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LBNF Target Concept Selection Report to Technical Board

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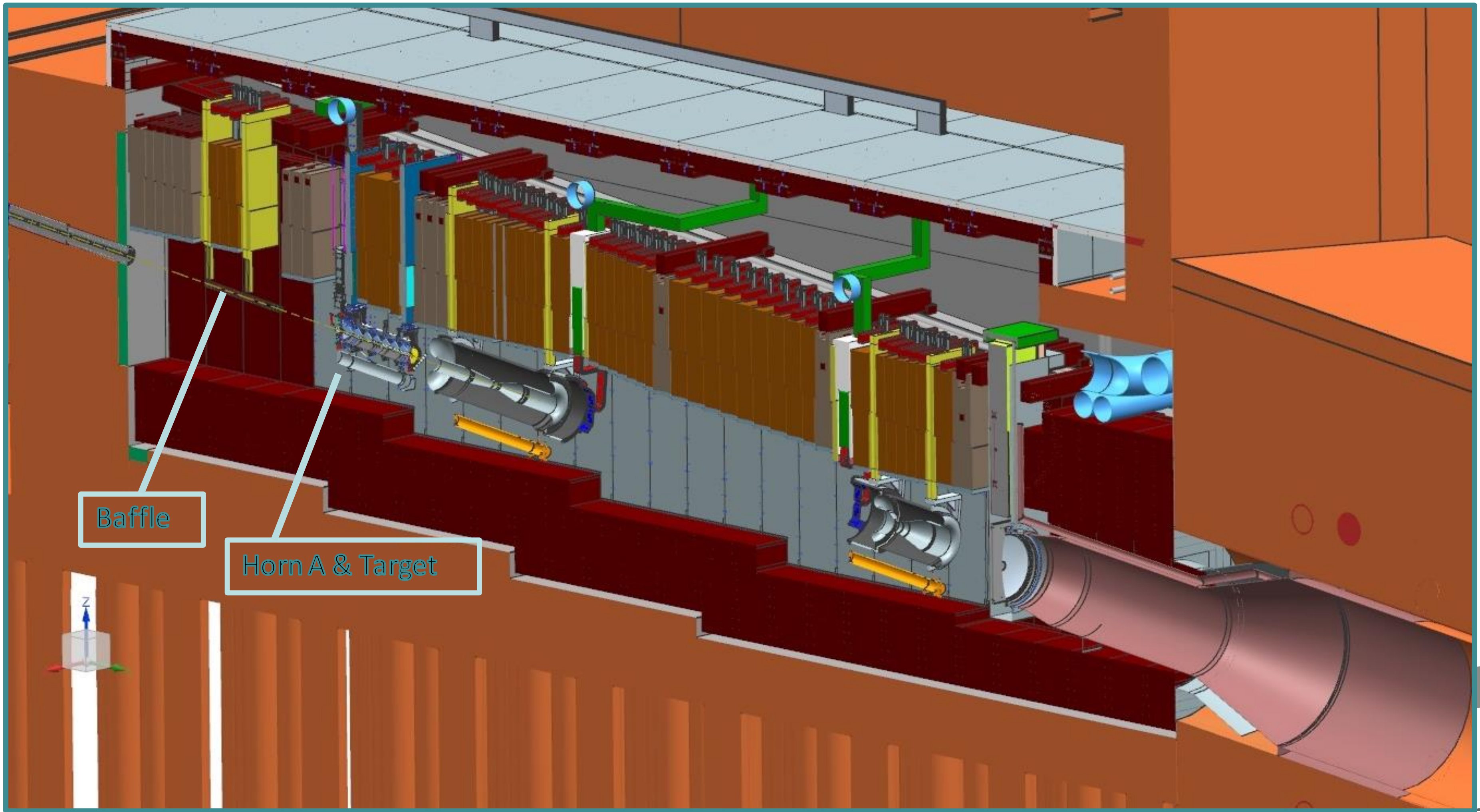
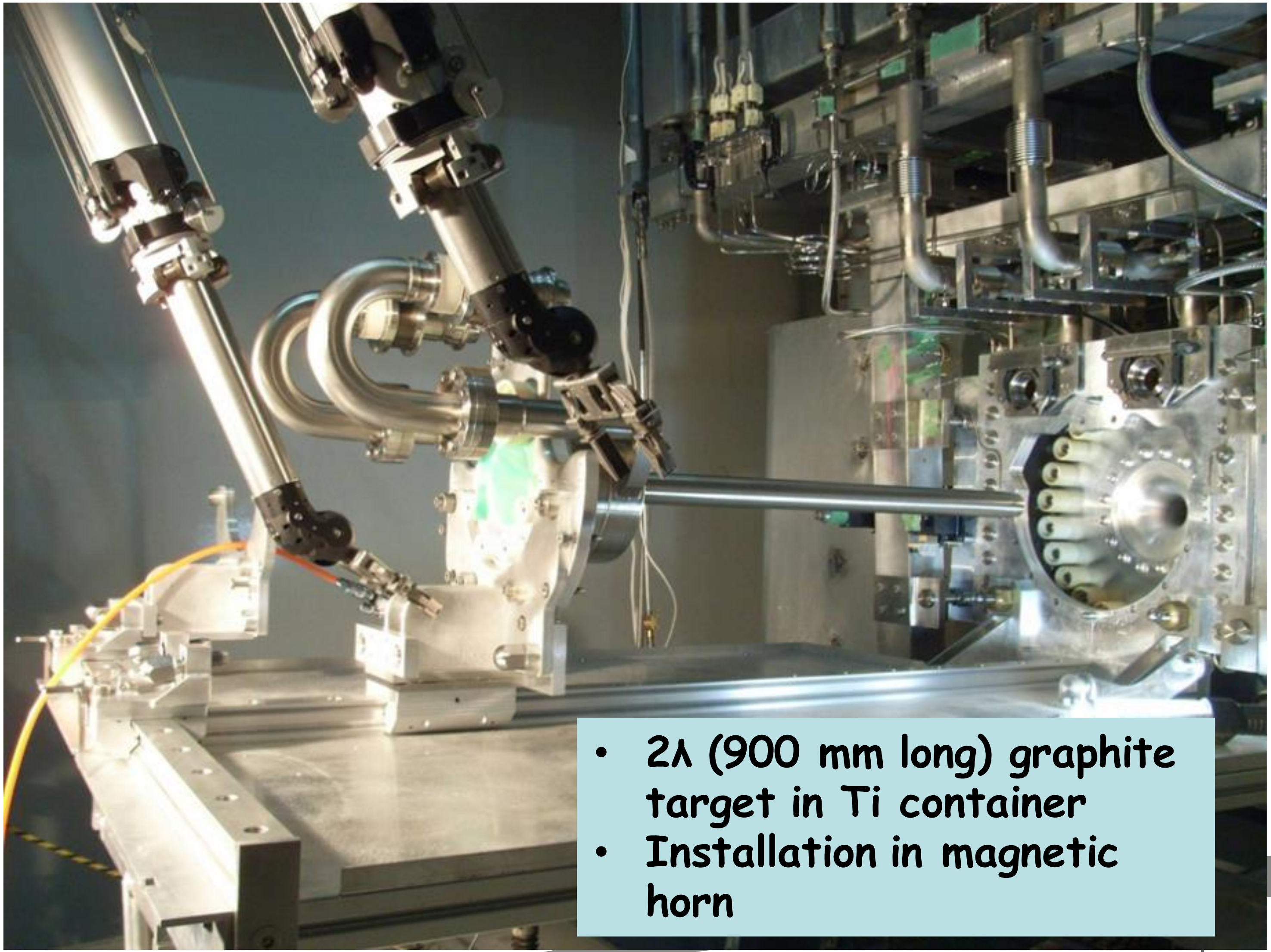
Fermilab Long-Baseline Neutrino Facility | DUNE Deep Underground Neutrino Experiment | Science & Technology Facilities Council | Warwick The University of Warwick

LBNF Neutrino Beamline



Our starting point: Helium Cooled T2K Target

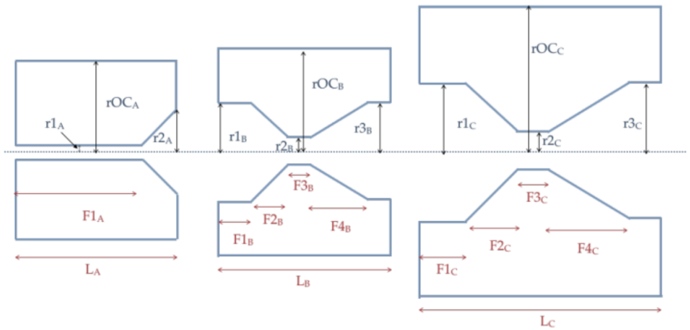


- 2λ (900 mm long) graphite target in Ti container
- Installation in magnetic horn

LBNF/DUNE Requires a *Long* Target

- **BOTF Report (L Fields et al):**
  *"We find that it is important that the target be significantly longer than the reference target, and are recommending that the LBNF team design a target that is at least **four interaction lengths**. Other details of the target, including cross sectional area, shape and material, are less critical to physics performance …*

  … At present, both a NuMI-style graphite fin target and a graphite cylindrical target appear to be good options"



1λ = 46cm of graphite

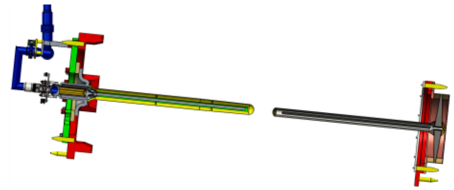
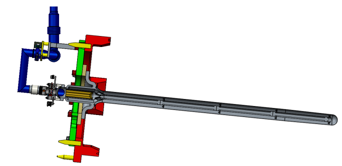
- **Fermilab LBNF Requirements Documentation "DOORS":**
  *"The target shall have an equivalent length of about **four interaction lengths** …*

  *… The amount of material needed in the target must be enough to maximise secondary particle production, while not absorbing too much. **Four interaction lengths** is an approximately optimal length"*

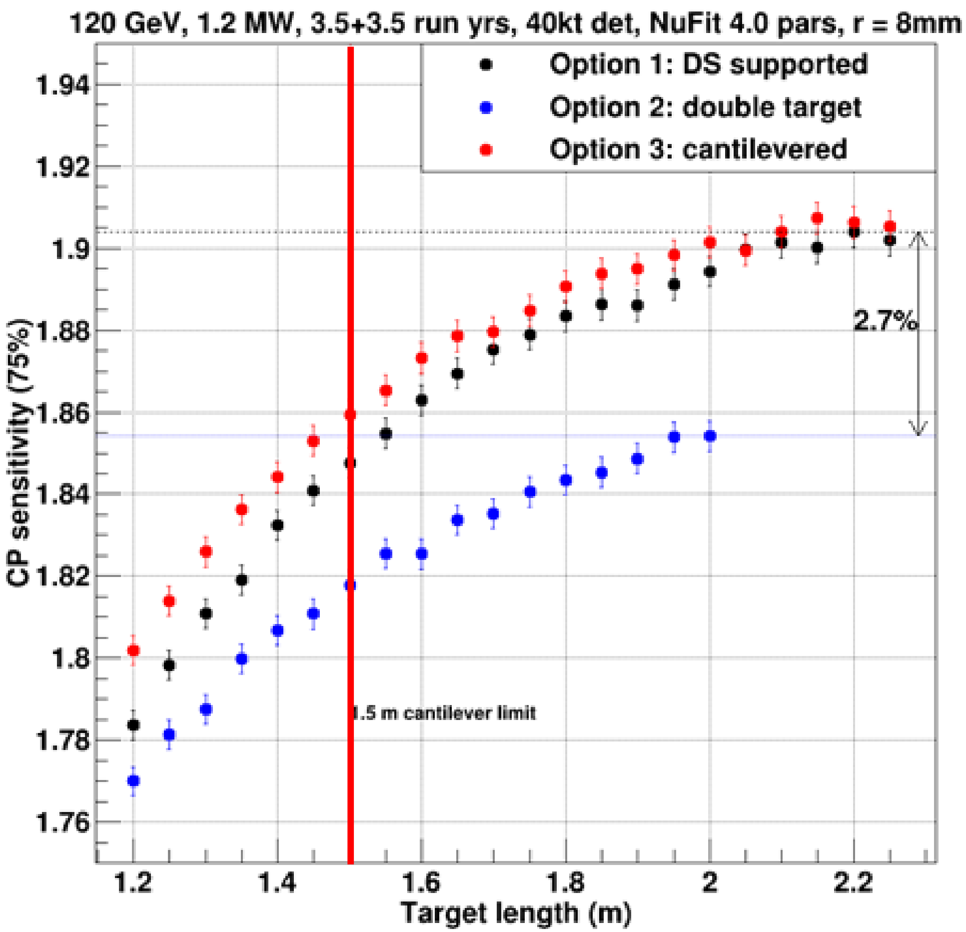
Target 'Optimum' Design

- $\lambda_{overall} = \lambda_{physics} \times \lambda_{reliability}$ *, where* $\lambda_{reliability} = fn(I,\sigma,L\ldots)$
- For CP sensitivity – small beam σ is favoured
- For target lifetime – bigger σ is better.
  - Lower power density – lower temperatures, lower stresses
  - Lower radiation damage rate
  - Lower amplitude 'violin' modes (and lower stresses)
- For CP sensitivity – long target (4λ, c.1.8m) is better
- For max lifetime – short and *simple* target is better
- **For integrated optimum performance, need to take both *instantaneous* performance and *reliability* into account**
  - E.g. How to achieve best physics performance possible for a target lifetime of a minimum of 1 year?
  - Answer depends on beam parameters & power, changeout time etc

Target Concept Selection Summary (July 2019) - consensus achieved!

	 Option 1: 1x2m long	 Option 2: 2x1m long	 Option 3: intermediate cantilever
Instantaneous physics	Best instantaneous physics.	Needs an extra 19 days/yr to match option 1.	1.5m needs an extra 19 days/yr (13 days/yr at 1.6m).
Engineering performance	High heat load. Unstable until supported.	High heat load but divided between 2 targets	Pushing at the limits on cantilever length.
Manufacturability	Difficult to make long tubes. DS support adds complexity.	2^{nd} target low-mass manifold is complex.	Difficult to make long tubes.
Ease of remote maintenance	≈3 weeks exchange time, DS support adds time and risk.	≈2 weeks exchange time, 2^{nd} target adds some time and risk.	≈1 week exchange time, lowest complexity and risk.
Cost and schedule impacts	DS support somewhat increases cost and time.	2^{nd} target greatly increases cost and time.	Cheapest and fastest to produce.

CP Sensitivity Comparison



- Simple cantilever gives best performance for a given length (but the achievable length will be limited)
- DS supported target gives best performance for lengths where a simple cantilever is not possible
- Double 1m targets offer similar performance to a single 1.5 m cantilever
- To achieve same instantaneous performance as 2.2 m long target need extra running time:
- Double Target 9.5% (19 days/run yr)
- 1.5m Cantilever 9.5% (19 days/run yr)
- 1.6m Cantilever 6.2% (13 days/run yr)

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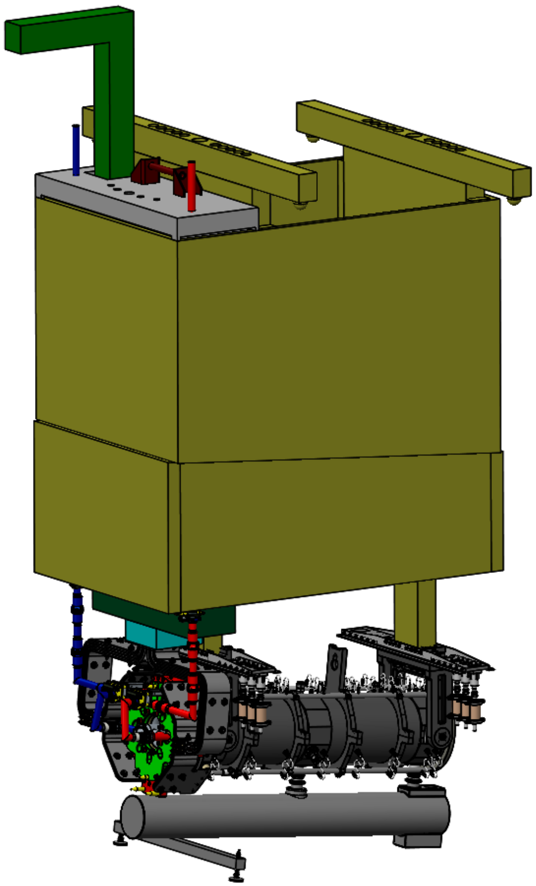
Target Concept Selection Result

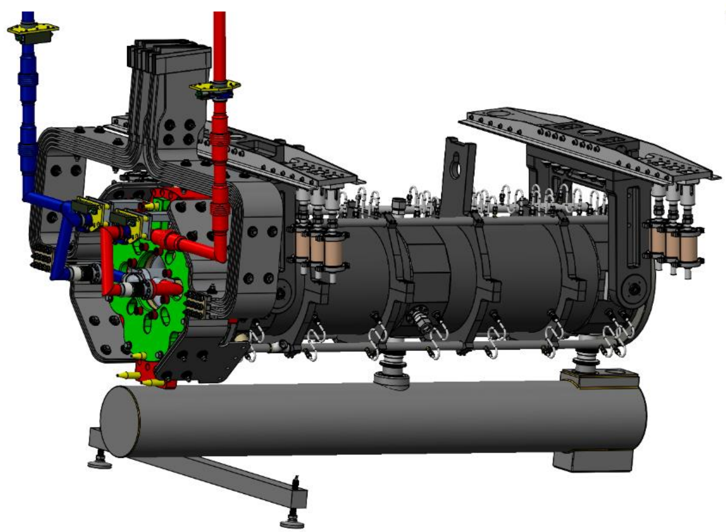
Single Intermediate Length Cantilever Target

→ Manufacturing prototype (operational spare?) to be **1.5m long**

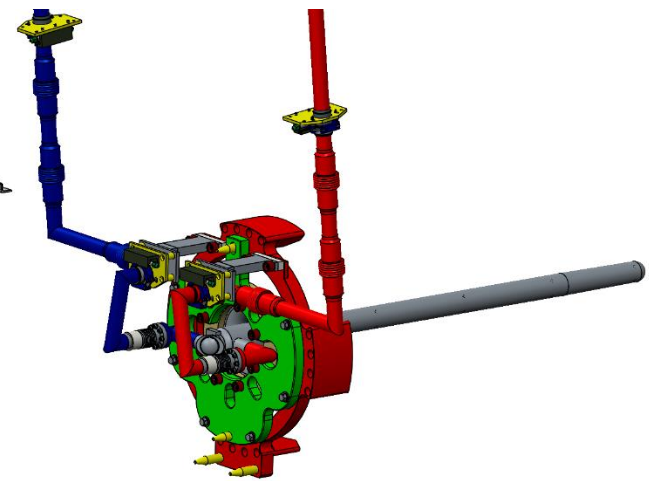
→ 1st operational target to be ***"as long as realistically achievable"***



Module Assembly

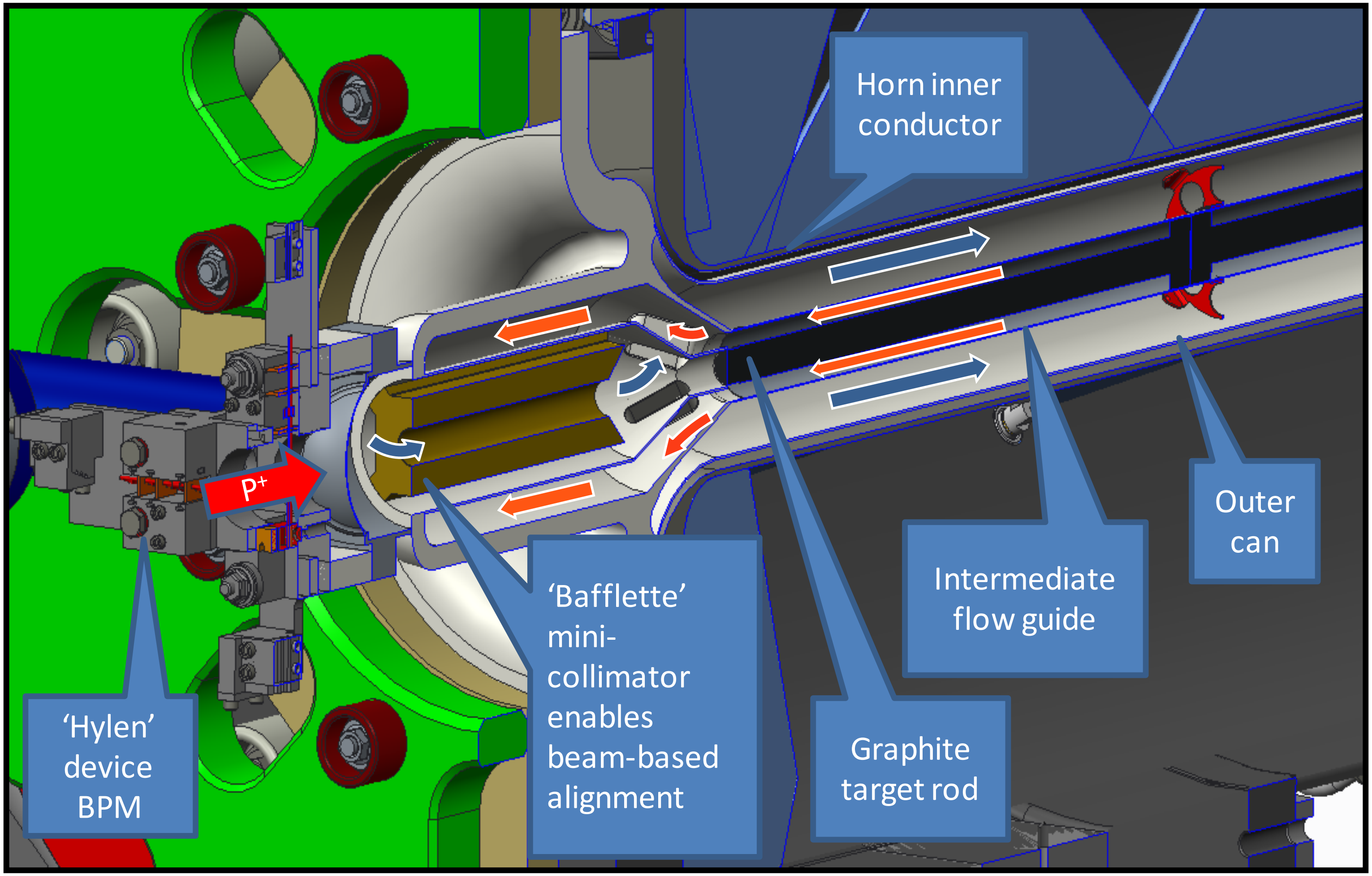


Horn Assembly

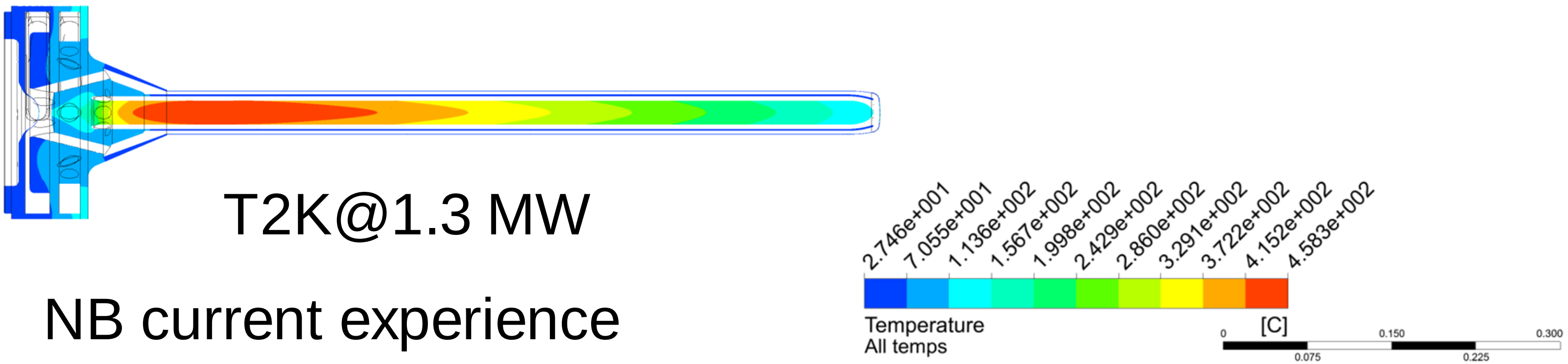


Target

Upstream Target Integration with Horn

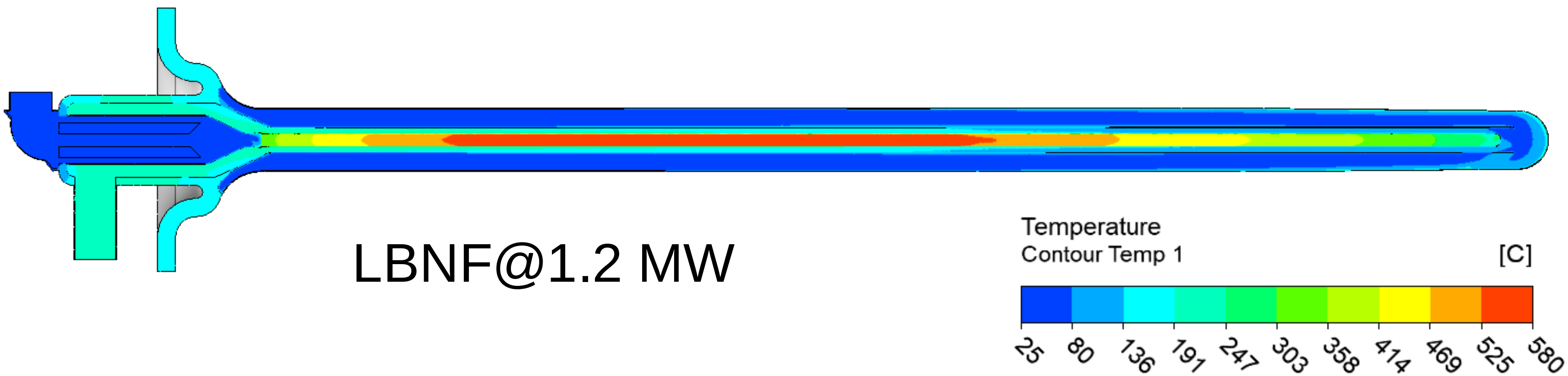


LBNF conceptual design compared with T2K ‘state-of-the-art’



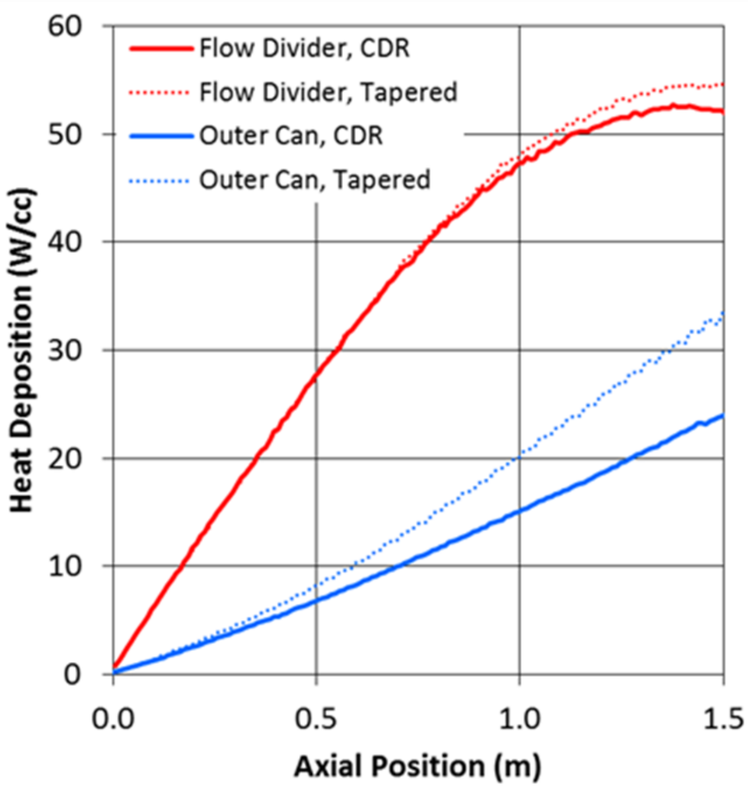
T2K@1.3 MW

NB current experience up to 500 kW



LBNF@1.2 MW

Thermal management

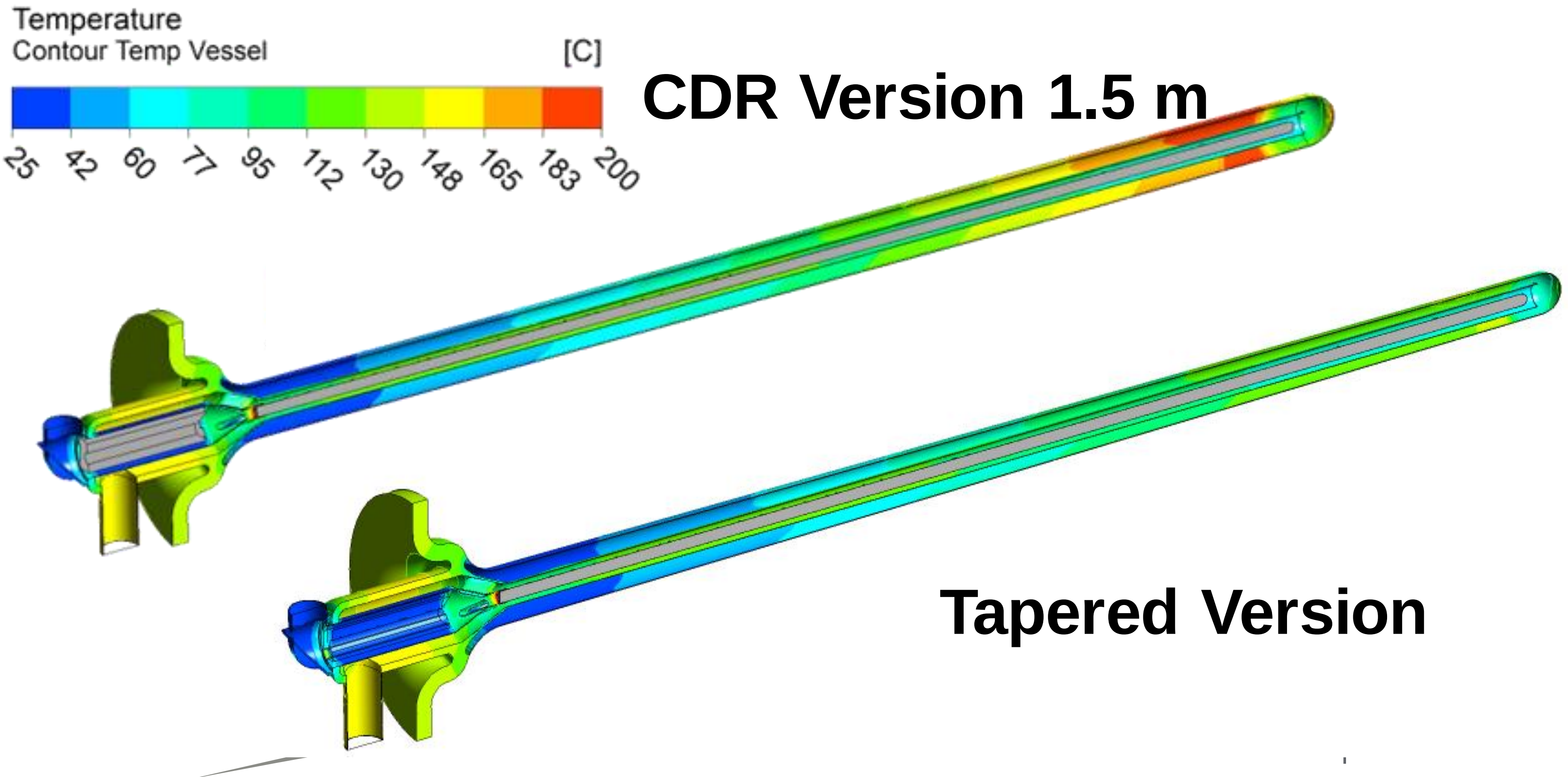


Heat loads in target tubes

- Heat load in outer can and flow divider increases towards downstream end as particle shower develops
- Need to increase heat transfer along length
- Idea: taper outer tube to accelerate flow along length

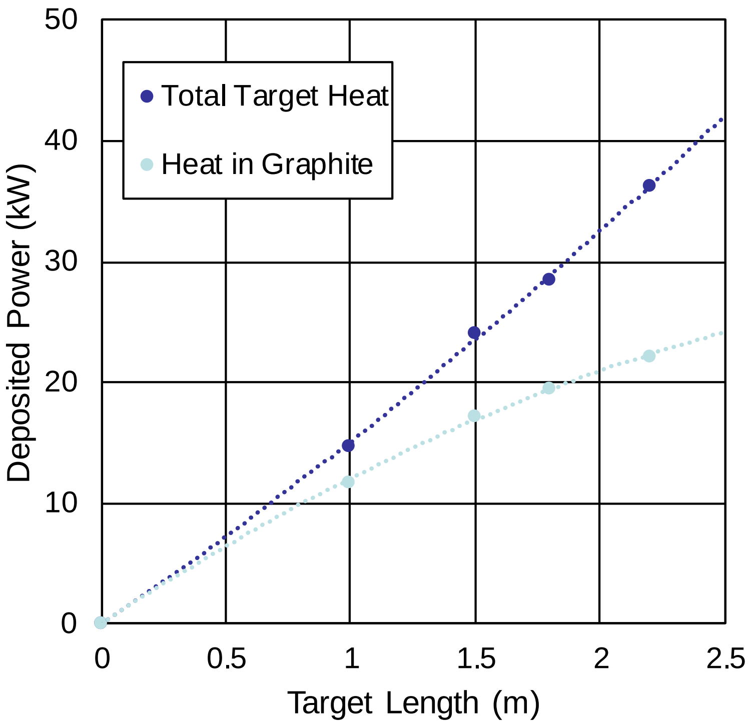
Thermal Management, CFD

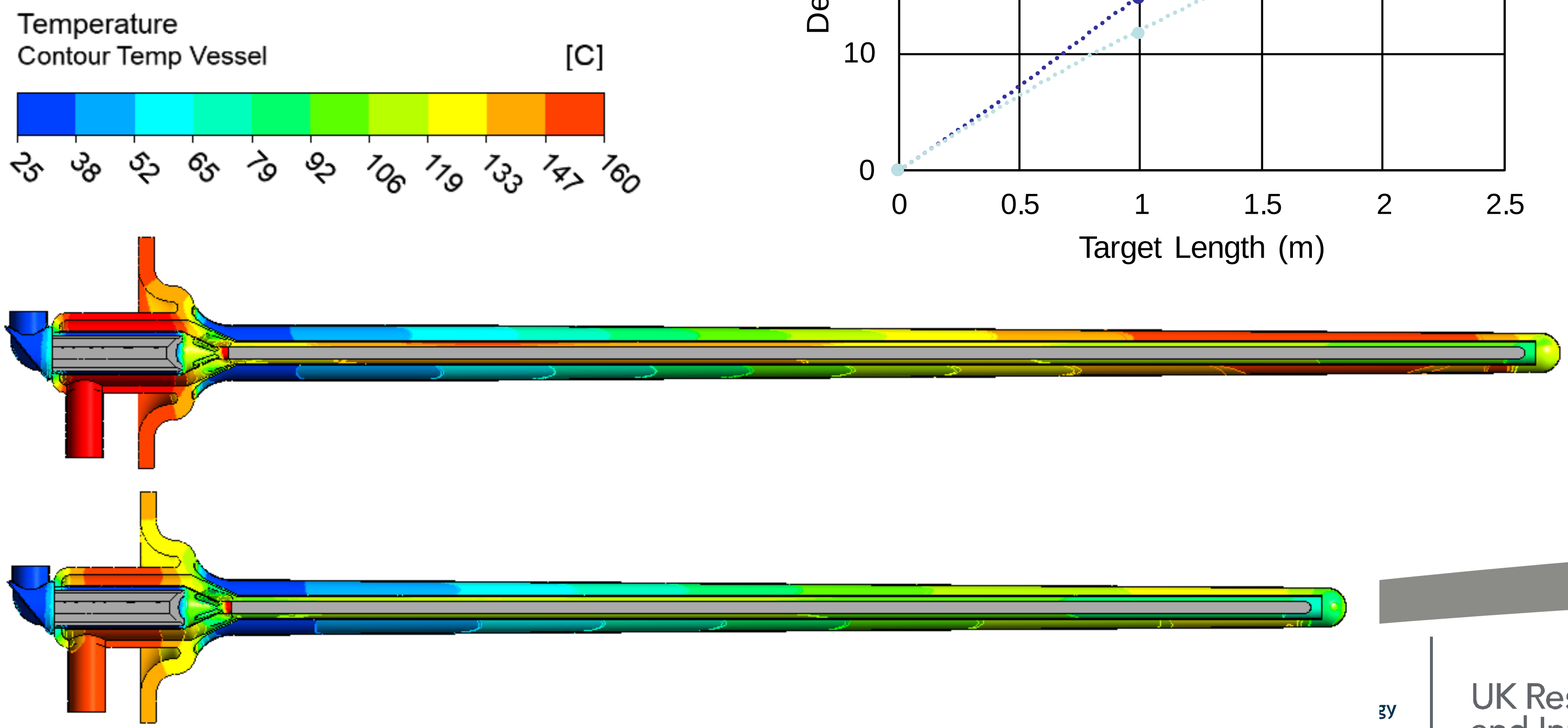
- CFD studies being carried out in concert with physics and mechanical studies
- Good potential to increase target length beyond 1.5 m



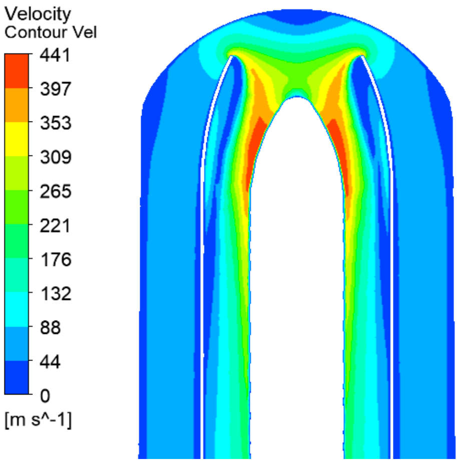
1.8m vs 1.5m Target – Thermal Issues

- Harder to keep vessel cool in longer (1.8m) target
- Solution → compensate by increasing helium flow from 35 to 46 g/s

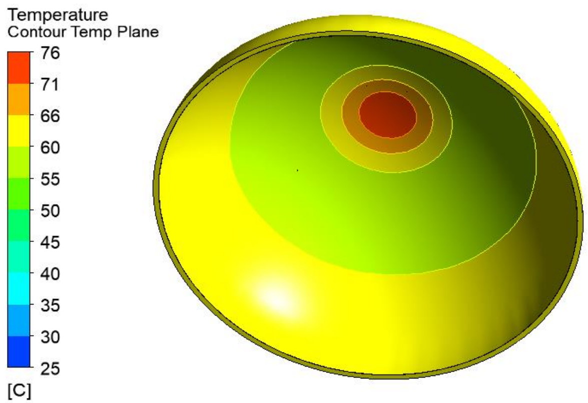




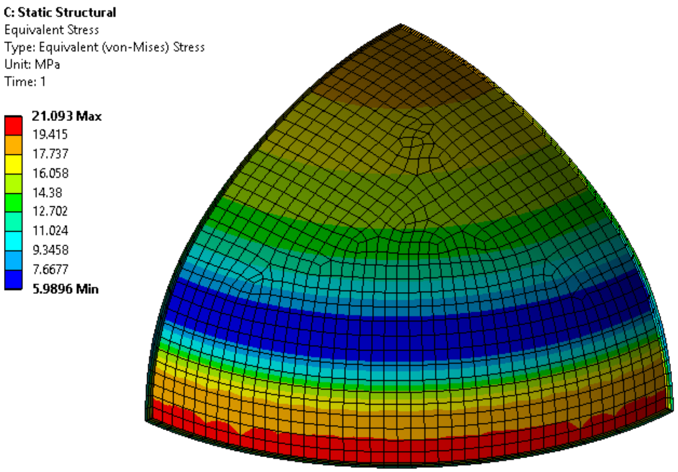
Downstream window temperature/ stress/ pressure drop optimization



Velocity contours



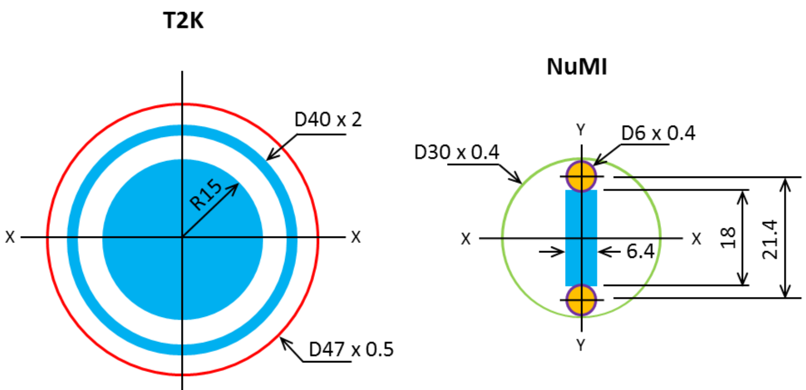
Temperatures

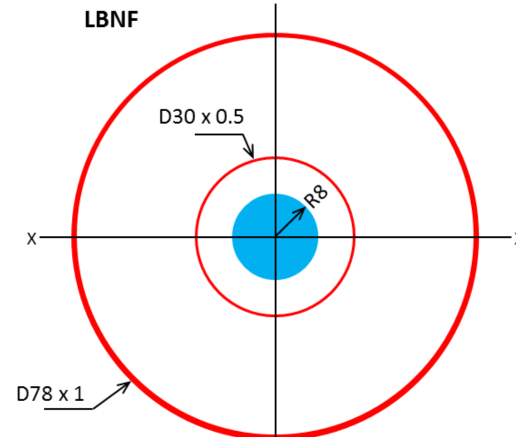


Combined thermal and mechanical stresses with 5 bar internal pressure

Parameter	LBNF	T2K
Mass flow (g/s)	35	60
Inlet pressure (bar)	2	5.3
V_{max} (m/s)	441	250
T_{max} (C)	136	102
σ_{max} (MPa)	21	41

Dynamic stability as an indicator of 'robustness'

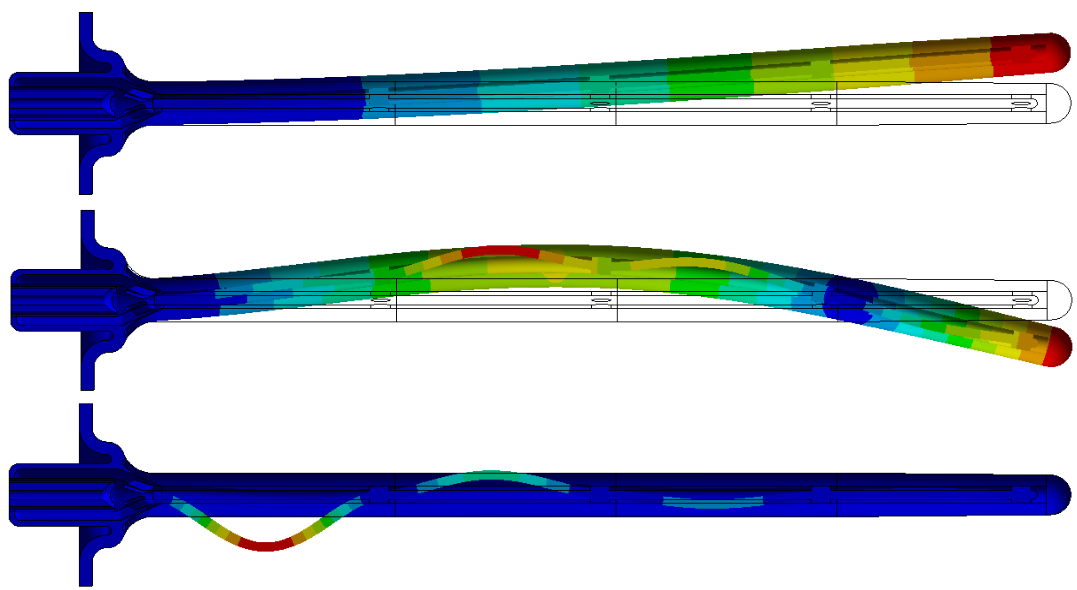




(high frequency → low amplitude)

		LBNF (1.5 m)	NuMI	T2K (0.9 m)
Deflection under gravity (mm)		0.79	≈0.9	≈0.5
Natural Freq (Hz) for mode:	**1**	**22**	**14 (Horizontal)**	**28**
	2	135		
	3	228		

First 3 natural frequency modes:



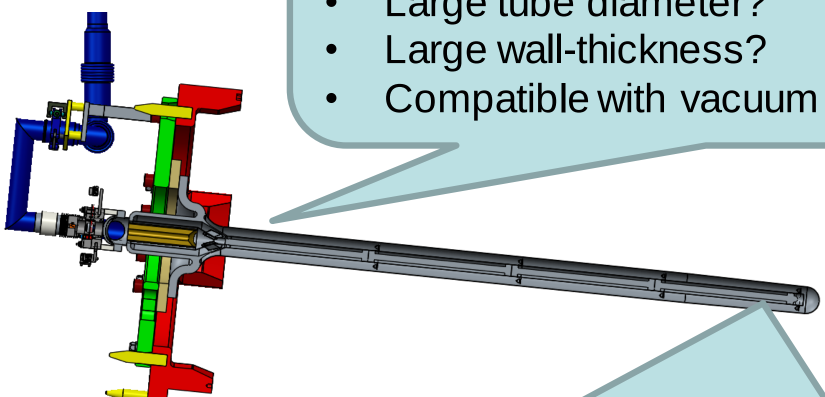
How can we maximise target length?

- Factors point towards a tapered (cone shaped) outer container
  - potentially good for mechanics, thermal management, and physics!
- Currently working to optimise present design

Upstream part of Cantilever

Bending moment → High, Volumetric heating → Low

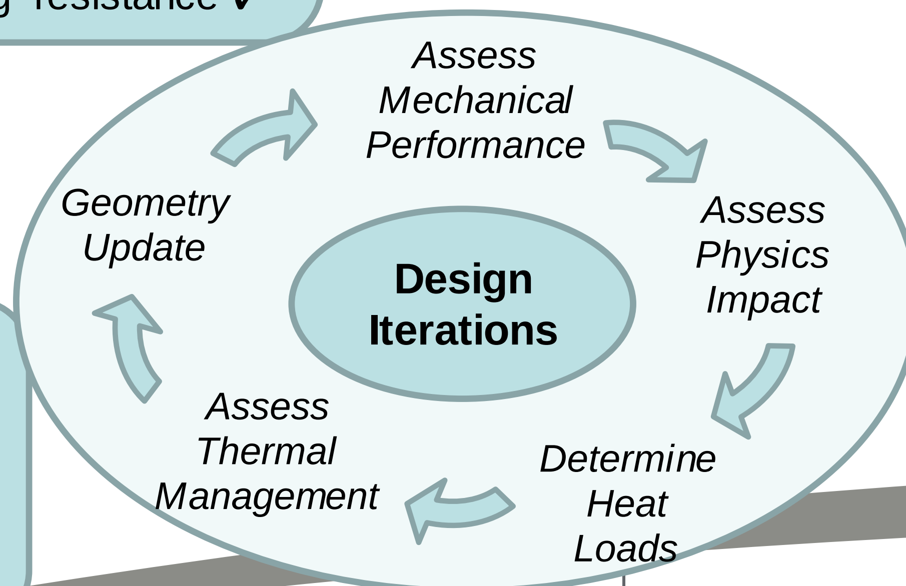
- Large tube diameter?
- Large wall-thickness?
- Compatible with vacuum buckling resistance ✓



Downstream part of Cantilever

Bending moment → Low , Volumetric heating → High

- Small tube diameter?
- Small wall-thickness?
- Compatible with vacuum buckling resistance ✓



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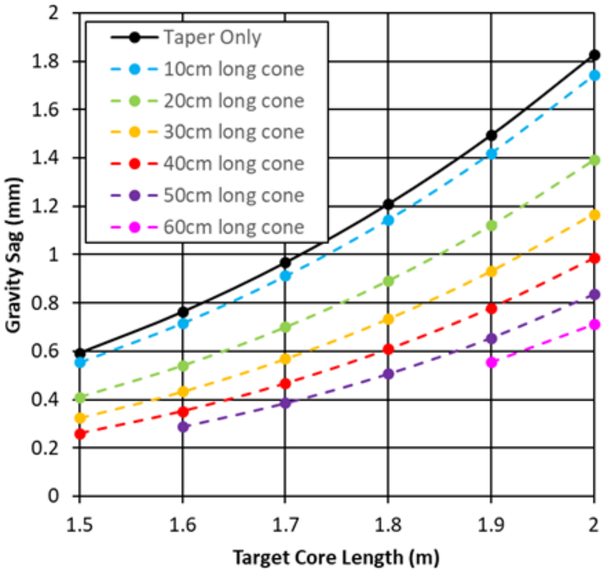
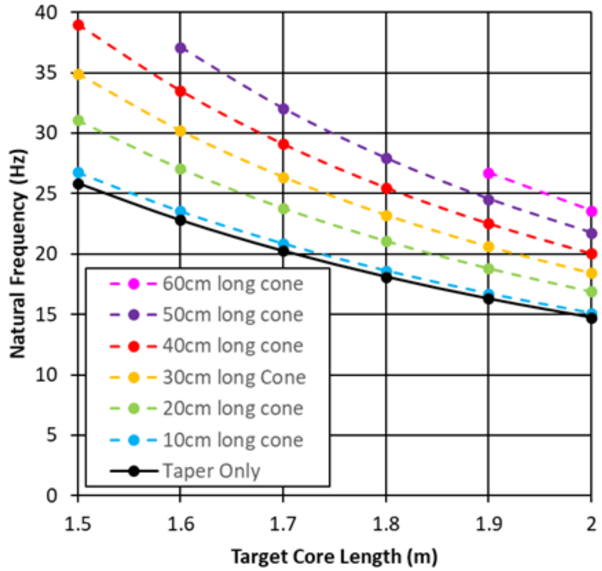
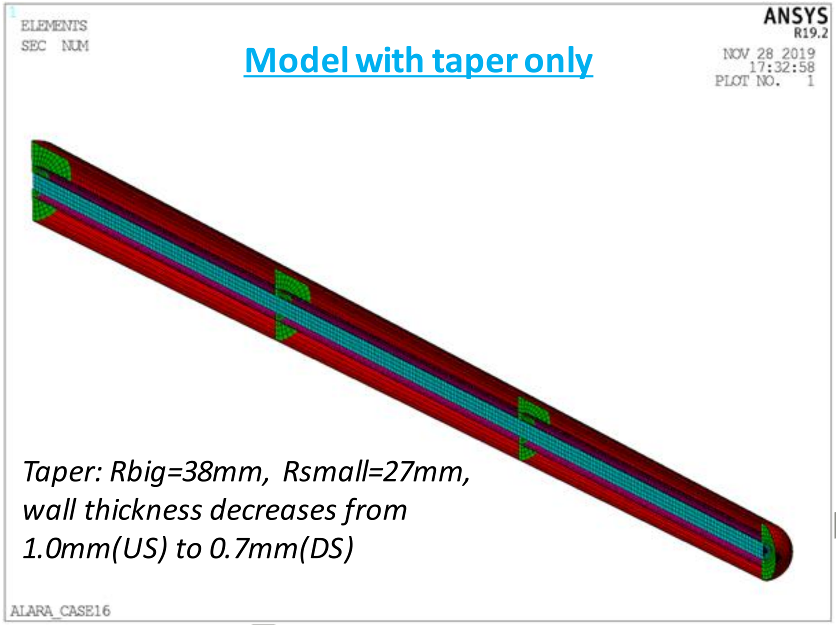
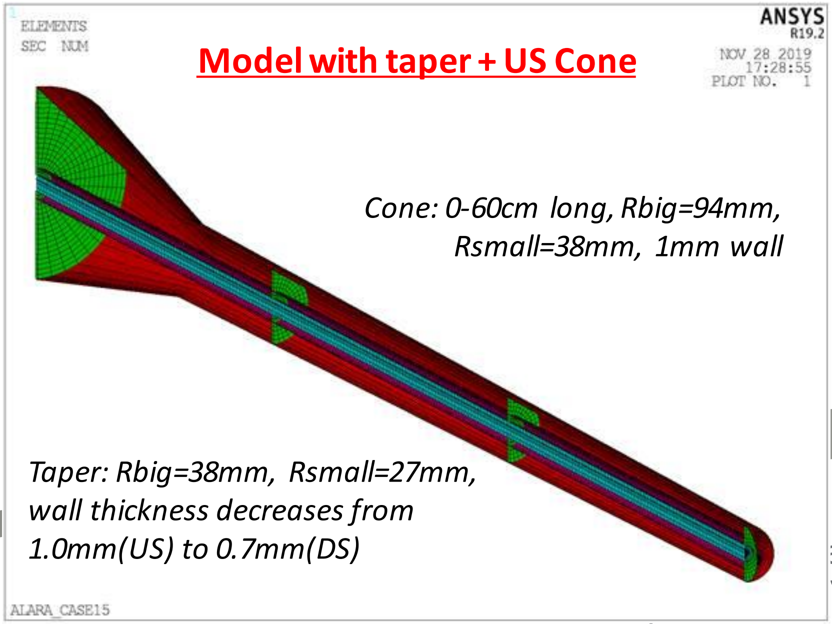
US cone potentially "buys" us some extra target length

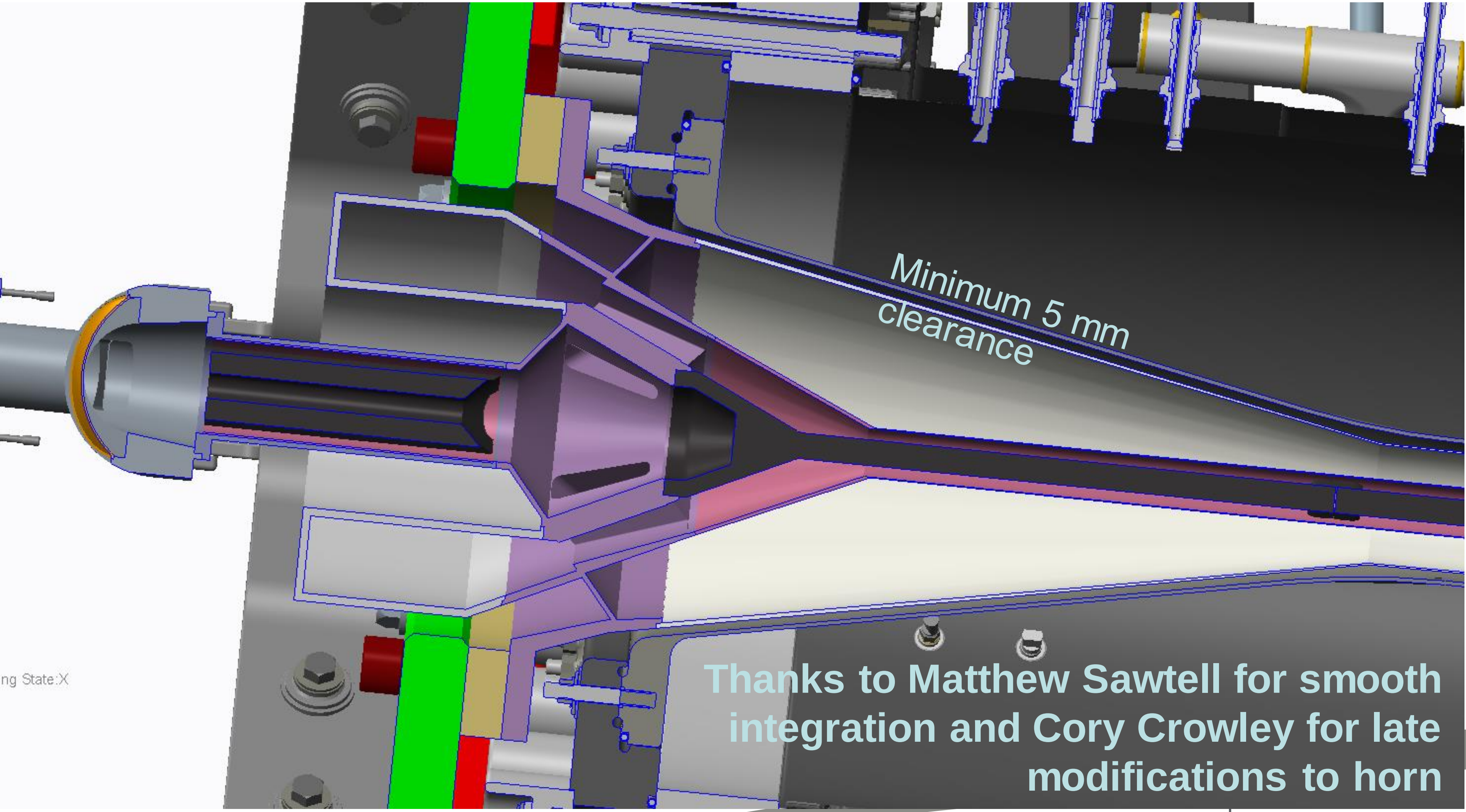






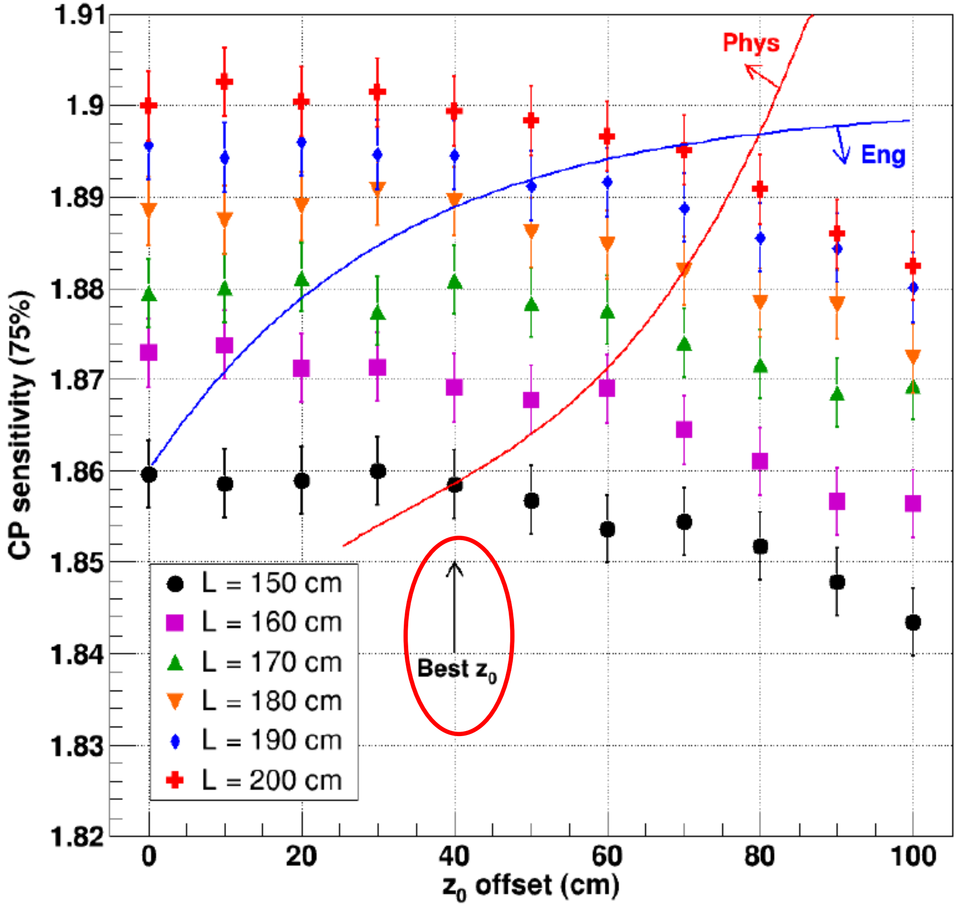


Tapered Target & Horn Integration



Thanks to Matthew Sawtell for smooth integration and Cory Crowley for late modifications to horn

Physics/engineering optimization



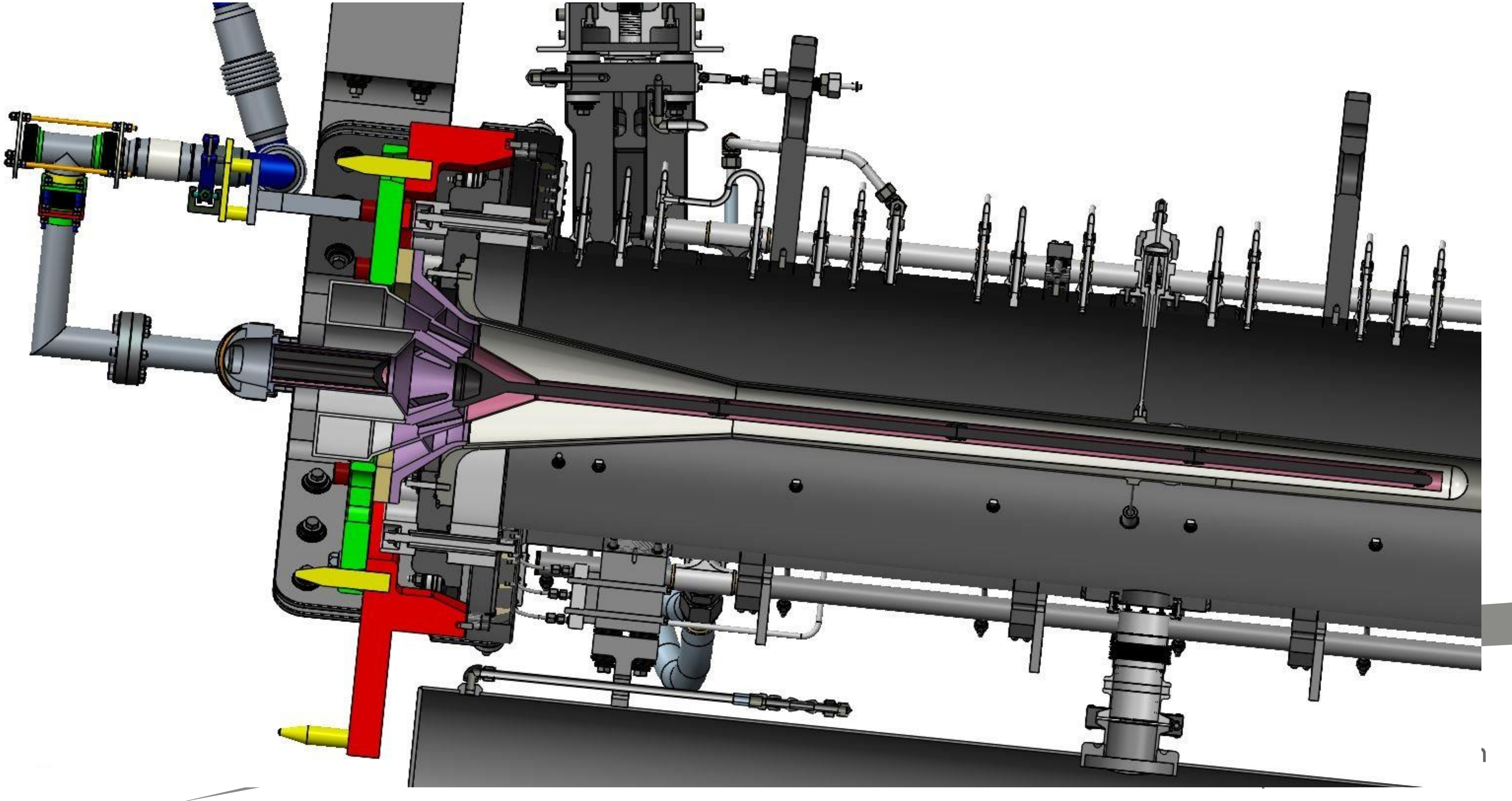
Upstream cone length

Target core length L (cm)	Vessel cone min length z_0 (cm)	Extra time needed per run year (days)
150	0	19
160	17	13
170	28	11
180	**42**	**6**
190	56	5
200	73	4

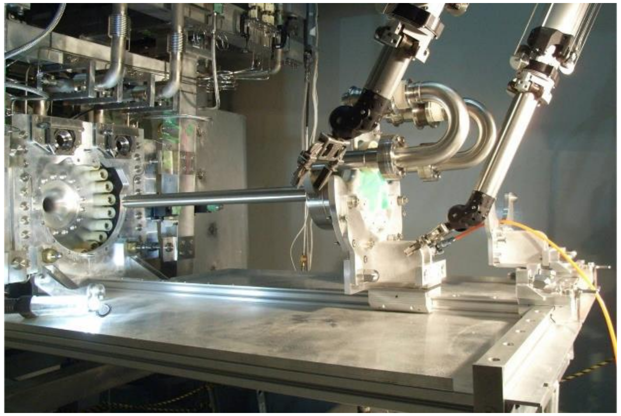
Target/horn integration and remote handling

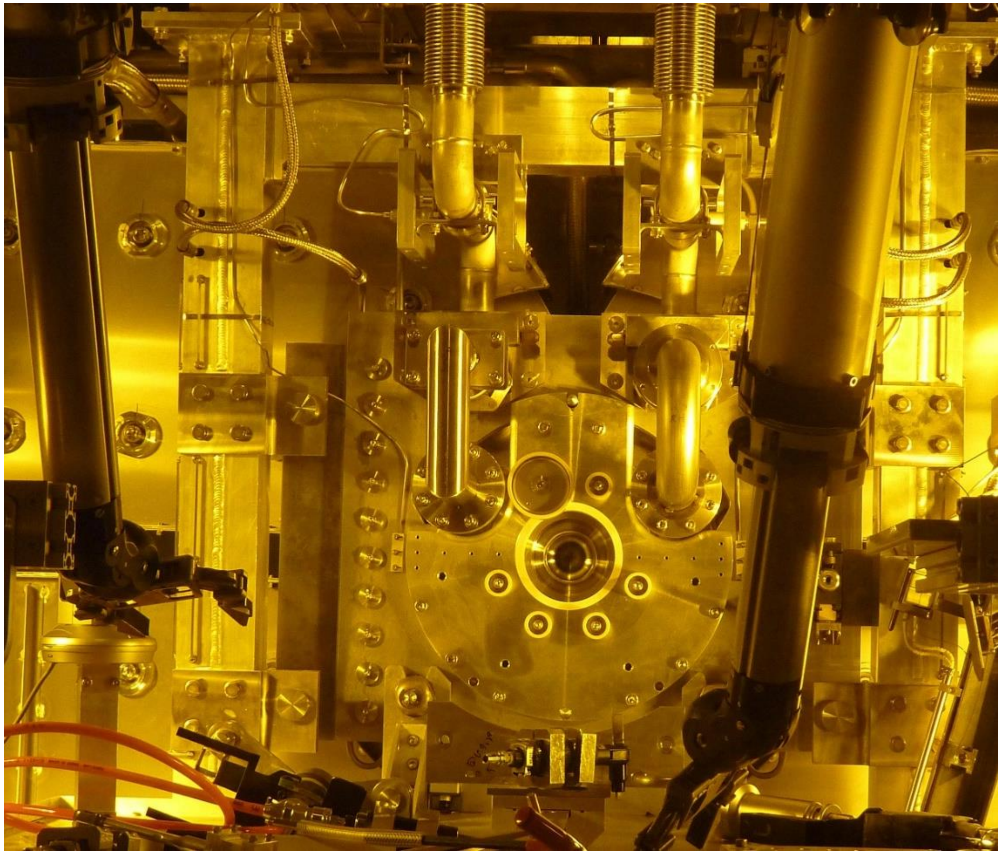
- Expect targets to fail
- Horns are inherently complex, costly and take a long time to produce
- Target cost ≈1/10th horn cost, and spares can be produced more readily

→ Hence the need for an independently exchangeable target



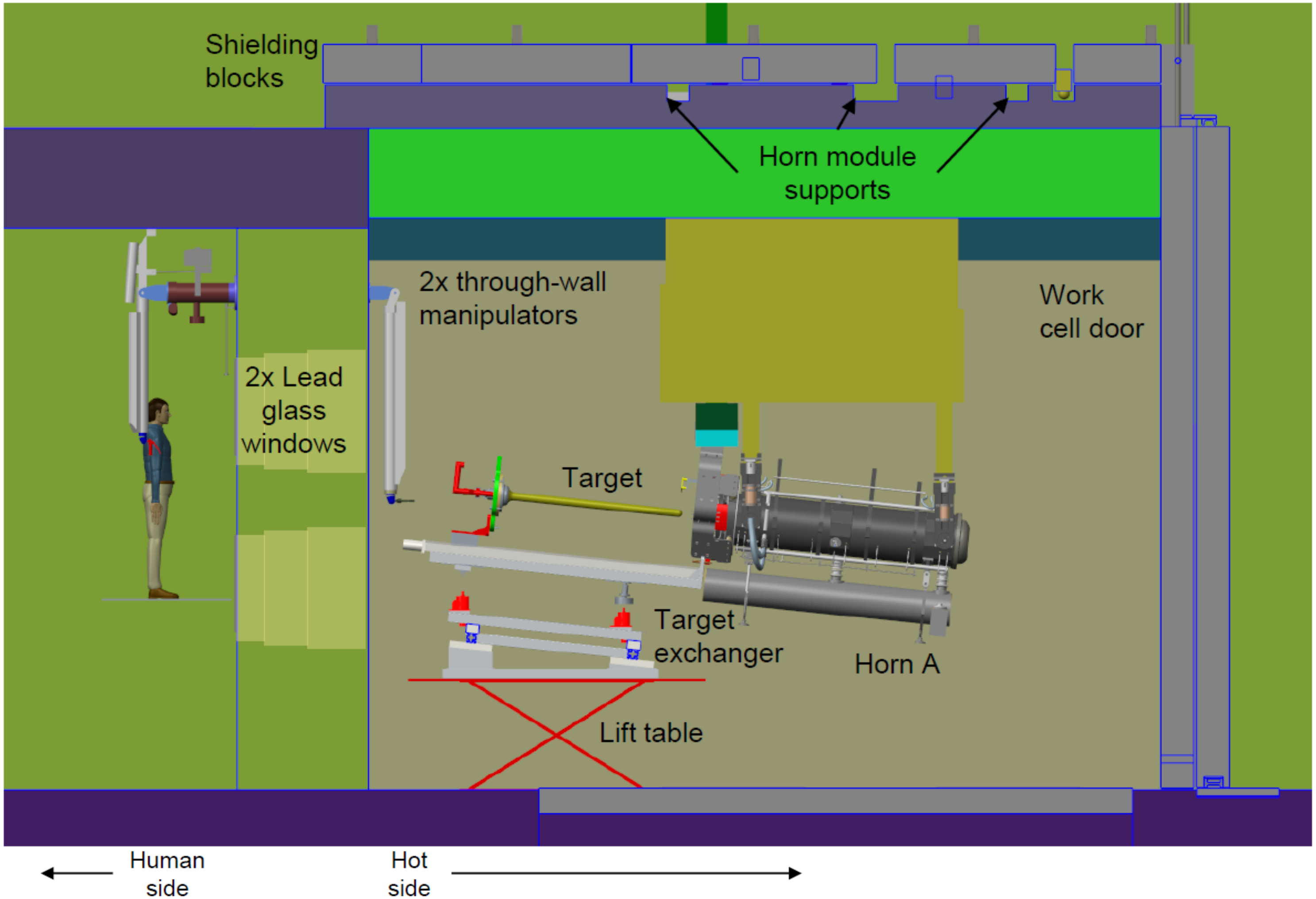
Current Experience – T2K





- Experience from T2K will feed into LBNF exchanger design
- NB Never needed to replace a failed T2K target

LBNF Work Cell During Target Exchange



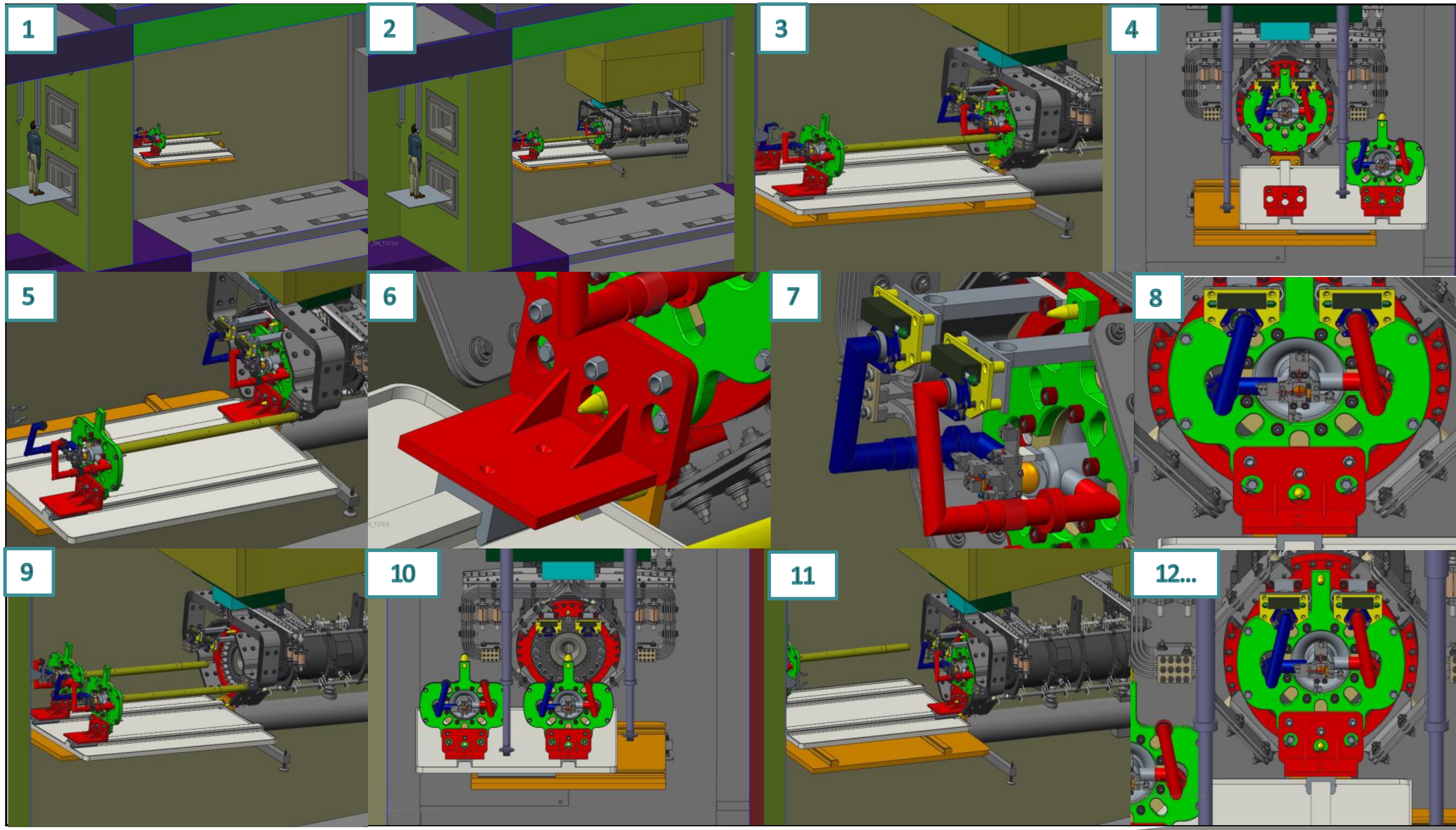
Horn module supported from the top of the work cell

Target exchanger located on lift table on work cell floor

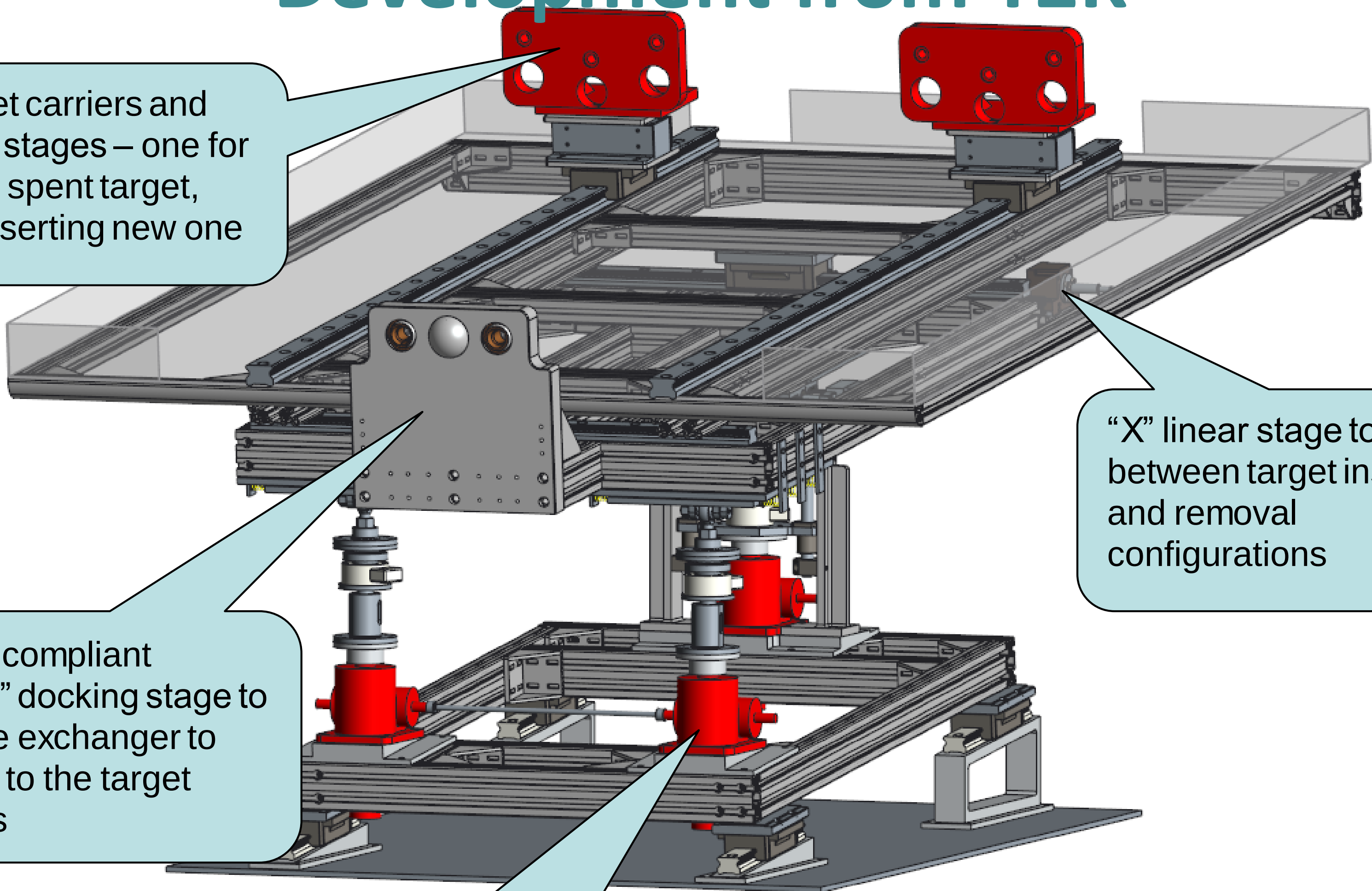
Persons using through-wall manipulators are approximately 4m away from the front face of the horn

Market survey has been carried out of suitable manipulators

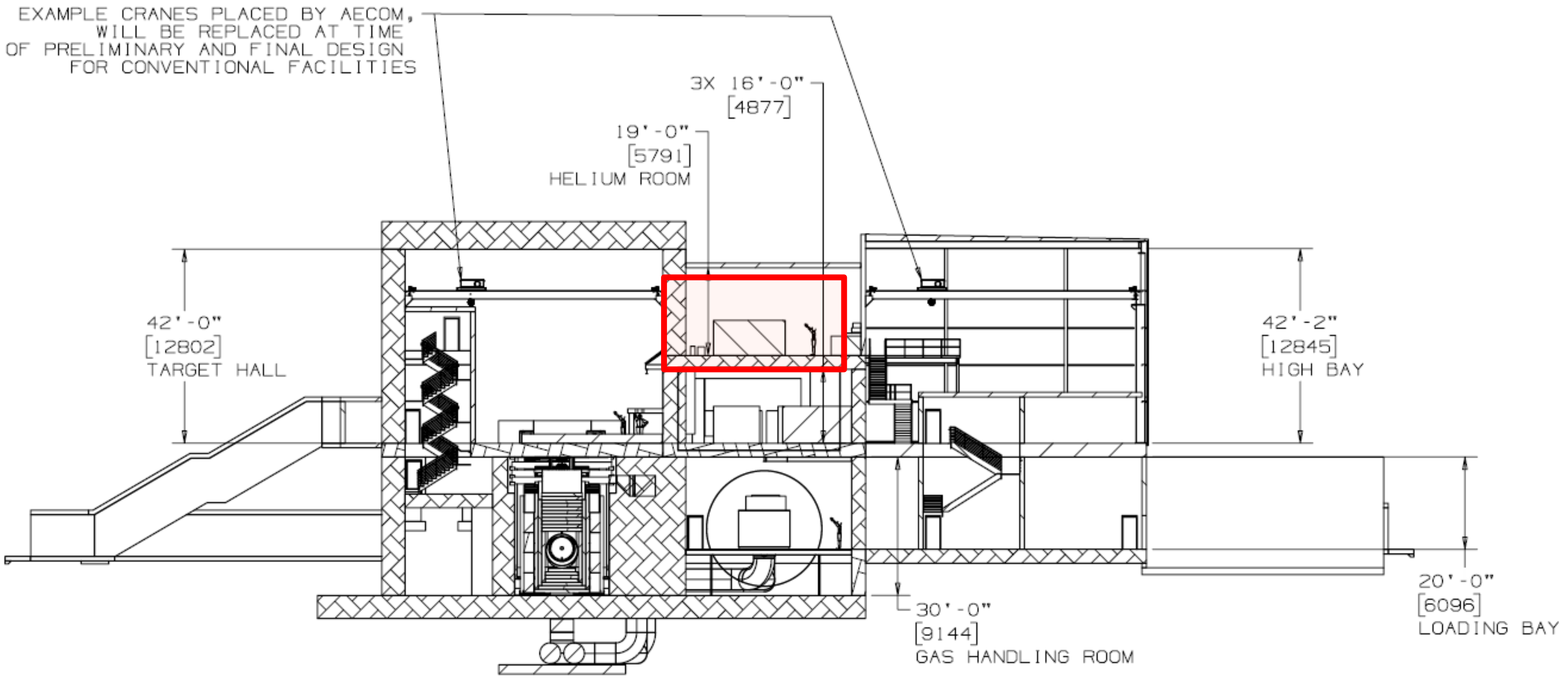
Outline Procedures for Target Exchange



Target Exchanger Concept – Development from T2K

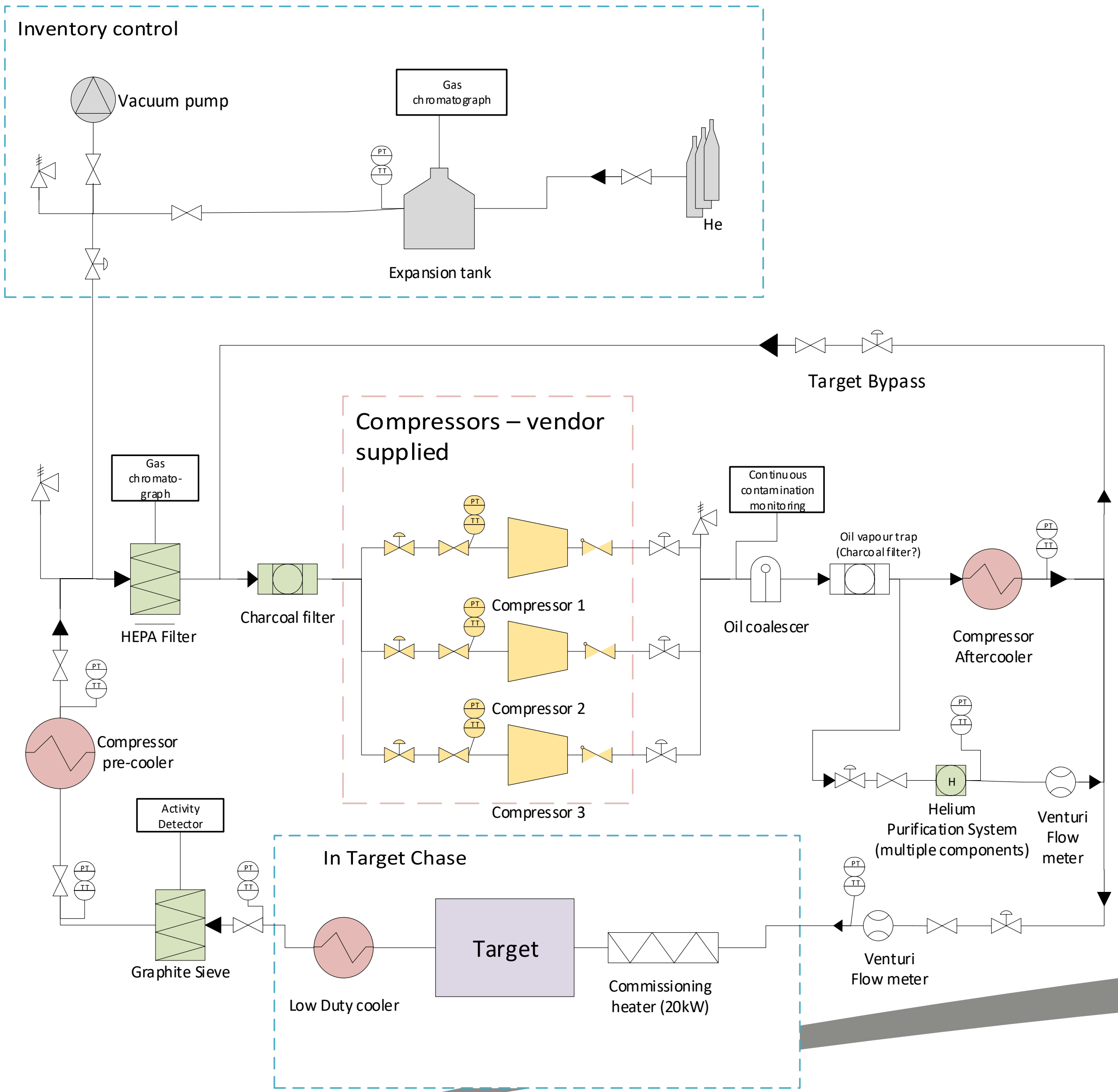


LBNF-20 Target Hall – Helium Room Location



Drawn by: Matthew Sawtell, Fermilab

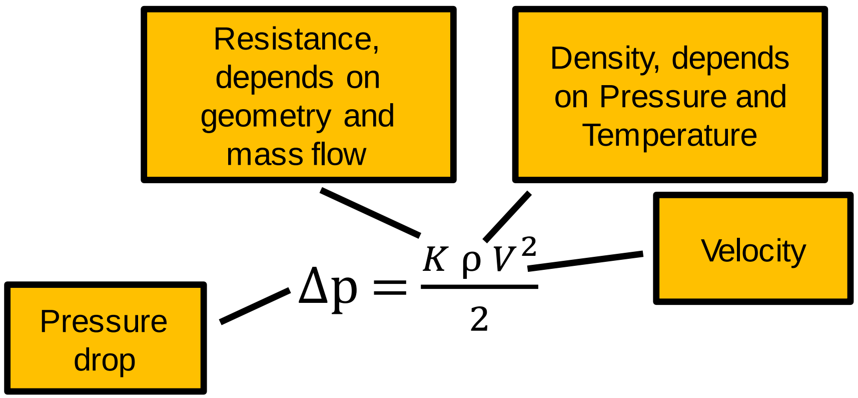
Target Helium Circuit



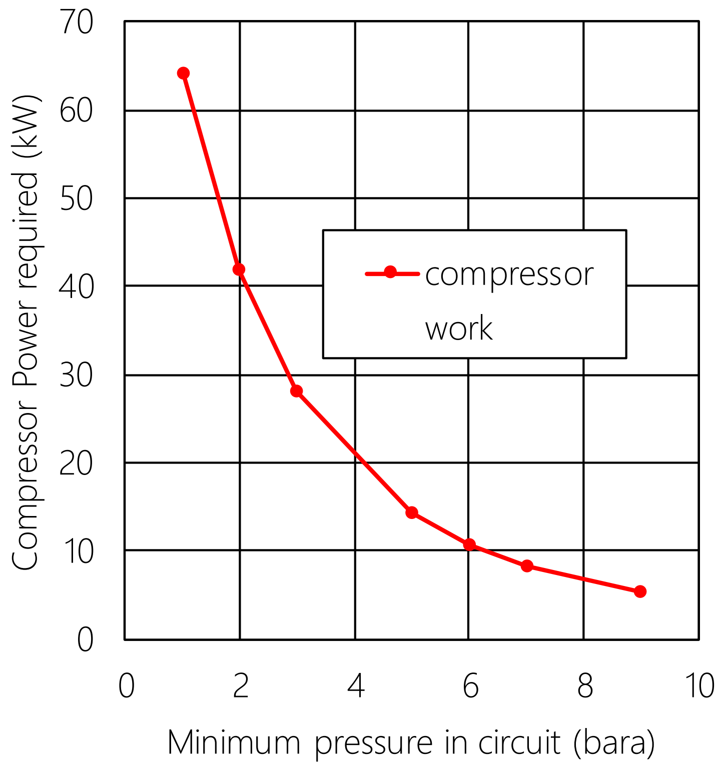
- Potential compressor and heat exchangers identified as future UK In-Kind Contributions
- Possibility to prototype flow control/ monitoring on T2K helium plant

System Pressure Considerations

- For a given helium mass flow, can increase system back pressure “Pmin” to reduce component pressure drops



$$\Delta p = \frac{K\,\rho\,V^2}{2}$$

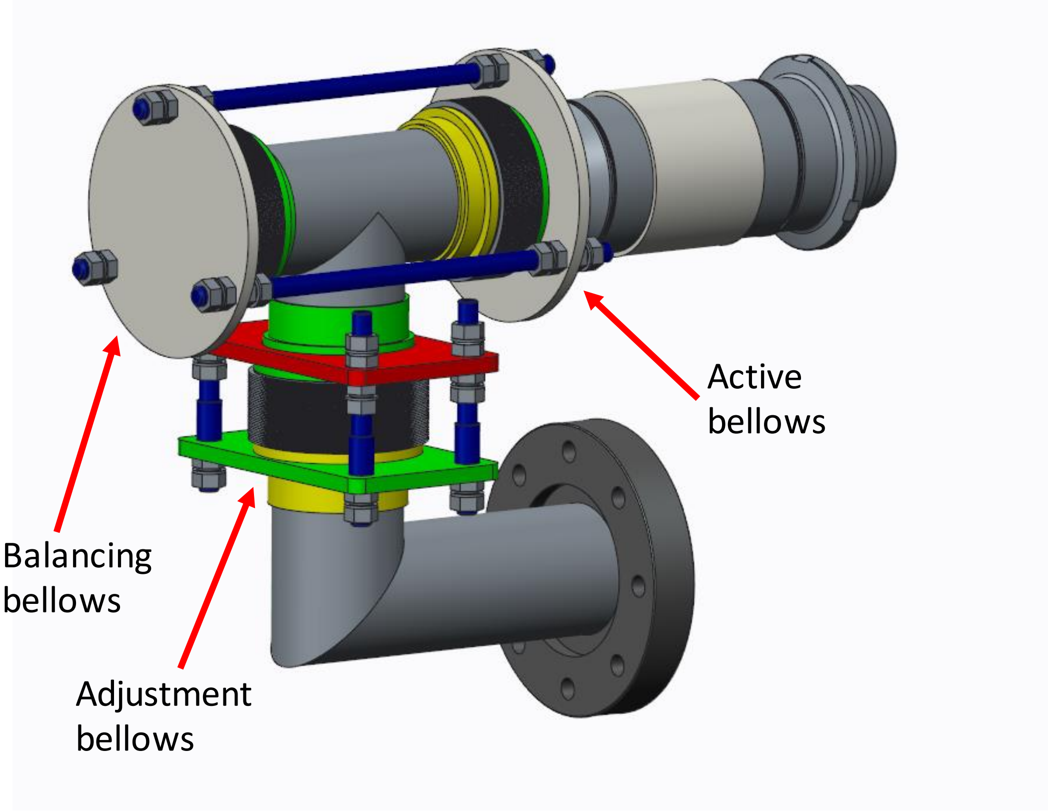


- Aim to reduce pressure ratio: $\frac{Pressure\ out}{Pressure\ in}$
- Leads to a reduction in compressor work (re: system cost, running cost, etc…)
- Win-win for heat-exchanger pressure drop due to reduced heating of fluid

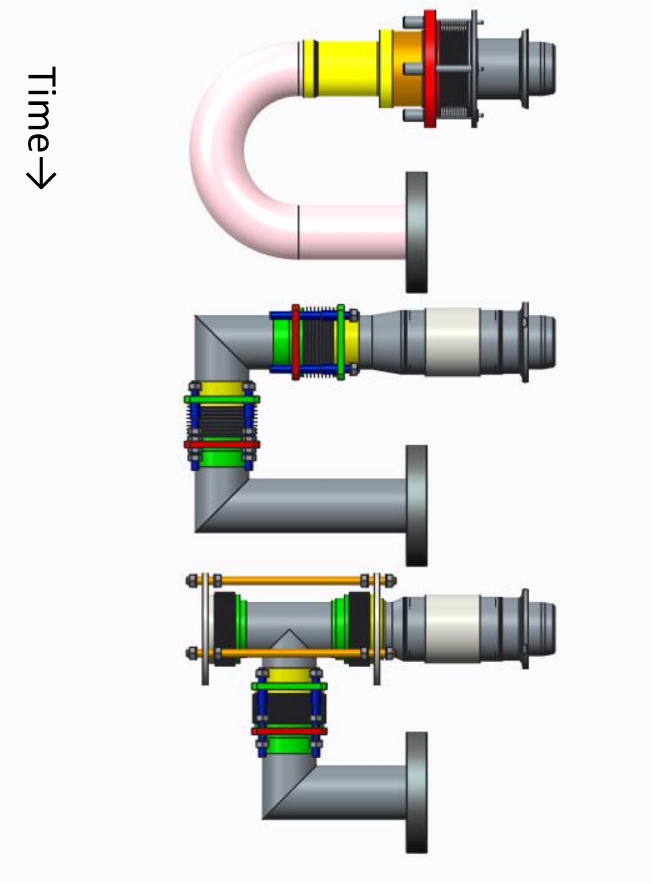
T2K: Pressure-balanced Bellows Arrangement

- Intend to profit from ongoing T2K target pipe R&D, enabling high pressure (5 bar) operation

Potential pressure balanced pipe design: Prototype under construction

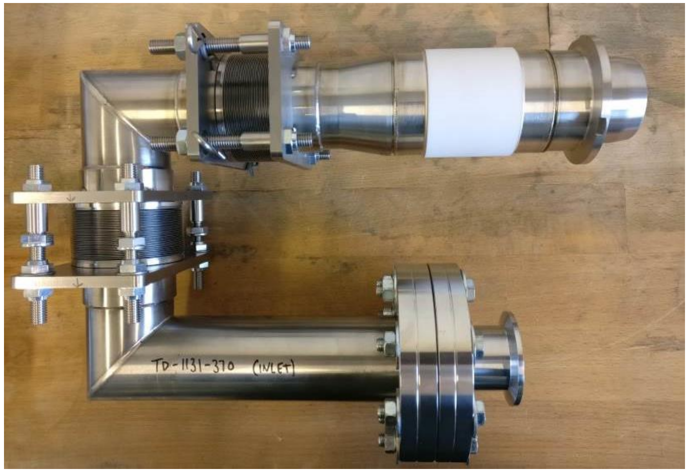


T2K Target Pipe Evolution:



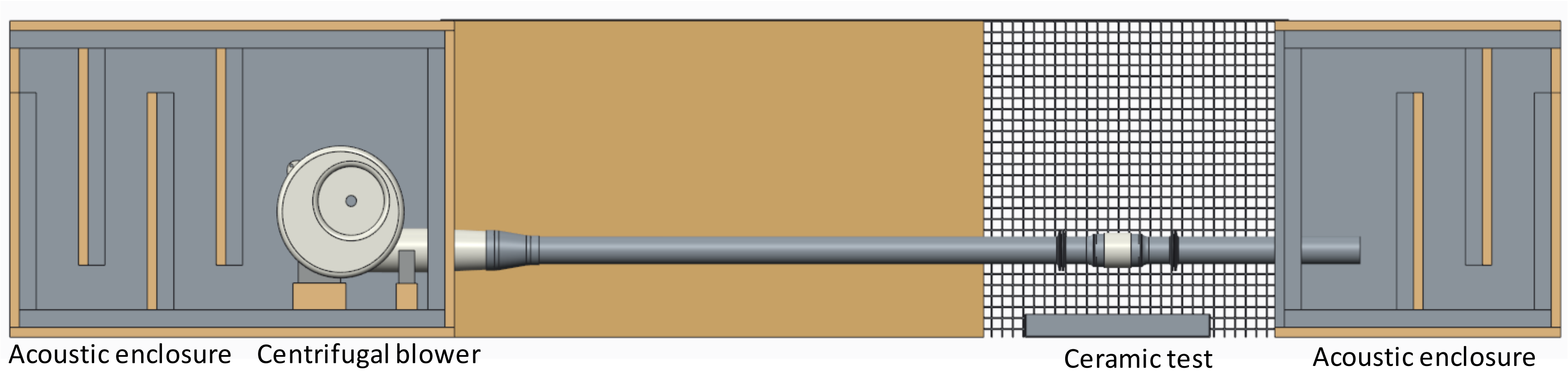
T2K: Ceramic Isolator Development

- Ceramic breaks are a necessity for electrical isolation in all Neutrino facilities (used in target, horn, striplines etc.)
- They are brittle, fragile and easily broken if loaded in any manner except axial compression
- Intend to profit from historical testing of various types of isolator for T2K with varying degrees of success
  - Diffusion bonded
  - Bolted
  - Brazed



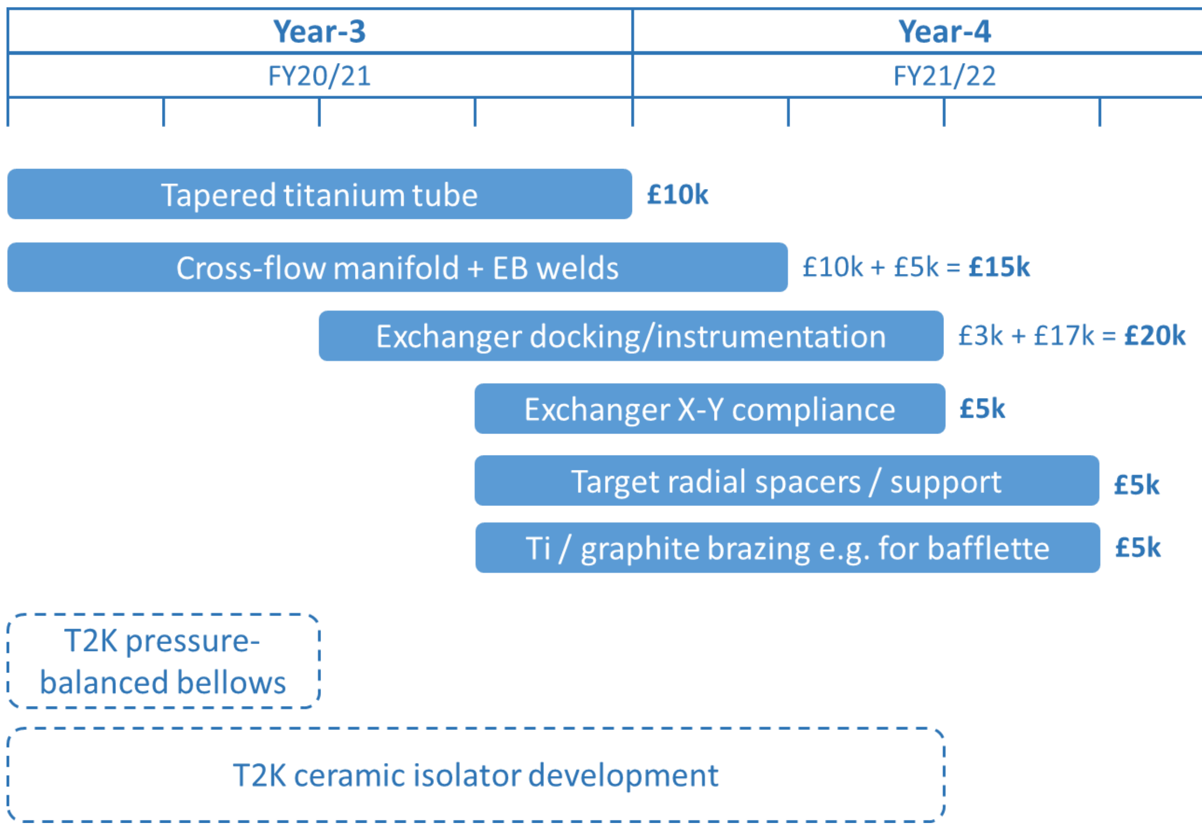
Target helium pipes with brazed alumina isolator for 750kW operation

- A test-bed has been used at RAL to address the issue of thermal shock/fatigue on target ceramics



Phase-1 Prototyping Plan

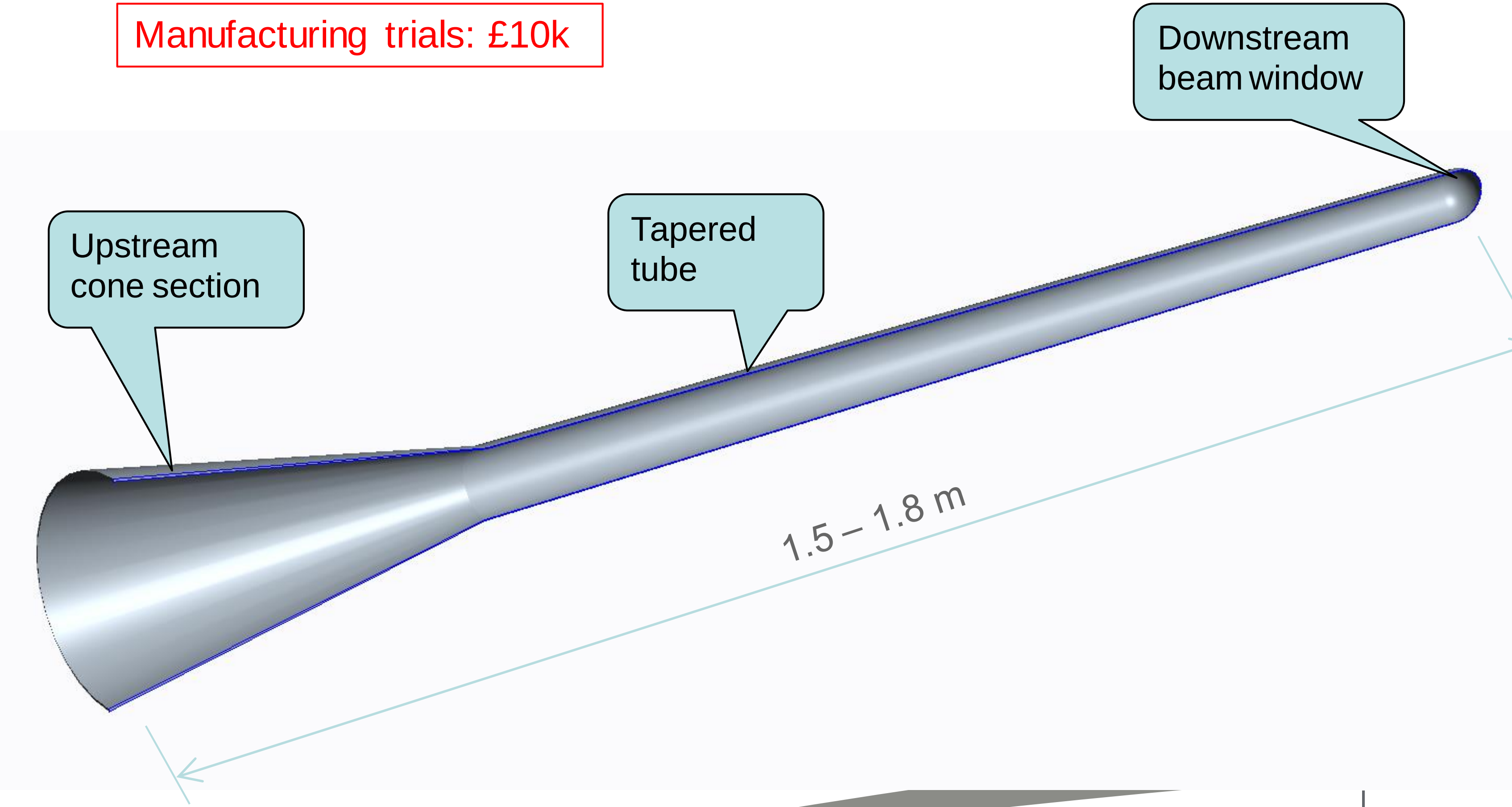
- Feature-prototyping required to inform preliminary-design, identify manufacturing routes / make technology choices and improve cost estimates for LBNF single cantilever target option
- Intend to spend LBNF prototyping budget in FY20/21 and FY21/22
- Will also profit from T2K prototyping activities



Prototyping Plan: Tapered Titanium Tube

- Demonstrate manufacturing route for outer container (we expect this to be more challenging than for T2k)
  - Longer, Variable wall thickness, Tapered, Precision achievable?

Manufacturing trials: £10k



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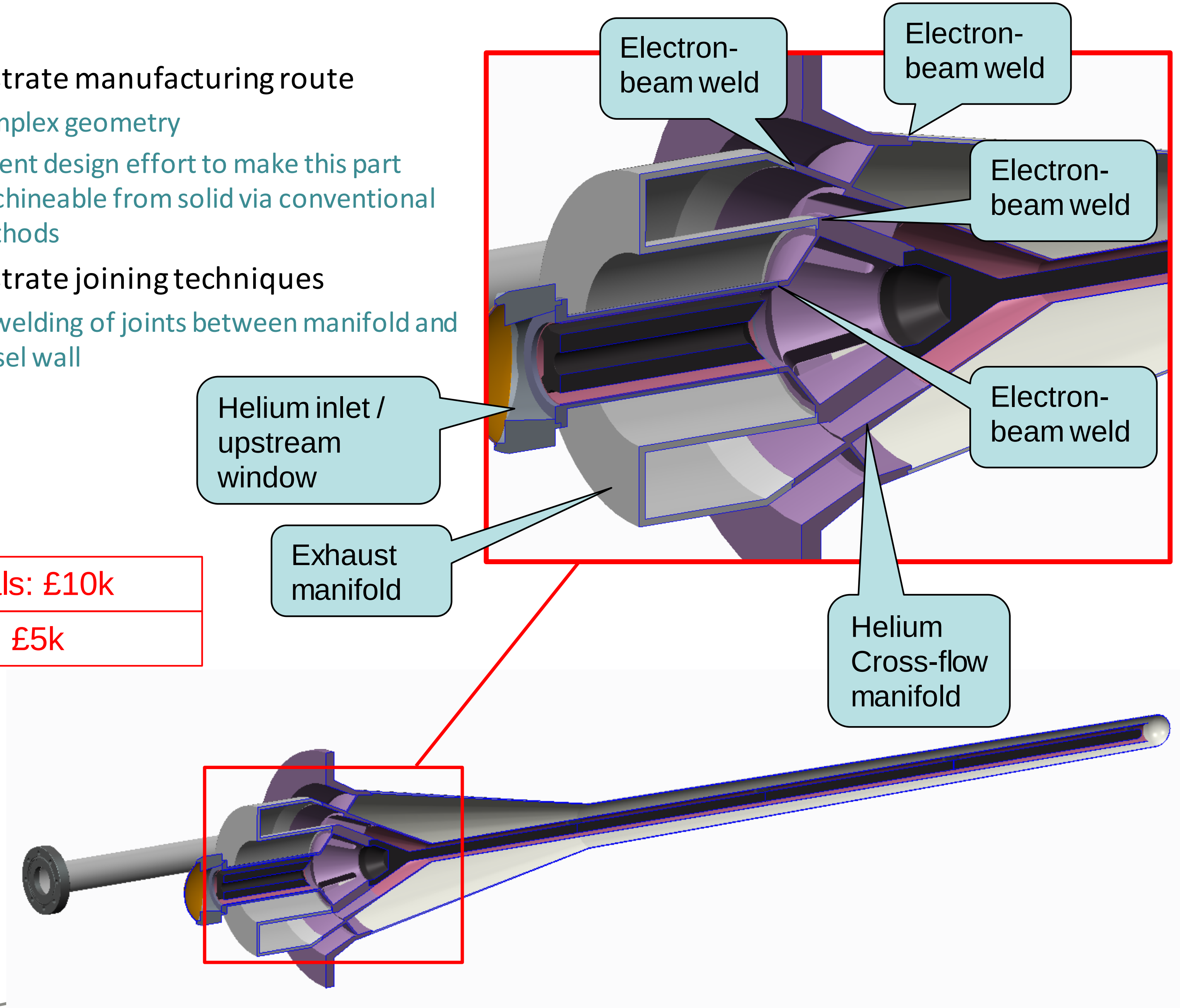
Prototyping Plan: Cross-flow manifold + EB welds

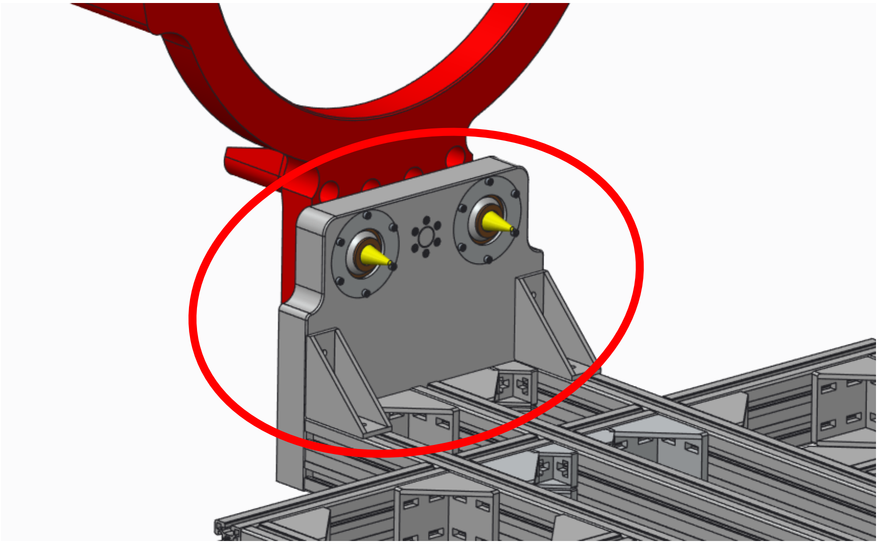
- Demonstrate manufacturing route
  - Complex geometry
  - Recent design effort to make this part machineable from solid via conventional methods
- Demonstrate joining techniques
  - EB welding of joints between manifold and vessel wall



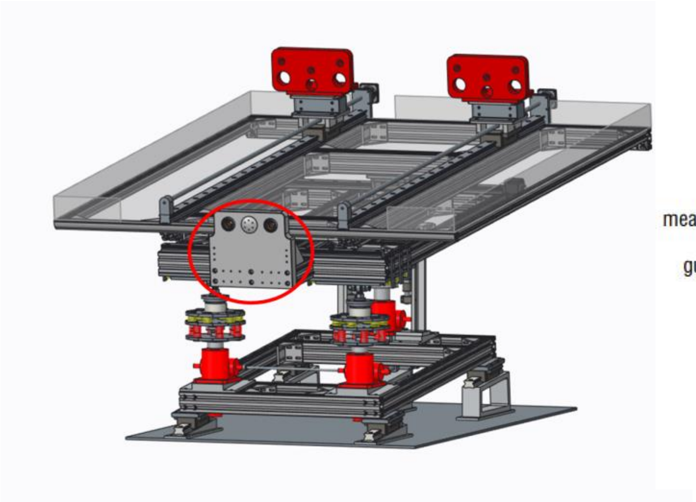
Machining trials: £10k	
Welding trials: £5k	

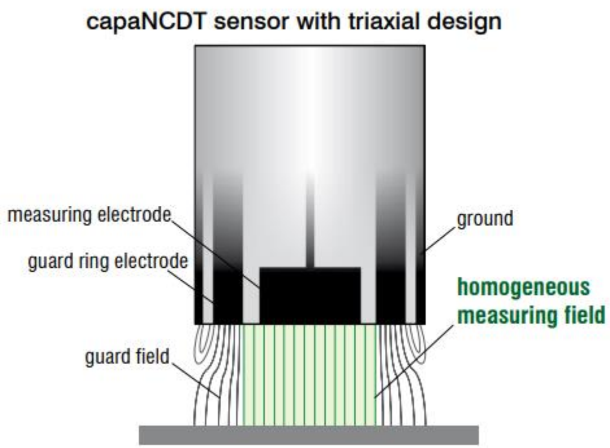
Prototyping Plan: Exchanger Docking / Instrumentation

- Prototype the proposed exchanger remote docking interface and remote alignment instrumentation
- Select non-contact instrumentation technology
- Instrumentation could be re-used in production exchanger if successful

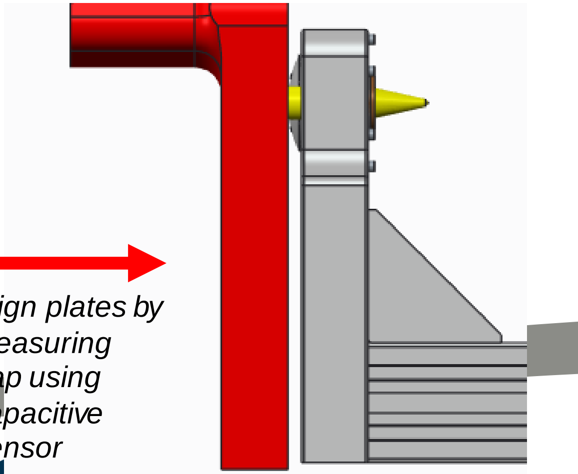


Instrumentation: £17k	
Hardware interface: £3k	





Align plates by measuring gap using capacitive sensor

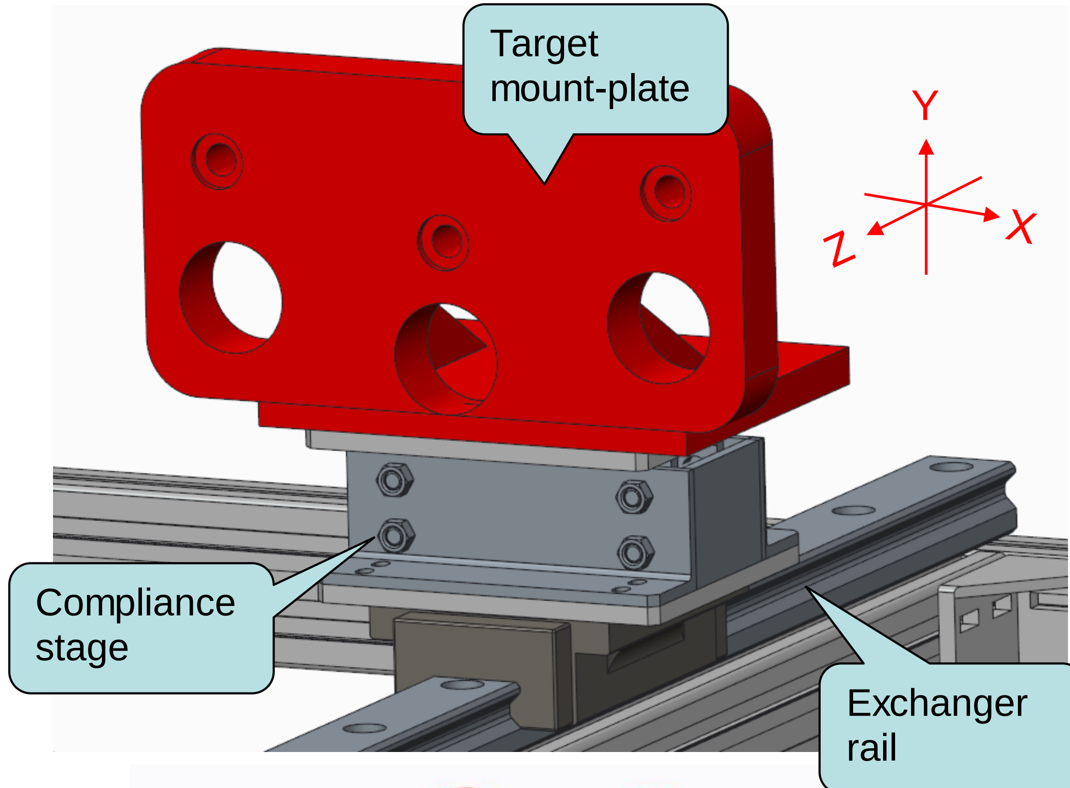


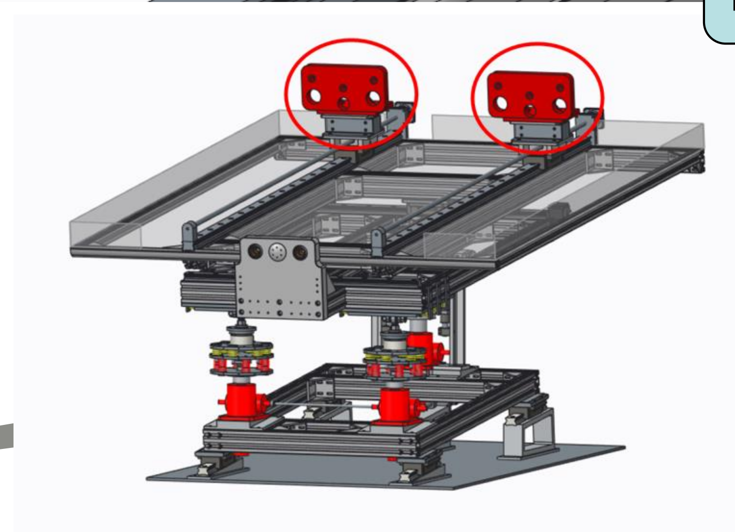
Prototyping Plan: Exchanger X-Y Compliance

- Need ***rigid*** mounting system to attach target to exchanger tooling that is also ***compliant*** in X-Y to permit docking onto precision remote alignment pins

- May be integrated with remote docking / instrumentation prototype (see previous slide)

Manufacturing trials: £5k





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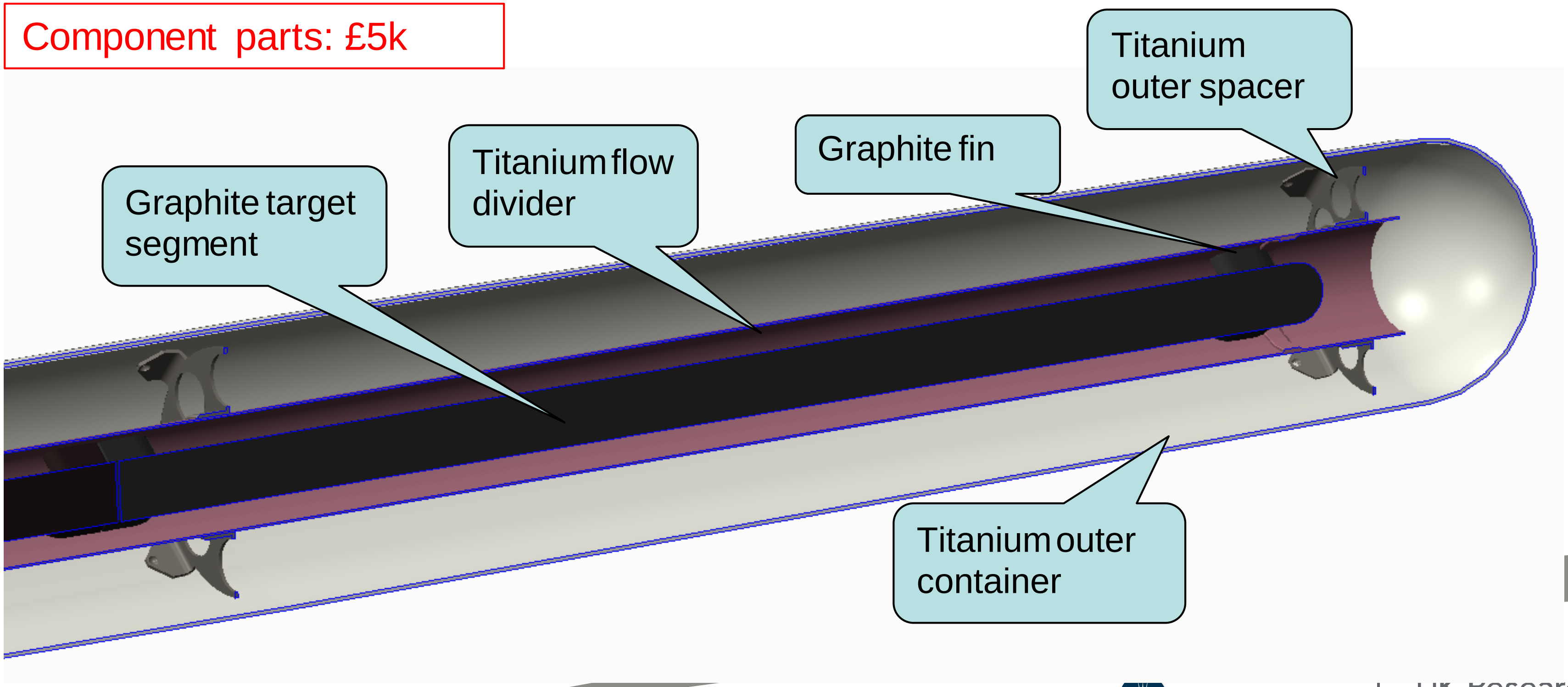
Prototyping Plan: Radial Spacers / Support

- Graphite target is arranged in segments, which are supported by the outer container using radial spacers
- Different radial support scheme to T2k
  - Titanium outer spacer in particular needs to be prototyped and tested
  - Plan to make a short section demonstrator (e.g. 1 segment long)
  - Identify build sequence

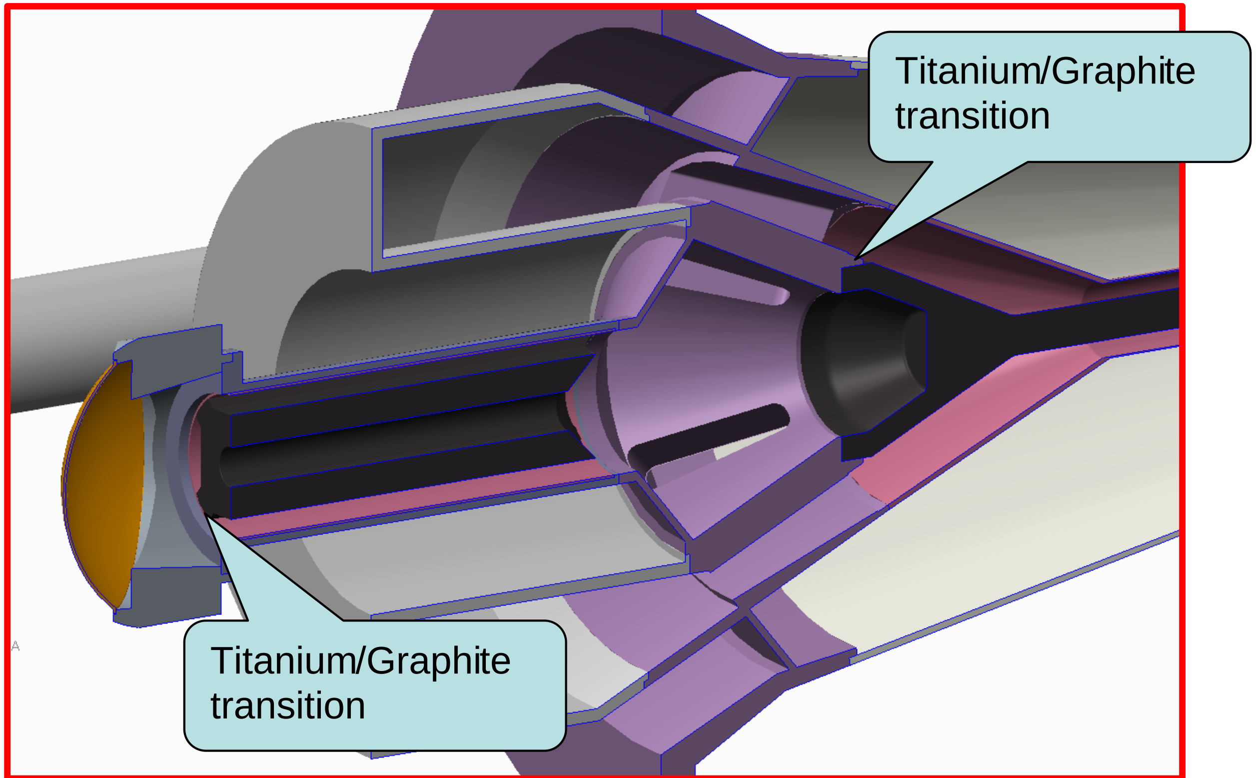
Component parts: £5k

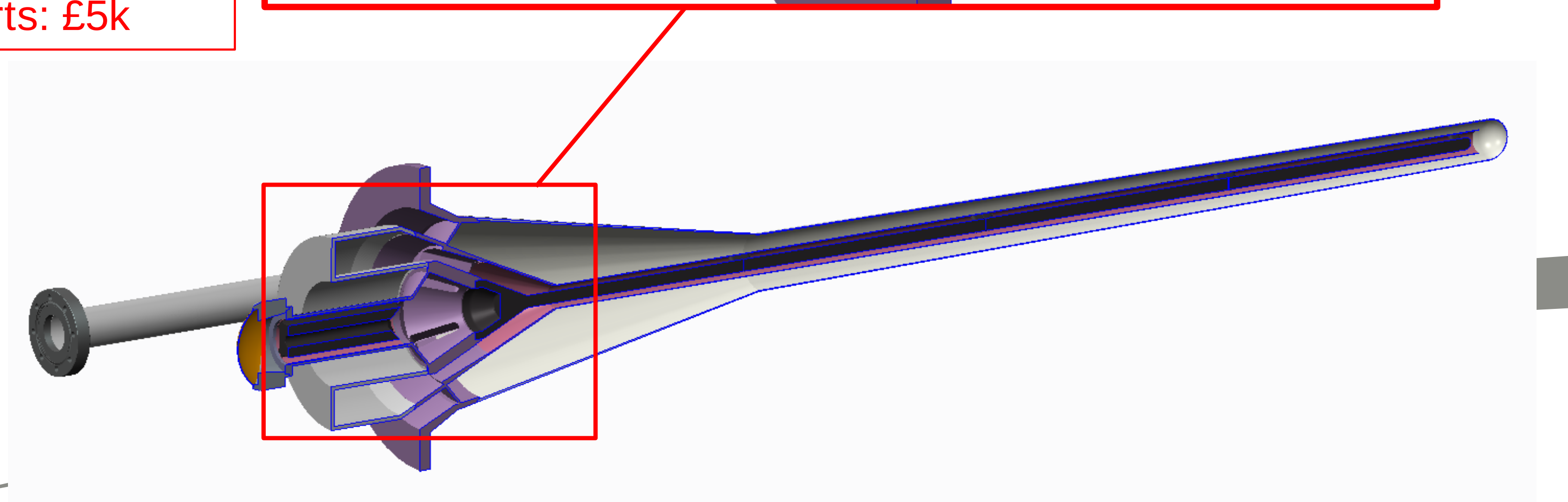


Prototyping Plan: Titanium / Graphite Brazing

- Demonstrate joining technique for titanium/graphite transitions
- Have identified promising vacuum brazing route
  - Trials using in-house facilities (vacuum furnace)
  - This is on a larger scale to anything we have demonstrated previously

Component parts: £5k





CDR Recommendation #1:
Formal Performance & Specification requirement

Parameter/Specification	Include in Summary	Value for CD4 1.2 MW	Ultimate Value LBNF Final Phase - 2.4 MW	Units
PROTOTYPE TARGET / OPERATIONAL SPARE				
Construction:				
Core Material		Graphite		
Core Geometry		Cylindrical		
Core Length		1.5		m
Core Diameter		16		mm
No. Core Segments		2 to 5		
Vessel Material		Titanium Alloy		
Support Plate Material		Aluminium Alloy		
Weight of Target Assembly		??		kg
Beam Operating Limits:				
Beam Energy (nominal)		120		GeV
Beam Power (max)		1.2		MW
Protons per Pulse (max)		7.5E+13		PPP
Max. protons on target / year		??		POT/yr
Beam Sigma (nominal)		2.667		mm
Beam Sigma (max)		??		mm
Beam Sigma (min)		??		mm
Beam Offset (max)		??		mm
Thermal Management:				
Heat deposited in target assembly		??		kW
Cooling Medium		Helium gas		
Colant flowrate		??		g/s
Helium Inlet Temperature (nominal)		30		°C
Helium Exhaust Temperature (max)		180		°C
Maximun Graphite Temperature		700		°C
Maximum Titanium Temperature		200		°C
Maximum Aluminium Temperature		100		°C
Pressure drop across target		??		mbar
Electrical Isolation:				
Grounding Scheme		connected to horn conductor via resistor		
Resistor Size		??		Ohms
Min. nominal clearance to Horn-A Inner Conductor		5		mm

Outline LBNF beamline design parameters spreadsheet

- Work just starting
- Proceeding in parallel to horn parameters spreadsheet

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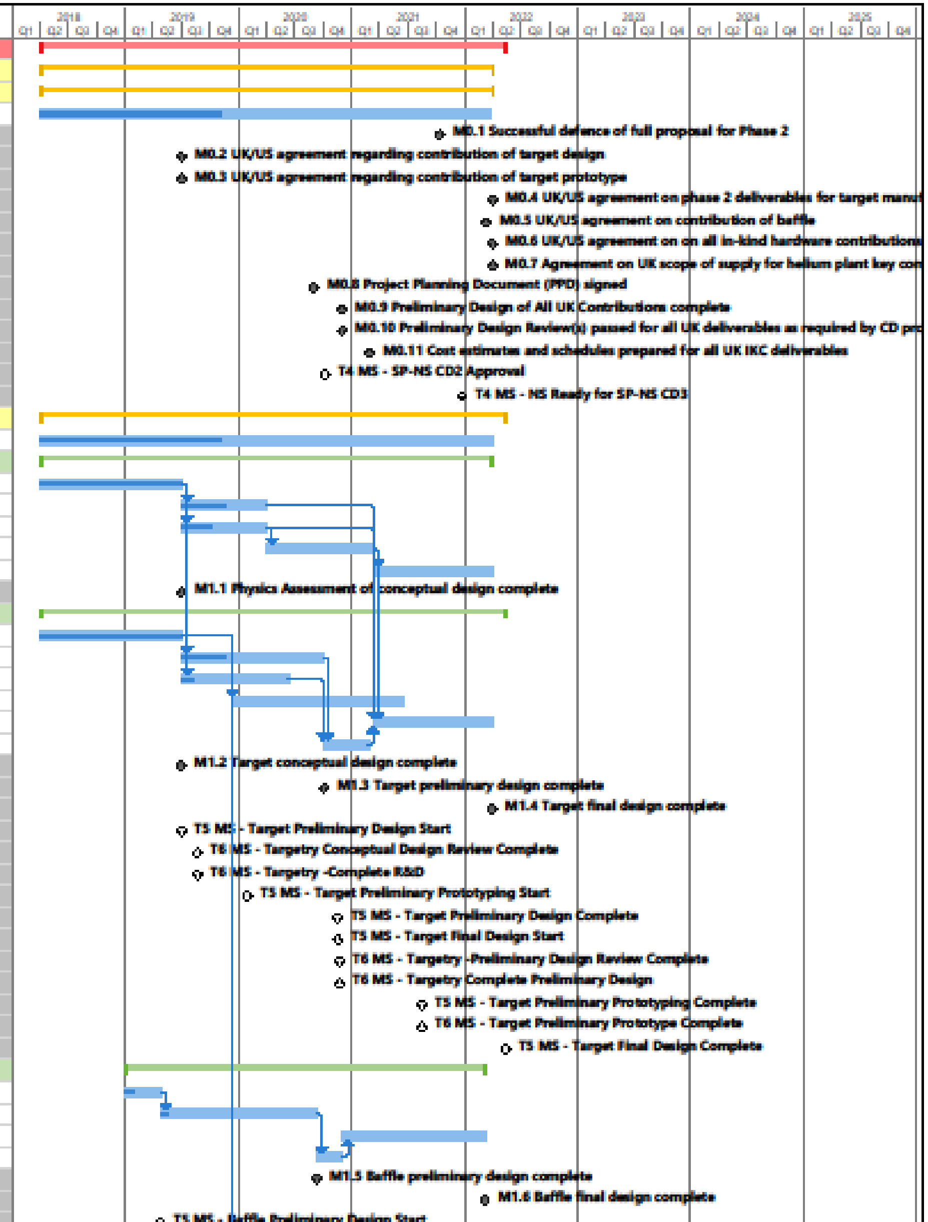
CDR Recommendation #2: Milestones (from draft PPD)

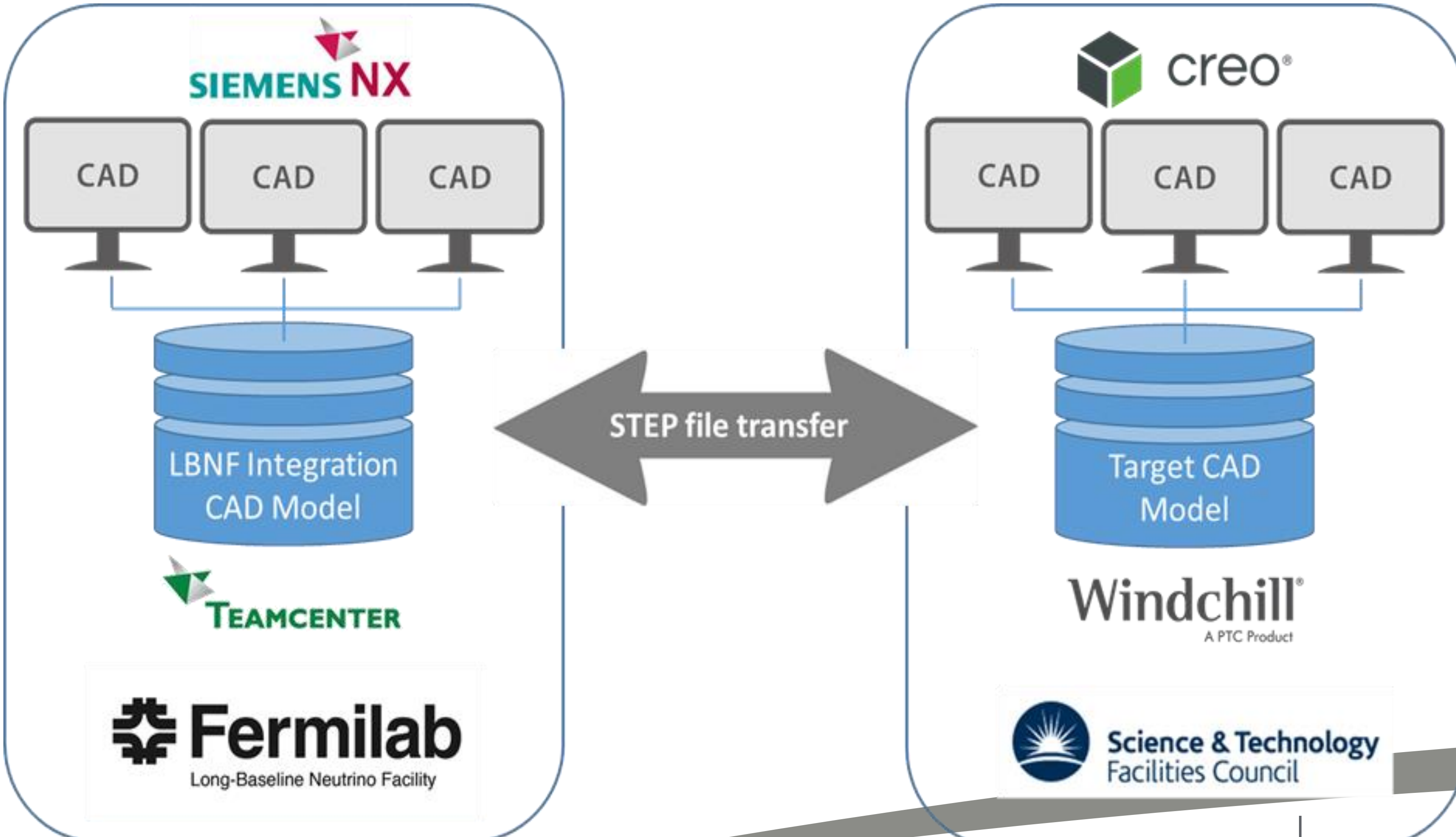
Completion Milestones	Planned/ Baseline date	Location	Comments
Phase 1: Preliminary Design Phase			
Preliminary design of target and baffle complete	17 Nov 2020	RAL	
Preliminary design of target exchange system and remote handling equipment complete	02 Dec 2020	RAL	
Preliminary design of He gas cooling system complete	13 Oct 2020	RAL	Includes shielded He penetrations
Preliminary Design Review(s) of all UK contributions complete	10 Dec 2020	Fermilab?	May be one or several preliminary design reviews
Feature Prototyping Results Report complete	17 Aug 2021	RAL	

Phase 1: Target Schedule

ID	Task Name	Start	Finish
1	**Phases 0 and 1: Preparatory Work, Design and Costing**	**Mon 02/04/18**	**Fri 13/05/22**
2	**Non-Staff Costs**	**Mon 02/04/18**	**Fri 01/04/22**
20	**WP0 Management**	**Mon 02/04/18**	**Fri 01/04/22**
21	Task 0.0 Project Management	Mon 02/04/18	Fri 25/03/22
22	*M0.1 Successful defence of full proposal for Phase 2*	*Mon 11/10/21*	*Mon 11/10/21*
23	*M0.2 UK/US agreement regarding contribution of target design*	*Tue 02/07/19*	*Tue 02/07/19*
24	*M0.3 UK/US agreement regarding contribution of target prototype*	*Tue 02/07/19*	*Tue 02/07/19*
25	*M0.4 UK/US agreement on phase 2 deliverables for target manuf.*	*Fri 01/04/22*	*Fri 01/04/22*
26	*M0.5 UK/US agreement on contribution of baffle*	*Fri 11/03/22*	*Fri 11/03/22*
27	*M0.6 UK/US agreement on on all in-kind hardware contributions*	*Thu 31/03/22*	*Thu 31/03/22*
28	*M0.7 Agreement on UK scope of supply for helium plant key comp.*	*Wed 30/03/22*	*Wed 30/03/22*
29	*M0.8 Project Planning Document (PPD) signed*	*Tue 01/09/20*	*Tue 01/09/20*
30	*M0.9 Preliminary Design of All UK Contributions complete*	*Tue 01/12/20*	*Tue 01/12/20*
31	*M0.10 Preliminary Design Review(s) passed for all UK deliverables as required by CD process*	*Tue 01/12/20*	*Tue 01/12/20*
32	*M0.11 Cost estimates and schedules prepared for all UK IKC deliverables*	*Mon 01/03/21*	*Mon 01/03/21*
33	*T4 MS - SP-NS CD2 Approval*	*Wed 07/10/20*	*Wed 07/10/20*
34	*T4 MS - NS Ready for SP-NS CD3*	*Thu 23/12/21*	*Thu 23/12/21*
35	**WP1 Target and Baffle**	**Mon 02/04/18**	**Fri 13/05/22**
36	Task 1.0 Workpackage management	Mon 02/04/18	Wed 30/03/22
37	**Activity 1.1 Target Physics Design and Optimisation**	**Mon 02/04/18**	**Mon 28/03/22**
38	Task 1.1.1 Physics performance of various target concepts	Mon 02/04/18	Tue 02/07/19
39	Task 1.1.2 Study impact of target on facility infrastructure	Tue 02/07/19	Wed 01/04/20
40	Task 1.1.3 Optimise preliminary design	Tue 02/07/19	Wed 01/04/20
41	Task 1.1.4 Combined performance assessment	Wed 01/04/20	Wed 10/03/21
42	Task 1.1.5 Final target design and off-normal conditions	Wed 10/03/21	Mon 28/03/22
43	*M1.1 Physics Assessment of conceptual design complete*	*Tue 02/07/19*	*Tue 02/07/19*
44	**Activity 1.2 Target Engineering Design and Optimisation**	**Mon 02/04/18**	**Fri 13/05/22**
45	Task 1.2.1 Target concepts	Mon 02/04/18	Tue 02/07/19
46	Task 1.2.2 Target preliminary design	Tue 02/07/19	Wed 30/09/20
47	Task 1.2.3 Target windows	Tue 02/07/19	Tue 09/06/20
48	Task 1.2.4 Target prototyping	Thu 12/12/19	Mon 14/06/21
49	Task 1.2.5 Target final design	Wed 10/03/21	Tue 29/03/22
50	Task 1.2.6 Target cost and schedule preparation	Wed 30/09/20	Mon 22/02/21
51	*M1.2 Target conceptual design complete*	*Mon 01/07/19*	*Mon 01/07/19*
52	*M1.3 Target preliminary design complete*	*Mon 05/10/20*	*Mon 05/10/20*
53	*M1.4 Target final design complete*	*Thu 31/03/22*	*Thu 31/03/22*
54	*T5 MS - Target Preliminary Design Start*	*Mon 01/07/19*	*Mon 01/07/19*
55	*T6 MS - Targetry Conceptual Design Review Complete*	*Wed 21/08/19*	*Wed 21/08/19*
56	*T6 MS - Targetry -Complete R&D*	*Wed 21/08/19*	*Wed 21/08/19*
57	*T5 MS - Target Preliminary Prototyping Start*	*Thu 30/01/20*	*Thu 30/01/20*
58	*T5 MS - Target Preliminary Design Complete*	*Tue 17/11/20*	*Tue 17/11/20*
59	*T5 MS - Target Final Design Start*	*Wed 18/11/20*	*Wed 18/11/20*
60	*T6 MS - Targetry -Preliminary Design Review Complete*	*Tue 24/11/20*	*Tue 24/11/20*
61	*T6 MS - Targetry Complete Preliminary Design*	*Tue 24/11/20*	*Tue 24/11/20*
62	*T5 MS - Target Preliminary Prototyping Complete*	*Tue 17/08/21*	*Tue 17/08/21*
63	*T6 MS - Target Preliminary Prototype Complete*	*Tue 17/08/21*	*Tue 17/08/21*
64	*T5 MS - Target Final Design Complete*	*Fri 13/05/22*	*Fri 13/05/22*
65	**Activity 1.3 Instrumented Baffle/Collimator**	**Tue 01/01/19**	**Mon 07/03/22**
66	Task 1.3.1 Baffle specification	Tue 01/01/19	Wed 24/04/19
67	Task 1.3.2 Baffle preliminary design	Wed 24/04/19	Wed 09/09/20
68	Task 1.3.3 Baffle final design	Thu 03/12/20	Mon 07/03/22
69	Task 1.3.4 Baffle cost and schedule preparation	Wed 09/09/20	Thu 03/12/20
70	*M1.5 Baffle preliminary design complete*	*Fri 11/09/20*	*Fri 11/09/20*
71	*M1.6 Baffle final design complete*	*Mon 07/03/22*	*Mon 07/03/22*
72	[illegible]	[illegible]	[illegible]

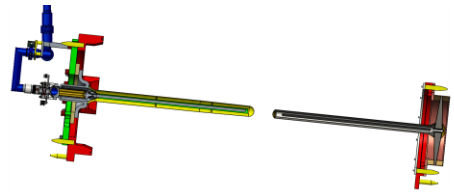
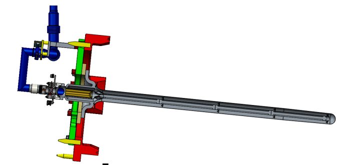


CDR Recommendation #3:
CAD Integration & version control

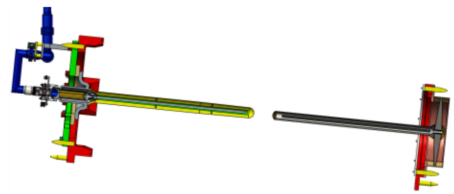
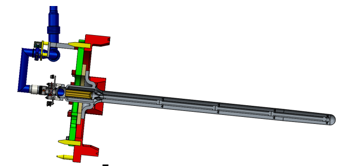


Backup Slides

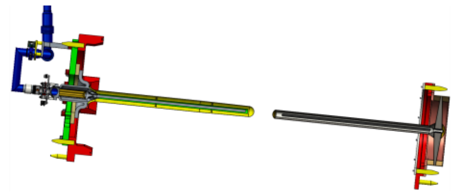
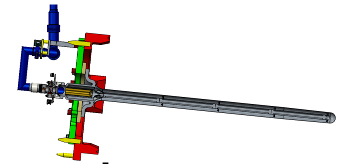
Key Design and Manufacturing Issues

	 Option 1:1x2m long	 Option 2: 2x1m long	 intermediate cantilever
Complexity of horn Interface	Interfaces at both US and DS of horn, plus self interface! Needs Helium services routing to DS end.	Interfaces at both US and DS of horn. Needs Helium services routing to DS end.	Interface to horn US end only
Departure from Proven Technology	Departure from T2K in terms of length / segmentation and Self docking interface.	Closest to two-interaction length T2K target	Departure from T2K in terms of length / segmentation
Design Challenges	DS support design for radial stiffness + longitudinal compliance, requires prototyping.	DS support/manifold design w.r.t. pressure stress and thermal distortion.	Pushing for longest feasible length (re: deflection, violin modes)
Manufacturing Challenges	DS support manufacture is complex. Manufacture of long thin-walled titanium tube to tight dimensional tolerances.	US target most similar to T2K. DS low-mass manifold manufacture is complex.	Manufacture of long thin-walled titanium tube to tight dimensional tolerances.
Cost	Relatively high cost of manufacture and outstanding design tasks	Relatively high cost of manufacture and outstanding design tasks	Relatively low cost of manufacture and outstanding design tasks

Key Operation Issues

	 Option 1:1x2m long	 Option 2: 2x1m long	 intermediate cantilever
Spare Production	Intermediate cost Build two in parallel?	Highest cost Build four (2 US + 2 DS) in parallel?	Lowest cost Build two in parallel?
Thermal Management	Highest heat load, single target cooling loop. Also need to cool DS support.	High heat load but divided between two cooling loops	Lowest total heat load
Mechanical loads	DS prop required to keep self-weight deflection and natural frequency in check	Most "robust" structure as measured by natural frequency and self-weight deflection	Inherently pushing at the limits on cantilever length
Complexity / number of failure points	High complexity due to cooled downstream mount	High complexity due to additional downstream target system	Low Complexity / number of components
Alignment Issues	Relies on DS support for target placement precision	Perceived difficulties with beam based alignment	Single object to align but largest self-weight deflection

Key Remote Maintenance Issues

	 Option 1:1x2m long	 Option 2: 2x1m long	 . intermediate cantilever
Time estimate for planned target exchange	3 weeks	2 weeks	1 week
Risk / complexity	High (number of operations)	High (number of operations)	Medium (number of operations)
Work Cell Interfaces	Two sets of exchange tooling with mechanical/services interface	Two sets of exchange tooling with mechanical/services interface	One exchanger tool
Manipulator operations	Ergonomics compromised when module rotated. Long-reach manipulators.	Ergonomics compromised when module rotated	Can optimise reach/view for the single required configuration
Crane operations	Two module rotations, including re-configuration of supports etc	One module rotation, including re-configuration of supports etc	All work achieved with single module configuration