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Testing Irradiated Titanium Alloys for High-Cycle Fatigue

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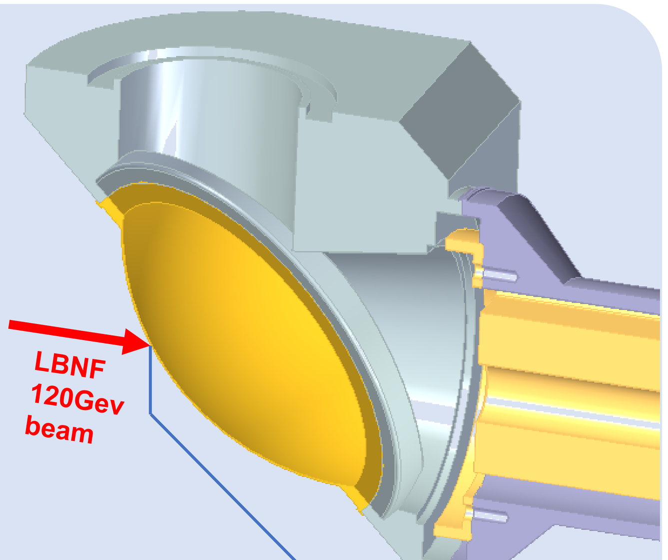
Abstract

The LBNF-DUNE project will highly irradiate titanium beam windows on the target, accumulating 2.5 Displacements Per Atom (DPA) every year. Due to pulsed beam heating effects, these windows are also subject to oscillating stresses, which may lead to fatigue failure. The fatigue life of irradiated titanium is not well studied, particularly in temperature-controlled environments. A novel technique for estimating stress in mesoscale (~3mm) ultrasonically oscillated fatigue samples has been implemented at the UKAEA's Materials Research Facility to produce the Ultrasonic Fatigue Rig (UFR). The first irradiated samples to be tested on the UFR will come from the BLIP irradiation at Brookhaven, and further samples will come from an installation at the Birmingham University MC40 Cyclotron, where 96 samples will be irradiated and cooled by a nitrogen gas flow, replicating in-beam conditions at LBNF.

1. Fatigue of irradiated beam windows

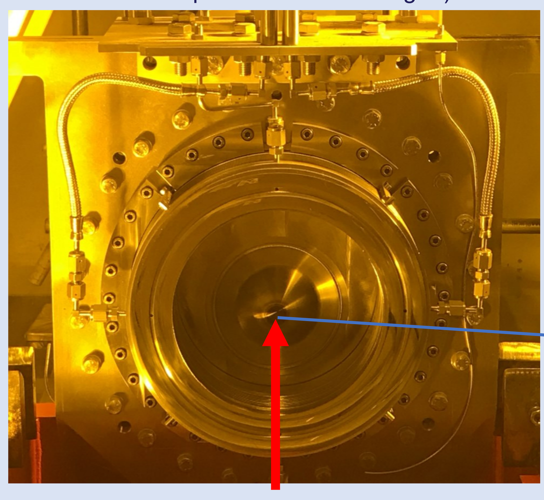
Neutrino-producing target windows suffer high levels of irradiation. The upstream beam window for LBNF is the most highly irradiated part of the target structure, suffering 2.5 DPA-SCO/yr at nominal conditions (approximately 5 DPA-NRT) and up to 15 DPA-SCO/yr at overfocused conditions. The second T2K beam window has experienced 4 DPA-NRT over its entire lifetime and has now been replaced. The new window is expected to accumulate the same level of damage **every year** during the Hyper-K phase.



LBNF Target Upstream Window

Transient beam heating and cooling causes alternating stresses on windows, particularly on T2K, where shockwave resonances can cause stresses up to 600MPa every pulse (depending on window thickness). At these levels fatigue failure may become a limiting factor on target lifetimes. Irradiated titanium shows significant hardening and ductility reduction [1], and fatigue lifetimes can decrease by 20% for only 0.24 DPA in grade 23 [2], but data on higher irradiations is unavailable.

T2K 1st upstream window (Ti-6-4, survived 2.2×10^{21} protons and exchanged)



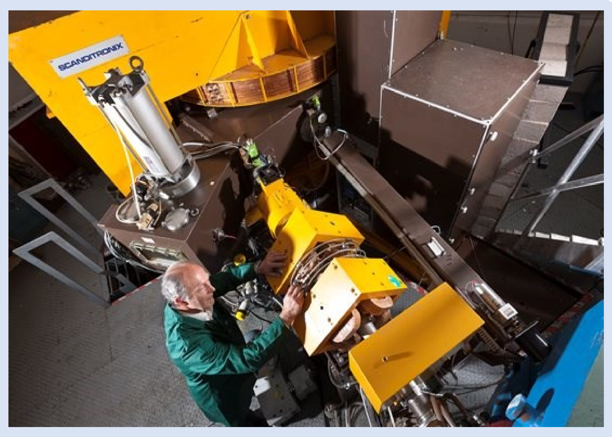
LBNF:
2.5 DPA-SCO / year
(~5 DPA-NRT)
21 MPa alt. stress
15×10^6 cycles / year
5 bar pressure

HyperK:
4 DPA-NRT / year
~45 MPa alt. stress
18×10^6 cycles / year
5 bar pressure

2. Irradiation campaigns

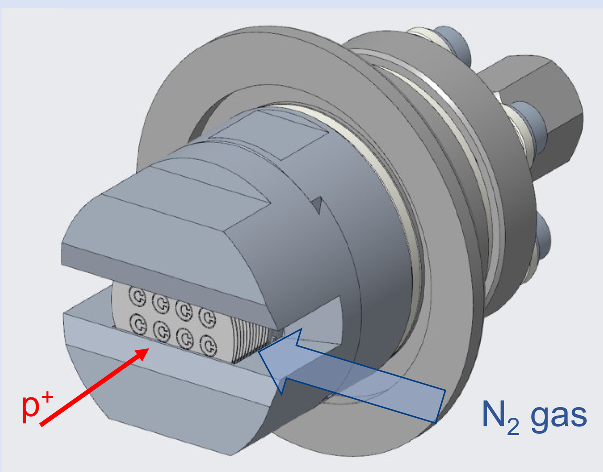
RAL is involved in two campaigns to provide more data on the fatigue life of irradiated titanium. One campaign at the Brookhaven Linear Isotope Producer (BLIP) has produced samples already:

- Grade 23 (annealed and STA), Grade 2, and Ti-15-3 samples, in 0.25mm foils
- Irradiated with ~200MeV protons to ~1 DPA-NRT [1]


Birmingham's MC40 Cyclotron

Another campaign is underway to design, build and install a sample irradiation environment at MC40 Cyclotron at Birmingham University:

- 96 samples in 0.15mm foils, likely Ti-6-4 and Ti-15-3 at different aging states
- Irradiated with 28MeV protons to between 4 and 5 DPA-NRT
- Face cooled with pressurised N2 to between 90 and 210°C, replicating the LBNF target hall.
- Designed with ease of disassembly in a hot cell in mind to simplify post-irradiation process



Sample environment for installation at MC40 Cyclotron

3. Samples and Testing Methods

Ultrasonic testing is a recent development in the fatigue field and has one major distinct advantage: 20kHz operation means testing times can decrease by a factor of 200 or more, allowing much more data collection at high cycles.

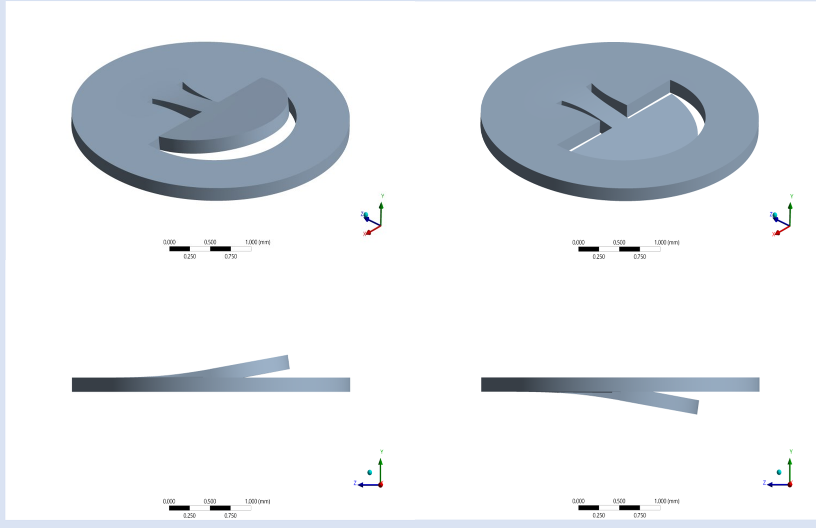
Dr Jicheng Gong (Oxford University) has developed a technique to oscillate small cantilever samples, using their own inertia to cause fatigue. As they are too small to apply a strain gauge, a laser is used to infer sample deformation. This has led to the creation of the UFR, allowing small irradiated samples to be tested in a safe environment and at high speed.

The mesoscale samples have two distinct benefits for irradiation fatigue studies:

- **Low mass causes lower total activities** – reduction in mass by a factor of >5000 compared to normal samples reduces risk of PIE testing to workers, reduces expense and difficulty of radiation controls
- **Thin samples makes irradiation process easier** – lower energy, MeV-range beams can simulate the DPA of higher beam powers in the GeV range.

However, this technique only allows fully reversed stress cycles, and as the samples are small, care must be taken not to lose them!

Time to **10^8 cycles**:
100 Hz (classic): **11.6 days**
20 kHz (ultrasonic): **1.4 hours**


Sample deformation estimated by finite element analysis, used to determine the stress from measured deflection of the sample.

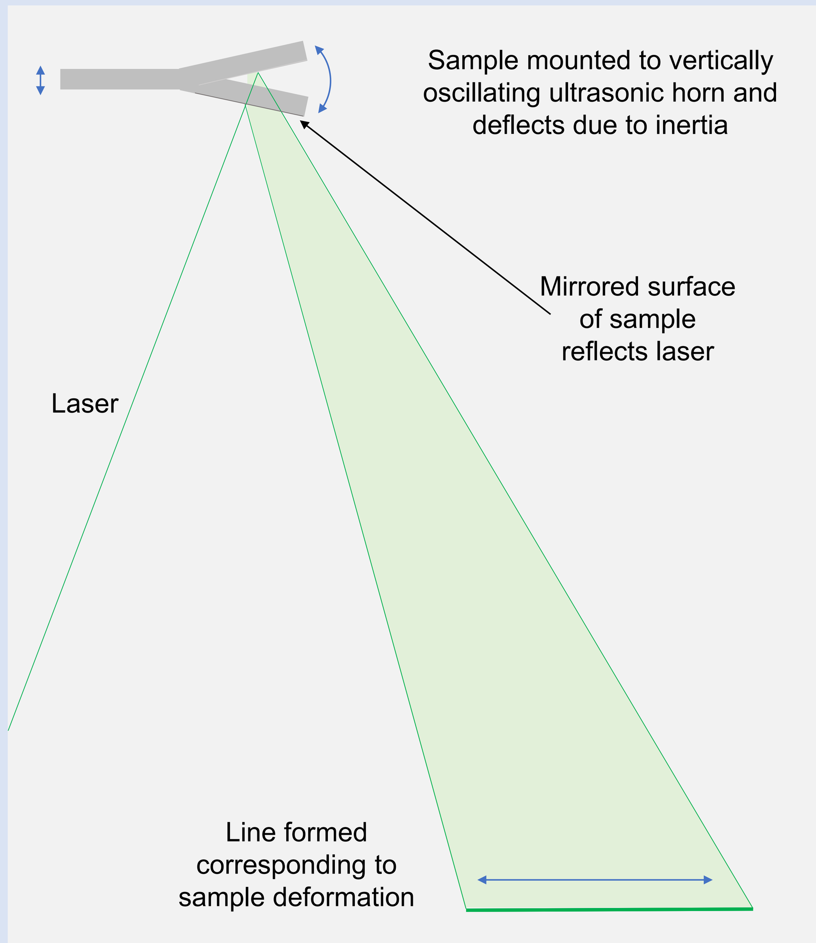


Diagram of how the laser deflection inference process works [not to scale]


One style of meso-scale cantilever on the end of a finger

5. Rebuilding and commissioning of the Ultrasonic Fatigue Rig

The UFR was initially conceived as a material science rig using a high frequency quad-pole detector to infer sample movement at 200kHz, fast enough to detect the intra-oscillation movement of the samples. However, due to issues with commissioning and calibrating this system, it has been de-scoped into a simpler machine which can produce S-N curves. This is enough to generate a lot of useful data for the future engineering of target beam windows.

Commissioning steps:

Completed:

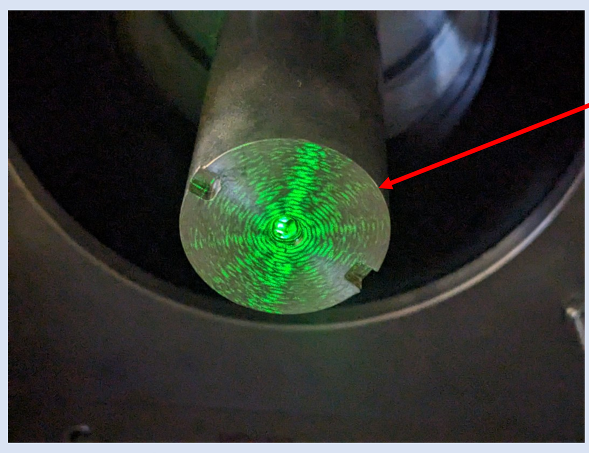
- Deconstruct laser optics and rebuild as thin-beam laser
- Perform FEA analysis to establish angle – stress curve

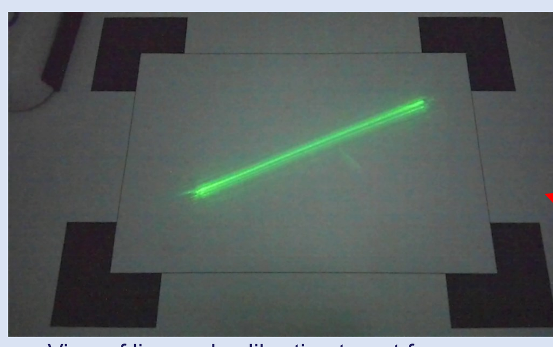
In Progress:

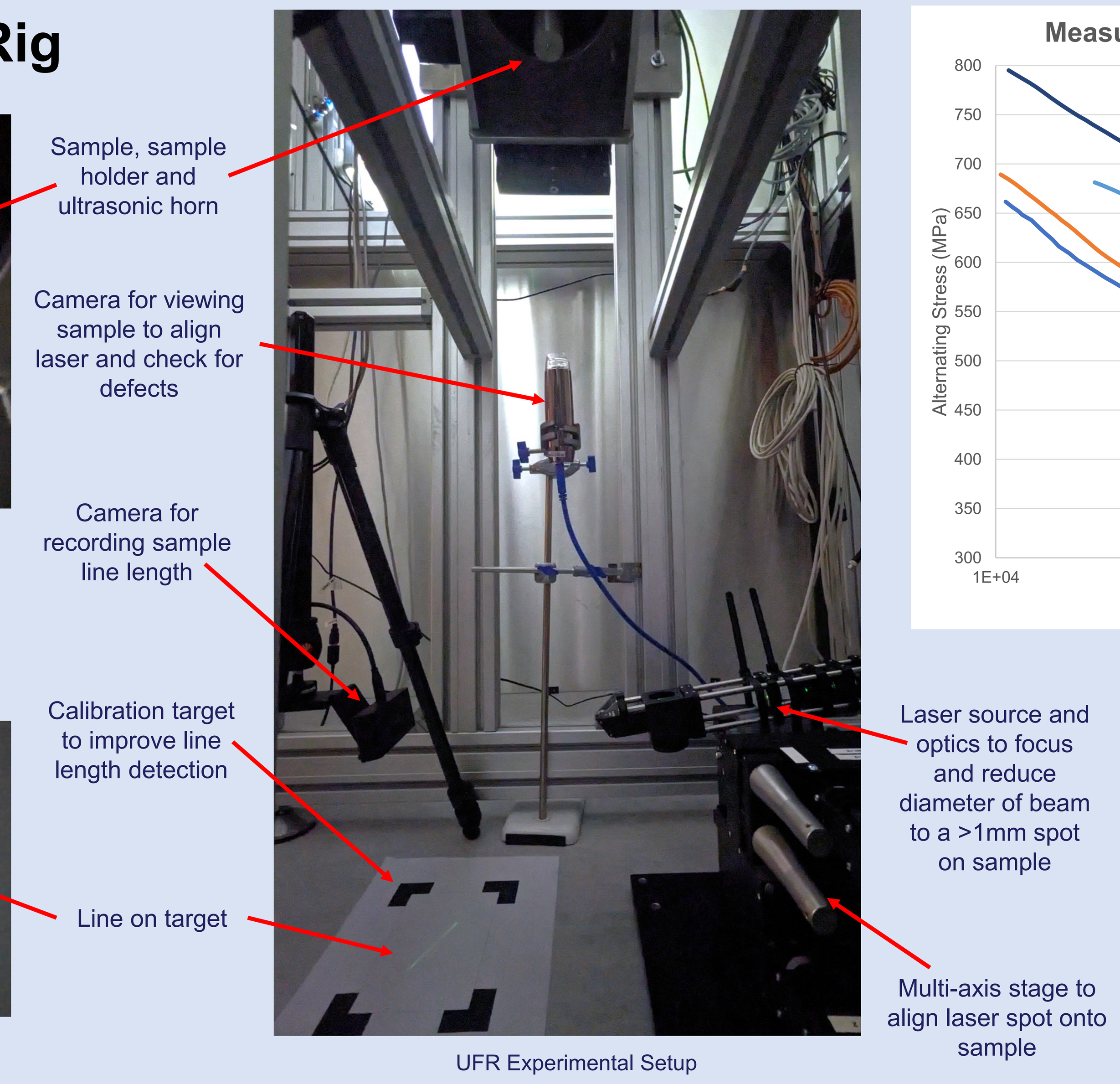
- Test dummy (unirradiated) samples to ensure calibration and validate FEA model
- Develop parts to prevent loss of irradiated material

Future Work:

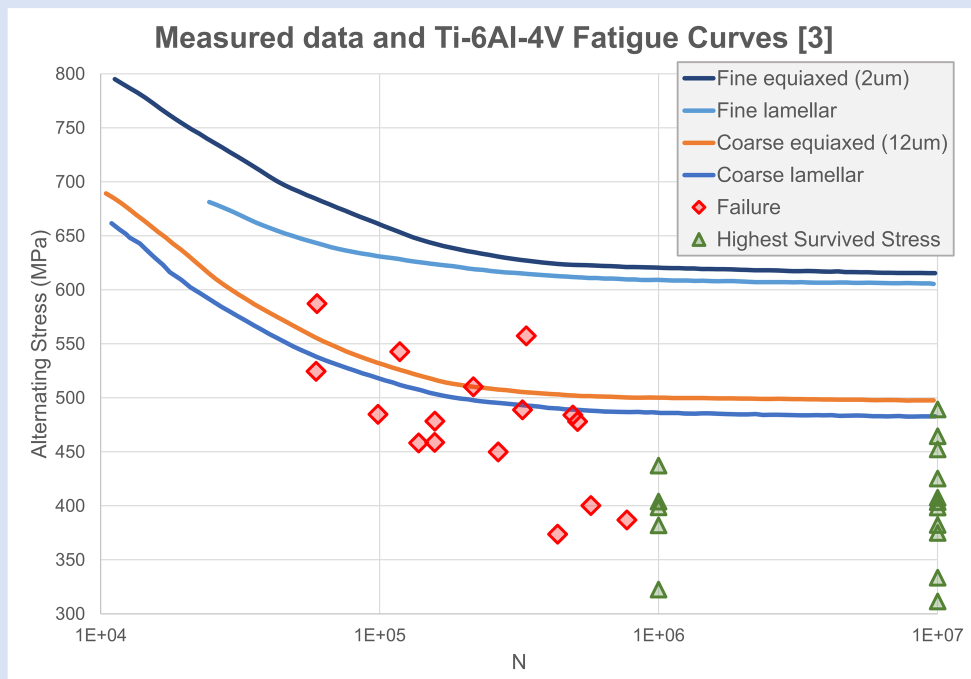
- Test irradiated BLIP samples
- Develop software to ease use of UFR by researchers/users


Laser at full brightness shining on sample and spilling onto ultrasonic horn head. The sample, held tightly in place by a custom-made grub screw with a through hole, must be aligned with the laser carefully to ensure a good result


View of line and calibration target from camera



UFR Experimental Setup



Initial analysis of the dummy sample data from step-stress tests shows a reasonable fatigue curve forming with a similar gradient but a lower endurance limit. However, the grade, microstructure and surface roughness of the dummy samples is currently uncharacterised so more testing is required.

References:

[1] Taku Ishida et al, "Radiation Damage Studies on Titanium Alloys as High Intensity Proton Accelerator Beam Window Materials", 14th IWSMT
[2] Sujit Bidhar, "Fatigue Performance of Proton Irradiated Ti6Al4V Alloy", RaDIATE 2019
[3] R Boyer, G Welsch, E.W. Collings, Titanium Alloys, Material Properties Handbook, ASM

Acknowledgements:

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High Power Targets

Fermilab Long-Baseline Neutrino Facility

DUNE Deep Underground Neutrino Experiment

Materials Research Facility

University of Oxford

RaDIATE Collaboration Radiation Damage In Accelerator Target Environments