UK Atomic Energy Authority

Materials Testing 2.0 for Creep: Accelerating High Temperature Materials Qualification

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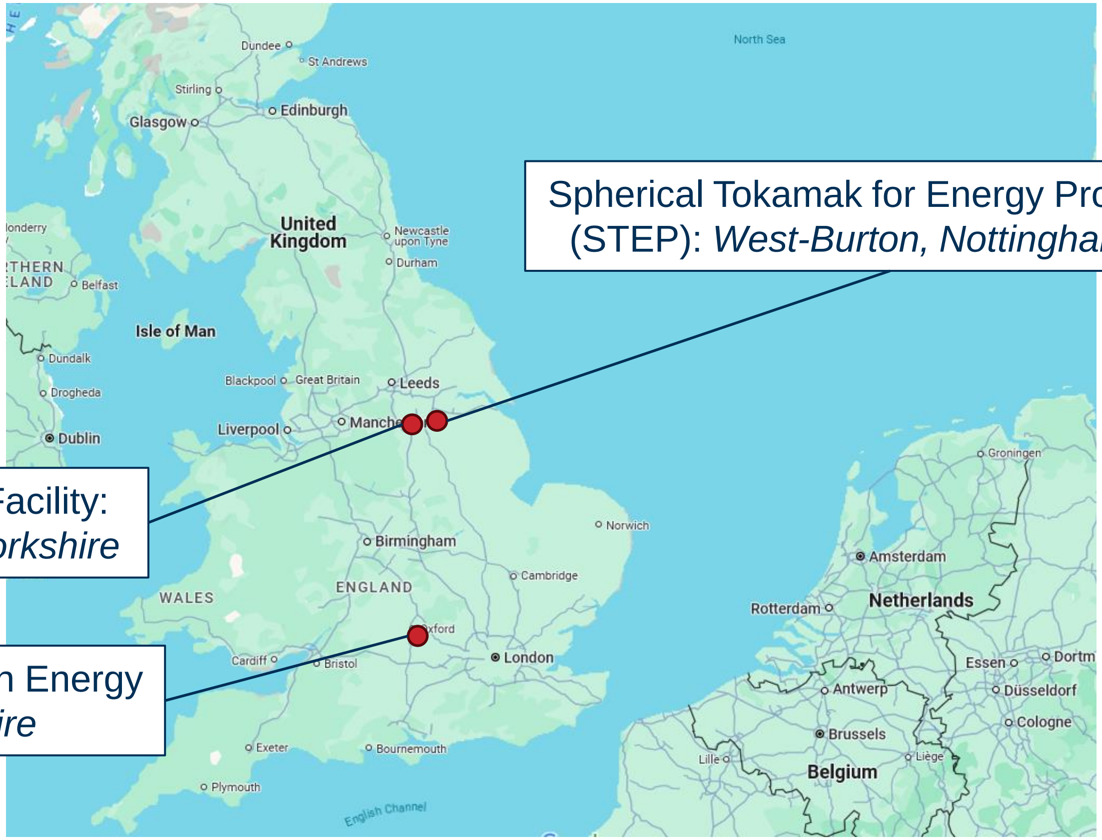
UK Atomic Energy Authority (UKAEA)

Mission:

“To lead the delivery of sustainable fusion energy and maximise the scientific and economic benefit”

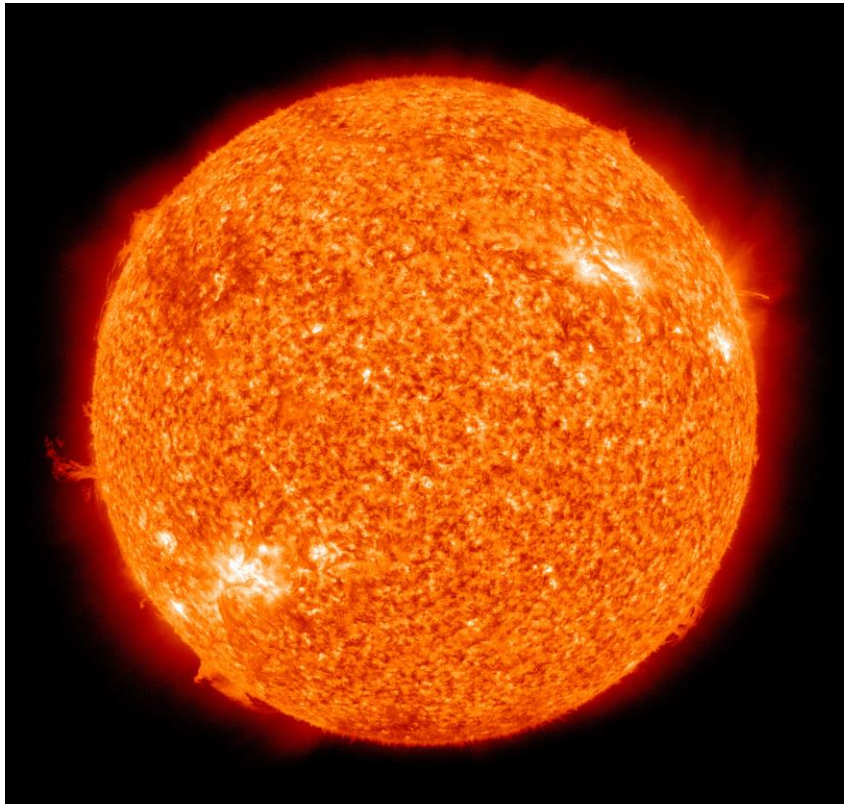
Activities:

Operate fusion devices (MAST-U, ex JET)
Research (plasma physics, materials)
Develop components for future devices
Contribute to EUROFusion program
Robotics
High performance computing

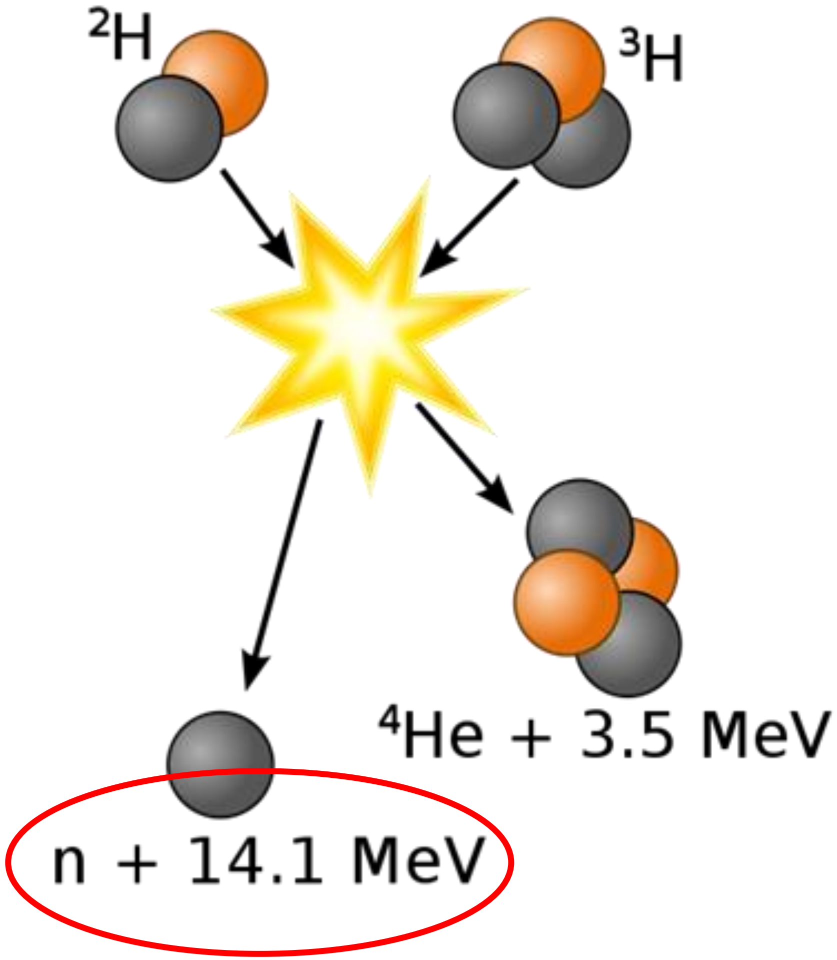


Fusion Energy

In Space:
Intense heat & pressure due to gravity
~15 million K (core), 5,500K (surface)

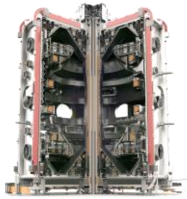


On Earth:
Need plasma temp. of ~150 million K
+ pressure (confinement)

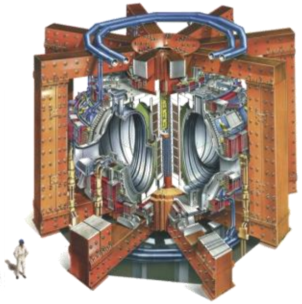


Fusion Reactors (Tokamaks)

A donut shaped magnetic bottle for confining and heating plasma to create fusion

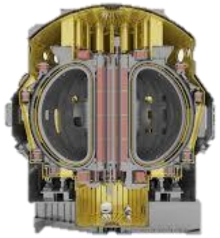


MAST-U

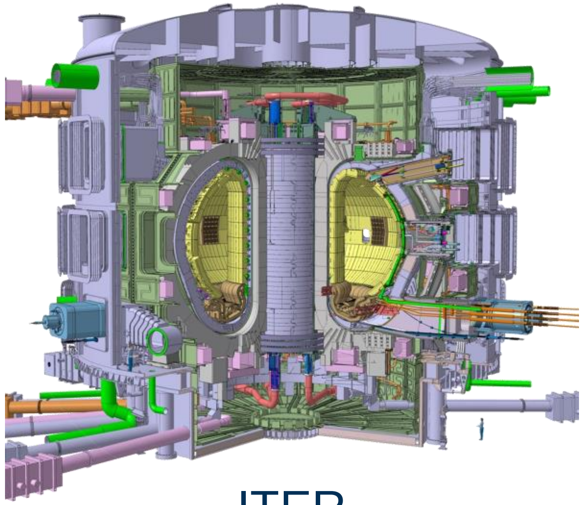


~~JET~~

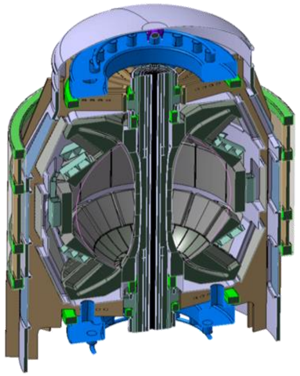
Shutdown end 2023



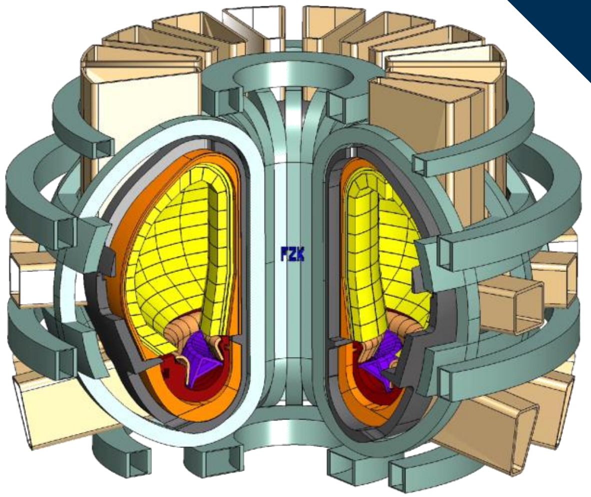
JT60-SA



ITER



STEP



DEMO

Present

Low power
Low utilisation

Late 2020s

Higher power
Low utilisation
New components
Net energy

2040s

High power
High utilisation
New components
Net energy
Power generation

Materials Challenges

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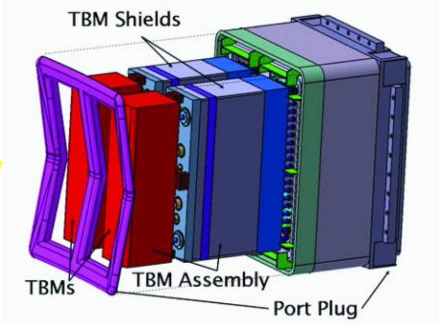
Degradation Mechanisms

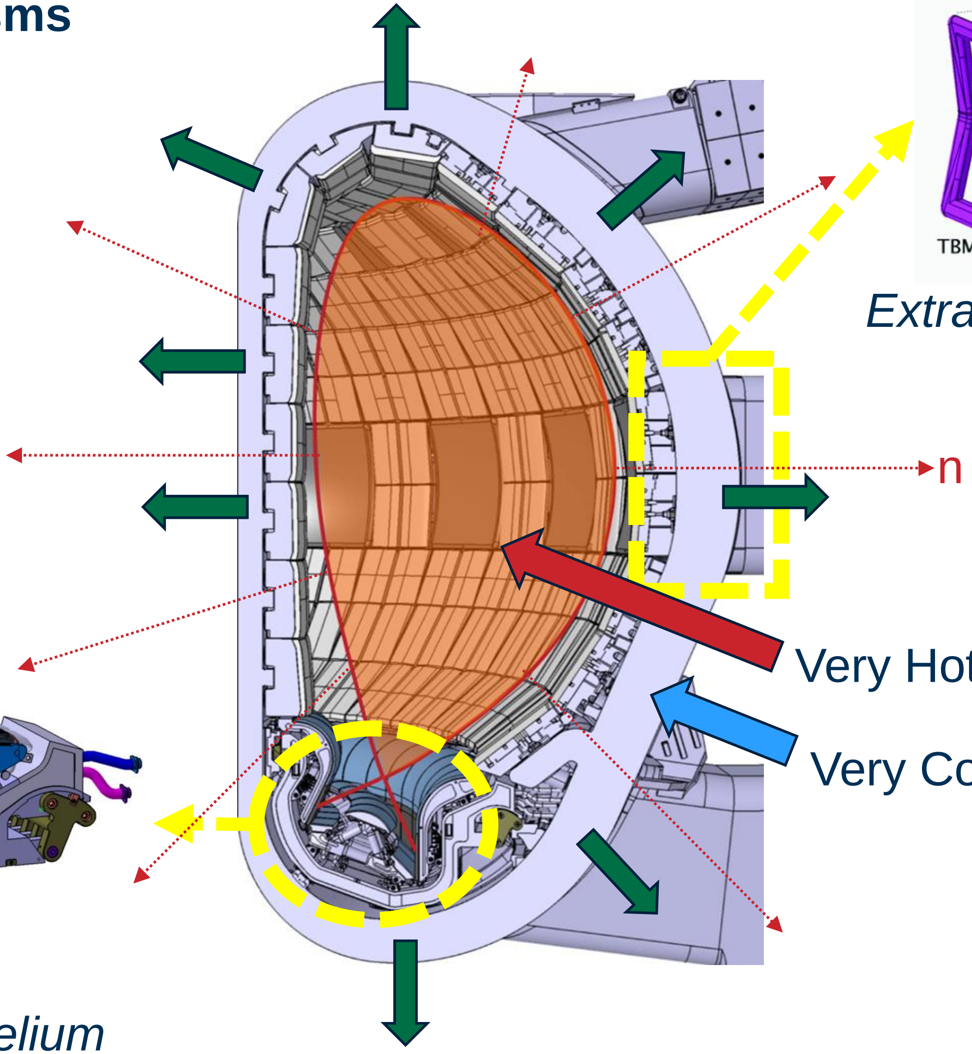
(Irradiation) Creep
Fatigue
Embrittlement
Transmutation
Thermal Transients

Vacuum Vessel

Test Blanket Module (TBM)



Extract heat & produce tritium

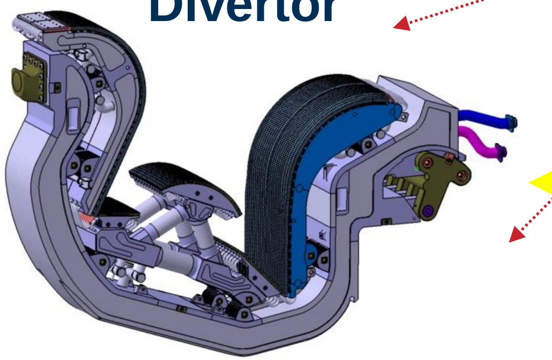


Very Hot! (~150 Million K)

Very Cold! (~4 K)

Magnetic Forces

Divertor



Extract heat & helium

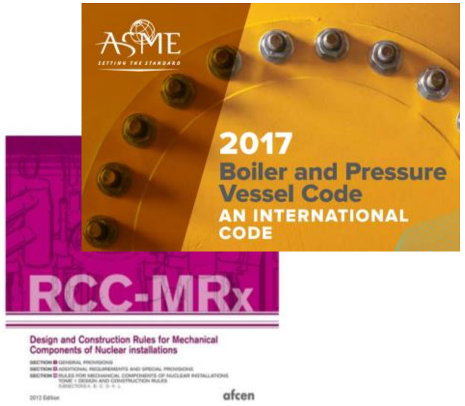
New Materials

RAFM Steels
ODS Steels
Exotic Metals
Ceramics & Composites

New Processes

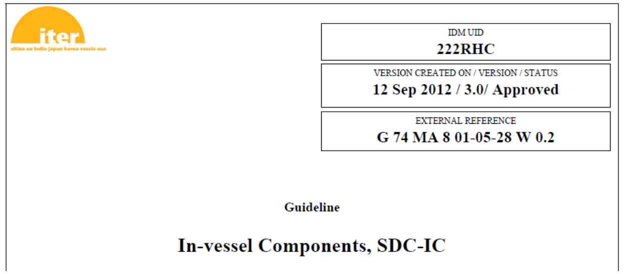
Additive Manufacturing
Hot Isostatic Pressing
Field-Assisted Sintering

Design Data



Existing Design Codes
ASME BPVC
R5/6
RCC-MRx

Fusion Design Codes
ITER SDC-IC
DEMO DC



Failure Modes
Plastic Collapse
Fatigue
Ratchetting
Creep
Local Failure
Fast Fracture
Creep-Fatigue

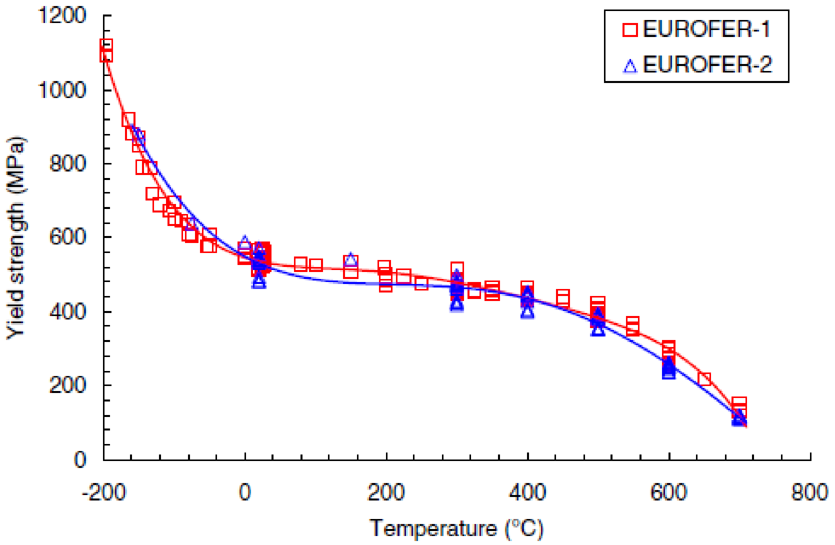
Needs data over

Temperature

Stress

Irradiation Damage

For Eurofer97 this has taken >20 years



Eurofer97 Yield Strength vs temperature (unirradiated) Lucon & Vandermeulen 2009

Why focus on creep?

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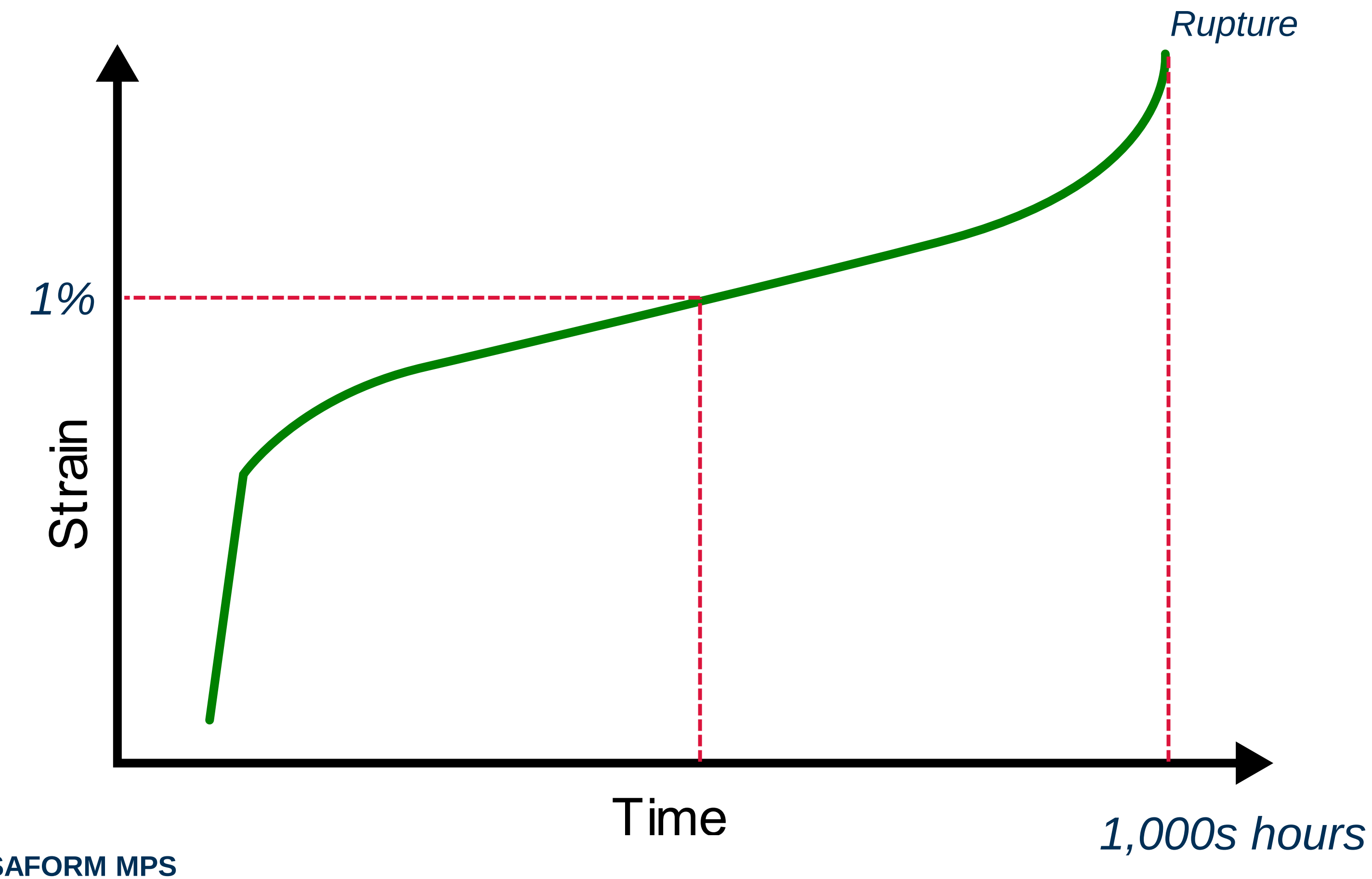
Creep is a key failure mode

Higher temperatures, higher efficiency, worse creep

Development of new radiation tolerant, creep-resistant steels

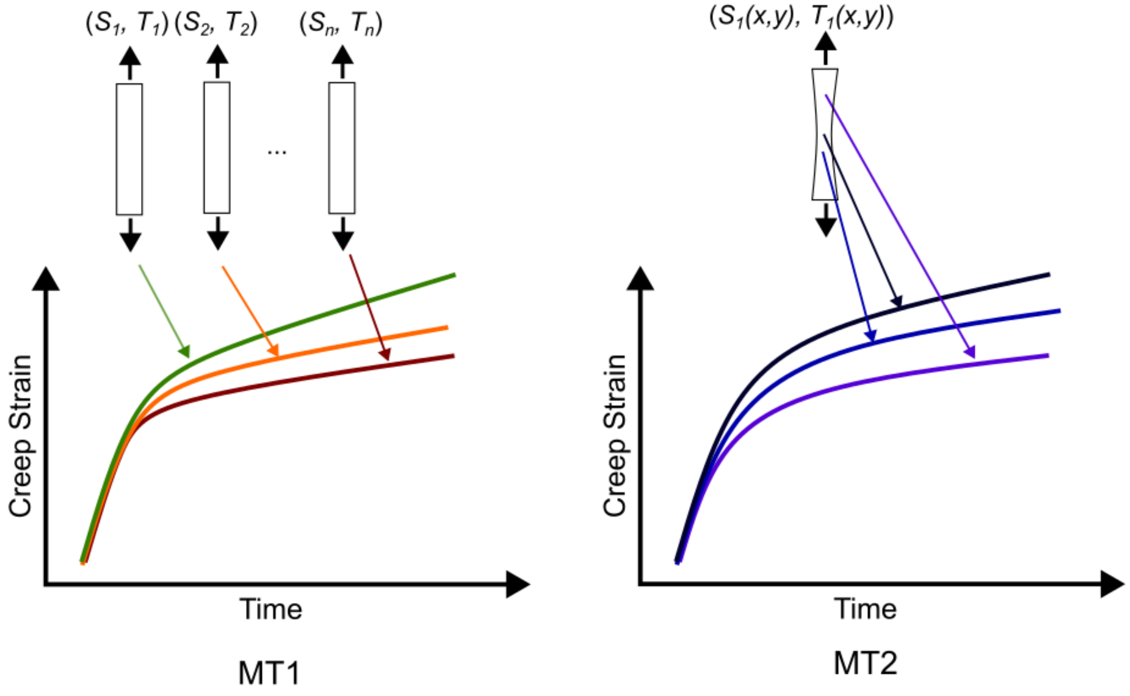


Why Materials Testing 2.0?

Material Testing 2.0 uses **complex tests**, **full-field measurements** and **inverse identification** to determine constitutive models.

Creep tests are long – 1,000’s of hours, machines, time & resources to do them are expensive.

Can we use the Materials Testing 2.0 philosophy to get more data from a reduced number of tests?

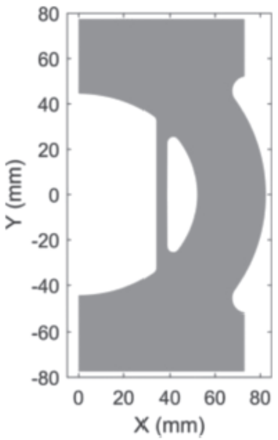


Does data from MT2 tests match that from MT1 tests?

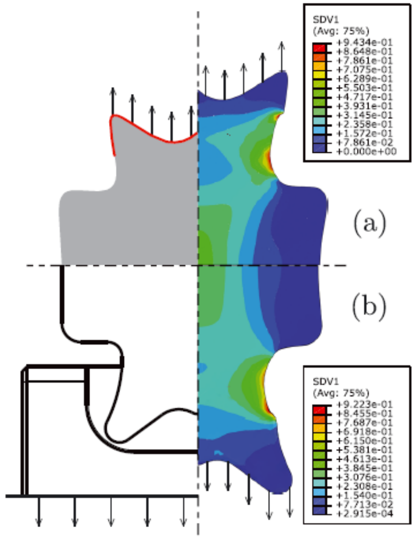
Exploiting MT2: Test Design

In MT2 the test design space is now **infinite**, so how do you choose a suitable geometry? From [1]:

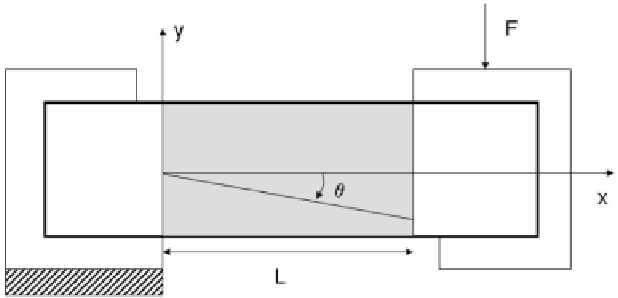
Intuition	Strain State	Identification Quality	Full Simulation
What do we think would work?	*What gives the best spread of strain states?*	*What gives the least uncertainty on outputs?*	*What is the effect of the measurement system?*



Viscoplastic Model Specimen [2]



Anisotropic Model Specimen [3]



Anisotropic Elasticity Test [4]

[1] F. Pierron, M. Grediac, *Strain* 2020, e12370. 10.1111/str.12370,
[2] E. M. C. Jones, J. D. Carroll, K. N. Karlson, S. L. B. Kramer, R. B. Lehoucq, P. L. Reu, D. Z. Turner, Comput. Mater. Sci. 2018, 152, 268.
[3] J. Aquino, A. G. Andrade-Campos, A. Gil, J. M. P. Martins, S. Thuillier, Strain 2019, 55, e12313.
[4] F. Pierron, G. Vert, R. Burguete, S. Avril, R. Rotinat, M. R. Wisnom, *Strain* **2007**, *43*, 250.

‘Stress State’ Optimisation Strategy

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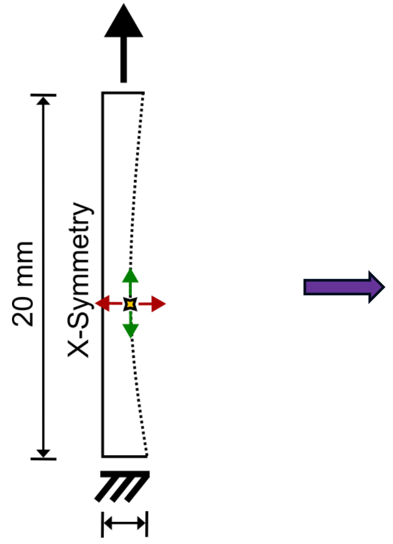
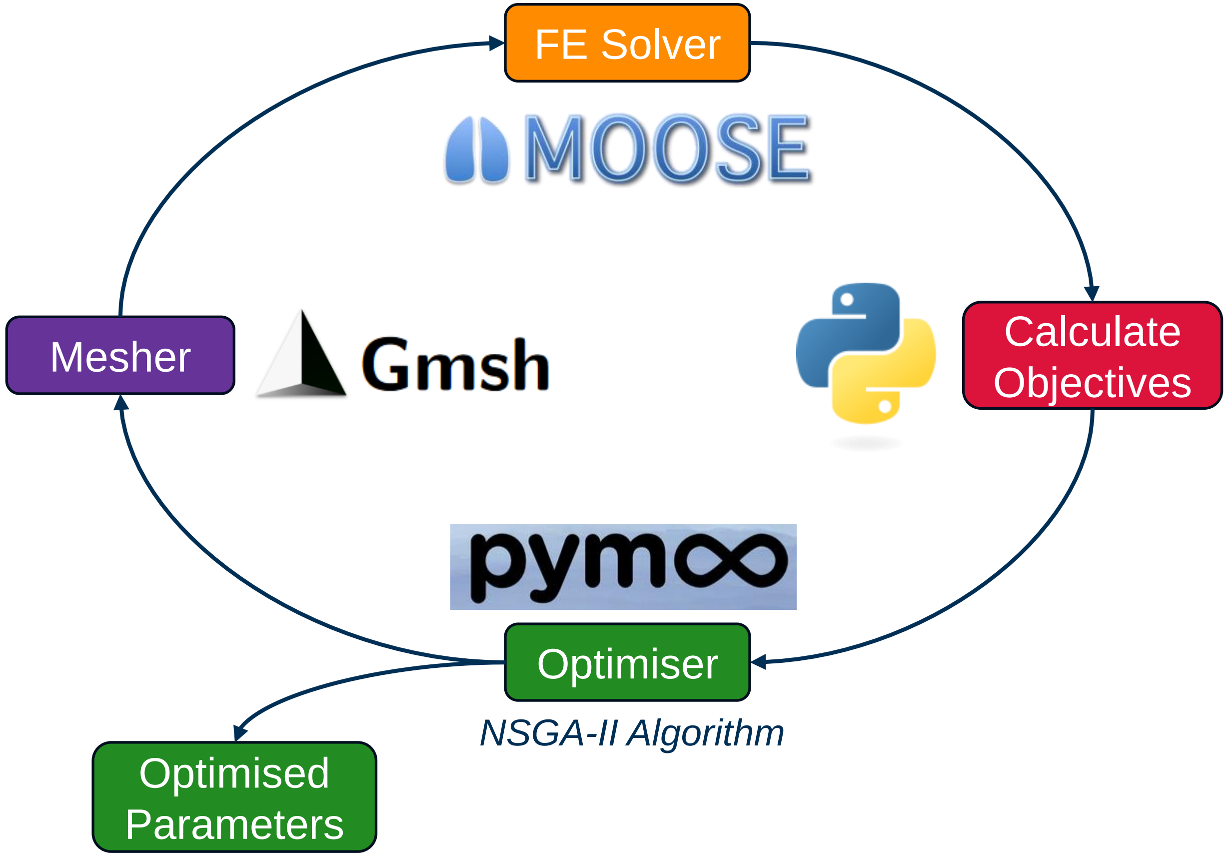
Geometry envelope - 20 x 5mm
Free moving point
Spline constructed through



Simulate load up
to test force at RT
Voce-type plasticity model



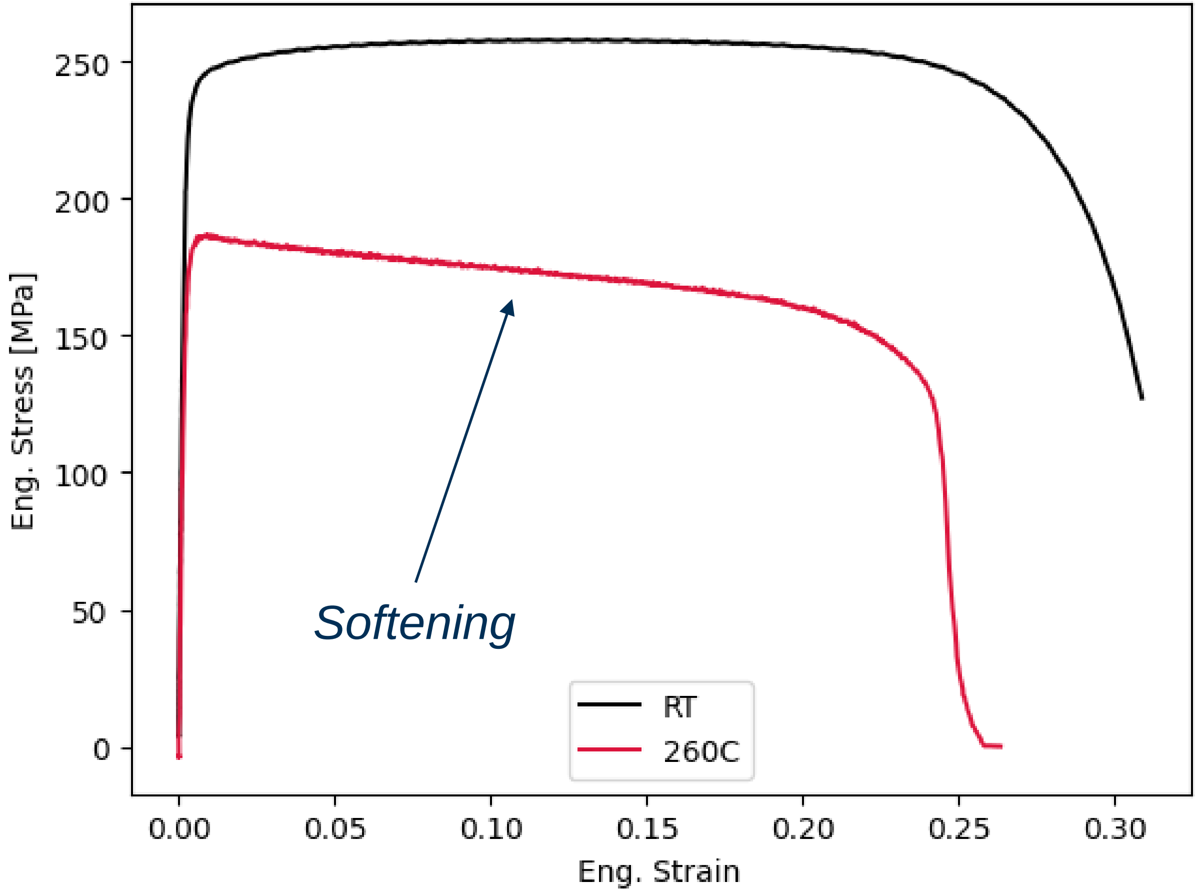
NSGA-II Algorithm

Multi Objective Optimisation
Maximise Max Stress
Minimise Max Plastic Strain

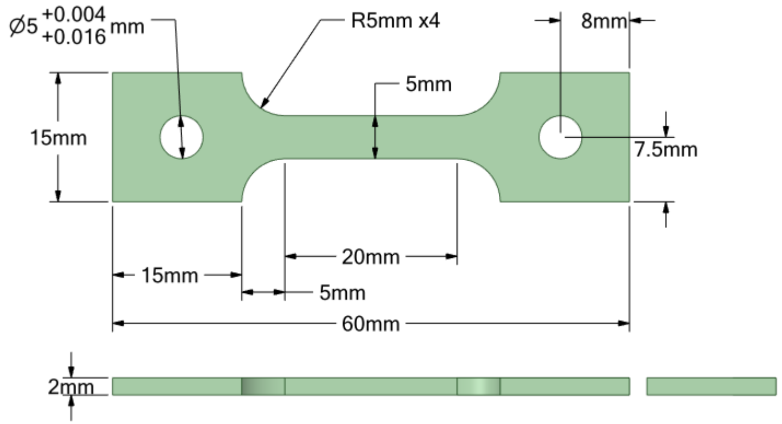
All parts are open-source and in a python package *pyfemop* available: *https://github.com/Applied-Materials-Technology/pyfemop*

Material & Uniaxial Tensile Tests

OFHC Cu – Rolled Sheet, ½ Hard
Proposed for interlayer between CuCrZr pipes and W armour



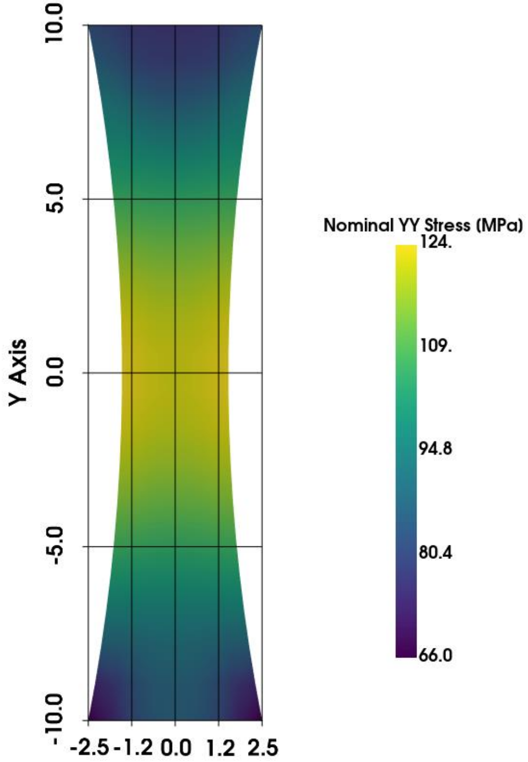
Temperature [C]	Elastic Modulus [GPa]	Yield Strength [MPa]	Tensile Strength [MPa]	'Uniform Elongation'
20	110	160	258	0.125
260	98	122	122	0.009



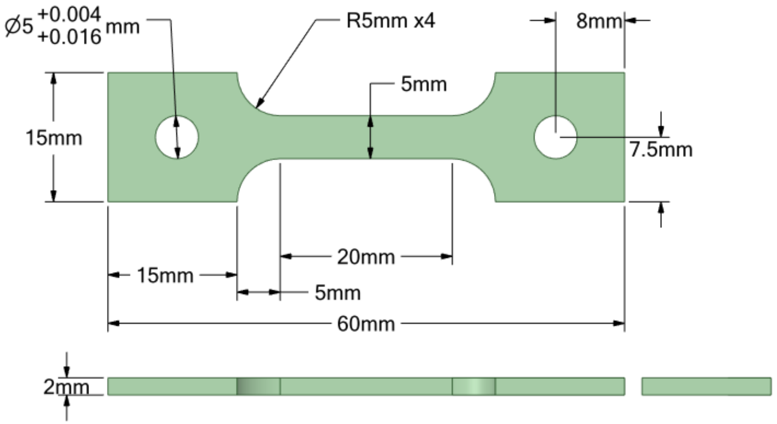
Based on ASTM-E8

MT2 Geometry

MT2 Specimen
MT2 tapered specimen geometry
Load - 750N
Approx Stress range 70-125MPa
Temp ~ 300°C



Uniaxial Specimens
ASTM E8 type specimen, ~20% subsize
Loads – 800, 1000, 1200N
Stresses – 80, 100, 120MPa
Temp ~ 300°C



Experimental Setup

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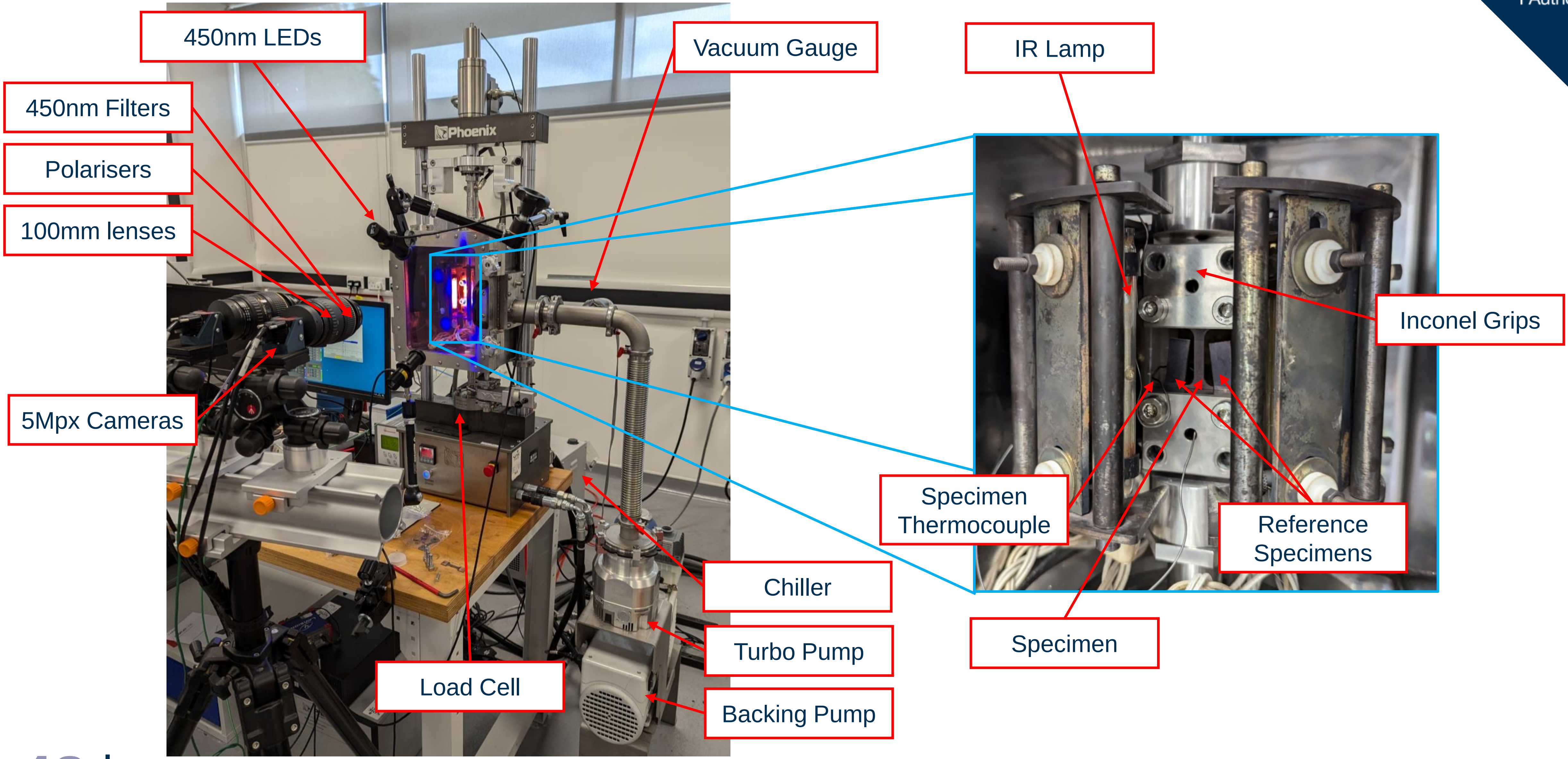
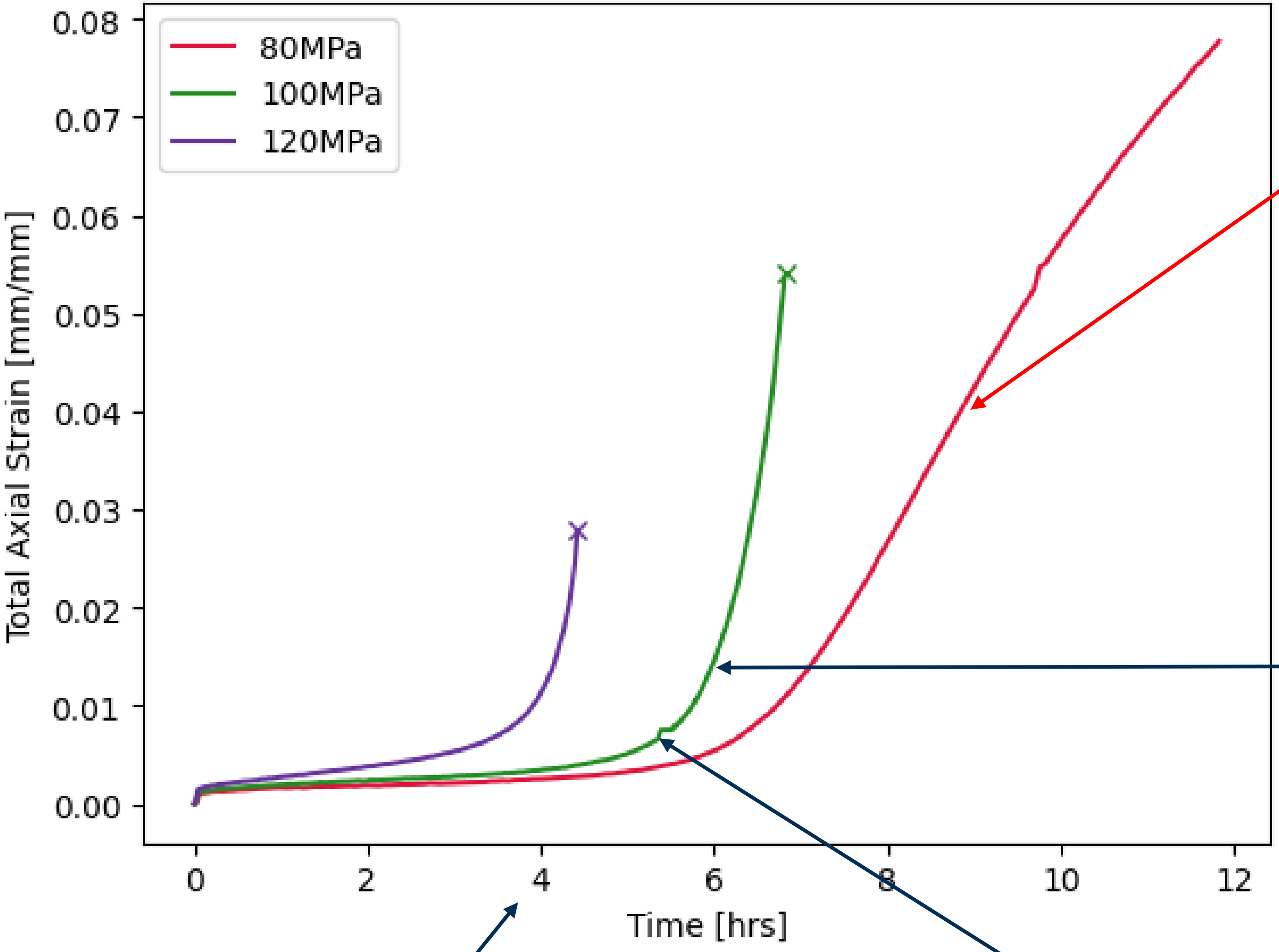


MT1 Creep Tests

Creep of ½ Hard OFHC Cu at 265^{o}C

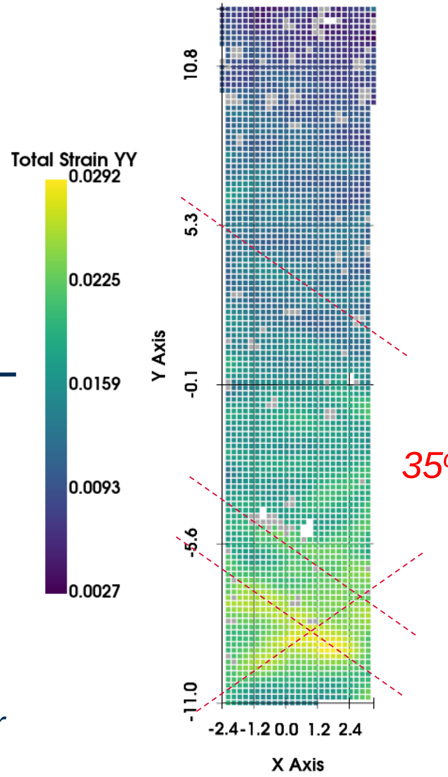


Thermal drift?

High stress, short test time, iterate faster

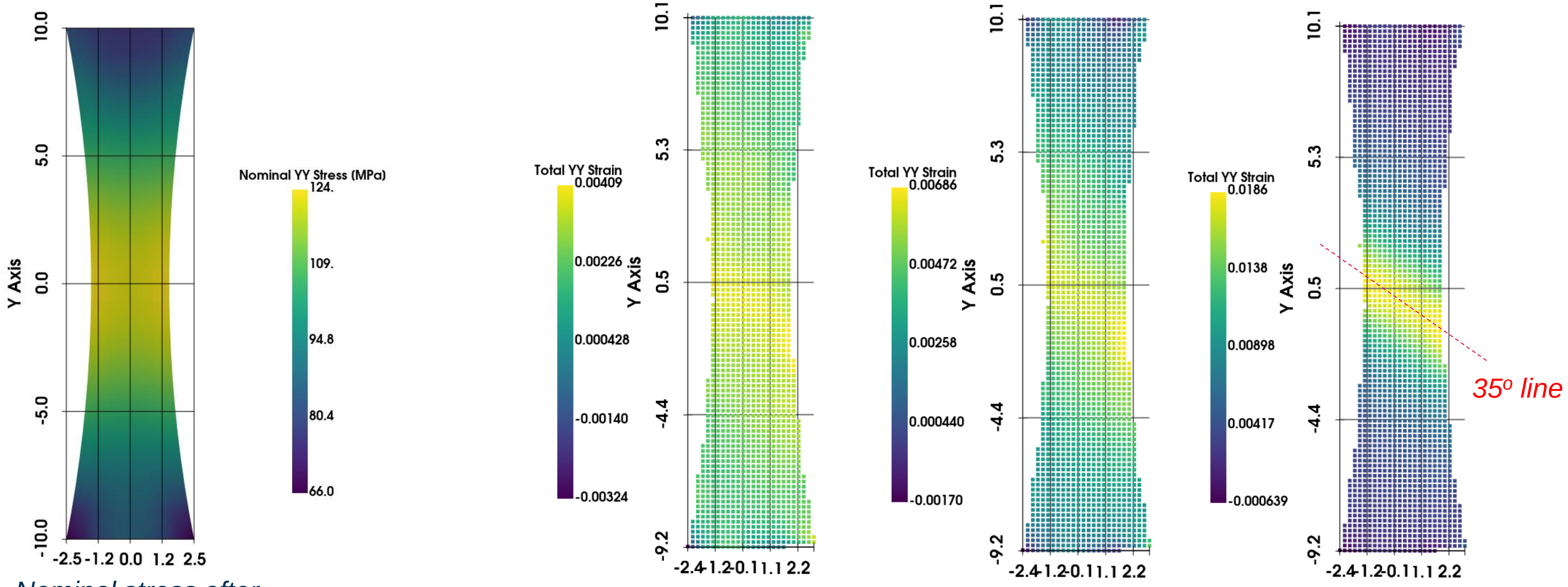
DIC Control PC fell over

100MPa, t=6hrs



35^{o} lines

MT2 Specimen Results



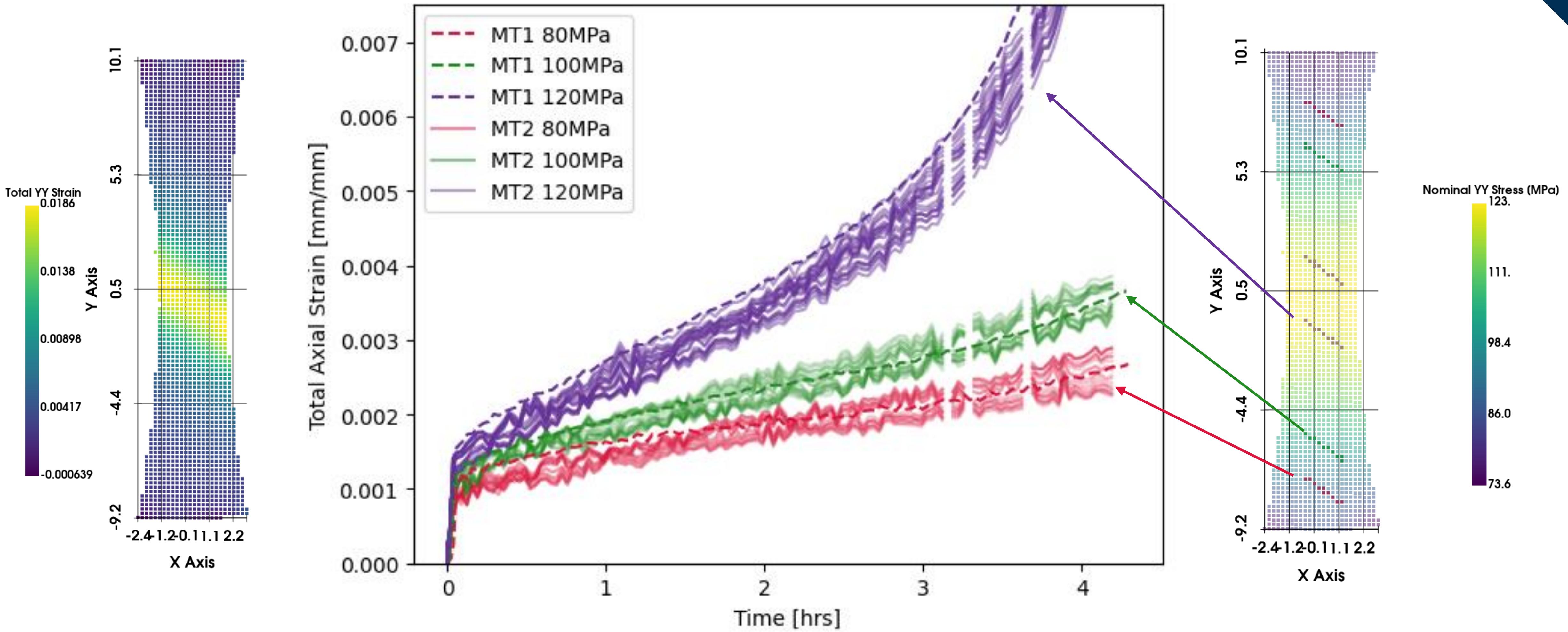
Nominal stress after elastic loading

t=1.5hrs

t=3hrs

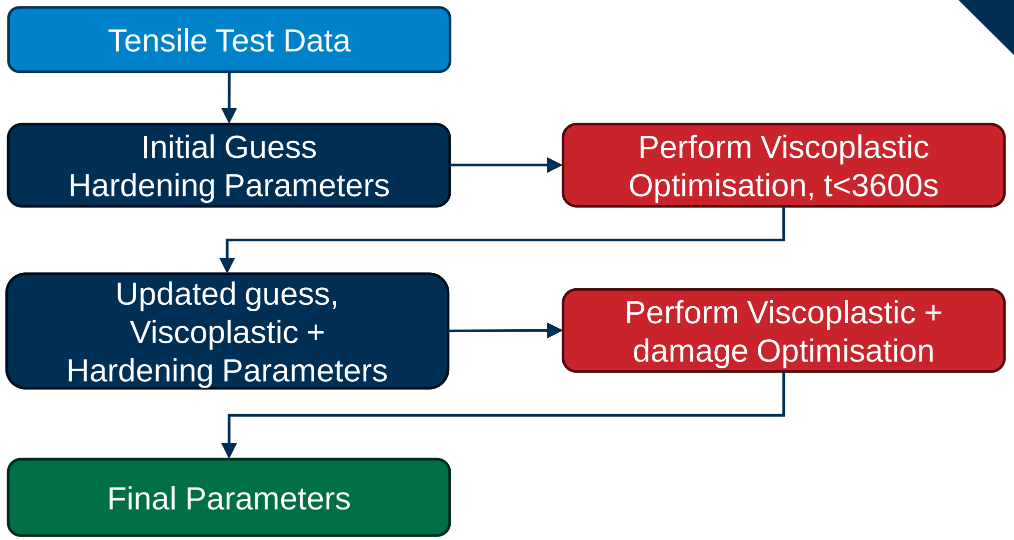
t=4.18hrs

MT1-2 Comparison



Modelling

- Isotropic model (neglect anisotropy)
- Unified Viscoplasticity with Damage
- Damage degrades elastic stiffness
- Implemented in MOOSE Open-Source FE Solver



Strain Partitioning

$$\varepsilon = \varepsilon_{el} + \varepsilon_{vp}$$

Rate Sensitivity / Viscoplasticity

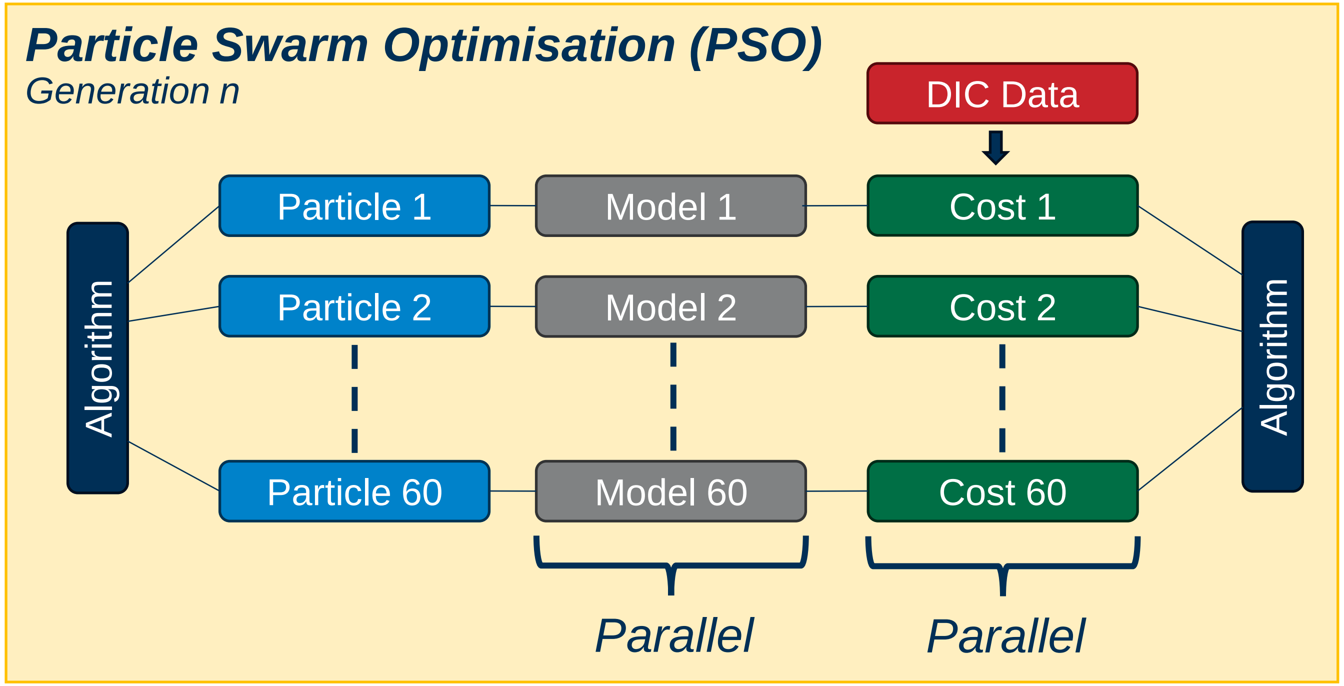
$$\dot{\varepsilon}_{vp} = \alpha \sinh \beta \left(\frac{\sigma}{1-\omega} - R - \sigma_y \right)$$

Voce Strain Hardening

$$R = \sigma_s \left(1 - e^{b\varepsilon_{vp}}\right) + h\varepsilon_{vp}$$

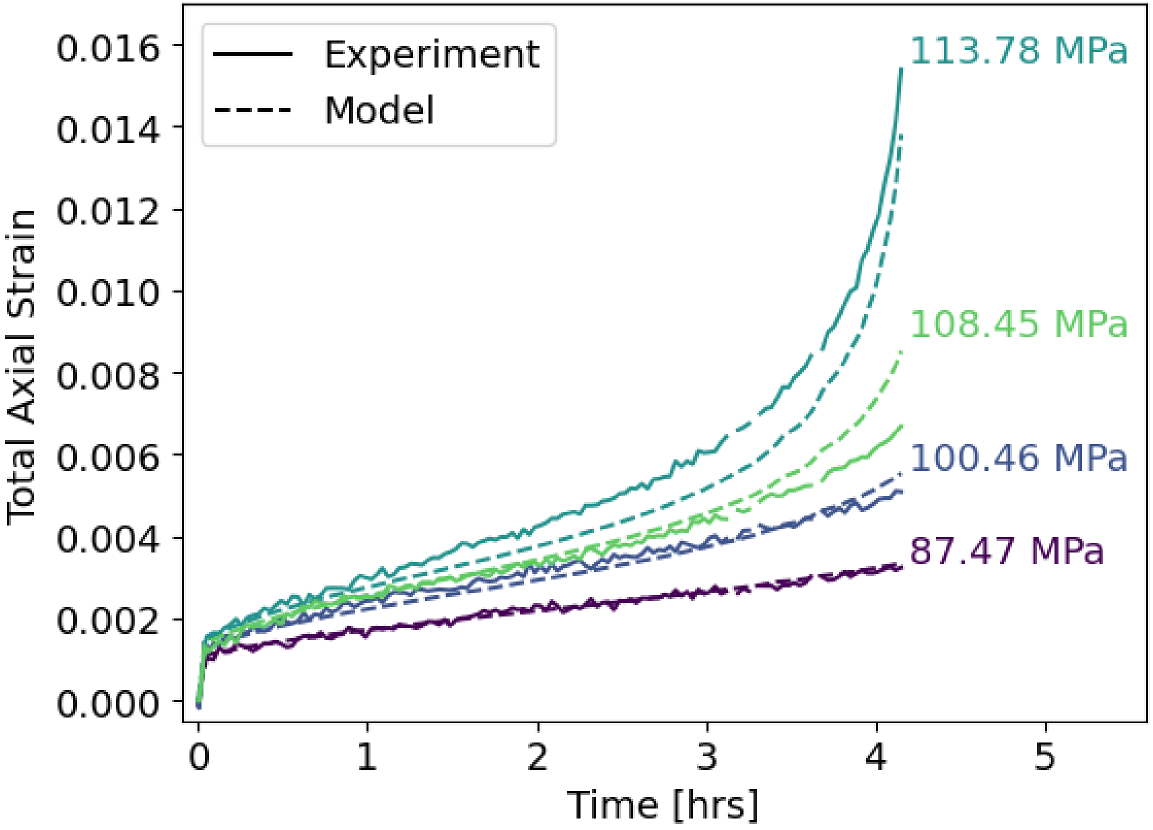
Leckie & Hayhurst Damage

$$\omega = 1 - \left[1 - \frac{t}{\left(\frac{\sigma}{A}\right)^{-\zeta} (1+\phi)^{-1}} \right]^{\frac{1}{1+\phi}}$$



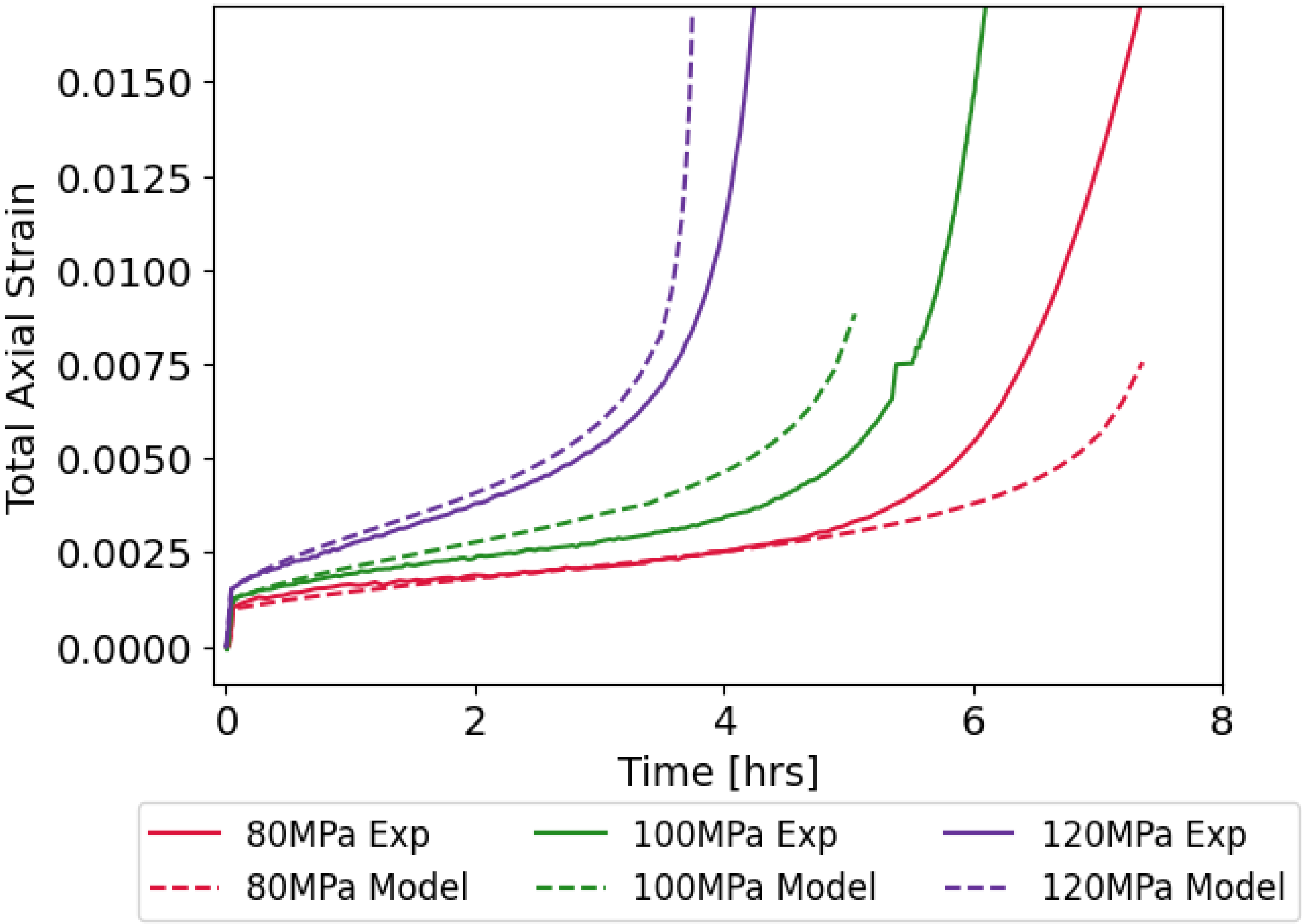
Modelling Results

MT2



- Agreement is promising, given lack of anisotropy
- Experimental temperature inaccuracy

Uniaxial



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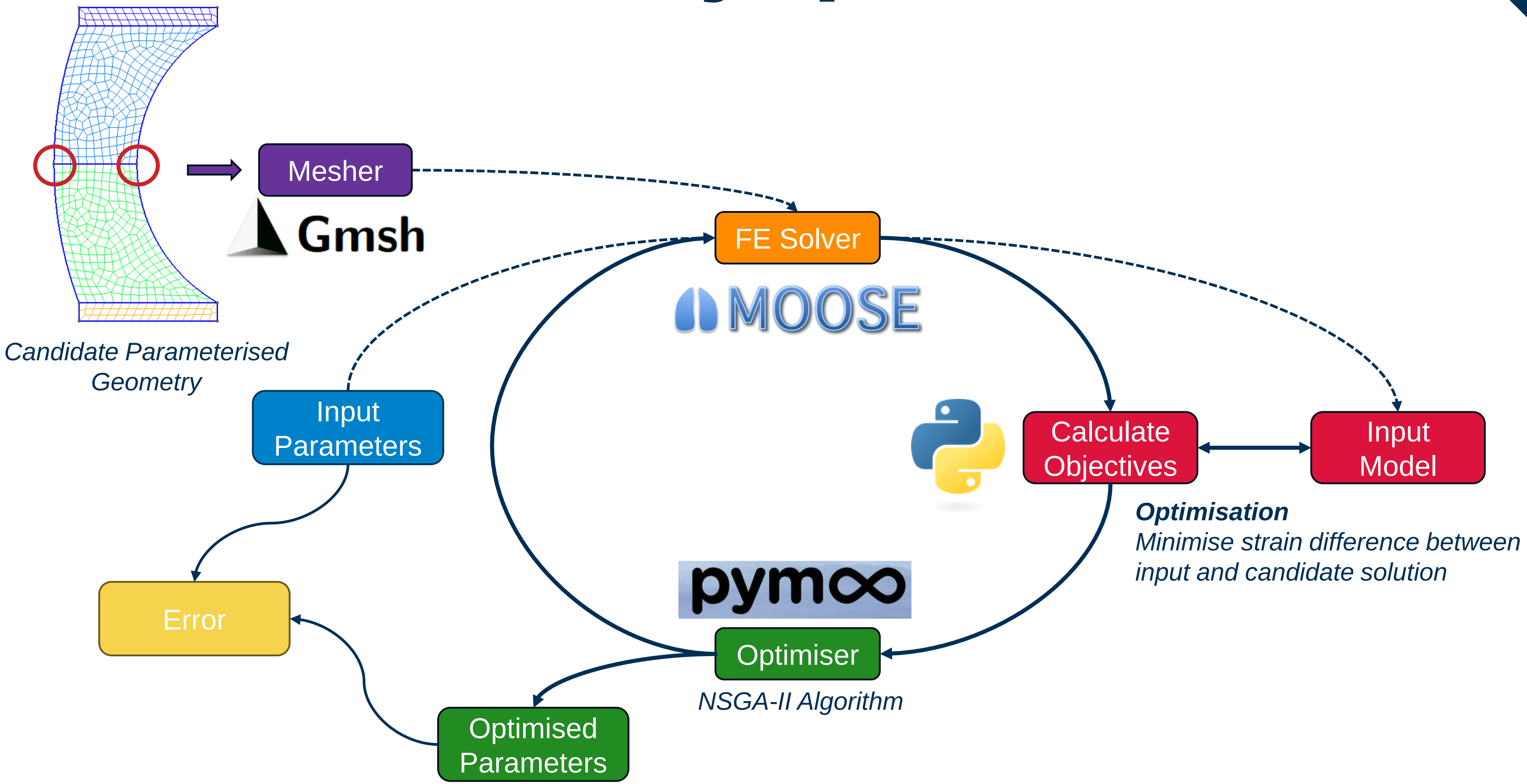
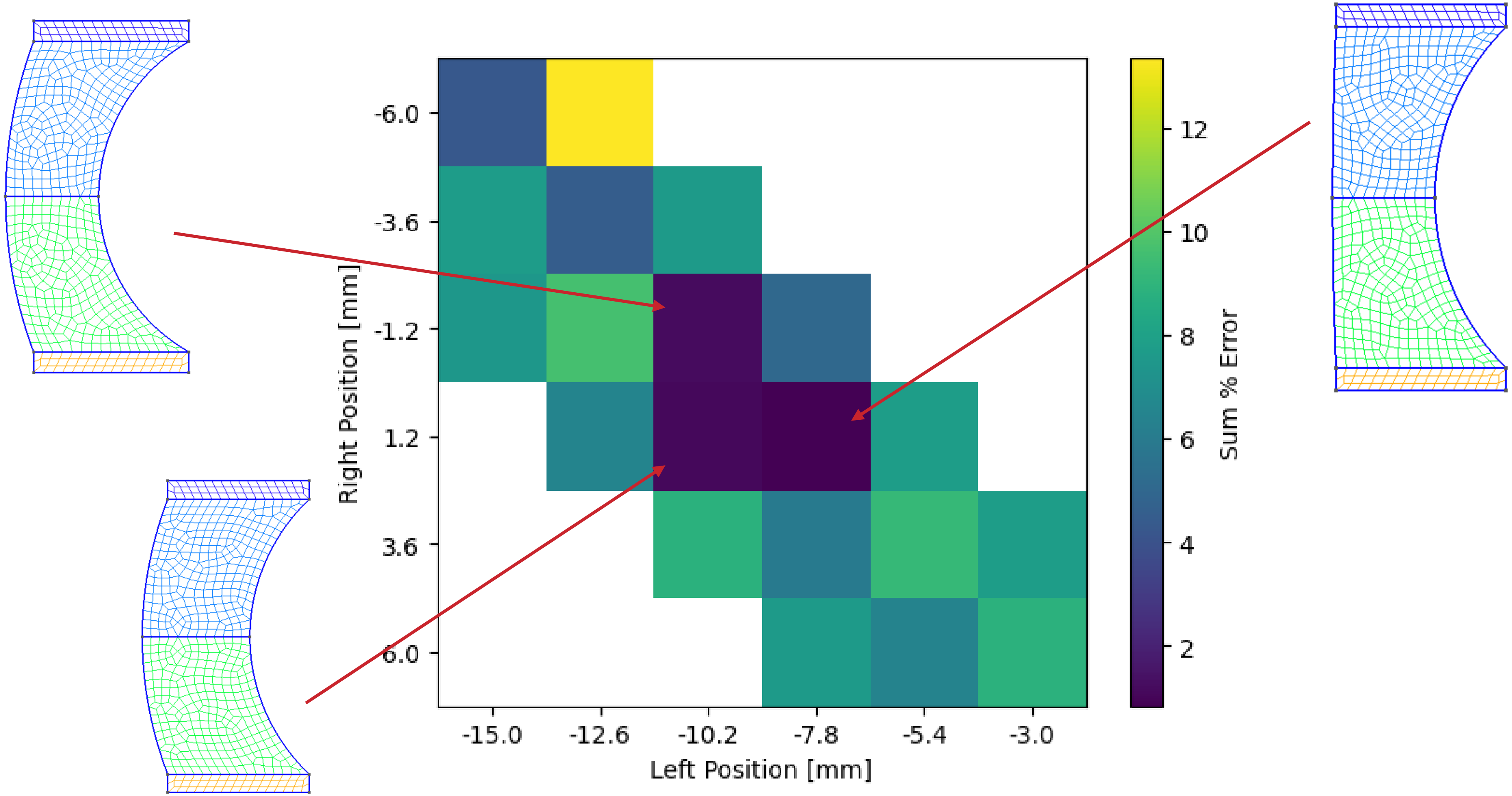
Identification Quality Optimisation



Identification Quality Grid Search



Towards Full Simulation

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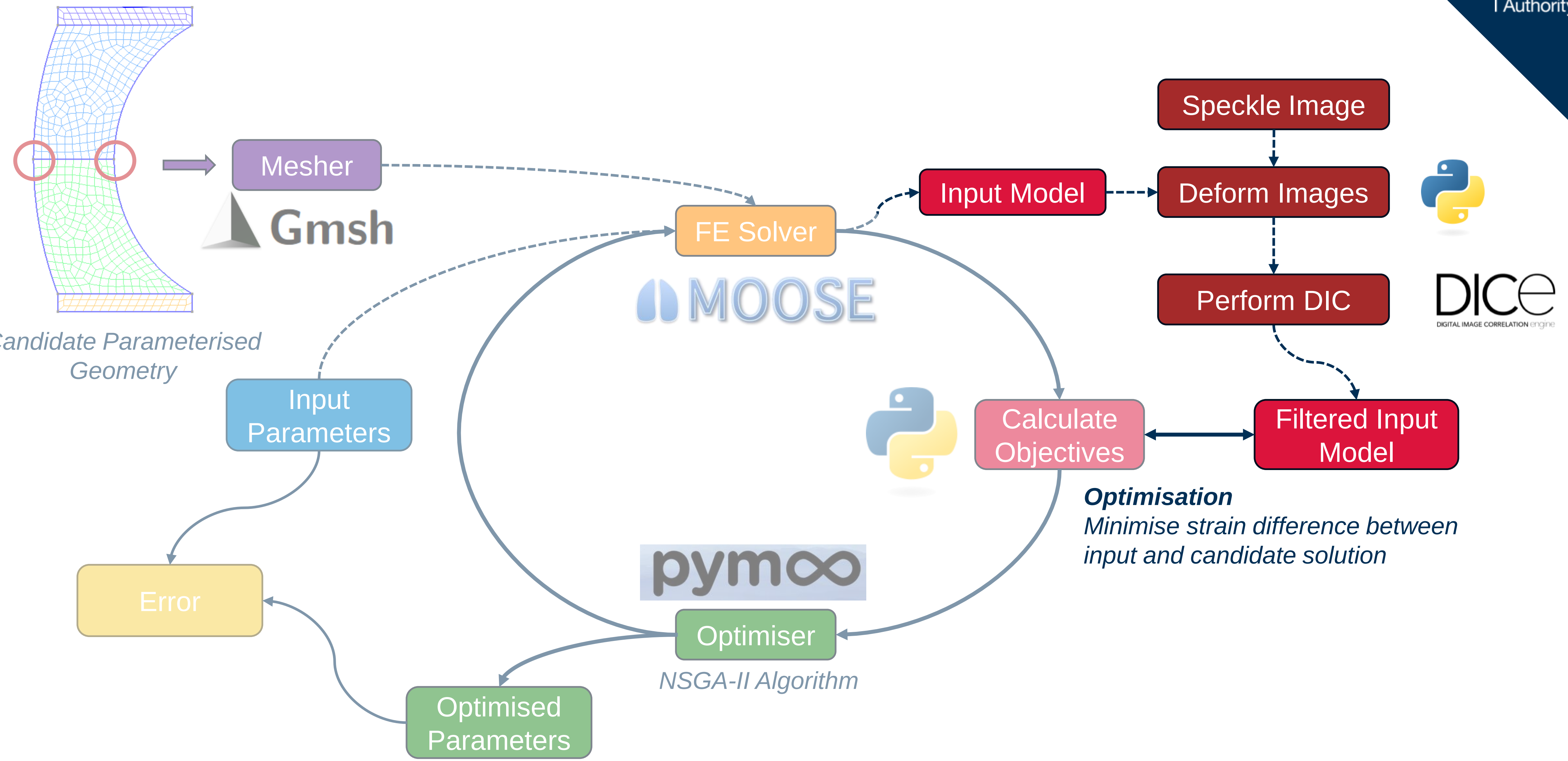


Optimisation

Minimise strain difference between input and candidate solution

Conclusions & Outlook

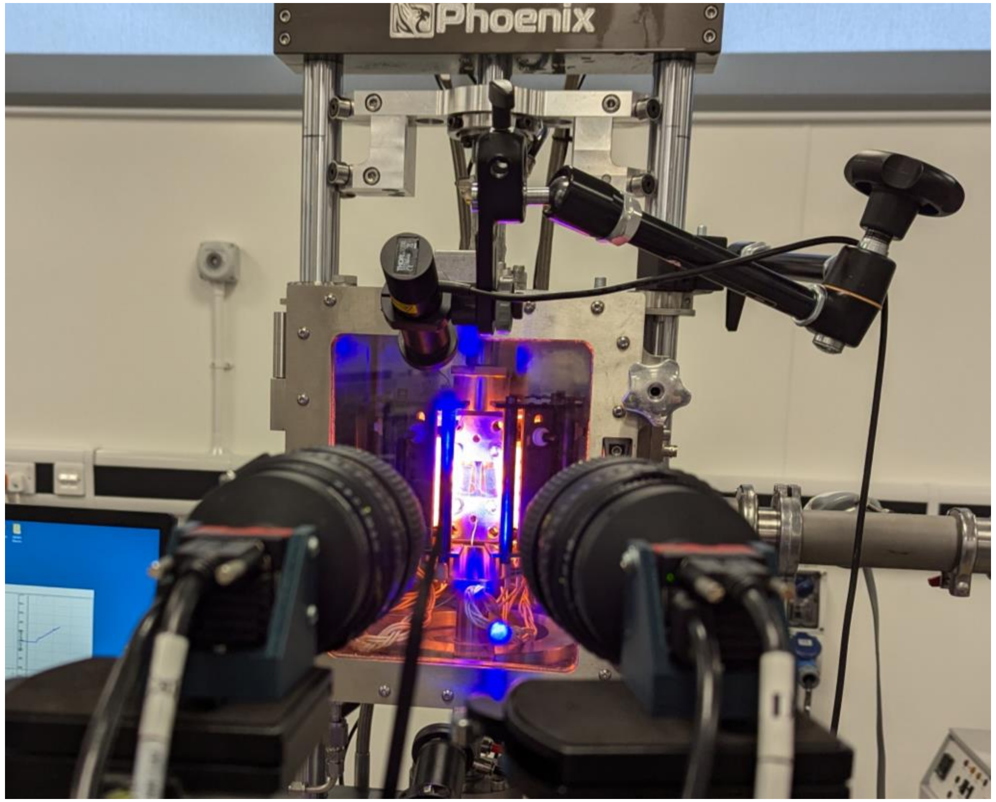
Tested novel geometry & uniaxial specimens at high temperature with similar creep stresses

Demonstrated multiple creep curves from one specimen at high temperature

Fitted isotropic model to data and demonstrated reasonable agreement with experiment

Going forward:

- Improved design optimisation
- Targeting Gr91 steel 600-700^{o}C
- Data from uniaxial and MT2 geometries



Thank you
Any questions?

Contact: rory.spencer@ukaea.uk

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