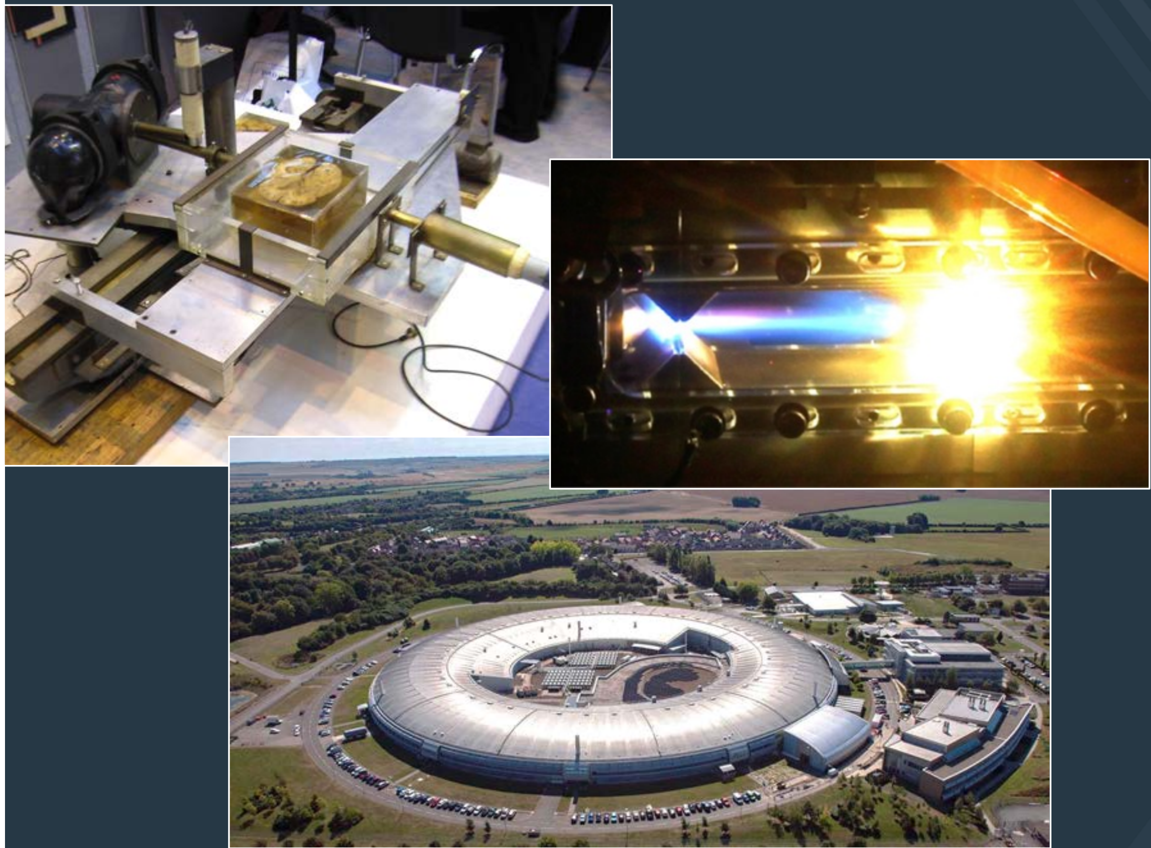


University of Southampton

X-ray Tomography – Past, Present, Future Challenges

Prof. Ian Sinclair
i.sinclair@southampton.ac.uk

NXCT National X-ray Computed Tomography

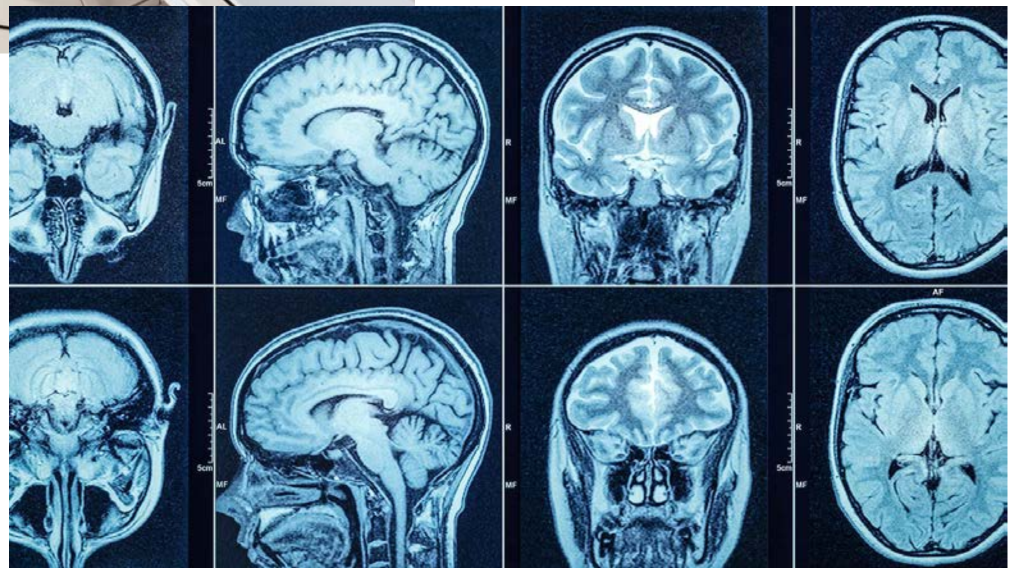
μ-VIS X-Ray Imaging Centre
www.muvis.org

3D XRH X-ray Histology
www.xrayhistology.org

Computed tomography

University of Southampton

μ-VIS X-Ray Imaging Centre www.muvis.org



- ‘Non-destructive’ radiographic method for imaging by **slices** (Greek: *tomos*)
- Hospital ‘CT’ scanner (or ‘CAT’, computed axial tomography)

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Computed tomography?

- ‘Non-destructive’ radiographic method for imaging by **slices** (Greek: *tomos*)
- Hospital ‘CT’ scanner (or ‘CAT’, computed axial tomography)

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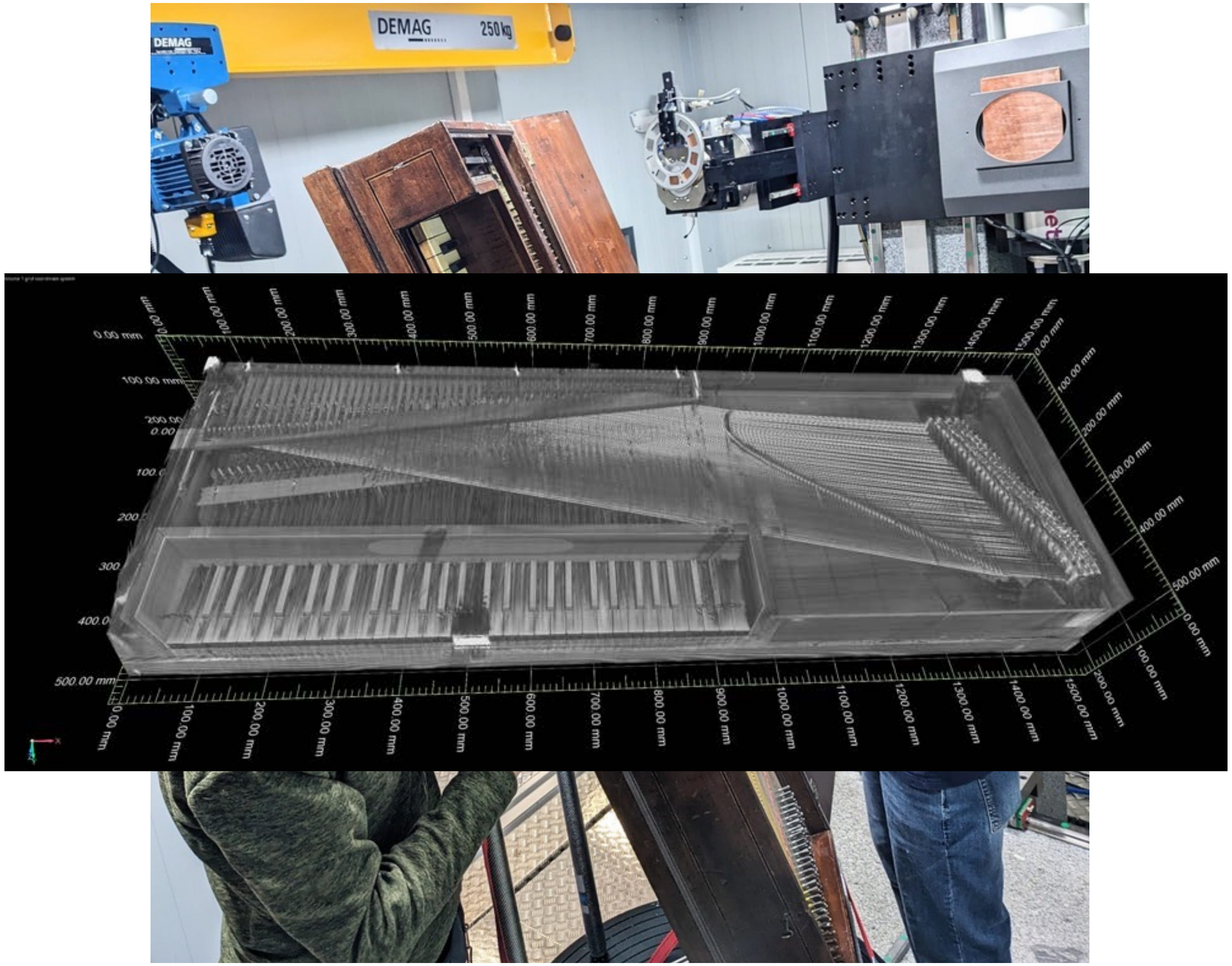
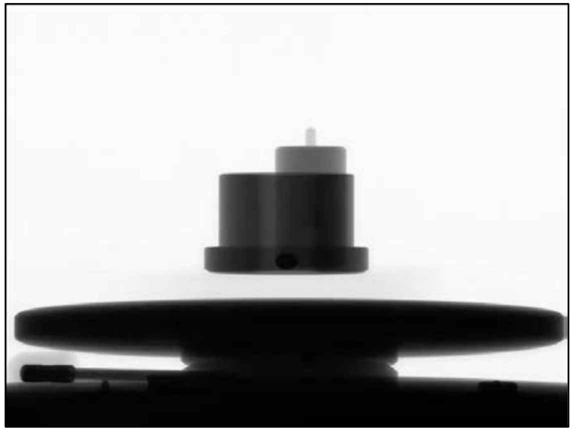
Computed tomography

- ‘Non-destructive’ radiographic method for imaging by **slices** (Greek: *tomos*)
- Hospital ‘CT’ scanner (or ‘CAT’, computed axial tomography)
- diondo d5
  - 300kV µ-focus/450kV mini-focus
  - 3x3k flat panel: 4x stitching
  - 200kg, 2.25m tall samples
  - Helical & laminographic modes
  - VDI/VDE 2630-1.3 metrology qualified



Principles

- XCT images are ***mathematical models*** derived from:
  - Inverse-Radon transform of X-ray attenuation in 3D ('reconstruction')
- Typical XCT scan ➜ solving ~10 billion line-integrals
- Obtaining your 10^{10}+ voxel values is only half the fun!



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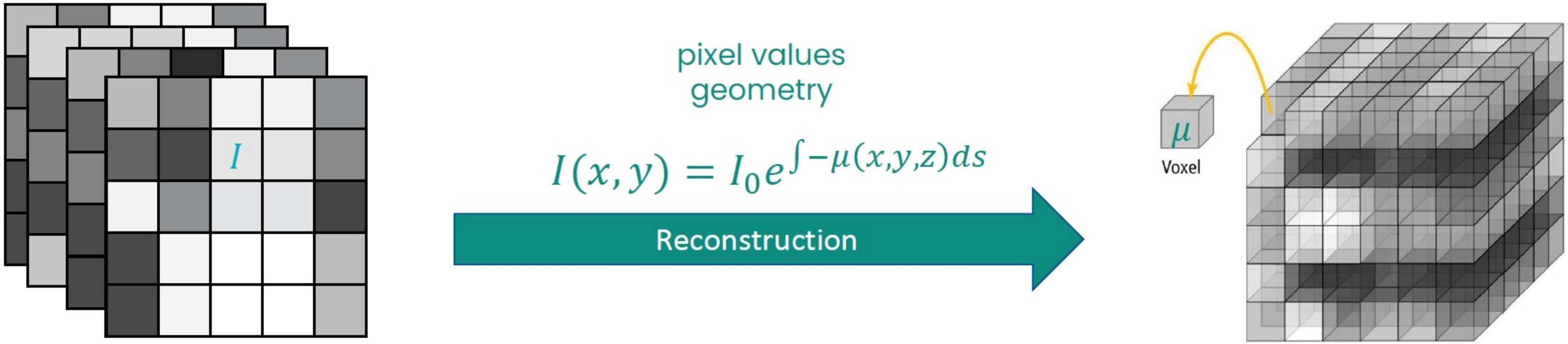
After Roth, Waygate Technologies



Radiographs (2,000+ per scan)

XCT volume

μ-VIS: What is it?

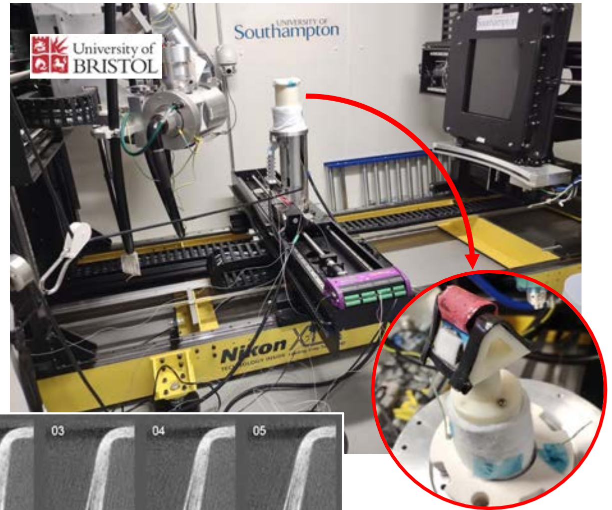
- See **www.muvis.org**
- 9 complementary XCT systems in Engineering & Medicine
- Distinctiveness within UK Universities:
    - **'Big!'** - largest, high energy *μ*-focus XCT systems in UK academic sector

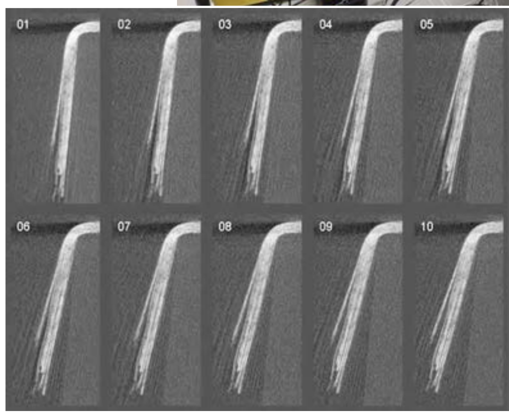
µ-VIS: What is it?

University of Southampton

µ-VIS X-Ray Imaging Centre
www.muvis.org

- See **www.muvis.org**
- 9 complementary XCT systems in Engineering & Medicine
- Distinctiveness within UK Universities:
    - **'Big!'** - largest, high energy *µ*-focus XCT systems in UK academic sector
    - *In situ* enthusiasm (thermal, mechanical, fluid, pyrotechnic...)
    - Macro to sub-micron
    - Dedicated computational infrastructure & workstation suite
        - Automated end-to-end workflows, G-RAID servers, 100GigE, GPU workstations...
    - 2x histology and 2x *in vivo* specialised scanners
    - Co-located: NCS (XRD), National Infrastructure Lab (NIL), Engineering Design/Manufacturing, SBF- & FIB-SEM , TEM/ET, SIMS, XRF, Confocal...
  - National: Diamond panels, CCPi, NPL/dXCT committee, ToScA 2019...
    - EPSRC National Research Facility (NRF/NXCT)





Vacuum forming & cure in CFRP

Courtesy Martin, Galvez-Harnandes, Kratz & co-workers

NXCT: What is it?

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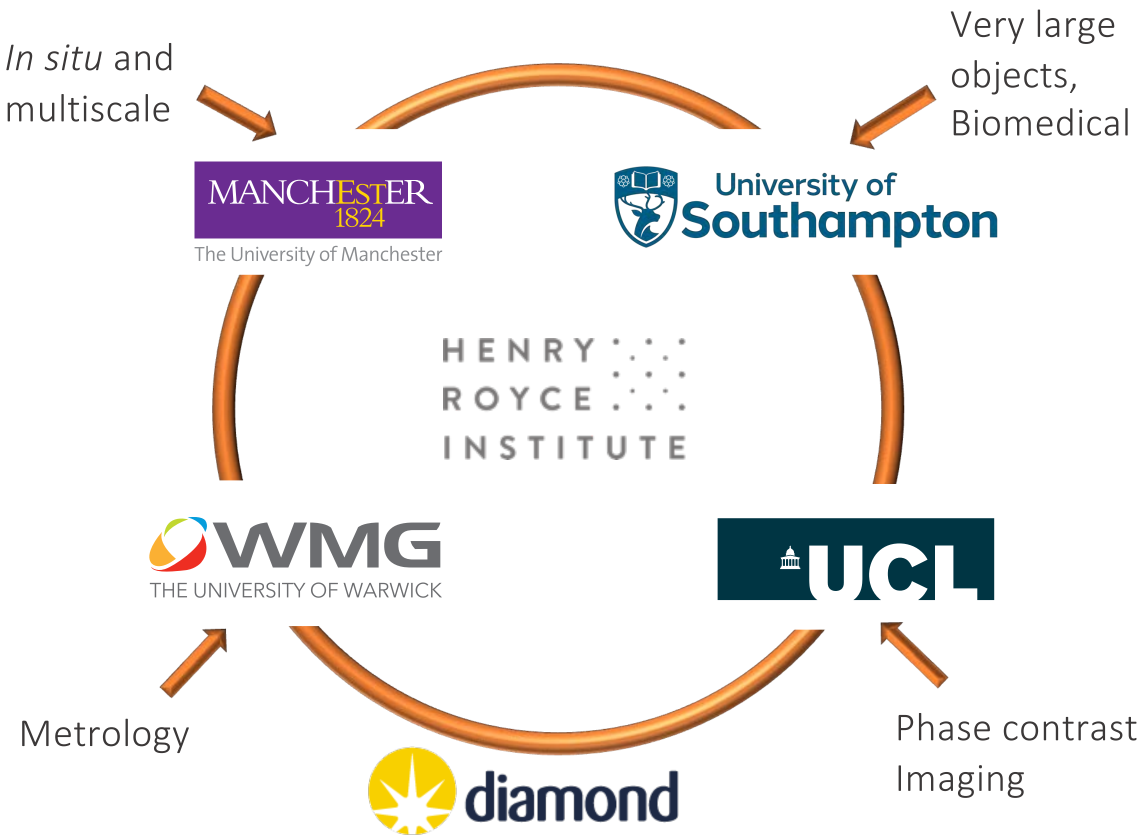
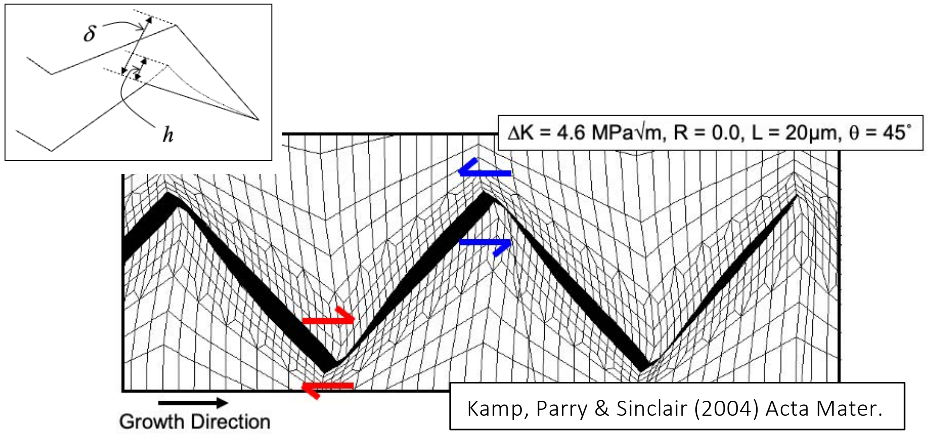


- £10M EPSRC funding to provide National XCT capabilities
  - 'National Research Facility' (NRF)
- >20 X-ray XCT system available
- Openly available to UK research
  - 'Free' to academia and SMEs
- FIND US HERE: www.nxct.ac.uk

Experimental mechanics perspective

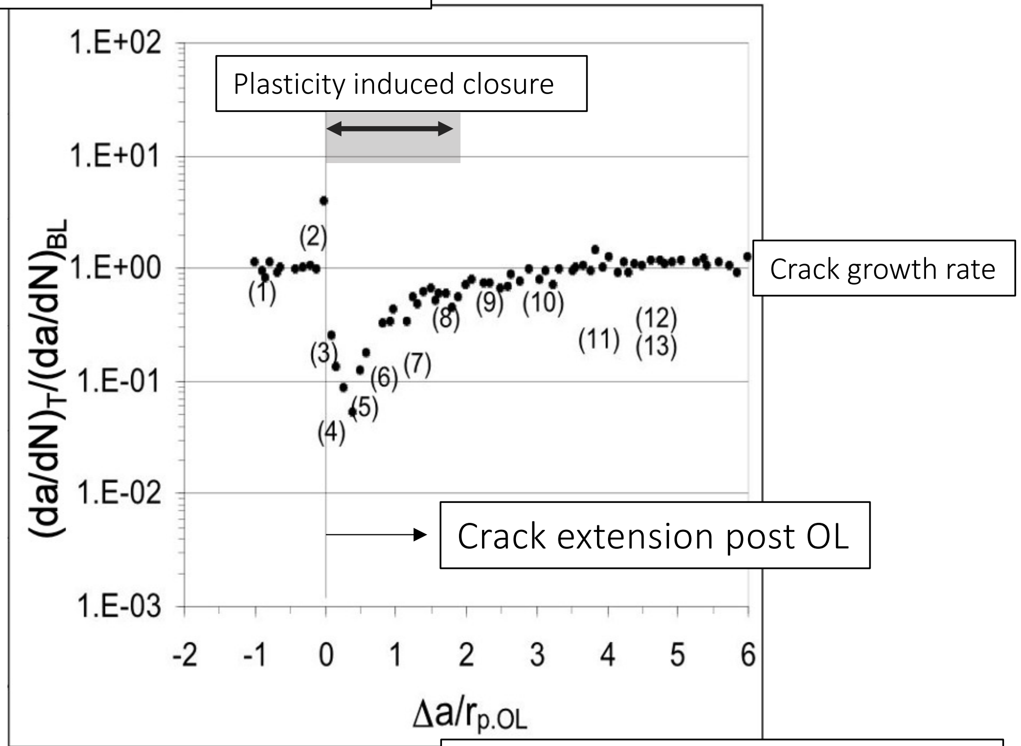
Fatigue crack growth in metals

- Crack closure is central to several aspects of contemporary fatigue understanding
  - Short cracks, variable amplitude behaviour, microstructural influence...
  - Controversy in characterisation & modelling...



Kamp, Parry & Sinclair (2004) Acta Mater.

Single OL transient in AA2024

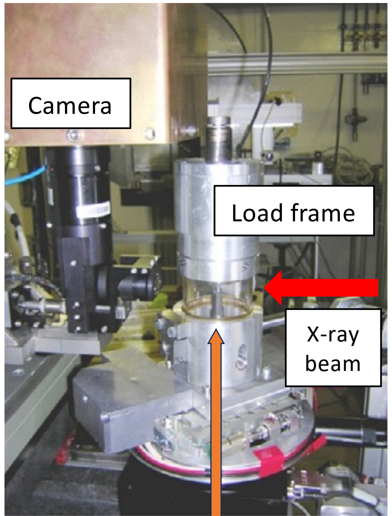


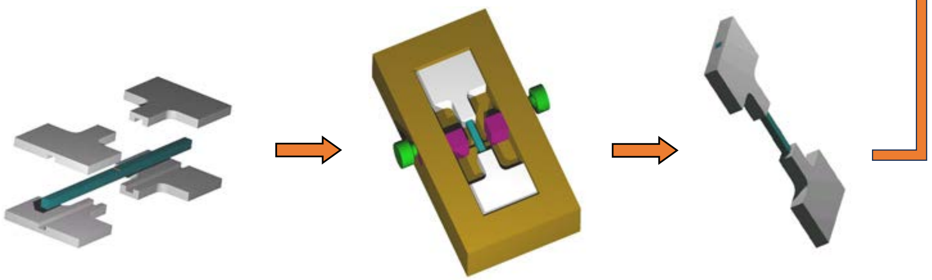
Xu, Gregson & Sinclair, (2000), Mater. Sci. Eng.

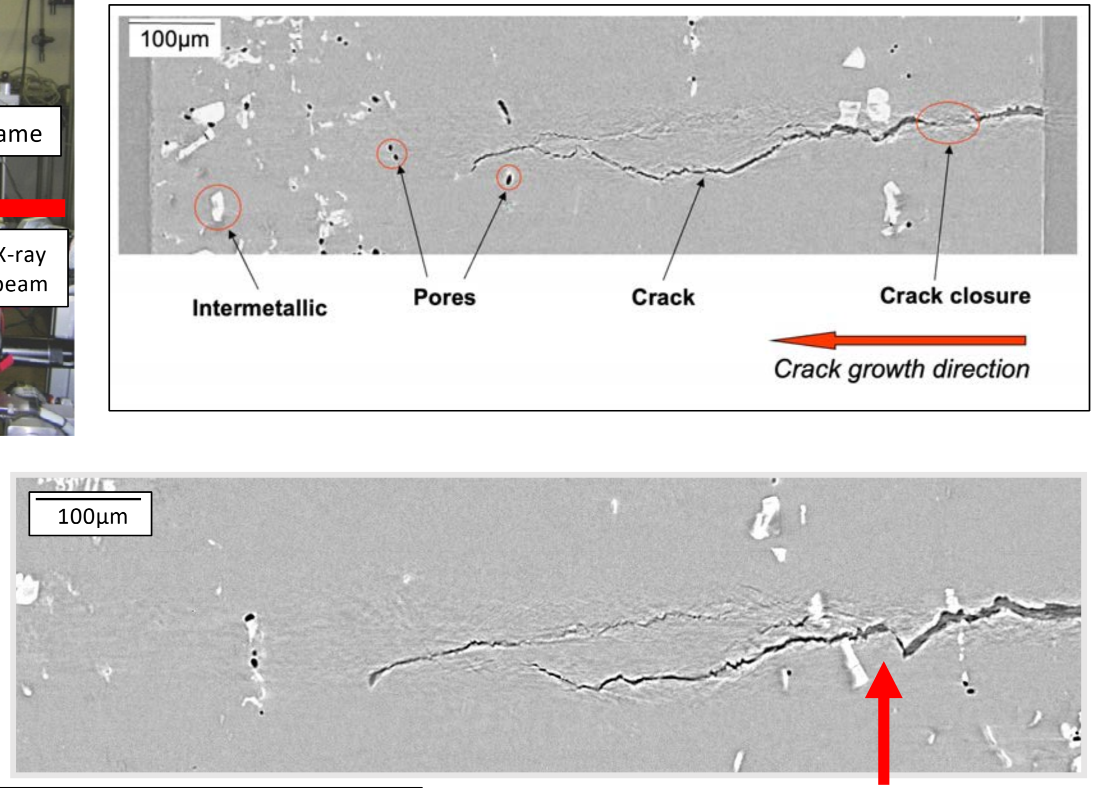
In situ visualisation of closure in bulk

University of Southampton

μ-VIS X-Ray Imaging Centre www.muvis.org







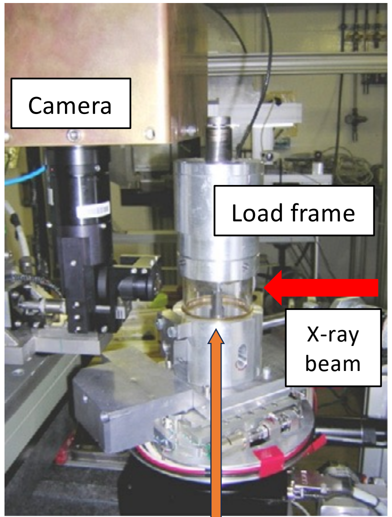
Toda, Sinclair *et al.* (2003), Phil. Mag.

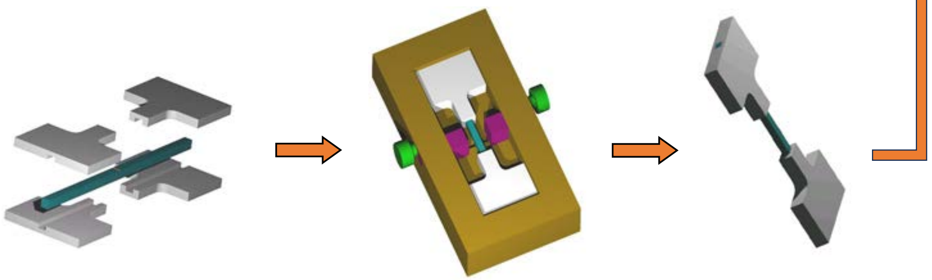
Roughness induced crack closure!

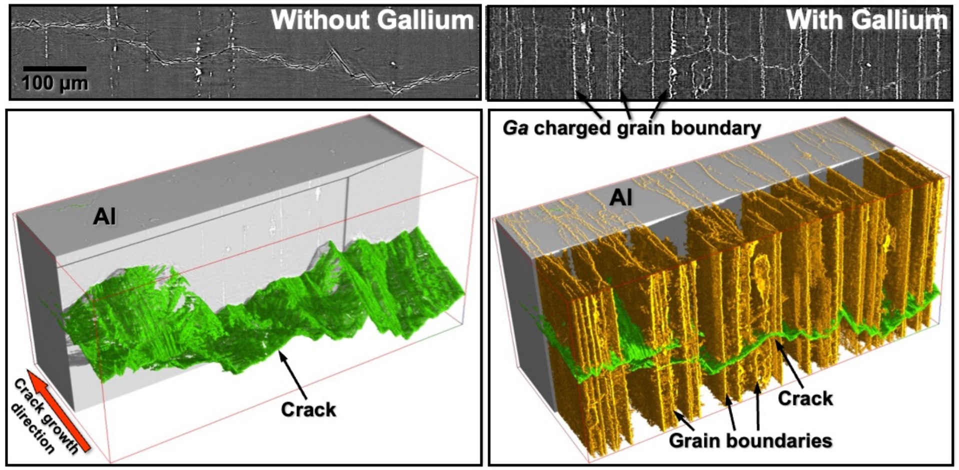
In situ visualisation of closure in bulk

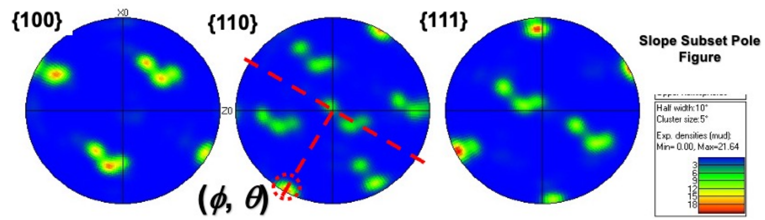
University of Southampton

µ-VIS X-Ray Imaging Centre www.muvis.org







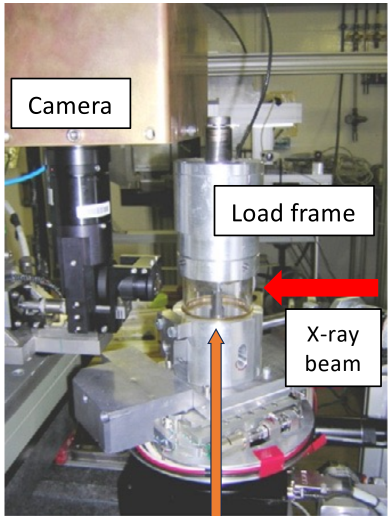


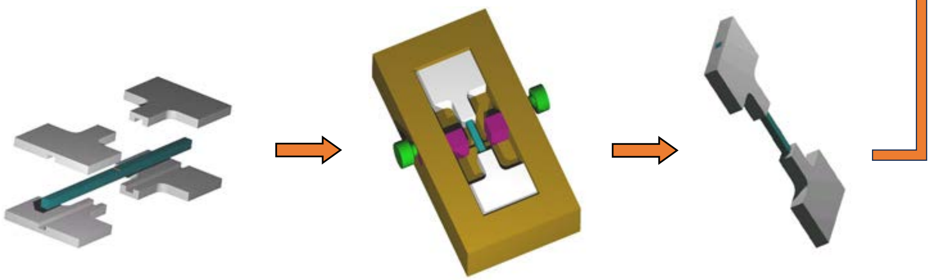
Khor, Sinclair *et al.* (2004), J. Physics. Condensed Matter

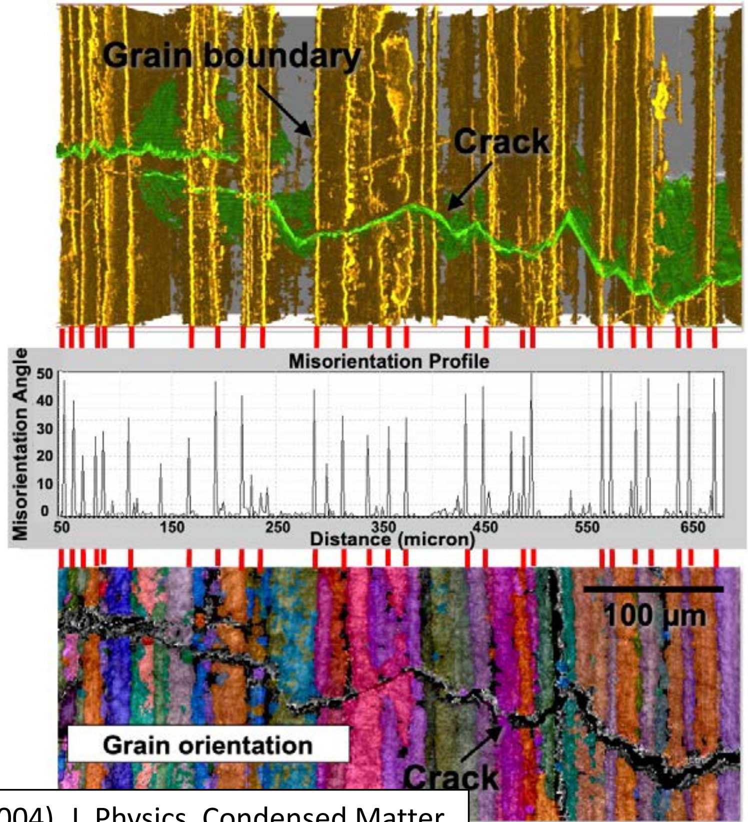
In situ visualisation of closure in bulk

University of Southampton

μ-VIS X-Ray Imaging Centre www.muvis.org

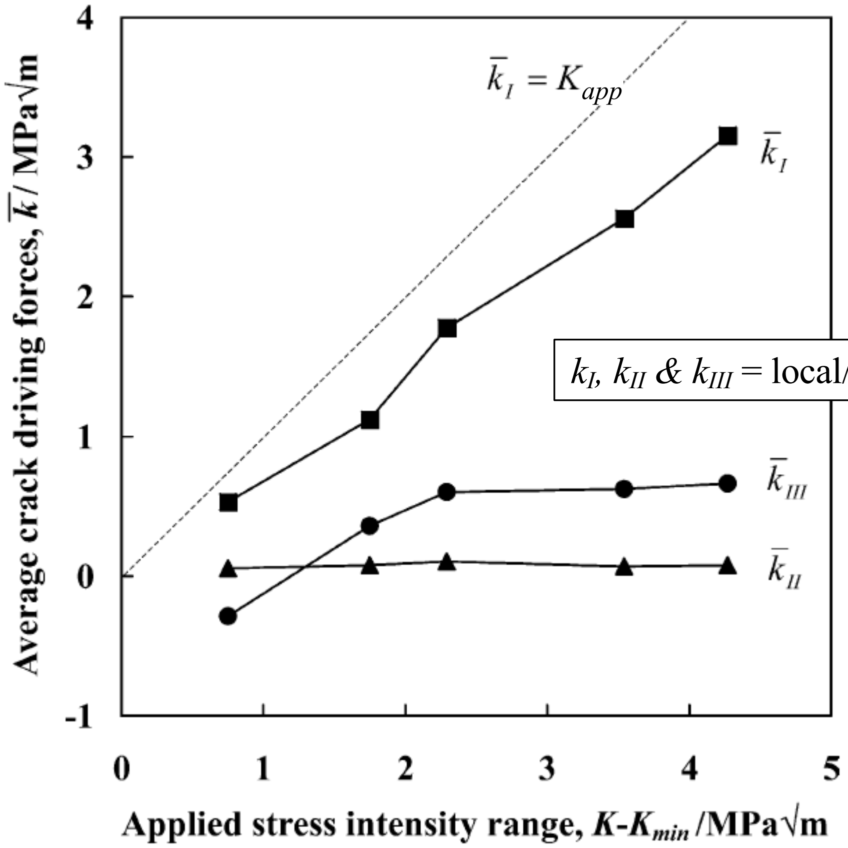






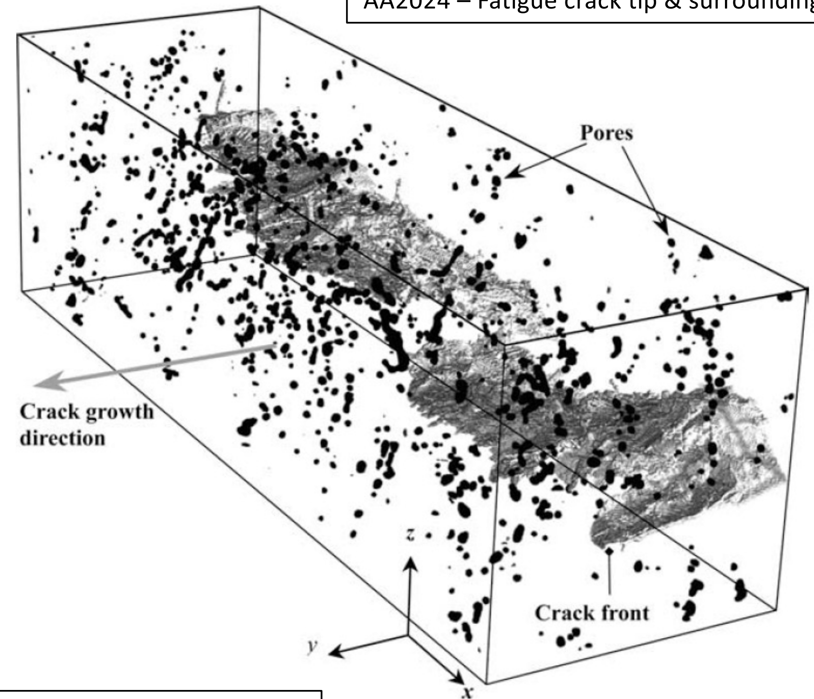
Khor, Sinclair *et al.* (2004), J. Physics. Condensed Matter

Local SIF determination



k_I, k_{II} & k_{III} = local/crack tip SIF

AA2024 – Fatigue crack tip & surrounding porosity

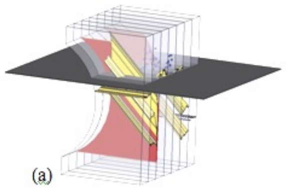


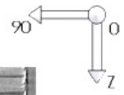
Toda, Sinclair *et al.* (2004), Acta Mater.

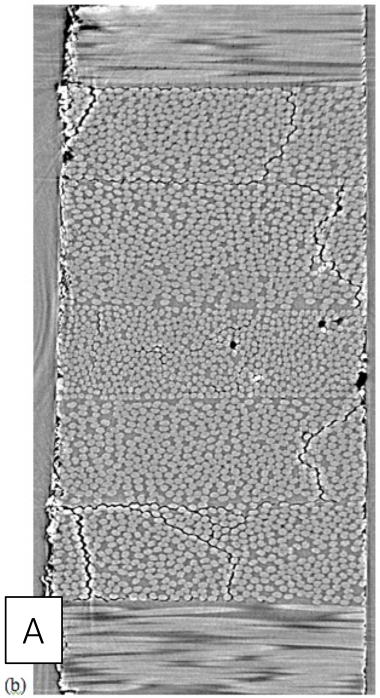
Rince & reuse... CFRP Fatigue Failure

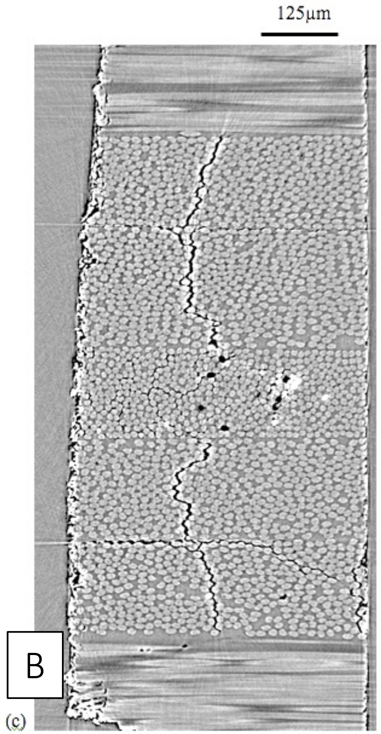
Early SRCT investigation: fibre & matrix damage, at 0.7 µm resolution

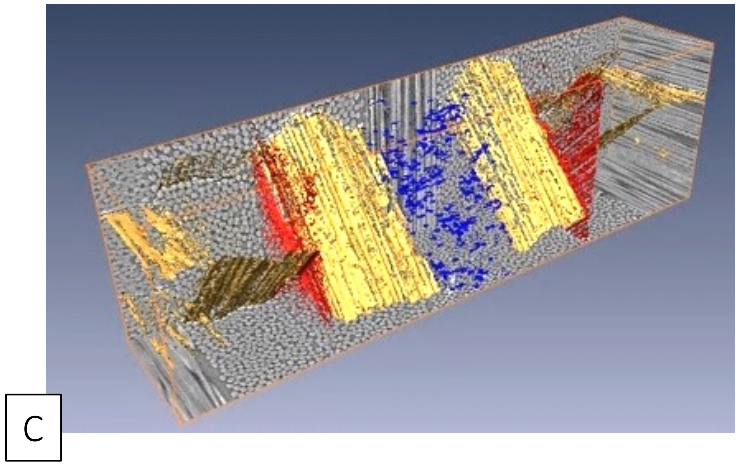
- 3D microstructural analysis
- 3D mechanism mapping & interactions











Axial slices showing crack paths and fibre breaks through the thickness of notched laminate: (A) 250µm above centre of notch, (B) Centre of notch, and (C) 3-D rendering (Wright *et al.* 2008)

CFRP Tensile Failure

University of Southampton

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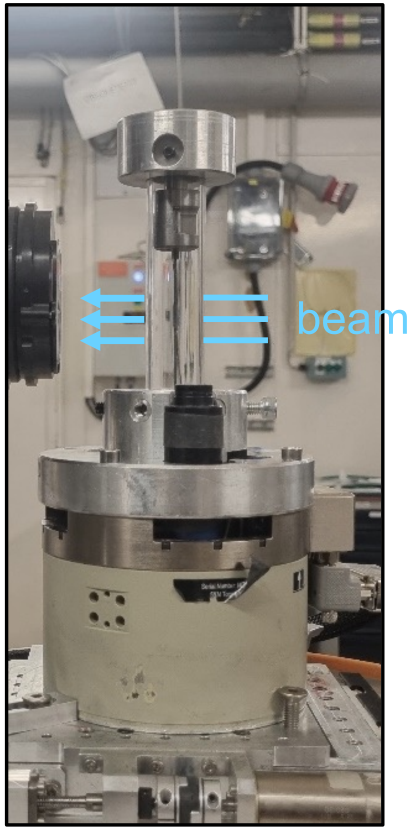
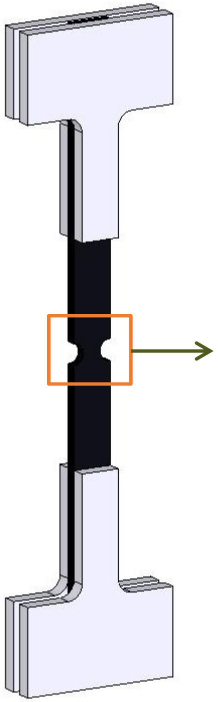
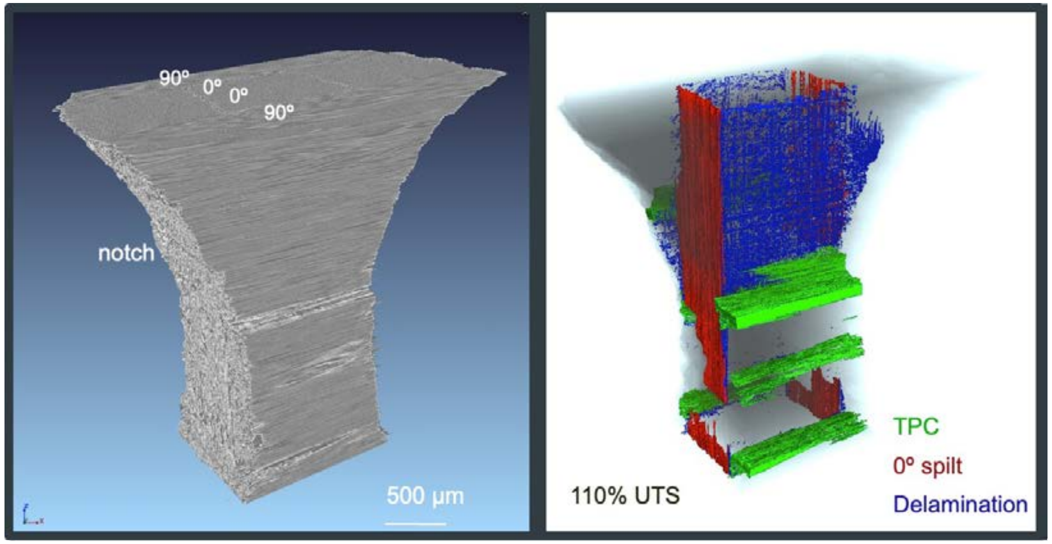


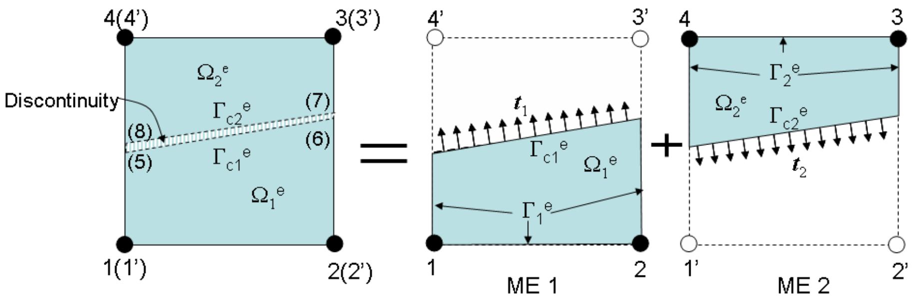




Scott, Sinclair *et al.* (2012), Composites A

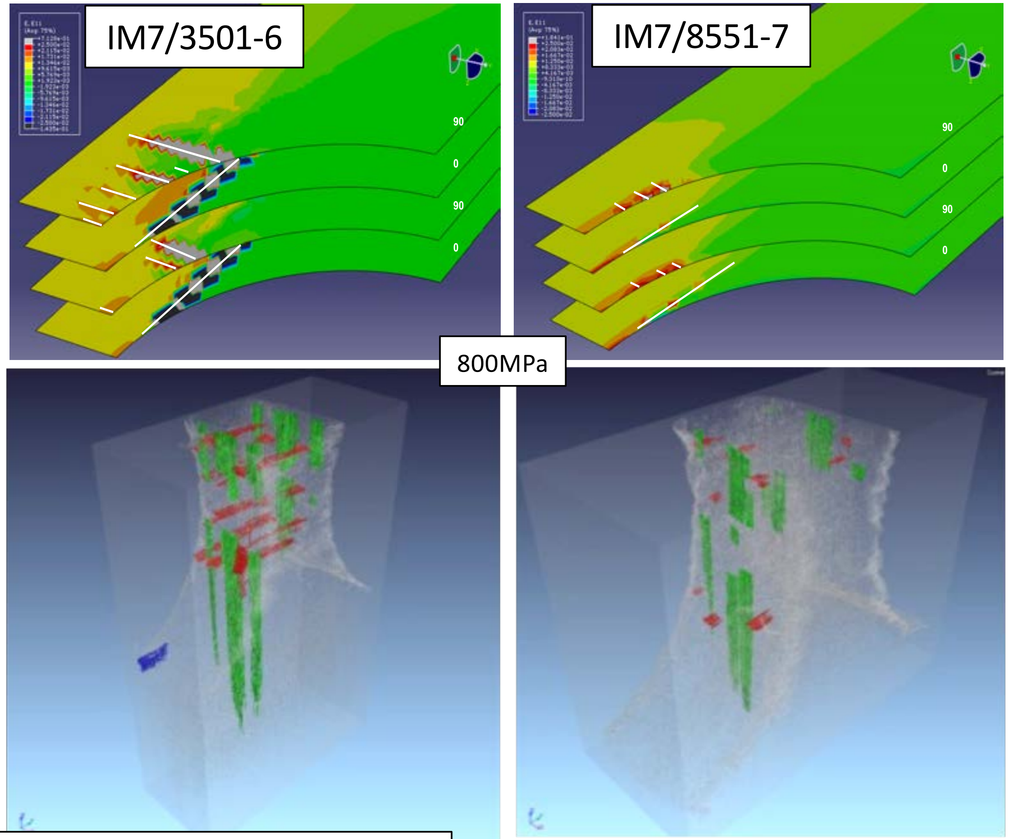
CFRP – A-FE Model validation

- Ghost elements add extra crack displacement
- Local – can set up as ABAQUS user element



Ling, Yang & Cox, 2008

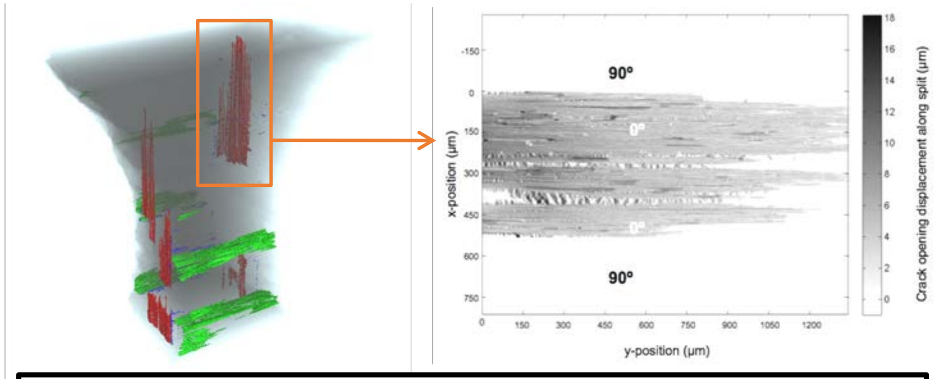
- Incorporate CZM
- Arbitrary crack initiation
- Stochastic processes

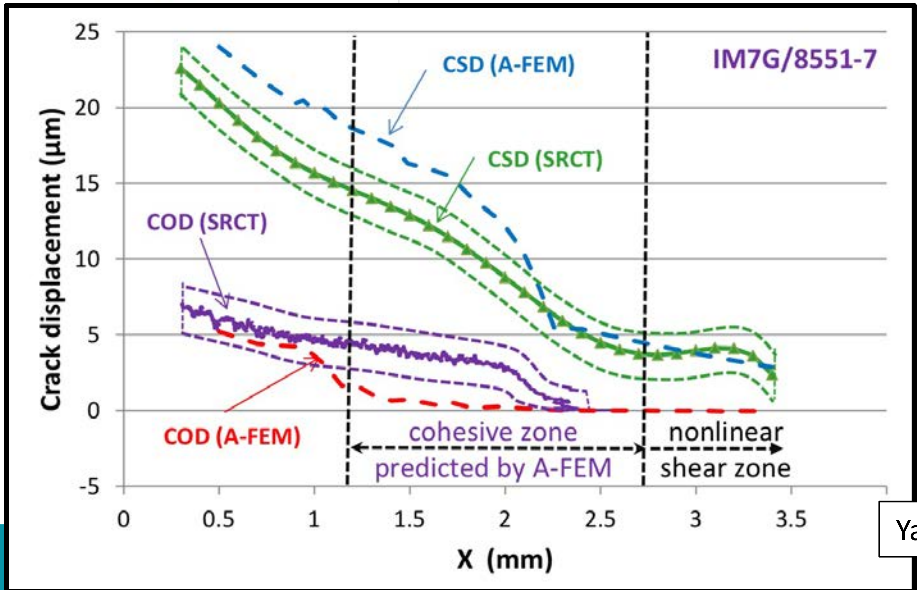


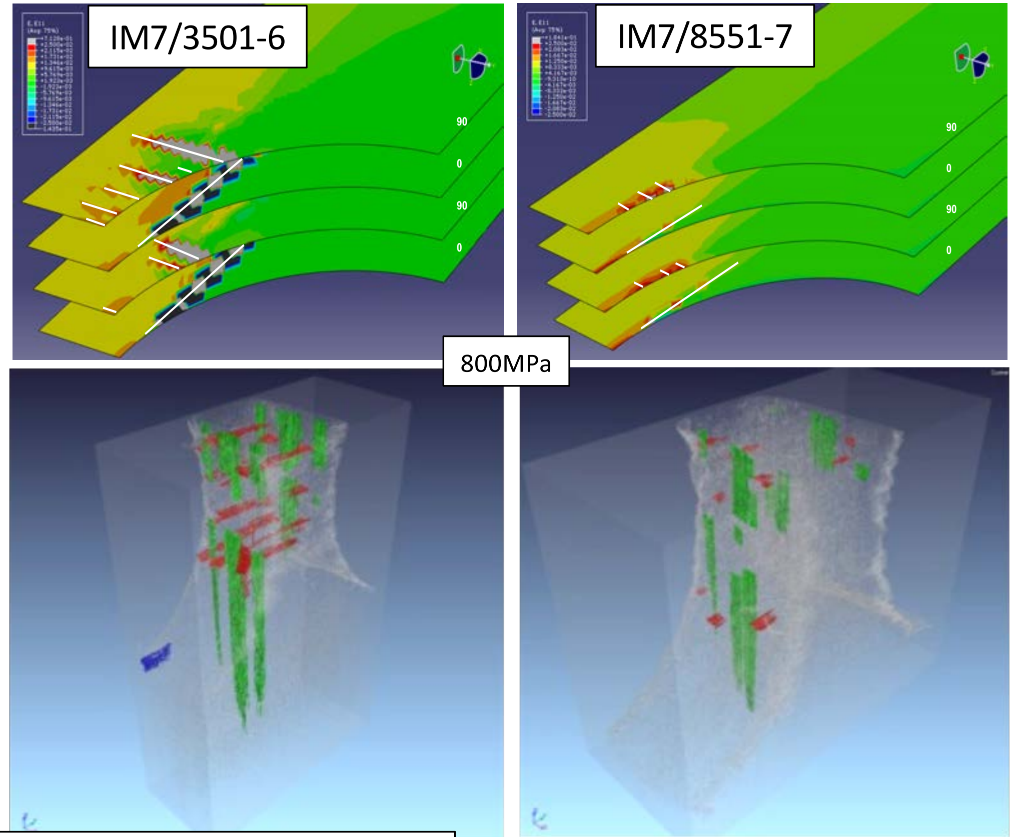
Yang, Sinclair *et al.* (2016), J. Mech. Phys. Sol.

CFRP – A-FE Model validation

- For 3 matrices: crack initiation, location, area/extension, CTOD & CTSD







Yang, Sinclair *et al.* (2016), J. Mech. Phys. Sol.

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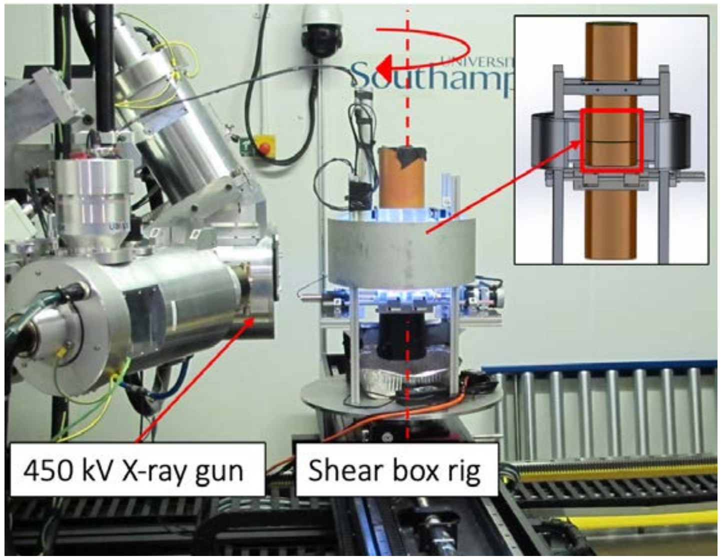
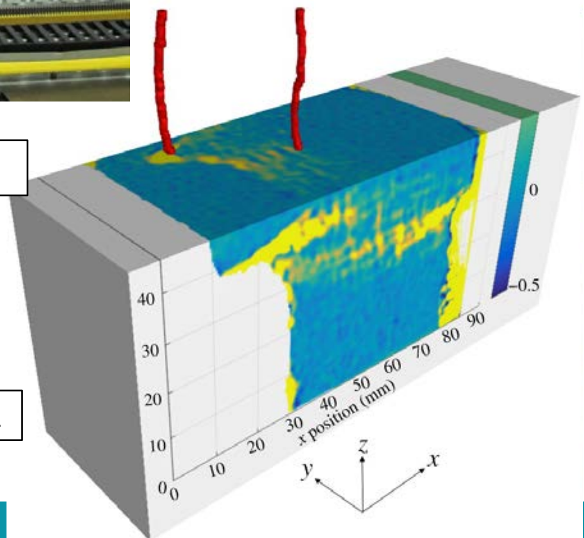
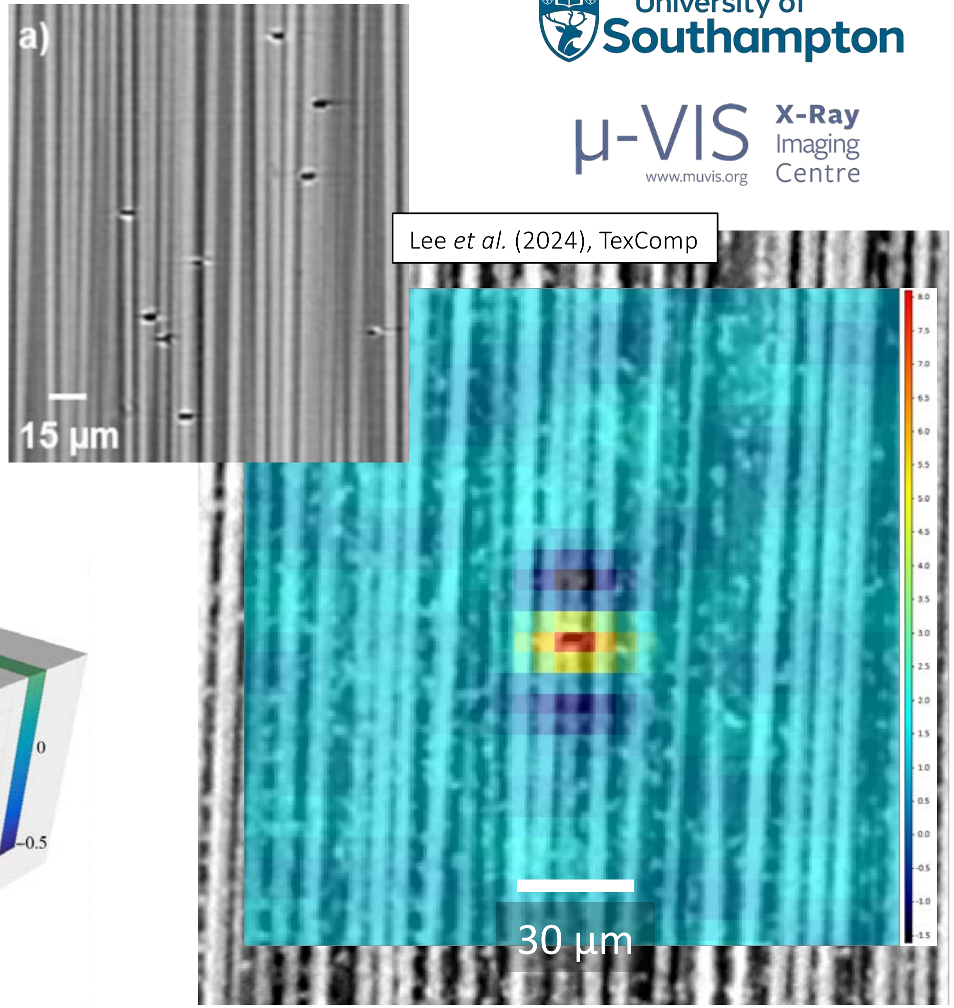
DVC applications...



Volumetric strain mapping in sheared soils



Bull *et al.* (2020), Proc. Roy. Soc. A



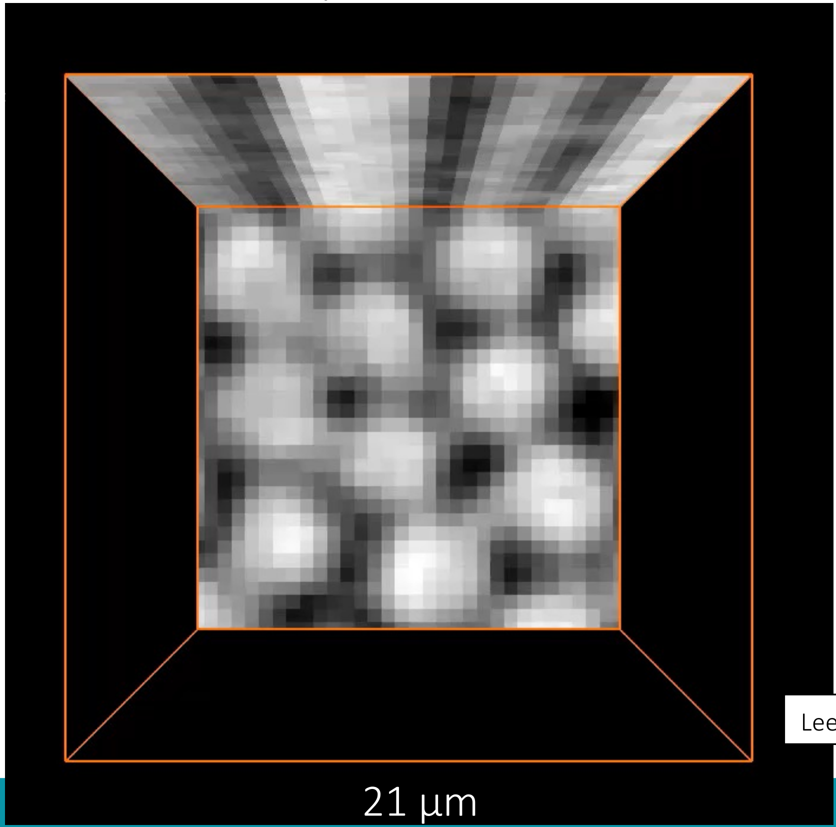
Lee *et al.* (2024), TexComp

CFRP Ineffective length assessment (SiO_2 doped ~ 2.3 v%)

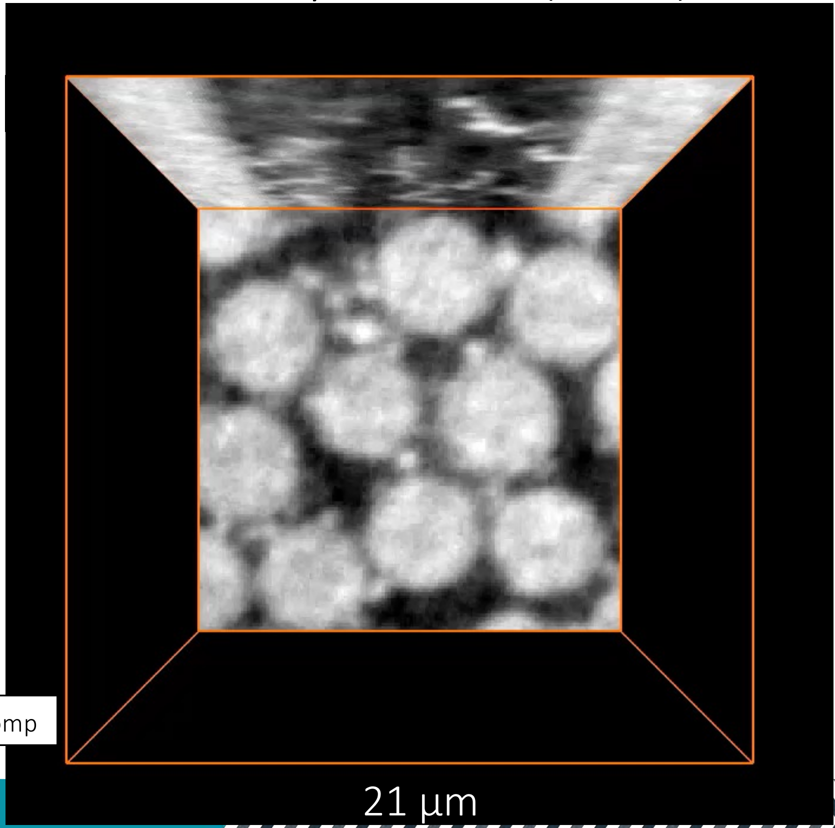
CFRP – Next Steps

DVC cubic sub-volume with a 21 μm edge length

650 nm synchrotron (ID19)



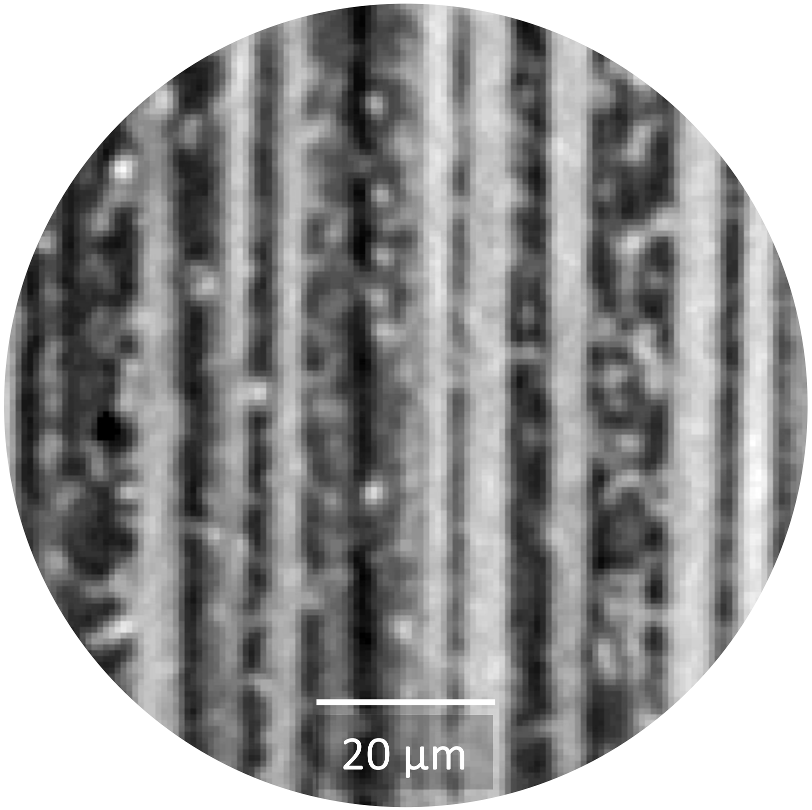
150 nm synchrotron (ID16B)



Lee, *et al.* (2024), TexComp

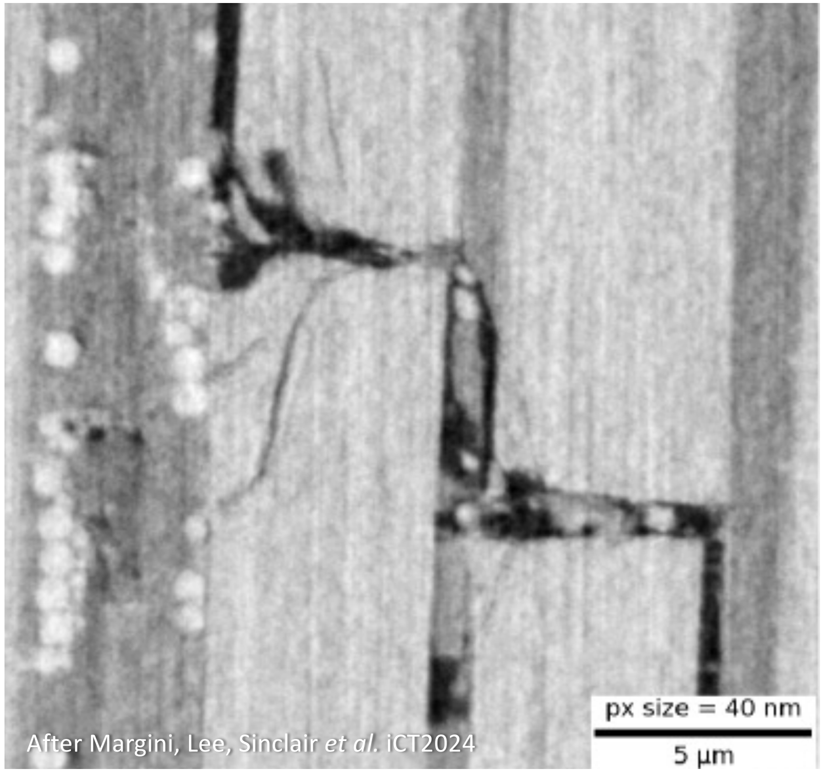
CFRP – Next Steps

650 nm Synchrotron (ID19)
Absorption based tomography



⇔

40 nm Synchrotron (ID16B)
Ptycho-tomography



CFRP fibre fracture & DVC, 40nm resolution

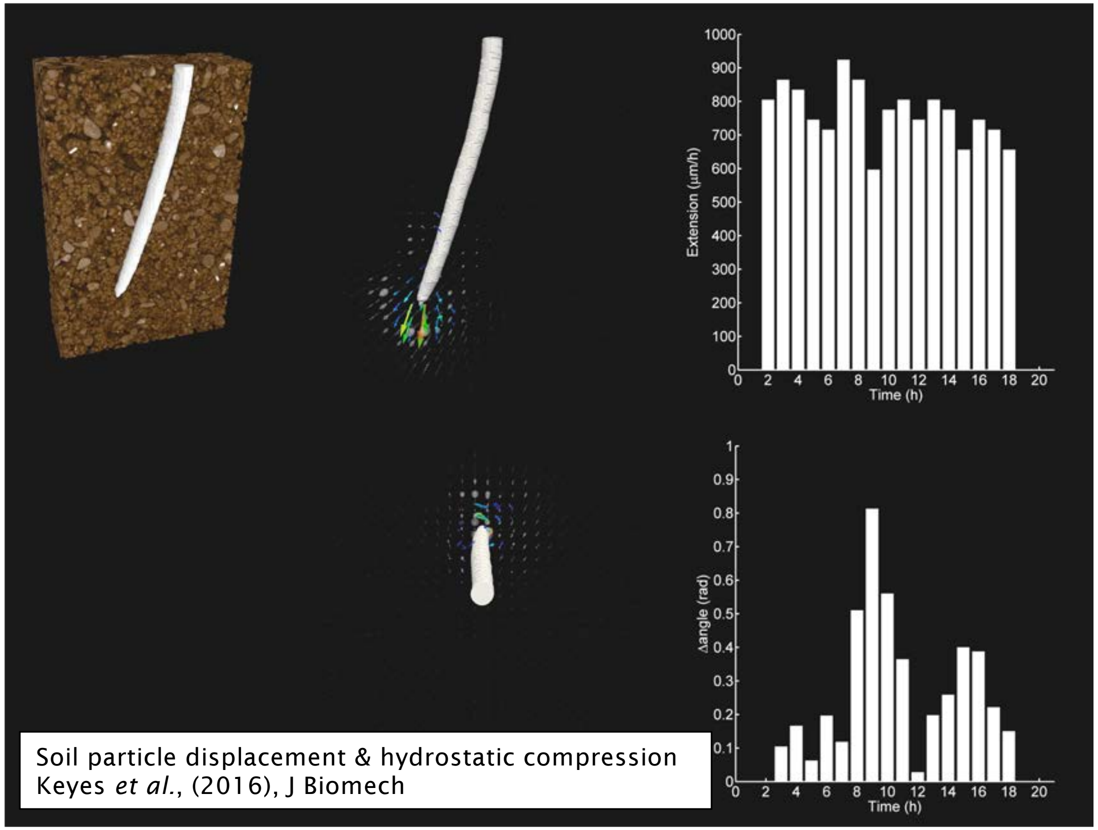
Data perspective

Data processing

University of Southampton

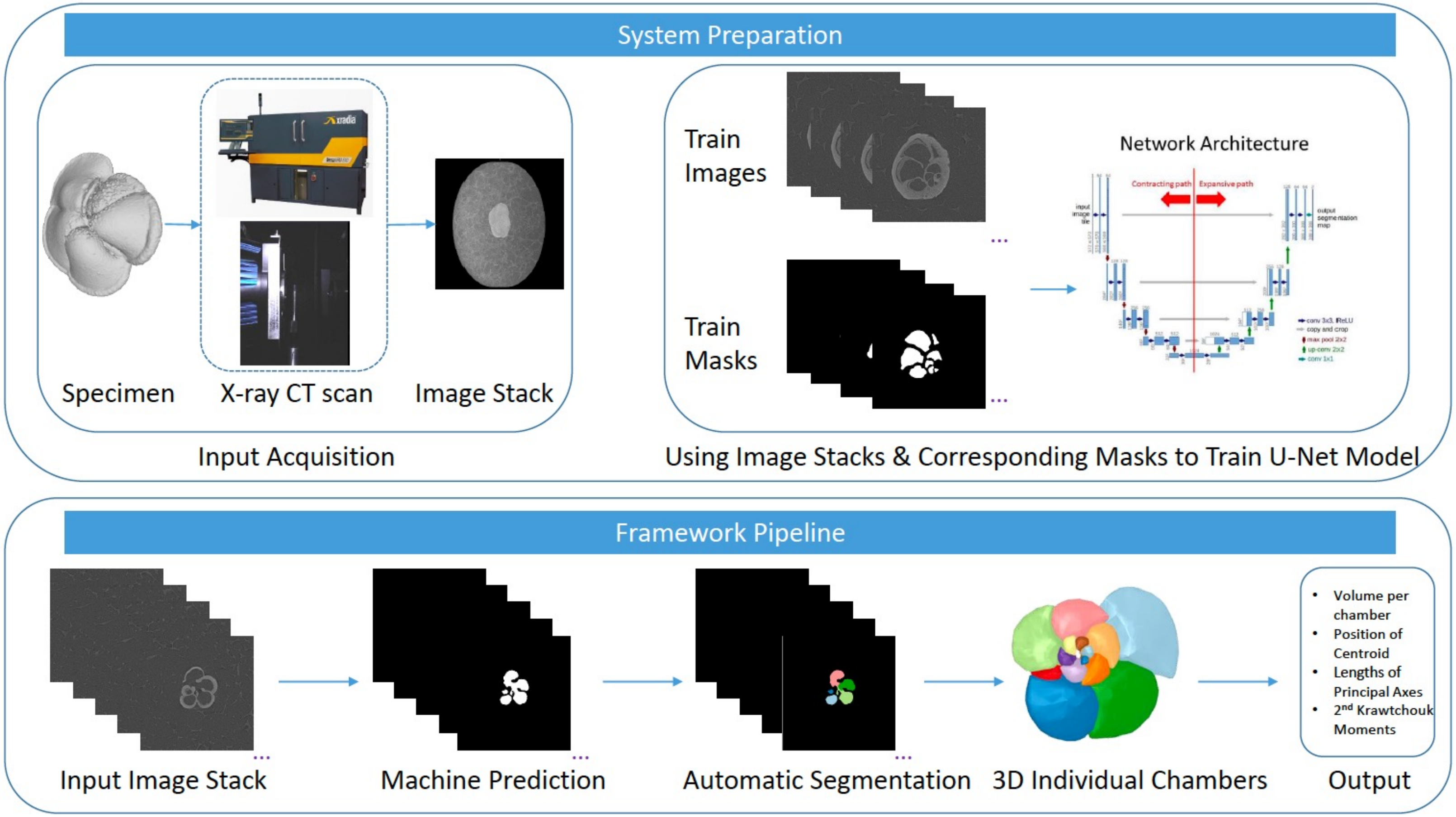
μ-VIS X-Ray Imaging Centre www.muvis.org

- ‘Advanced’ reconstruction
- Visualisation
- Segmentation
- Morphometry
- Metrology
- Image correlation
- Meshing & modelling
- Correlative imaging
- *Data and meta-data archiving*
- ***Numerous*** *of commercial and non-commercial tools to support & confuse users...*



Soil particle displacement & hydrostatic compression
Keyes *et al.*, (2016), J Biomech

Analysis & ML

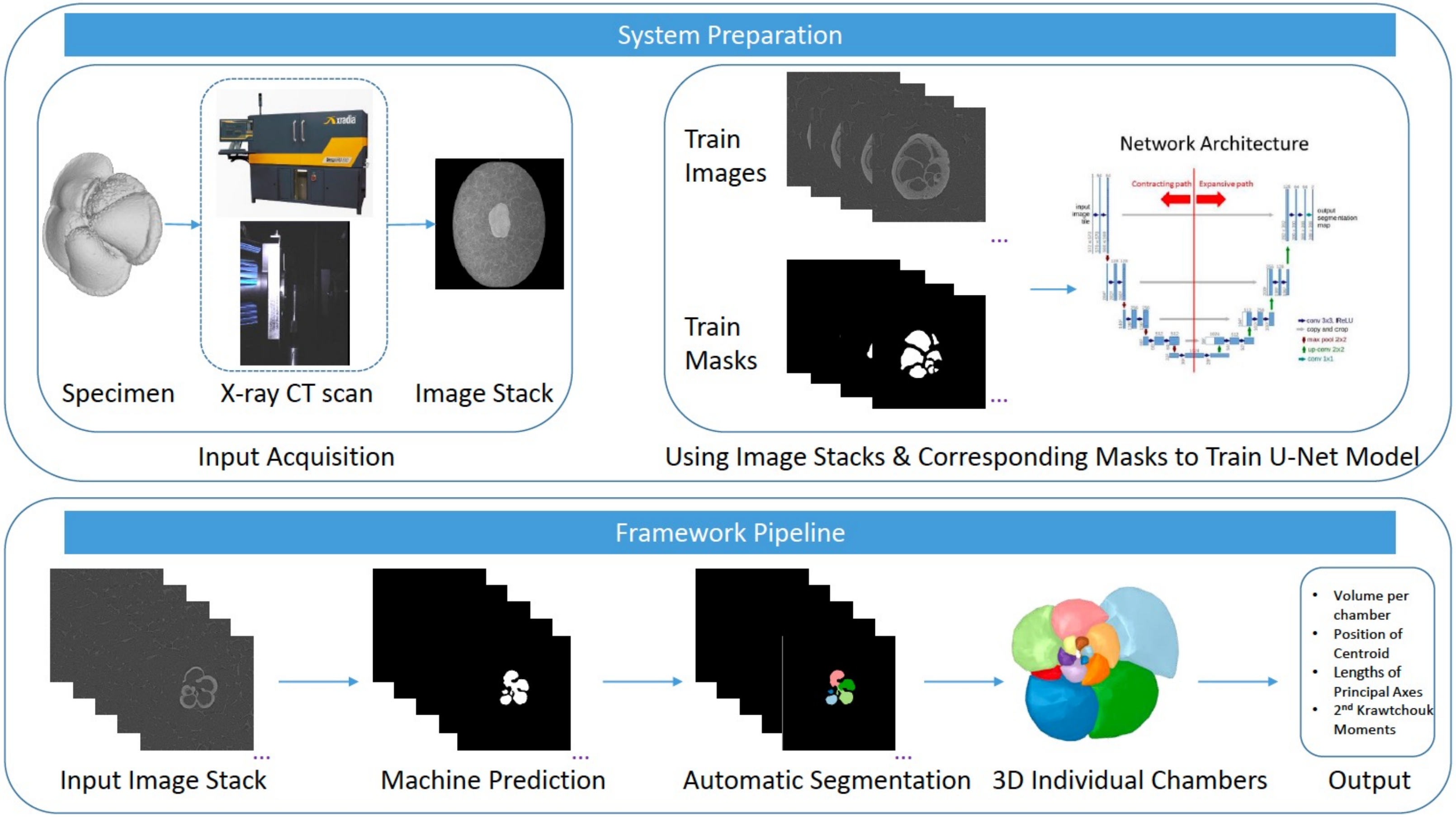


Zhang, Ezard *et al.*, (2020), SSIAI 2020, 30-33

- Structure analysis to inform ***fundamental models of speciation & evolution***
  - Count & size of voids
  - Quantify growth rates
  - Classify & quantify divergence

Planktonic forminifera microfossil

Analysis & ML



Zhang, Ezard *et al.*, (2020), SSIAI 2020, 30-33

- Structure analysis to inform ***fundamental models of speciation & evolution***
  - Count & size of voids
  - Quantify growth rates
  - Classify & quantify divergence

2,600 samples scanned and analysed
-> Machine Learning tool developed in Matlab & Python
800+ times faster than conventional analysis

-> *Enabled by compute capabilities*

Analysis & ML

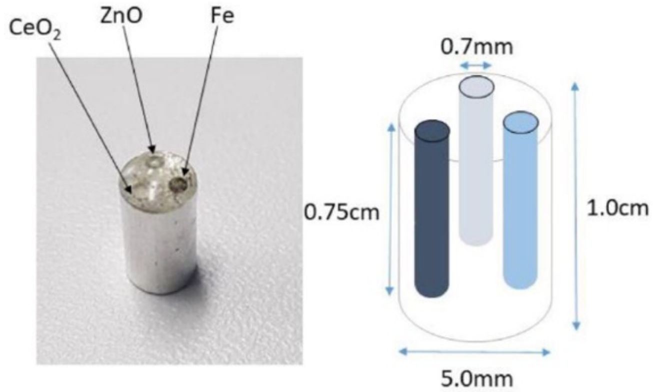
- Machine Learning ***can*** solve many data problems!

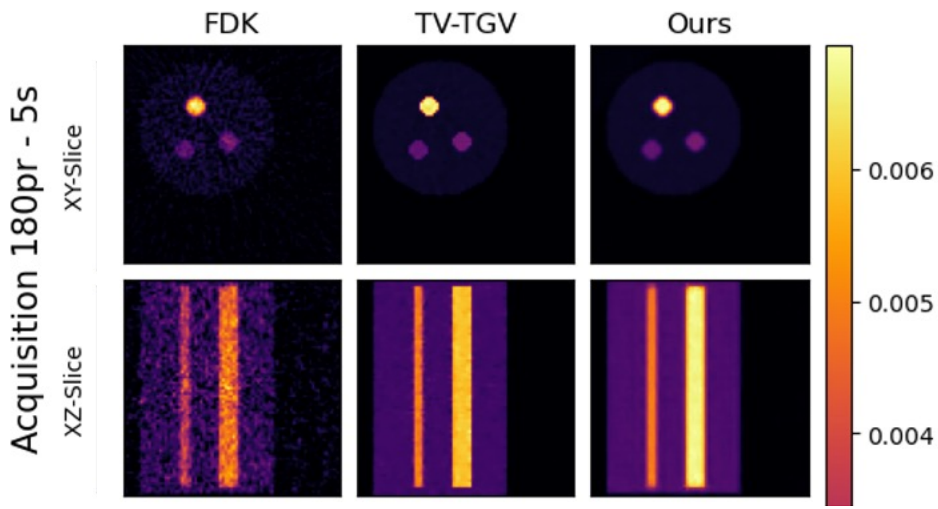
- Highlights for current/future XCT development
    - Acquisition (e.g. denoising)
    - Reconstruction (e.g. sparse data)
    - Analysis/segmentation (accuracy -> speed)

- Challenges:
    - Finding the right tool, for routine use?
    - Reliable/trustworthy?
    - Training data?

But this is not just an XCT problem of course
➜ An ongoing multi-disciplinary challenge for imaging experts, domain users, computer scientists, statisticians/applied mathematicians...

Unsupervised denoising of energy sensitive (colour) XCT



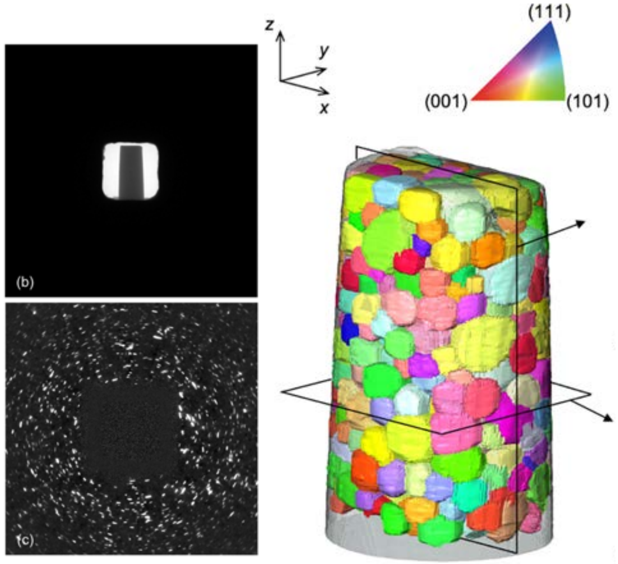


Kumrular & Blumensath, ToScA2024

Future

Advanced modalities – NXCT

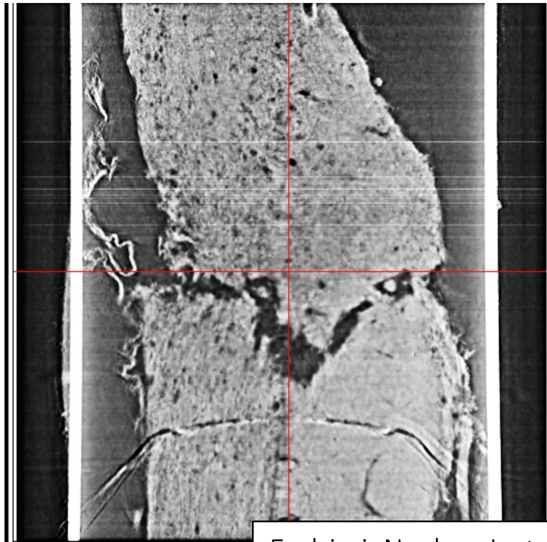
Manchester



- Diffraction Contrast Tomography (DCT)
- Zeiss Versa 620 DCT
- Grain size down to ~30 µm
- Can reconstruct most crystal structures
- Automated reconstruction

McDonald *et al.*, Scientific Reports volume 5, 14665 (2015)

UCL



- Multiple modalities including Talbot-Lau, Speckle, propagation, Zernike etc.
- Contrast on changes in refractive index
- Can be challenging to analyse

Endrizzi, Nuclear Inst. and Methods in Physics Research, A 878 (2018) 88–98

- **The future is bright!**
- More and more, higher dimensional data...

Remember 'big'?

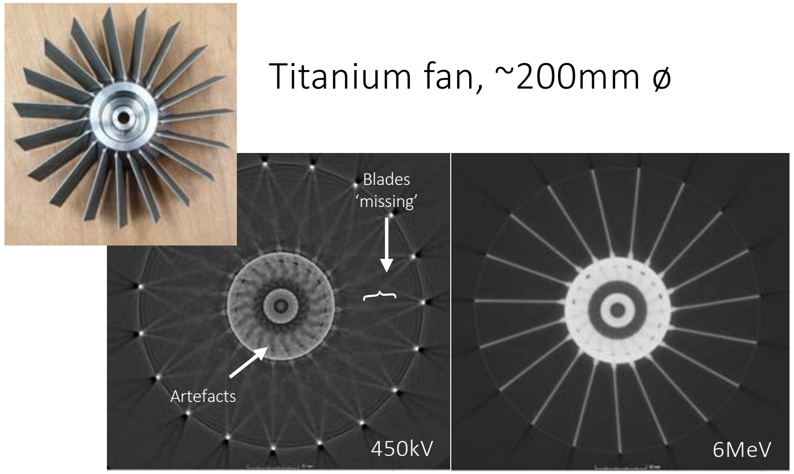
Courtesy Janice Dulieu-Barton

https://youtu.be/vifwoQa0G6A

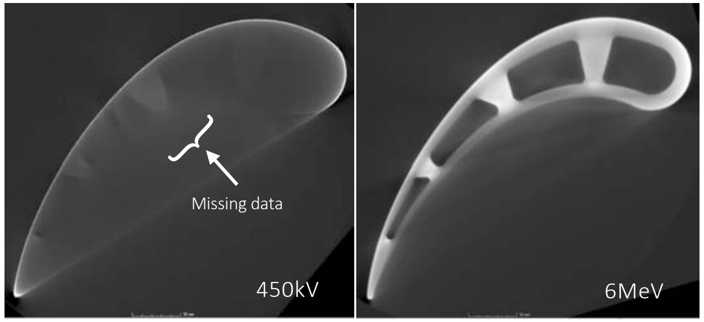
Measuring the unmeasurable

- Shift from keV to MeV...

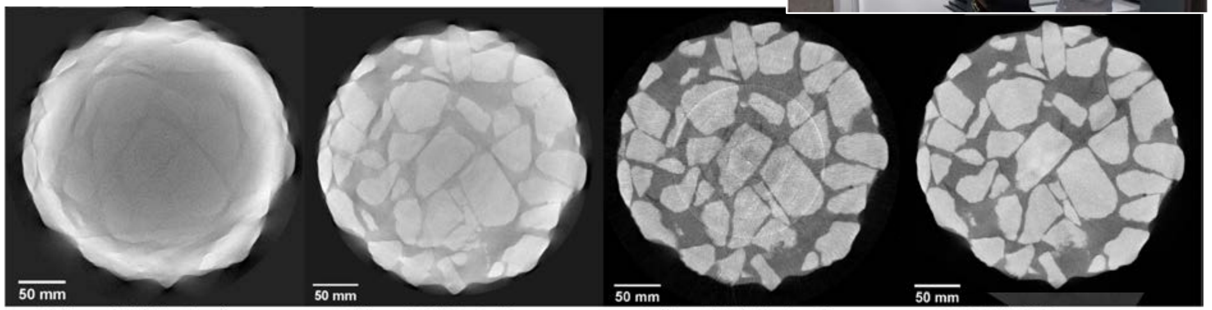
Titanium fan, ~200mm ø



Steel turbine blade, chord length ~240mm, wall thickness ~10mm



Railway ballast (crushed granite) ~270mm ø



- Collim. 450 kV microfocus
- Flat panel detector
- ~0.320 mm pixel size
- **~7h scan**

- Collim. 450 kV minifocus
- Flat panel detector
- ~0.370 mm pixel size
- **~12h scan**

- Collim. 450 kV microfocus
- CLDA detector
- ~0.340 mm pixel size
- **~200h scan**

- 6 MeV LINAC
- Flat panel detector
- ~0.100 mm pixel size
- **~2h scan**

A UK MeV XCT SERVICE...

University of Southampton

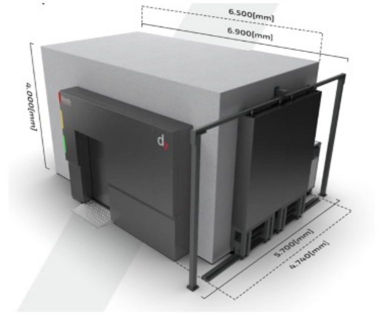
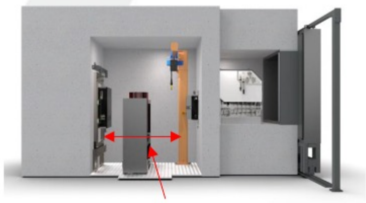
μ-VIS X-Ray Imaging Centre
www.muvis.org

High Energy Radiography And XCT for Large Engineering and Science - HERACLES

- Open access for industrial & academic users
- 9 MeV Linear accelerator (LINAC) source
    - Penetration x10 – 100 improved over conventional X-ray tubes
    - *Solid* metal: 50-60mm steel/Ni, 20mm tungsten, >100mm
- Rotate stages up to 1 ton capacity
- Maximum imaging volum
- Maximum ob
- E

Interested? email:
i.sinclair@southampton.ac.uk

SMALL
diondo, Germany
Weight: ~350t

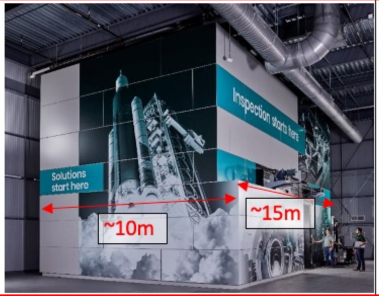



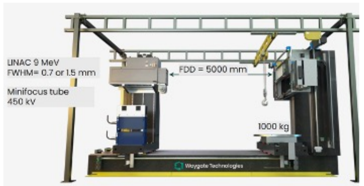
FDD ~ 3000mm
200kg rotation stage

MEDIUM-SMALL
diondo, Germany
Weight: ~700t

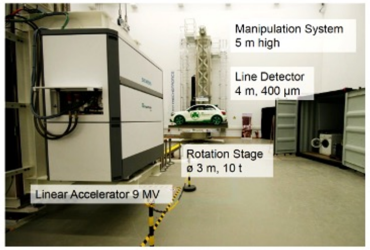
FDD = 4000mm
200-500kg rotation stage

MEDIUM-LARGE
Waygate/GE, USA
Weight: ~1600t





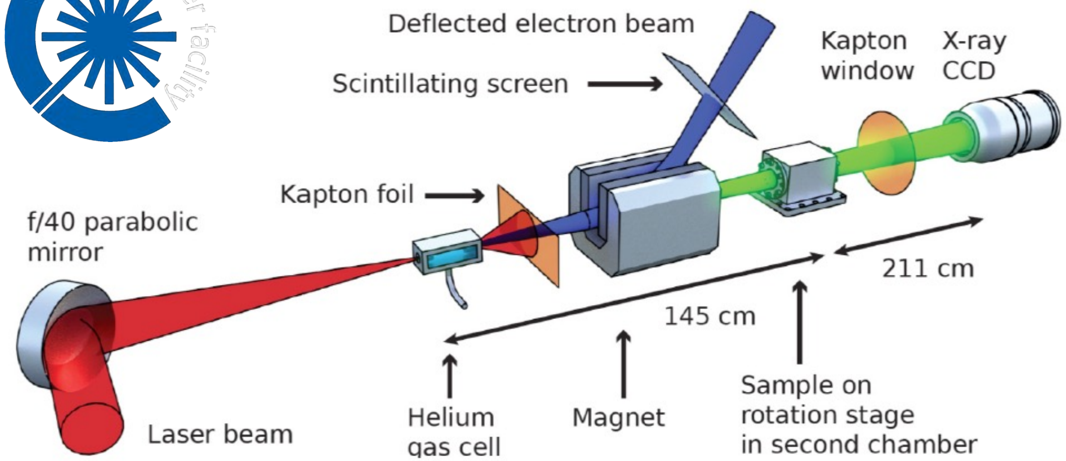
LARGE
Fraunhofer, Germany
Weight: ??

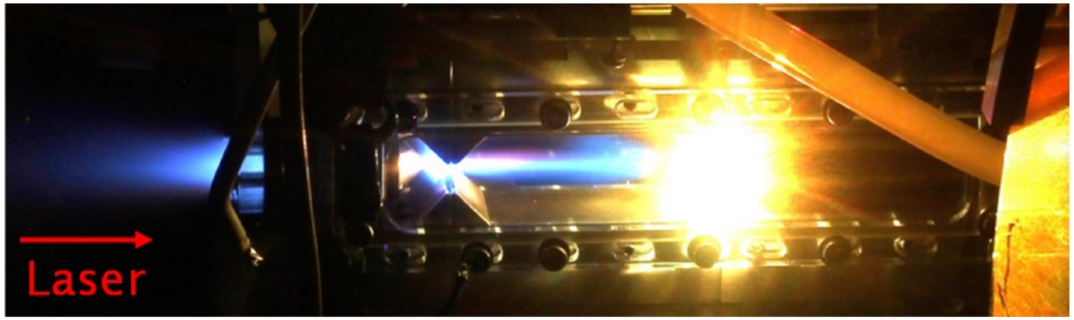


FDD = 12000mm

N.B. Specific systems shown for illustration only

STFC EPAC project: MeV X-ray via laser





Compact (cm-scale) GeV electron accelerator driven by a PW-class high power laser

Extreme accelerating fields created in plasma

X-rays with **micron-source-size**, sub-
and **tuneable energy (10 ke**

Short pulse

Interested? email:
CLFindustry@stfc.ac.uk

Grateful acknowledgements to...

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University of Southampton

THANK YOU!

Any questions?

www.muvis.org

www.nxct.ac.uk

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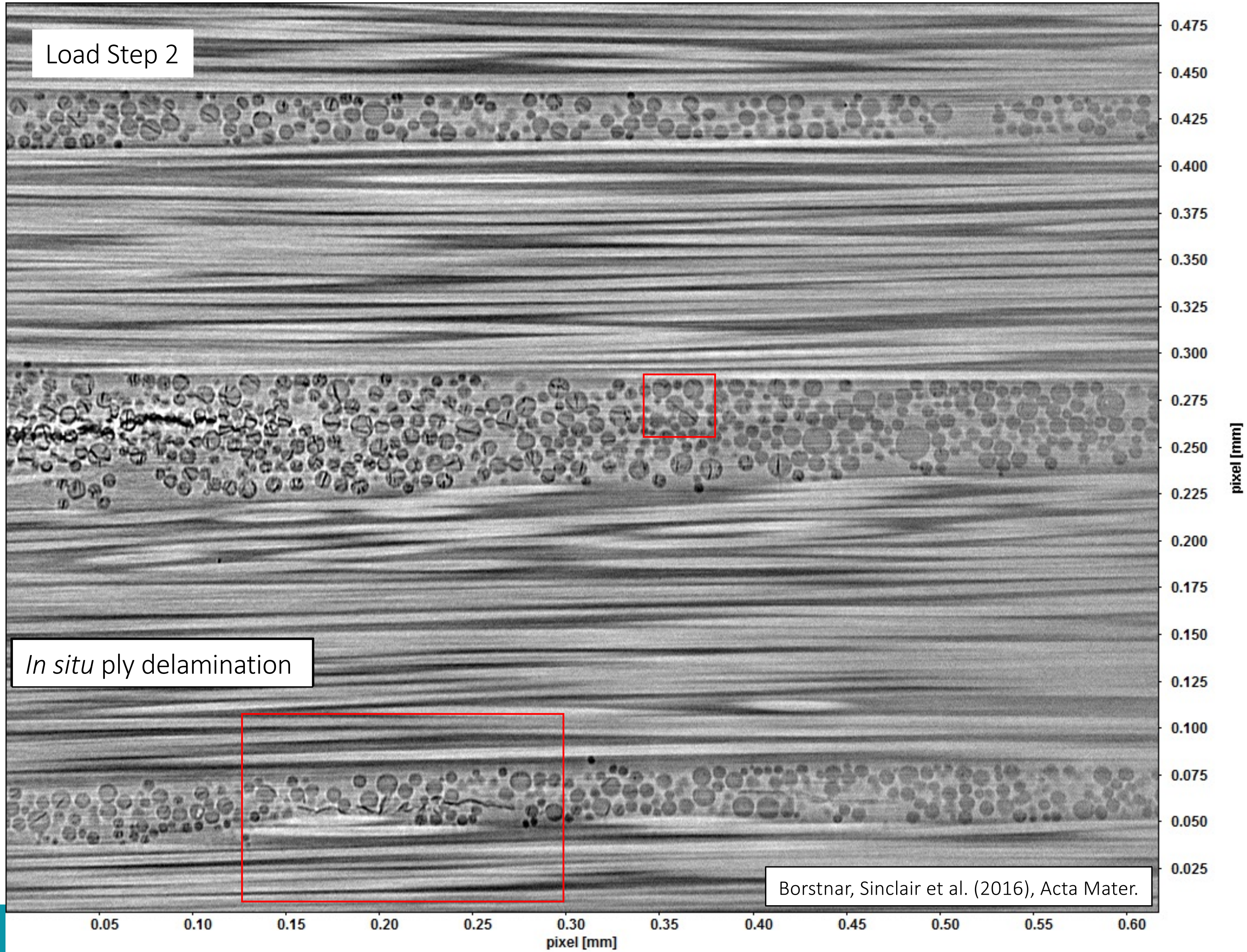
NXCT | National X-ray Computed Tomography

μ-VIS X-Ray Imaging Centre www.muvis.org

3D XRH | X-ray Histology www.xrayhistology.org

CFRP & DVC

- Thermoplastic toughening
  - Interply particles
- Micromechanical modelling and optimisation
  - Mode I toughness
- DVC using intrinsic microstructure



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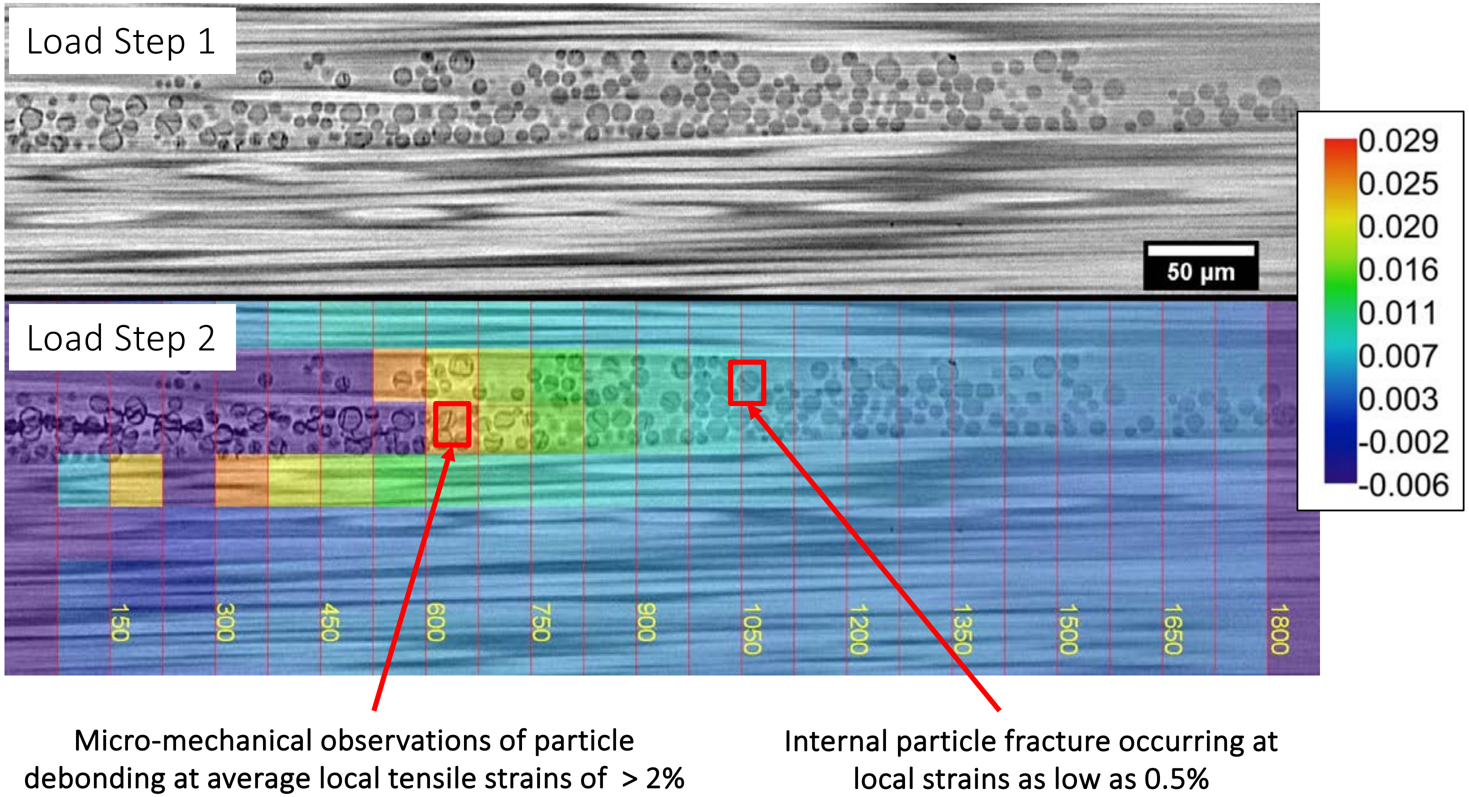

Borstnar, Sinclair et al. (2016), Acta Mater.