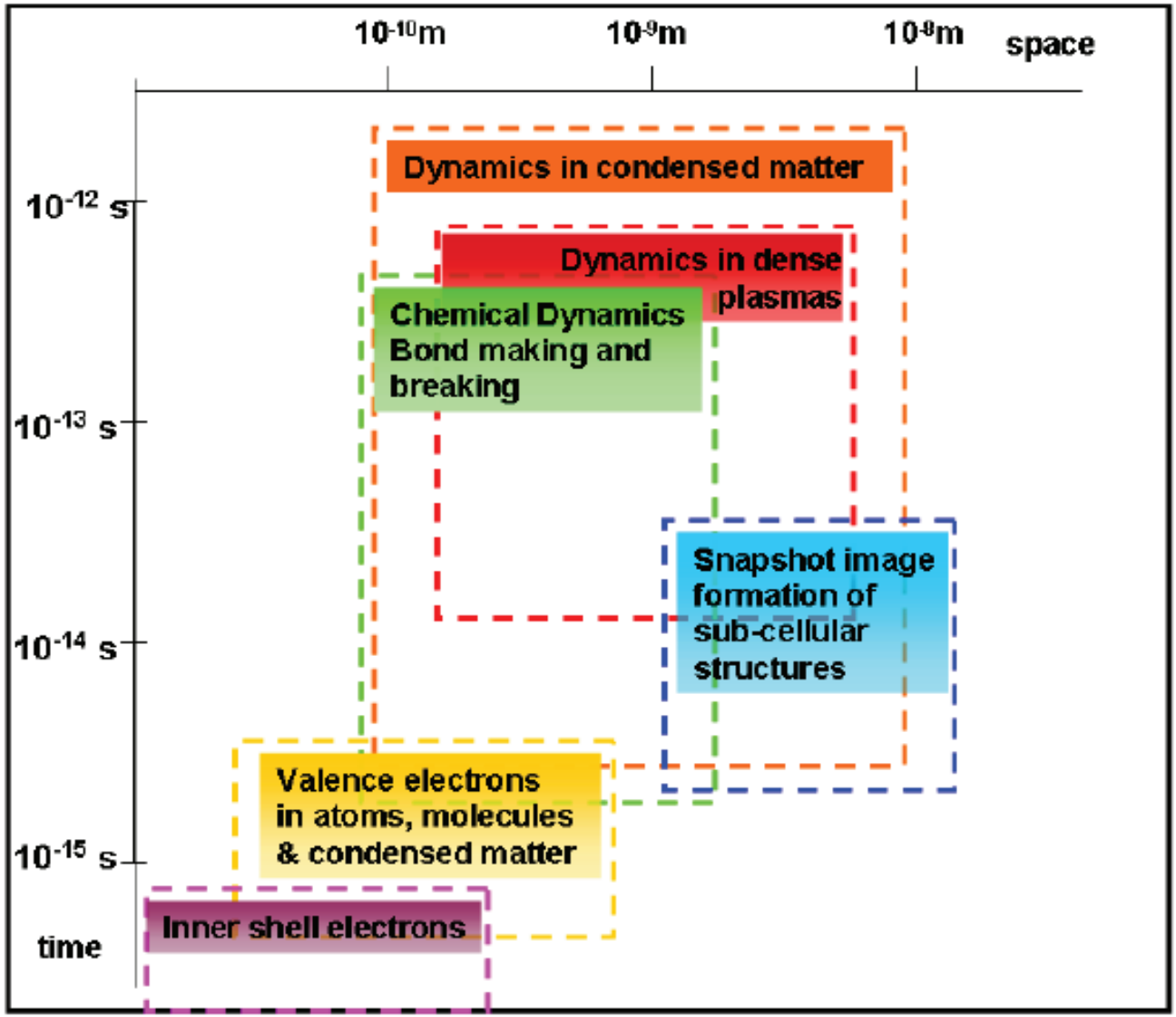
Ultrafast Science with X-ray FELS

A survey of technical progress and a sample of recent experiments that exploit X-ray FELS at the highest temporal resolution i.e. to the few-fs limit

Jon Marangos

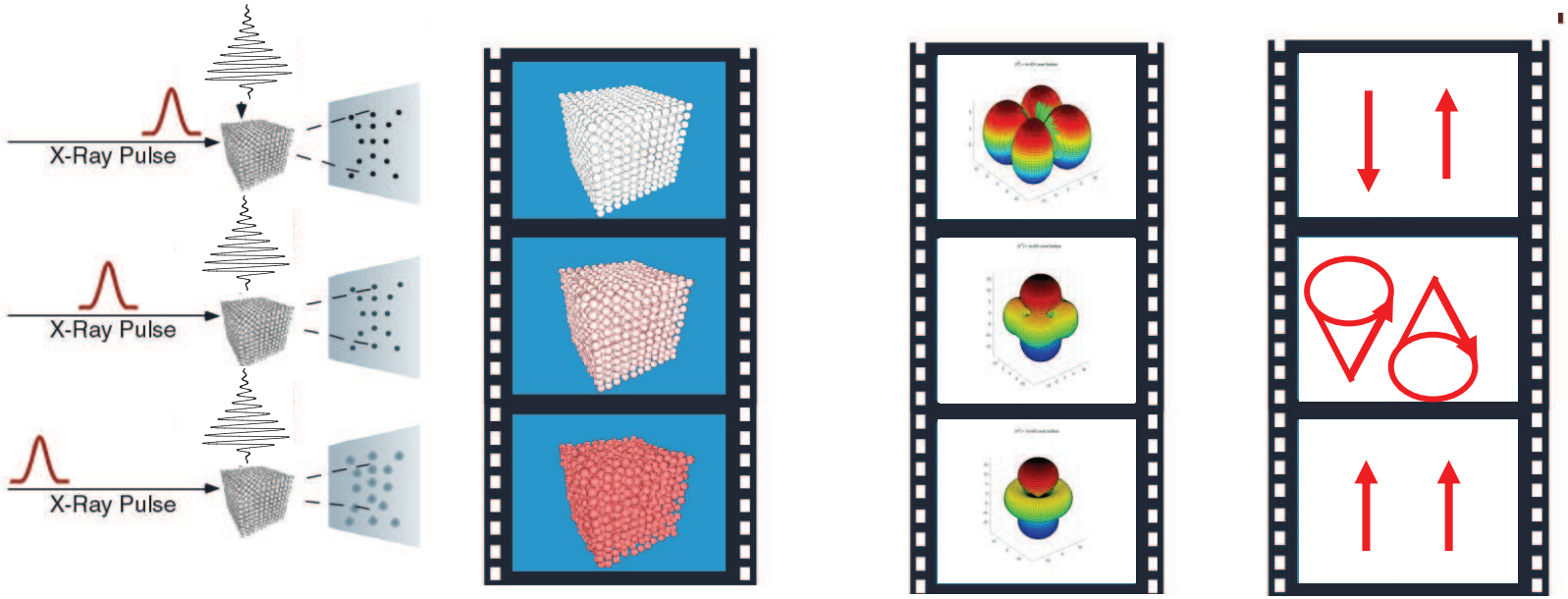
Imperial College

Nanometer Spatial and Femtosecond Temporal Resolution Key for Many Scientific Challenges



STRUCTURAL DYNAMICS UNDERLYING PHYSICAL AND CHEMICAL CHANGES

Pump-Probe Measurements of Structural Dynamics Require:
UV-THz short pulse pump to trigger change (or even X-rays)
Soft/Hard X-ray to probe
Dynamics studied by varying pump-probe delay



Ultrafast X-rays probe changes in atomic, electronic and magnetic structure following electronic or lattice excitation.

Motivation

- Local dynamics can be crucial for chemistry even in large molecules, these dynamics can be very fast!
- Nuclear dynamics can happen on a very fast timescale (< 10 fs for light atoms)
- We are also interested in electron dynamics that often happen even on sub-fs (attosecond) timescales

We need to push the temporal resolution to the few-femtosecond limit to capture these.

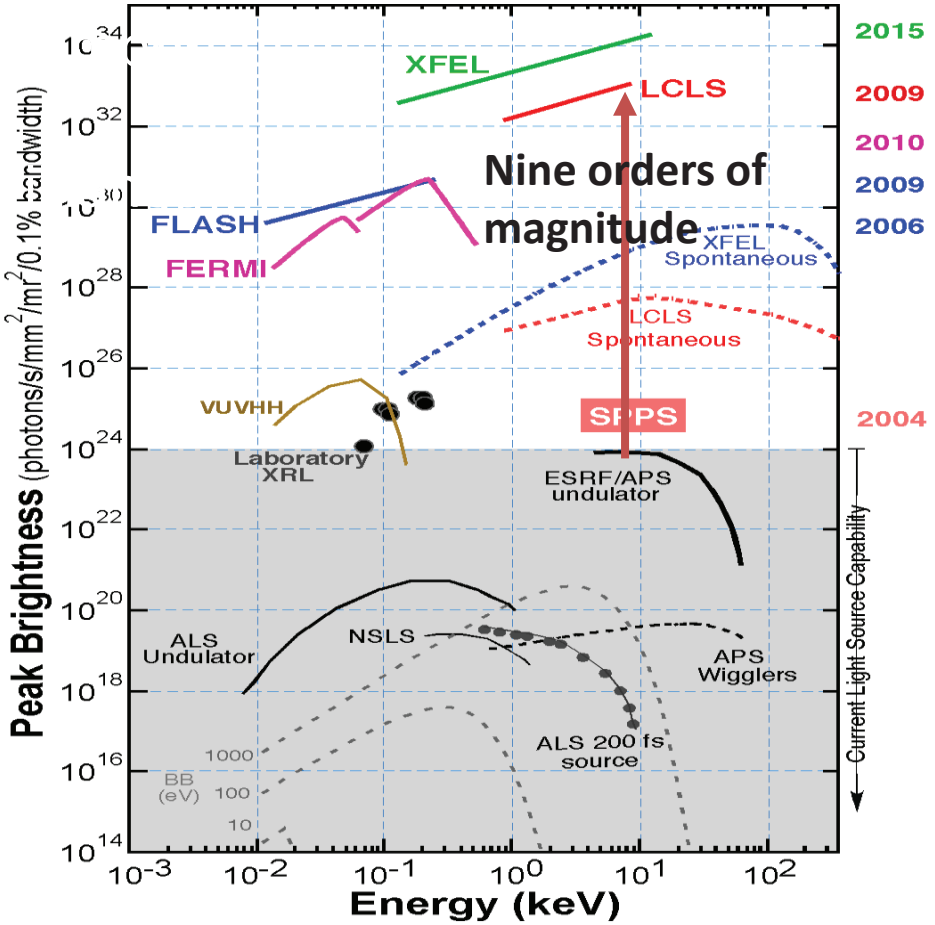
Free Electron Lasers & Ultrafast Structural Dynamics

FELs v Synchrotron

10^{9} Brighter

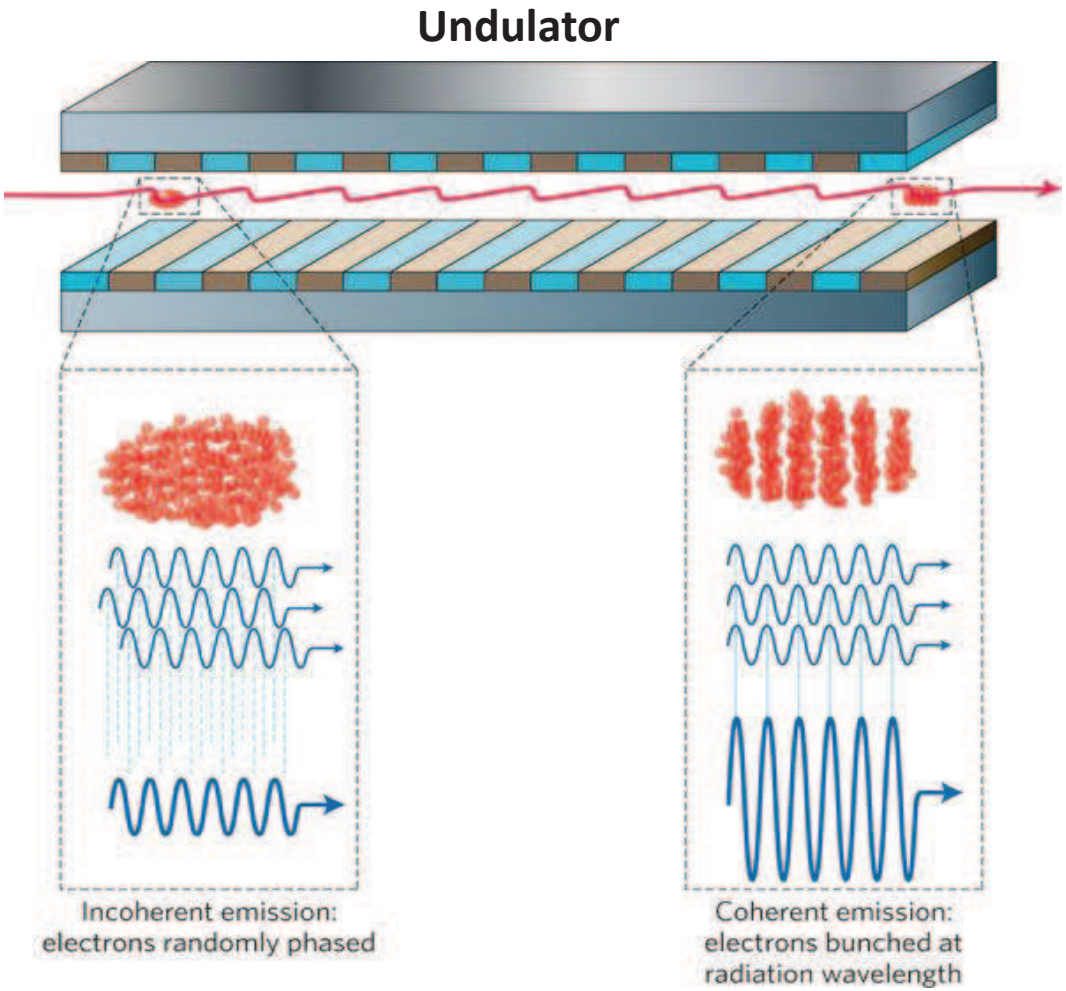
10^{-4} Shorter

Coherent



SASE (Self Amplified Spontaneous Emission) Operation for Coherent High Brightness Hard X-rays

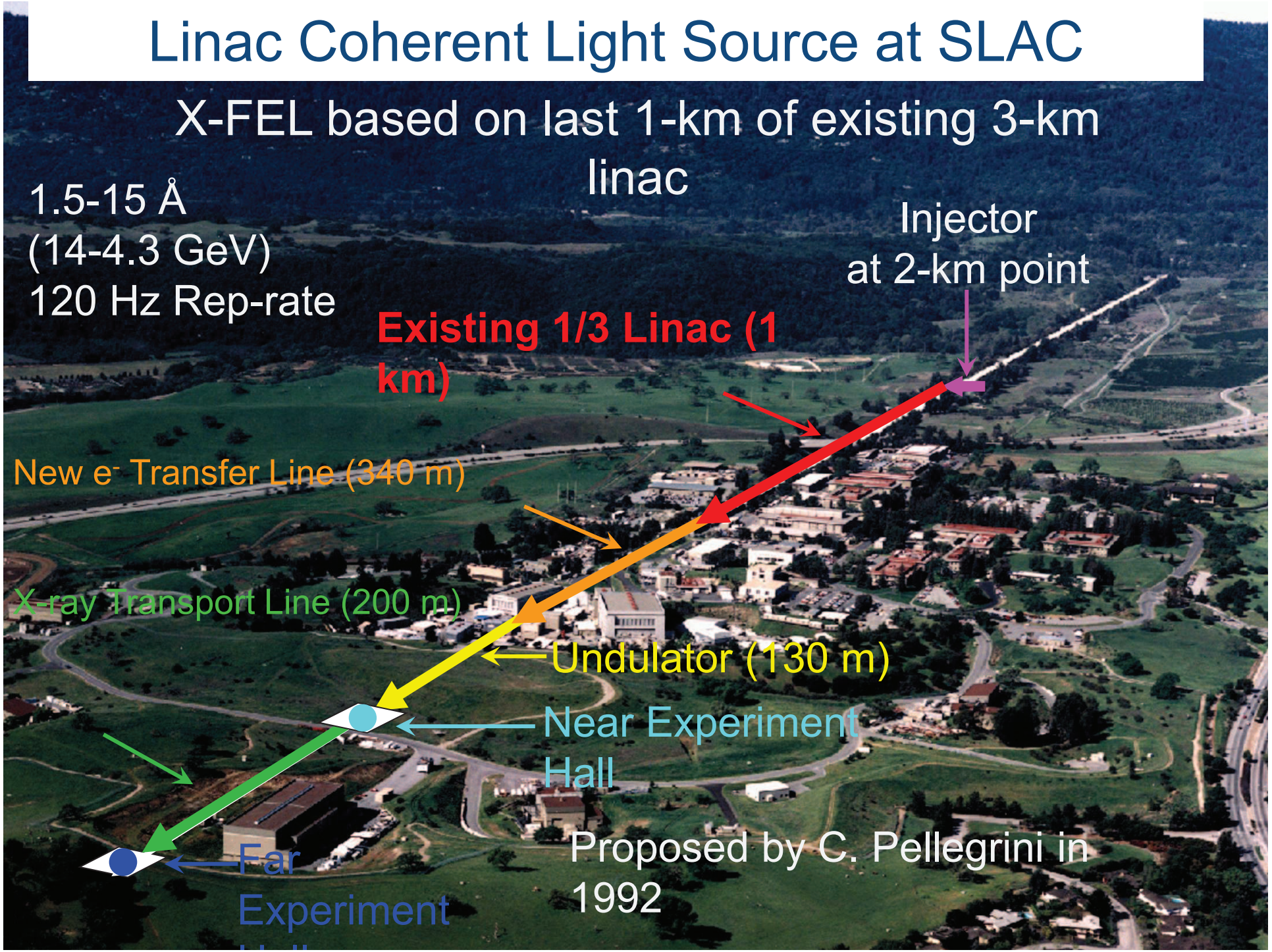
Input
Low emittance relativisitic electron bunch



Output
partially coherent, high brightness, short pulse of hard X-rays

B.W.J.McNeil and N.R.Thompson,, Nature Photonics, **4,** (2010) 814-821

Linac Coherent Light Source at SLAC



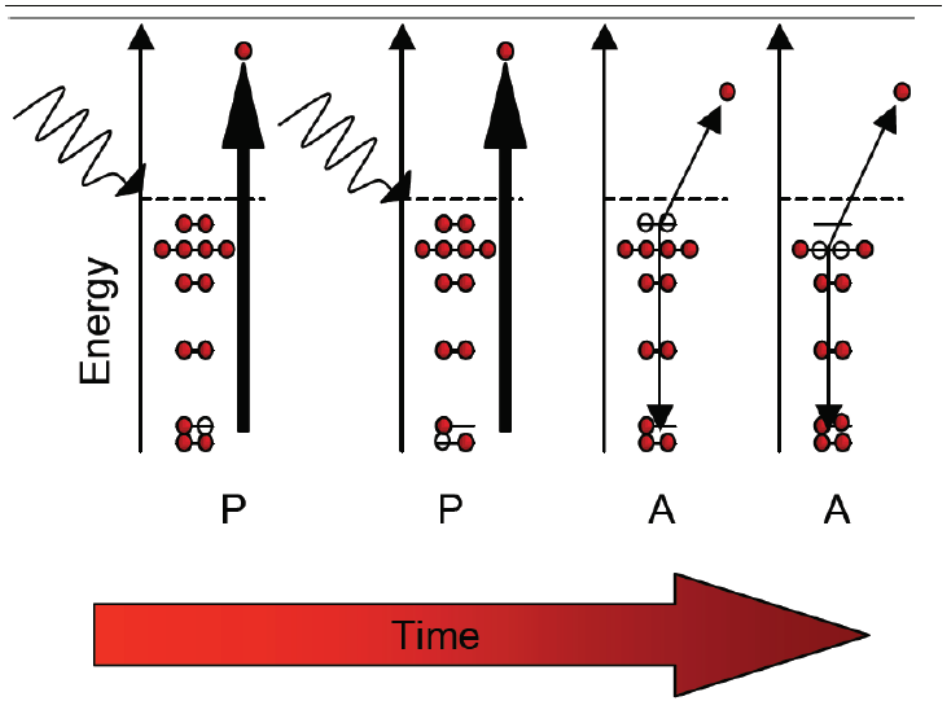
With “low bunch charge” operation intense few-fs X-ray pulses can be generated

TABLE I. Measured (@ 20-pC and 250-pC) and design (@ 1-nC) LCLS parameters.

Parameter[a]	20 pC	250 pC	1 nC	Unit
UV laser energy on cathode	1.5	20	250	μJ
UV spot diameter on cathode	0.6	1.2	2	mm
UV pulse duration (fwhm)	4.0	6.5	10	ps
Injector bunch length (rms)	1.3	2.5	2.8	ps
Initial peak current	5	30	100	A
Injector slice emittance	0.14	0.6	1.0	μm
Injector projected emittance	0.20	0.7	1.2	μm
Final bunch length (rms)	~3	~30	80	fs
Final peak current	~3	~3	3.4	kA
Final projected emittance	0.4	1.0	1.5	μm
FEL pulse duration (fwhm)[b]	~2	~60	230	fs
FEL peak power[b]	~400	~20	~10	GW

Ding et al PRL, 102 254801 (2009)

The high intensity short pulse FEL X-rays lead to new probes of chemical dynamics



Bright X-rays lead to new time resolved probing techniques for Chemistry:

- Double core holes created in molecules by an intense X-ray pulse could lead to highly sensitive analytical methods
- X-ray induced “sudden” fragmentation
- Time resolved analogues of X-ray spectroscopy and X-ray photoelectron spectroscopy

L. S. Cederbaum et al *On double vacancies in the core* J. Chem. Phys. 85 (1986) 6513
Fang et al ***PRL* 105,** 083005 (2010), Cryan et al ***PRL* 105,** 083004 (2010)
Berrah et al ***PNAS,* 108,** 16912 (2011), J.P.Marangos, ***CP 52,*** 551 (2011)