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Analysis of the ISIS Target Station 2 Proton Beam Window Failure

Service Conditions, Design Analysis and Irradiation Effects

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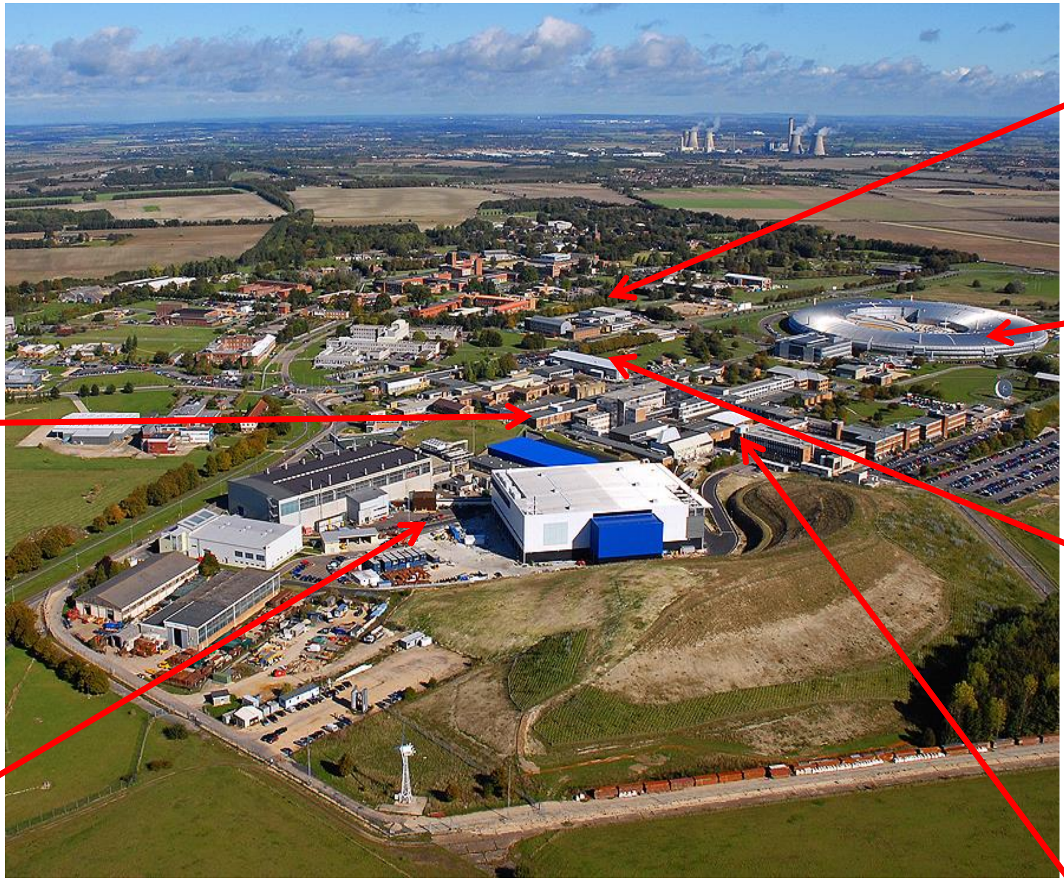
RaDIATE, 17-12st December 2018, CERN.

Introduction

Collaboration between High Power Targets and ISIS – STFC at RAL



RAL Space.

Diamond light source.

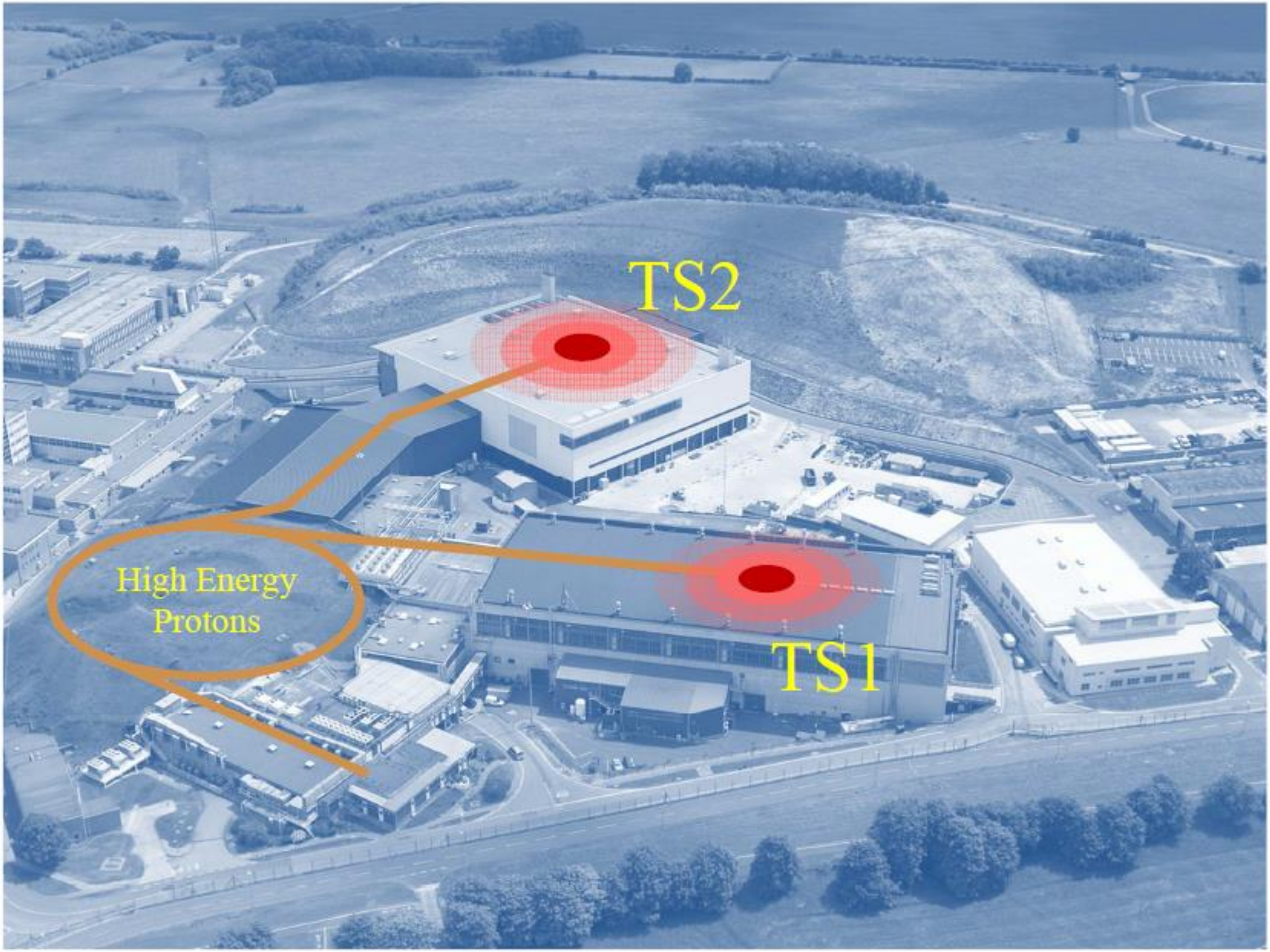
High Power Targets

Central Laser Facility.

ISIS High pulsed neutron source

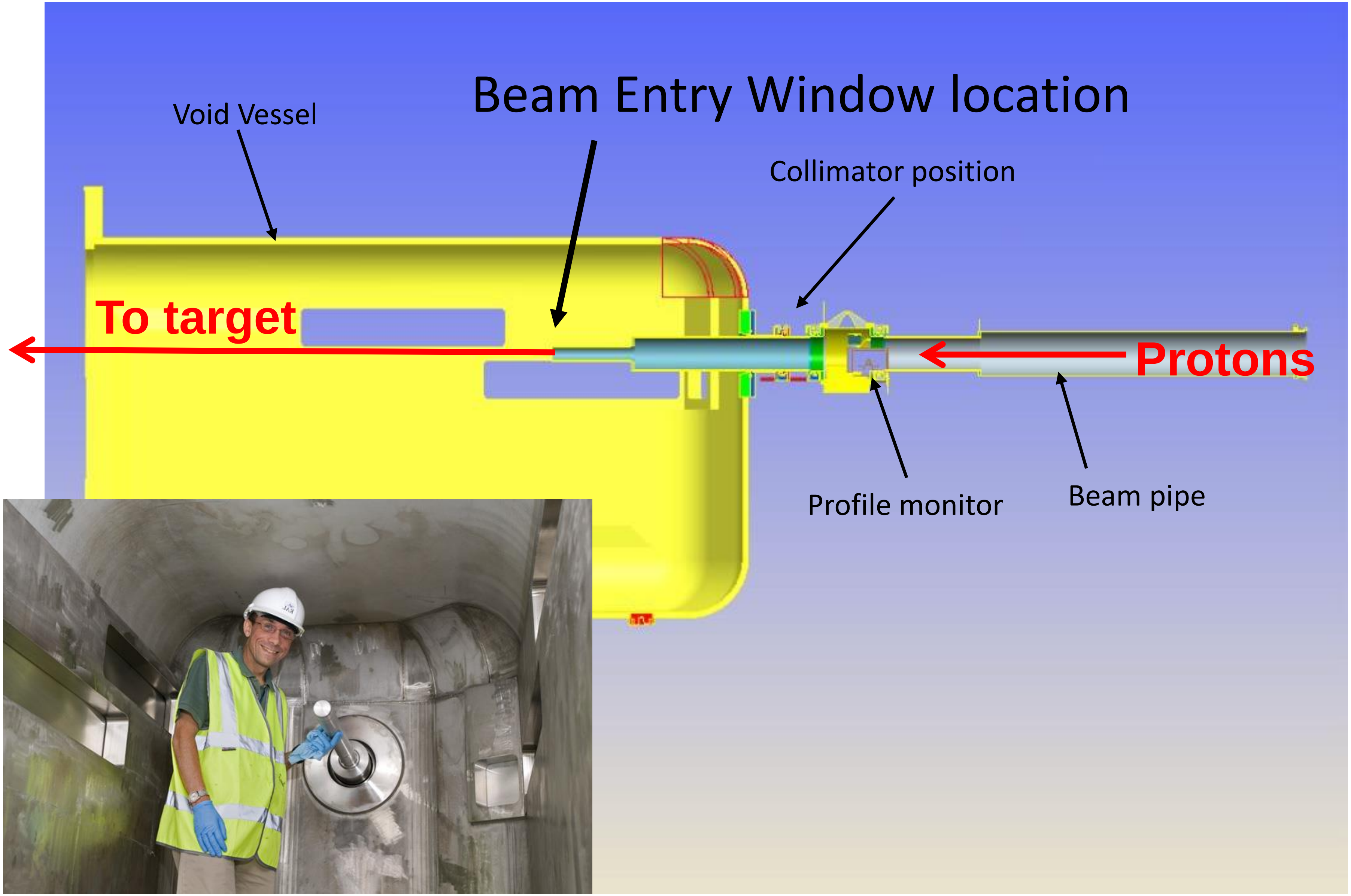
Many other groups

Slide courtesy Daniel Blanco Lopez



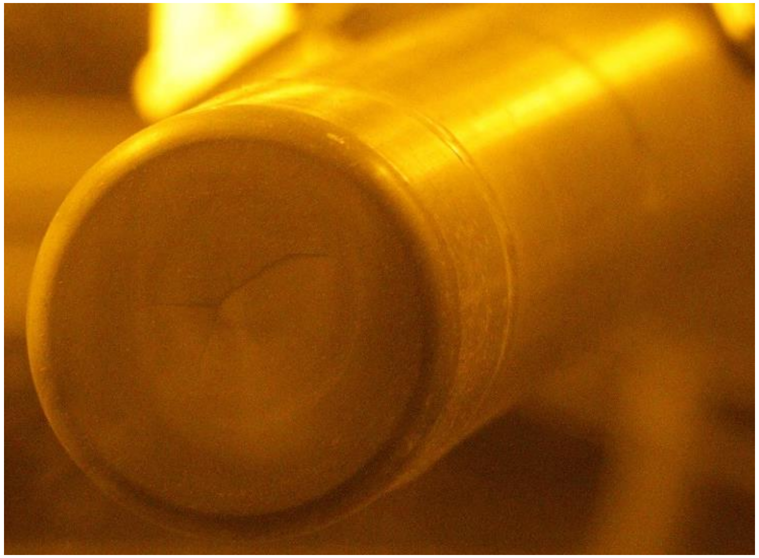
Slide courtesy Daniel Blanco Lopez

TS2 void vessel & BEW



Beam Entry Window Failure

BEW failure in October 2017. Replaced during planned shutdown.



This talk follows on from presentations by Dan Coates and Daniel Blanco Lopez given at HPTW. These cover the replacement and operation parameters in more detail.

Abnormal instrument reading and beam-scan

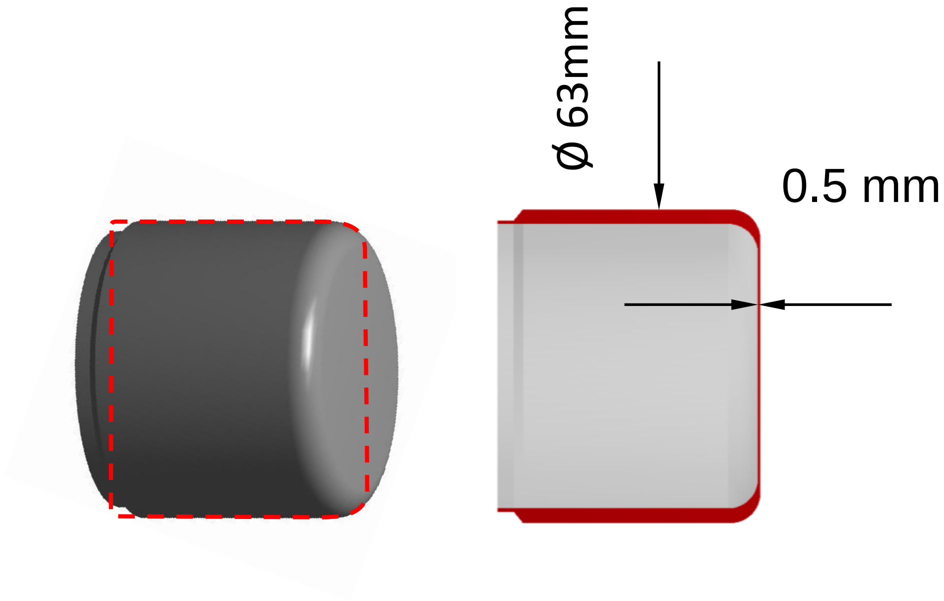
Was it an abnormal event?

Or did the window break due to radiation damage?

(how much did these factors contribute?)

Window operating conditions

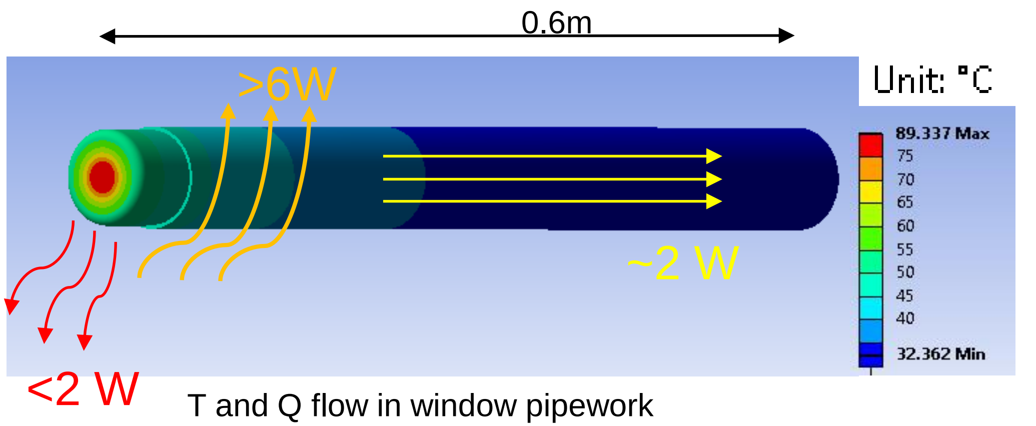
Beam Parameters	
Proton Beam	800 MeV 40 µA 10 Hz
Beam power deposited in window	10 W
Gaussian Beam Sigma	6 mm
Void vessel	Passively cooled Helium 1.01 bar abs 35°C



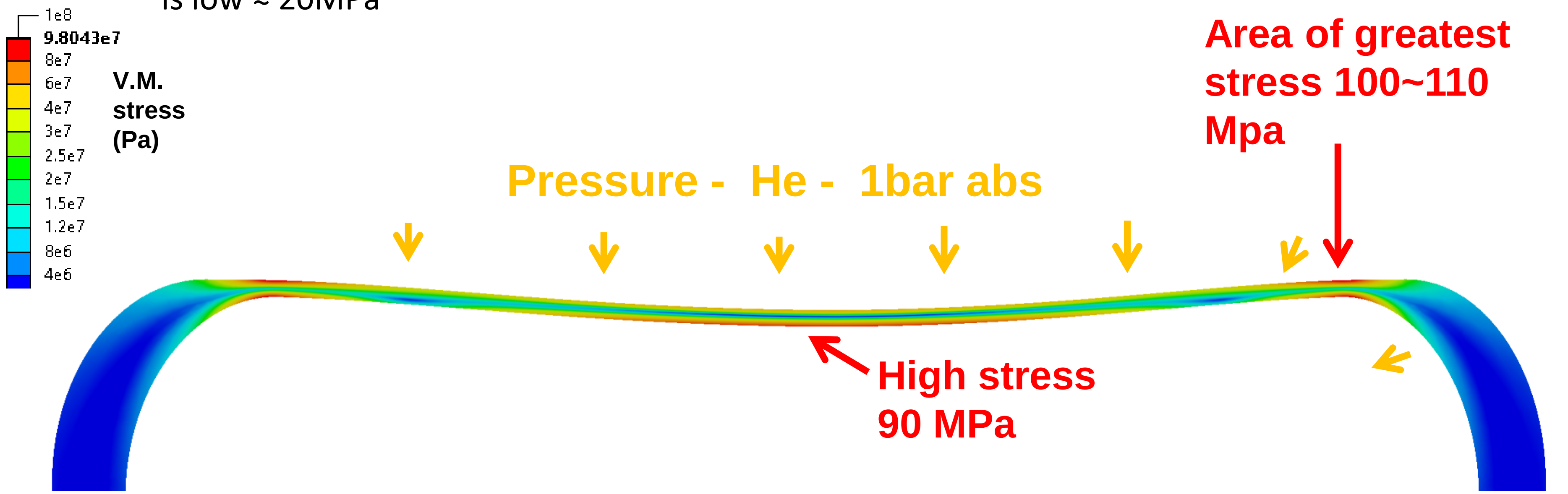
- **Material: Al 5083-O**
- **0.5mm thick**

Mechanical analysis

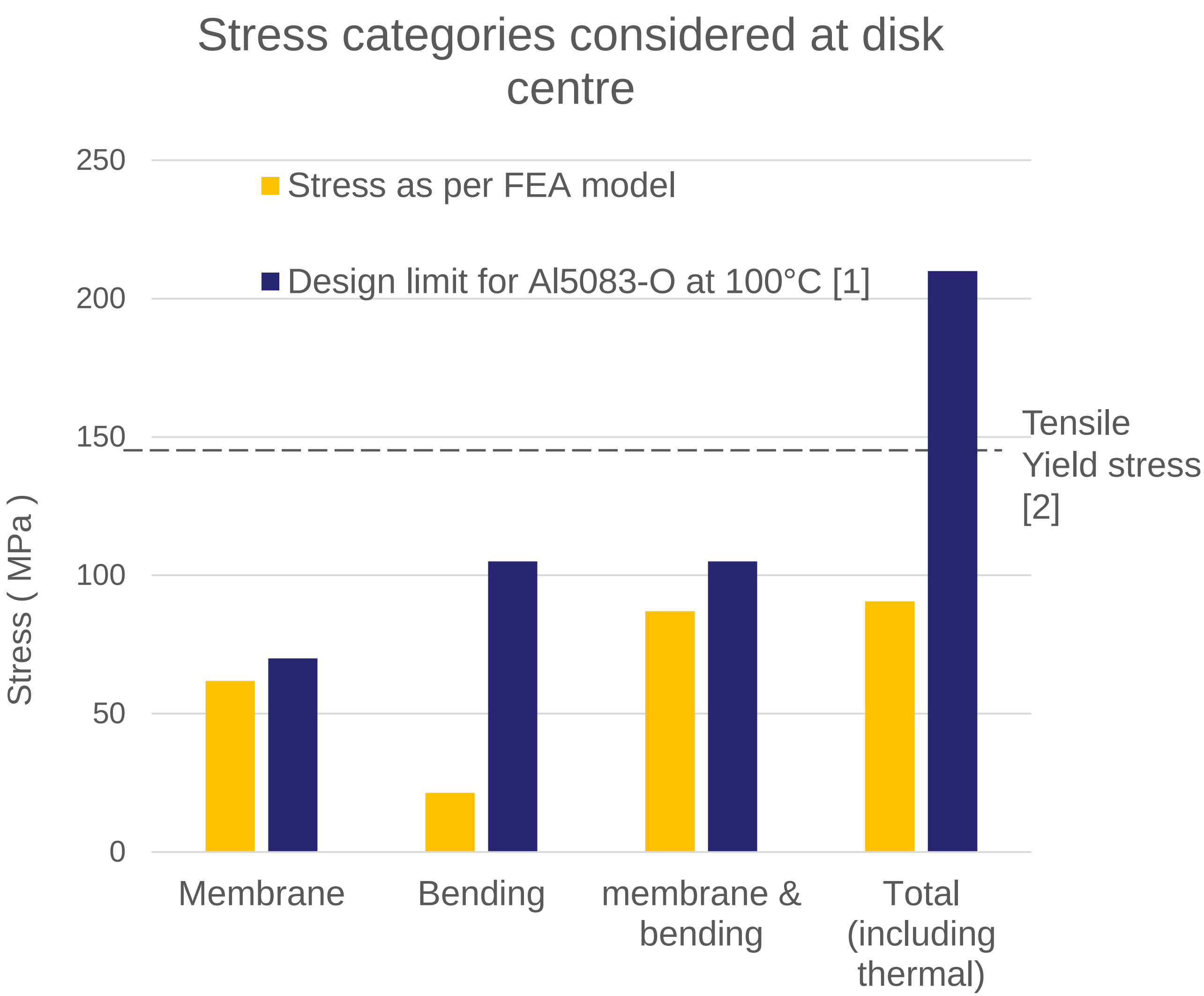
- Maximum operating temperature
  ≈ 90 °C
- Heat transfer from window face
  Primarily from conduction
- Bows inwards due to pressure
  ≈ 0.9mm
- High stress in materials
  ≈ 100MPa
- Stress due to thermal expansion is low ≈ 20MPa



T and Q flow in window pipework



Mechanical analysis



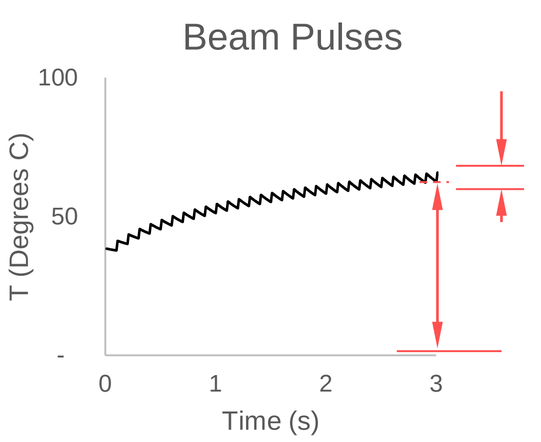
Nominal design strength of Al5083 at 100°C: 70MPa [1]

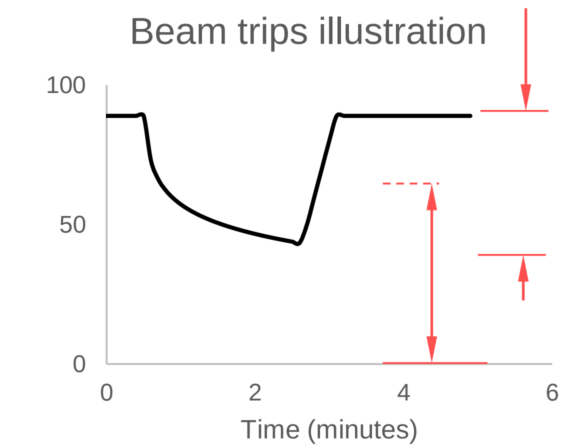
Design Limits per Stress Category (membrane, bending etc) are multiples of nominal design strength . Multiples defined by [3].

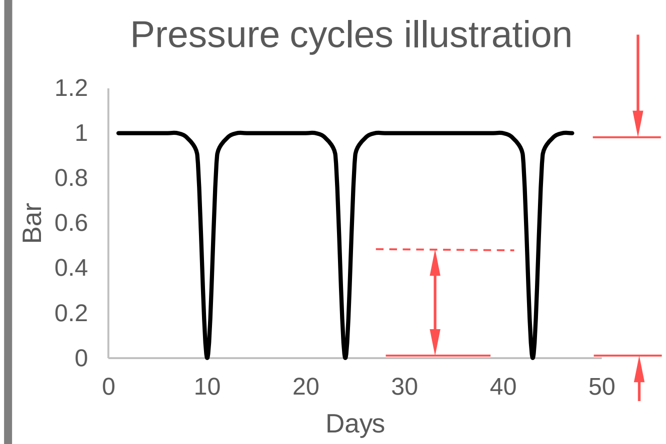
[1] EN 13445-8:2014/prA2:2018 (E)
[2] ASM aerospace materials datasheet
[3] PD 5500

Window operating loads

Cyclic loading for fatigue analysis



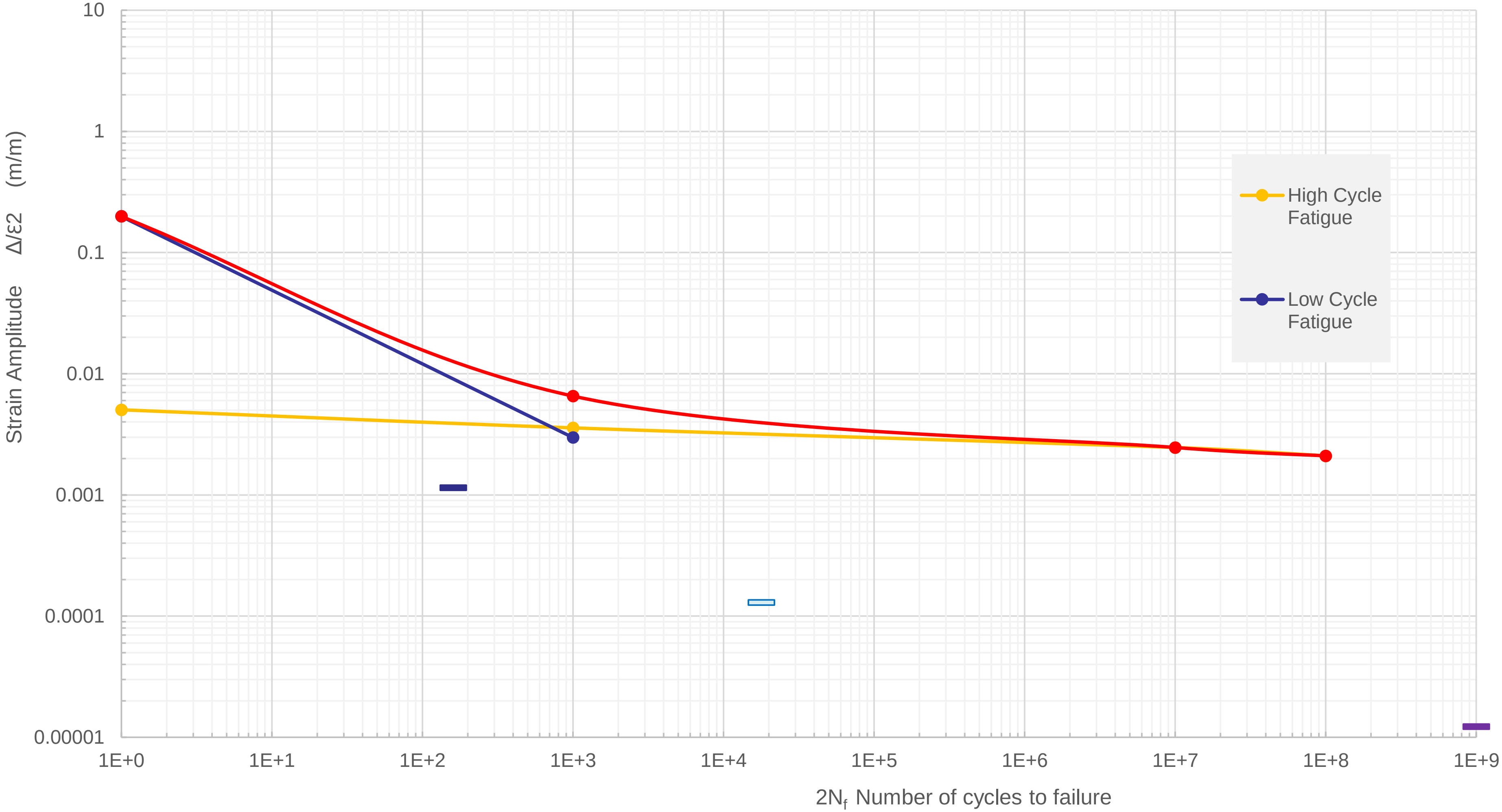




Beam Pulses	Beam trips	Pressure Cycles
Lower stress amplitude 0.3 MPa	Medium stress amplitude 9 MPa	Higher stress amplitude 9 MPa
High Frequency 10 Hz	Medium Frequency 2 x10^{-4} Hz	Lower Frequency 20 per year

Stress waves due to beam pulses not included

Expected Lifetime analysis AL5083



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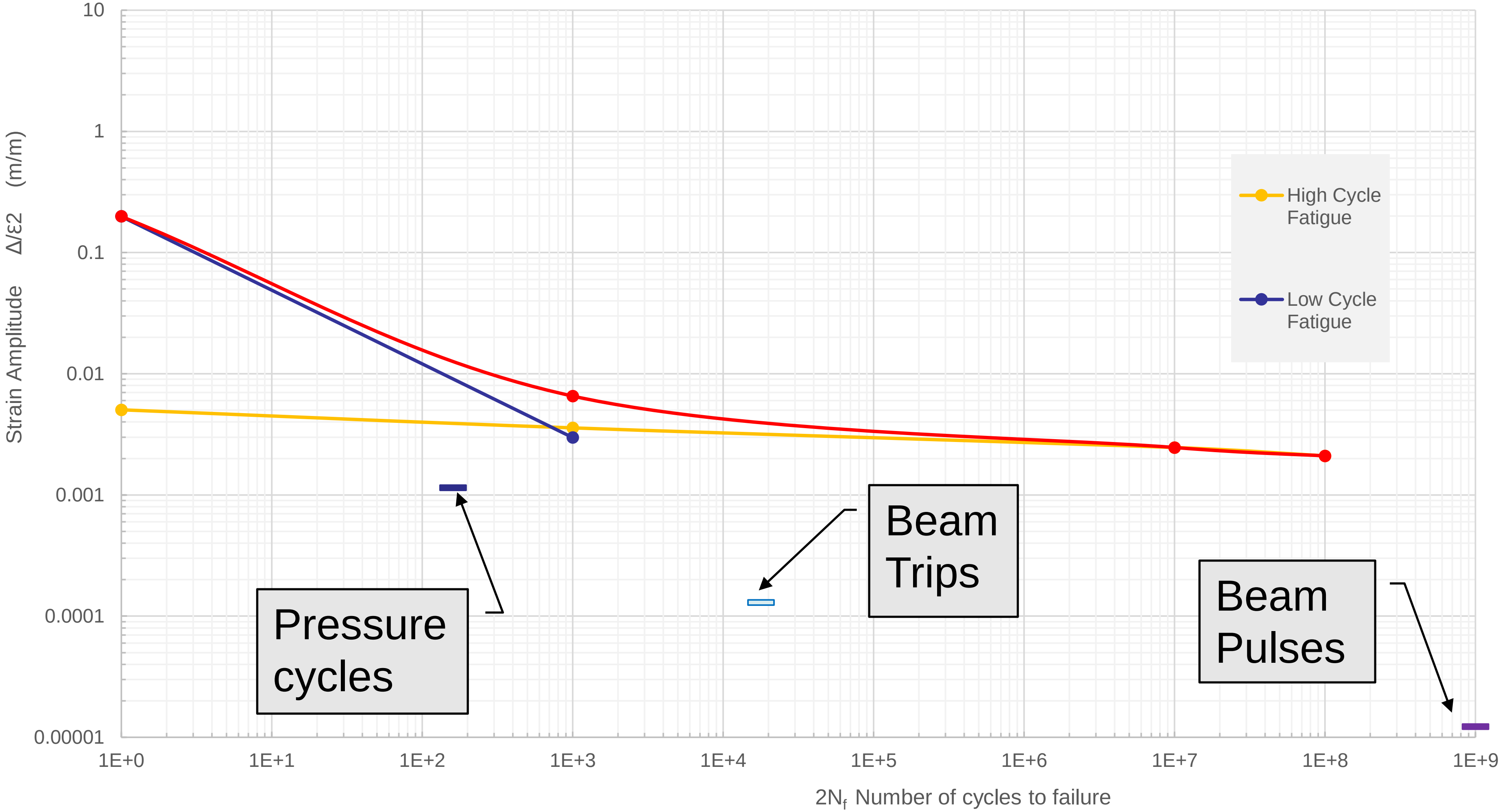
Expected Lifetime analysis AL5083



→ Very low risk of failure at 10 year design life.

- Assuming properties before irradiation
- At room temperature

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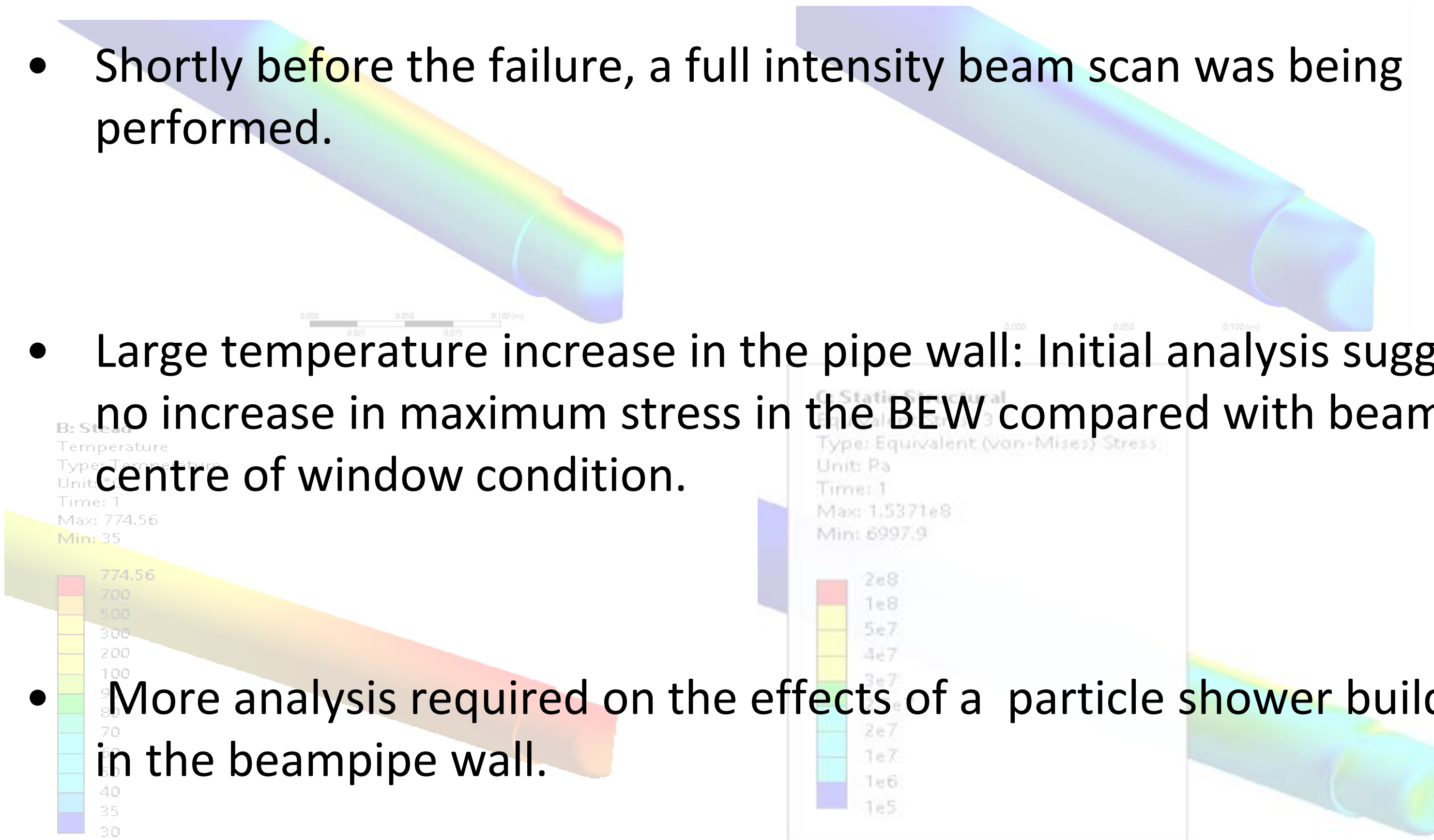
Beam mis-steer

- Shortly before the failure, a full intensity beam scan was being performed.

- Large temperature increase in the pipe wall: Initial analysis suggests no increase in maximum stress in the BEW compared with beam in centre of window condition.

- More analysis required on the effects of a particle shower build-up in the beampipe wall.



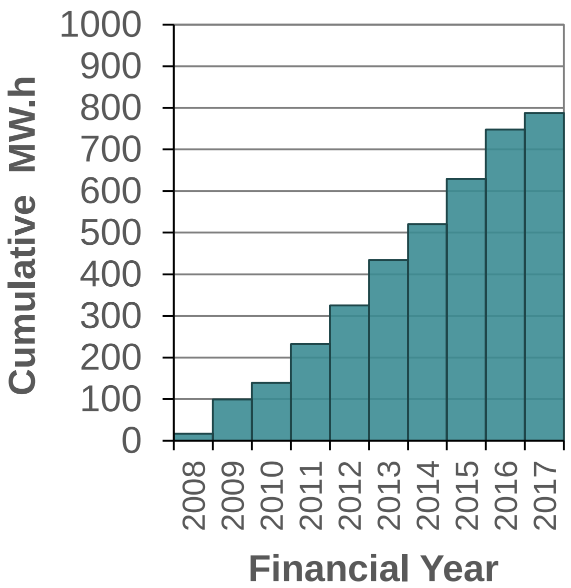
Window Irradiation Parameters

	BEW
Total number of protons	2.2×10^{22}
Fluence (cm^{-2})	0.85×10^{22}
DPA	3 - 5

Courtesy D. Findlay report 2017.

	BEW
H generation	8,500 appm
He generation	2,100 appm

Courtesy IFN report July 2014.

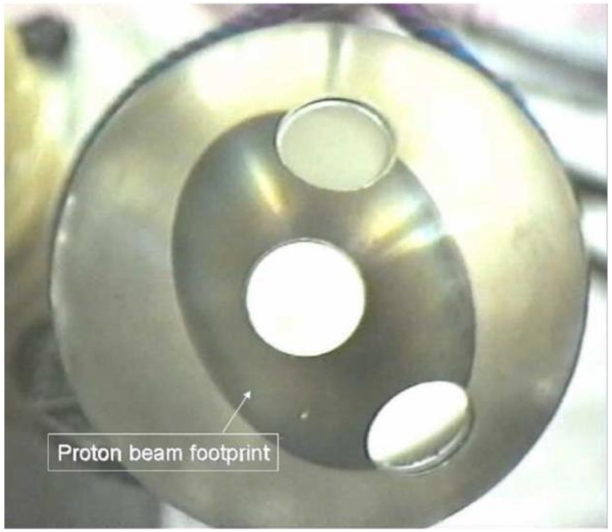


Over ≈8 years of operation.

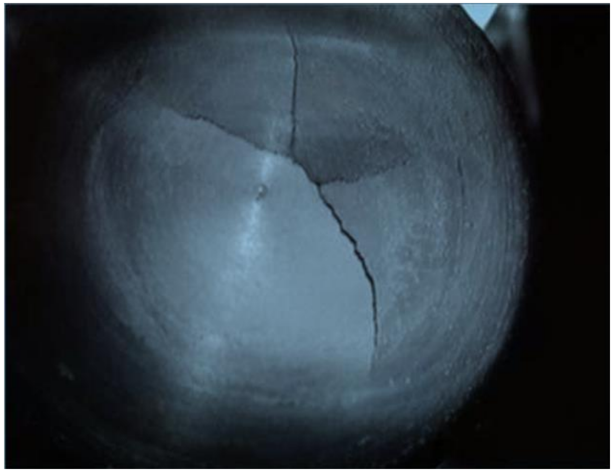
5xxx-series Al-alloy windows

Component	Beam	Material	Thickness	Thermal Management	Peak Fluence	Lifetime	References
SINQ Safety Hull - PSI	570 MeV protons	AlMg3	2x 3mm	forced convection to heavy-water	$3x10^{21}$ p/cm^2	No failure observed	Y. Dai, D. Hamaguchi, J. Nucl. Mater. 343 (2005) 184-190 W. Lu, M.S. Wechsler, Y. Dai, J. Nucl. Mater, J. Nucl. Mater. 318 (2003) 176-184
JSNS Beam Window	3 GeV protons	Al 5083	2x 2.5mm	forced convection to Water	* $1.8x10^{21}$ p/cm^2	* design life	M. Harada, N. Watanabe, C. Konno, S. MNeigo, Y. Ikeda, K. Niita, J. Nucl. Mater. 343 (2005) 197-204 S. Meigo, M. Ooi, M.Harada, H. Kinoshita, A. Akutsu, J. Nucl. Mater. 450 (2014) 141-146
ISIS BEW2	800 MeV protons	Al 5083-O	1x 0.5mm	Passive convection in He environment	$8.5x10^{21}$ p/cm^2	Failed in service after 8 years	D.Findlay Note <ISIS-DJSF-17-11-A>

JSNS Beam Window inspected after ~1000 MW h of operation



Samples extracted from SINQ safety hull


ISIS EPB2 post failure

5xxx-series Al-alloy windows

Component	Beam	Material	Thickness	Thermal Management	Peak Fluence	Lifetime	References
SINQ Safety Hull - PSI	570 MeV protons	AlMg3	2x 3mm	forced convection to heavy-water	3x10^{21} p/cm^2	No failure observed	Y. Dai, D. Hamaguchi, J. Nucl. Mater. 343 (2005) 184-190 W. Lu, M.S. Wechsler, Y. Dai, J. Nucl. Mater, J. Nucl. Mater. 318 (2003) 176-184
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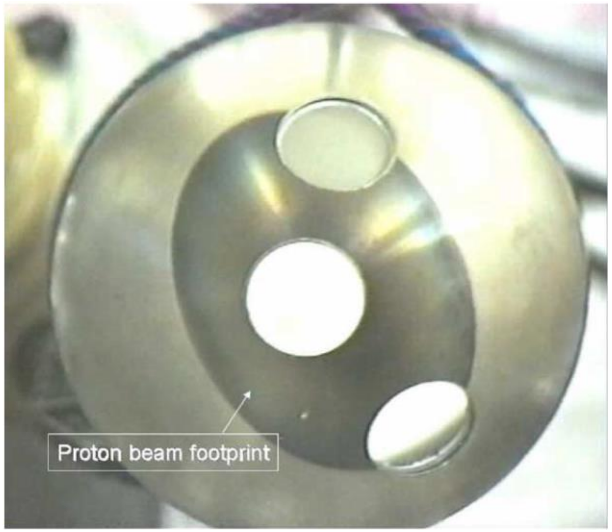
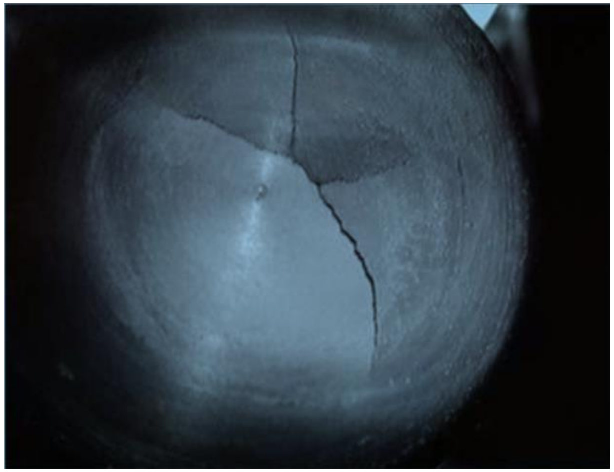
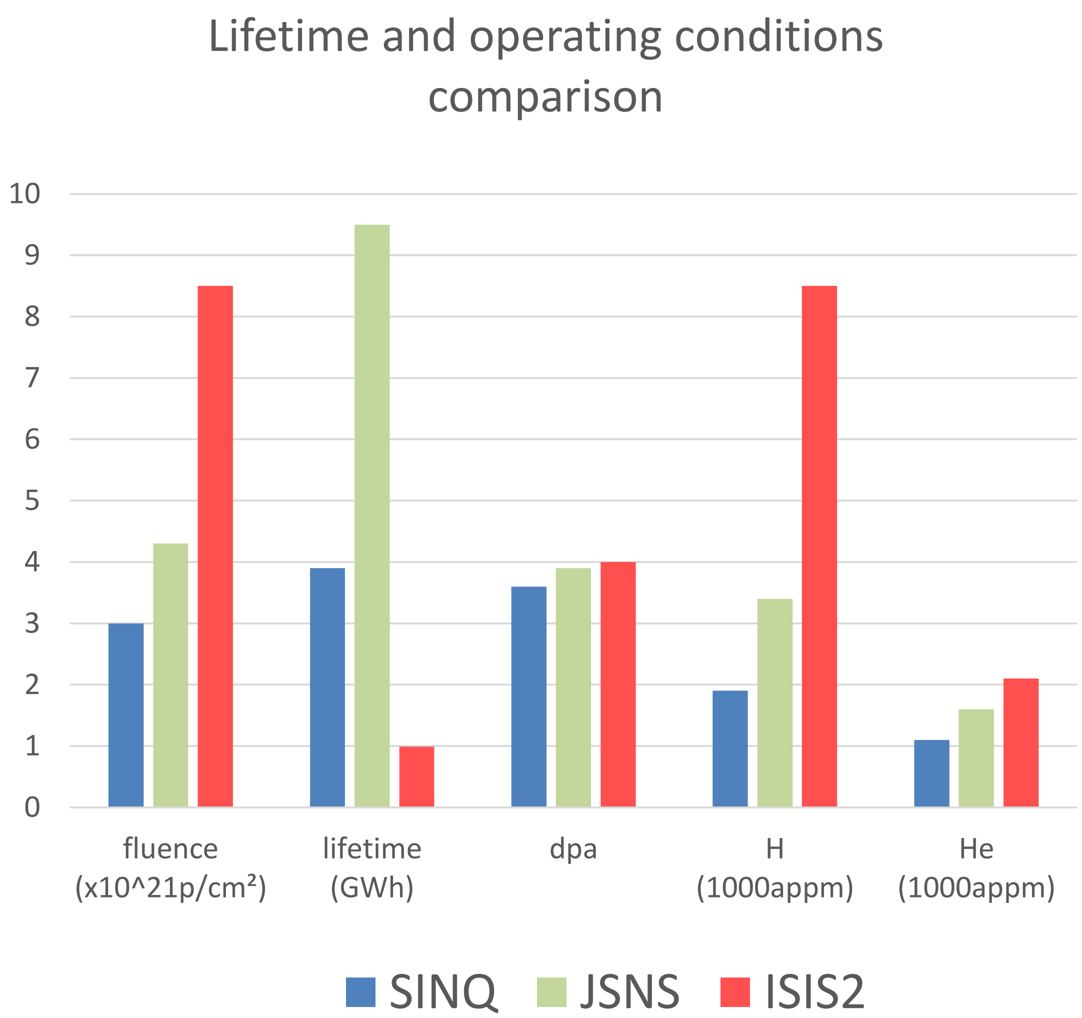


Samples extracted from SINQ safety hull



ISIS EPB2 post failure

5xxx-series Al-alloy windows



- Analysis indicates Isis BEW 2 runs at a high temperature of ≈ 90 °C.
- Use of Al 5083 not recommended above ≈ 70°C [PD5500, EN 13445-8]
- He appm >2000

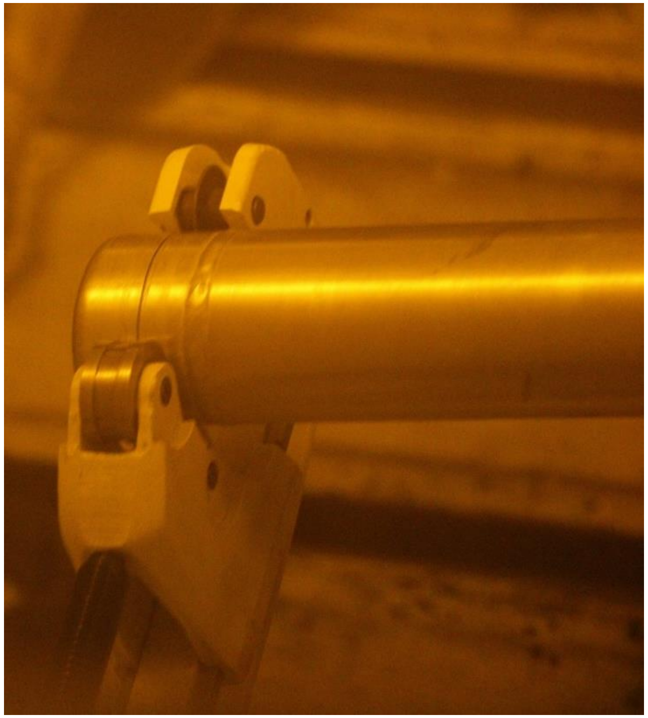
Irradiation material damage

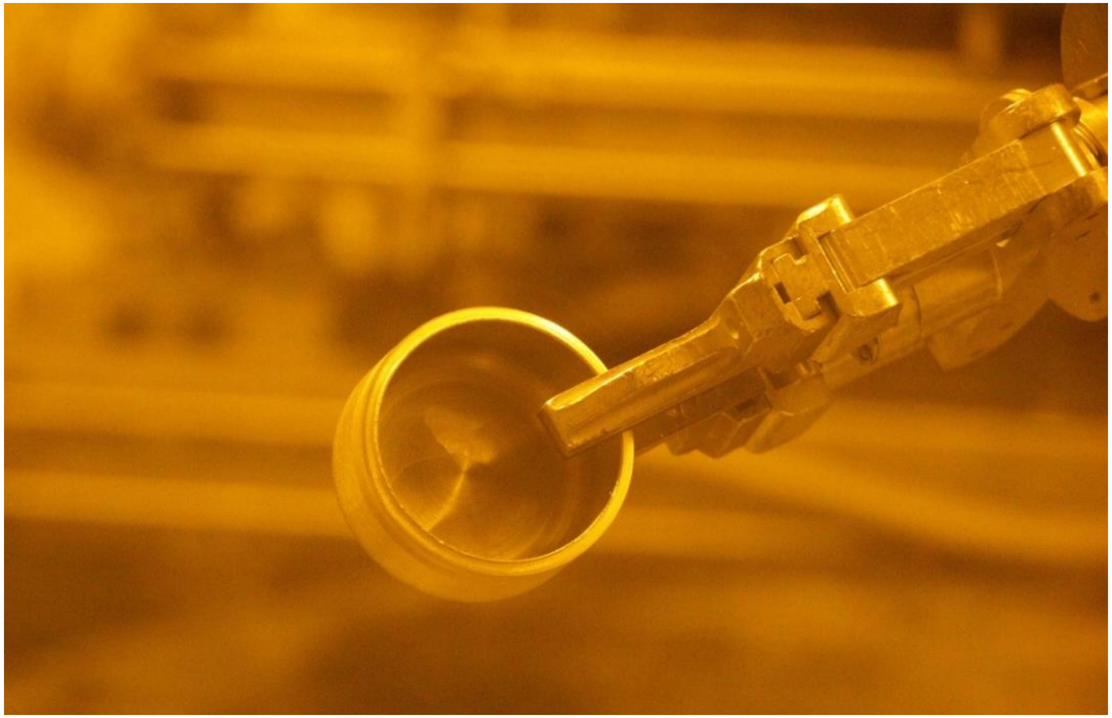
- Irradiation embrittlement
  - Transmutation
  - Loss of cold work microstructure
  - Gas nucleation
  - Formation of voids
    - stress raisers
    - lower thermal conductivity
  - Gas diffusion to micro-crack tips and grain boundaries
- 0.5mm thick

- Many unknowns at this point
- Many mechanisms at work
- How radiation effects are combining with beam scan conditions unknown
- How many grain boundaries across window thickness?

- AL 5083-O at high temperature is particularly susceptible to SCC [ML-HBK-5H]
  - Is a H and He stress-cracking process similar to SCC occurring?
    - The window bows out and surface is under tension force
  - Most methods of degradation made worse by high temperatures

Our next steps





- The cup is stored at STFC. We waiting until its cool enough to test.
  - Future PIE of the irradiated beam window (≈2 years away) collaboration between Leslie J. at ISIS and Culham Centre for Fusion Energy (UKAEA).
- We are currently planning a collaboration with Culham for materials investigation, including irradiated titanium.
- We seek collaborative efforts and your input
- Cyclic pressure testing of un-irradiated mock-ups – Daniel B.L.

summary

- Several possible causes – what level did they contribute?
  - Was it an abnormal beam scan made worse by prior material damage, caused by radiation?
  - Would helium production of this level alone cause a fail?
- Improvements to design
  - Change material
  - Geometry change to enhance conduction
  - Cooling fins etc
  - Geometry change to lower pressure based stresses
- More testing in future – more info
- Useful information for us, we hope for you too
- We welcome your input

thankyou