Target Design status for T2K2/HyperK and LBNF/DUNE

Chris Densham, Mike Fitton, Tristan Davenne,

Joe O'Dell, Peter Loveridge,

(STFC Rutherford Appleton Laboratory)

John Back (Warwick University)

T. Nakadaira, T. Ishida, M. Tada, T. Sekiguchi

(KEK Beam Group) & T2K Collaboration

Patrick Hurh, Bob Zwaska, Cory Crowley, Laura Fields, Jim Hylen,

Vaia Papadimitiou (Fermilab & LBNF project)

Fermilab

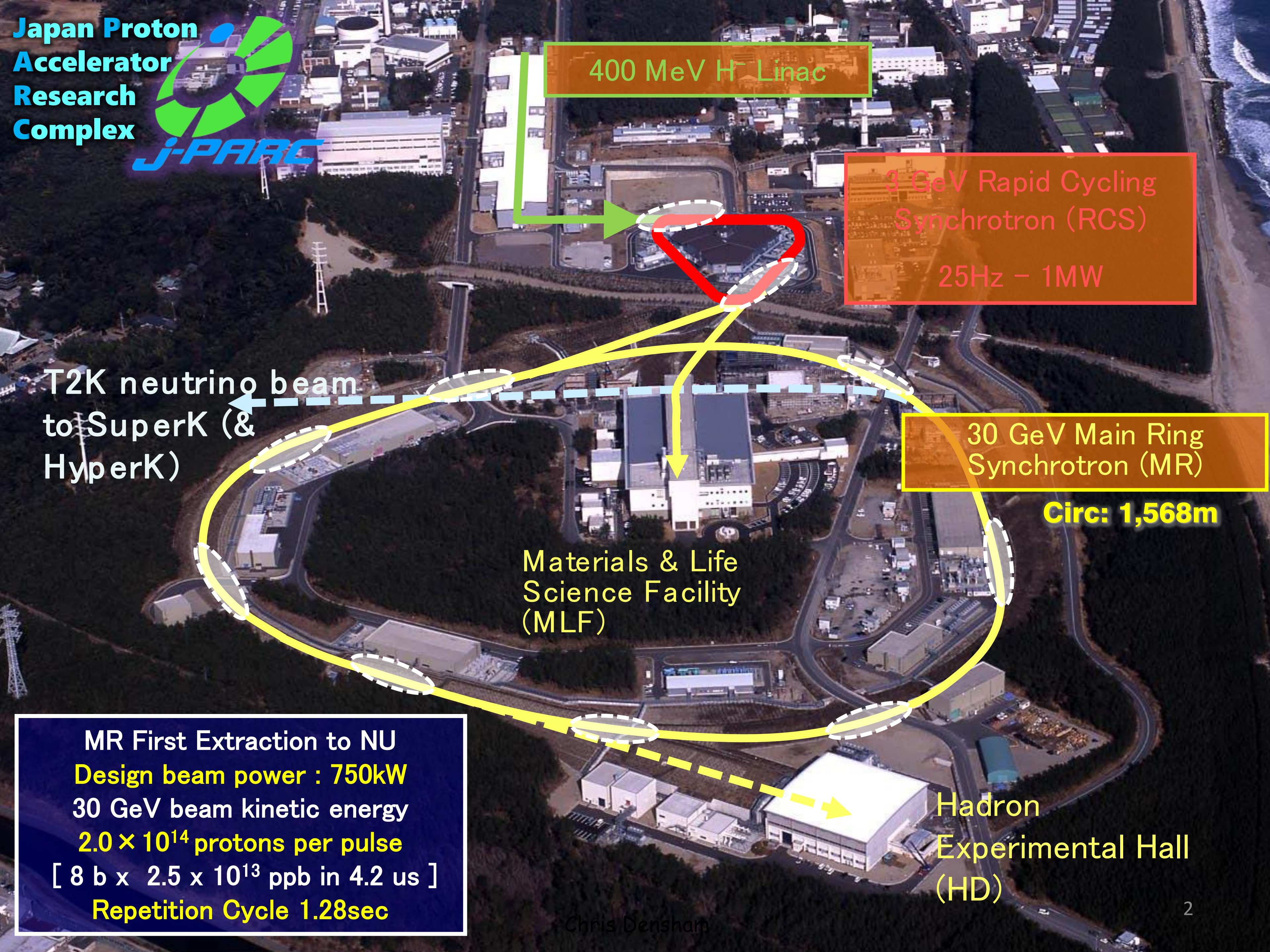
RaDIATE Collaboration
Radiation Damage In Accelerator Target Environments

T2K

Science & Technology Facilities Council
Rutherford Appleton Laboratory

Japan Proton Accelerator Research Complex

J-PARC



MR First Extraction to NU

Design beam power : 750kW

30 GeV beam kinetic energy

2.0×10^{14} protons per pulse

[8 b x 2.5 x 10^{13} ppb in 4.2 us]

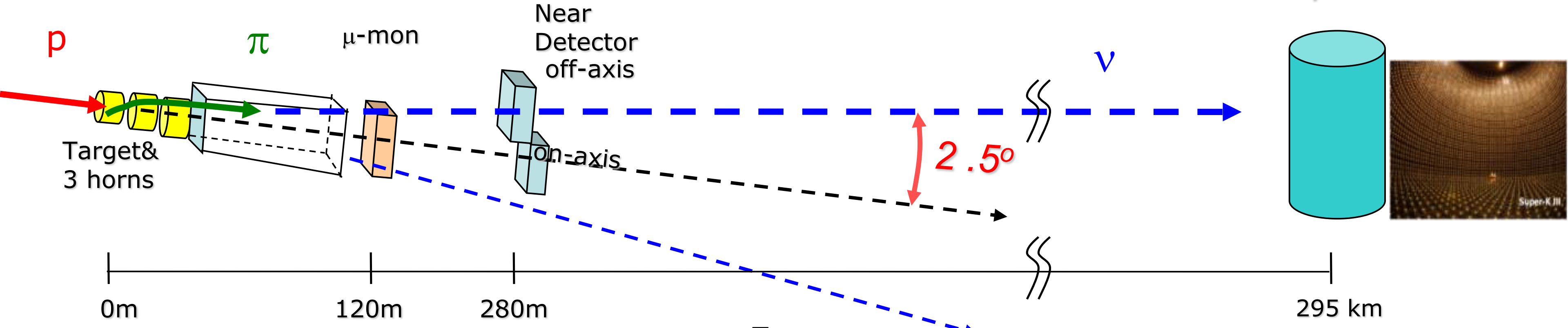
Repetition Cycle 1.28sec

Fermilab Accelerator Complex

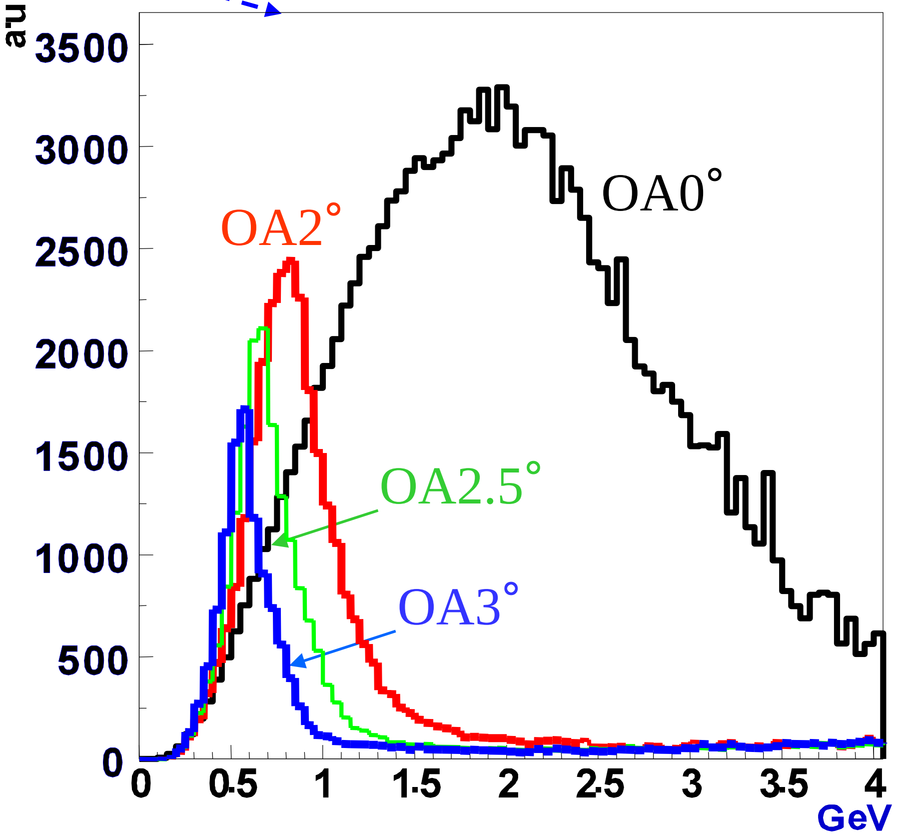
A few comparative parameters

	LBNF/DUNE	**T2K2/HyperK**
Beam energy	120 GeV	30 GeV
Beam cycle	1.2 s	1.16 s
Spill length	10 μs	4.1 μs
Protons/spill	7.5×10^{13}	3.2×10^{14}
Beam rms radius	~2.7 mm	4.2 mm
Maximum beam power to date	0.7 MW (NuMI/NoVA)	0.46 MW (T2K)
Approved upgrade beam power	1.2 MW	1.3 MW

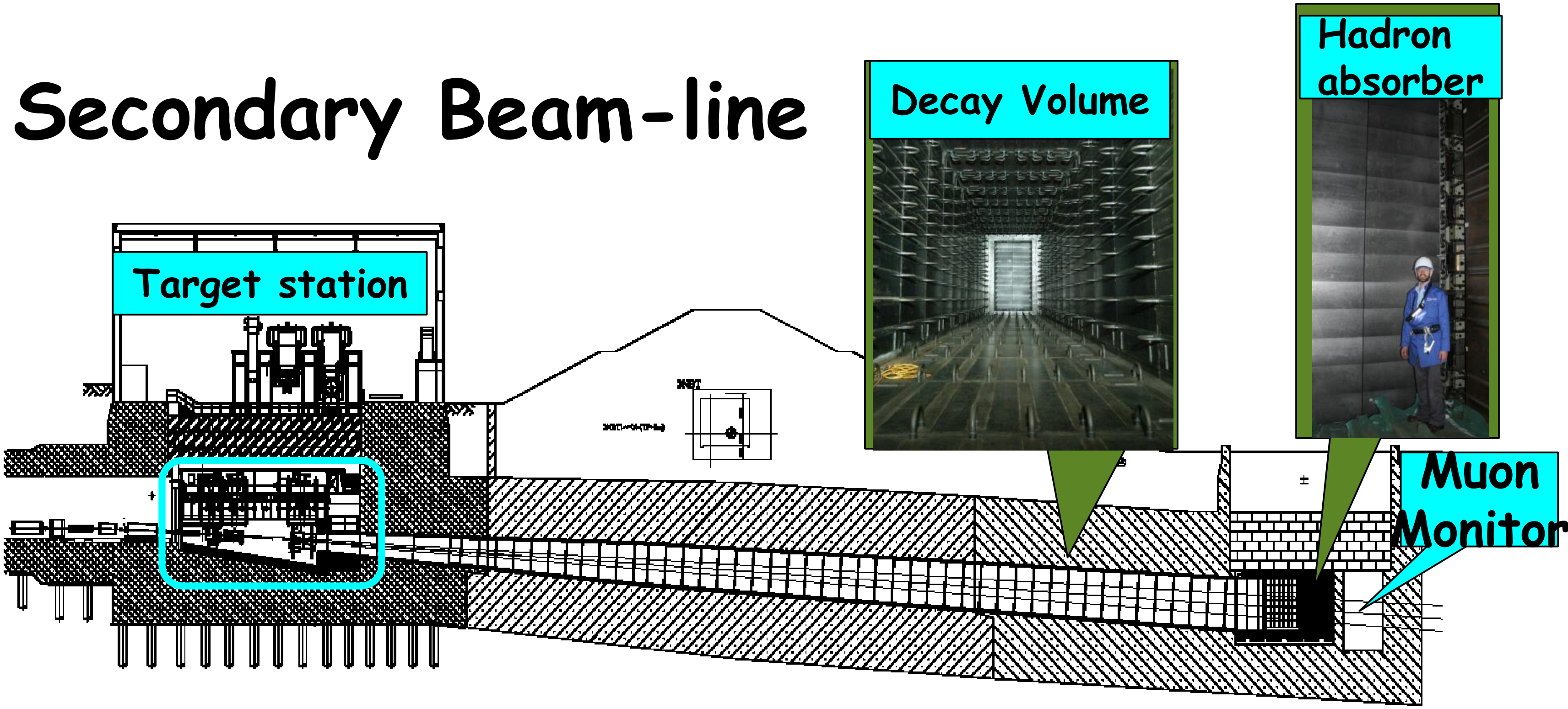
T2K Beam-line



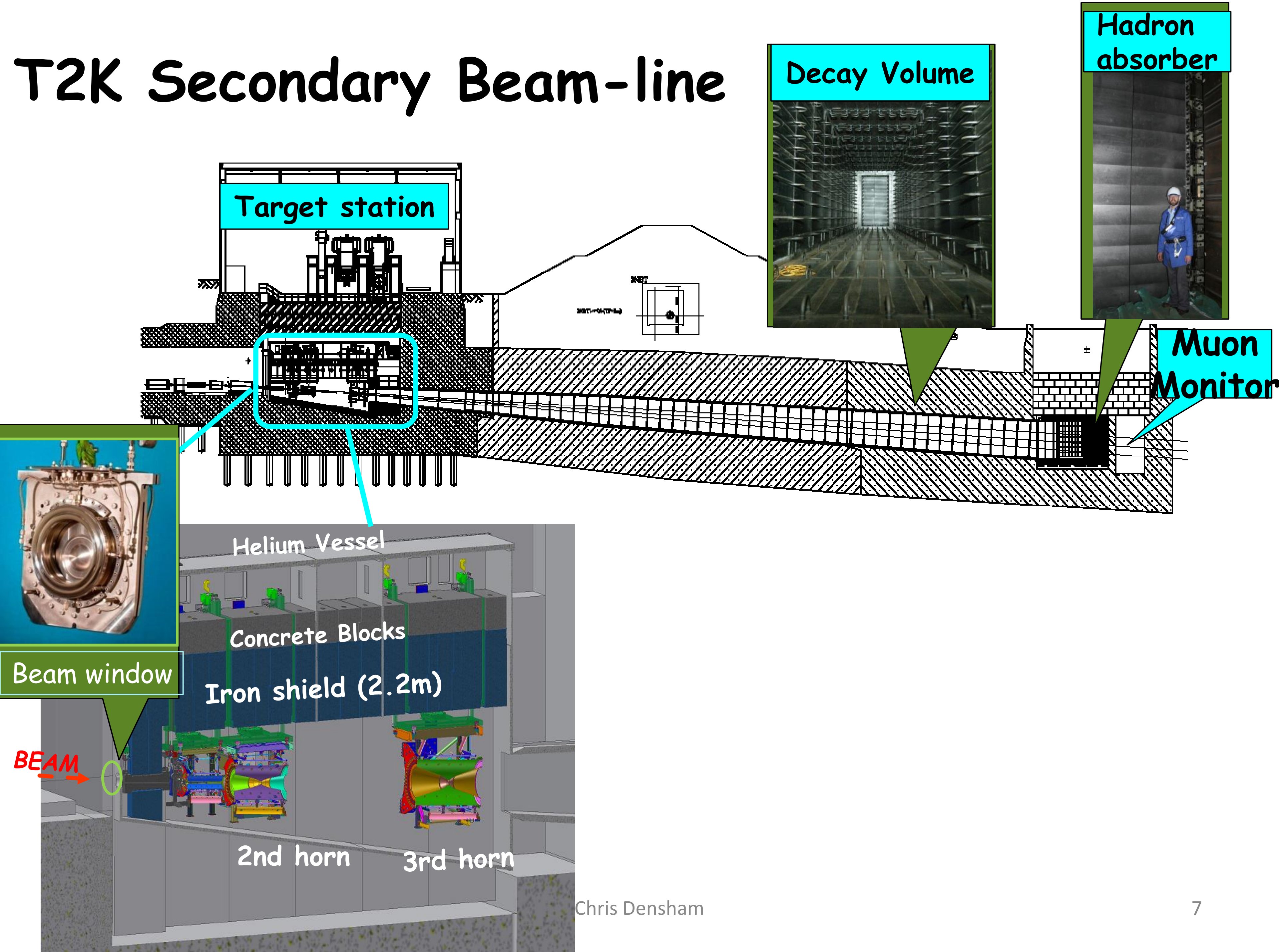
- Off-axis beam generates quasi-monochromatic ν_μ neutrino beam tuned to $\nu_\mu \rightarrow \nu_e$ oscillation maximum
- Also reduces ν_e background
- Anti-neutrinos generated by reversing polarity of horn current



T2K Secondary Beam-line



T2K Secondary Beam-line



Target station

Decay Volume

Hadron absorber

Muon Monitor

Beam window

Helium Vessel

Concrete Blocks

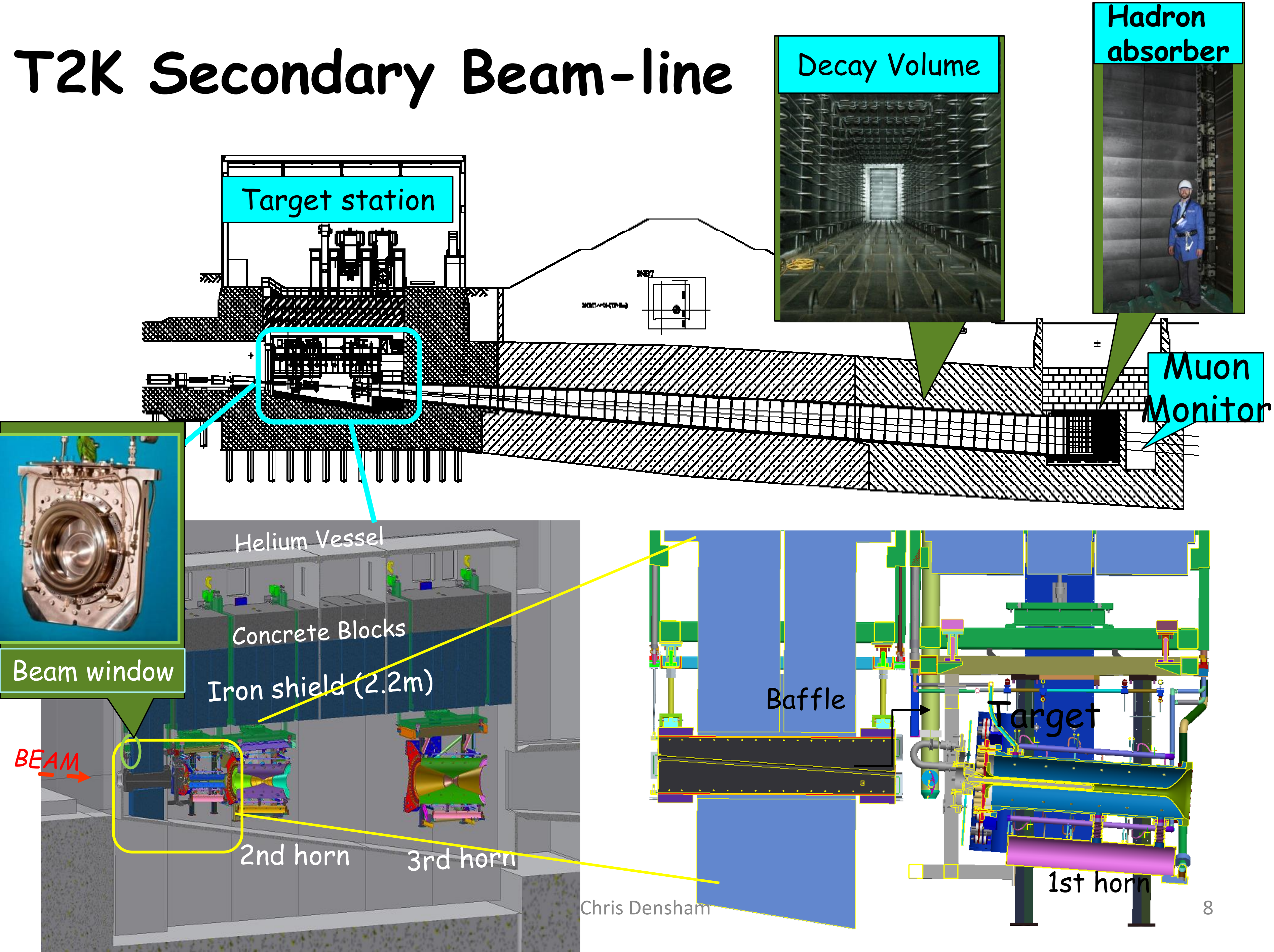
Iron shield (2.2m)

BEAM

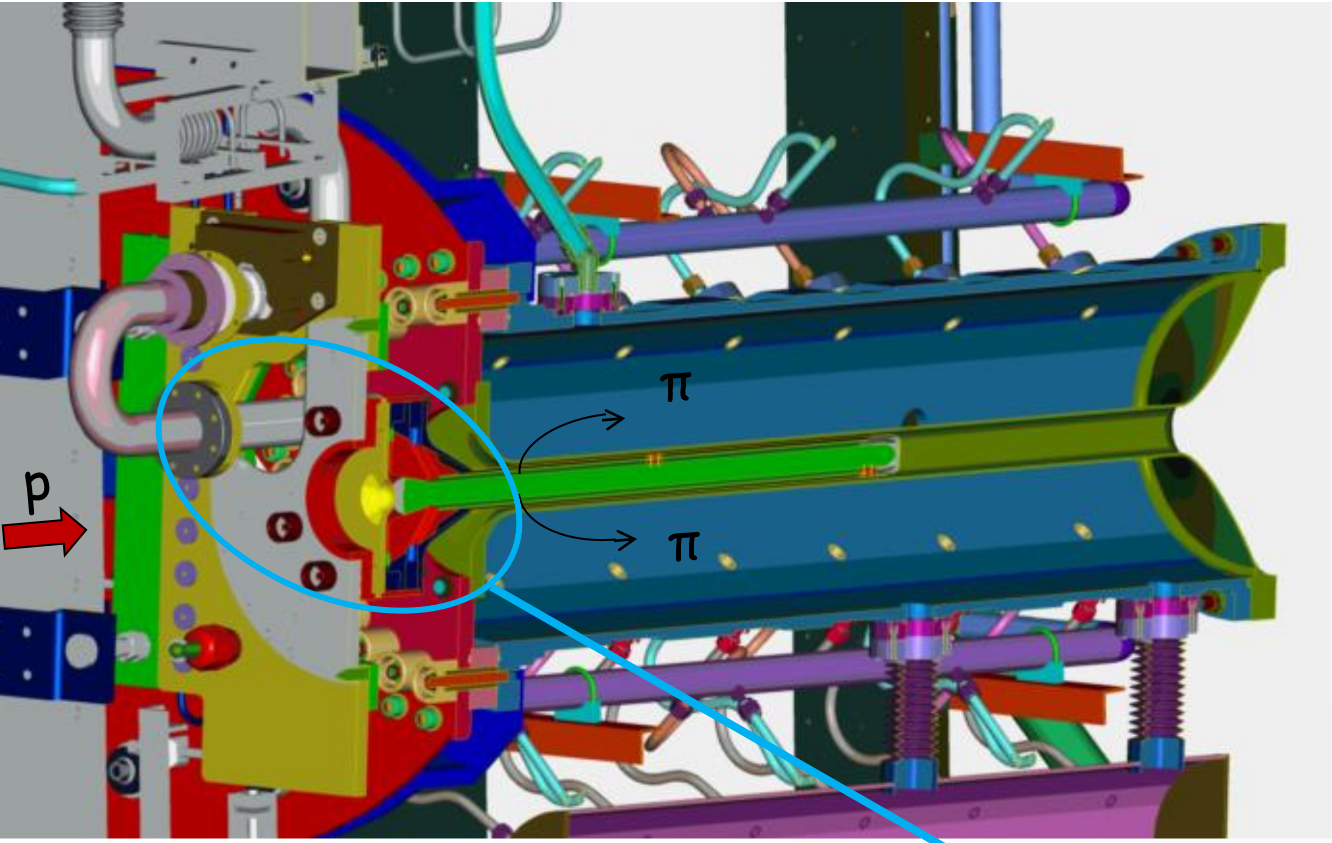
2nd horn

3rd horn

T2K Secondary Beam-line

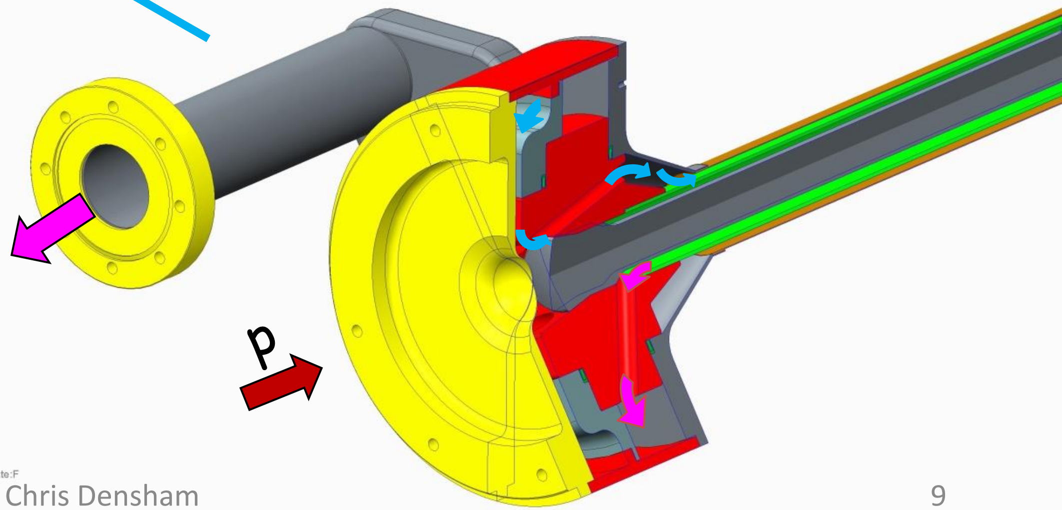


T2K Target & horn

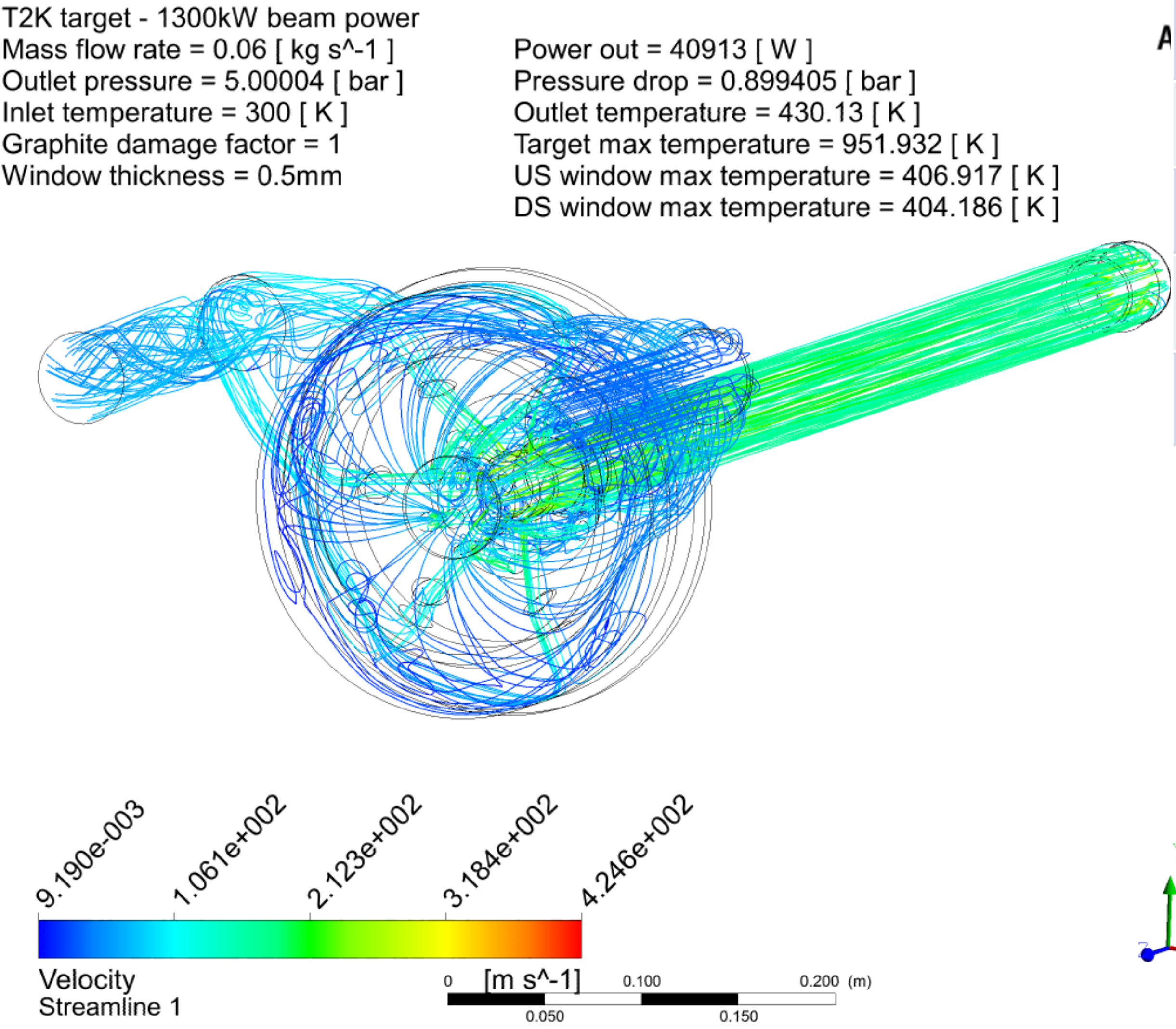


Next target under construction

- Helium cooled graphite rod
- Design beam power: 750 kW
- Beam power so far: 450 kW
- 3% beam power deposited in target as heat
- 1st target & horn replaced after 4 years, 6.5e20 p.o.t.
- 2nd target running with 2e21 p.o.t.



Higher power beam -> higher pressure helium



T2K target - 1300kW beam power
Mass flow rate = 0.06 [kg s^-1]
Outlet pressure = 5.00004 [bar]
Inlet temperature = 300 [K]
Graphite damage factor = 1
Window thickness = 0.5mm

Power out = 40913 [W]
Pressure drop = 0.899405 [bar]
Outlet temperature = 430.13 [K]
Target max temperature = 951.932 [K]
US window max temperature = 406.917 [K]
DS window max temperature = 404.186 [K]

	0.75 MW	**1.3 MW**
Heat load	23.5 kW	40.9 kW
Helium pressure	1.6 bar	5 bar
Helium mass flow	32 g/s	60 g/s
Pressure drop	0.83 bar	0.9 bar
Max velocity	400 m/s	425 m/s

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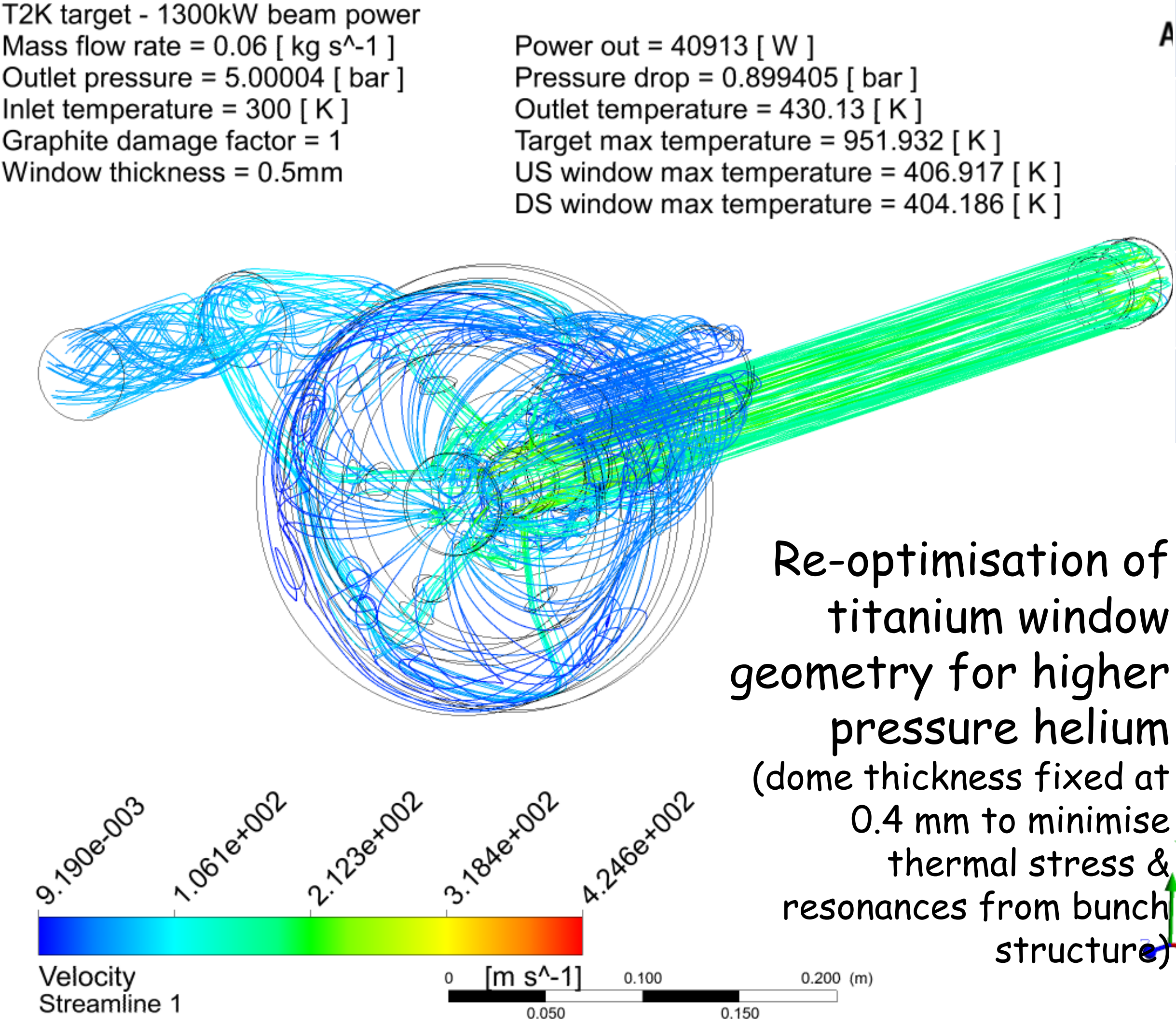

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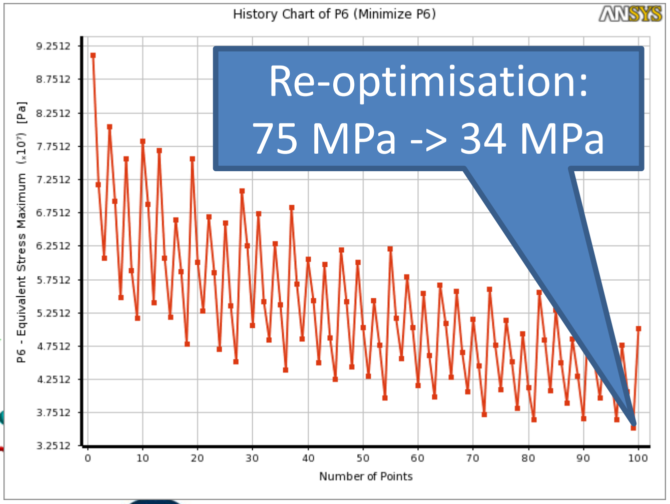
Re-optimisation of titanium window geometry for higher pressure helium

(dome thickness fixed at 0.4 mm to minimise thermal stress & resonances from bunch structure)

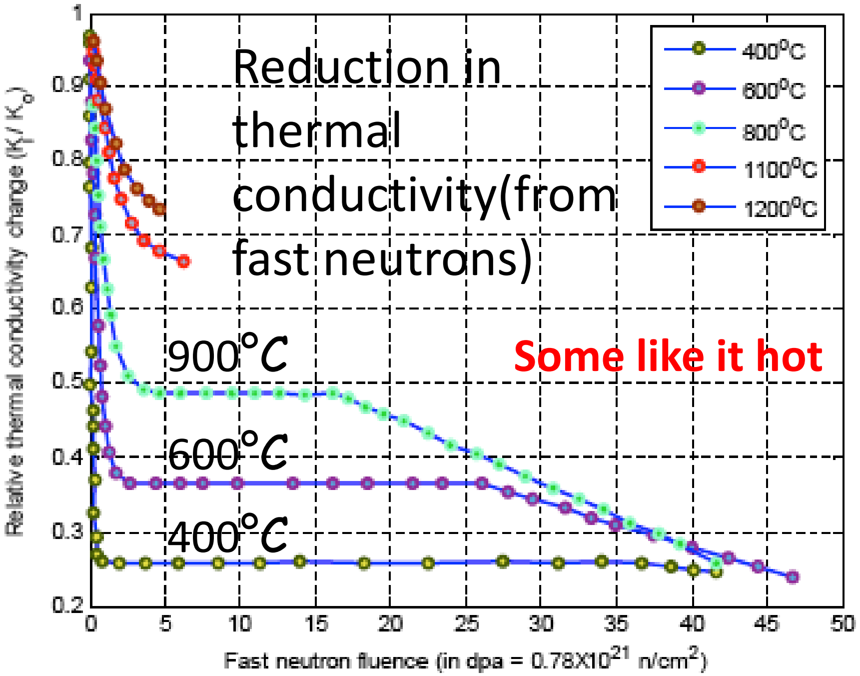


Re-optimisation:
75 MPa -> 34 MPa

Thermal analysis for 1.3 MW operation

	0.75 MW	1.3 MW
Helium pressure	1.6 bar	5 bar
Upstream window temp	105 °C	157 °C
Downstream window temp	120°C	130°C
Max graphite temp. (for 1/4 conductivity)	736°C	900°C

Some iterating still to do



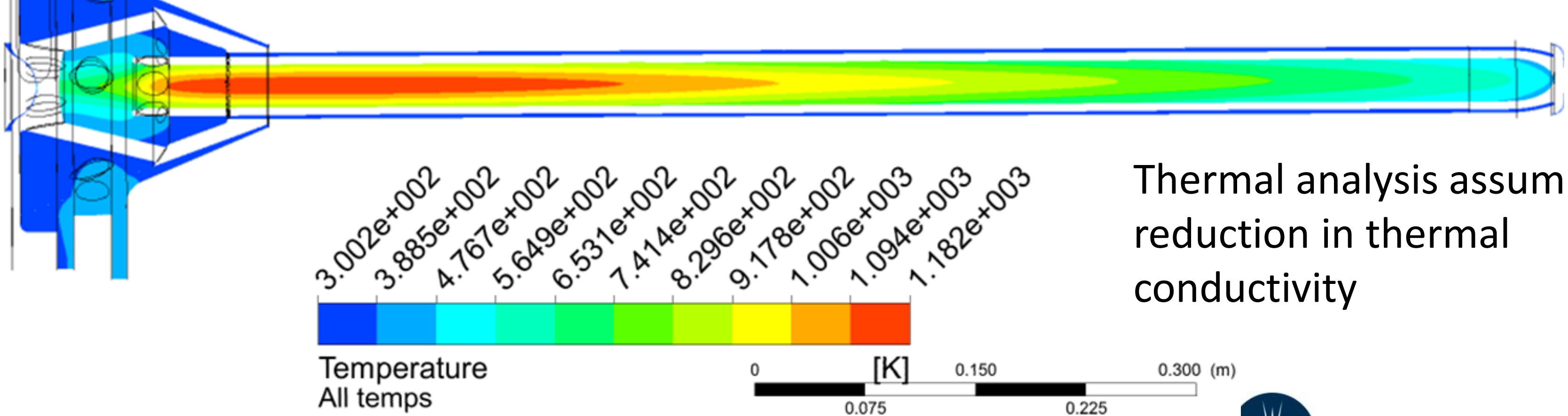
Reduction in thermal conductivity(from fast neutrons)

900°C

600°C

400°C

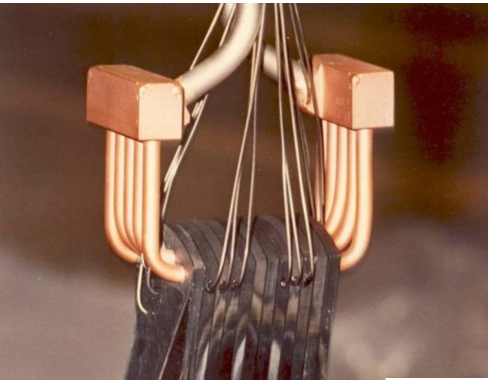
Some like it hot



Thermal analysis assuming x4 reduction in thermal conductivity

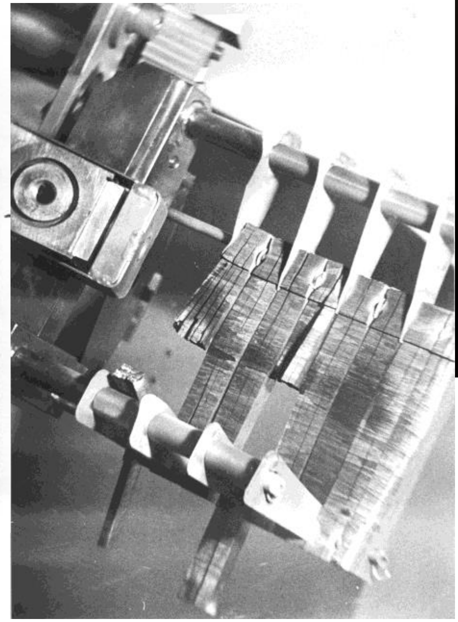
The ultimate destiny for all graphite targets?

(T2K: c.2 x 10^{21} p/cm^2 so far)



LAMPF fluence 10^22 p/cm2

PSI: fluence 10^22 p/cm2



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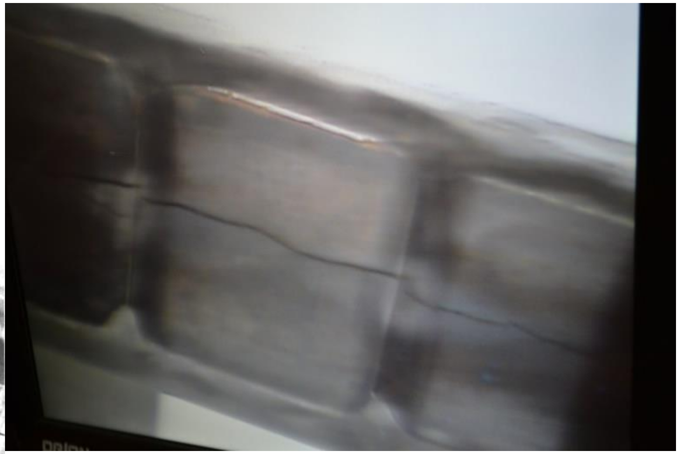
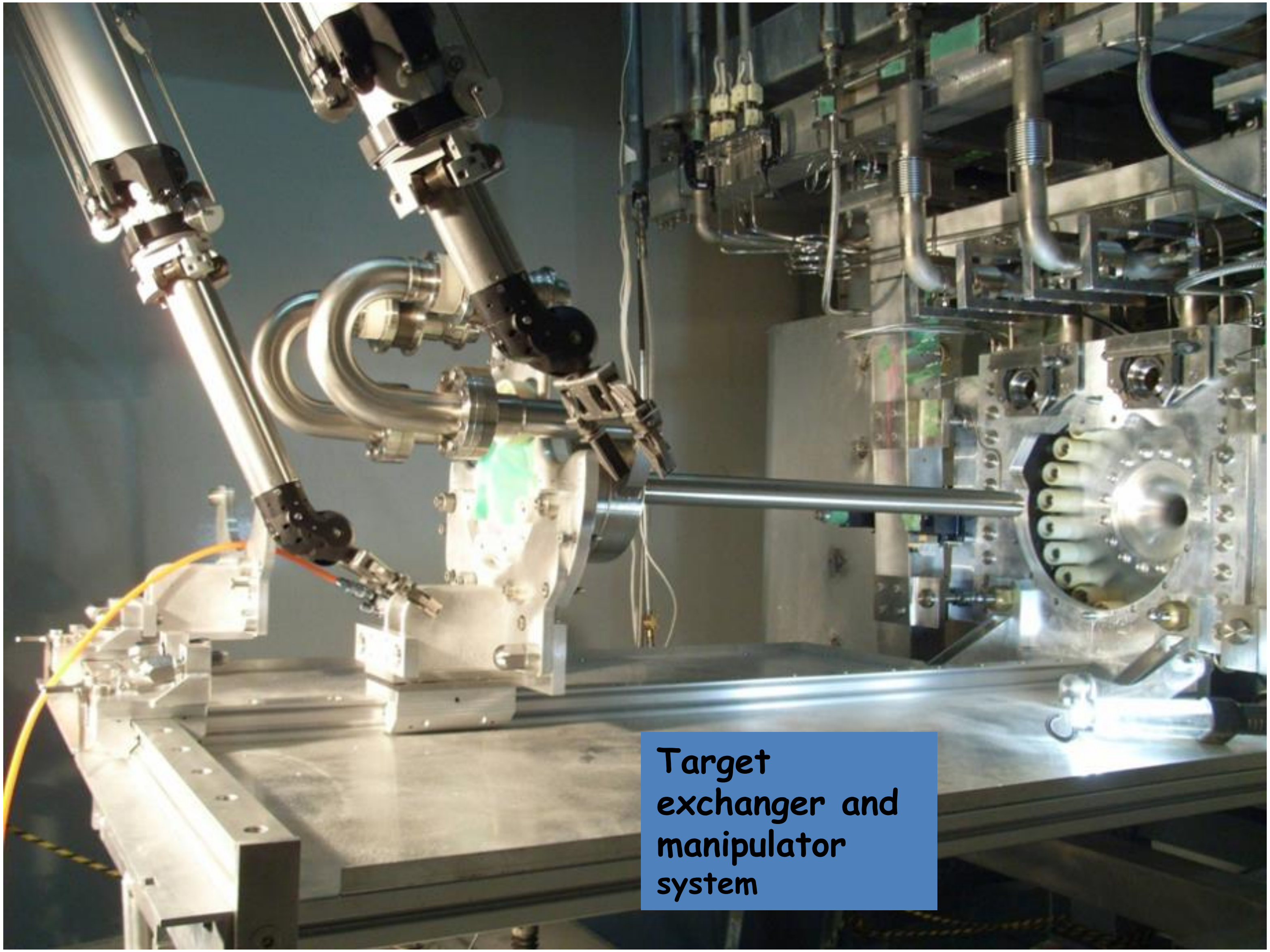
NuMI target



Remote Target Exchange System



Target exchanger and manipulator system

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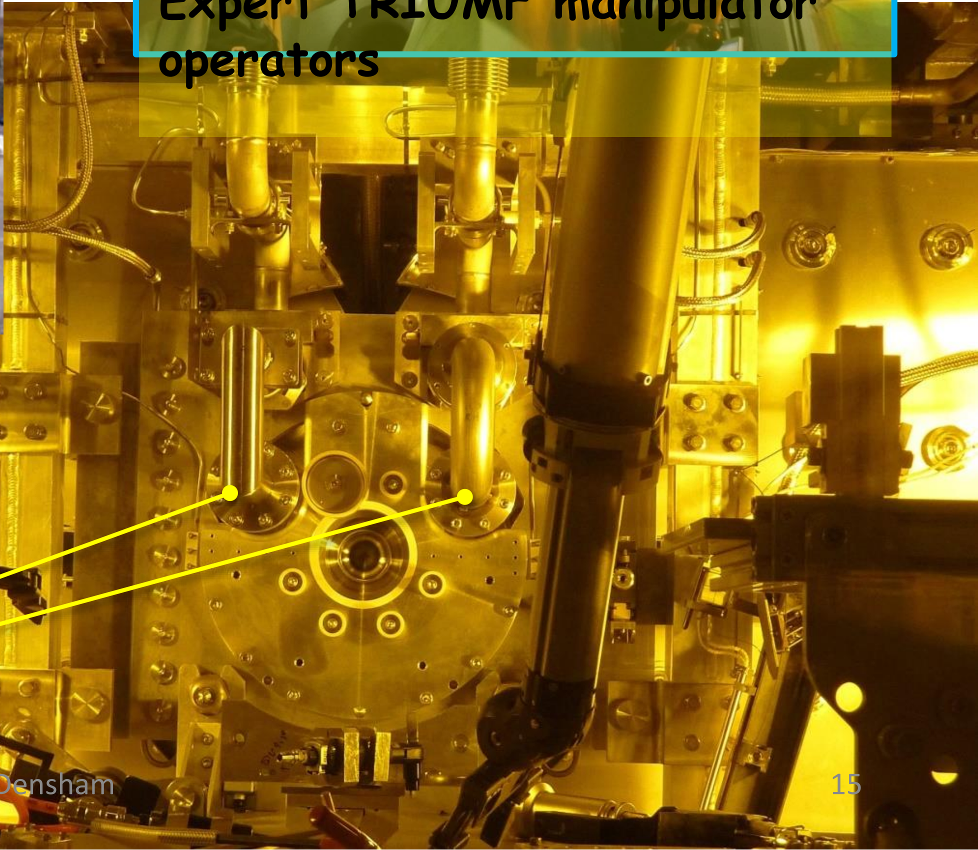
Science & Technology Facilities Council
Rutherford Appleton Laboratory

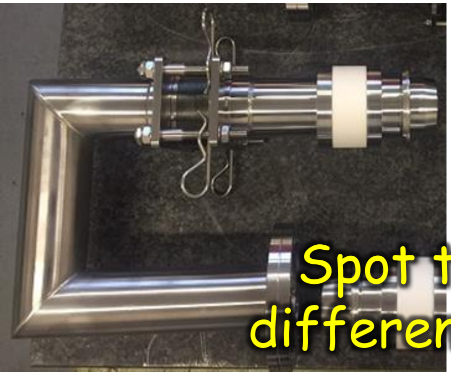
Helium pipe replacement

2015年12月17日

Rehearsal using 3D printed pipe and modified target exchanger

Expert TRIUMF manipulator operators

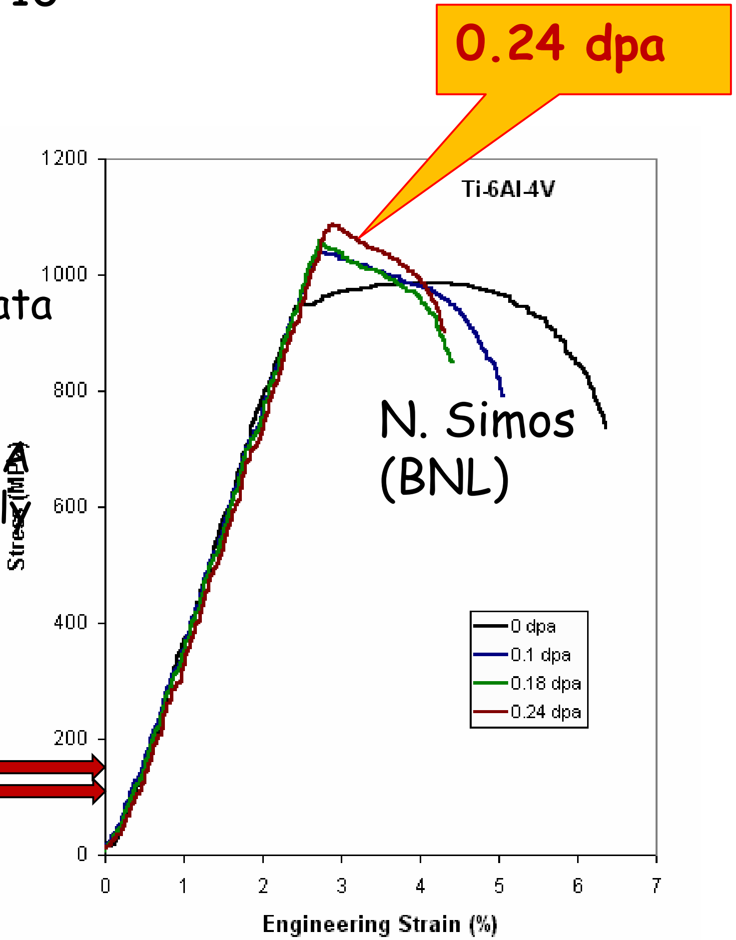




Vacuum-to-air beam window (Ti6Al4V)

First window run for 10 years
22.4x10^{20} protons
→ ~2 DPA (MARS)

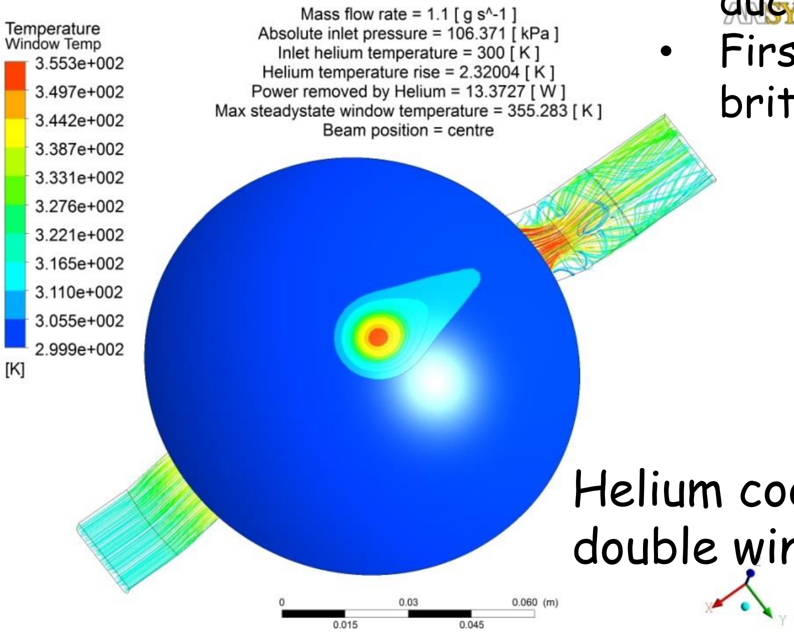
- Only have tensile data for up to 0.24 DPA
- Significant loss of ductility at 0.24 DPA
- First window entirely brittle?



N. Simos (BNL)

1.3 MW, 0.5 mm

0.75 MW, 0.3 mm



Mass flow rate = 1.1 [g s^-1]
Absolute inlet pressure = 106.371 [kPa]
Inlet helium temperature = 300 [K]
Helium temperature rise = 2.32004 [K]
Power removed by Helium = 13.3727 [W]
Max steadystate window temperature = 355.283 [K]
Beam position = centre

Helium cooling between double window skins

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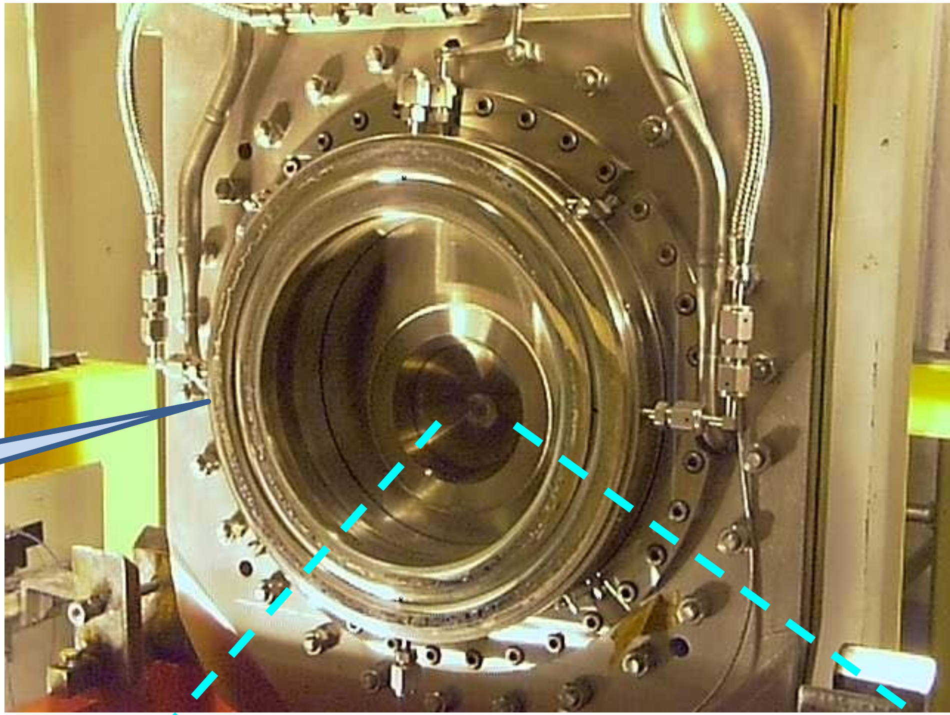
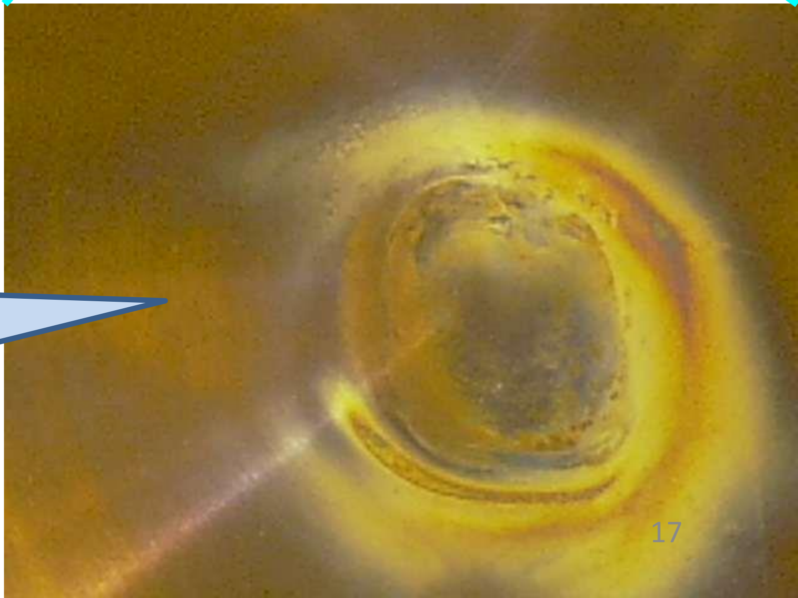
Beam window replacement 22 Aug 2017

- Want to avoid failure of window during operation
- -> Decided to replace with spare during 2017 scheduled shutdown



- Inflatable pillow vacuum seal appears deformed after removal
- Not possible to reuse the old beam window.



- Centre of beam window appears to be damaged / discoloured
- Need to conduct Post-Irradiation Examination -> talking to materials scientists

Plate vs bar for next beam window?

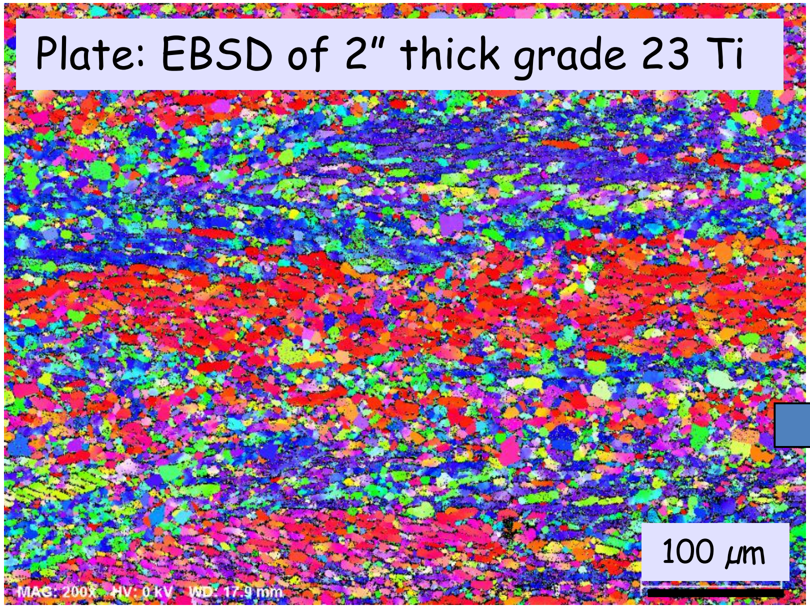
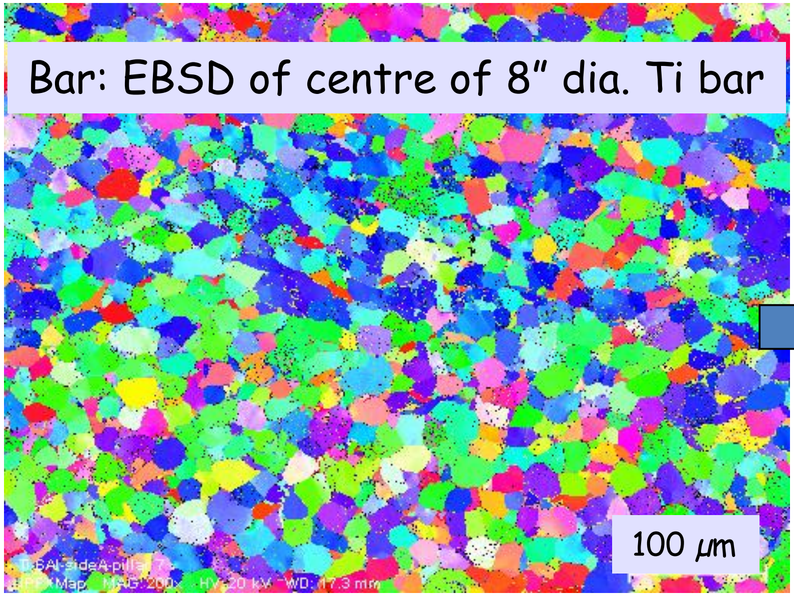


Plate: EBSD of 2" thick grade 23 Ti


Bar: EBSD of centre of 8" dia. Ti bar

Could plate material (with finer grain structure at surface) be better than bar (with larger grain size at centre)?

Plate:

- Large macrozones = regions with similar crystal orientations inherited from large prior beta grains.
- Could impact badly on fatigue properties.

- Bar: macrozones not evident
- Current window (from bar) has performed well so far
- Will continue with bar material
- -> Could low density of grain boundaries provide fewer sinks for radiation damage?

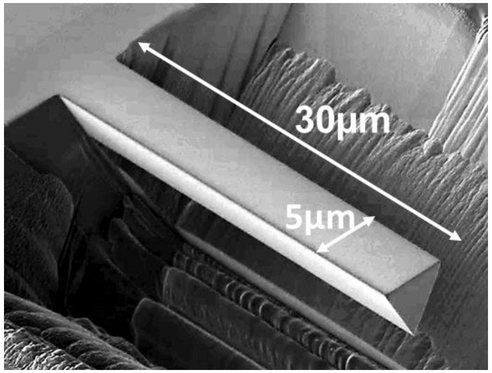
Small-scale Ultrasonic Fatigue Testing

High power 20 kHz
ultrasonic resonant
VHCF tests

- Prototype system at Oxford
- Being reproduced in activated materials at laboratory at Culham, UK (Materials Research Facility)

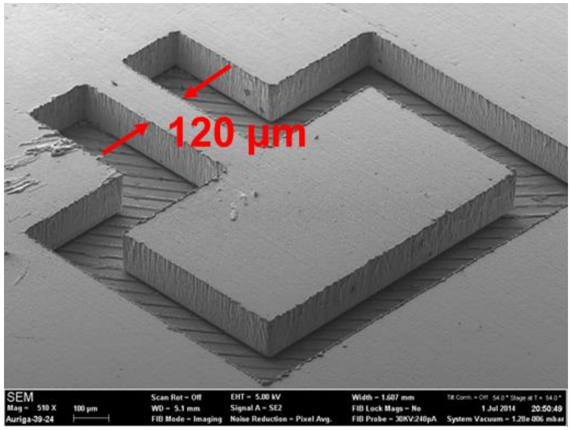
+

micro-cantilever



or

meso-cantilever



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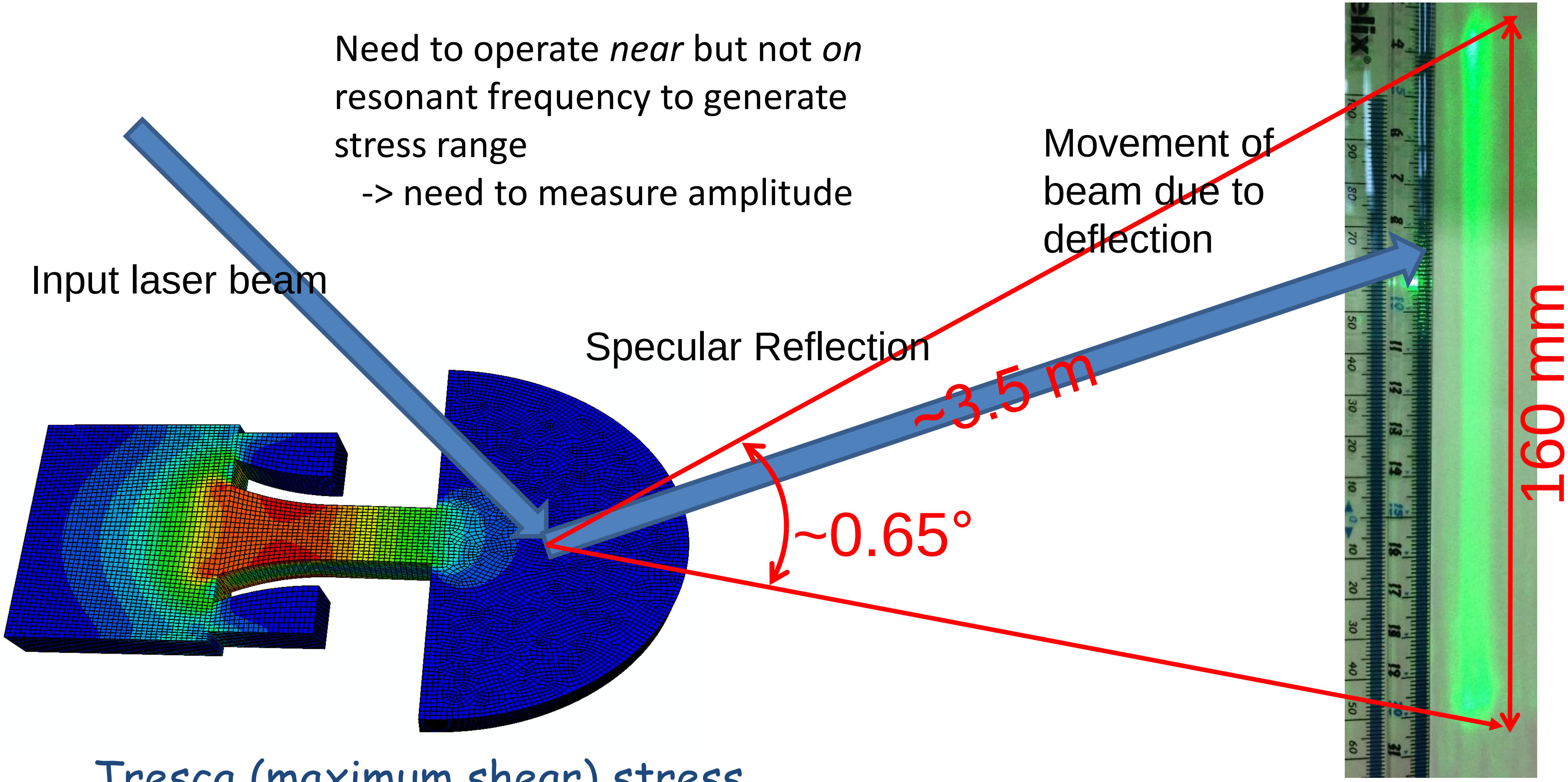
Fatigue testing?

- Can test many small samples of highly active foil material
- Lots of cycles in short time
- State-of-the-art

Measurement of deflection during resonant vibration of sample

Need to operate *near* but not *on* resonant frequency to generate stress range
-> need to measure amplitude



Input laser beam

Specular Reflection

Movement of beam due to deflection

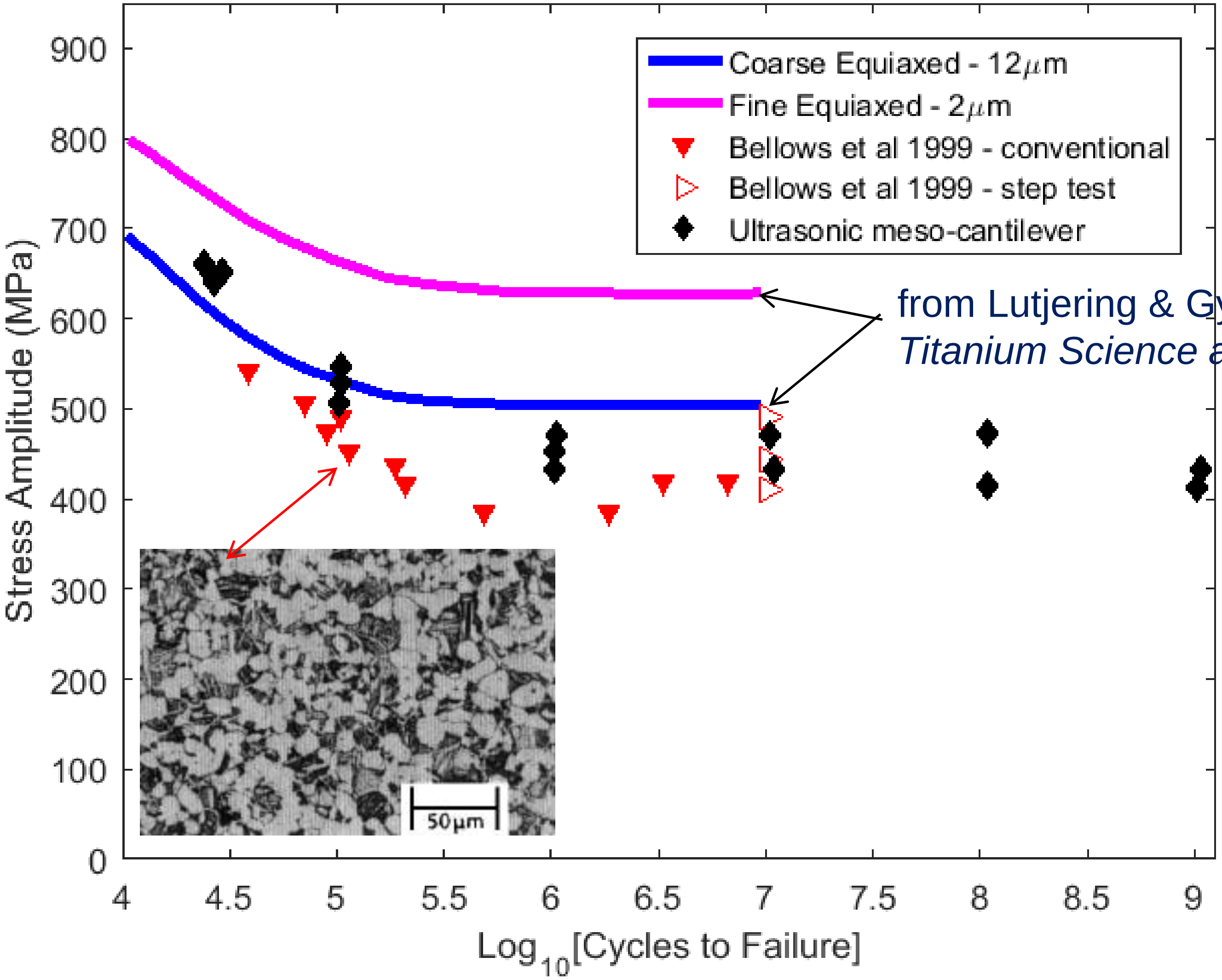
~3.5 m

~0.65°

160 mm

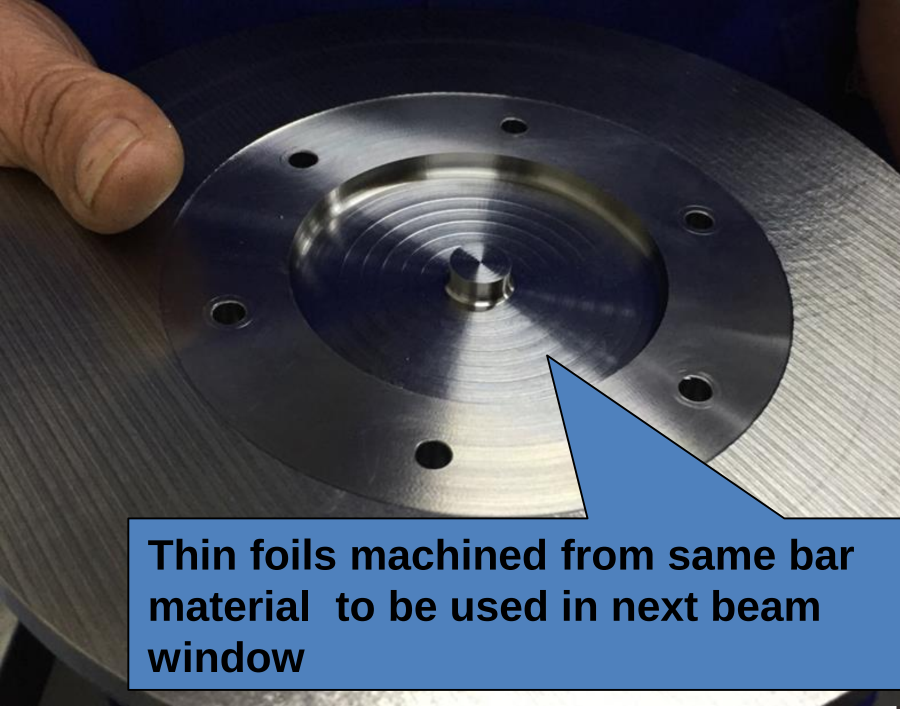
Tresca (maximum shear) stress

Ti-6Al-4V Fatigue Life Data

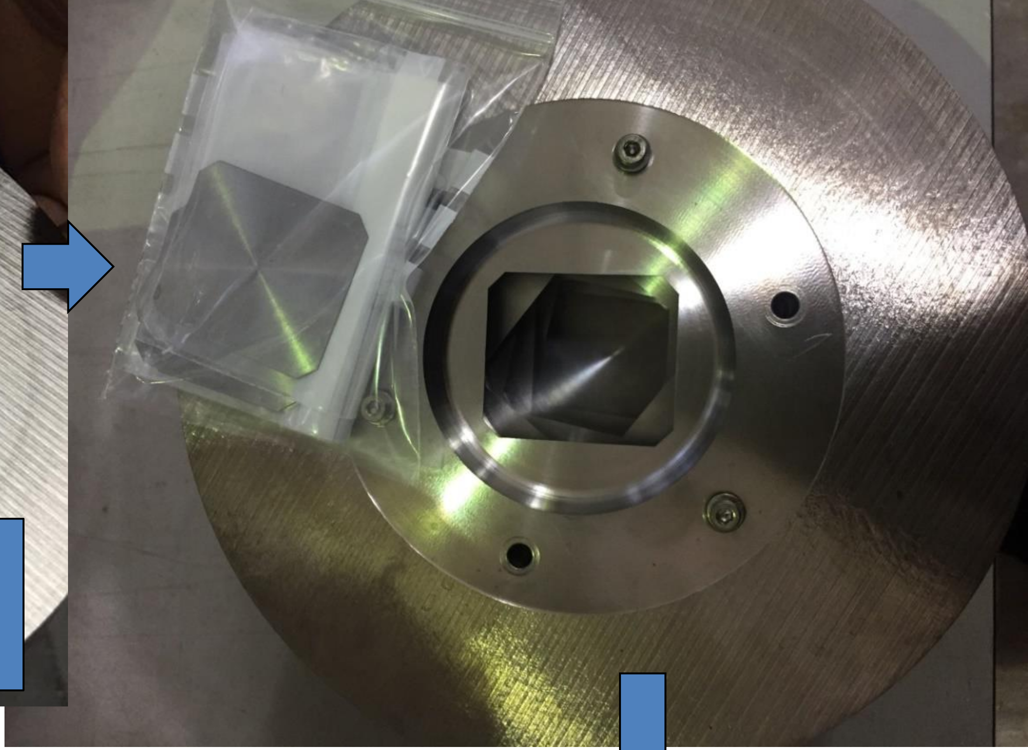


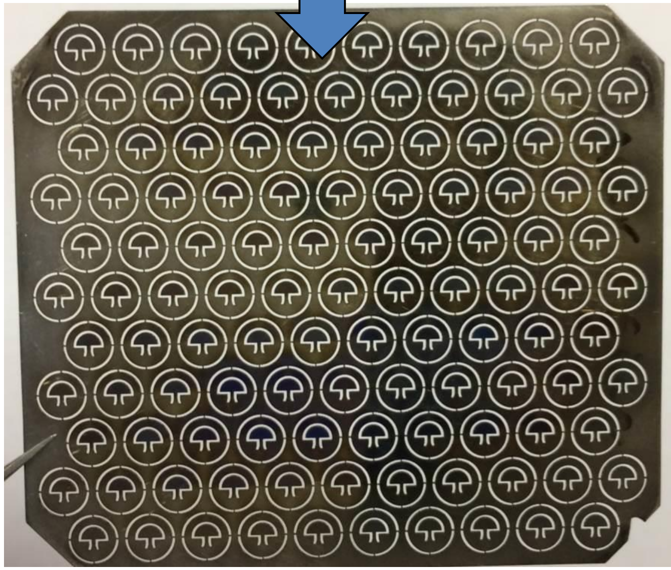
from Lutjering & Gysler
Titanium Science and Technology

Chris Densham



Thin foils machined from same bar material to be used in next beam window



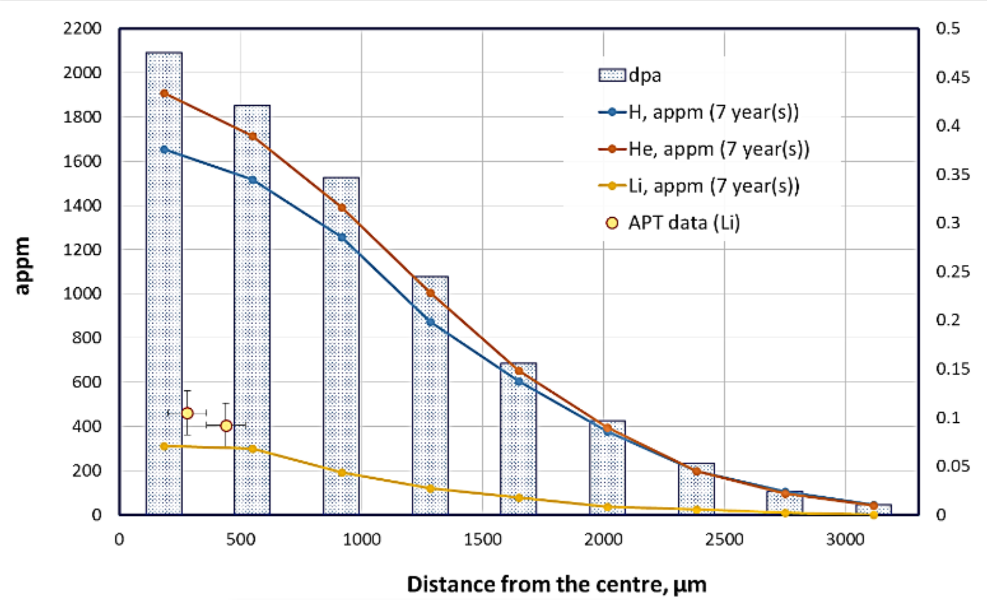


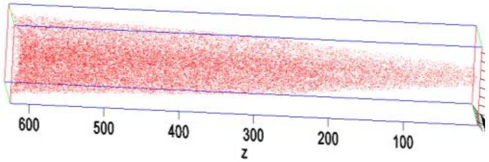
- 2 x sample foils machined from same 8″ Ti-6Al-4V bar being used for next T2K window domes
- Samples polished to 0.25 mm and laser cut using very fine scanning laser
- 3 weeks irradiation in 2017 at BNL/BLIP at c.180 MeV, 0.3 DPA
- 2nd irradiation run at BLIP imminent

Examination of irradiated Beryllium beam window indicates fracture toughness changes under irradiation

NuMI Be window examined at Oxford

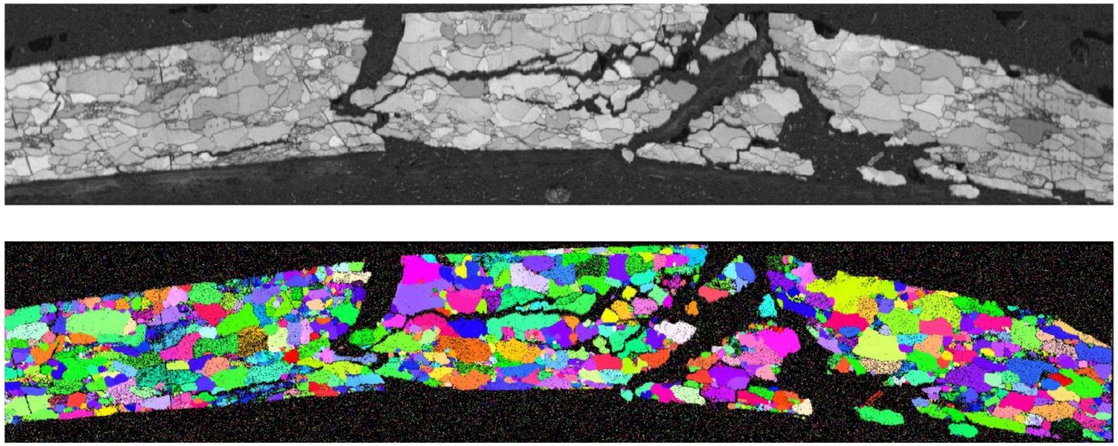
- Be window to 1.57E21 POT analyzed
- Advanced microscopy techniques
- Li matches predictions and remains homogeneously distributed at ~50 °C
- Crack morphology changes at higher doses (transgranular to grain boundary fracture)
- **Grains strengthened or GBs weakened?**

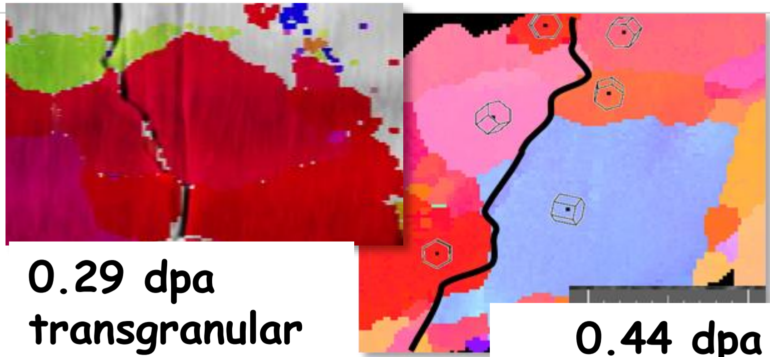




Li transmutant

Material fracture due to punch removal process



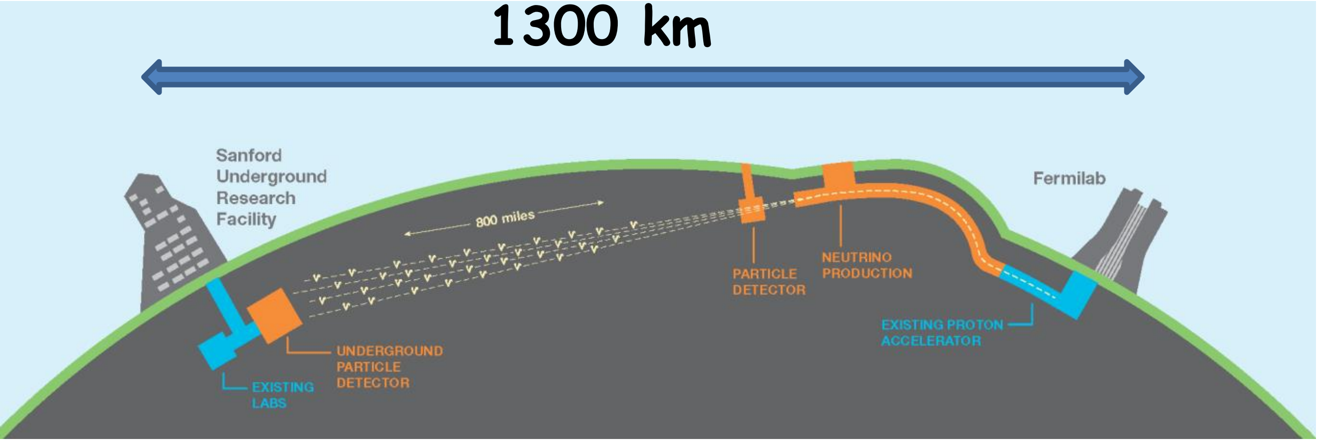


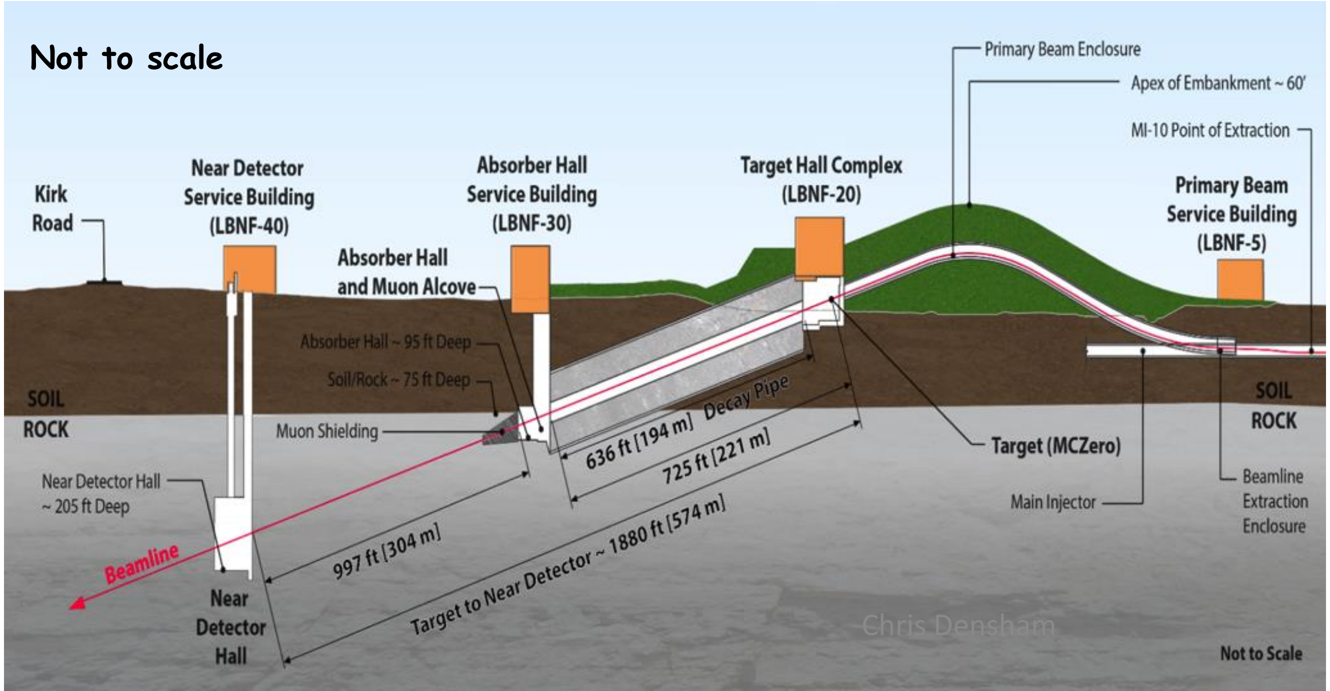
0.29 dpa transgranular fracture

0.44 dpa GB fracture

V. Kuksenko, Oxford University

The LBNF Beamline

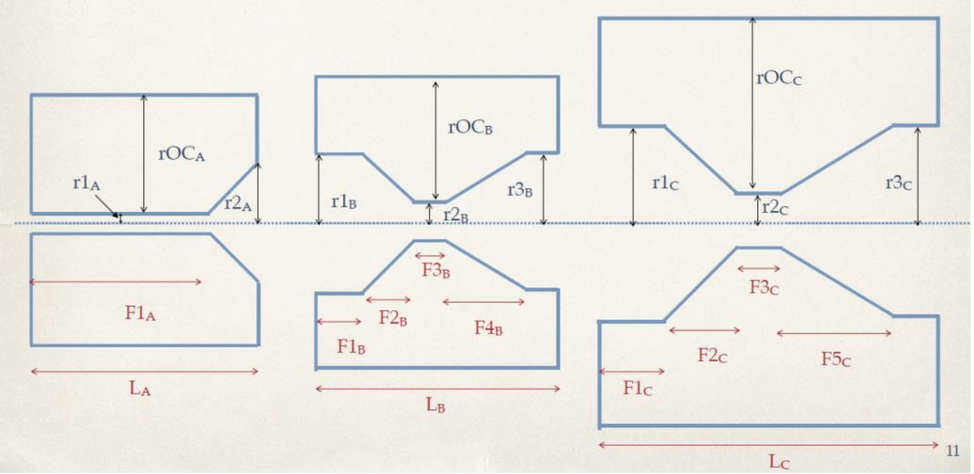




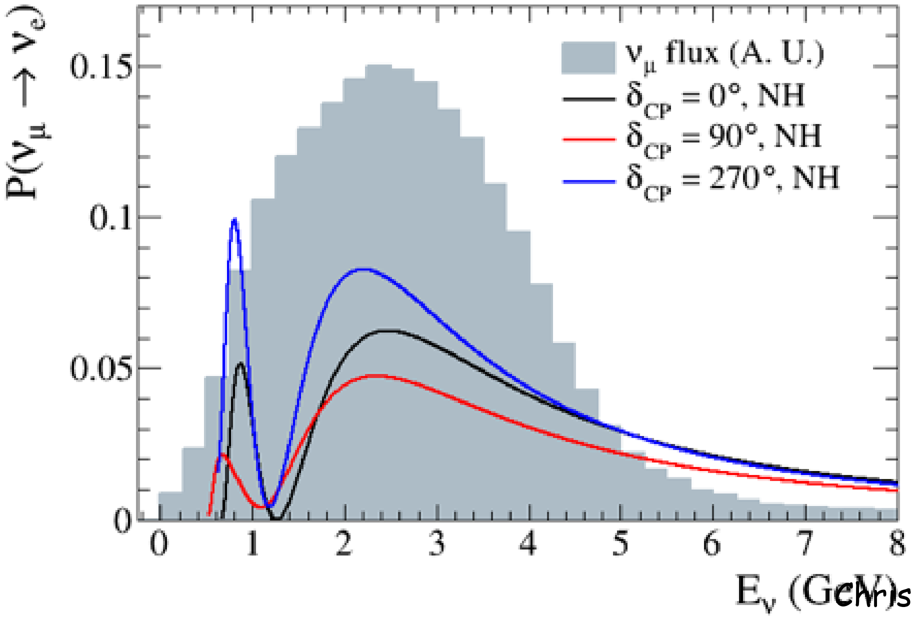
- On-axis, wide-band beam (wide range of neutrino energies ~ few GeV)
- Initial beam power 1.2 MW (PIPII)
- Upgradeable to 2.4 MW (PIPIII)

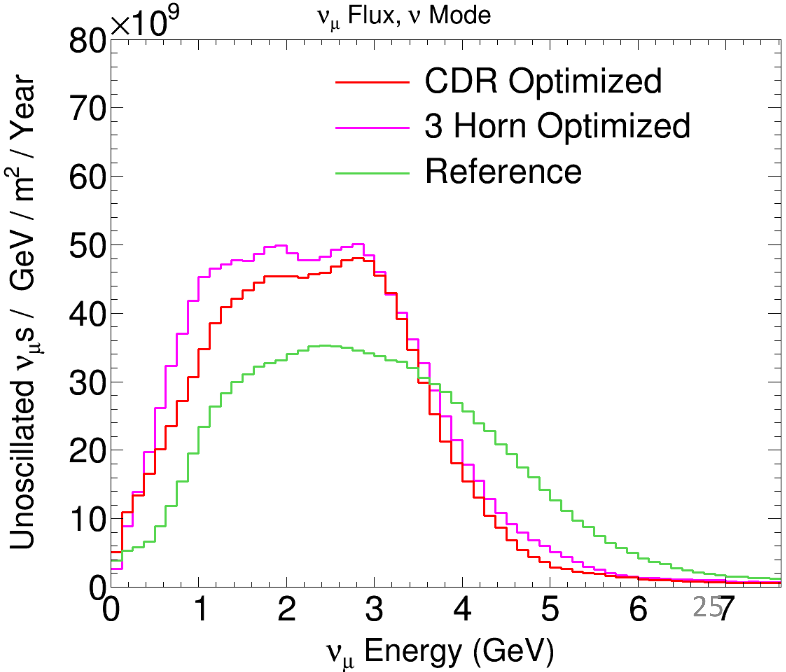
Beam size at target tunable between 1.0-4.0 mm sigma

Optimisation of LBNF/DUNE target & horn
(L. Fields)

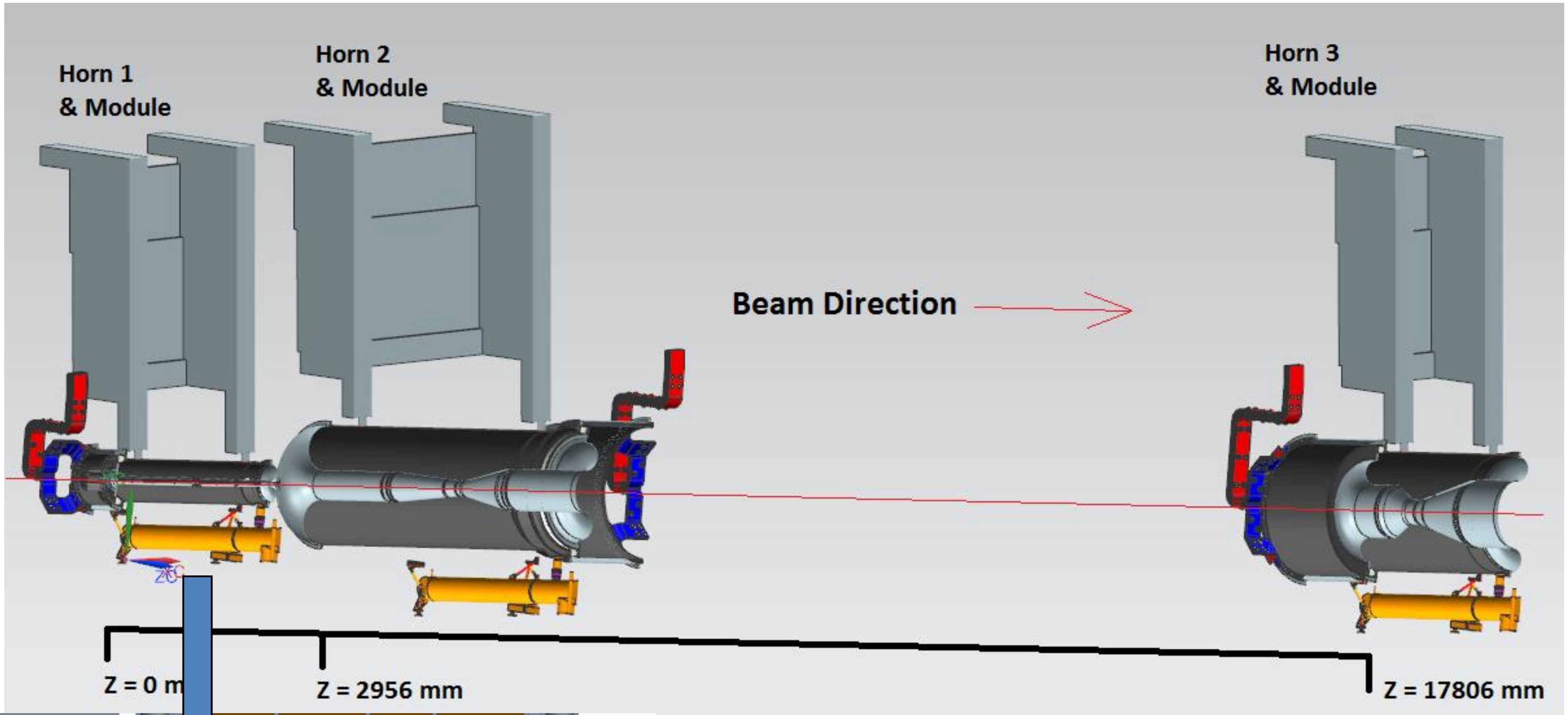


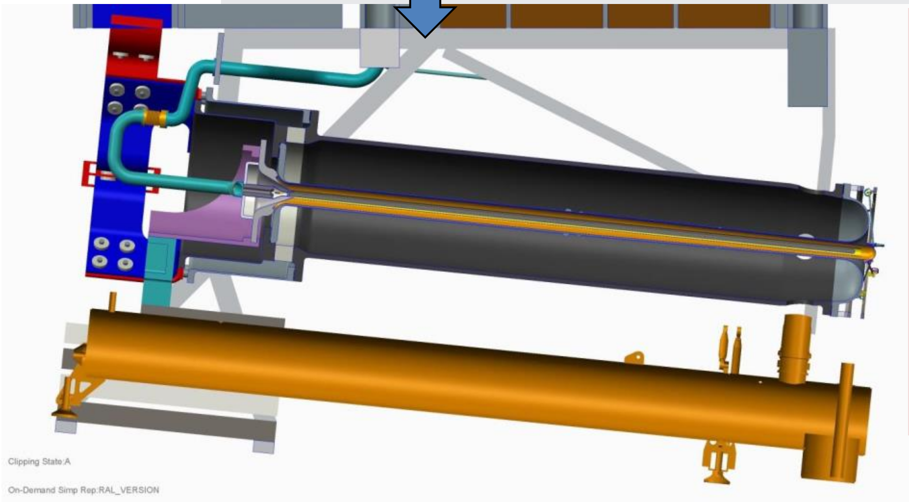
- Wide-band neutrino beam
- Genetic algorithm used to optimise horn & target (inspired by LBNO design study at CERN)





Target & horns optimized by genetic algorithm



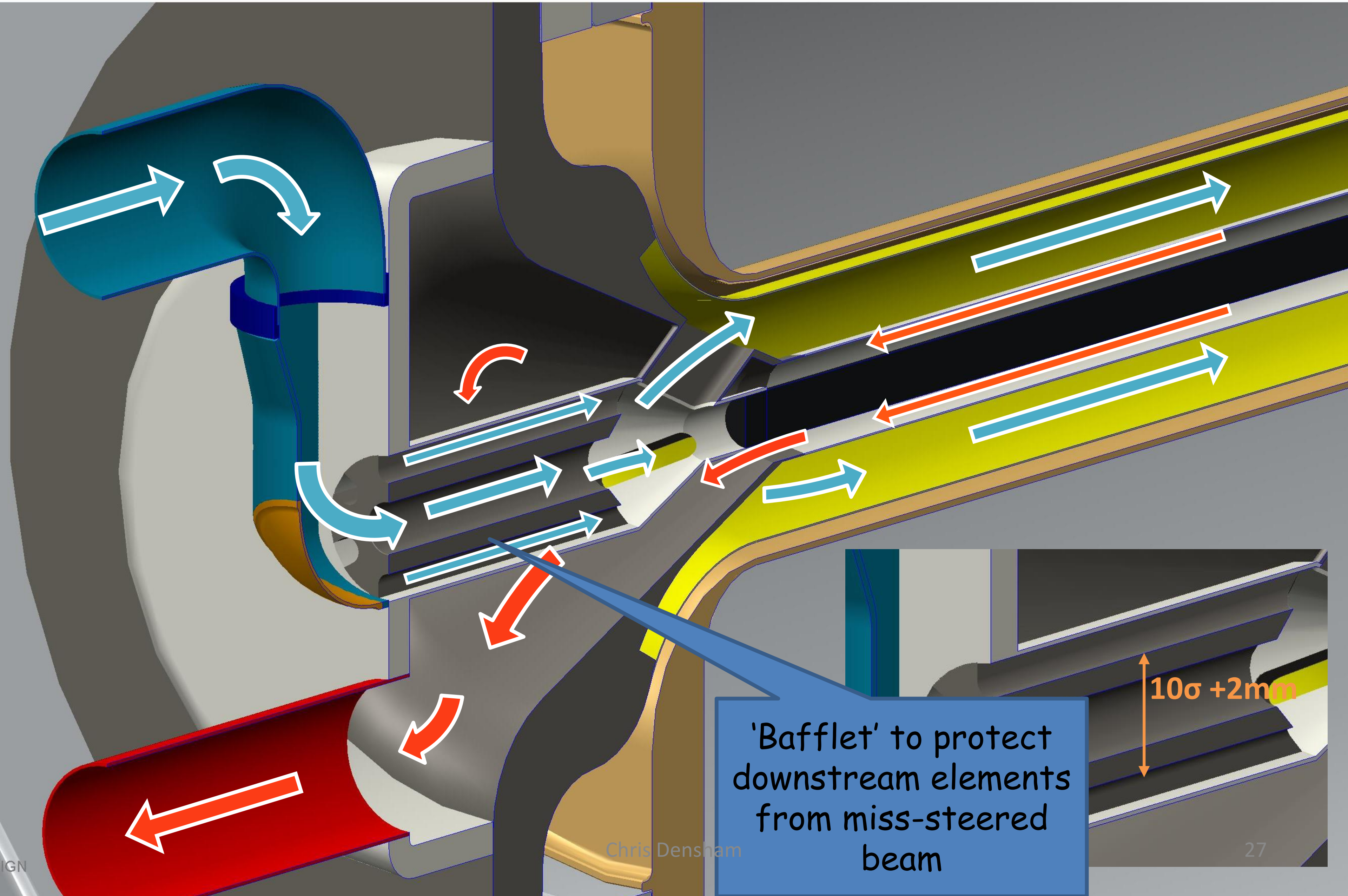


- 3 horn system (like T2K)
- New target plan:
- Change from water (like NuMI) to helium cooled graphite (like T2K)

- Long ($4\lambda_{int}$ 2 m): higher yield
- fewer on-axis wrong-sign pions
- but needs downstream support

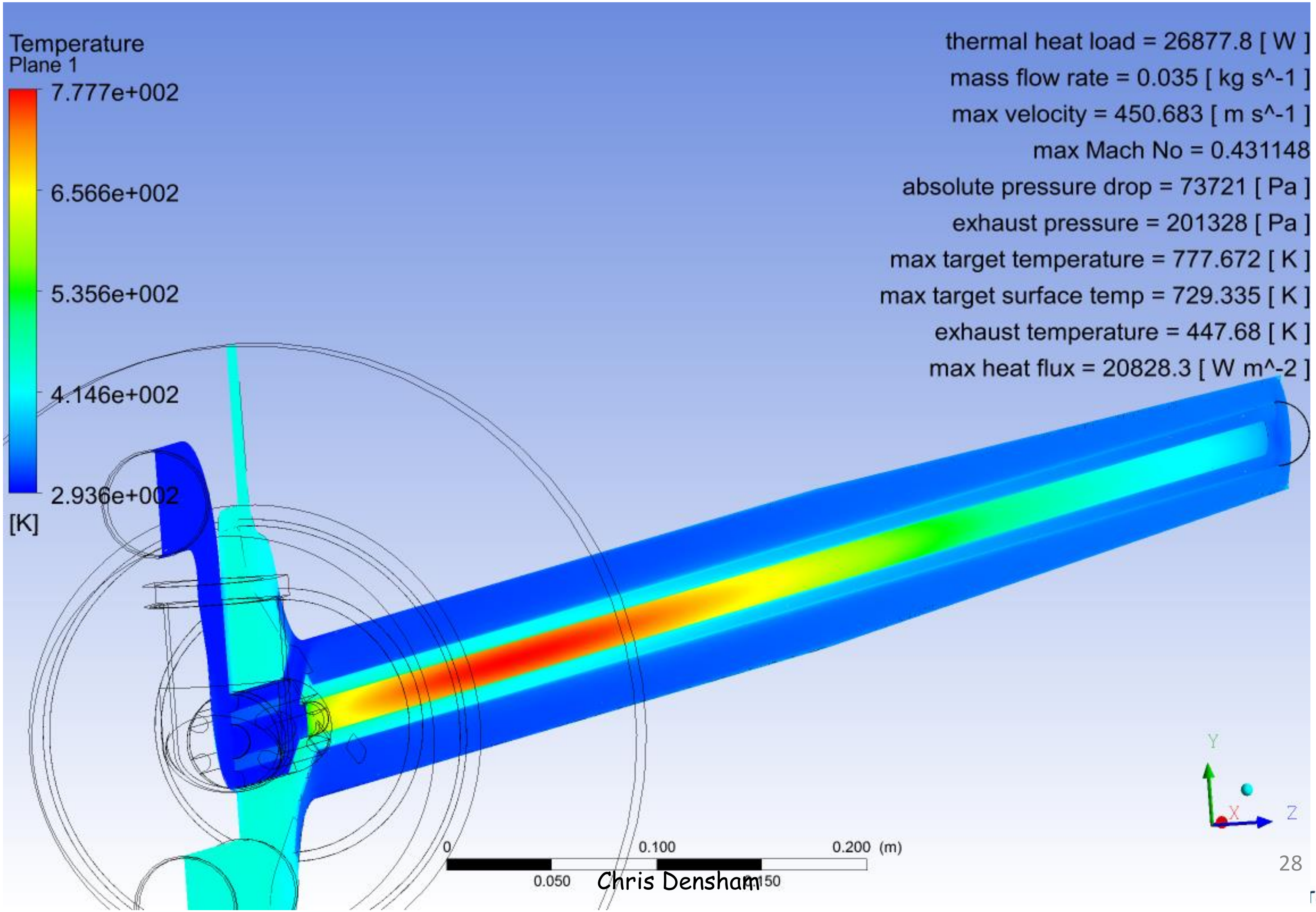
Densham

Optimised helium cooled target proposal



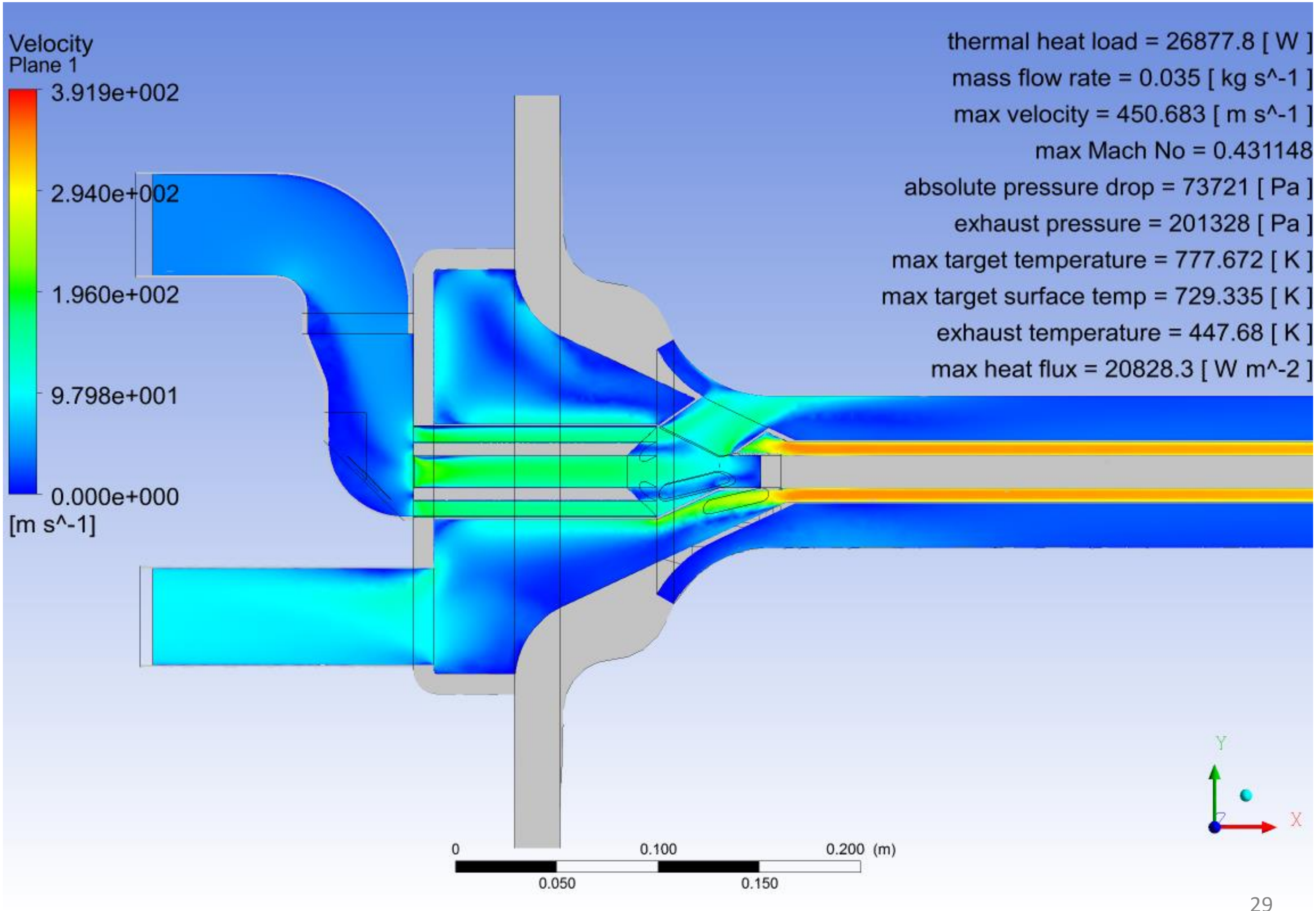
'Bafflet' to protect downstream elements from miss-steered beam

Temperatures at 1.2MW steady state simulation



thermal heat load = 26877.8 [W]
mass flow rate = 0.035 [kg s^-1]
max velocity = 450.683 [m s^-1]
max Mach No = 0.431148
absolute pressure drop = 73721 [Pa]
exhaust pressure = 201328 [Pa]
max target temperature = 777.672 [K]
max target surface temp = 729.335 [K]
exhaust temperature = 447.68 [K]
max heat flux = 20828.3 [W m^-2]

Helium Velocity at 1.2MW steady state simulation



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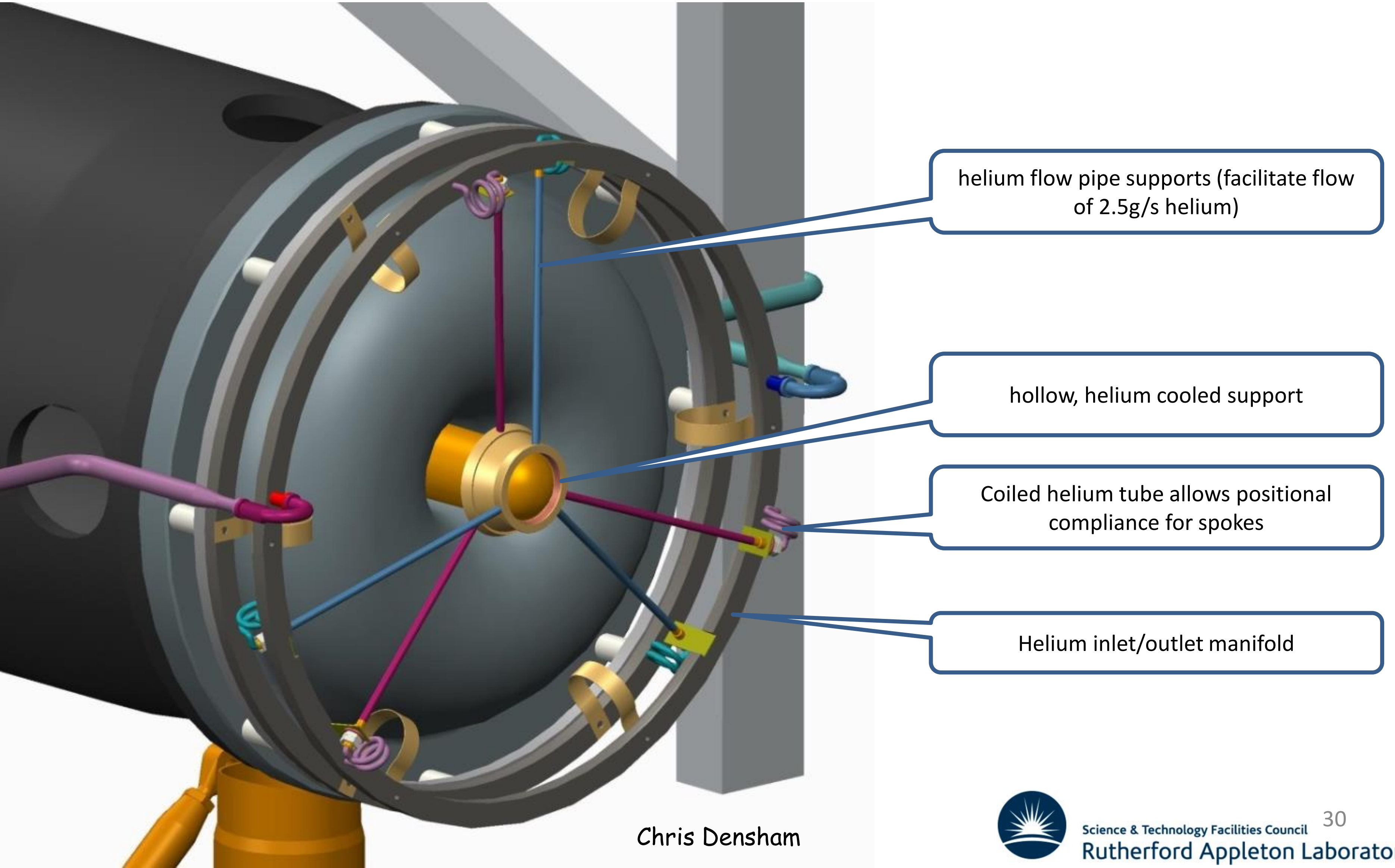
2 m long target: needs actively cooled downstream support



helium flow pipe supports (facilitate flow of 2.5g/s helium)

hollow, helium cooled support

Coiled helium tube allows positional compliance for spokes

Helium inlet/outlet manifold

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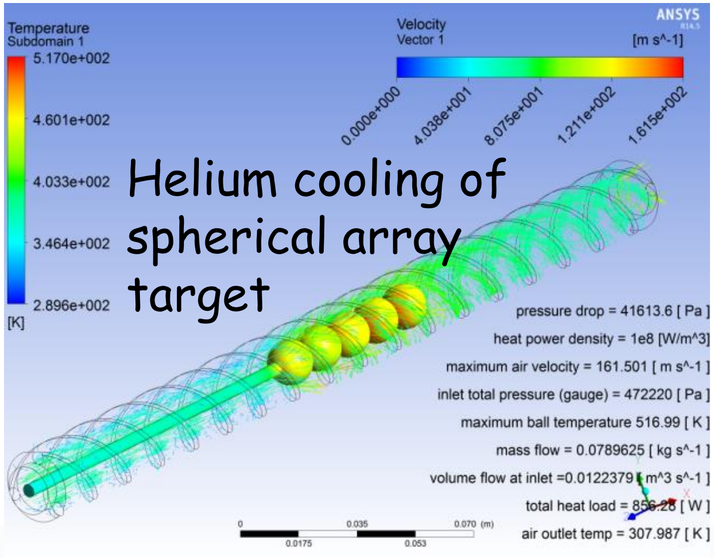
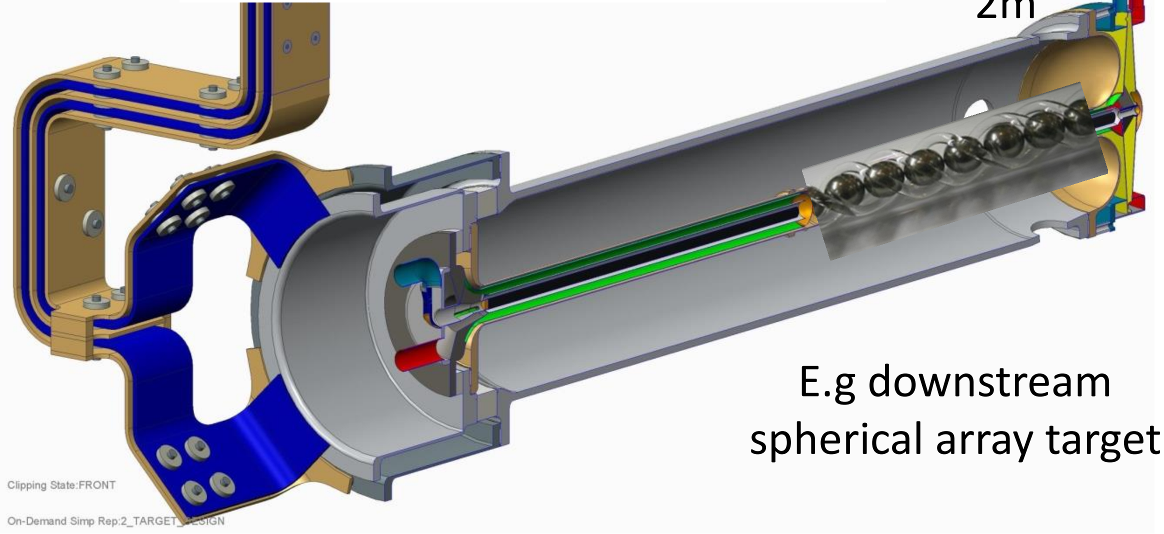
Hybrid target ideas

E.g. possibility to incorporate Spherical Array Target



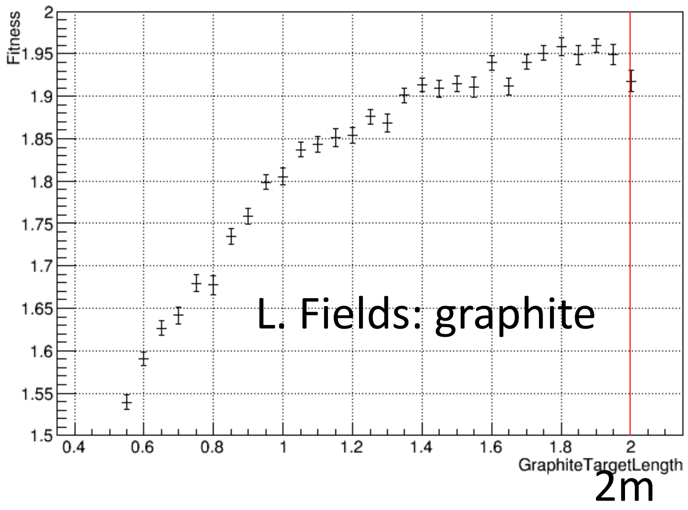
Helium cooling of spherical array target

Induction furnace tests of packed bed



E.g downstream spherical array target

LBNF target physics studies

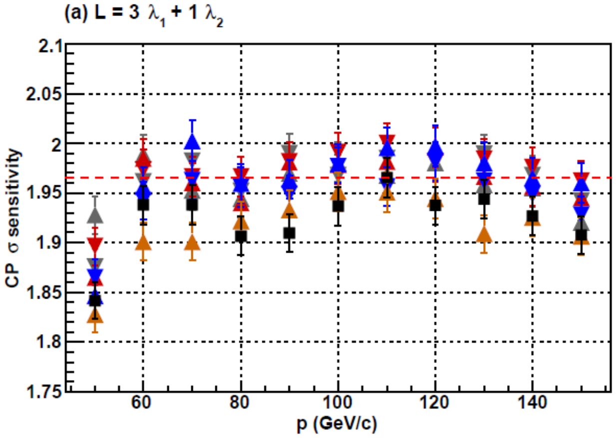


L. Fields: graphite

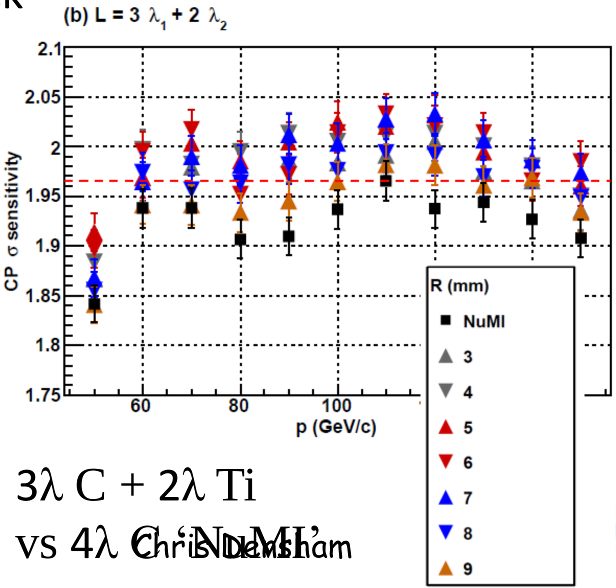
2m

- 4λ (c.2m long) graphite c. 10% better performance than 2λ graphite
- Can we do better with longer &/or higher-Z combinations of materials to:
  - increase pion yield?
  - reduce on-axis wrong-sign pions?

J.Back



3λ graphite + 1λ titanium
vs 4λ C 'NuMI'



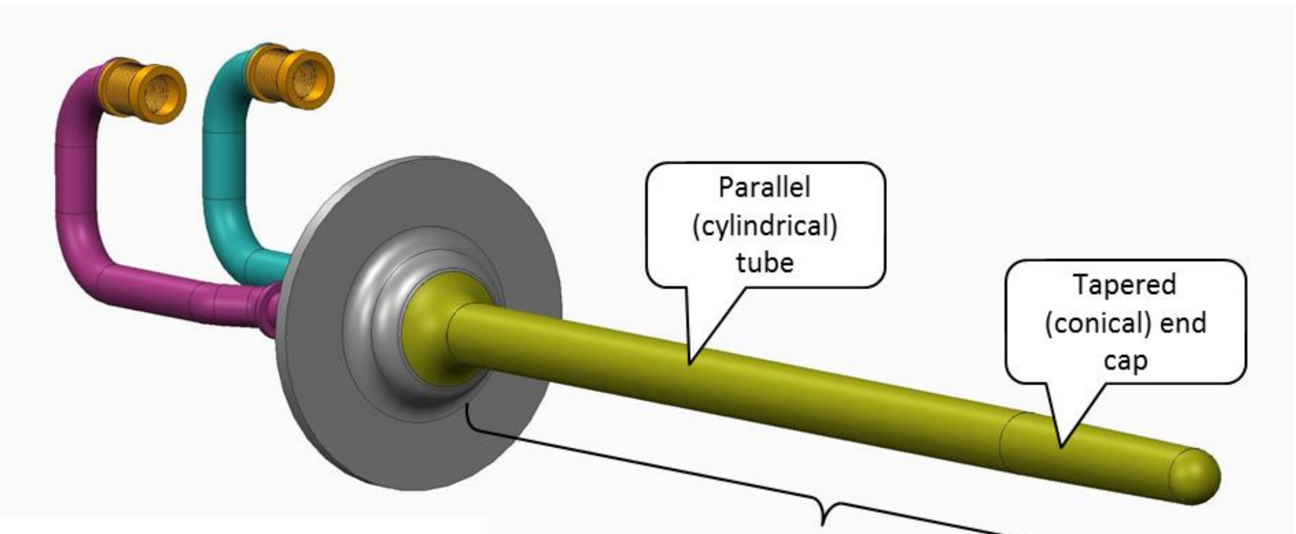
3λ C + 2λ Ti
vs 4λ C 'NuMI'

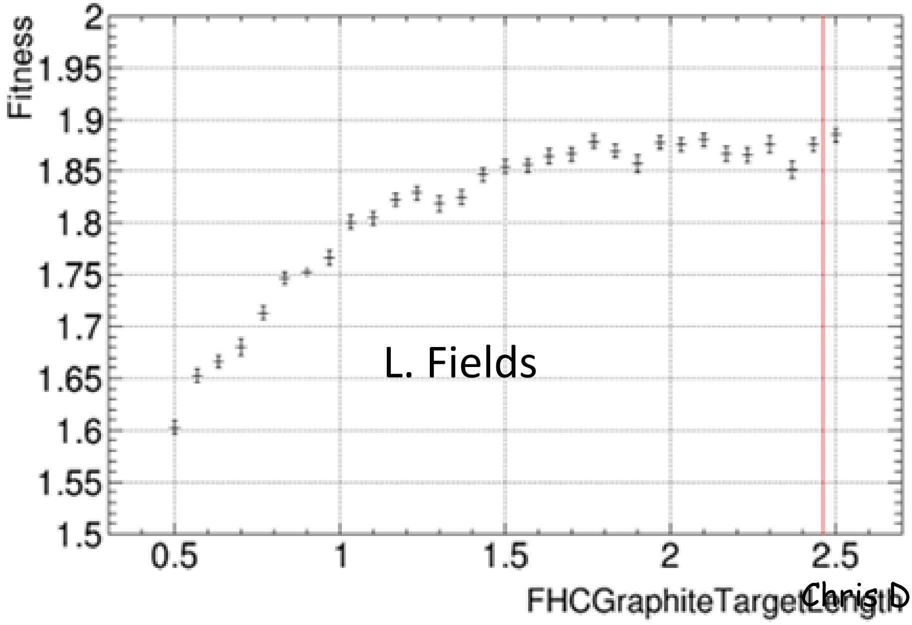
Can't get much better *and* stay within material & heat transfer limits –

4λ **graphite remains new baseline**

Possible simplification – longest practicable T2K-like cantilever c 1.5 m long

Two risks with 2m long design –
1. Manufacture of long target
2. Complications with down stream support





If the target is sufficiently short it could be supported as a simple cantilever with no downstream support

A c. 1.5m long cantilevered target appears potentially feasible and would have a negligible impact on physics performance

RaDIATE
Collaboration

Radiation Damage In Accelerator Target Environments

- to generate new and useful materials data for application within the accelerator and fission/fusion communities
- to recruit and develop new scientific and engineering experts who can cross the boundaries between these communities
- to initiate and coordinate a continuing synergy between research in these communities,

www-radiate.fnal.gov

JPARC and CERN sign in 2017

Chris Densham

Comparison of target heat loads

	T2K (Design)	T2K (Achieved)	NuMI	NoVA	LBNF RAL Design
Target Material	ToyoTanso IG-43	ToyoTanso IG-43	POCO ZXF-5Q	POCO ZXF-5Q	ToyoTanso IG-43
Beam Energy [GeV]	30	30	120	120	120
Beam Power [kW]	750	350	400	700	1200
Beam Current [µA]	25	12	3.3	5.8	10
Protons per Pulse [-]	3.3×10^{14}	1.8×10^{14}	4.0×10^{13}	4.9×10^{13}	7.5×10^{13}
Cycle Time [s]	2.1	2.5	1.9	1.3	1.2
Beam Sigma [mm]	4.2	4.2	1	1.3	2.7
Peak Energy Density in target material [J/g]	144	67	282	174	118
Peak Proton Fluence on Front Face [µA/cm²]	23	11	53	55	22

Total and pulsed heat loads lower than that seen on NoVA and NuMi and on T2K design