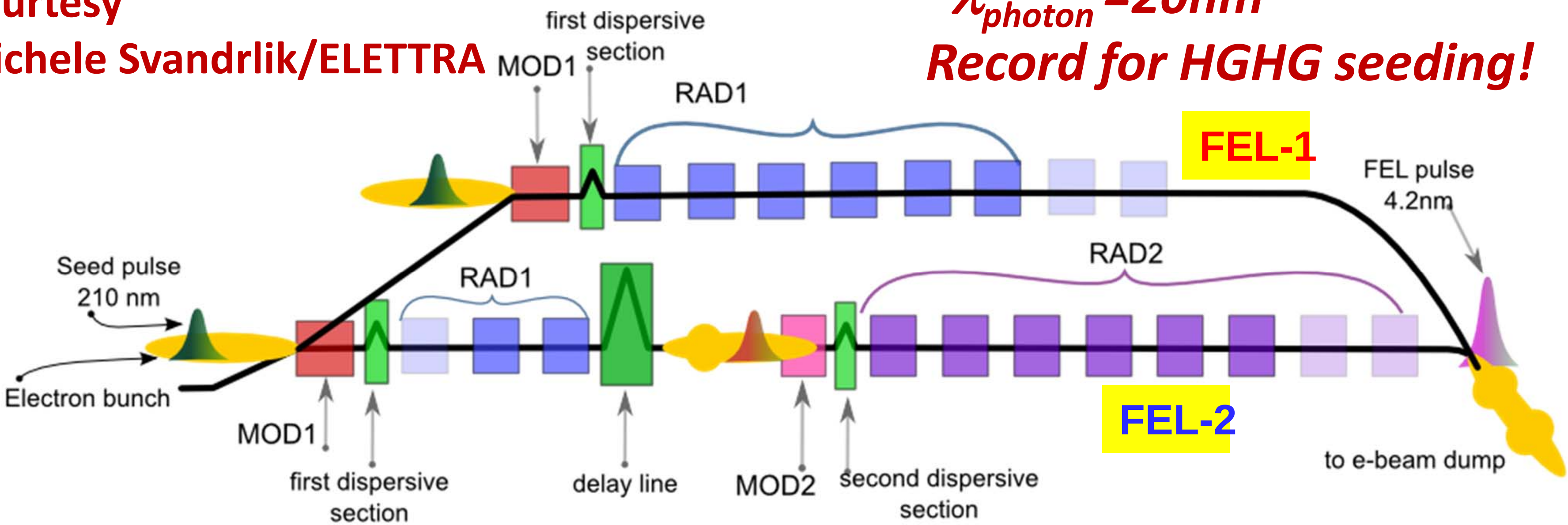
slide courtesy Dong Wang SINAP

FEL-1 and FEL-2

- **Two FEL lines** will cover different spectral regions.
- **FEL-1**, based on a single stage high gain harmonic generation scheme initialized by a UV laser, covers the spectral range from 80 nm down to 20 nm.

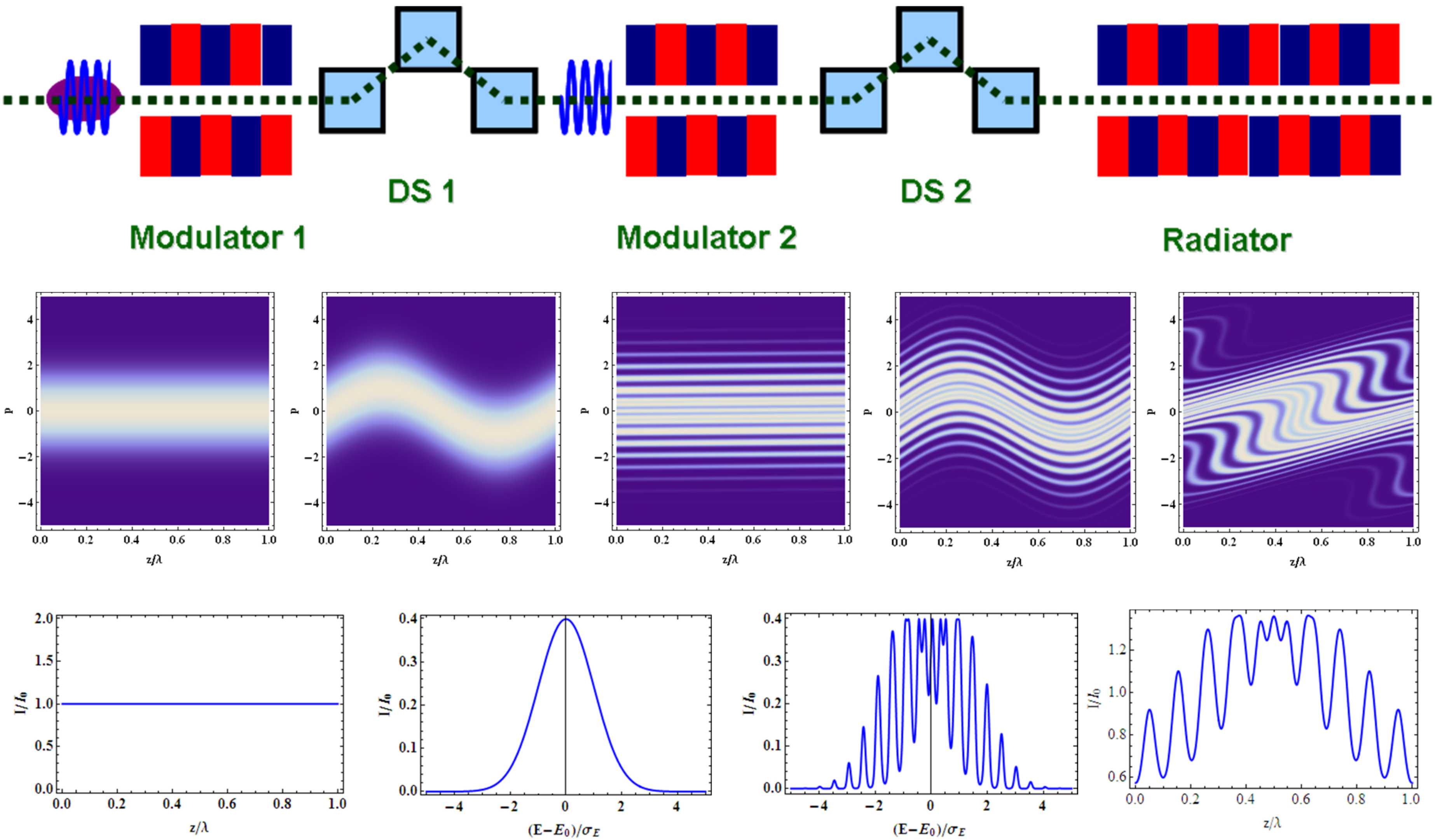
Courtesy
Michele Svandrlik/ELETTRA

λ_{photon} =20nm
Record for HGHG seeding!



- **FEL-2,** in order to be able to cover the wavelength range from 20 nm down to 4 nm starting from a seed laser in the UV, is based on a double cascade of high gain harmonic generation. A magnetic electron delay line is used in order to improve the FEL performance by using the fresh bunch technique.

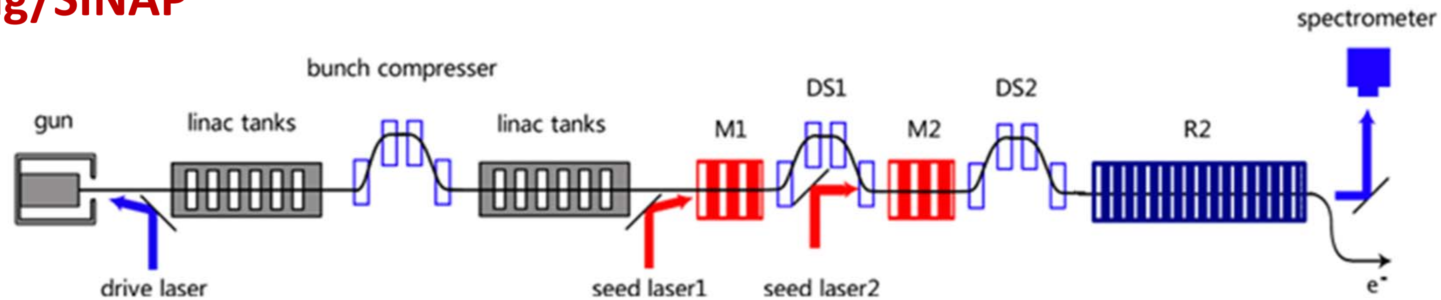
EEHG principle



G. Stupakov, PRL 102, 074801 (2009)

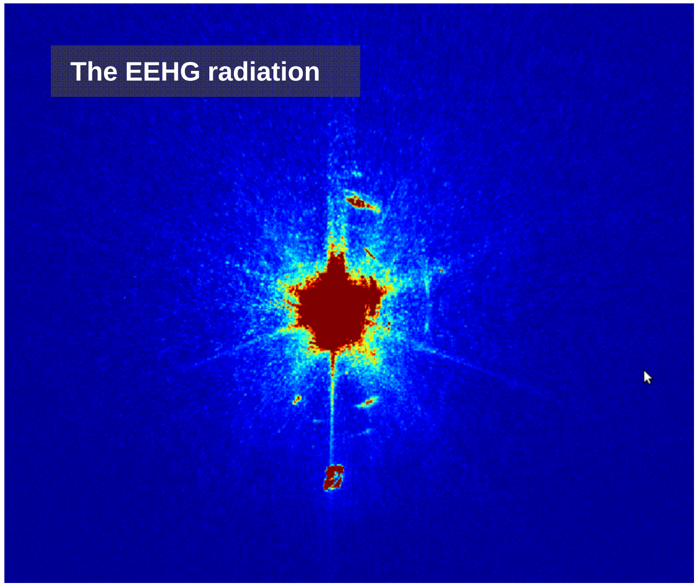
slide courtesy Dong Wang SINAP

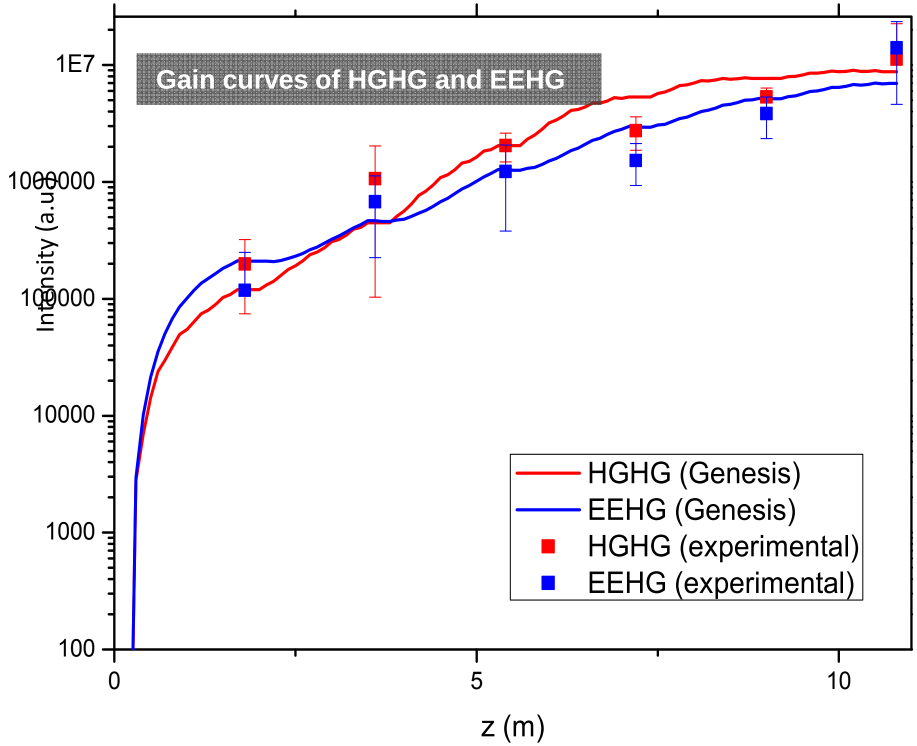
Courtesy
Dong Wang/SINAP



First lasing of EEHG FEL at Shanghai SDUV

(3rd harmonic, 350nm, April 2011)





Difficulties of seeding with external laser for short wavelength

1. External laser amplifier has $\lambda_{photon} \approx 1\mu m$
   Seeding FEL with λ_{photon}=1nm requires generation of harmonic 1000!

2. Spectral power of e^- shot noise increases with $1/\lambda_{photon}$
   Seed signal power has to exceed shot noise, otherwise SASE radiation will dominate

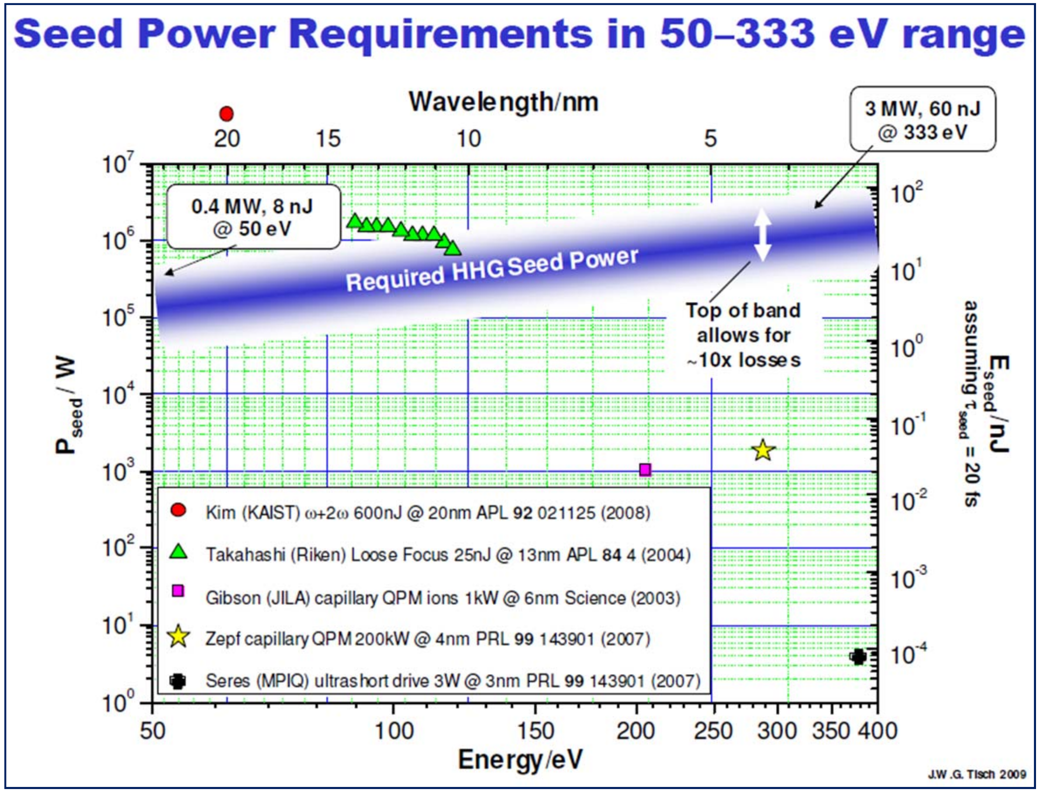
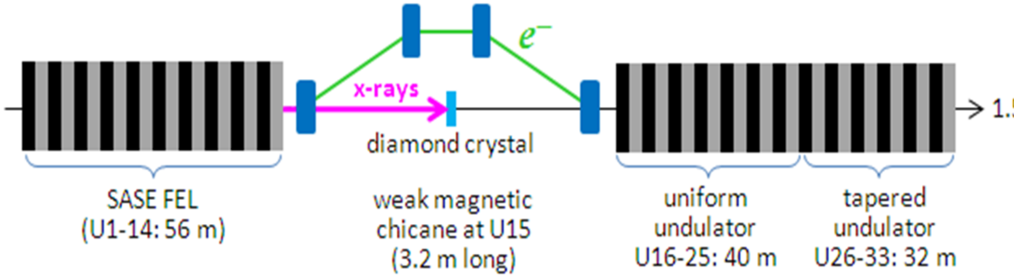
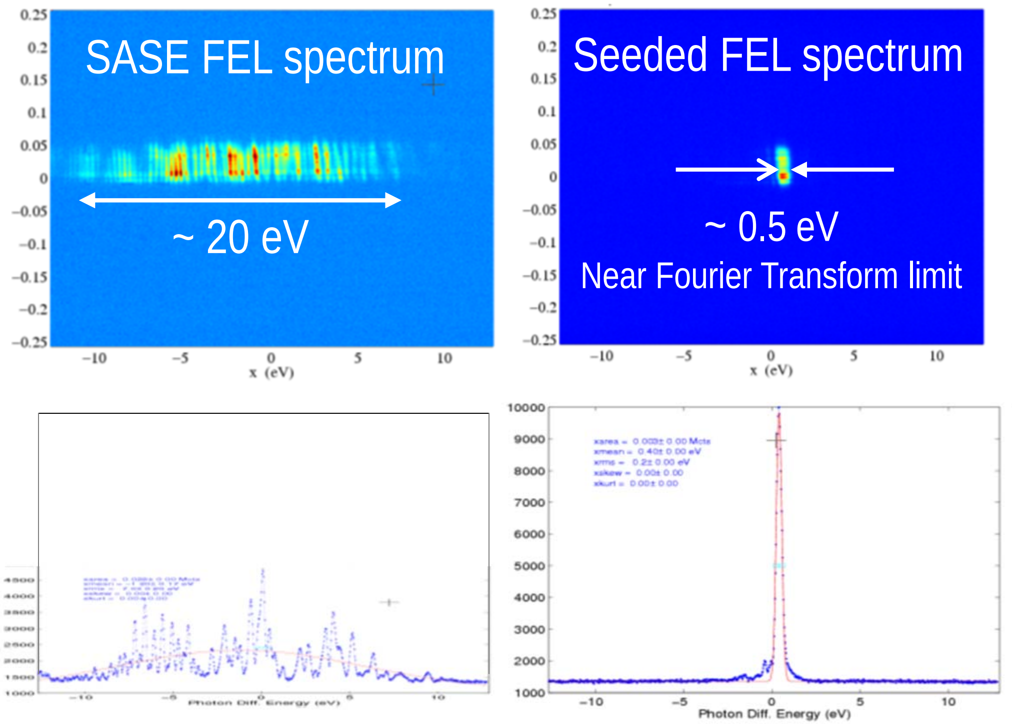


figure from http://www.newlightsource.org/events/presentations/open_meeting/Tisch.pdf

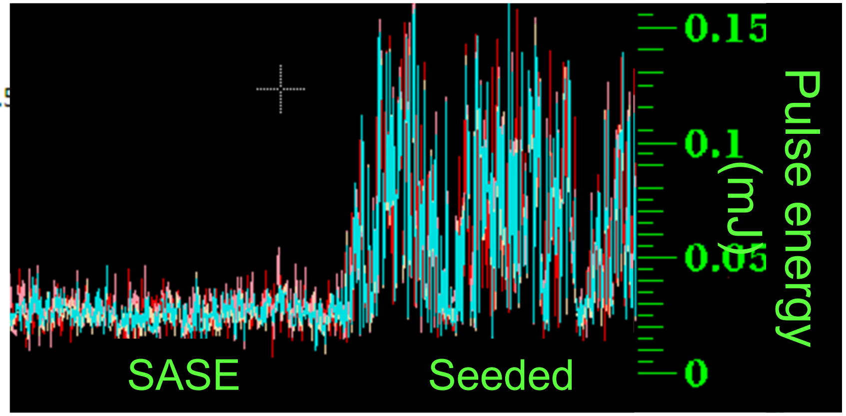
First Demonstration of Hard X-ray Self Seeding at LCLS

Courtesy Paul Emma / LBNL, WEYB02





SASE and Seeded spectra recorded on single shots. The left panels are SASE with 150 pC, 3kA peak current, un-seeded. The FWHM of the SASE spectrum is 0.2 % Bandwidth. The right panels are the seeded beam with the same electron beam parameters. The FWHM of the seeded beam is 0.5 eV (5×10^{-5} bandwidth)



Single shot pulse energy from the gas detectors with 40pC charge

- Concept developed by Geloni, Kocharyan and Saldin, DESY 10-053 (2010).
- The mean seeded FEL power is 8 GW with a 2.5 GW SASE background at 8 keV for 40 pC bunch charge.
- Peak seeded power is in excess of 15 GW, comparable to SASE but with a spectral bandwidth reduction by the factor of 40.
- Next steps include system optimization of the LCLS undulator beamline including additional undulators which should increase seeded power and reduce intensity fluctuation.

Seeding does not only improve bandwidth and longitudinal coherence
but allows also for much better e^- to photon conversion with tapering of undulator strength

TOWARD TW-LEVEL, HARD X-RAY PULSES AT LCLS*

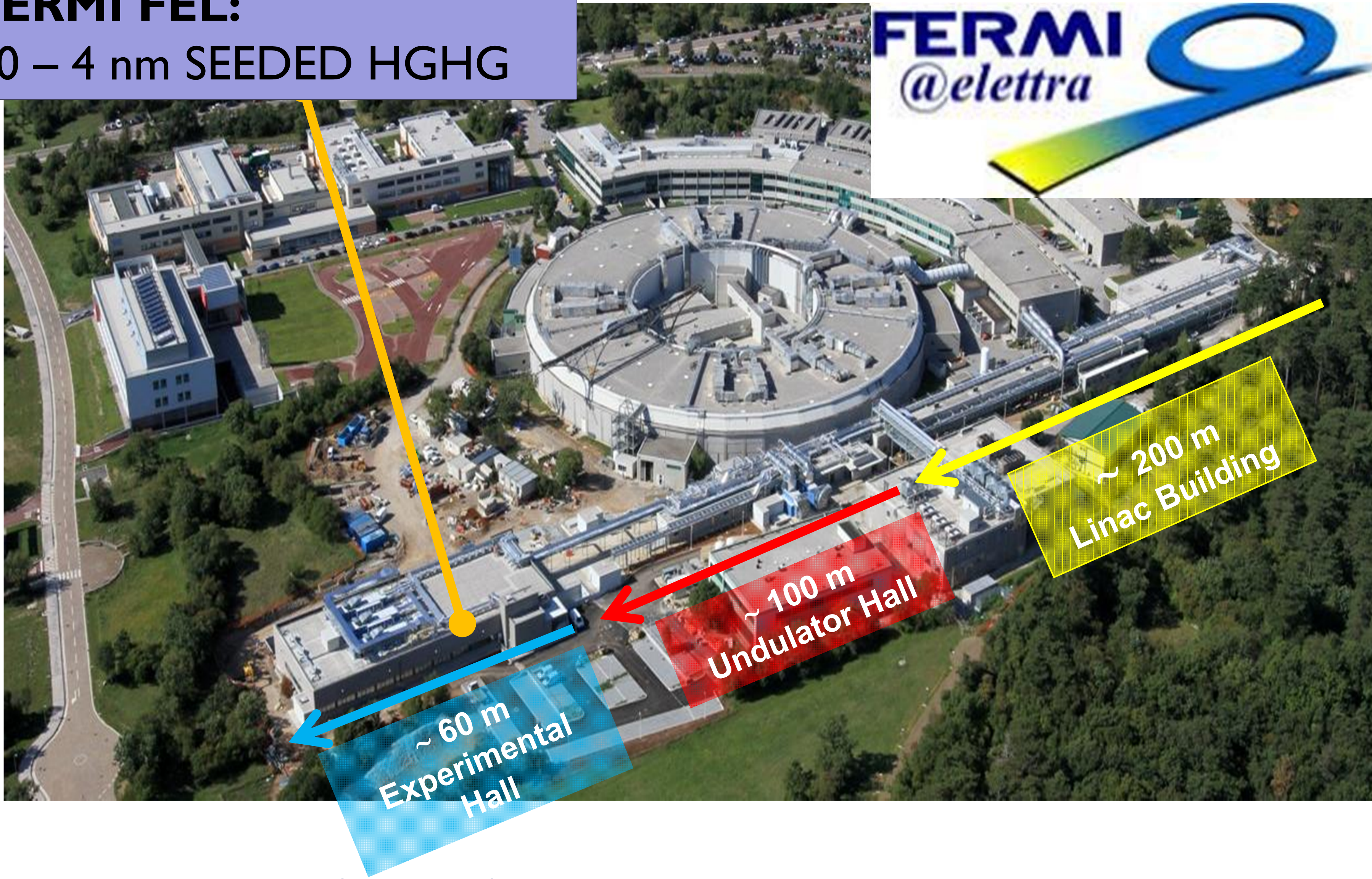
W.M. Fawley[1], J. Frisch[1], Z. Huang[1], Y. Jiao[1], H.-D. Nuhn[1], C. Pellegrini[1,2], S. Reiche[3], J. Wu[1†]
[1]SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA
[2]Department of Physics and Astronomy, UCLA, Los Angeles, CA 90095-1547, USA
[3]Paul Scherrer Institute, Villigen PSI, 5232, Switzerland

X-ray FEL facilities, the near future (until the end of this decade)

First beam parties, reserve date in your agenda

2012	FERMI FEL II, 4nm HGHG seeding cascade, circular polarization with Apple II
2013	FLASH II, second FEL undulator line with variable gap and seeding upgrade
2013	SX FEL based on SCSS in SACLA undulator hall, *Hitoshi Tanaka WEYB01*
2015	European XFEL, HX FEL1, HX FEL2 and SX FEL3
2015	PAL XFEL HX and SX
2016	Shanghai SX FEL
2016	SwissFEL HX FEL
2017	LCLS II, HX and SX
2019	Shanghai HX FEL
2019	SwissFEL SX FEL
?	NGLS
?	MaRIE

FERMI FEL:
80 – 4 nm SEEDED HGHG

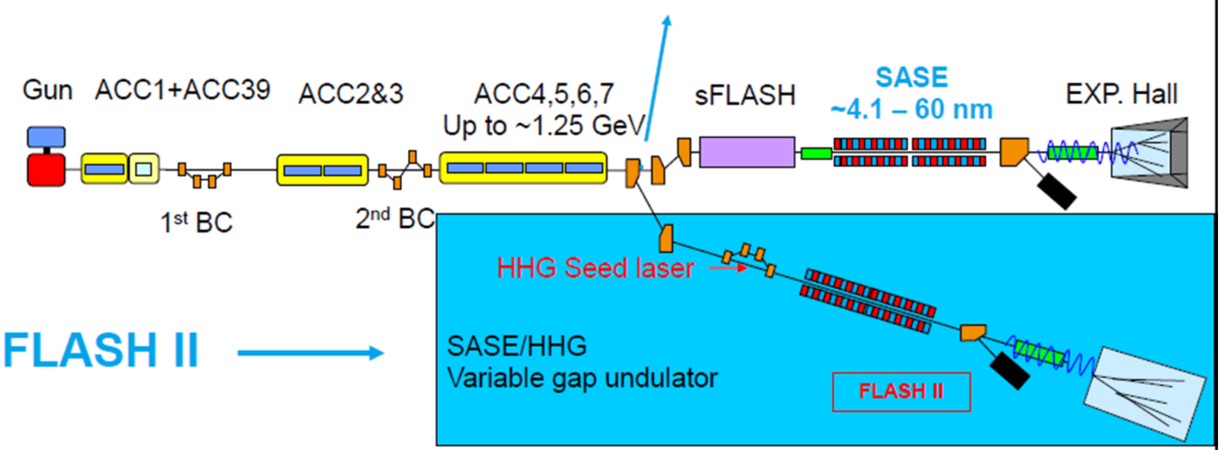


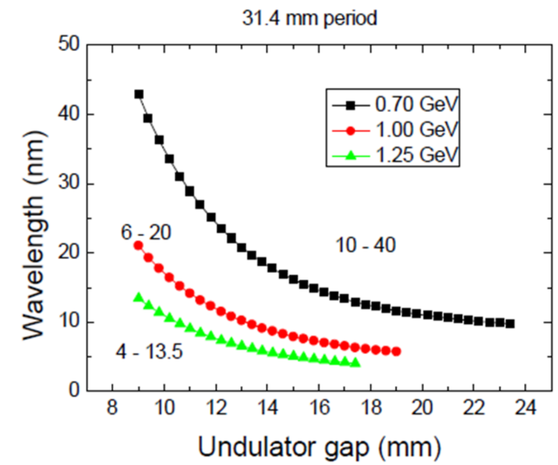
FEL I in operation (20-80 nm),
FEL II commissioning starting this year aiming for 4nm with cascaded HGHG seeding!
Talk Michele Svandrlik ,TUOBB03

FLASH II

courtesy of Bart Faatz/DESY

- Separation FLASH and FLASH II behind last accelerator module
- Tunability of FLASH II by undulator gap change
- Extend user capacity with SASE and HHG seeding
- Use of existing infrastructure up to last accelerating module

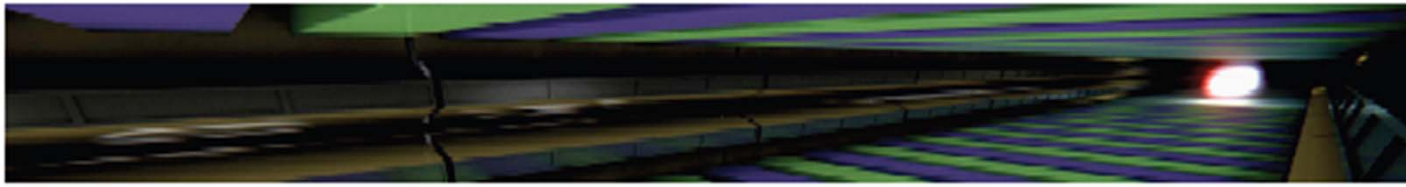


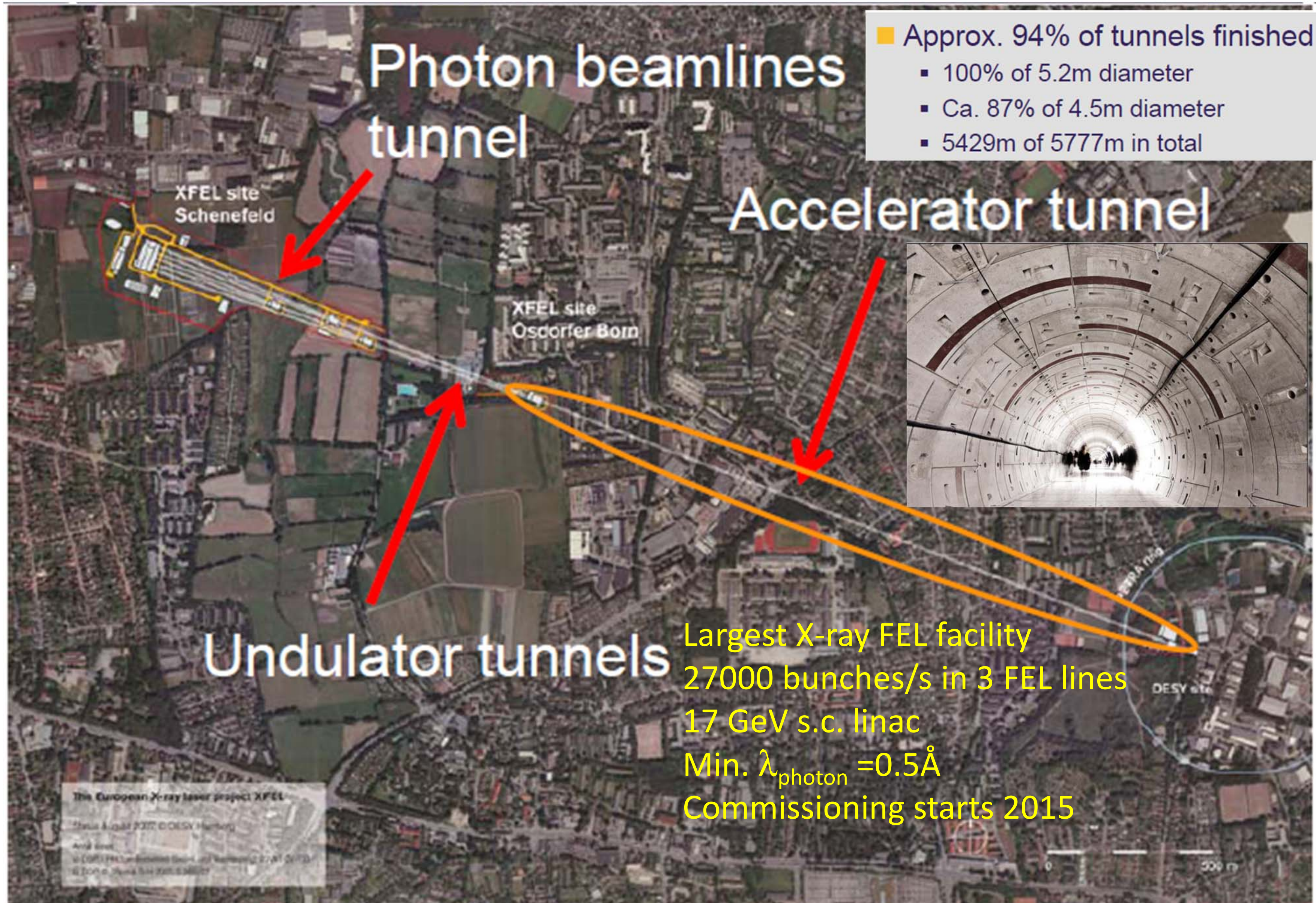


Start commissioning 2013

Electron Beam Parameter	
Beam Energy	0.5 – 1.25 GeV
Normalized Emittance	1.4 mm mrad
Energy Spread	0.5 MeV
Peak Current	2.5 kA
Number of bunches /second	<8000***
Undulator Parameter	
Period	31.4 mm
Segment Length	2.5 m
Number of Segments	<=12
Focusing	F0D0
Radiation	
Wavelength SASE*	4-60 nm
Wavelength HHG*	10-40 nm

European XFEL

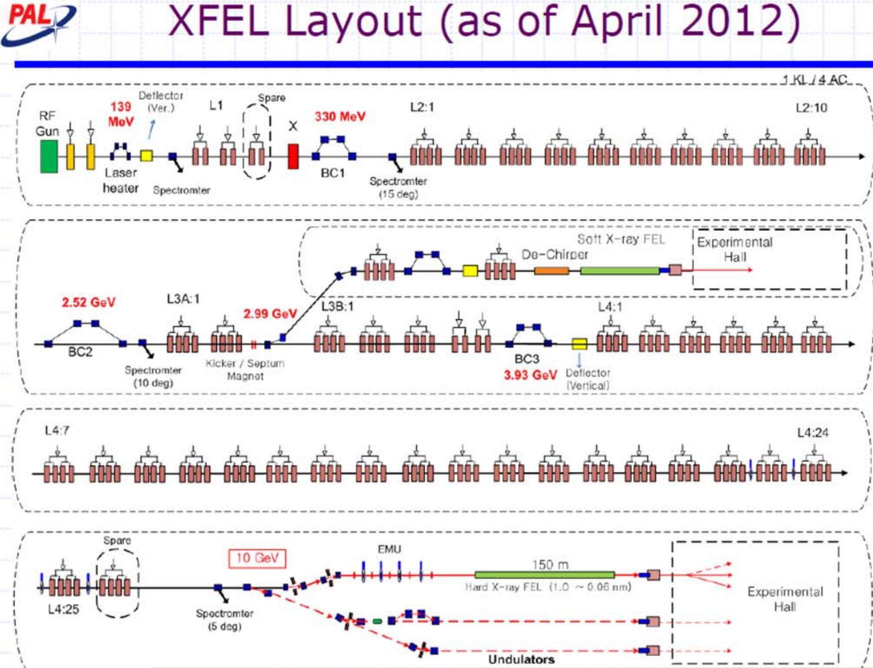




- Approx. 94% of tunnels finished
  - 100% of 5.2m diameter
  - Ca. 87% of 4.5m diameter
  - 5429m of 5777m in total

Largest X-ray FEL facility
27000 bunches/s in 3 FEL lines
17 GeV s.c. linac
Min. λ_{photon} =0.5Å
Commissioning starts 2015

PAL XFEL courtesy of In Soo Ko/PAL

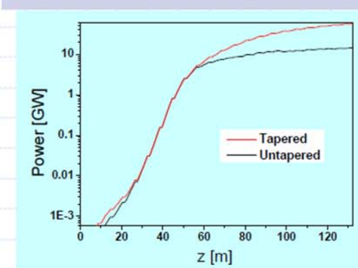


Major Parameters

	FEL wavelength [nm]	0.1
Electron Linac	Beam energy [GeV]	10
	Beam charge [nC]	> 0.2
	Beam emittance [mm-mrad]	< 0.5
	Injector Gun	Photocathode RF-gun
	Peak current at undulator [kA]	> 3
	Repetition rate	120 Hz
	Number of bunches	Single or Two
	Linac structure	S-band
Undulator	Undulator type	Out-vacuum
	Undulator period [cm]	2.46
	Undulator gap [mm]	6.8
	Undulator parameter, K	2.076
	Saturation length [m]	56
FEL	FEL radiation power [GW]	> 29
	Photon beam length [fs]	60
	FEL photons/pulse	> 1.0 E+12

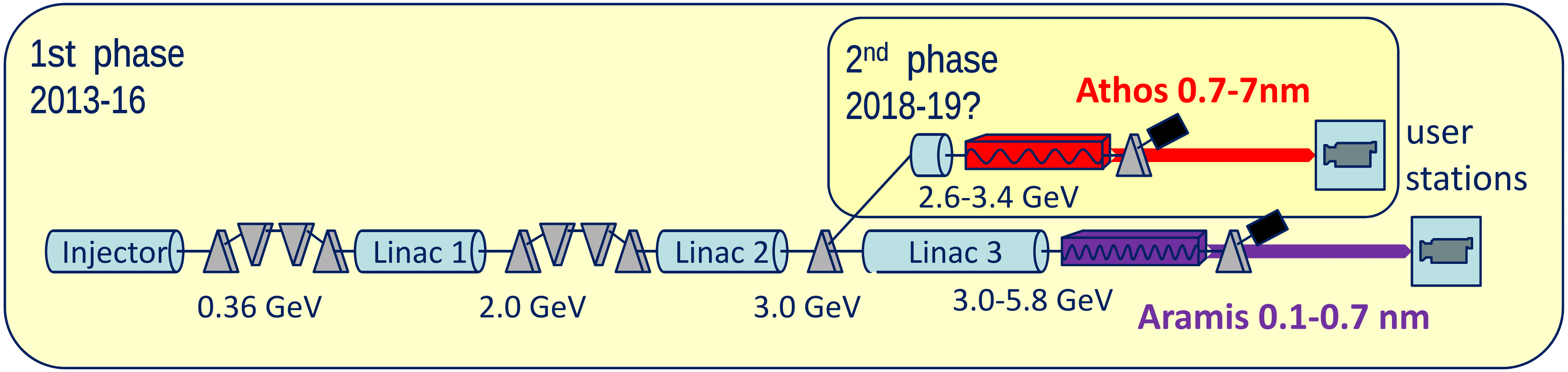
- Wavelength
  - Soft x-ray: 1 nm ~ 10 nm
  - Hard X-ray: 0.7 ~ 0.1 nm
    - Extended to 0.06 nm
- Photon beam Length
  - Nominal : 30 ~ 100 fs (200 pC)
  - Short : < 5 fs (20 pC)
  - Ultra short: < 0.5 fs by ESASE scheme
- Undulator Beamline

  3 Hard X-ray / 2 Soft X-ray lines



Radiation Power of 0.1 nm @Z=132 m
- Untapered : 14 GW (4.7E+11 photons)
- Tapered : 55 GW (1.8E+12 photons)

SwissFEL



Aramis

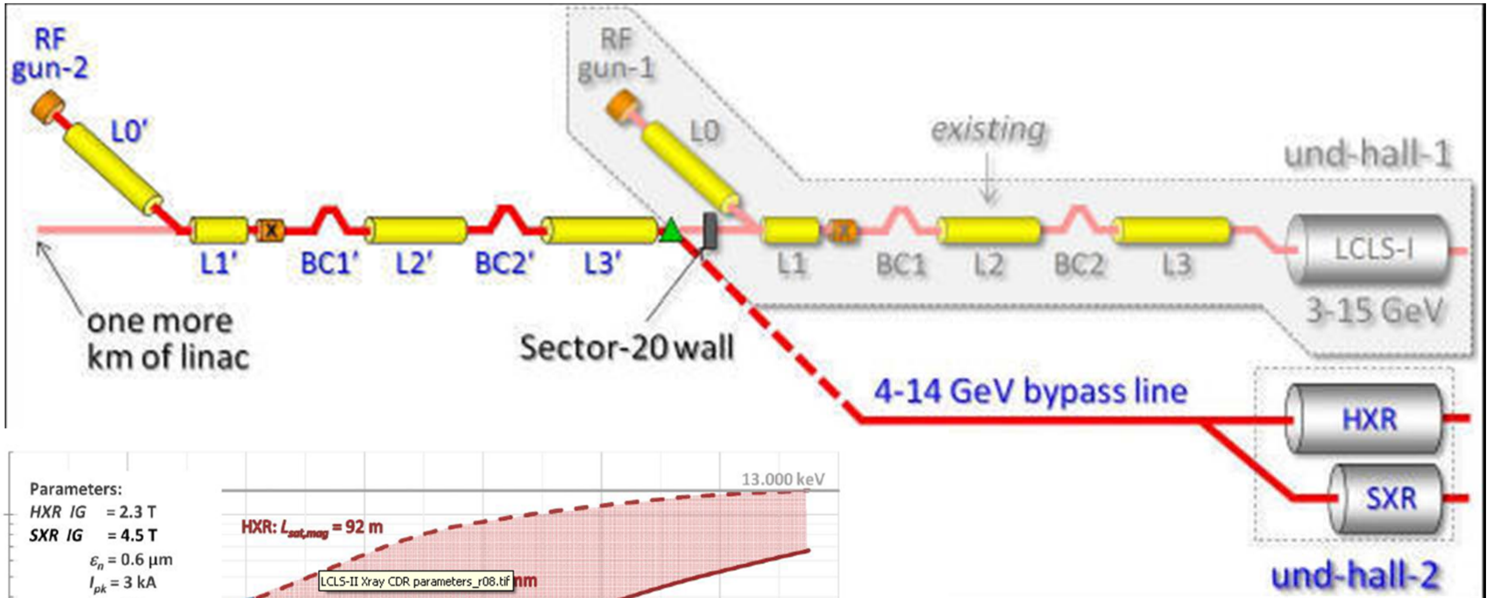
1-7 Å hard X-ray FEL for **SASE with reservations for self seeded** operation,
In-vacuum, planar undulators with variable gap.
User operation from 2017

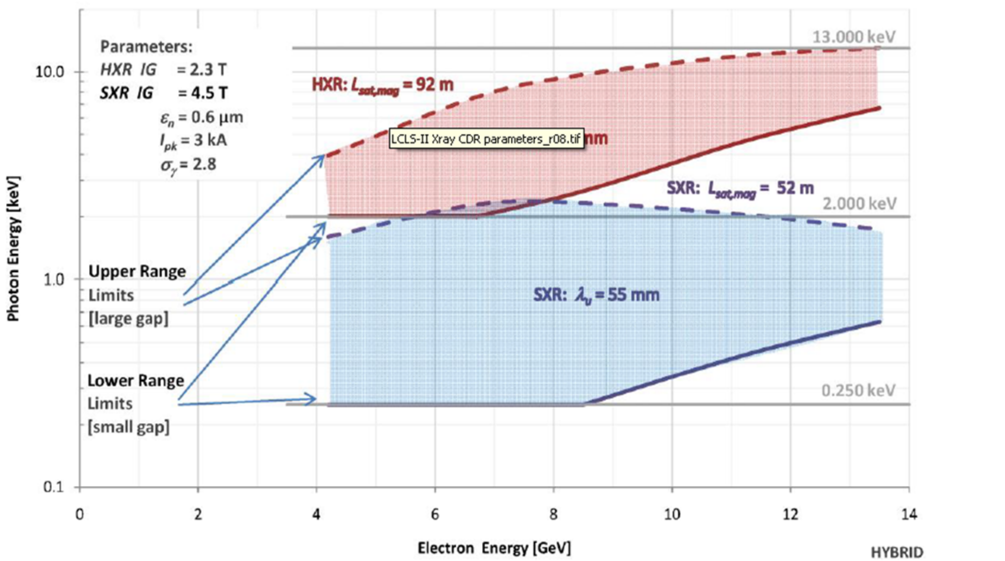
Athos

7-70 Å soft X-ray FEL for **SASE & self seeded** operation .
APPLE II undulators with variable gap and full polarization control.
User operation from 2019

LCLS II

From https://slacportal.slac.stanford.edu/sites/lcls_public/lcls_ii/Published_Documents/CDR%20Index.pdf



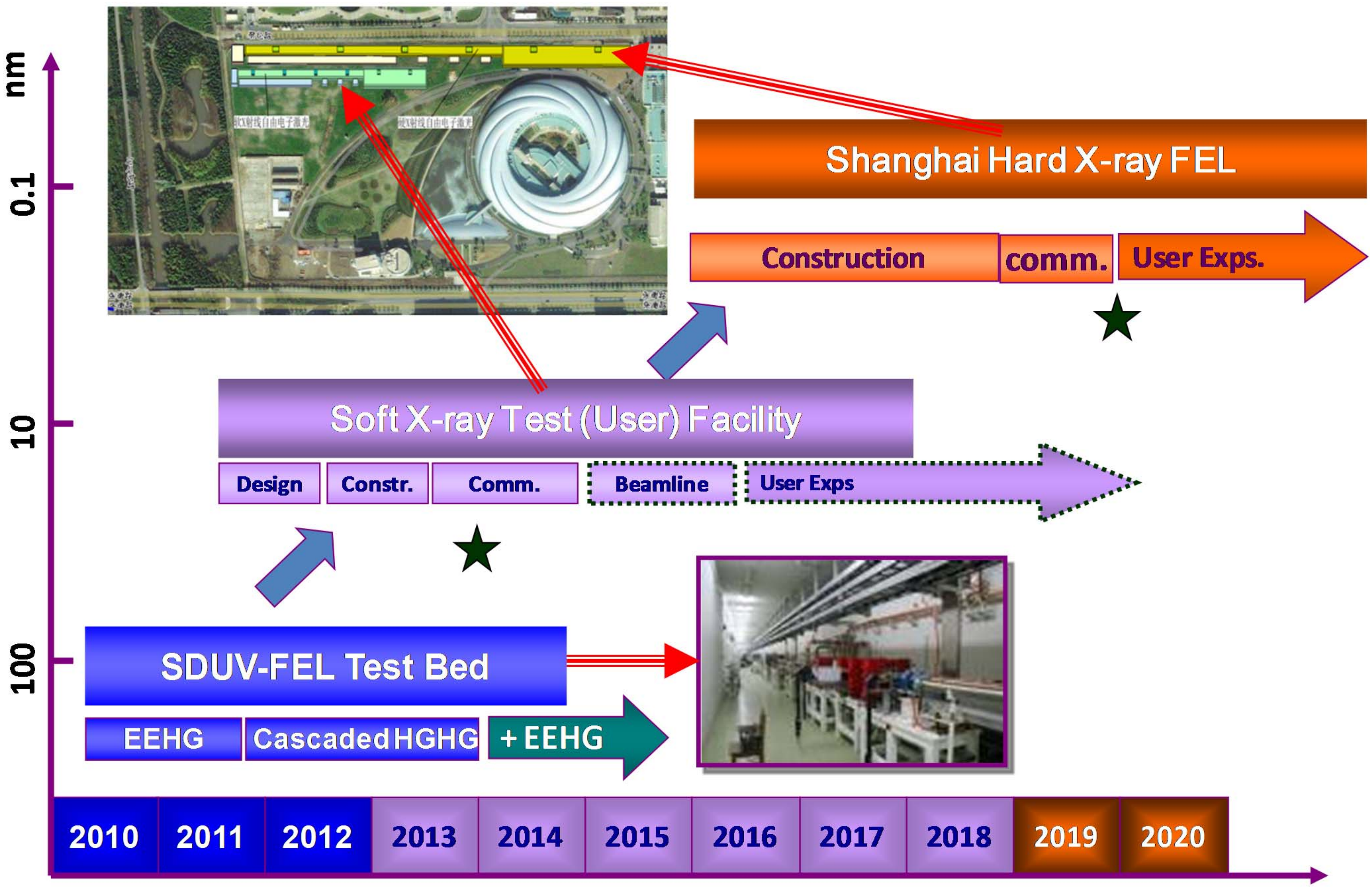


Ranges of available photon energy for the two parallel undulators (HXR, red lines; SXR, blue lines) using the same electron beam parameters.

first beam foreseen for 2017

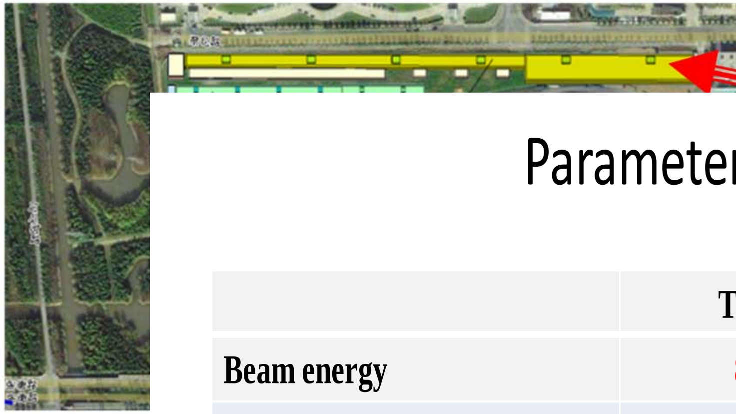
FEL Roadmap at SINAP

courtesy of Dong Wang/SINAP



FEL Roadmap at SINAP

courtesy of Dong Wang/SINAP



Parameters of SXFEL

	Test facility	User facility
Beam energy	840 MeV	1.3 GeV or higher
Beam energy spread	0.1%	0.1%
Normalized emittance	1~2mm-mrad	1~2mm-mrad
Bunch charge	50~500pC	50~500pC
Linac structures	S-band + c-band	S-band + c-band
Seed laser wavelength	260nm+OPA	260nm+OPA
FEL output wavelength	8.8 nm	3.75 nm
FEL pulse duration	30 fs - 1ps	30 fs - 1ps
FEL scheme	Cascade HGHG	depends

nm
0.1
10
100
SDU
EEHG
ray FEL
User Exps.
2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020

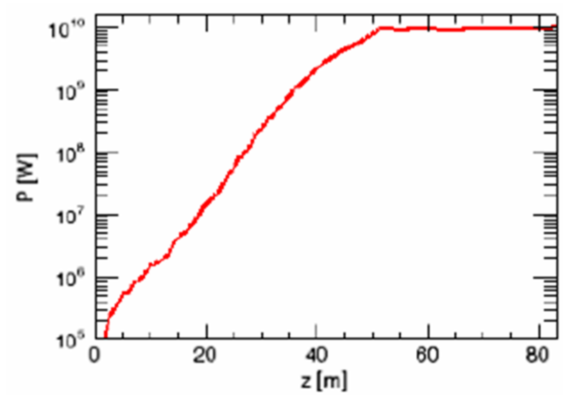
FEL Roadmap at SINAP

courtesy of Dong Wang/SINAP

Parameters of Compact XFEL

Electron beam parameters	
Energy/GeV	6.4
Peak current/kA	3
Bunch charge/pC	250
Normalized slice emittance/mm-mrad	0.4
RMS slice energy spread	0.01%
Full bunch length/fs	100
Undulator parameters	
Period/cm	1.6
Segment length/m	4.8
Full undulator length	70
Peak undulator field/T	0.93
K	1.4
Gap/mm	6
Average beta function/m	20

FEL parameters	
Radiation wavelength/nm	0.1
ρ	3.41e-4
Peak coherent power/GW	10
Peak brightness/*	2e33
Pulse repetition rate (Max.)/Hz	60
3D gain length/m	2.156
Saturation length/m	50



nm

0.1

10

100

FEL

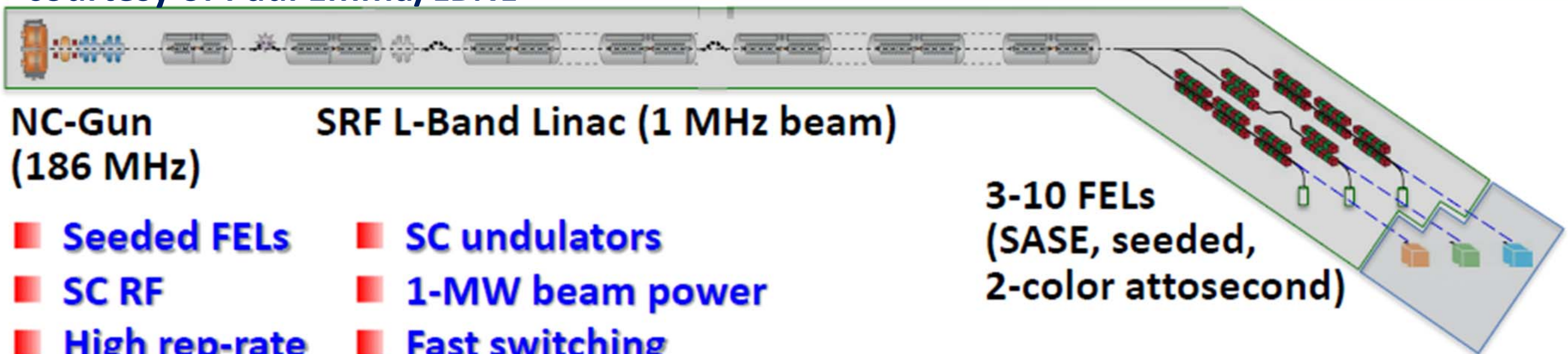
er Exps.

E

2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020

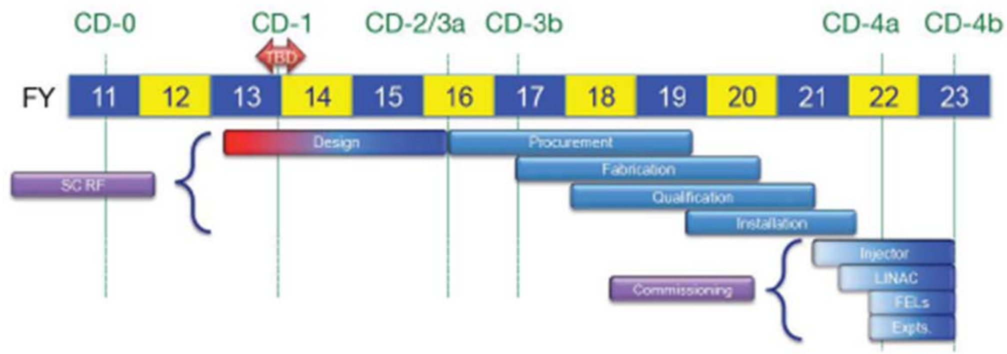
CW Soft X-Ray FEL Facility

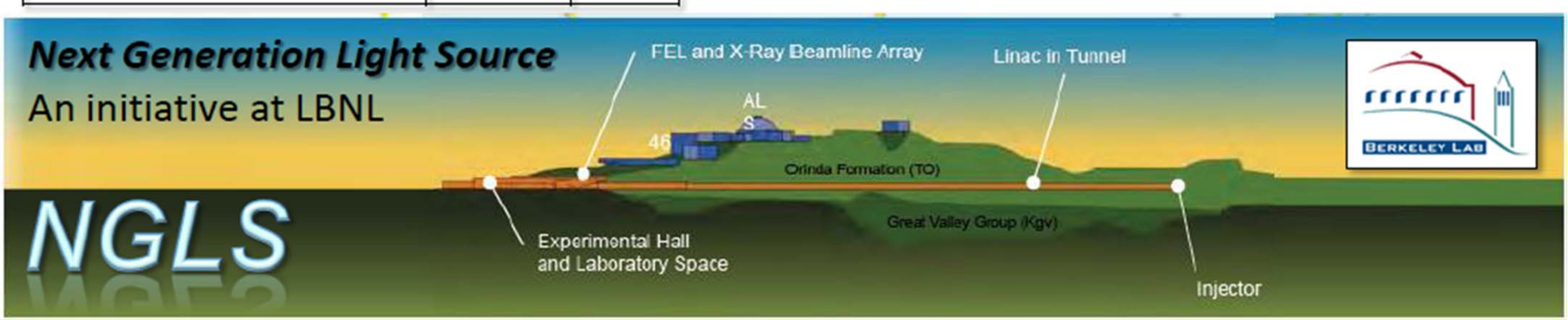
courtesy of Paul Emma/LBNL



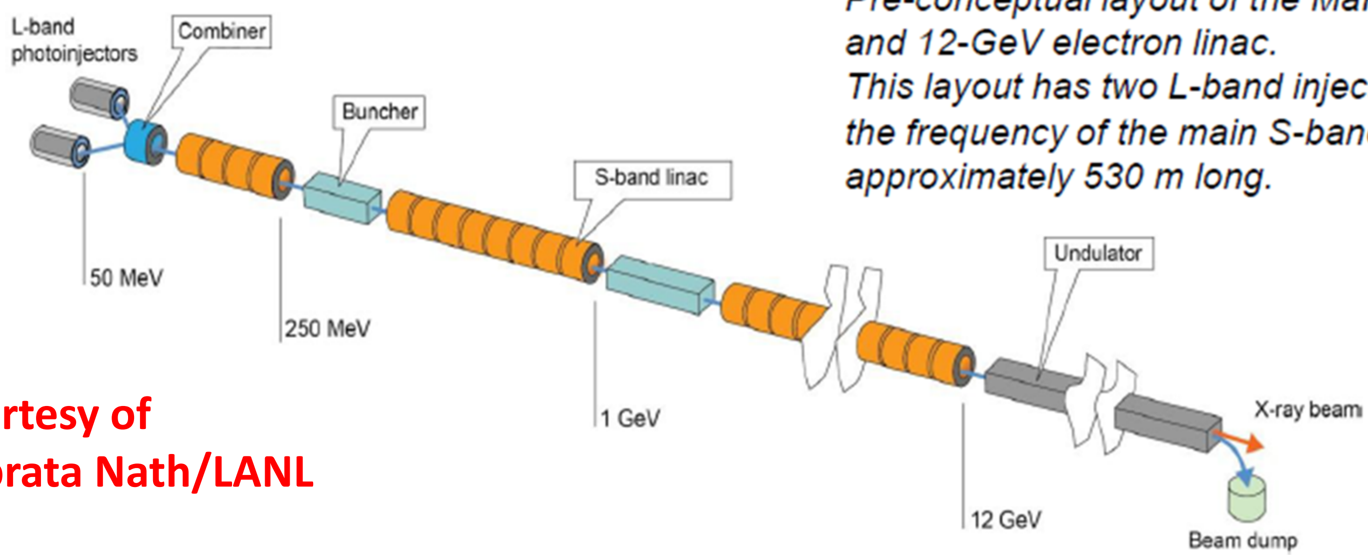
- Seeded FELs
- SC RF
- High rep-rate
- SC undulators
- 1-MW beam power
- Fast switching

Electron Beam Energy	2.4	GeV
FEL Wavelength Range	1 - 4.6	nm
Linac Beam Rate (CW)	1	MHz
Avg. Linac Current	0.3	mA
First Operation	2023	-





Proposed MaRIE 1.0 (Matter - Radiation Interactions in Extremes) will be an Accelerator user facility, leveraging LANSCE 0.8 – GeV proton accelerator adding to it an XFEL - a unique source of very hard, coherent, brilliant photons



Pre-conceptual layout of the MaRIE 42-keV XFEL and 12-GeV electron linac.
This layout has two L-band injectors operating at ½ the frequency of the main S-band linac. The linac is approximately 530 m long.

courtesy of Subrata Nath/LANL

Pre-conceptual Design Parameters

Energy	12 GeV
Linac frequency	3 GHz
Linac type	RT Cu
Cavity gradient	25* MV/m
Maximum beamline θ	4 degrees
Bunch compressor 1	6 m
Bunch compressor 2	22 m

RF pulse duration	1.5 µs
RF pulse rise time	0.8 µs
RF peak power	80 MW
RF Repetition rate	60 Hz
Accelerator active length	480 m
Accelerator length from injector to linac end	528 m

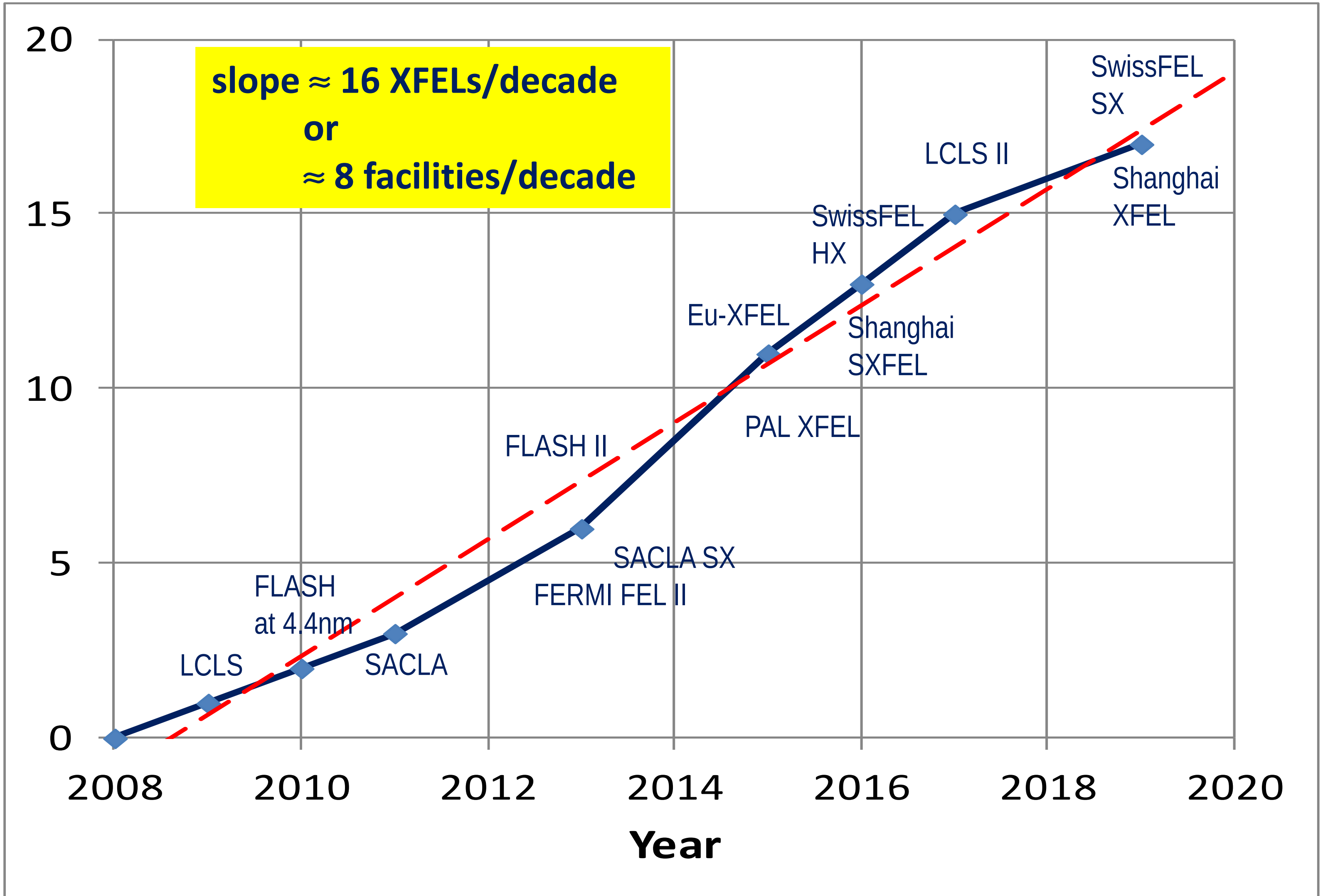
X-ray FEL Megatable

blue: in operation, green: under construction or advanced planning, orange: design in progress

	LCLS	LCLS II	Eu-XFEL	SACLA	FLASH	FLASH II	FERMI	SwissFEL	PAL XFEL	Shanghai XFEL	NGLS	MaRIE
Shortest wavelength	1.5 Å	1 Å	0.5 Å	1 Å	40 Å	40 Å	40 Å	1 Å	1 (0.6) Å	1 Å	10 Å	0.3 Å
Undulator type hard X-ray.	Fixed gap	Variable gap	Variable gap	In-vacuum Var. gap	n.a.	n.a.	n.a.	In-vacuum var. gap	Variable gap	Variable gap	n.a.	?
Undulator type soft X-ray.	n.a.	Variable gap	Variable gap	n.a.	Fixed gap	Variable gap	Apple II	Apple II	Apple II	?	Var. gap & Apple	n.a.
Injector	S-band RF gun	S-band RF gun	L-band RF gun	Pulsed Diode	L-band RF gun	L-band RF gun	S-band RF gun	S-band RF gun	S-band RF gun	S-band RF gun	VHF c.w. RF Gun	?
Cathode	Cu	Cu	Cs_2Te	CeB_6 (thermionic)	Cs_2Te	Cs_2Te	Cu	Cu	Cu	Cu	K_2CsSb	?
Main linac technology	n.c. Pulsed	n.c. pulsed	s.c. pulsed	n.c. pulsed	s.c. pulsed	s.c. pulsed	n.c. pulsed	n.c. pulsed	n.c. pulsed	n.c. pulsed	s.c. c.w.	n.c. pulsed
RF frequency	S-band	S-band	L-band	C-band	L-band	L-band	S-band	C-band	S-band	C-band	L-band	S –band
RF Rep. rate	120 Hz	120 Hz	10 Hz	60 Hz	10 Hz	10 Hz	10-50 Hz	100 Hz	60 Hz	60 Hz	n.a.	60 Hz
FEL pulses/RF pulse	1	1	2700	1	2700	2700	1	2	1	1	1 MHz c.w.	100
max. bunch charge	0.25 nC	0.25 nC	1 nC	0.2 nC	1 nC	1 nC	0.5 nC	0.2 nC	0.2 nC	0.2 nC	0.3nC	0.1 nC
max. electron energy	13.6 GeV	14 GeV	17.5 GeV	8 GeV	1.2 GeV	1.2 GeV	1.5 GeV	5.8 GeV	10 GeV	6.4 GeV	2.4 GeV	12 GeV
No. RF stations	81	81	29	69	5	5	15	34	49	?	?	?
Approx. facility length	1.7km	1.7km	3.4 km	0.8km	0.32 km	0.32 km	0.5 km	0.7km	1.1 km	0.6 km	0.8 km	1.0 km
Start operation	2009	2017	2015	2011	2005	2013	2010	2016	2015	2019	2023	?

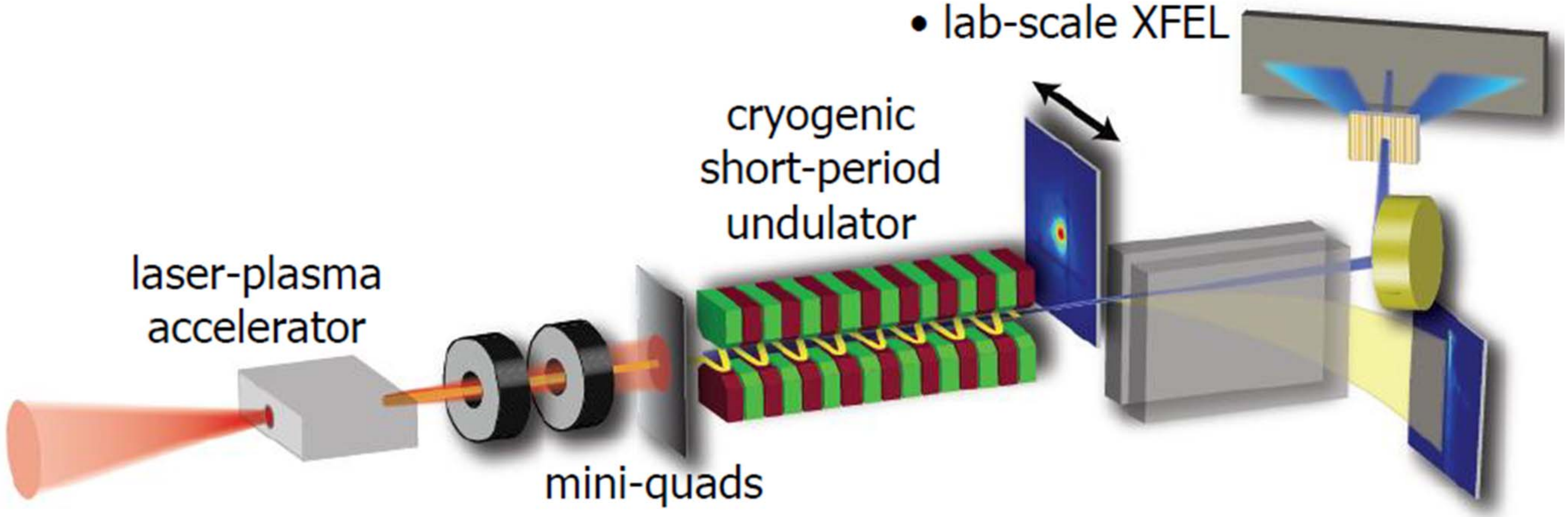
No. X-ray FELs worldwide

(undulator lines with λ_{photon}<50Å)



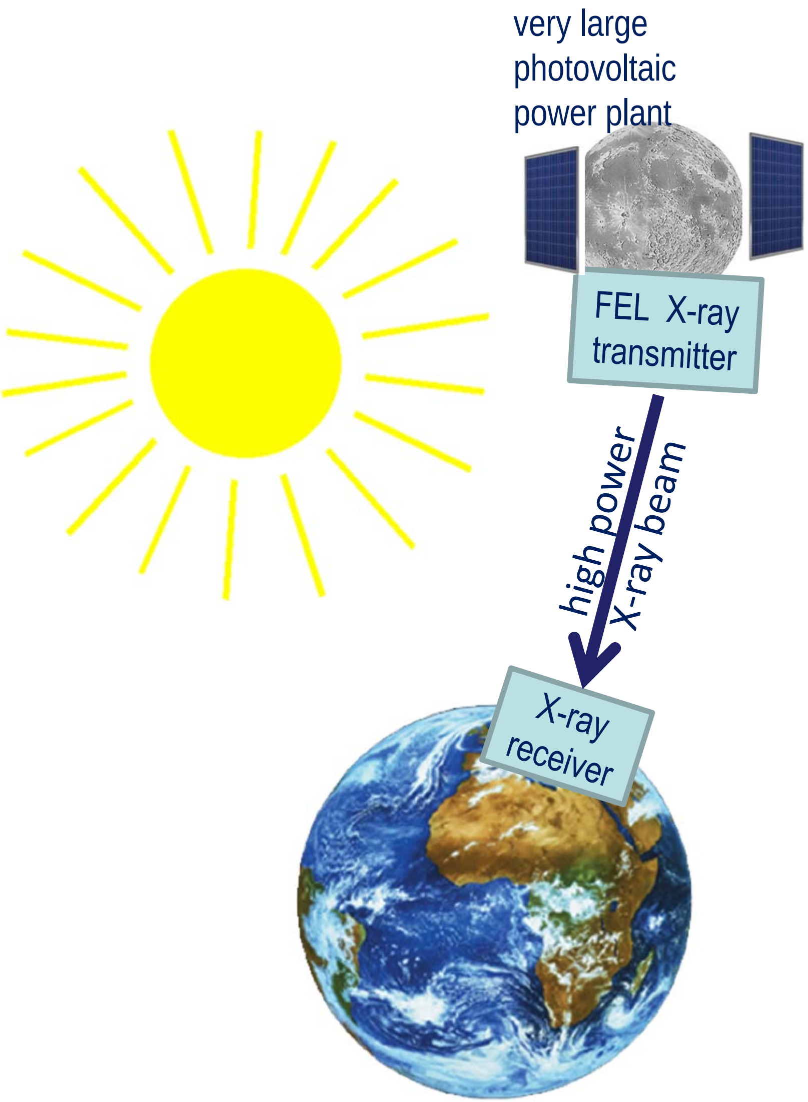
X-ray FEL's Mid Term Future

see also Wim Leemans, WEIC03



courtesy Florian Grüner

X-ray FEL's Long Term Future



Some benefits from bandwidth and collimation properties of diffraction limited coherent X-ray beams

- Energy problem solved (see left)
- World communication network backbone based on 100 beam XFEL links with 10 Zettabyte/s
- Near light velocity space probe powered by XFEL beam from ground station on their way to Sirius
- Novel "Black&Decker iFEL" drill, cut, welding tool revolutionizes quality of do-it-yourself products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