LBNF Beam in Phase II

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University of Warwick

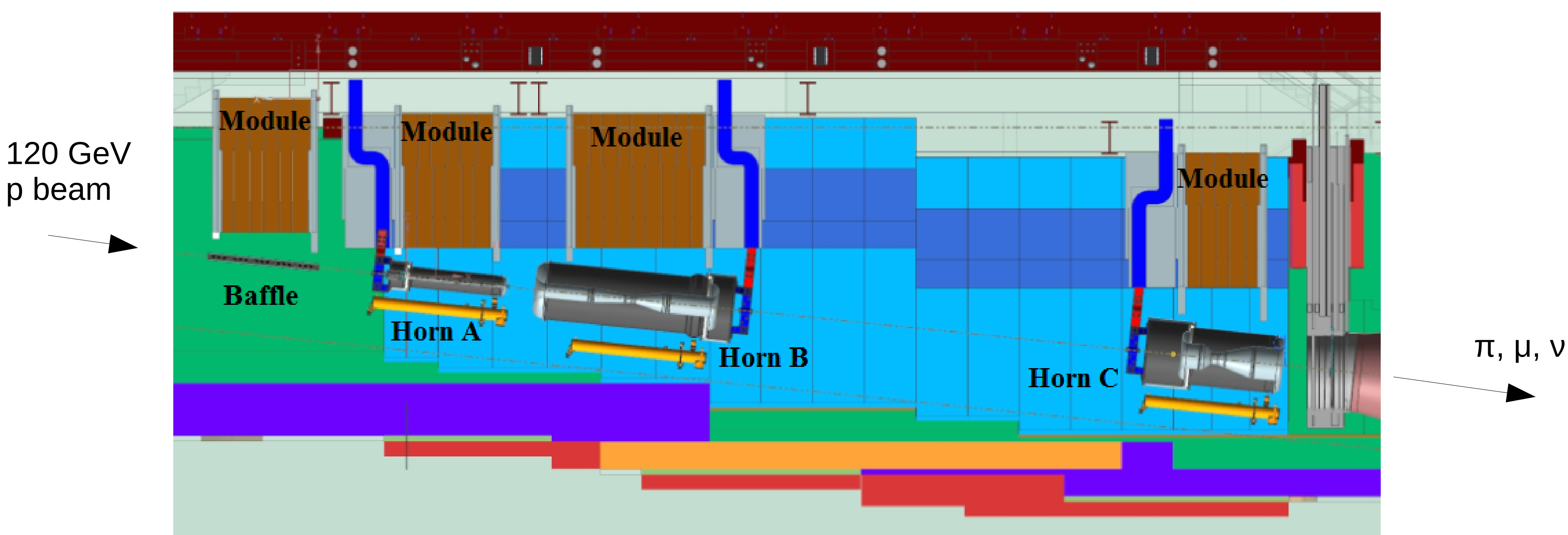
on behalf of the DUNE collaboration

20-22 June 2023

Outline

- Accelerator Complex Evolution (ACE)
  - Upgrading proton beam power from 1.2 MW to > 2 MW

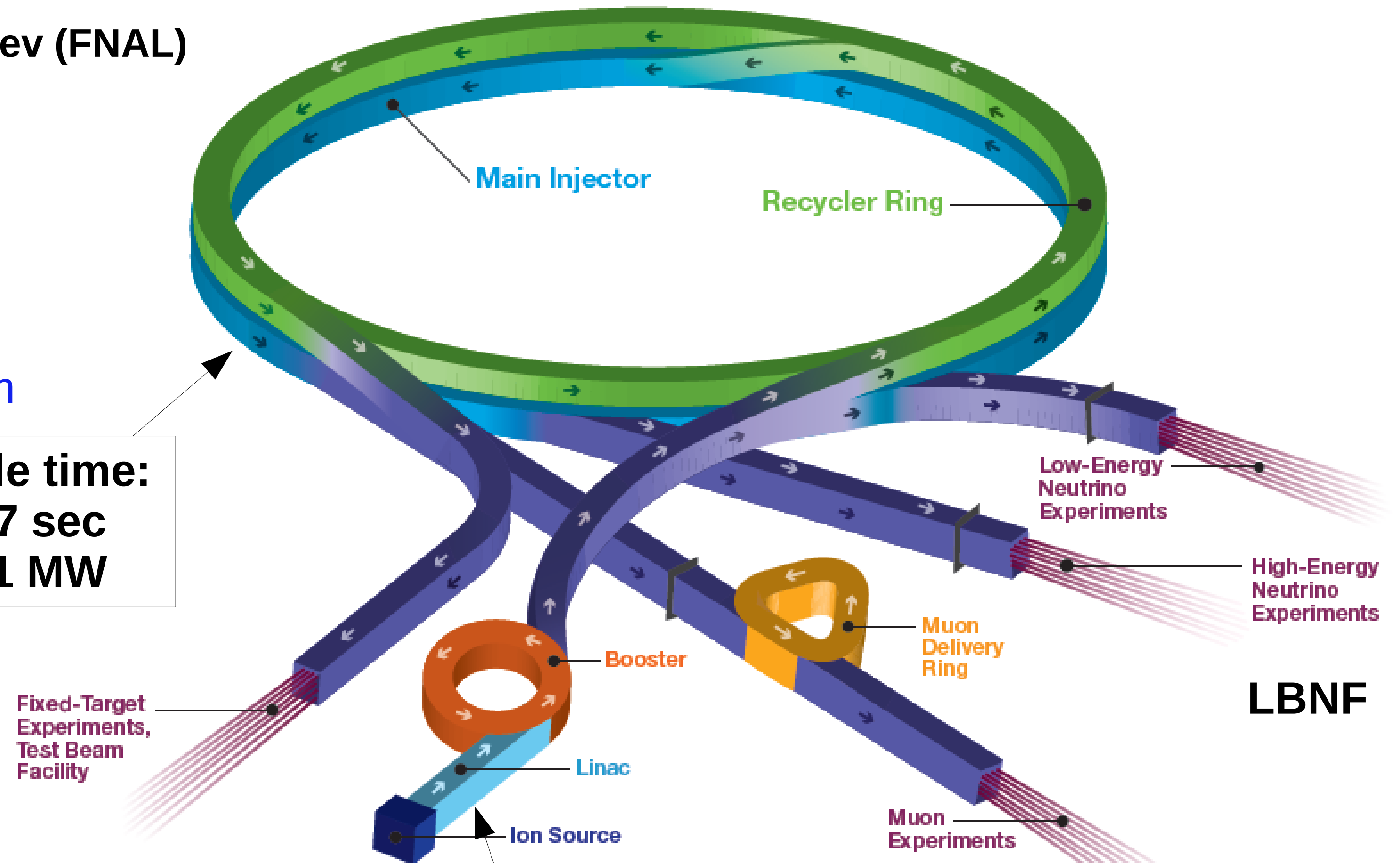
- Considerations for target & 3-horn focusing system
  - Design updates since TDR (2023 P5 assumes TDR design)
  - Physics impact of 1.2 MW design changes
  - Choices for > 1.2 MW running



Fermilab's ACE plan

Fermilab

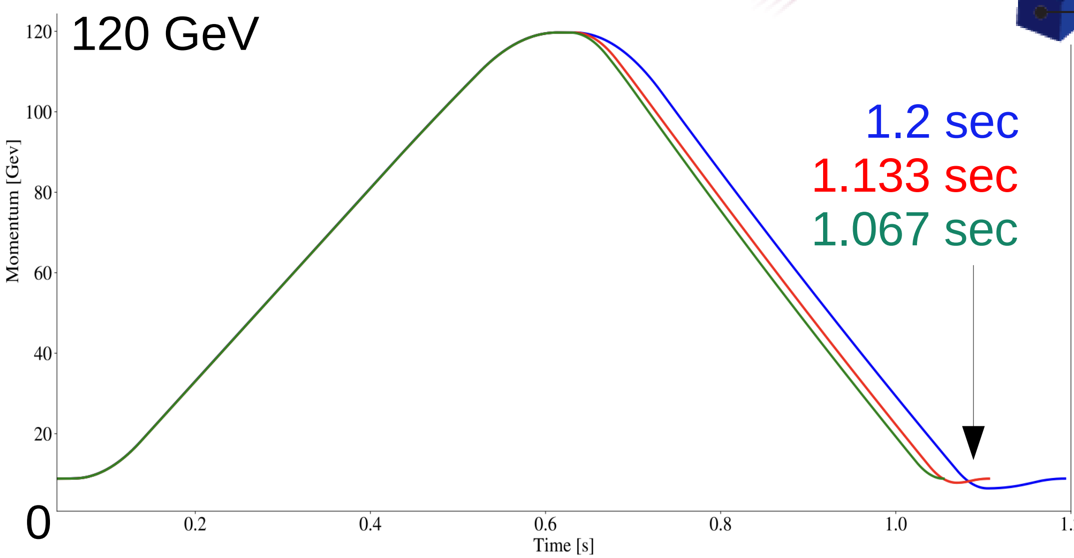
Courtesy **Alexander Valishev (FNAL)**



2024-2031 program

PIP-II & reduced MI cycle time:
1.2 sec → 0.9 sec → 0.7 sec
1.2 MW → 1.6 MW → 2.1 MW

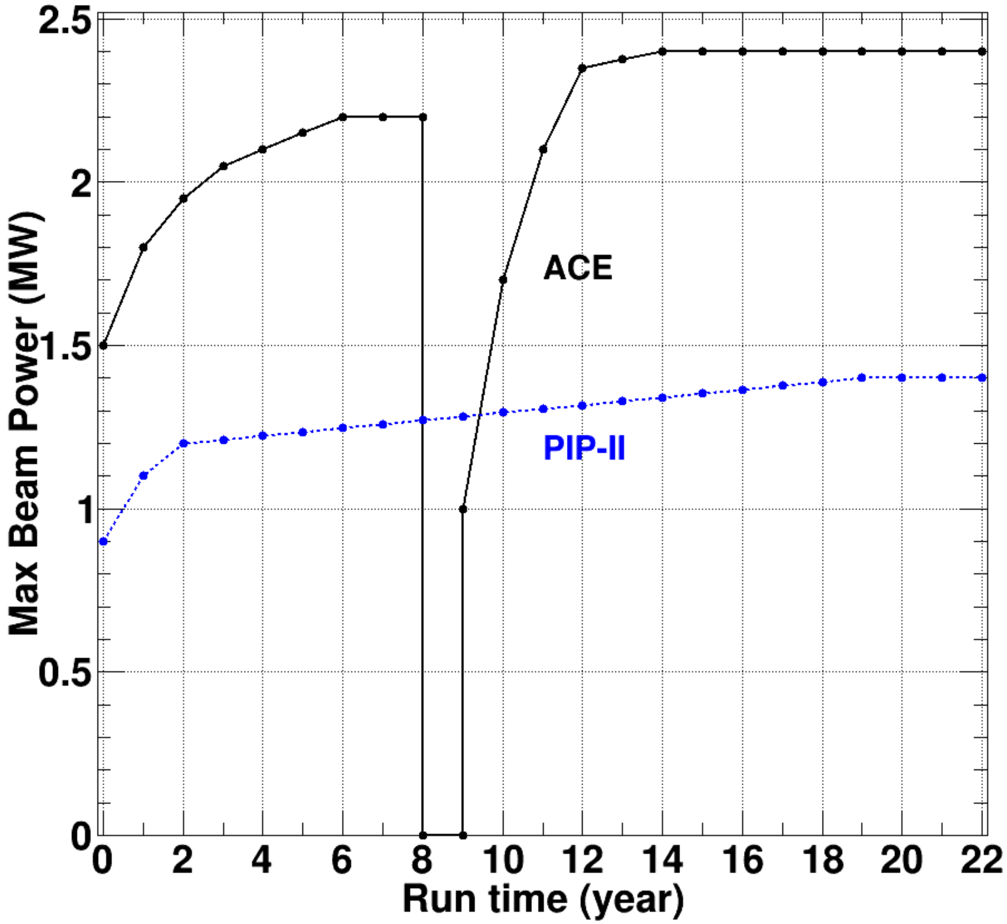
PIP-II Linac: 1.2 MW



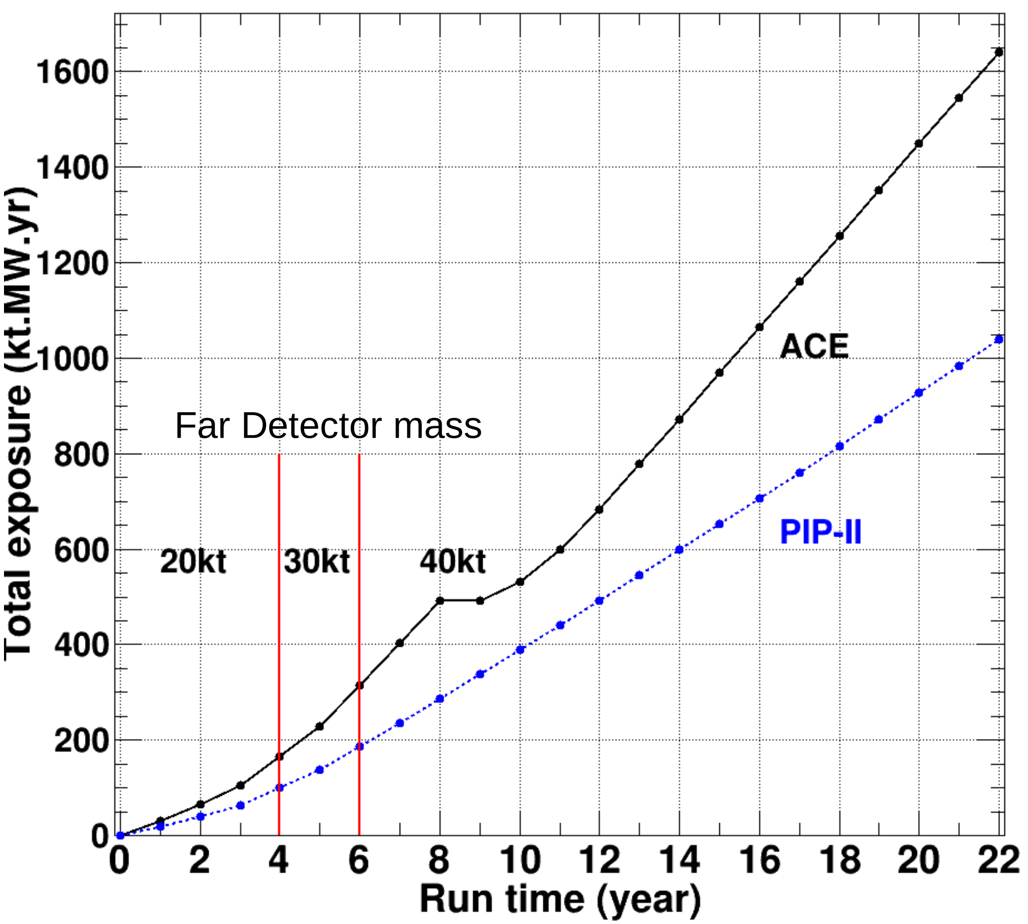
1.2 sec MI cycle time

Booster upgrades for 2.4 MW (beyond 2031)

LBNF beam scenarios



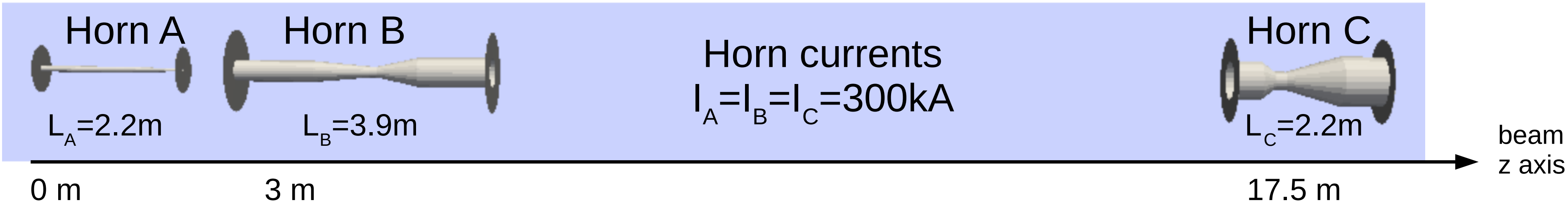
Beam Power Profile

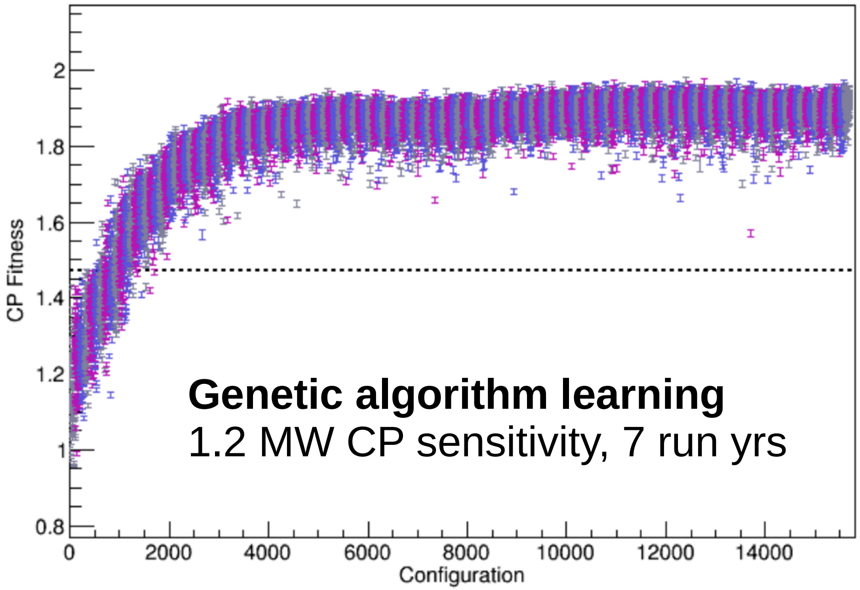


Total Exposure

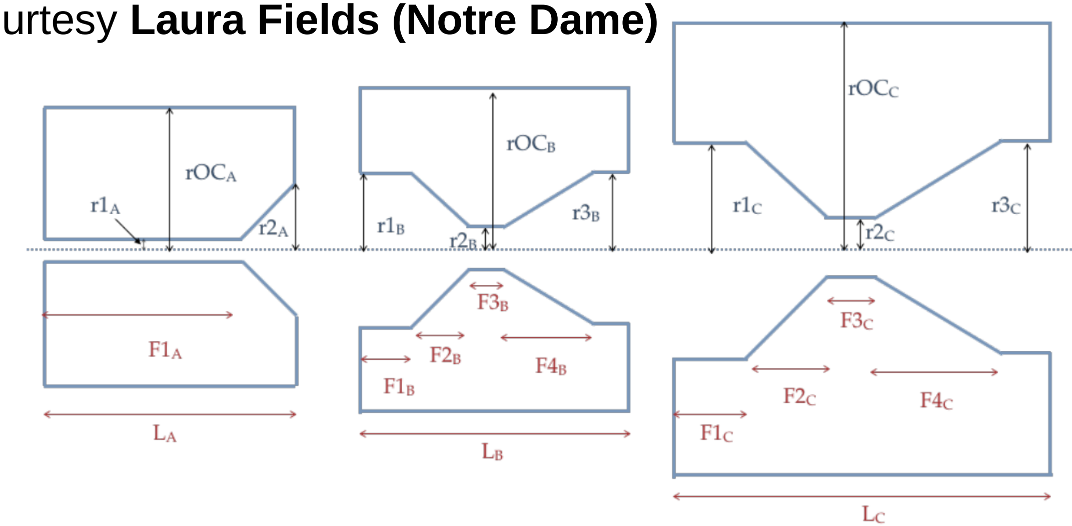
Courtesy **Alexander Valishev (FNAL)**

LBNF target & 3-horn system (1.2 MW design)





Courtesy **Laura Fields (Notre Dame)**

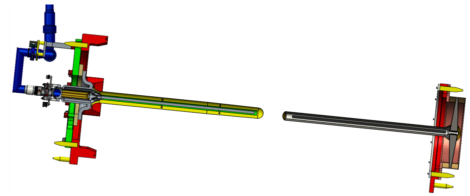
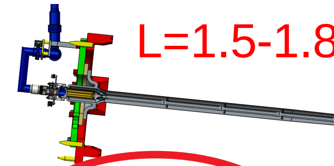


Horn A (& target) **Horn B** **Horn C**

Horn A, B & C engineering design & construction by **Fermilab**

Graphite target design & construction by **RAL High Power Targets Group**:
Chris Densham (PI), Peter Loveridge (PM), Richard Cowan, Joe O'Dell, Michael Fitton, Eric Harvey-Fishenden, Andrew Lintern, Michael Parkin, Ben Suitters, Dan Wilcox

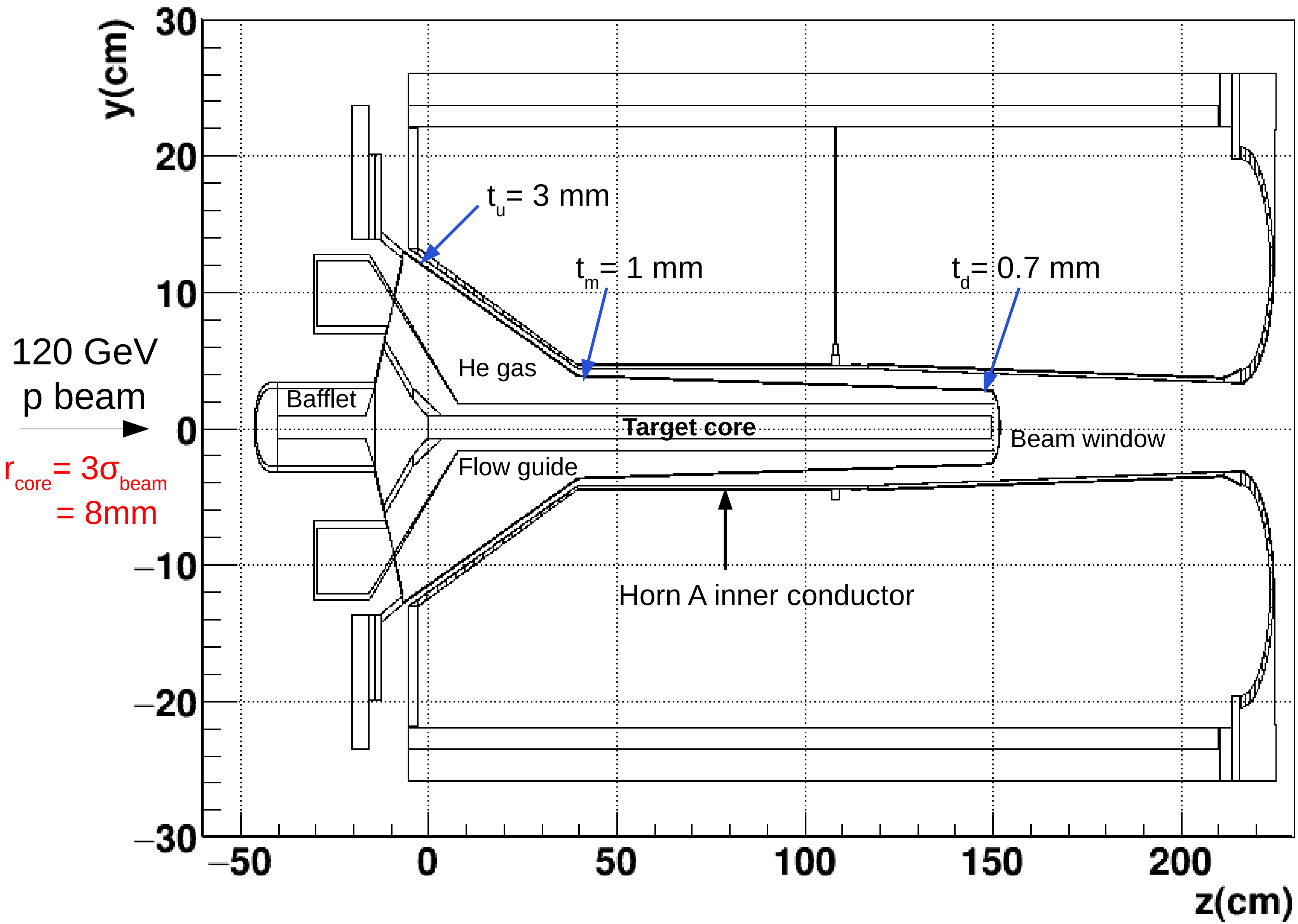
Target Conceptual Design Review (July 2019, FNAL)

Courtesy **RAL High Power Targets Group**	 **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.	2nd 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, 2nd 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.	2nd target greatly increases cost and time.	Cheapest and fastest to produce.

Target performance = physics x reliability

⇒Consensus for **option 3: cantilever** with **L = 1.5 m** (minimum) up to **1.8 m** (aspiration)

Cantilevered graphite target inside horn A (1.2 MW)



Tapered **Ti outer container thickness**: t_u = 3 mm, t_m = 1 mm & t_d = 0.7 mm

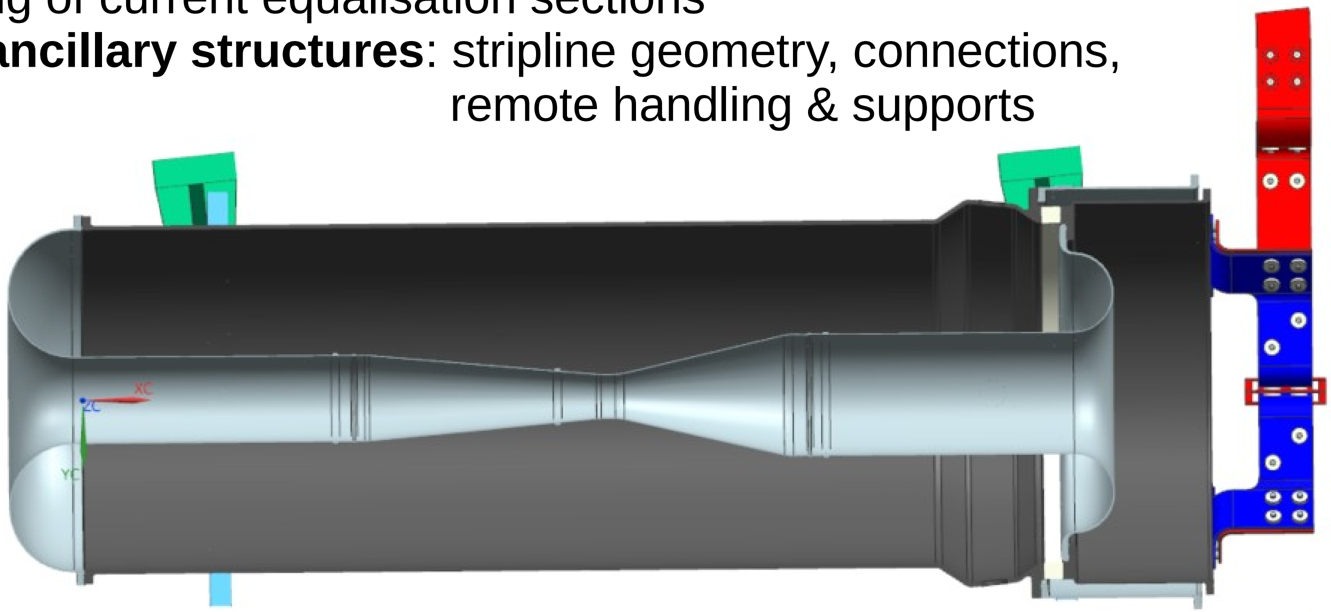
Minimum requirement to **prevent vacuum buckling**

Horn B (& C) Modifications (1.2 MW)

Courtesy **Cory Crowley**

Reduce heating of current equalisation sections
Standardize ancillary structures: stripline geometry, connections, remote handling & supports

TDR
conceptual
engr. design
r_{OC} = 63.4 cm

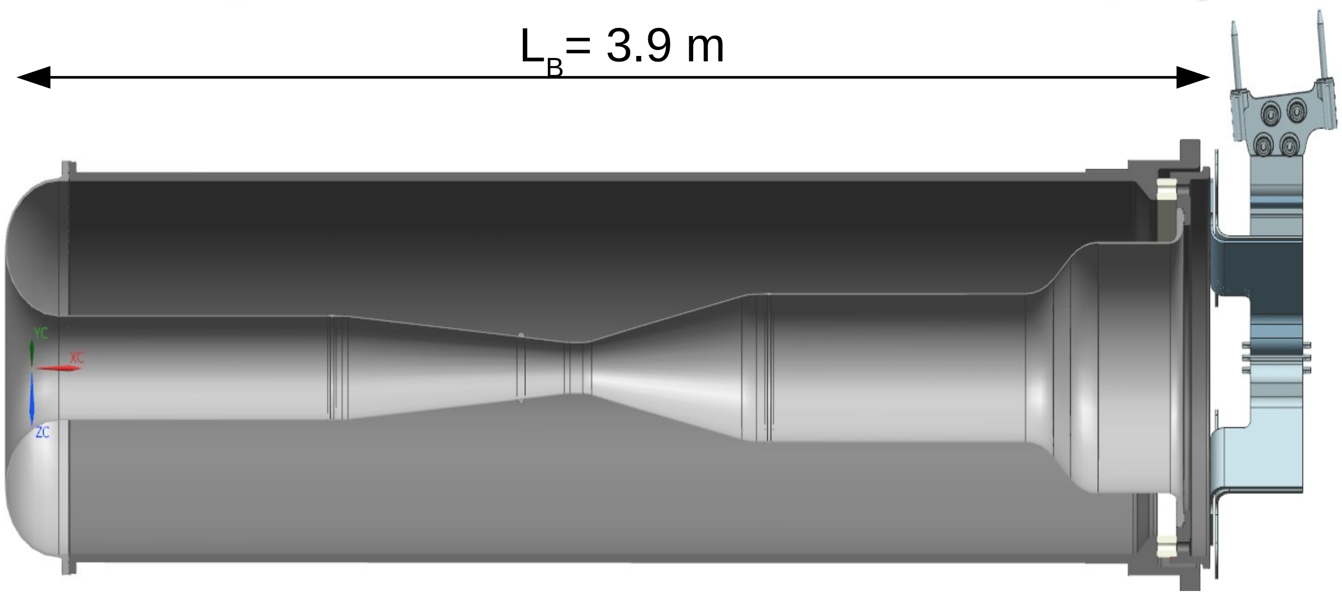


Striplines
not simulated

L_B = 3.9 m

$I_B = I_C = 300 kA$

Current
standardized
engr. design
r_{OC} = 60 cm
max radius to
fit in target hall

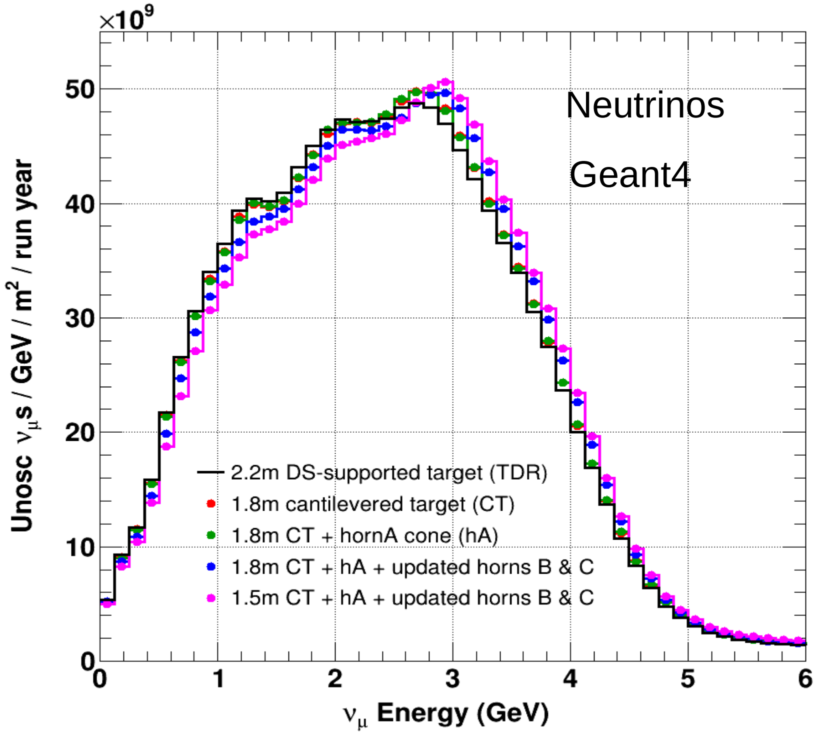


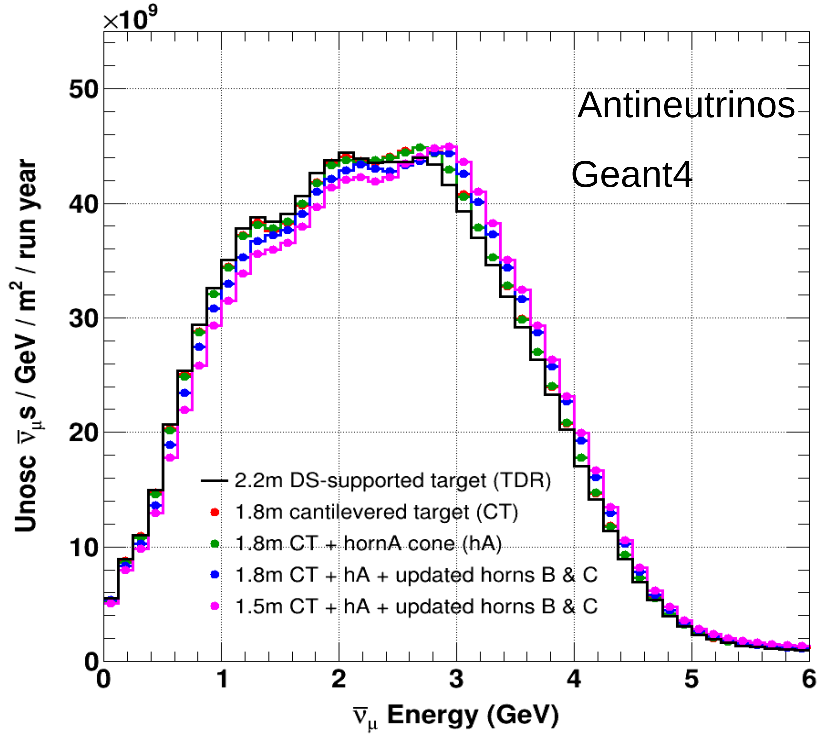
Striplines &
their **B** fields
included

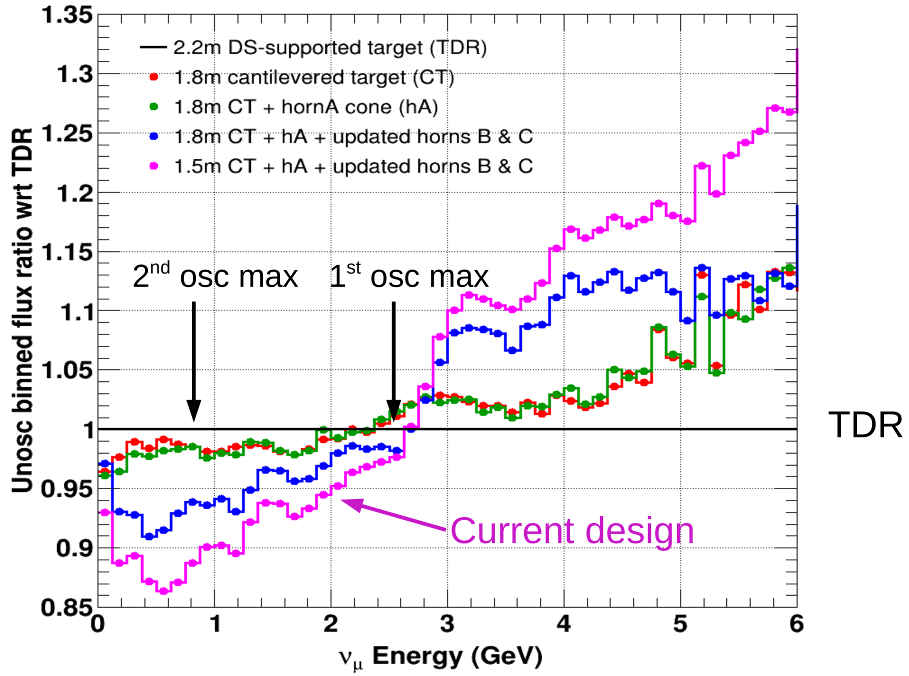
Similar for Horn C, L_C = 2.2m (essentially a mirror image)

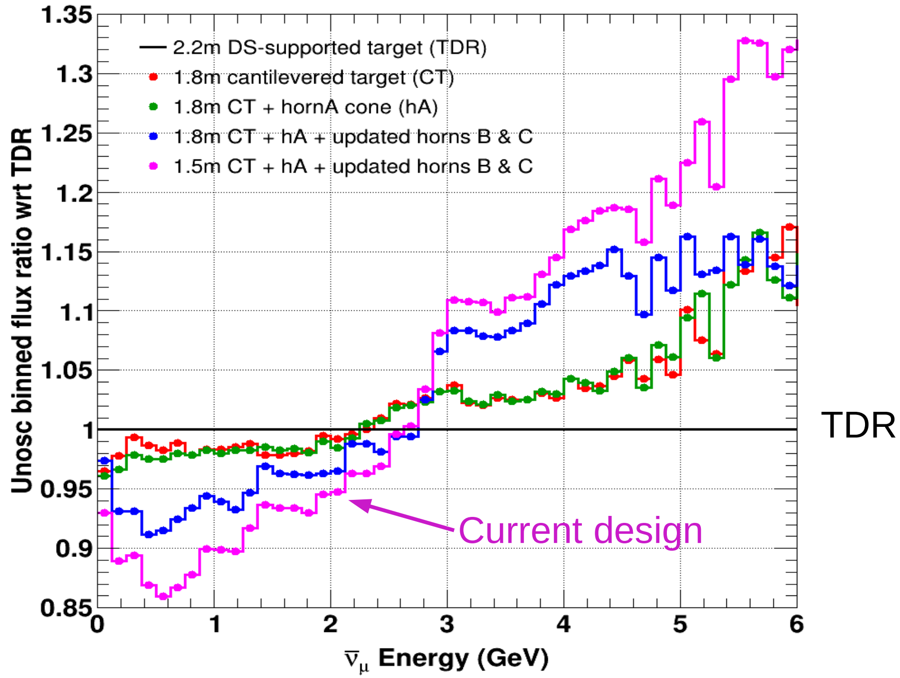
Signal ν flux changes since DUNE TDR (1.2 MW)

IPAC'21, WEPAB212

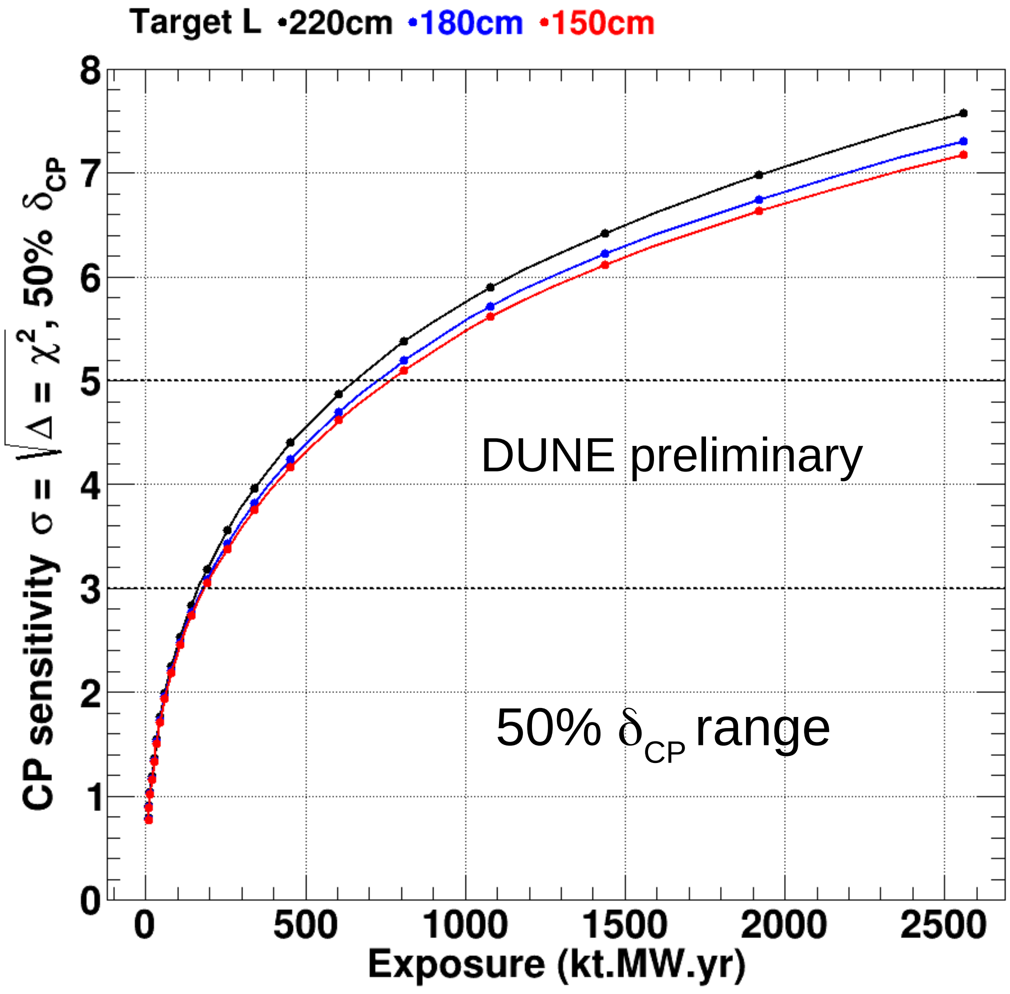


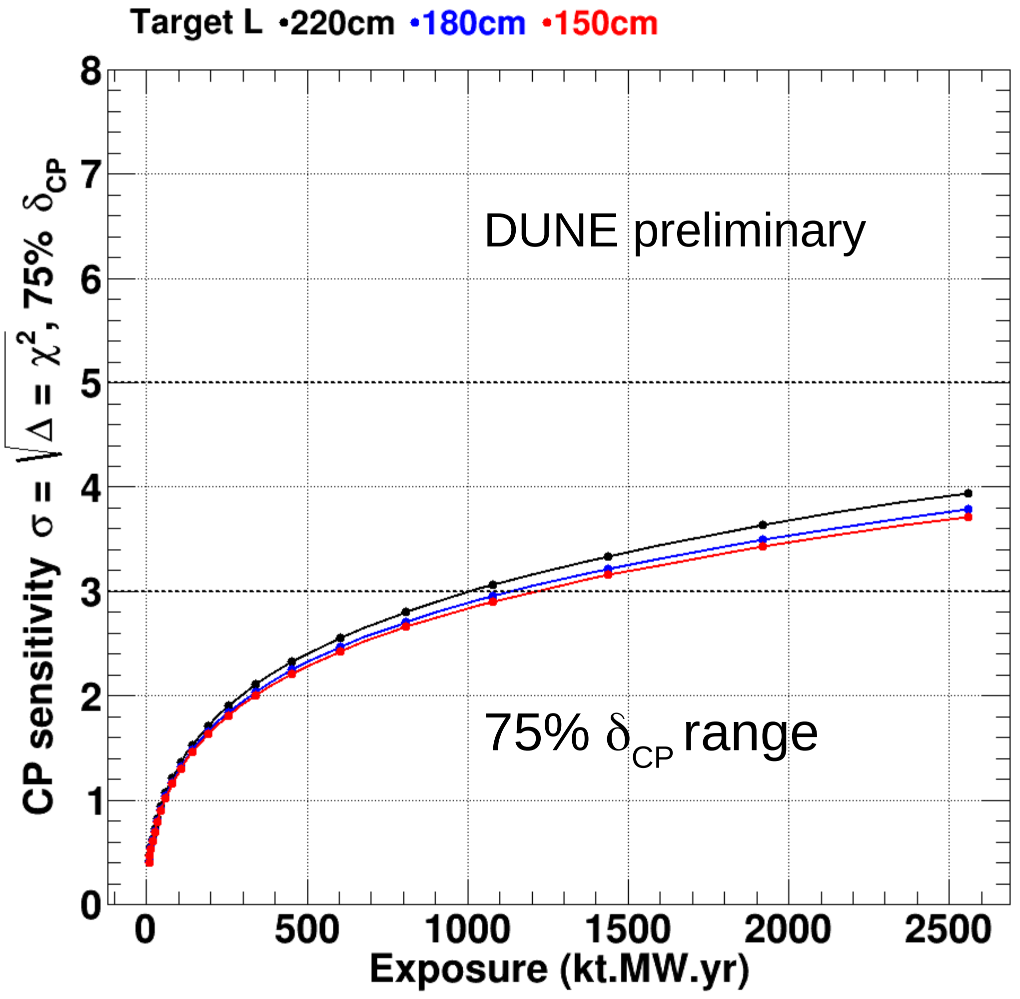






CP sensitivity vs exposure

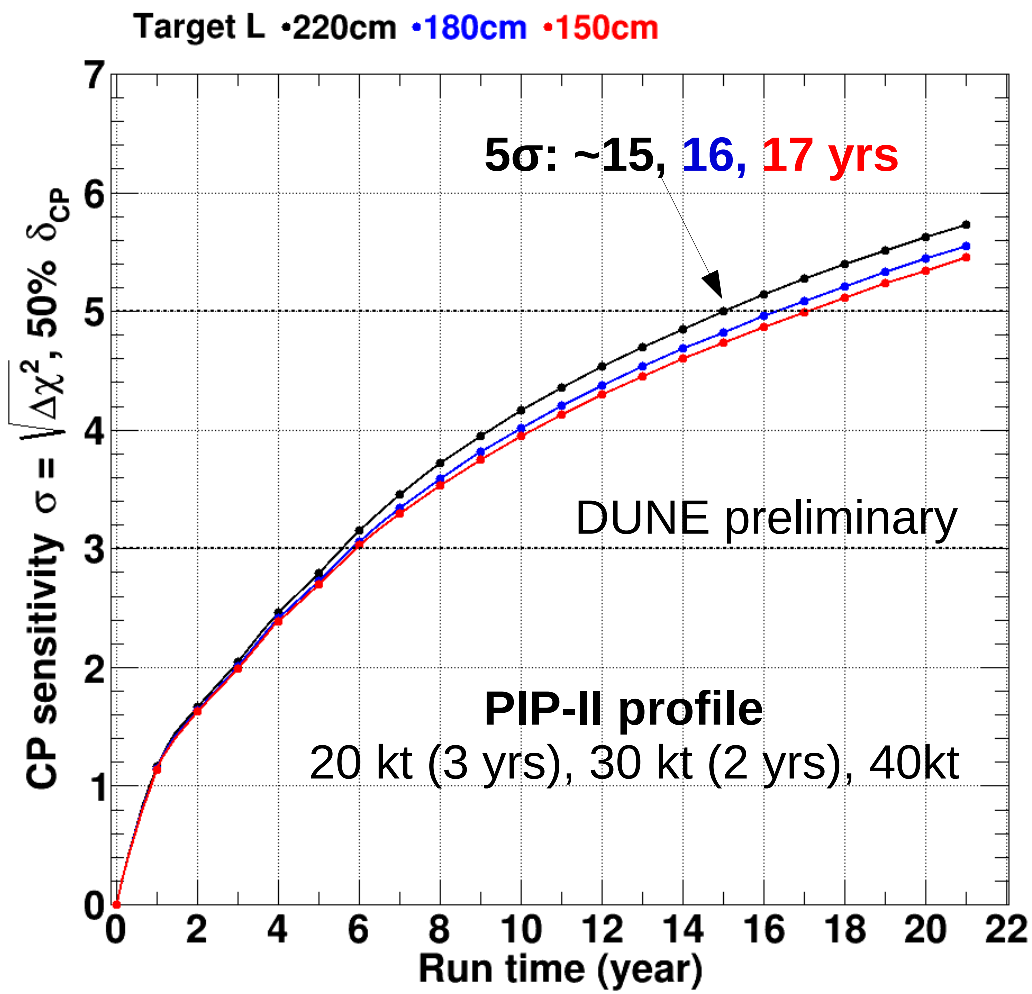


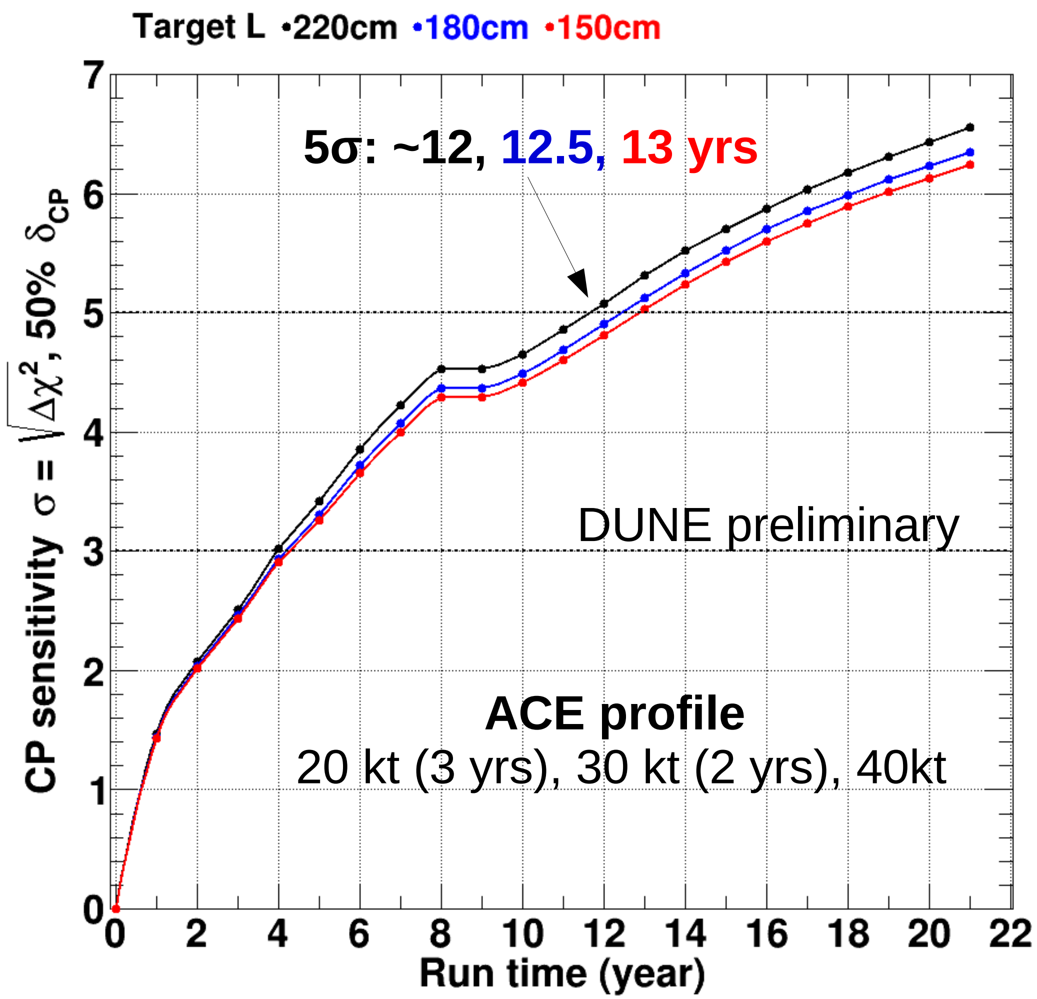


Since TDR: target length reduction **2.2 m (4.6 λ)** to **1.5 - 1.8 m (3.1 - 3.8 λ)** and reduced horn B & C outer conductor **r = 63 to 60 cm** ⇒ **more exposure needed**

Using GLoBES approximation of DUNE long-baseline analysis

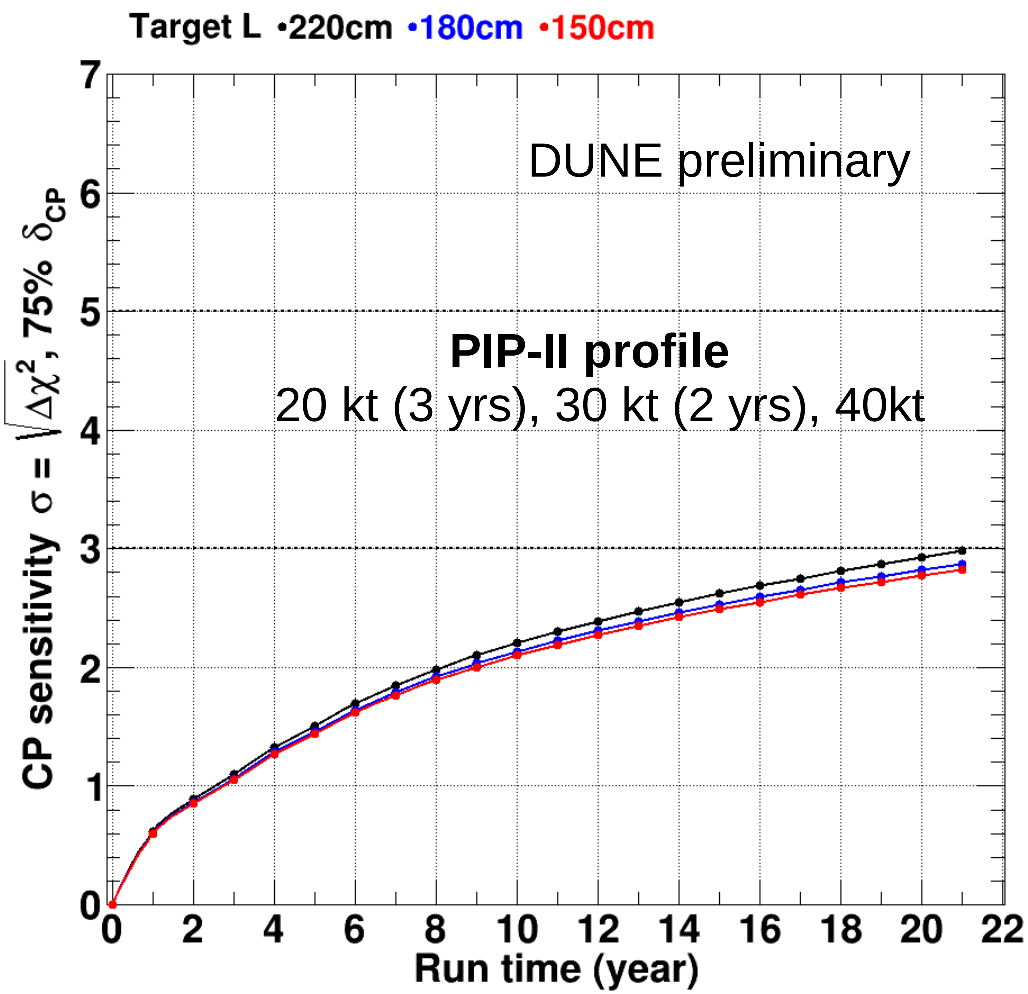
CP sensitivity vs run time, 50% δ_{CP}

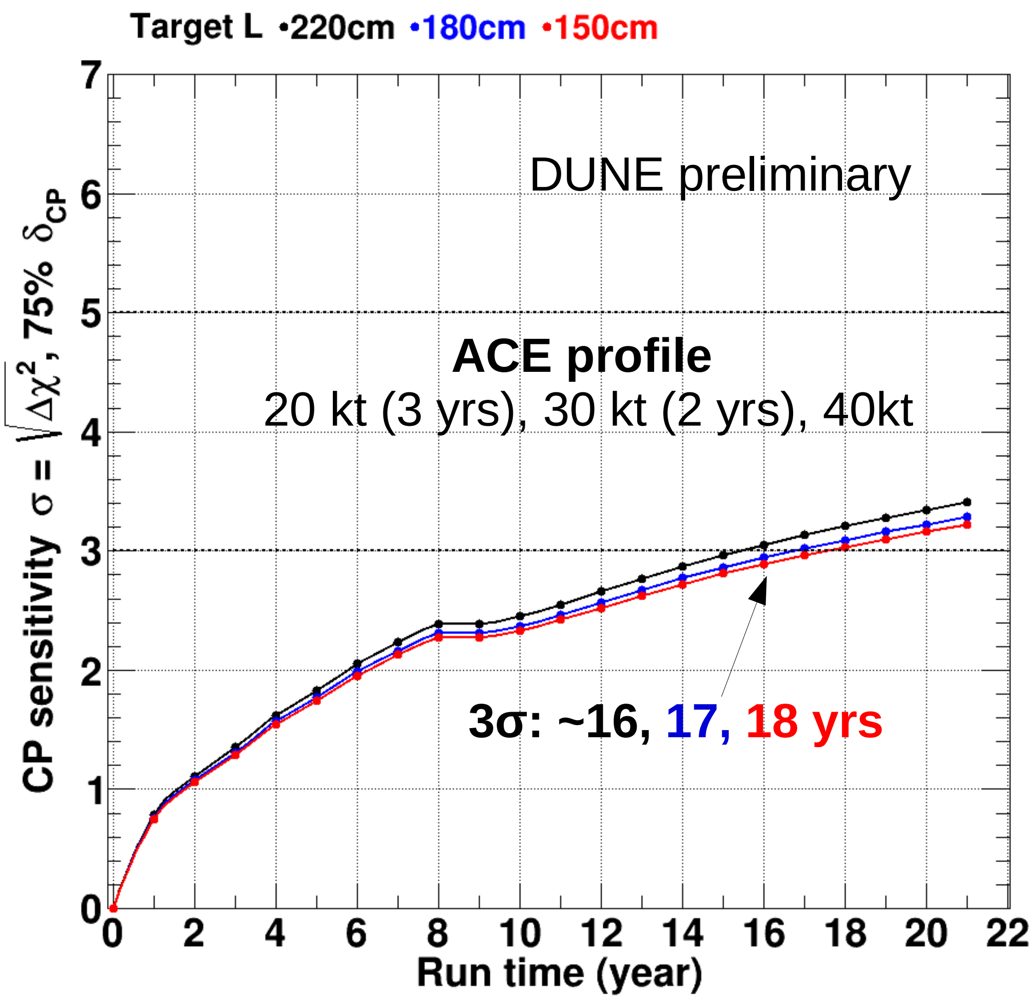




Assuming 57% run efficiency (208 run days per calendar year)
Using GLoBES approximation of DUNE long-baseline analysis

CP sensitivity vs run time, 75% δ_{CP}

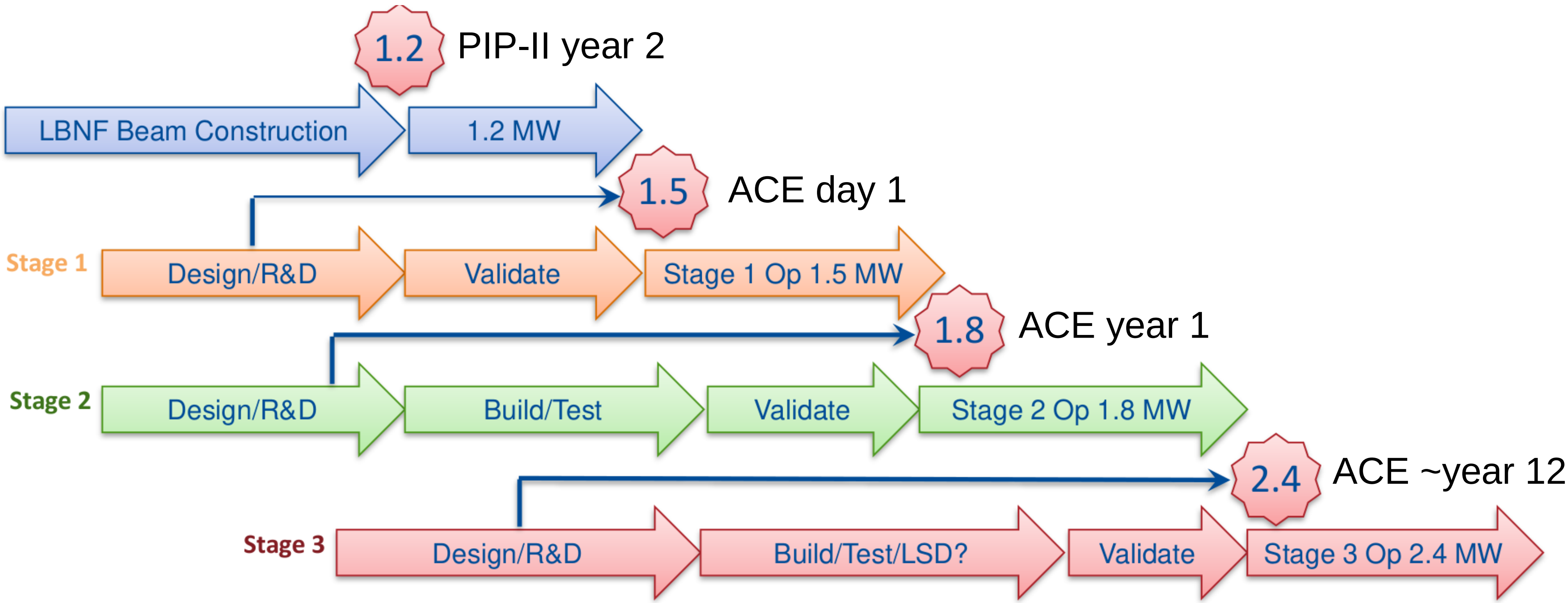




Assuming 57% run efficiency (208 run days per calendar year)
Using GLoBES approximation of DUNE long-baseline analysis

Staged targetry upgrade path

Courtesy **Patrick Hurh (FNAL)**



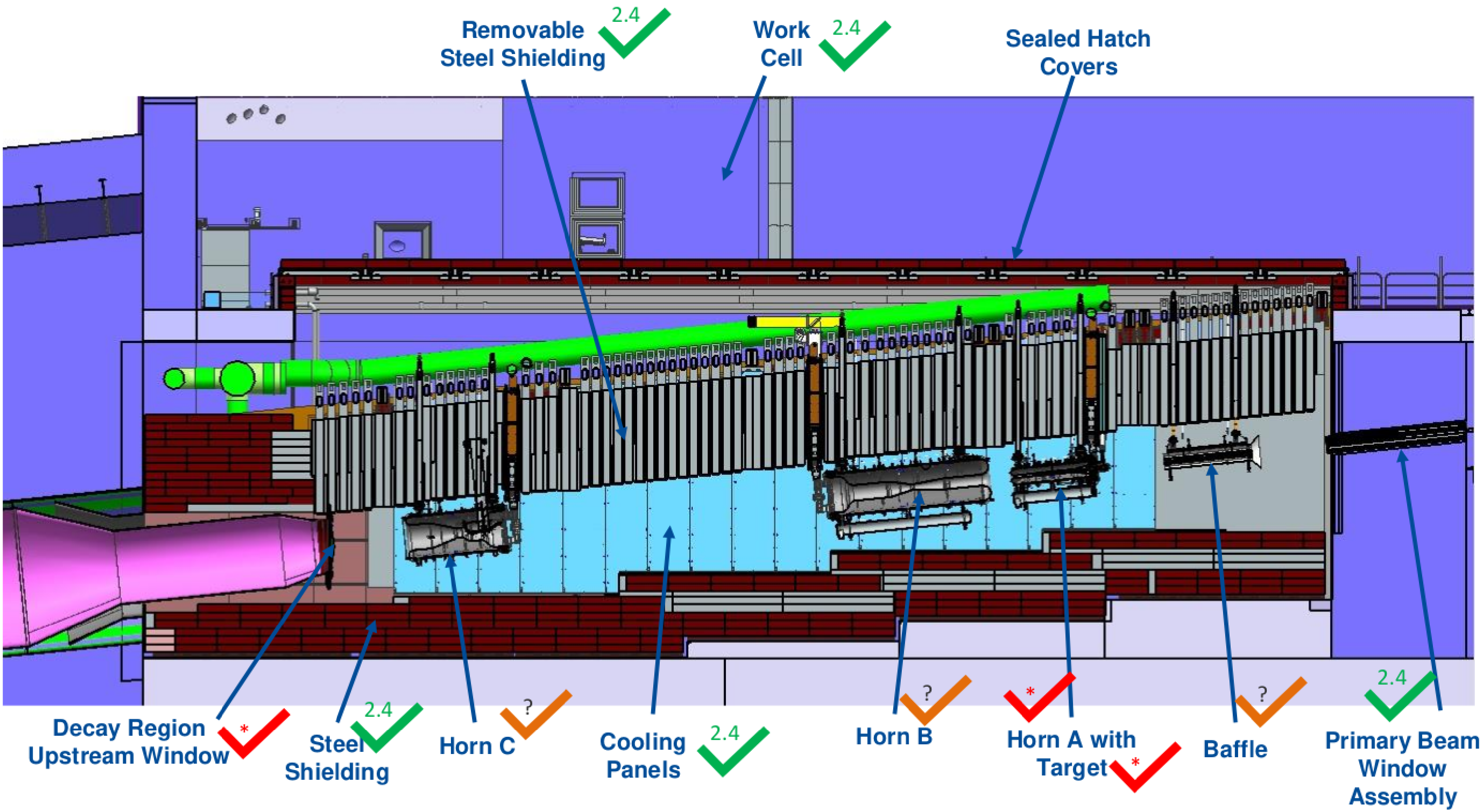
Stage **1**: Push and validate **1.2 MW** target (RAL deliverable) up to **1.5 MW**
May need target & horn design changes for 1.5 MW, could reduce ν flux/POT

Stage **2**: Design & build 2nd generation components, raising limits up to **1.8 MW**

Stage **3**: Design & build next generation systems to take full advantage of **2.4 MW**

LBNF target system readiness for 2.4 MW

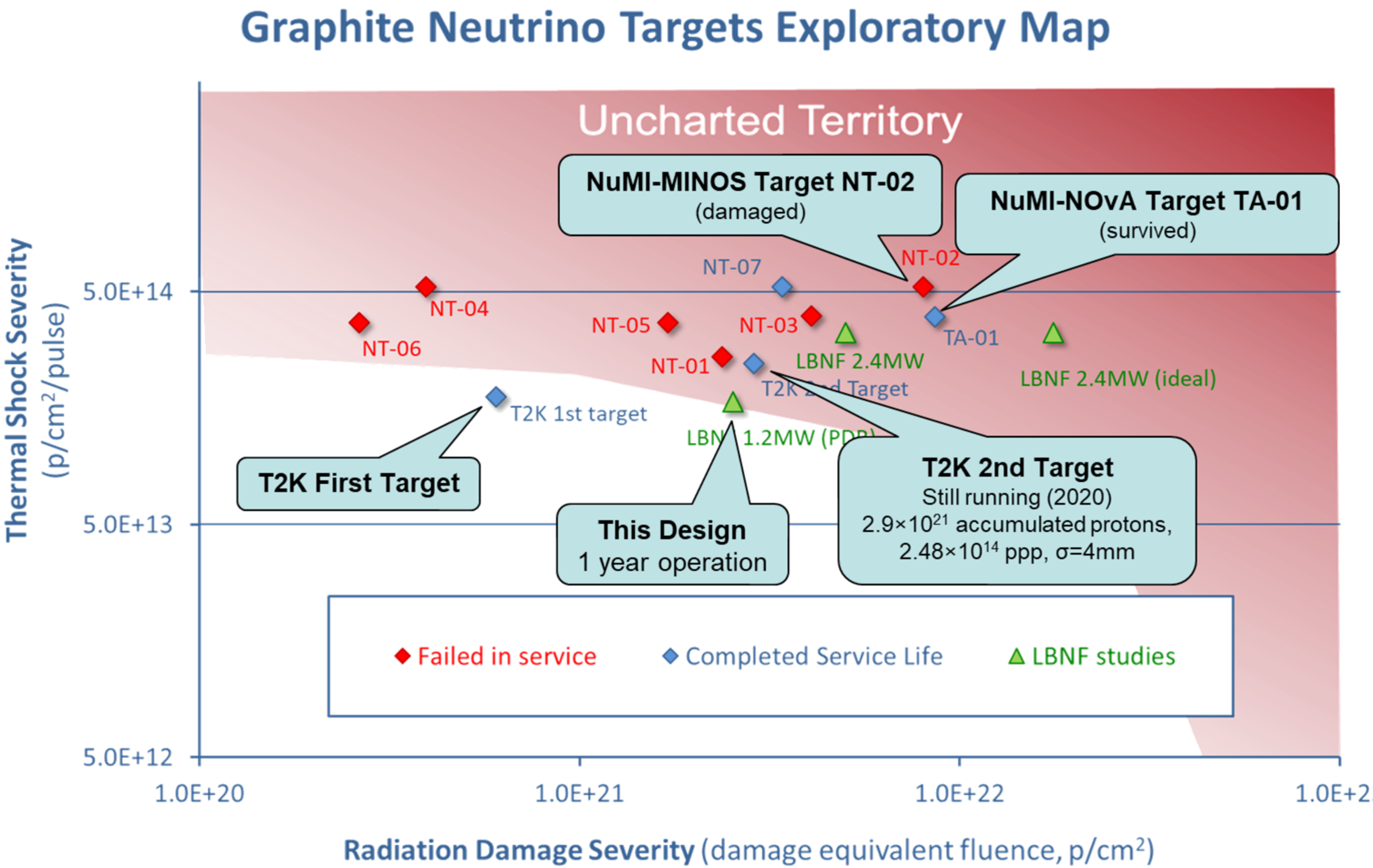
Courtesy **Patrick Hurh (FNAL)**



OK 2.4 ✓   Maybe ? ✓   Needs more R&D * ✓

Target reliability: thermal shock & radiation damage

Courtesy **Patrick Hurh (FNAL)**



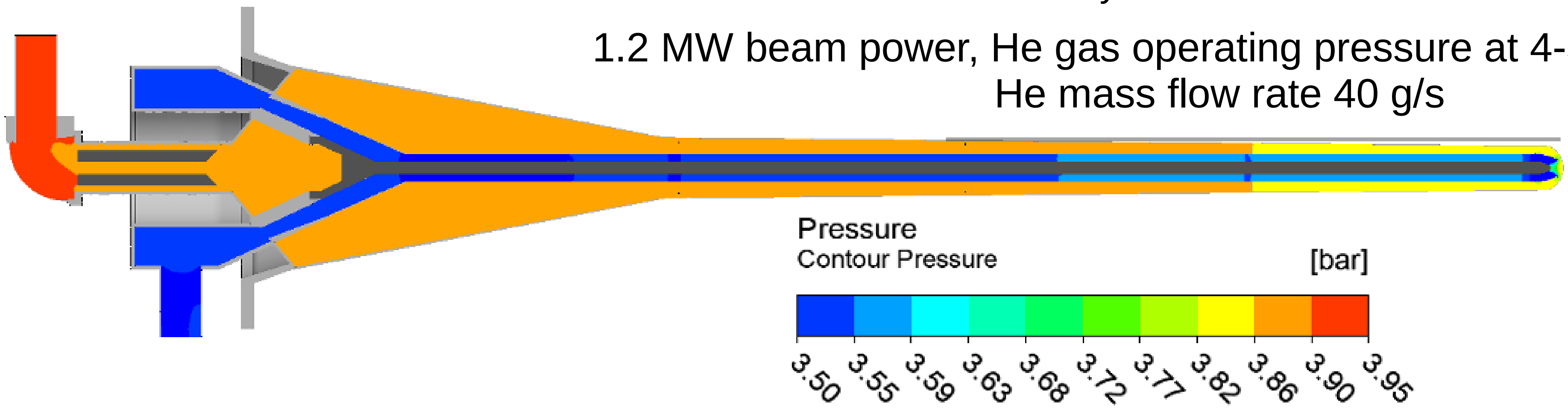
Can cantilevered graphite target operate & survive at 2.4 MW?

Target He gas cooling considerations

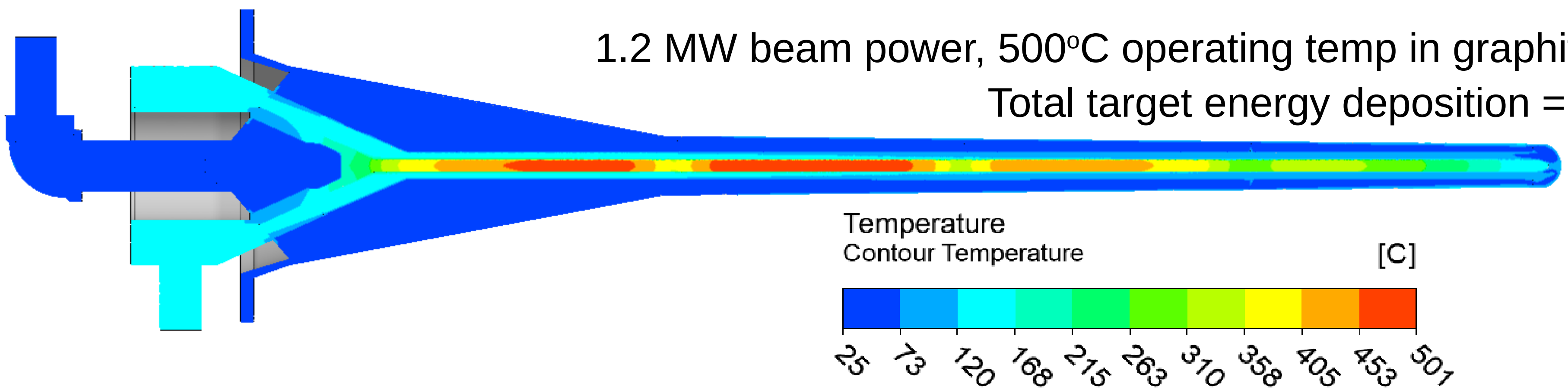
Science and Technology Facilities Council

Courtesy **Michael Parkin & Dan Wilcox (RAL)**

1.2 MW beam power, He gas operating pressure at 4-5 bar,
He mass flow rate 40 g/s



1.2 MW beam power, 500^{o}C operating temp in graphite core
Total target energy deposition = 24 kW

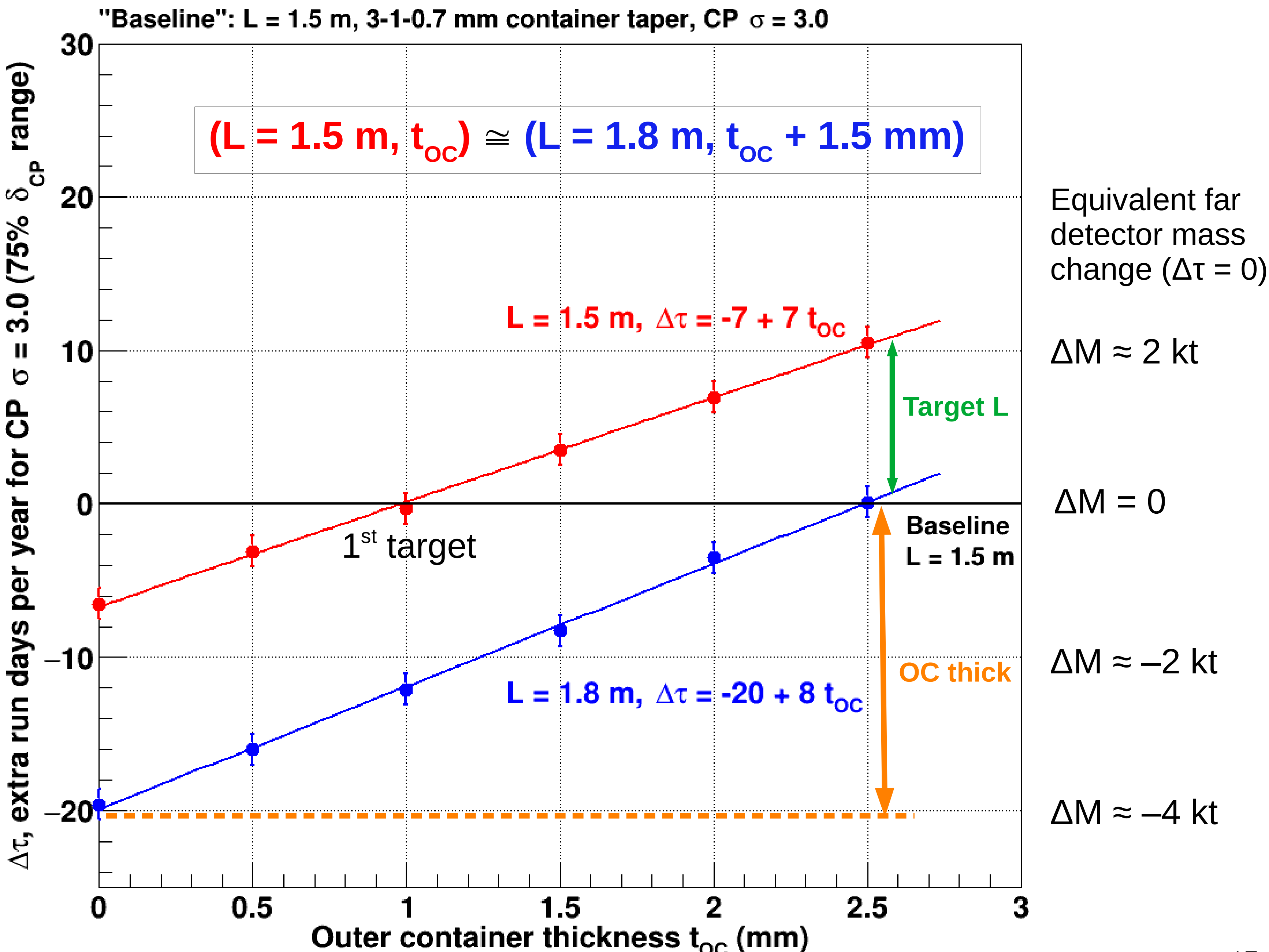


2.4 MW: increase cooling by x2, raise system pressure to ~8 bar, mass flow to 80g/s

Titanium outer container needs thicker walls? Container thickness for 1.2 MW = 1 mm

Needs to satisfy **F**ermilab **E**nvironmental **S**afety & **H**ealth **M**anual (US DOE) requirements:
American **S**ociety of **M**echanical **E**ngineers (ASME) **B**oiler & **P**ressure **V**essel **C**ode

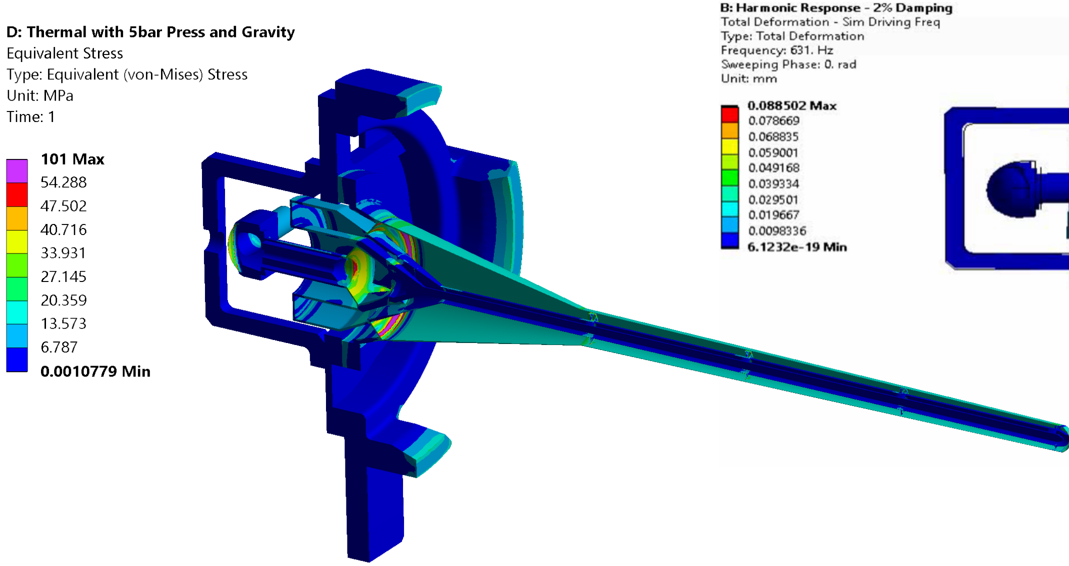
Extra run days per year (1.2 MW) vs outer container thickness t_{OC}

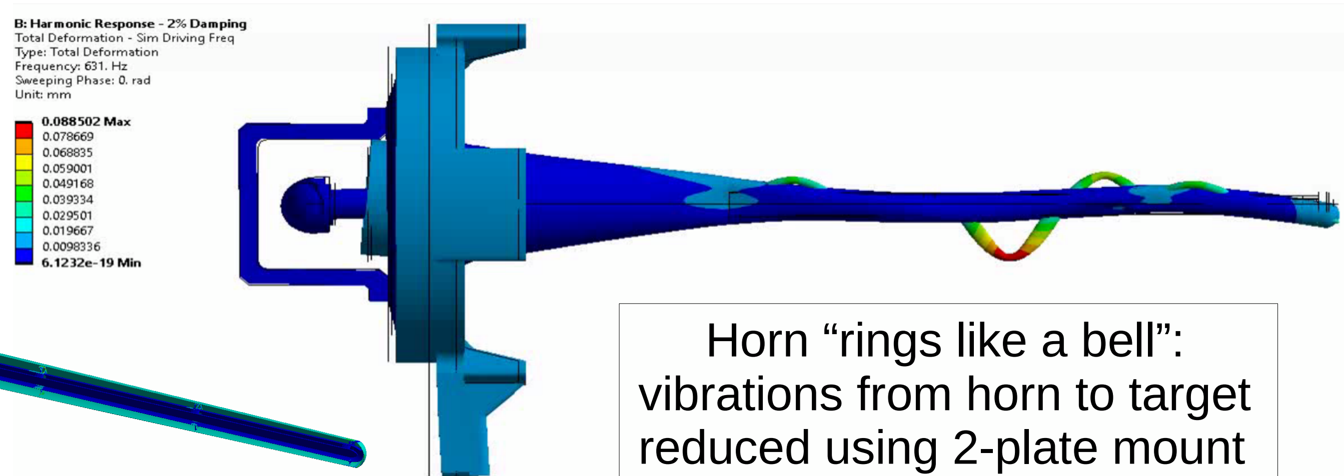


Δτ extra days/yr = fractional exposure change x 208 days (**40 kt** FD mass)

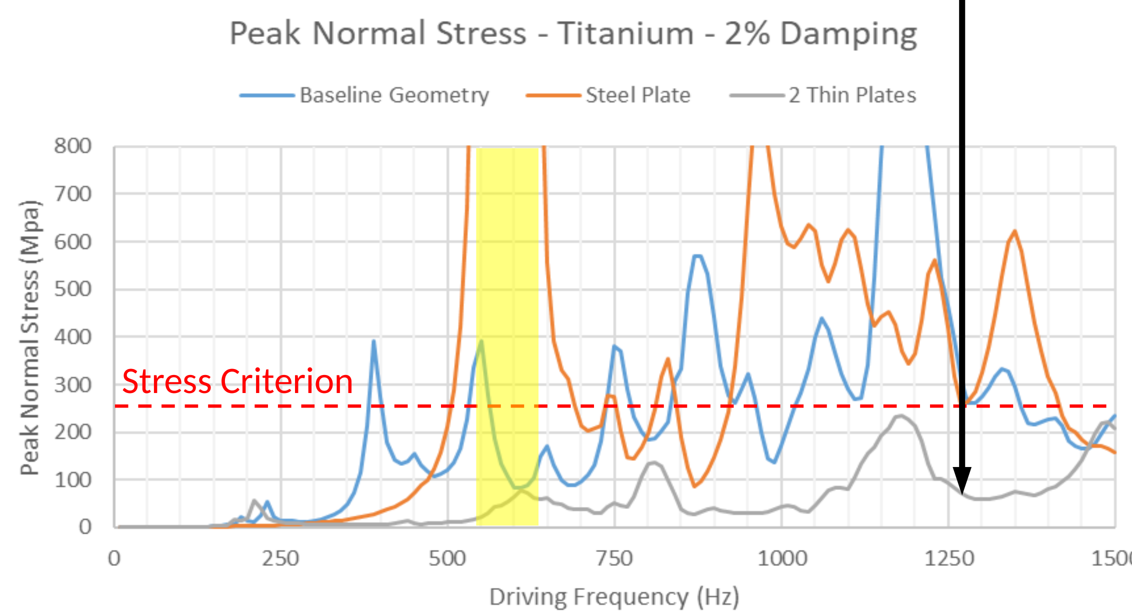
Target thermal stress & horn pulse vibrations

Courtesy **Peter Loveridge & Dan Wilcox (RAL)**





Horn "rings like a bell":
vibrations from horn to target
reduced using 2-plate mount



1.2 MW endurance: graphite = limit/14
titanium = limit/30

2.4 MW stress amplitudes will double,
still within endurance limits

Should be effective for 2.4 MW (to be confirmed):
same horn pulse current **I = 300 kA**

Radiation damage: graphite & Ti fatigue

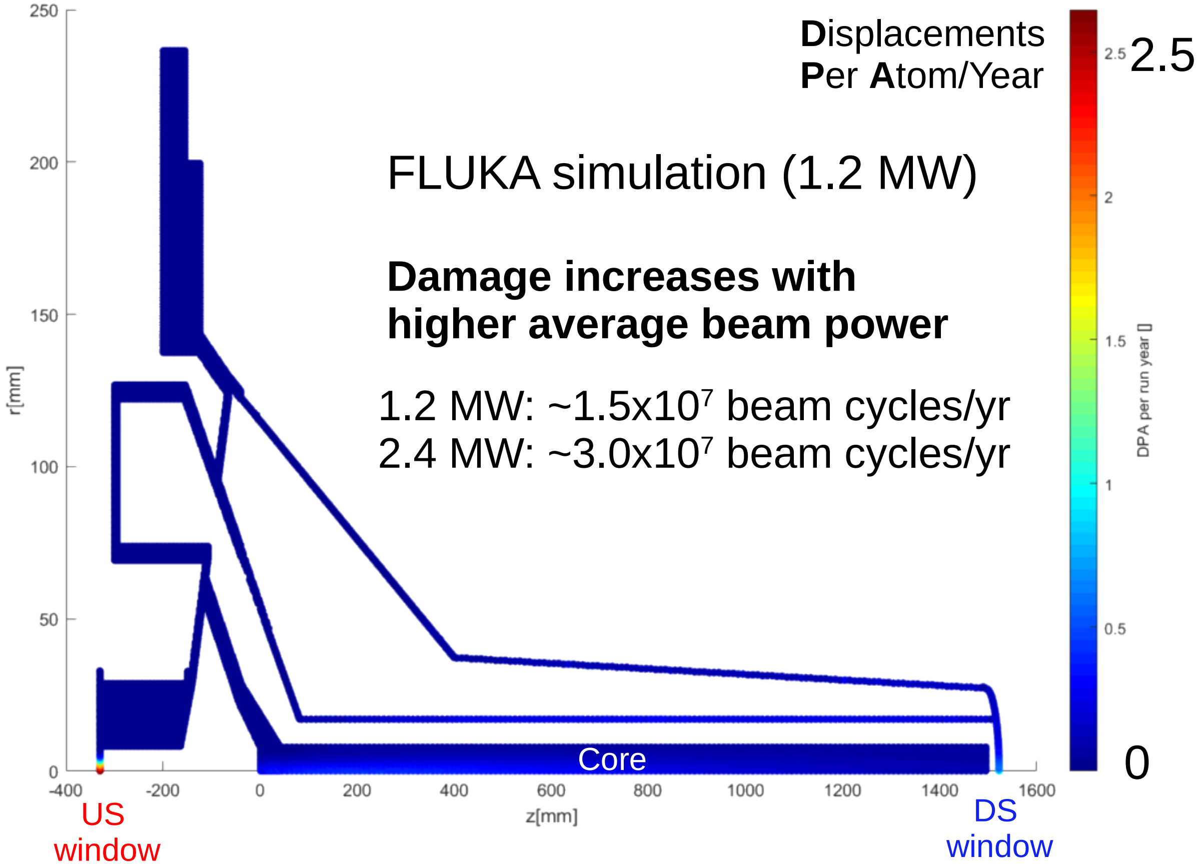
Science and Technology Facilities Council

Courtesy **Dan Wilcox & Michael Fitton (RAL)**

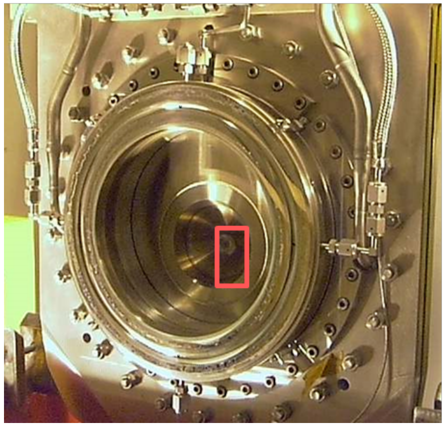
FLUKA simulation (1.2 MW)

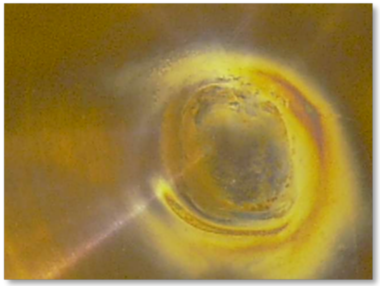
Damage increases with higher average beam power

1.2 MW: ~1.5x10^7 beam cycles/yr
2.4 MW: ~3.0x10^7 beam cycles/yr



Cracked NuMI-MINOS graphite target





T2K beam window after c.2 DPA

Component	DPA/yr (FLUKA)	1.2 MW irradiated peak stress (MPa)	Ultimate tensile strength (MPa)
Graphite core	0.5	~4.4	~37
Ti US window	2.5	~21	~240
Ti DS window	0.7	~6	~240

Need more irradiation DPA data: ongoing work of RaDIATE collaboration

Summary

- ACE beam scenario for $\geq$ 2 MW
  - Significantly reduces required run years for DUNE physics goals
  - Aiming to improve run-year efficiency beyond 57% (208 days/calendar yr)

- 1.2 MW target & horn focusing system updates since DUNE TDR
  - Target L = 1.5 m (& 1.8 m) reduced from 2.2 m (TDR & 2023 P5)
  - Horn B & C outer conductor radii reduced to fit inside target hall
  - Increases required runtime by ~1 to 2 years for 5σ (3σ) CP sensitivities for 50% (75%) δ_{CP}

- RAL High Power Targets group
  - Delivering 1st production graphite target L_{min} = 1.5 m for 1.2 MW
  - Understand requests from ACE plan for higher beam power
  - Keeping path open to push target operation beyond 1.2 MW
  - Challenging to get pressure vessel safety code (welding) compliance: in progress for 1.2 MW

- Target & horn design changes needed for > 1.2 MW, will impact ν flux/POT
  - Significantly more R&D required
  - Beam power compromises: target lifetime (& safety) vs physics goals

Backup

PIP-II & LBNF timeline

Courtesy **Alexander Valishev (FNAL)**