MANCHESTER 1824

The University of Manchester

# *In situ* Fracture Studies in Reactor Materials


## Paul Mummery

**Nuclear Graphite Research Group**

**Dept of Mechanical, Aerospace and Civil Engineering,**

**University of Manchester**

MANCHESTER 1824
The University of Manchester

# Outline

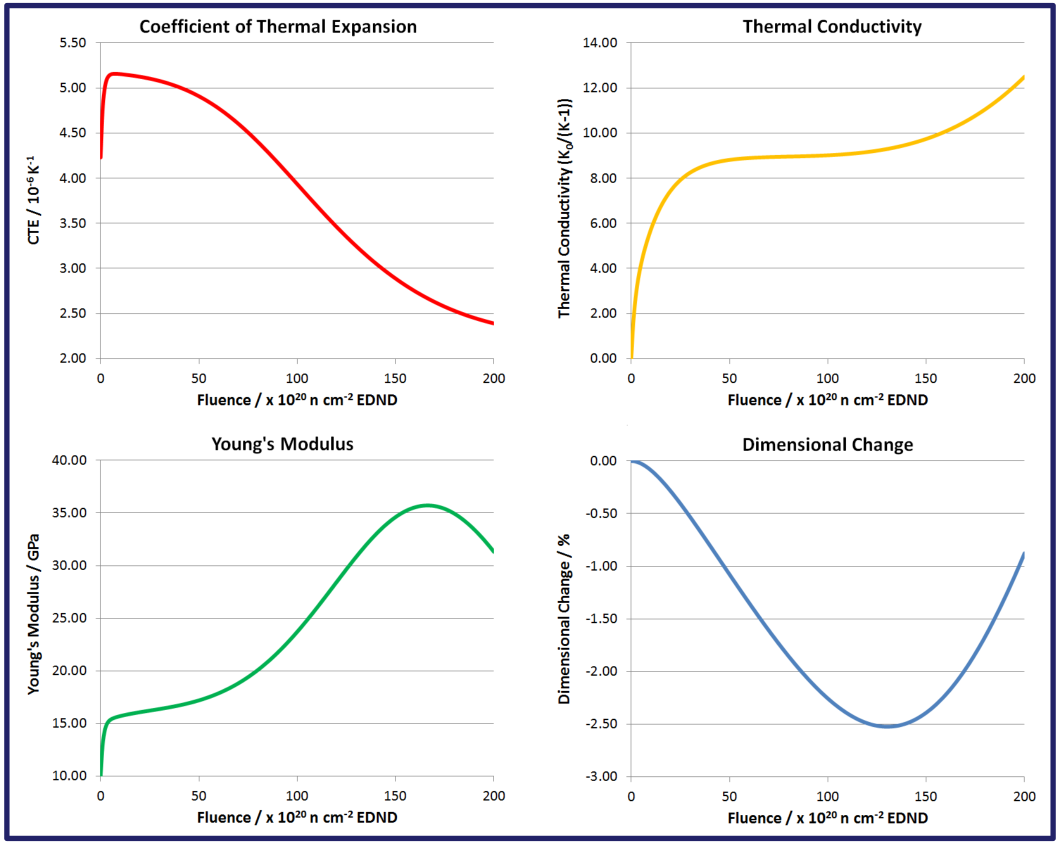
- Why the need for crack growth studies in materials for reactors in virgin and irradiated state
- Imaging facilities
  - What is tomography?
- Crack growth in virgin and irradiated graphite
  - *In situ* tomographic studies
  - Toughness determination
- Crack growth in toxic materials
- Conclusions
- Acknowledgements

# Why need for fracture studies?

- Mechanical behaviour and failure mechanisms are affected by irradiation
- Design rules, structural integrity calculations, and safety cases are often based on extrapolations from properties of virgin material
- It is necessary to assess the reliability of these extrapolation by (limited) experimentation
  - Doing fracture tests on large irradiated samples is a challenge…
  - Establishing procedures for safe transport, handling, testing, disposal of radioactive specimens is key

MANCHESTER
1824
The University of Manchester

# Property changes with irradiation

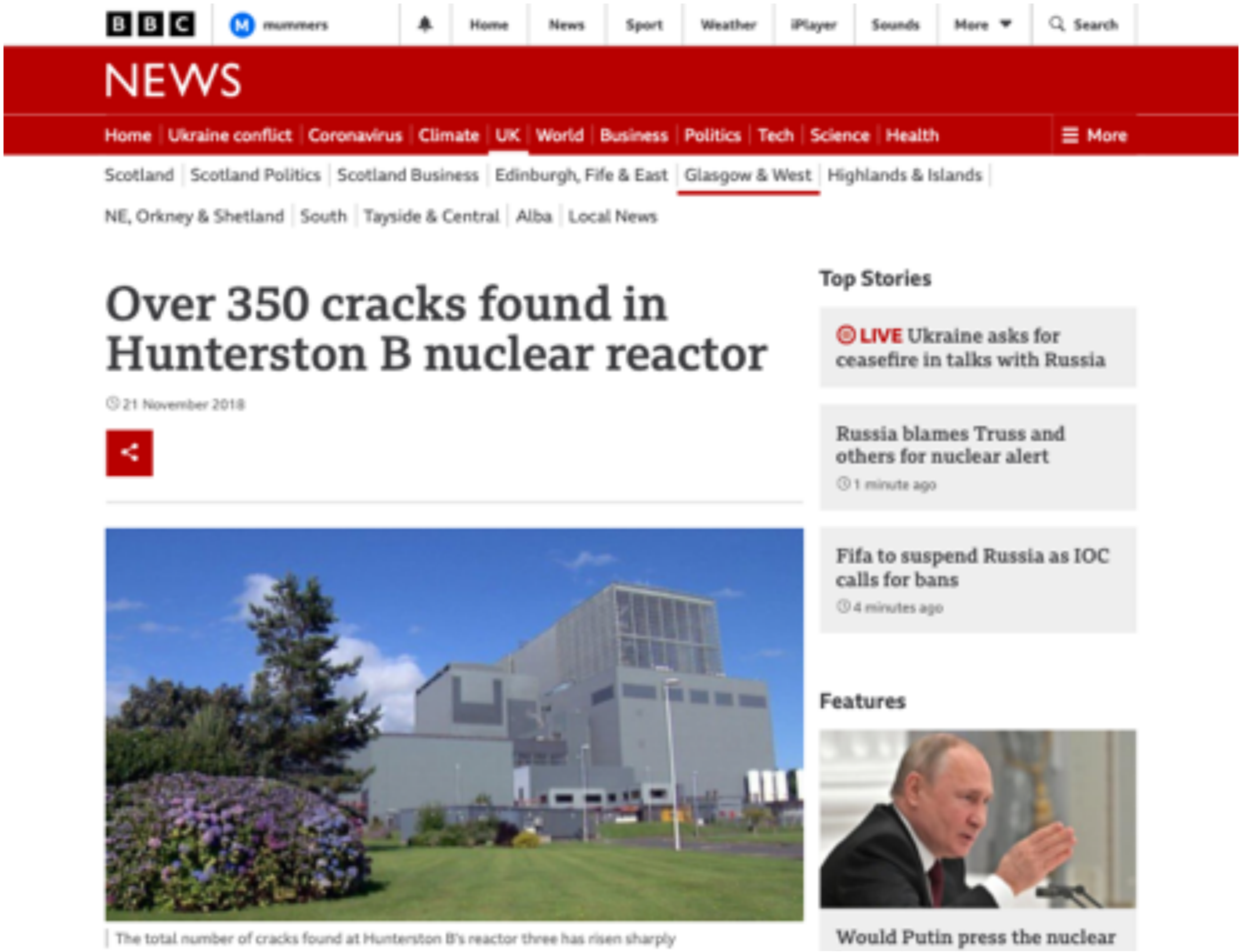



Prediction of behaviour in full scale components challenging

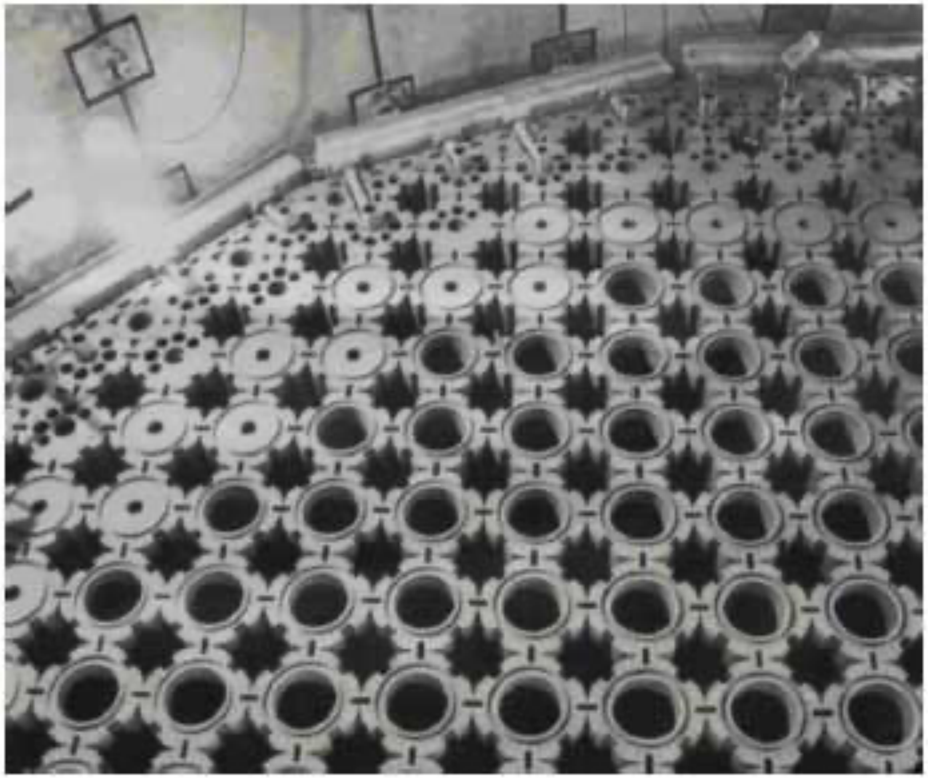
# Why need for fracture studies?

- Mechanical behaviour and failure mechanisms are affected by irradiation
- Design rules, structural integrity calculations, and safety cases are often based on extrapolations from properties of virgin material
- It is necessary to assess the reliability of these extrapolation by (limited) experimentation
  - Doing fracture tests on large irradiated samples is a challenge…
  - Establishing procedures for safe transport, handling, testing, disposal of radioactive specimens is key

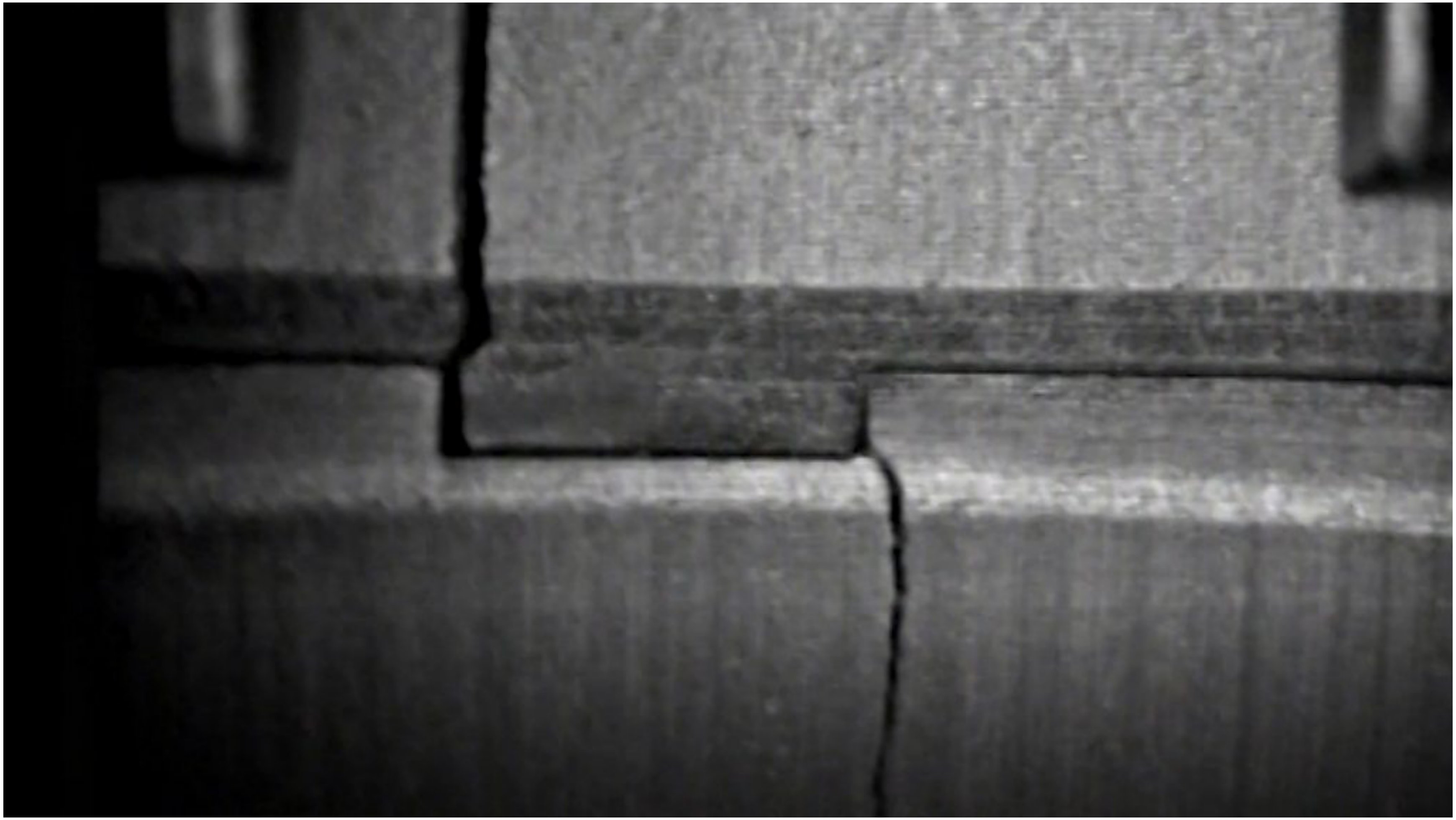
MANCHESTER 1824
The University of Manchester




Is it safe to continue operation?



AGR core is a complex, interconnected structure of large faceted bricks containing sharp corners



How do cracks grow? Do they impair critically safe operation?
Can we validate predictions of numerical models?

# Why need for fracture studies?

- Mechanical behaviour and failure mechanisms are affected by irradiation
- Design rules, structural integrity calculations, and safety cases are often based on extrapolations from properties of virgin material
- It is necessary to assess the reliability of these extrapolations by (limited) experimentation
  - Doing fracture tests on large irradiated samples is a challenge…
  - Establishing procedures for safe transport, handling, testing, disposal of radioactive specimens is key

The University of Manchester

# X-Ray Tomography

# What is X-ray Tomography?

- Transmitted intensity from a series of line projections of a cross section of the object at different angular orientations reconstructed to give **3-D map of x-ray absorption**
- Advantages
  - Non-intrusive
  - Good spatial resolution (currently $\approx$ 0.1 $\mu$m in lab; $\approx$ 5 nm at synchrotron sources)
  - Very sensitive to composition and density
  - Independent of specimen geometry
    - Can decouple $\mu$ and x

# What do you get?

# How can it be used?

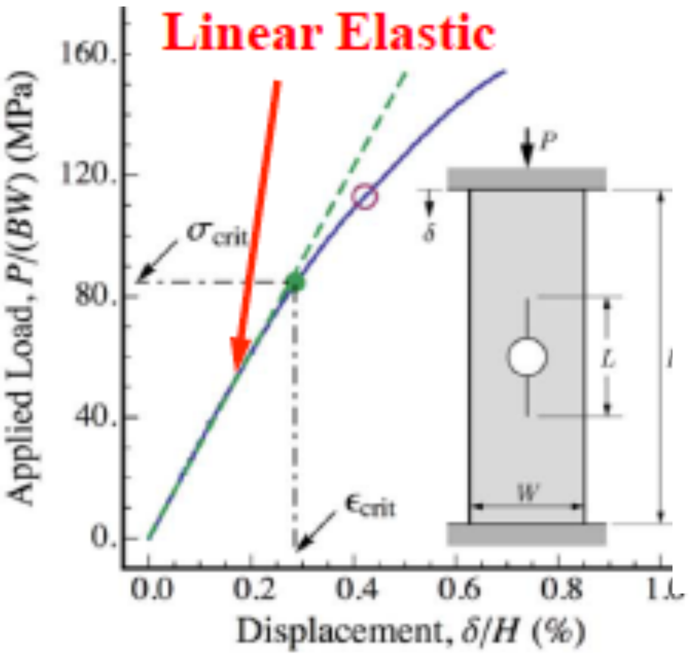
- Non-destructive 3D determination of structure
- *In situ* development of specimen (component, material) during environmental change
  - Loading, thermal, irradiation
  - Strain mapping through image correlation
- Basis for numerical model/digital engineering
  - Predictions based on actual structure
  - Solid mechanics; fluid dynamics; thermal transport

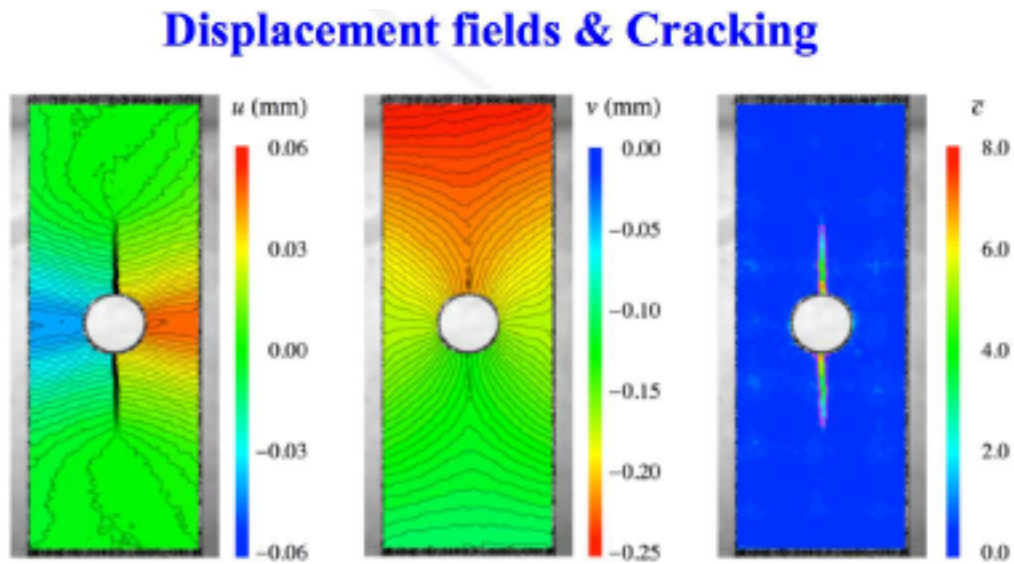
The University of Manchester

# CRACK GROWTH IN VIRGIN AND IRRADIATED GRAPHITE USING SYNCHROTRON X-RAYS IN A NOVEL GEOMETRY

The University of Manchester

# Test Geometry




- Easy to machine geometry
- Inherently stable crack propagation – enables tomography
- Measurement of toughness – properties and mechanisms

$$K_{IC} = \left(\frac{a_{top} + a_{bottom}}{2a}\right)^{1/2} \left\{\frac{1.1}{\left(1 + \frac{a_{top} + a_{bottom}}{2a}\right)^{3.3}}\right\} \sigma\sqrt{\pi a}$$

# Experimental Details

- **Specimen geometry:** 18 x 8 x 3 mm plates with a 2.8 mm hole in the centre.
- **Loading condition:** Uniaxial compression

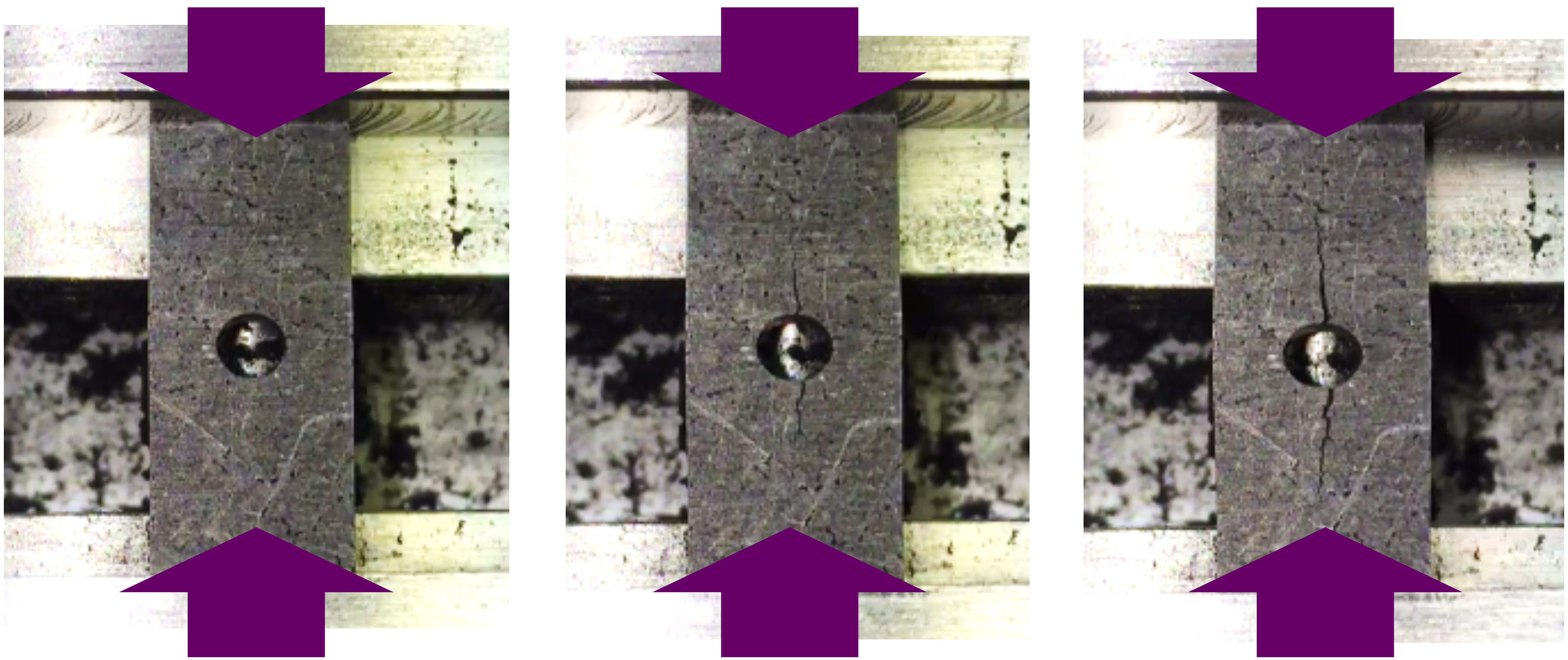
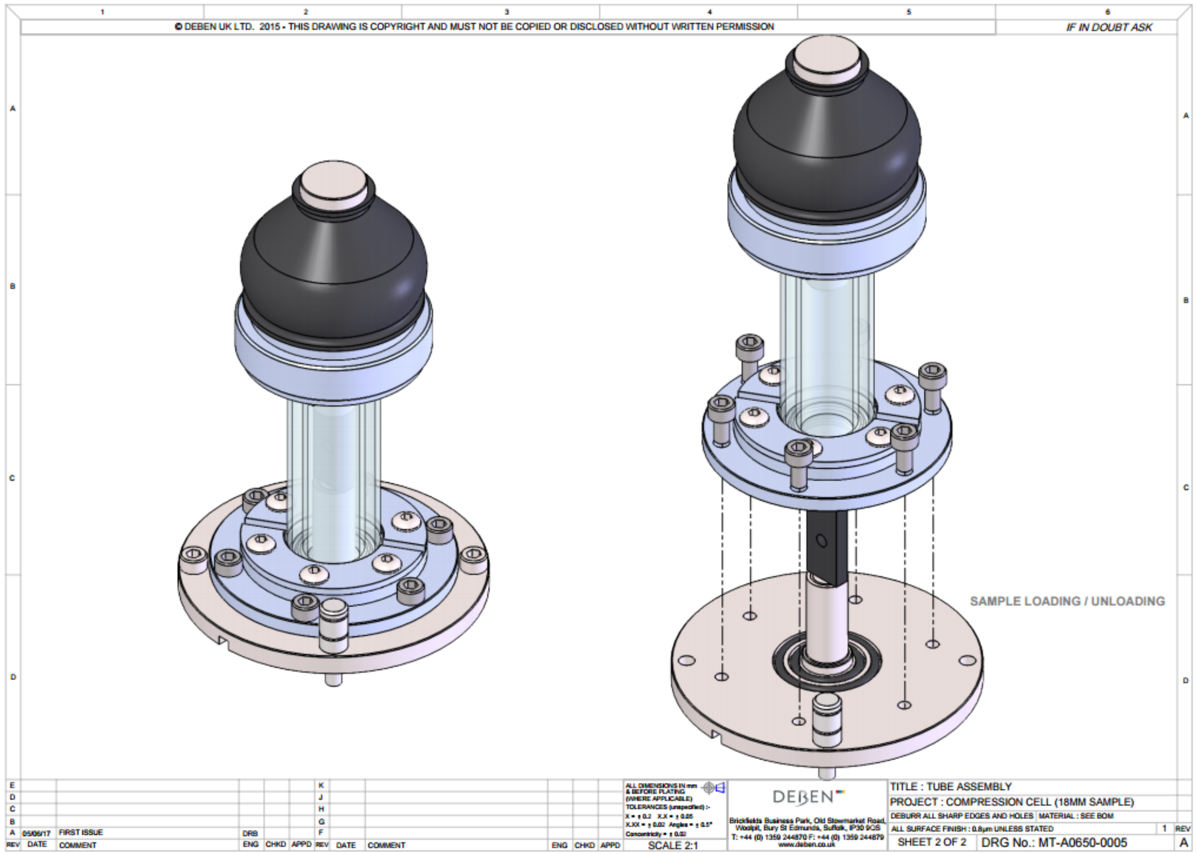


**Fig. 4:** The initiation and progressive growth of a crack around the hole in a plate of graphite in *in situ* SEM study

MANCHESTER 1824

The University of Manchester

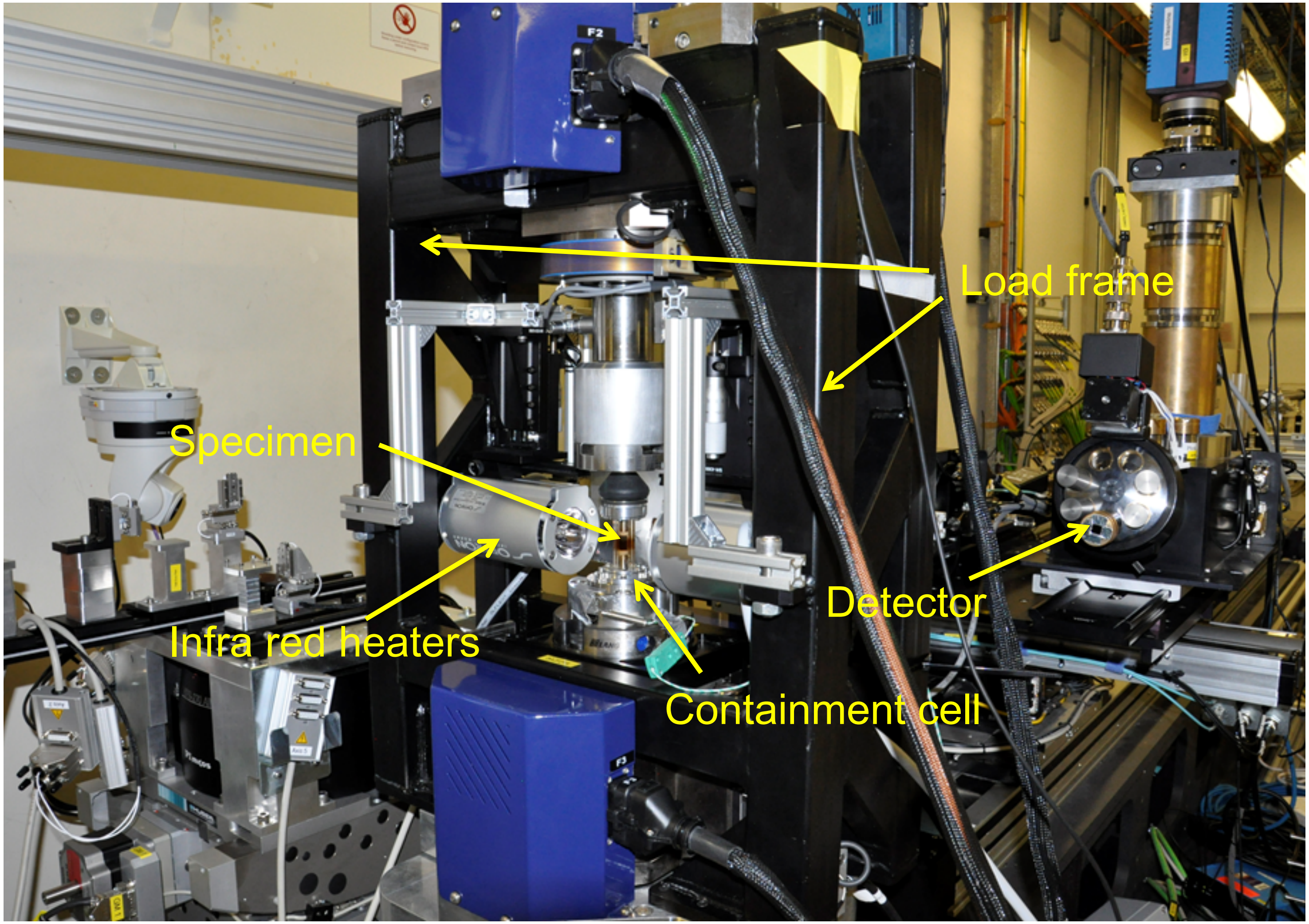
# Double-Walled Containment Cell



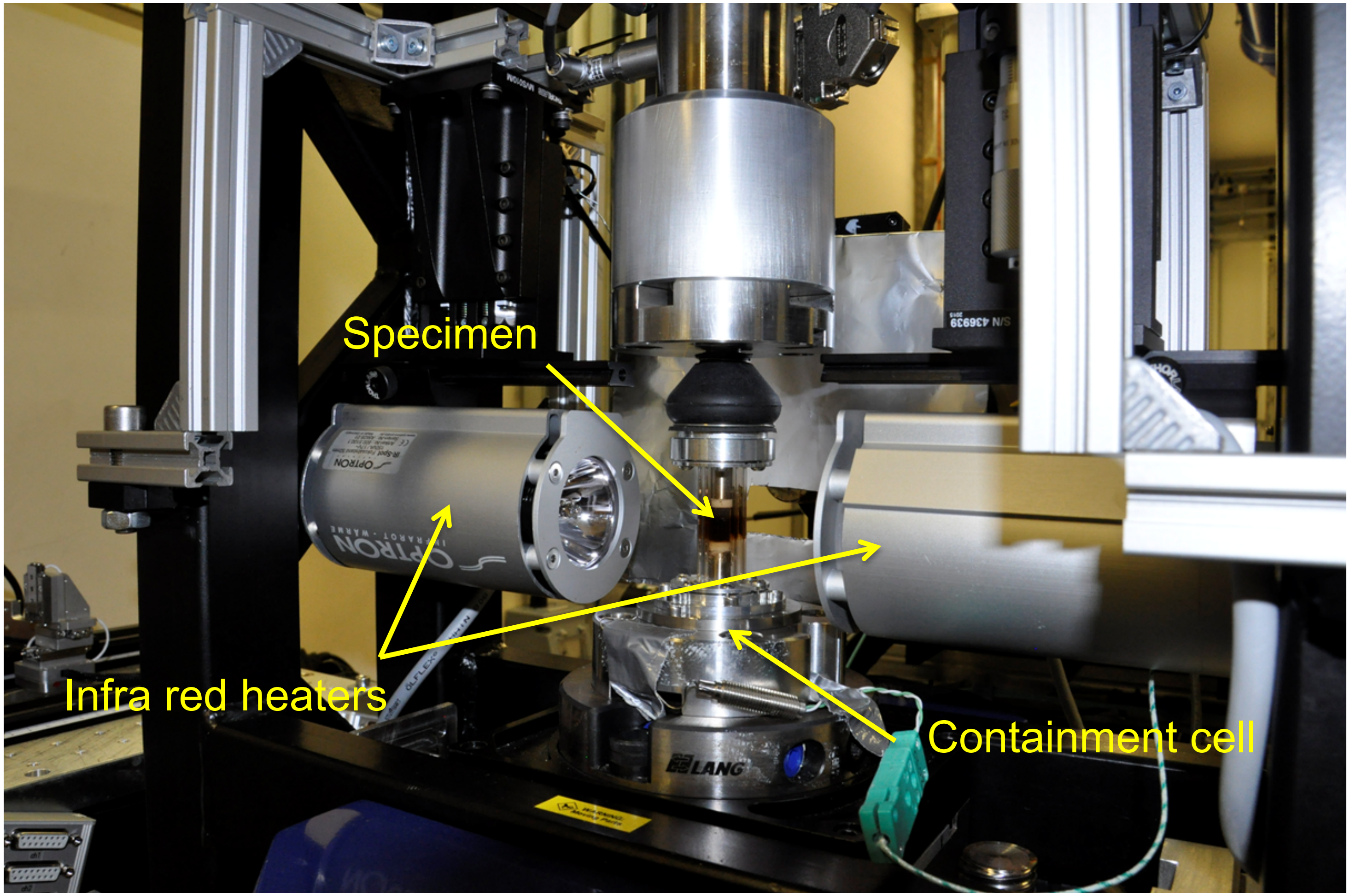

Designed in partnership with H&S group at DLS

**World first *in situ* tomographic study of crack growth in irradiated graphite**

# Experimental Setup: I13 Diamond Light Source



# Experimental Setup: I13 Diamond Light Source



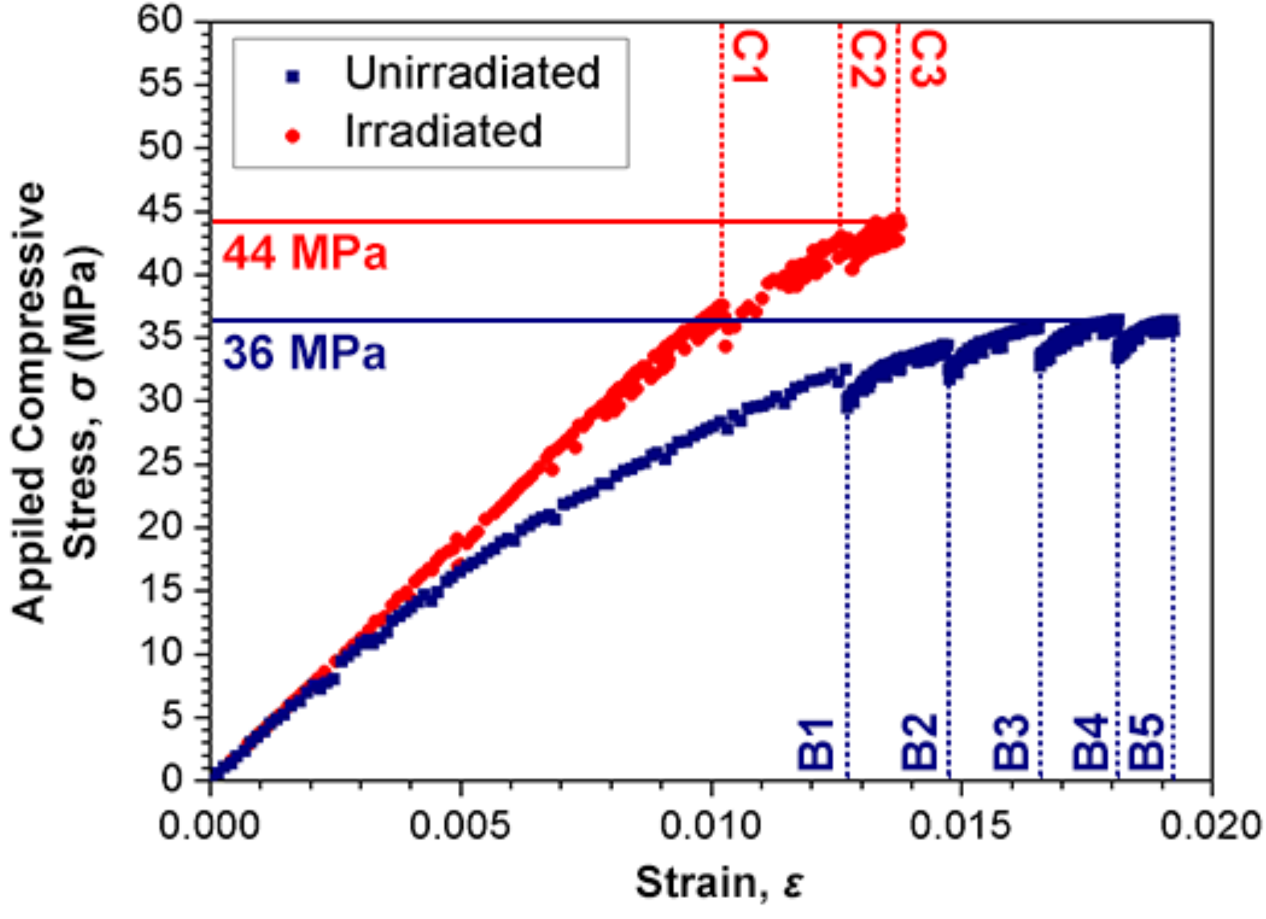
MANCHESTER 1824
The University of Manchester

# Experimental Details

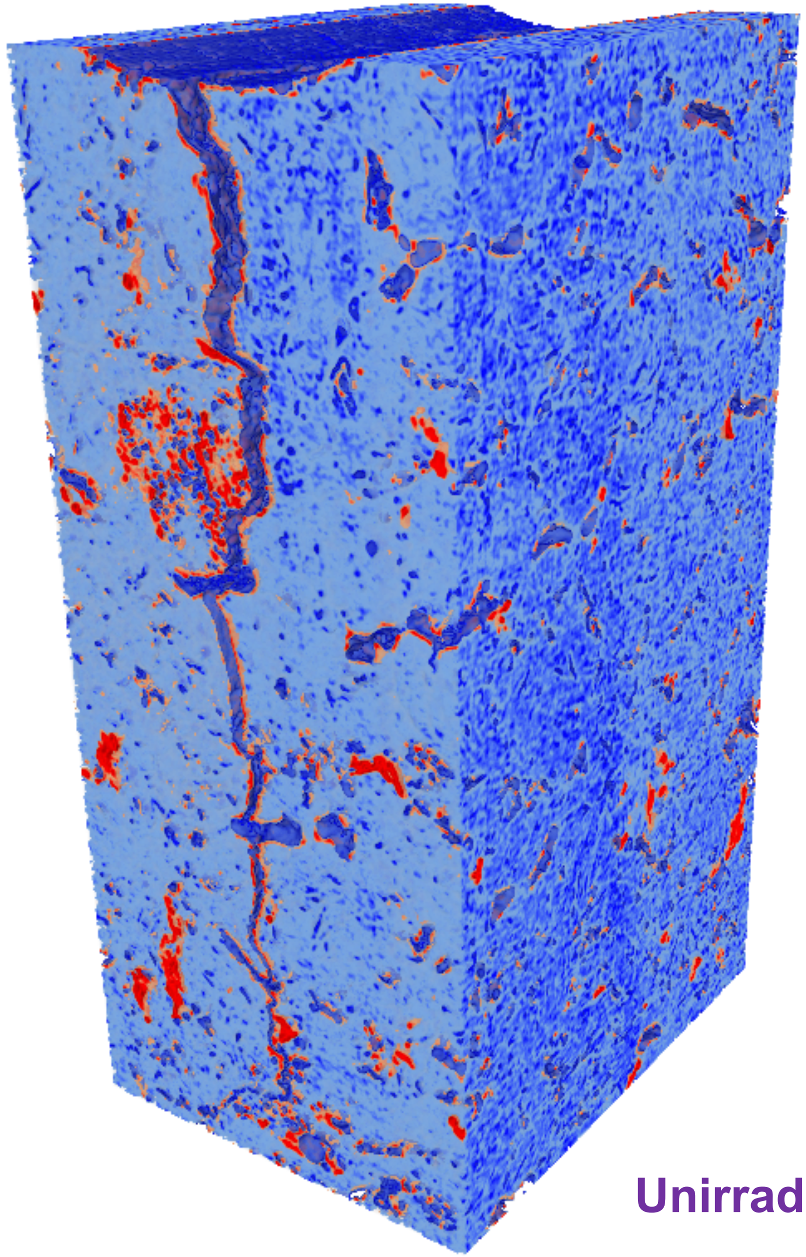
- **Specimen geometry:** 18 x 8 x 3 mm plates with a 2.8 mm hole in the Centre.
- H = 18mm, B = 8mm, W = 3mm, d = 2.8mm
- **Loading condition:** Uniaxial compression
- **Materials**:
  - Virgin Gilsocarbon (HPB)
  - Neutron Irradiated Gilsocarbon from HPB installed set
    - EDND 19.7 x $10^{20}$ n $cm^{-2}$; 4% weight loss
    - Machined from wings of WoF specimens
    - Measured bend strength 34.4MPa

Wade *et al. Carbon* **168,** 230-244 (2020)

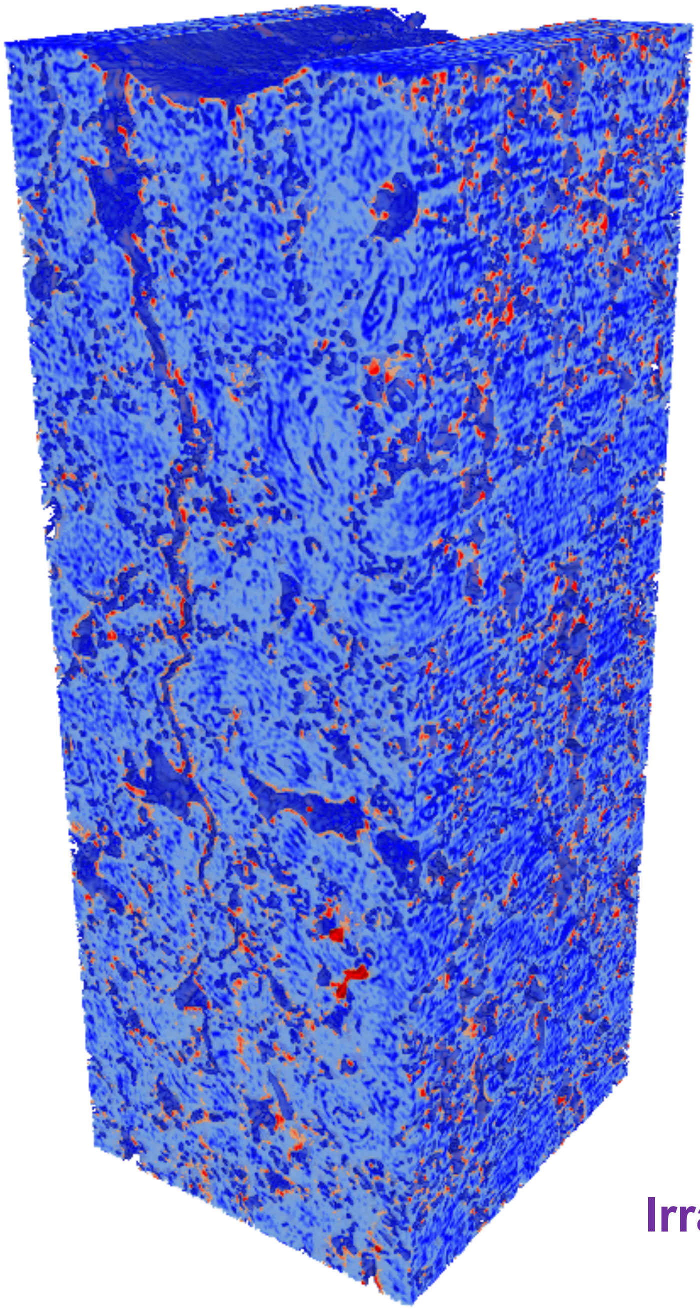
# Mechanical behaviour



MANCHESTER 1824
The University of Manchester



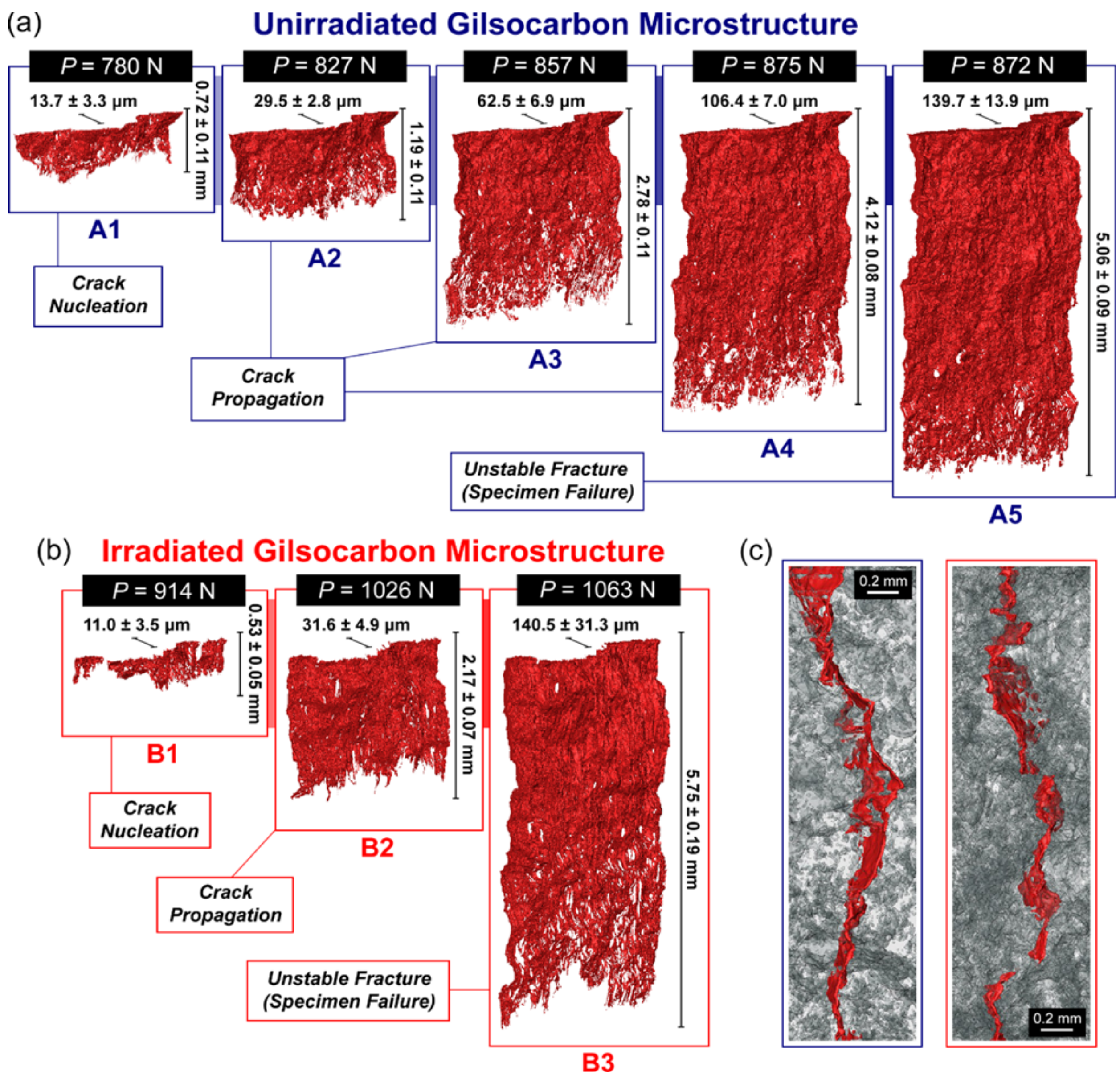
Unirradiated Gilsocarbon



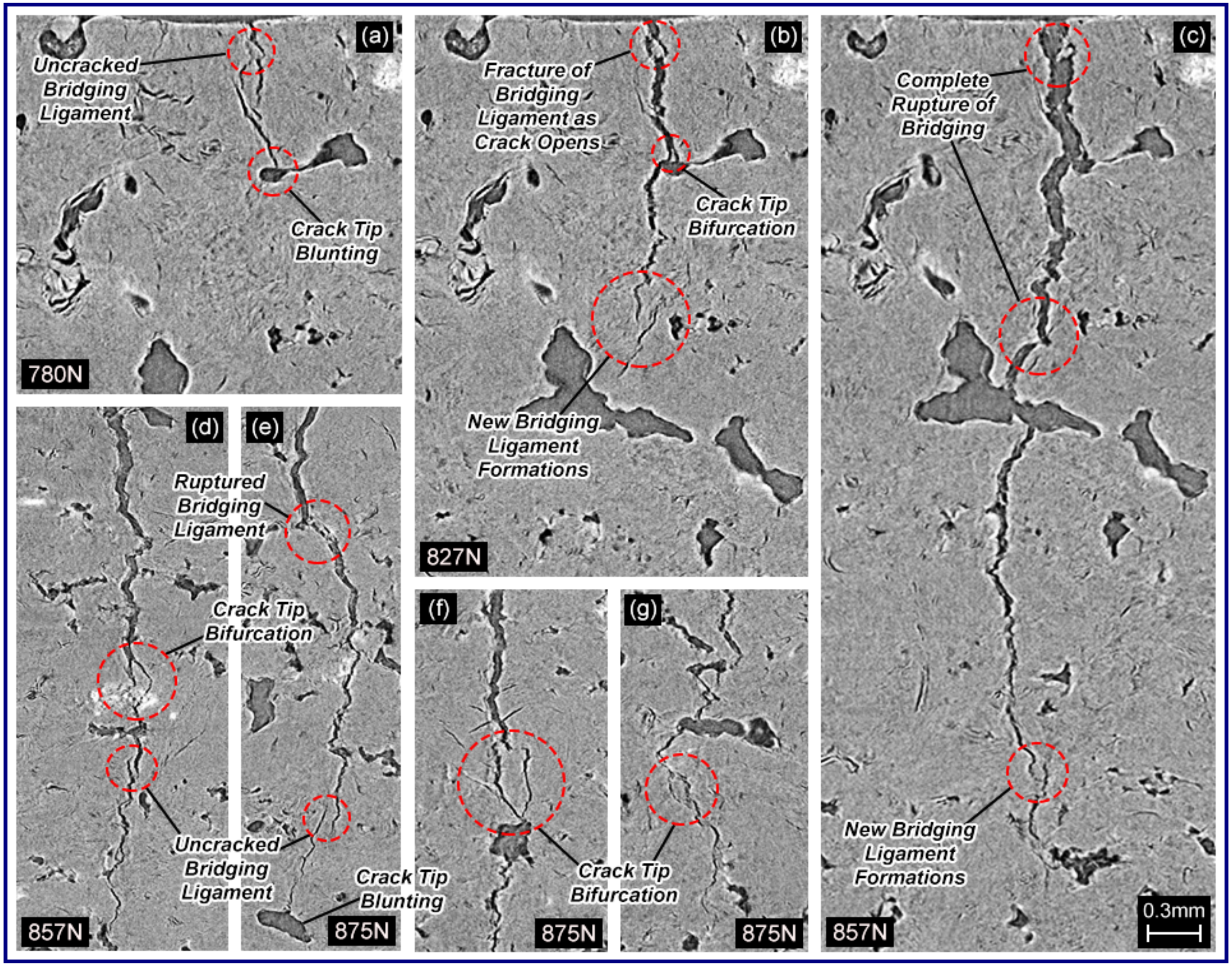
Irradiated Gilsocarbon

MANCHESTER
1824
The University of Manchester

# Crack geometries



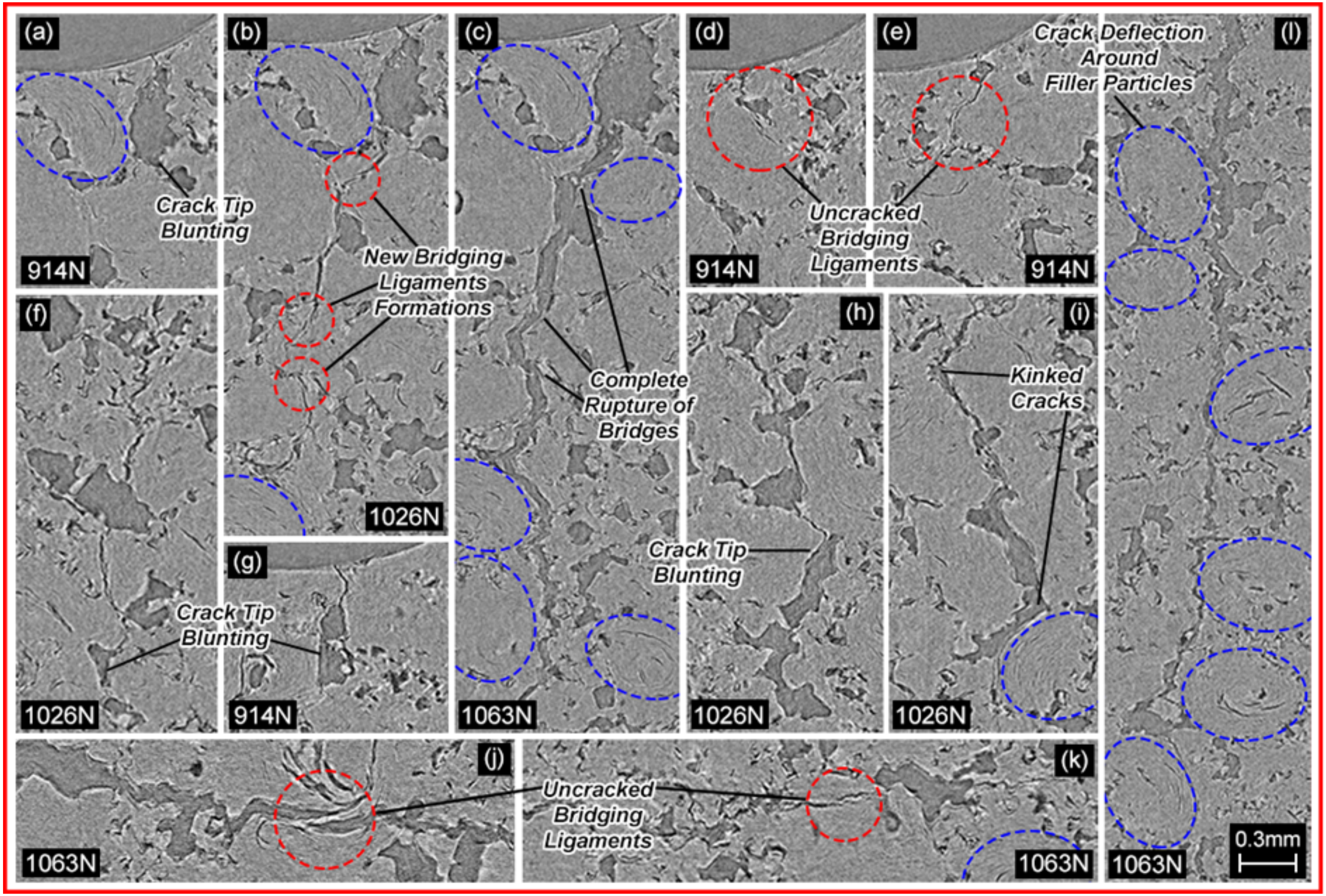
# Virgin crack path



MANCHESTER 1824

The University of Manchester

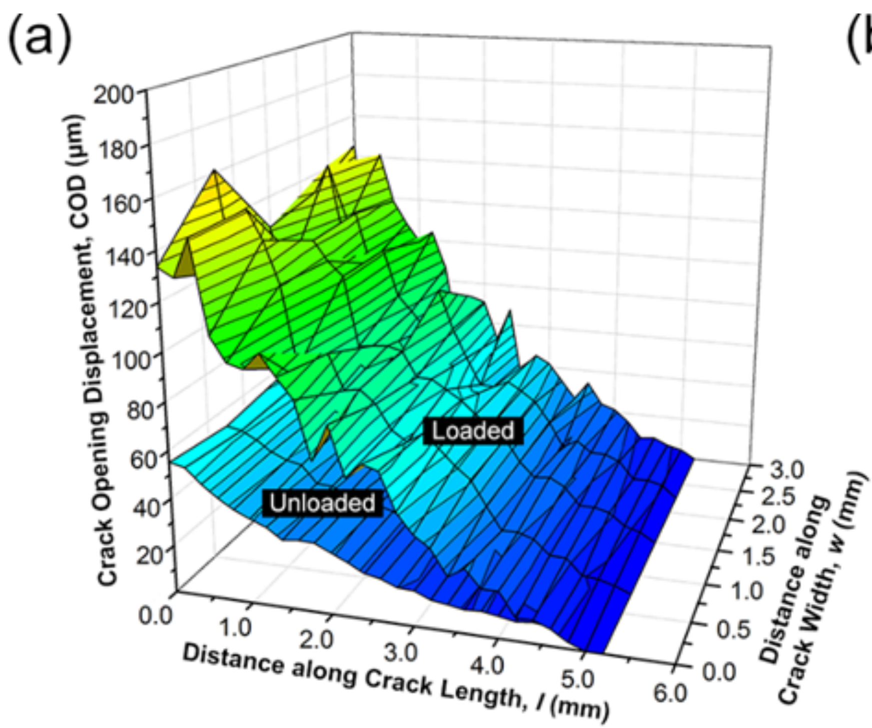
# Irradiated crack path



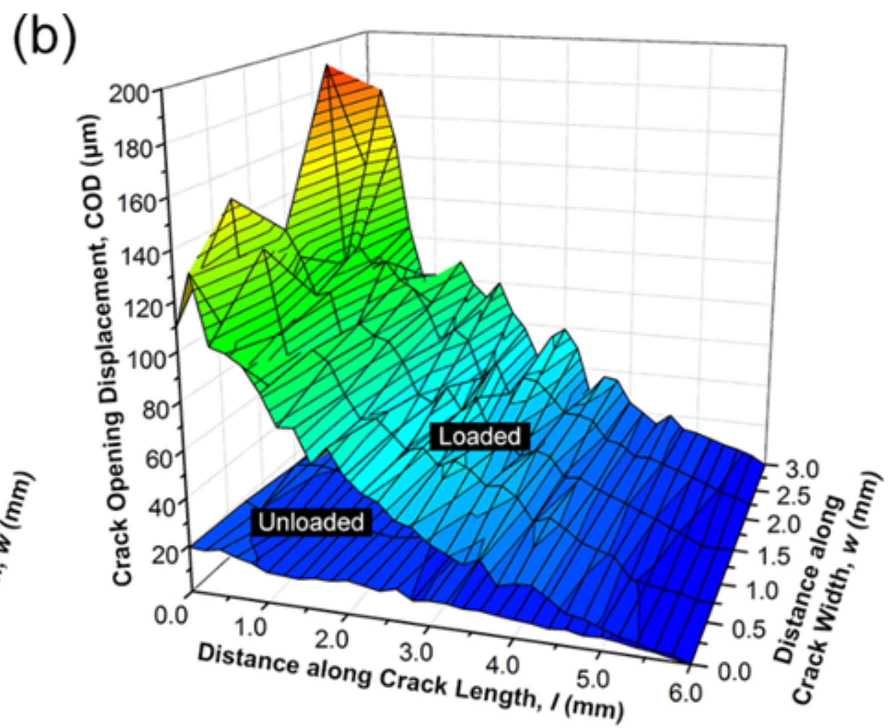
MANCHESTER
1824
The University of Manchester

# Crack mouth opening

## Virgin

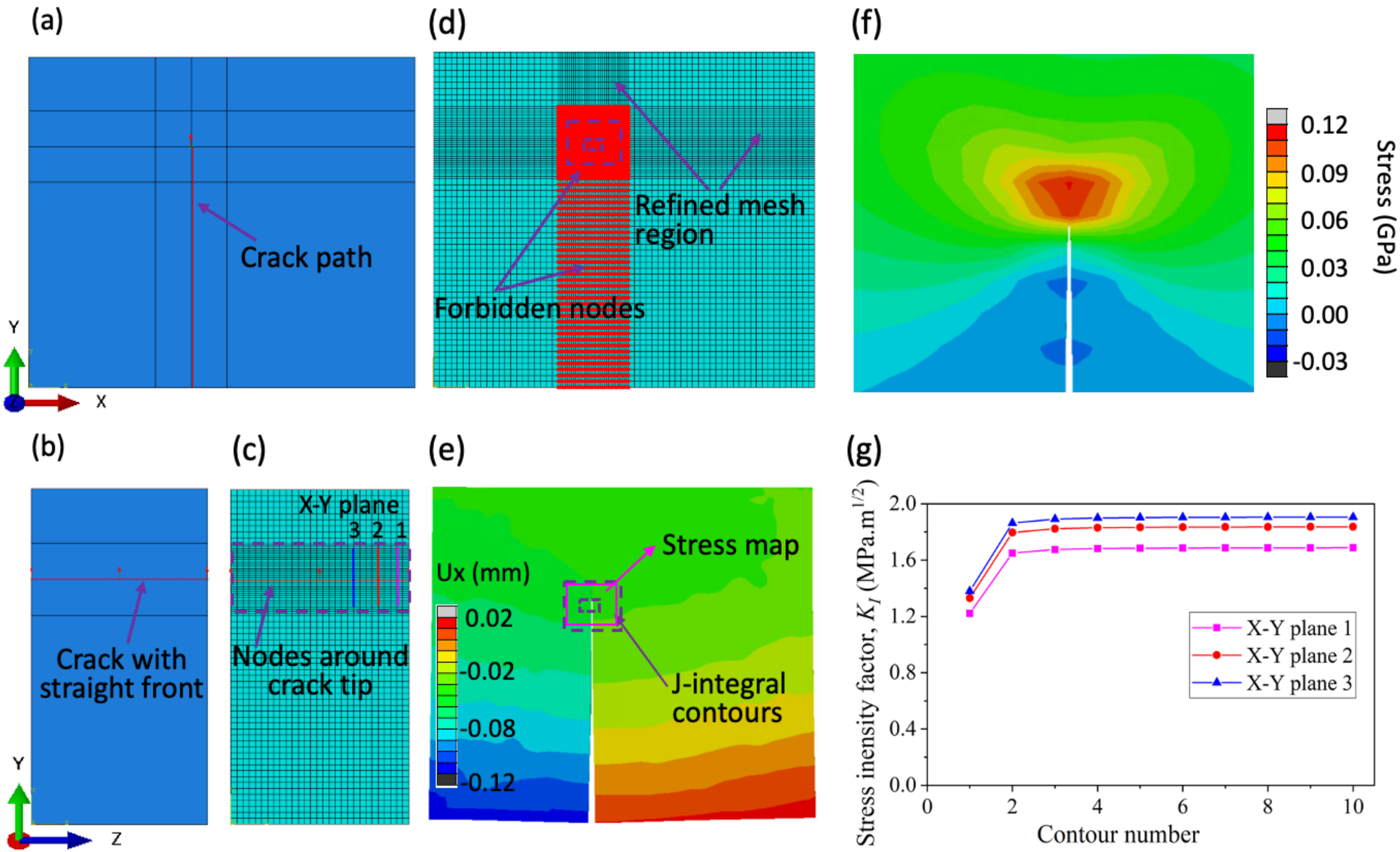



## Irradiated




On unloading, the virgin material displays significant residual opening, consistent with substantial plastic deformation. Conversely, the irradiated material recovers all deformation, consistent with elastic loading. This is a key indicator of reduced toughness of irradiated material

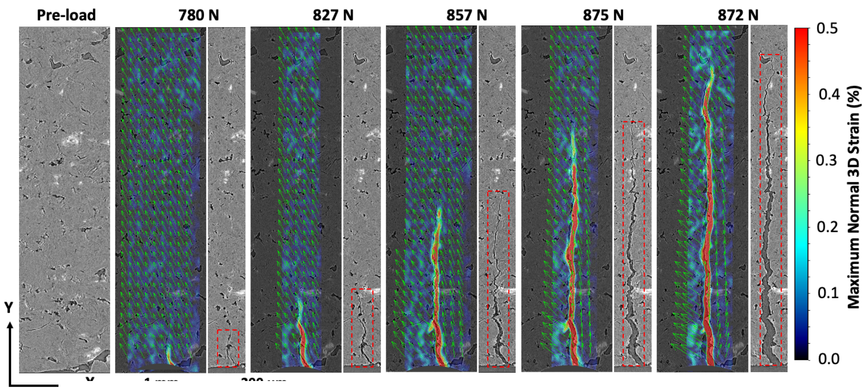
# Toughness by J-integral

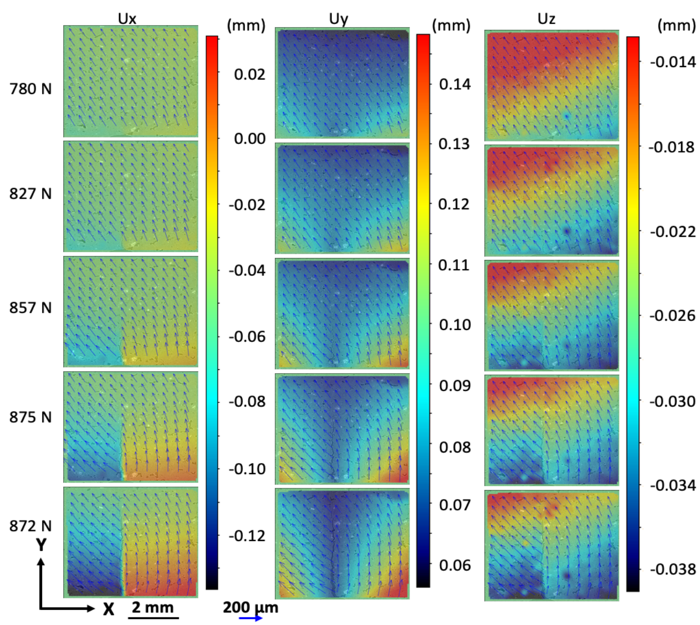


MANCHESTER 1824
The University of Manchester

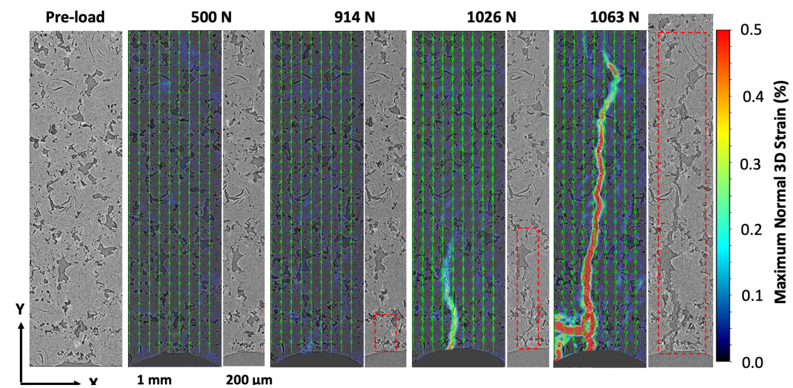
# Crack paths and displacement fields

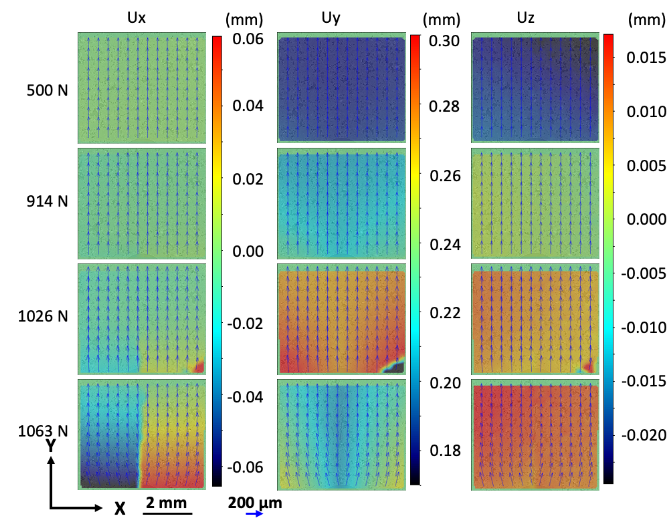
## Virgin



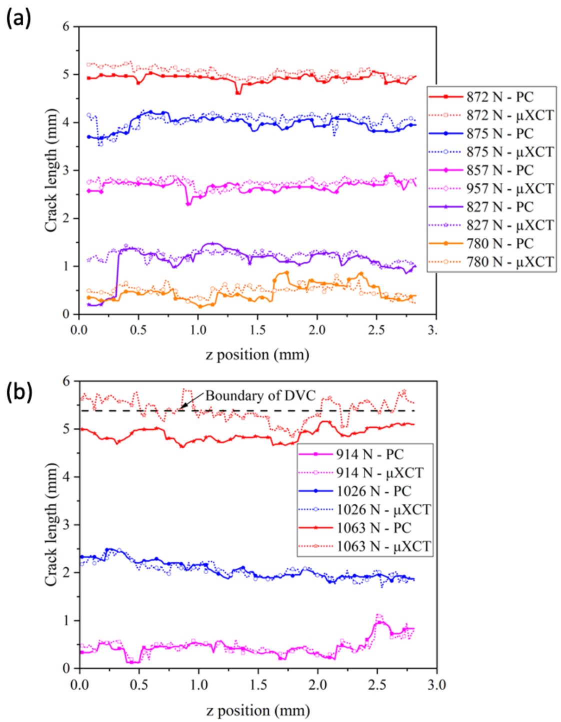

## Irradiated

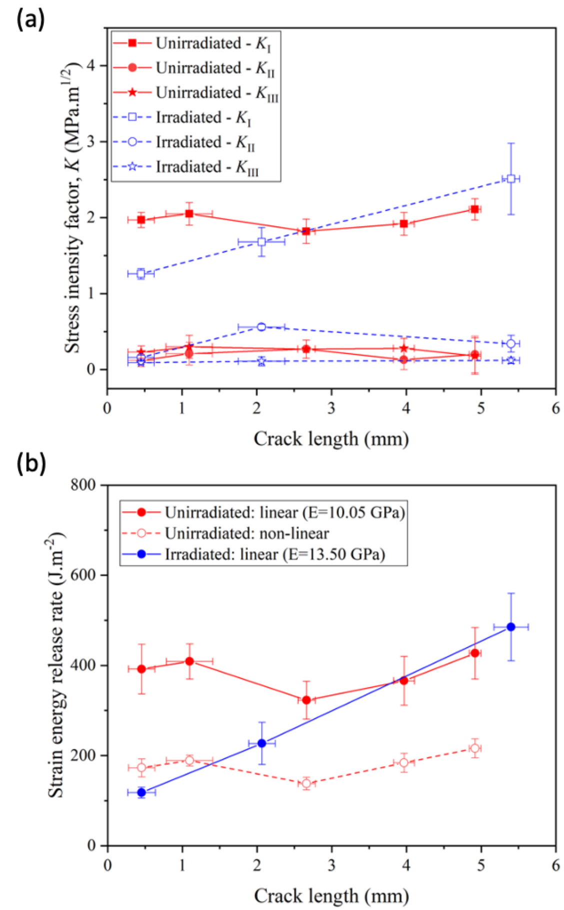


MANCHESTER 1824
The University of Manchester

# SIFs and fracture energy



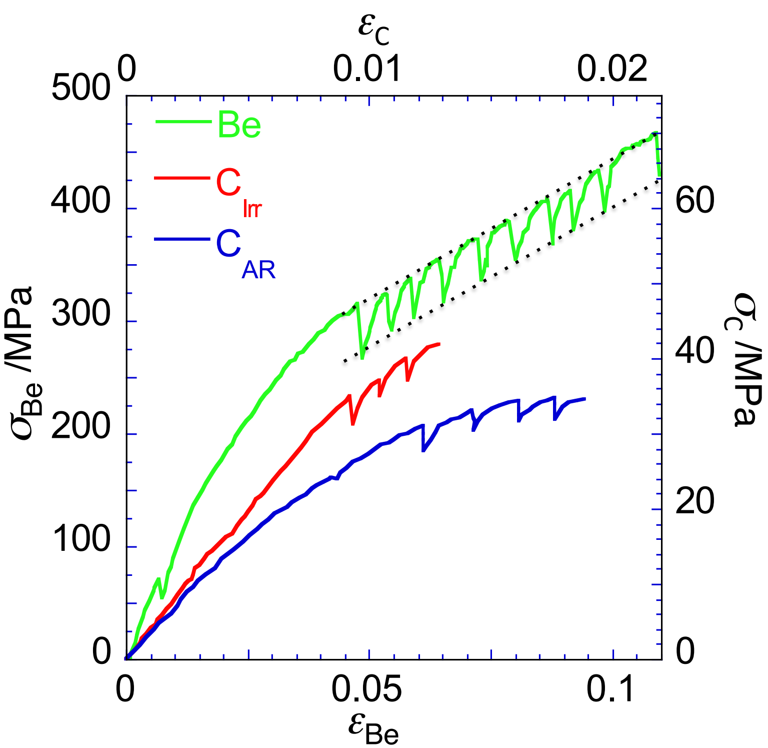




Relatively straight crack front implies analysis robust

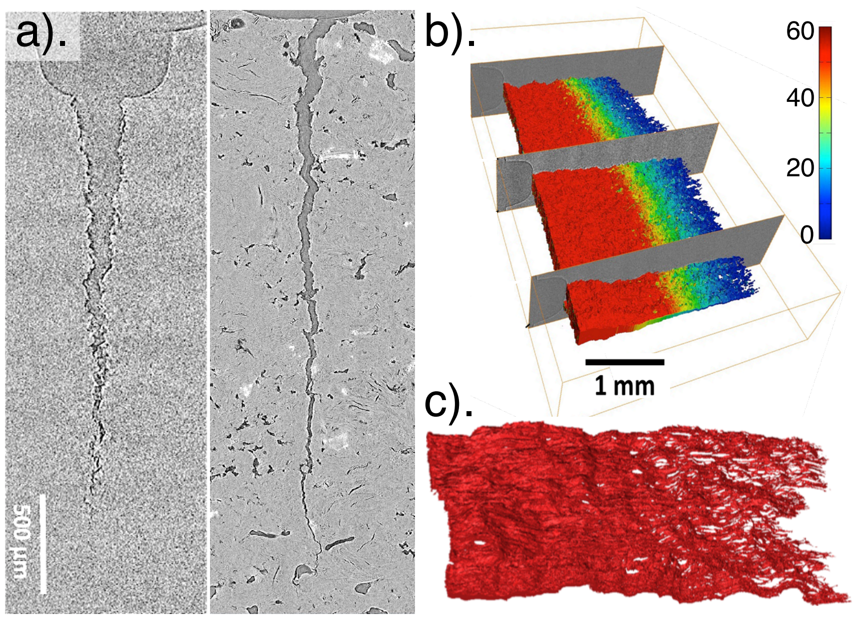
Both SIF and strain energy release rate reduced significantly on irradiation

Jin *et al. Carbon* **171**, 882-893 (2021)

# Comparison of graphite and beryllium

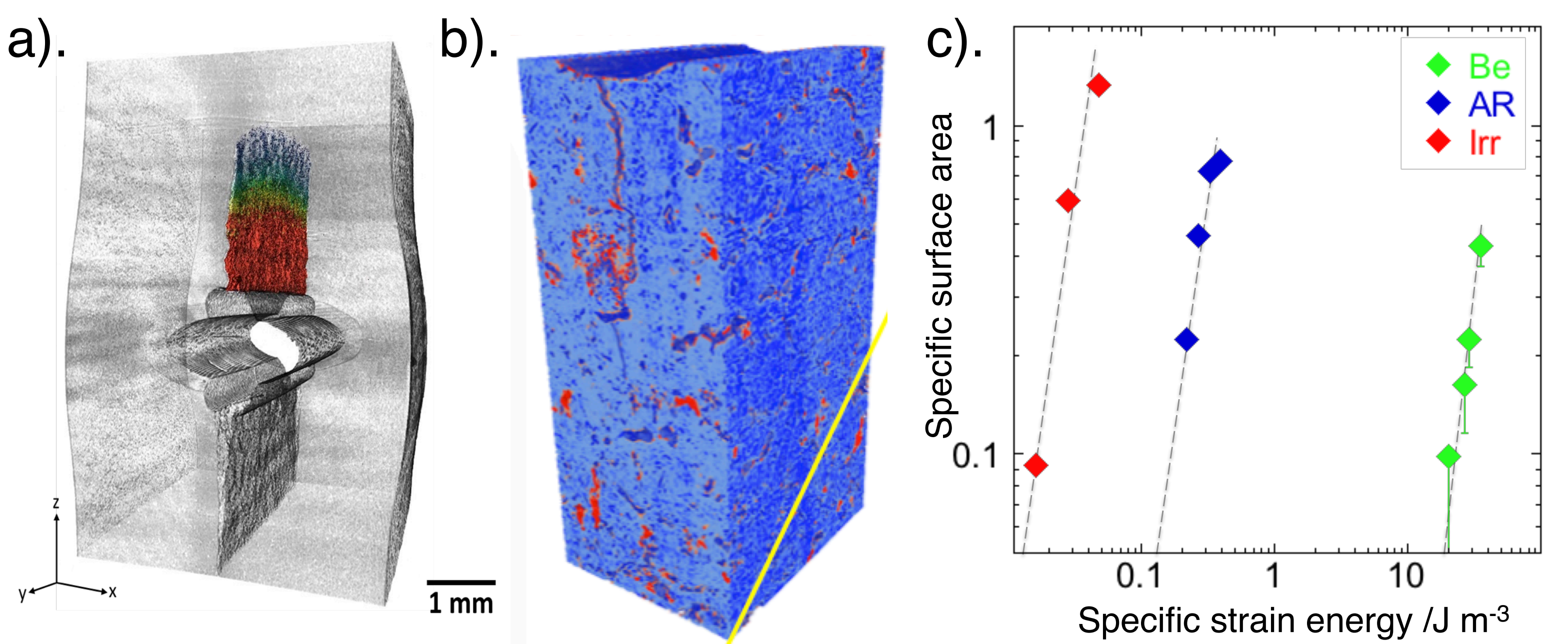



Stress/strain behaviour




Crack paths and profiles

# Fracture energy

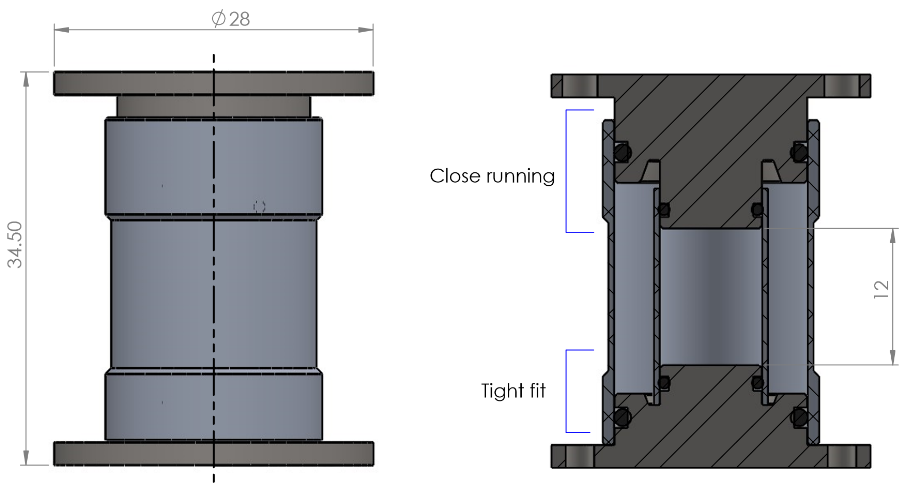



Crack profiles and surface areas

Effects of irradiation and fracture mechanism

MANCHESTER 1824
The University of Manchester

# New Containment Cell




Aluminium

Each containment layer is gas leak proof

84% of absorption @ 20 keV

Structural integrity remains at > 5 kN

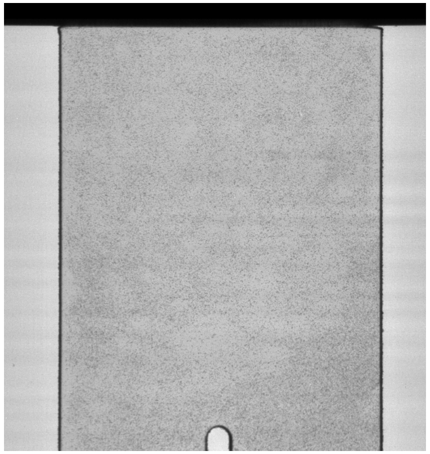
Simpler to use but no ability for infra red heating

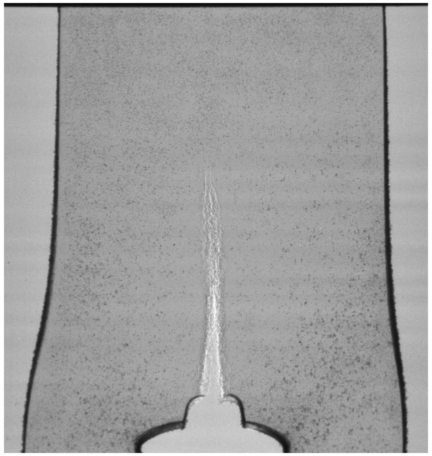
Simple manufacture so can be adapted to meet specimen and radiological needs

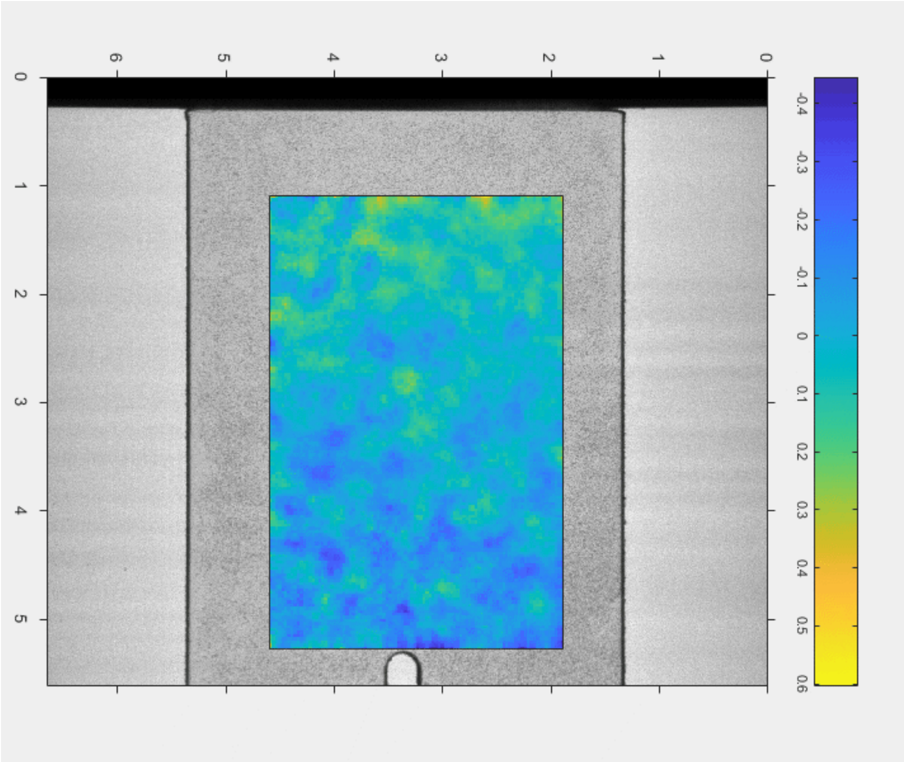
# Beryllium: ITER first wall, toxic and lack of contrast

## Contrast enhancement:

- Natural contrast : porosity, inclusions -> weak, work in progress
- Additional contrast : W powder








Surface displacement field (DIC):

# Summary

- First *in situ* tomographic crack growth of irradiated graphite and beryllium
  - Compare effects of irradiation on propagation mechanisms
  - Measure strength and fracture energy
- Establishment of User Facility at DLS
  - Supports Active Handling Facility
  - Load frames and containment cells for radioactive and toxic materials
  - Experimental officers and Research Fellows

The University of Manchester

# Acknowledgements

The authors would like to acknowledge the contributions of other University of Manchester staff and project collaborators, as well as thank our project sponsors:

- **UoM:** Matthew Roy, William Bodel, Joshua Taylor, Tristan Lowe, Neil Bourne.
- **Diamond:** Andrew Bodey, Shashidhara Marathe, David Eastwood, Kaz Wanelik, Christoph Rau
- **NNL:** Nassia Tzelpi, Jon Bradley, Sam Wilkinson, Matthew Jordan
- **EDF:** Jonathan Wright, Mark Davies, Bruce Davies, Alan Steer and Jim Reed
- **InnovateUK**