Free Electron Lasers :

Novel X-ray Light Sources for Science Discoveries

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2018 National School on Neutron & X-ray Scattering

Argonne Nat. Lab. 07/2018

SLAC NATIONAL ACCELERATOR LABORATORY

U.S. DEPARTMENT OF ENERGY Office of Science

Layout

Take-away messages indicated by

1) **Free Electron Lasers**
   1) **What is an FEL ?**
   2) **Status of FEL's worldwide vs Storage Rings**

2) FELs vs. Synchrotron Sources:
   1) Understand the Peak Brilliance graphs
   2) LCLS
   3) In depth comparison from the experimentalist point of view

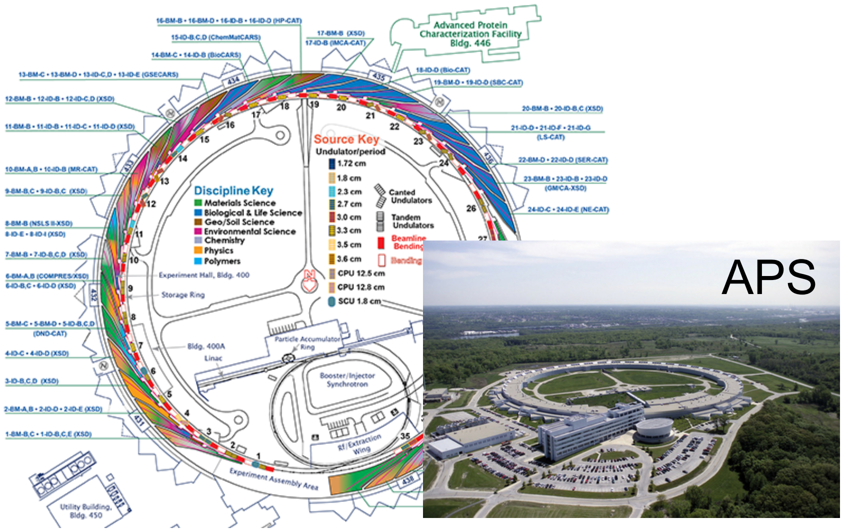
3) Experimental Strategies to use FELs

4) What's coming next ?

1.1) What is a Free Electron Laser ?

SLAC

Synchrotrons

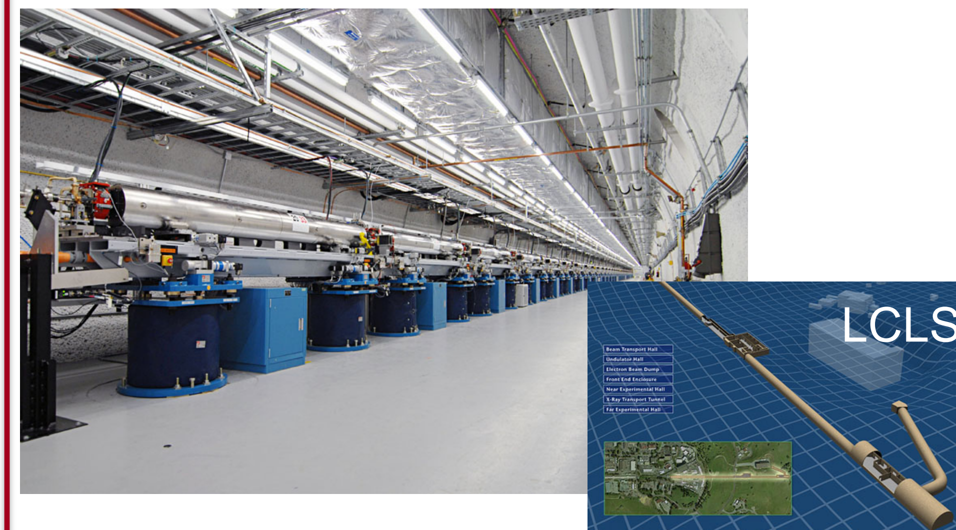


Ultimate e-recycling

Storage Ring

- **MANY** Insertion Devices (ID) & BMs
- $\geq$ 1 instrument per Undulator
- Independent operation of ID’s

Free Electron Lasers



Pulsed & single path

Linear accelerator

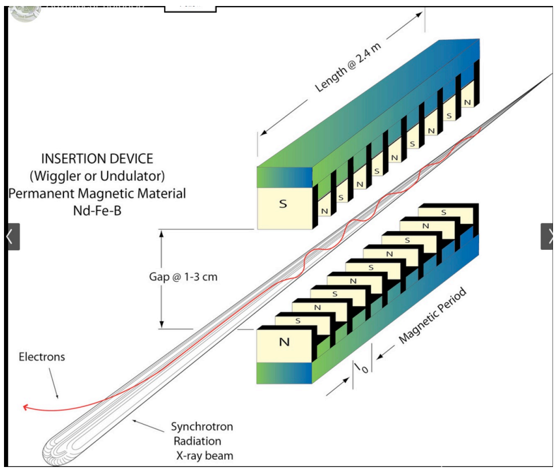
- Very limited number of Undulators (1 to 5)
- $\geq$ 1 instruments per undulator
- Almost one instrument at a time

1.1) What is a Free Electron Laser ?

SLAC

Synchrotrons

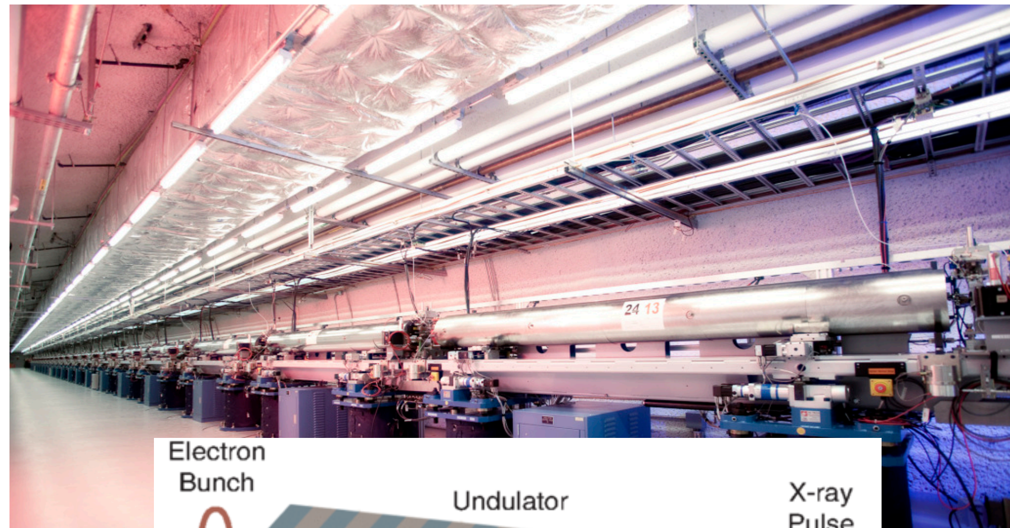
Typ. 1 to 5 meter long

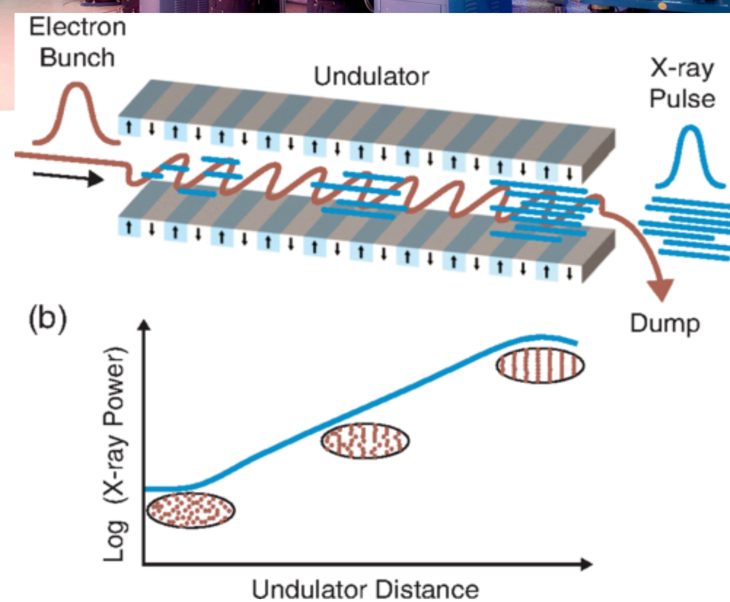


Free Electron Lasers

VERY long : typ. >100 meters

Small e-beam emittance





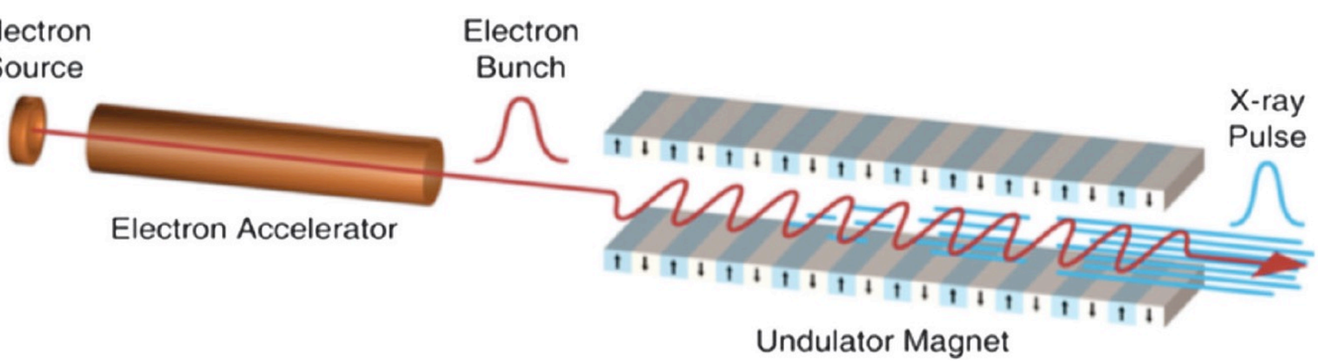
1.1) Reading Suggestions : What is a Free Electron Laser ?

SLAC

Eur. Phys. J. H
DOI: 10.1140/epjh/e2012-20064-5
Vol **35** (5), pp 659-708 (2012)
THE EUROPEAN PHYSICAL JOURNAL H

The history of X-ray free-electron lasers

C. Pellegrini[1,2,a]



REVIEWS OF MODERN PHYSICS, VOLUME 88, JANUARY–MARCH 2016

The physics of x-ray free-electron lasers

C. Pellegrini
Department of Physics and Astronomy, University of California at Los Angeles, Los Angeles, California 90095, USA and SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA

A. Marinelli
SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA

S. Reiche
Paul Scherrer Institute, 5232 Villigen PSI, Switzerland

1.2) FELs and Synchrotrons Worldwide

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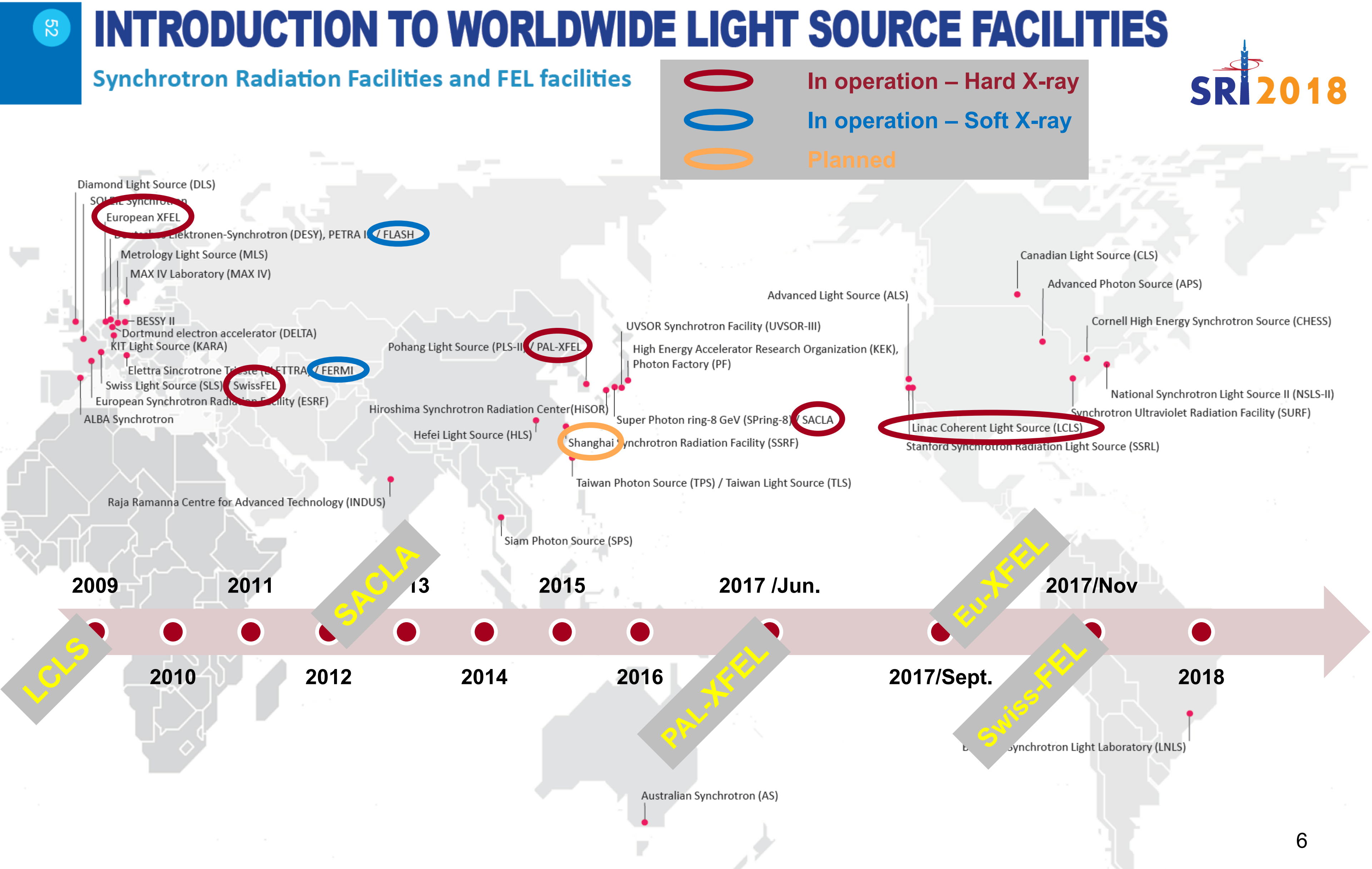


FEL vs. SR

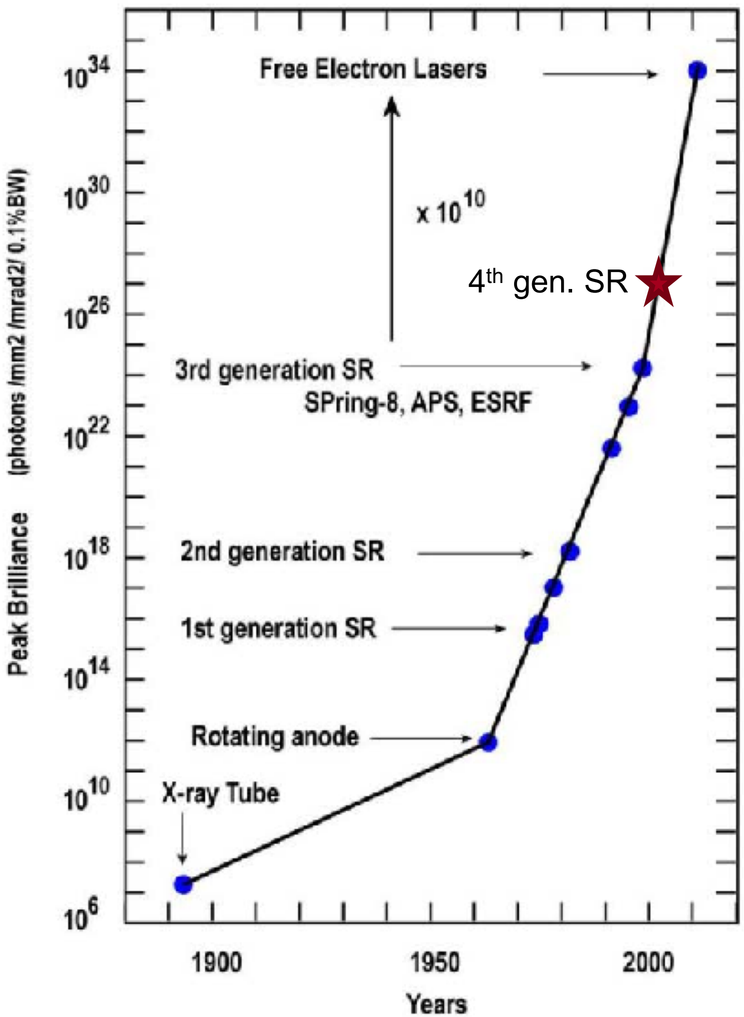
1) Free Electron Lasers
   1) What is an FEL ?
   2) Status of FEL's worldwide vs Storage Rings

2) **FELs vs. Synchrotron Sources:**
   1) **Understanding generations and the Brilliance graphs**
   2) LCLS
   3) In depth comparison from the experimentalist point of view

3) Experimental Strategies to use FELs

4) What's coming next ?

2.1) FEL vs. SR : Understanding Generation and Peak Brilliance



Shintake, T. (2007). Proc. of IEEE PAC, pp 89 - 93.

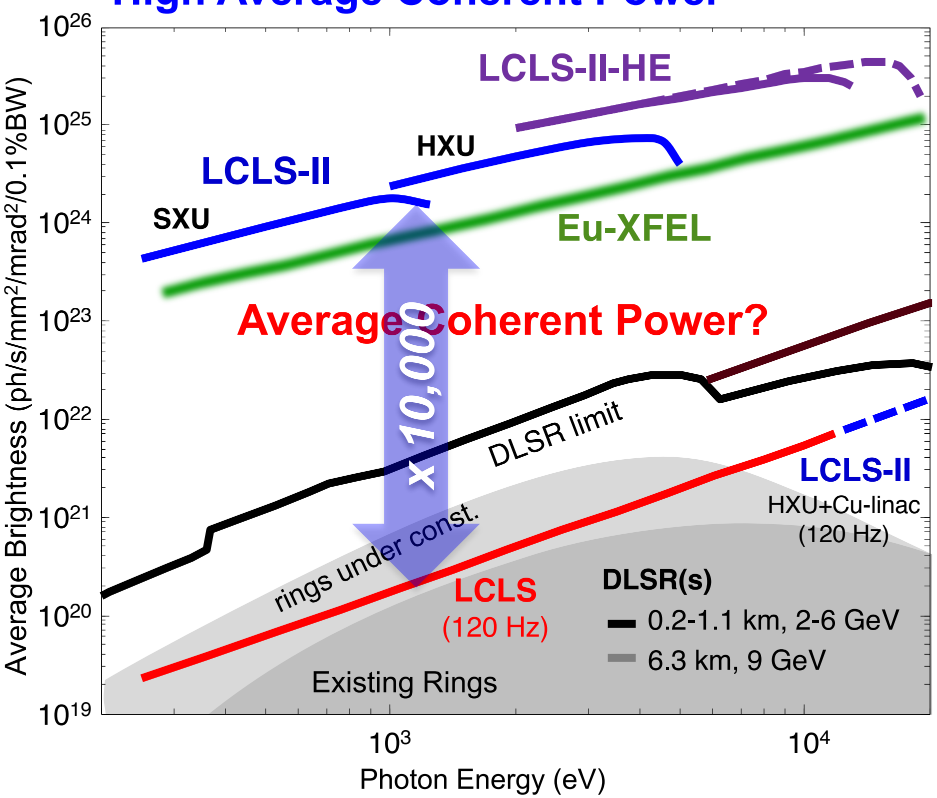
"… it is clearly a misnomer to classify an X-ray FEL as a `fourth-generation light source'. The fourth-generation light sources are now clearly identified as diffraction-limited storage ring sources …"

White, Robert, Dunne, J. Synch. Rad. **22** (3), pp 472-476 (2015)

Pay Attention to the Units !

$$\frac{Photon}{s \quad mm^2 \quad mrad^2 \quad (0.1\%\, BW)}$$

Ballpark	SR	FEL	Gain
s	~100ps	~50fs	x 2.10³
mm	~2	~0.05	x 0.5.10²
mrad	~30-50	~1	x 4.10³
(0.1% BW)	~ 2-3%	~0.1%	x 0.3.10²



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(0.1% BW)	~ 2-3%	~0.1%	x 0.3.10^2

x10^4 rep. rate

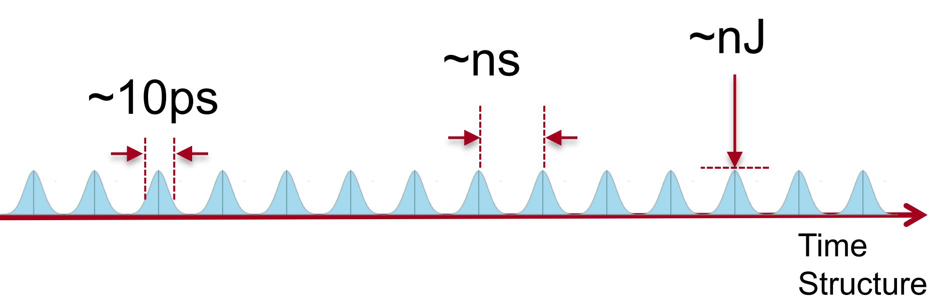
x 0.5.10^2 diffraction limit

2.1) FEL vs. SR : Big Picture

Storage Ring

Pulse duration : typ. 50-100ps

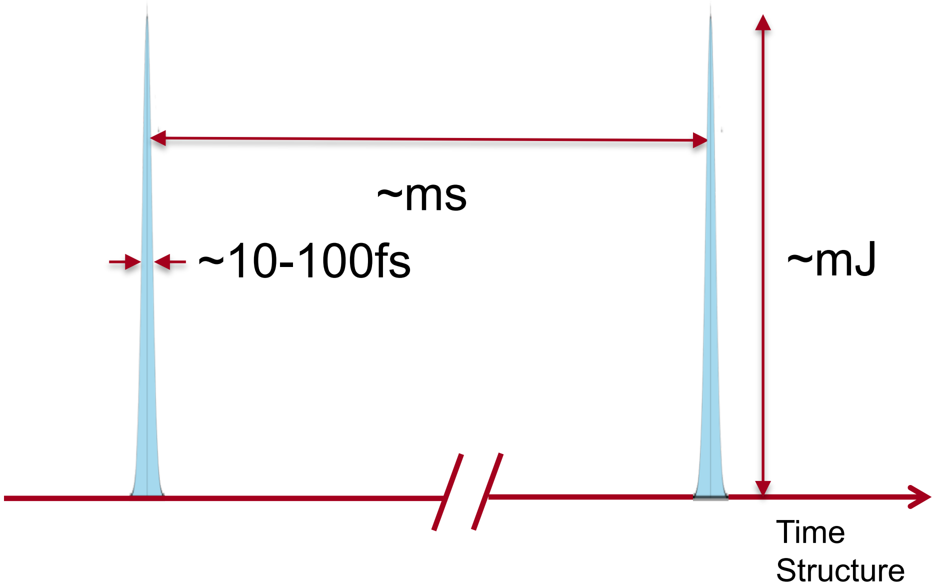
High repetition rate (100sMHz)



FEL : LCLS

Pulse duration : typ. < 100fs

Repetition rate ~50-100Hz



1mJ = 6.242 10^{12} keV

1mJ @ 8keV ~ 7.8 10^{11}

1mJ @ 1keV ~ 6.2 10^{12}

The average number of photon per second on a storage ring is similar to the number of photon on average per shot on a FEL

FEL vs. SR

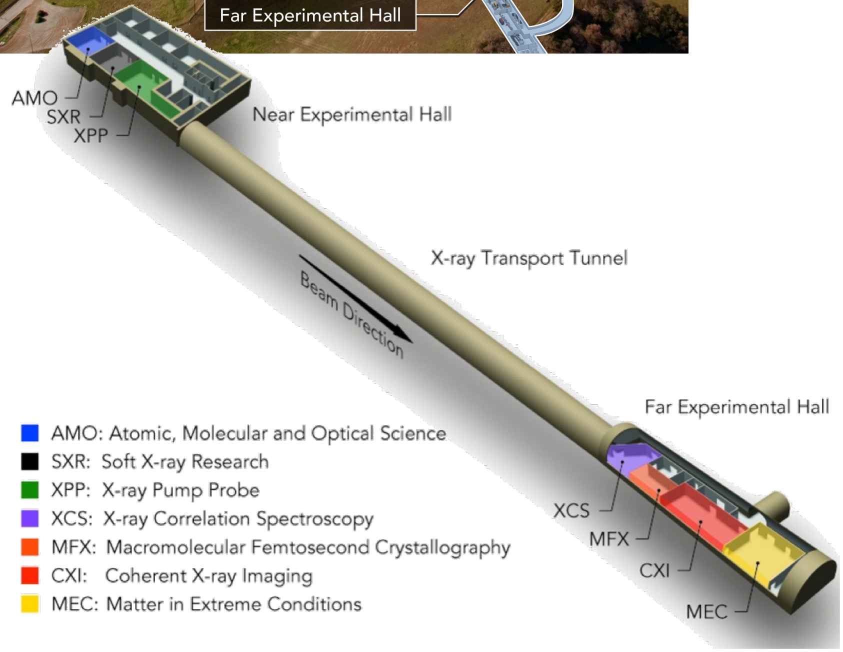
1) Free Electron Lasers
    1) What is an FEL ?
    2) Status of FEL's worldwide vs Storage Rings

2) **FELs vs. Synchrotron Sources:**
    1) Understanding generations and the Brilliance graphs
    2) **LCLS**
    3) In depth comparison from the experimentalist point of view

3) Experimental Strategies to use FELs

4) What's coming next ?

2.2) LCLS



White, Robert, Dunne, J. Synch. Rad. **22** (3), pp 472-476 (2015)

http://LCLS.slac.Stanford.edu

	LCLS PARAMETERS		Unit
Linac	e-beam energy	2.5-16.9	GeV
	Length	~1	km
	Slice emittance	0.5-1.2	µm
Undulator	Active Length	~112	m
	Period	30	mm
	K	3.5	--
	Peak Field	1.25	T
	Typical SASE Parameters		
X-ray Beam	Photon Energy (1st harm.)	0.28-12.8	keV
	Number Photons	$\sim 10^{12}$	ph/pulse
	Rep. Rate	Up to 120	Hz
	Pulse Duration	~1-200	fs
	Size (unfocused)	200-500	µm
	Divergence	1-2	µrad
	Trans. Coherence	Full	--
	Polarization	Horiz.	--
	Bandwidth $\Delta\lambda/\lambda$	0.1	%

FEL vs. SR

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4) What's coming next ?

2.3) SR vs FEL : Important Parameters

SLAC

What are the important parameters ?

① Flux
② Collimated beam
③ Beam position
④ Intensity
⑤ Pulse durations
⑥ Temporal fluctuations
⑦ Energy spectrum
⑧ Coherence

2.3) Synchrotron Sources

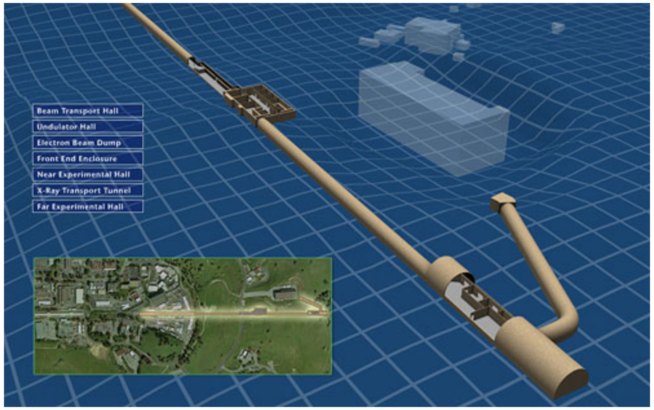


Highly **stable** (intensity, position, pointing, energy) and partially coherent storage rings sources with high brilliance in the hard X-ray Regime

Parameter	Comment
Time Structure	Continuous
Intensity	Stable
Position/ pointing	Stable
Energy spectrum	Stable
Timing	Stable
Coherence	Partial

2.3) Free Electron Lasers

SLAC



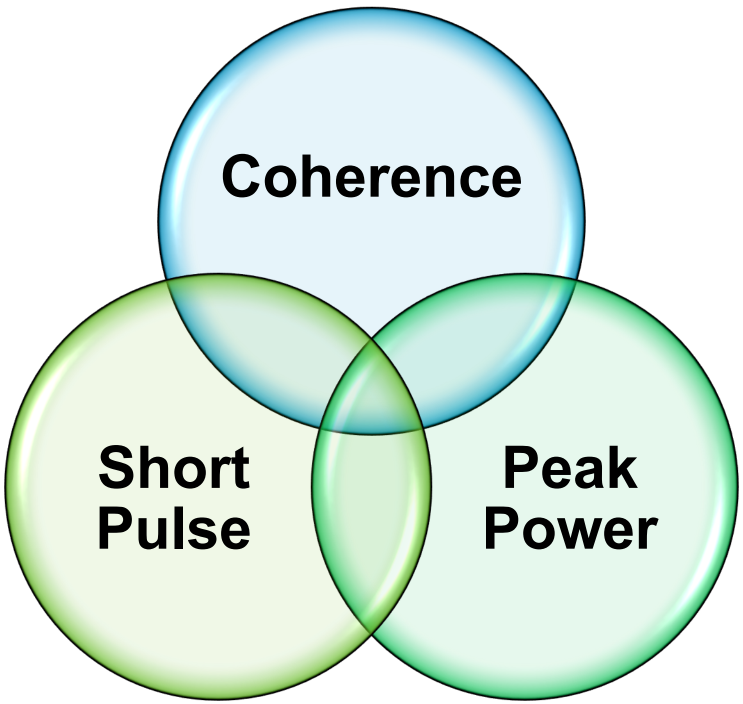
Measuring Ultra-Fast phenomena (< 100ps)

Parameter	Storage Ring	FEL
Time Structure	Continuous	**Pulsed**
Intensity	Stable	**Fluctuations**
Position/ pointing	Stable	**Fluctuations**
Energy spectrum	Stable	**Fluctuations**
Timing	Stable	**Fluctuations**
Coherence	Partial	**Full**

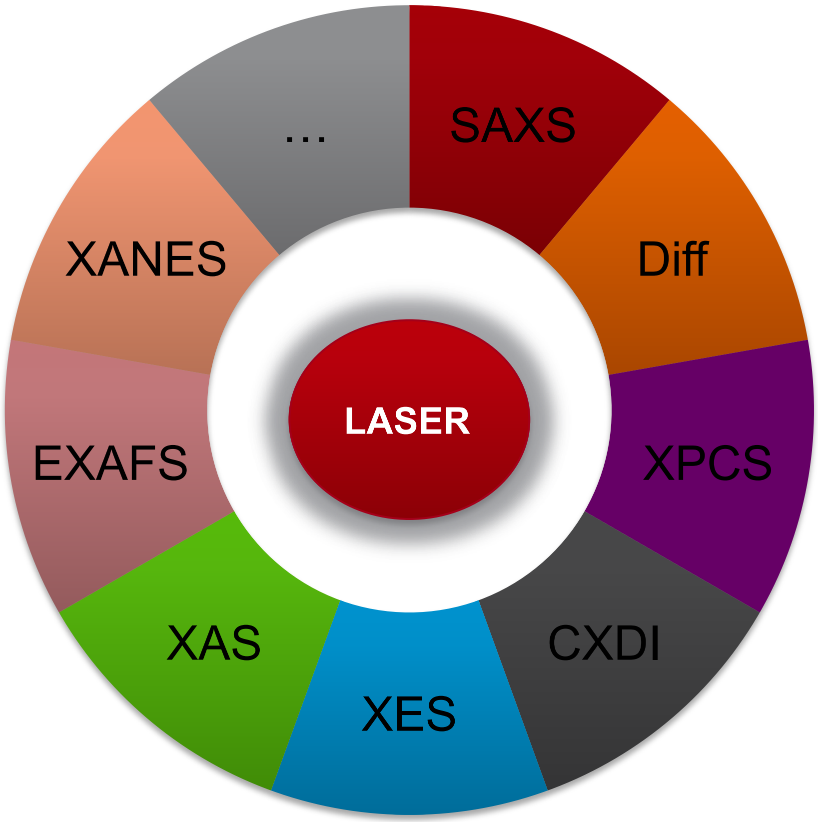
JITTER

2.3) Free Electron Lasers : X-ray Scattering

- Experiments use at least one of the FEL beam properties

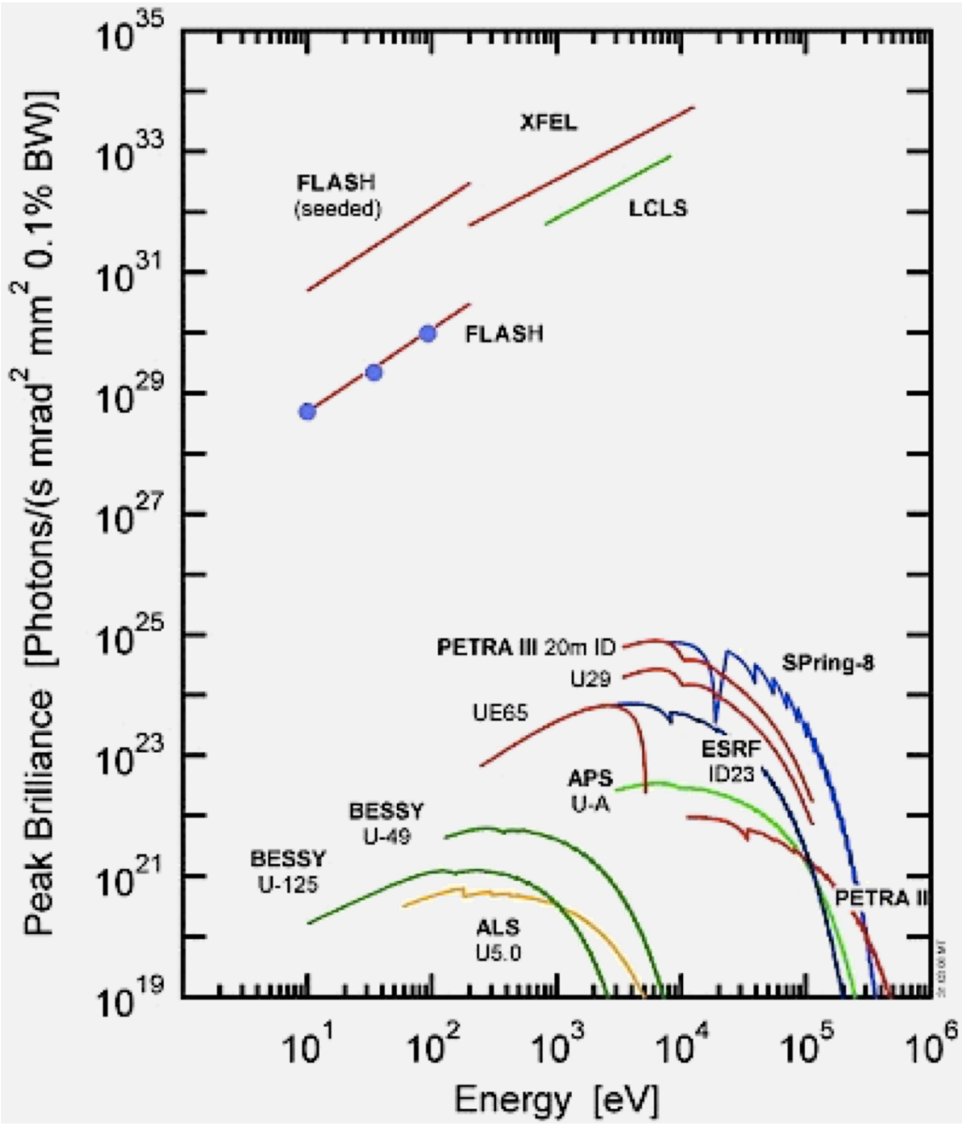


- Some experiments use more than one technique simultaneously or sequentially



Quizz : meaning of the acronyms

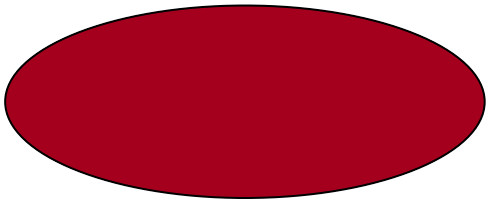
(1) FLUX



- FEL sources provide unprecedented peak brilliance
- This originates from the pulsed nature of these sources.
- One typically gets per shot what one gets per second on a SR

(2) COLLIMATION

Storage Ring



Typ. beam size @40-50m

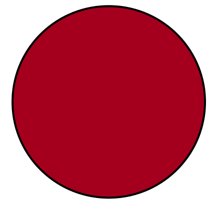
2-3 x0.5-1mm (h,v)

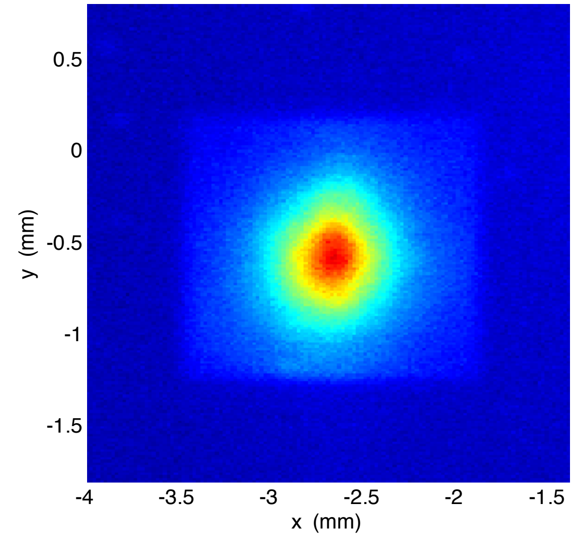
Typ. divergence high-β

30 x 15µrad (h,v)

(example : Troika ID10A at the ESRF)

FEL





Typ. beam size @200-400m

0.5-1 x0.5-1mm (h,v)

Typ. Divergence

1-2 x 1-2µrad (h,v)

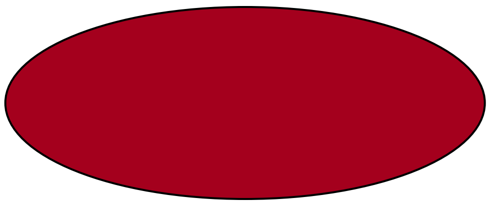
MOIANB01 Proceedings of BIW10, Santa Fe, New Mexico, US H. Loos et al.

OPERATIONAL PERFORMANCE OF LCLS BEAM INSTRUMENTATION*

It can have a huge impact on X-ray optics (e.g. focusing)

(3) POSITION

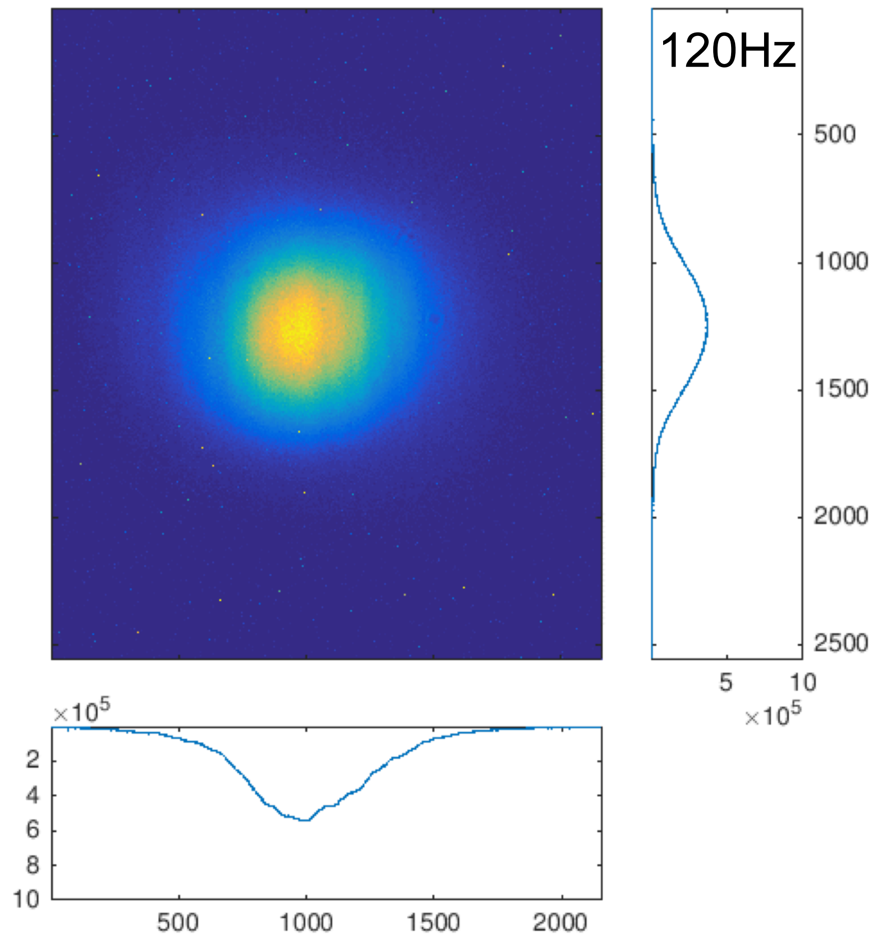
Storage Ring



Rock Stable !

FEL

XPP Instrument



Beam fluctuates in position (>10% of its size)

(4) INTENSITY

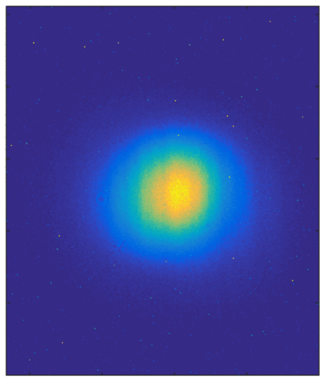
Storage Ring

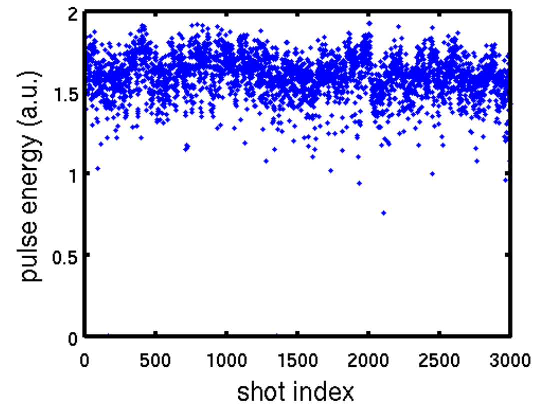
Rock Stabl

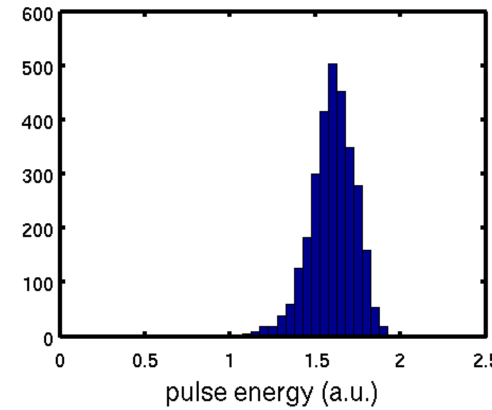
With
Or
Without
Top-up

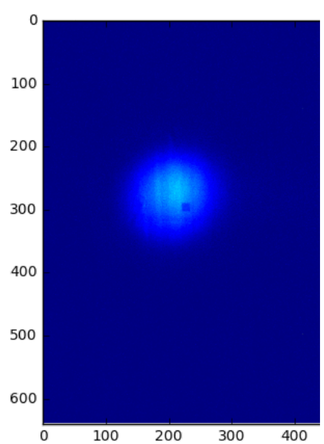
FEL

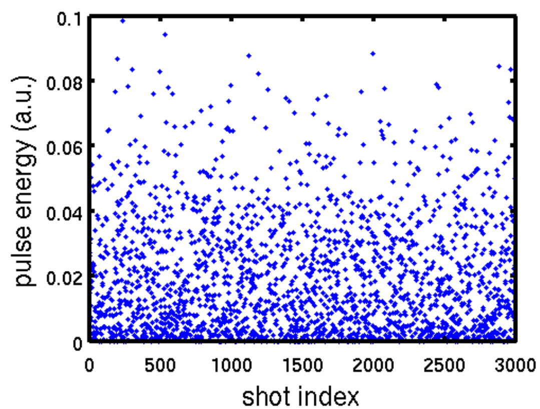
Drastic difference between pink and mono beam

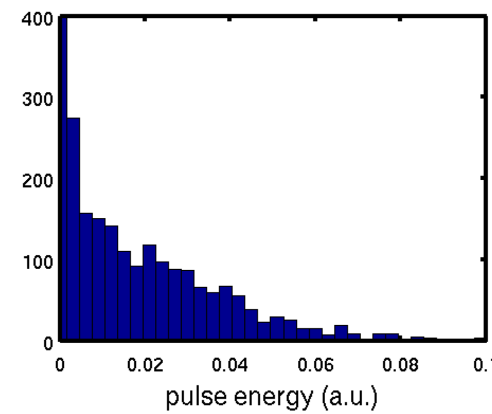












Courtesy of XPP

SLAC

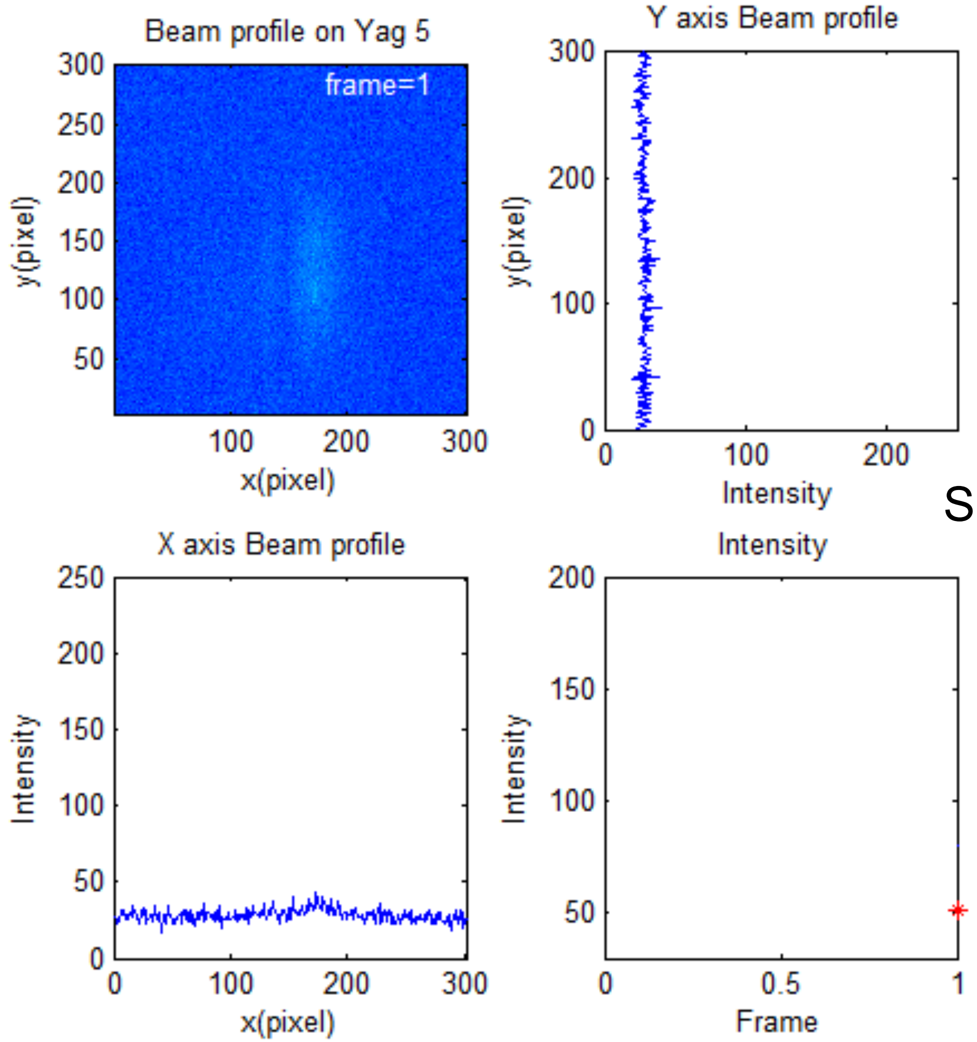
Storage Ring

Rock Stable !

With
Or
Without
Top-up

FEL

Intrinsic intensity fluctuation coming from the SASE process itself, in addition of machine instability and special behavior in monochromatic beam



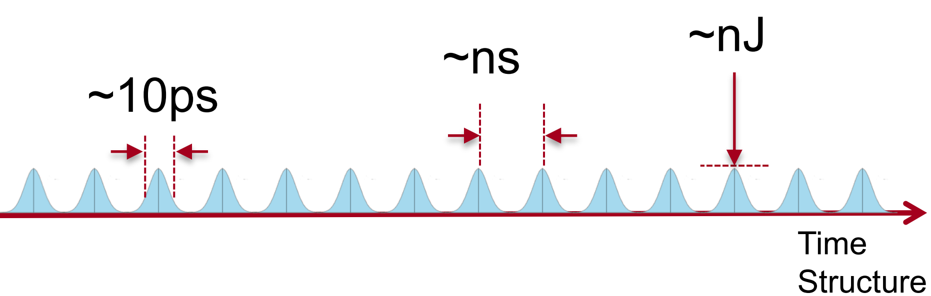
Si(111)

(5) PULSE DURATION & (6) TIMING

Storage Ring

Pulse duration : typ. 50-100ps

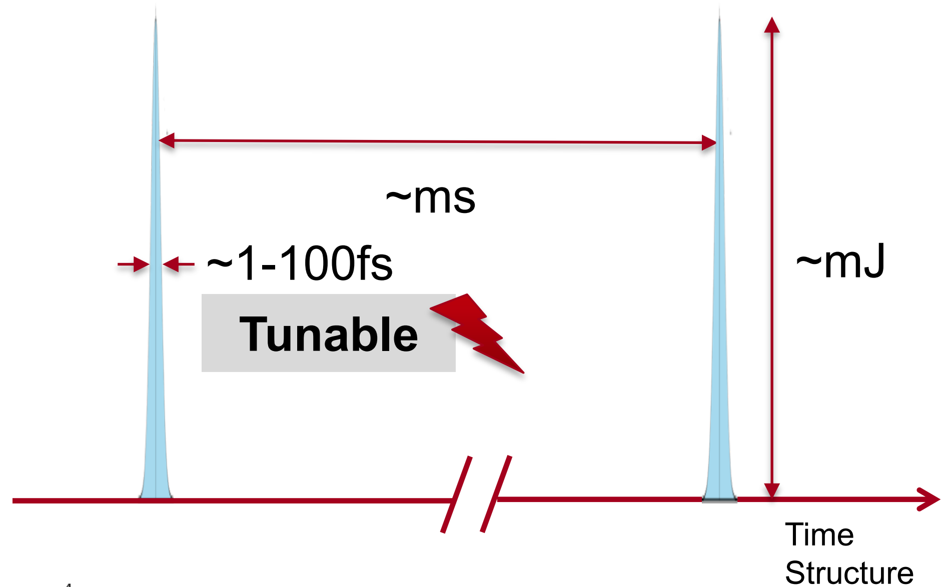
High repetition rate (100sMHz)

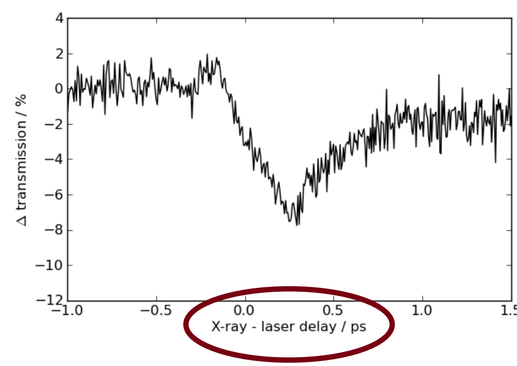


FEL : LCLS

Pulse duration : typ. < 100fs

Repetition rate ~50-100Hz





Step position indicates arrival time

(7) E-spectrum

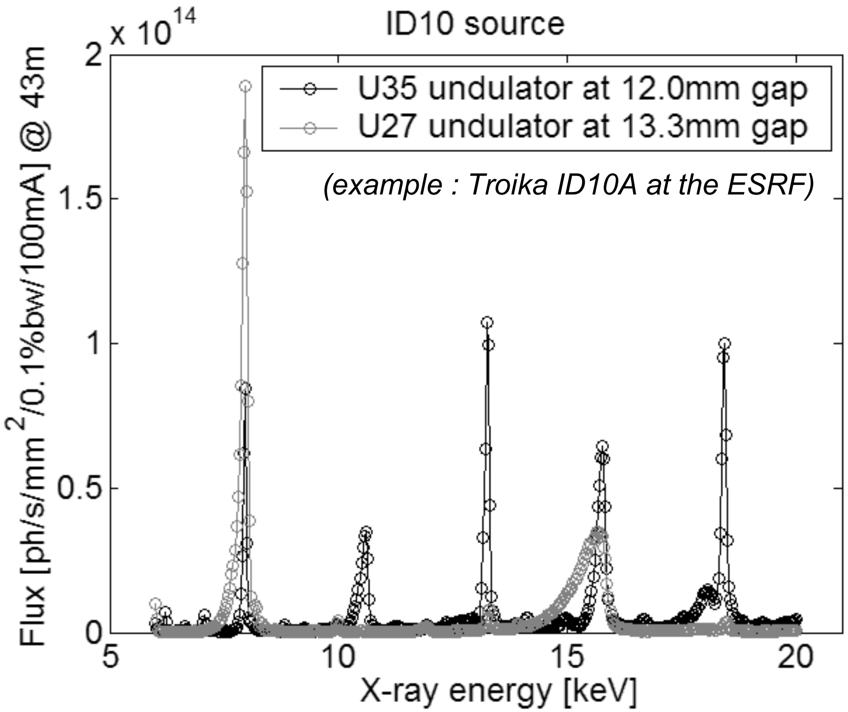
SLAC

Storage Ring

Access to high Energies with 3rd harmonic

Stable and well define energy spectrum

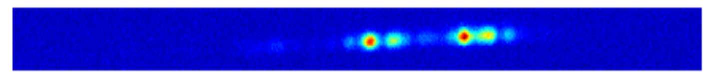
1st harmonic width : 1-4%



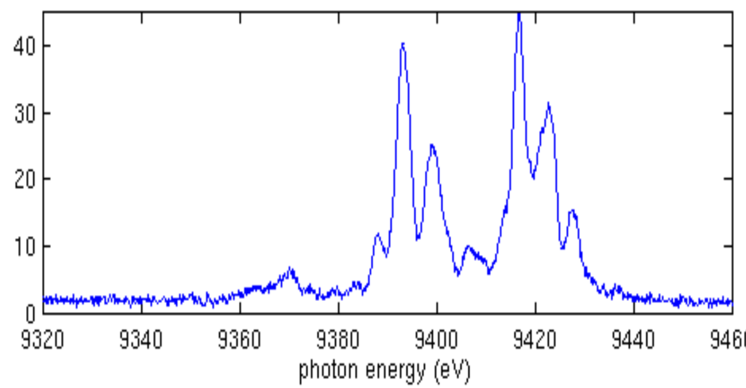
FEL

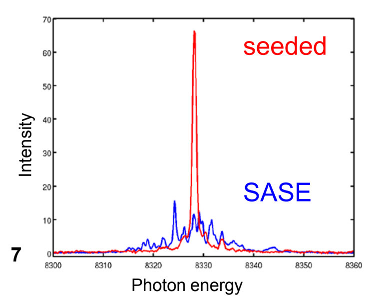
Access to high Energies with 3rd harmonic

1st harmonic width : 0.1-0.2% (<dE/E>=0.7%)



Fluctuating spectrum : e-beam jitter and structure





7

“seeding” will fix this

(8) Degree of Coherence

Storage Ring

Limited degree of Coherence

Slit down the beam to typ. 20x20 micron beams to extract the coherent fraction of the beam.

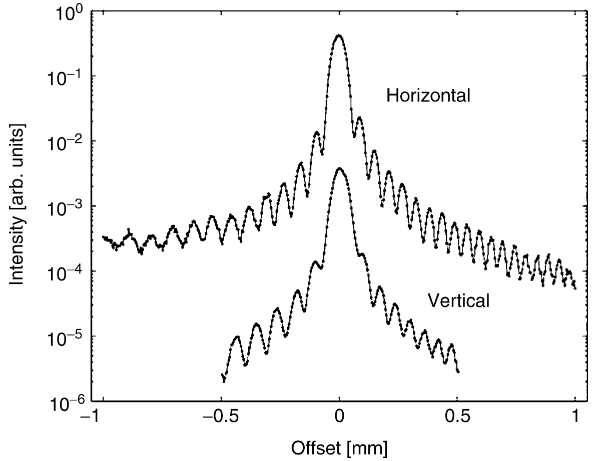
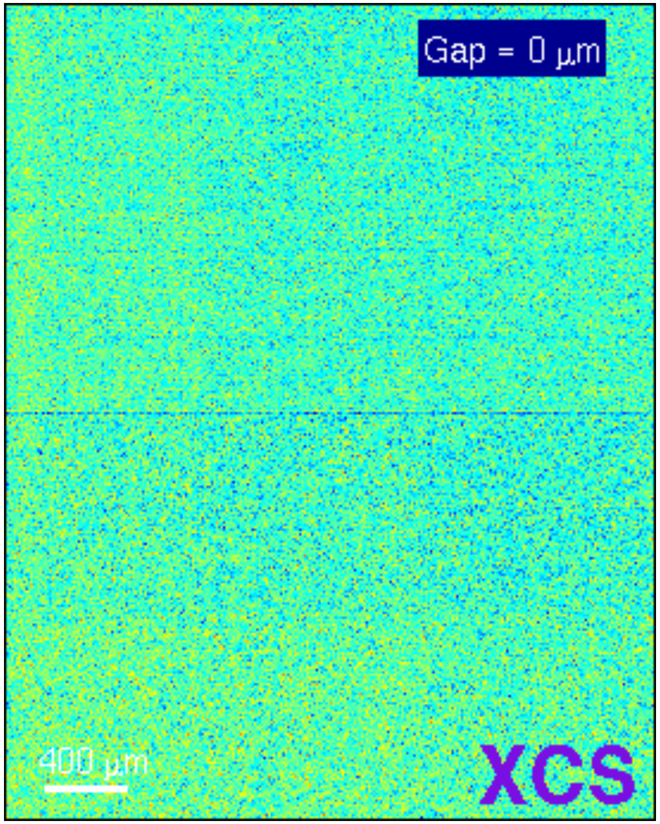


Figure 18-2
Airy fringes from a 5 × 5 μm^2 slit, recorded with λ = 1.54 Å radiation at 1.5 m from the slit. The visibility V of the fringes can be quantified by $V = (I_{max} - I_{min})/(I_{max} + I_{min})$, where I_{max} is a fringe maximum and I_{min} is an adjacent minimum

Grübel, Madsen, Robert ,XPCS , Springer (2008)

FEL

The beam is fully transversely coherent



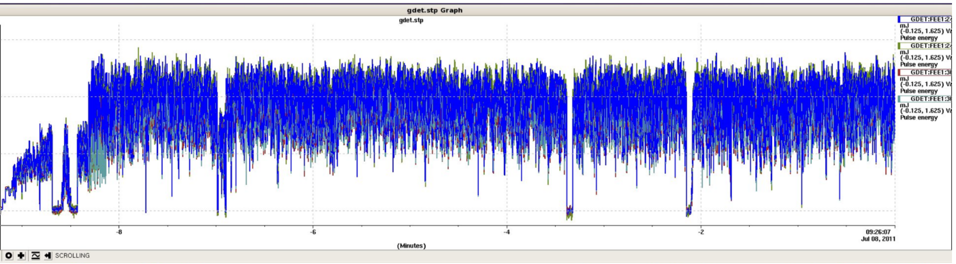
A. Robert et al., J. Phys : Conf. Ser. **425,** 212009 (2012)

Day to day operation

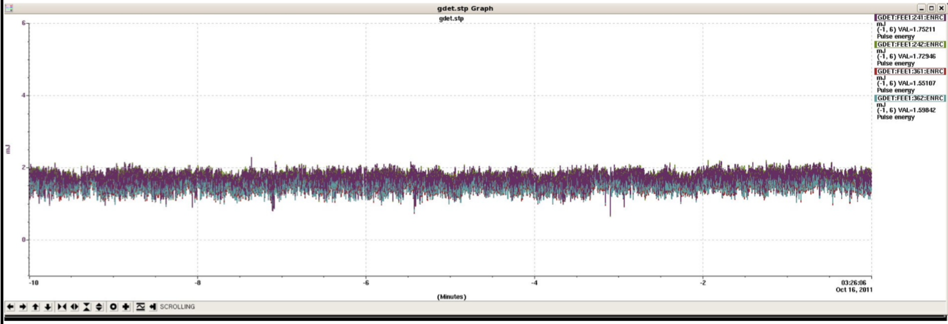
Something very different from SR sources , we have :

" BAD" days and **"GOOD" days**

- a little less than 1mJ
- Very large intensity fluctuations



- more than 1.5mJ up to 5 mJ
- 10-15% intensity fluctuation and no loss at all



3) FEL Experimental Strategies

1) Free Electron Lasers
   1) What is an FEL ?
   2) Status of FEL's worldwide vs Storage Rings

2) FELs vs. Synchrotron Sources:
   1) Understand the Peak Brilliance graphs
   2) LCLS
   3) In depth comparison from the experimentalist point of view

3) **Experimental Strategies to BEST use FELs**

4) What's coming next ?

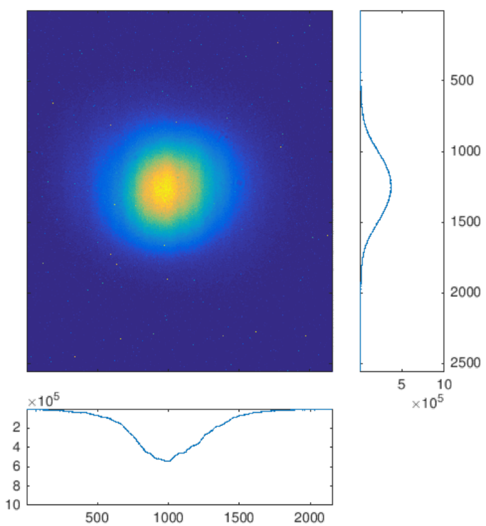
3.1) Normalizing, Filtering, Binning

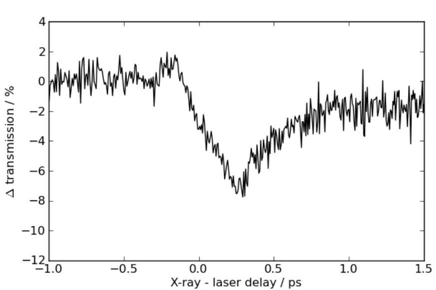
SLAC

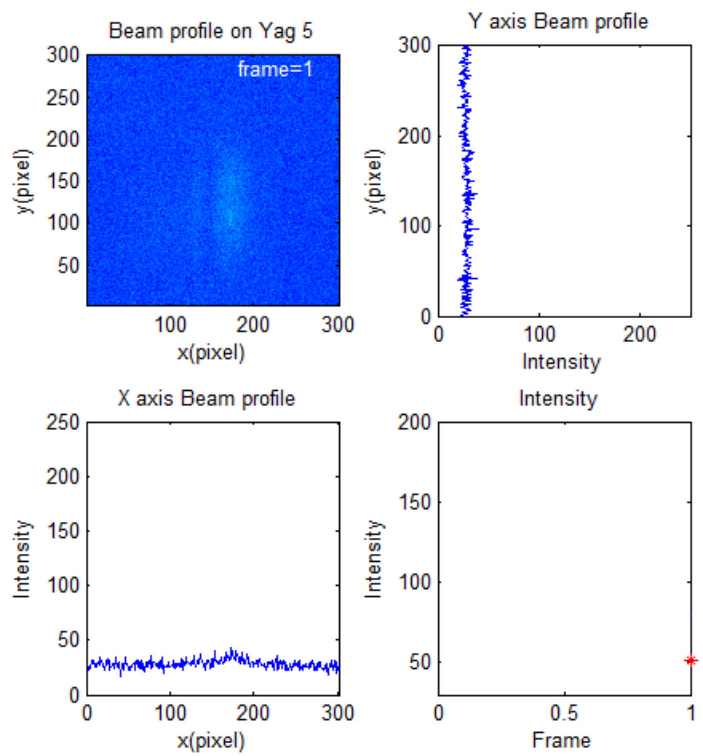
- Each X-ray Pulse is UNIQUE
- Each X-ray pulse fluctuates in many ways

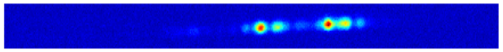
- Necessity to characterize with precision every pulse to the extent possible
- Diagnostics are critical

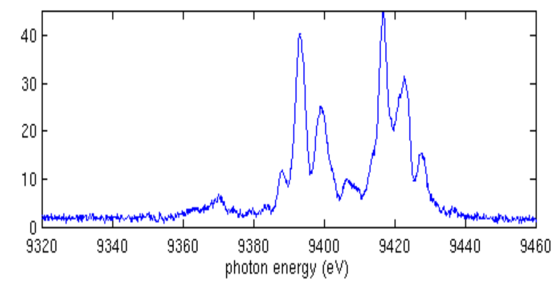
- Filtering
- Normalizing
- Binning
- Averaging



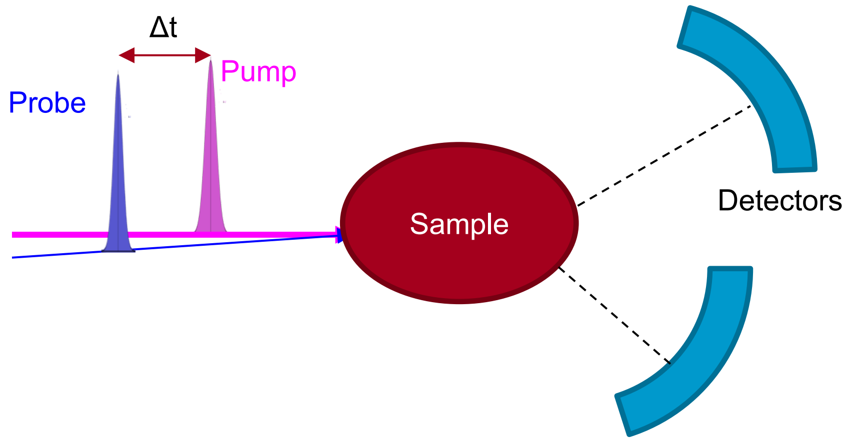






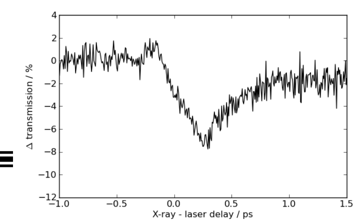


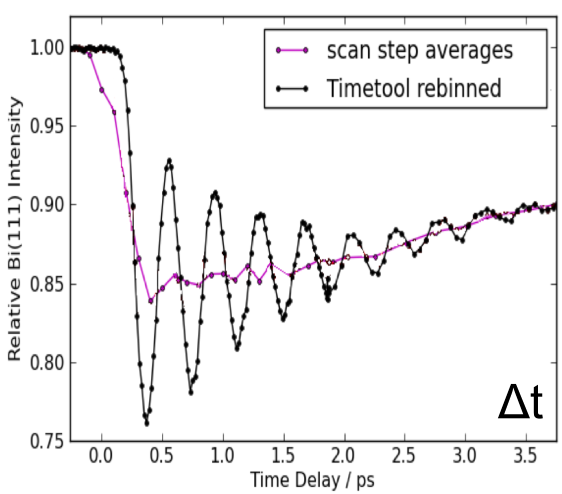
3.2) Pump- Probe (c.f. L. Young)

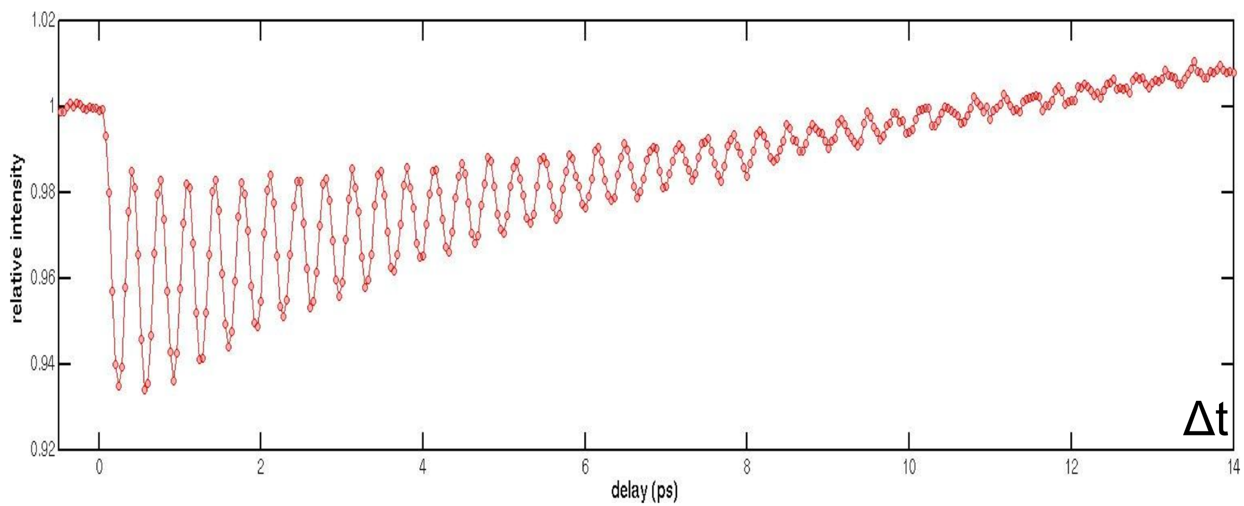


Pump-Probe : evolution of relative signal with X-ray probe at different time delays Δt after excitation (probe)

- **Reproducibility of the excited state**
- **Reproducibility of the sample if damaged**
- **Ability to synchronize two short pulses**
- **Correct for timing jitter**





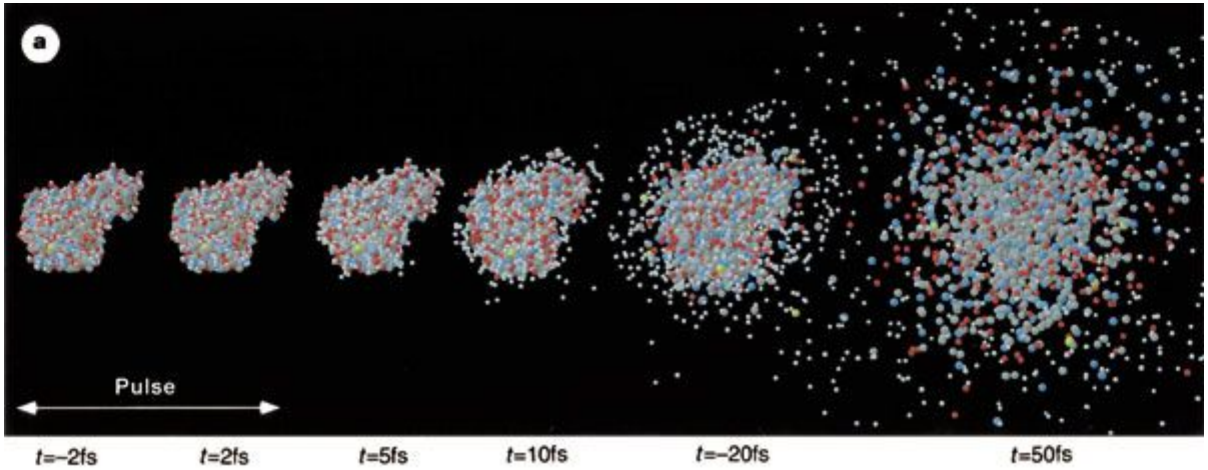


Courtesy XPP (Zhu et al.)

3.3) Diffract before destroy

Let's correct a misconception !
Most samples survive a single shot FEL beam

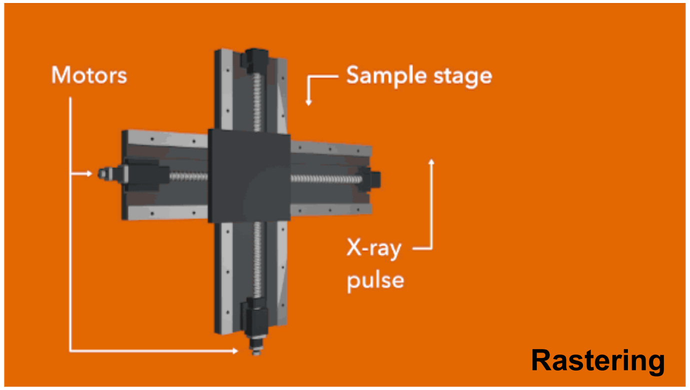
If all photons are focused in a very small spot size (<2-5 micron) nothing survive a single shot

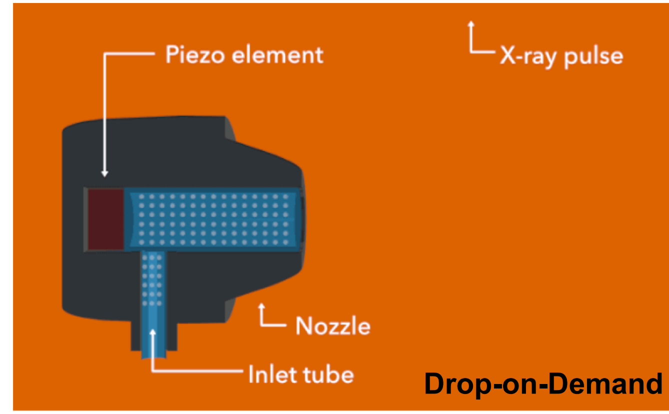


Neutze et al., Nature **406**, pp752 (2000)

"Diffract-Before-Destroy" take advantage of the peak power to obtain information before the systems reacts to the X-ray probe

3.4) Sample Delivery



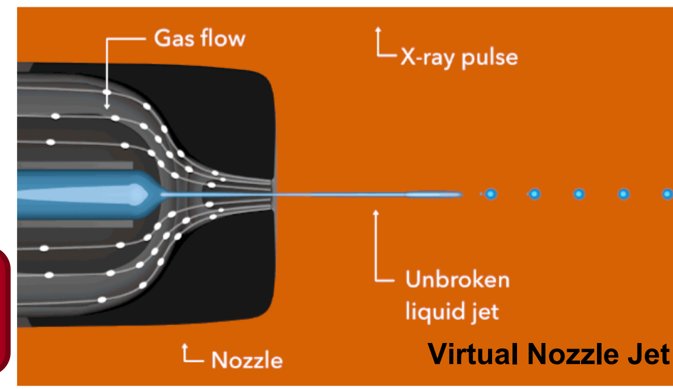


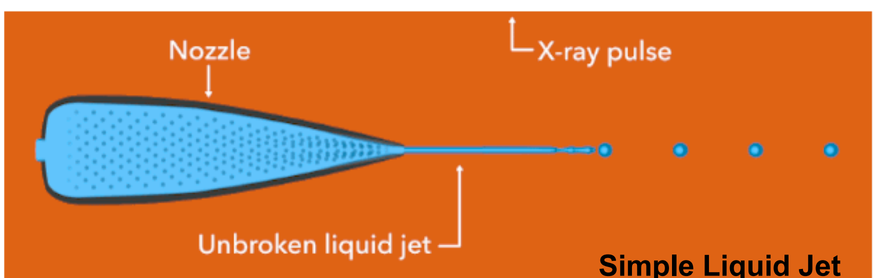
SOLIDS

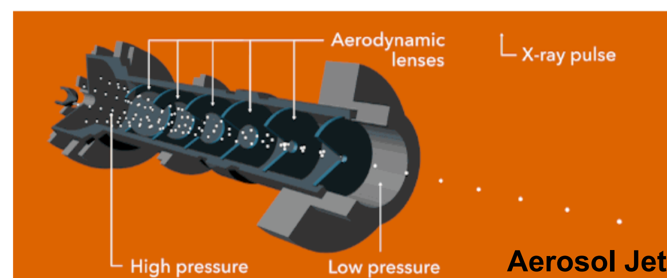
Ability to change the sample when damage by the FEL

Optimized for each sample

LIQUIDS







https://www6.slac.stanford.edu/news/2015-02-02-5-ways-put-tiny-targets-front-x-ray-laser.aspx

4) What is coming next : LCLS-II and LCLS-II-HE

SLAC

1) Free Electron Lasers
    1) What is an FEL ?
    2) Status of FEL's worldwide vs Storage Rings

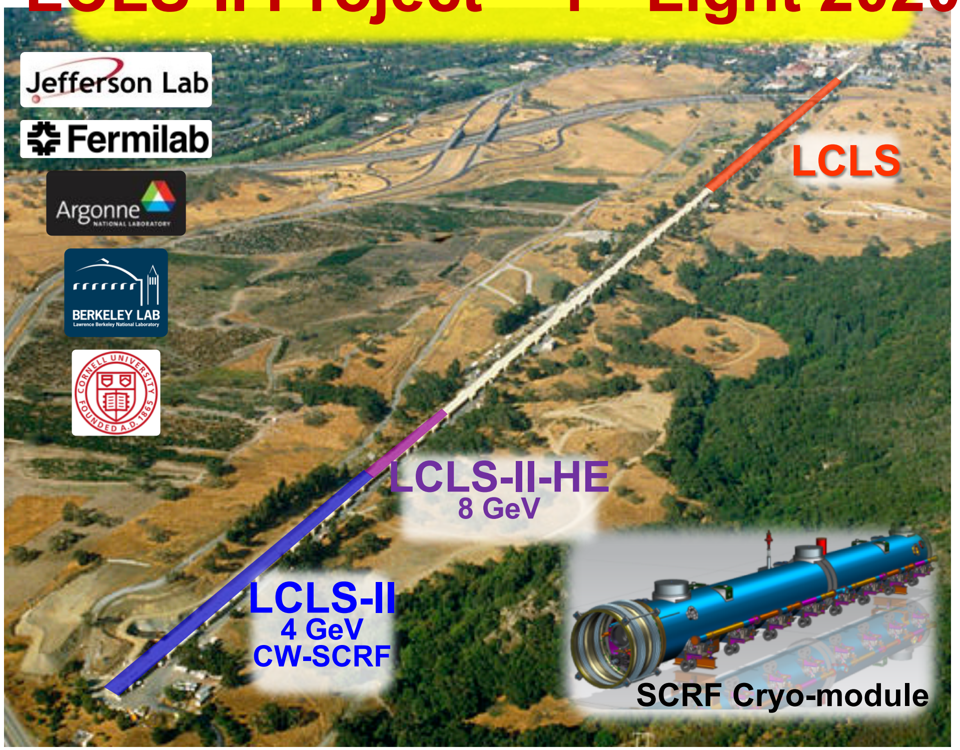
2) FELs vs. Synchrotron Sources:
    1) Understand the Peak Brilliance graphs
    2) LCLS
    3) In depth comparison from the experimentalist point of view

3) Experimental Strategies to BEST use FELs

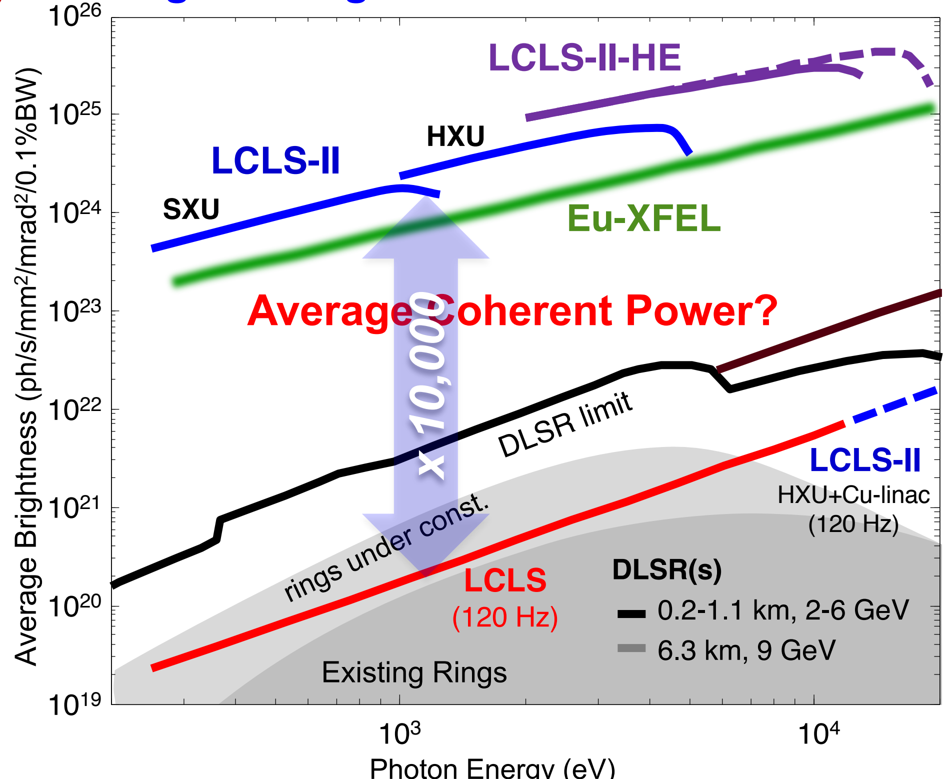
4) **What's coming next ?**

4) What is coming next : LCLS-II and LCLS-II-HE

LCLS-II Project – 1st Light 2020



High Average Coherent Power

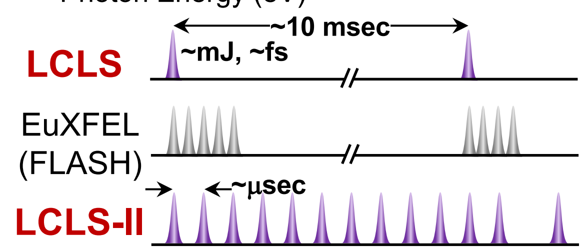


LCLS-II:

- CW-SCRF linac (4 GeV) in 1st km of linac
- Two new tunable undulators
- Repetition rate up to 1 MHz
- Photon energy reach – 25 keV (120 Hz)
- Stability, coherence (seeding)

LCLS-II-HE:

- More cryomodules
- Increase X-ray photon energy

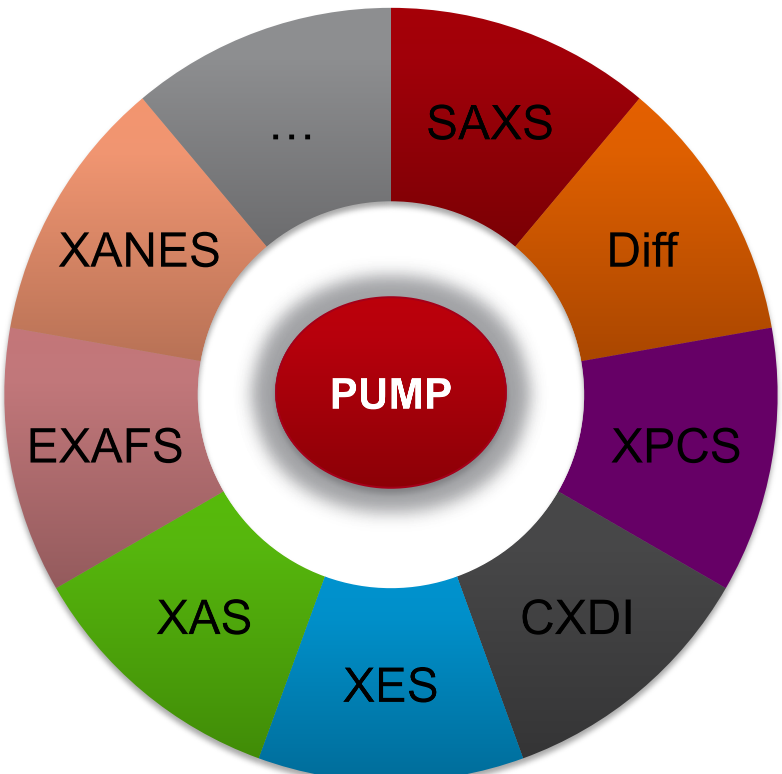


Free Electron Lasers : using X-rays for Science

SLAC

"Linac Coherent Light Source: the first five years", *Rev. Mod. Phys.* **88**, 015007 (2016)

Materials Science	Chemistry	Atomic & Molecular Dynamics	High Energy Density	Life Sciences



- **Relying on the long experience of synchrotron Storage Ring sources**
- Experiments use at least one of the FEL beam properties
- **Ideal for ultrafast dynamics, radiation sensitive samples, pump-probe (optical, THz, Field, etc.)**
- Some experiments use more than one technique simultaneously or sequentially
- **More detailed science examples w/ L. Young**