Mega-Watt Neutrino Targets for LBNF/JPARC

Chris Densham, Tristan Davenne, Joe O'Dell, Peter Loveridge, Mike Fitton (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, Alberto Marchionni, Jim Hylen, Vaia Papadimitiou (Fermilab)

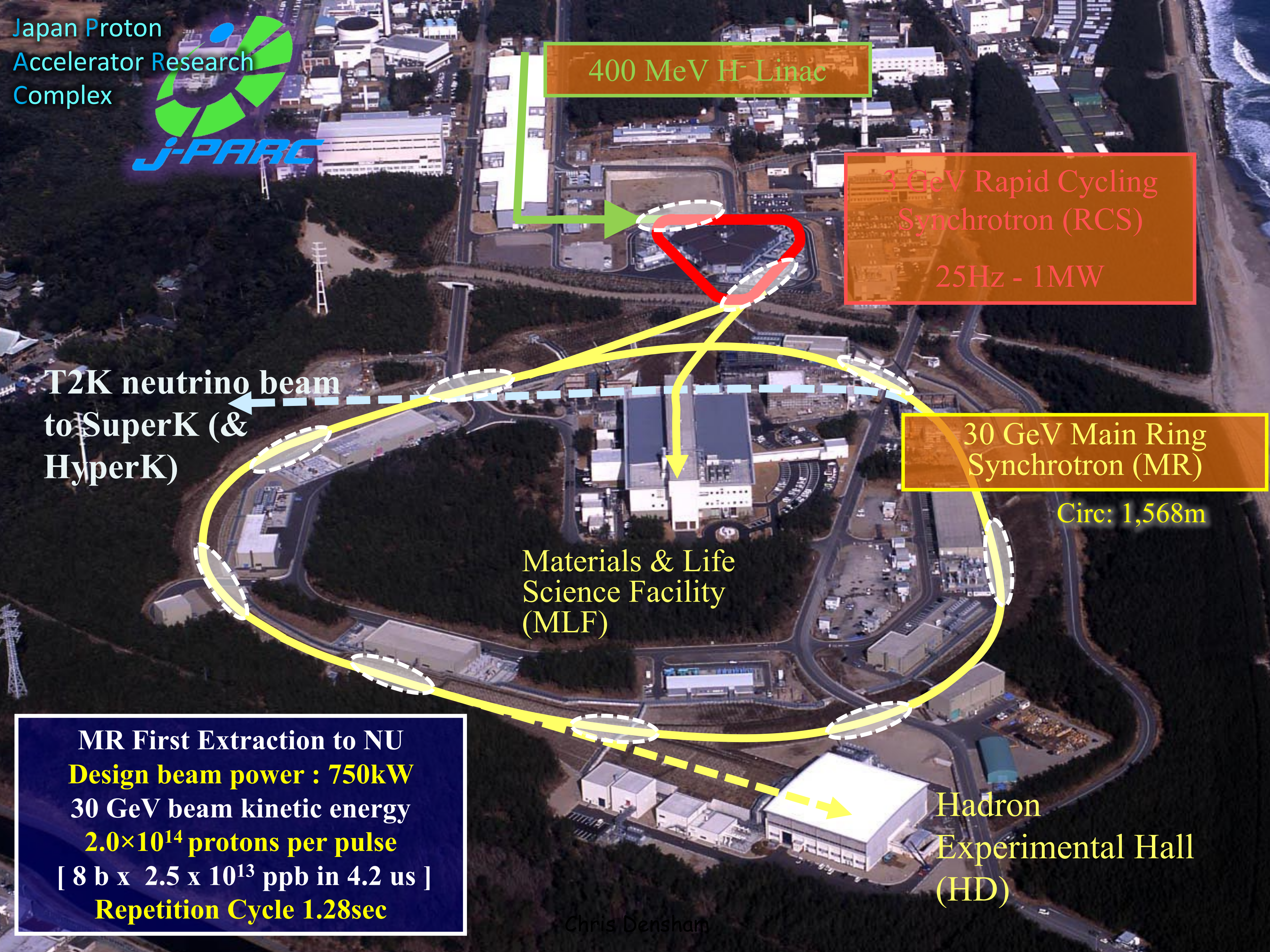
& DUNE Collaboration

Fermilab

RaDIATE Collaboration
Radiation Damage In Accelerator Target Environments

T2K

Science & Technology Facilities Council
Rutherford Appleton Laboratory


Japan Proton
Accelerator Research
Complex
J-PARC
400 MeV H^- Linac
3 GeV Rapid Cycling
Synchrotron (RCS)
25Hz - 1MW
T2K neutrino beam
to SuperK (&
HyperK)
30 GeV Main Ring
Synchrotron (MR)
Circ: 1,568m
Materials & Life
Science Facility
(MLF)
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
Hadron
Experimental Hall
(HD)
Chris Densham

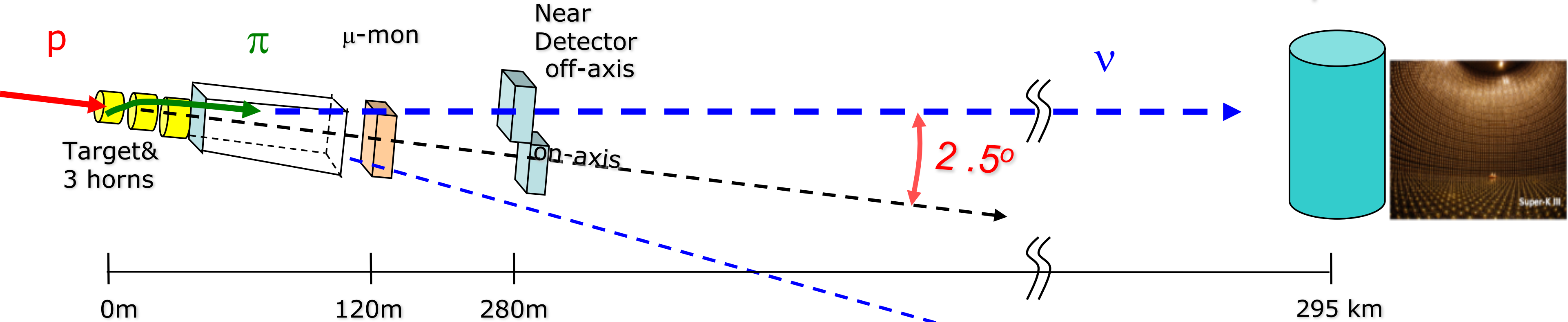
Fermilab Accelerator Complex

Chris Densham

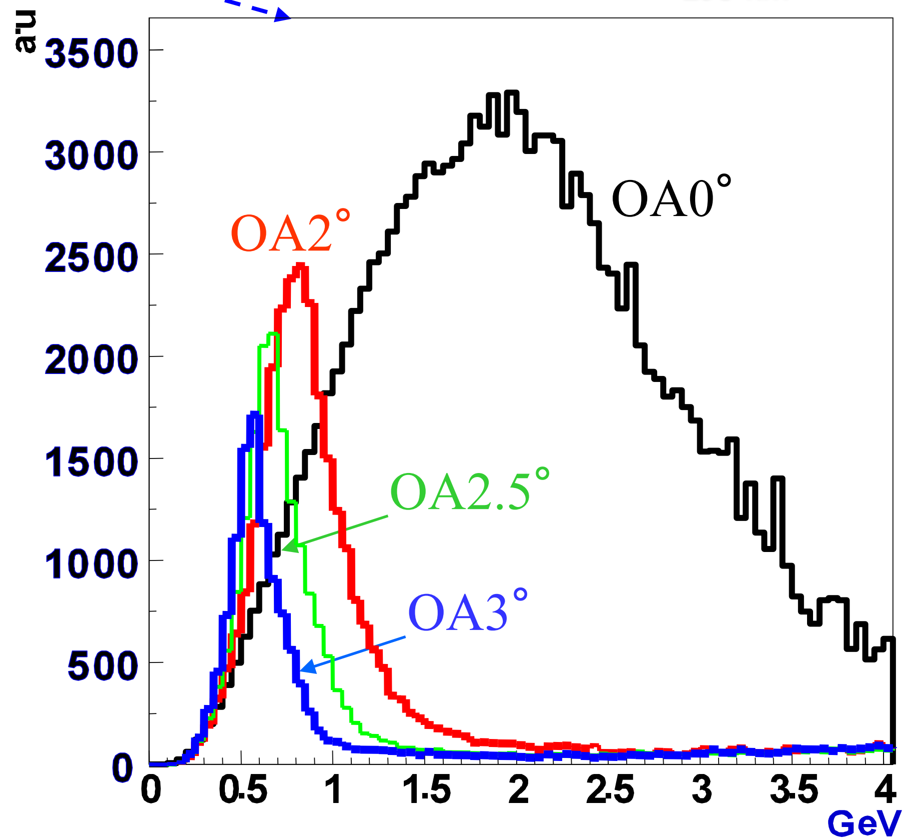
A few comparative parameters

	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

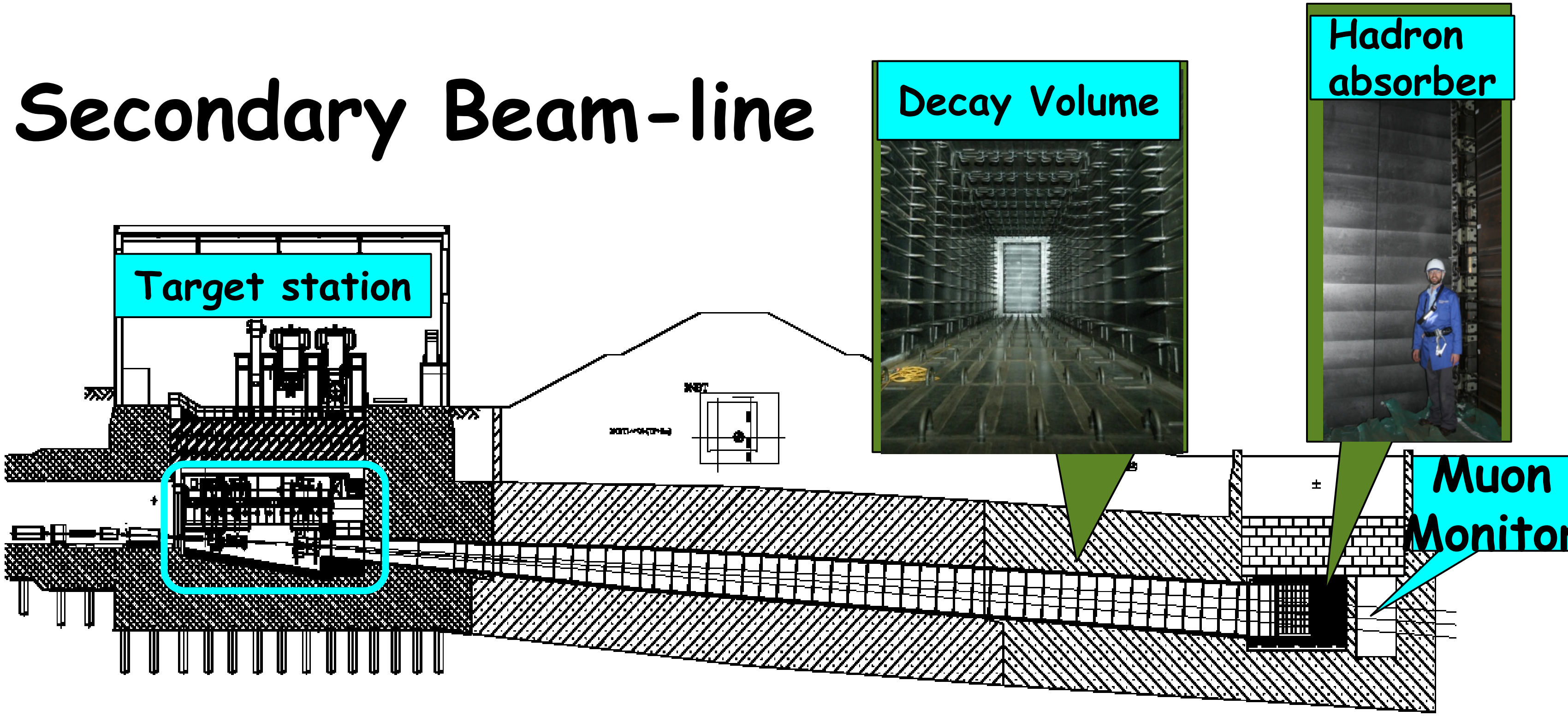
T2K Beam-line



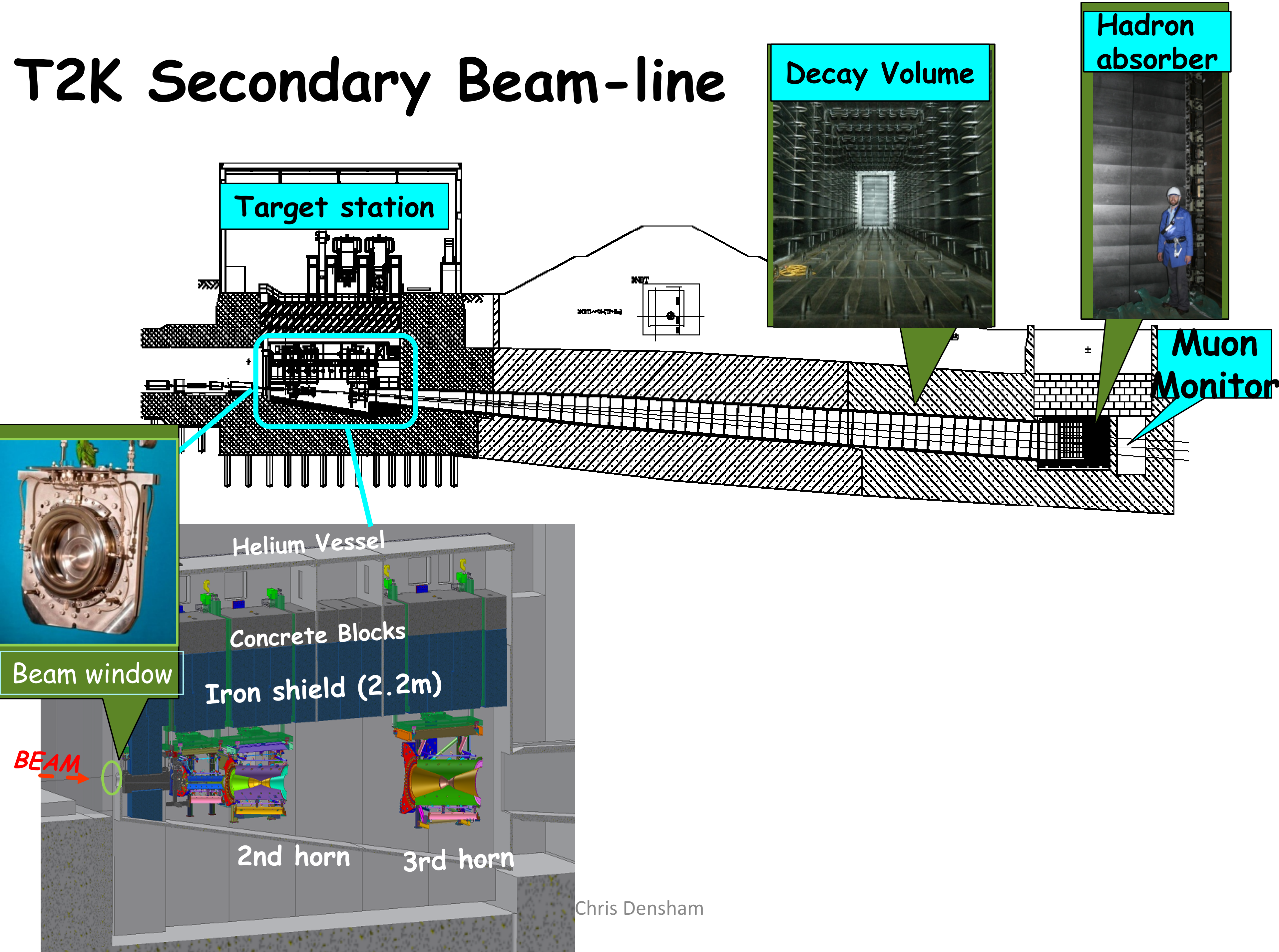
- Off-axis beam generates quasi-monochromatic ν_μ neutrino beam tuned to $\nu_\mu \rightarrow \nu_e$ oscillation maximum
- Also reduces ν_e background
- Anti-neutrinos generated by reversing polarity of horn current



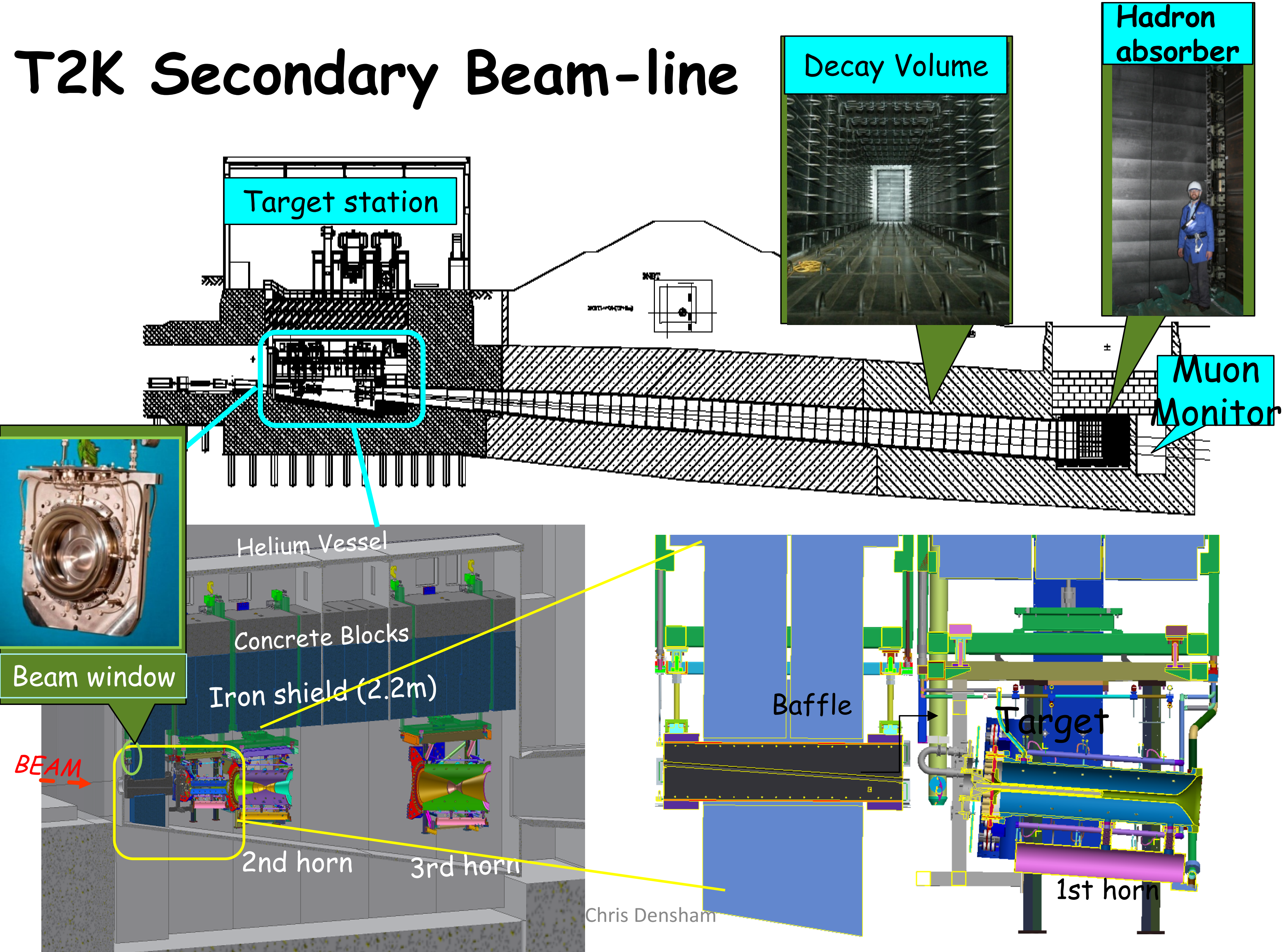
T2K Secondary Beam-line



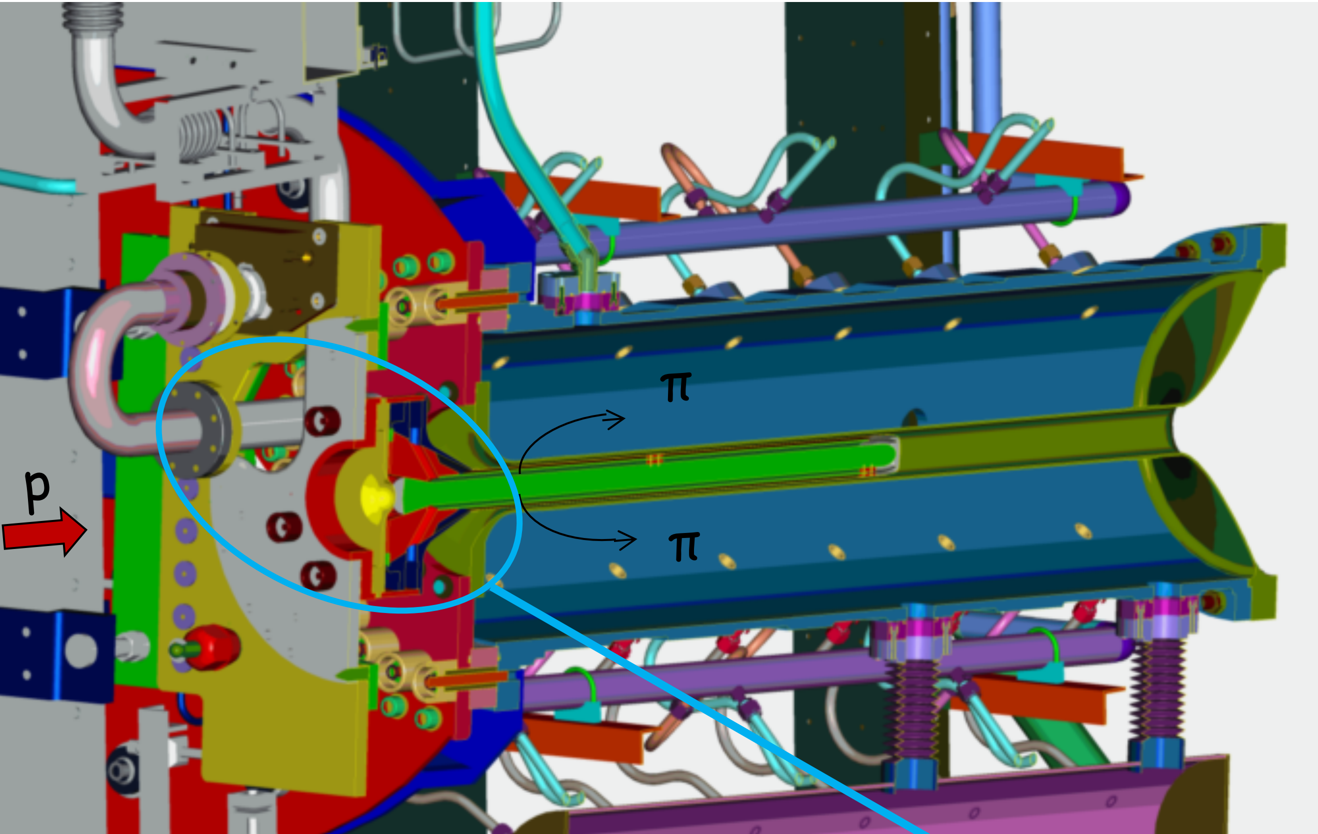
T2K Secondary Beam-line



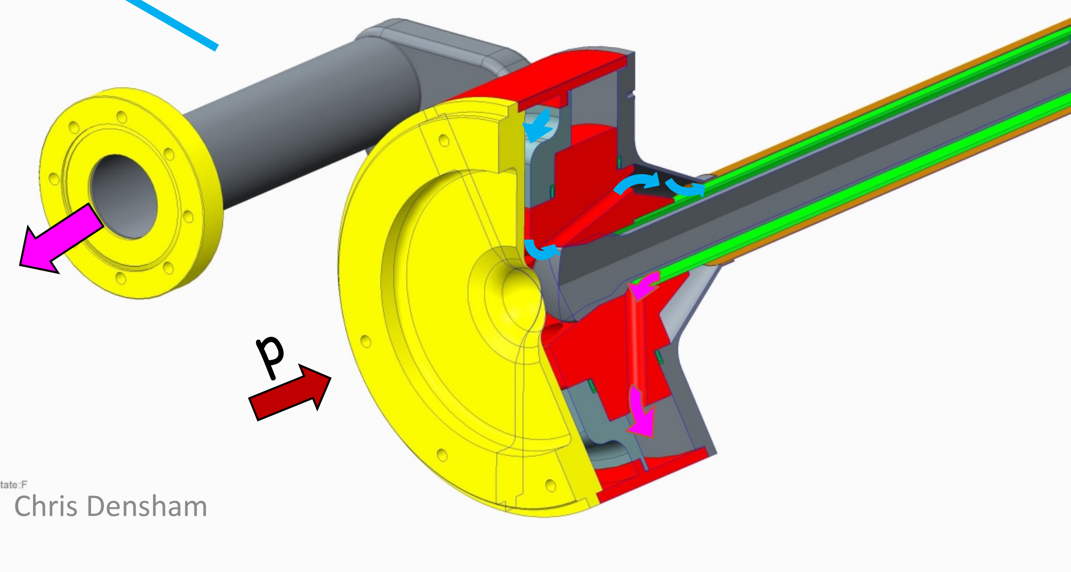
T2K Secondary Beam-line



T2K Target & horn

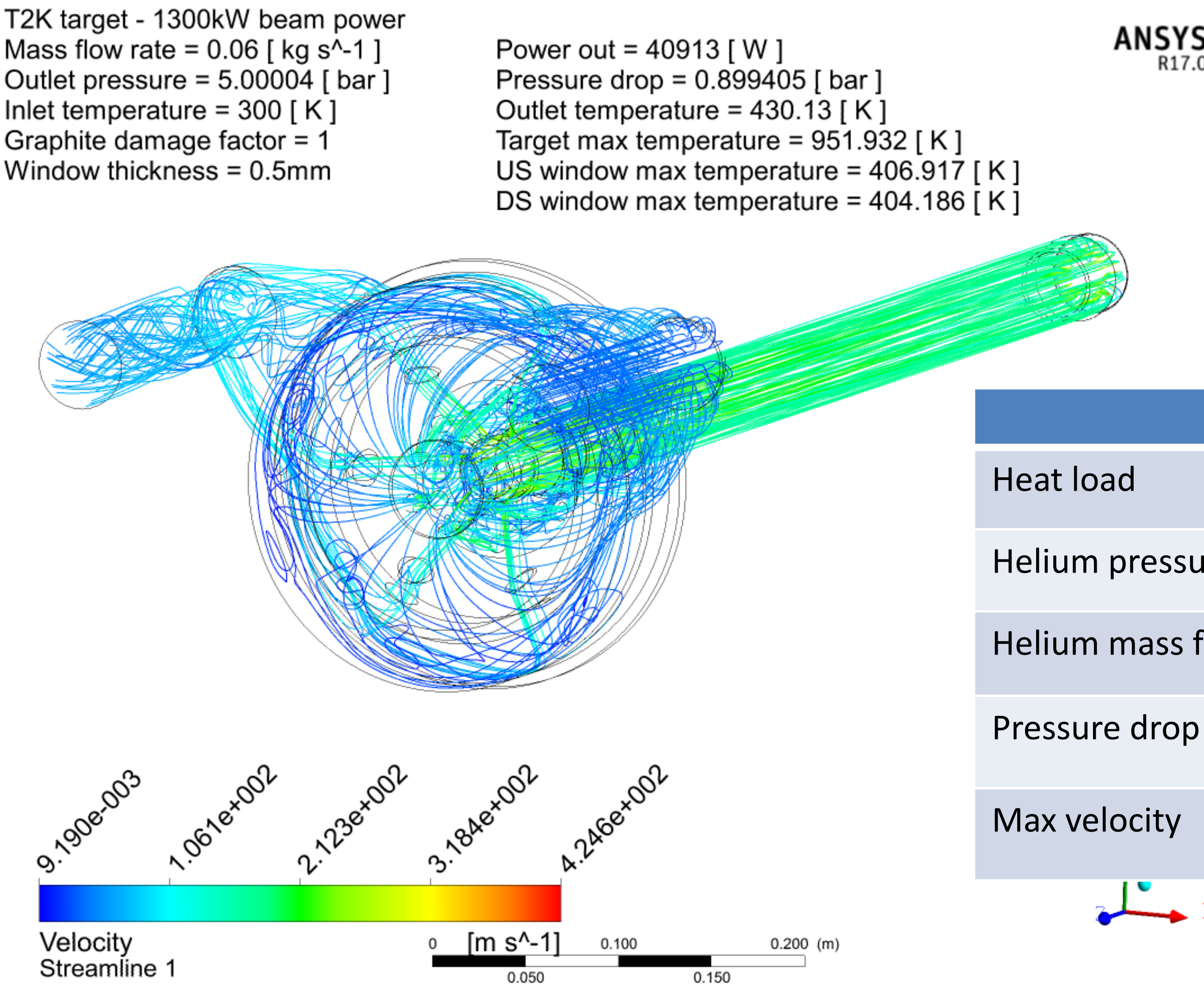


Next target under construction



- 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 1.5 e21 p.o.t.

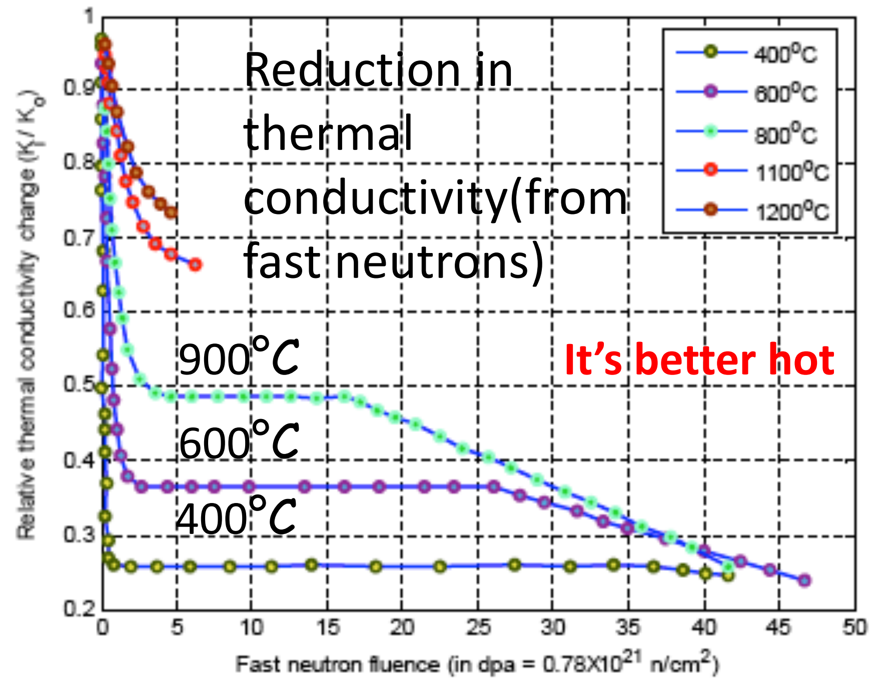
Higher power beam -> higher pressure helium



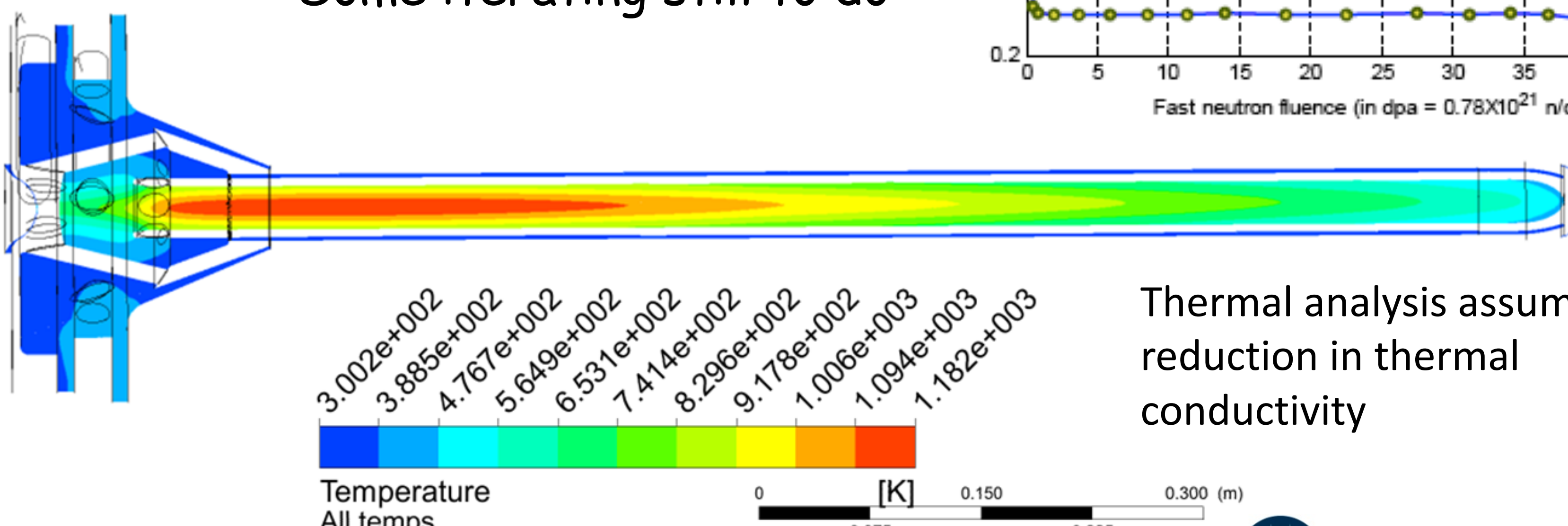
	0.75 MW	1.3 MW
Heat load	23.5 kW	40.8 kW
Helium pressure	1.6 bar	5 bar
Helium mass flow	32 g/s	60 g/s
Pressure drop	0.83 bar	0.88 bar
Max velocity	400 m/s	425 m/s

Thermal analysis for 1.3 MW operation

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



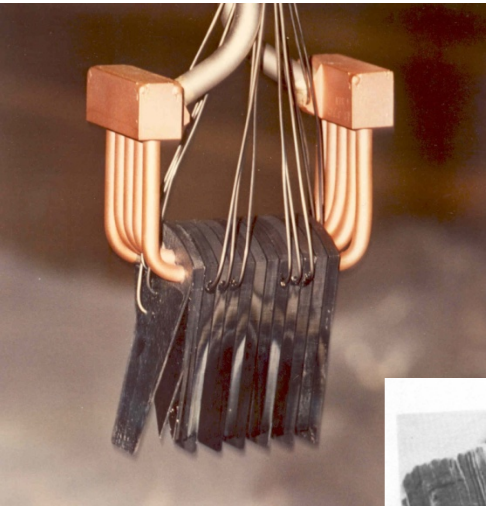
Some iterating still to do



Thermal analysis assuming x4 reduction in thermal conductivity

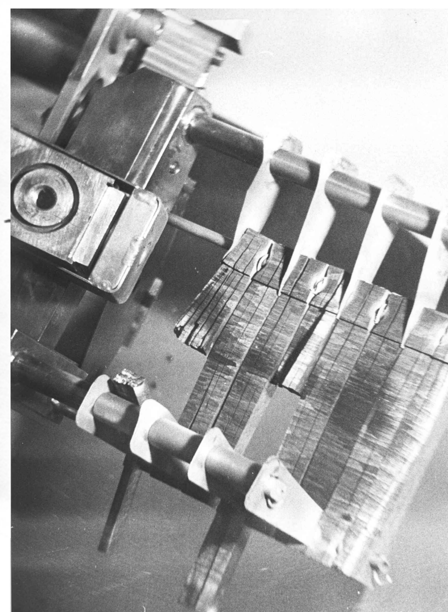
The ultimate destiny for all graphite targets?

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

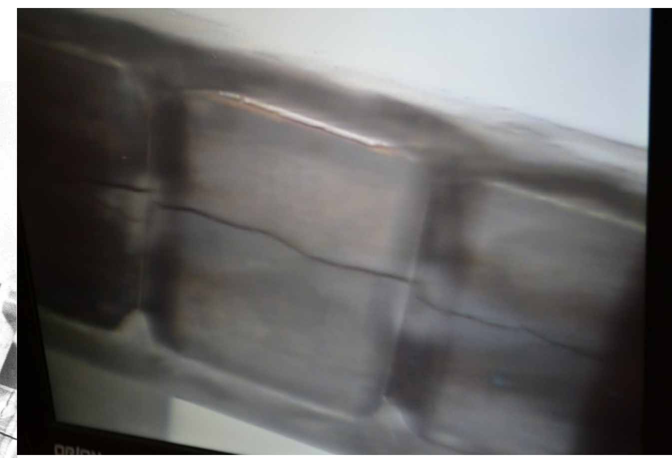


LAMPF
fluence
10^22
p/cm2

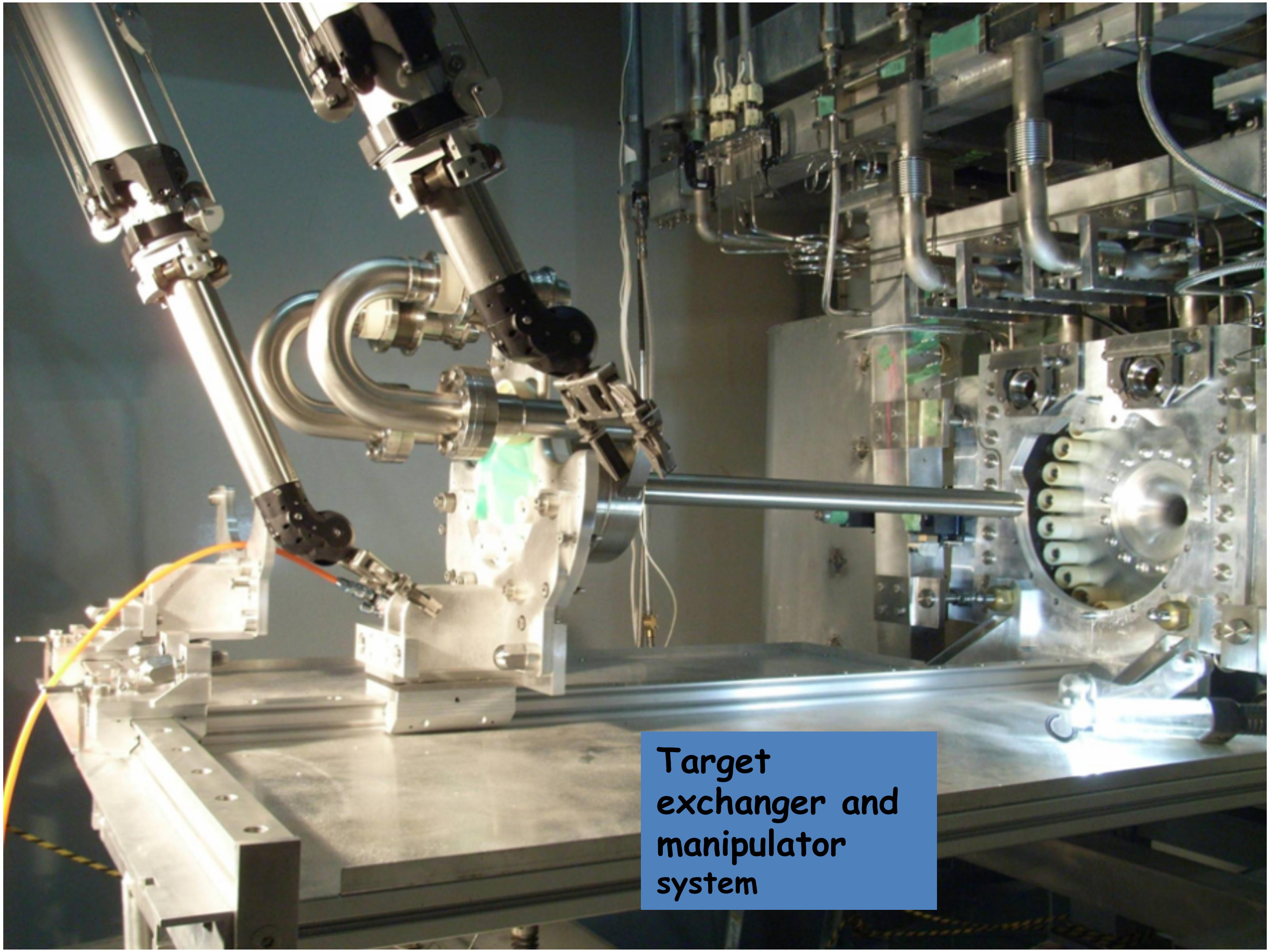
PSI: fluence
10^22 p/cm2



NuMI target

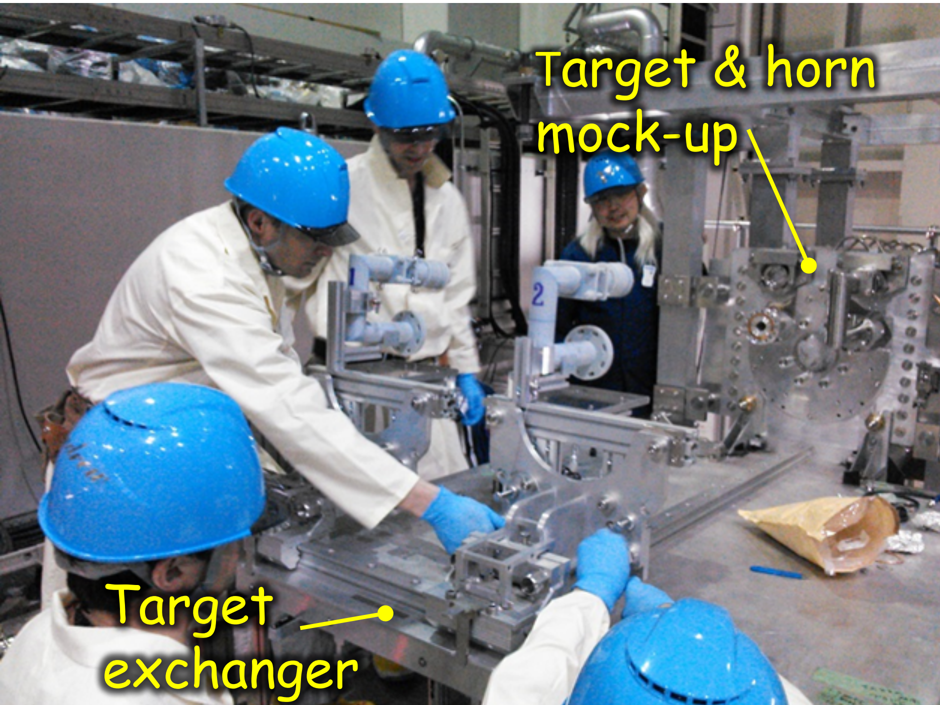


Remote Target Exchange System

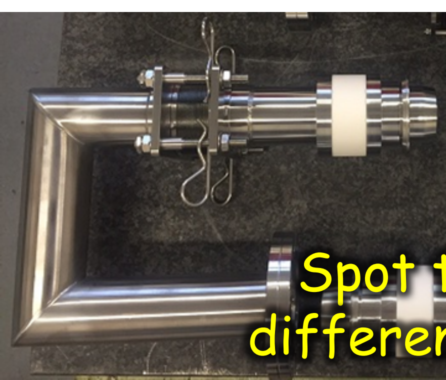


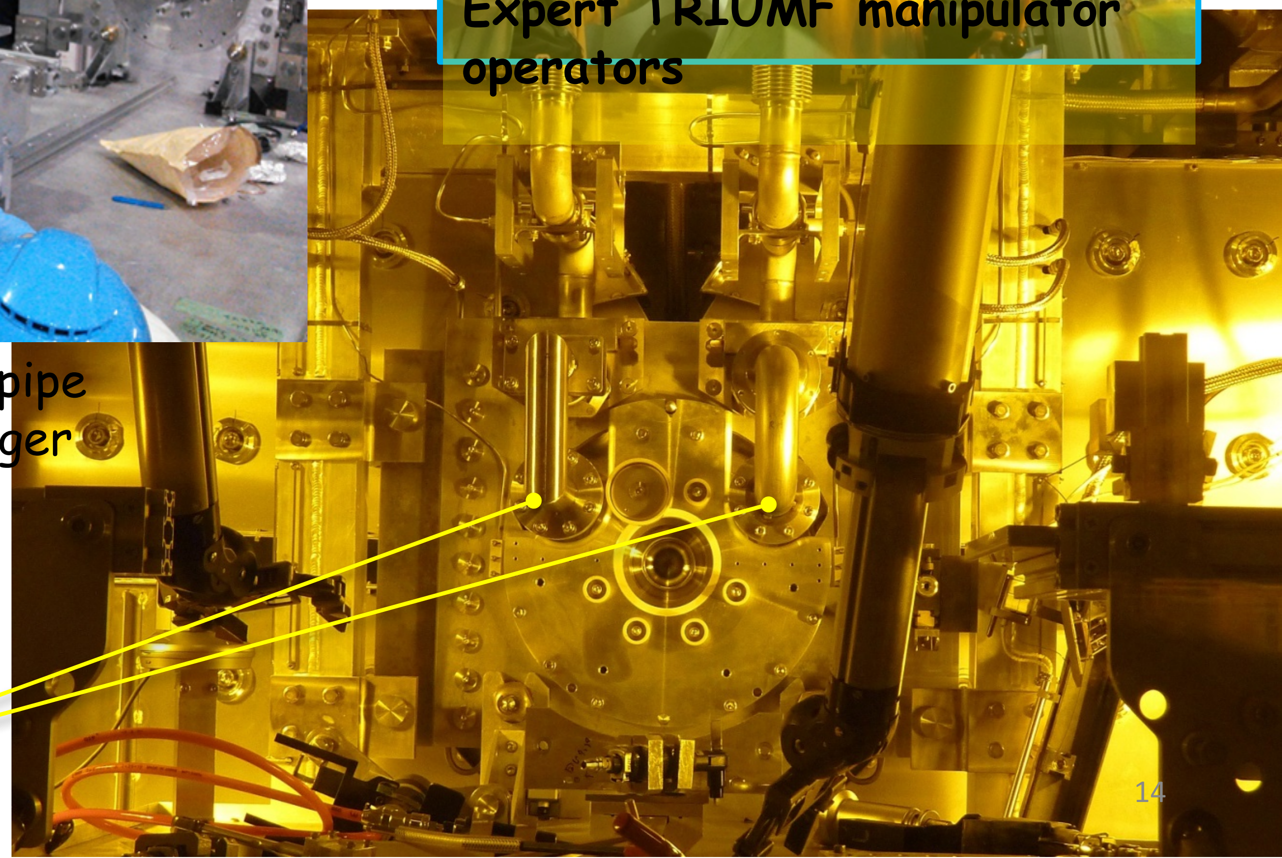
Helium pipe replacement

2015年12月17日



Rehearsal using 3D printed pipe
and modified target exchanger





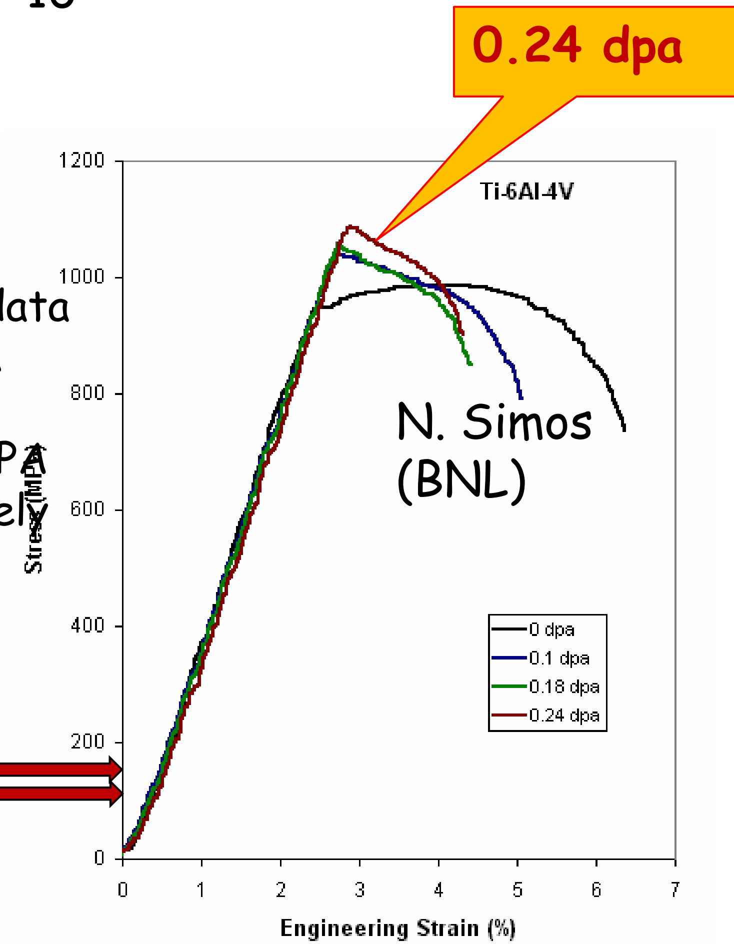
Vacuum-to-air beam window (Ti6Al4V)

First window run for 10 years

22.4×10^{20} protons

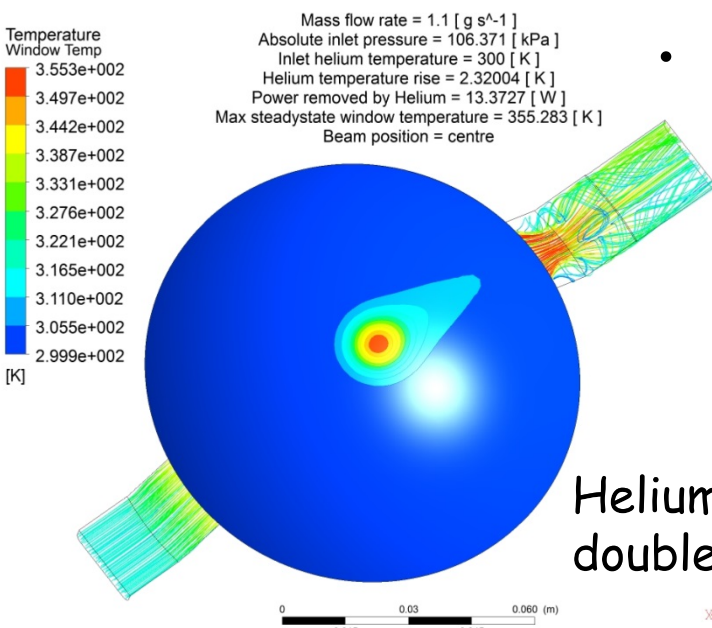
→ ~2 DPA (MARS)

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



1.3 MW, 0.5 mm

0.75 MW, 0.3 mm

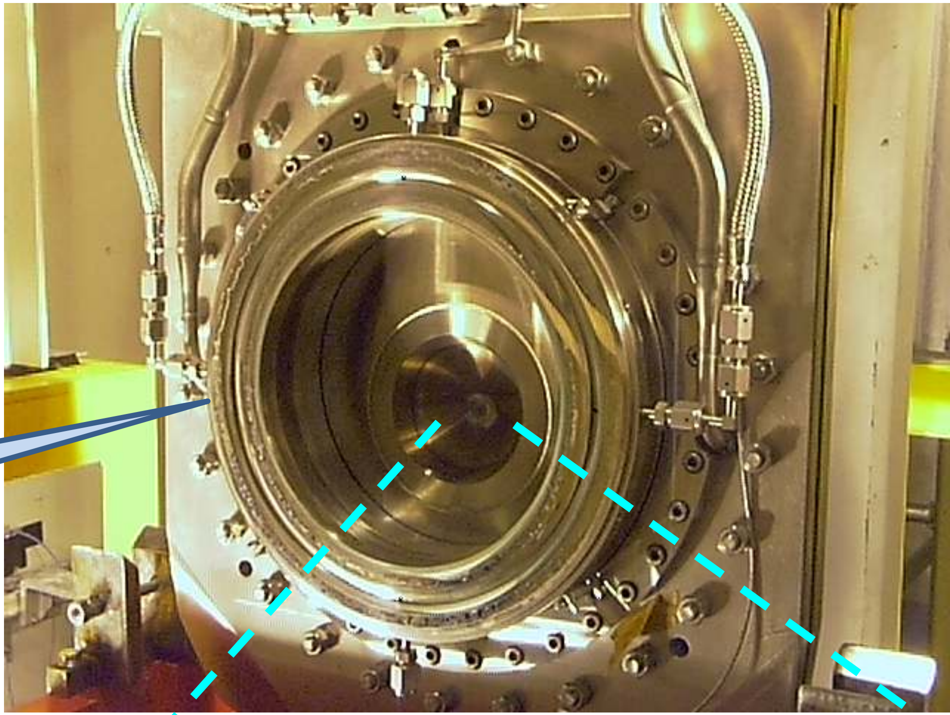


Helium cooling between double window skins

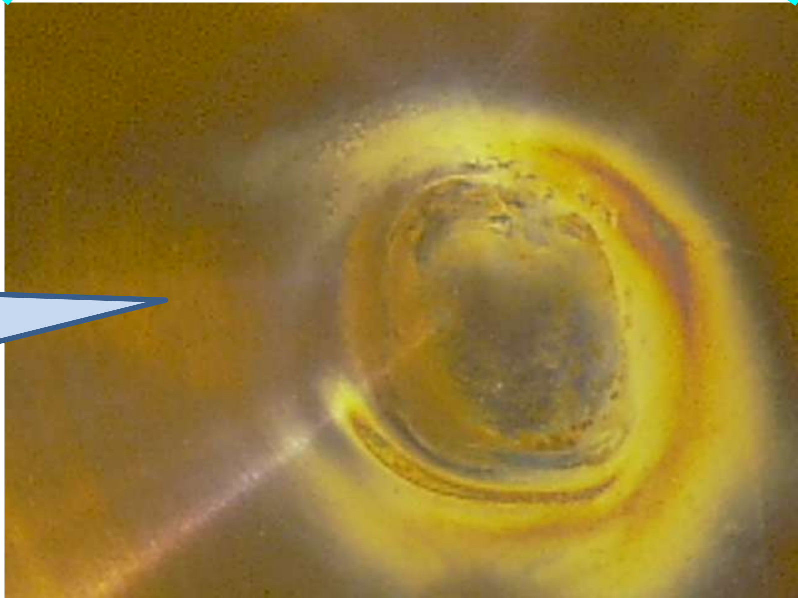
Science & Technology Facilities Council
Rutherford Appleton Laboratory

Beam window replacement 22 Aug 2017

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

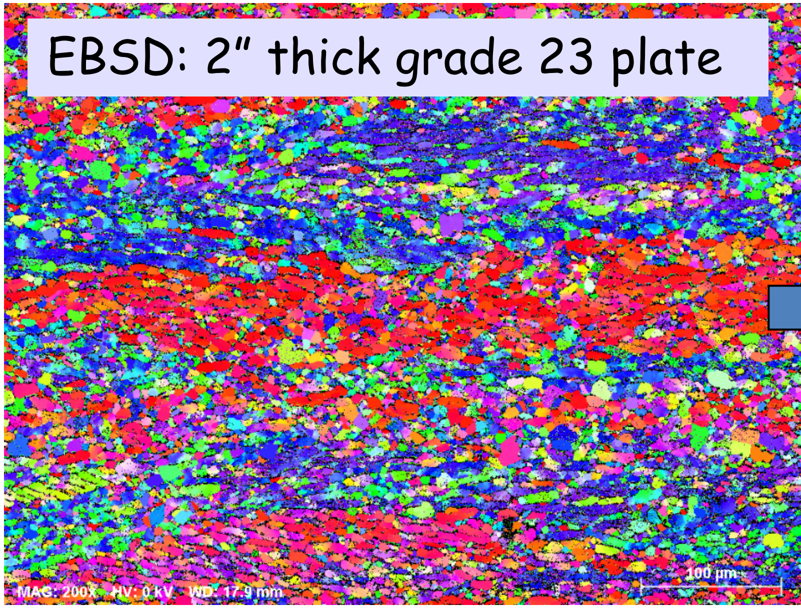


- Inflatable pillow vacuum seal appears deformed after removal
- Not possible to reuse the old beam window.

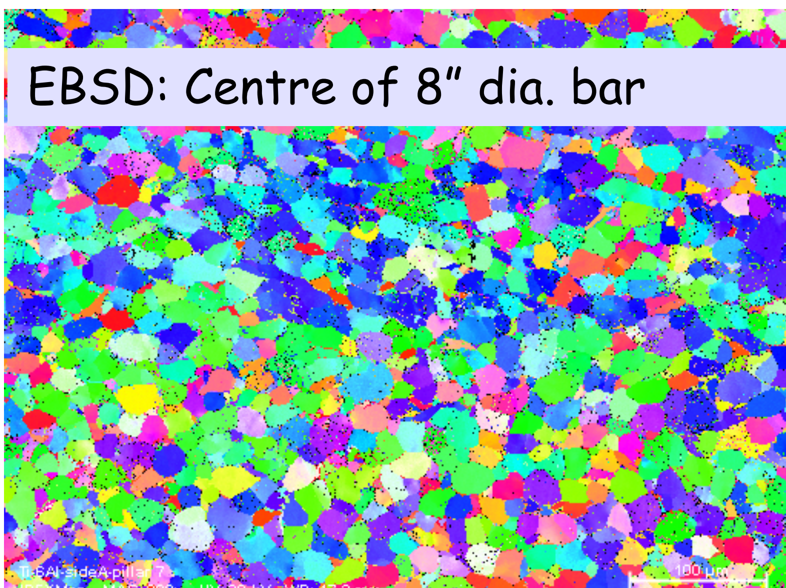


- Centre of beam window appears to be damaged / discoloured
- Need to conduct Post-Irradiation Examination -> talking to materials scientists

Plate vs bar for next beam window



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



- Macrozones not evident in the bar
- Current window (from bar) has performed well so far
- Will continue with bar material
- -> but low grain boundary density could be bad for radiation damage?

Chris Densham

Rutherford Appleton Laboratory

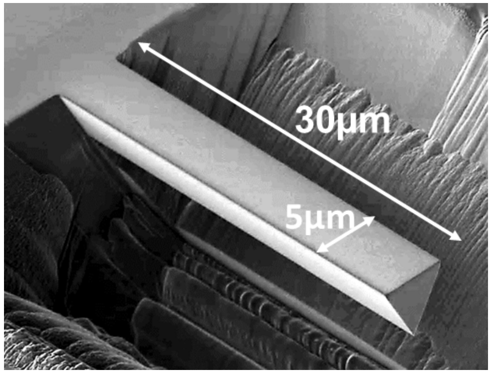
Small-scale Ultrasonic Fatigue Testing

High power 20 kHz ultrasonic resonant VHCF tests

- Prototype system at Oxford
- Need to reproduce at Culham laboratory (Materials Research Facility) for activated materials

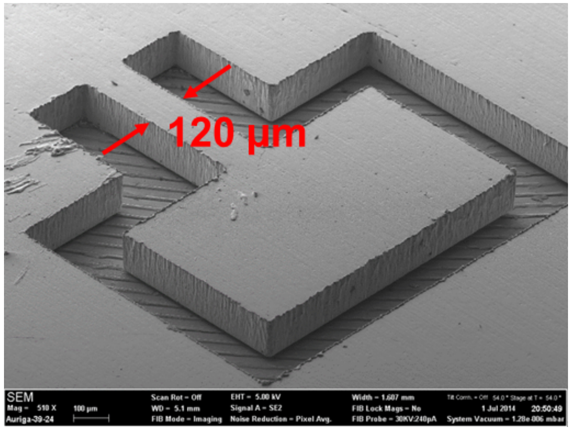
+

micro-cantilever



or

meso-cantilever



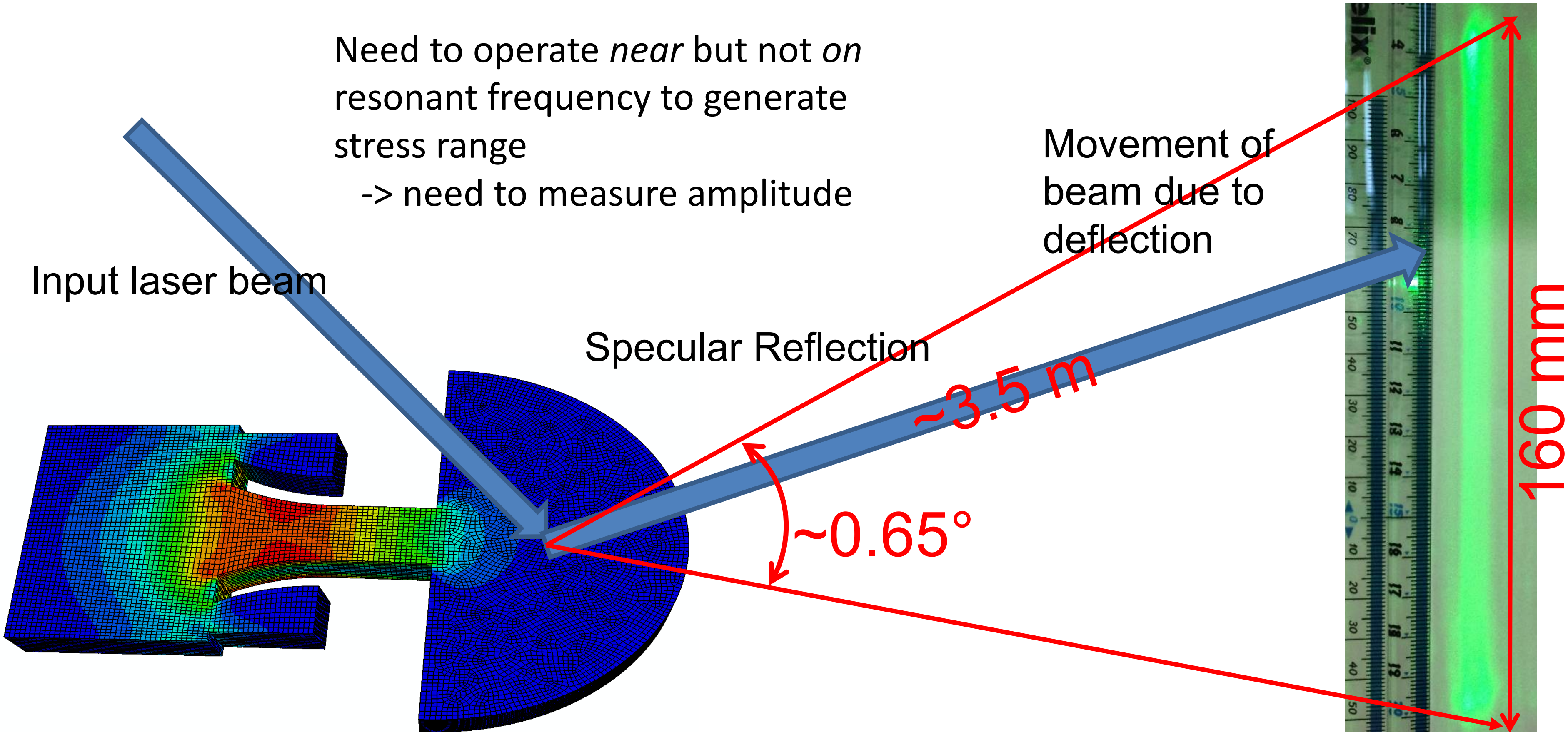
=

Fatigue testing?

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

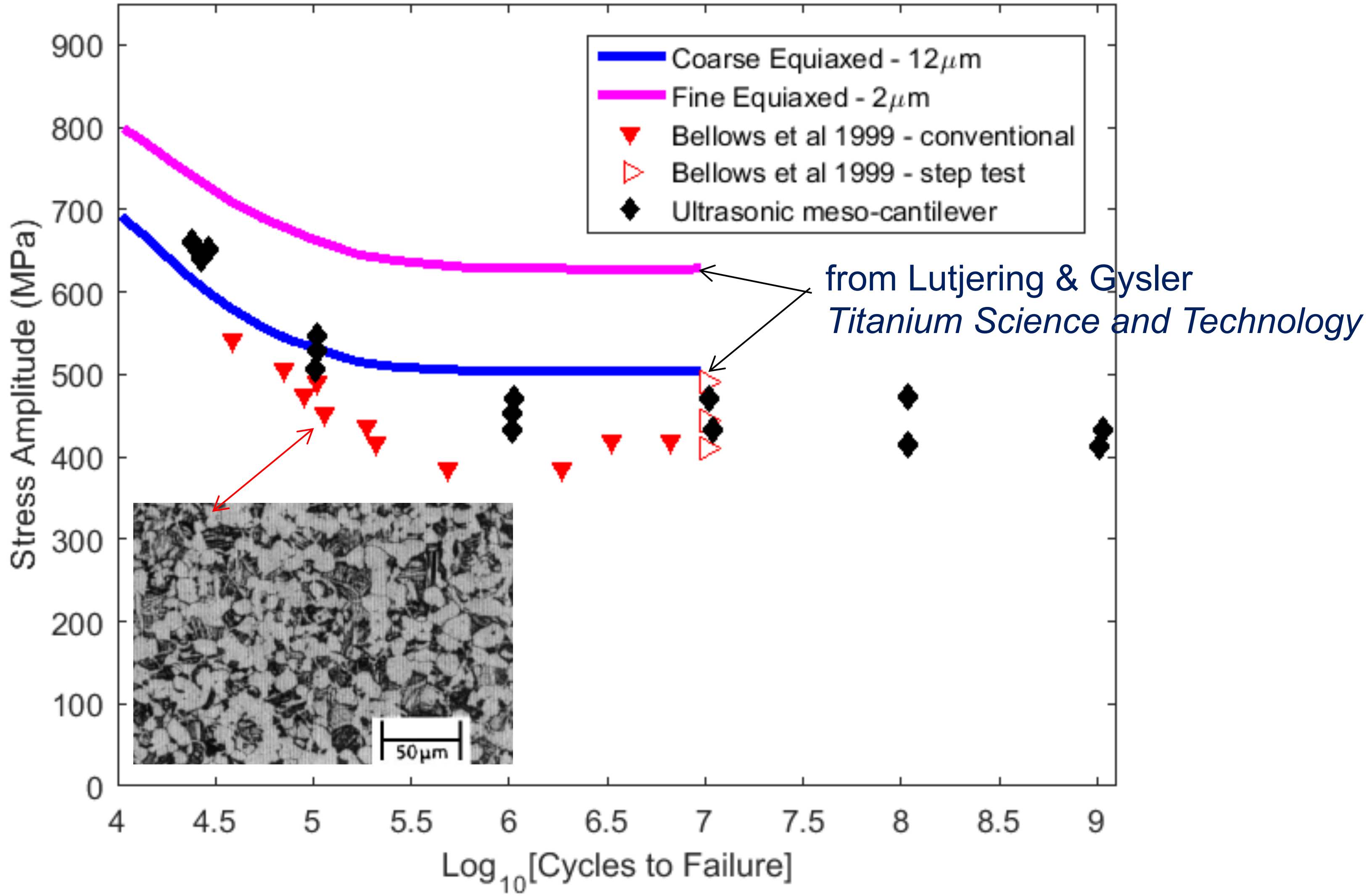
Measurement of deflection during resonant vibration of sample

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



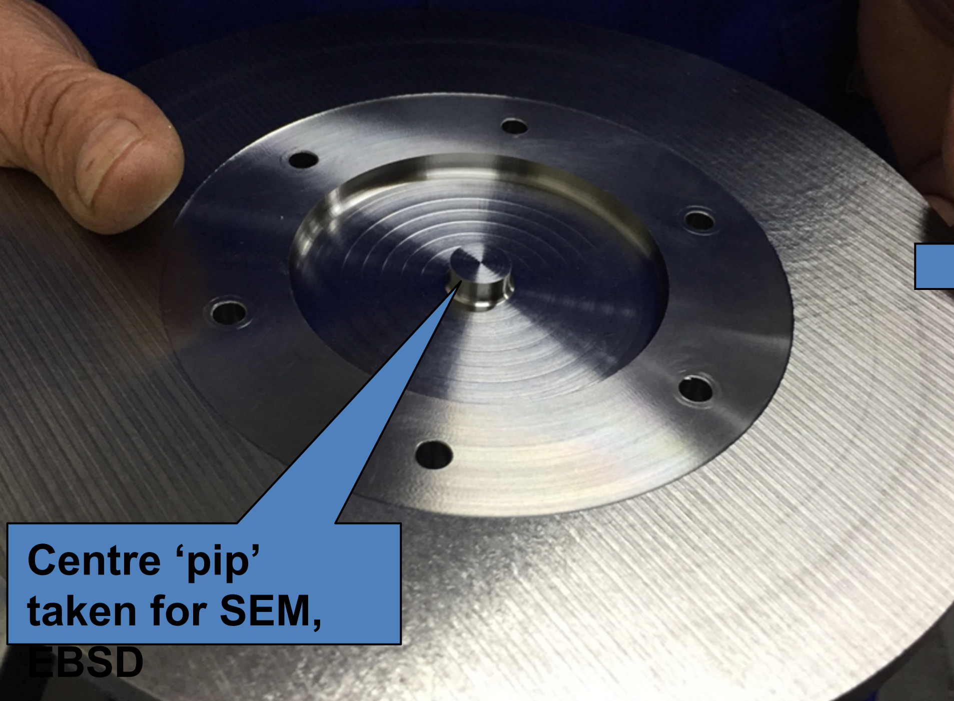
Tresca (maximum shear) stress

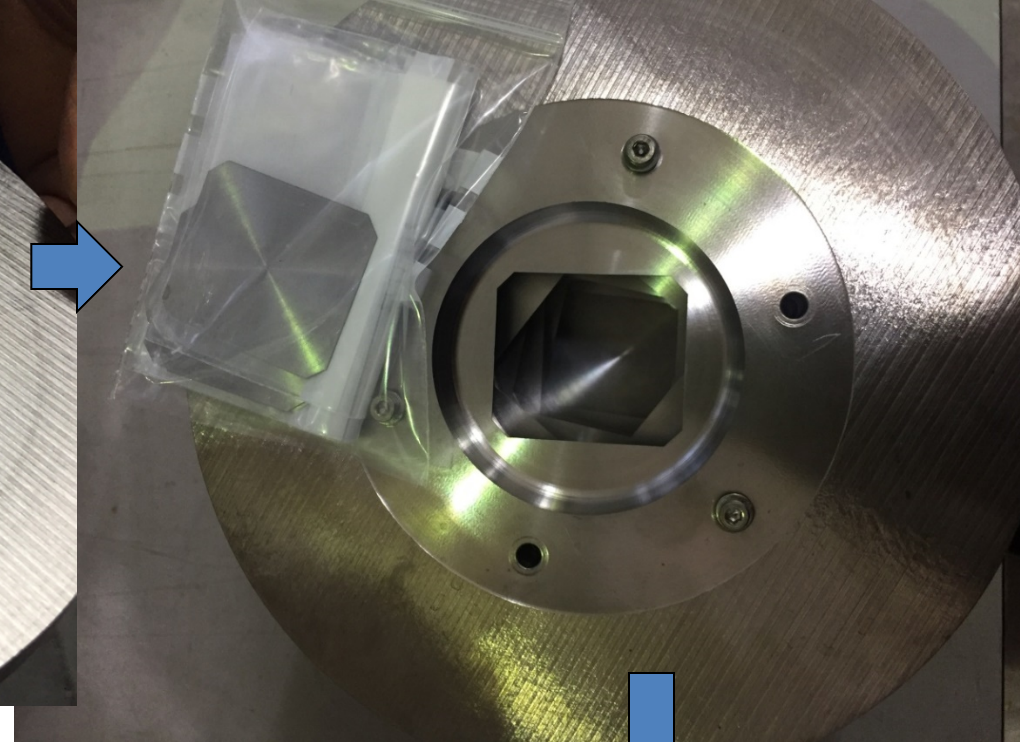
Ti-6Al-4V Fatigue Life Data

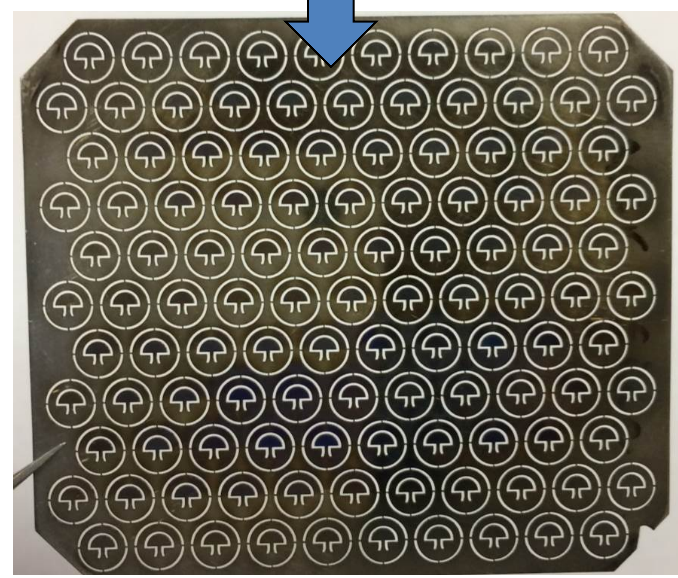


Chris Densham

Science & Technology Facilities Council
Rutherford Appleton Laboratory



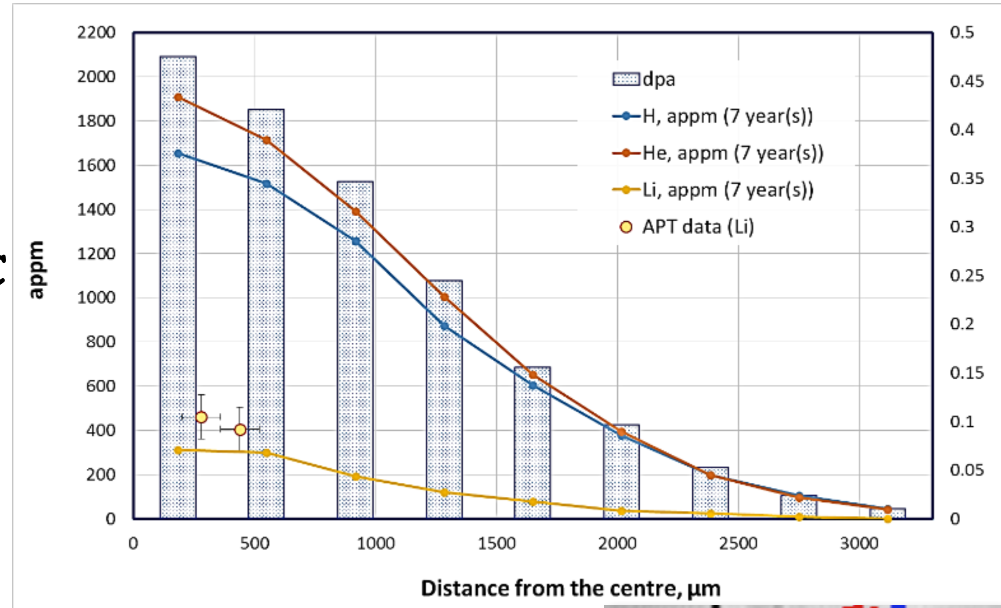


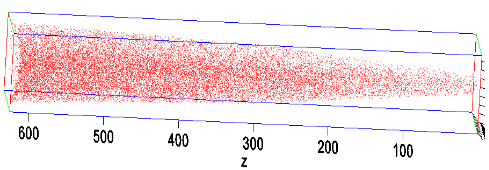


- 2 x sample foils machined from same 8″ Ti-6Al-4V bar purchased for next T2K window domes
- Samples polished to 0.25 mm and laser cut using very fine scanning laser
- C. 2 weeks irradiation so far at BNL/BLIP at c.180 MeV, c.0.2 DPA

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

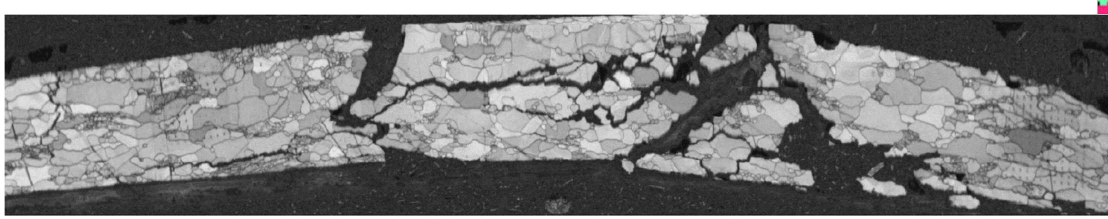
- NuMI Be window examined at Oxford
  - Be window to 1.57E21 POT analyzed
  - Advanced microscopy techniques ongoing
  - Li matches predictions and remains homogeneously distributed at ~50 °C
  - Crack morphology changes at higher doses (transgranular to grain boundary fracture)

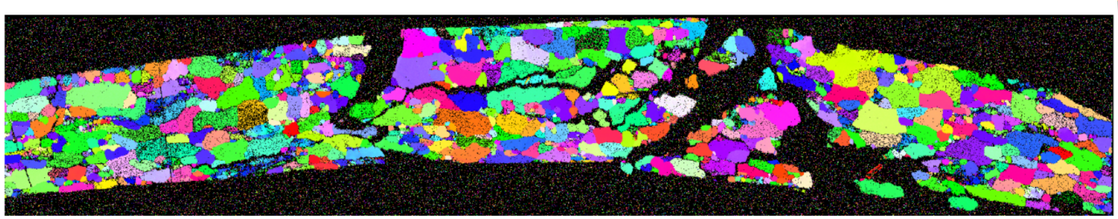


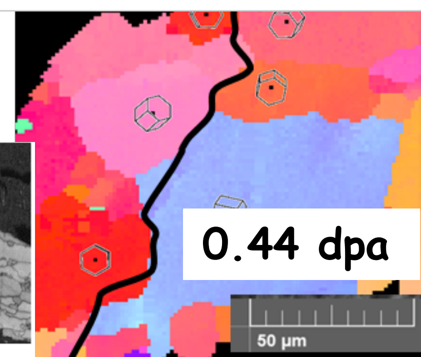


Li transmutant

Material fracture due to punch removal process





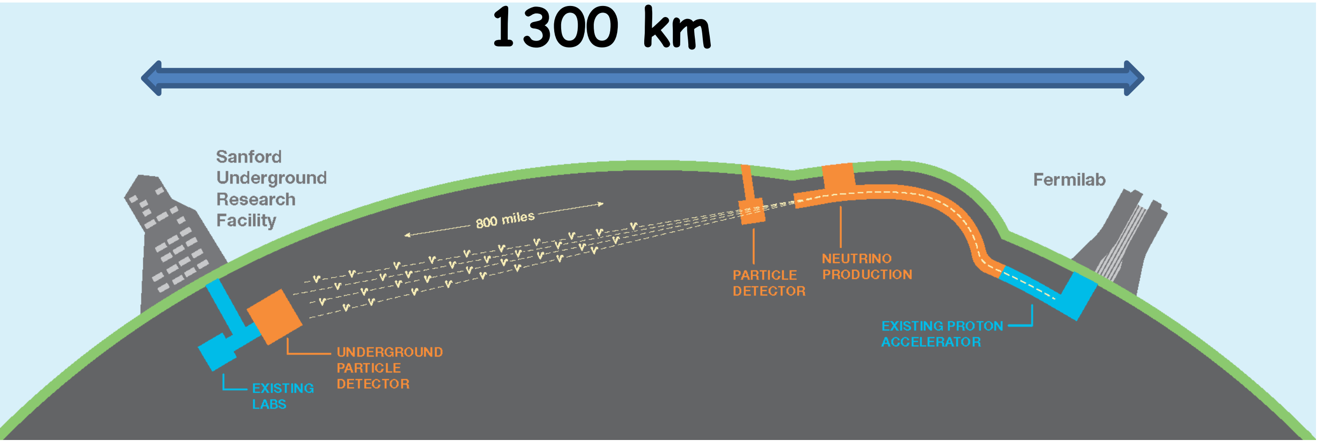


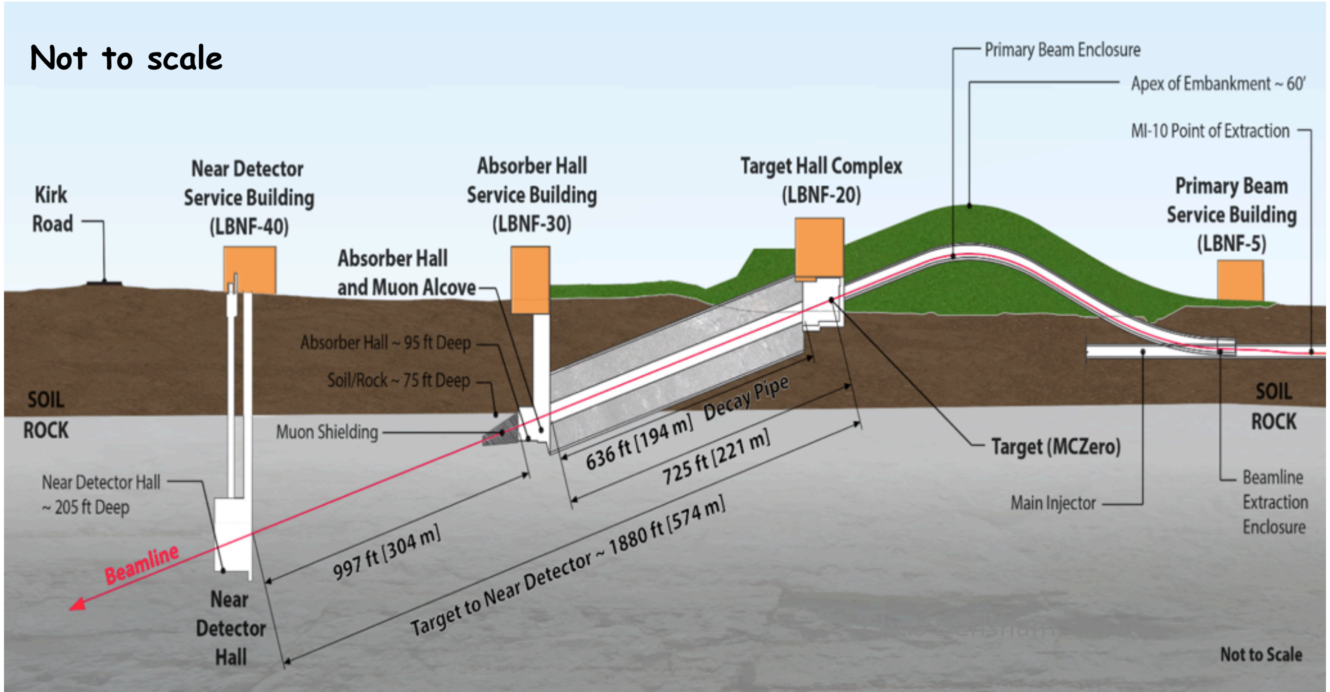
0.29 dpa

V. Kuksenko, Oxford University

Science & Technology Facilities Council
Rutherford Appleton Laboratory

The LBNF Beamline



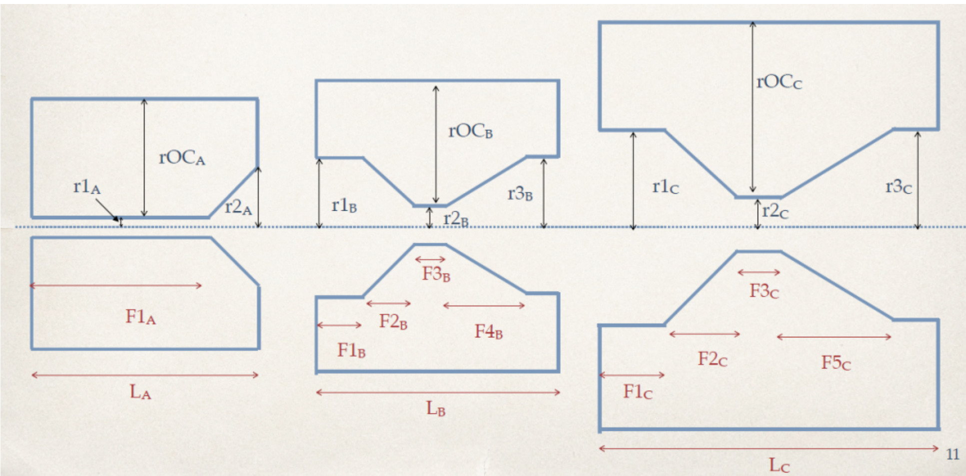


- On-axis, wide-band beam (wide range of neutrino energies ~ few GeV)
- Initial beam power 1.2 MW (PIPII)
- Upgradeable to 2.4 MW (PIPIII)

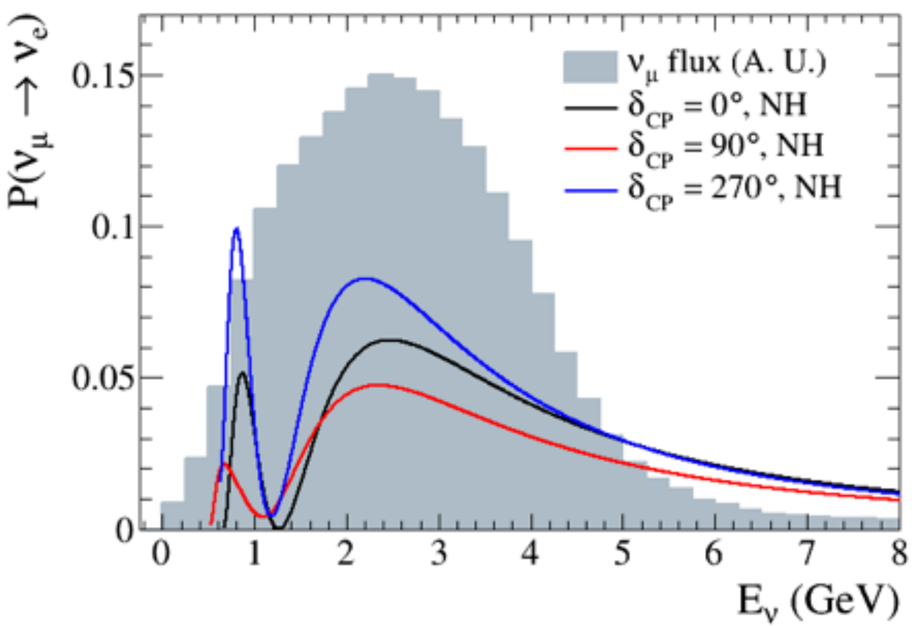
Beam size at target tunable between 1.0-4.0 mm sigma

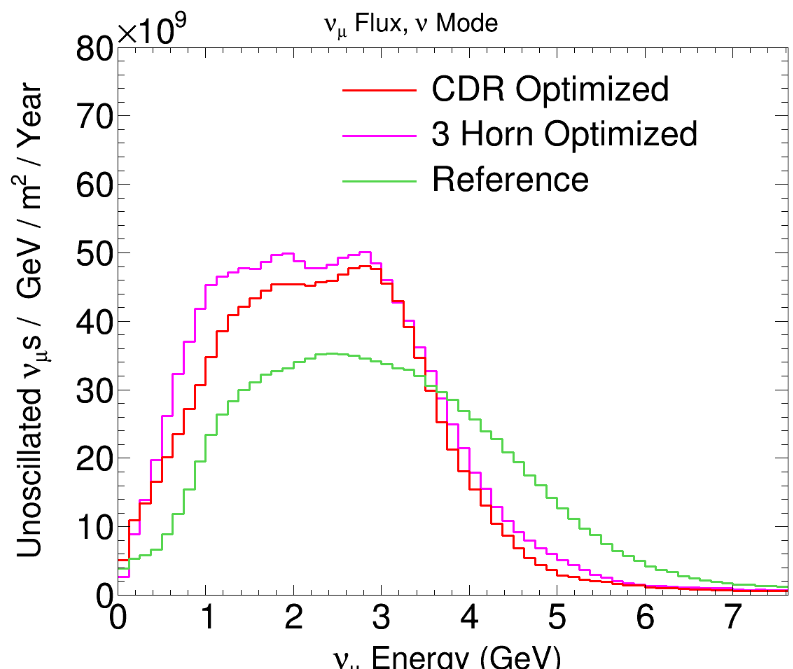
Optimisation of LBNF/DUNE target & horn

(L. Fields)

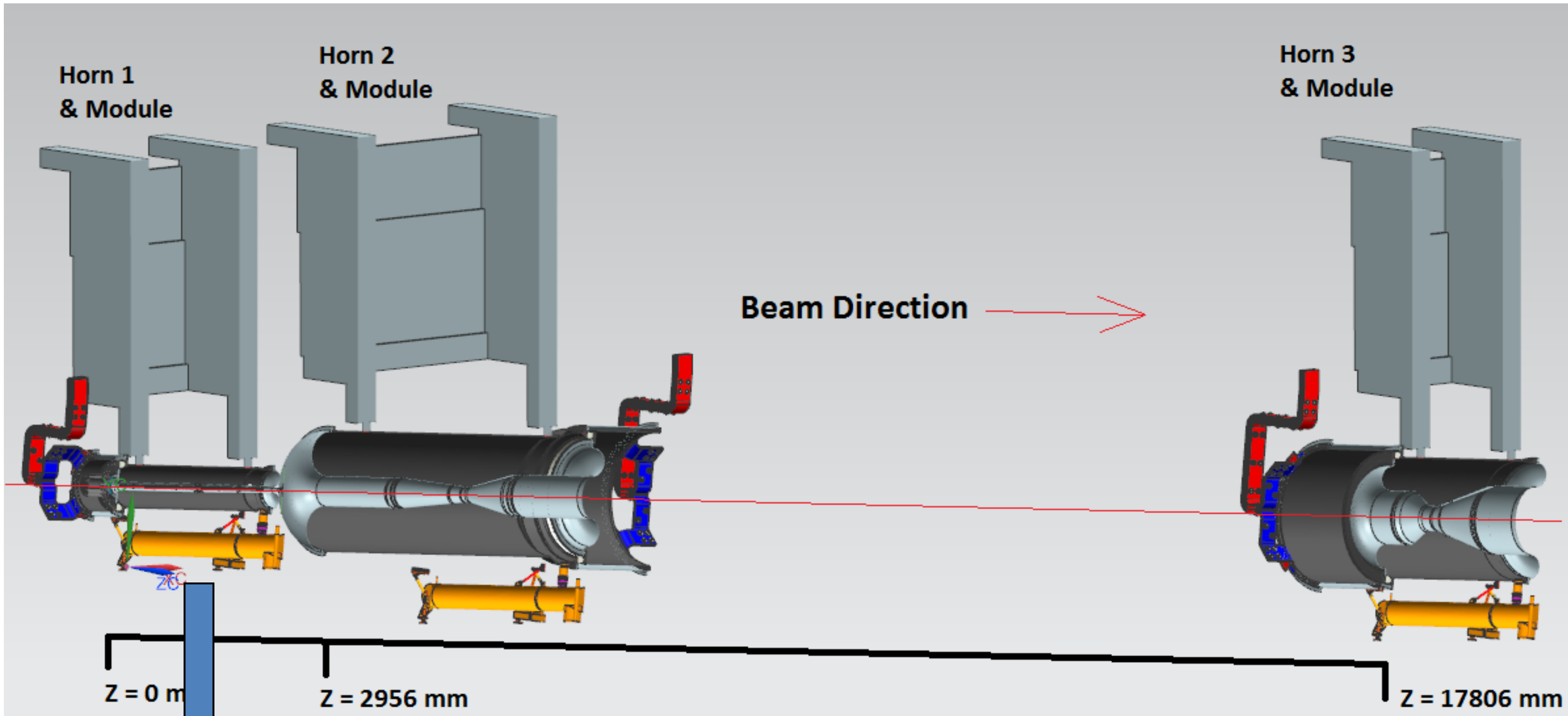


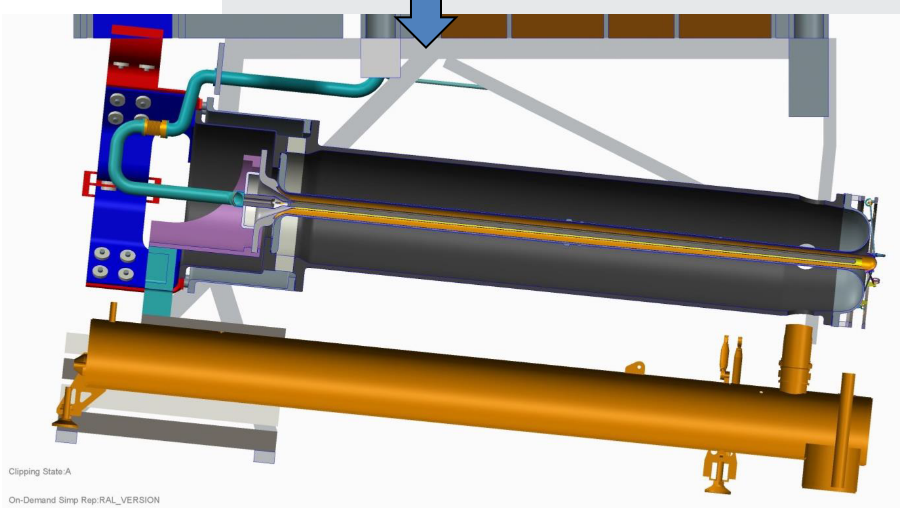
- Wide-band neutrino beam
- Genetic algorithm used to optimise horn & target (inspired by LBNO design study at CERN)





Target & horns optimized by genetic algorithm

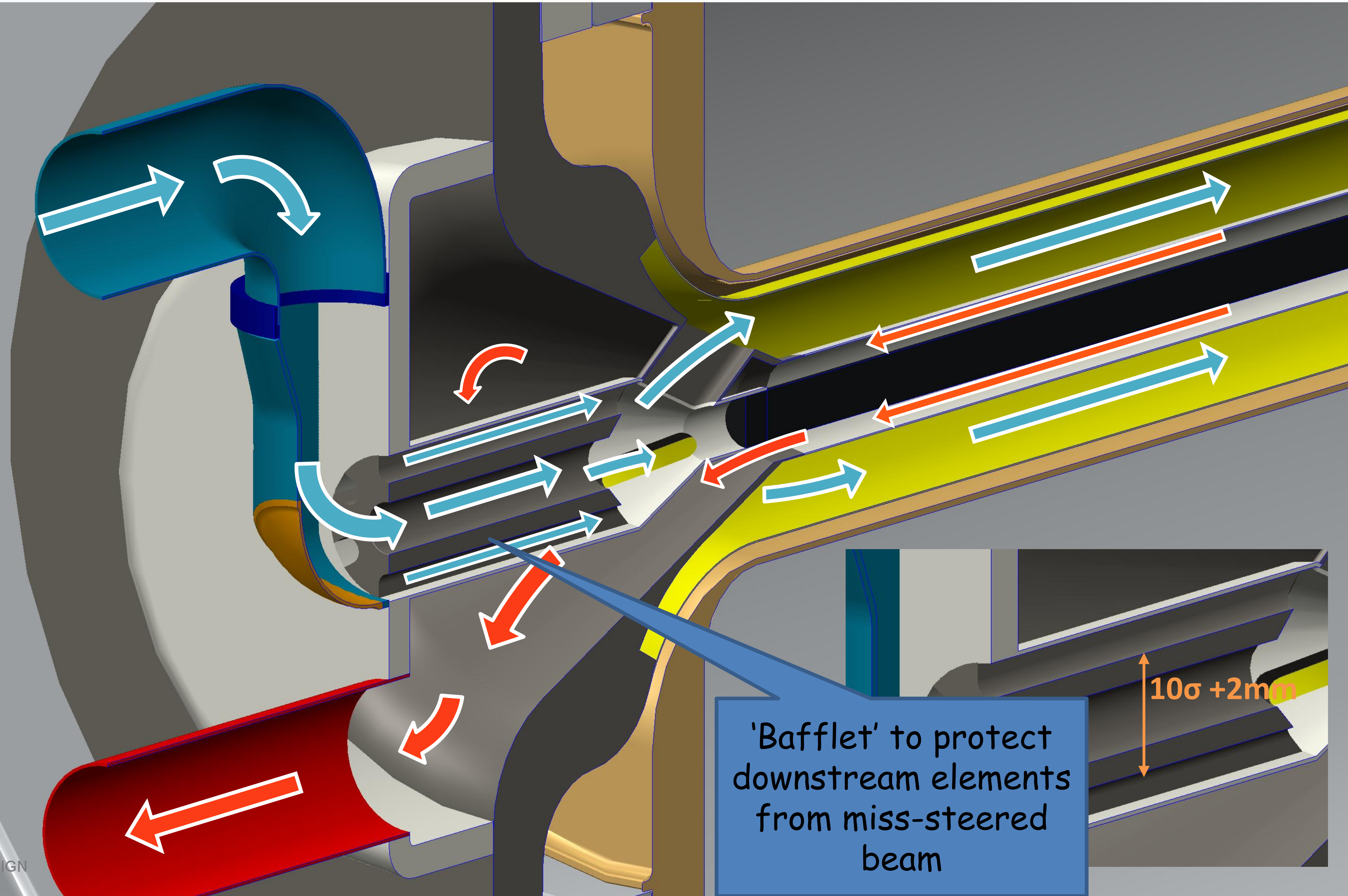




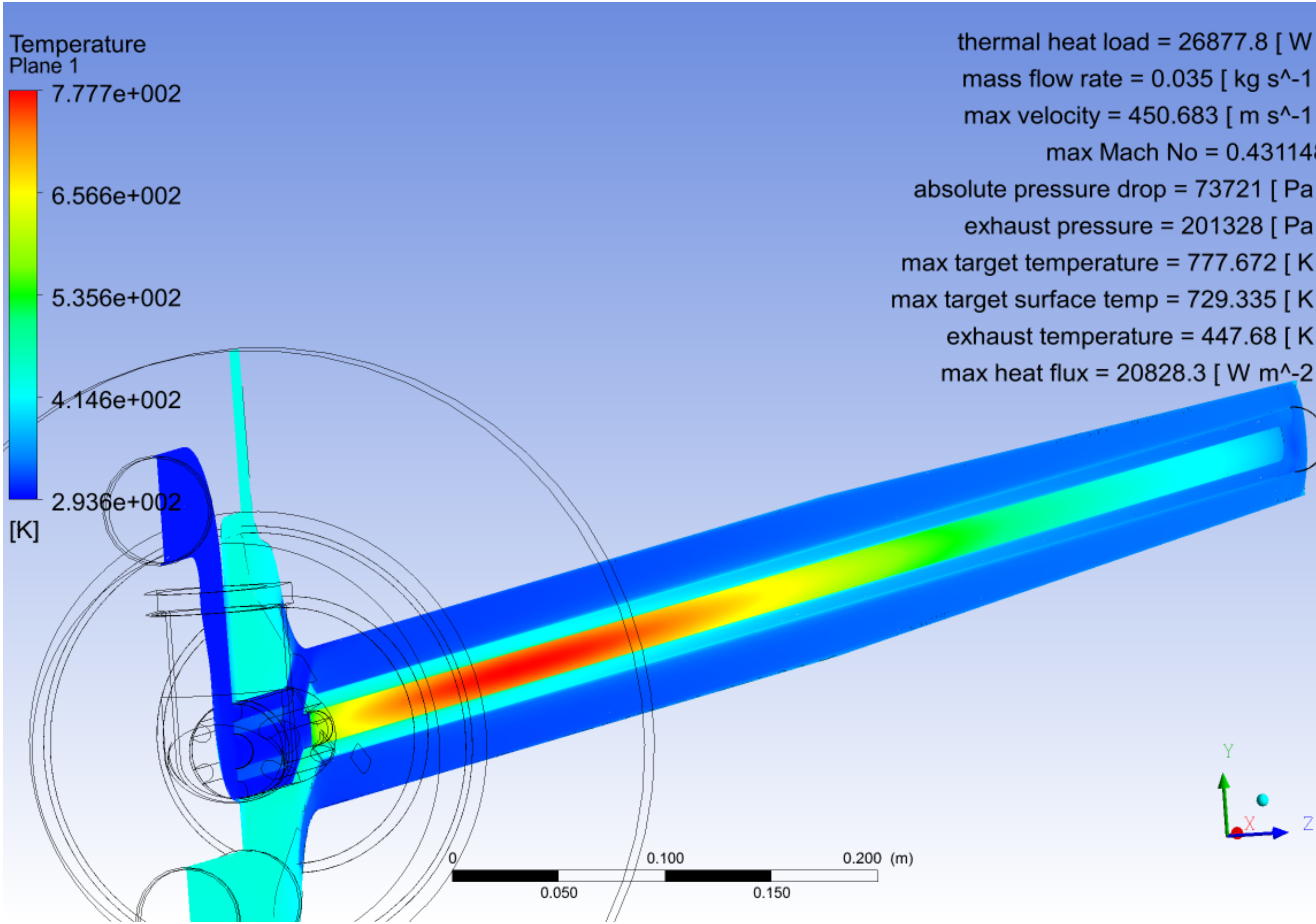
- 3 horn system (like T2K)
- New target plan:
- Change from water (like NuMI) to helium cooled graphite (like T2K)

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

Optimised helium cooled target proposal

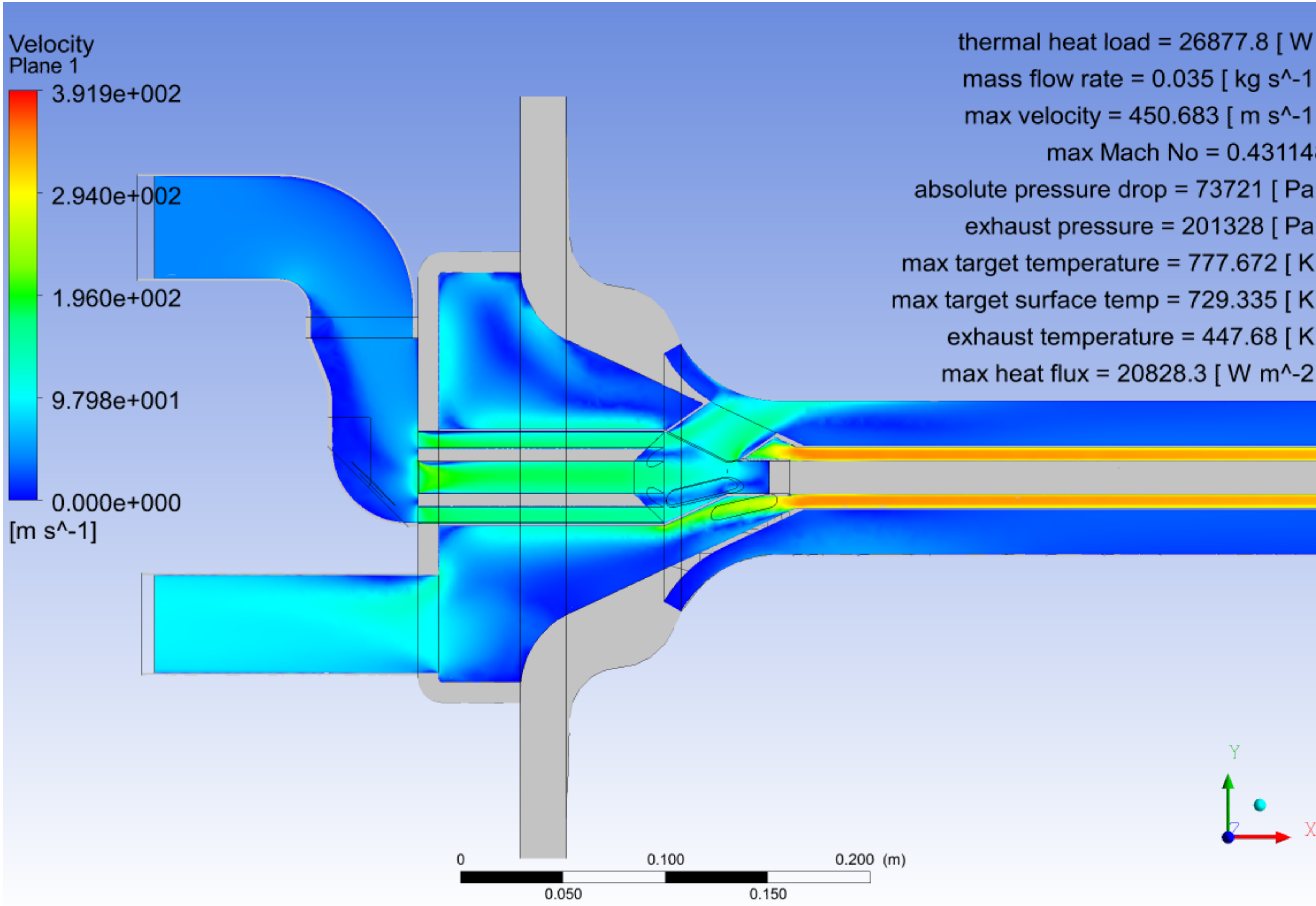


Temperatures at 1.2MW steady state simulation

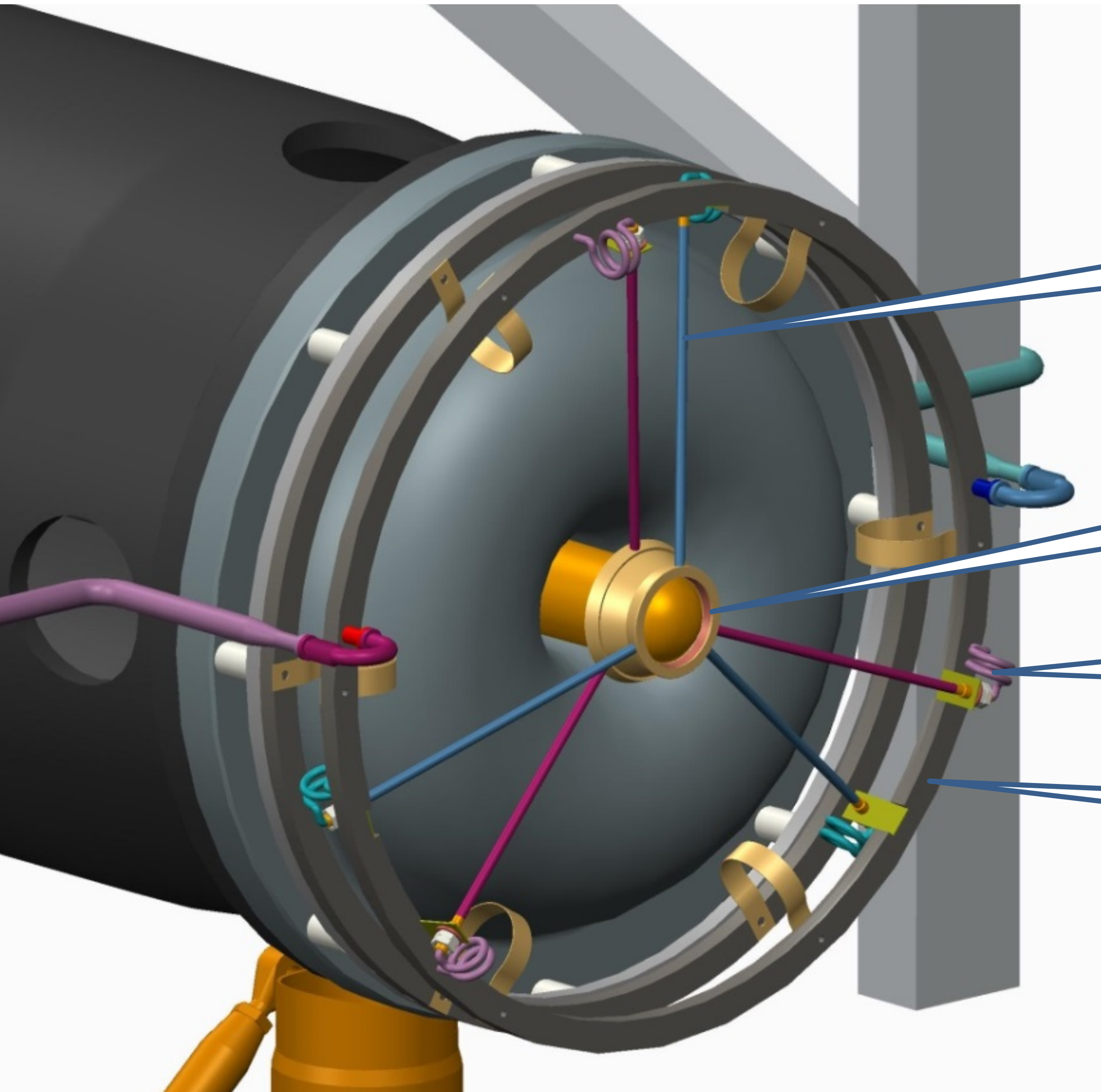


ratory

Helium Velocity at 1.2MW steady state simulation



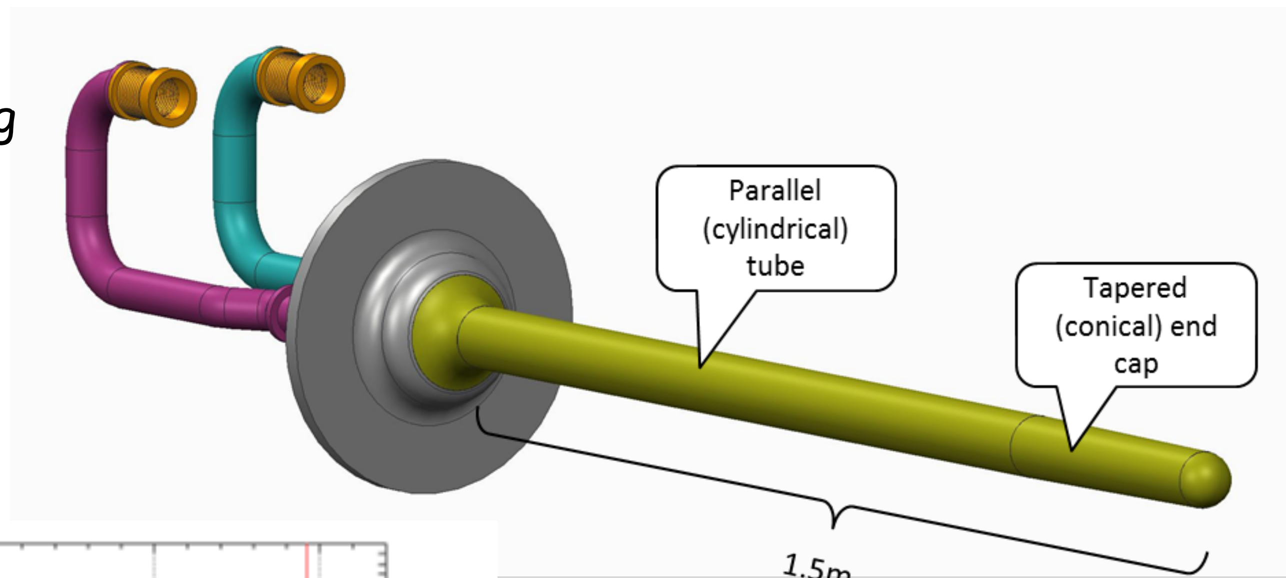
2 m long target: needs actively cooled downstream support

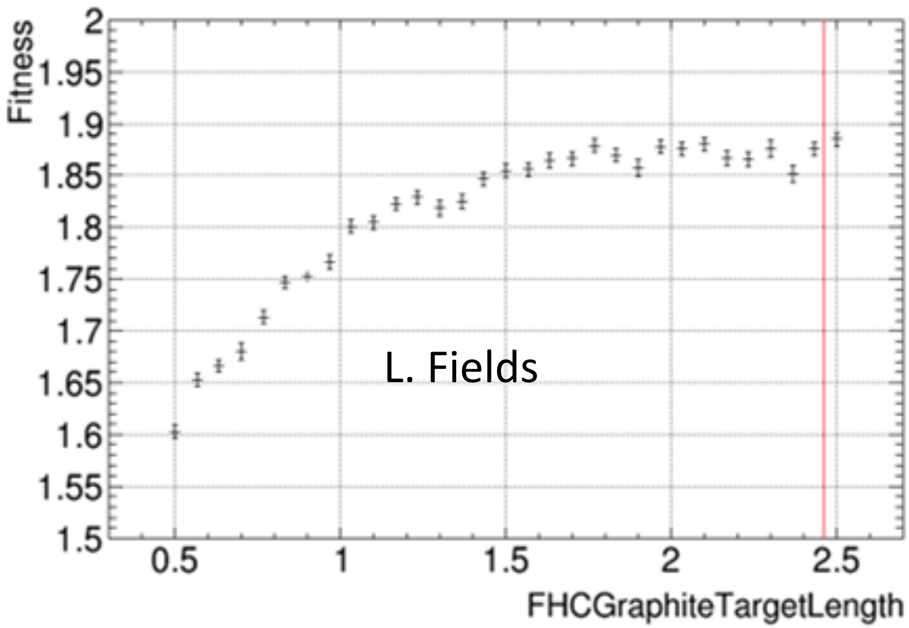


Possible simplification – longest practicable T2K-like cantilever c 1.5 m long

Two risks with proposed design –

1. Manufacture of long target
2. Reliably coupling with down stream support

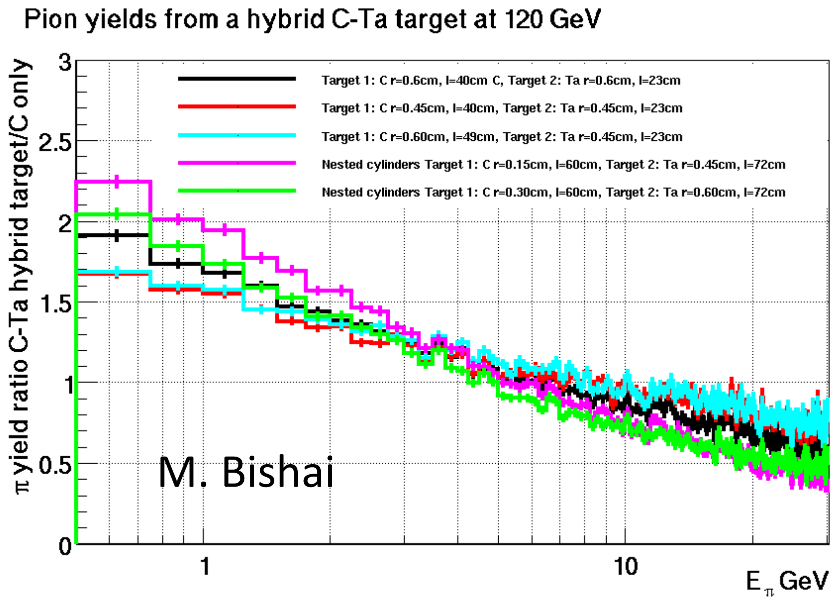


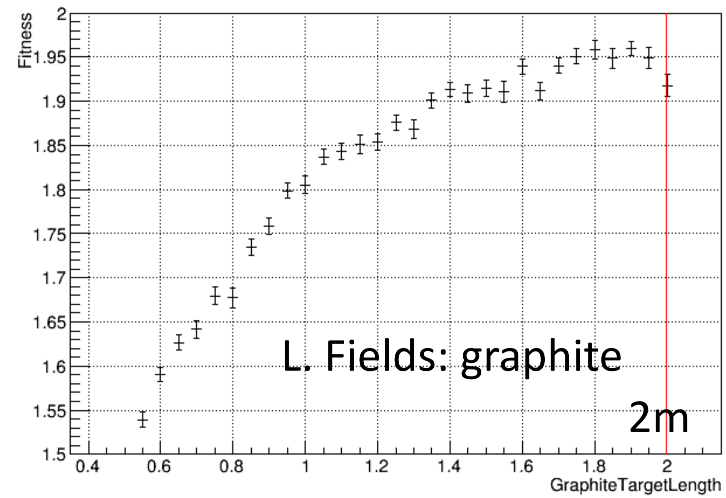


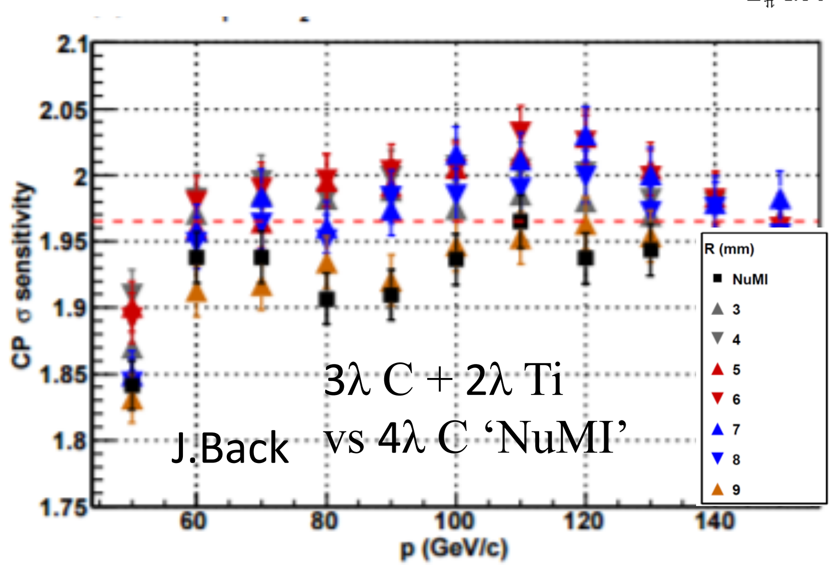
If the target is sufficiently short it could be supported as a simple cantilever with no downstream support

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

Target physics studies







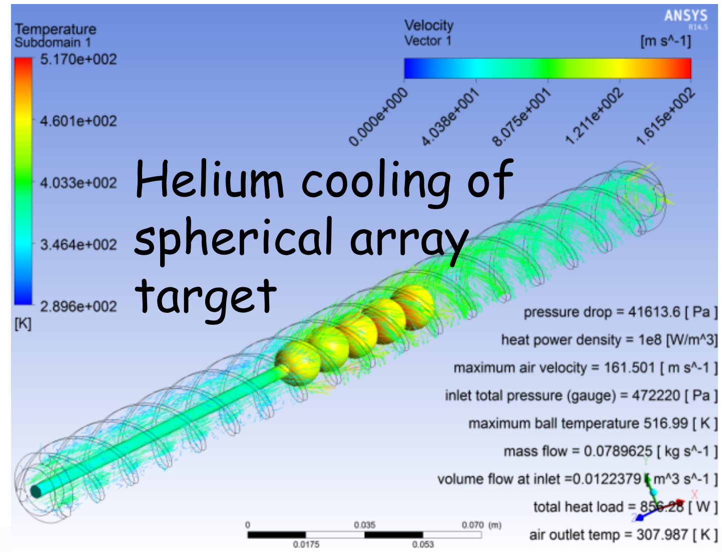
Investigations of longer &/or higher-Z materials to:

- increase pion yield
- reduce on-axis wrong-sign pions

Long (up to 2m / 4λ) graphite target offers best performance without excessive increase in complexity / heat loads etc

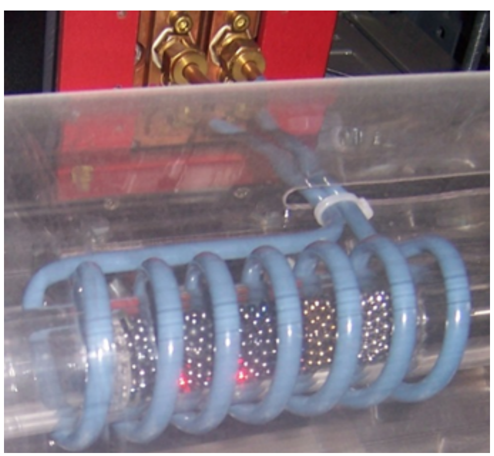
Hybrid target ideas

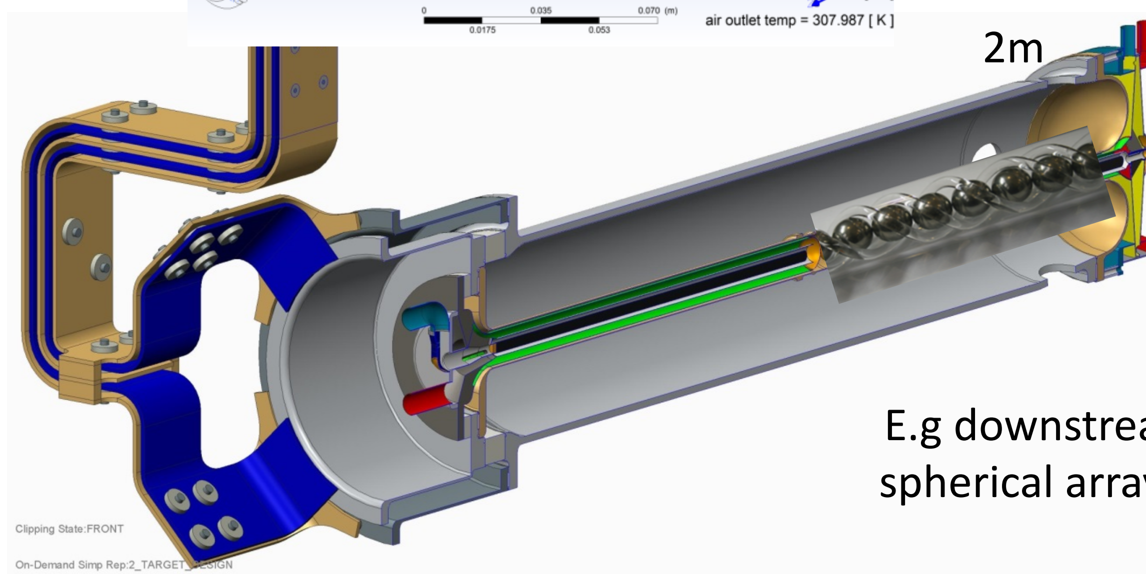
E.g. possibility to incorporate Spherical Array Target



Helium cooling of spherical array target

Induction furnace tests of packed bed



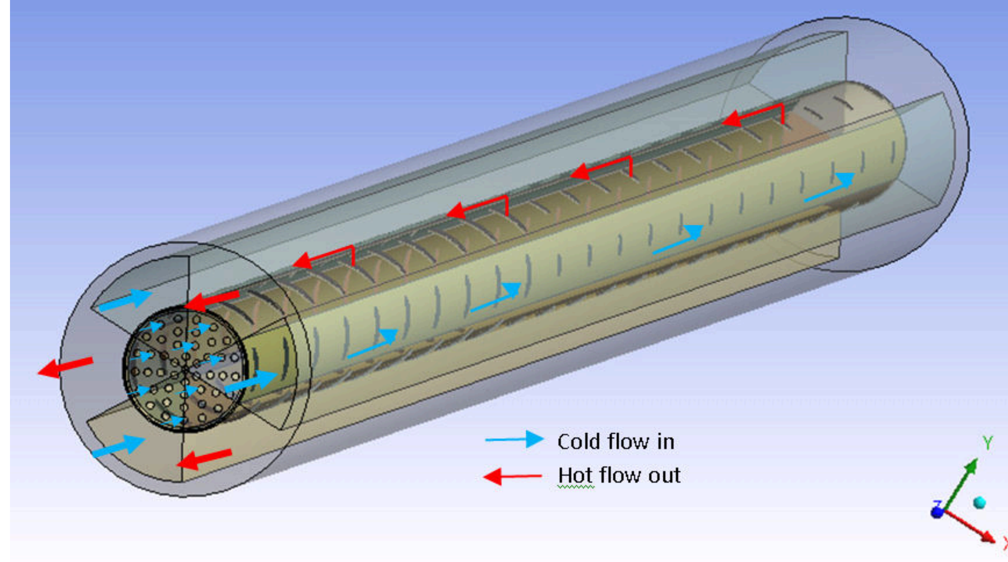


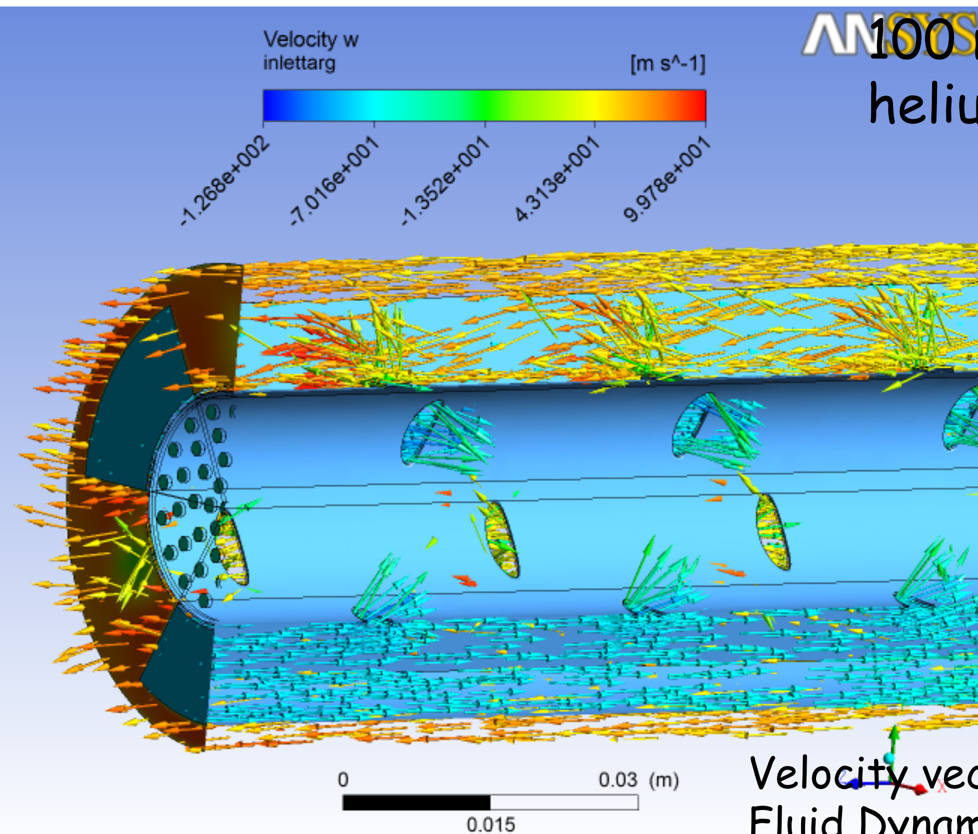
2m

E.g downstream spherical array –

Science & Technology Facilities Council
Rutherford Appleton Laboratory

Exploring limits of static, solid targets

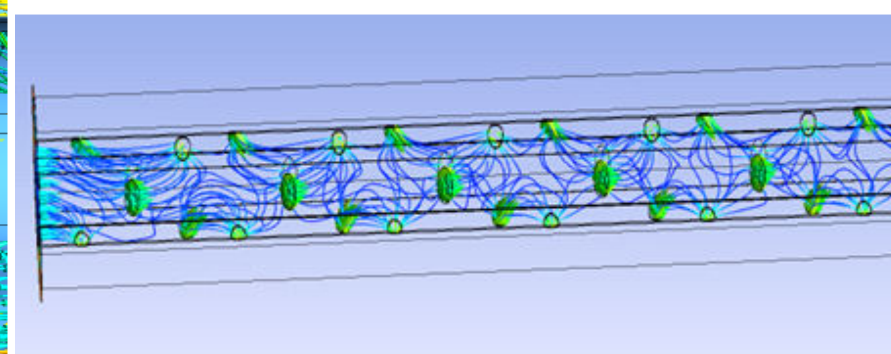




100 m/s helium

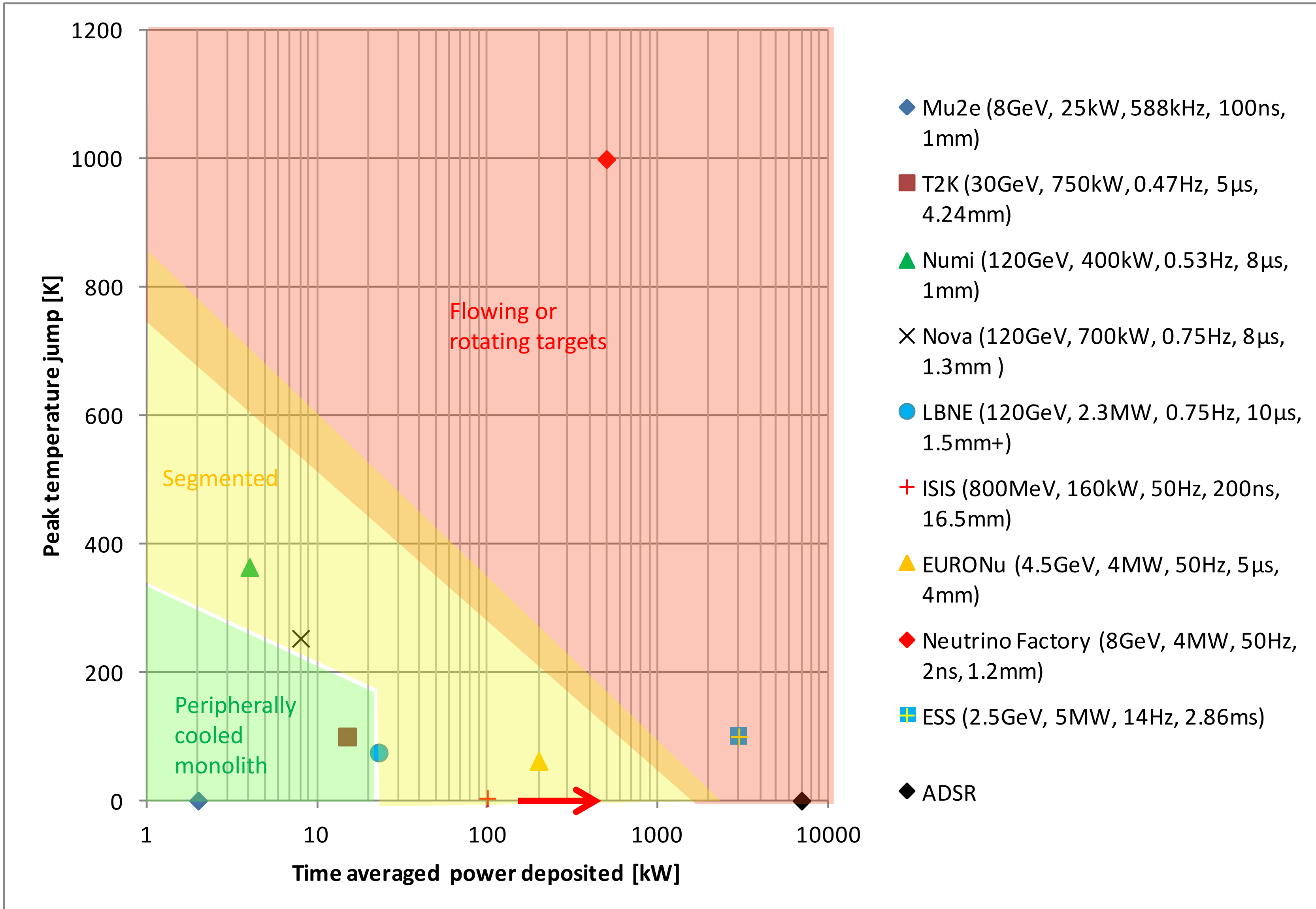
Packed bed target concept (Tristan Davenne)

Study for 4 MW Neutrino Superbeam



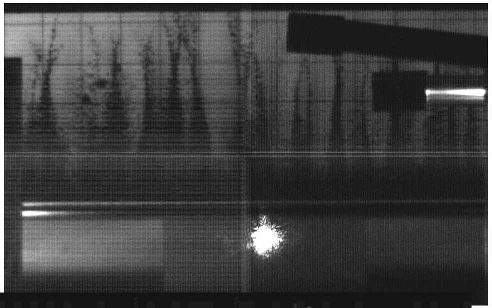
Velocity vectors from Computational Fluid Dynamics simulations

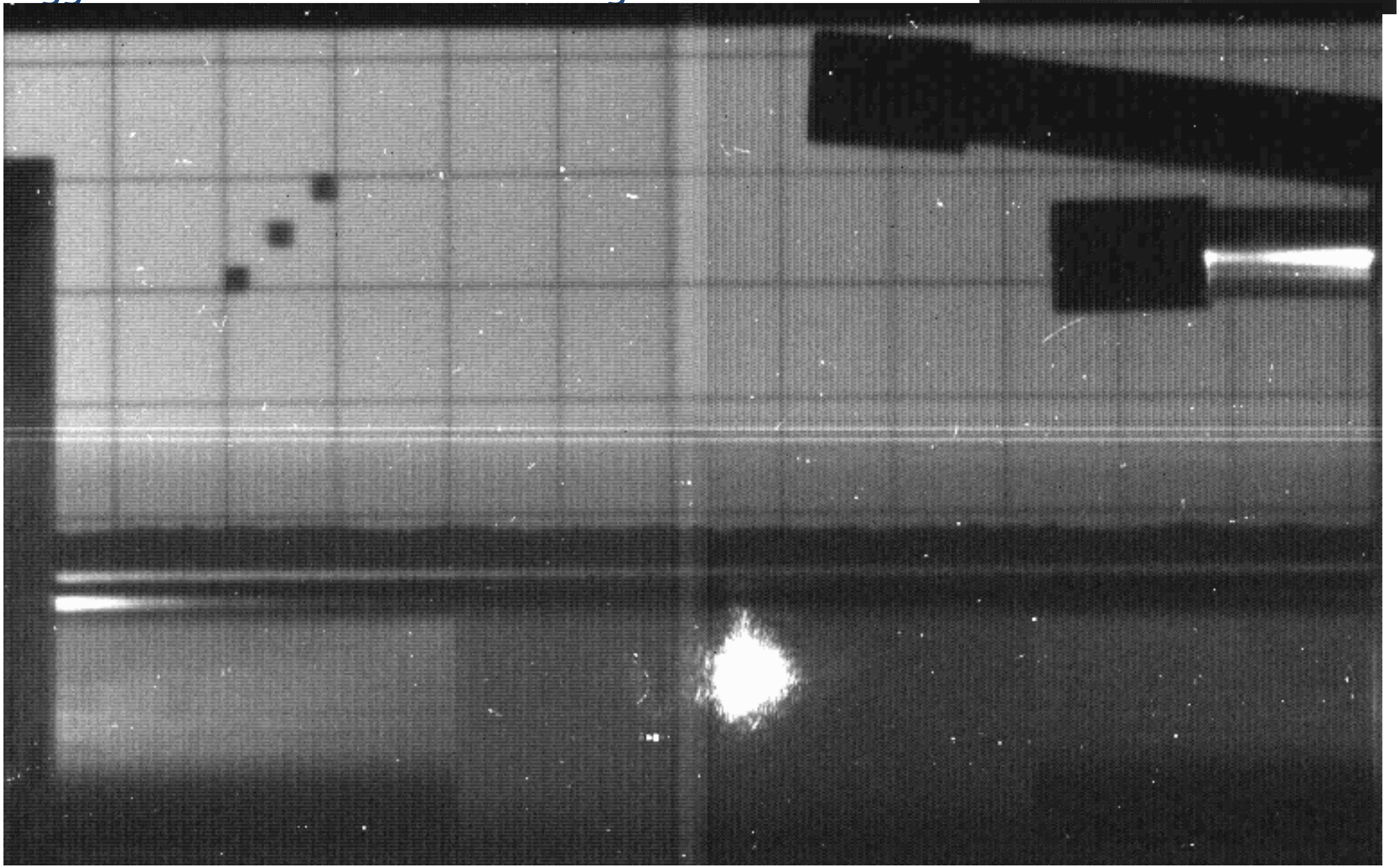
Limitations of target technologies



1st experiment on HiRadMat at CERN

- 3E+11 protons on tungsten powder in helium atmosphere (ΔT=c.365°C in 7μs)
  Bigger effect in vacuum -> charge induced





RaDIATE Collaboration

Radiation Damage In Accelerator Target Environments

www-radiate.fnal.gov

- 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,

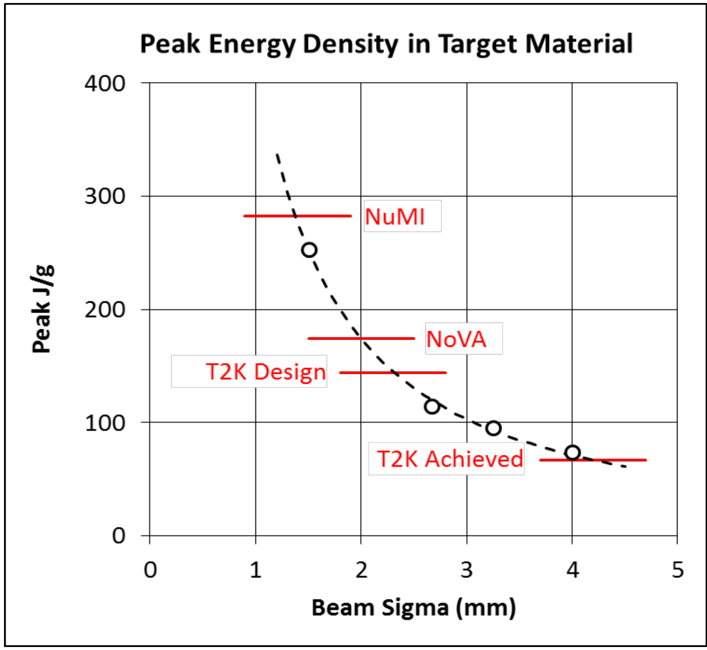
Fermilab
University of Oxford
Brookhaven National Laboratory
European Spallation Source
Argonne National Laboratory
Science & Technology Facilities Council
FRIB
Pacific Northwest National Laboratory
Oak Ridge National Laboratory
Los Alamos National Laboratory EST. 1943
Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
Science & Technology Facilities Council Rutherford Appleton Laboratory

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



Science & Technology Facilities Council
Rutherford Appleton Laboratory