J-PARC Titanium Beam Window Upgrade

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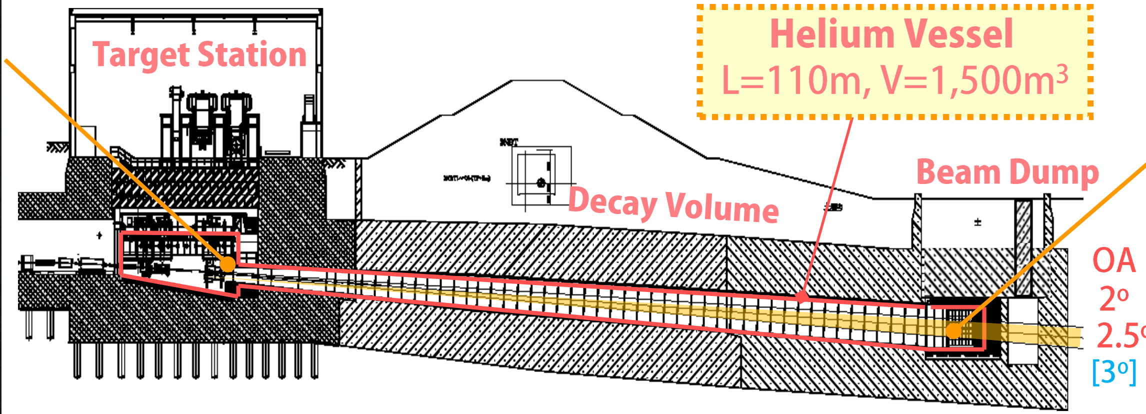
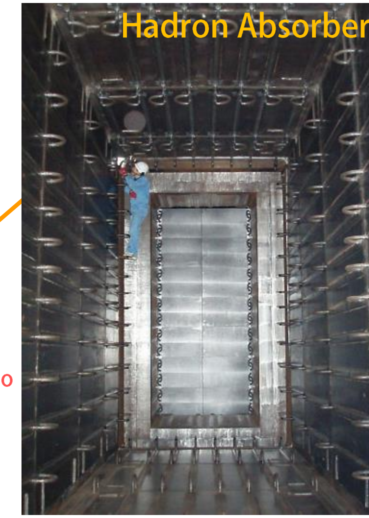
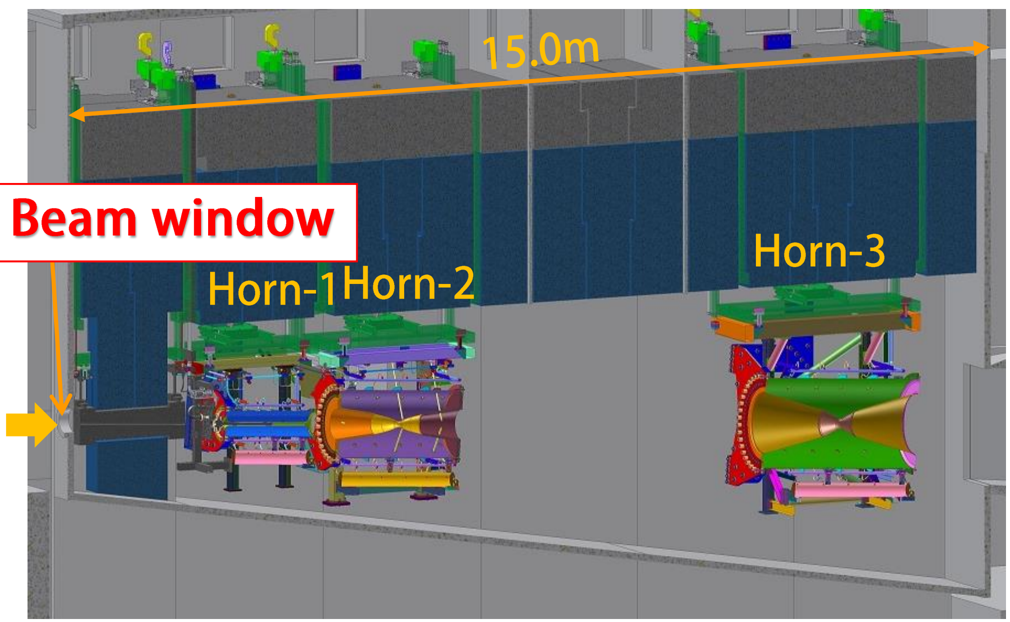
Titanium Alloy as Beam Window Material

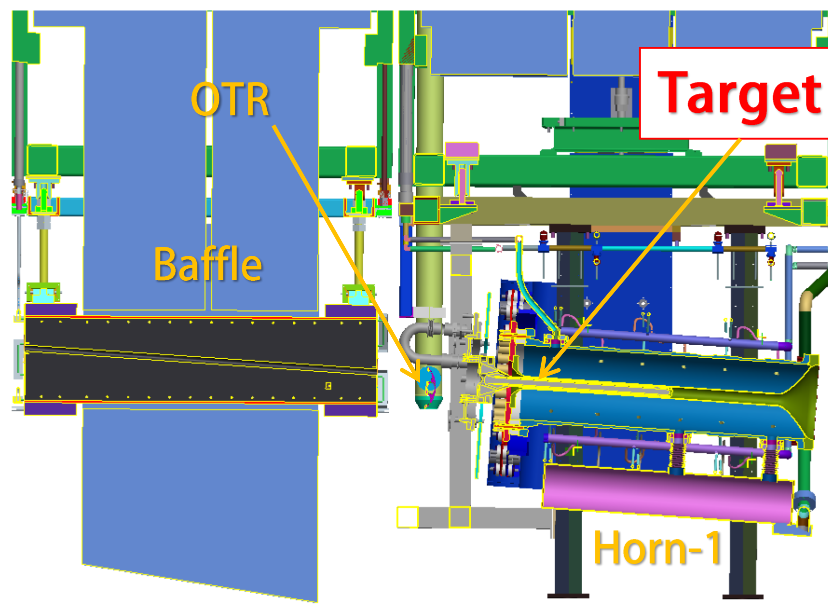
- Titanium alloys are widely utilized as structural materials for shipbuilding, chemical and aerospace applications. This is because of their high specific strength, good fatigue endurance limits, and good corrosion/erosion resistance, even at elevated temperatures. They also satisfy low-activation requirements for use as nuclear power materials.
- The dual phase alloy Ti-6Al-4V (α-phase: HCP; β-phase: BCC) is one of the most used titanium alloys.
  - It shows remarkably high strength at room-temperature (~1GPa) up to 300^{o}C and demonstrates good fatigue performance.
- For several accelerator facilities utilizing high-intensity pulsed proton beam, these properties are excellent as material for a beam window, which separates accelerator vacuum and target station vessel atmosphere, such as helium or nitrogen.
  - The J-PARC neutrino facility utilizes this alloy for both its primary beam window and target containment window.
  - Likewise, the Long Baseline Neutrino Facility (LBNF), under design at Fermilab, plans to adopt it as a target containment window.

J-PARC Neutrino Secondary Beamline

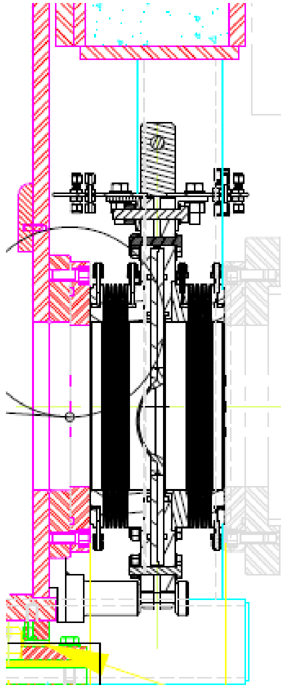


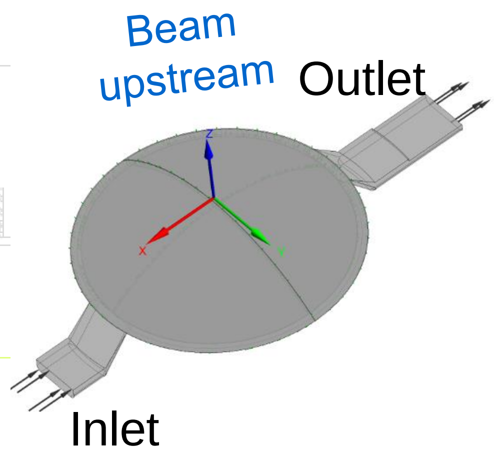


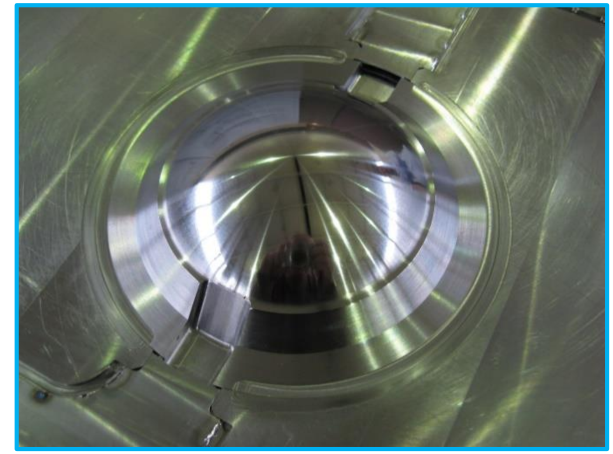




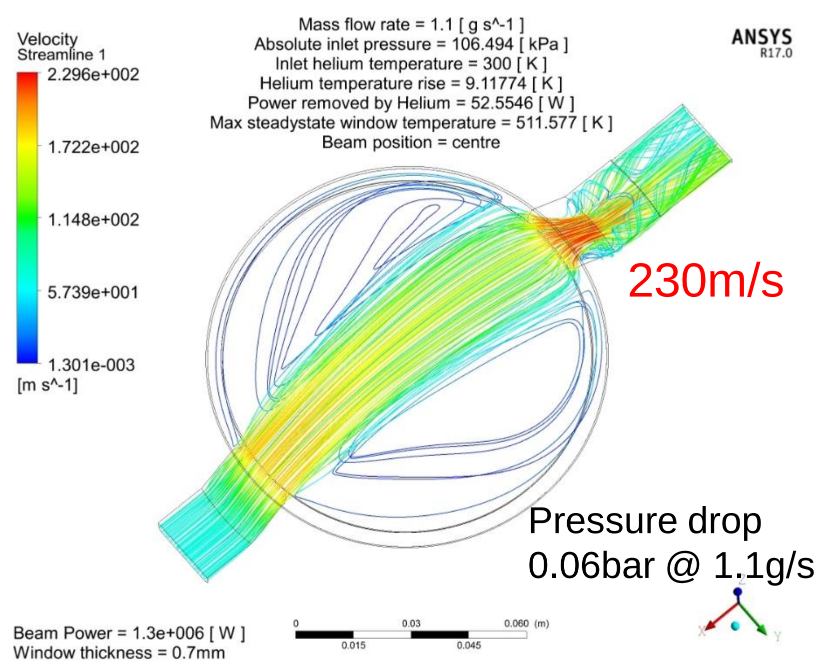
Primary Beam Window



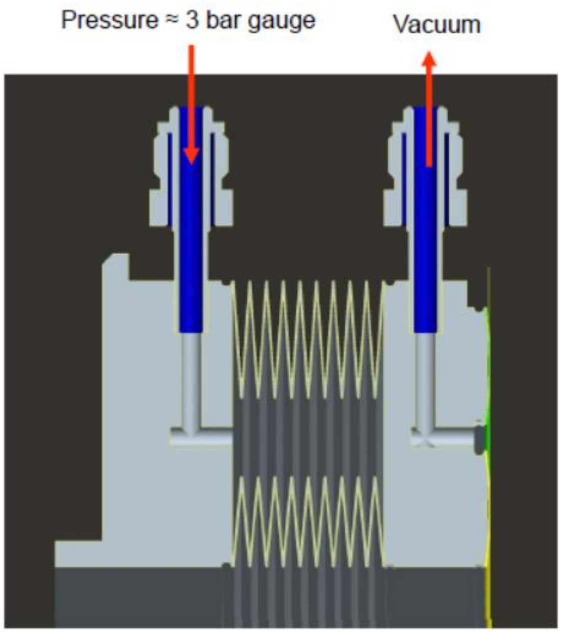


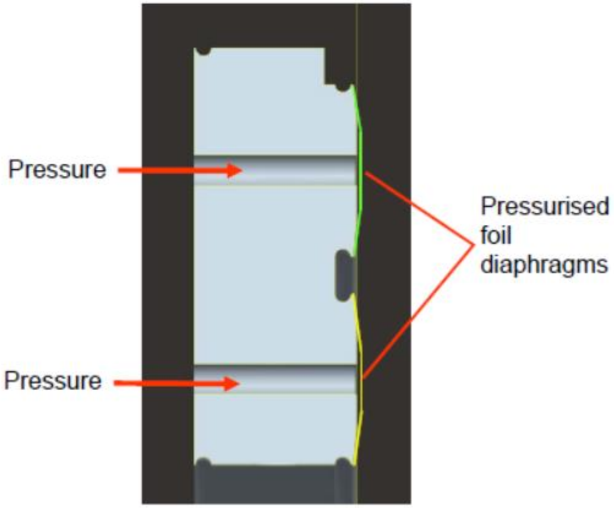


- 0.3mm-thick doubled Ti alloy domes
  - Ti-6Al-4V Grade 5 bar
- Cooled by Helium gas flowing 2mm gap between them
  - Mass flow rate = 1.1 g/s
- The inflatable bellow seal - "pillow seal" - for remote exchange



Inflatable Bellow Seal - “Pillow Seal”





Seal foils (surface roughness, Ra = 0.004 μm, Rt = 0.030 μm)

Polished flange (surface roughness, Ra = 0.020 μm)

Our Discussions on BW Material Choice

"Thermal stress resistance"

$$R = \frac{UTS}{\alpha . E . \Delta T}$$,where $$\Delta T = \frac{EDD}{C_p}$$

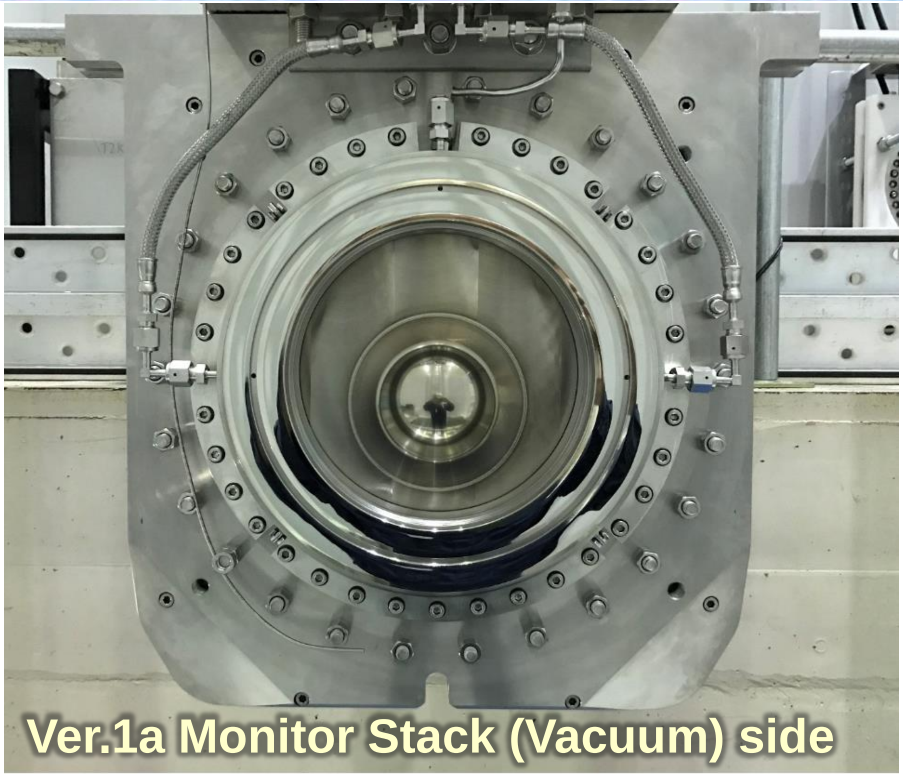
C.J.Densham NBI2014
(More detail in backup)

UTS : ultimate tensile strength
α : coefficient of thermal expansion
E : Young's modulus
ΔT : temperature jump
EDD : energy deposition density
Cp : specific heat capacity

	ΔT	shock resistance
Graphite	100	10.05
beryllium	37	2.08
titanium	245	4.12
albemet	51	3.26

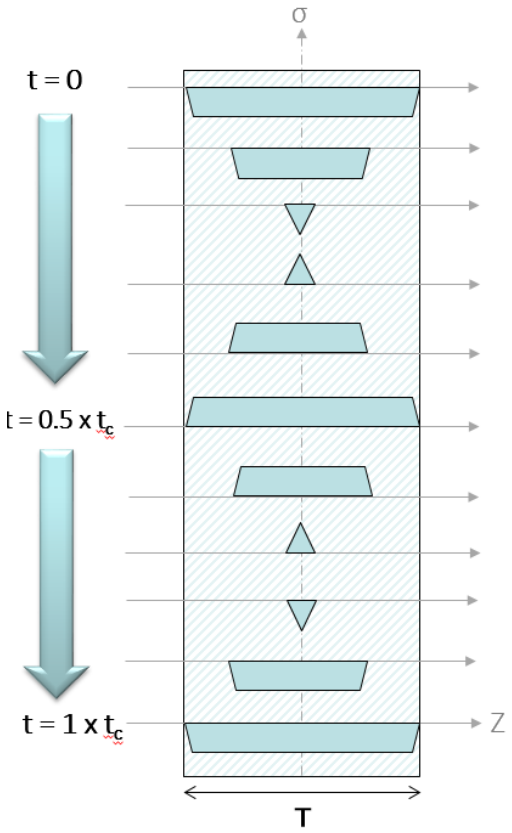
- Titanium alloys are readily available and have the advantage that they are not toxic and easier to machine into the thin domes.
- It can be joined by welding (TIG, EB, laser, etc).
  - Most Beryllium windows are brazed into a dissimilar material mount and at many facilities (including NoVA) this braze has failed in operation.
  - EBW adopted for new version may make situation improved.
  - Mechanical joint available for a fusion application (to be adopted at J-PARC Hadron F)
- ✓ If the T2K window was not surface cooled then the choice would be different.
  - We would need a good thermal conductivity to remove the heat and would probably have led to the selection of Beryllium (S65B:177W/mK) over Titanium alloy (Ti-6Al-4V:6.7W/mK).

Beam Window Upgrades



- Ver.1 : replaced in 2017 (22e20pot, ~470kW) → M.Tada@NBI2017
- Ver.1a : in use (+9.6e20pot, 2.5×10^{14} ppp/2.48s, 485kW)
  - (Almost) identical to Ver.1.
  - Domes machined from bulk Ti-6Al-4V (ASTM Grade 5) Round Bar
- Ver.2 : under production at RAL
  - Struggles on choice of alloy grades: ASTM Grade-5 round bar → Extra Low-Interstitial Grade 23 Plate → Gr.5 round bar

Stress Wave Propagation



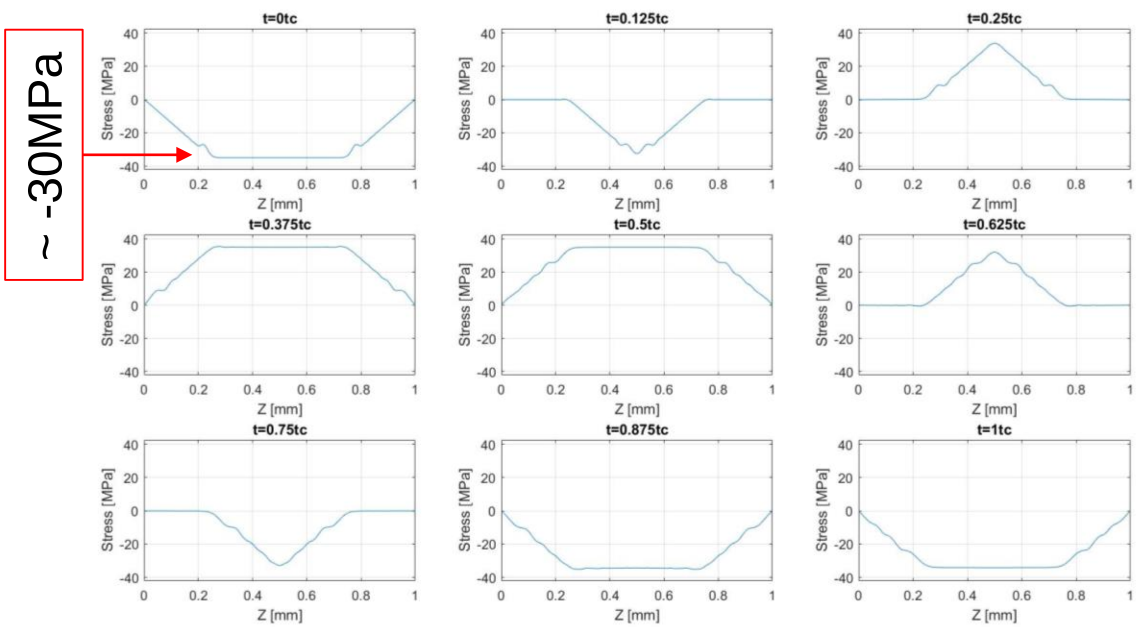
stress wave propagation along centre axis following one single 58 ns bunch @ 1.3 MW beam power for 1 mm thick beam window (Tc = 322 ns)

- Characteristic time t_c is the time taken for a stress wave to propagate through the window thickness T and back:

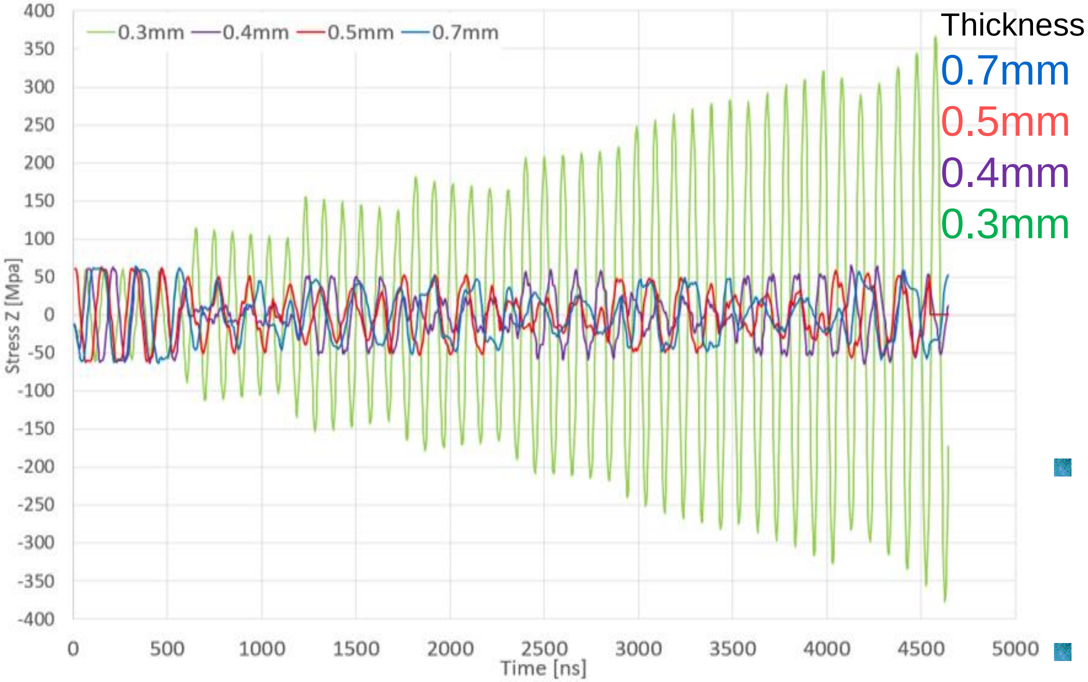
$$t_c = \frac{2T}{c} \quad \text{,where} \quad \boxed{c = \sqrt{E/\rho}}$$

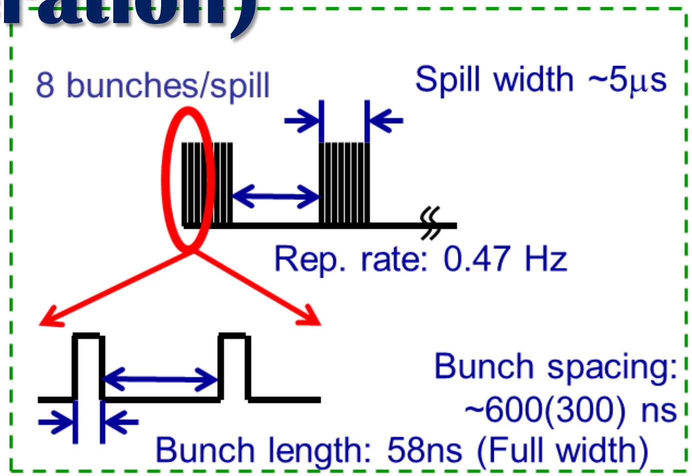
Speed of sound in the material
E: elastic modulus
ρ: density.

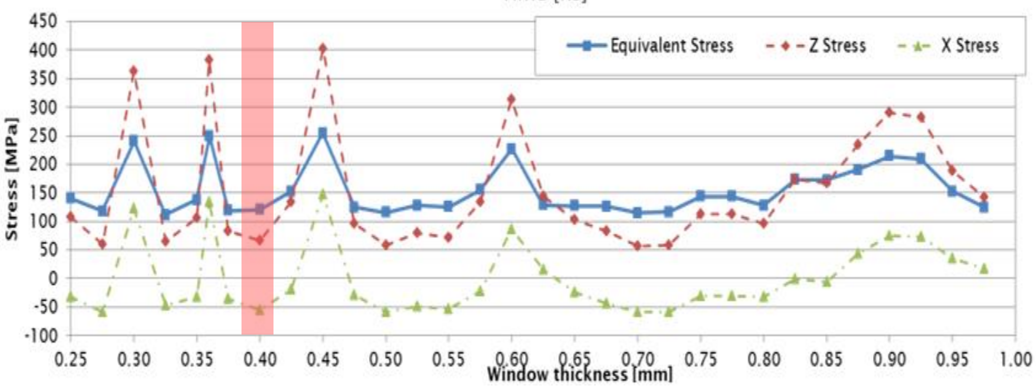
- The schematic diagram illustrates the propagation of a stress wave through a window caused by a bunch at time t = 0.
- Resonance maximum if t_c = bunch spacing
- Resonance minimum if t_c = 0.5 x bunch spacing
- These wave profiles are evident in the ANSYS simulations



Stress in Beam Direction at Window Centre (1.3 MW beam operation)





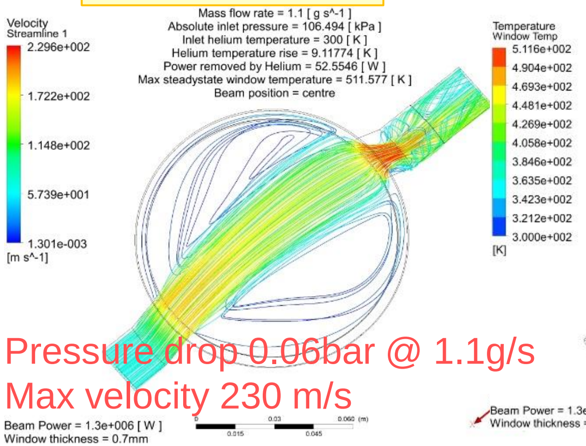


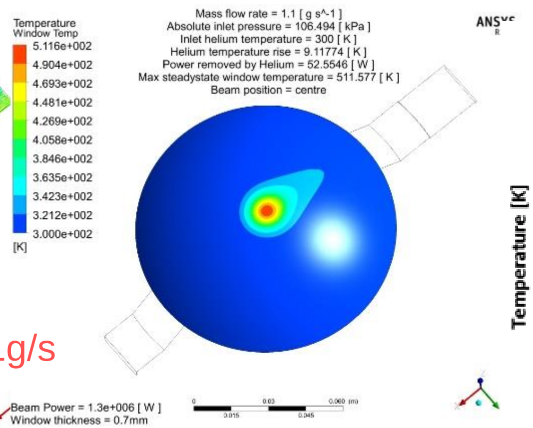
- Beam bunch structure generates stress resonance within material thickness
- Constructive interference at 0.30 mm (S.F.=1.5)
- Destructive interference at 0.40 mm (S.F.=2.6)
- 0.4 mm selected for next Ver.2 beam window
- Taking changes of E under high temperature into account: 0.39±0.01mm

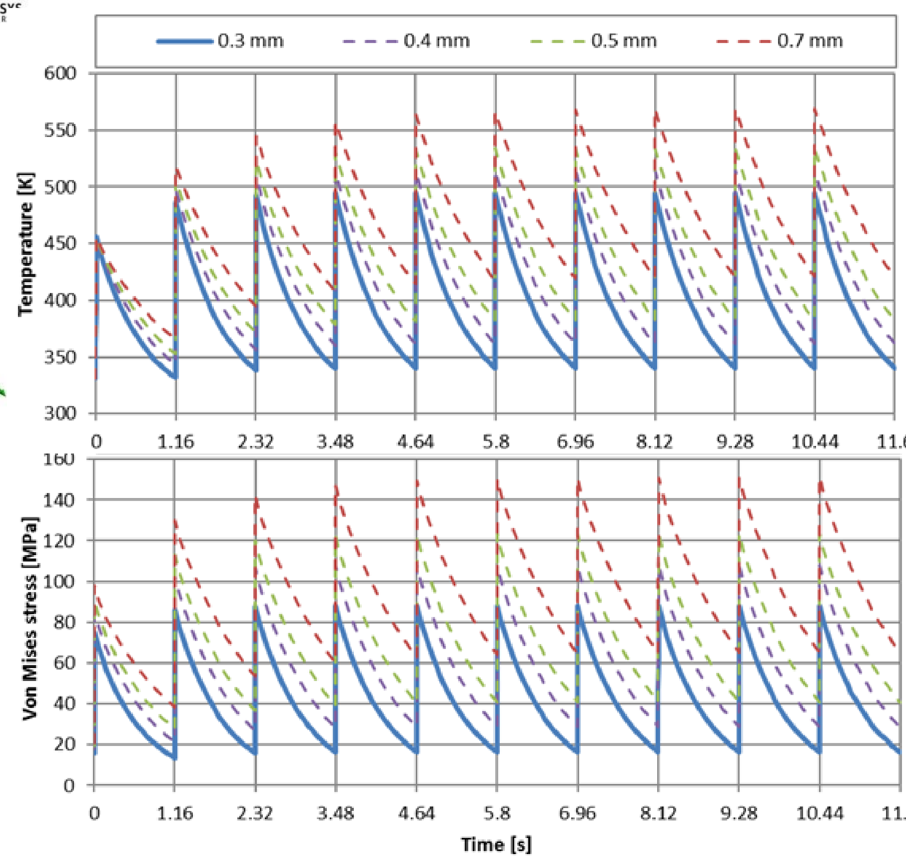
Transient Thermal Analysis – 1.3MW

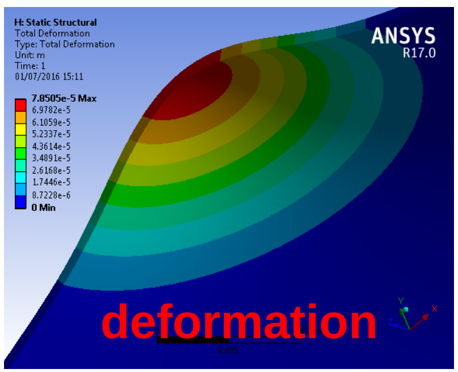
0.7mm-thick

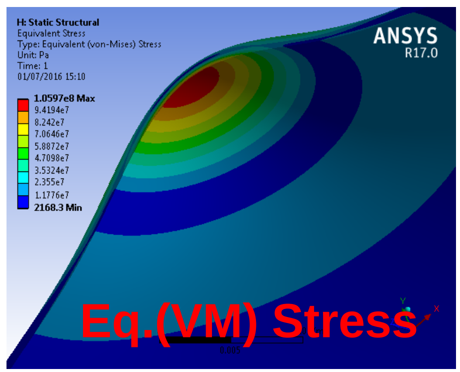
3.2 x 10^{14} ppp @ 1.16 s rep rate









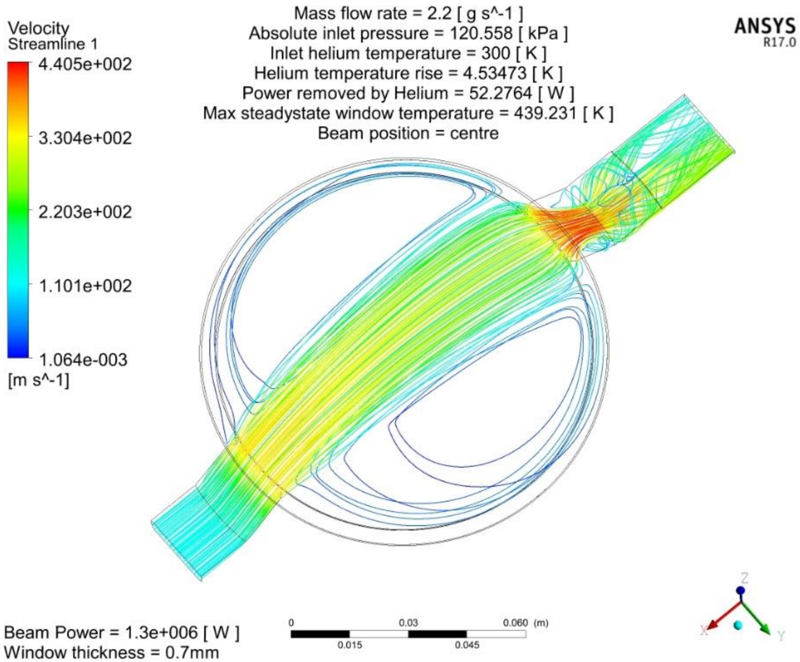


With a single beam pulse injection, steady state temperature and thermal stress increase by +156.3degC and +106MPa, respectively.
Maximum displacement is 78um

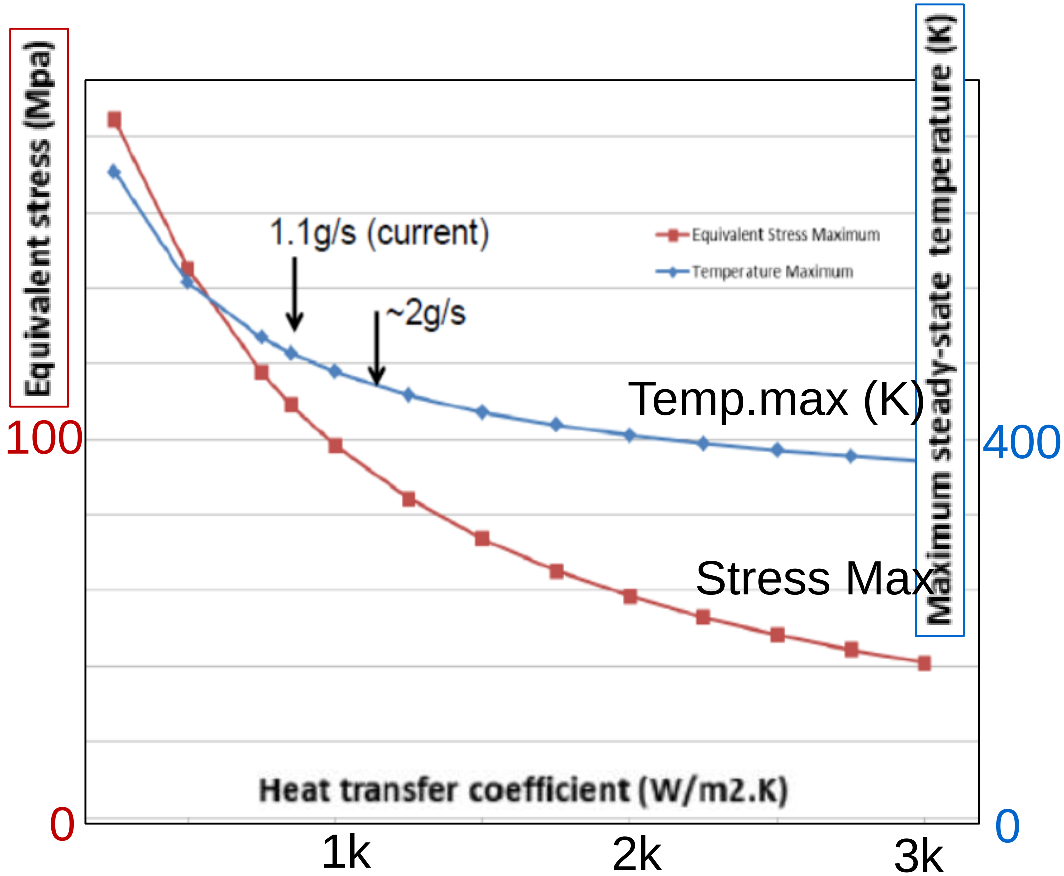
Temperature (upper) and equivalent stress (lower) of beam window with three typical thicknesses as function of time for 10 successive beam pulses at 1.3 MW operation

Increase Mass Flow Rate

Flow rate doubled (1.1→ 2.2g/s)



Pressure drop 0.2bar (x4 higher)
Max velocity = 440m/s (x2 higher)



- Pressure drop/velocity becomes fairly high. Further increases would need to consider helium system pressurization.
- Current cooling capacity is already aggressive (as larger compressor was purchased than originally specified). Probably not a top priority.

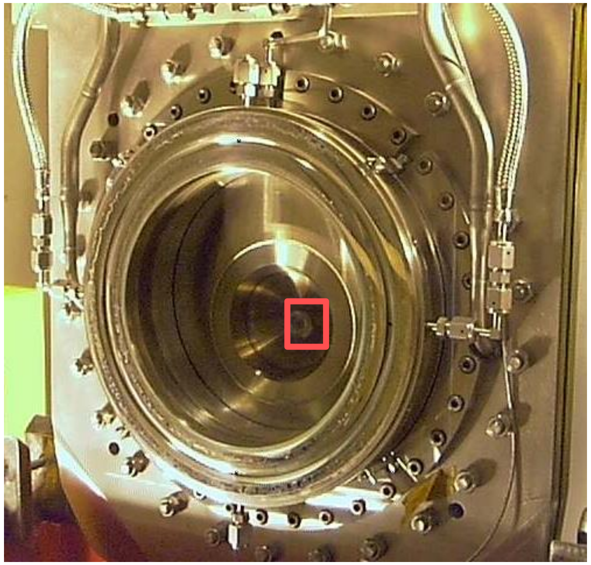
Stress and Cooling Analysis Summary

	Str. Wave	Quasi-Static Transient			Static	Total	YS	Fatigue	
Thickness [mm]	Max. Str. [MPa]	Peak T. [℃]	Max. Str. [MPa]	Min. Str. [MPa]	Stress [MPa]	$SW+QS_{min}+S$ [MPa]	at PeakT [MPa]	YS*1/2 [MPa]	Safety Factor
0.3	240.6	221.7	88.3	16.6	-12.5	244.7	730	365	1.5
0.4	120.5	241.8	108.1	28.9	-9.4	140.0	720	360	2.6
0.5	115.9	261.2	123.4	41	-7.5	149.4	710	355	2.4
0.7	115.1	296.2	151.2	65.1	-5.4	174.8	690	345	2.0

- To increase the thickness from existing 0.3mm to 0.4 mm is a viable candidate, with sufficient tolerance to machining, while minimizing the resultant increase in temperature, stress and activation of upstream beam-line area.
- By considering variation of elastic modulus (speed of sound) due to the thermal cycle between 25 to 200 ℃, the engineering tolerance on the thickness is recommended to be 0.39±0.01mm (0.38 ~ 0.40mm) . This is a challenging machining tolerance, but achievable with regards to the past experience.
- Current mass flow rate (1.1g/s) already guarantees enough cooling capacity, as larger compressor was purchased than originally specified (0.08g/s). To increase the flow rate is still desirable, but probably not a top priority.

✓It is desirable to introduce better Titanium alloy with better radiation damage tolerance. This will occur in synergy with the RaDIATE collaboration program.

Radiation Damage Effect on Ti-6Al-4V ??



- Periodic thermal stress wave caused by the intense proton beam energy deposition
- 1.3MW operation will cause radiation damage of ~2 displacement per atom(DPA)/ops-year, whereas significant irradiation hardening and loss of ductility has been reported with 0.1~0.3DPA (*no higher DPA data exists*)
- No known data exists on high cycle fatigue (>10^3 cycles) of irradiated titanium alloys

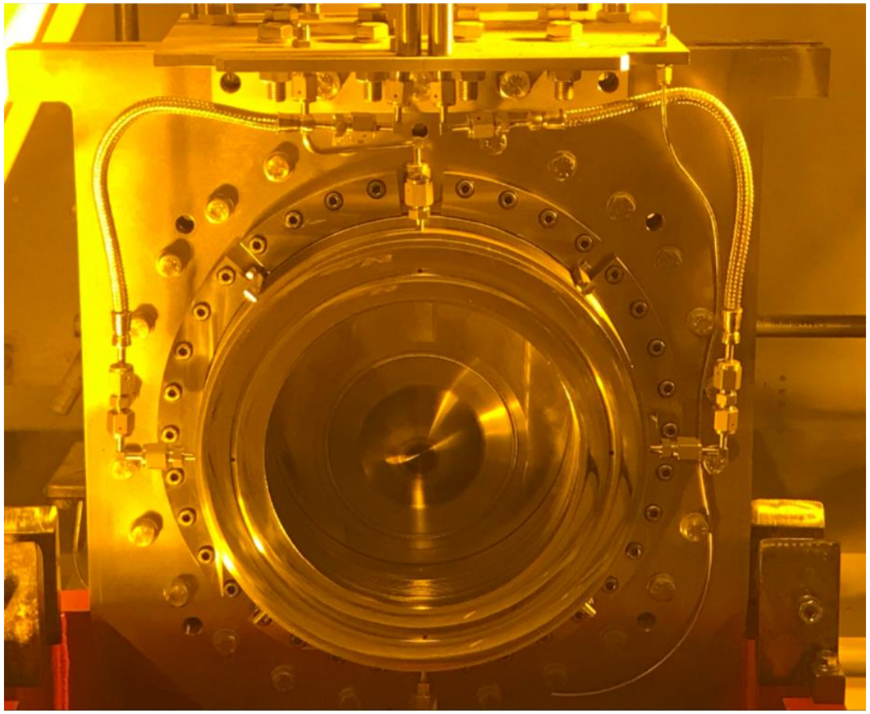
Beam Power	PPP	Rep. cycle	POT / 100 days
485kW (achieved)	2.5 x 10^{14}	2.48 sec	0.9 x 10^{21}
750kW (proposed)	2.0 x 10^{14}	1.3 sec	1.3 x 10^{21}
750kW [original plan]	3.3 x 10^{14}	2.1 sec	1.3 x 10^{21}
1.3 MW (proposed)	3.2 x 10^{14}	1.16 sec	2.4 x 10^{21}

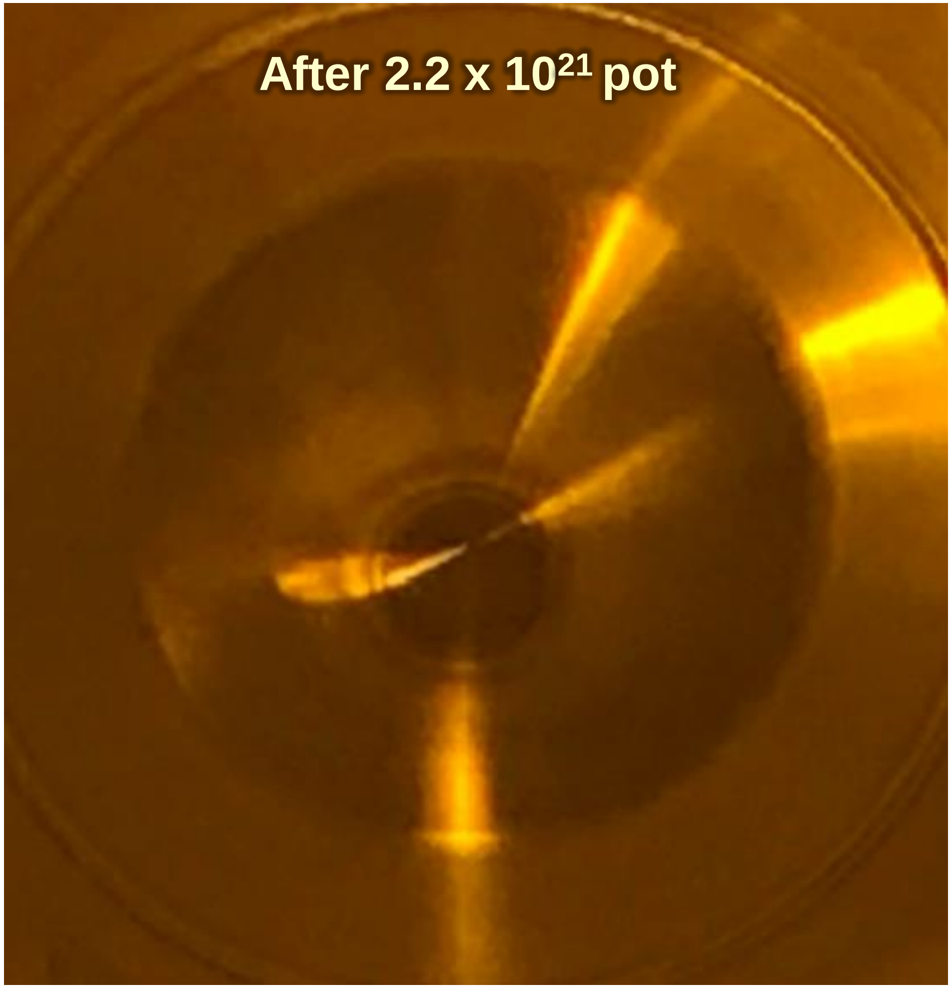
designed

～8M pulses/yr

～1DPA/yr

Monitor Stack (Vacuum) Side of Ver-I Window



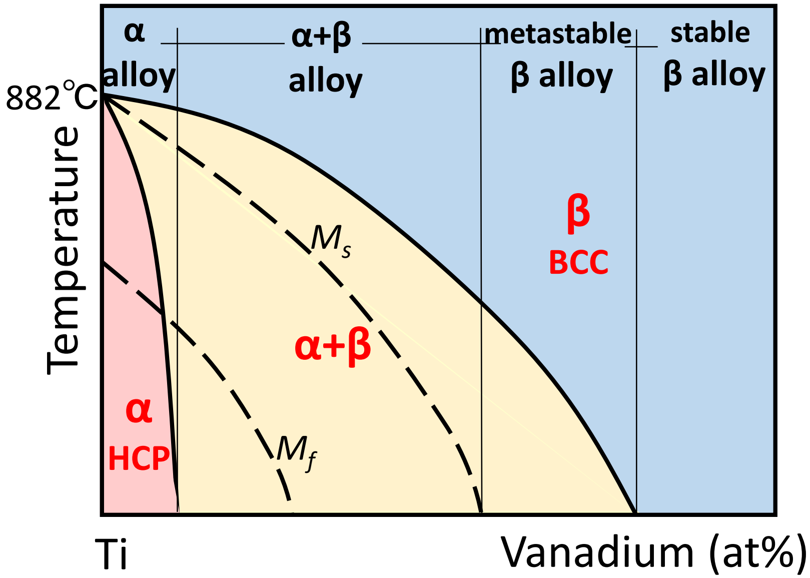


M.Tada

Classification of Titanium Alloys

Properties of an alloy material, particularly its mechanical properties such as elastic and plastic deformation behavior, are quite dependent on its crystalline microstructure.

Titanium-to-Vanadium Phase Diagram



- Vanadium is one of typical β stabilizer elements for titanium, which lowers β-transus for pure titanium (882°C).
- The titanium alloys can be classified into three categories, i.e., α, α+β, and metastable β alloys.

List of titanium alloy grades included in the BLIP irradiation (→ *Pat-san's talk*)

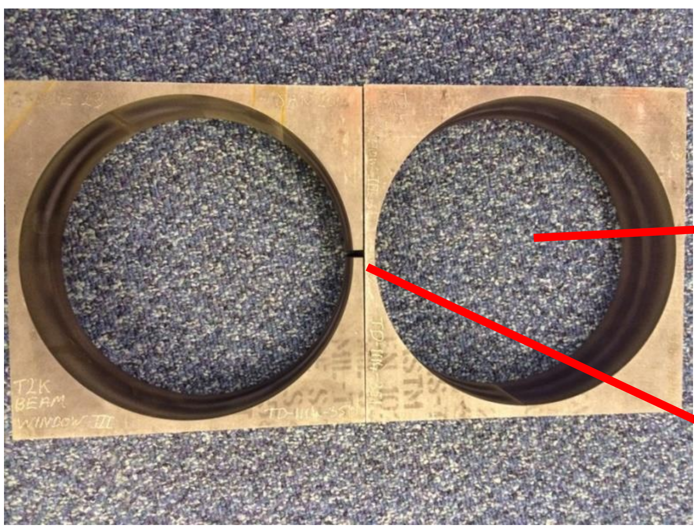
ASTM Grade	Composition	HT*	Tensile Properties Tensile (MPa)	Yield (MPa)	El.. (%)
Commercially Pure (CP) Titanium					
• Gr-1		A	270~410	≧165	≧27
• Gr-2		A	340~510	≧215	≧23
α alloy					
• Gr-6	Ti-5Al-1.5Sn	A	862	804	16
α + β alloy					
• Gr-9	Ti-3Al-2.5V	A	686	588	20
• Gr-5/Gr-23 ELI		A	980	921	14
	Ti-6Al-4V	STA	1,170	1,100	10
Metastable β alloy					
• Ti-15V-3Cr-3Al-3Sn		STA	1,230	1,110	10

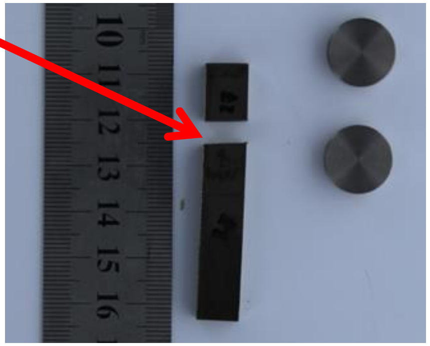
*Heat Treatment: 'A' stands for mill-annealing, and 'STA' solution treatment and aging.

How these wide variety of phase compositions affects to the radiation damage behavior on their mechanical properties ??

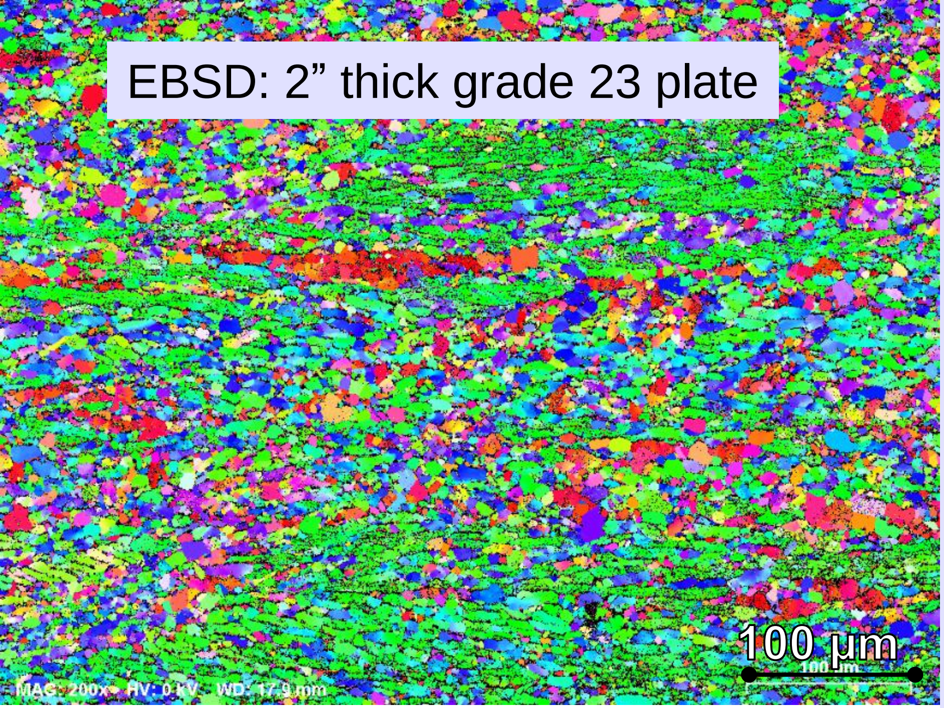
Struggles on Ver.2 window material choice

- Domes made from Ti-6Al-4V ELI (Grade 23)
  - ELI stands for Extra Low Interstitial.
  - Reduced interstitial elements oxygen and iron improve ductility and fracture toughness with some reduction in strength.
- Plate used instead of bar – maybe better properties at centre (or not?)
- Spare material used for material characterisation.

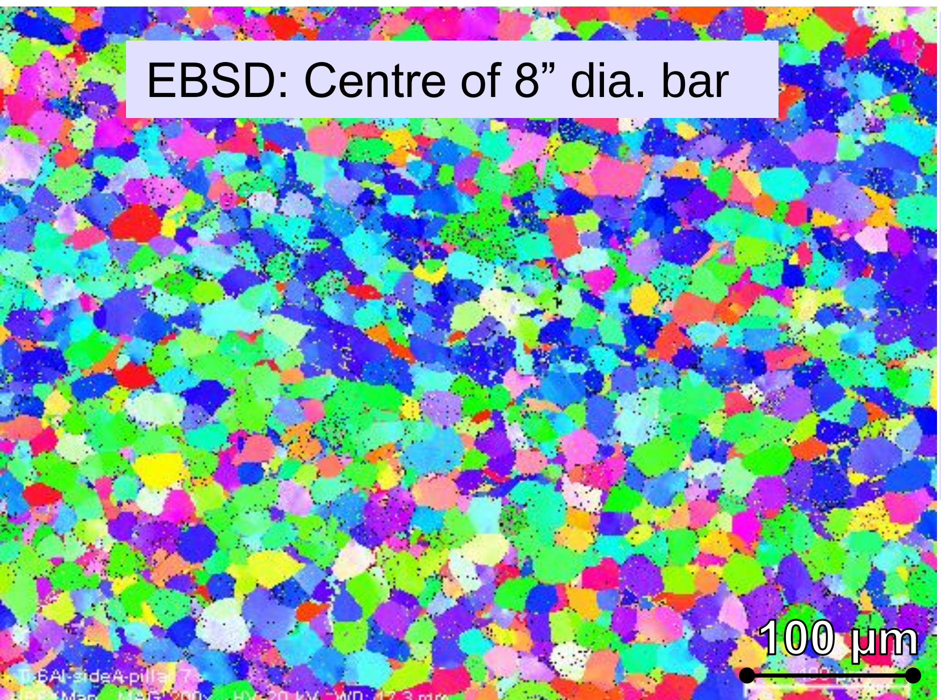




C.J.Densham
HPT Roadmap WS 2017



- Plate: fine grains but large macrozones (= regions with similar crystal orientations inherited from large prior beta grains).
- Microstructure not as refined as it first appears.
- The effective structural unit size may be much larger than it initially appears
- **Could impact badly on fatigue properties.**



- Larger grains but less texture, macrozones less evident in the bar
- Current window (from bar) has performed well so far
- **Recommend staying with bar**
- Irradiation samples taken from 200 mm (8”) diameter bar

Microstructure Strongly Dependent on Grade and Way of Fabrication

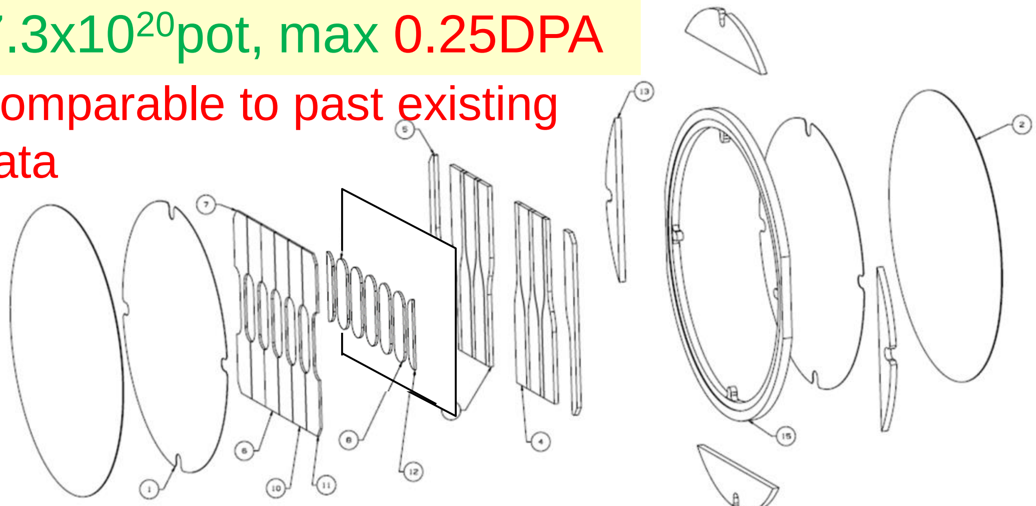
BLIP Ti Capsule Specimen Assembly

DS-Ti1

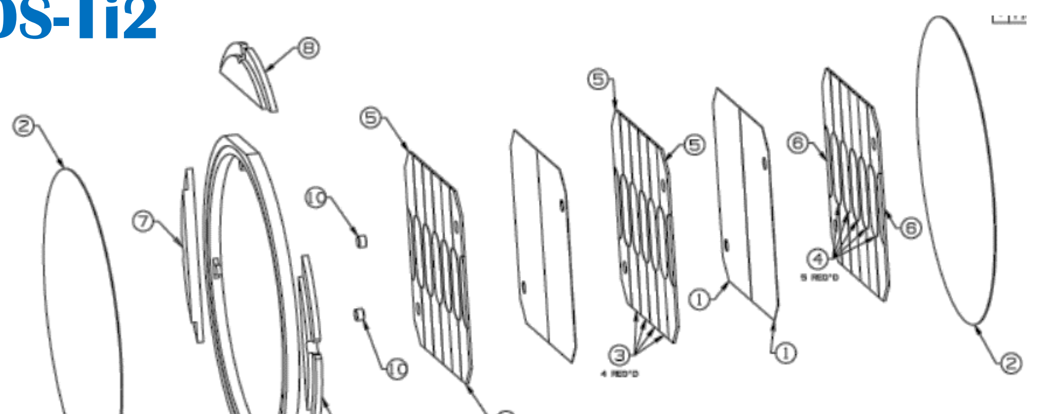
1.75mm total thicknes
Ed=4.9 MeV, 110~135℃ at center

7.3×10^{20}pot, max 0.25DPA

Comparable to past existing data



DS-Ti2



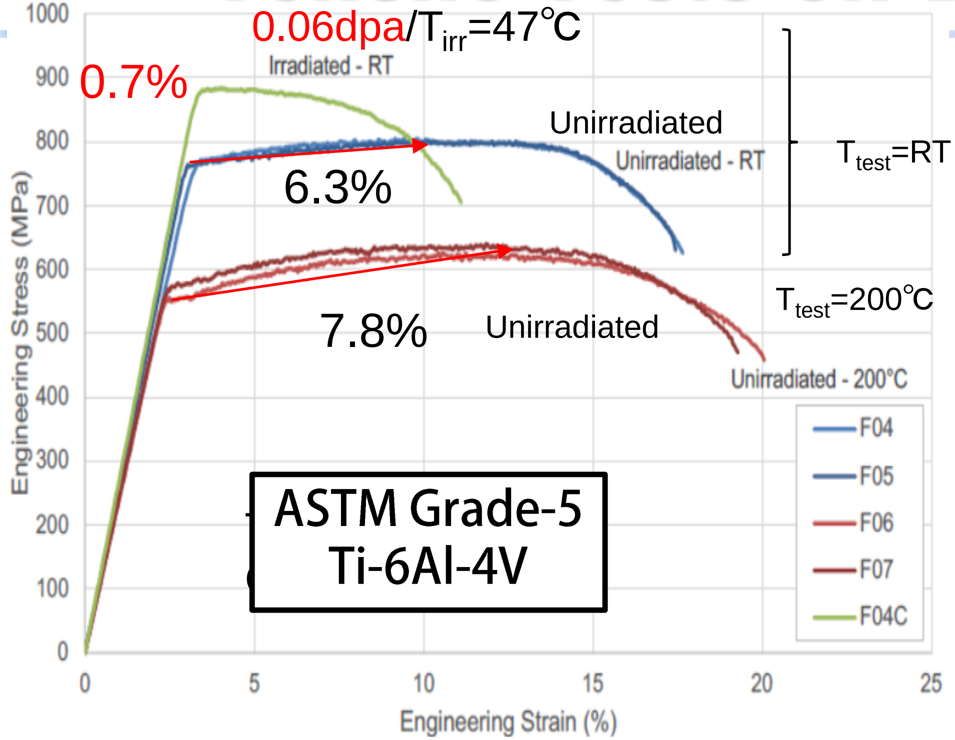
2.8×10^{21}pot, max 0.95DPA

More than pot/yr for 1.3MW oper.

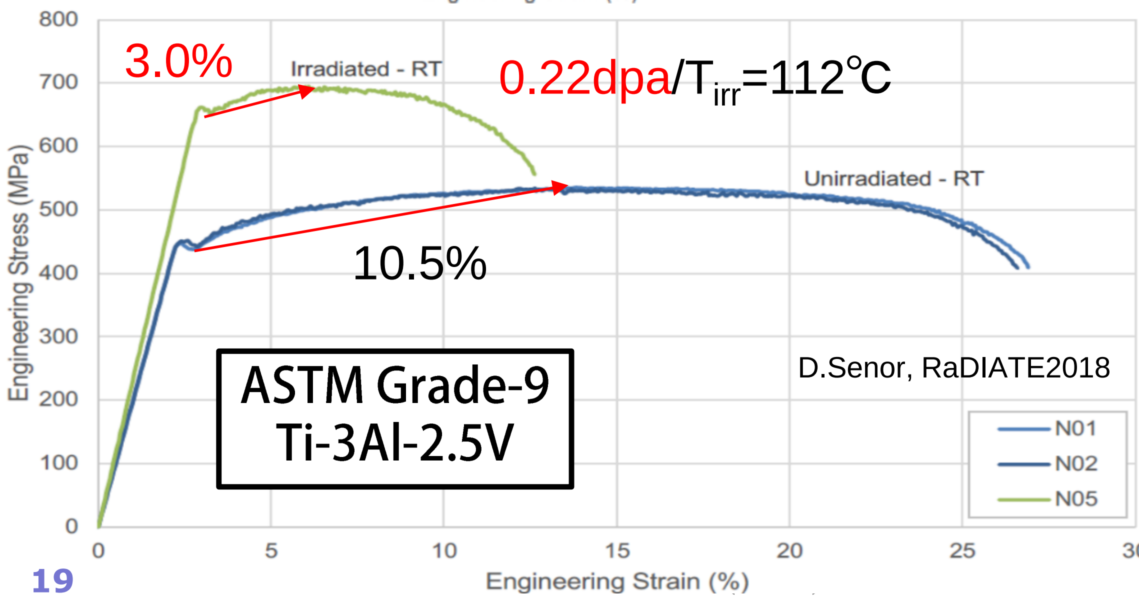
- Ti-6Al-4V
  - Gr5 A
  - Gr23 ELI (Annealed, Forged)
- Ti-3Al-2.5V Gr.9

- CP-Ti (Gr1/Gr2)
- Ti-5Al-2.5Sn (Gr6)
- Ti-6Al-4V (Gr5/Gr23)
  - Annealed
  - Solution-Treat & Aged (STA)
  - Ultra-Fine grain
- Ti-15V-3Cr-3Sn-3Al

Tensile Tests on DS-Ti1 Specimens



- Ti-6Al-4V (most typical dual $\alpha+\beta$ phase alloy) showed increased hardness and a large decrease in ductility only with 0.06dpa
  - Uniform Elongation (6.3% → 0.7%) at RT
  - Testing at elevated temperature reduced the strength significantly, but increase elongation in non-irradiated condition
  - No significant change on Elastic Modulus (thus speed of sound)
- Ti-3Al-2.5V (α-like $\alpha+\beta$ phase alloy) still exhibits uniform elongation (3%) after 0.22dpa irradiation



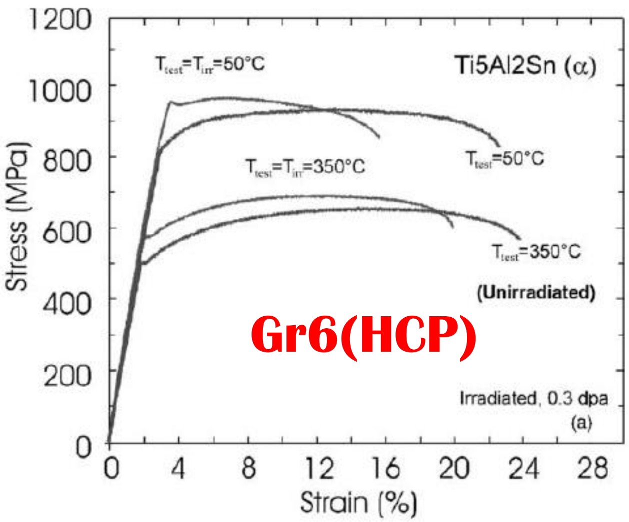
What microstructural difference/change do cause a larger decrease in ductility for Ti-6Al-4V than for Ti-3Al-2.5V ?

→ Possible answer to be presented at ICFRM-19 next week

Radiation-Resistant Candidates in DS-Ti2

HCP α alloy Gr6

Better ductility (n 0.3DPA) with enough strength

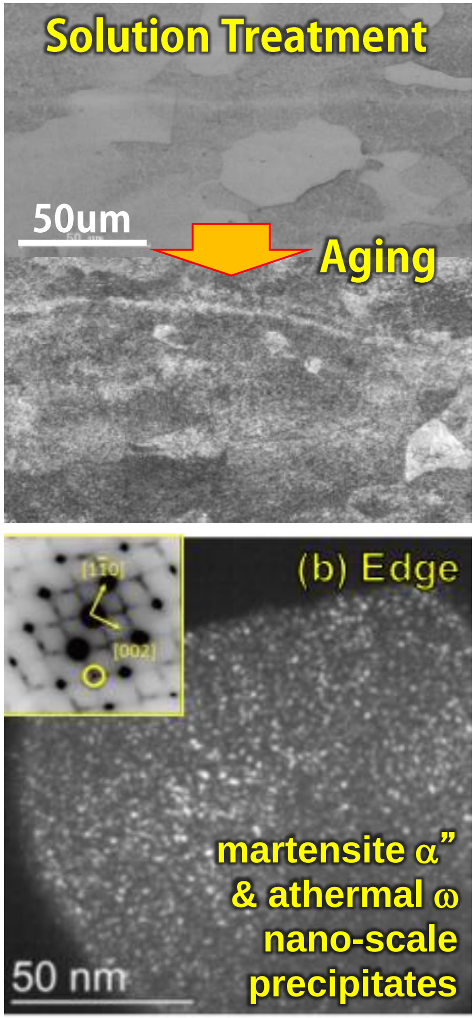


S. Tähtinen et al.
JNM 307-311 (2002) 416

Utilize
Nano-scale Precipitates
& Grain Boundaries
as Radiation-induced
Point Defect Sink Sites

Metastable β 15-3Ti

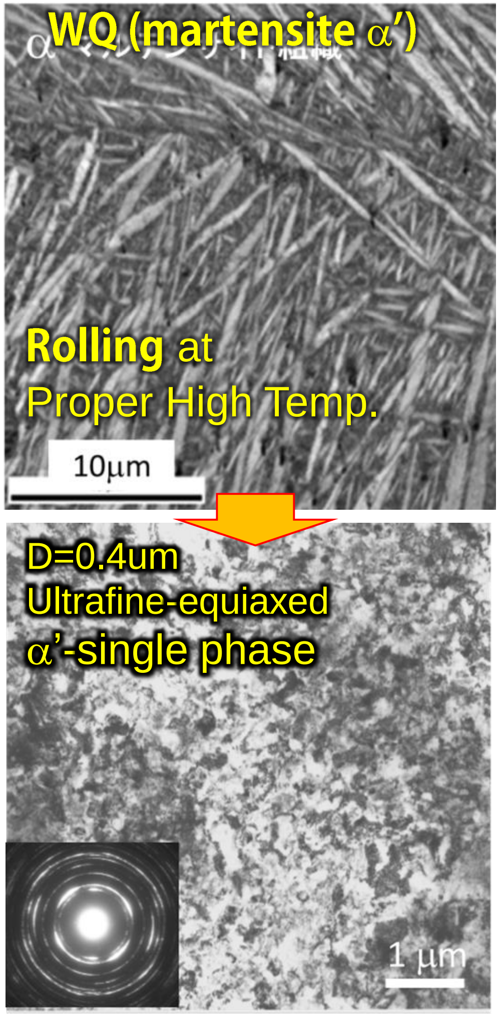
Rich Nanoscale precipitates



T.Ishida, E. Wakai et al,
Nucl.Mat En.15 (2018) 169

64Ti α′-Ultra FineGrain

Rich grain boundaries

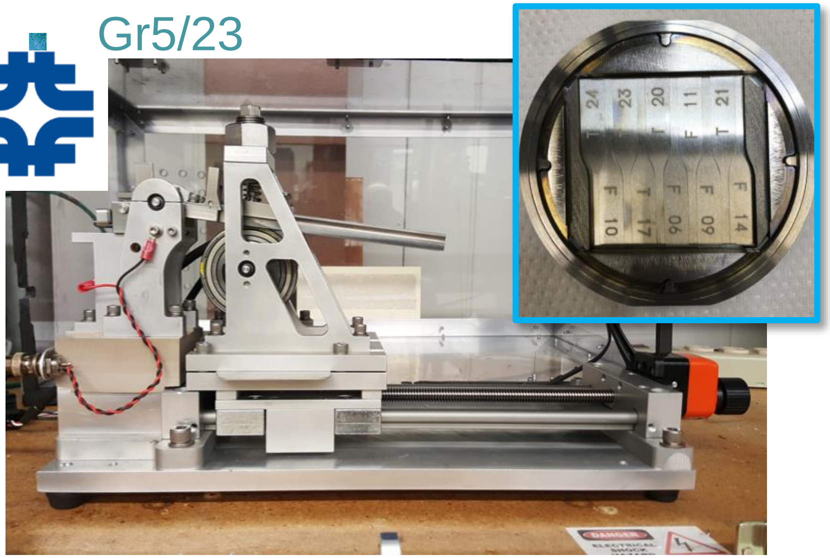


H.Matsumoto et al.,
Adv.Eng.Mat.13 (2011) 470

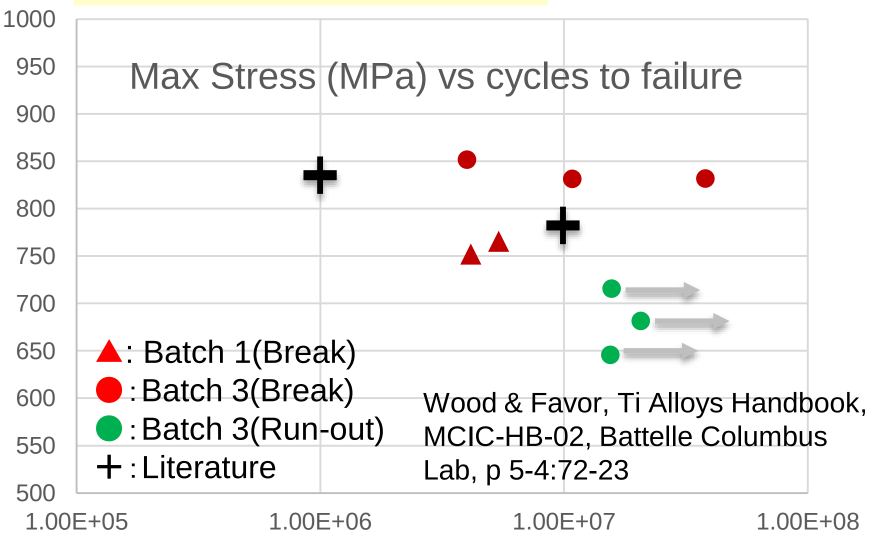
High Cycle Fatigue Testing

Macro-scale Fatigue Testing

- Gr5/23

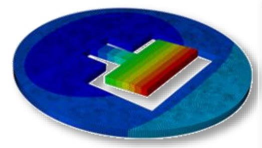


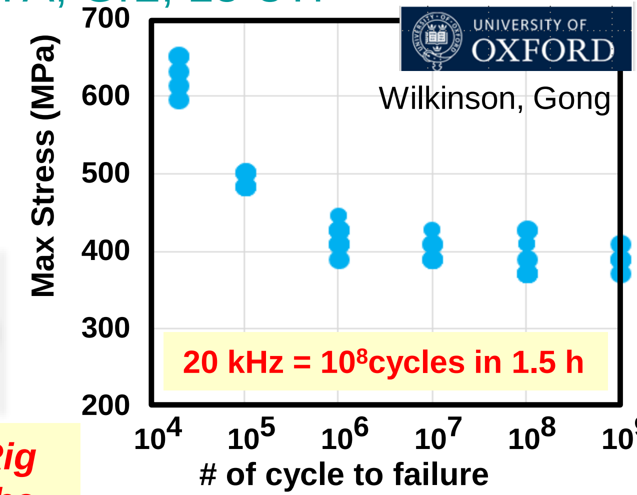
Test on Cold Specimens



Mesoscale Ultrasonic Fatigue Testing

- Gr23 A&STA, Gr2, 15-3Ti





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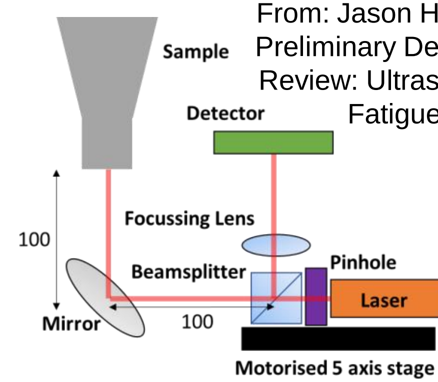
Meso-Fatigue Rig Installation in the UKAEA-MRF (2018)

UK Budget Secured

Science & Technology Facilities Council

UK Atomic Energy Authority

MATERIALS RESEARCH FACILITY



From: Jason Hess. Preliminary Design Review: Ultrasonic Fatigue Rig

Summary

- Plan to upgrade beam window thickness from 0.3 mm → 0.4 mm to increase tolerance of beam window to thickness/bunch structure
  - Operation at 1.3 MW appears feasible for upgraded beam window
- Radiation damage in window material is main question
  - Alternatives to currently used 'industry standard' α+β phase Ti alloy under investigation as RaDIATE collaboration program
  - High intensity proton irradiation at BLIP facility completed. Post-Irradiation Examination underway.
  - Macro-scale and meso-fatigue samples irradiated in BLIP facility for testing at Fermilab and at Culham : 1st High Cycle Fatigue data on irradiated Ti alloys to be obtained.

Lesson Learnt :

Make enough microscopic / macroscopic investigations before you fabricate apparatus

BACKUP

Materials Choice for Beam Window

Properties for target/beam window materials

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	Density [g/cc]	CTE (α) [/K]	Modulus (E) [Pa]	Poisson's ratio	Specific heat [J/Kg.K]	Thermal cond. (K) [W/(m.K)]	Tensile strength (σ_f) [Pa]
Toyo Tanso IG-43	1.82	4.80E-06	1.08E+10	0.20	711.8	140	3.70E+07
Glassy carbon GC20	1.51	2.00E-06	2.80E+10	0.20	800	5.8	4.40E+07
Beryllium - S65B	1.82	1.19E-05	3.06E+11	0.08	1901	177	3.38E+08
V-5Cr-5Ti	6.1	9.30E-06	1.26E+11	0.37	575	21	6.88E+08
Ti-6Al-4V	4.43	8.60E-06	1.14E+11	0.34	565	6.7	8.60E+08

The 3D instantaneous thermal shock resistance

	Instantaneous thermal shock resistance (σ_f(1-2ν))/(Eα))	Δt for 1J/g [K]	thermal shock resistance for 1 J/g (σ_f(1-2ν))/(Eα(ΔT)))
Toyo Tanso IG-43	428	1.40	305
Glassy carbon GC20	471	1.25	377
Beryllium - S65B	78	0.53	148
V-5Cr-5Ti	153	1.74	88
Ti-6Al-4V	281	1.77	159

- For thermal shock resistance alone, Ti-6Al-4V looks to be superior to Beryllium.
- As we have fast internal heat generation, we have included the 3D state of stress which gives the (1-2v) term.
- To include beam heating I have also tried to compare for a heat deposition of 1J/g. The assumption is that the energy deposition between Be and Ti are similar in J/g and therefore removing density from the equation.
- This leads to beryllium looking much better, but still not as good at titanium. As shown graphite and glassy carbon are better still.

Speed of Sound & Stress Resonance

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$$c = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}}$$

Where:
E = Young's modulus
ρ = Density
ν = Poisson's ratio

Temperature (°C)	Young's modulus (GPa)	Speed of sound (m/s)
25	114	6217
100	109	6079
200	103	5909
300	96.1	5708

Table 1 – Variation is calculated speed of sound with temperature

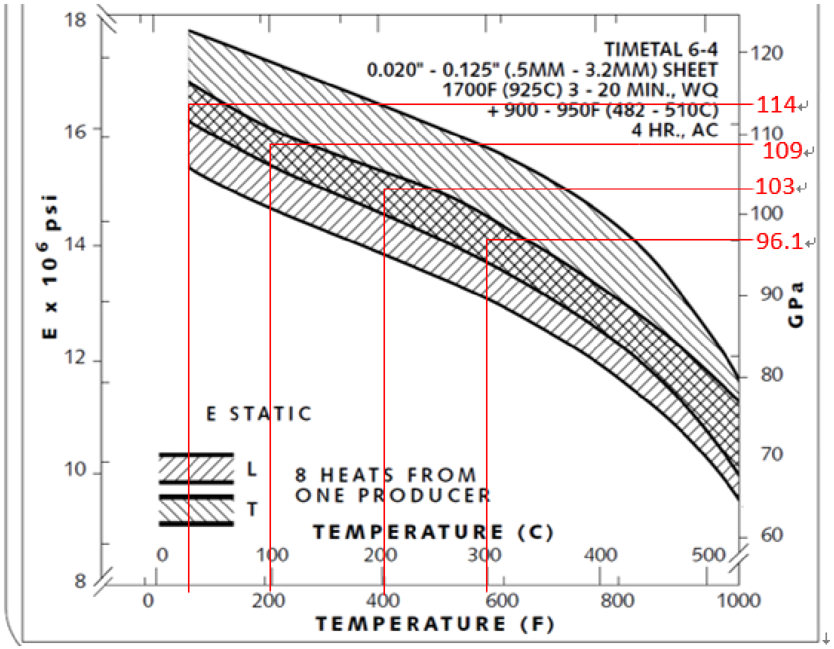

Figure 1 – Elastic modulus of Ti-6Al-4V at room and elevated temperature