Megawatt targets (and horn) for Neutrino Super-Beams

RAL High Power Targets Group: Chris Densham, Tristan Davenne, Mike Fitton, Peter Loveridge, Matt Rooney, Otto Caretta

LBNE study in collaboration with : Patrick Hurh, Bob Zwaska, James Hylen, Sam Childress, Vaia Papadimitriou (Fermilab)

EUROnu Superbeam study in collaboration with:

Andrea Longhin, Marco Zito (CEA Saclay) ;

Benjamin Lepers, Christophe Bobeth, Marcos Dracos (Universite de Strasbourg)

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‘Conventional’ neutrino beams: where we are

	NuMI (Fermilab)	CNGS (CERN)	T2K (JPARC)
Beam energy	120 GeV	400 GeV	30 GeV
Beam cycle	2.2 s	6 s	2.1 s
Spill length	10 μs	2 x 10.5 μs	4.2 μs
Design beam power	400 kW	750 kW	750 kW
Maximum beam power to date	375 kW	311 kW (448 kW over 30s)	135 kW
Beam size (rms)	1.1 mm	0.5 mm	4.2 mm
Physics	ν_μ disappearance	ν_μ -> ν_τ appearance	ν_μ -> ν_e appearance, ν_μ disappearance
First beam	2005	2006	2009

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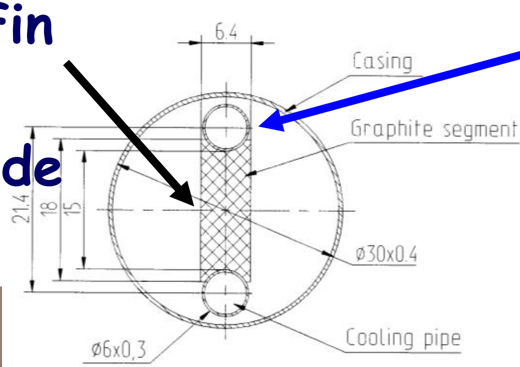
NuMI MINOS target (J.Hylen)

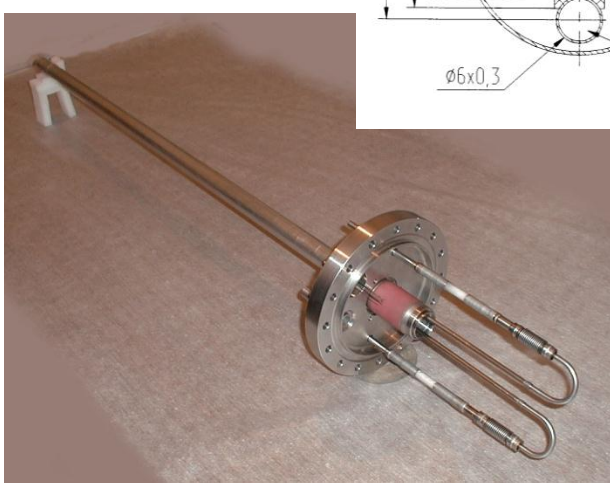
2 int. length long; narrow so pions get out sides without re-interacting

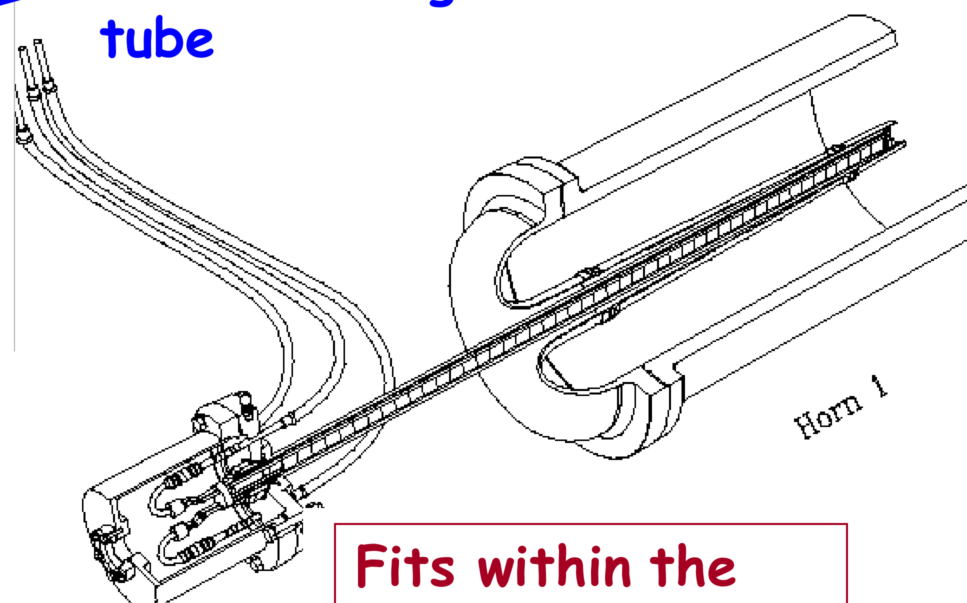
Graphite Fin Core

6.4 mm wide



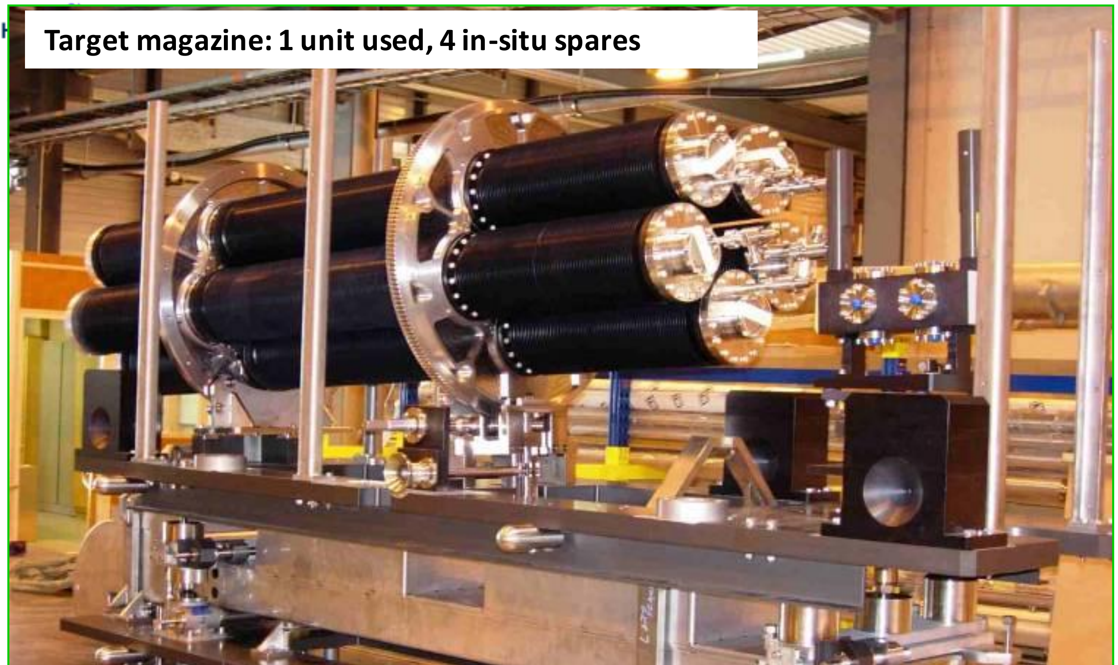
Water cooling tube





Fits within the horn without touching.

CNGS Target

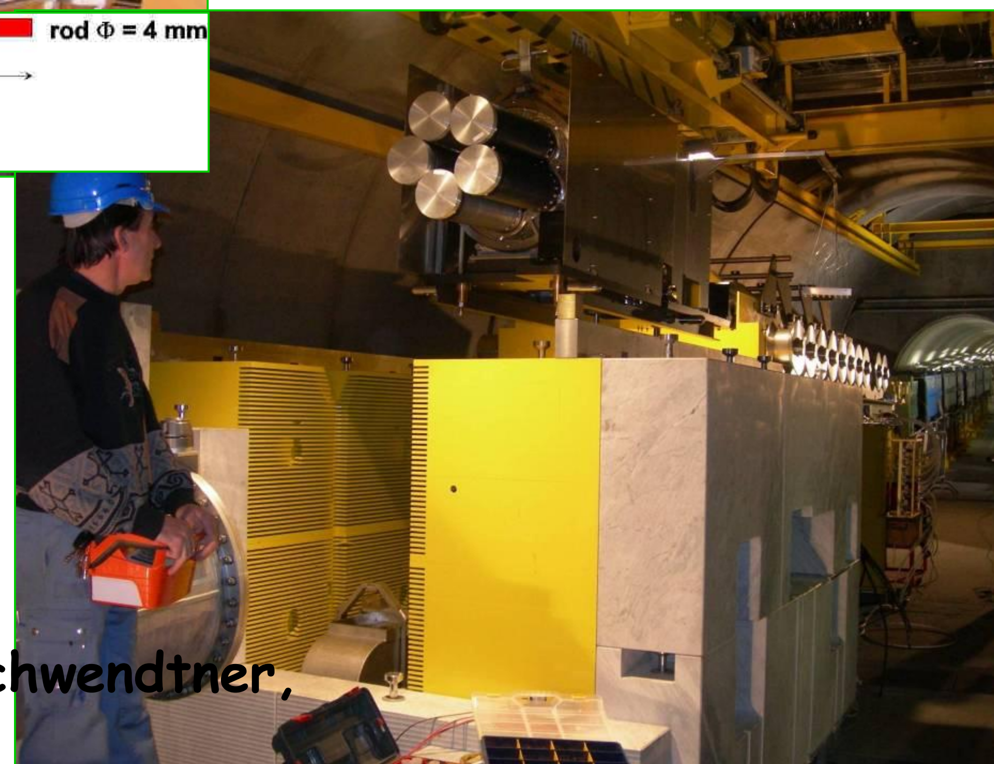


13 graphite rods, each 10cm long,

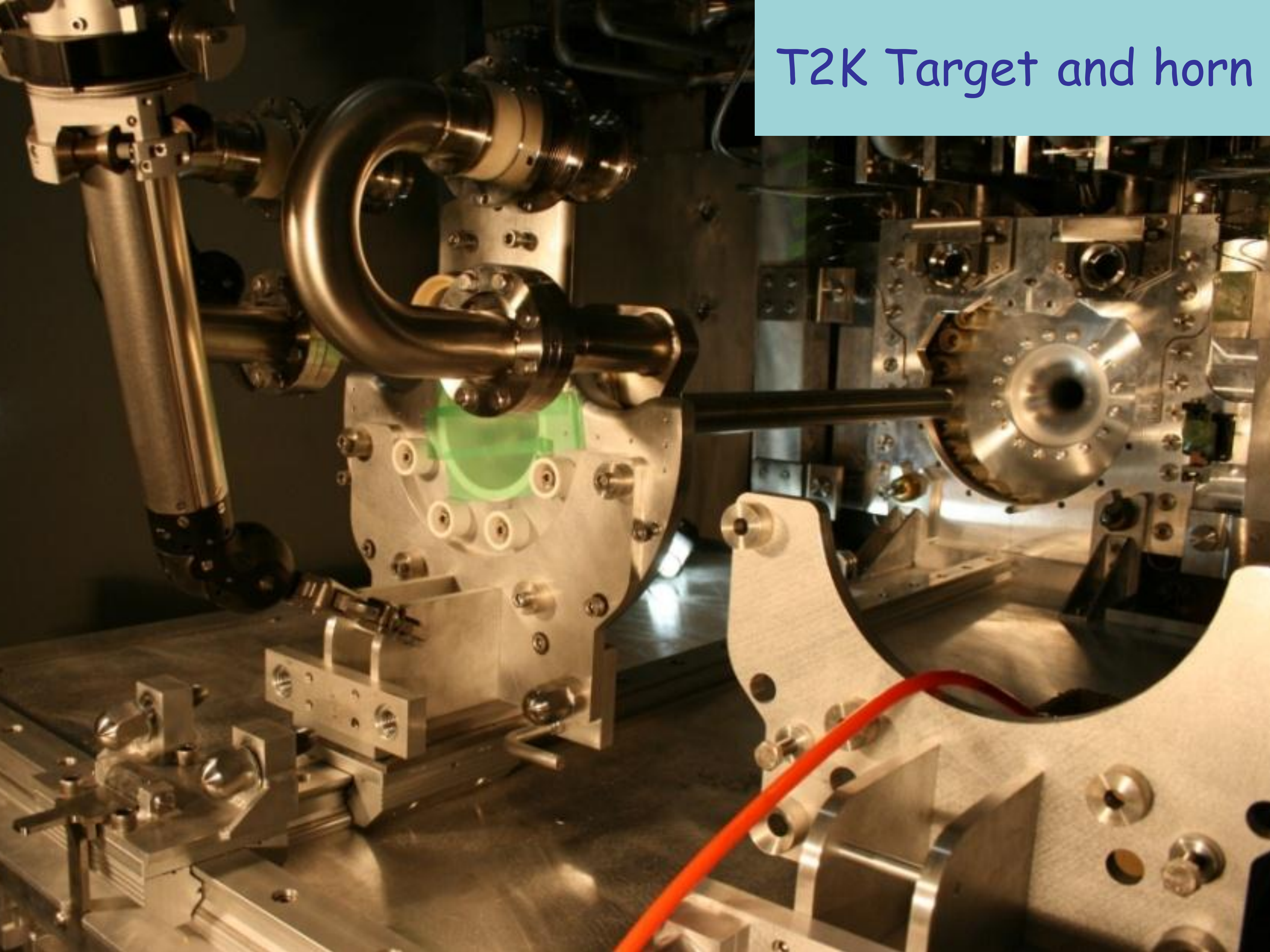
Ø = 5mm and/or 4mm

2.7mm interaction length

Ten targets (+1 prototype) have been built. → Assembled in **two magazines.**



T2K Target and horn



Existing target technologies

	NuMI/NOvA	CNGS	T2K
Target material	Graphite: POCO ZXF-5Q	Graphite and Carbon-carbon	Graphite: IG 430
Target arrangement	Subdivided	subdivided	monolithic
Cooling	Water (forced convection)	Helium (natural convection)	Helium (forced convection)
Limitations for higher power operation	•Radiation damage •Water hammer, cavitation •Hydrogen + tritium + water activation	• Only possible for low deposited heat loads	•Heat transfer •Radiation damage •High helium volumetric flow rate (and high pressure or high pressure drops)

High Power Targets

Neutrino 'Superbeams': where we want to go

	Fermilab LBNE (/Project X)	CERN: SB to Frejus using HP SPL	LBNO	JPARC T2K 'Roadmap'
Design beam power	2.3 MW	4 MW	2 MW	1.66 MW
Beam energy	120 GeV	5 GeV	400 GeV	30 (50) GeV
Rep rate	0.75 Hz	50 Hz (4 x 12.5 Hz)		0.48 Hz
Beam sigma (range)	1.5 – 3.5 mm	4 mm		4.2 mm
Heat load in: C		4 x 50 kW		51.8 kW
Be	10.5 – 23.1 kW			
Ti pebble bed		4 x 110 kW		

Target Basics (J.Hylen)

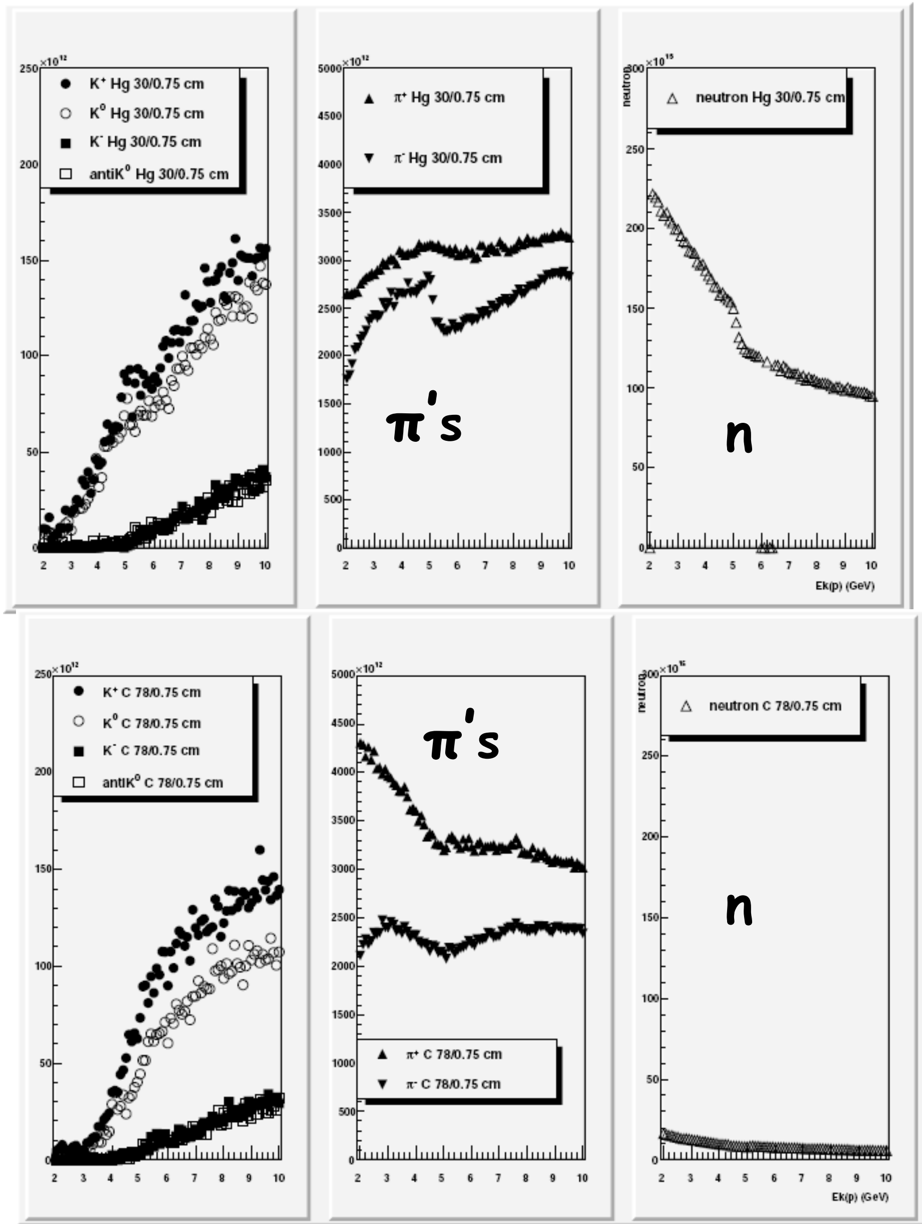
Long enough (2 interaction lengths) to interact most protons
Dense enough that 2 λ_{int} fits in focusing system depth-of-field
Radius: R_{target} = 2.3 to 3 R_{beam} (minimize gaussian tails missing target)
Narrow enough that pions exit the sides without re-absorption
(but for high E_{proton} and low E_{ν}, secondary shower can help)
High pion yield (but to first order, ν flux α beam power)
Radiation hard
Withstand high temperature
High strength (withstand stress from fast beam pulse)
Low density (less energy deposition density, hence less stress; don't re-absorb pions)
Low dE/dx (but not much variation between materials)
High heat capacity (less stress induced by the dE/dx)
Low thermal expansion coefficient (less stress induced by the dE/dx)
Low modulus of elasticity (less stiff material does not build up stress)
Reasonable heat conductivity
Reasonable electrical conductivity (monitor target by charge ejection)

CNGS, NuMI, T2K all using graphite

CERN=> Frejus SB: Target material & particle yields

Hg

C

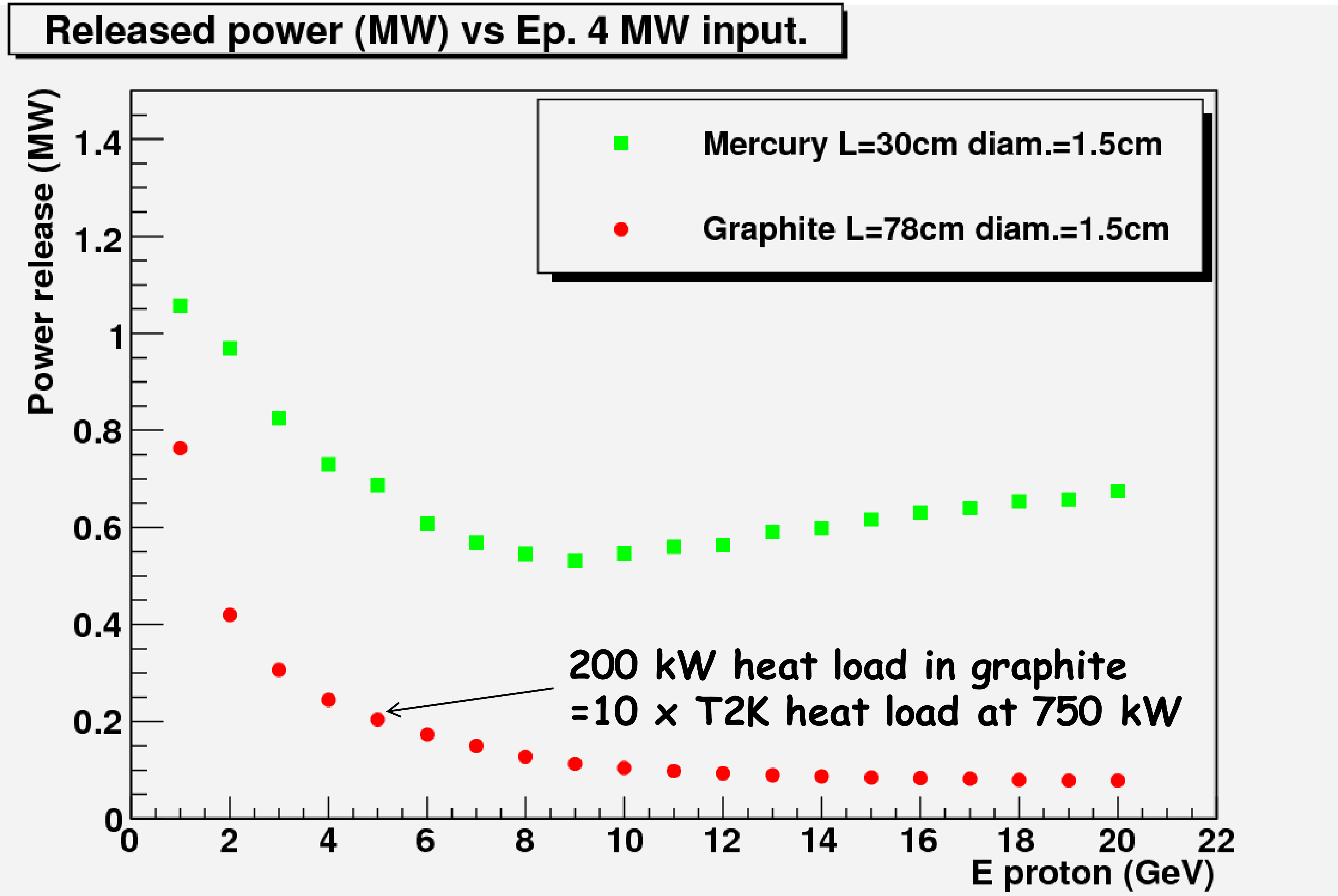


Pion yields comparable for carbon and mercury targets
Neutron flux for Hg reduced by ~ x15 with C !!

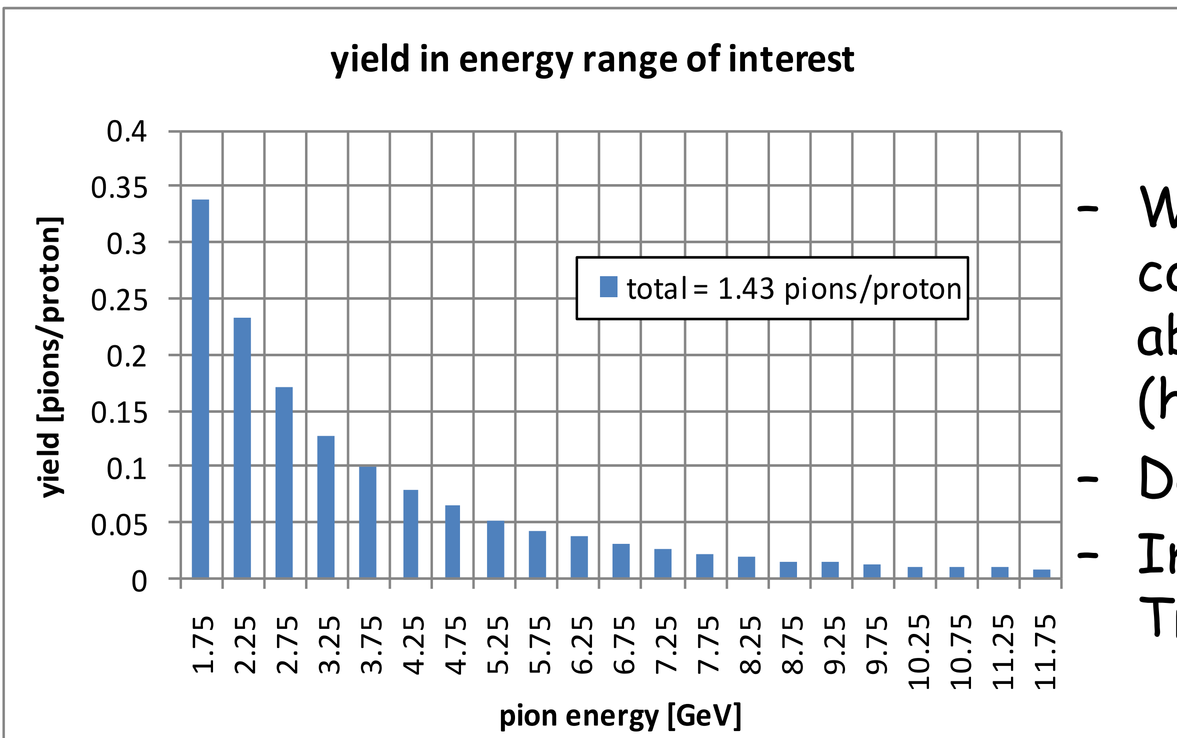
(lower neutron flux => lower heating and radiation damage to horn)

(A. Longhin)

Target material & heat loads (A. Longhin)



LBNE optimisation of Target and Beam dimensions: a simple 'Figure of Merit'



- Target performance evaluated using FLUKA to generate a simple 'Figure of Merit'
- 'FoM' is convolution of selected pion energy histogram by a weighting function:
- $W(E)=E^{2.5}$ for
  - 1.5 GeV < E < 12 GeV
  - pT <0.4 GeV/c
- Weighting function compensates for low abundance of most useful (higher energy) pions
- Devised by R.Zwaska (FNAL)
- Implemented in FLUKA by Tristan Davenne

High Power Targets

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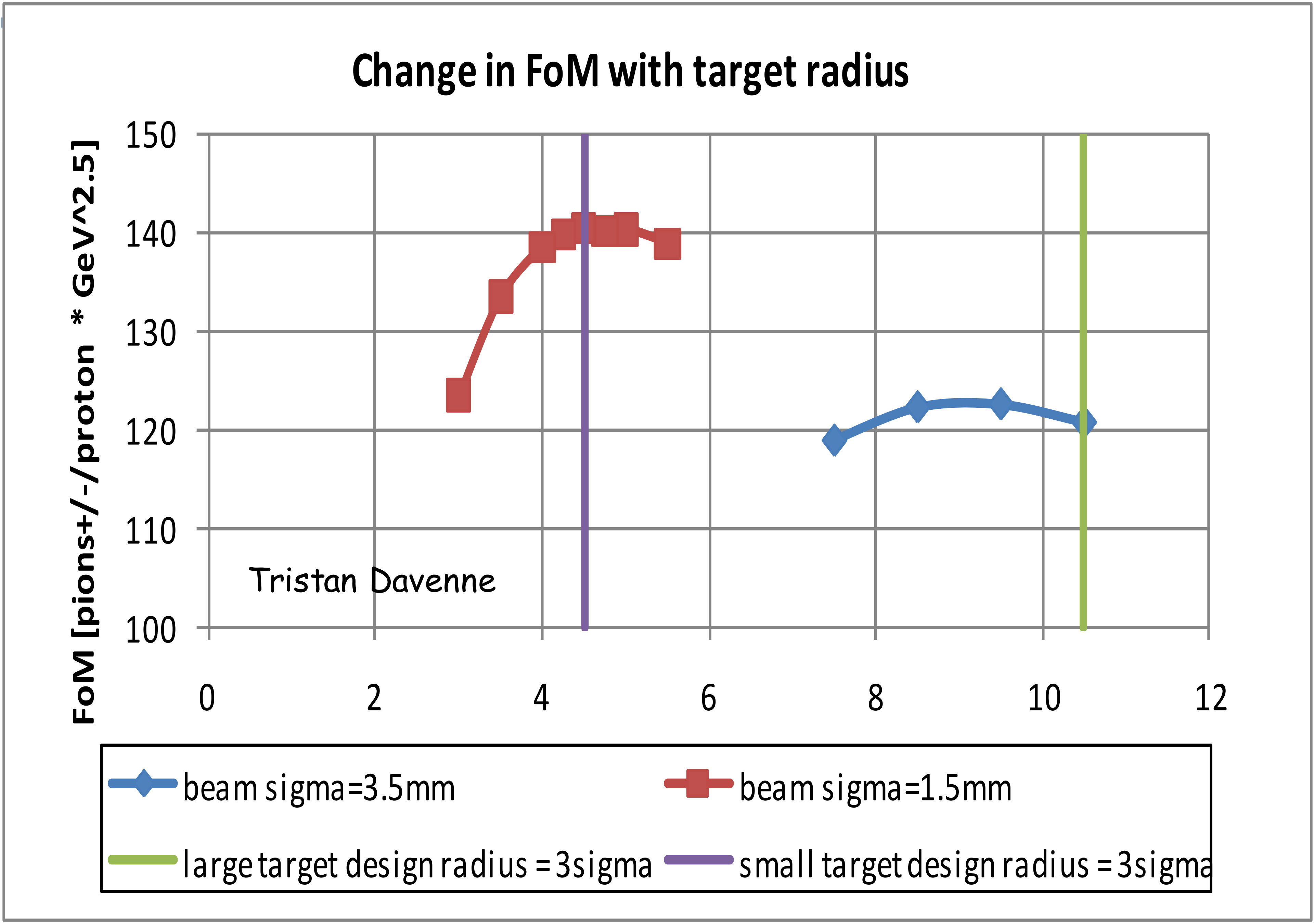

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Physics vs Engineering Optimisation ?
Target and Beam Dimensions

- For pion yield – smaller is better
  - Maximum production and minimum absorption (shown by FoM)
- For target lifetime – bigger is better
  - Lower power density – lower temperatures, lower stresses
  - Lower radiation damage density

- For integrated neutrino flux, need to take both neutrino flux and lifetime factors into account
  - Want to make an assessment of trade off between target lifetime vs beam and target dimensions
  - Answer will depend on Target Station engineering (time to change over target and horn systems)

Target configurations considered for Superbeams

1. LBNE at Fermilab

- Integral target and horn inner conductor
  - Solid Be rod
  - water spray cooled
- Separate target installed inside bore of horn inner conductor
  - Graphite, water cooled (IHEP study (baseline))
  - Be: subdivided in z, water cooled
  - Be: spheres, helium cooled

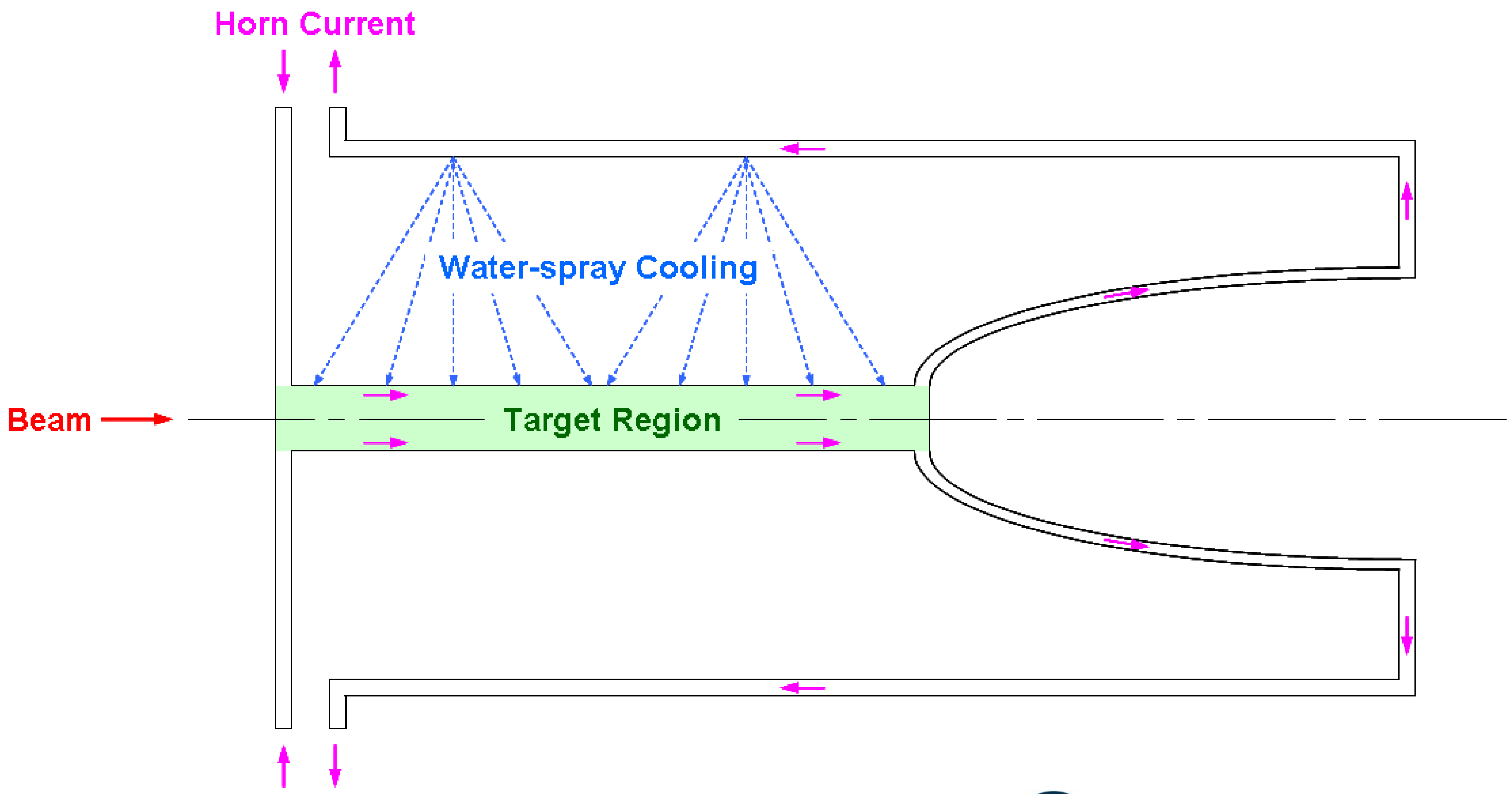
2. EUROnu SuperBeam using high power SPL at CERN
   4-horn system (4 x 12.5 Hz)

- 'Pencil' shaped beryllium rod
- 'Packed bed' of titanium beads
- Integral target and horn inner conductor
- (Graphite excluded due to radiation damage concerns)

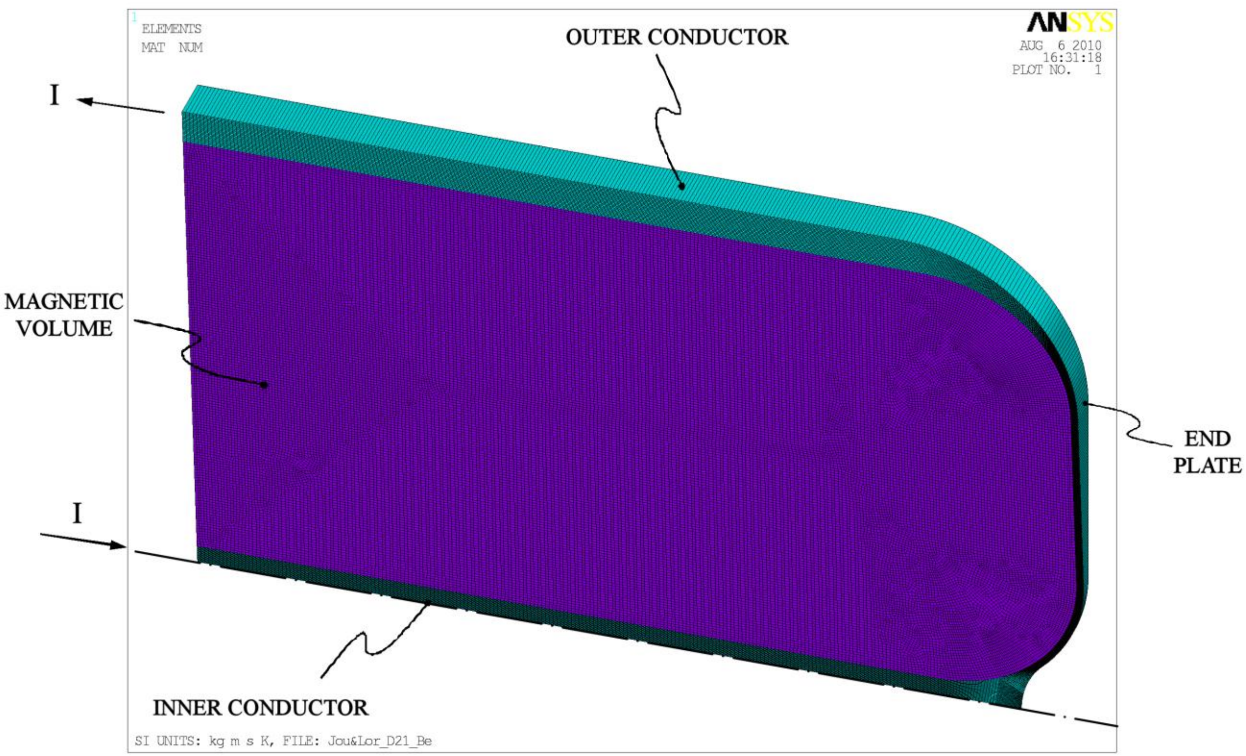
3. Other ideas

   Fluidised bed for ultra-high powers

LBNE: Combined target and horn inner conductor?

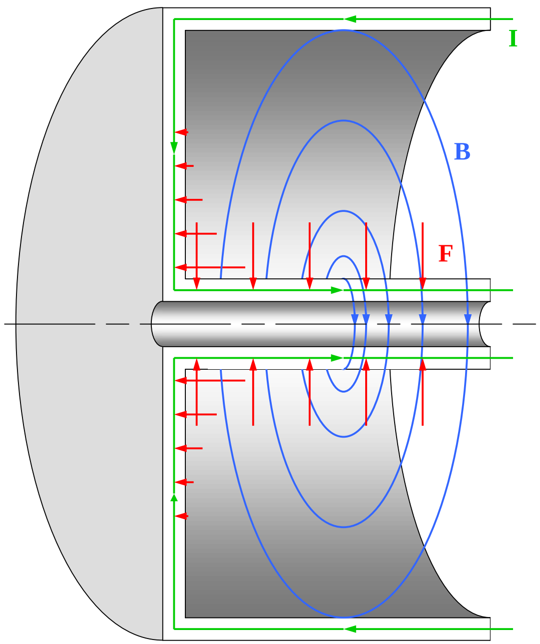


Magnetic modelling



Longitudinal force in inner conductor

$$F_{long} = \frac{\mu_0 I^2}{4\pi} \ln\left(\frac{R_2}{R_1}\right)$$



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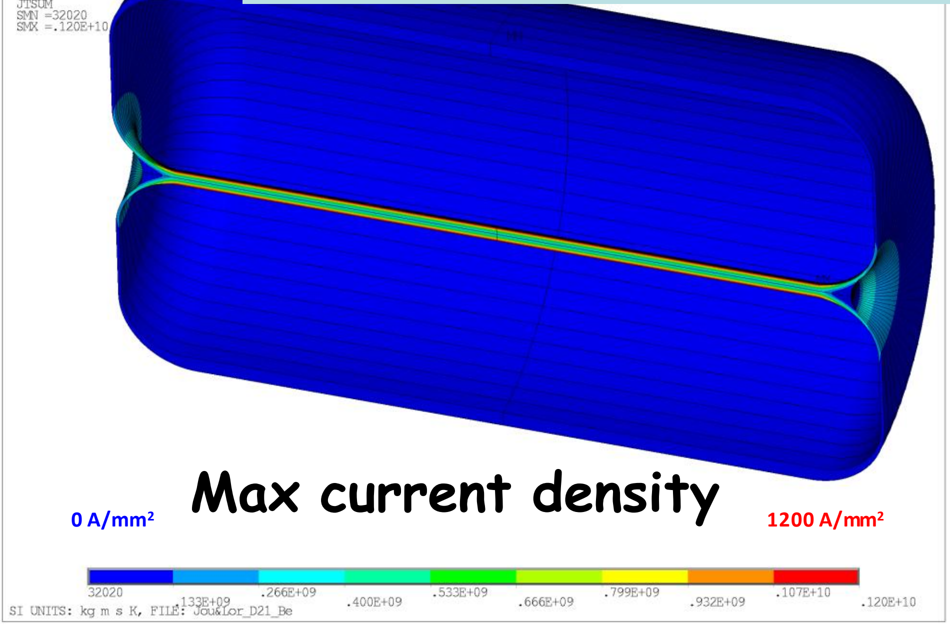
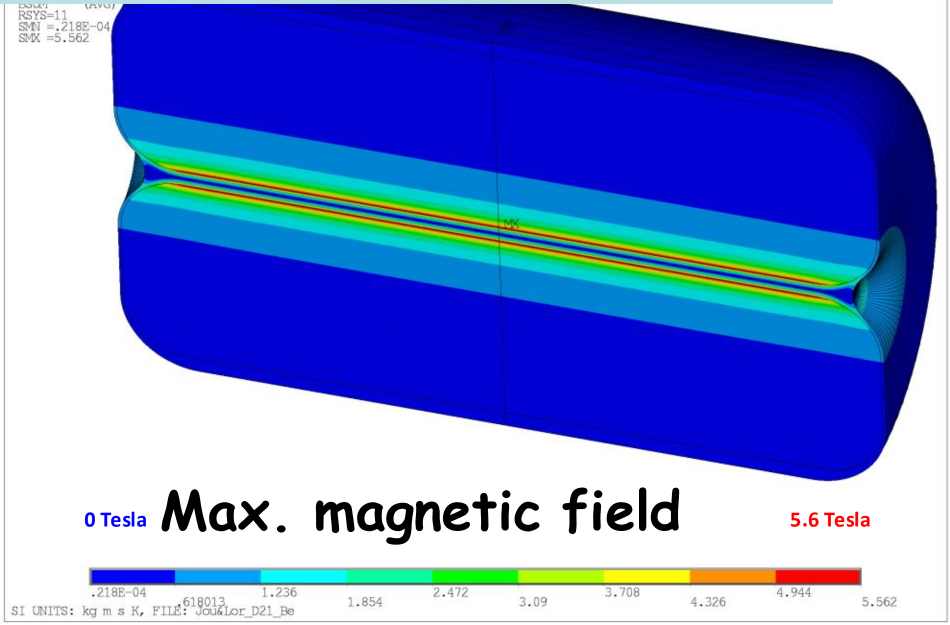
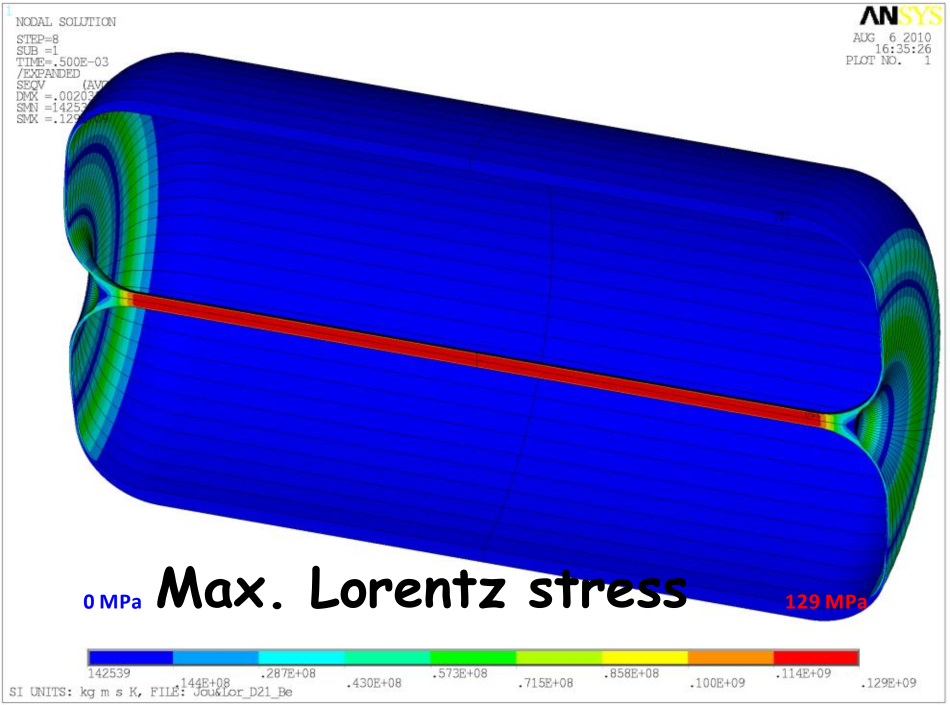
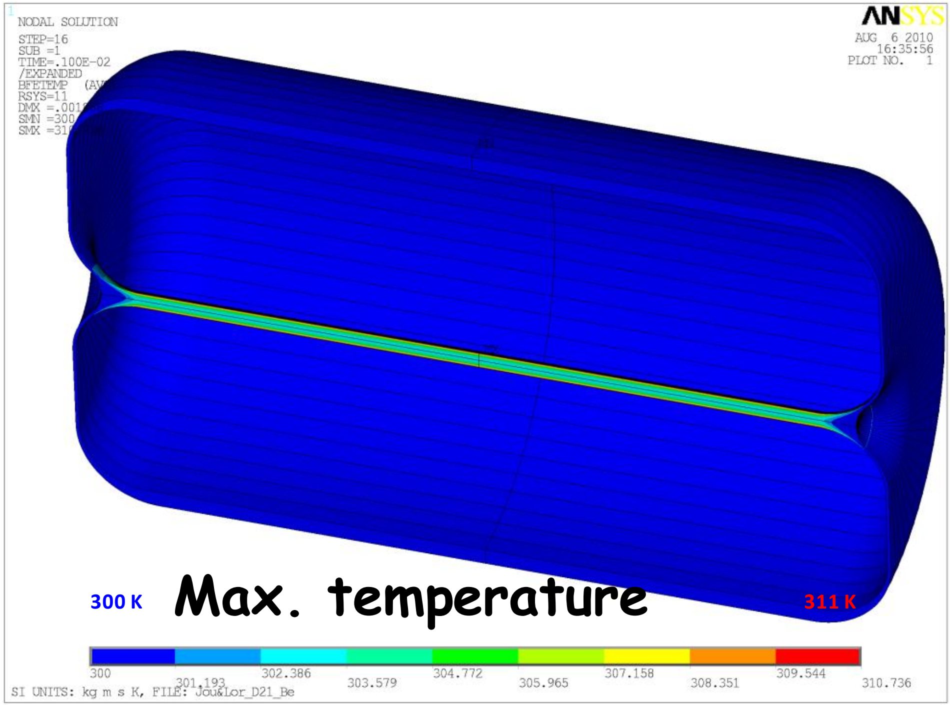
Solid beryllium inner conductor diameter = 21mm



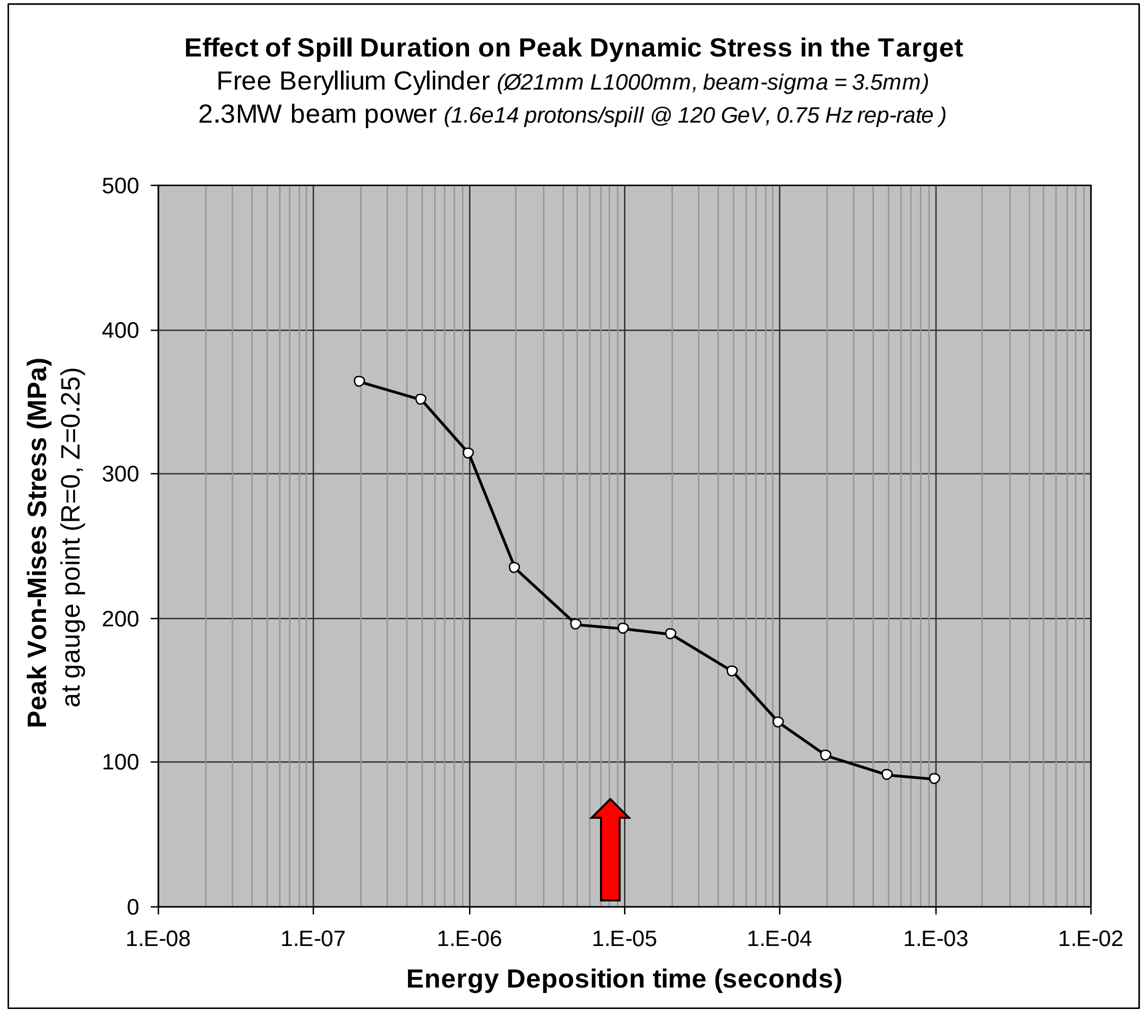






High Power Targets

LBNE target: Stress-Waves

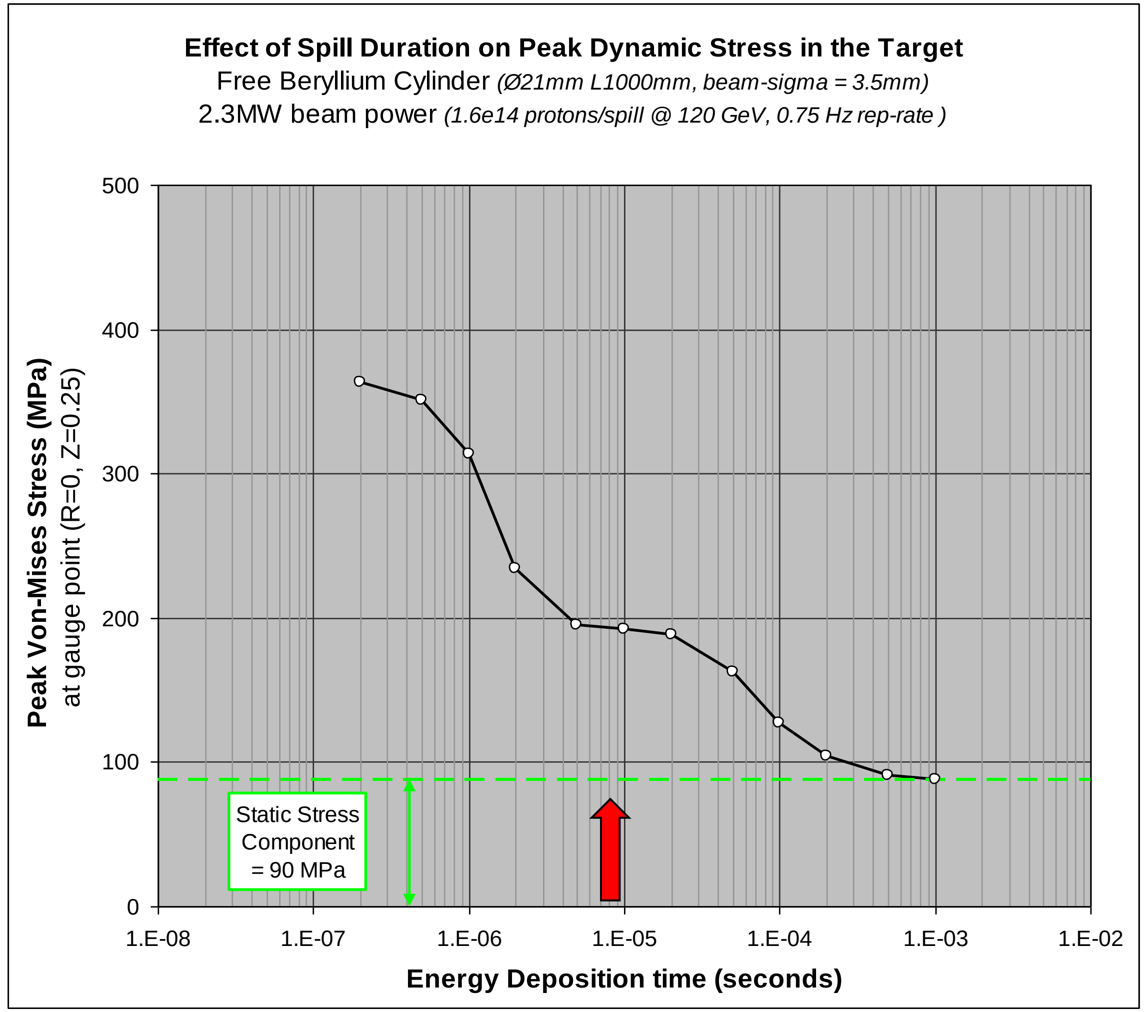


Effect of beam spill time on the peak dynamic stress in the target

High Power Targets

Stress-Waves

- "static" stress component is due to thermal gradients
  - Independent of spill time



Effect of beam spill time on the peak dynamic stress in the target

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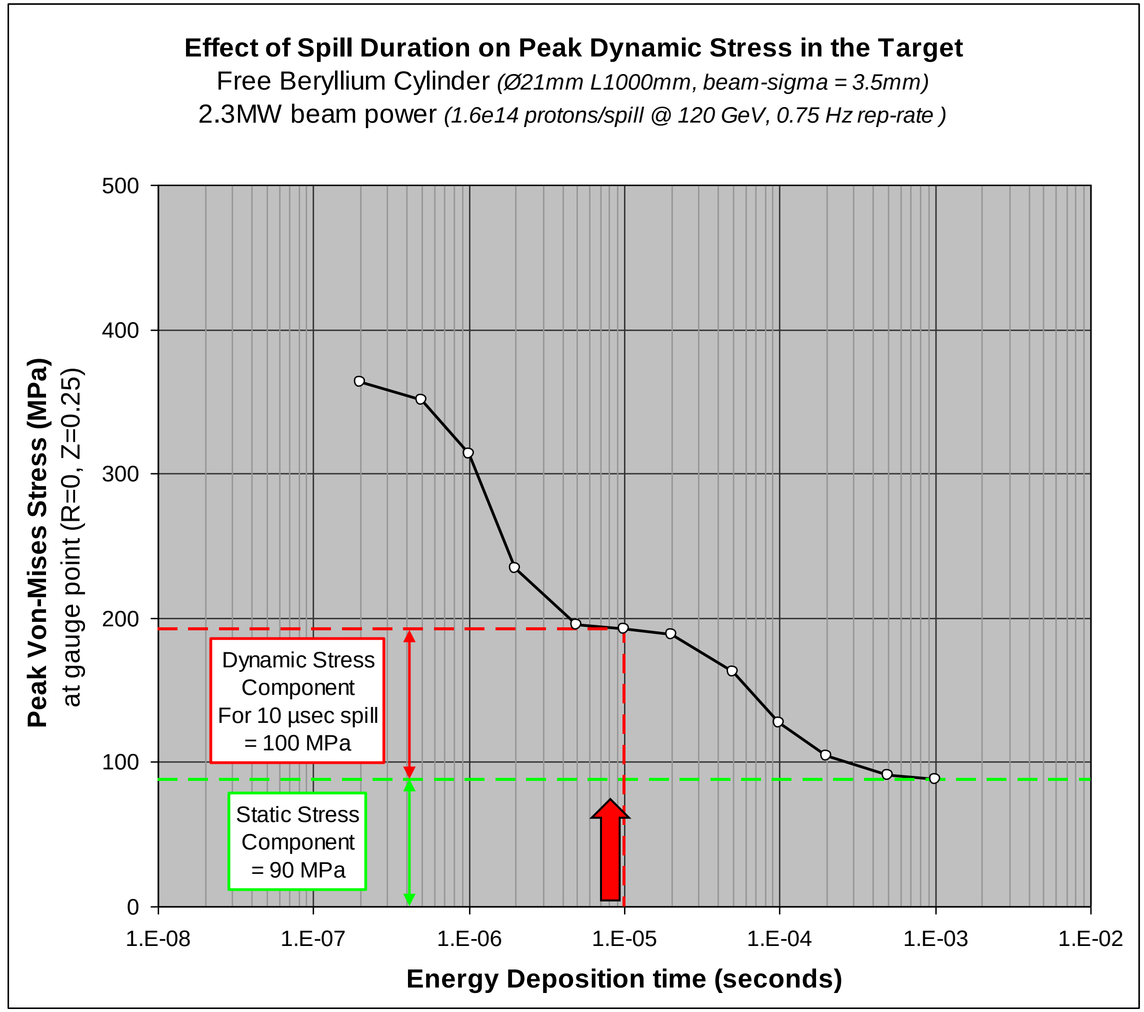
High Power Targets

Stress-Waves

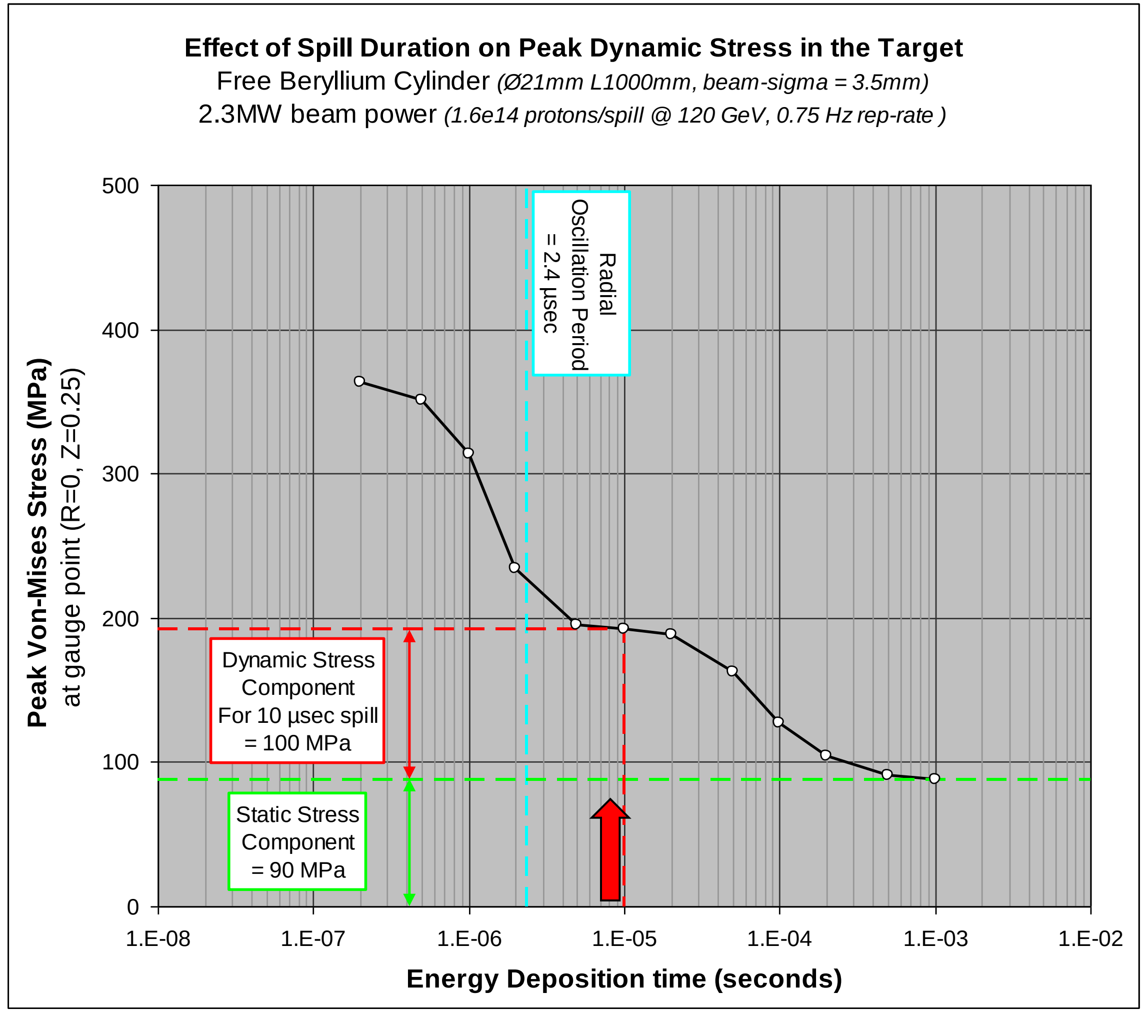
- "static" stress component is due to thermal gradients
  - Independent of spill time
- "dynamic" stress component is due to stress waves
  - Spill time dependent



Effect of beam spill time on the peak dynamic stress in the target

Stress-Waves

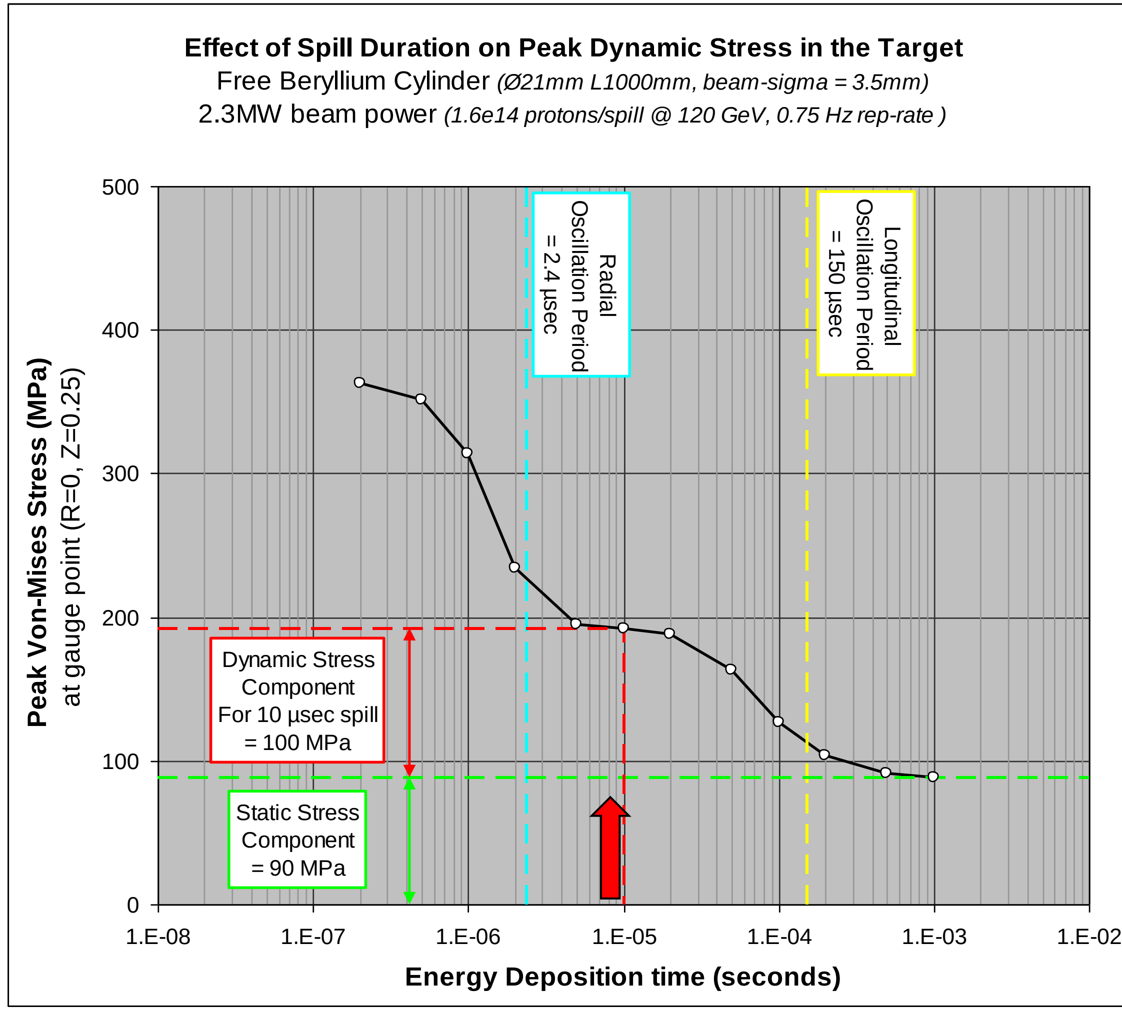
- "static" stress component is due to thermal gradients
  - Independent of spill time
- "dynamic" stress component is due to stress waves
  - Spill time dependent
- Tspill > Radial period
  - Radial stress waves are not significant



Effect of beam spill time on the peak dynamic stress in the target

Stress-Waves

- "static" stress component is due to thermal gradients
  - Independent of spill time
- "dynamic" stress component is due to stress waves
  - Spill time dependent
- Tspill > Radial period
  - Radial stress waves are not significant
- Tspill < Longitudinal period
  - Longitudinal stress waves are important!



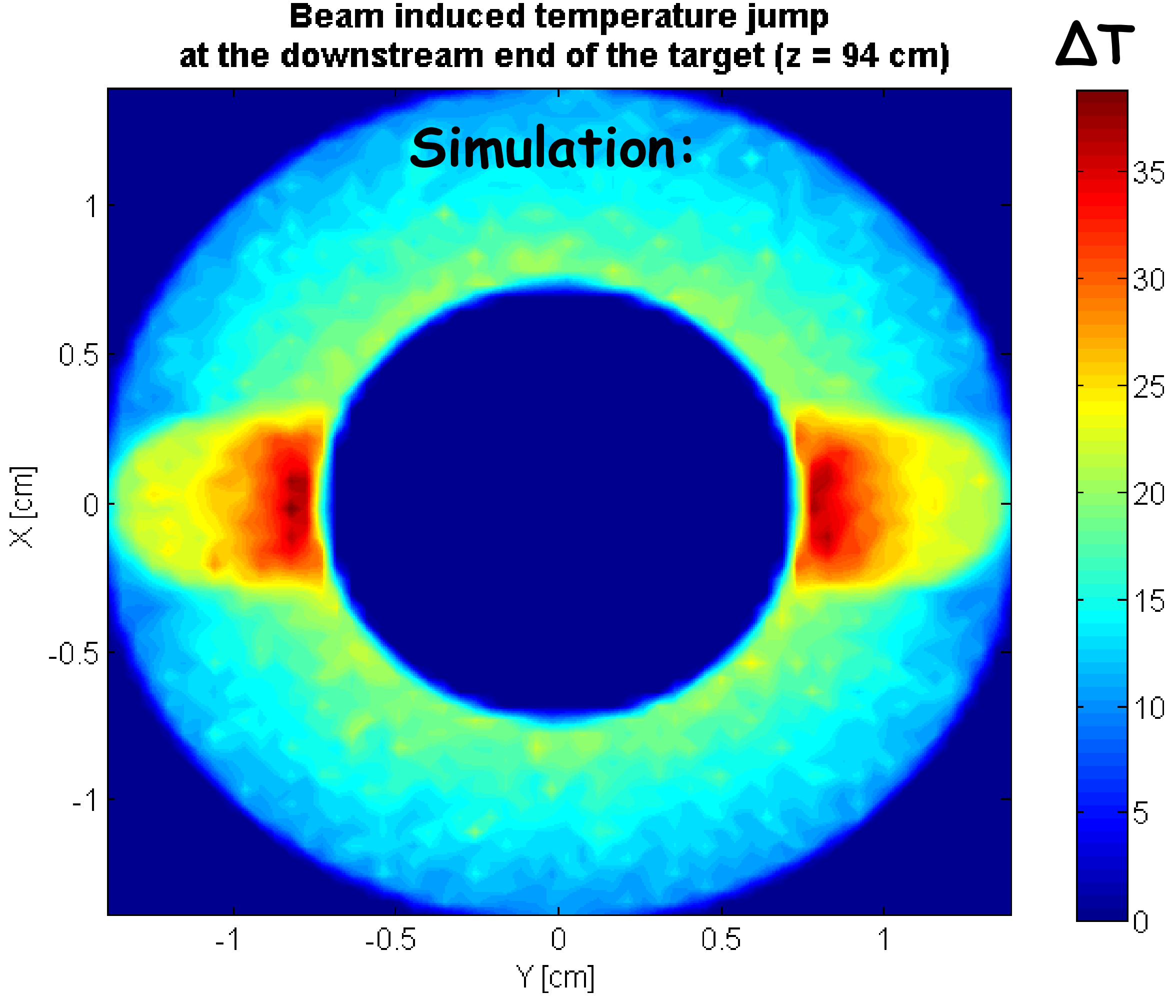
Effect of beam spill time on the peak dynamic stress in the target

Conclusions on combined target/horn IC

- Very simple design concept
- But complex, combined horn current pulse and beam pulse effects
- Need to reduce longitudinal Lorentz stresses requires target diameter to be larger than desired for optimum pion yield
- Effects of off-centre beam 'violin modes' problematic, in combination with longitudinal vibration modes
- Recommend looking at longitudinally segmented target separate from horn

Direct water cooling?

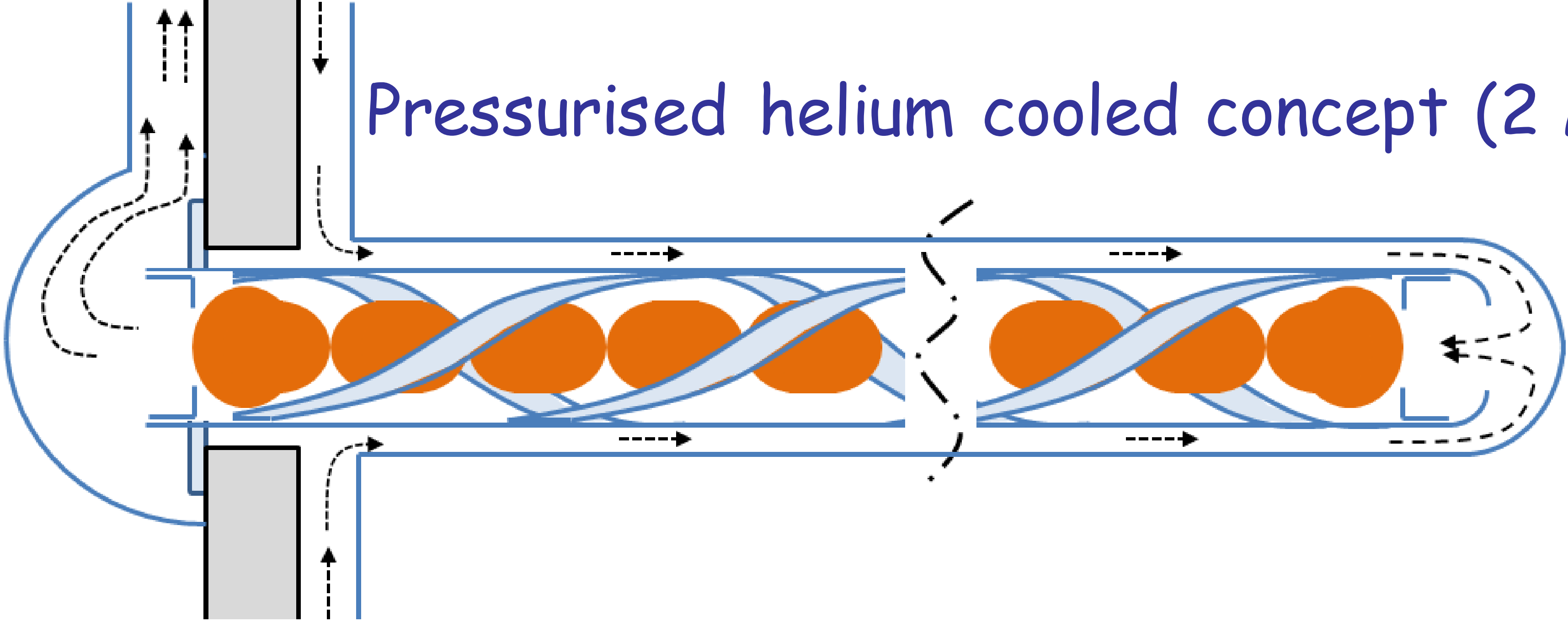
Effects of pulsed beams on NuMI target



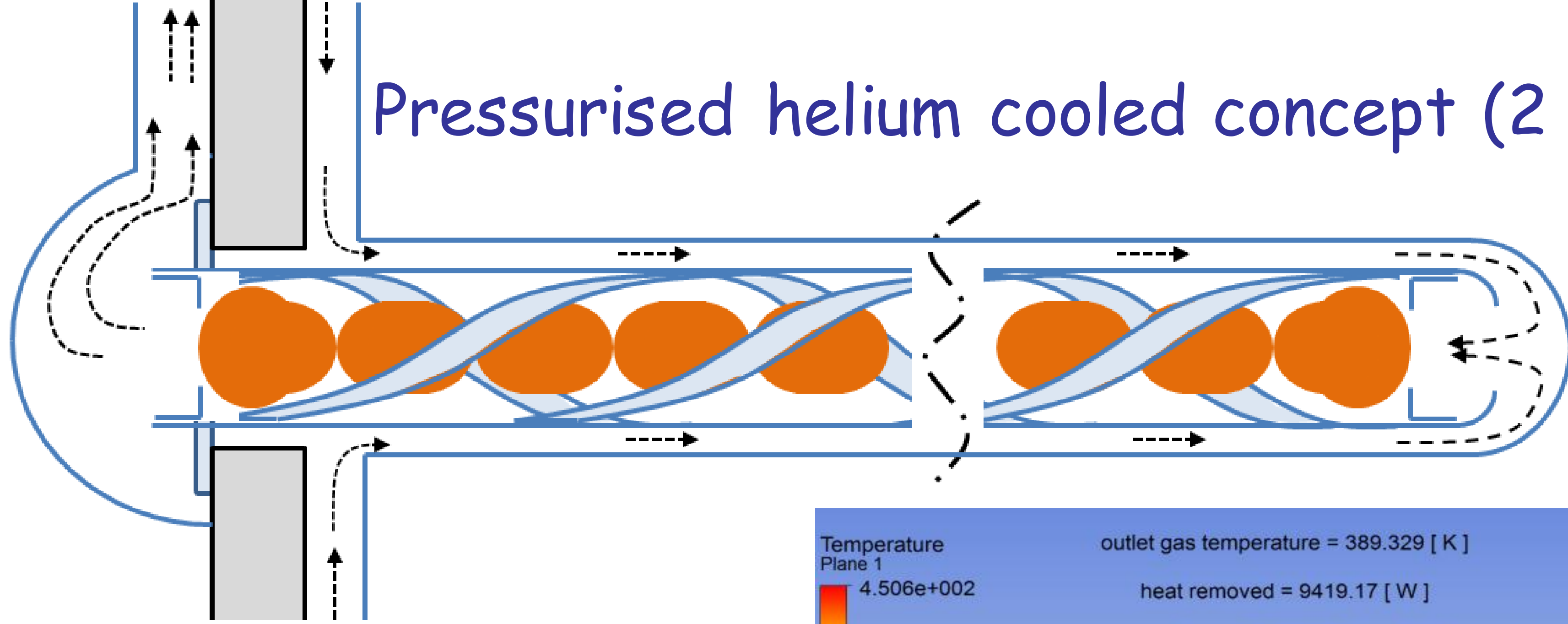
Result:

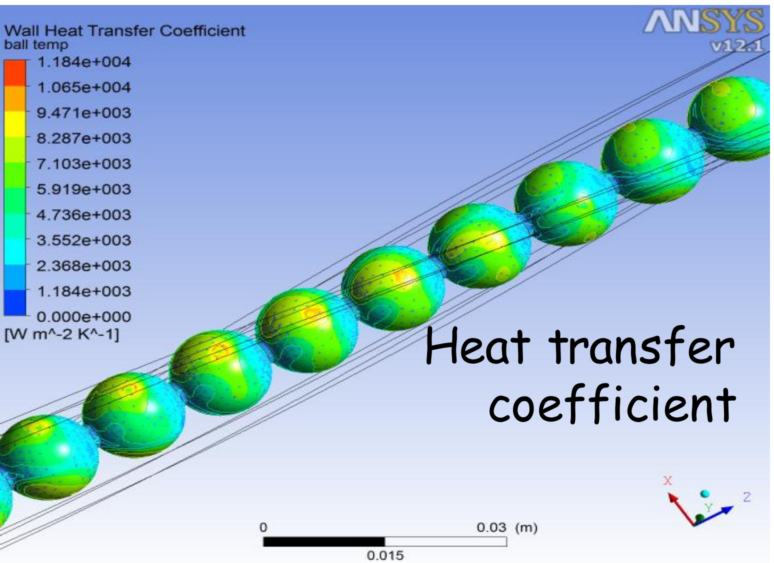
Conclusions:
Try to avoid using contained water in close proximity to intense pulsed beams

Pressurised helium cooled concept (2 MW)

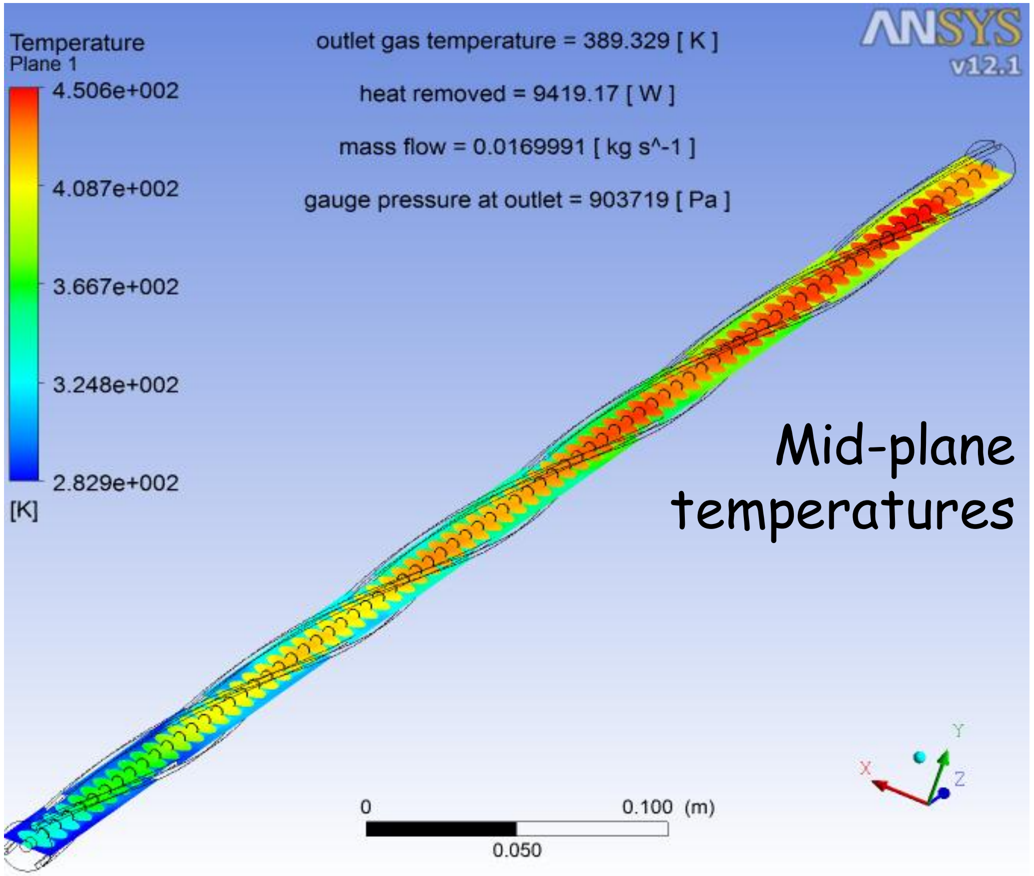


Pressurised helium cooled concept (2 MW)





Heat transfer coefficient



Mid-plane temperatures

Otto Caretta & Tristan Davenne

Pressurised helium cooled concept (2 MW)

Beryllium sphere diameter	13 mm
Beam sigma	2.2 mm
Helium mass flow rate	17 g/s
Inlet helium pressure	11.1 bar
Outlet helium pressure	10 bar
Inlet velocity	40 m/s
Maximum velocity	185 m/s
Total heat load	9.4 kW
Maximum beryllium temperature	178 C
Helium temperature rise, ΔT (T_{in}-T_{out})	106 C

Otto Caretta & Tristan Davenne

High Power Targets

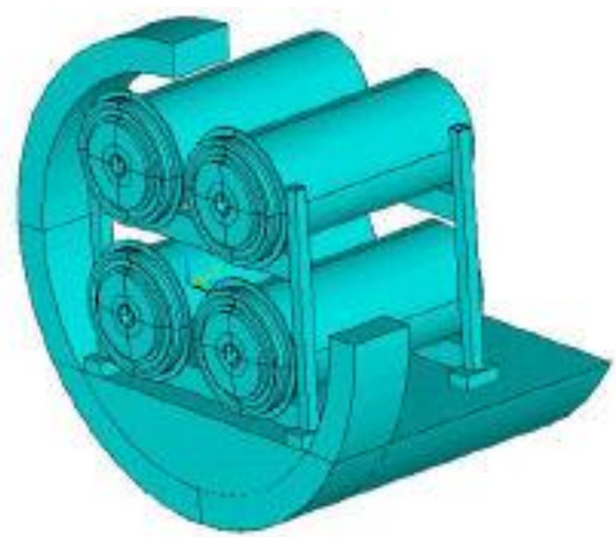
LBNE target study: conclusions for 2.3 MW

- Combined target/horn inner conductor
  - Not recommended as dimensions dominated by horn current pulse Lorentz forces rather than pion production
- Candidate beryllium target technologies for further study:
  1. Water cooled longitudinally segmented (possible)
  2. Pressurised helium cooled separate spheres (recommended)

EURONu Super Beam study using HP SPL -> Frejus

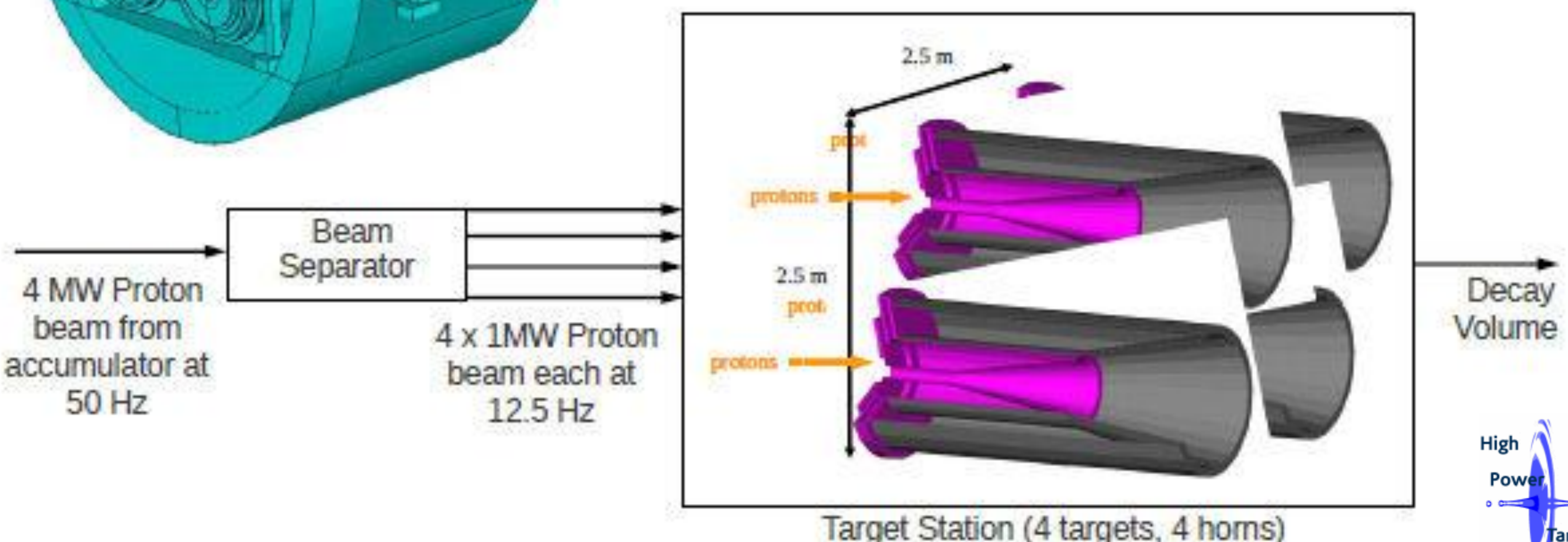
50 Hz horn operation and 4 MW beam power on target 'very challenging'

⇒ 4 x 12.5 Hz operation using beam separator proposed



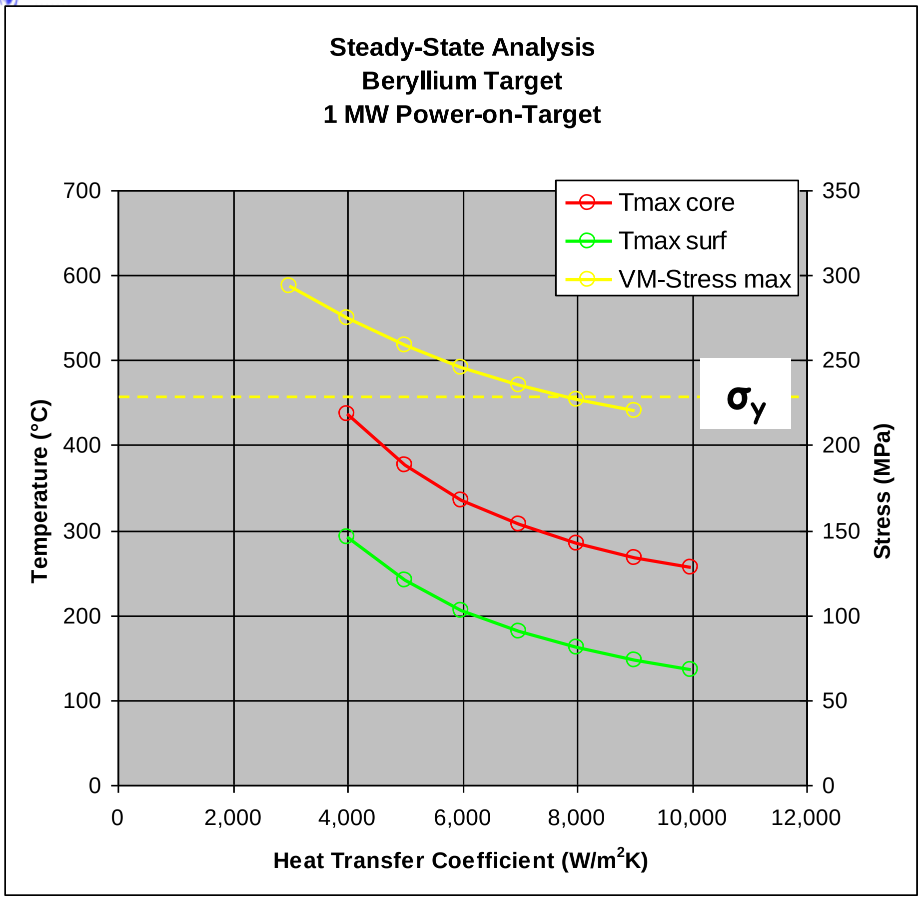
Beam parameters used:

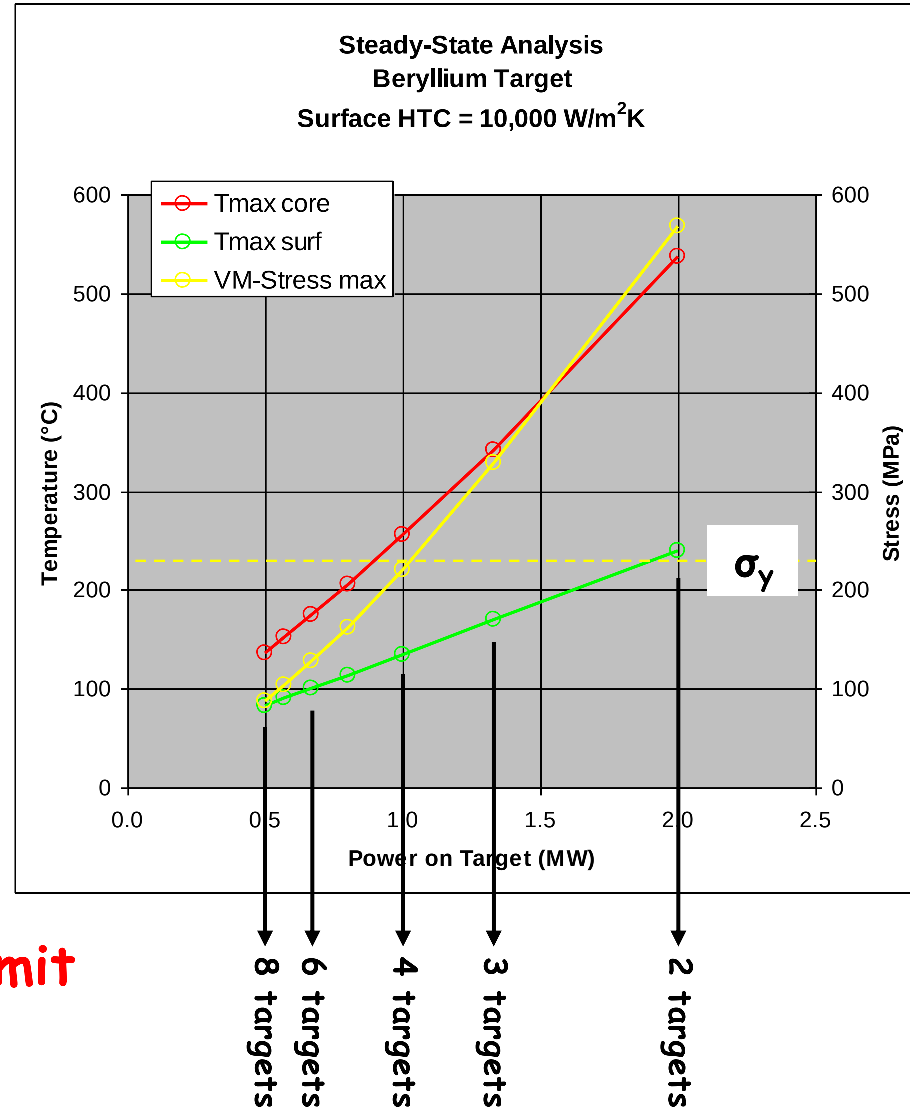
- Beam KE: 4.5GeV
- 1.11e14 protons/bunch
- Beam Sigma: 4mm
- Beam Power: 4 x 1 MW



High Power Targets

Stress in a solid peripherally cooled beryllium rod





1 MW beam power = limit for a solid peripherally cooled target for this beam energy

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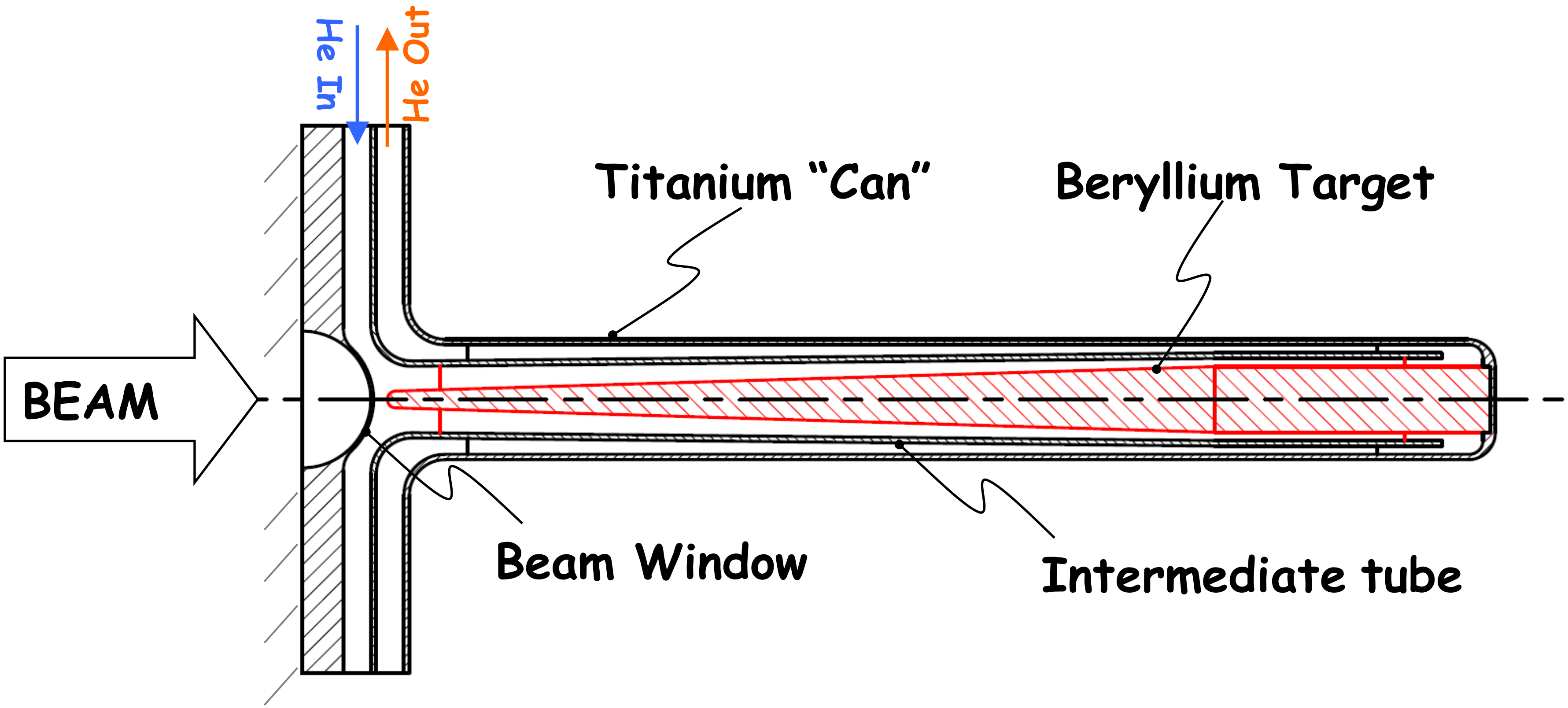
"Pencil" Target Concept Design

- Pencil shaped Beryllium target contained within a Titanium "can"
- Pressurised Helium gas cooling, outlet at 10 bar
- Supported as a cantilever from the upstream end



Drawing not to scale!

High Power Targets

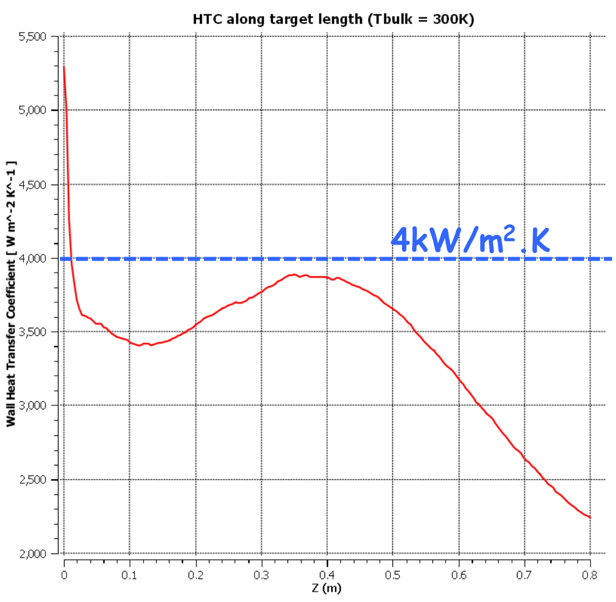
Optimisation of channel profile: it works…

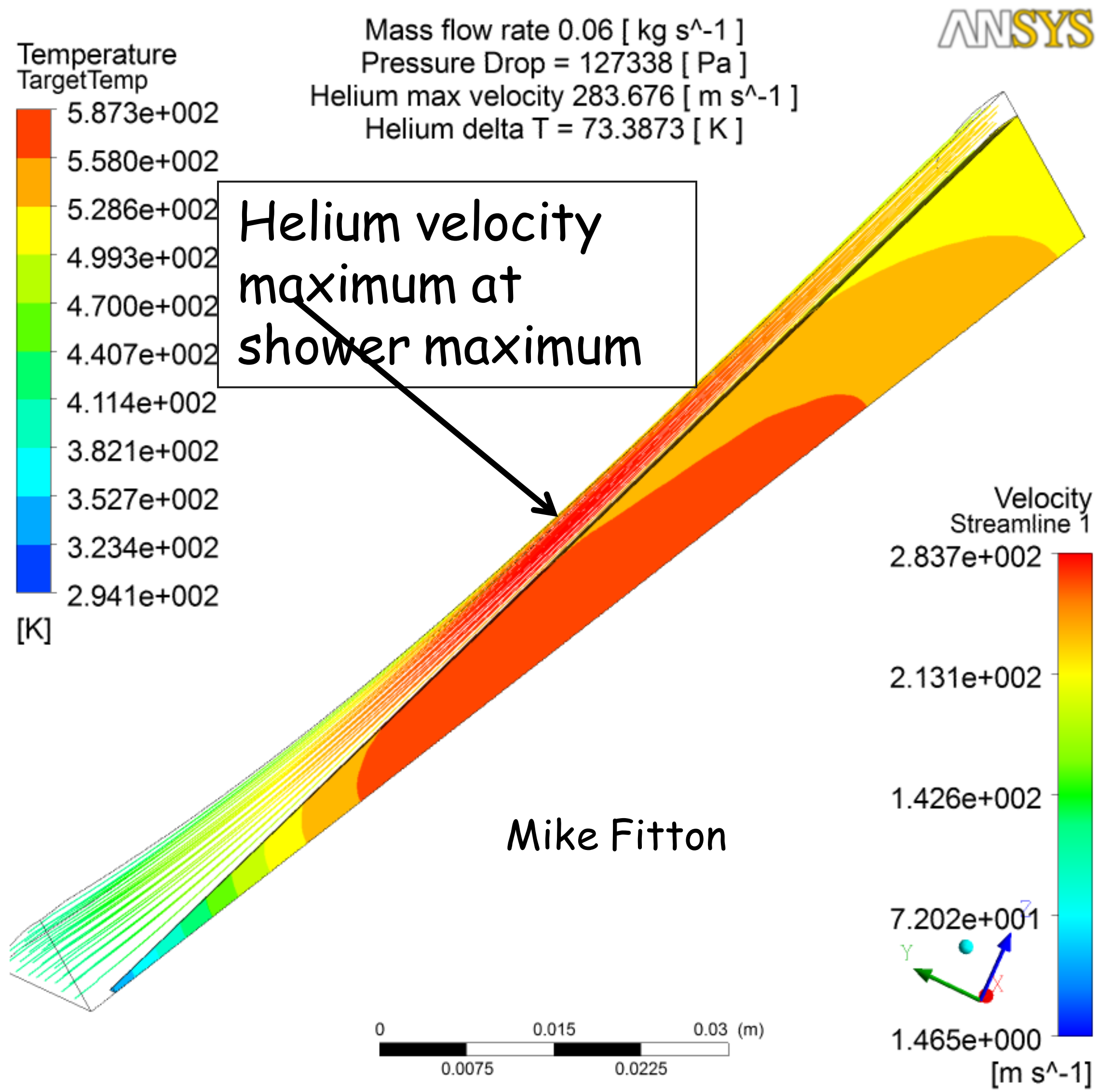
Cooling channel

R1 = 9mm

R2 = 9mm

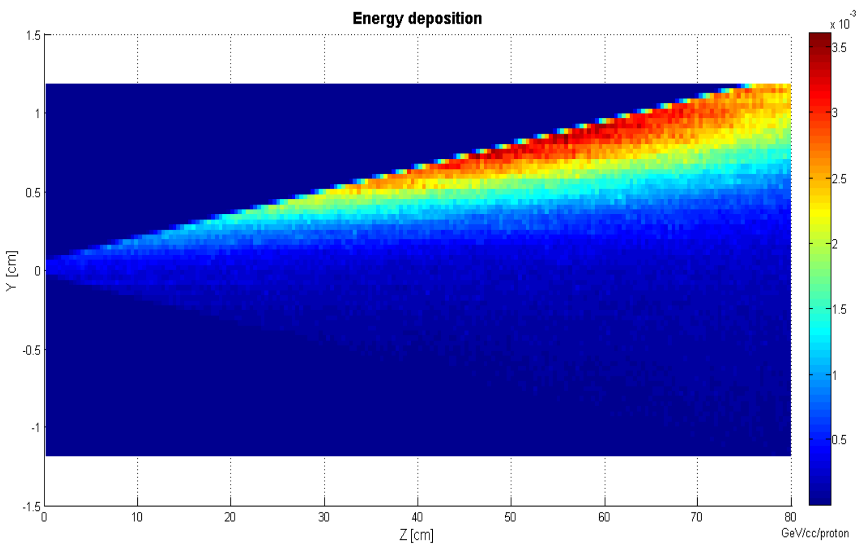
R3 = 14.4mm

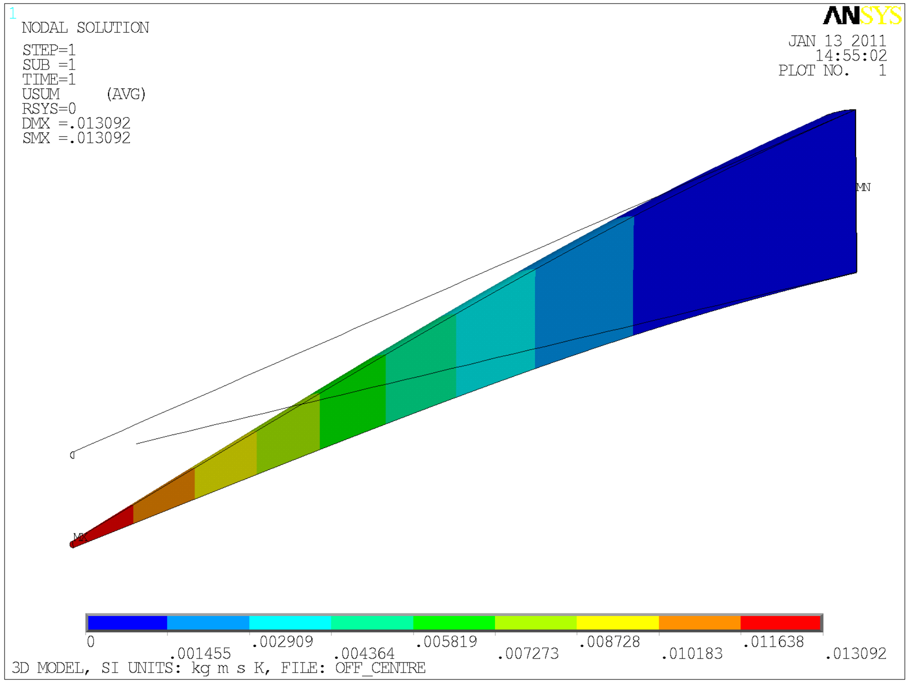




But: 'dancing on head of pin' for off-centre beam

- Lateral deflection 50% greater, and in opposite direction, to beam mis-steer





Energy deposition for 2 sigma beam offset

0 mm 13 mm

=> Unstable

=> not recommended

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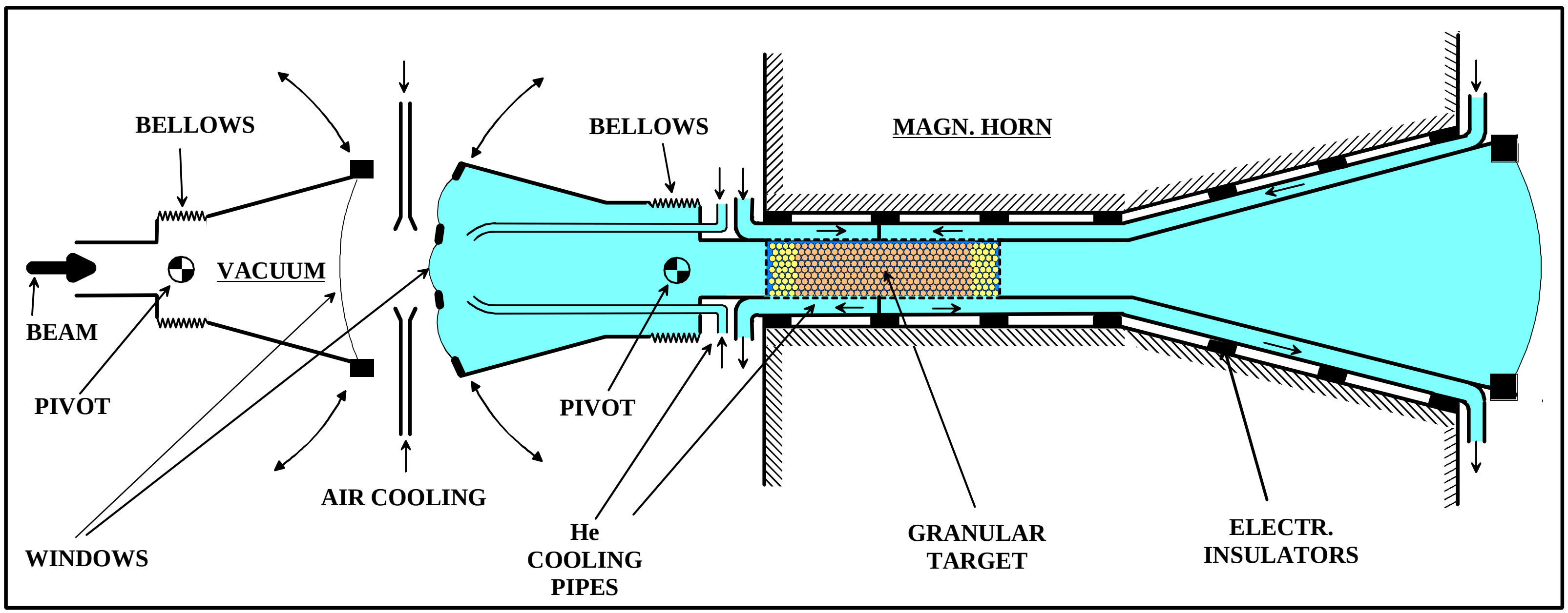
How about that particle bed idea?

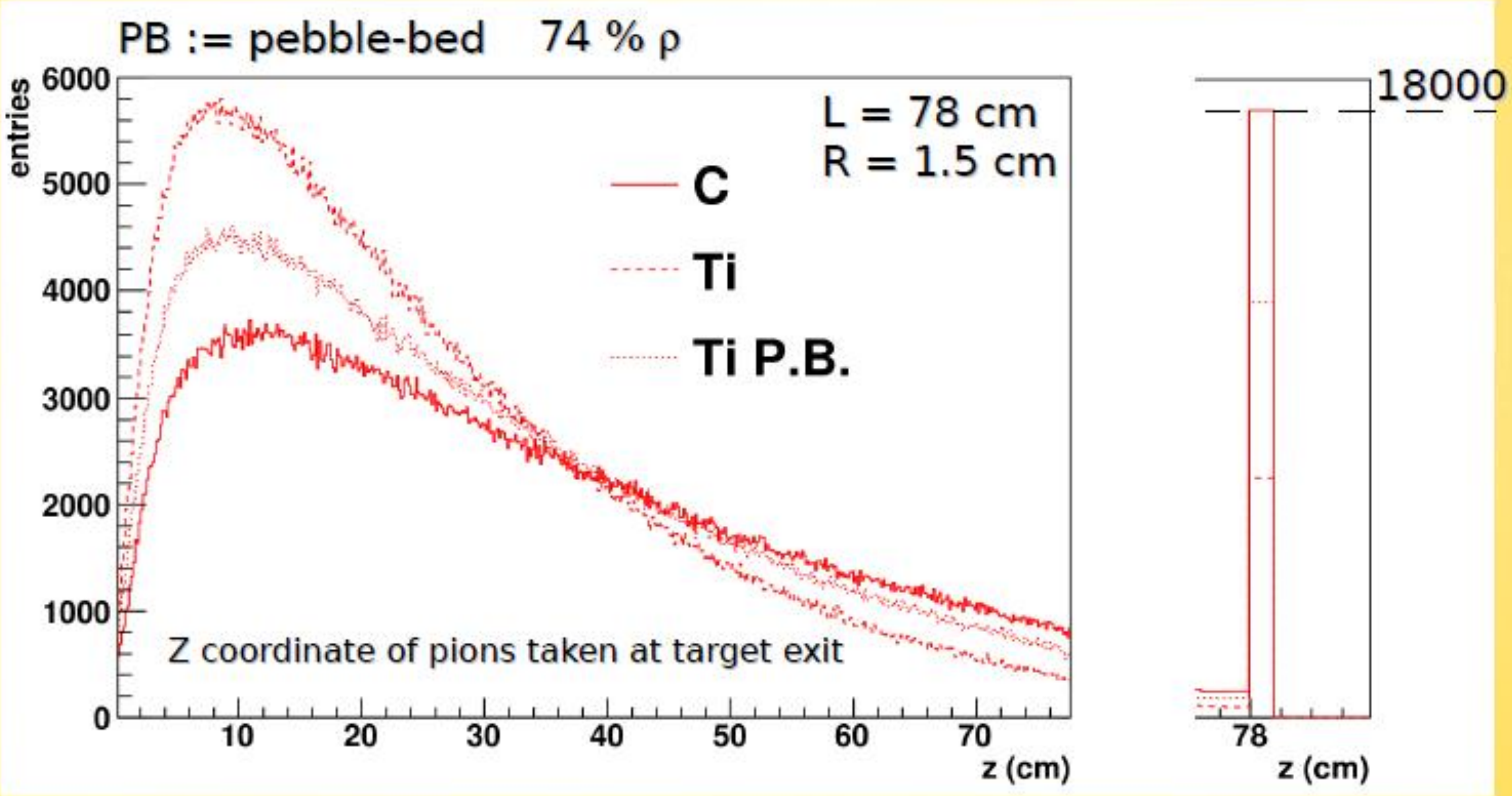
Helium gas cooled granular target proposed by Sievers and Pugnat



Pion production comparison (FLUKA)

$\rho(Ti) = 4.506$ g/cm^3
0.74 $\rho(Ti) = 3.336$ g/cm^3
ρ(graphite) = 1.85 g/cm^3

	Multiplicity		downstr. face
C	1.11 $\pi^{\pm}/p$	+16%	1.6 %
Ti	1.29 $\pi^{\pm}/p$		1.0 %
Ti P.B.	1.20 $\pi^{\pm}/p$	-8%	0.6 %



Longitudinal profile with PB "similar" to the graphite one (and more π!)

$\rightarrow$

The horn should work well

Particle bed advantages

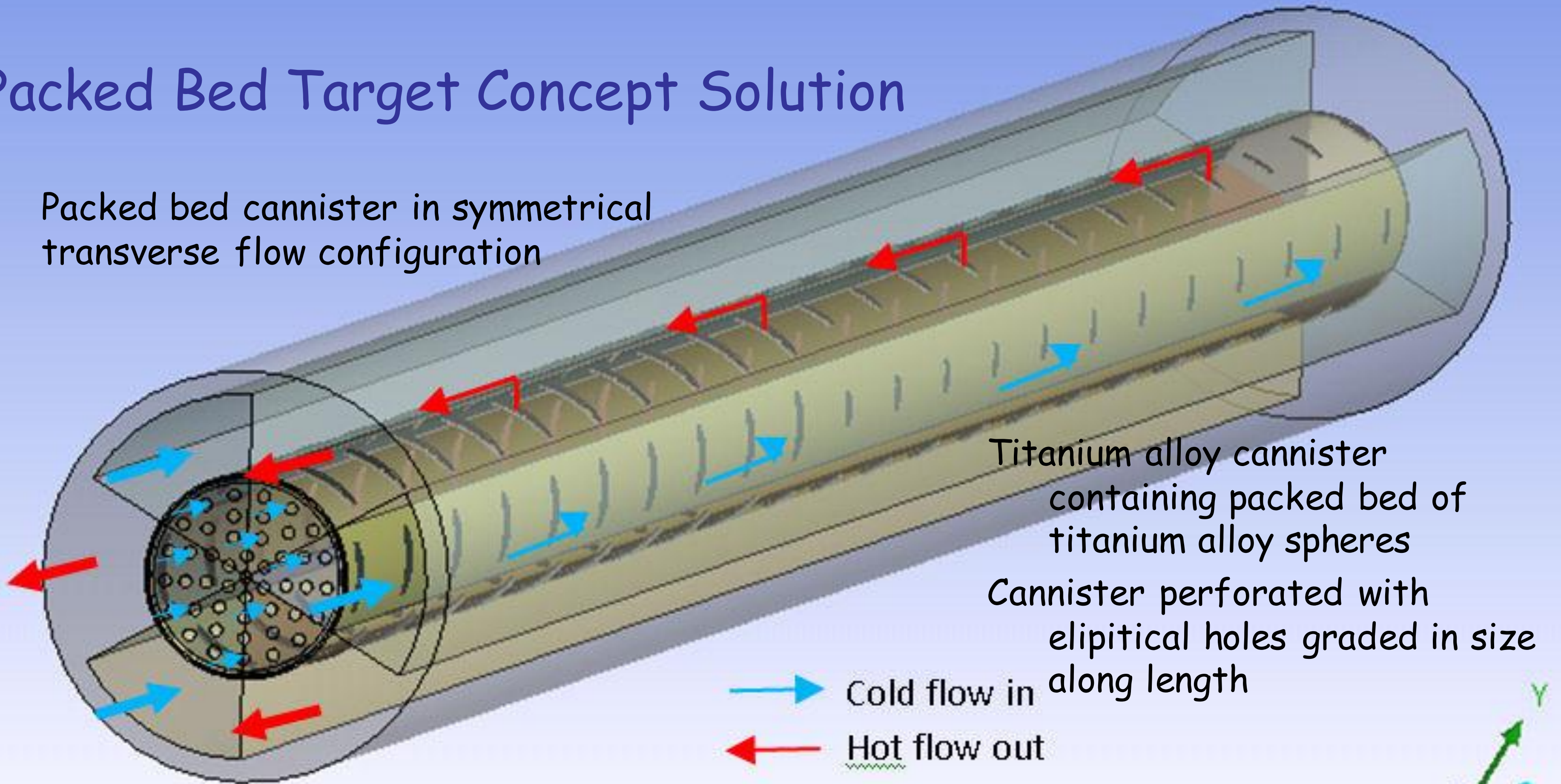
- Large surface area for heat transfer
- Coolant can pass close to maximum energy deposition
- High heat transfer coefficients
- Low quasi static thermal stress
- Low dynamic stress (for oscillation period <<beam spill time)

… and challenges

- High pressure drops, particularly for long thin superbeam target geometry
  - Need to limit gas pressure for beam windows
- Transverse flow reduces pressure drops – but
  - Difficult to get uniform temperatures and dimensional stability of container

Packed Bed Target Concept Solution

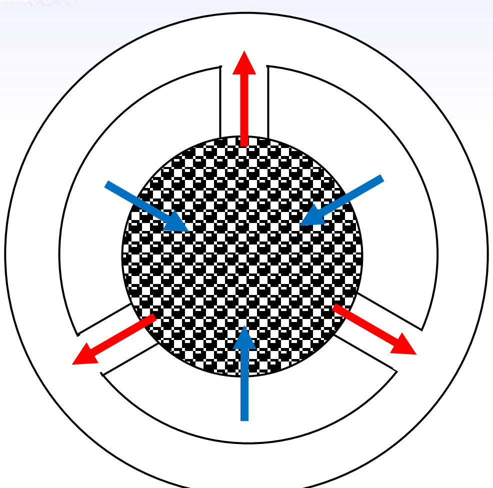
Packed bed cannister in symmetrical transverse flow configuration



Titanium alloy cannister containing packed bed of titanium alloy spheres

Cannister perforated with elipitical holes graded in size along length

T.Davenne



Model Parameters

Proton Beam Energy = 4.5GeV

Beam sigma = 4mm

Packed Bed radius = 12mm

Packed Bed Length = 780mm

Packed Bed sphere diameter = 3mm

Packed Bed sphere material : Titanium Alloy

Coolant = Helium at 10 bar pressure

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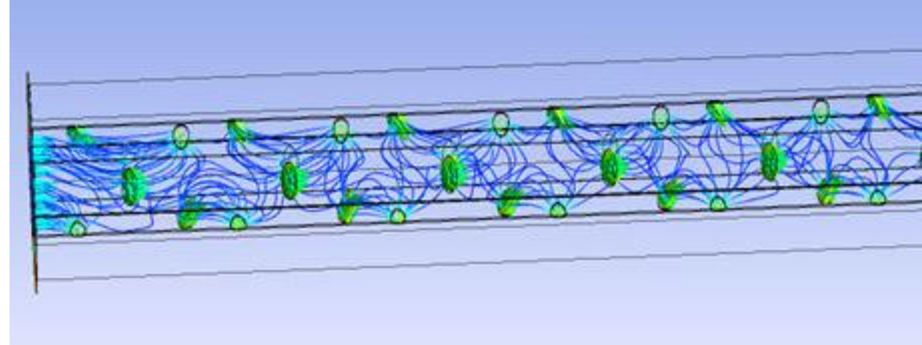
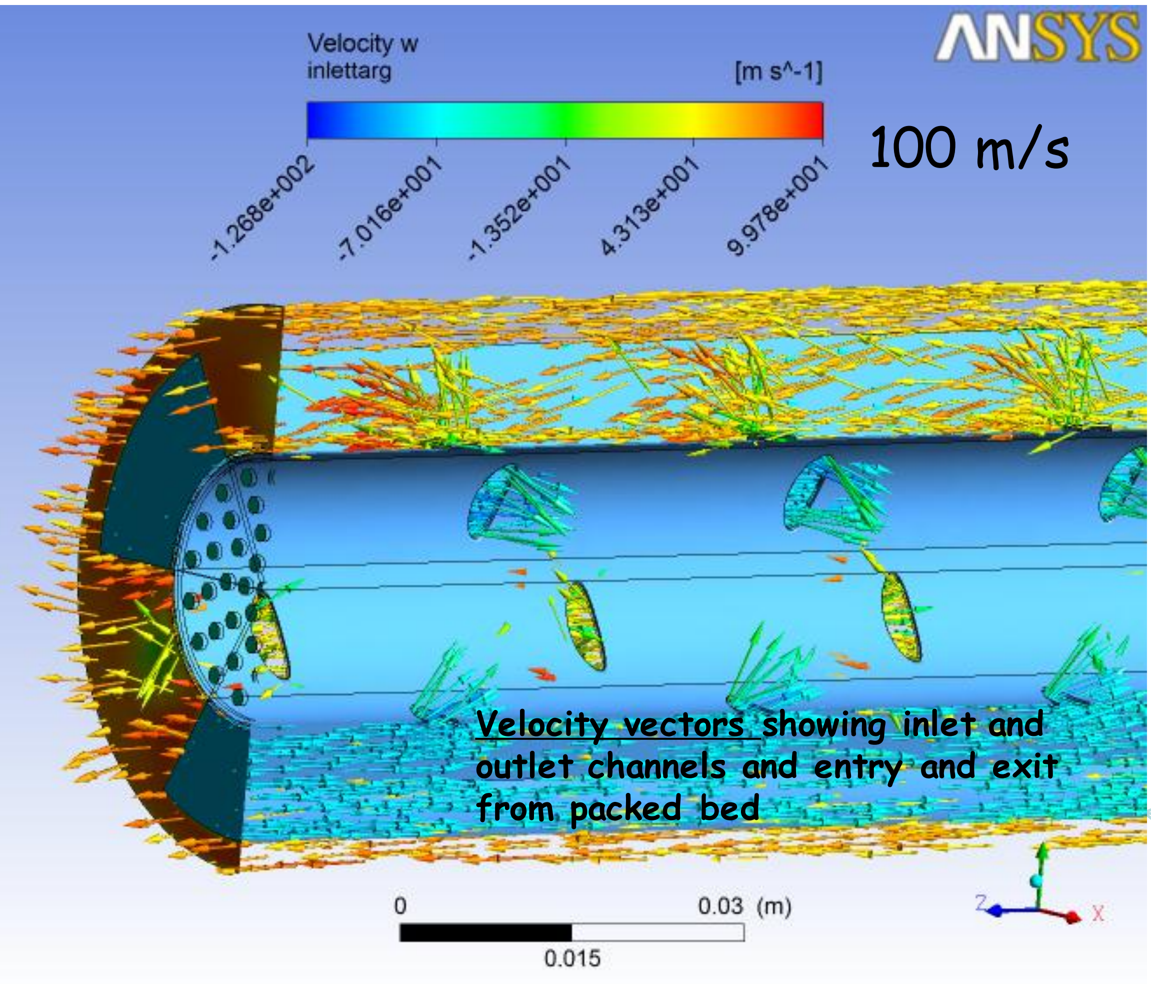
High Power Targets

Packed Bed Model (FLUKA + CFX v13)





<u>Velocity vectors showing inlet and outlet channels and entry and exit from packed bed</u>

<u>**Streamlines in packed bed**</u>

- Packed bed modelled as a porous domain
- Permeability and loss coefficients calculated from Ergun equation (dependant on sphere size)
- Overall heat transfer coefficient accounts for sphere size, material thermal conductivity and forced convection with helium
- Interfacial surface area depends on sphere size
- Acts as a natural diffuser flow spreads through target easily

T.Davenne

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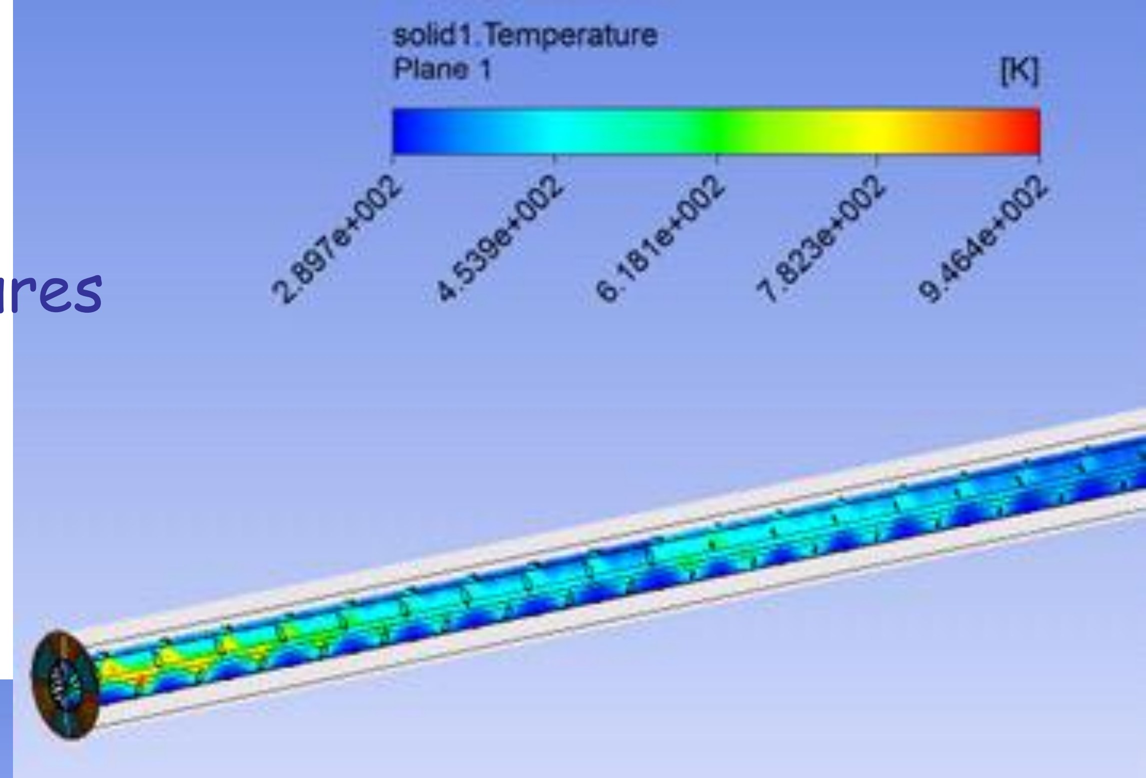
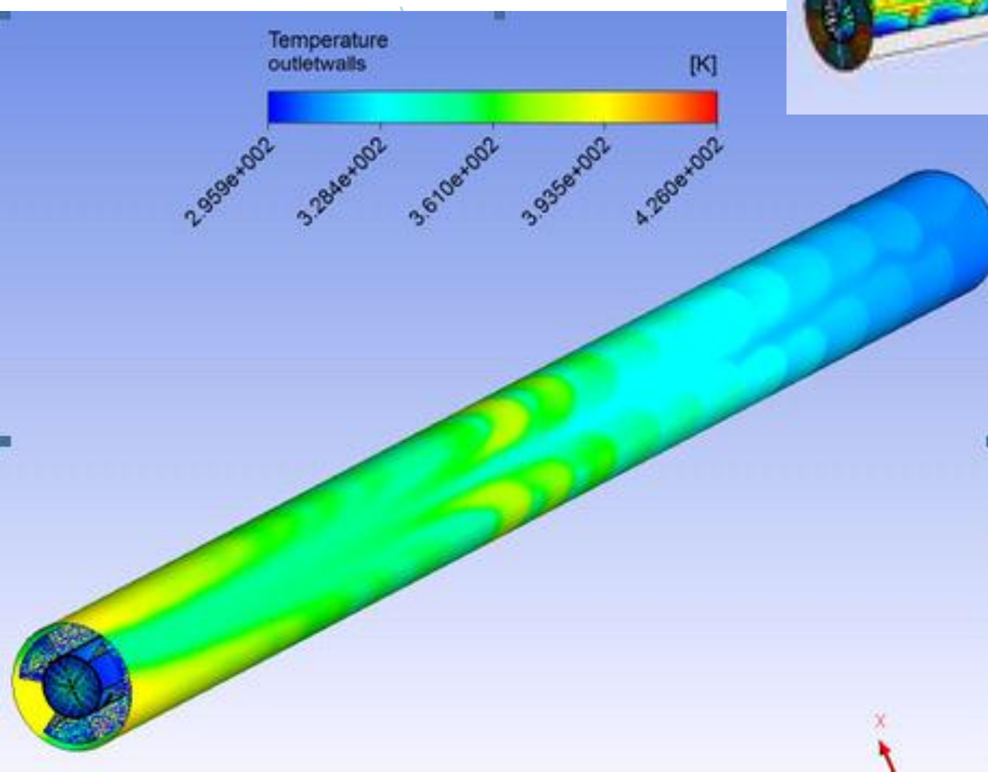
Packed Bed temperatures





<u>Outer Can Surface Temp</u>

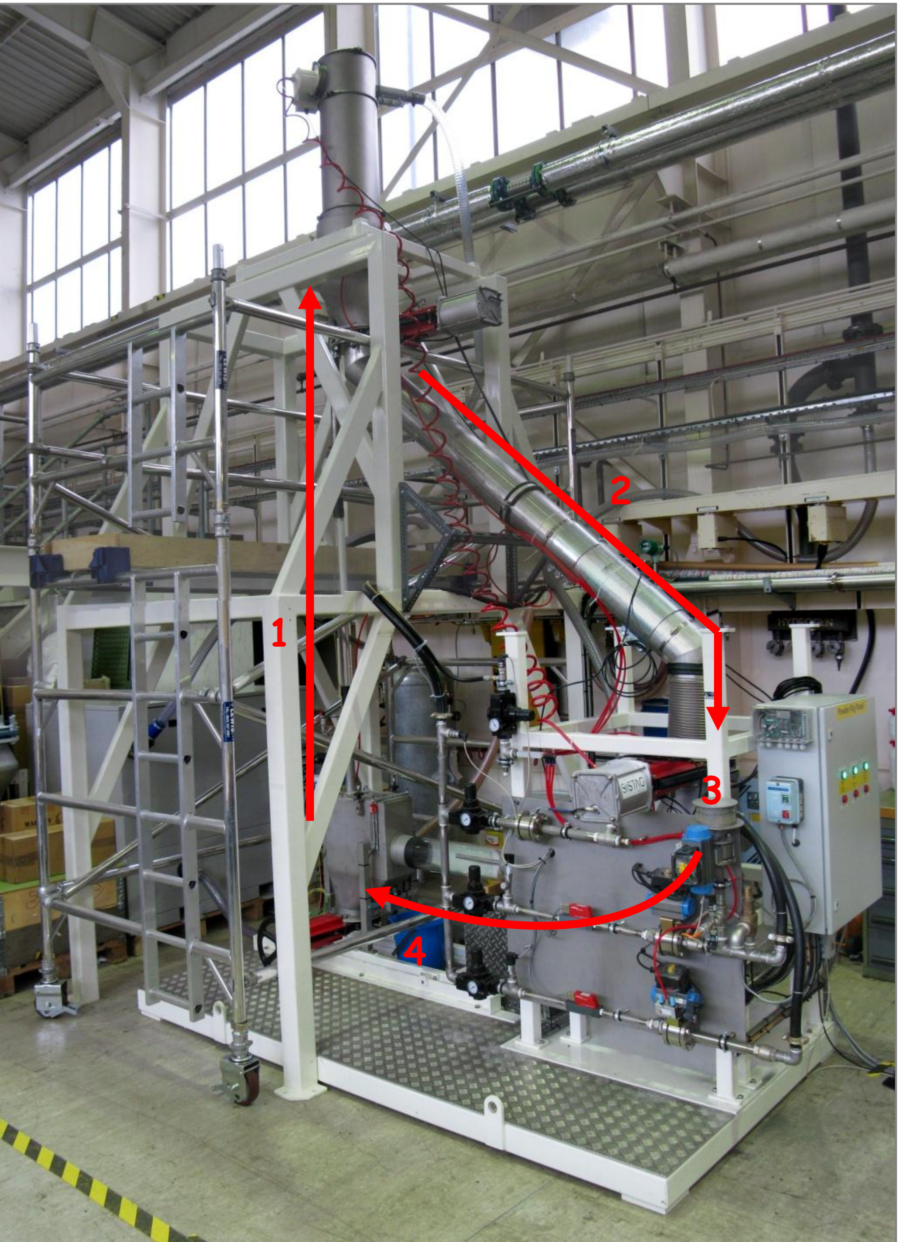
Almost Symmetric Temperature contours

Maximum surface Temperature = 426K = 153°C

<u>NB windows not included in model yet</u>

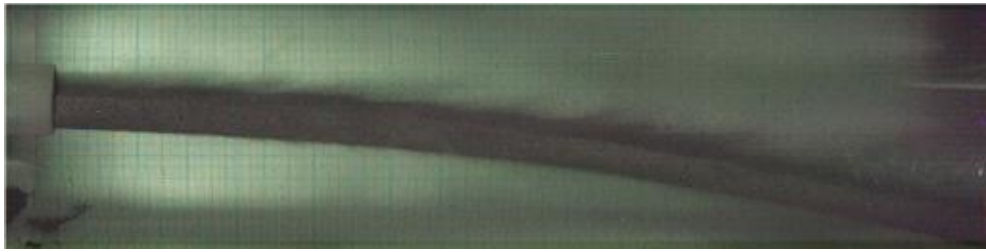
<u>- Double skin Be should withstand both heat and pressure loads</u>

And finally: a flowing powder target for the highest beam powers?



Test rig at RAL

Still image from video clip of tungsten power ejected from 1.2 m long x 2 cm diameter pipe



On-line 'Powder thimble' experiment on HiRadMat planned for this autumn

Conclusions: ‘Divide and Rule’ for higher powers

Dividing material is favoured since:

- Better heat transfer
- Lower static thermal stresses
- Lower dynamic stresses from intense beam pulses

Helium cooling is favoured (cf water) since:

- No ‘water hammer’ or cavitation effects from pulsed beams
- Lower coolant activation, no radiolysis
- Negligible pion absorption – coolant can be within beam footprint

Static, low-Z target concepts proposed for 4 x 1 MW for SPL SB @CERN and 2 MW for LBNE @FNAL