U.S. DEPARTMENT OF ENERGY | Office of Science

Synchrotron Radiation Light Sources

Briefing for SEAB

20 June 2014

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Synchrotron Radiation Light Sources

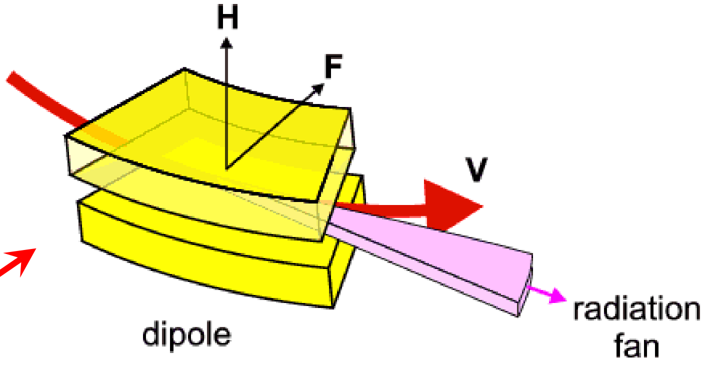
- What, why, how, where?
- Office of Science light sources
  - Storage rings
  - Free electron lasers
- What's next for U.S. light sources?

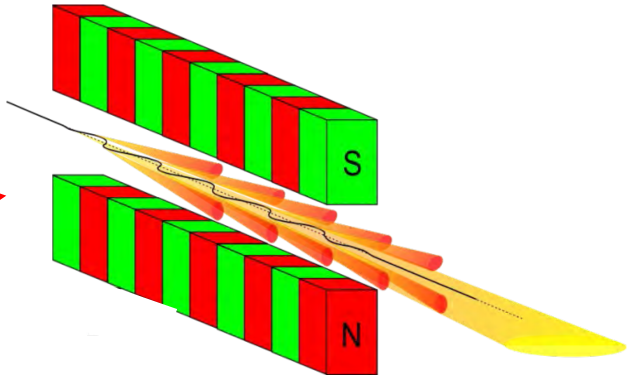
(This is a 100% equation-free presentation.)

What is Synchrotron Radiation?

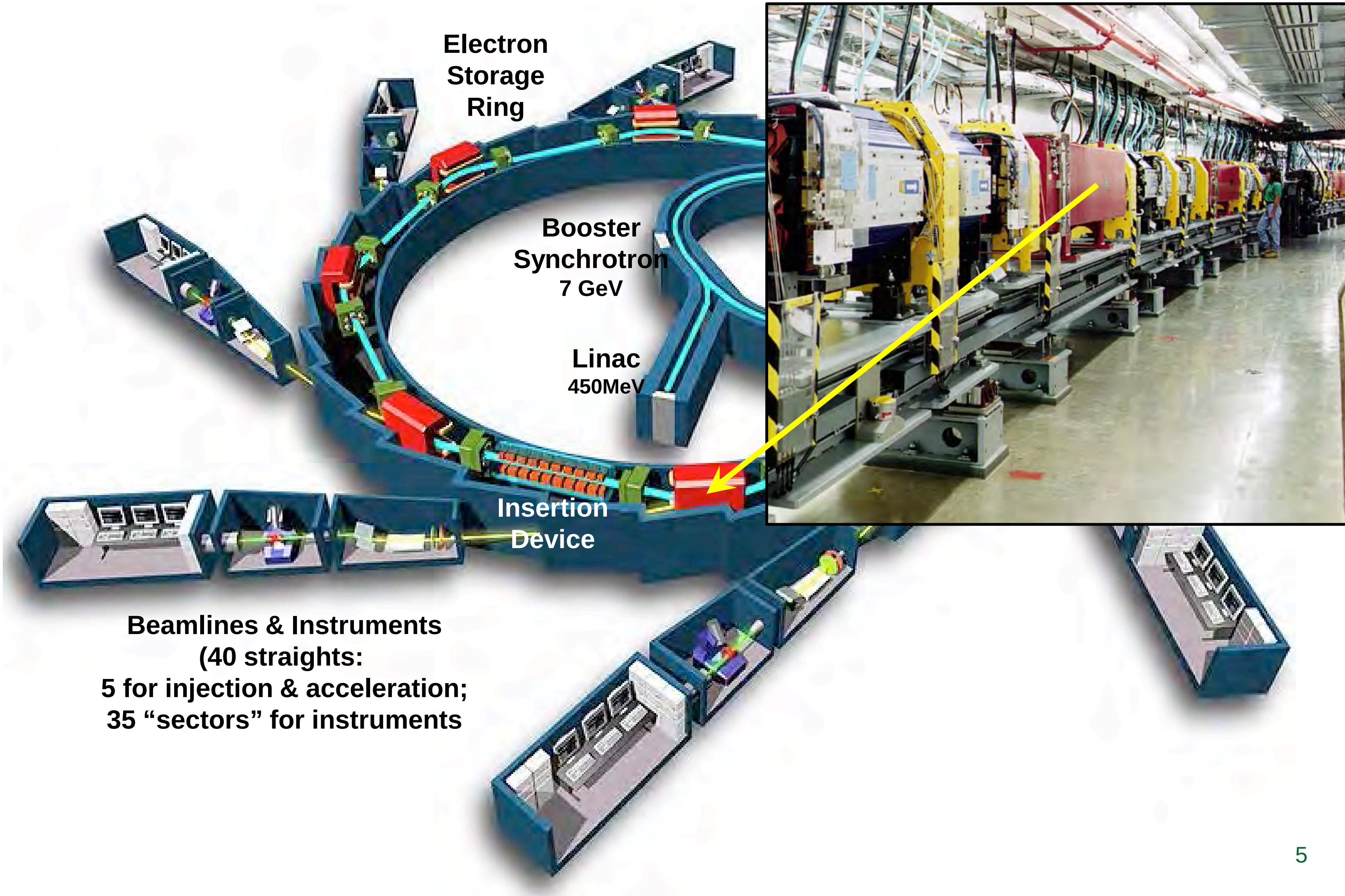
What is Synchrotron Radiation?

- Synchrotron radiation is electromagnetic radiation emitted when charged particles—in this case, electrons—are accelerated radially using magnetic fields.
- Specially designed magnets or arrangements of magnets produce radiation with specific, desired properties.
- Magnet configurations include simple bending magnets or arrays of magnets called undulators and wigglers.

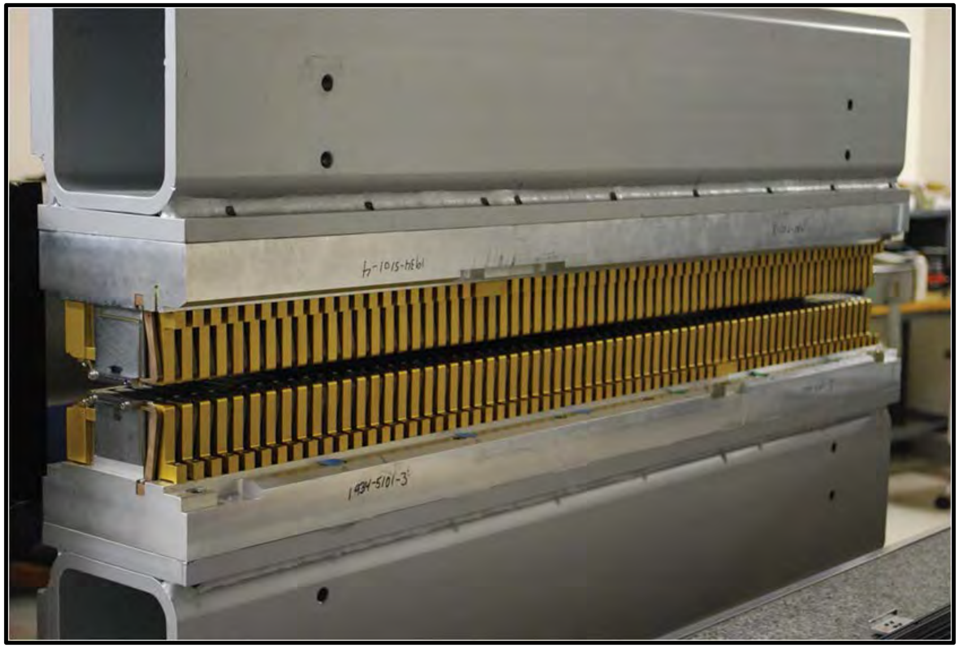


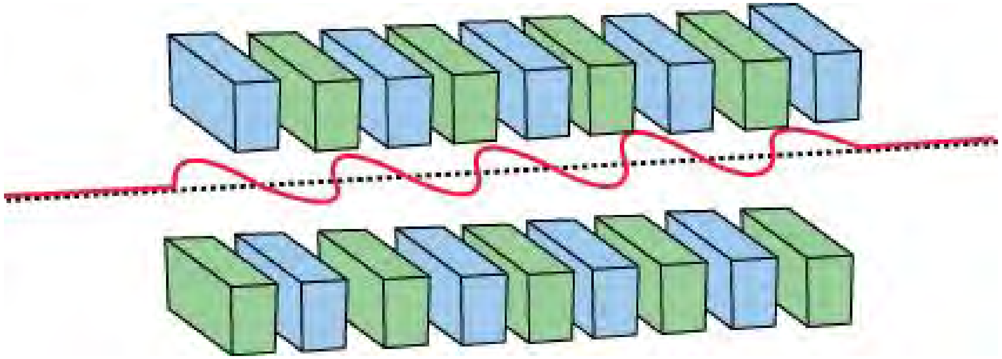


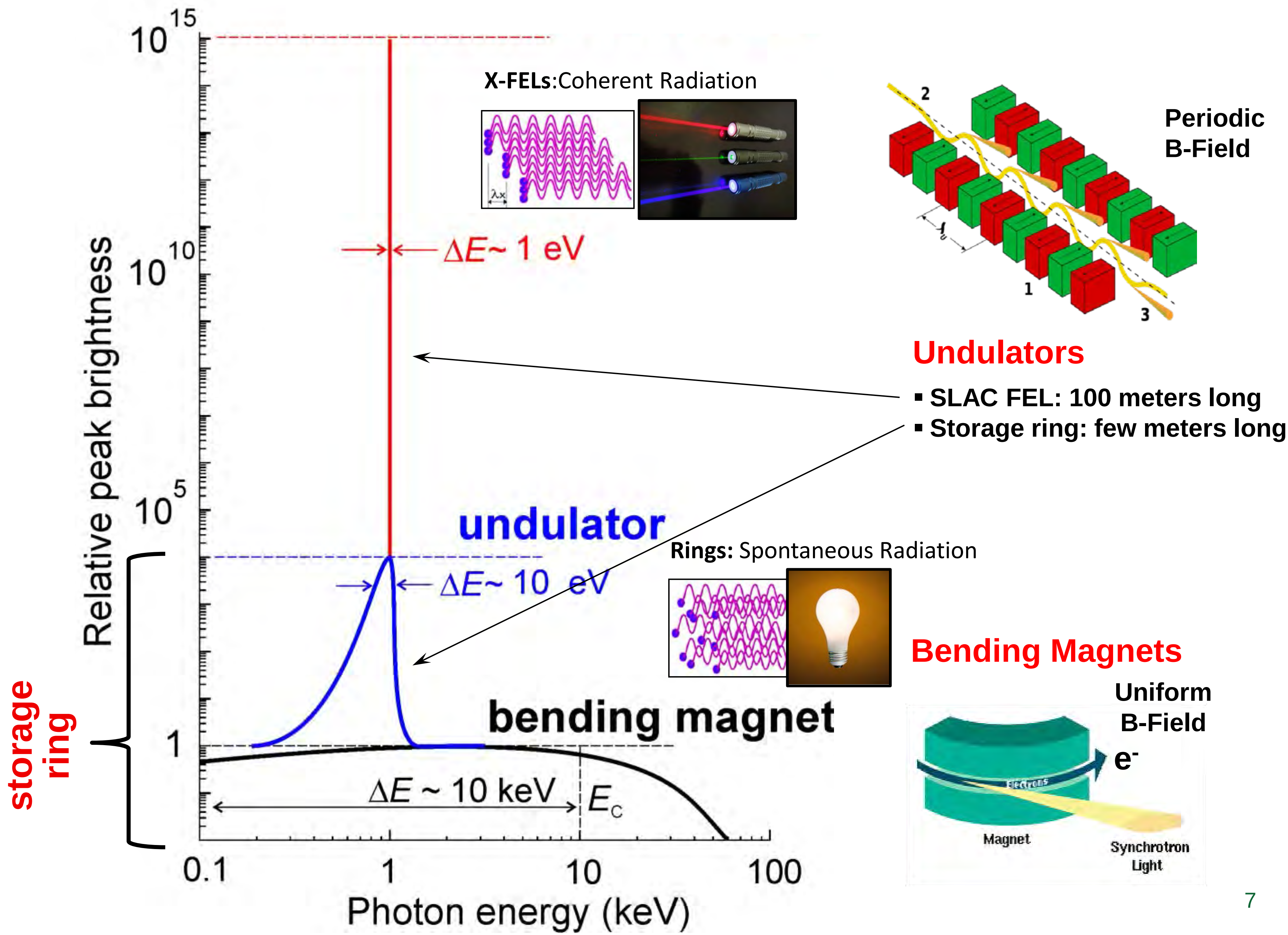
Radiation from Bending Magnets



Radiation from Insertion Devices
Wigglers and Undulators

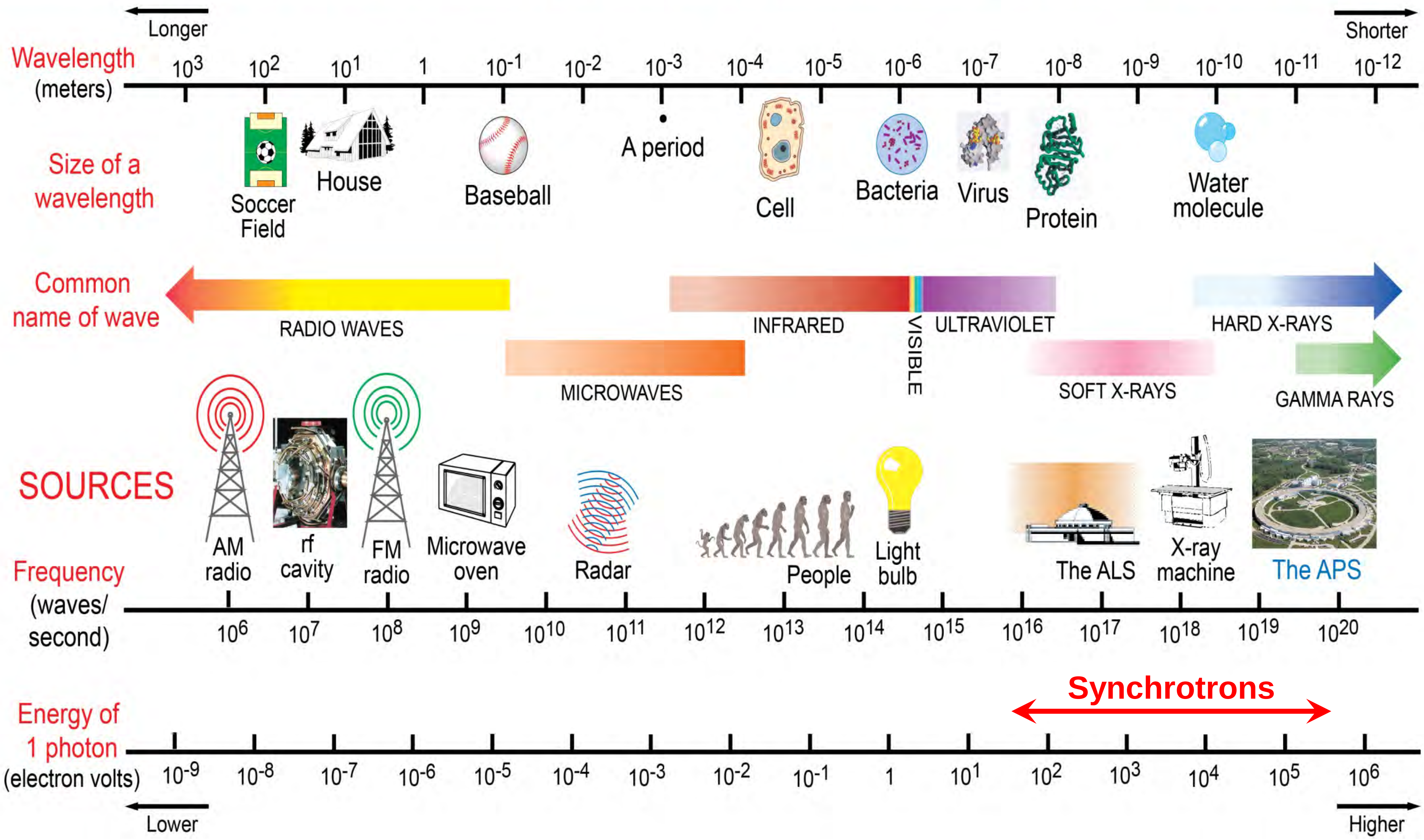






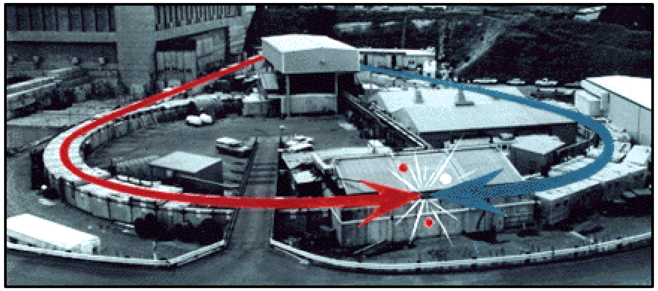
Relative peak brightness
10^15
10^10
10^5
1
Photon energy (keV)
0.1
1
10
100
storage ring
X-FELs:Coherent Radiation
λx
ΔE~ 1 eV
undulator
ΔE~ 10 eV
bending magnet
ΔE ~ 10 keV
E_C
Rings: Spontaneous Radiation
Periodic B-Field
2
1
3
Undulators
▪ SLAC FEL: 100 meters long
▪ Storage ring: few meters long
Bending Magnets
Uniform B-Field
e-
Electrons
Magnet
Synchrotron Light

THE ELECTROMAGNETIC SPECTRUM



Synchrotron Light Sources Evolution by Generation

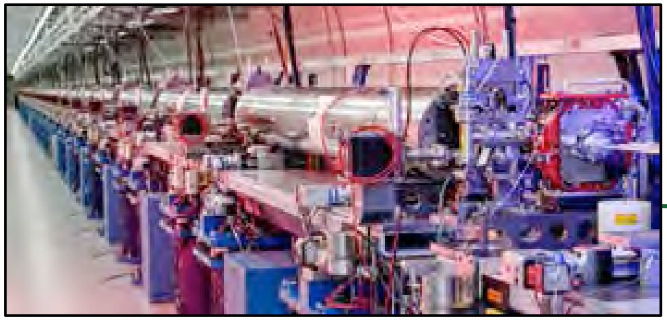
First observation of manmade synchrotron radiation @ General Electric in 1947



- **1st Generation:** parasitic synchrotron radiation source from the dipoles of an HEP collider storage ring (SPEAR, 1975)

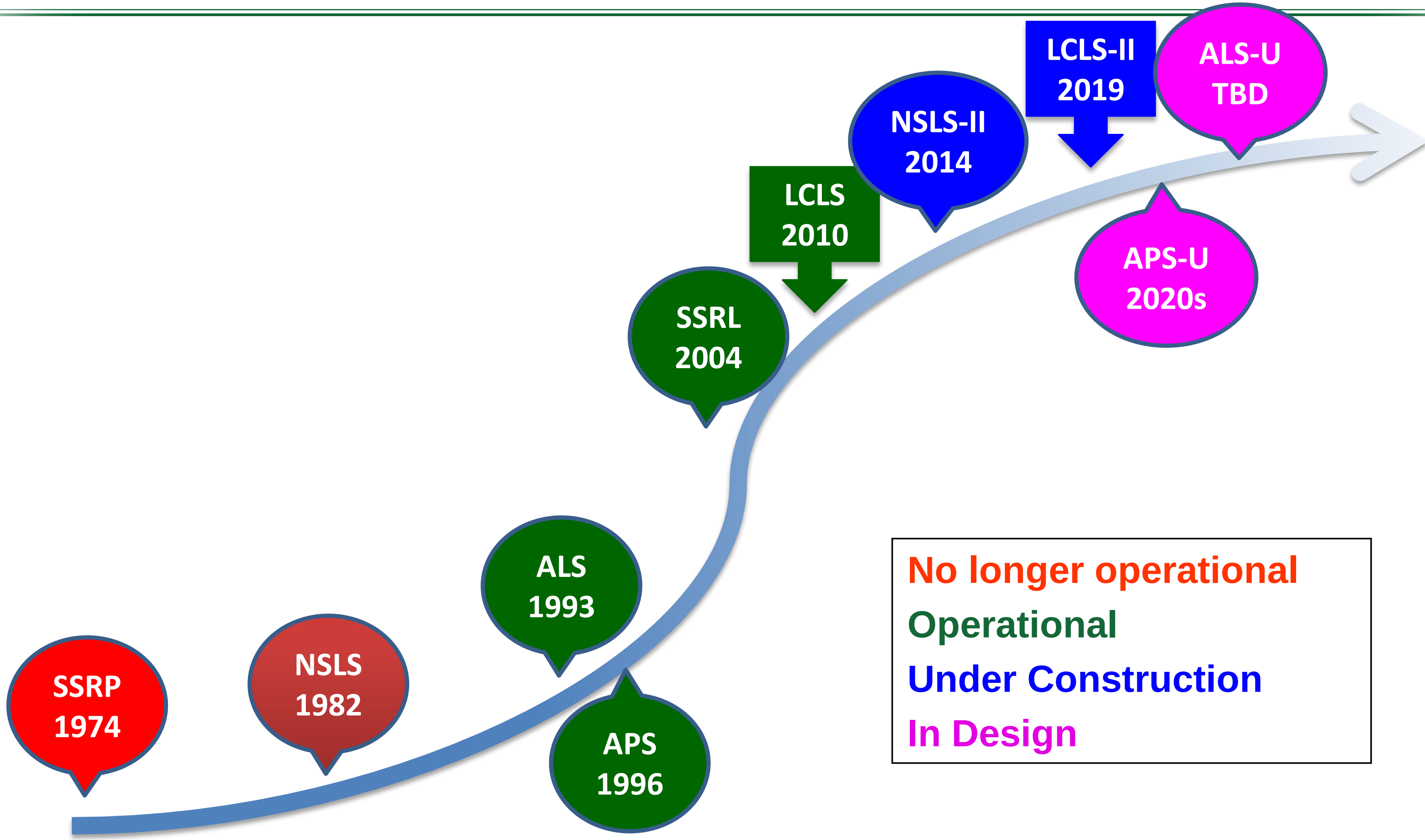
- **2nd Generation:** dedicated storage ring for synchrotron radiation, dipole radiation & some undulators (NSLS, 1982)

- **3rd Generation:** dedicated storage ring optimized for undulator radiation; very high brightness (ALS, 1993; APS, 1996; SSRL, 2004; NSLS-II, 2014)



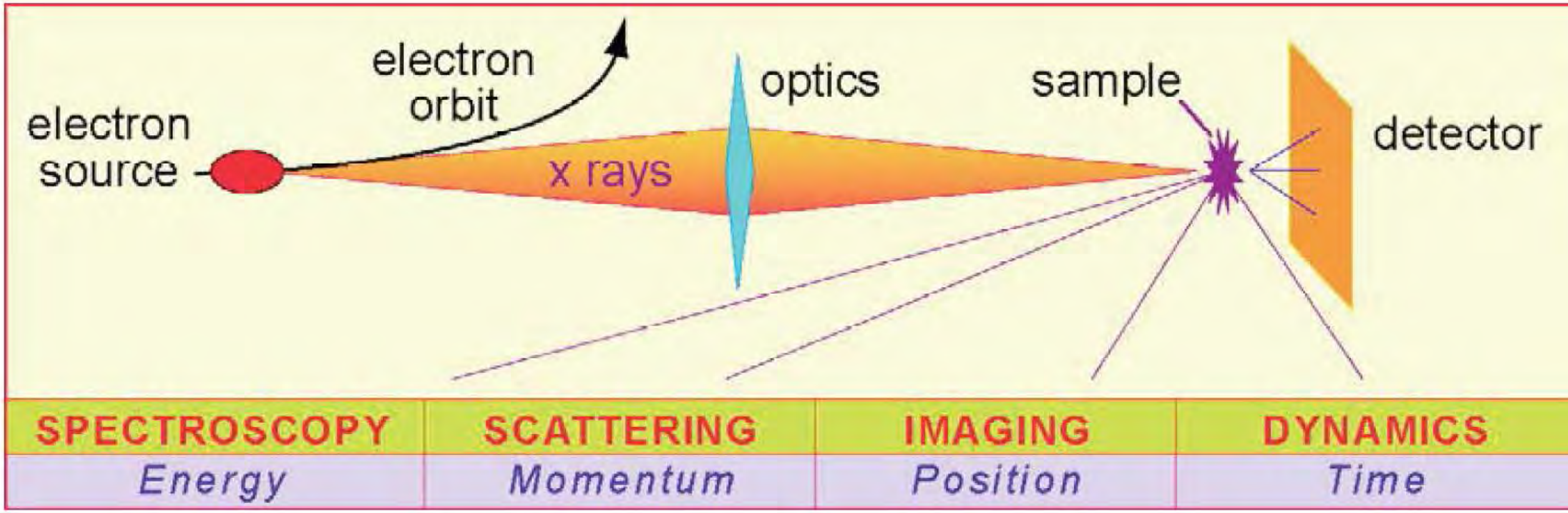
- **4th Generation:** dedicated linac driven free electron laser (LCLS, 2009)

The History of SC/BES Light Sources



What are X-rays Used for?

Experimental Techniques

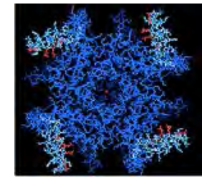


The fundamental parameters that we use to perceive the physical world (energy, momentum, position, and time) correspond to three broad categories of synchrotron experimental measurement techniques: spectroscopy, scattering, and imaging. By exploiting the short pulse lengths of synchrotron radiation, each technique can be performed in a timing fashion.

4 Nobel Prizes in Biochemistry with SC Storage Ring Light Sources & the Prospect of Single-Molecule, Single-Shot Imaging with FELs

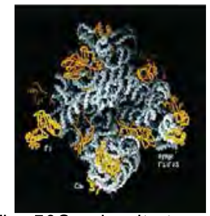
Nobel Prizes with SC storage rings in protein structures

2003	Roderick MacKinnon (Chemistry) for "structural and mechanistic studies of ion channels."
2006	Roger Kornberg (Chemistry) "for his studies of the molecular basis of eukaryotic transcription."
2009	Venkatraman Ramakrishnan, Thomas A. Steitz, and Ada E. Yonath (Chemistry) "for studies of the structure and function of the ribosome."
2012	Robert J. Lefkowitz and Brian K. Kobilka (Chemistry) "for studies of G-protein-coupled receptors."



The overall view of a voltage-dependent potassium ion channel.

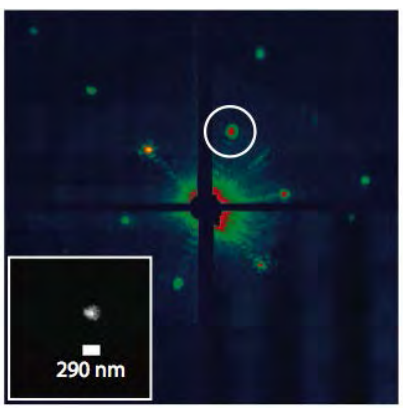
The visualized transcription process.



The 50S subunit at 2.4Å resolution.

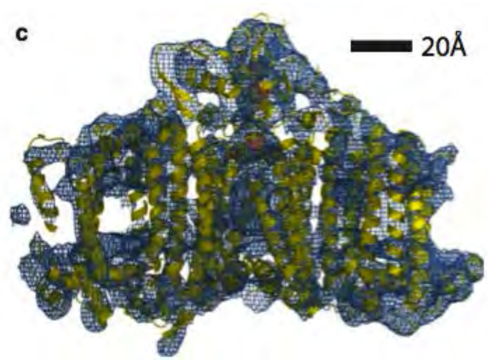
The structure of the β2AR-Gs complex.

Early experiments in single-molecule, single-shot imaging at LCLS



Single Shot Diffraction Pattern

HN Chapman *et al. Nature* 470, 73-77 (2011)



The structure of the β2AR-Gs complex.

Reconstructed Image

FY14: First de novo 3D structure of lysozyme

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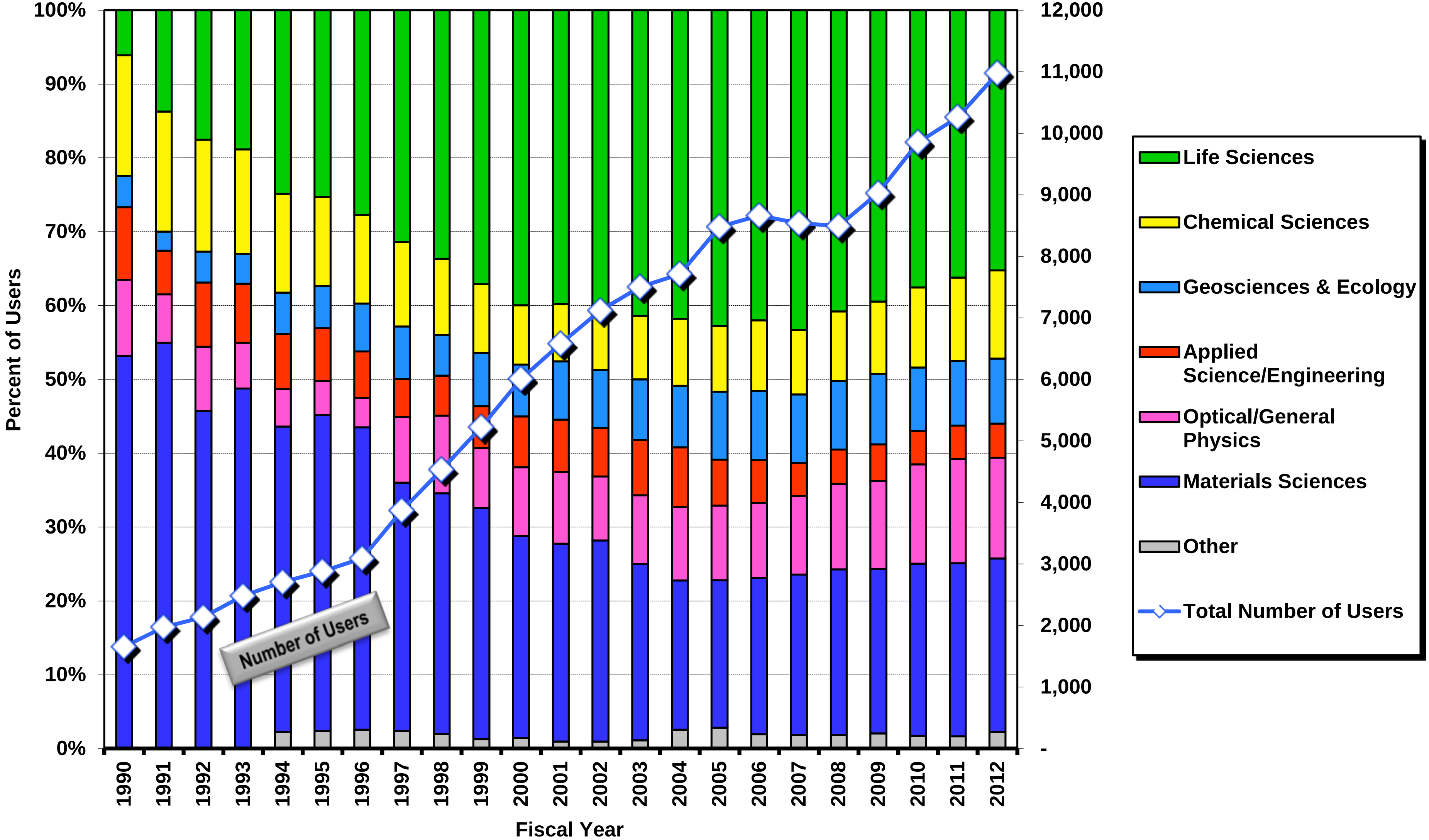
What Do We Care Most About in Light Sources?

Some key properties of the x-rays are inherited from the electrons

- **Wavelength Range**
  - Determines science reach—atomic or electronic structure and dynamics
- **Brightness: Average and Peak**
  - Determines measurement sensitivity
- **Pulse Width**
  - fs pulses opens the window on ultrafast dynamics and 'probe before destroy' technology
- **Coherence**
  - Allows new techniques (e.g. coherent imaging)
  - Leads to high brilliance of the beams (transform limited pulses)
- **Stability**
  - Source stability in energy, position, time, intensity
- **Number of Undulators/Beamlines/Endstations**
  - Determines the number of users in parallel that can be accommodated and ultimately how much science gets delivered

Who Uses Light Sources?

Users by Discipline at the Light Sources



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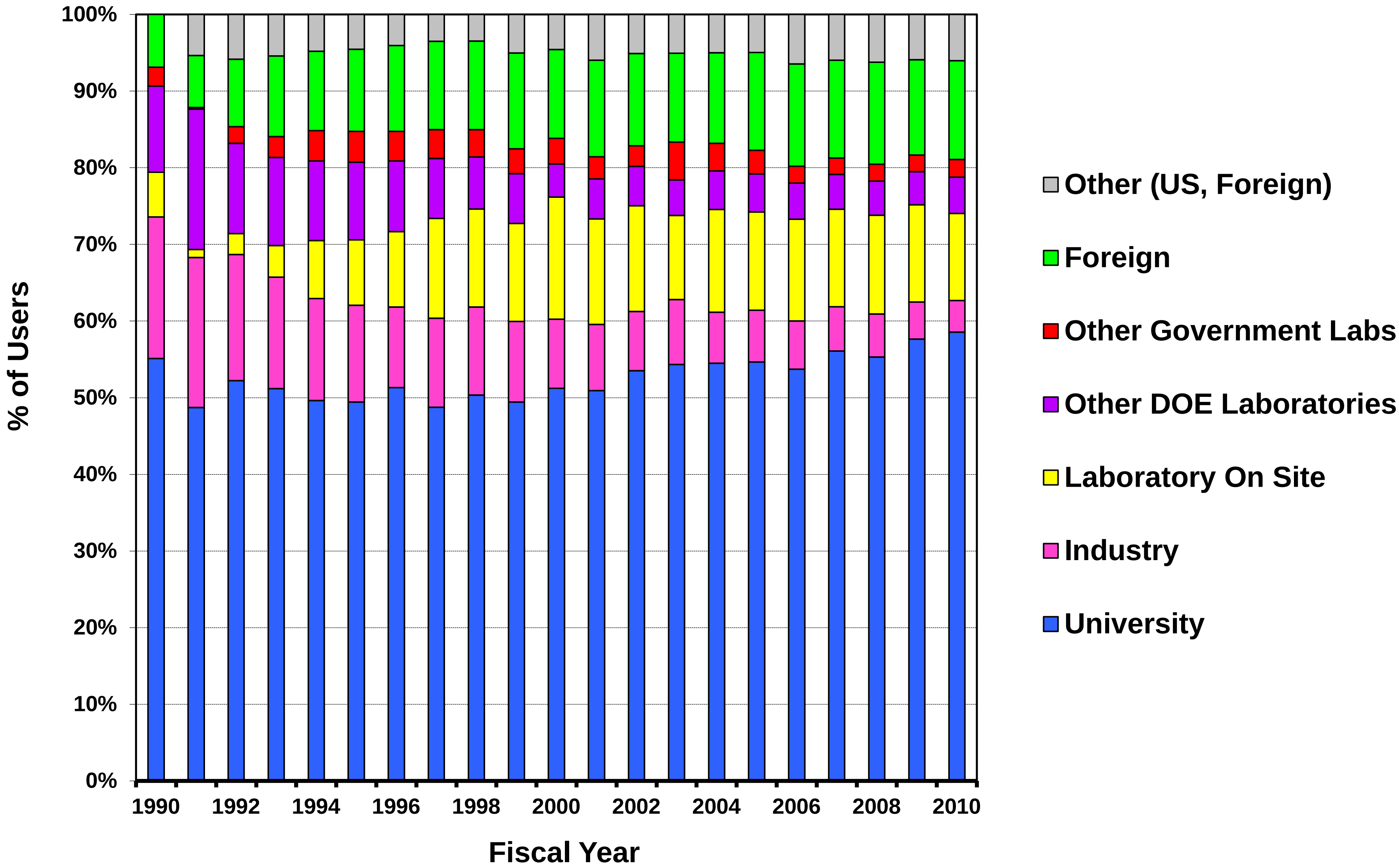
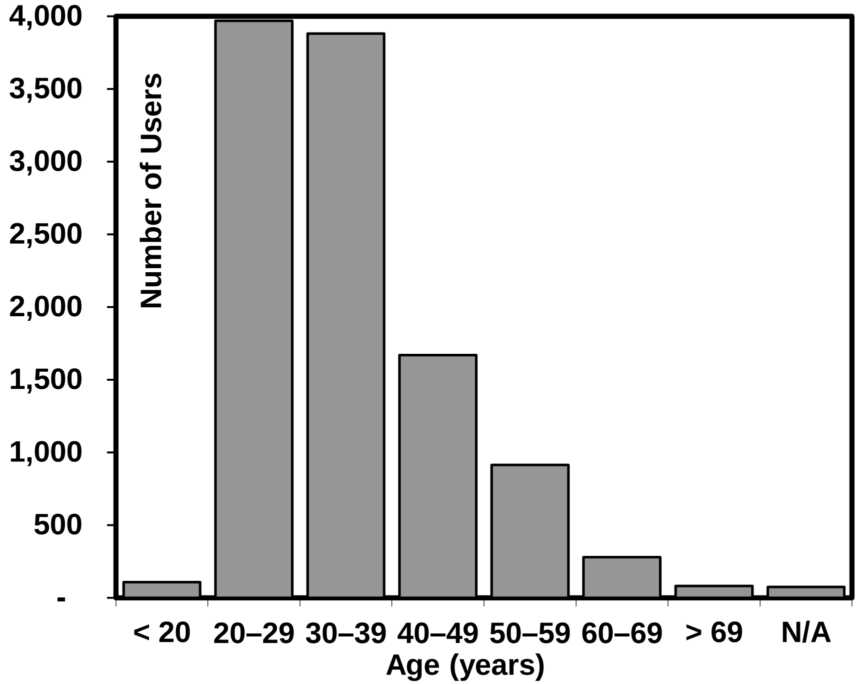
Users by Employer at the Light Sources

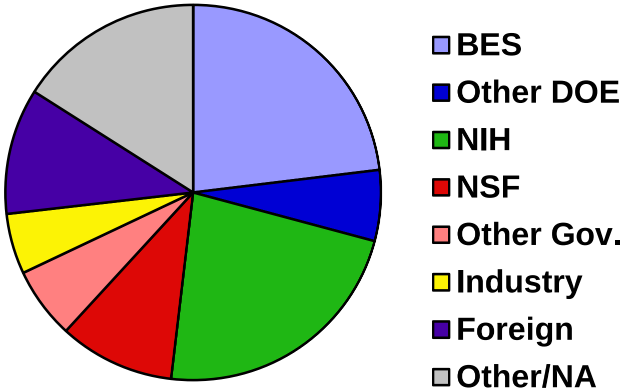


Other Demographics of Users at Light Sources

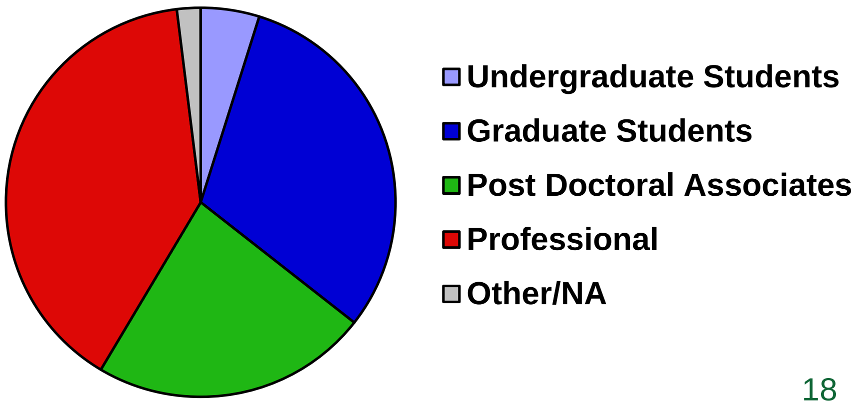
33%	First-Time Users
27%	Female
	Citizenship
50%	United States
29%	Foreign, Non-Sensitive Countries
21%	Foreign, Sensitive Countries
	Nature of Research
98%	Nonproprietary research only
1%	Nonproprietary & proprietary research
1%	Proprietary research only



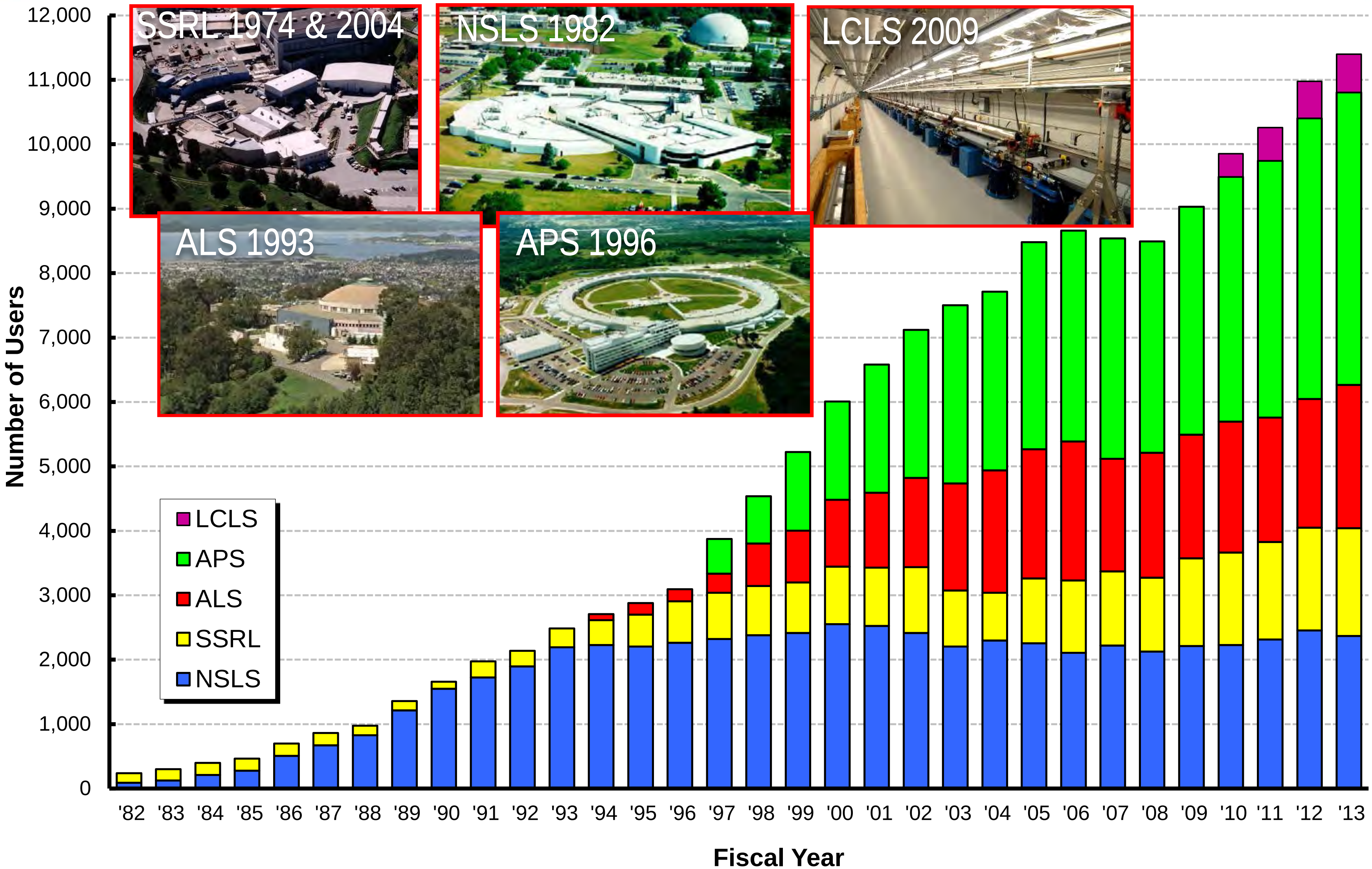
Source of User Support



User Employment Level



Users by Facility at the Light Sources



Strategic Plans: Past and Present

Plans: Past

BESAC Report: *Novel Coherent Light Sources*, January 1999

Given currently available knowledge and limited funding resources, the hard X-ray region (8-20 keV or higher) is identified as the most exciting potential area for innovative science. DOE should pursue the development of coherent light source technology in the hard X-ray region as a priority. This technology will most likely take the form of a linac-based free electron laser device using self-amplified stimulated emission or some form of seeded stimulated emission. The developers of such a source should seek to attain both temporal and spatial coherence, as well as precise timing with ultrashort pulsed lasers, which will be required for laser pump/X-ray probe experiments.

LCLS Commissioned, April 2009

Plans: Present—Charge to BESAC on X-ray Light Sources

- On January 2, 2013, Bill Brinkman issued a charge to the Basic Energy Sciences Advisory Committee (BESAC).
- The charge requested:
    - assessment of the grand science challenges
    - evaluation of the effectiveness of the present light source portfolio
    - enumeration of future light source performance specifications
    - prioritized recommendations on future light source concepts
    - prioritized research and development initiatives
- John Hemminger, the Chair of BESAC, served as Chair of a 22 member Subcommittee, which used previous BESAC and BES reports and new input from the x-ray sciences communities to formulate findings and recommendations.
- The final report was accepted by BESAC on July 25, 2013.

Findings and Recommendations

- At the present time, the U.S. enjoys a significant leadership role in the x-ray light source community. This is a direct result of the successes of the major facilities managed by BES … and the particularly stunning success of the first hard x-ray free electron laser, the Linac Coherent Light Source (LCLS).
- However, it is abundantly clear that international activity in the construction of new diffraction limited storage rings and new free electron laser facilities will seriously challenge U.S. leadership in the decades to come.
- The U.S. will no longer hold a leadership role in such facilities unless new unique facilities are developed …

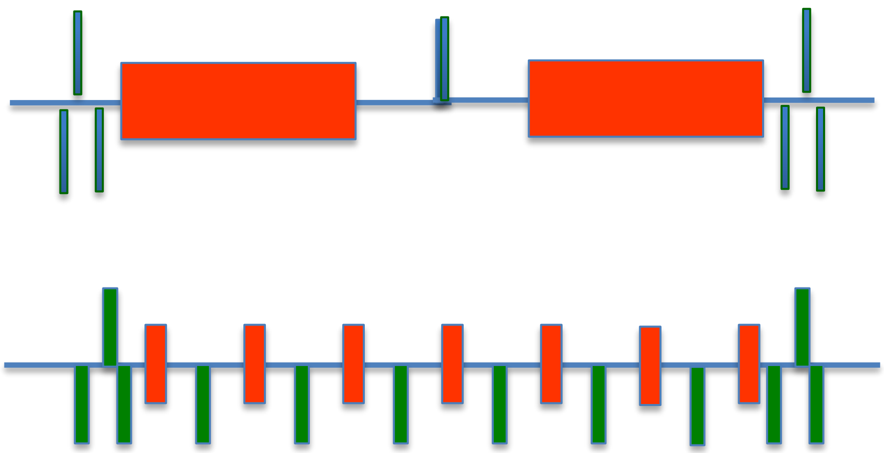
Storage Rings

Findings and Recommendations – Storage Rings

… BES should ensure that U.S. storage ring x-ray sources reclaim their world leadership position. This will require a careful evaluation of present upgrade plans to determine paths forward that will guarantee that U.S. facilities remain at the cutting edge of x-ray storage ring science. The very large, diverse U.S. user population presently utilizing U.S. storage rings represents a major national resource for science and technology. It is essential that the facilities this science community relies on remain internationally competitive in the face of the innovative developments of storage rings in other countries. Such developments include diffraction-limited storage rings with beamlines, optics, and detectors compatible with the 10^2-10^3 increase in brightness afforded by upgraded storage rings.

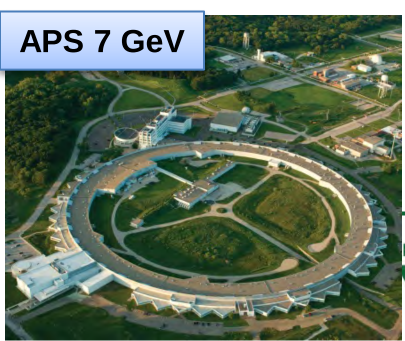
High Energy, Hard X-ray Ring Upgrade Plans

APS, ESRF & SPring-8 are all designing upgrades to incorporate multi-bend achromat lattices to reduce the emittance towards the diffraction limit to enhance brightness.

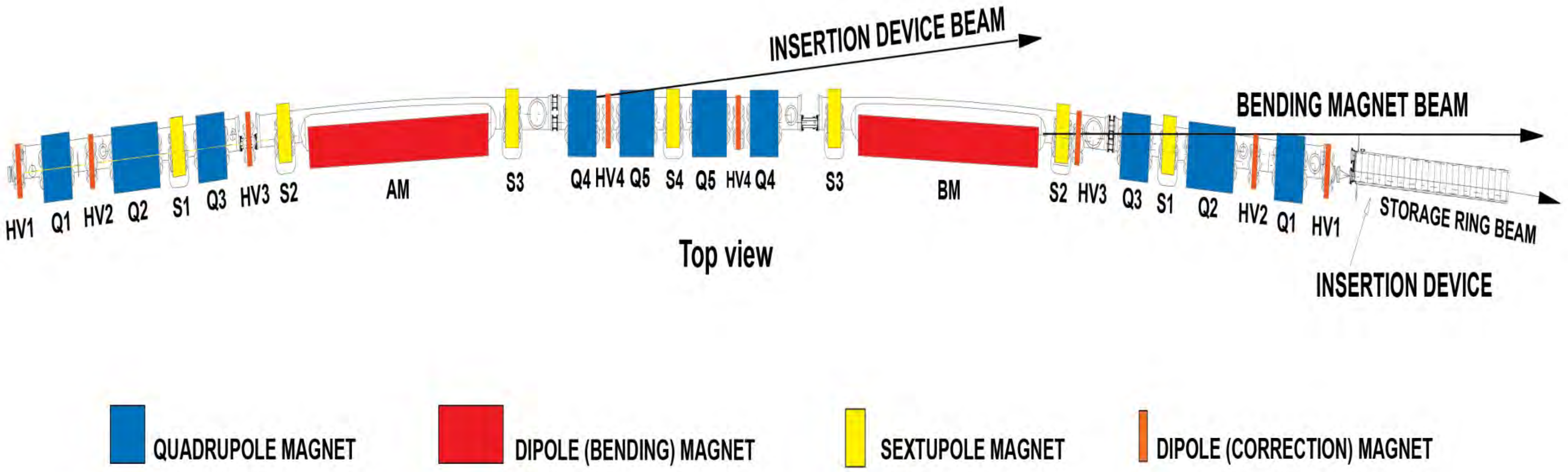


Double Bend Achromat

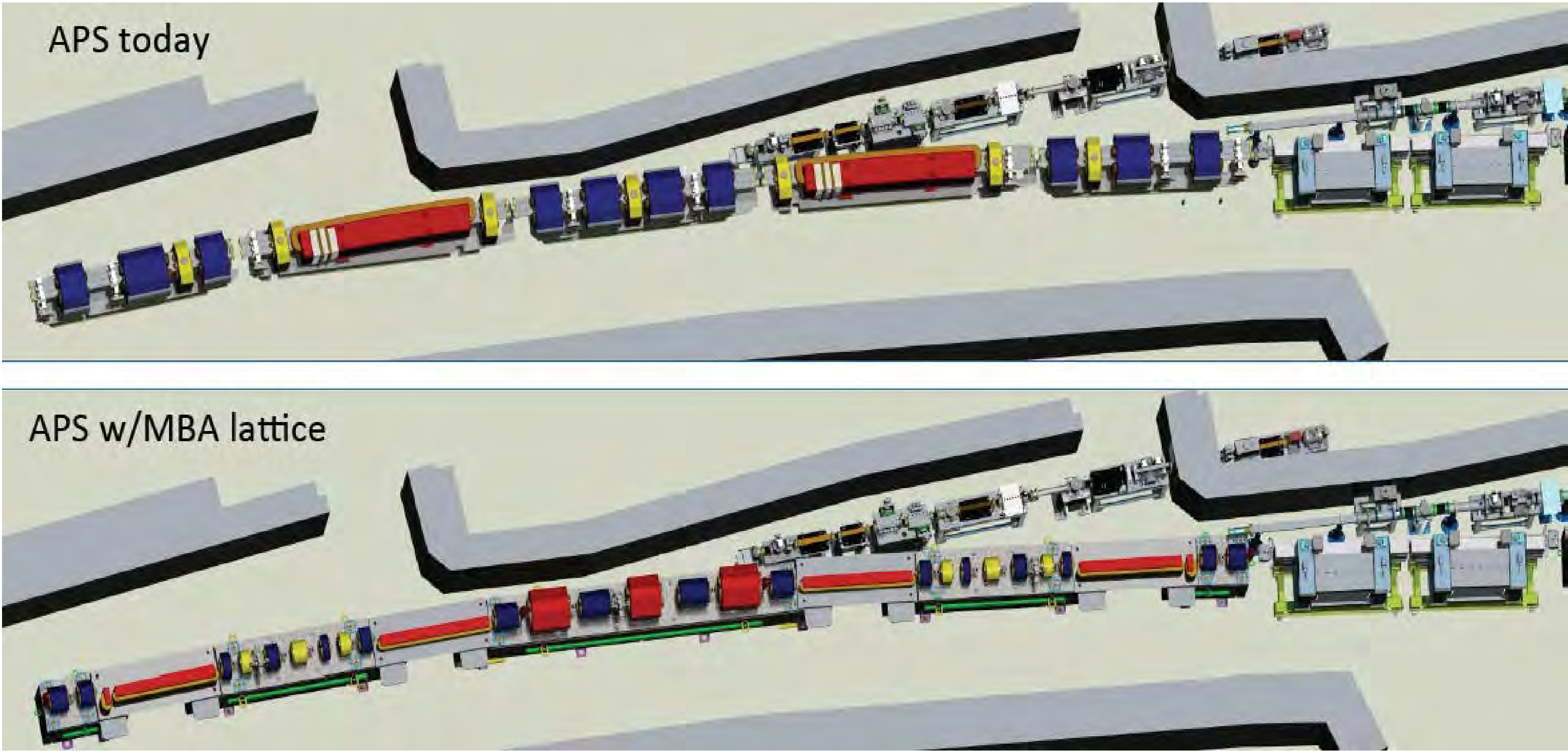
Seven Bend Achromat



APS – One Sector of the Ring – a Double Bend Achromat

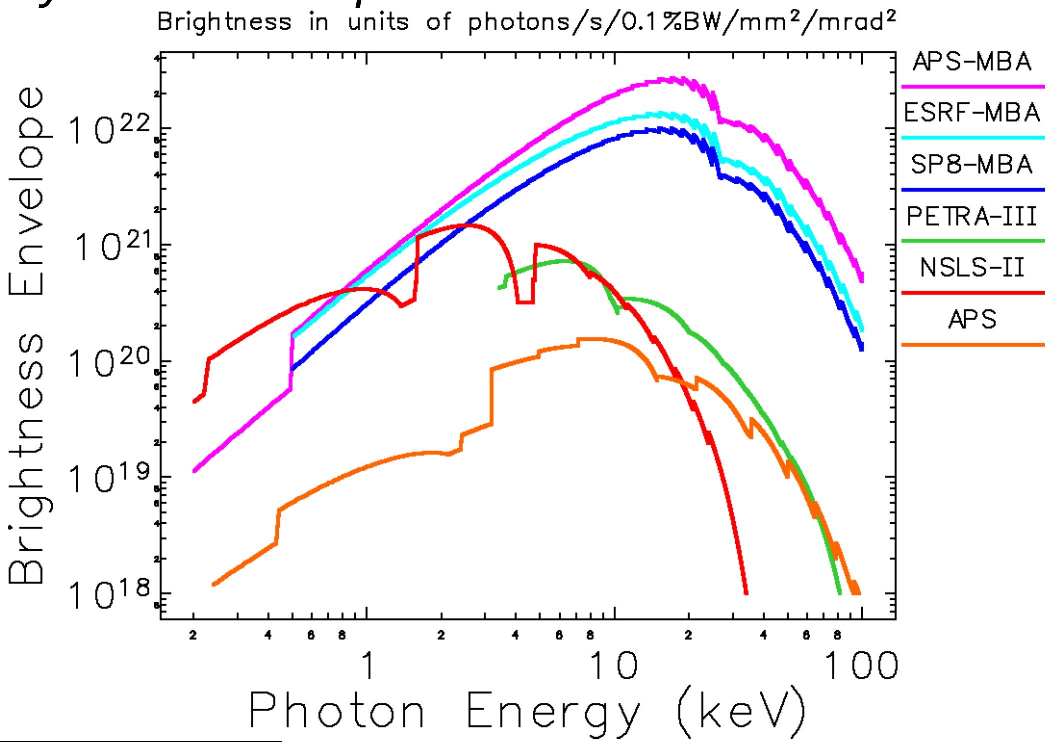


APS-U: 7 Bend Achromat will Replace the 2 Bend Achromat

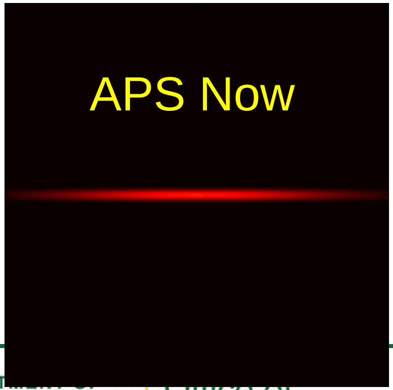


APS-U MBA Brightness Improvement

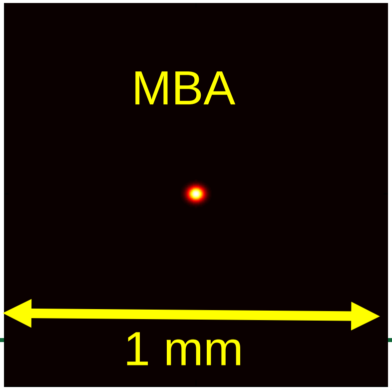
Dramatically enhance the performance of the APS as a hard x-ray source



3100 pm natural emittance at 7 GeV



Particle Beam Profiles



67 pm natural emittance at 6 GeV

Free Electron Lasers

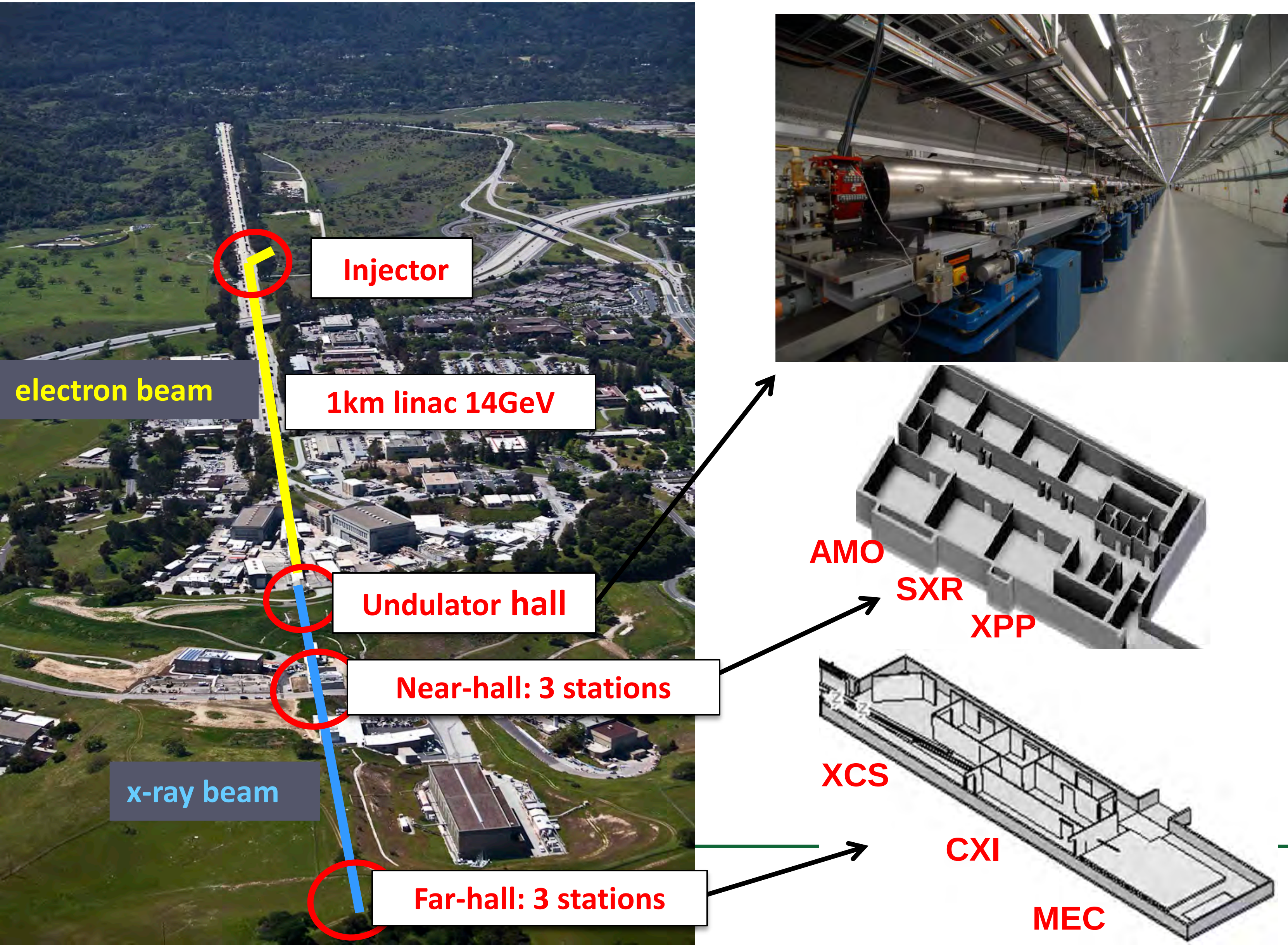
Findings and Recommendations – FELs

Recommendation: The new light source should provide **high repetition rate**, **ultra-bright, transform limited**, **femtosecond x-ray pulses** over a **broad photon energy range** with **full spatial and temporal coherence**. **Stability** and **precision timing** will be critical characteristics of the new light source.

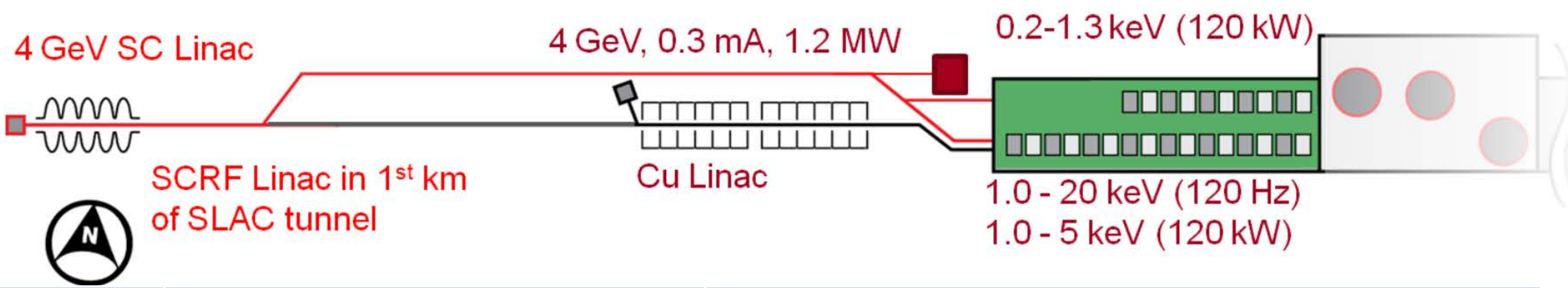
- The best approach for a light source would be a linac-based, seeded, free electron laser.
- The linac should feed multiple, independently tunable undulators each of which could service multiple endstations.
- The new light source must have pulse characteristics and high repetition rate to carry out a broad range of “pump probe” experiments, in addition to a sufficiently broad photon energy range (~0.2 keV to ~5.0 keV).

Linac Coherent Light Source (LCLS)

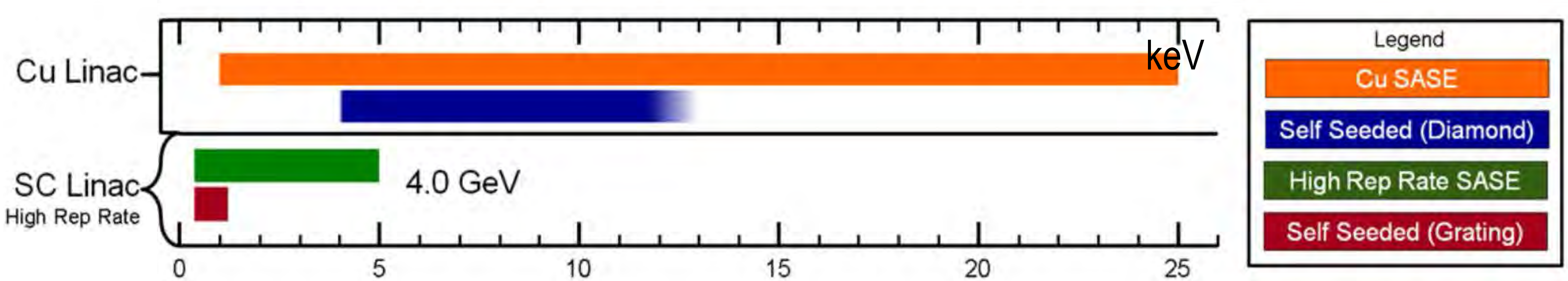
The World's First X-ray Free Electron Laser



LCLS-II: CW High Rep & High Pulse Energy FEL

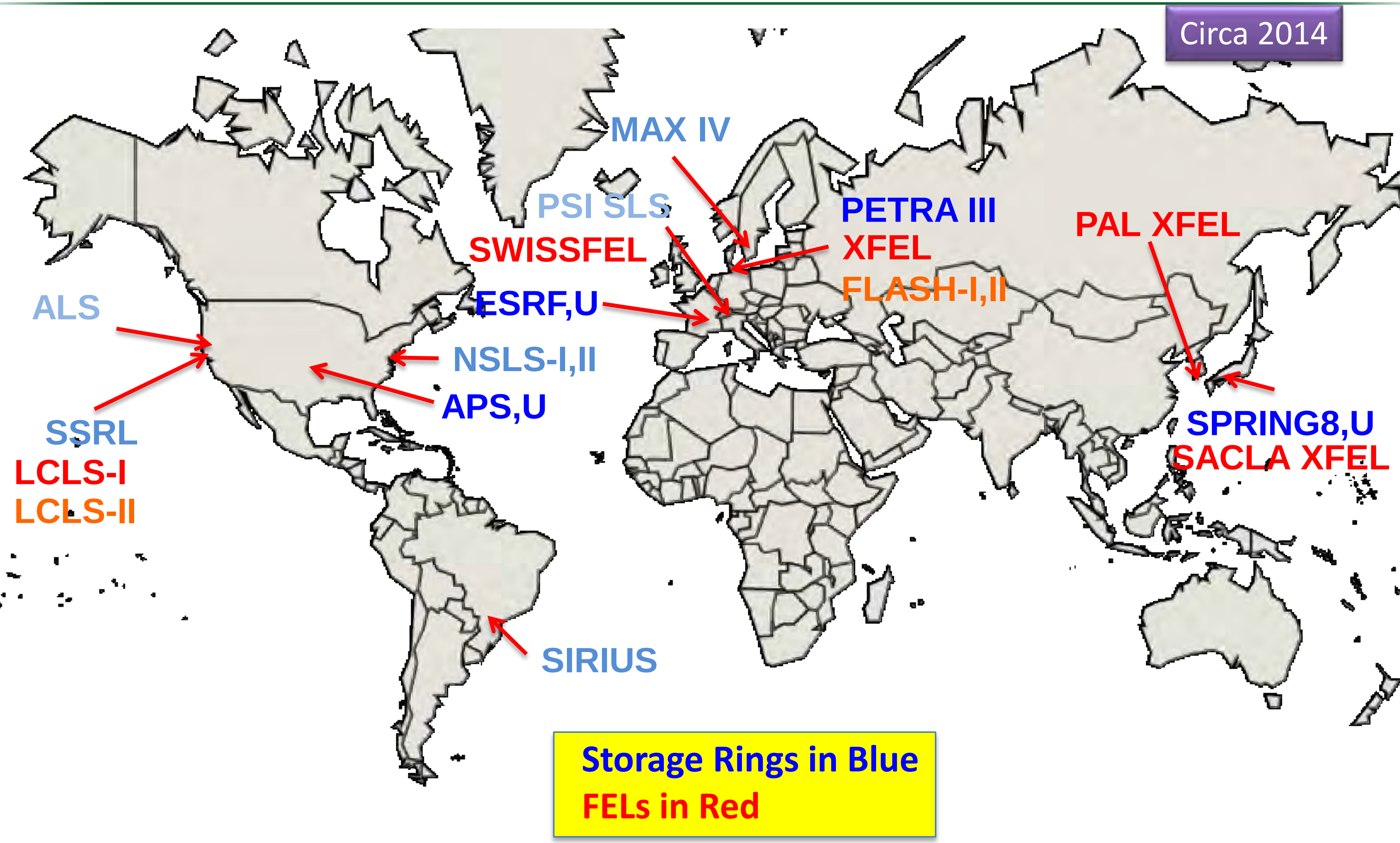


	Recommendation	Implementation
✔	High Repetition Rate	CW Linac with MHz Capability
✔	Broad Energy Range	SC & Cu linacs with variable gap undulators
✔	Transform Limited	Self seeding narrow bandwidth monochromator
✔	Ultra-Bright	14.7 GeV linac & high K undulator
✔	Multiple Undulator Sources	Two undulators



Worldwide Competition

DOE Light Sources & Key Worldwide Competitors



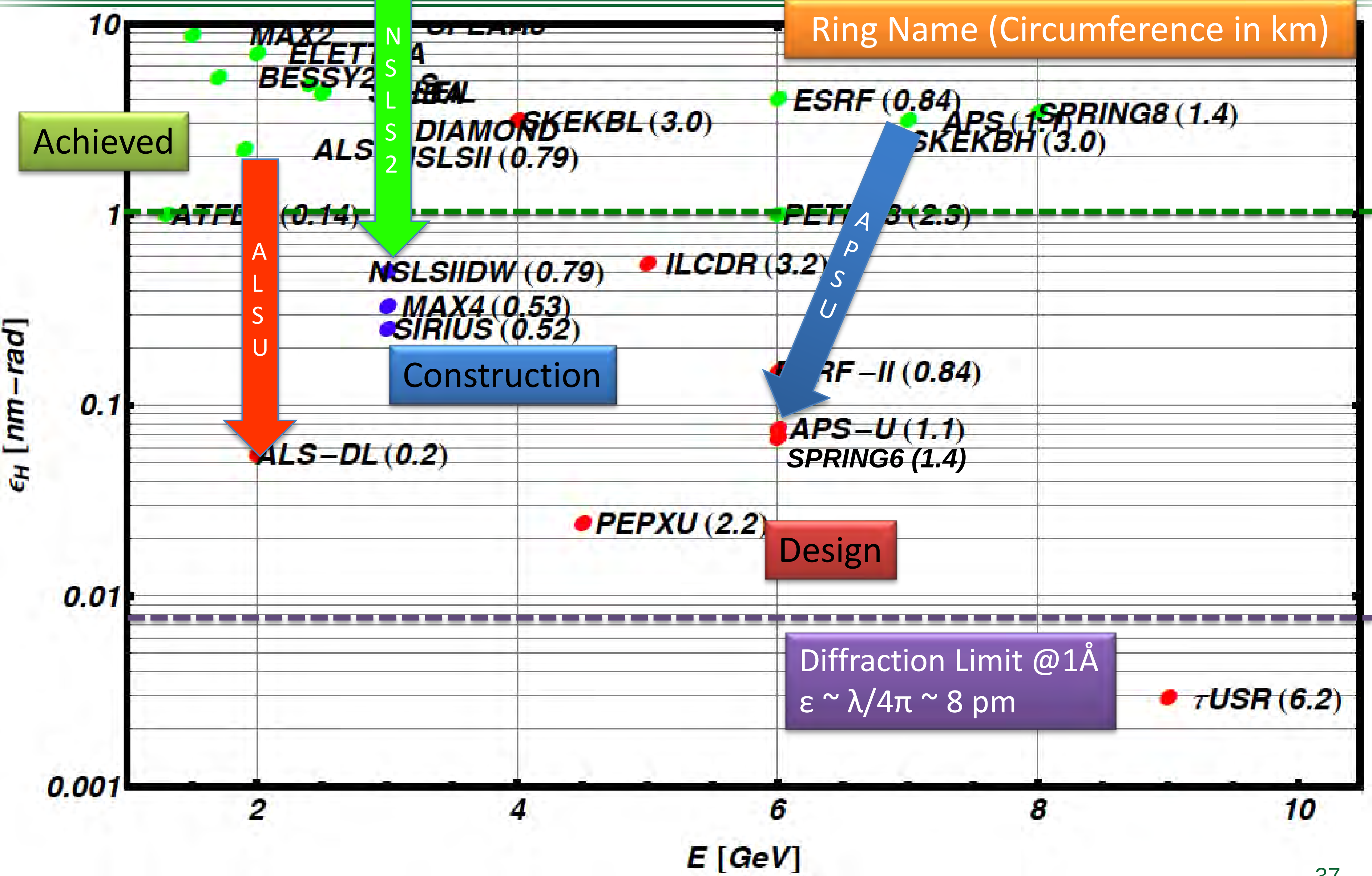
There are many more UV/X-ray rings, IR/UV FELs & a few ERLs

Investments @ DESY Over 5 Years

	Projects	Costs
2009	Construction of European XFEL	1150 Mio
2010	Successful construction of PETRA III	300 Mio
2010	Decision for Center for Structural System Biology (CSSB) Start construction 2013	50 Mio
2011	Construction of 2nd branch for X-ray laser FLASH: FLASH II	30 Mio
2012	Successful construction of Center for FEL Science (CFEL)	60 Mio
2013	Start construction of PETRA III Extension North and East International partners: India, Russia, Sweden	80 Mio
2013	Shutdown of DORIS	

1 Euro = $1.30

Ring Equilibrium Emittance vs Ring Energy



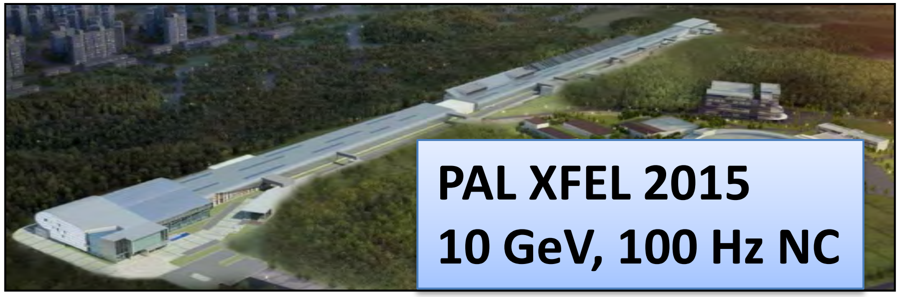
Summary Remarks

- The BES strategic plan, developed with input from the BESAC Future X-ray Light Sources report, will ensure that the USA light sources will maintain world leadership for decades to come
- Strong competition from Asia & Europe on light source facilities will require exceptional quality science to be performed at the USA light sources as the facilities alone will not be sufficient to set the USA apart from the pack
- Robust R&D programs on accelerator physics/technology, detectors & optics will be needed to fully leverage the new sources and provide a pathway to the future.

Backup

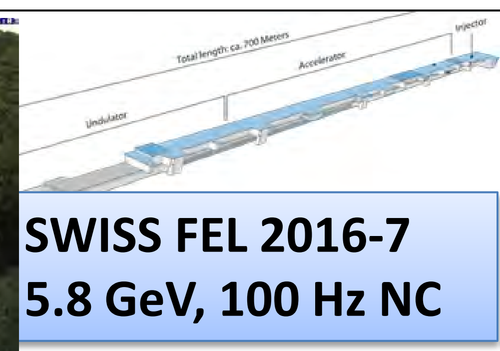
Asian Strategy

- Current Status:
  - Spring-8: High performing 3rd generation SR
  - Many other 'regional' storage rings
  - SACLA: 60 Hz, one beam line hard x-ray FEL
- Near Future:
  - Upgrade Spring-8 to 'USR'
  - Upgrade SACLA
    - SACLA with additional injector and ** additional undulators
  - New FEL in Korea: PAL XFEL
    - One beam line, 100Hz
- Far Future:
  - 3 GeV ERL @ KEK



European Strategy

- Current Status:
  – Several high performance hard-x-ray SR
    - ESRF, PETRA-3
  – Several high performance soft/medium x-ray SR
    - BESSY, SLS, Diamond
  – Two soft x-ray FEL's
    - FLASH I & Fermi with1 undulator each
- Near Future
  – Upgrade ESRF to 'USR', build new high performance ring (MAX-4), expand PETRA-3
  – Expand FLASH I → FLASH II
  – Two new hard x-ray FEL's:
    - XFEL: rep rate 3000 x 10; 6 undulators
    - SwissFEL: rep rate 100 Hz and 1 undulators



European Strategy (cont'd)

- *By 2020, Europe will challenge the USA for the most advanced suite of light source tools in the world*
- Enormous concentration of tools in Hamburg
  - FLASH I, II
  - PETRA-3
  - XFEL (managed by XFEL corporation)
- German strategy includes tremendous investments in infrastructure to exploit the light sources and deliver science
  - CFEL
  - CSSB
  - Nanocenter

} Nano-Bio-Femto

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