LBNF/DUNE target - development of design

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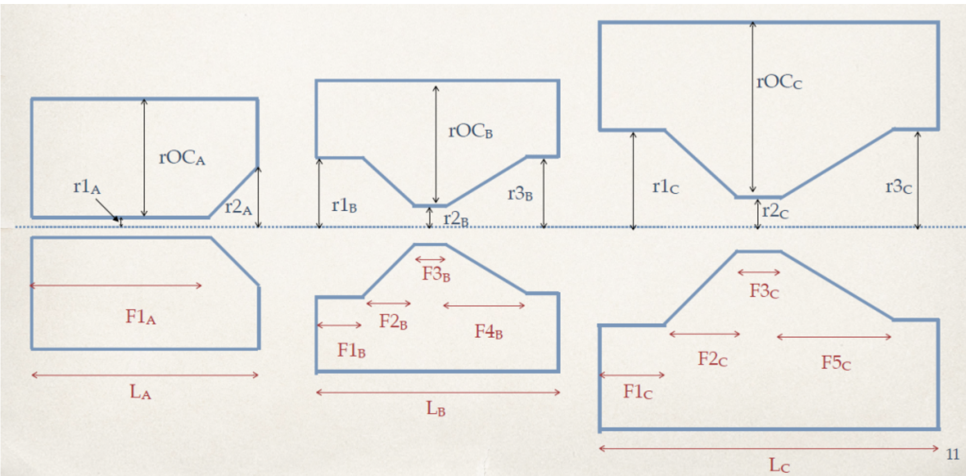
+ DUNE Collaboration

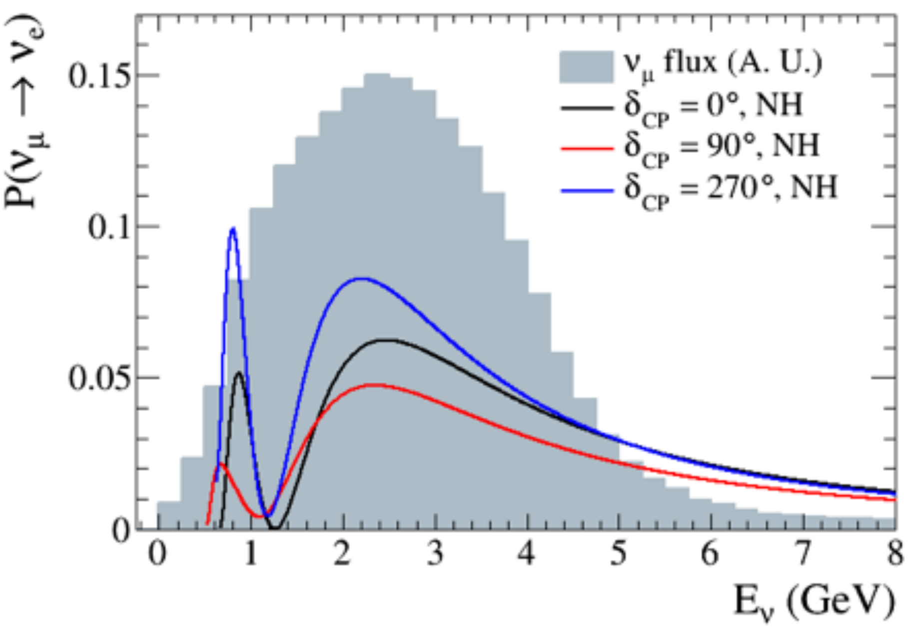
Fermilab

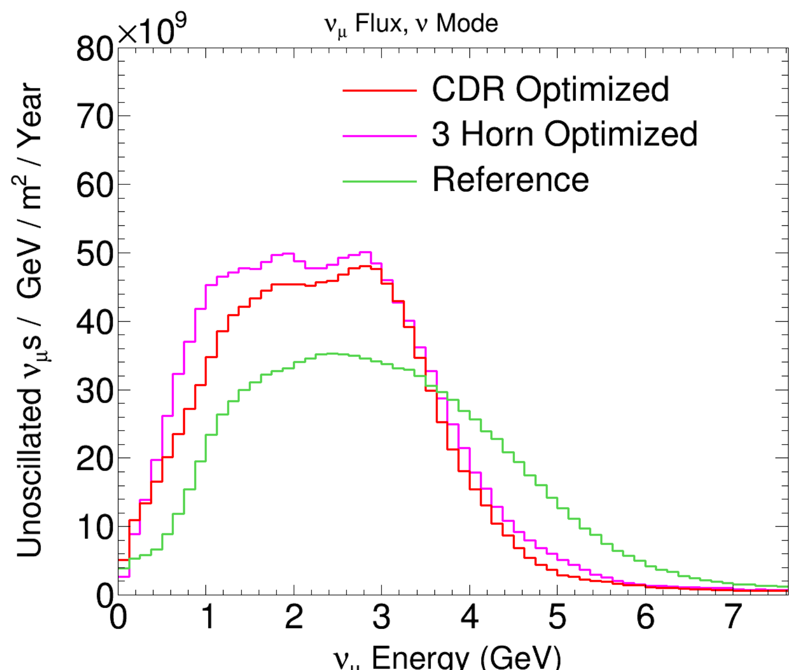
Science & Technology Facilities Council
Rutherford Appleton Laboratory

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

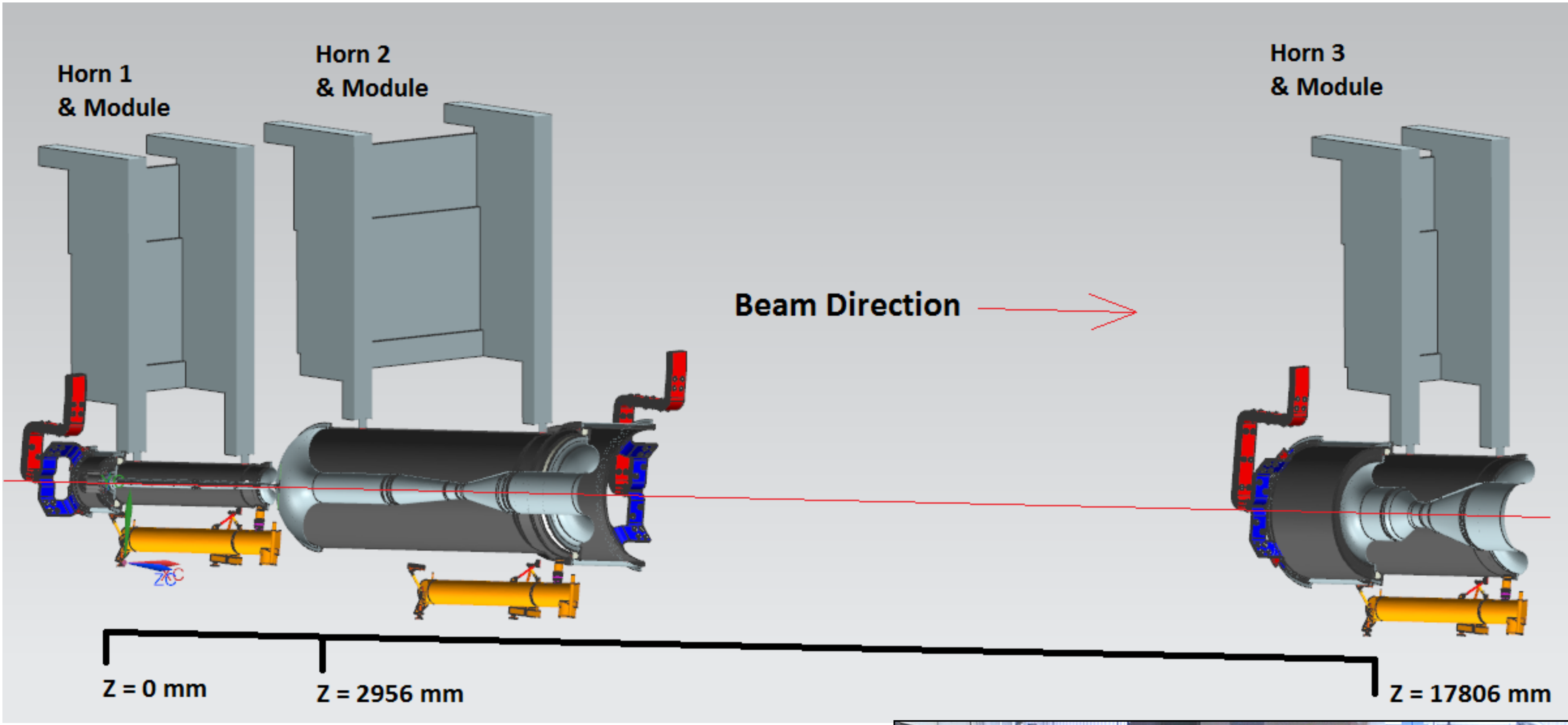


- Genetic algorithm used to optimise horn & target (inspired by LBNO design study at CERN)
- Long ($4\lambda_{int}$) target optimal:
    - higher yield
    - fewer on-axis wrong-sign pions

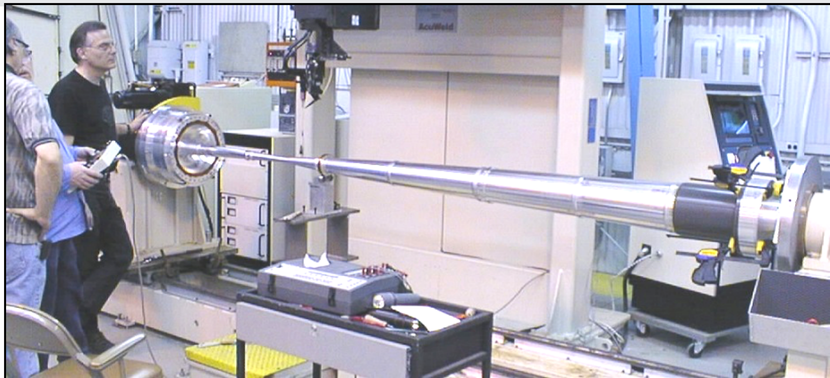




Optimized target & horns



C. Crowley

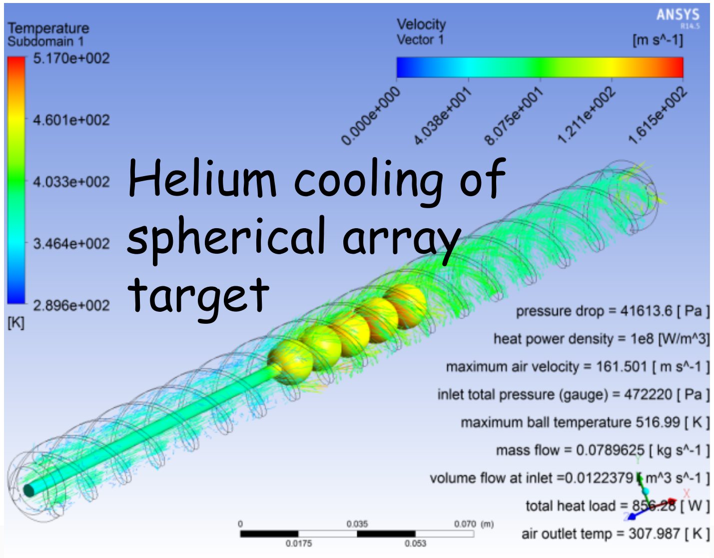


LBNF / T2K2 similarities

Current Project	NuMI, NOvA	T2K/SuperK
Beam energy	120 GeV	30 GeV
Beam cycle	2.2 s	2.48 s
Spill length	10 µs	4.2 µs
Target	2λ graphite	2λ graphite
Maximum beam power to date	0.74 MW	0.47 MW
Planned upgrade beam power	1.2 MW	1.3 MW
Upgrade project	LBNF/DUNE	T2K2/HyperK

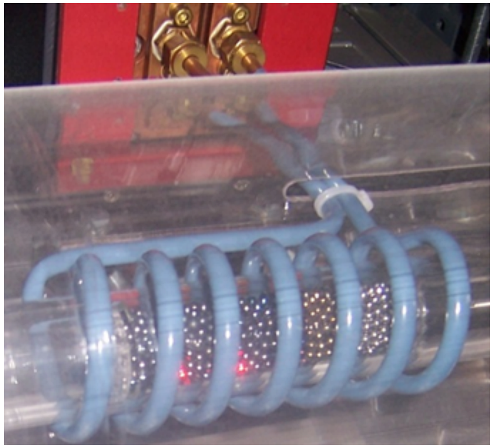
Hybrid target ideas

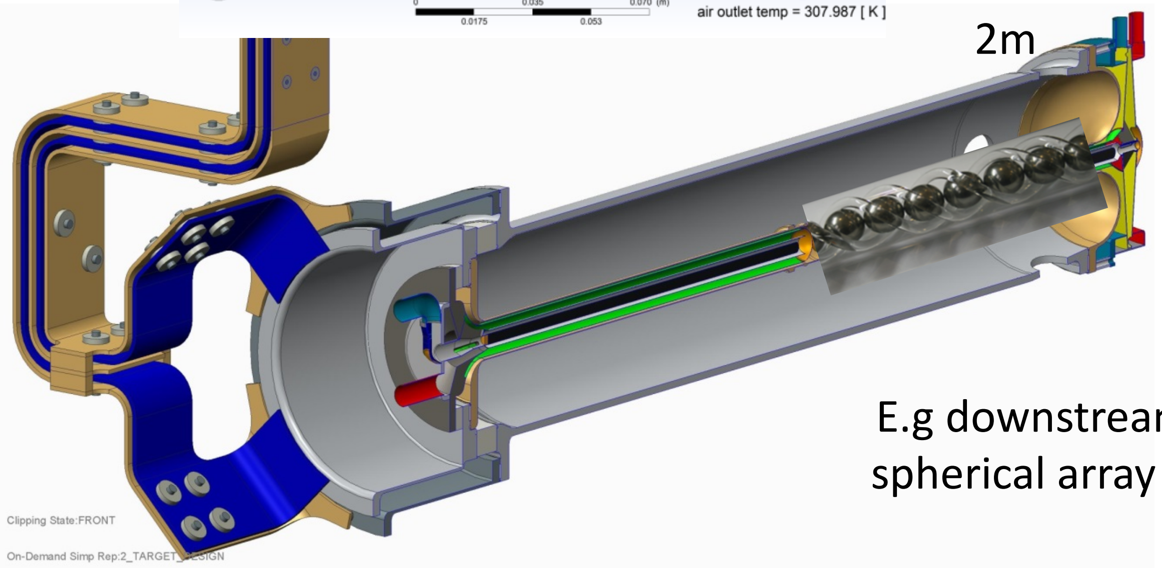
E.g. possibility to incorporate Spherical Array Target



Helium cooling of spherical array target

Induction furnace tests of packed bed

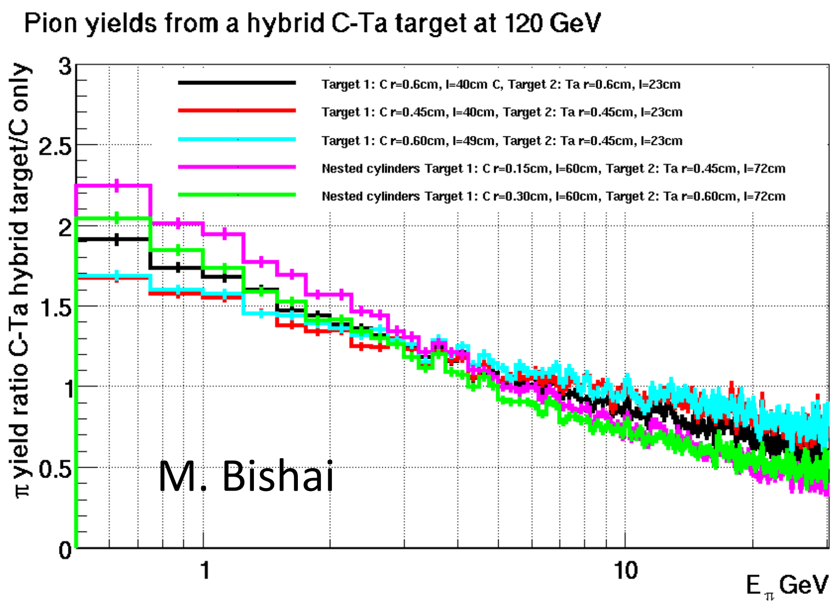


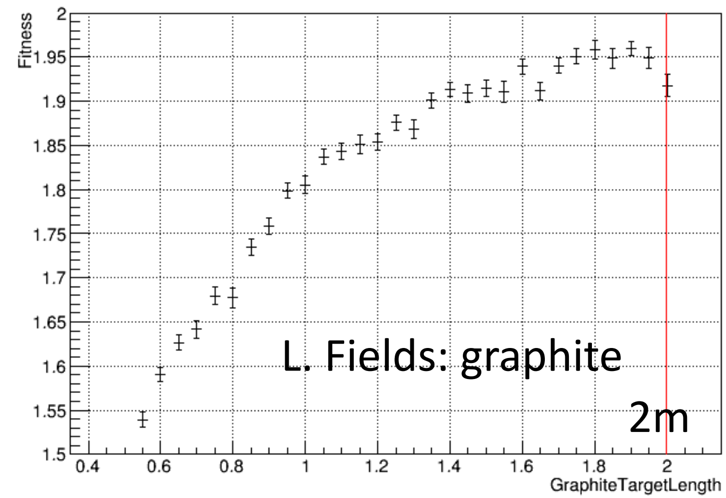


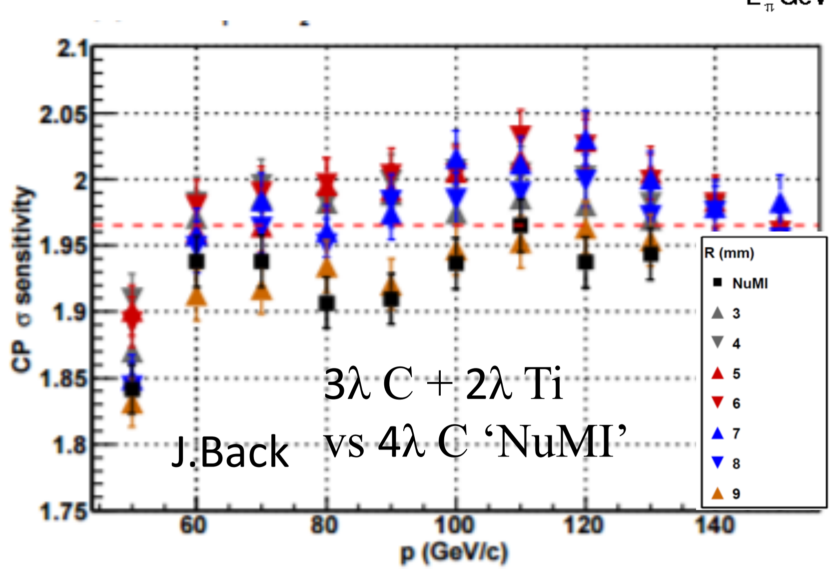
2m

E.g downstream spherical array –

Target physics studies







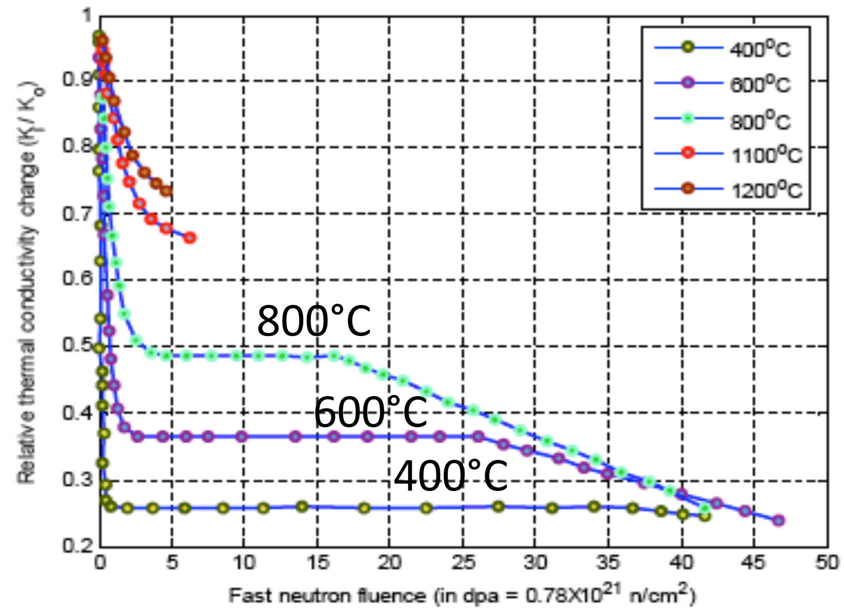
Investigations of longer &/or higher-Z materials to:

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

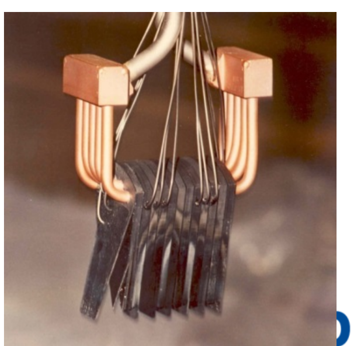
Long (c.2m / 4λ) graphite target offers best performance without excessive increase in complexity / heat loads etc

Radiation damage of graphite vs temperature

Graphite thermal conductivity degradation by radiation damage



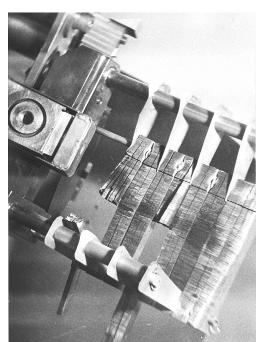
Degradation of thermal conductivity due to fast neutron irradiation damage on graphite IG110



←LAMPF

PSI→

10^{22} p/cm^2



NuMI water cooled target

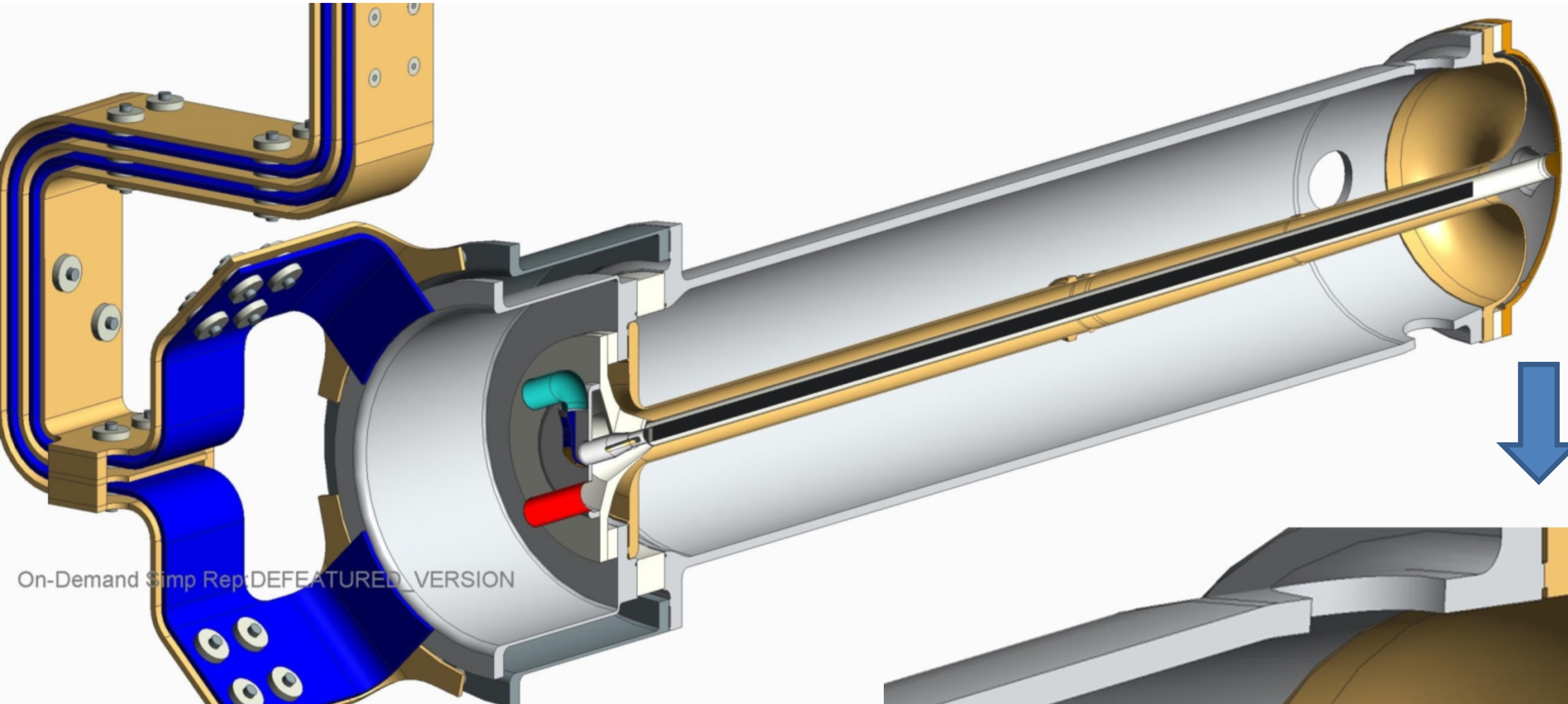
Target cooling

	NuMI/NOvA	T2K
Target material	Graphite: POCO ZXF-5Q	Graphite: IG 430
Cooling	Water (forced convecion)	Helium (forced convection)
Pros	•Efficient (High HTC) •Simple system	•Low pion absorption •No shock issues •Allows graphite to run hot (longer lifetime) •Reduced activity
Cons	•Water hammer, cavitation •Hydrogen + tritium + water activation • Pion absorption in coolant •Increased radiation damage of graphite	•High flow rate (large compressors etc) •Complex plant •Possible contamination from failed target?

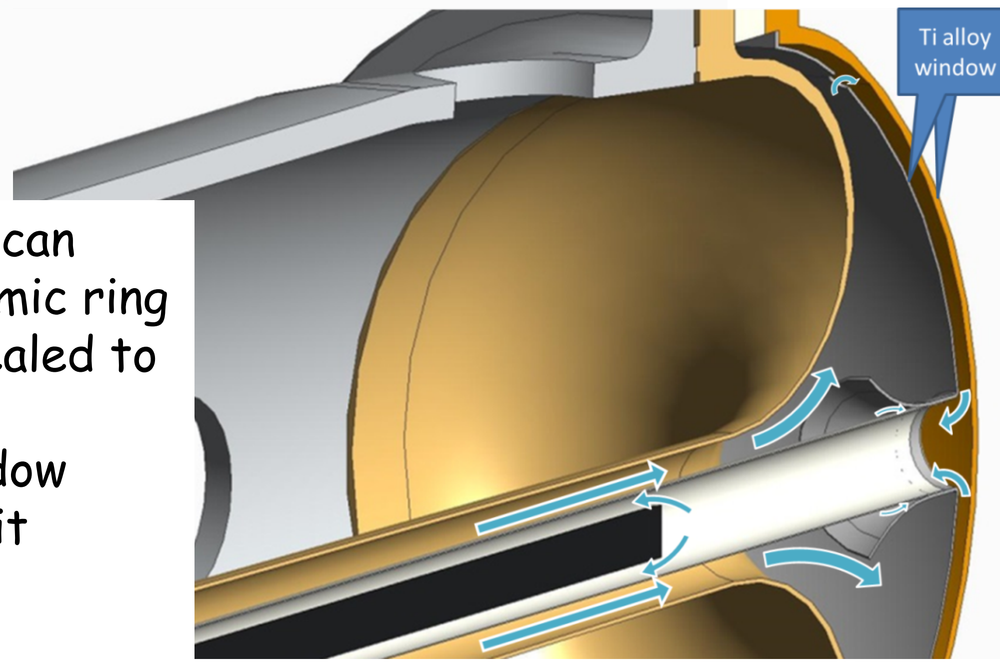
LBNF target design objectives

- 4λ (c.2 m) long graphite target fully installed in first horn
- Target radius r = 3σ, σ = 1-4 mm
  - First iteration with σ = 4 mm (now σ = 2.667 mm)
- Investigate simplified target, fully helium cooled a la T2K
- Investigate replaceable target mounting concept
- Identify potential impact of design on horn, remote handling and plant/services

Option 'A': LBNF helium cooled graphite target concept integrated with Horn

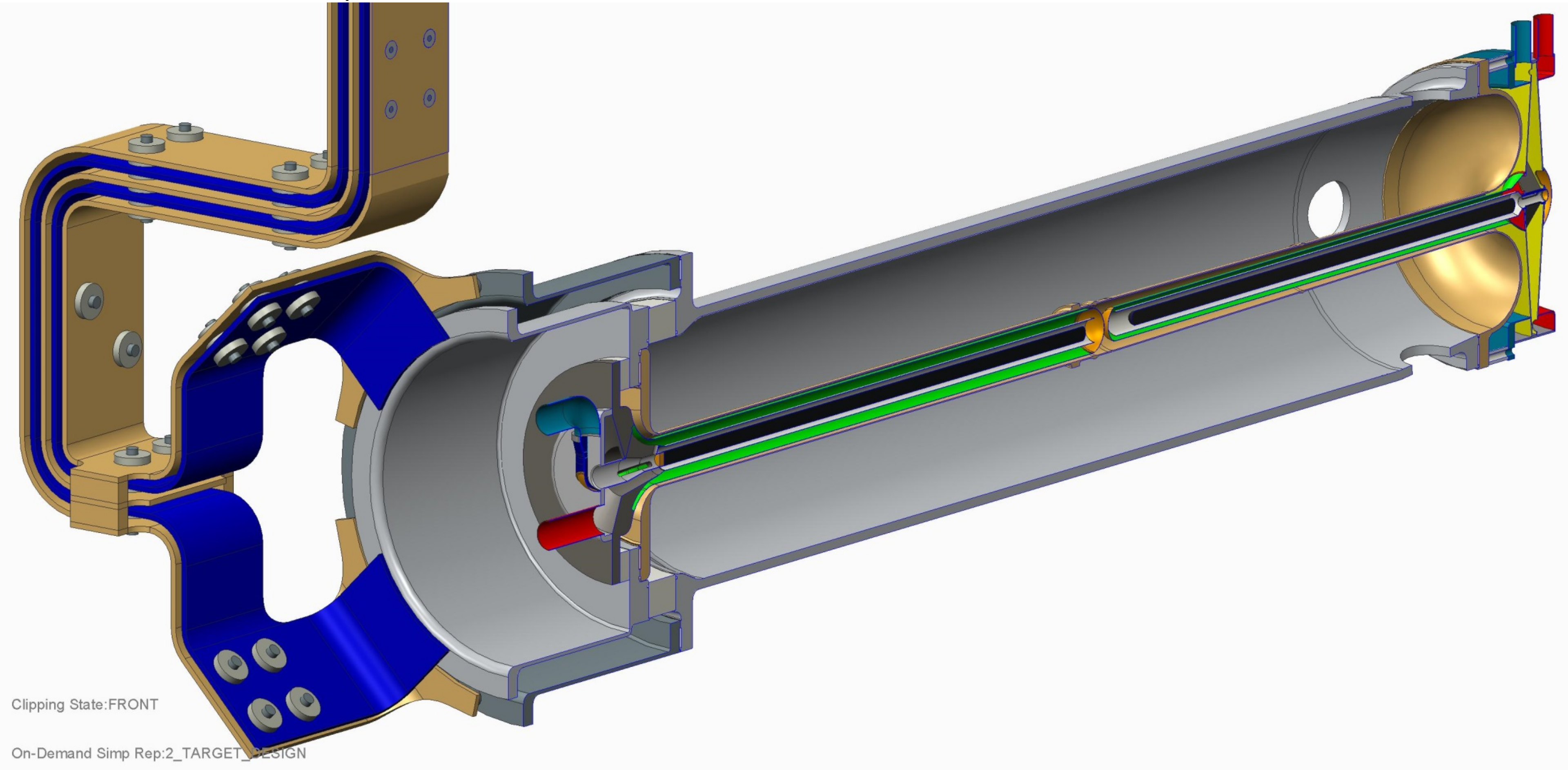


- Horn IC used as target outer helium can
    - Target sealed upstream via ceramic ring
    - New downstream horn window sealed to horn via ceramic ring
- Both Upstream and Downstream window cooled by target helium cooling circuit
- Target and downstream window both remotely replaceable



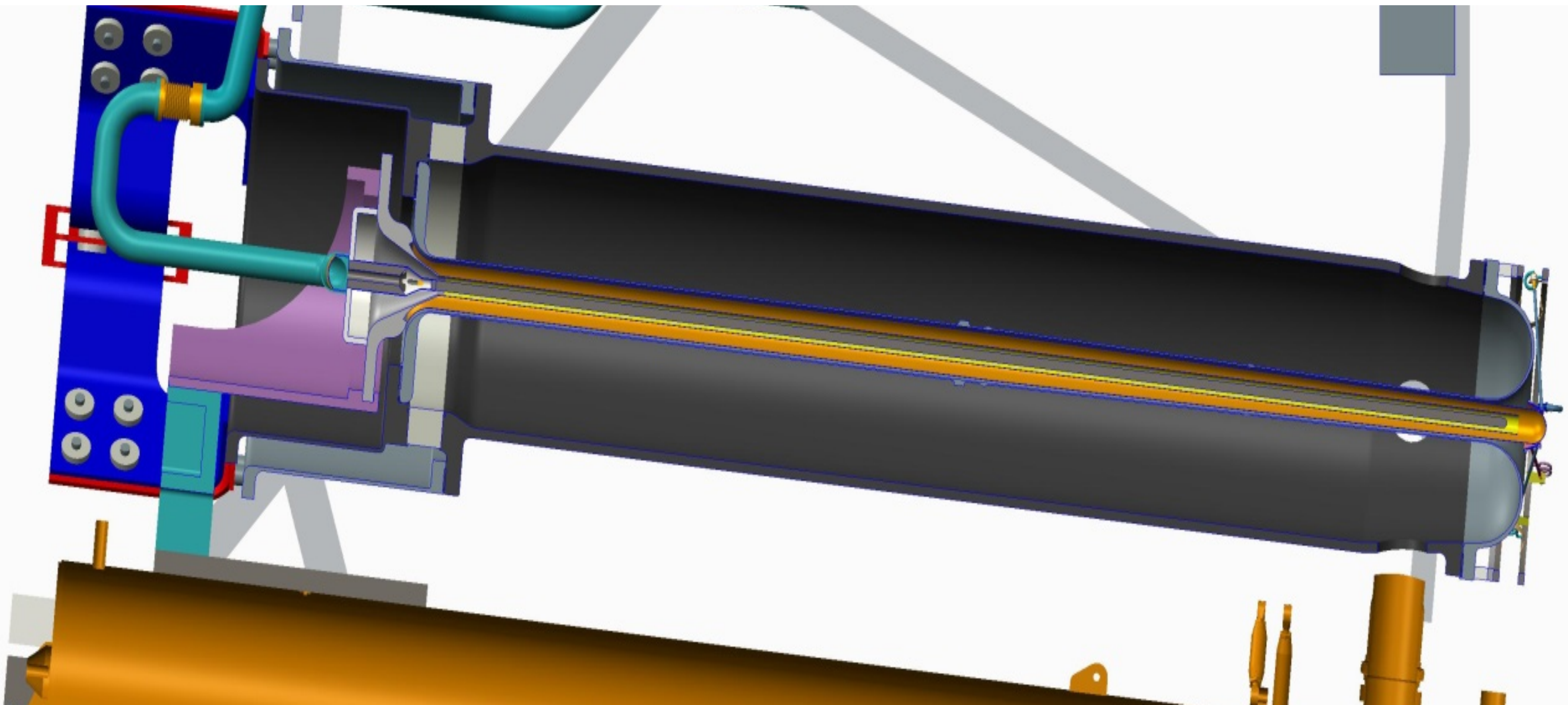
Option 'B': Double target concept

Target at each end of the horn
DS target has a stiff, low weight structure to minimise impact on physics
Outer sheath of the DS target smaller in diameter than the US end due to the shape of the horn.



Option C – long target concept – possible new 1.2 MWbaseline

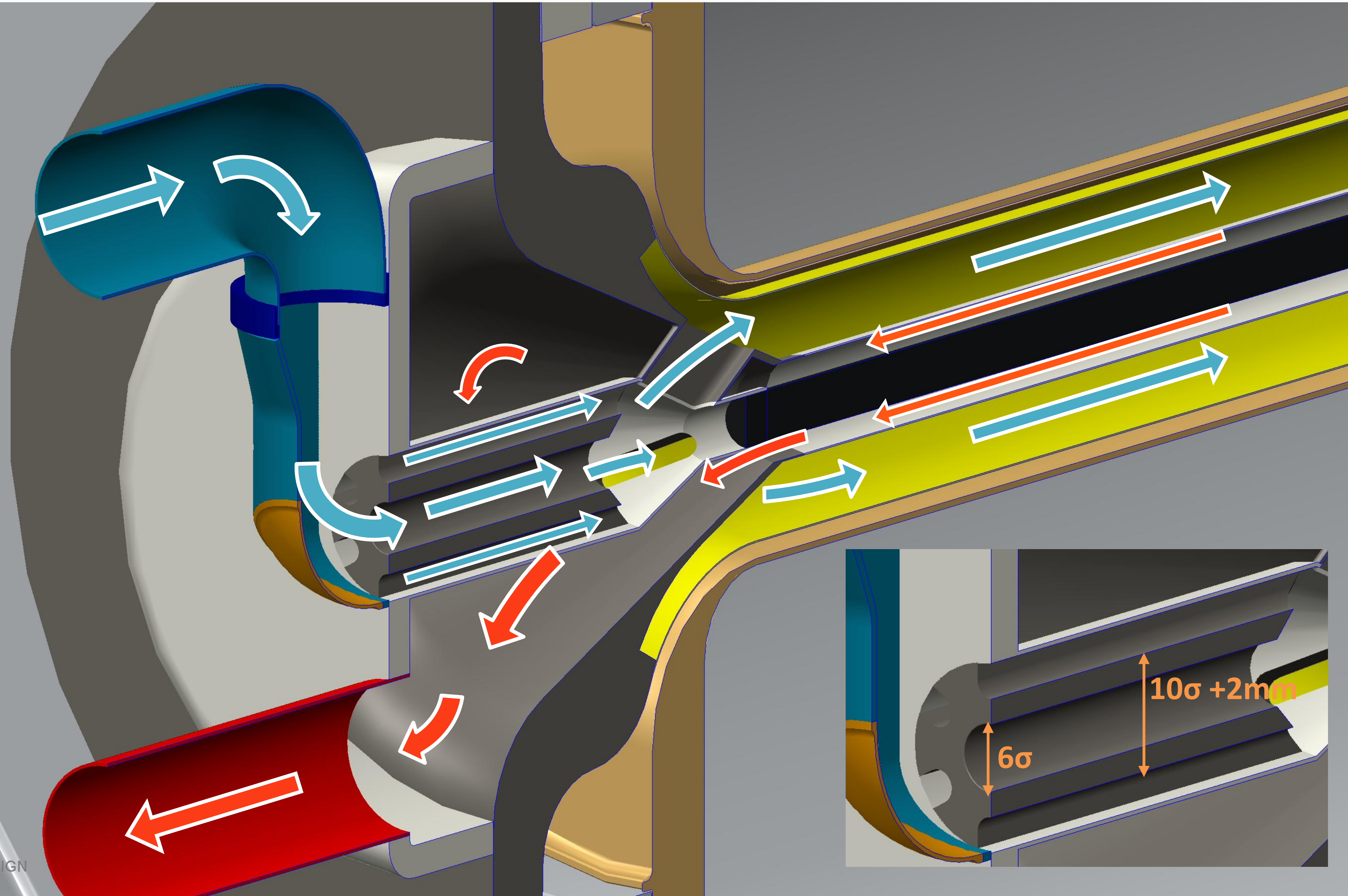
- Target docks into separate helium cooled downstream support
- 'Bafflet' incorporated into target container
  - Bafflette 12 cm long, covers radius 3σ→5σ + 1mm
  - Currently sized to protect beam dump (not target tubes)



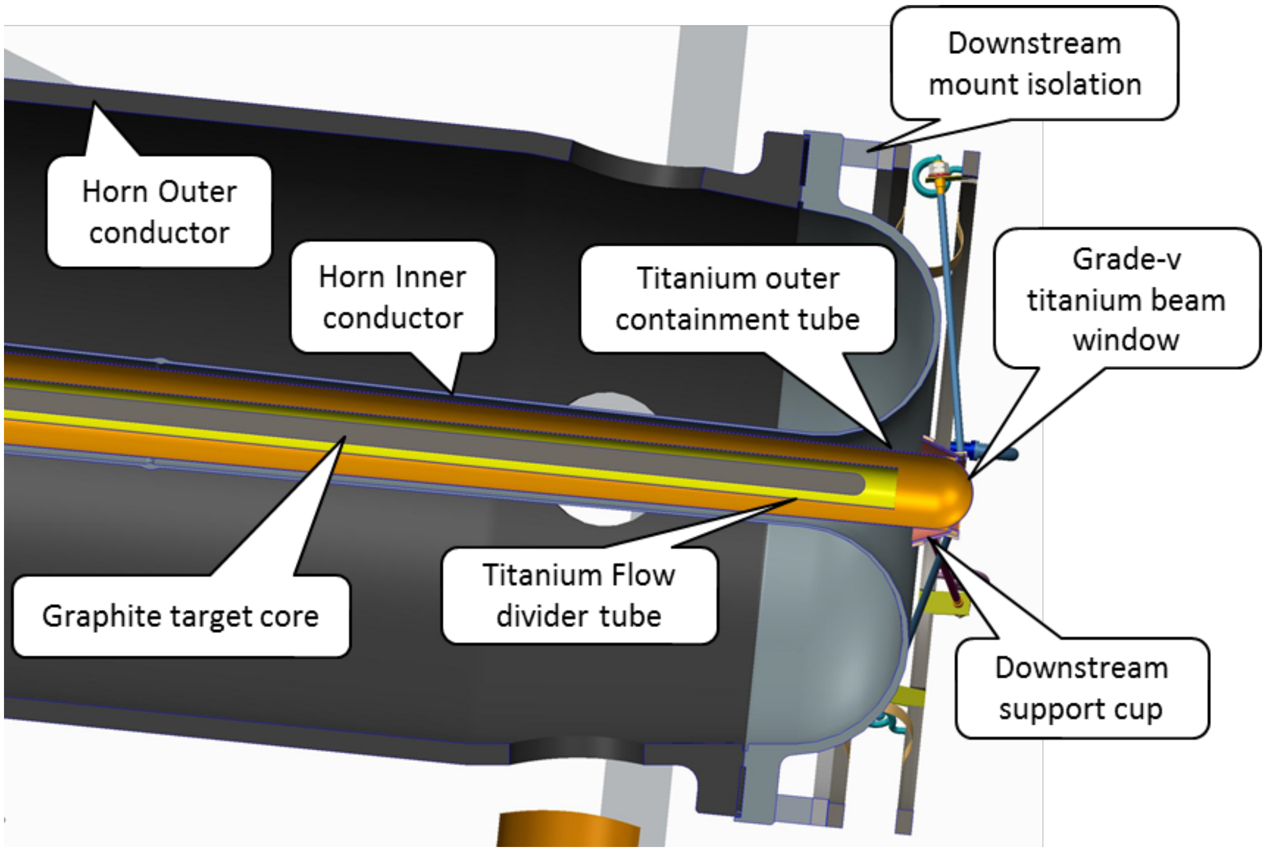
Pros & Cons: Easy as A,B,C?

Concept	Advantages	Disadvantages
A – One 2m long target using the inner bore of the horn as containment for the coolant	• Large flow area and low speed turn around lead to low coolant pressure drop • Single coolant circuit cools target and downstream support	• Requires large helium seals to horn • Requires 2m long thin walled titanium tubes (tapered) , may have to consider grades other than grade 5
B – Two self contained 1m long targets, one inserted each end of the horn	• Least departure from successful T2K target design • Easier to manufacture shorter targets • Modular approach makes testing and fault diagnosis easier • Most easily upgradable to higher power	• Downstream manifold may have a greater physics penalty • Additional alignment challenges • Two separate coolant circuits
C – One self contained 2m long target	• 'Simple' downstream support with small coolant flow and minimal physics impact	• Highest pressure drop • Two separate coolant circuits • Requires 2m long thin walled titanium tubes (tapered), may have to consider grades other than grade 5

Option C: + Incorporation of a bafflet



Downstream support - required for 2 m long target



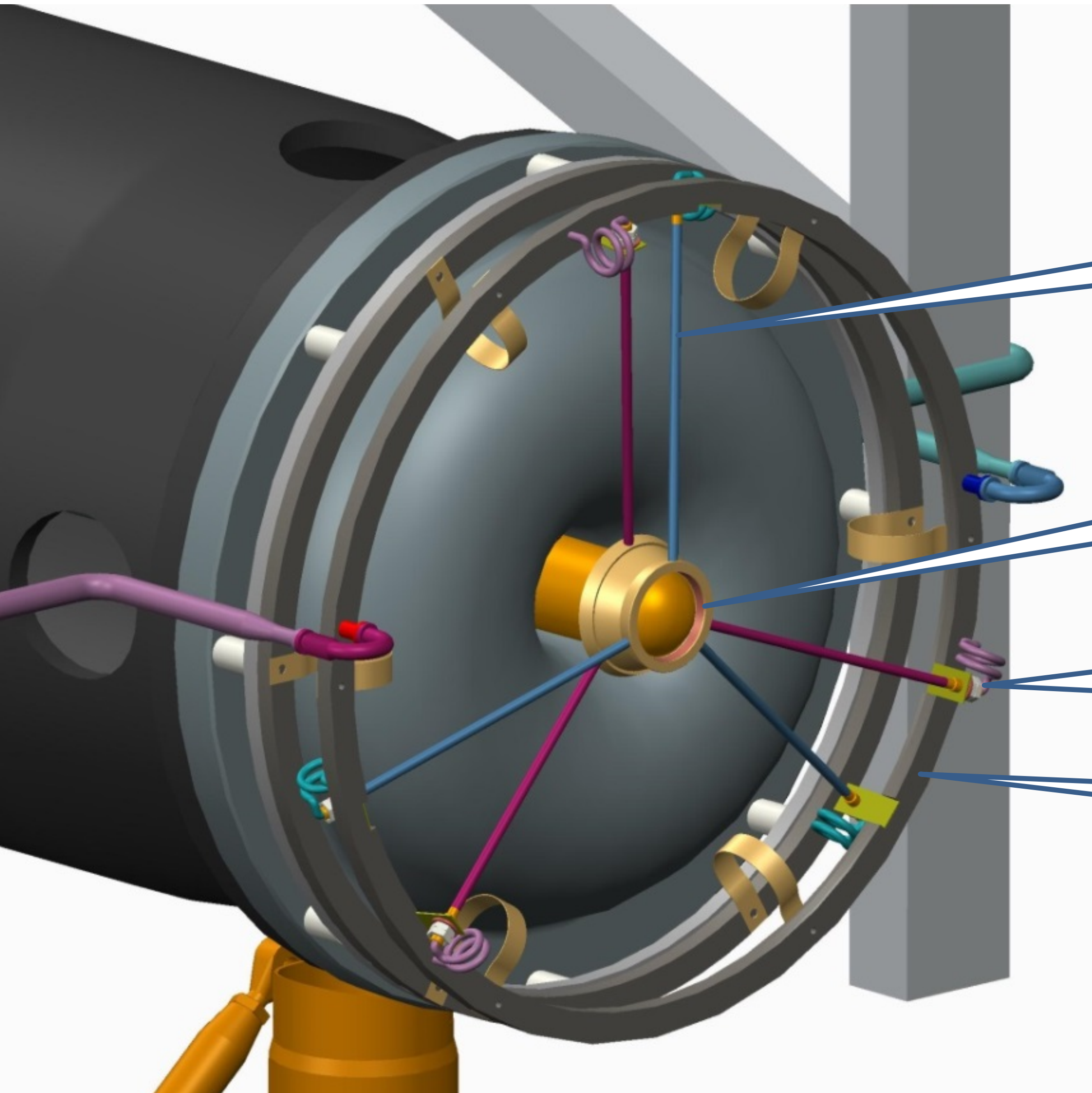
Calculations on the bending stiffness of a 2m cantilever target show the need for down-stream support. This DS support has been considered with reference to:

- Interface with target outer can (install and remove)
- Light weighting
- Amount of heat generated in mounting material
- Cooling required
- Conceptually the support can be made up of a support cup, rods or tubes, and an adjustable mounting ring.

Actively cooled DS support

- A cooled support does not rely on a good thermal connection to the cooled target can, which removes the risk of overheating.
- It can also be heavier and more robust than the un-cooled version, meaning it could potentially be permanently built into the horn without the need for remote replacement
- Requires additional helium circuit (probably tapped off of main target helium circuit)

Actively cooled DS 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

CFD of downstream support

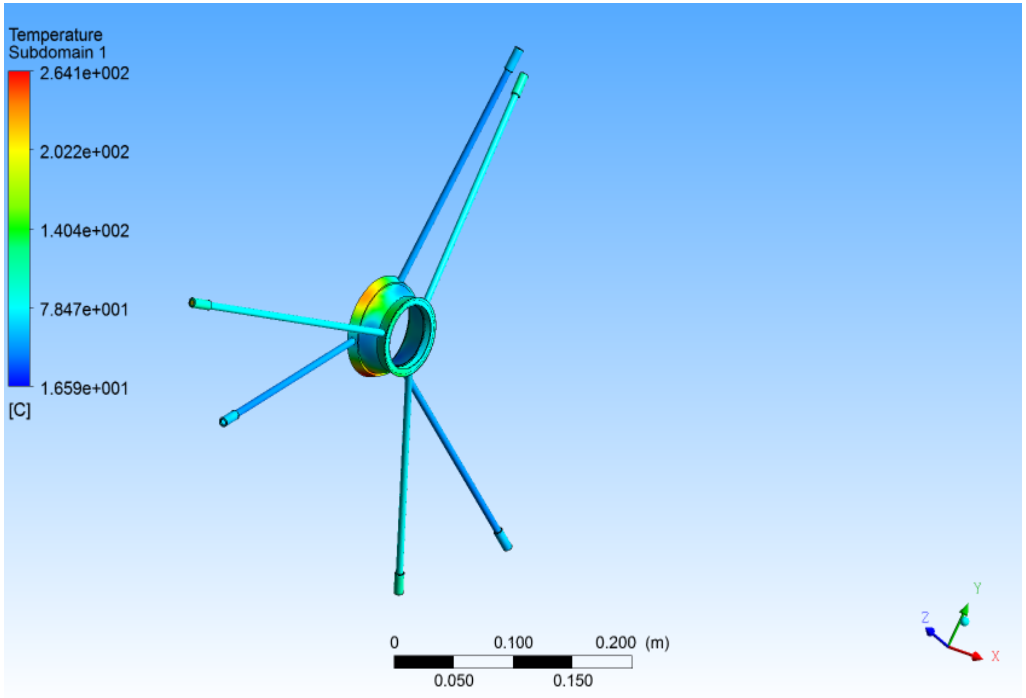
Titanium hub mounted on 6 helium flow spokes (6mm external diameter, 4mm internal diameter)

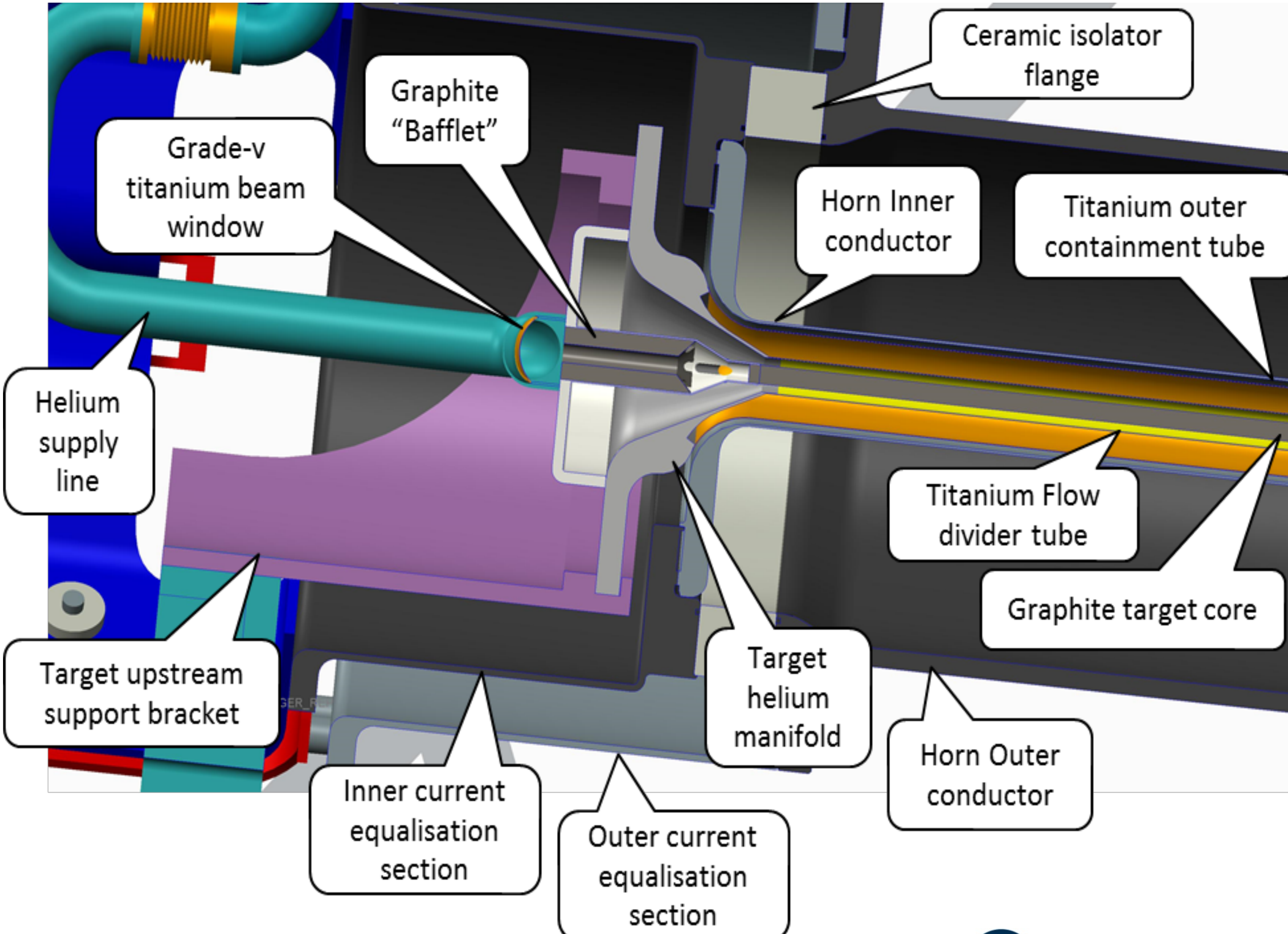
Total heat load = 650W

Helium Mass flow = 2.5gram/s

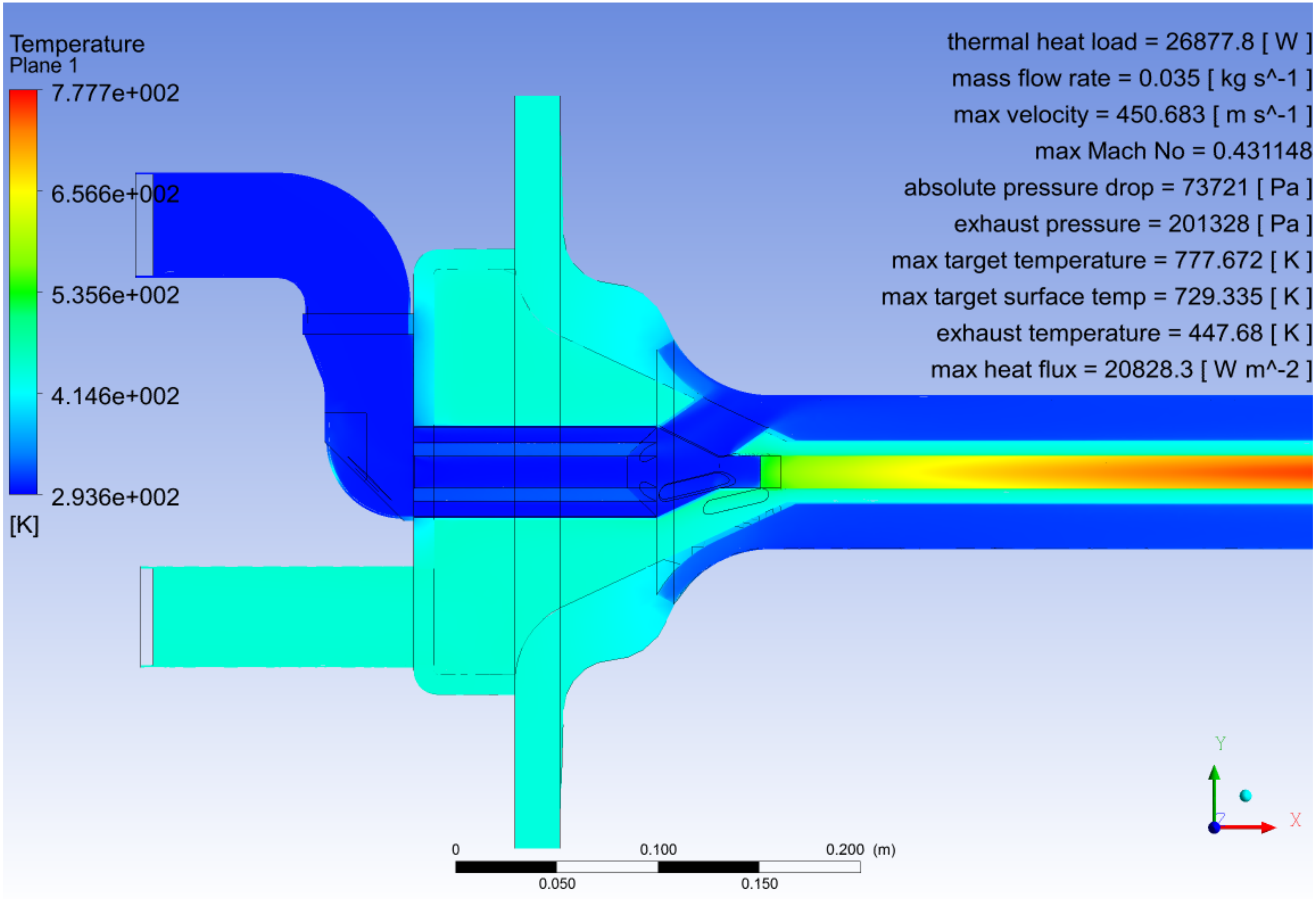
Helium pressure drop = 0.3bar

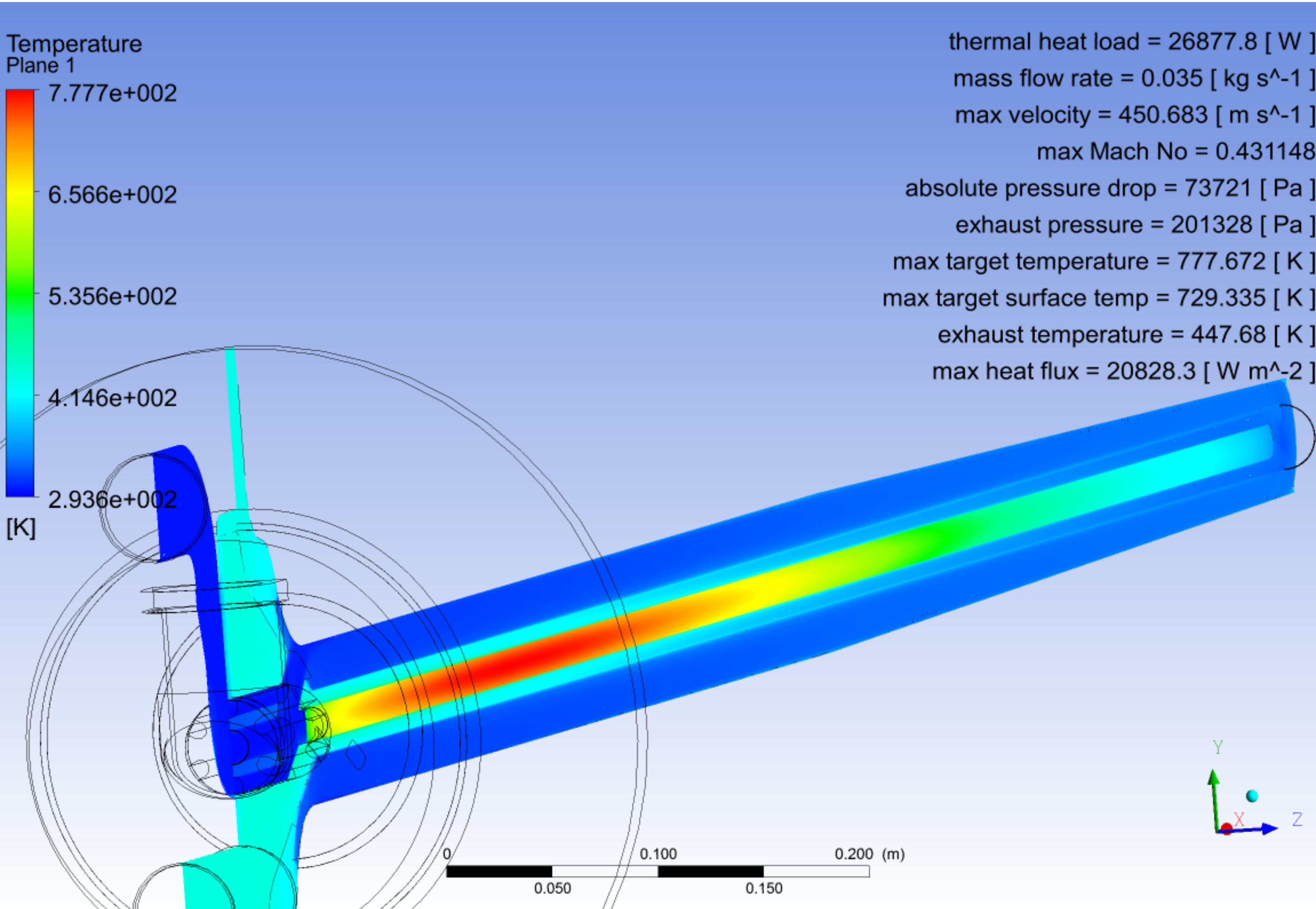
Max hub temperature = 264°C (could be reduced with flow guides to ensure all parts of the hollow hub are well cooled)



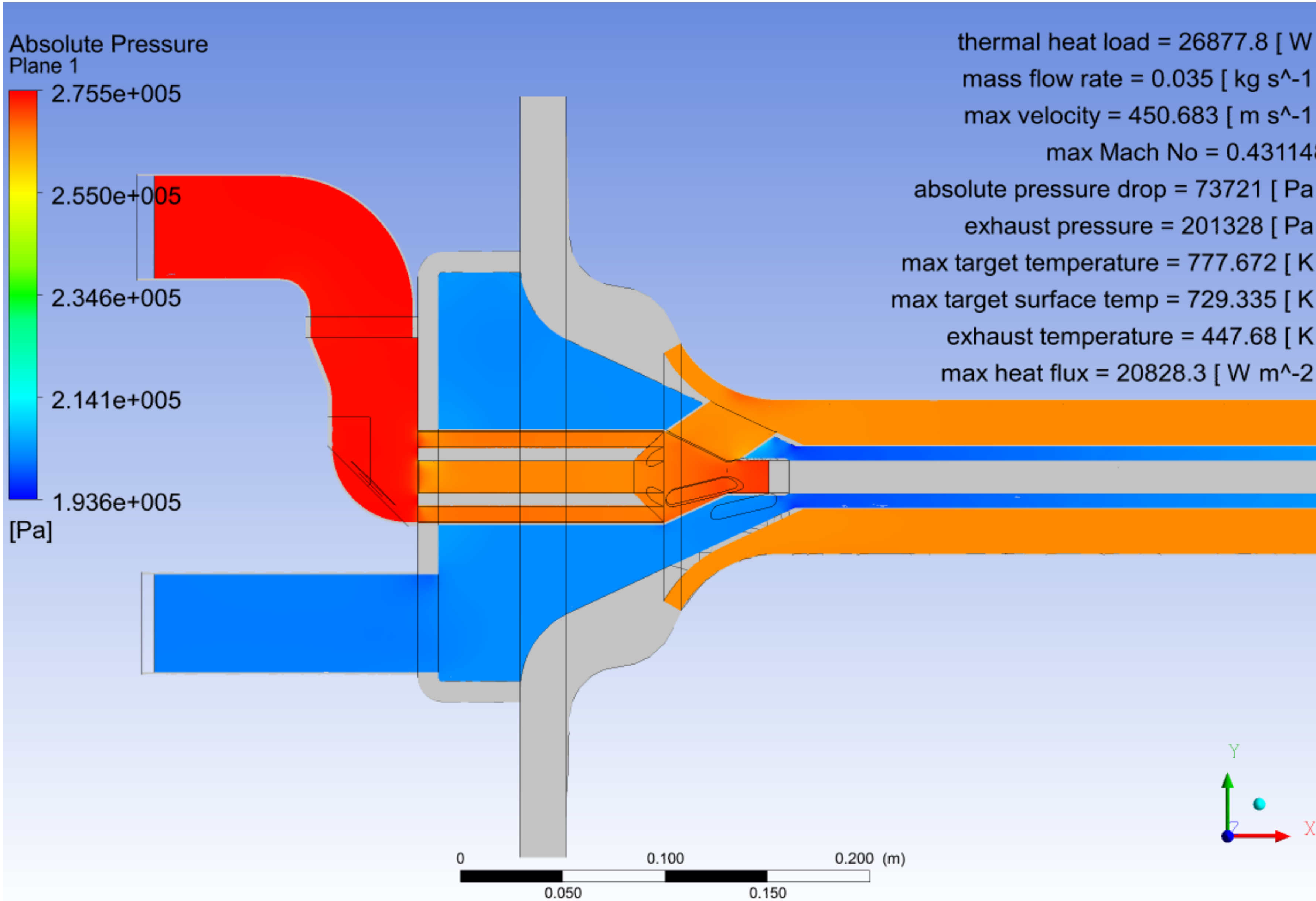

Ceramic isolator flange
Graphite "Bafflet"
Grade-v titanium beam window
Horn Inner conductor
Titanium outer containment tube
Helium supply line
Titanium Flow divider tube
Graphite target core
Target upstream support bracket
Target helium manifold
Horn Outer conductor
Inner current equalisation section
Outer current equalisation section

Temperatures at 1.2MW steady state simulation

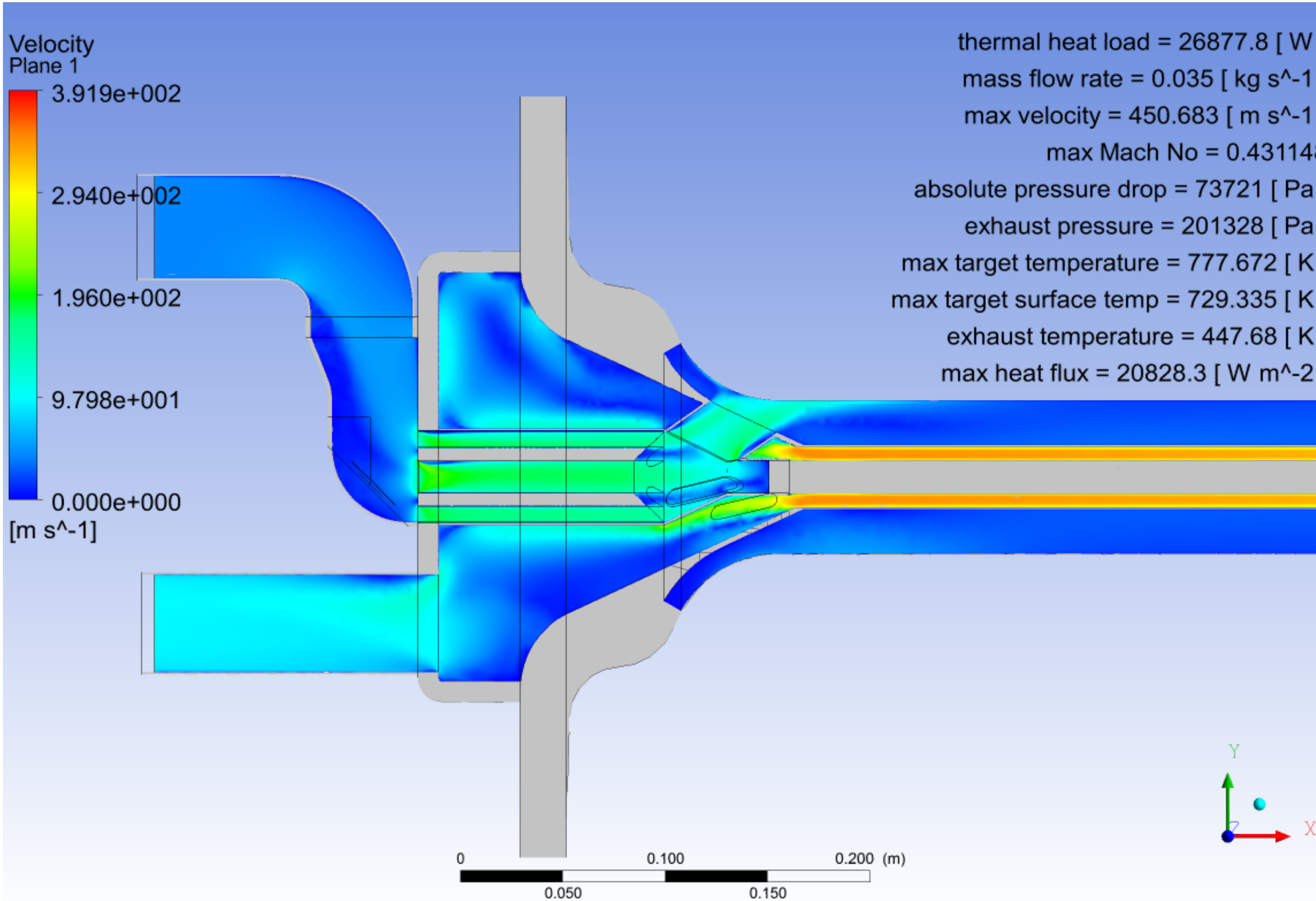



Temperature
Plane 1
7.777e+002
6.566e+002
5.356e+002
4.146e+002
2.936e+002
[K]
thermal heat load = 26877.8 [W]
mass flow rate = 0.035 [kg s^-1]
max velocity = 450.683 [m s^-1]
max Mach No = 0.431148
absolute pressure drop = 73721 [Pa]
exhaust pressure = 201328 [Pa]
max target temperature = 777.672 [K]
max target surface temp = 729.335 [K]
exhaust temperature = 447.68 [K]
max heat flux = 20828.3 [W m^-2]
0
0.100
0.200 (m)
0.050
0.150
Y
X
Z

Absolute Pressure at 1.2MW Steady state Simulation



Helium Velocity at 1.2MW steady state simulation



CFD Model

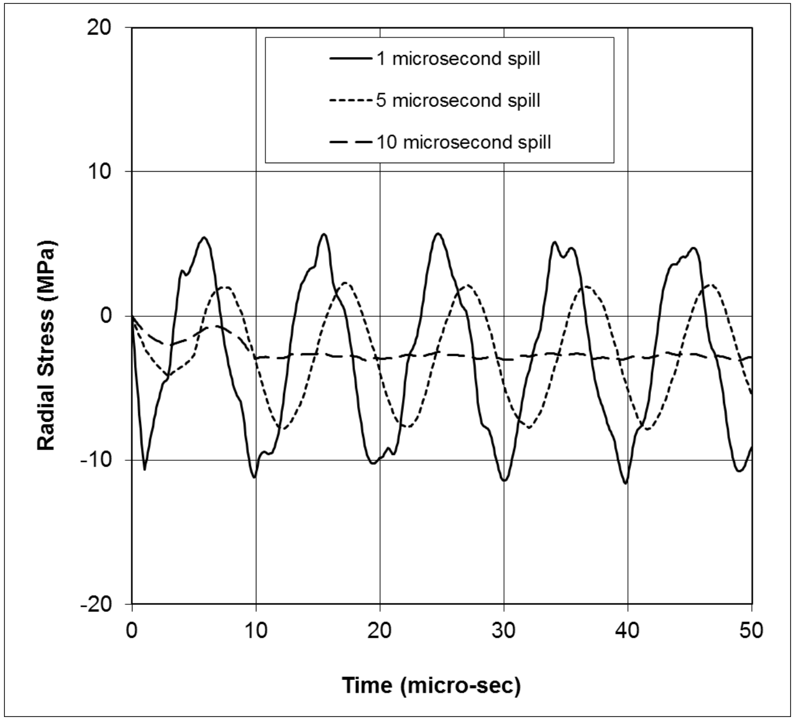
IG43 has Temperature dependant thermal conductivity taken as 1/3 of unirradiated value
No heat transfer from outside of target can
Beam Power = 1.2MW
Mass flow = 35g/s
Exhaust pressure = 2bar absolute
Total Thermal Power Deposited in target, baffle, up and downstream windows, guide and outer can ≈ 27kW
Steady state and transient models

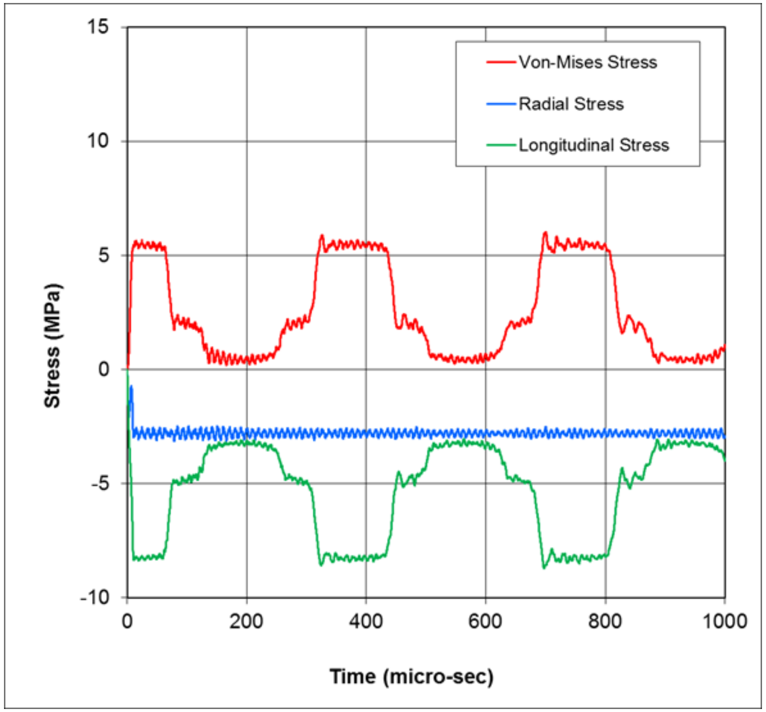
Results

Maximum target temp < 600°C
Maximum target surface temp = 500°C
Maximum front window temp = 177°C (N.B. temp jump per pulse ≈90K)
Exhaust helium temperature = 175°C
Pressure drop across target = 0.7bar
Max Mach number = 0.43

Dynamic stress response

close to the shower maximum in a cylindrical graphite LBNF target following a single beam spill, 7.5e13 protons, 120 GeV, beam sigma = 2.67mm, target diameter = 16 mm, target segment length = 0.45m





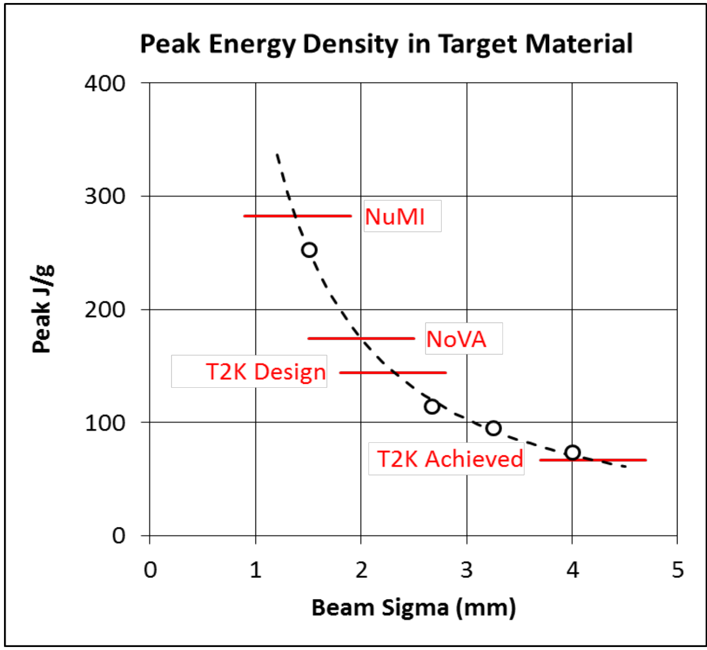
Note sensitivity of radial stress component to spill time

predicted longitudinal stress oscillation is not excessive

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 [$\mu A/cm^2$]	23	11	53	55	22

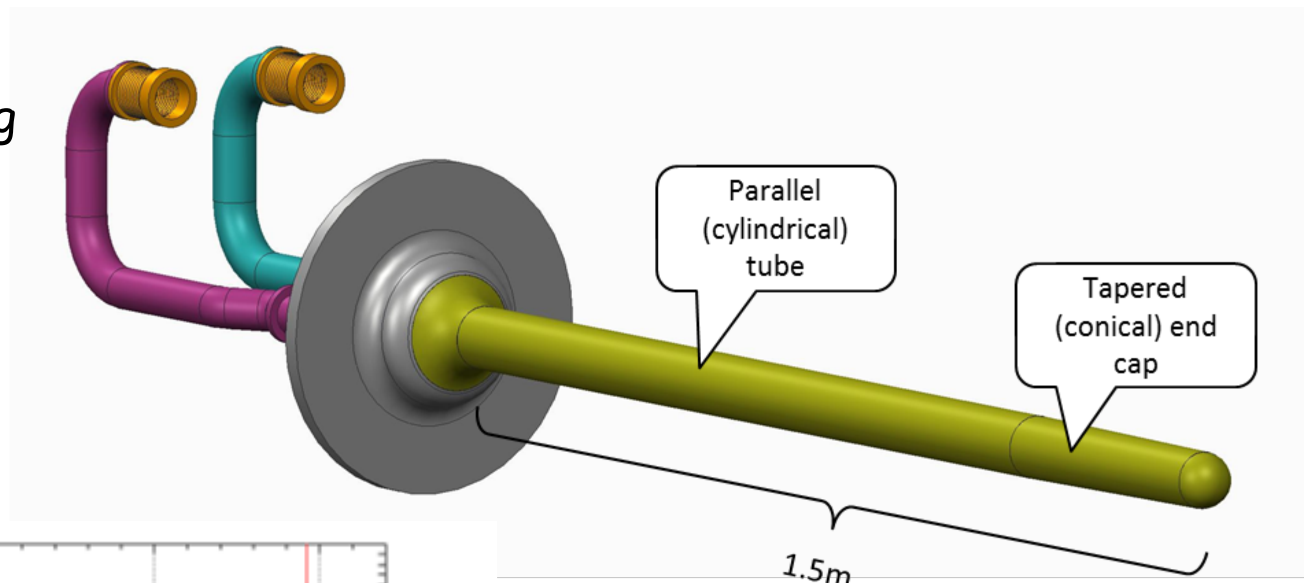
Total and pulsed heat loads lower than that seen on NoVA and NuMi and on T2K design

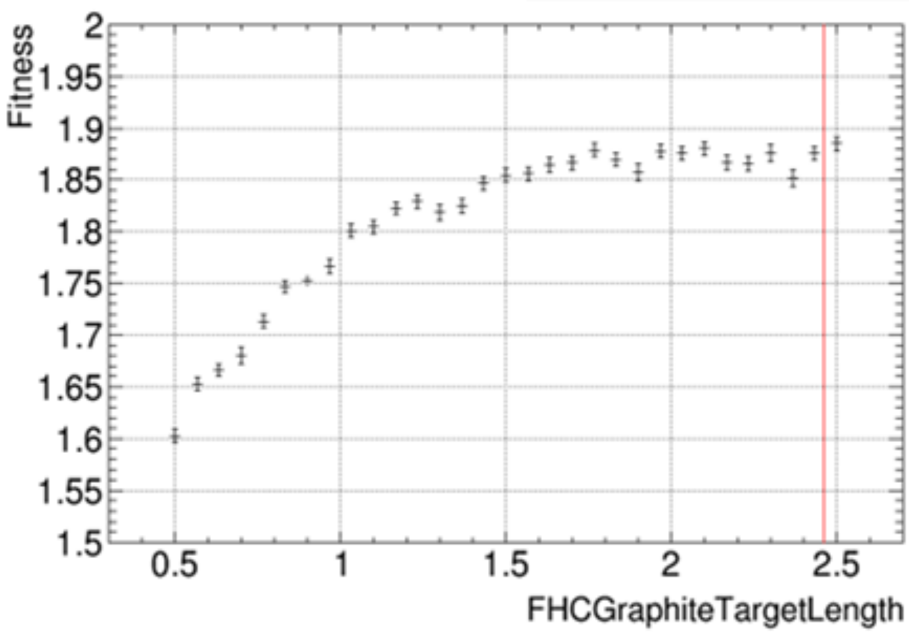


Possible simplification – longest practicable T2K-like cantilever

Two risks with proposed design –

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

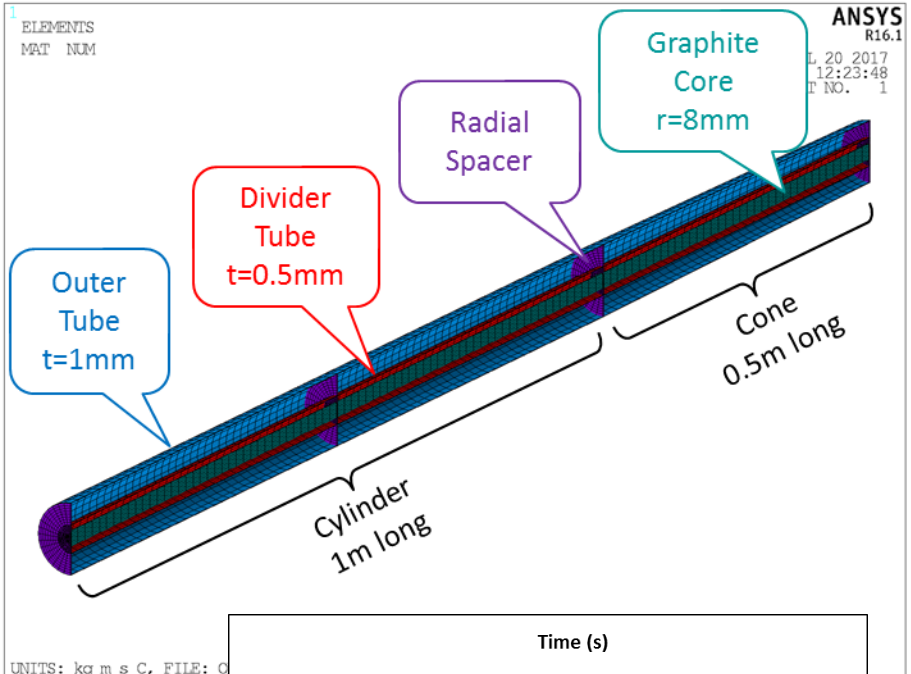




If the target is sufficiently short it could be supported as a simple cantilever with no downstream support

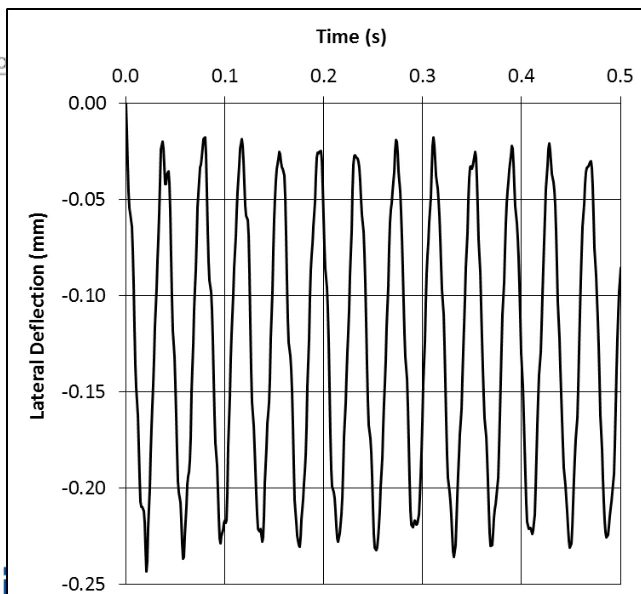
A c. 1.5m long cantilevered target appears potentially feasible and would have a negligible impact on physics performance

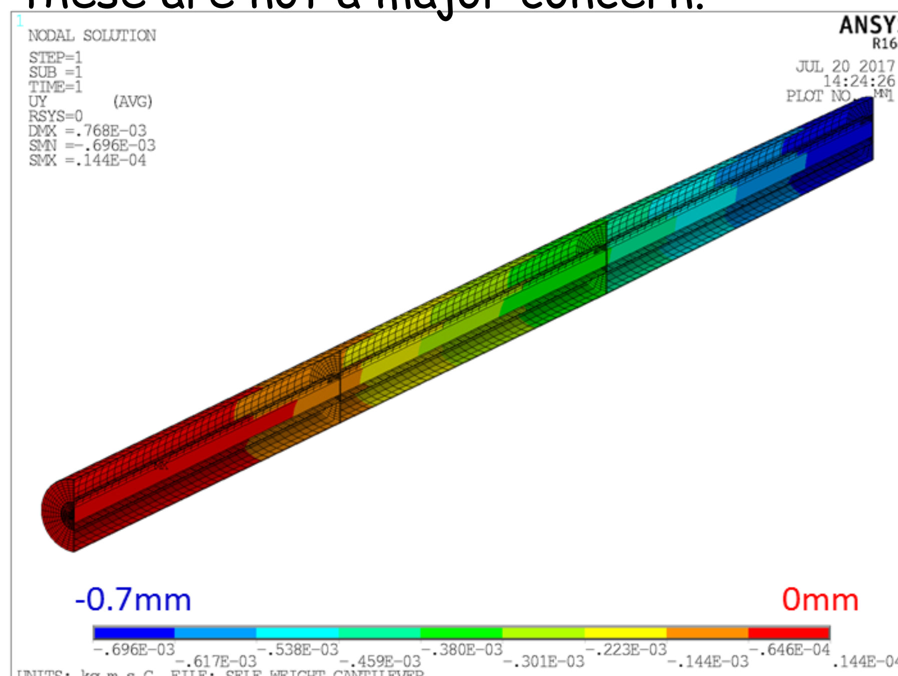
Risk Mitigation



If the target length is reduced to 1.5m, the self weight deflection at the downstream end is calculated to be approximately 0.7mm.

In addition to self-weight deflection, off -centre beam pulses may generate lateral vibrations of amplitude about 0.25mm at a frequency of about 25Hz, these are not a major concern.





Conclusions

- Several different possible concepts for a 2.3 m long helium cooled graphite target have been considered, based on the successful T2K design.
- A conceptual design of a single, remotely replaceable target installed into horn A docking into a downstream support has been selected and studied for a 1.2MW LBNF beam.
- Operating temperatures, transient and steady-state stress levels are expected to be within levels experienced by NuMI, NoVA and T2K.
- Helium flow requirements are expected to be similar to that of the current T2K target design.
- An independent review did not identify any show-stoppers, but more detailed work is required as part of the preliminary design.
- A back-up risk mitigation strategy of a shorter cantilevered target, closest to T2K design, has also been identified.