Imperial College London
Department of Materials

Some initial experiments on shocks; transformation, textures and strains

David Dye

Extreme Conditions XFEL Science Workshop, Edinburgh, 2 Oct 2019

Acknowledgements: EPSRC, Rolls-Royce

EPSRC Engineering and Physical Sciences Research Council
Rolls-Royce
DARE
HEXMAT

Jet Engines

Industry

Rolls-Royce is: £13bn revenue, 90% exported, 80% civil, ~50% of the twin-aisle market, a £76bn order book, 20% gross margins (civil aero), £1.2bn R&D spend, is 2.5% of UK GVA, employs 24,000 people in the UK + 150,000 in the supply chain - 0.6% of UK total employment.

Emissions Civil Aero is 6.6tn RPK, 7 $GtCO_2e$ or 170 gCO_2e/person-km, US$105bn in fuel.

Noise The B787 is 7dB quieter than the B767/ A330 (4X lower perceived noise)

Safety 3bn people took 25m flights with 224 deaths in air accidents. In the UK you have 100X the chance of dying in a road traffic accident than in the air - 1 in 3.5 m each yr.

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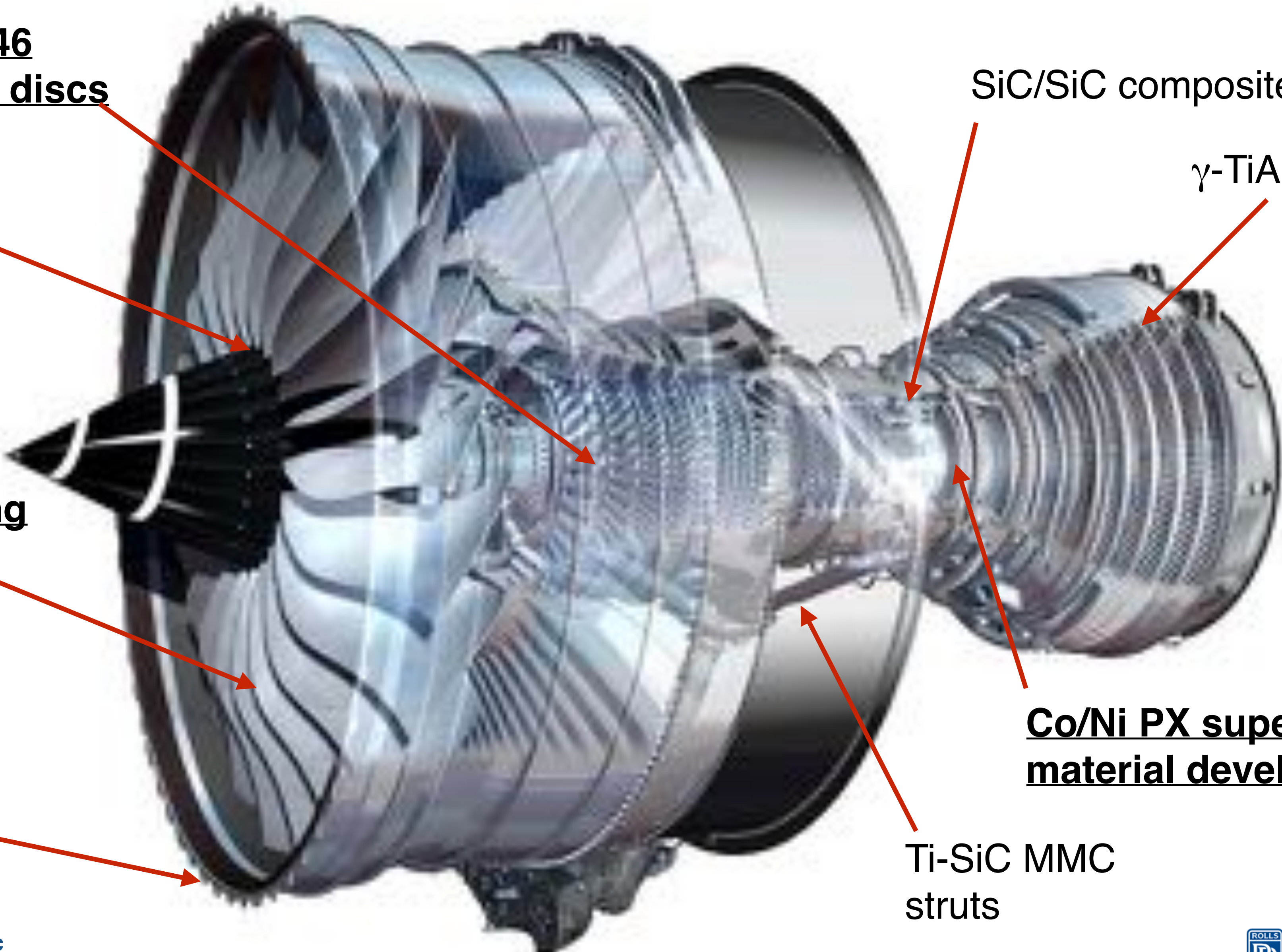


Trent XWB https://www.flickr.com/photos/rolls-royceplc/14095537270/in/album-72157658567683743/

Rolls-Royce

Rolls-Royce

the magazine
for customers

ISSUE 141 JUNE 2014

Marine machine
F-35Bs are operational in Arizona

X-ray vision
Spot an atom in a femtosecond

Canada's powerhouse
Driving natural gas for TransCanada PipeLines

Blue Ocean thinking
Marine's best minds at work

Fans of the future
The next generation of aero engines

the magazine TECHNOLOGY

Rolls-Royce researchers came to the Stanford Linear Accelerator Center (SLAC) to perform a series of experiments to test titanium and zirconium alloys. Titanium and its alloys are used in the manufacture of aero engines due to their lightweight, super-strong properties, while zirconium alloys are used as pressure tubes in nuclear reactors due to their low neutron scattering cross section and corrosion resistance. The goal of this research was to investigate the real time behaviour of these two alloys under shock loading by a laser.

SLAC National Accelerator Laboratory is one of ten US Department of Energy (DOE) Office of Science laboratories and is operated by Stanford University on behalf of the DOE. Founded in 1962, the facility is located in Menlo Park, California – just west of the University's main campus. The main accelerator is two miles long, the longest linear accelerator in the world.

Rolls-Royce was there to use SLAC's Linac Coherent Light Source X-ray laser (LCLS). It produces pulses of X-rays more than a billion times brighter than the most powerful existing sources, the so-called synchrotron sources which are also based on large electron accelerators. The ultrafast LCLS X-ray flash captures images of events with a 'shutter speed' of less than 100 femtoseconds (100 femtoseconds = 1/10 of a trillionth of a second).

An aerial view of the Stanford Linear Accelerator Center (SLAC).

Below left Tom D Swinburne, PhD student, Imperial College London; Despina Milathianaki, LCLS staff scientist and Michael G Glavicic, materials specialist for Rolls-Royce Corporation.

X-RAY VISION

As part of a study on the properties of metals, scientists from Rolls-Royce are the first from industry to have used an extraordinary super-fast X-ray facility at Stanford University in the US.

the magazine ISSUE 141 7

Gum Metal - conventional sXRD (e.g. I12) micromechanics experimentation

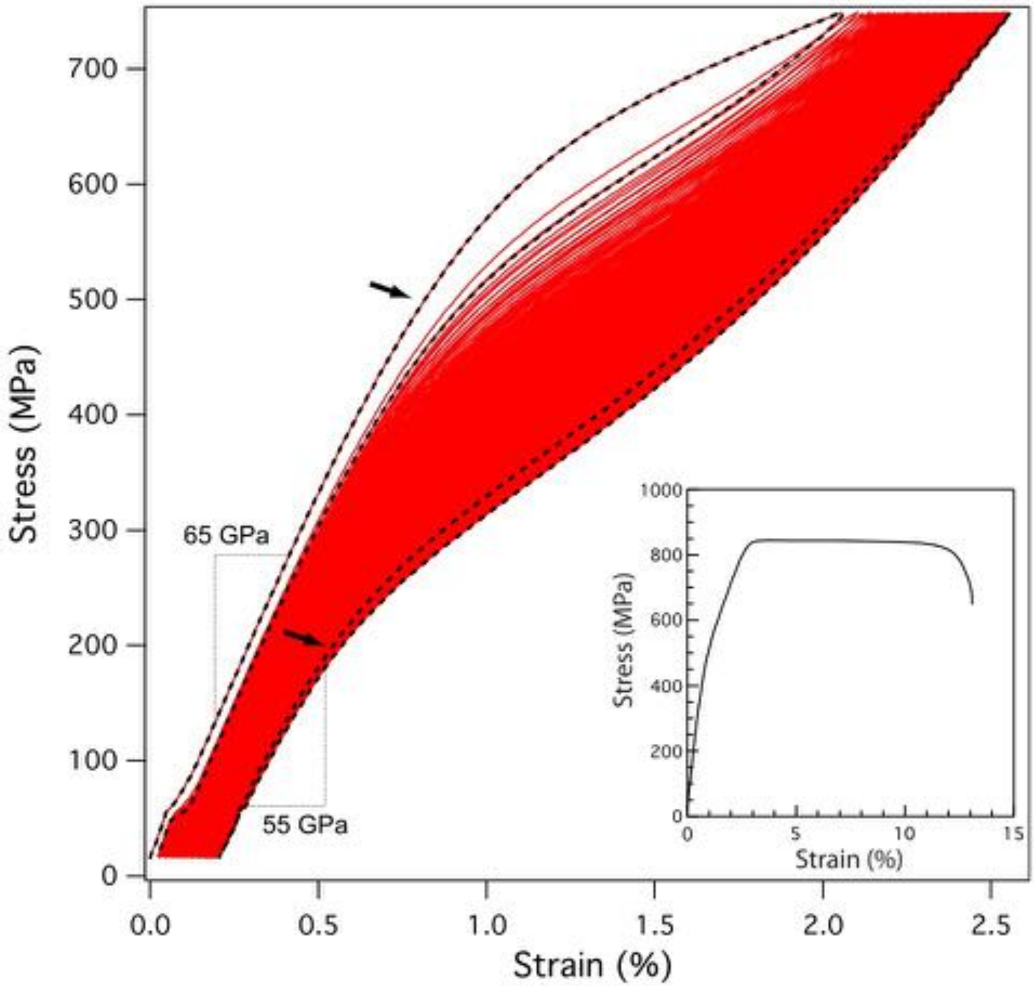
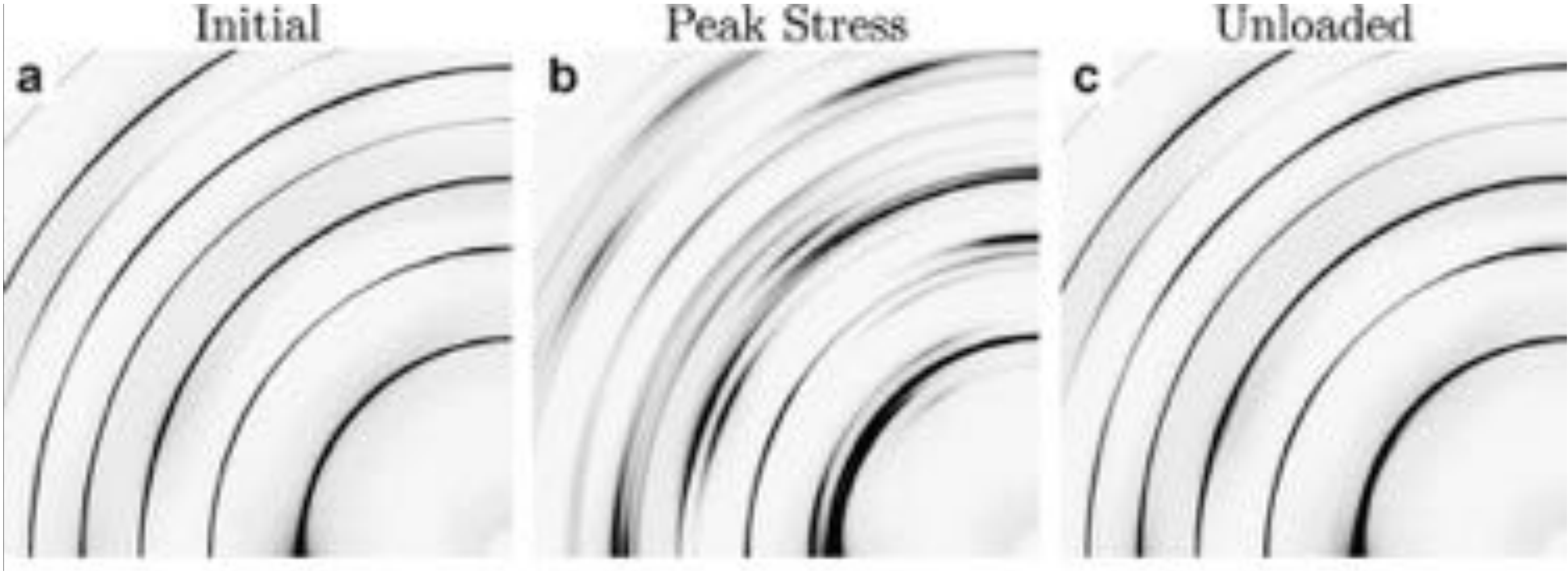
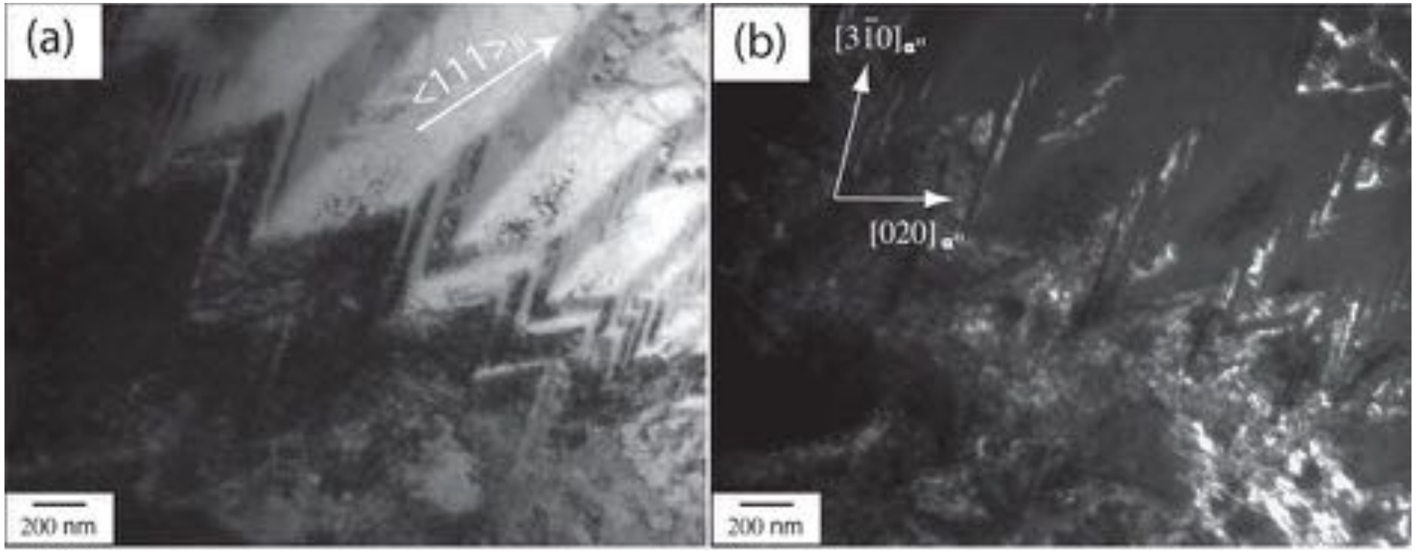


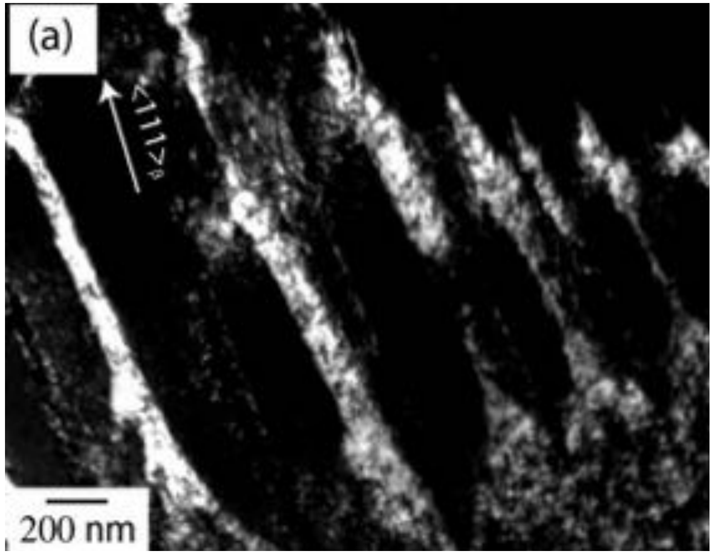
Image source: ESRF

Superelasticity



Superelasticity





Images: Talling, Dye et al, Acta Mater (2009)

nature COMMUNICATIONS

ARTICLE

Received 28 May 2016 | Accepted 29 Nov 2016 | Published 1 Feb 2017 DOI: 10.1038/ncomms14210

Complexion-mediated martensitic phase transformation in Titanium

J. Zhang[1,2], C.C. Tasan[3], M.J. Lai[1], A.-C. Dippel[4] & D. Raabe[1]

The α→ω transformation in Zr (and Ti)

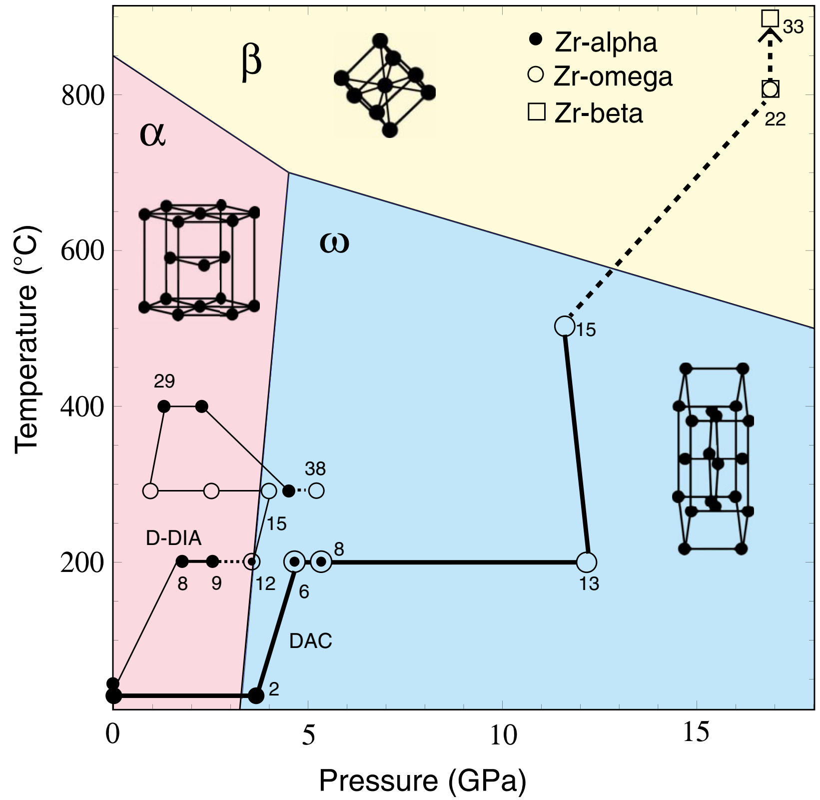
$\beta \leftrightarrow \omega$: $\{111\}_\beta \parallel \{0001\}_\omega$,

$\beta \leftrightarrow \alpha$: $\{110\}_\beta \parallel \{0001\}_\alpha$, $<111>_\beta \parallel <1120>_\alpha$

$\alpha \leftrightarrow \omega$:

Silcock (exp't): $\{0001\}_\alpha \parallel \{1120\}_\omega$, $<1120>_\alpha \parallel <0001>_\omega$

Trinkle (DFT): $\{0001\}_\alpha \parallel \{0111\}_\omega$, $<1120>_\alpha \parallel <0111>_\omega$



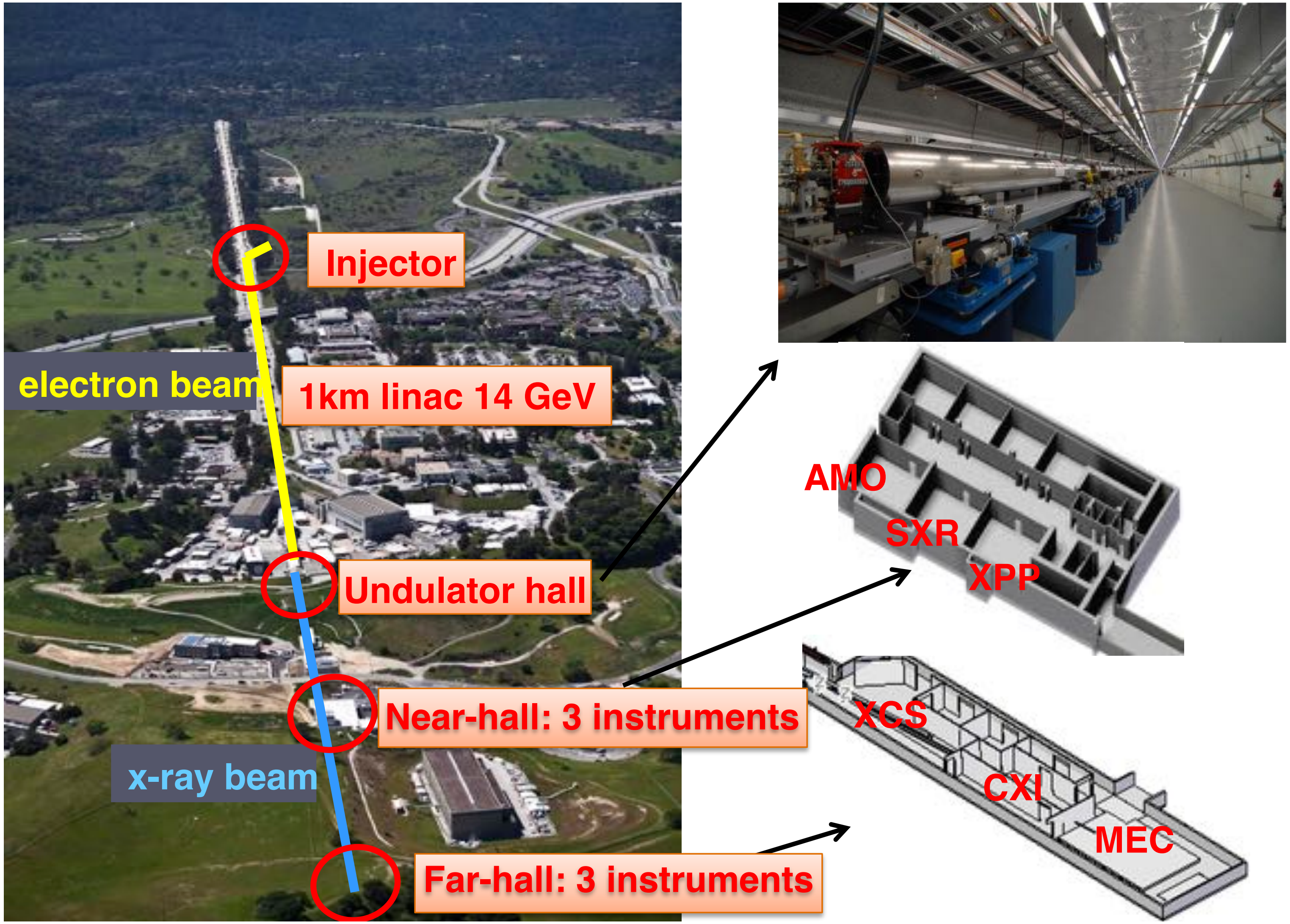
H-R Wenk et al, Phys.Rev.Lett. (111):195701, 2013

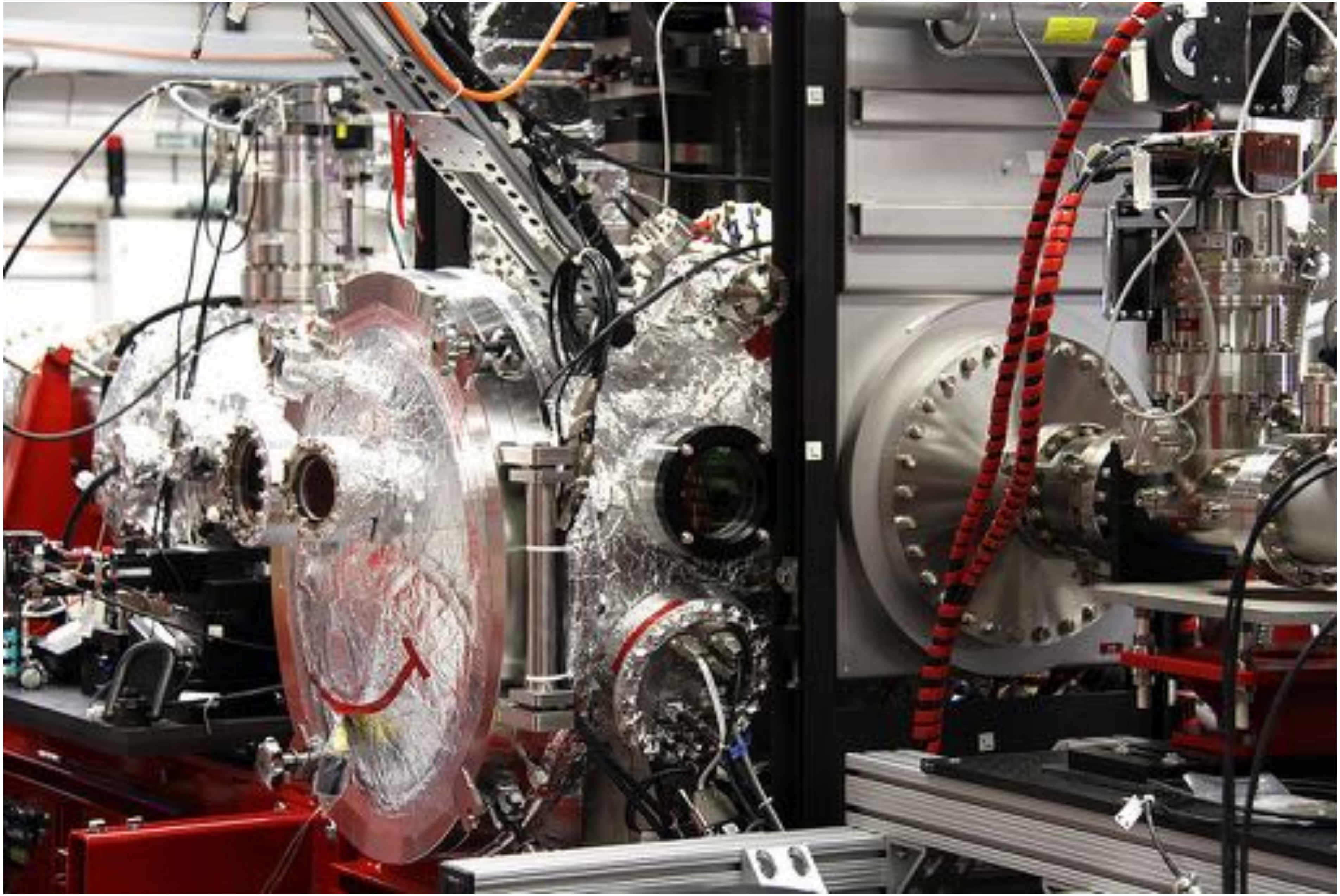
Linac Coherent Light Source @SLAC

World's first hard X-ray Free Electron Laser, built using the Stanford Linear Accelerator Laboratory tunnel, 14 GeV linac. Photons 0.27-11 keV, 10^{12}-10^{13} photons/pulse, 50-550 fs duration, $\Delta E/E$ 0.2 - 0.5 %, up to 120Hz, linearly polarised.

c.f. ESRF UpgradeII: 6GeV ring, photons to 200 keV, ~10MHz, 11 ps bunch, $\Delta E/E$ 0.1%,

Linac Coherent Light Source @SLAC



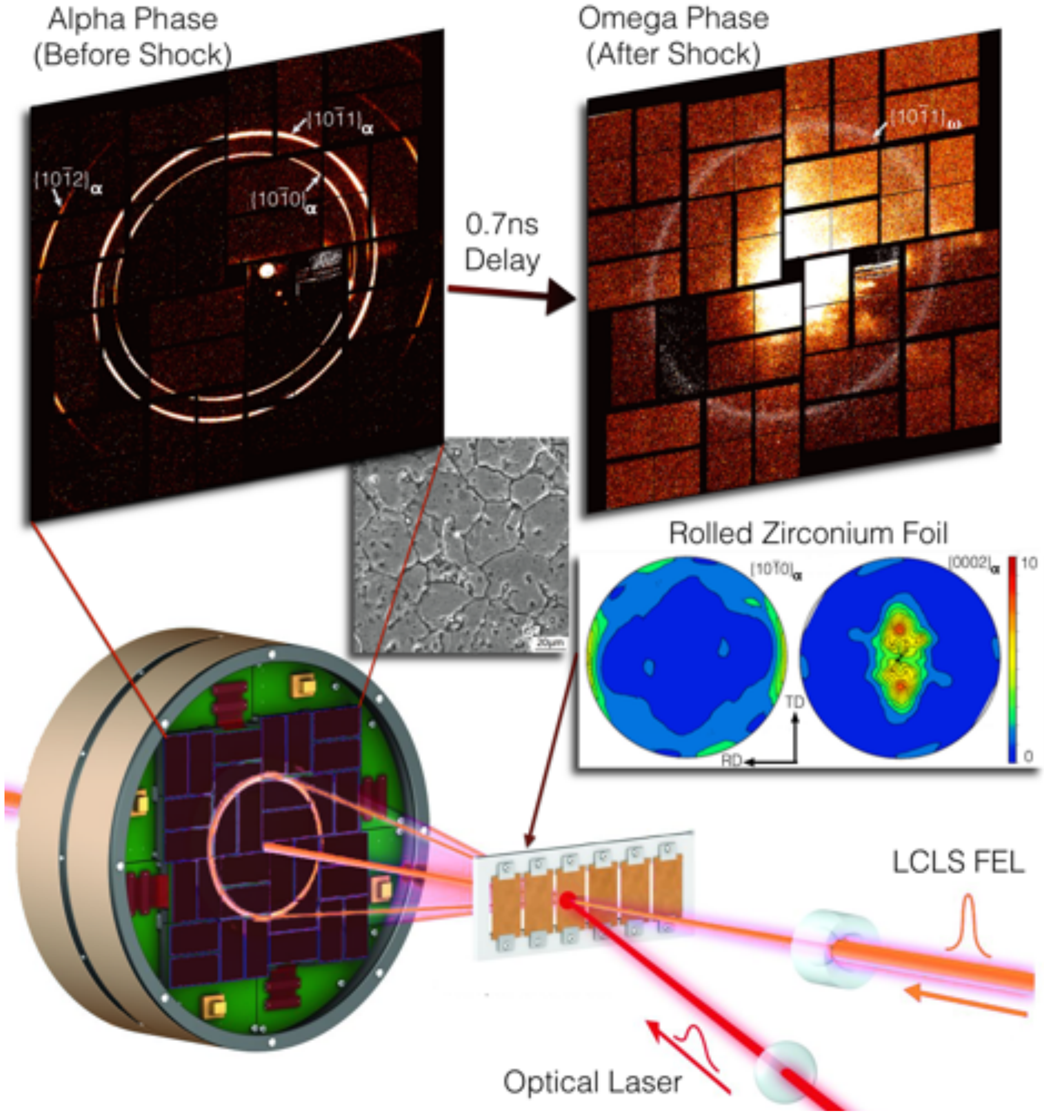


160fs Diffraction @ CXI, LCLS, SLAC

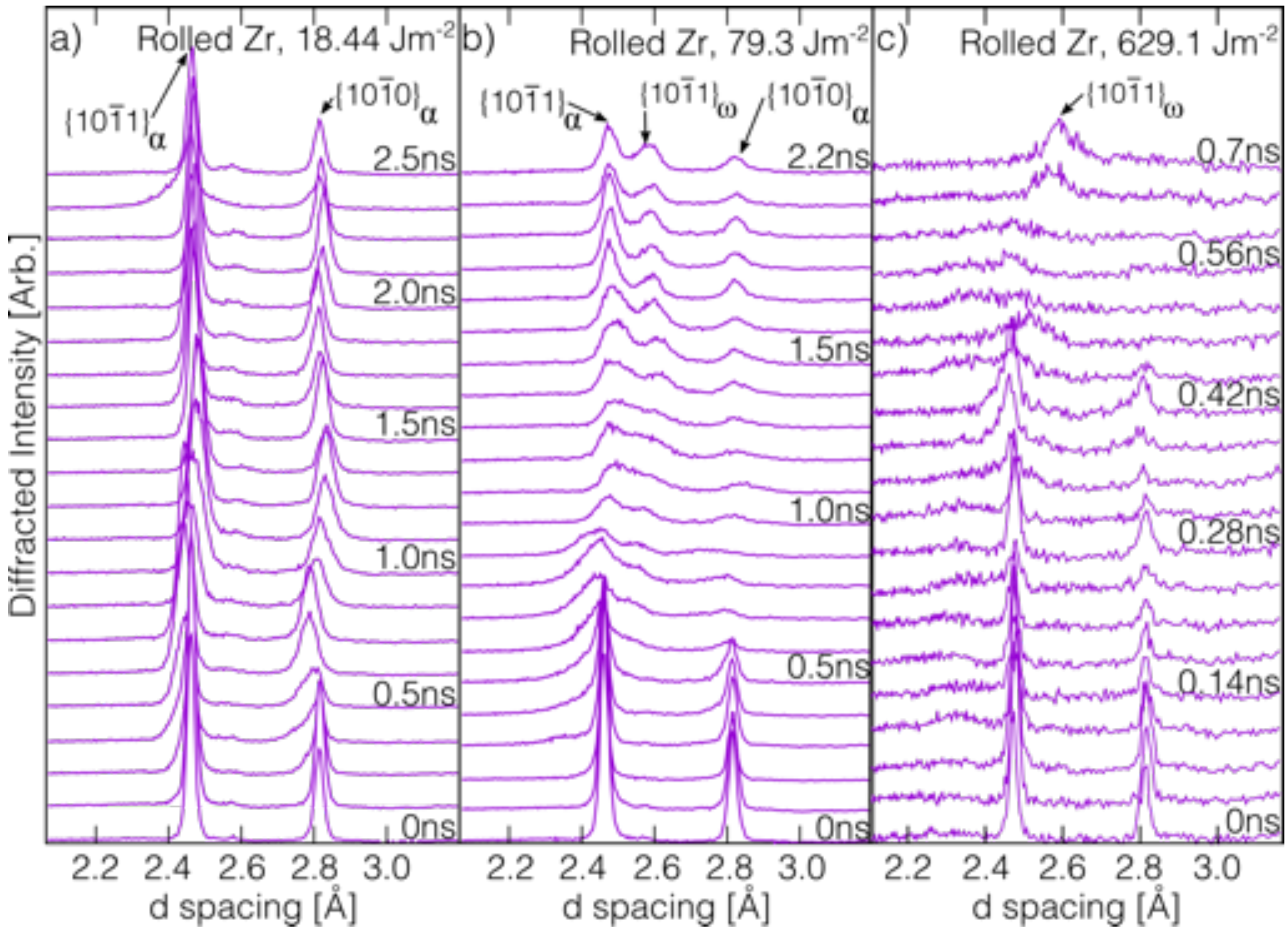
Collect data at 50ps intervals

2μm Zr foil - shock traverses foil in ~600 ps

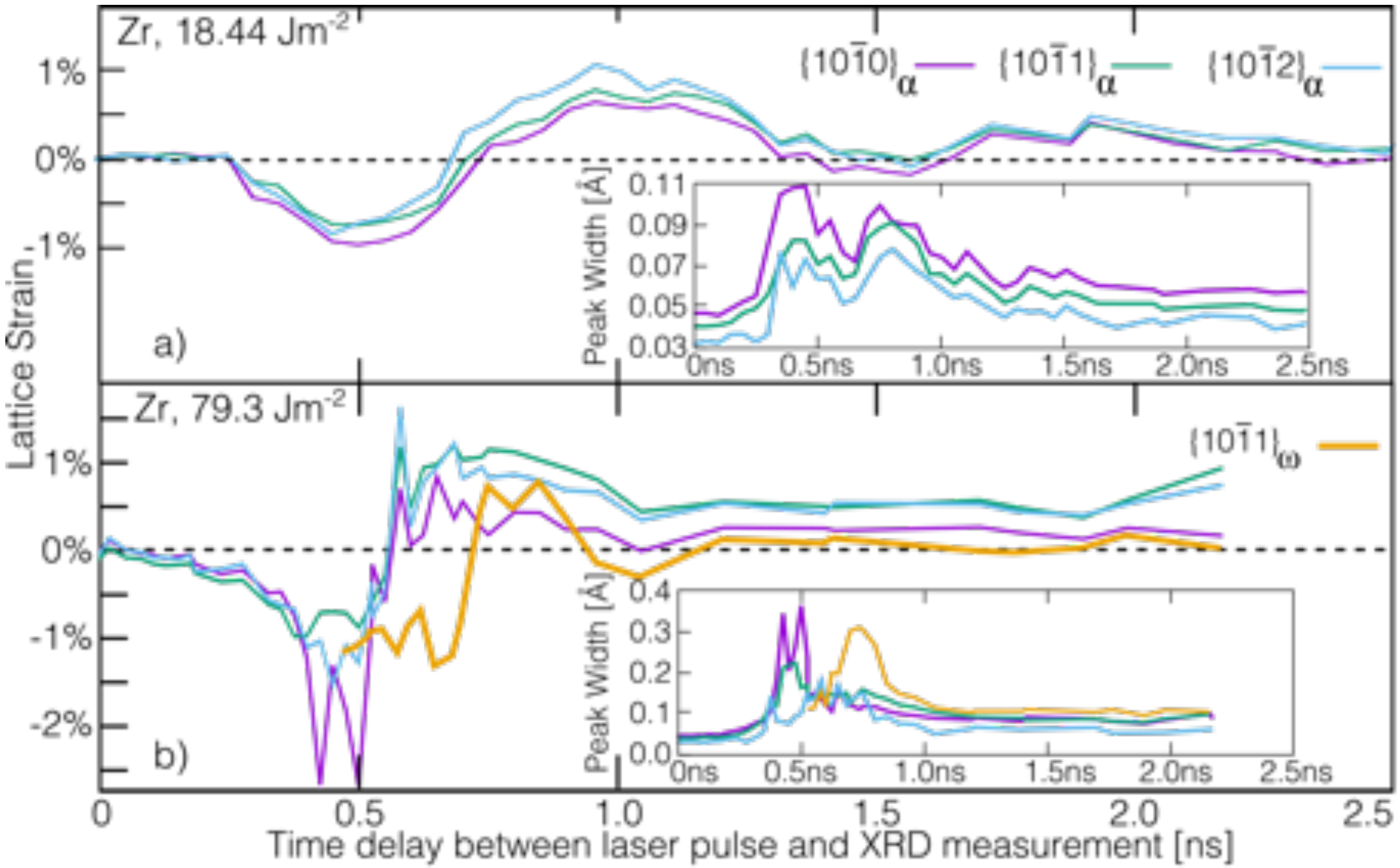
Pump-Probe: optical laser w/ 130-500μm spot size (FWHM), using X-ray laser (λ=0.129nm) of 30μm spot size



TD Swinburne et al, Phys.Rev.B (93):144119, 2016



TD Swinburne et al, Phys.Rev.B (93):144119, 2016



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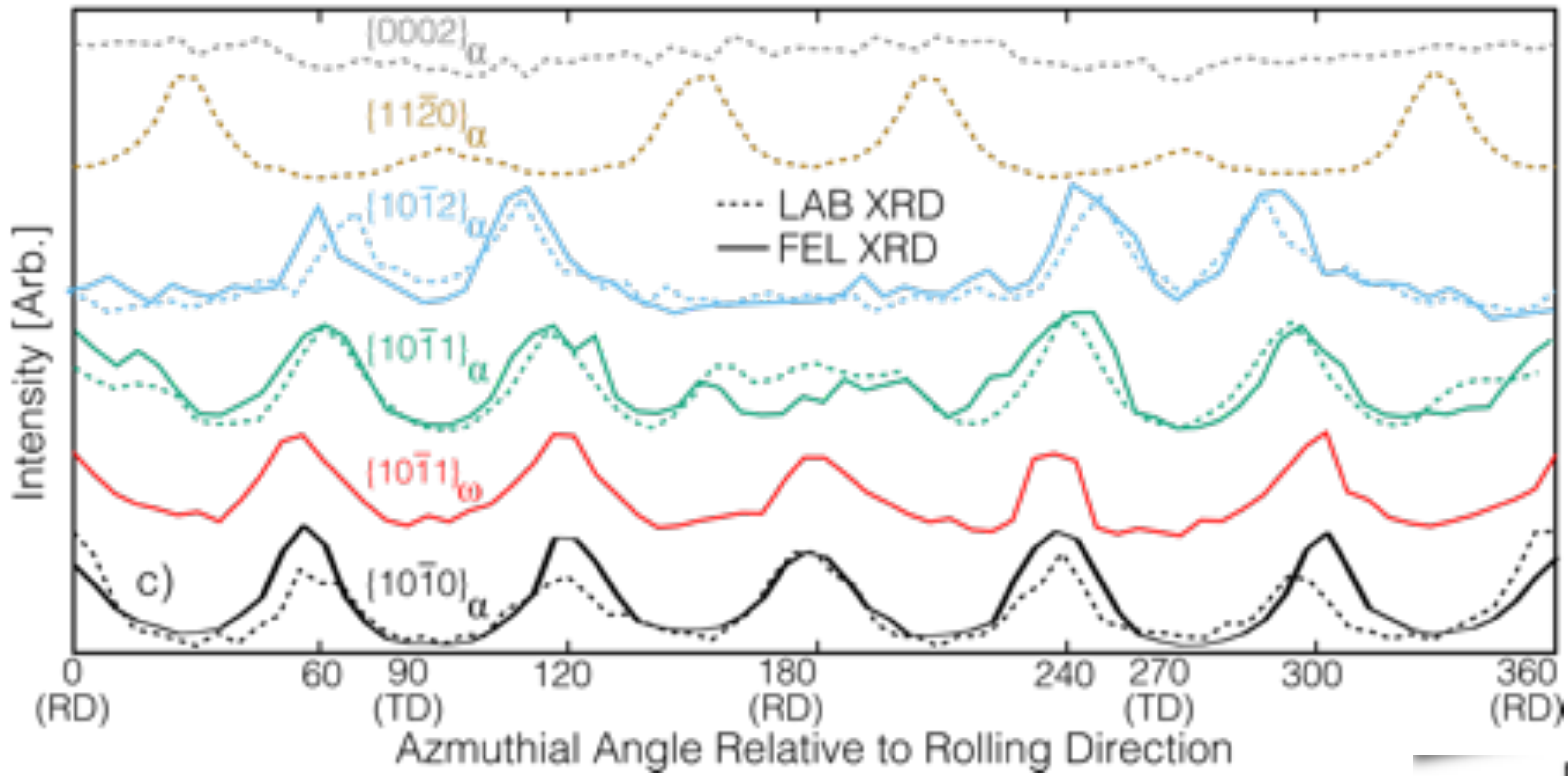
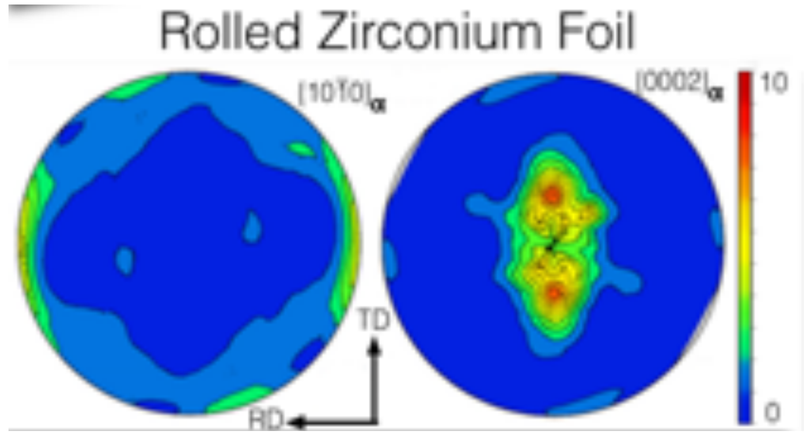




TD Swinburne et al, Phys.Rev.B (93):144119, 2016

The α→ω transformation

Silcock (quasi-static exp't):

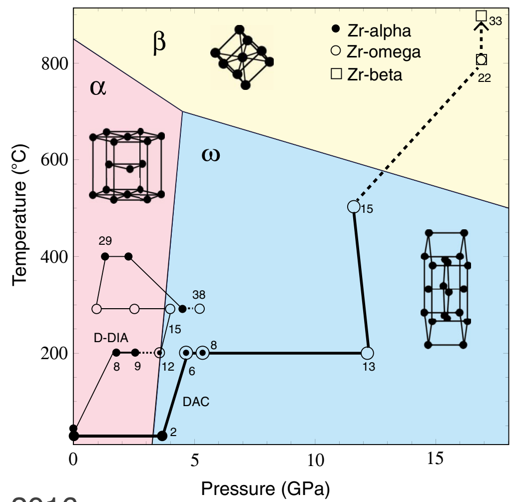
$\{0001\}_\alpha \,||\, \{1120\}_\omega$, $\langle 1120\rangle_\alpha \,||\, \langle 0001\rangle_\omega$

Trinkle (DFT):

$\{0001\}_\alpha \,||\, \{0111\}_\omega$, $\langle 1120\rangle_\alpha \,||\, \langle 0111\rangle_\omega$

Shock (exp't):

$\{1010\}_\alpha \,||\, \{0111\}_\omega$, $\langle 0001\rangle_\alpha \,||\, \langle 1210\rangle_\omega$



TD Swinburne et al, Phys.Rev.B (93):144119, 2016

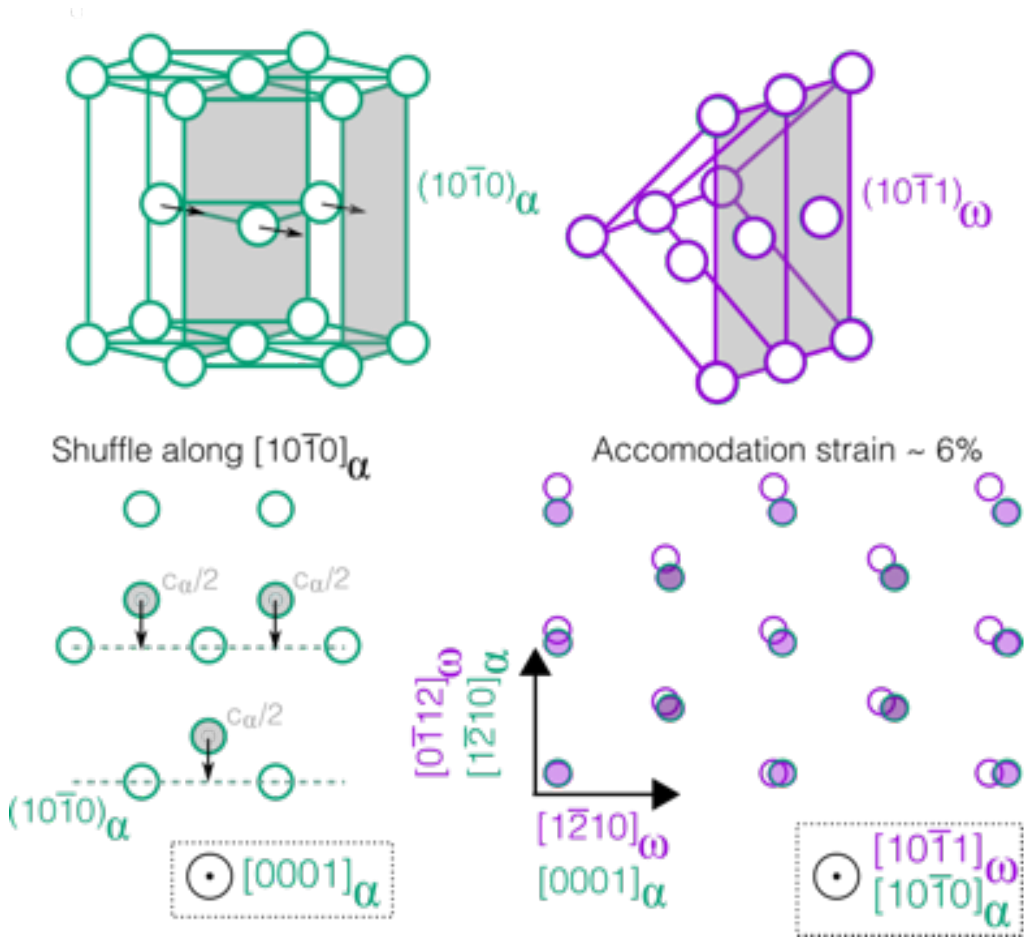
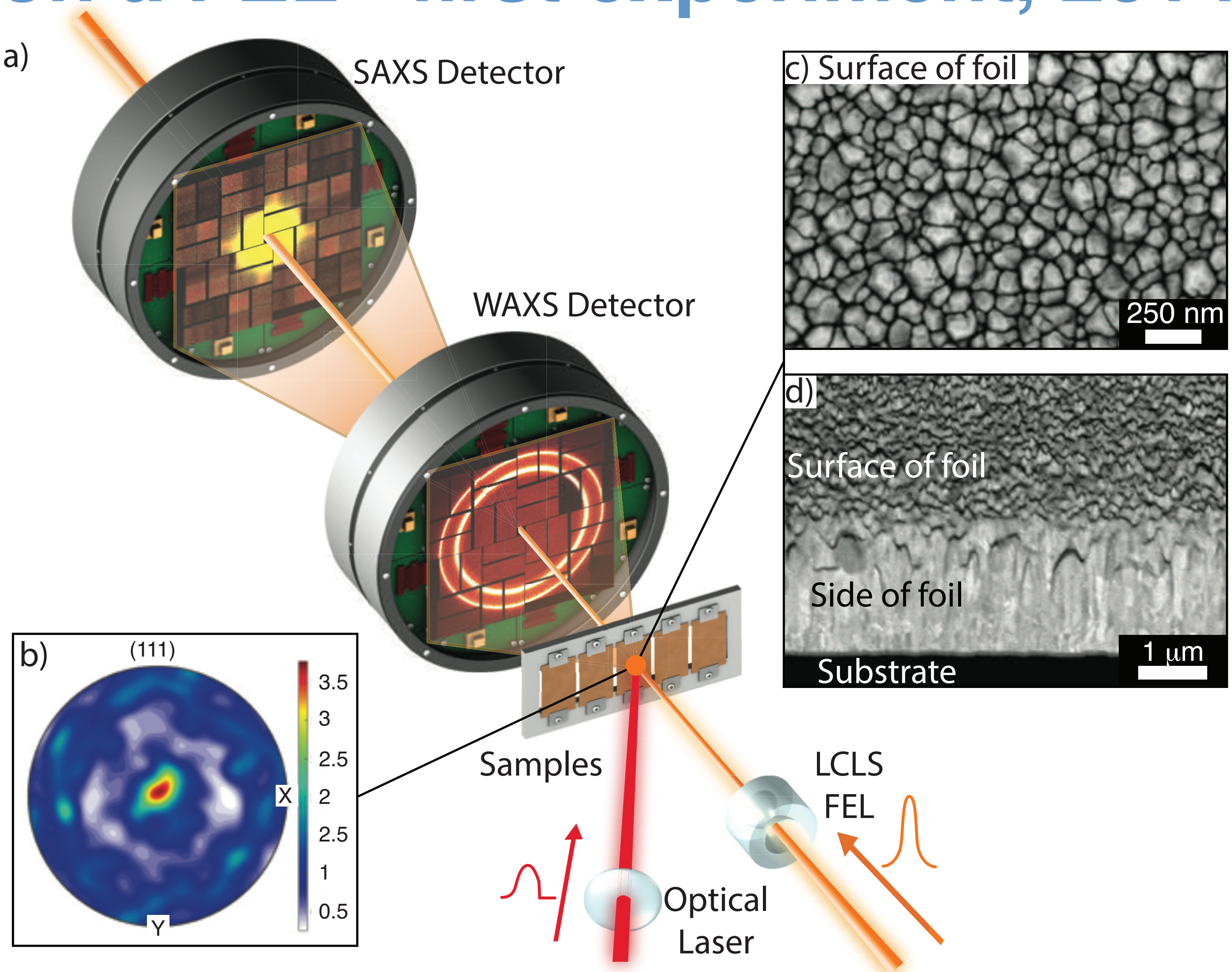


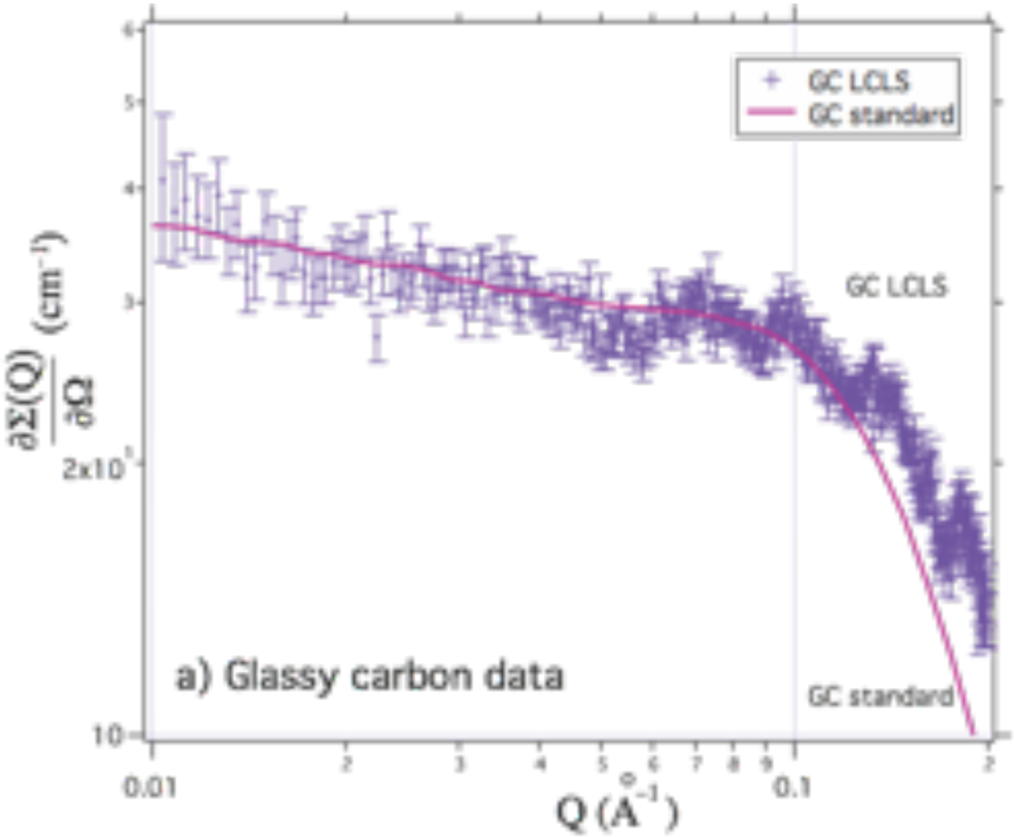
FIG. 4. Proposed $\alpha \rightarrow \omega$ transformation mechanism consistent with dynamic texture measurements of $(10\bar{1}0)_\alpha||(10\bar{1}1)_\omega$. Left: Inter-basal α atoms shuffle along $[10\bar{1}0]_\alpha$ directions onto $(10\bar{1}0)_\alpha$ prismatic planes. Right: Overlay of the post-shuffle $(10\bar{1}0)_\alpha$ with the $(10\bar{1}1)_\omega$ plane, such that $[0001]_\alpha||[1\bar{2}10]_\omega$. The two planes are coincident after a homogeneous strain.

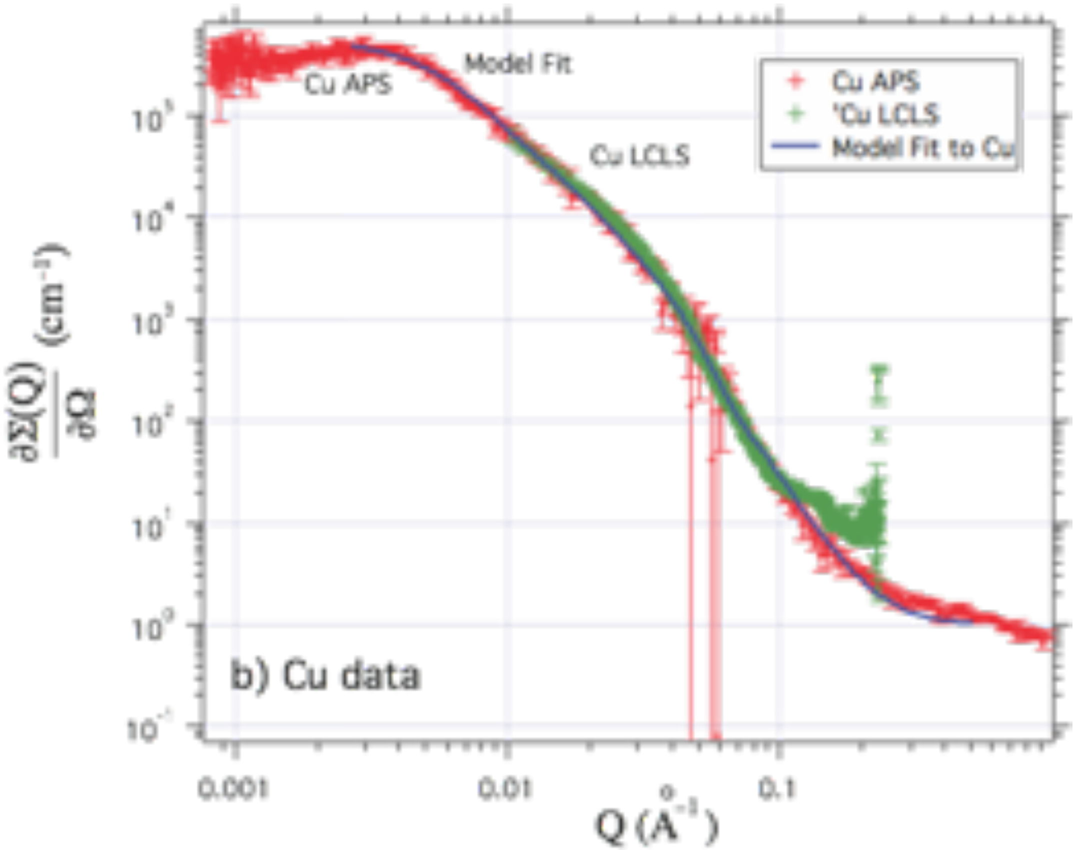
SAXS on a FEL - first experiment, 2014



Collaboration w/ Milathianaki, Ilavsky, Wark, Coakley, Swinburne, Voronstov, Rahman, Lane, McGonegle, Higginbotham

SAXS on a FEL - standards comparison to APS

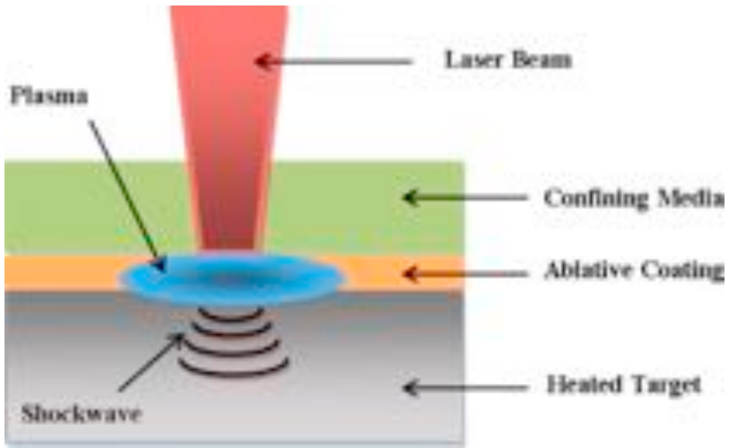




Unpublished collaboration w/ Milathianaki, Ilavsky, Wark, Coakley, Swinburne, Voronstov, Rahman, Lane, McGonegle, Higginbotham

- <readacted slides>

Thoughts on possible sub-ns FEL experiments:
I. Laser Shock Peening



e.g. to manage stresses from Hertzian contact (fan blades, bearings eg wind turbines, automotive, rail etc)

<u>Imaging elastic strains</u>

Shock at 4-10E3 m/s

1mm resolution

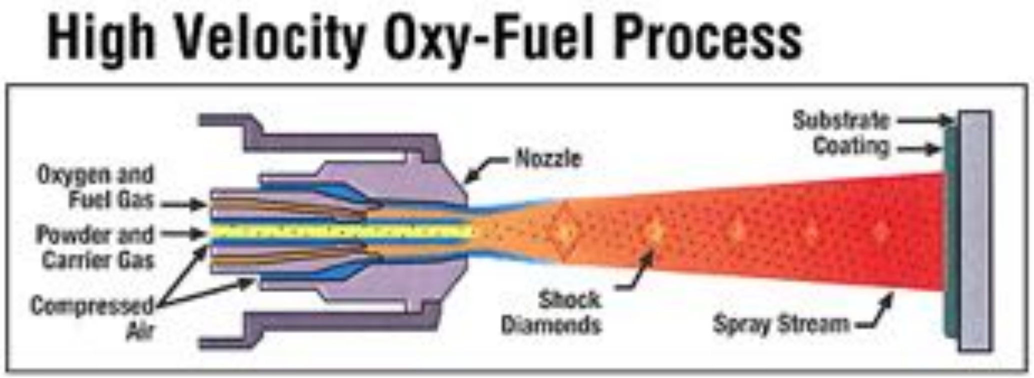
Shock moves 1mm in 100 ns

c.f. ESRF (800m ring, 32 bunch) - pulse every 10 ns

-> Just about doable on a synchrotron [but, brightness?]

Also, dynamics of the ablation and shock generation process (much shorter timescale, more like the talk)

Thoughts on possible sub-ns FEL experiments: II. C-D nozzles in industrial processes



e.g. nanoparticle generation (turbulent flow)

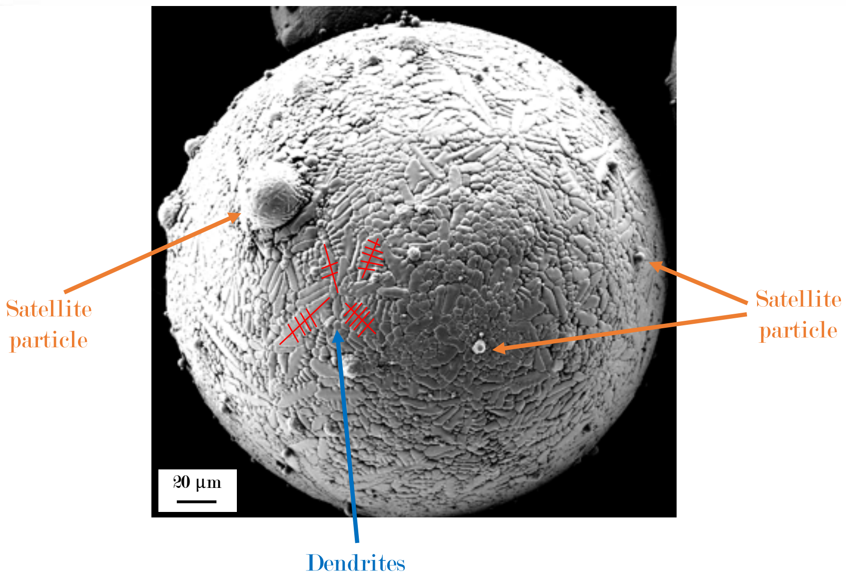
e.g. melting of metal powders and their in-flight solidification. (cf additive manufacturing)

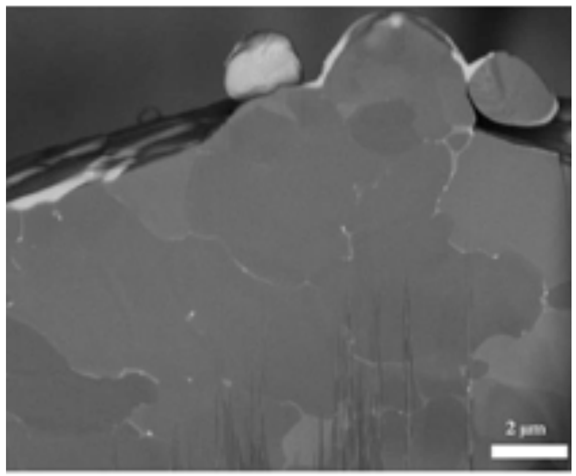
<u>Imaging</u>

Exit velocity 1500 m/s

10um resolution

O(1-10) ns time resolution





c.f. ESRF (800m ring, 32 bunch) - pulse every 10 ns

-> Starting to challenge synchrotrons [but, brightness?]

Thoughts on possible sub-ns FEL experiments: II. Particle stick/bounce

fastFT Rolls-Royce Holdings PLC + Add to myFT

Rolls-Royce warns airlines of fresh Trent 1000 engine delays

Number of aircraft grounded set to remain in double digits until second quarter of 2020

e.g. multi-$bn corrosion fatigue problem in gas turbine blades.

Associated with entrained S-containing particulate, residence/drying time, water vapour and particle velocity

So: ‘launch’ particle using laser ablation, observe particle interaction with surface, formation of surface reaction products…

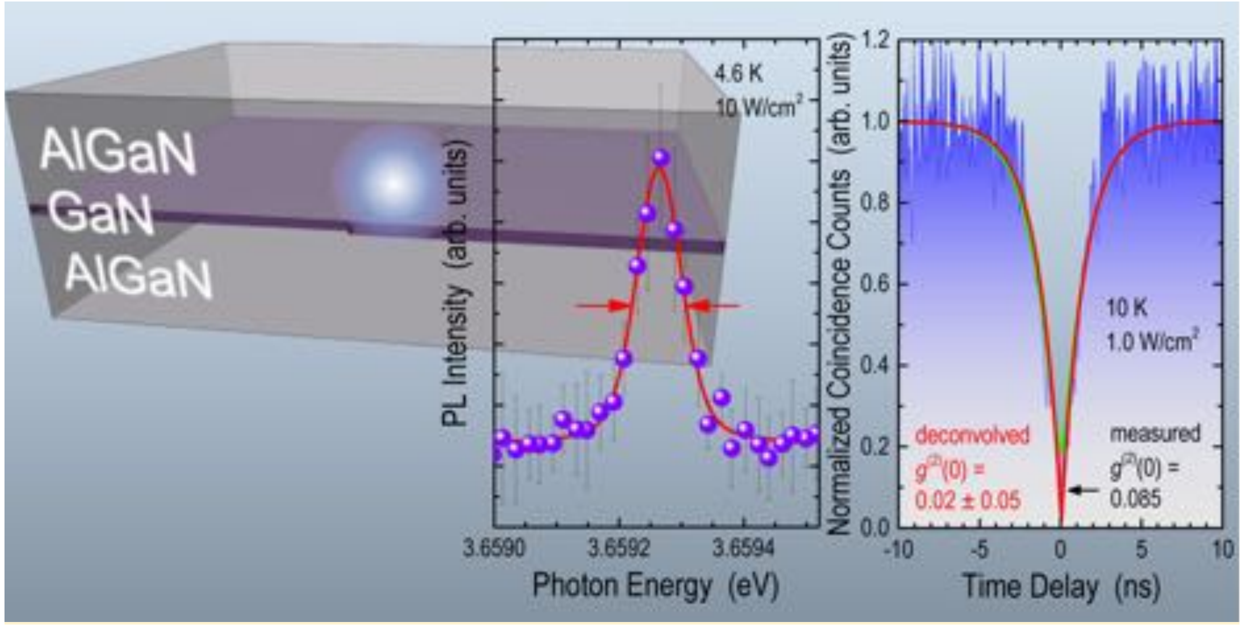
<u>Imaging</u>

Velocity 1500 m/s

sub-um resolution

O(10) ps time resolution, nano beam required

Thoughts on possible sub-ns FEL experiments: III. Device physics



Arita et al, Nano Lett 2017, 17, 2902-2907. dx.doi.org/10.1021/acs.nanolett.7b00109

Thoughts on possible sub-ns FEL experiments:
IV. Scientific instruments

ns and fs lasers (eg tribeam system), atom probe needle evaporation, ion beam ablation (FIB)