LBNF Target and Associated Equipment

Status, Issues, Plans

17th January 2022

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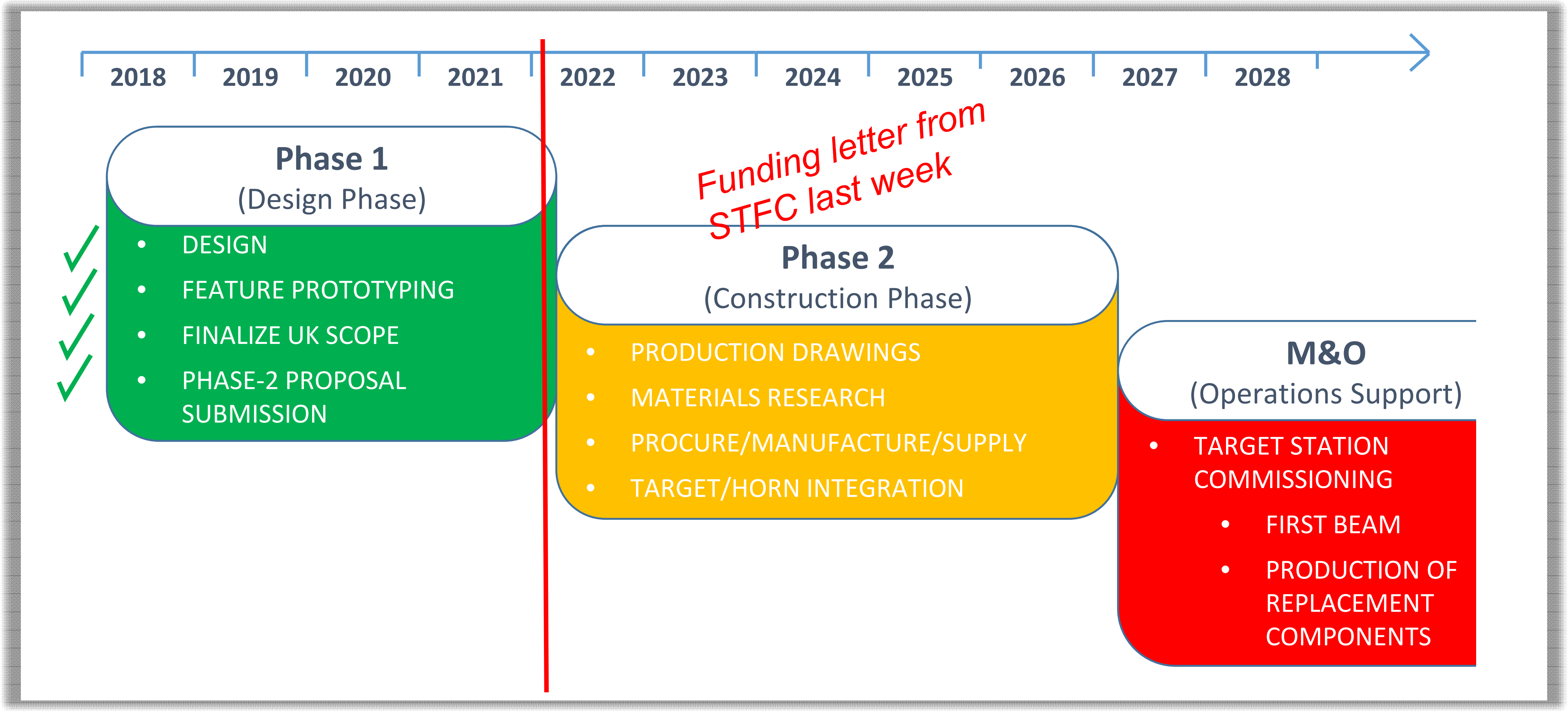
John Back *(University of Warwick)*

Biao Cai *(University of Birmingham)*

Dong Liu *(University of Bristol)*

LBNF-UK Target and Associated Equipment: *Project Phases and Status*



LBNF-UK Target and Associated Equipment
Phase 2 Division of Scope

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RAL / High Power Targets Group
- Project management
- Engineering design and construction
- Procurement
- Commissioning

WARWICK
THE UNIVERSITY OF WARWICK

University of Warwick
- Target: physics performance simulations

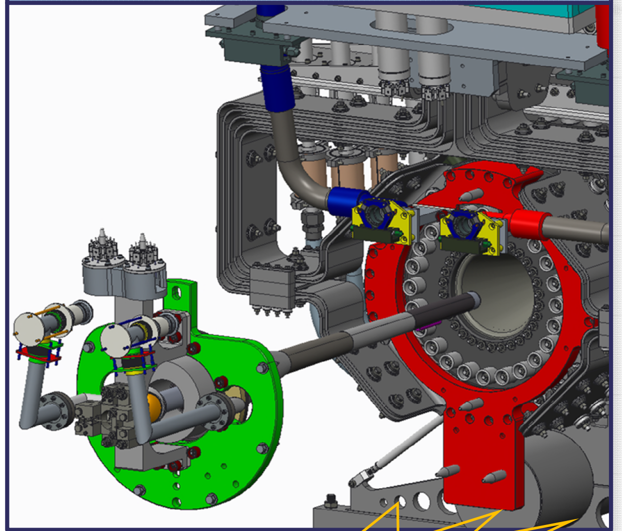
Birmingham / Bristol / Oxford / Culham
- Target: materials research

WP0: Project Management
PI: Densham / PM: Loveridge

PDR Dec 2021 ✓

WP1
"Target and Beamline Apparatus"
(Loveridge)

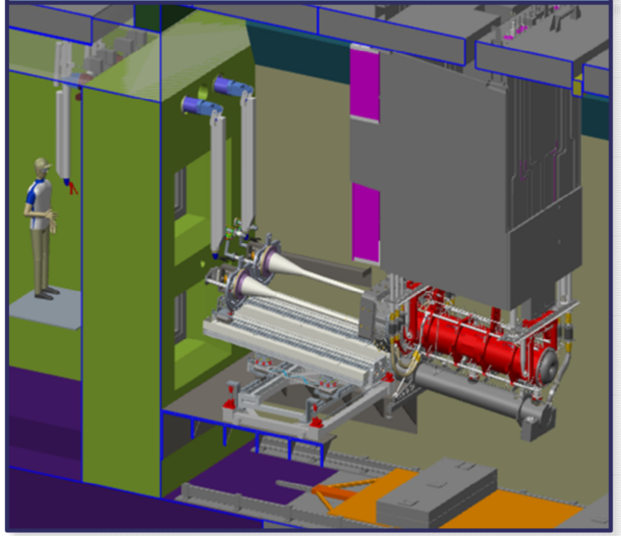
PDR Dec 2020 ✓



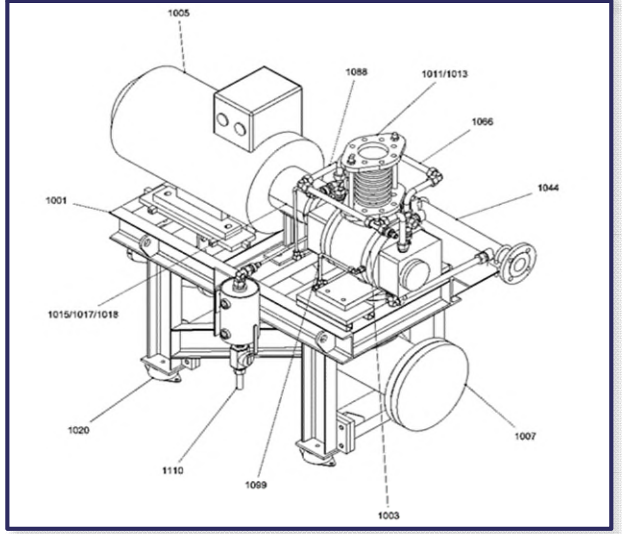
PDR Mar 2022

WP2
"Remote Handling"
(Harvey-Fishenden)

PDR Dec 2020 ✓



WP3
"Helium and Ancillary Plant"
(Davenne)



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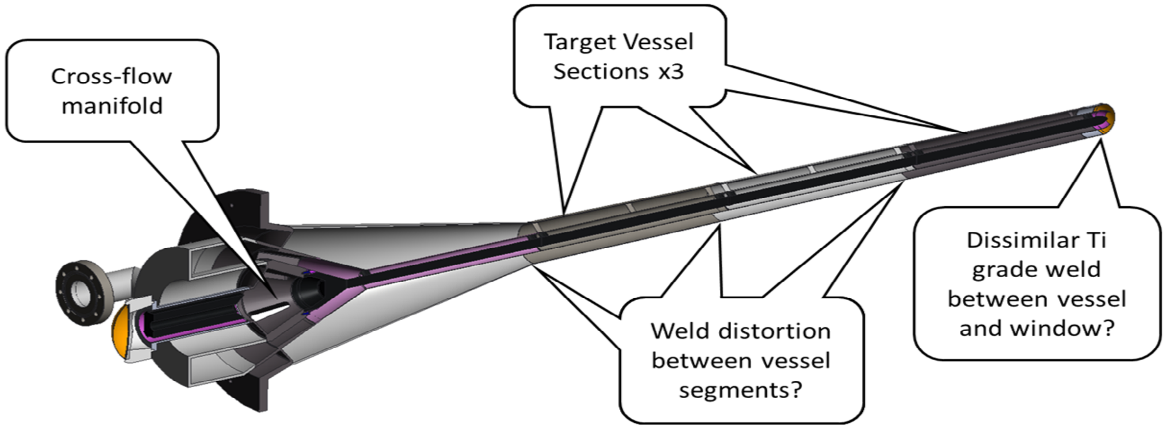
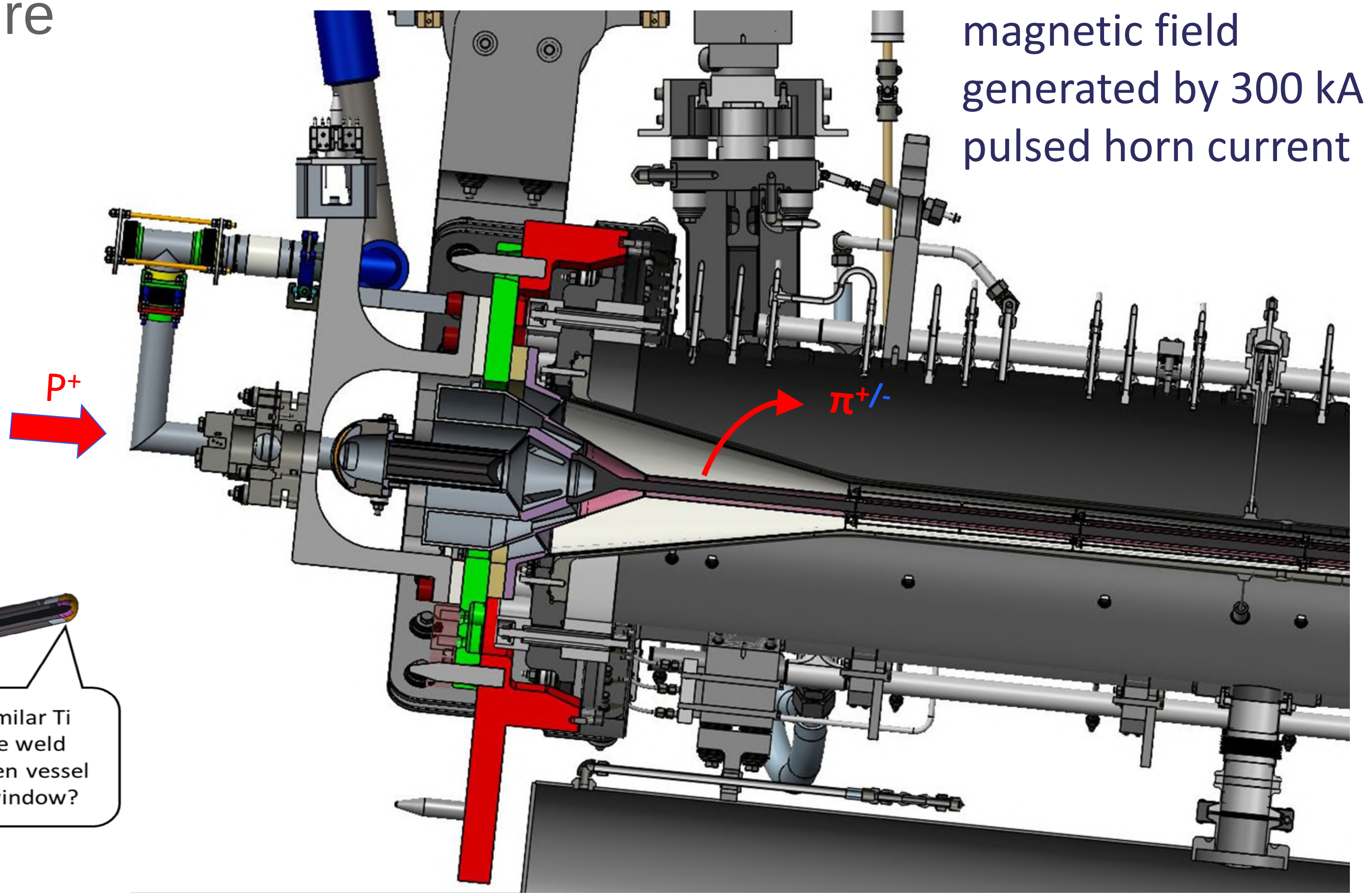
Target (RAL) and magnetic horn (Fermilab)

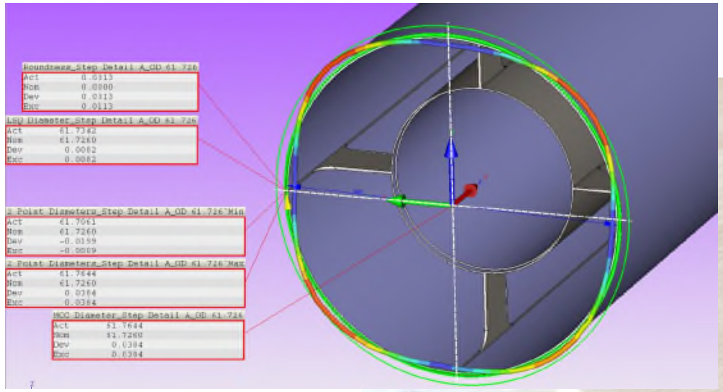
- We have spent 4 years on preliminary design and feature prototyping of:
  - Target
  - Target Exchange System
  - Helium cooling system
- Next stage: construction

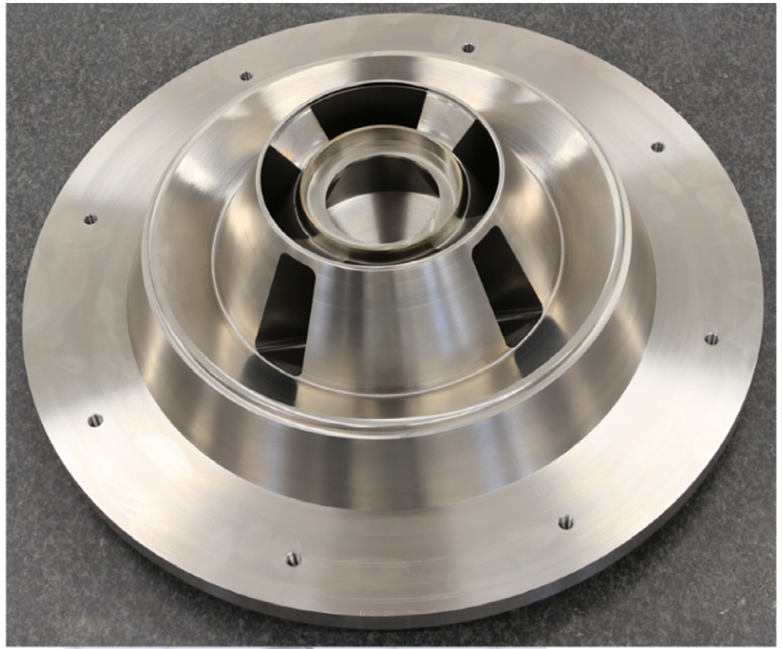
Single sign of pions focussed by toroidal magnetic field generated by 300 kA pulsed horn current

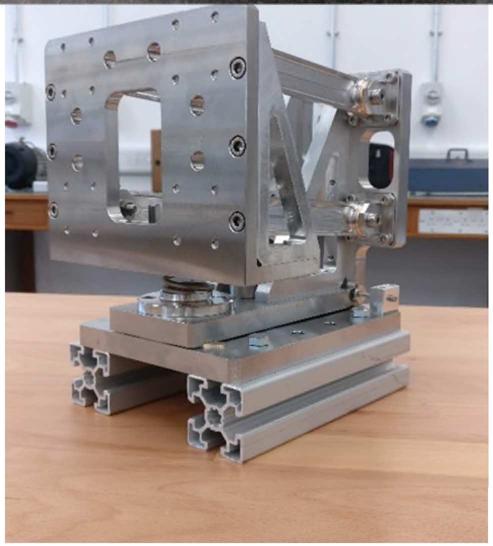


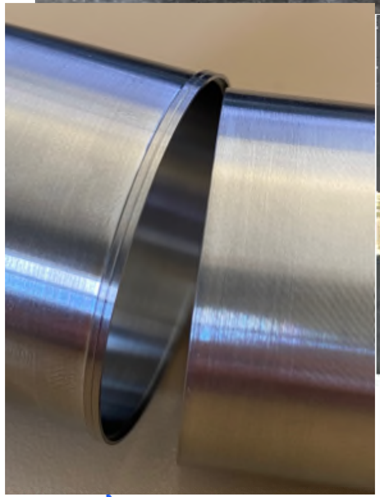


Feature Prototyping Status (UK)









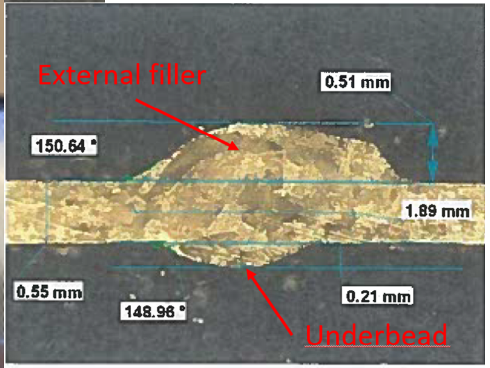


Image No. A02075_000002
Comment:
HSD 433 - Section view of circumferential weld full penetration and profile. This weld is deemed acceptable I.A.W. EBP/QAS/01 iss.9 CLASS I.

STFC Technology Department Calendar February 2022 photo

EDM machined titanium shroud

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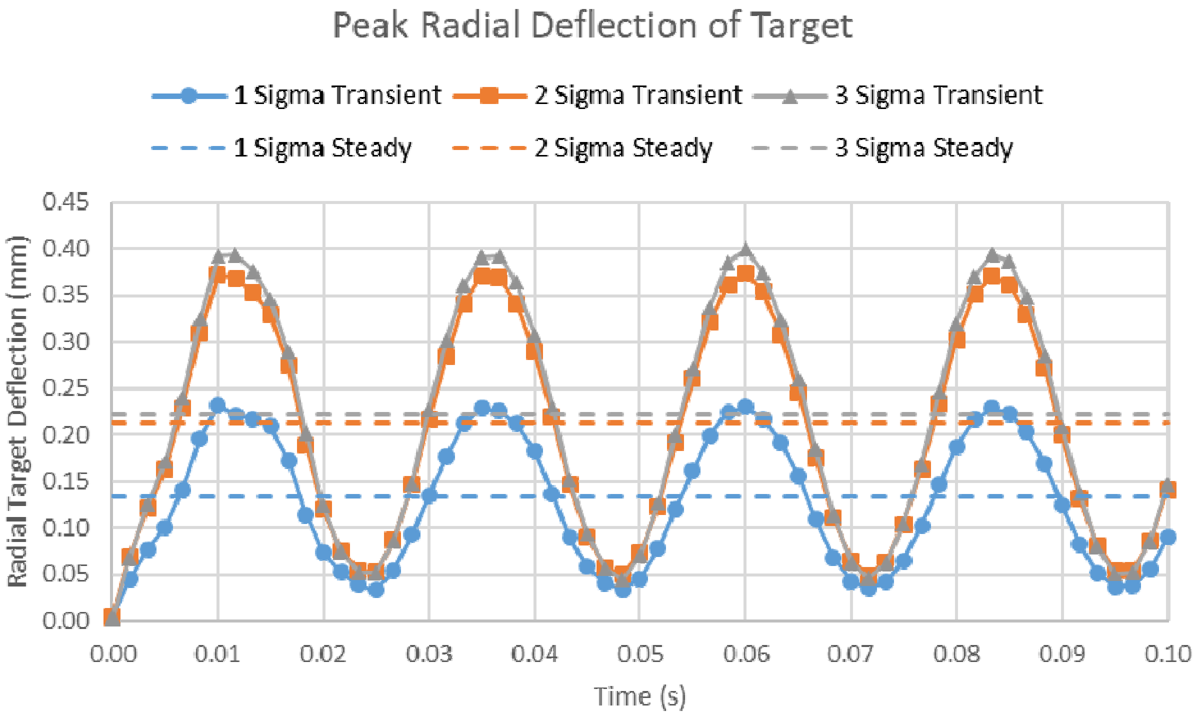
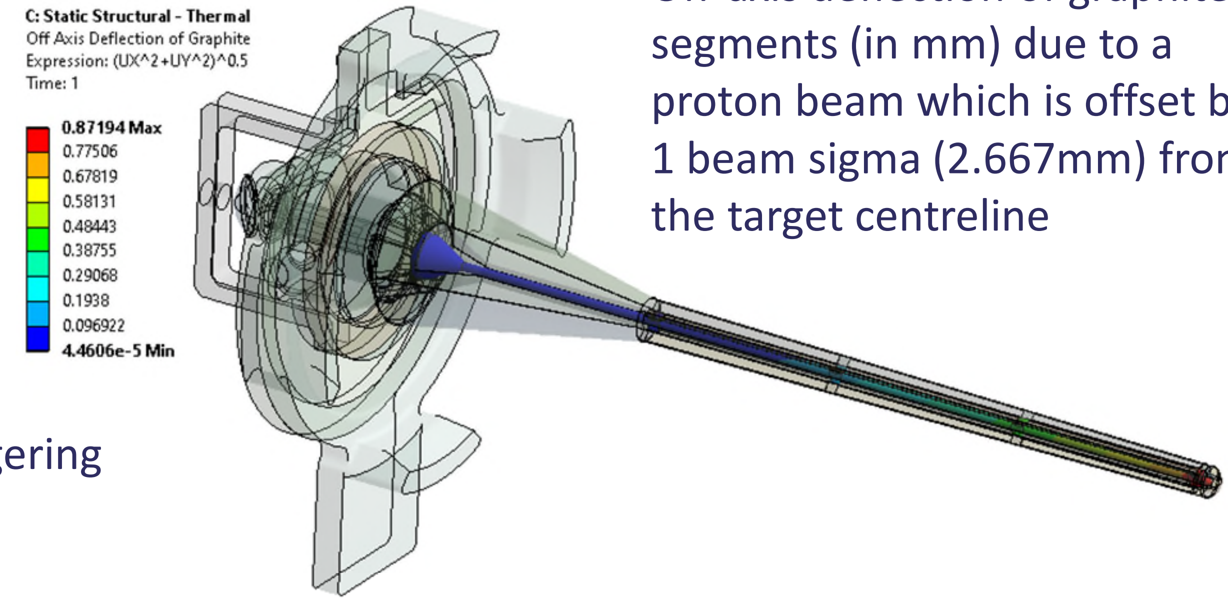
Off-Axis Beam on Target – Single Pulse



In all cases the target oscillates at the first natural frequency of 43Hz.

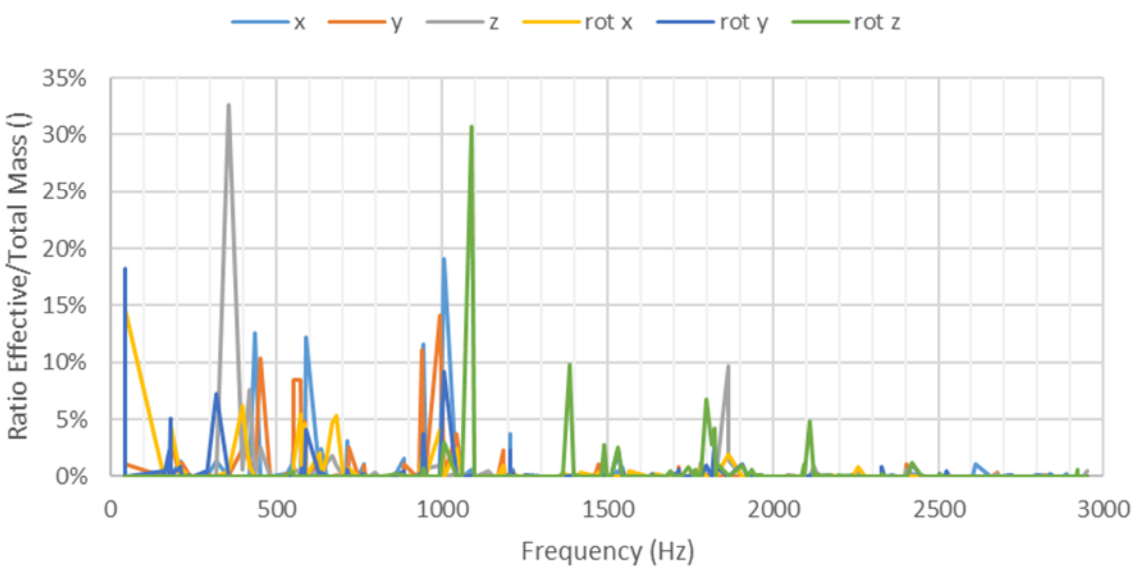


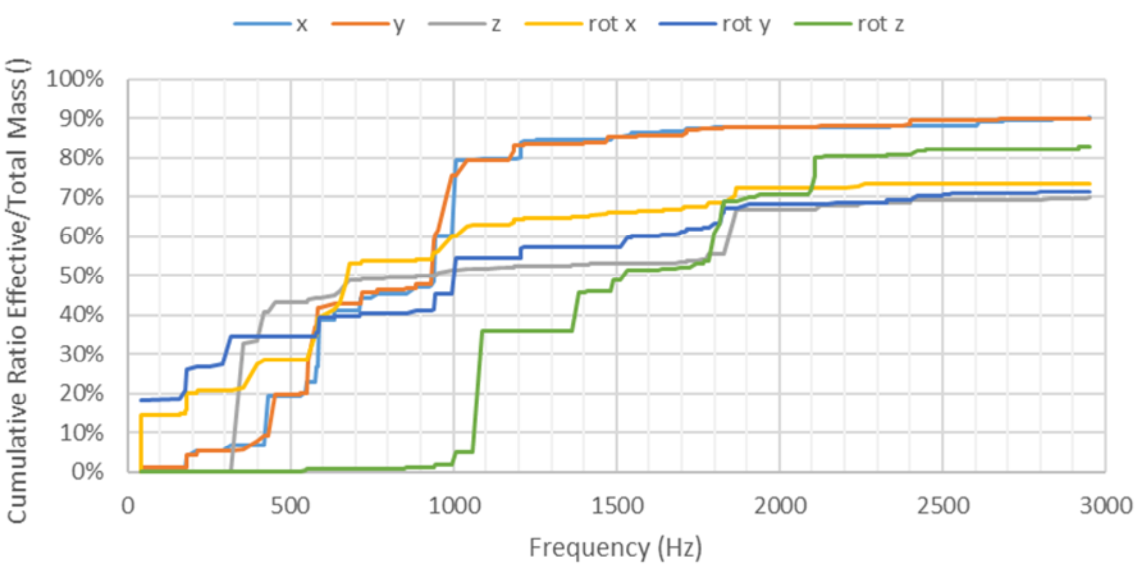
Off-axis deflection of graphite segments (in mm) due to a proton beam which is offset by 1 beam sigma (2.667mm) from the target centreline

Beam centroid could vary by ≈ ±2mm (0.75 sigma) without triggering a beam trip, or ±25mm for two pulses before the beam trips

Modal Analysis of Target – Results

- First 250 modes found, covering frequencies from 43-2950Hz
  - ~90% total mass participation in x and y, but only ~70% in z
  - Range extends to almost 3x the frequency of interest (1000Hz); at least 1.5x is required for accurate downstream mode superposition analyses
  - Solution takes up >350GB after solving, >550GB while solving





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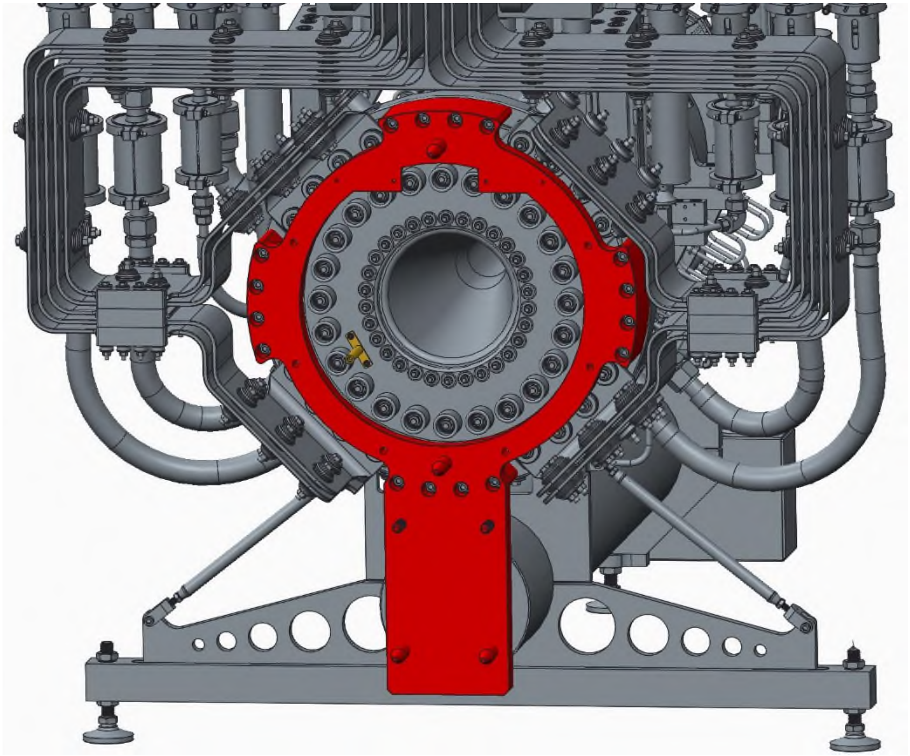
Pulsed horn issues for target

- LBNF Target/Horn integration approach involves mechanically mounting the target from the horn outer-conductor flange. This is a ***different approach*** to the one taken at NuMI and T2K.
- We have planned to examine the target response to horn current pulsing at the pulse test stand when the prototype-target and prototype-Horn become available (~late 2024?).
- We have initiated a study to gain some insight ahead of time.



Target Docking Interface Plate (red) attached directly to horn outer-conductor flange

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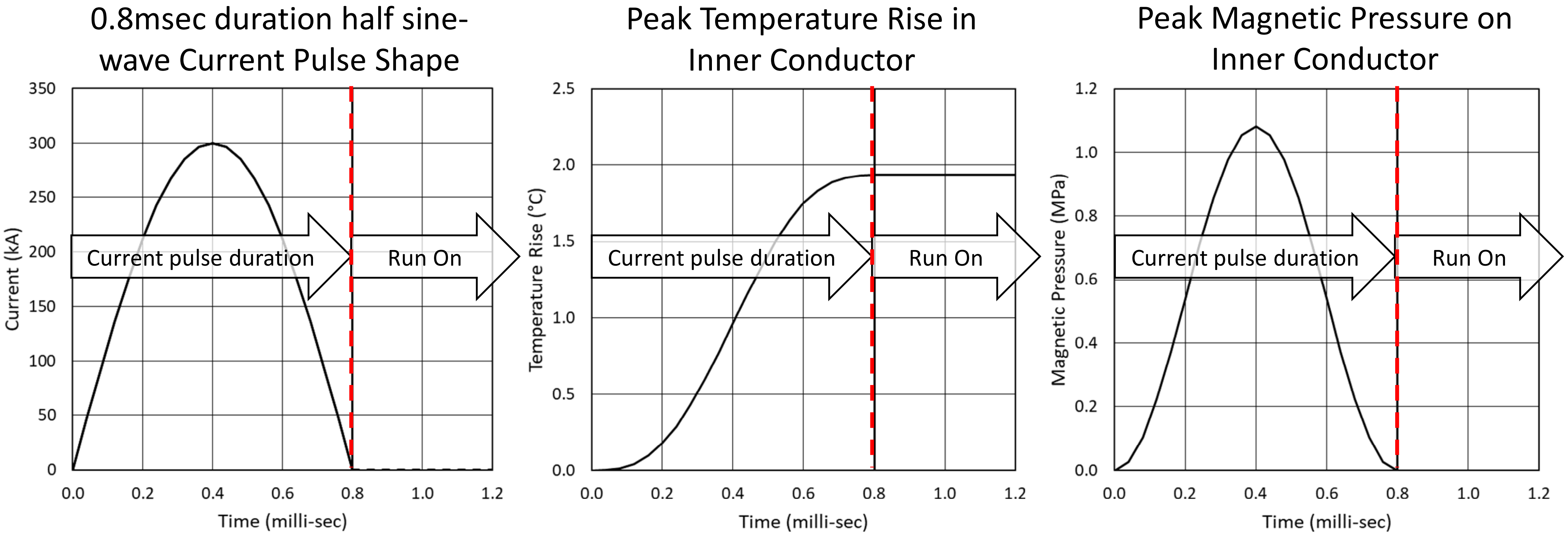
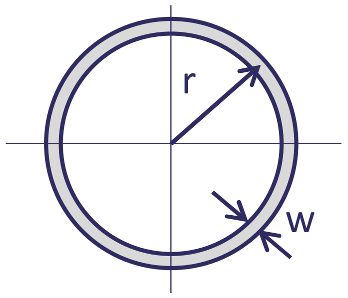
Procedure for Horn Pulsing Study (P. Loveridge)

- Model i) magnetic pressure and ii) temperature rise for a single pulse (approximated by 20 linearly ramped steps)
- Then run on with 40μs time steps (aiming to capture effects up to few kHz)

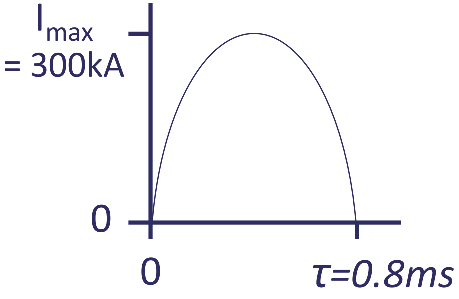


Joule Heating

Inner conductor as a thin-walled tube:



Half sine-wave shaped current pulse:



$$Q = \frac{J^2}{\gamma} = \frac{I^2}{A^2\gamma} \quad (W/m^3)$$

$$A = 2\pi r w \quad (m^2)$$

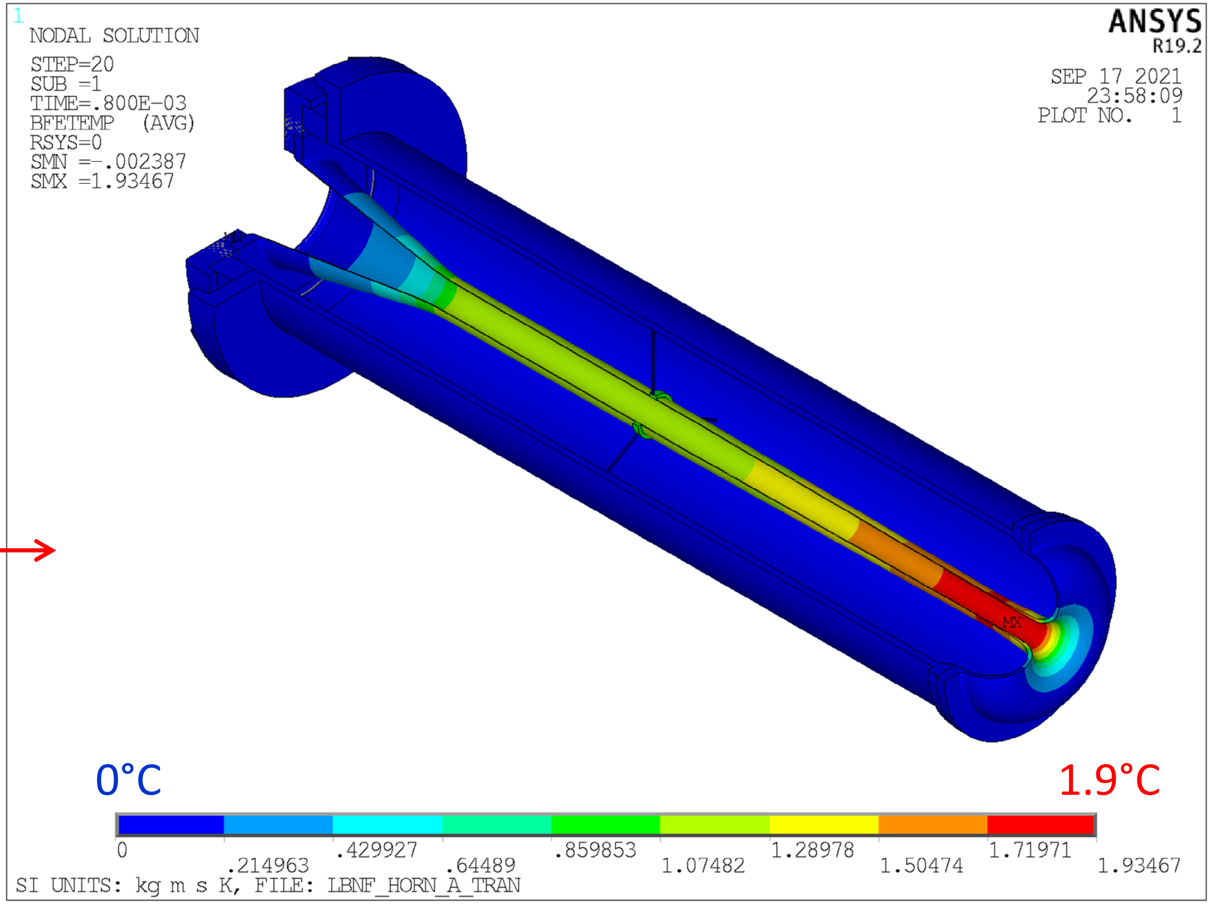
$$Q = \frac{I^2}{4\pi^2 r^2 w^2 \gamma} \quad (W/m^3)$$

→ *Use this in ANSYS* →

$$E = \frac{1}{4\pi^2 r^2 w^2 \gamma} \times \int_0^\tau I^2(t)\, dt \quad (J/m^3)$$

$$E = \frac{1}{4\pi^2 r^2 w^2 \gamma} \times \frac{I_{max}^2 \tau}{2} \quad (J/m^3)$$

$$\Delta T = \frac{I_{max}^2 \tau}{8\pi^2 r^2 w^2 \gamma \rho C_p} \quad (°C)$$



Taking:

$r_{min} = 35\ (mm), w = 2.5\ (mm), I_{max} = 300\ (kA), \tau = 0.8\ (ms),$

$\gamma = 26.3\ (MS/m), \rho = 2700\ (kg/m^3), C_p = 900\ (J/kg.K)$

Gives a peak temperature rise of $\boldsymbol{\Delta T_{max} = 1.9\ °C}$

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Magnetic “Pressure”

In the magnetic horn we have three perpendicular vectors:

Current , Magnetic Field and Force, with the relation $F = J \times B$

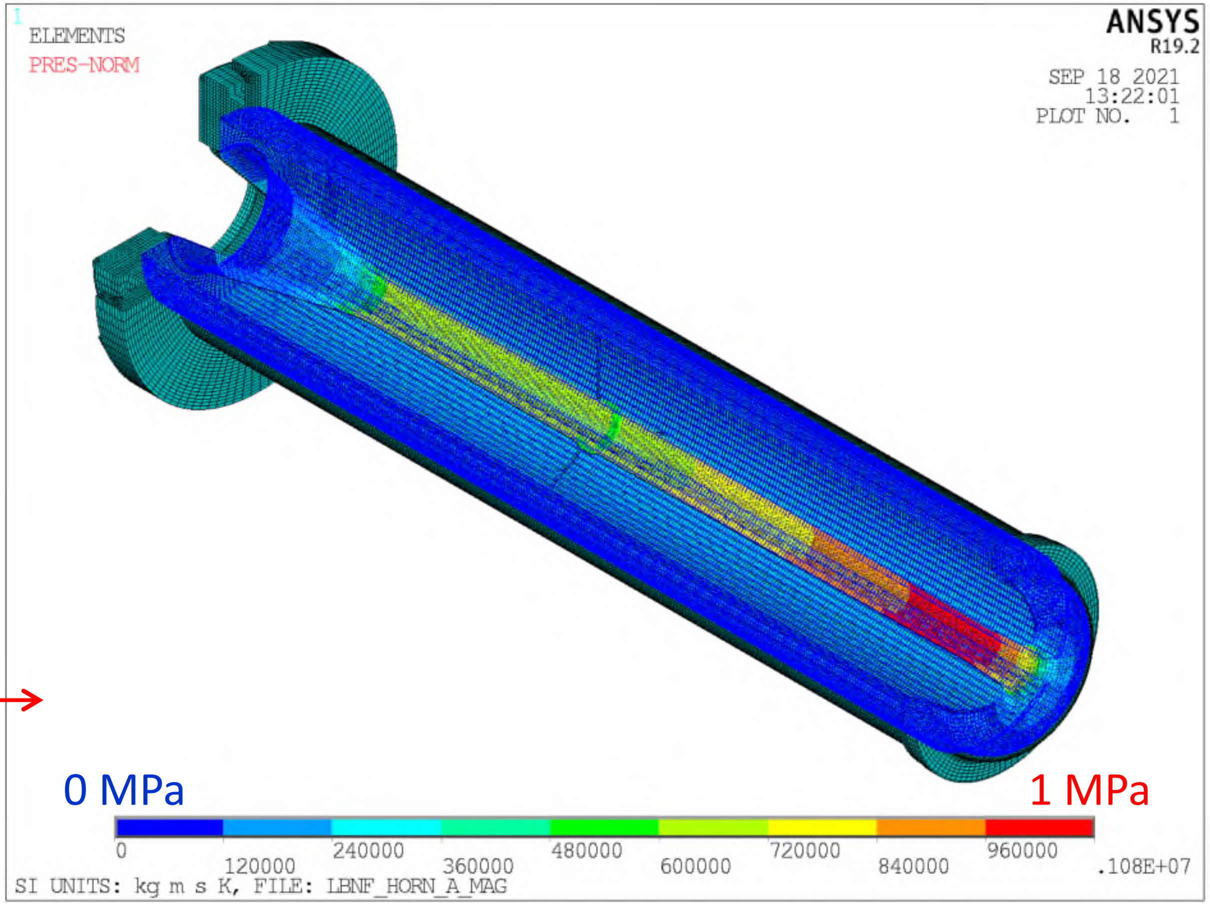
Inside the magnetic volume the field Varies with r according to:

$$B = \frac{\mu_0 I}{2\pi r} (T)$$

It is convenient to express the magnetic force acting on the horn conductor as a “pressure”

$$P = \frac{\mu_0 I^2}{8\pi^2 r^2} \quad (N/m^2)$$

Use this in ANSYS



The total longitudinal force is found from

$$F_{long} = \int_{R\,in}^{R\,out} \frac{\mu_0 I^2}{8\pi^2 r^2} \, 2\pi r \, dr \quad (N)$$

$$F_{long} = \frac{\mu_0 I^2}{4\pi} \ln\left\{\frac{R_{out}}{R_{in}}\right\} \quad (N)$$

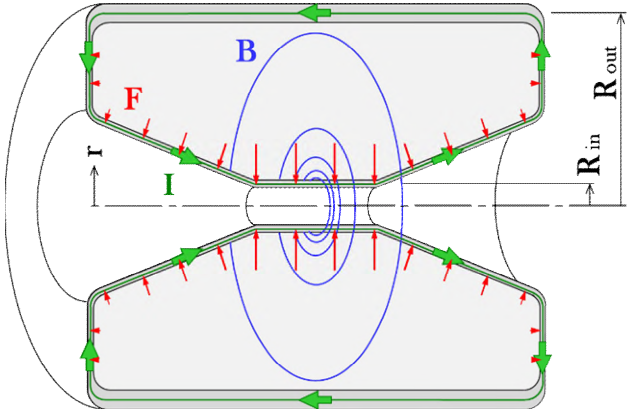
Taking:

$\mu_0 = 4\pi \times 10^{-7}\ (H/m)$, $I_{max} = 300\ (kA)$,

$R_{out} = 220\ (mm)$, $R_{in} = 36\ (mm)$

Gives a peak longitudinal force of

$F_{long\ max} = 16\ kN$



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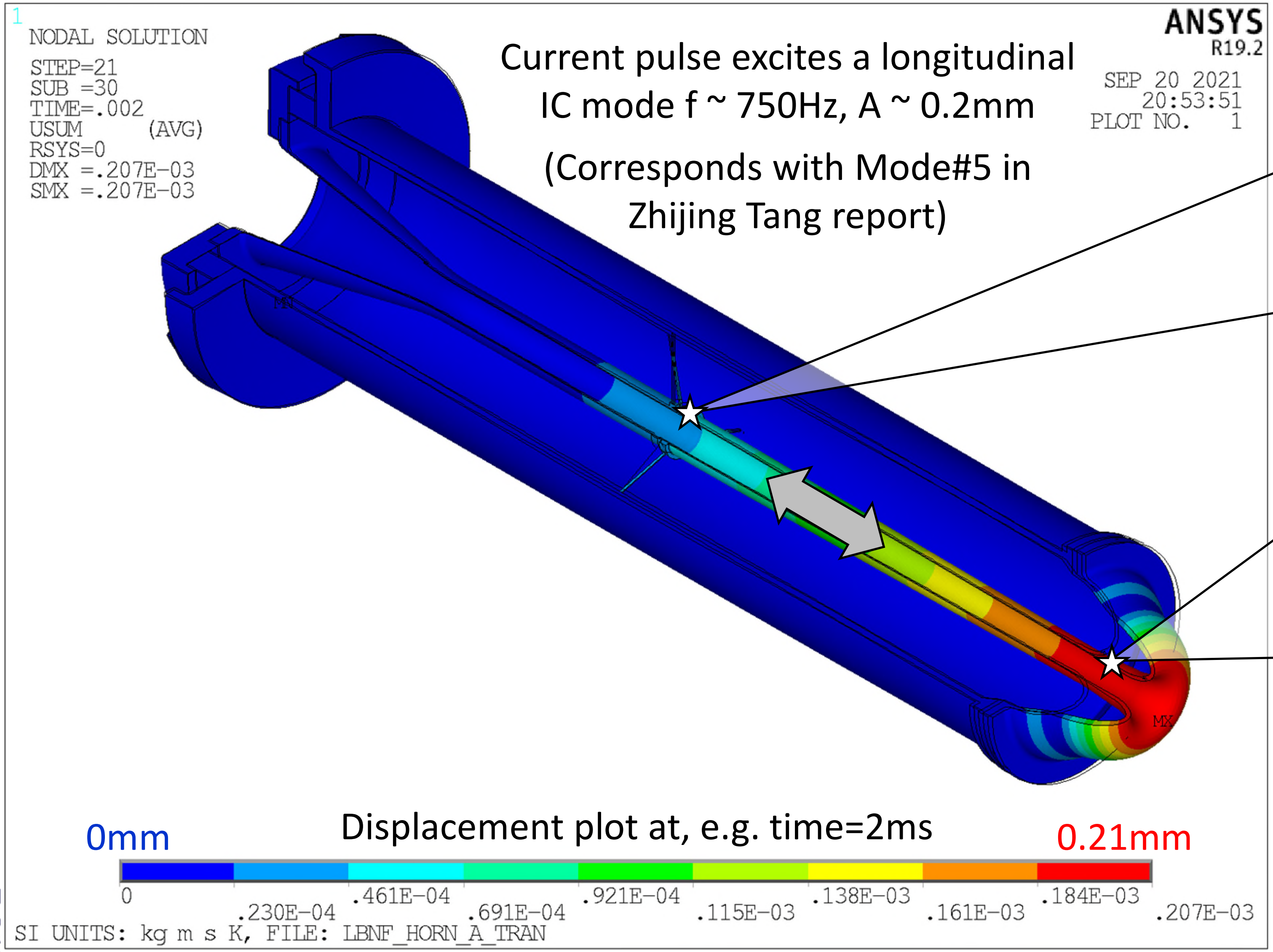
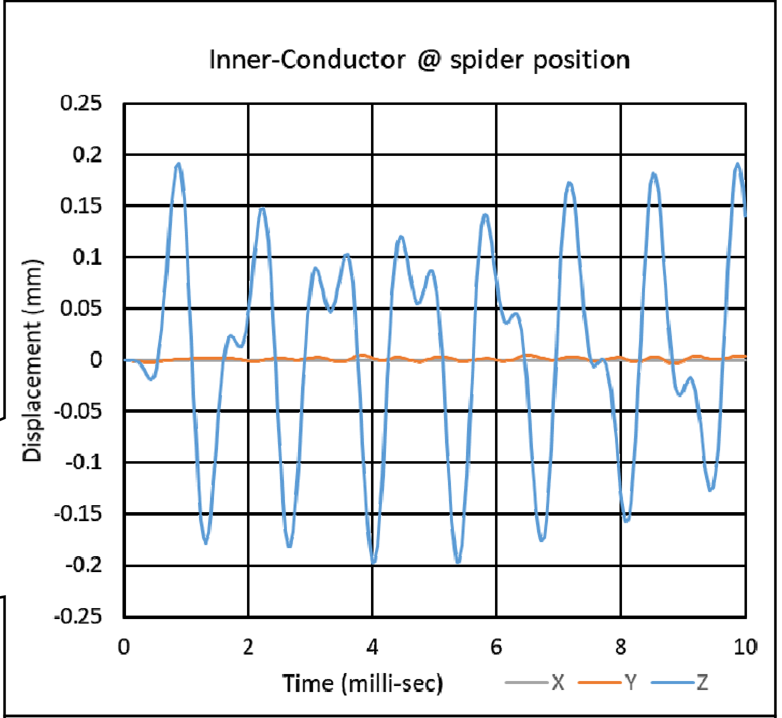
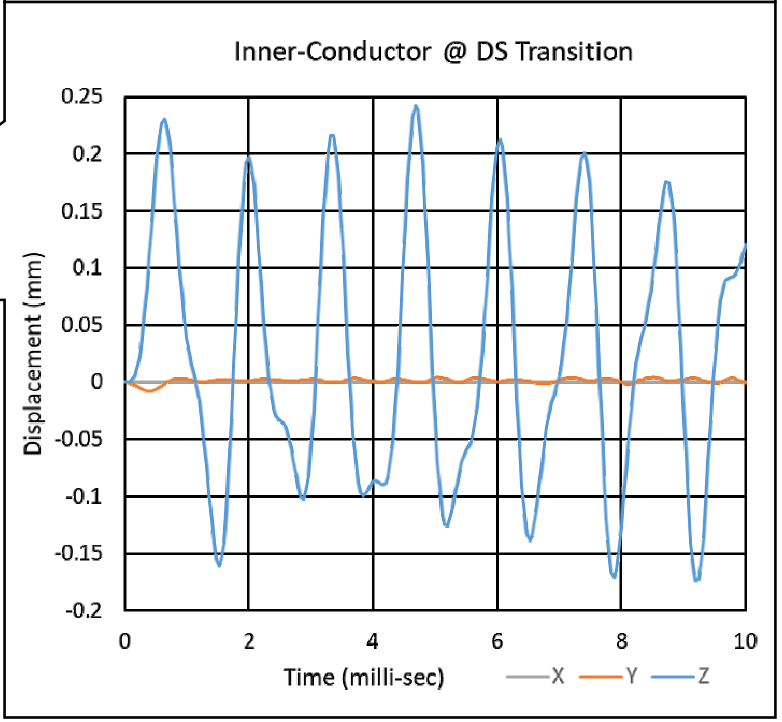
Response at Inner Conductor







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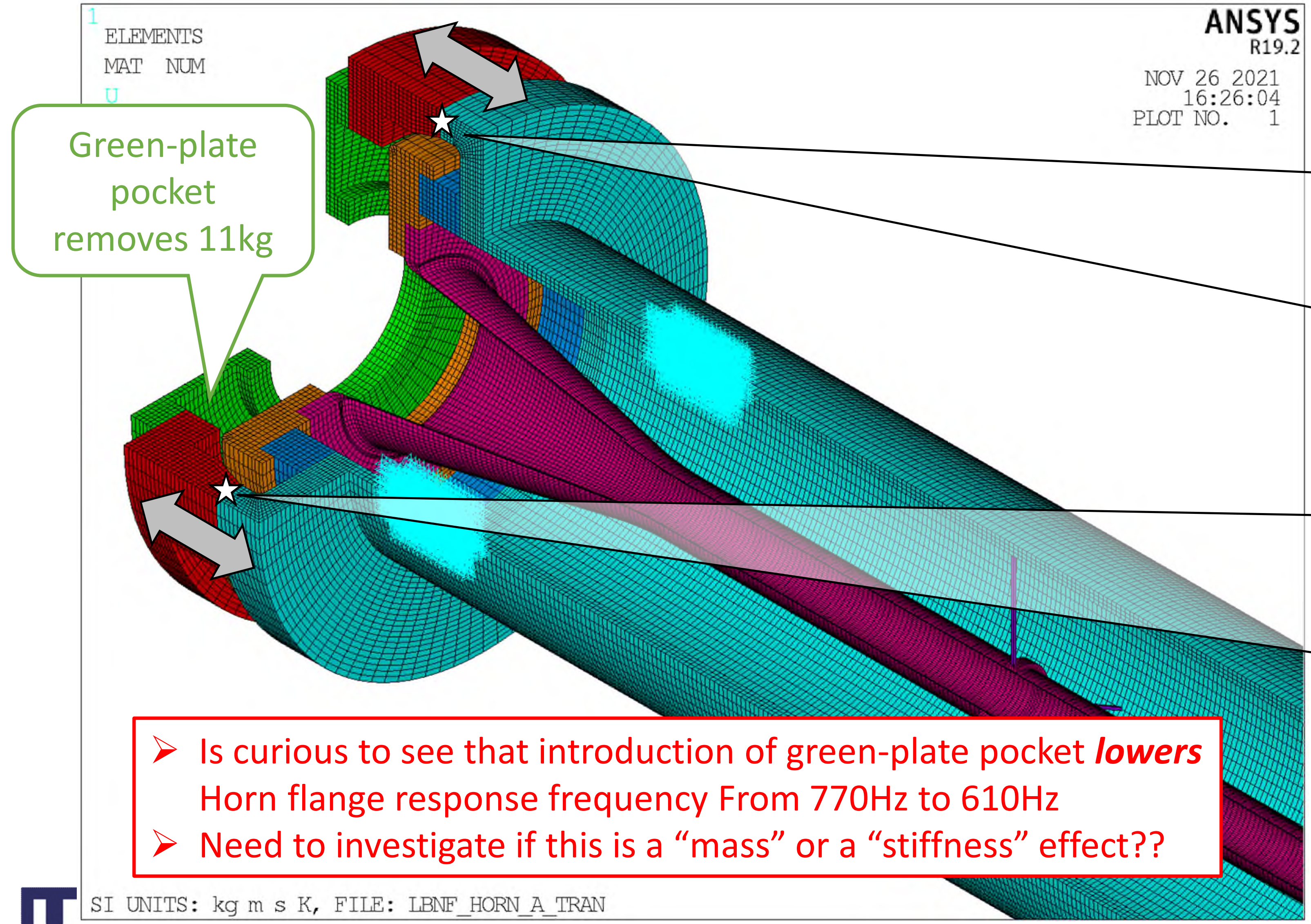
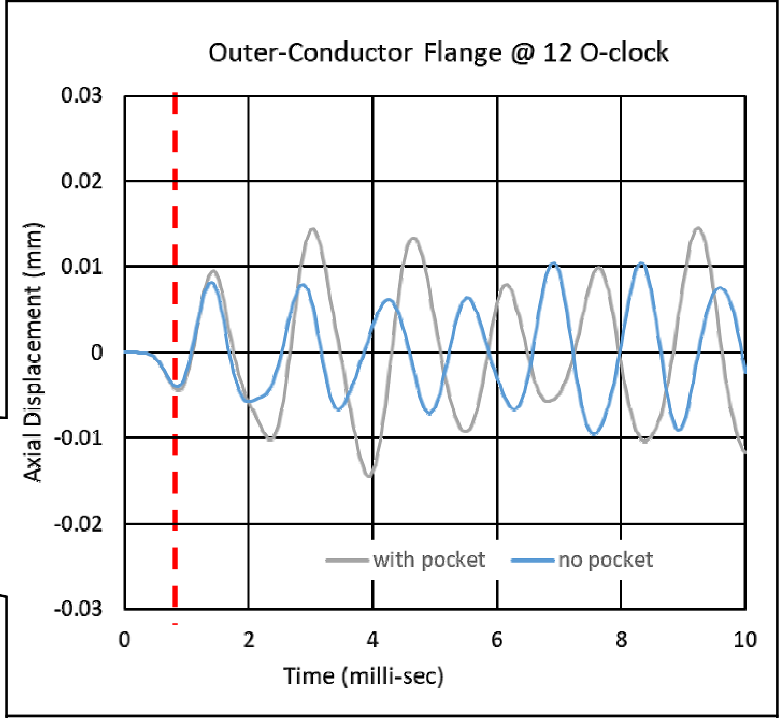
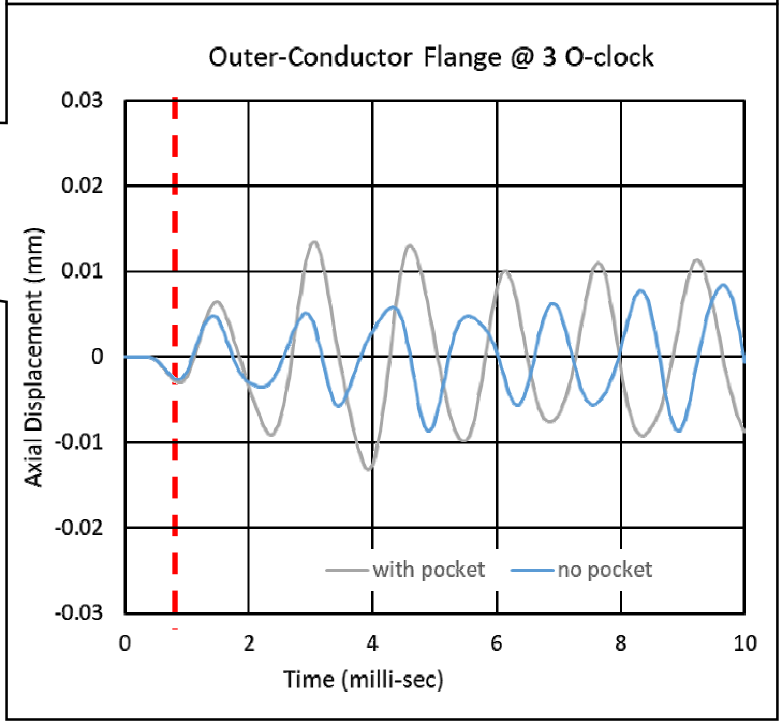
Response at target mounting position



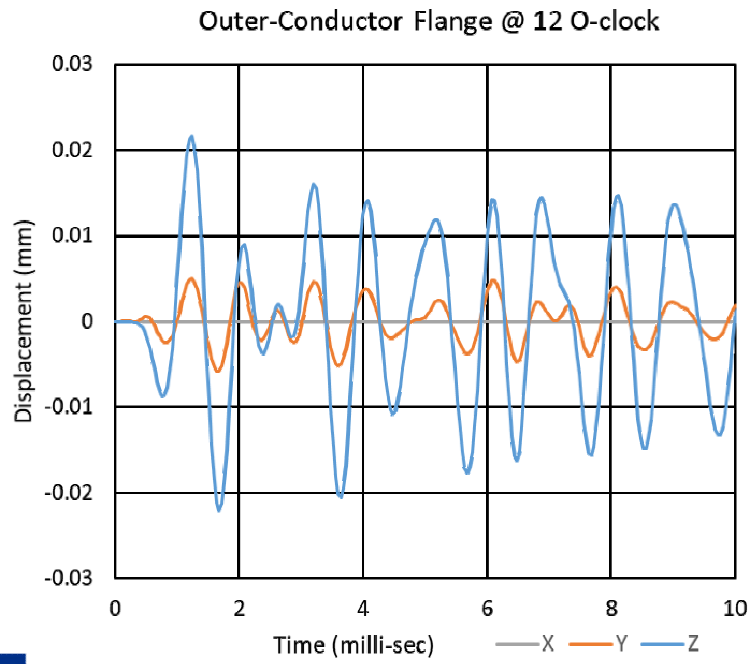


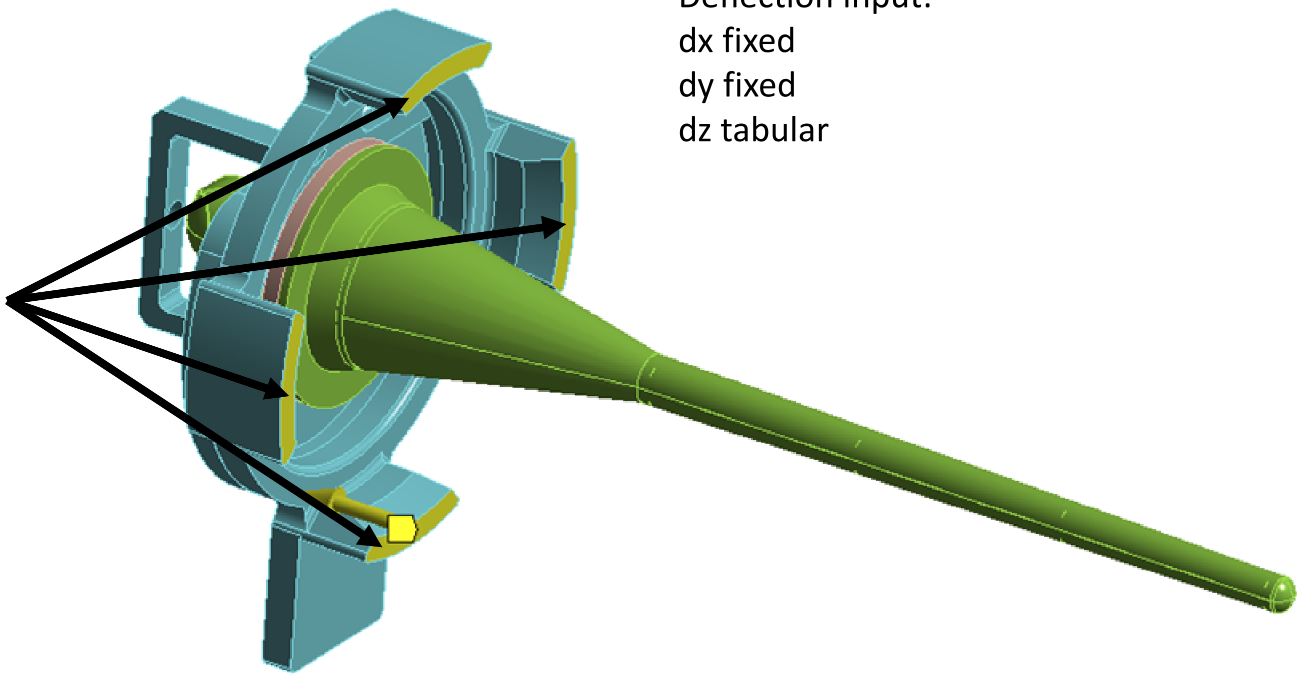


- ➢ Is curious to see that introduction of green-plate pocket ***lowers*** Horn flange response frequency From 770Hz to 610Hz
- ➢ Need to investigate if this is a "mass" or a "stiffness" effect??

Full Transient Analysis

- Transient analysis with a very small timestep and inertial effects included
- Full displacement vs time response (250 steps) input at the target supports
- Took 27 hours to solve, using >100GB solid state RAM
- No damping included





Deflection input:
dx fixed
dy fixed
dz tabular

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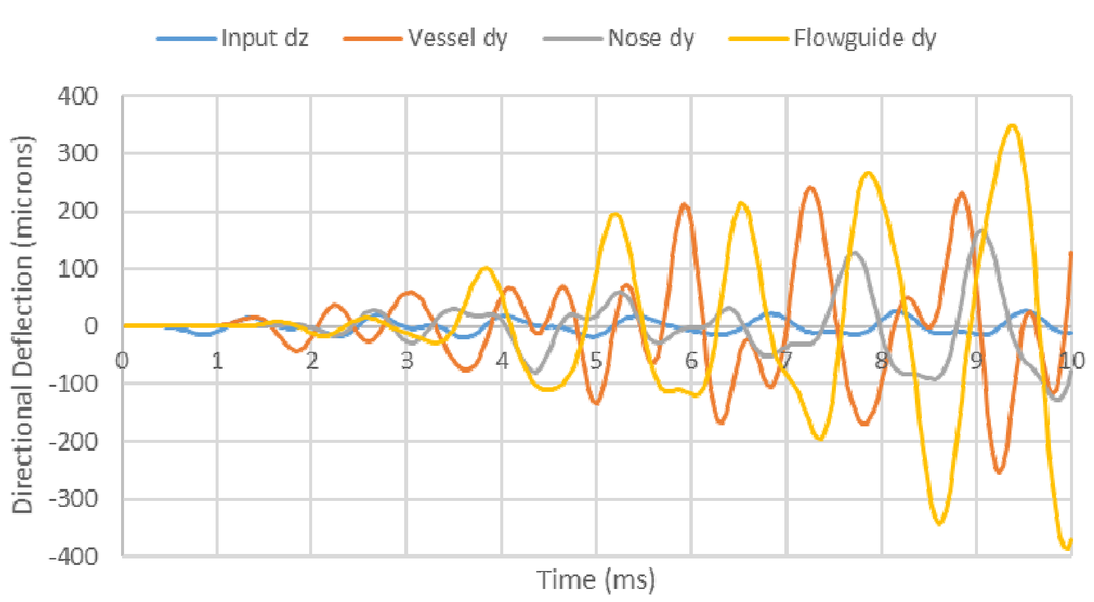
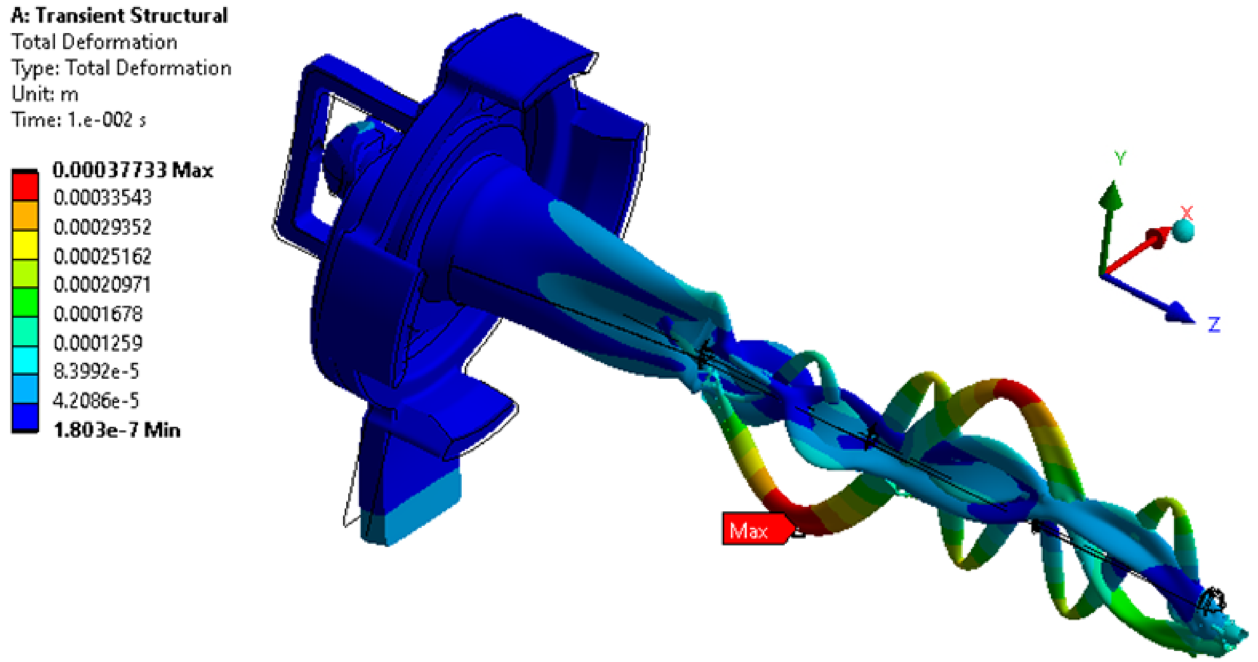
Full Transient Analysis – Results

- After 10ms, peak deflection is only ~12% of expected maximum
  - Would take more than 85ms to reach the maximum (3280um with 0% damping), by which time damping in the horn may have reduced the driving amplitude

- Appears to excite similar modes to the harmonic analyses





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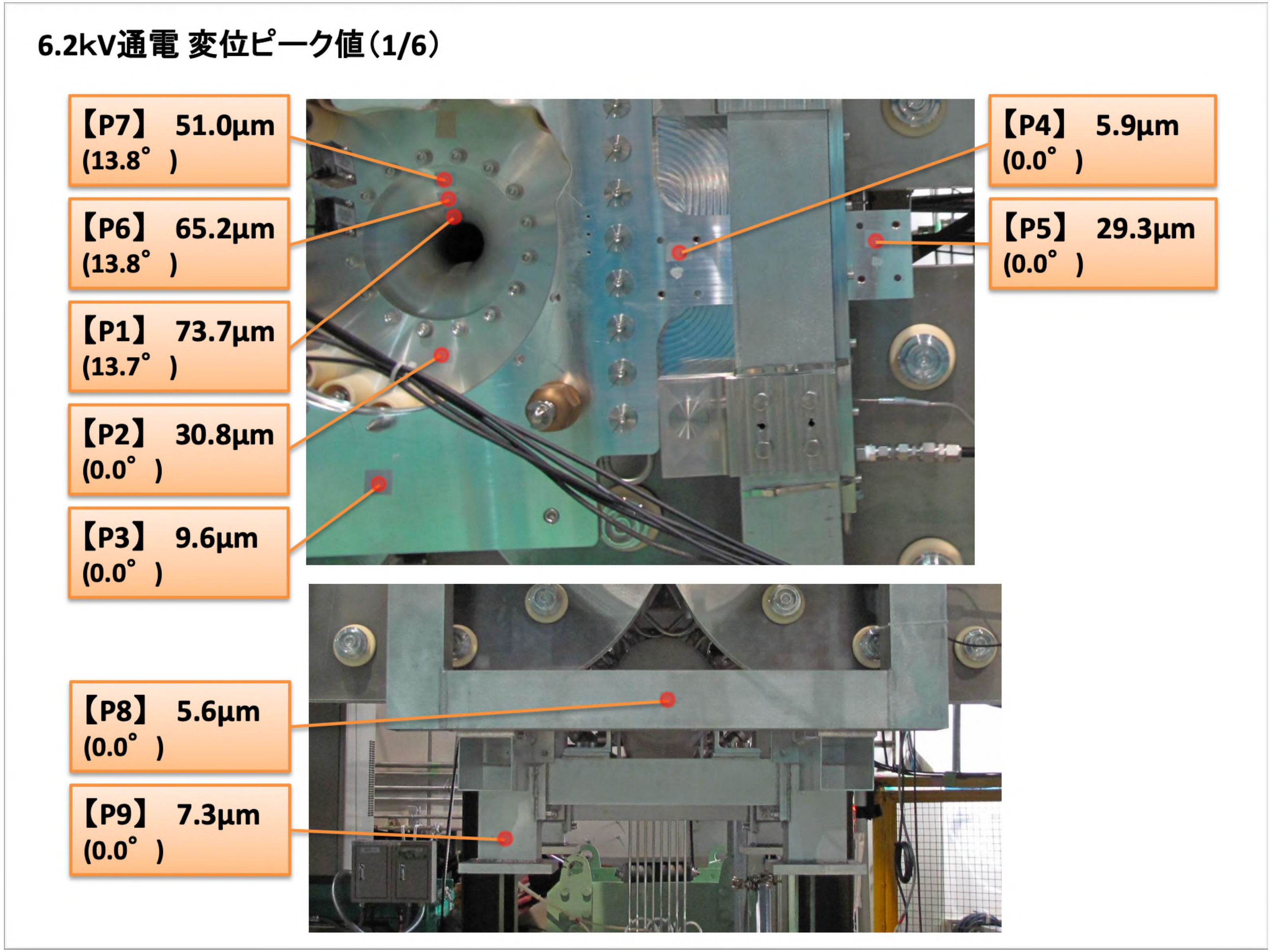
Benchmarking opportunity: T2K horn pulse testing

- KEK performed pulse testing of latest Horn 1 (without target) at J-PARC
- Vibration was measured at several locations during testing with LDV sampled at ~5kHz
- Closest locations to target are P3 and P4 – the data from these points is available for analysis



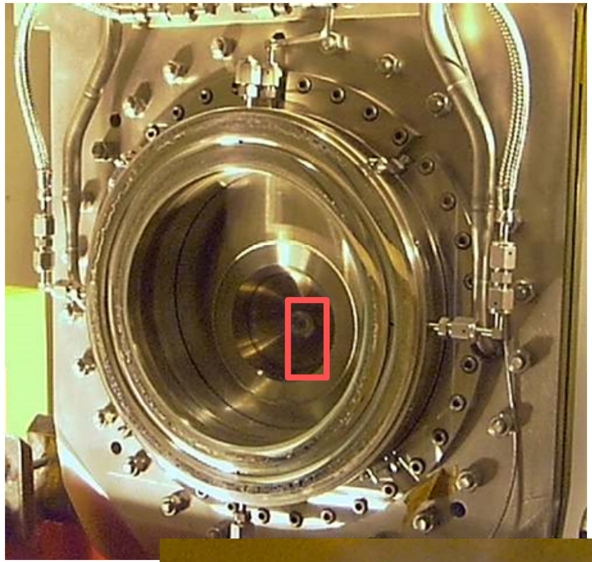
Max vibration amplitude at various locations – T. Sekiguchi, KEK

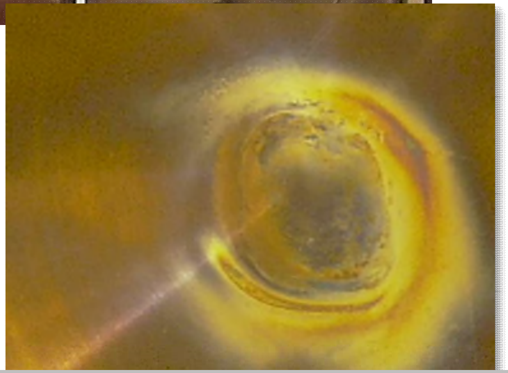
Horn–target vibration study status

- Target has many modes, and a lower natural frequency (43Hz) than the horn it is bolted to (750 Hz)
- Issue has potential to limit target length (ambition for 1.5m – 1.8m long target)
- Natural damping of structures expected to mitigate (2% damping reduces deflection from 3 mm to c. 0.3 mm (OK)
- T2K horn 1 pulse testing provides benchmarking opportunity
- More analysis required
- Possibility to test future prototype target using RAL Space vibration test facility

Radiation damage in graphite and titanium targets

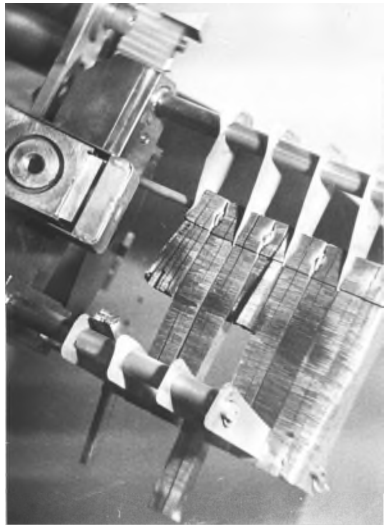
Motivation for materials science activity in Phase 2 project





1st T2K beam window after c.2 DPA (c. 1 year at LBNF)

Some graphite targets after 1 year equivalent proton fluence on LBNF



NuMI-MINOS
10^22 p/cm2
- Active sample on way to Bristol University
- Experiment at ISIS (ENGIN-X) approved

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Materials Science – UK contributions to target/window materials research

Strong contributions to RaDIATE materials science program from various sources

- Initial funding from HyperK-UK project
- LBNF Phase 2 funding decision for PDRA support and access to Culham lab's Materials Research Facility

- RAL (Coordination)
- ISIS (Bristol study of NuMI graphite on ISIS/ENGIN-X instrument approved)

Bristol University (graphite research)

Birmingham University, PDRA (MC40 cyclotron for sample irradiation, c.30 MeV protons)

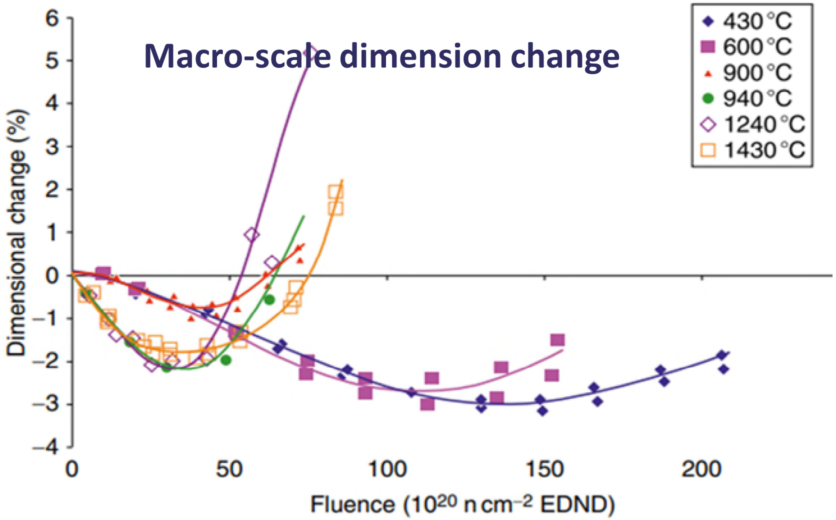
Oxford University PDRA (micromechanics) PhD (titanium - our irradiated samples)

Culham Laboratory (Materials Research Facility for all Post-Irradiation Examination)

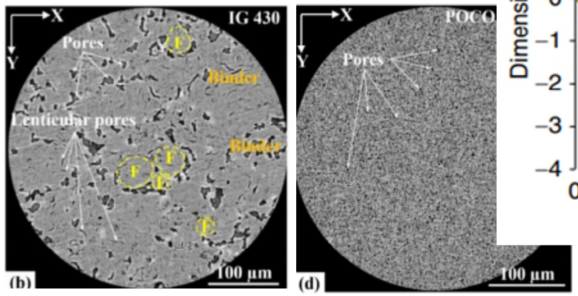
Phase 2: Materials Science Objectives (i)

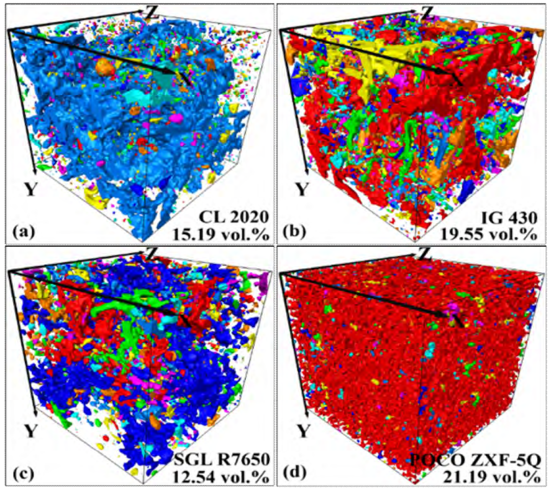
- Evaluate nanostructure to microstructure of candidate graphites
- Compare irradiated with non-irradiated samples
- Multiple-length scale microstructure determines the irradiation behaviour

Macro-scale dimension change

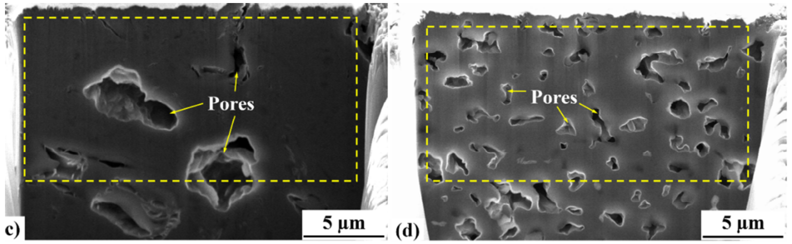


Macro-scale (X-ray tomography)

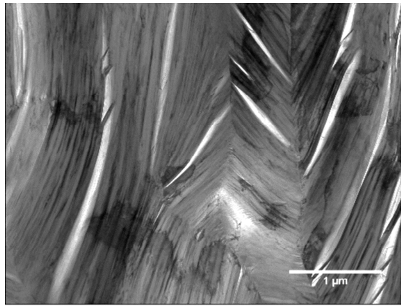


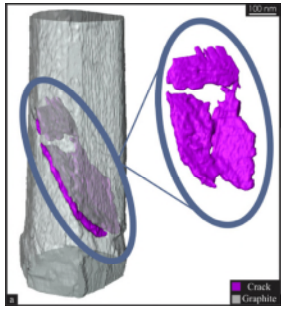


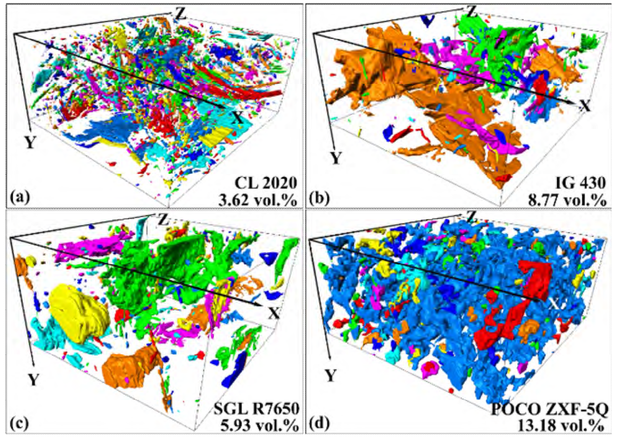
Sub-micrometre (FIB/SEM tomography)



Nanometre scale (Electron tomography)







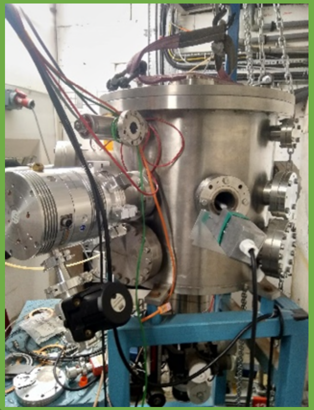
University of BRISTOL

Arregui-Mena *et al*, JNM, 2021
Jiang *et al*, JNM, 2021

LBNF Funding request: Materials Science Objectives (ii)

Irradiated titanium fatigue sub-project collaboration

Sample & environment



Sample design **(Oxford)**
Sample environment **(RAL & Birmingham)**

MC40 irradiation (Birmingham)

Proton and He irradiation at high current, low energy

Post-Irradiation Examination (PIE) (Oxford, Birmingham @Culham)

- Micro/nano indentation
- TEM/XRD
- High cycle fatigue testing

Challenges:
- Maintain sample temperature at 160 °C under high energy proton e.g. 15 MeV/6.0 µA

Solutions:
- PID controlled nitrogen cooling inside a vacuum chamber

Challenges:
- Produce irradiated Ti samples with a high dpa, e.g. 2 dpa;
- He/H production.

Solutions:
- Long term exposure
- Proton/He implantation
- Vary beam energy

Challenges:
- Handling, mechanical and microstructural testing of active samples.

Solutions:
- MRF has expertise and equipment to handle and test active samples

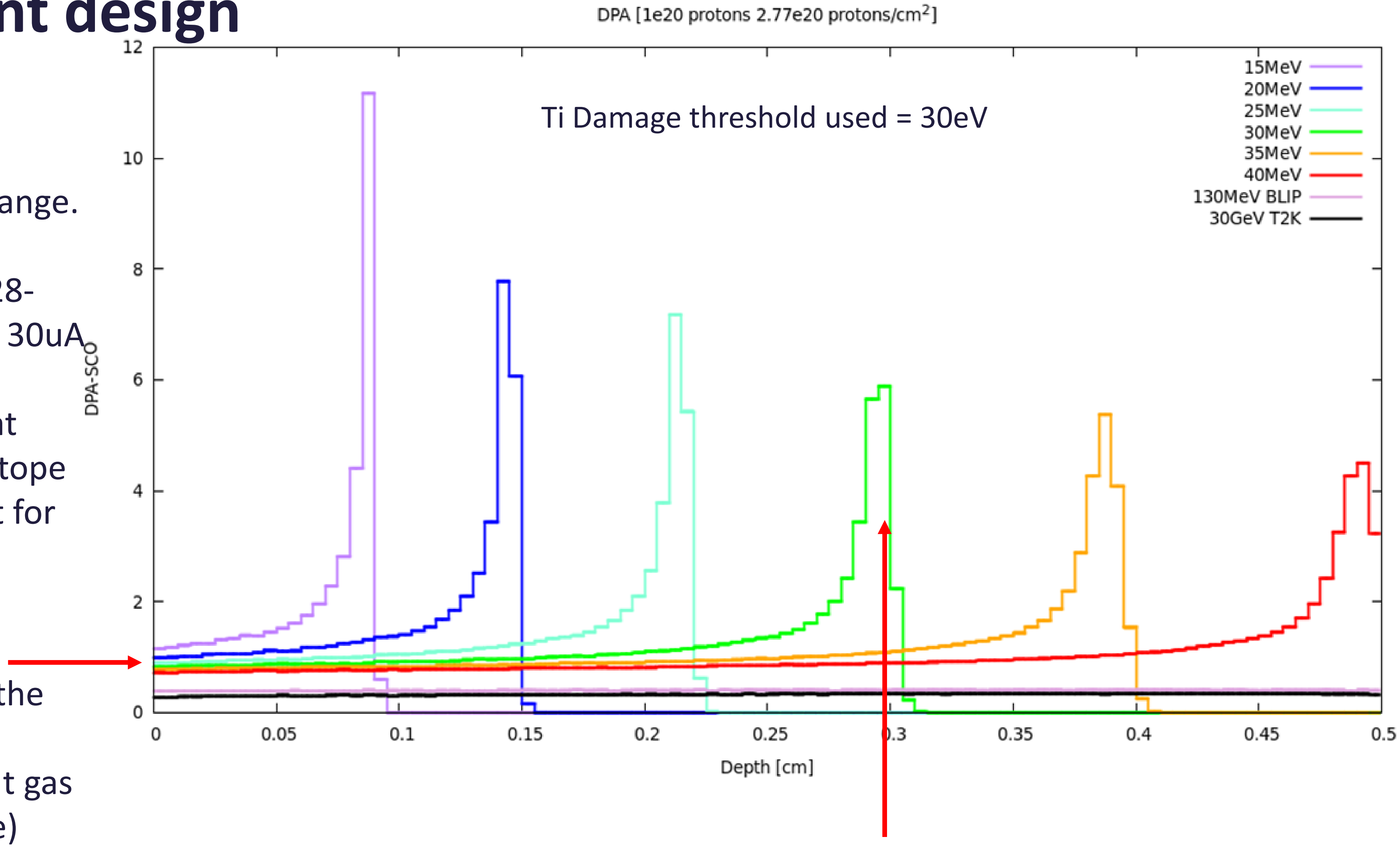
Titanium damage studies – Irradiation at Birmingham cyclotron – Sample environment design

Birmingham cyclotron can deliver protons at energies in 15-40MeV range.

Optimum performance is around 28-30MeV where the beam current is 30uA

Most beam time will be available at 28MeV as the same as medical isotope production (a regular commitment for MC40)

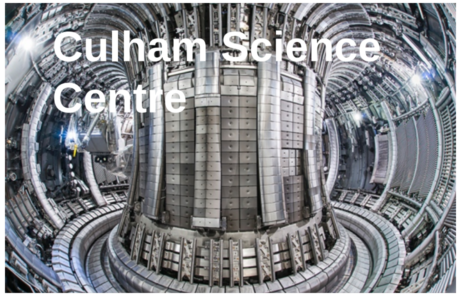
With 30 days irradiation ~1DPA in the titanium is achieved.
Damage is higher at Bragg peak but gas production is unrealistic (next slide)



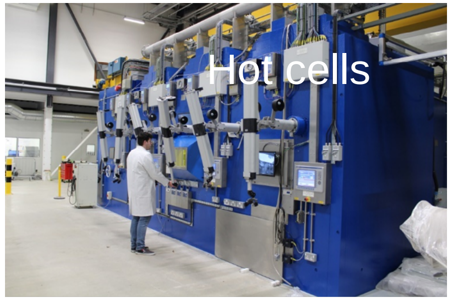
At 30MeV the range in titanium is approximately 3mm

Materials Research Facility at UKAEA (Culham)

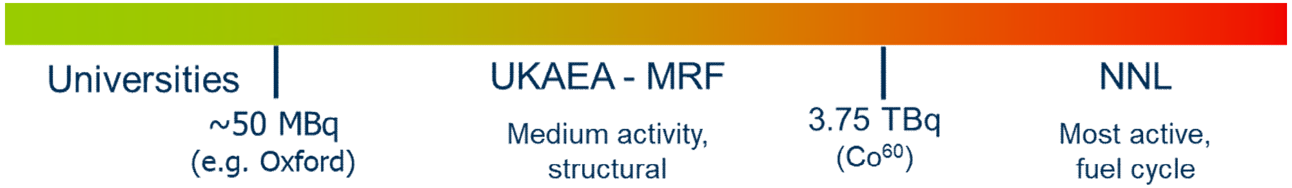
- New facility (opened May 2016) for processing and analysis of radioactive materials
- Broad nuclear experience on a non-licensed site: total inventory up to 3.75 TBq (Co^{60})
- Extensive collaboration with international particle accelerators and high-power targets communities (FNAL, ESS, CERN, RAL)
- Broad nuclear materials expertise of the scientific team to support experiments and data analysis

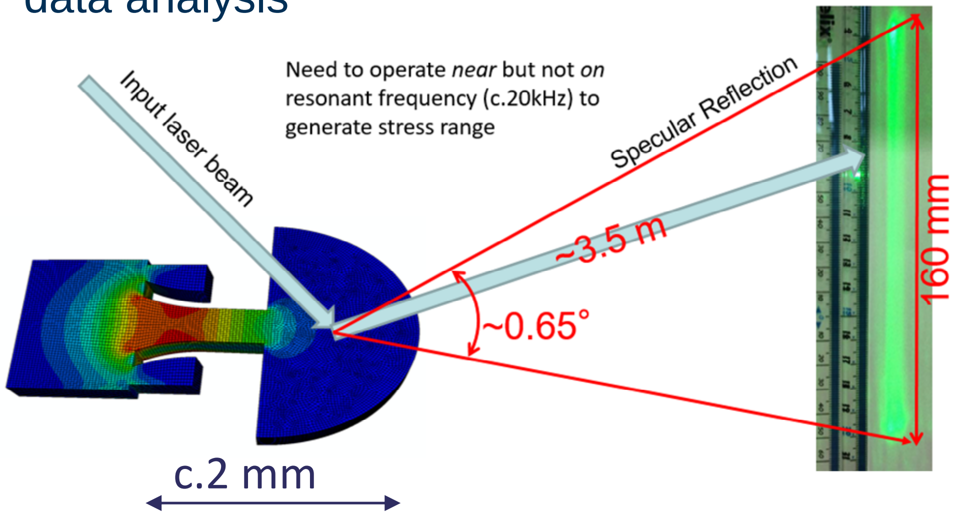


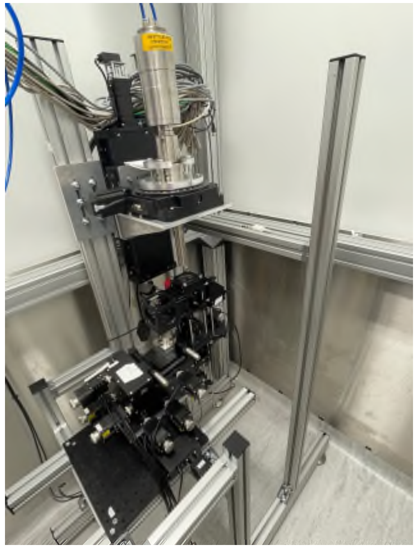
Operates JET and MAST-U experiments



Material Research Facility (MRF)







- Ultrasonic Fatigue Rig
  - Invented by Oxford (Gong)
  - Developed for active samples (Culham, including STFC Innovations PDRA (Earp))
- Integrated into shielded research room at MRF
- **Ready to test active samples for Phase 2 project**

Target status summary

- Phase 1 target project (preliminary design and prototyping) nearing completion on time, within scope and within budget
- Phase 2 (construction) project funding awarded at 100% as requested
  - Includes extra scope of NA61 replica target
- Welcoming new members of UK target project - materials scientists from:
  - Bristol University
  - Oxford University (+DPhil student)
  - Birmingham University (+PhD student)
  - UKAEA Culham laboratory (including former STFC ‘PASI post-doc’ + STFC Innovations PDRA)
  - Full collaboration with KEK colleagues on T2K
  - Good future source of ‘Benefits Realisation’

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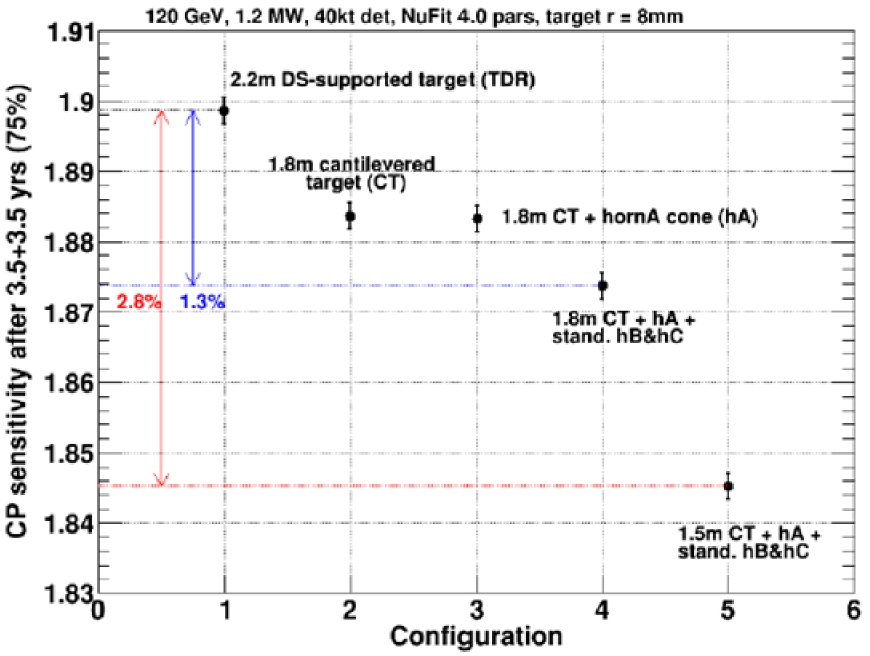
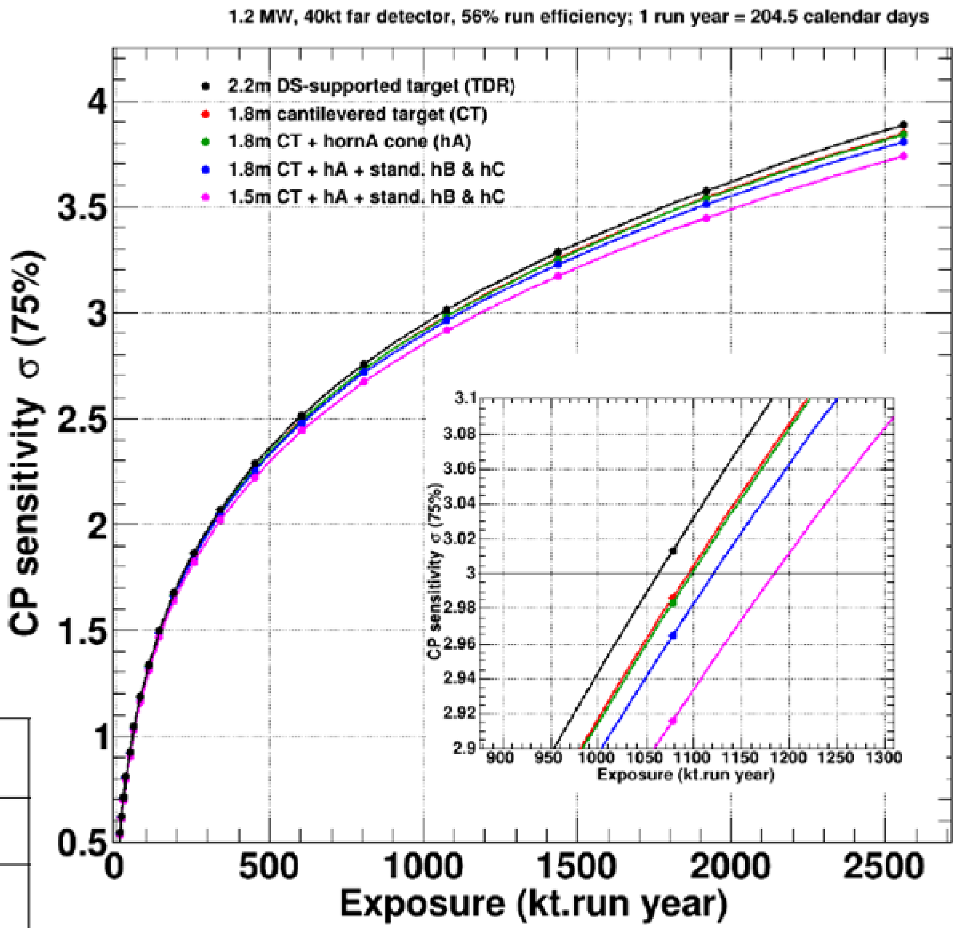
Questions?

CP sensitivity vs target length & exposures





Configuration	Extra time per run year (1 run year = 204.5 days)
1.8m cantilevered target (CT)	6 days (3 %)
1.8m CT + horn A cone (hA)	6 days (3 %)
1.8m CT + hA + standardized horns B & C	11 days (5 %)
1.5m CT + hA + standardized horns B & C	23 days (11 %)

← Approx extra time needed to reach **3σ** level of CP exposure performance of TDR 2.2 m target

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Excludes target exchange downtime variations

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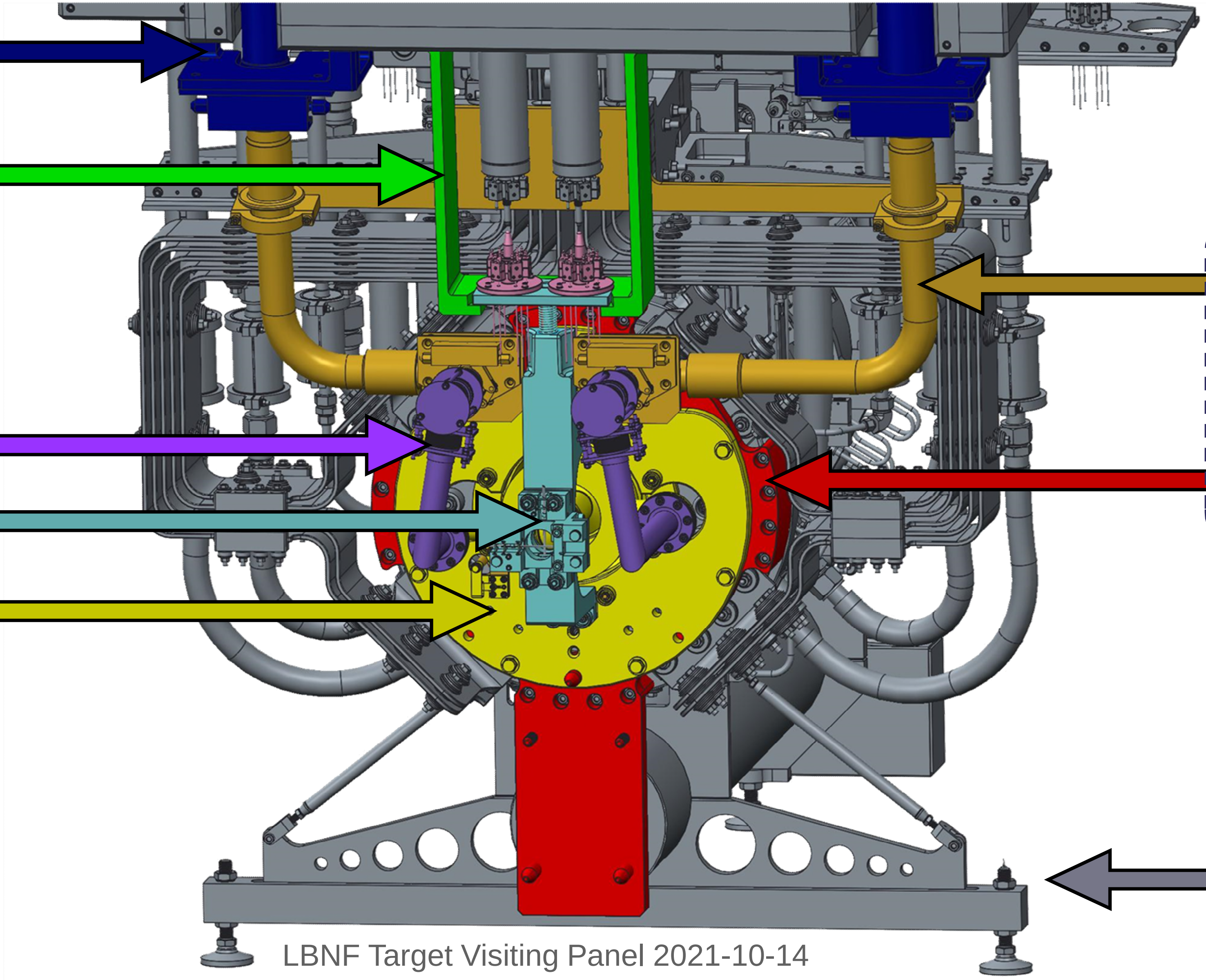
Hardware Deliverables: Target and Beamline Apparatus

Helium line-set
(× 1)
Instrumentation connection bracket
(× 1)

These items attach to the shielding module

Target pipes
(× 2)
TPT “Hylen Device”
(× 2)
Target Assembly
(× 2)

These items are replaced in a “target exchange”



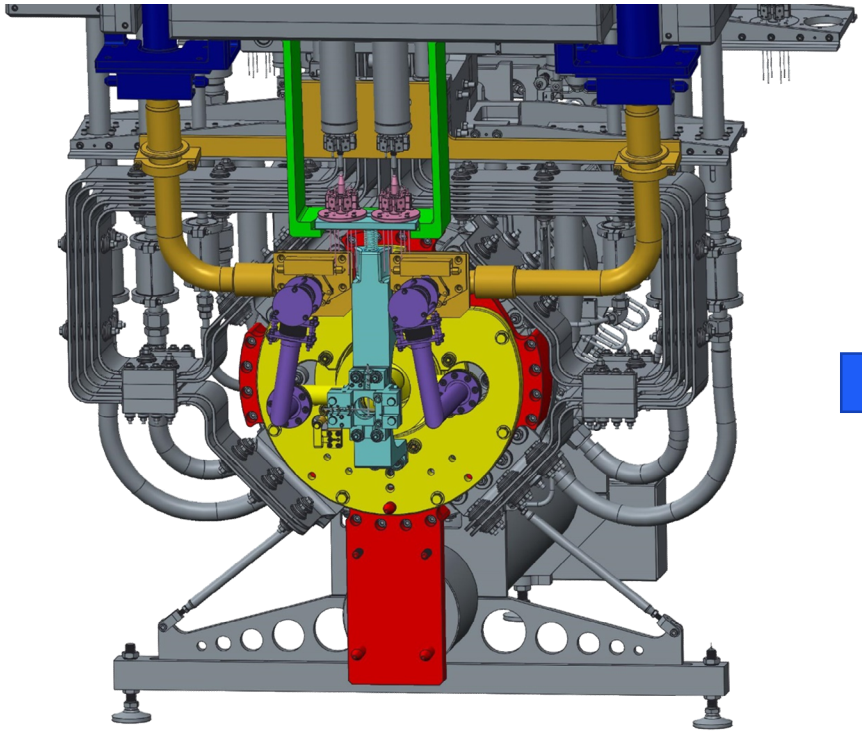
Horn Mounted Flex-pipes
(× 2)

Docking Interface Plate
(× 2)

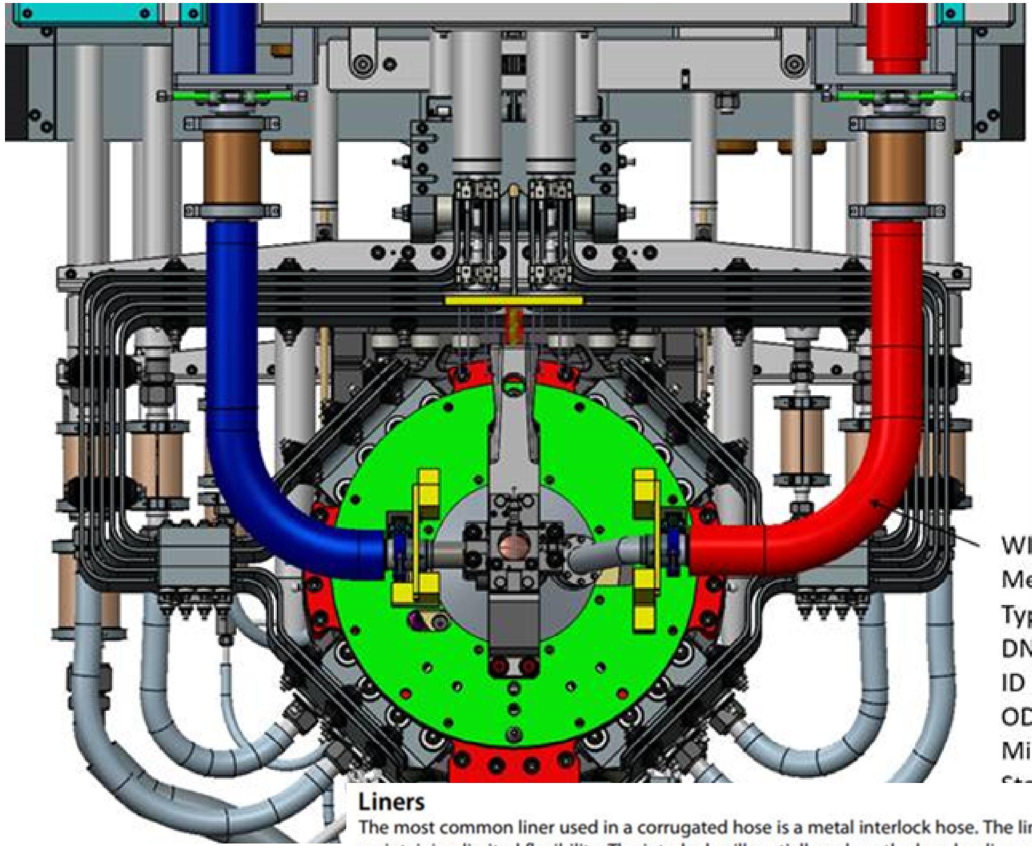
These items fixed to the magnetic horn

Not part of UK contribution

Re-design of helium lines: simpler, larger ID



‘T2K’-like preliminary design



Towards final design

Path to future upgrade to 2.4 MW

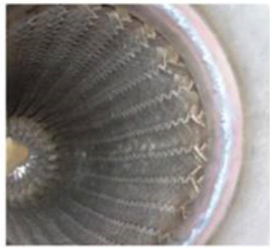
WITZENMANN HYDRA
Medium Duty Flexible Hose
Type RS 341
DN80 RS341S12
ID 80.6mm [3.2” Bore]
OD 98mm
Min Bend Radius 240mm
… 20°C

Liners

The most common liner used in a corrugated hose is a metal interlock hose. The liner will allow a smooth flow rate whilst maintaining limited flexibility. The interlock will partially reduce the bend radius and inside diameter of the corrugated hose. The smooth liners reduce associated noise. Another alternative liner is braid which doesn’t reduce the bend radius of the hose.

Interlock Liner

Braid Liner



Liner to smooth flow & reduce vibrations

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