U.S. DEPARTMENT OF ENERGY | Office of Science

X-Ray Light Sources: An International Perspective

BESAC Meeting
23-24 Feb 2017

Persis S. Drell
Stanford

Helmut Dosch
DESY

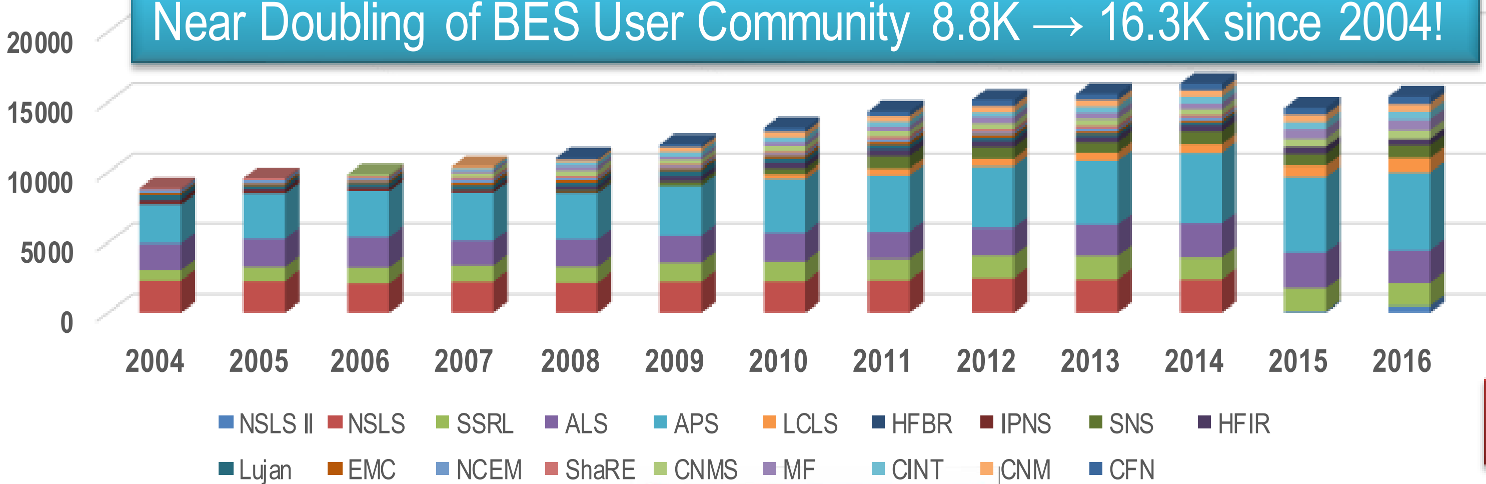
Outline

- **Introduction**
- **BESAC Contributions & Impact**
  - John Hemminger's Leadership
  - Most recent recommendations on future BES light source facilities
- **Americas Perspective**
  - Science Results & Drivers
  - New Rings & FELs
- **Asia & Europe Perspective**
  - Science Results & Drivers
  - New Rings & FELs
- **Concluding Remarks**

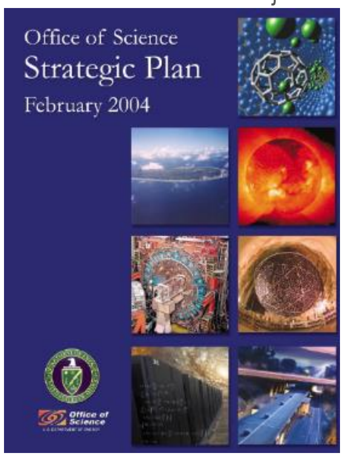
BESAC Contributions & Impact to BES Facilities

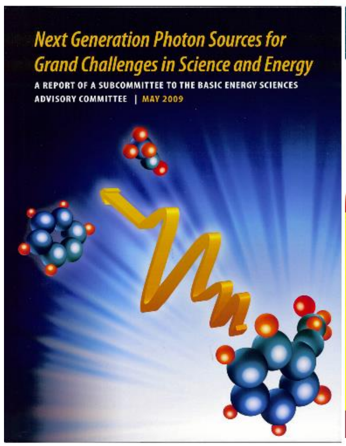
- **Dr. John Hemminger: 13 years as BESAC Chairperson**
  - Key BESAC & SC Strategic Planning Reports (See Below)
  - New Facilities: SNS, 5 NSRCs, LCLS, NSLS-II, LCLS-II, APS-U, …

Near Doubling of BES User Community 8.8K → 16.3K since 2004!



LS Users: 7.7K → 11K





Basic Energy Sciences Facilities Prioritization

Co-Chaired by:

John C. Hemminger, Chair
University of California, Irvine

&

William Barletta
MIT

February 26-27, 2013

Report of the BESAC Subcommittee on Future X-ray Light Sources

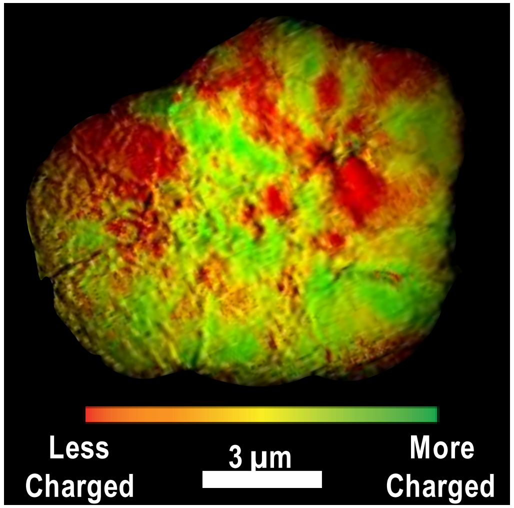
Approved by the Basic Energy Sciences Advisory Committee on July 25, 2013

BESAC Report on Facility Upgrades

Approved by the Basic Energy Sciences Advisory Committee on June 9, 2016

Motivation: Desire to Probe Nature at Atomic Length (Å) & Time (fs) Scales

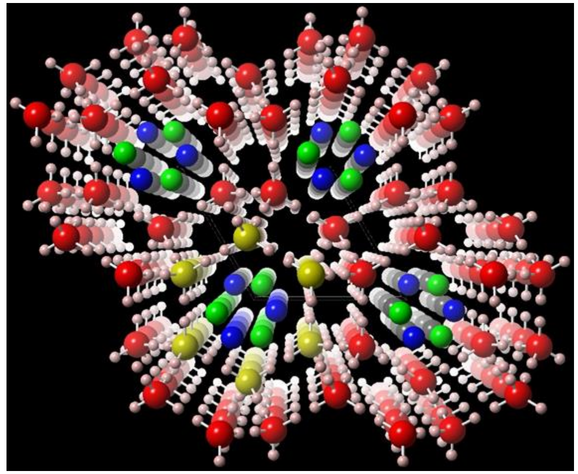
Seeing the Invisible in Real Materials



Compositional heterogeneity in a $LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$ battery hundreds of hours after charging

Adv. Materials (2016)

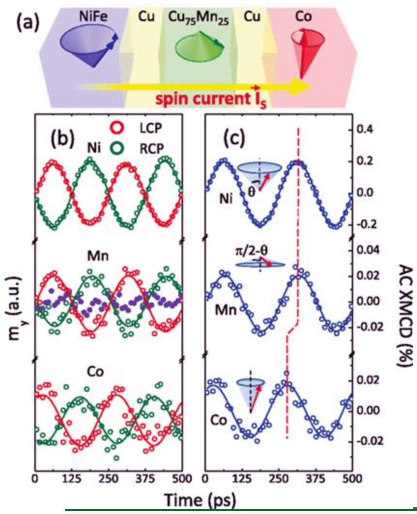
Where are the Atoms?



Newly discovered structure of a hydrogen-stuffed, quartz-like form of ice

JACS (2016)

Where are the Electrons & Spins?



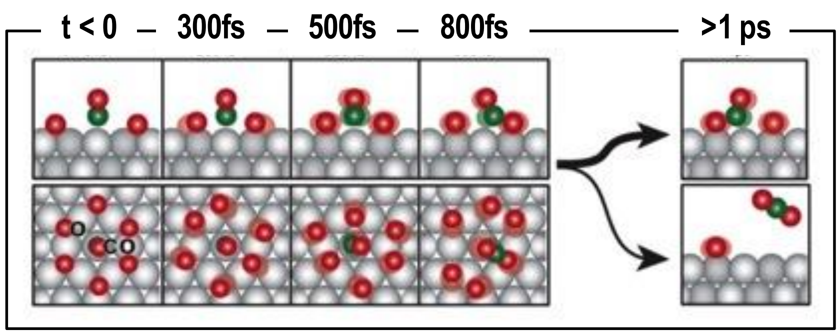
Direct measurements of "pure" ac spin currents (flow of spin angular momentum without flow of charge)

PRL (2016)

What are the Dynamics?

Capturing the transient behavior of catalytic bond formation

Science (2015)



Goal: Control Matter & Energy on These Scales!

Light Sources Are Alive & Kicking: 60+ Facilities Worldwide & Growing

Many other new & upgraded facilities are in the design stage…
Take Away Message: It's a very competitive landscape!

BES Light Sources | Ring Upgrades | New Rings | Upgraded & New FELs

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USA Response: BES Community Consensus Building Guided by BESAC

BESAC Report on Facility Upgrades

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Subcommittee on BES Facility Upgrade Prioritization
Agenda
14-16 April 2016

MEETING FORMAT:

- Lab Presentation of Upgrade (90 min)
- Subcommittee Q&A with Lab (60 min)
- Subcommittee Discussion of Upgrade (60 min)

- Thu PM: LBNL ALS-U
- Fri AM: ANL APS-U
- Fri PM: ORNL PPU/STS
- Sat AM: SLAC LCLS-II-HE
- Sat PM: Subcommittee Discussion & Closeout

Chair: John Hemminger

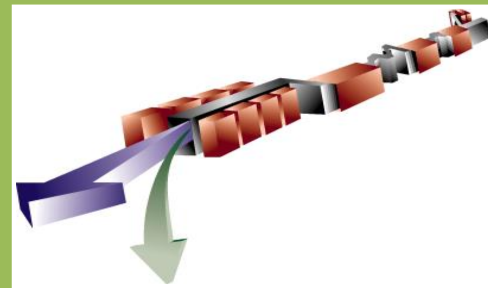
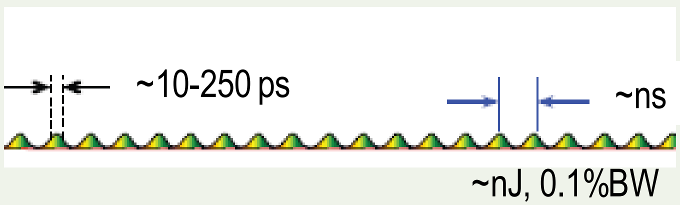
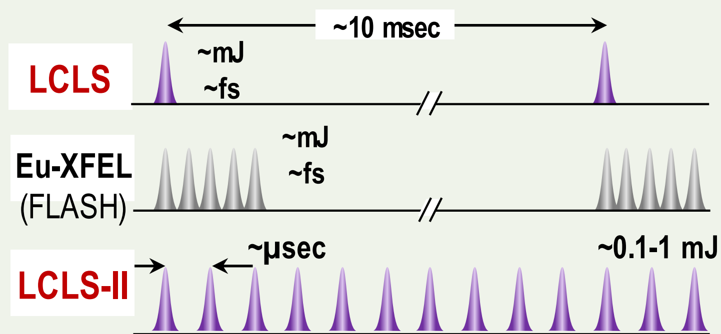
BESAC Report Also Included Neutron Sources

USA Response: BESAC Report on Light Source Facility Upgrades (June 2016)

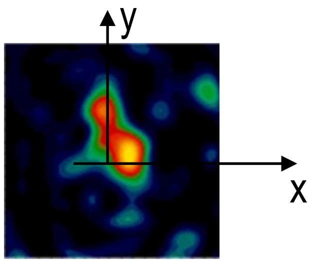
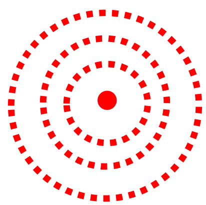
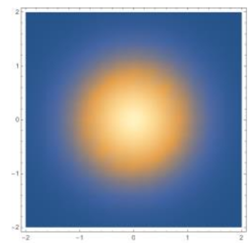
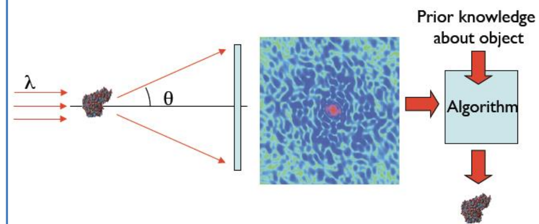
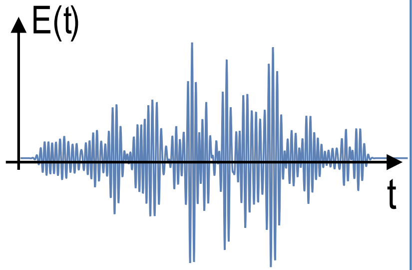
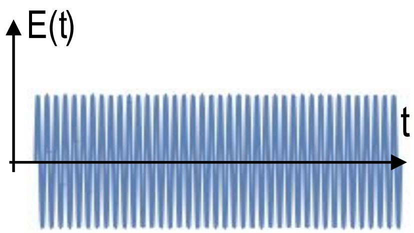
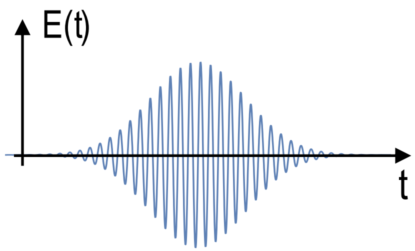
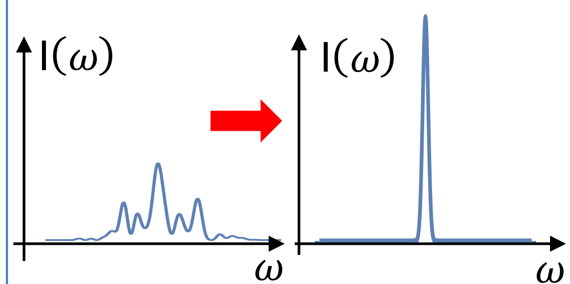
	Storage Rings		FEL
Project	**ANL** **APS-U**	**LBNL** **ALS-U**	**SLAC** **LCLS-II-HE**
Project Scope	Hard X-ray ~Diffraction Limited 6 GeV Multi-Bend Achromat (MBA) Ring	Soft X-ray ~Diffraction Limited 2 GeV Multi-Bend Achromat (MBA) Ring	High Rep-Rate, High Energy X-ray FEL, 8 GeV SC Linac
Current Status of Facility	APS is operational since 1996; ring will be replaced	ALS is operational since 1993; ring will be replaced	LCLS is operational since 2010; LCLS-II is under construction
Worldwide Competition	EU **ESRF** Germany **PETRA 3,4** Japan **SPring-8-II** China **BLS**	Sweden **MAX-IV** Brazil **SIRIUS** CH **SLS-II**	EU **XFEL** Japan **SACLA** Korea **PAL XFEL** CH **Swiss FEL**
Dark Time	~1 yr	~0.75 yr	0 yr
Status FY2017	**CD-3b**	**CD-0**	**CD-0**

The ALS-U, APS-U & LCLS-II-HE proposals were each deemed "absolutely central to contribute to world leading science & ready to initiate construction"

Storage Rings & Free Electron Lasers are Complementary

Parameter	Storage Rings	FELs
		
Beam Stability	Excellent	Very Good
Number of Beamlines	Up to 70+	1-5
Brightness (Ave, Peak)	(High, Low)	(Up to Very High, Extreme)
Transverse Coherence	Partial-Full	Full (@ Saturation)
Longitudinal Coherence	Poor	Moderate (SASE)-Very Good (seeding)
Pulse Time Structure Pulse Energy		

New Sources Will Provide Enhanced Transverse & Longitudinal Coherence

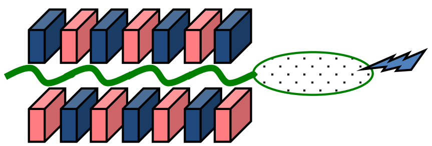
Coherence Level	**Realistic Partial**	**Idealized Full**	**Realistic Full**	**Coherence Advantages**
Transverse (Spatial Profile)	Multi-Mode  $\Delta x \cdot \Delta\theta_x > \lambda/4\pi$	Point Source (Spherical Waves)  $\Delta x, \Delta y \to 0$	Gaussian Laser Mode  $\Delta x \cdot \Delta\theta_x = \lambda/4\pi$	Coherent Diffractive Imaging, Ptychography & Nanoprobes  Imaging w/o Lenses
Longitudinal (Temporal Profile)	Noisy Pulse  $c\,\Delta t \cdot \frac{\Delta\omega}{\omega} > \lambda/4\pi$	Monochromatic Wave Train  $\Delta\omega \to 0, \Delta t \to \infty$	Gaussian Laser Pulse  $c\,\Delta t \cdot \frac{\Delta\omega}{\omega} = \lambda/4\pi$	FEL SASE vs Seeded Spectrum  Maximize Number of Photons in Minimum BW

Physics & Technology for Maximizing the Photon Beam Brightness, B_{ave}

Rings ~ 10^{22}

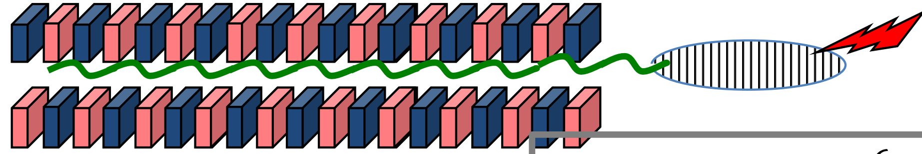
FELs ~ 10^{25}

Spontaneous Emission from a Random Beam

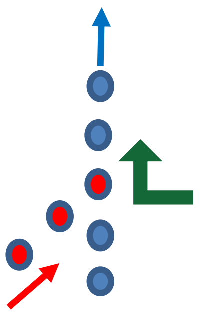


$$N_{ph}^{spon} \approx \alpha N_e \approx \frac{N_e}{137}$$

Stimulated Emission from a Self Bunched Beam (SASE)

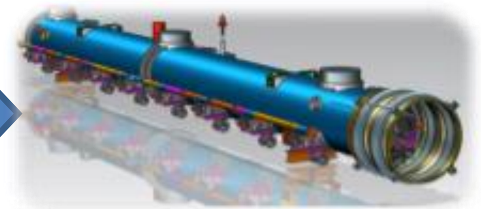


$$N_{e/coop} \approx 10^6$$
$$N_{ph}^{stim} \approx 10^6 N_{ph}^{spon}$$



On Axis Injection
Bunch-by-Bunch
or Bunch Trains

$$B_{ave} = \frac{f_{reprate}}{4\pi^2} \frac{photons / pulse / 0.1\% \, BW}{(\varepsilon_{ex} \oplus \varepsilon_{Lx})(\varepsilon_{ey} \oplus \varepsilon_{Ly})}$$

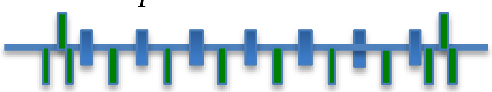


SC RF CW Linac (1.3 GHz)

Diffraction Limit

$$\varepsilon_{Lx}\varepsilon_{Ly} \to \left(\lambda/2\right)^2$$

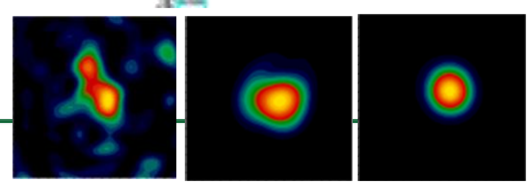
$$\varepsilon_x \propto \frac{E_e^2}{N_{dipole}^3}, \quad N_{MBA} \approx 2,3 \to 7,9$$



Multi-Bend Achromat (MBA)

High Brightness
High Rep Rate
Photoinjector

$$B_{peak} = \frac{B_{ave}}{\tau_e \cdot f_{reprate}} \xrightarrow{FEL} 10^{10} B_{ave}$$



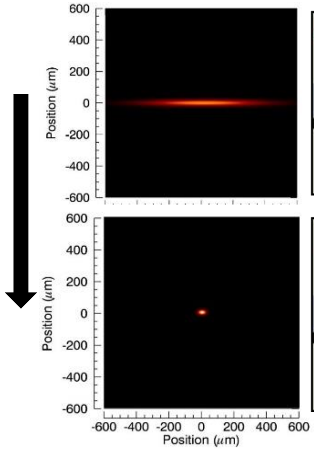
Z = 25 m   Z = 50 m   Z = 75 m

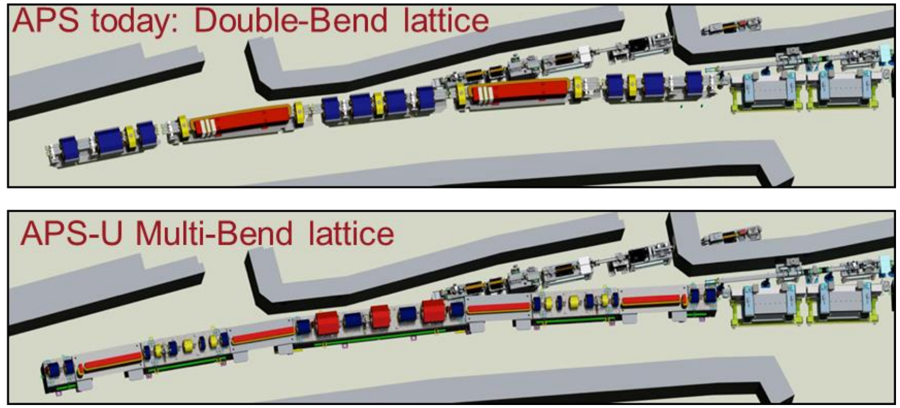
Advanced Photon Source Upgrade (APS-U) at ANL

Project Developments:

- Design optimized to provide penetrating high-energy x-rays
- MBA-7 lattice incorporating reverse bends to reduce emittance from 67pm to 41pm
- Beamline proposal selection and roadmap complete
- Technical prototypes well along; Preliminary Design Report underway; ready for next step

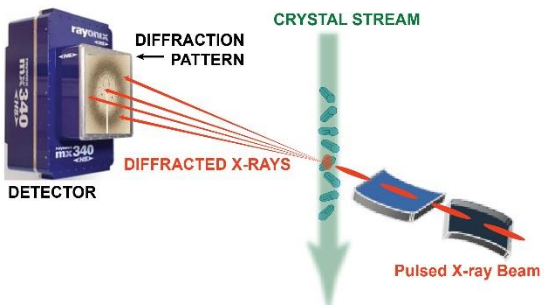
APS-U MBA-7 lattice uses 7 bending magnets/sector (was 2)





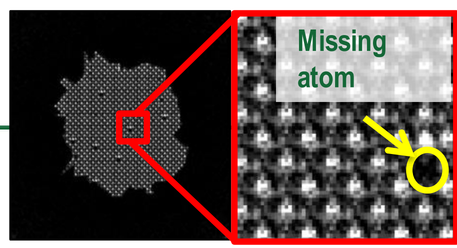
Small-Beam Scattering & Spectroscopy

- Nanometer imaging with chemical and structural contrast; few-atom sensitivity
- Room-temperature, serial, single-pulse pink beam macromolecular crystallography



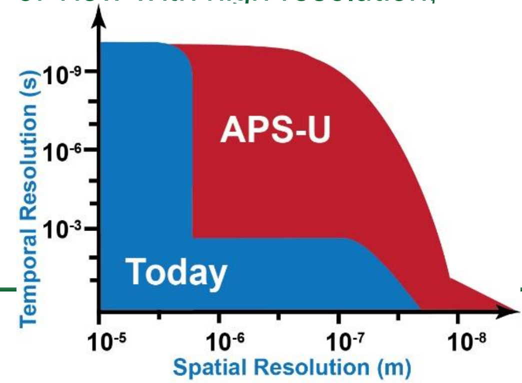
Coherent Scattering & Imaging

- Highest possible spatial resolution: 3D visualization; imaging of defects, disordered heterogeneous materials
- XPCS to probe continuous processes from nsec onward, opening up 5 orders of magnitude in time inaccessible today,



Resolution @ Speed

- Mapping all of the critical atoms in a cubic millimeter
- Detecting and following rare events
- Multiscale imaging: enormous fields of view with high resolution;

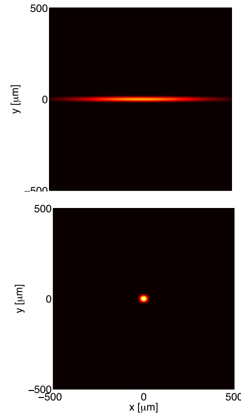


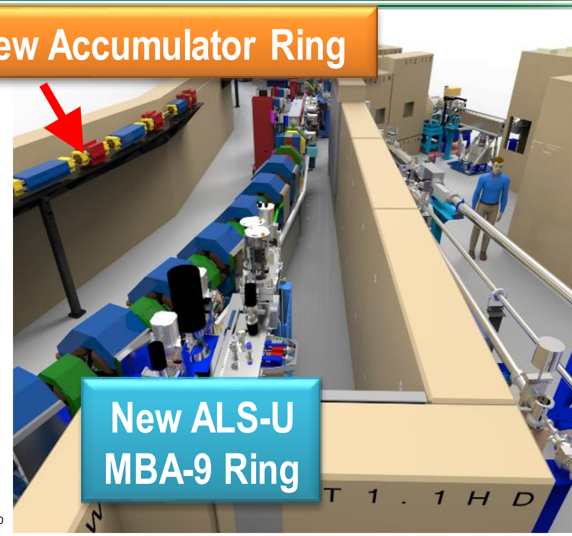
Advanced Light Source Upgrade (ALS-U) at LBNL

Goal: High CW soft x-ray coherent flux necessary to resolve nm-scale features & enable real-time observation of chemical processes & materials as they function

Project Developments:

- Replace the existing MBA-3 ring with a new MBA-9 ring
- New accumulator ring for on-axis bunch train injection
- Critical Decision 0 approved on Sept 2016

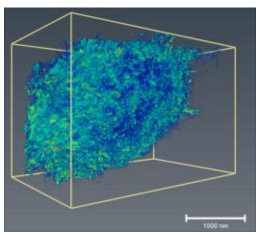




Map nano-objects' 3D electronic, chemical, & magnetic structure

Understand Roles of Heterogeneity

- Connect spatial, chemical, & temporal heterogeneity with real-time movies

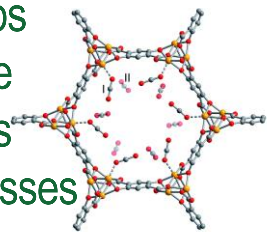


- Potential benefit – optimize material processes & properties, e.g., low carbon footprint concrete

Control chemical kinetics in confined spaces

Master Hierarchical Architectures

- Reveal relationships between nanoscale chemical structures & the kinetic processes they support

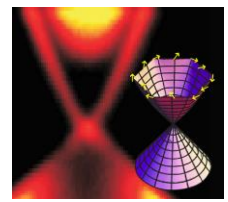


- Potential benefit – chemical catalytic reactors, solar fuel production, water purification

Deploy spin, quantum, and topological materials

Harness Coherence in Light & Matter

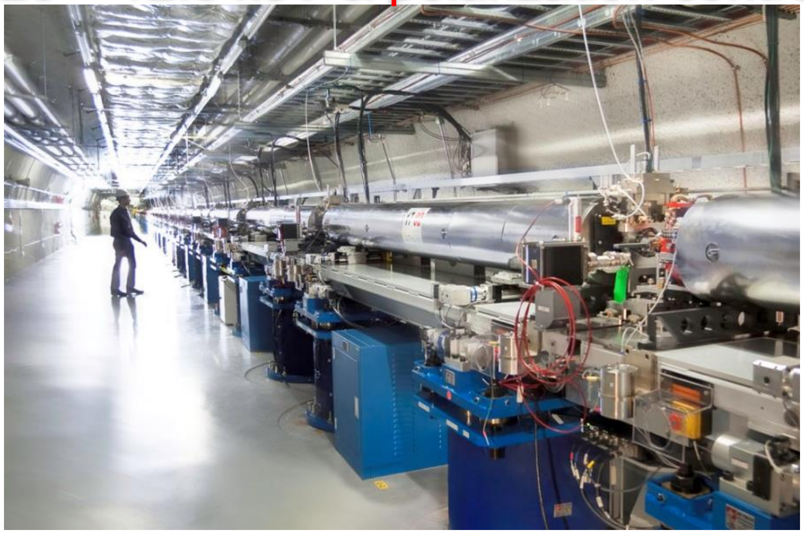
- Probe electronic structure of single domains and gated structures of complex materials



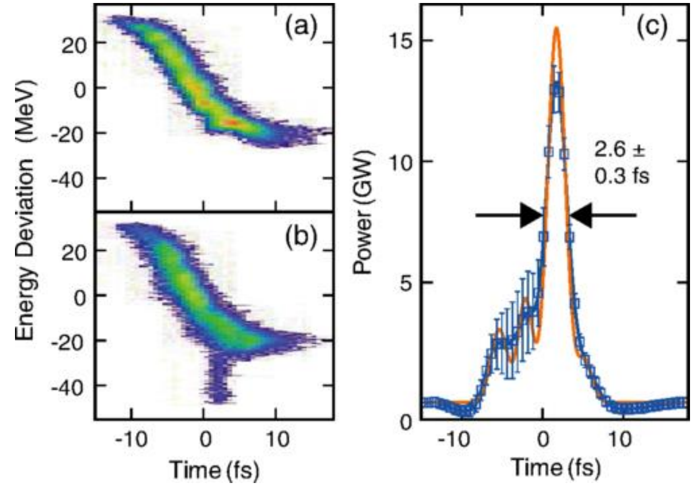
- Potential benefit – ultralow-power computing, new classes of sensors, spin-based devices

LCLS Performance Has Advanced Far Beyond Its Baseline Parameters Since 2009

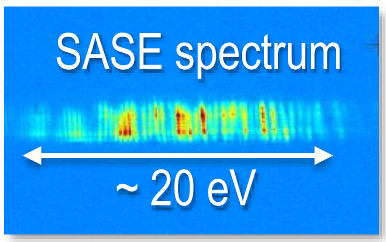
Expanded photon energy range, 0.25 – 12.8 keV & polarization control

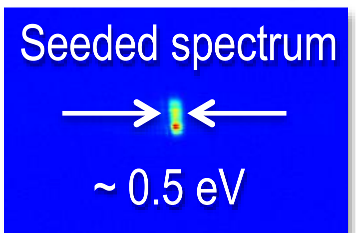


Generation of few-fs x-ray pulses & measurements with XTCAV



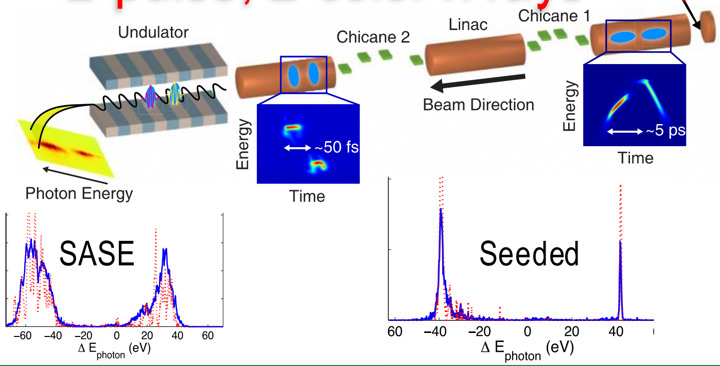
From SASE fluctuations to controlled pulse width & spectrum (seeding)





40x Increase in Temporal Coherence!

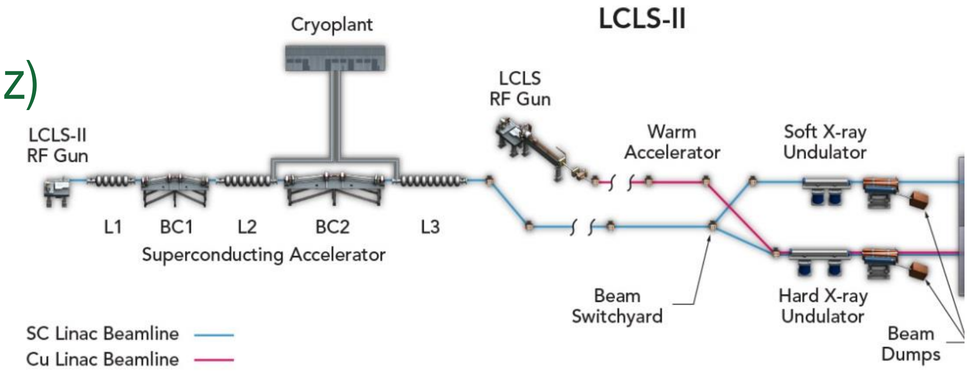
Creation of multiple options for 2-pulse, 2-color x-rays



Linac Coherent Light Source II (LCLS-II) at SLAC

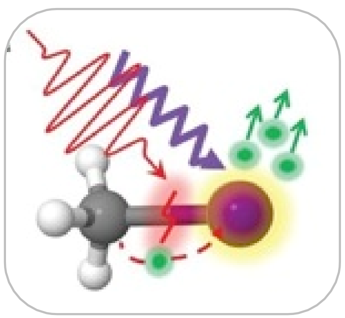
Project Scope & Status:

- 200-5,000 eV x-rays at up to 1 MHz (from 120 Hz)
- Double the energy reach of LCLS to 25 keV
- 4 GeV CW SC linac, 2 new variable gap IDs
- CD-2, CD-3 approved in 2016



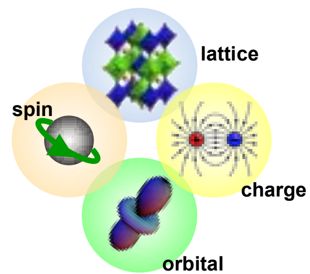
Charge dynamics on fundamental timescales

- Reveal coupled electronic and nuclear motion in molecules
- Capture the initiating events of charge transfer chemistry with sub-fs resolution



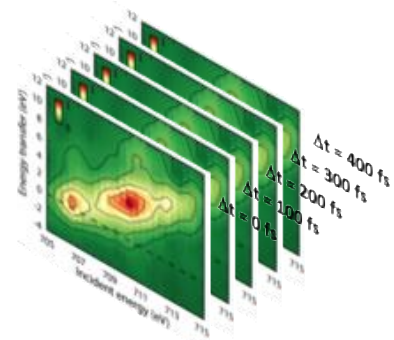
Emergent phenomena in quantum materials

- Connect spontaneous fluctuations, dynamics and heterogeneities on multiple length- and time-scales to bulk material properties
- Study interacting degrees of freedom (e.g. unconventional superconductors)



Molecular dynamics with exquisite resolution

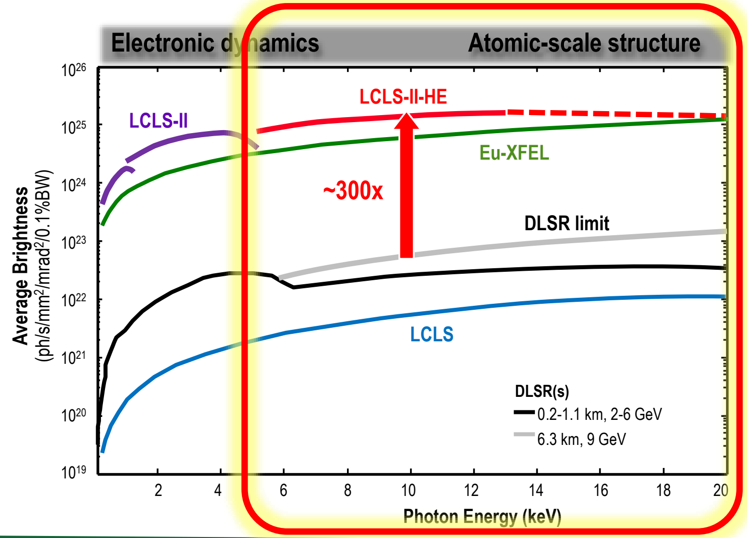
- Measure element-specific, local chemical structure and bonding
- Study efficient, robust, selective photo-catalysts



LCLS-II-HE is Needed to Probe Structural Dynamics at the Atomic Scale (~1 Å)

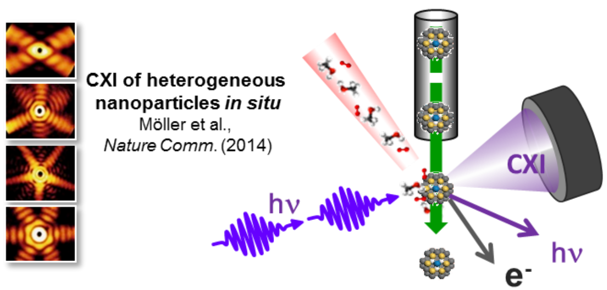
Project Scope & Status:

- Extend CW-SCRF linac from 4 to 8 GeV
- Provide high rep-rate capability beyond 1Å (>12 keV)
- Injector development to enable lasing up to 20 keV
- Average coherent x-ray power (spatial & temporal) is transformative
- CD-0 approved in Dec 2016



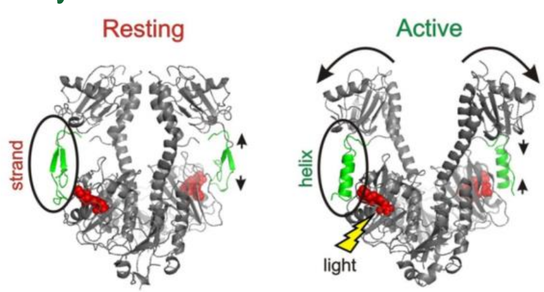
Heterogeneity & complexity in ground & excited states

- Correlate catalytic reactivity and structure
- Real-time evolution with chemical specificity and atomic resolution



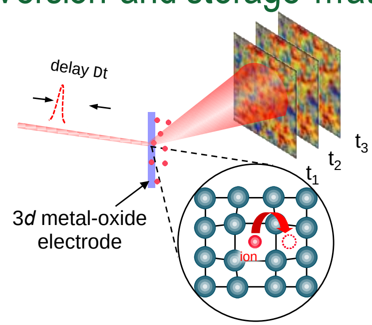
Dynamics of biomolecules and molecular machines

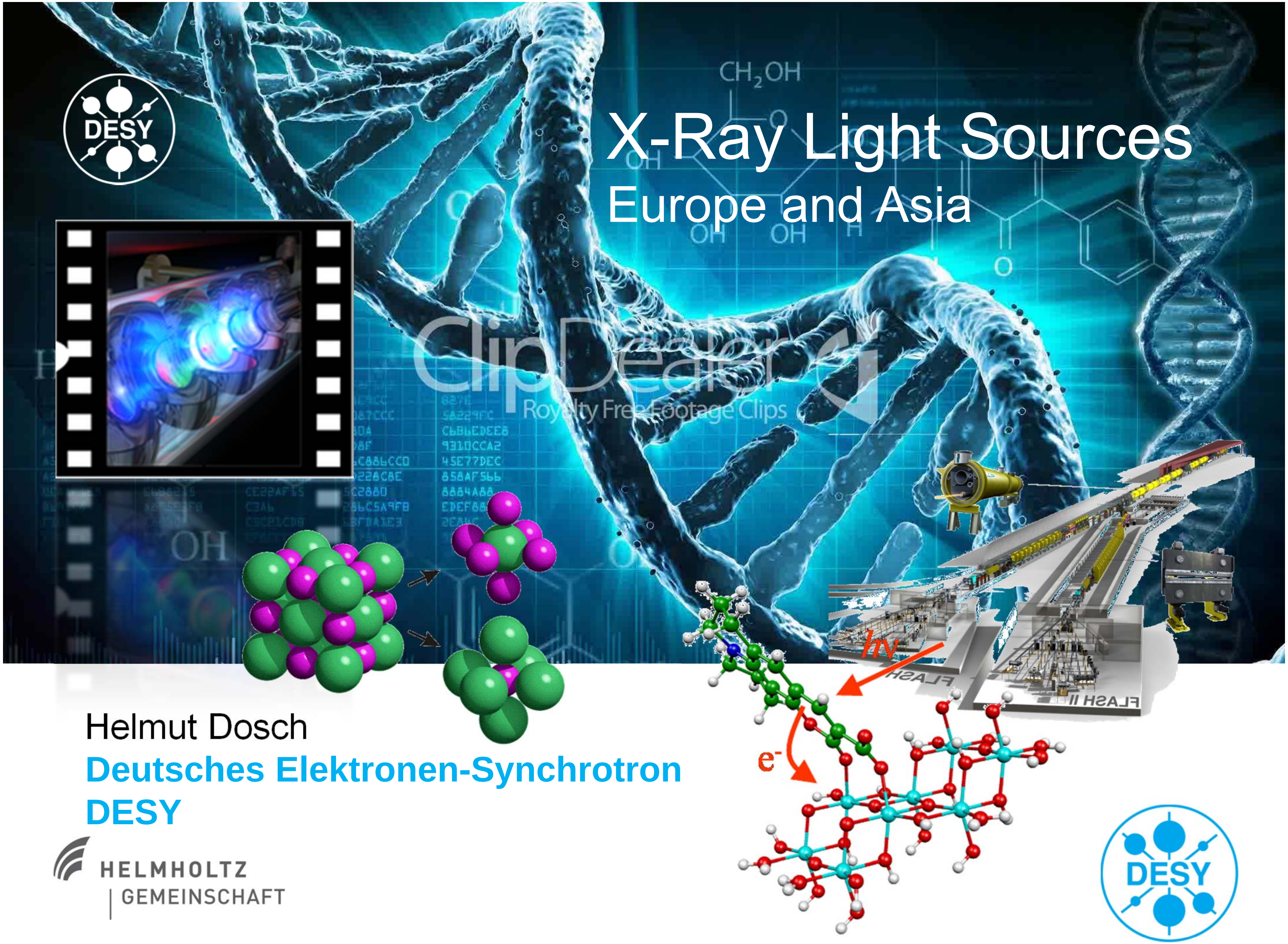
- Study large scale conformational changes via solution scattering
- Physiological conditions
- Dynamics ties structure to function



Fluctuations in the ground state and spontaneous evolution

- Characterize statistically dynamic systems without long-range order
- Inform directed design of energy conversion and storage materials





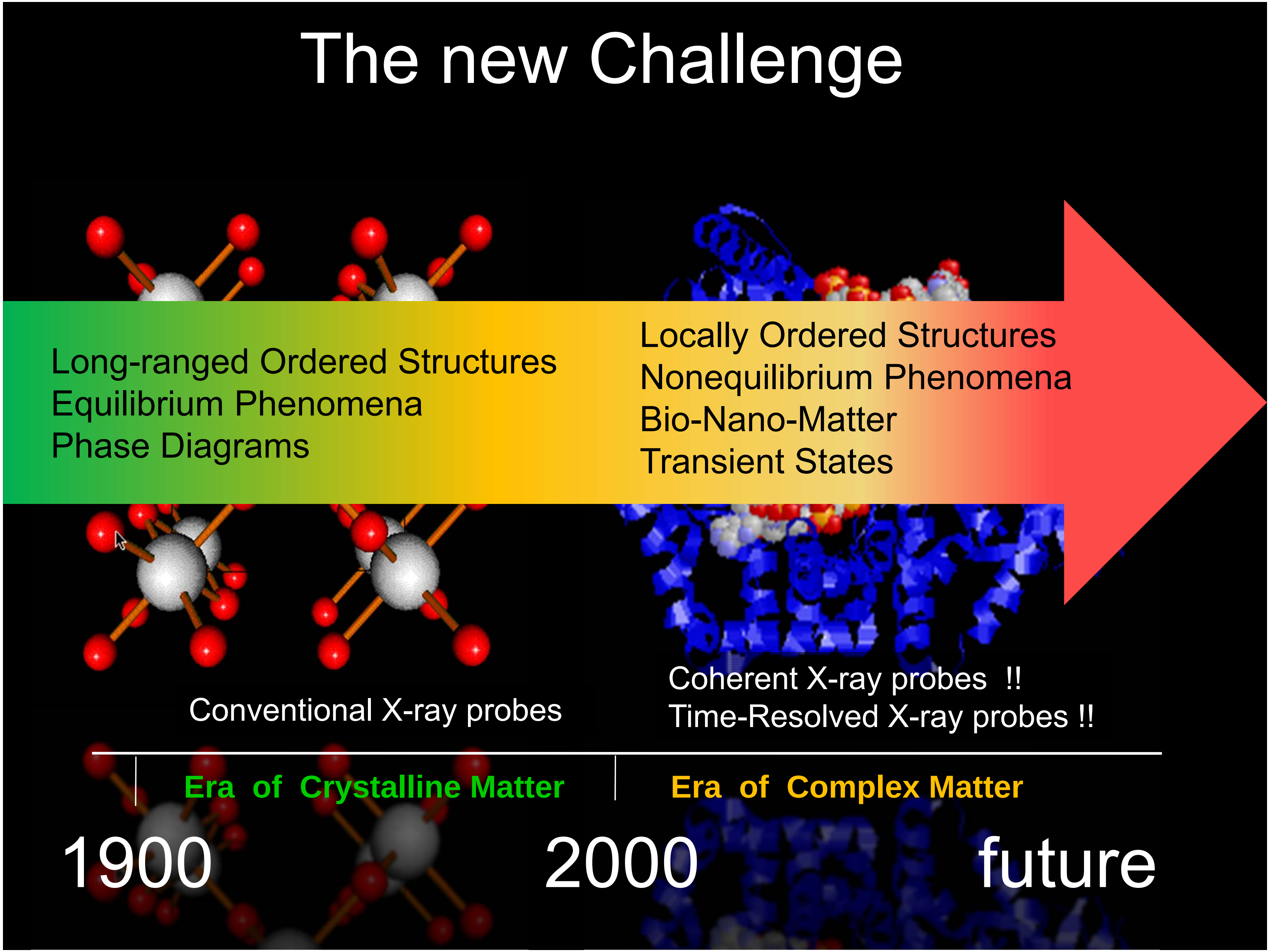
X-Ray Light Sources

Europe and Asia

Helmut Dosch

Deutsches Elektronen-Synchrotron DESY

HELMHOLTZ | GEMEINSCHAFT


The new Challenge
Long-ranged Ordered Structures
Equilibrium Phenomena
Phase Diagrams
Locally Ordered Structures
Nonequilibrium Phenomena
Bio-Nano-Matter
Transient States
Conventional X-ray probes
Coherent X-ray probes !!
Time-Resolved X-ray probes !!
Era of Crystalline Matter
Era of Complex Matter
1900
2000
future

European Strategy - X-Ray Sources 2000+

Soft X-Rays
100 eV – 1 keV

Focus on electrons, spins

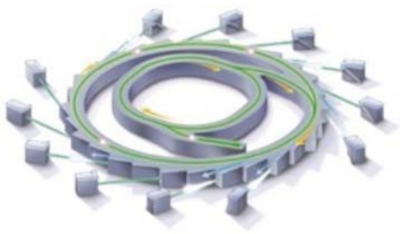
Electronic structure of matter
Magnetic structure of matter
Bond formation and breaking

Hard X-Rays
5 keV – 100 keV

Focus on atoms, ions, microstructure

Chemical structure of matter

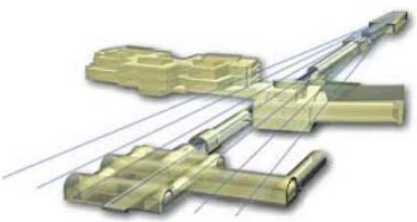
Bond formation and breaking



Storage Ring Sources
100 eV – 100 keV

Soft and Hard X-rays

Structure of matter and materials
Crystallography
Mature technology
Applied Sciences



Free Electron X-ray Laser
100 eV – 100 keV

Soft and Hard X-rays

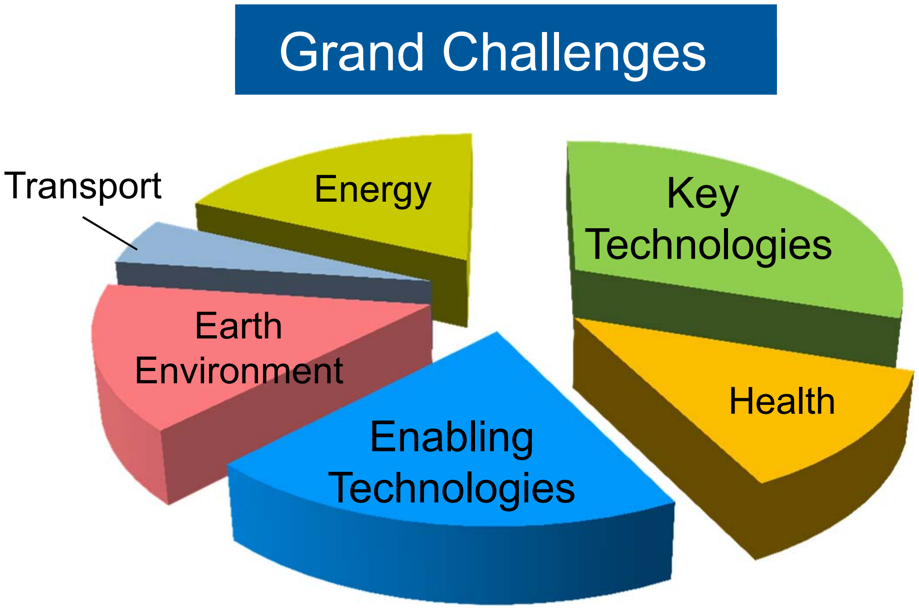
Ultrafast sciences
Nonequlibrium matter
SFX, HEDM, Nonlinear X-rays
„Discovery Channel“

Science Case : SR and FEL complementary

SR

Mature Technology

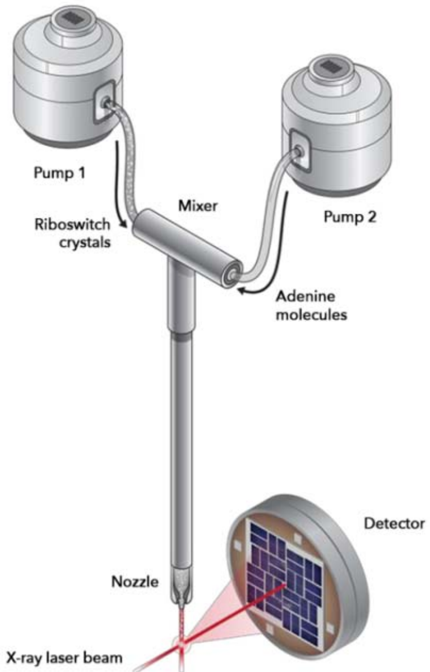
MBA → „Ultimate 4d Microscopes"
In-situ, operando interrogation of matter
Fundamental – applied - industry
GC of our society



FEL

Novel Disruptive Technology

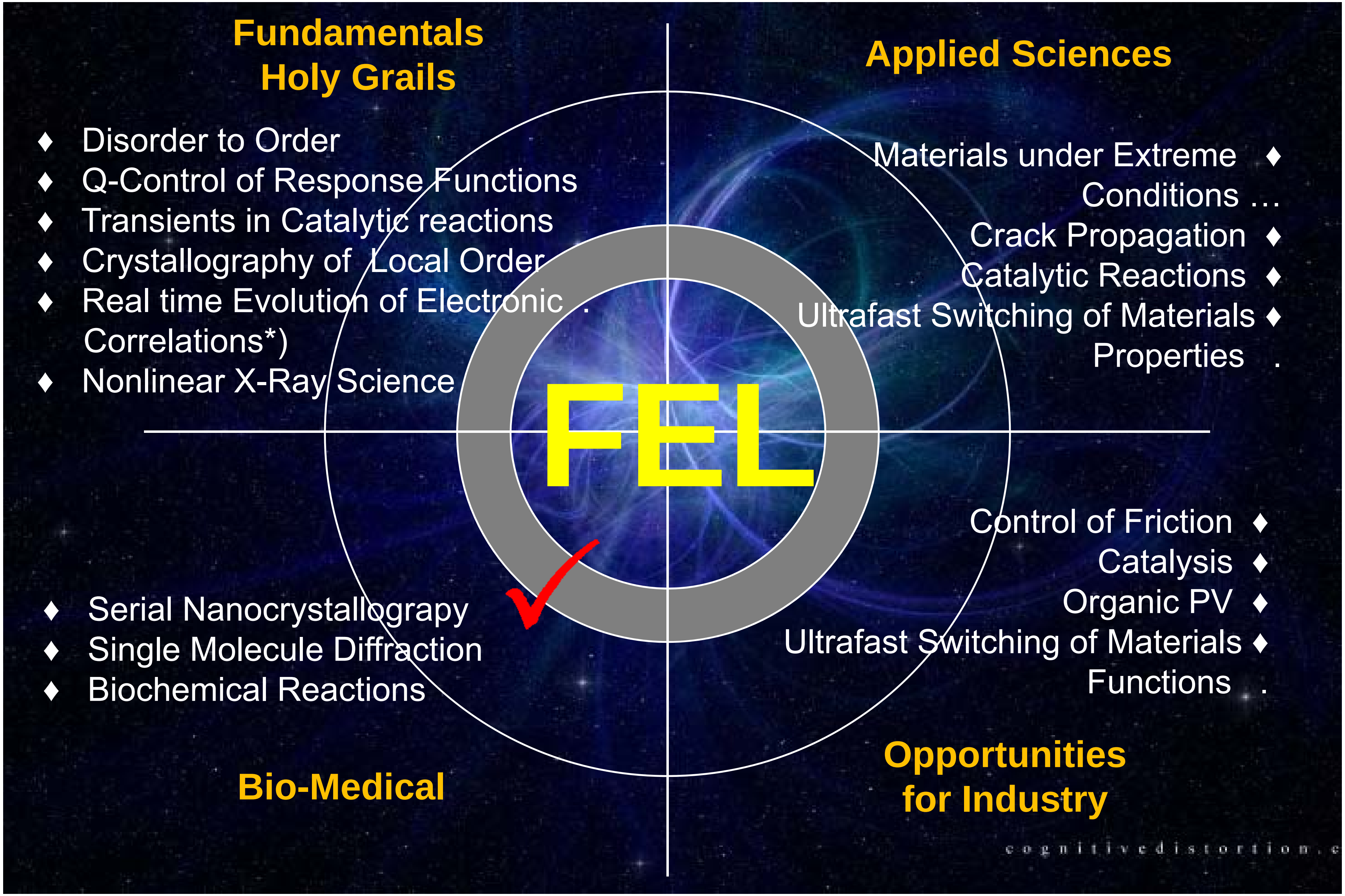
„Discovery Channel"
Ultrafast Science, „Molecular Movie"
Pathfinder of new technologies



Status in Europe: Storage Rings

Facility	Location	Energy	Lab Info	Comments
Storage Rings				
ESRF	Grenoble/FR	6 GeV	Upgrade MBA 2018-2020 „ESRF-EBS“	Hard Energy X-ray Facilities
PETRA III	Hamburg/DE	6 GeV	Upgrade MBA 2022-24 „PETRA IV“	
ALBA	Barcelona/ ES	3,0 GeV	Not fully instrumented	Medium Energy X-ray Facilities
Diamond	Didcot/UK	3,0 GeV	Upgrade MBA planning phase	
MAXIV	Lund/SE	3,0 GeV 1,5 GeV	7BA Lattice commissioning	
SOLEIL	Paris-Saclay/FR	2,75 GeV	Upgrade plans no details yet	
ANKA	Karlsruhe/DE	2,5 GeV	closes user ops in 2017	
SLS	Villigen/CH	2,4 GeV	Upgrade plans No details yet	
ELETTRA	Trieste/IT	2,0-2,4 GeV		Soft X-ray Facilities
BESSY II	Berlin/DE	1,7 GeV	Upgrade VSR 2018	
SOLARIS	Krakow/PL	1,5 GeV	Under construction	
ASTRID2	Aarhus/DK	0,58 GeV	Operating, no upgrade plans	

Science Case :   FEL

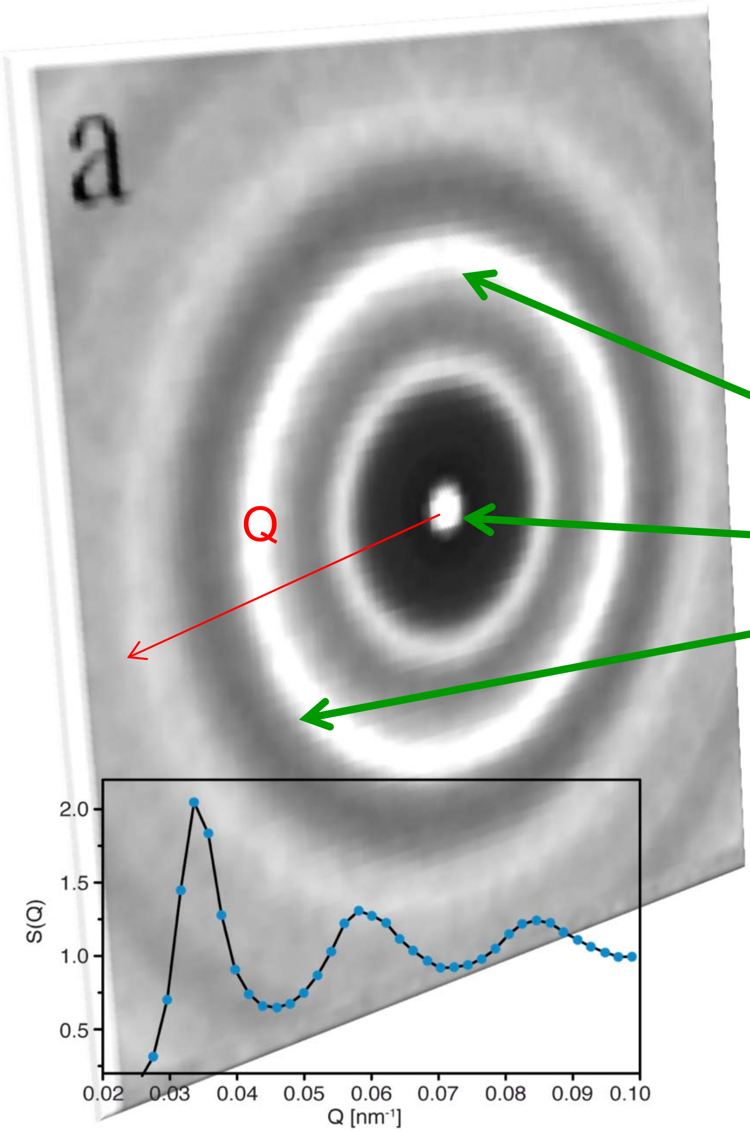


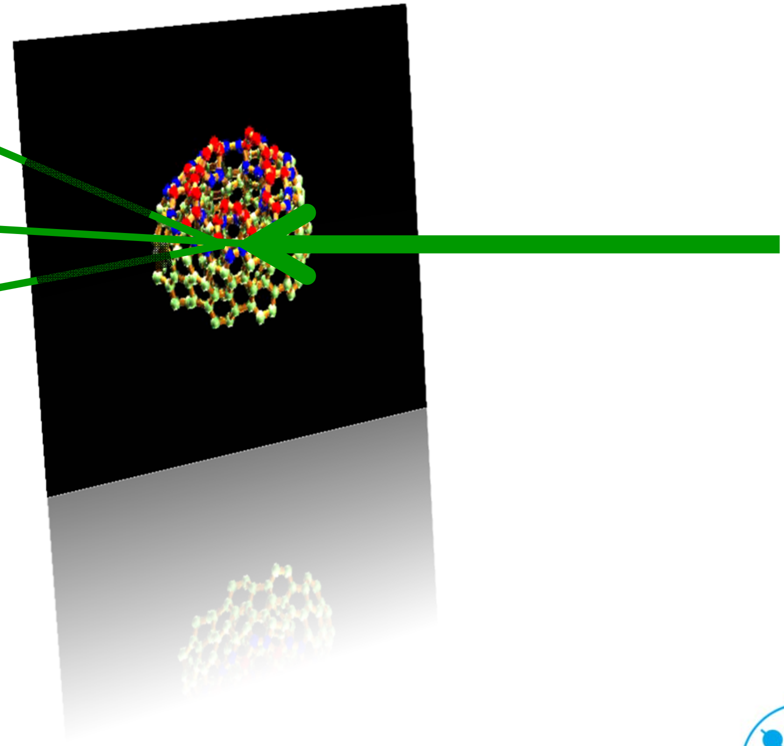
Conventional X-ray scattering from noncrystalline matter

$$I(\mathbf{Q}) = \left|f_a(\mathbf{Q})\right|^2 \cdot N \cdot S(\mathbf{Q})$$

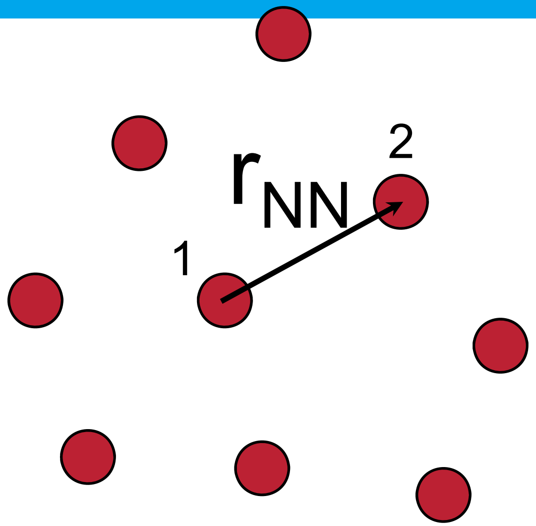
$$S(\mathbf{Q}) = 1 + \int (g_2(\mathbf{r}) - 1) e^{i\mathbf{Q}\cdot\mathbf{r}}\, d\mathbf{r}$$

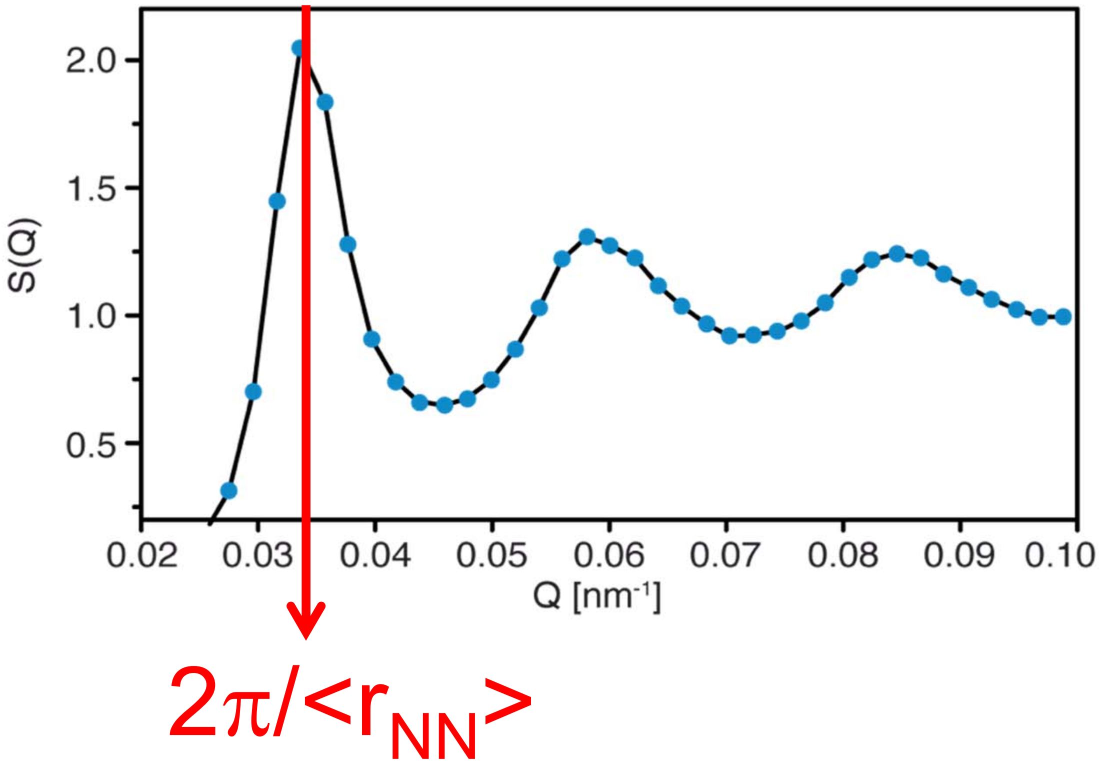
$$g_2(\mathbf{r},\mathbf{r}') = n_0^{-2}\left(\langle \rho(\mathbf{r})\rho(\mathbf{r}')\rangle - \delta(\mathbf{r})\right)$$ pair correlation function





2-Point Correlation Function





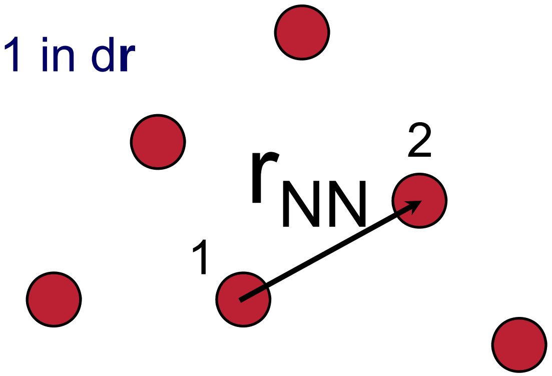
$n_0 g_2(\mathbf{r})d\mathbf{r}$ Average probability to find particle 2 at distance **r** from particle 1

$$g_2(\mathbf{r}_1,\mathbf{r}_2) = n_0^{-2}\left\langle \sum_i^N \sum_{j\neq i}^{N-1} \delta(\mathbf{r}_1 - \mathbf{R}_i)\delta(\mathbf{r}_2 - \mathbf{R}_j)\right\rangle$$

- $g_2(\mathbf{r})$ independent of bond angles !! no information on local structure/symmetry

Local Symmetry in Disordered Matter
From Higher Order Correlation Function

$n_0 g_2(\mathbf{r})d\mathbf{r}$ probability to find particle 2 at distance **r** from 1 in d**r**

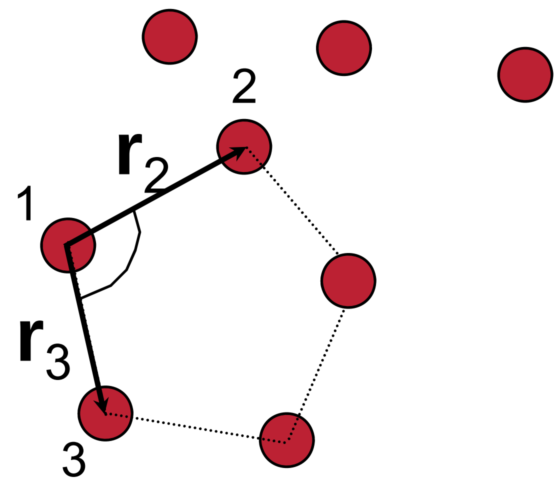


$$g_2(\mathbf{r}_1,\mathbf{r}_2) = n_0^{-2}\left\langle \sum_{i}^{N}\sum_{j\neq i}^{N-1}\delta(\mathbf{r}_1-\mathbf{R}_i)\delta(\mathbf{r}_2-\mathbf{R}_j)\right\rangle$$

- $g_2(\mathbf{r})$ independent of bond angles

- n-point distribution function
  depend on angles
  e.g.: $g_3(\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3)$

bond angles



$$n_0\int g_3(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3)d\mathbf{r}_3 = (N-2)g_2(\mathbf{r}_1,\mathbf{r}_2)$$

- N-2 different arrangements with same $g_2(\mathbf{r})$

local nano-angle in matter
coherent position of >3 atoms

Higher Order Correlation functions

$$g_2(\mathbf{r}_1,\mathbf{r}_2) = n_0^{-2} \left\langle \sum_{i}^{N} \sum_{j \neq i}^{N-1} \delta(\mathbf{r}_1 - \mathbf{R}_i)\delta(\mathbf{r}_2 - \mathbf{R}_j) \right\rangle$$

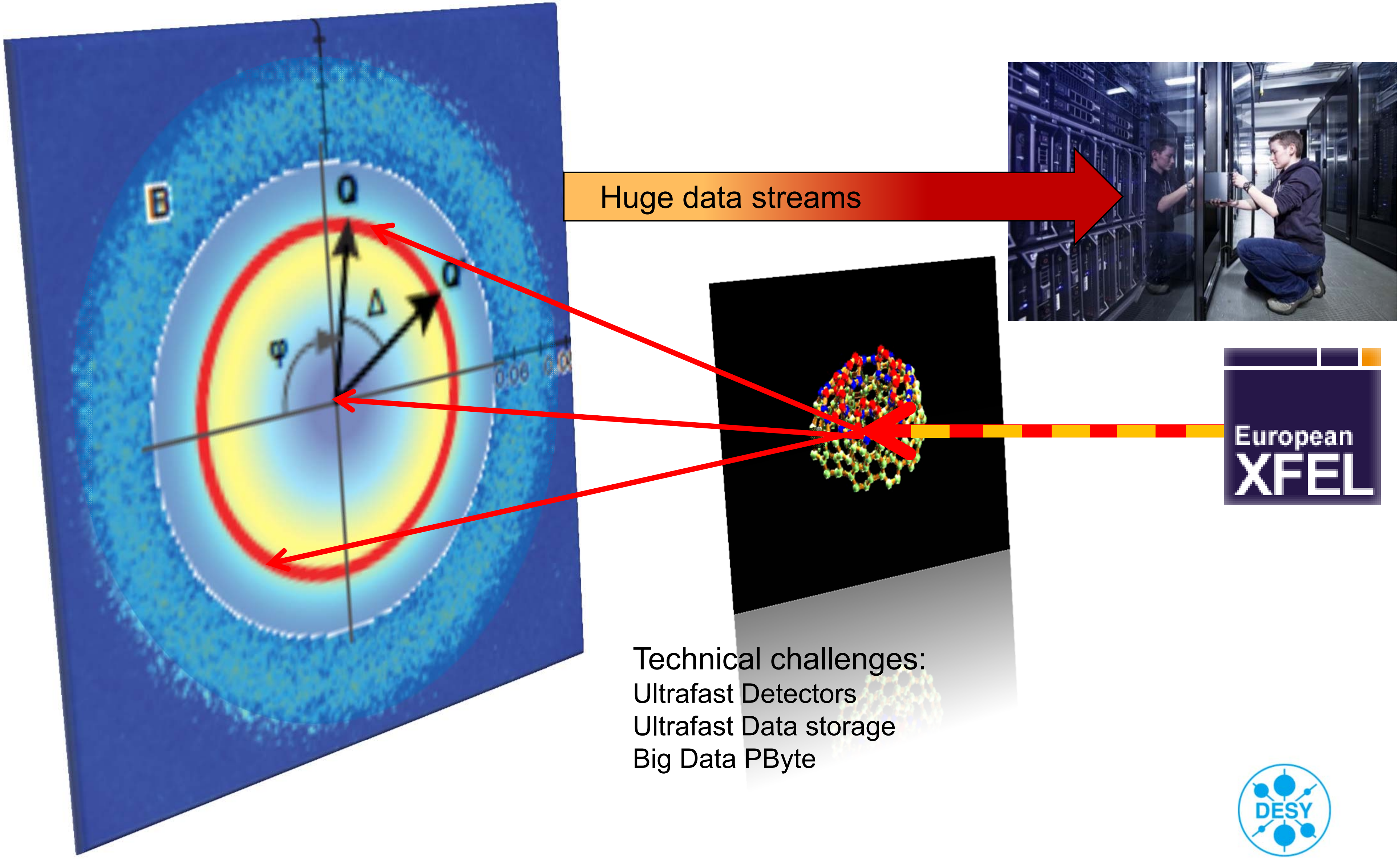
- Eliminate intrinsic **spatial** and **temporal** averaging

  spatial → Coherent diffraction

  temporal → Snap shot diffraction

- Construct new higher order correlations by hand

21st century challenge: Crystallography of noncrystalline matter



Technical challenges:
Ultrafast Detectors
Ultrafast Data storage
Big Data PByte

XFELs: Welcome to Nonlinear X-ray Physics !

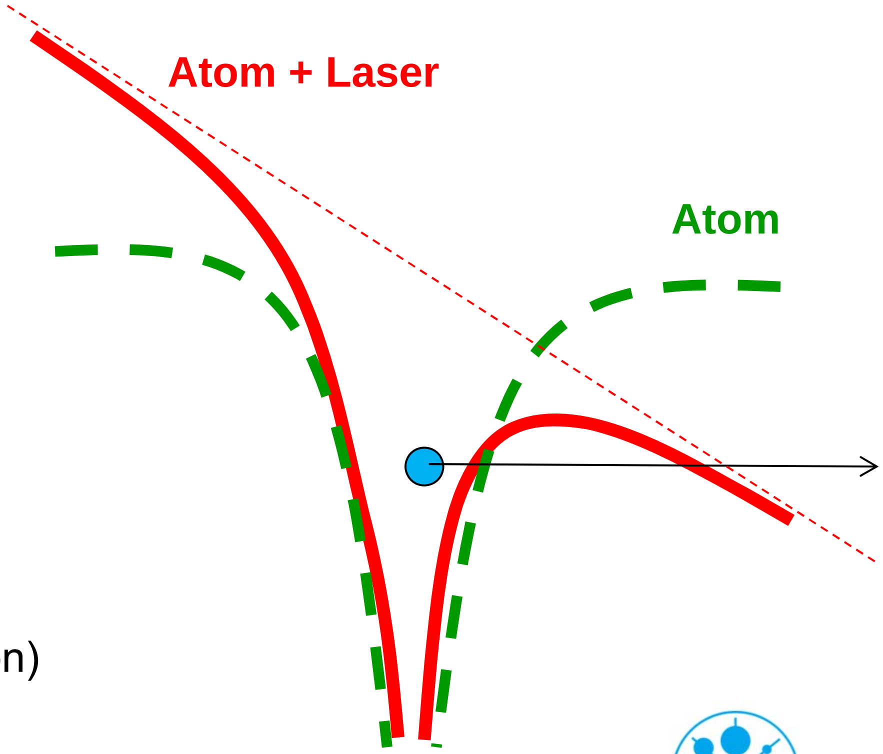
- Synchrotron 10^5 ~1 keV photons/ 10^{-11}s on a μm^2 spot
- X-ray FEL 10^{12} ~1 keV photons / 7 10^{-14} s on a μm^2 spot

Synchrotron: $< \mathcal{E}_{rms} > \sim 10^6$ V/cm

X-ray laser: $< \mathcal{E}_{rms} > \sim 10^{10}$ V/cm

Field inside an atom:

$$\mathcal{E}_{at} \sim e/a^2_B = 27.2 \text{ V}/a_B \sim 5 \times 10^9 \text{ V/cm}$$



Applying Keldysh theory:

Tunneling time:
10eV, 10^{10}V/m (γ>>1): t=10^{-15} sec

X-ray period: t= 10^{-18} sec

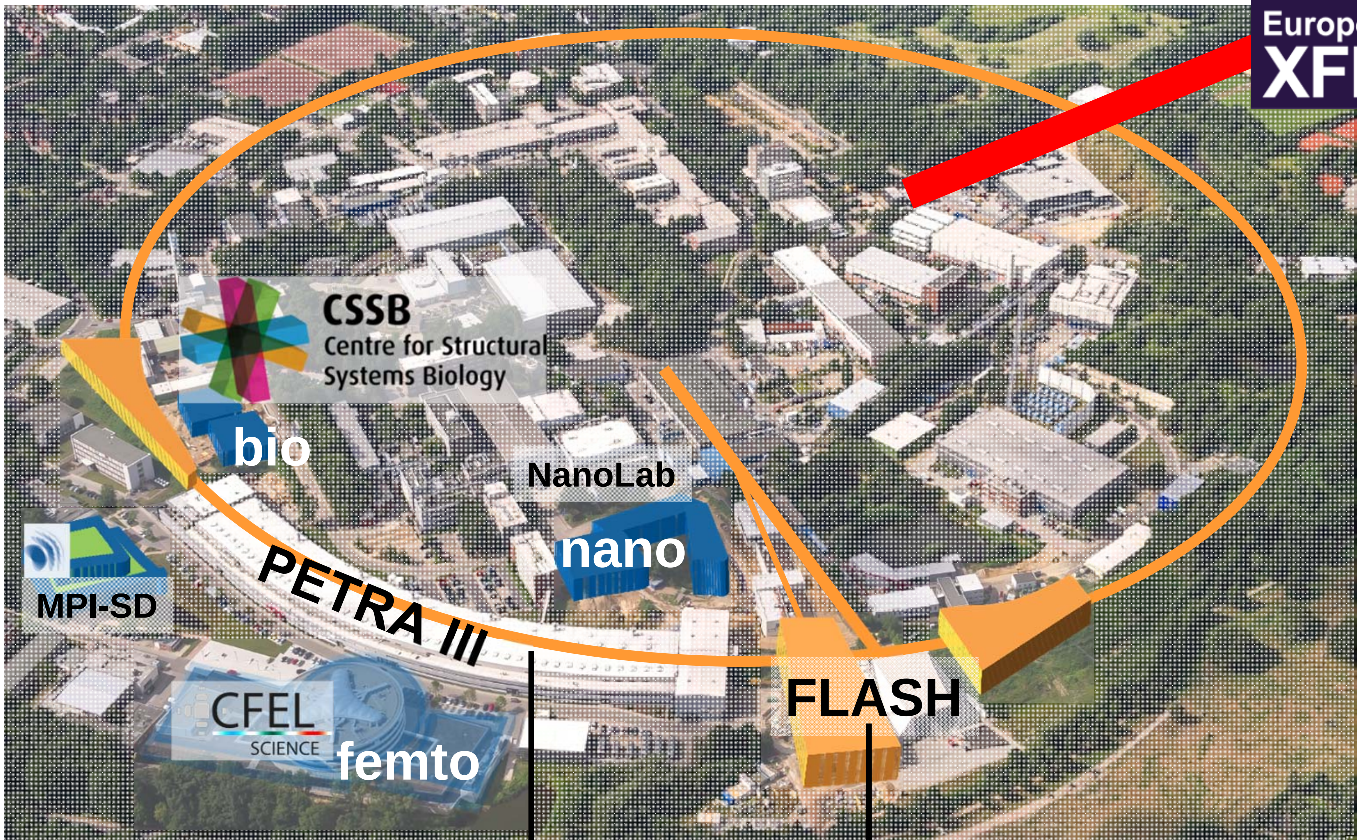
no time for tunnelling ! (no x-ray tunneling ionisation)
but lots of new nonlinear physics !!

Status in Europe: FELs

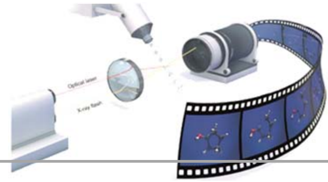
Facility	Location	Energy	Lab Info	Details	Comments
X-ray Lasers					
EU.XFEL	Hamburg	17,5 GeV	Commissiong First beam fall 2017	Europ. X-ray Laser D, RUS, and EU countries	Soft and Hard Xrays
Swiss FEL	Villigen	2,1-5,8 GeV	commissioning	National facility 2 branches: soft and hard	
FLASH	Hamburg	1,8 GeV	Upgrade 2020 Seeding, cw	1st (soft) x-ray FEL Soft x-ray laser upgrade FLASH II National facility	Soft X-rays
FERMI-1	Trieste	1,5-1,8 GeV	λ= 100nm-10nm 20-90fs, 10-50 Hz	2012 HGHG laser	
FERMI-2	Trieste	1,5-1,8 GeV		2016 HGHG Laser	
ELBE	Dresden	100-150 MeV	Upgrade Plans „DALI“	IR/THz-FEL	IR and THz
FELIX	Nijmegen	10-50 MeV	λ= 3-1500 μm	IR/THz-FEL	

DESY Photon Science

European XFEL



Angstrom X-ray laser
fs-dynamics
complex Matter



CUI THE HAMBURG CENTRE FOR ULTRAFAST IMAGING

High brilliance Synchrotron radiation
Modern Material Science and Drug Design

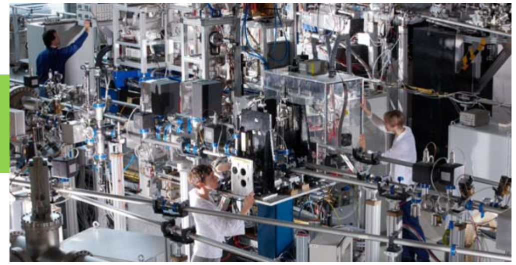
Nanometer X-ray laser
Femtosecond dynamics of Matter

DESY

On the way to the International Photon Science Mekka.

Photon Science Facilities

XFEL 2017 | **PETRA IV 2025** | **FLASH 2020**



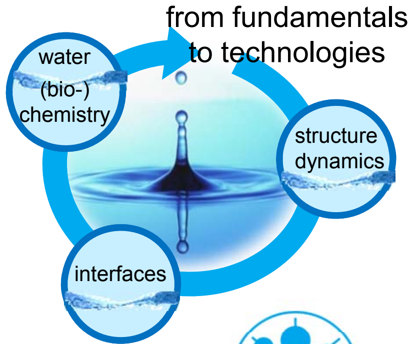
Photon Science Research Centers

CFEL SCIENCE

CSSB Centre for Structural Systems Biology

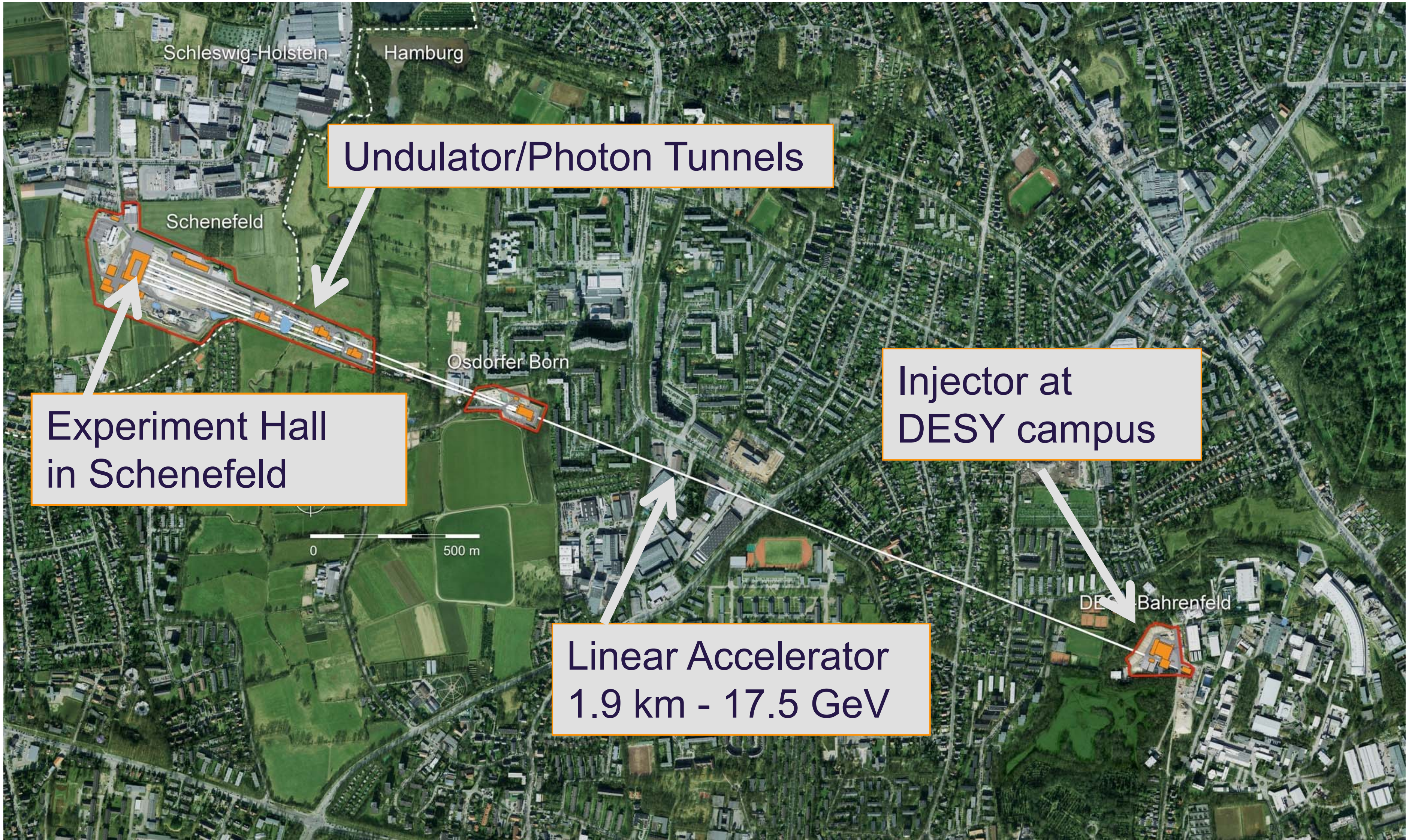
Photon Science 2018
DESY NanoLab

H_2O Institut 2020+



DESY

European XFEL Layout



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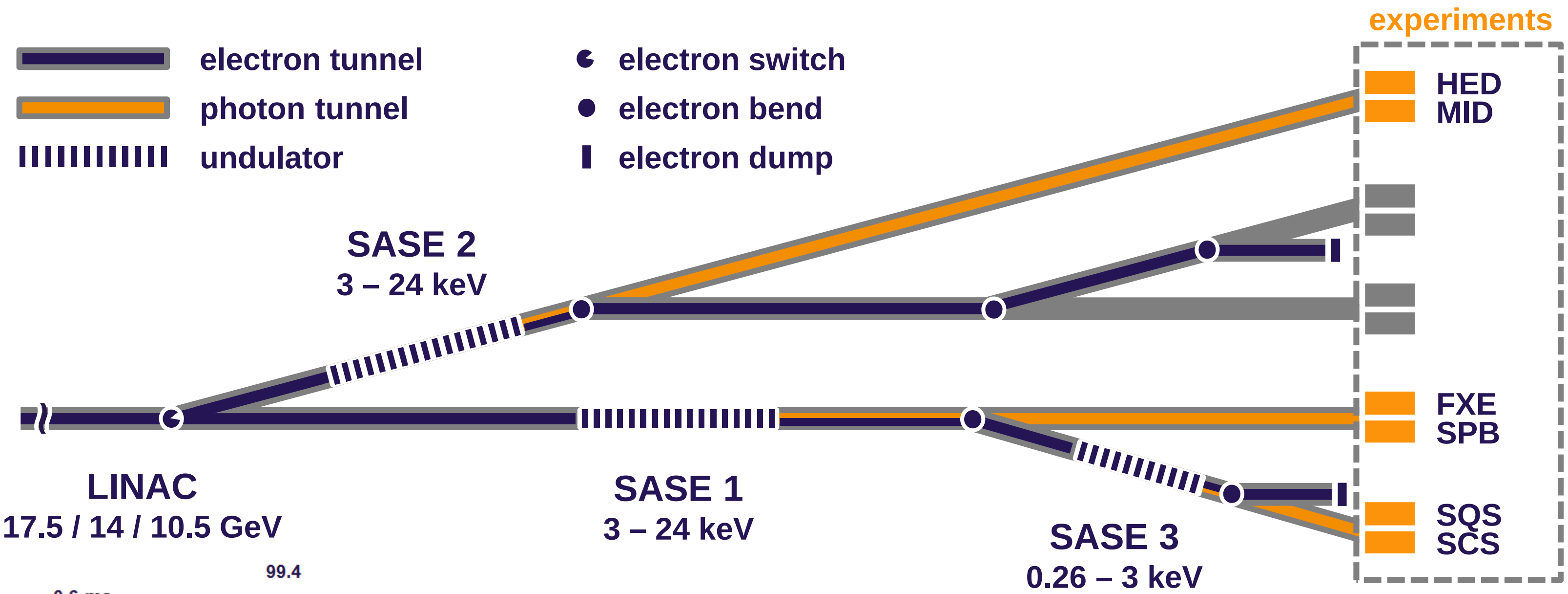
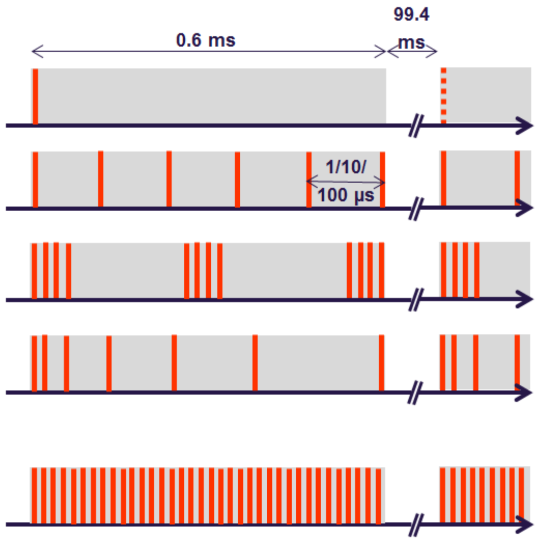
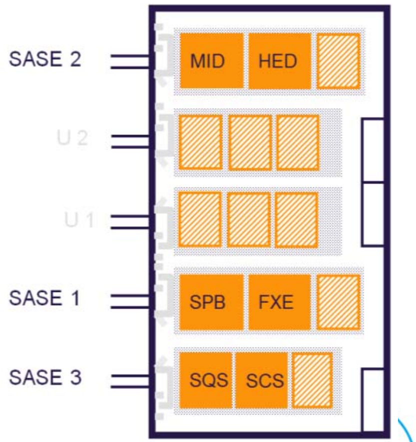
Layout European XFEL

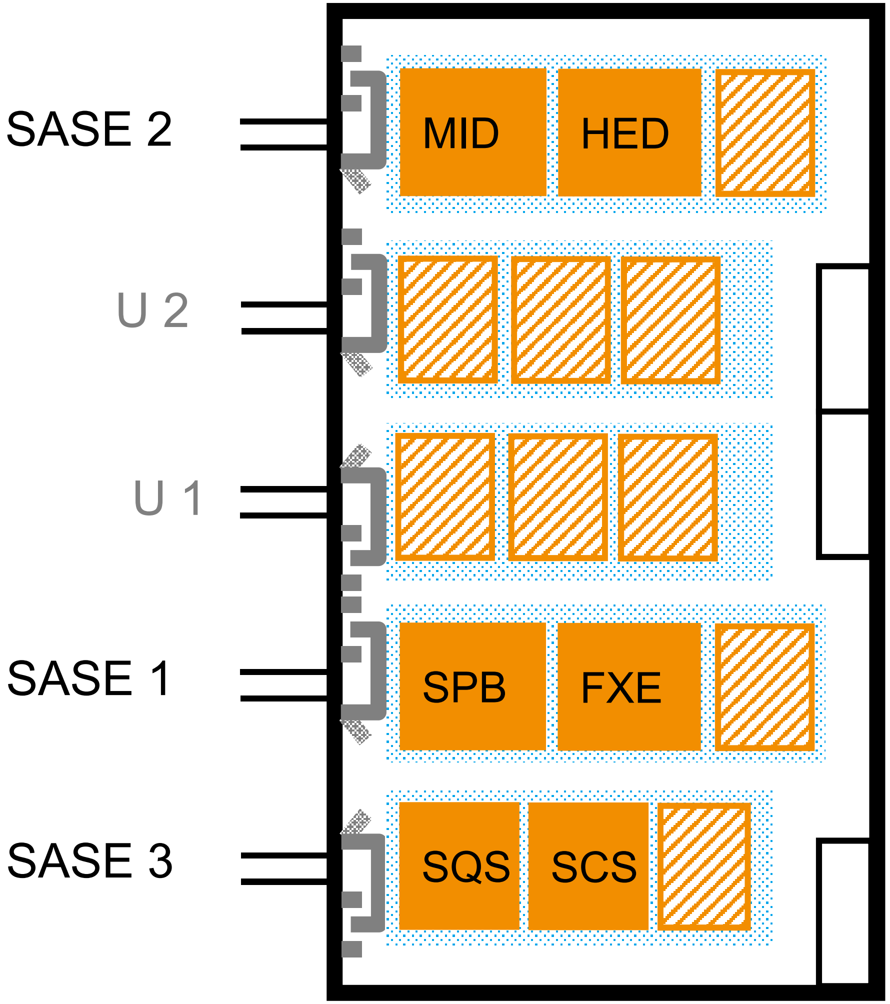


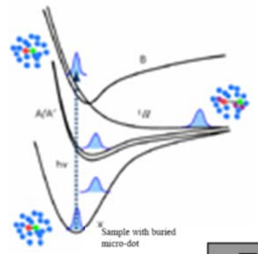


- 2 hard x-ray undulators and beam transport with 4 instruments
- 1 soft x-ray undulator and beam transport with 2 instruments
- all undulators planar and tunable

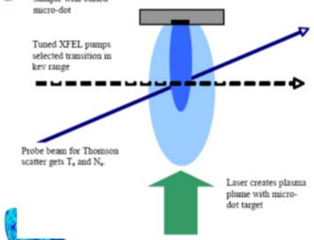


The Suite of Instruments

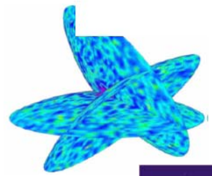




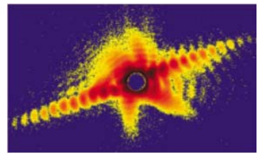
FXE Femtosecond X-ray Experiments



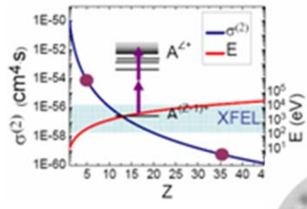
HED High Energy Density Science



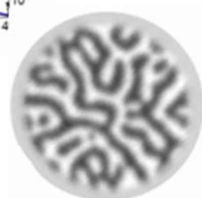
SPB Single Particle & Biomolecules



MID Materials Imaging & Dynamics



SQS Small Quantum Systems



SCS Spectroscopy & Coherent Scattering

More about experiments: http://www.xfel.eu

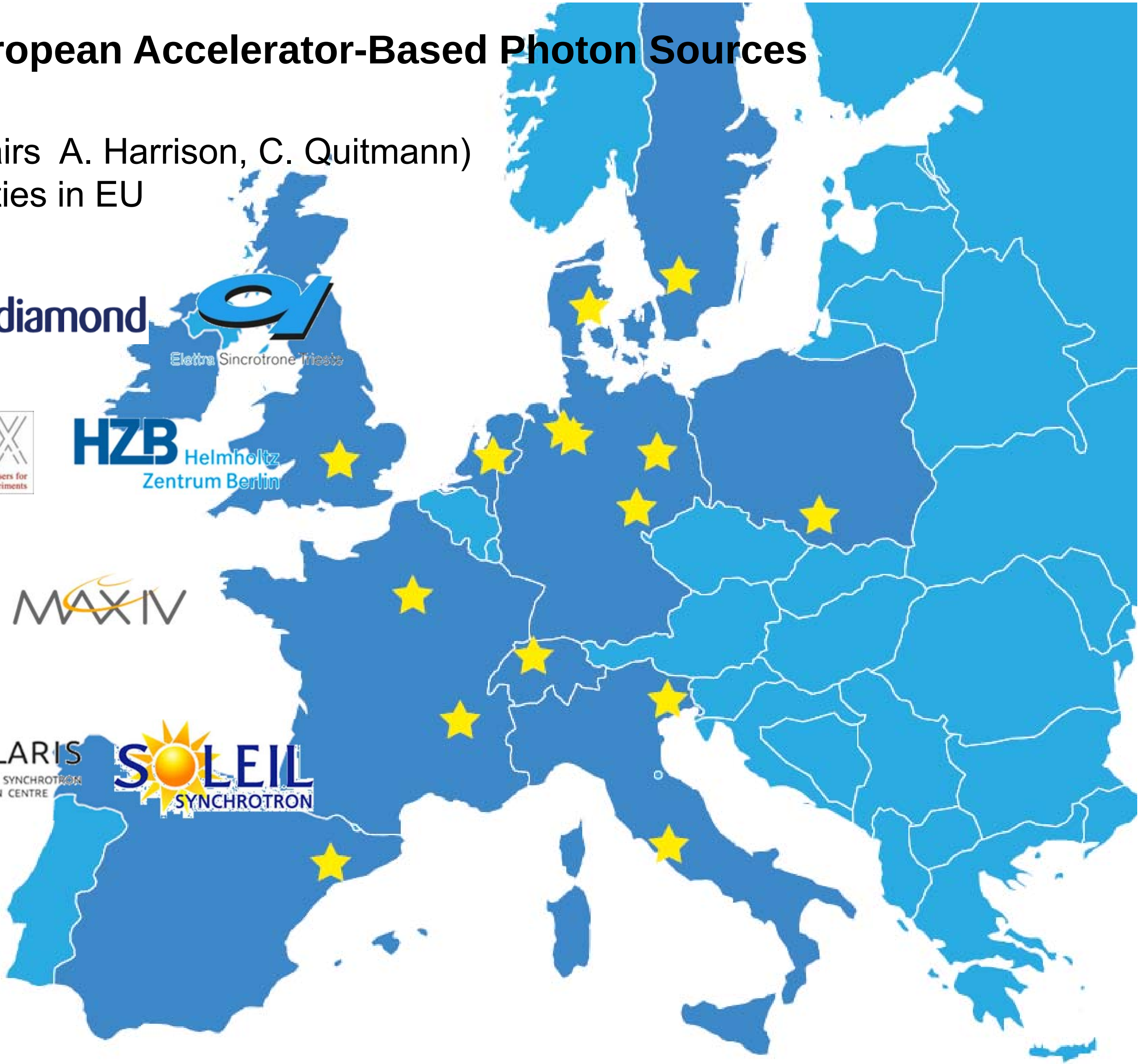
European Commission View

- **More integration** between RI ("smart specialisation") and the e-infrastructures and with other parts of Horizon 2020, to exploit synergies and complementarities
- New and reinforced emphasis on **long term sustainability**, innovation, and contribution to the EOSC
- Support to large scale initiatives for **innovation**
- Continuation of the different approach between **Starting and Advanced Communities** for integrating activities, and potential launch of pilot actions in 2020
- Training of **future lab managers**

LEAPS initiative

LEAPS - League of European Accelerator-Based Photon Sources

Launched: 2015
Chair: H. Dosch (co-chairs A. Harrison, C. Quitmann)
Members: 14 Photon Facilities in EU



LEAPS initiative

LEAPS - League of European Accelerator-Based Photon Sources

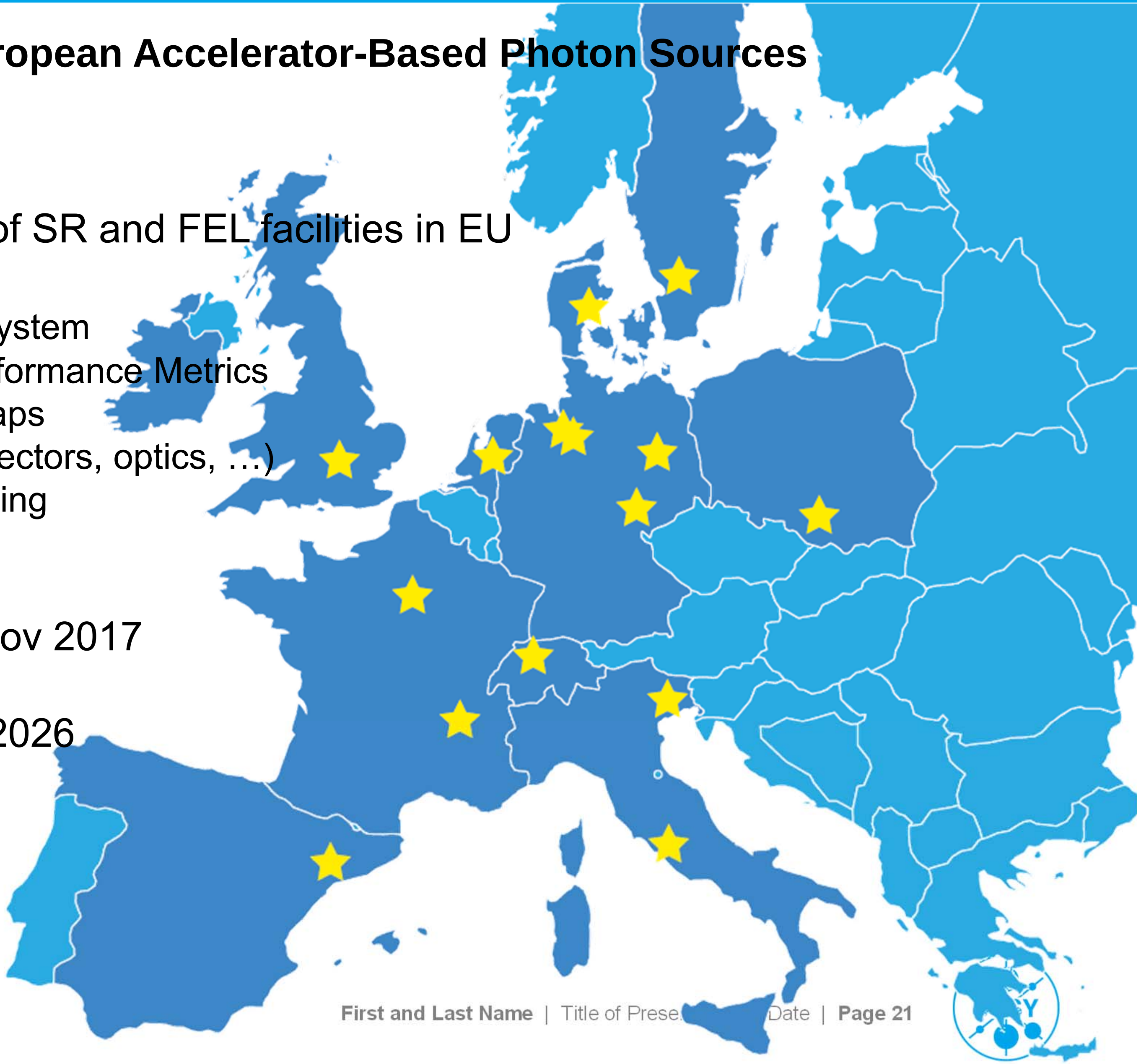
Goals:

- Coherent Roadmap of SR and FEL facilities in EU
- Better Integration:

- Standardized Proposal System
- Standardized Facility Performance Metrics
- Joint Technology Roadmaps
  (data management, detectors, optics, …)
- Joint Education and Training

LEAPS Charter
LEAPS Strategy Doc Nov 2017

Input to EC FP 9 2020-2026



China Strategy

Beijing

- Beijing Synchrotron Radiation Facility BSRF at IHEP
  ~1990ies, various upgrades, 2.5 GeV, 12 beamlines, parasitic
- Beijing Free Electron Laser BFEL at IHEP
  ~1990ies, 30 MeV RF-Linac, mid-Infrared-FEL

- New: High Energy Photon Source HEPS
  Approved project, will be 50 km north from IHEP Beijing
  6 GeV SR, 1.3 km circumference, 7BA, 60pm-rad
  ~700M$ approved, earliest operation in 2022

  Plans for a XFEL as well

Shanghai

- Shanghai Synchrotron Radiation Facility
  opened in 2012
  3.5 GeV, 432 m circumference, DBA lattice, 3.9 nm-rad
  13 beamlines in operation, 20 more to come over the next years (until 2022)

- SXFEL at SINAP/Shanghai
  Started as test facility in 2014
  40 MeV linac, (C-band, S-Band) 8.8nm seeded FEL, 1-10 Hz
  Upgrade to 1.6 GeV with undulator halls and 4-5 experimental stations to soft x-ray user facility
  Future extension to hard x-ray possible

- Dalian Coherent Light Source (University in cooperation with Max Planck Society)
  300 MeV LINAC, VUV-FEL, 50-150 nm
  Developed together with SINAP
  Lasing by end of 2016

Other: National Synchrotron Radiation Laboratory, Hefei (University)
1991, various upgrades, 800 MeV SR

Korea Strategy

Pohang

Pohang, PLS-II SR
- Upgrade from PLS in 2011 to 3.0 GeV, 32 beamlines
- DBA, 5.8 nm
- Currently, no further upgrade planned

Pohang, PAL-XFEL
- Just recently commissioned, lasing/saturation at 0.15nm achieved in November last year
- First call for proposals published in February/March 2017
- 10 GeV S-Band LINAC, 60Hz, 0.1nm FEL wavelength
- Beamlines:
  - Soft x-ray scattering & spectroscopy
  - X-ray scattering & spectroscopy
  - nano-crystallography, coherent diffraction

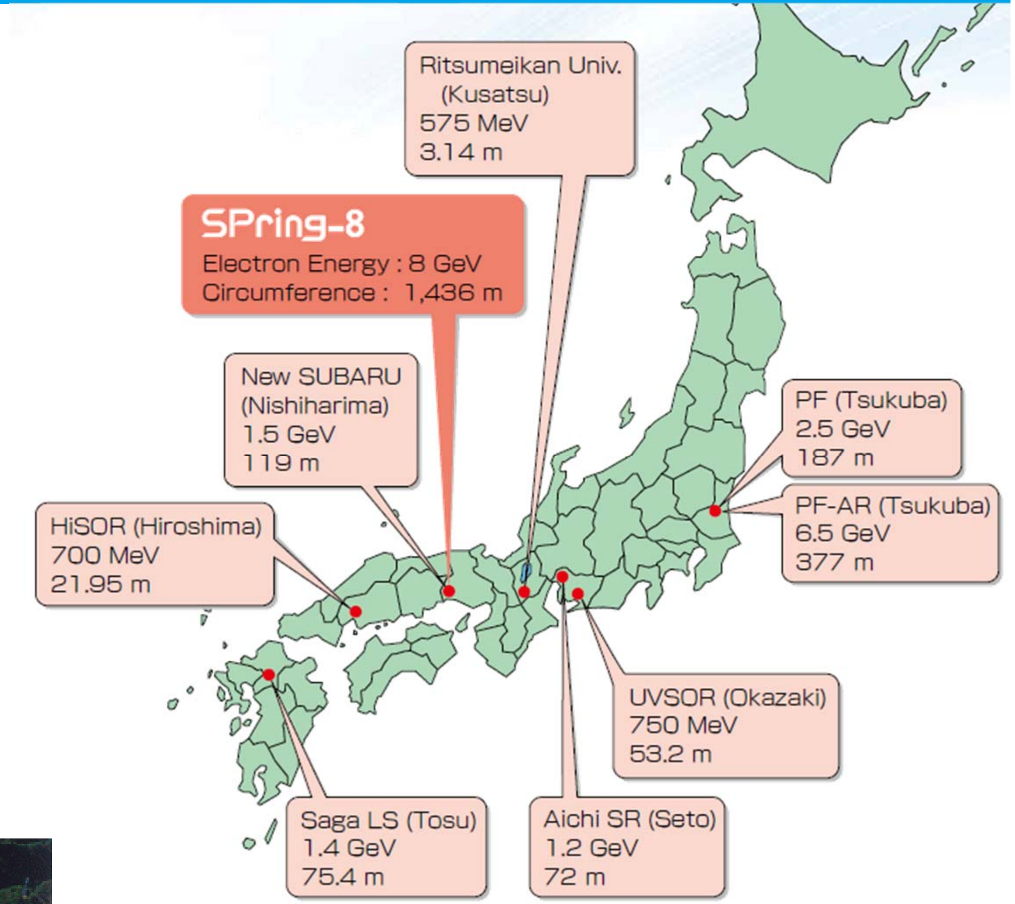
Japan Strategy

Harima

- Spring-8: High performing 3rd generation SR
  8 GeV
  Upgrade Plans USR next years
- SACLA: 60 Hz, one beam line hard x-ray FEL
  Upgrade SACLA
  additional injector and additional undulators

Tsukuba (KEK)

- Photon Factory 2,5 GeV SR machine (Tsukuba)
  no upgrade plans known
- cERL 20 MeV in operation since 2013
- Plans for EUV-FEL for Lithography



Concluding Remarks

- Light sources are generating exciting breakthrough science around the globe
  - BES user community has nearly doubled since 2004 to over 16,000 users including the 11,000 light sources users
  - New & upgraded facilities are driving the frontiers
- John Hemminger has provided a steady hand of leadership throughout these developments
  - As chair of BESAC he has shepherded the US light source strategy
  - The US light source strategy has influenced the international landscape
- Given the wealth of new ideas, new technology and the scientific opportunities, we anticipate light sources around the globe to be a continuing source of discovery for decades to come