High Power Targets

Megawatt target studies for Neutrino Super-Beams

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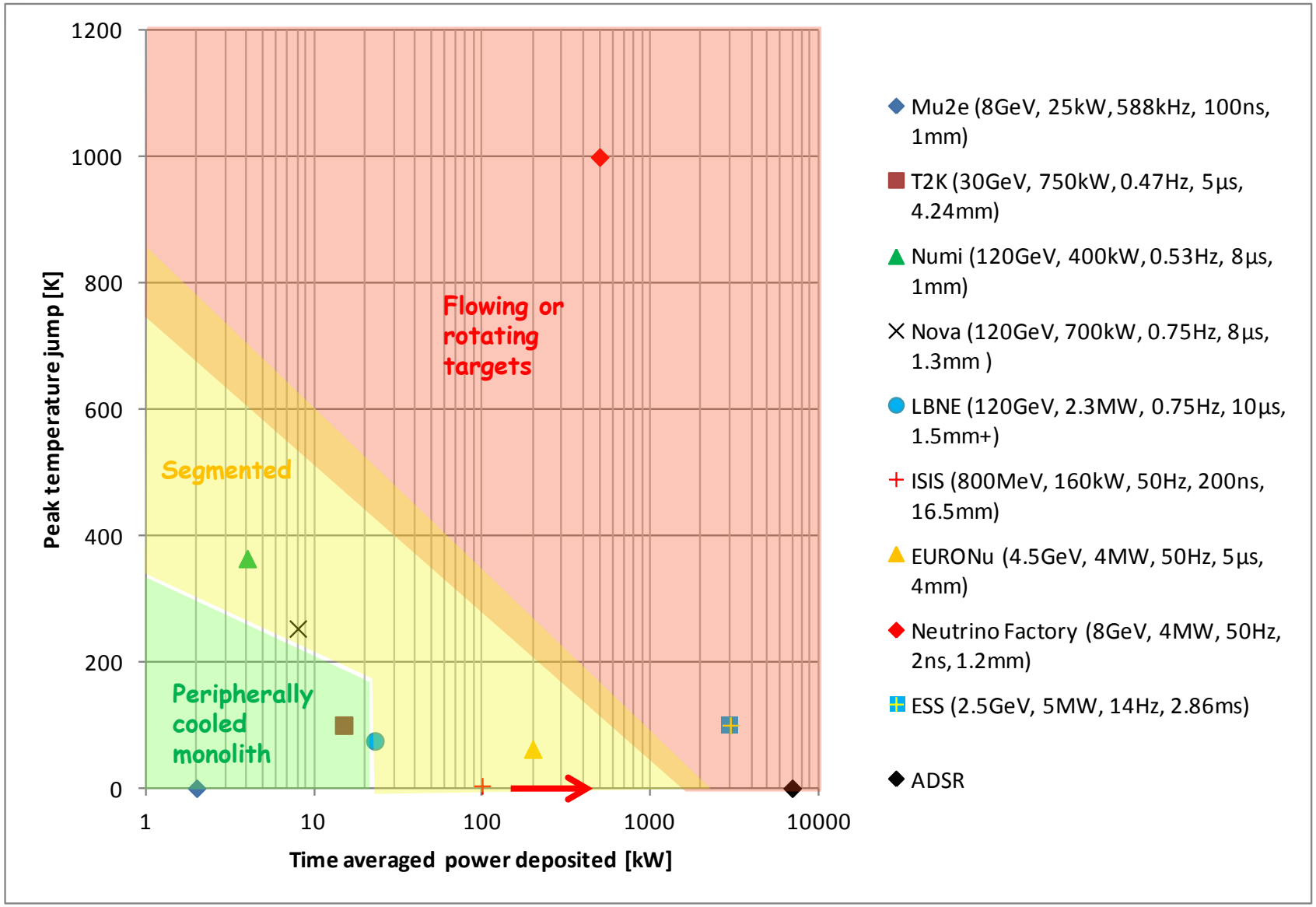
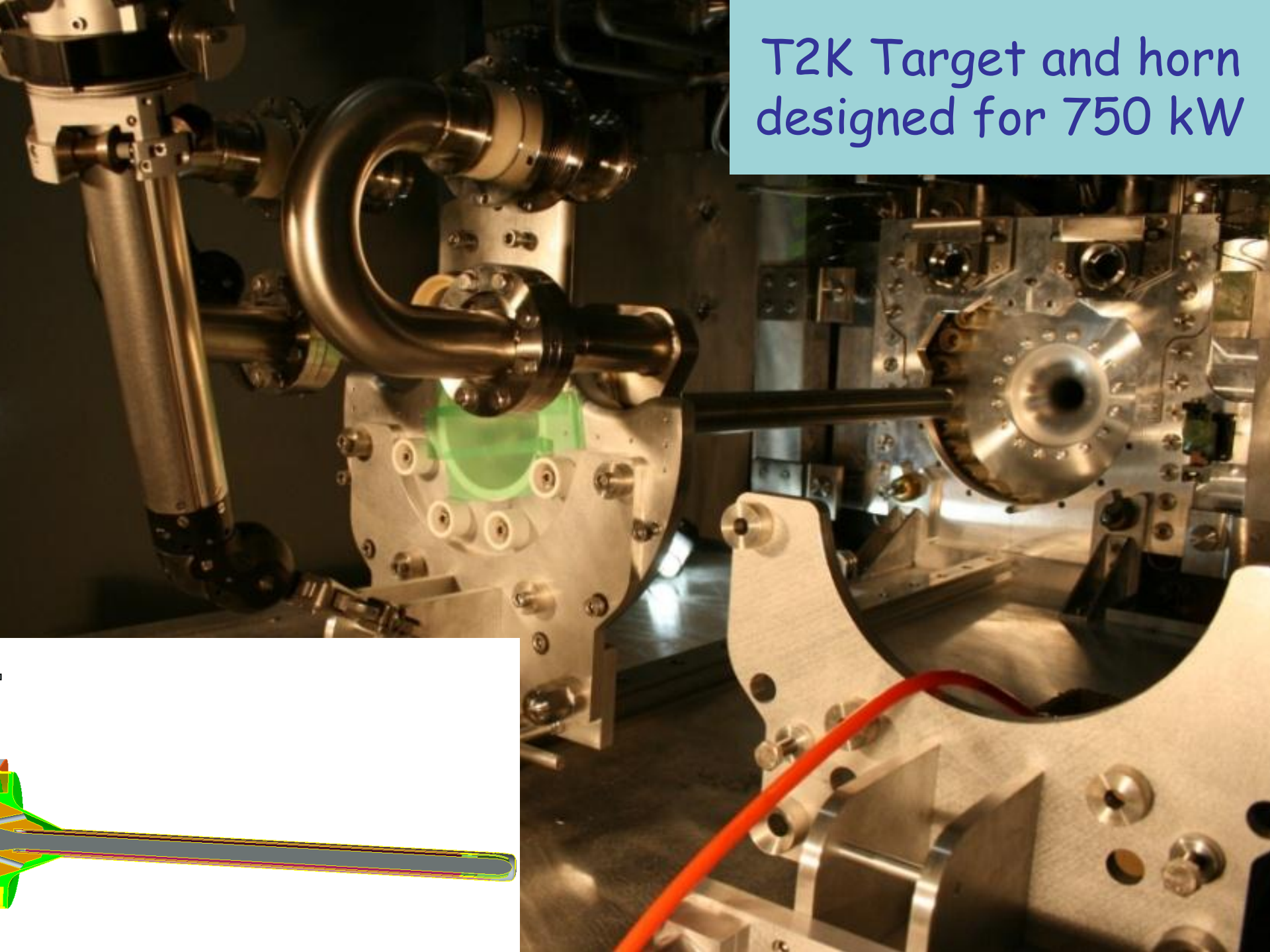
Contents

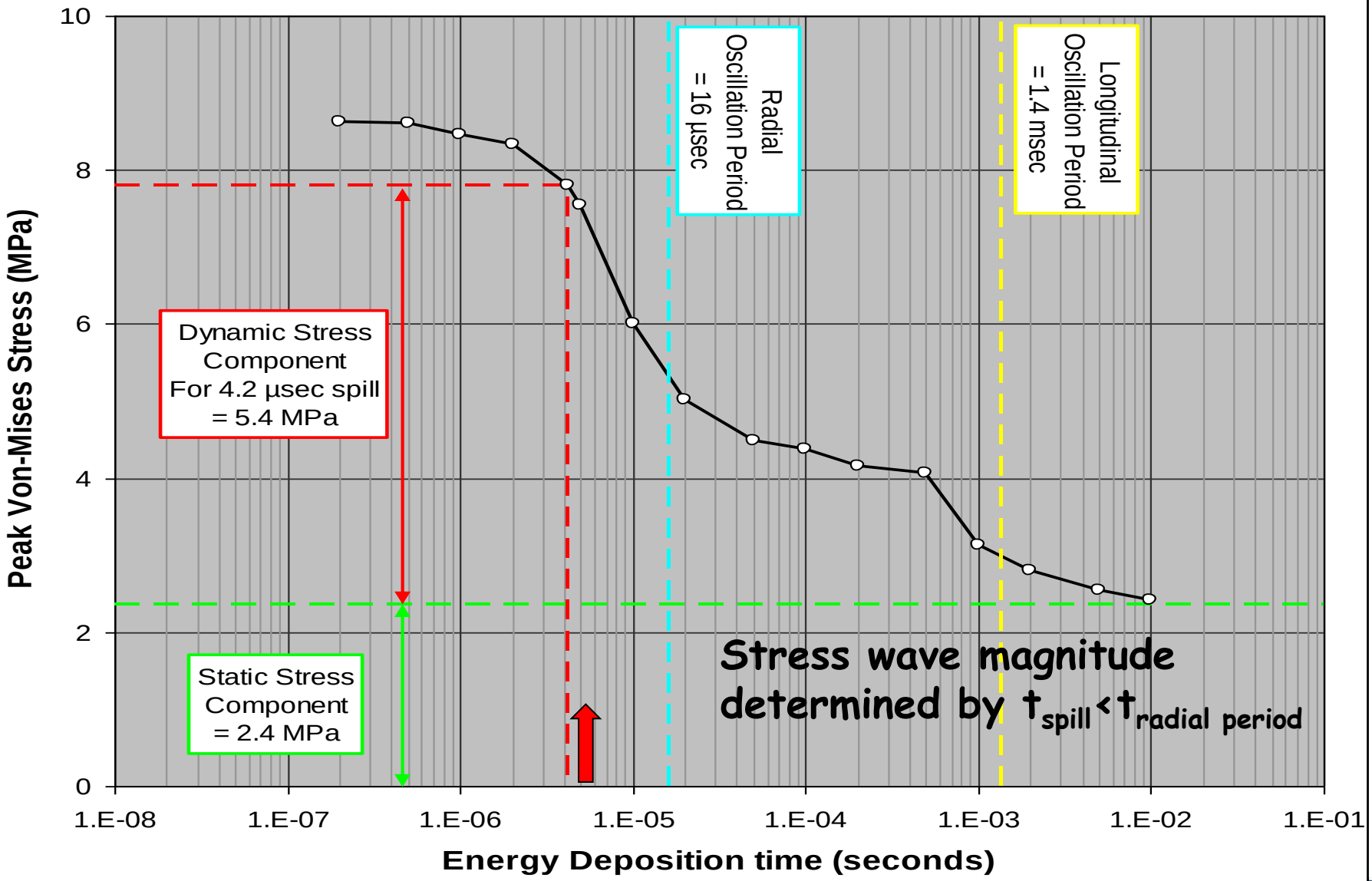
- LBNE 2.3 MW Super Beam design study results
- SPL Super Beam design study for EUROnu
- General principles mixed in throughout

Beam and target pulsed and total powers

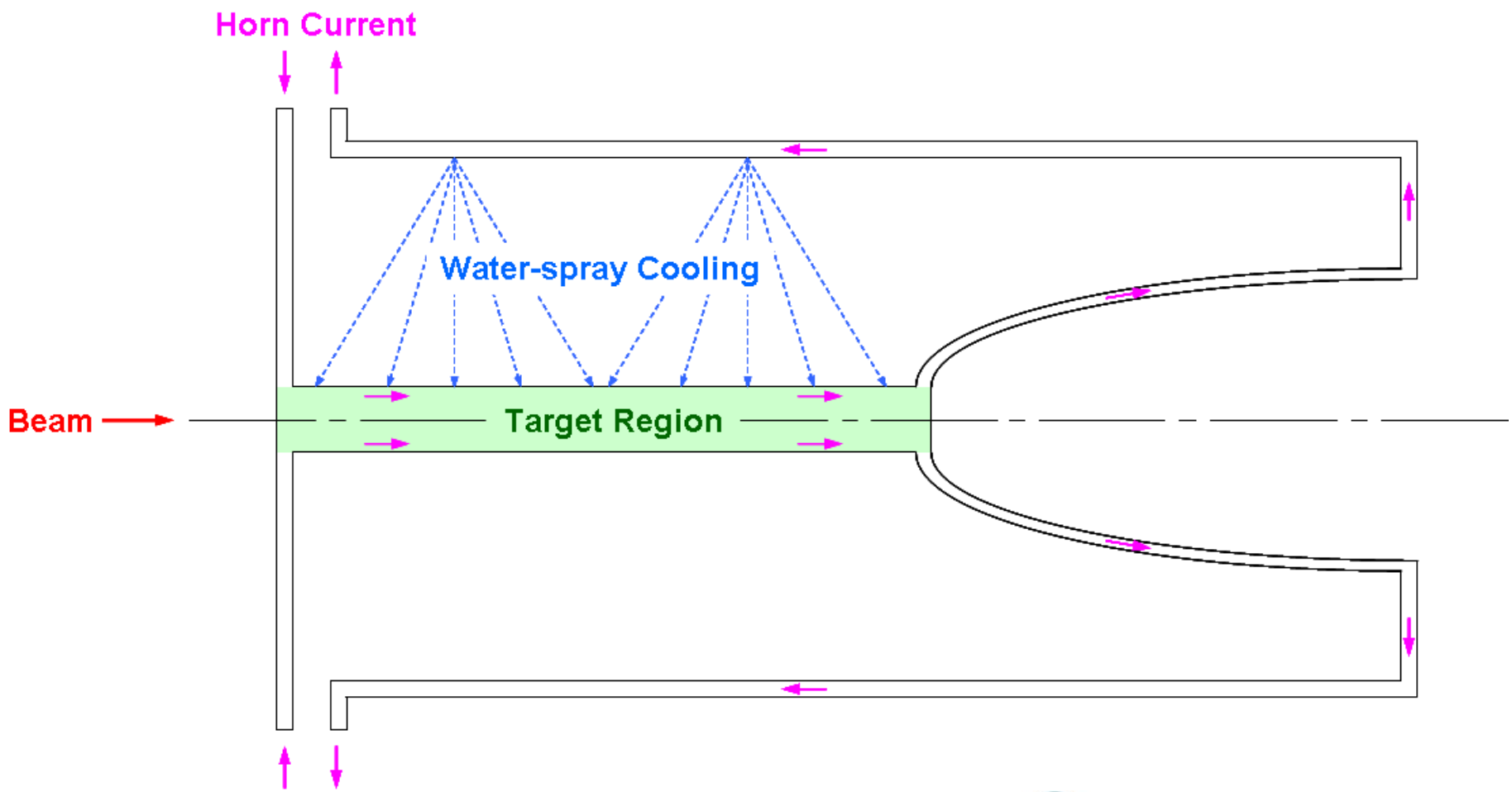


T2K Target and horn designed for 750 kW



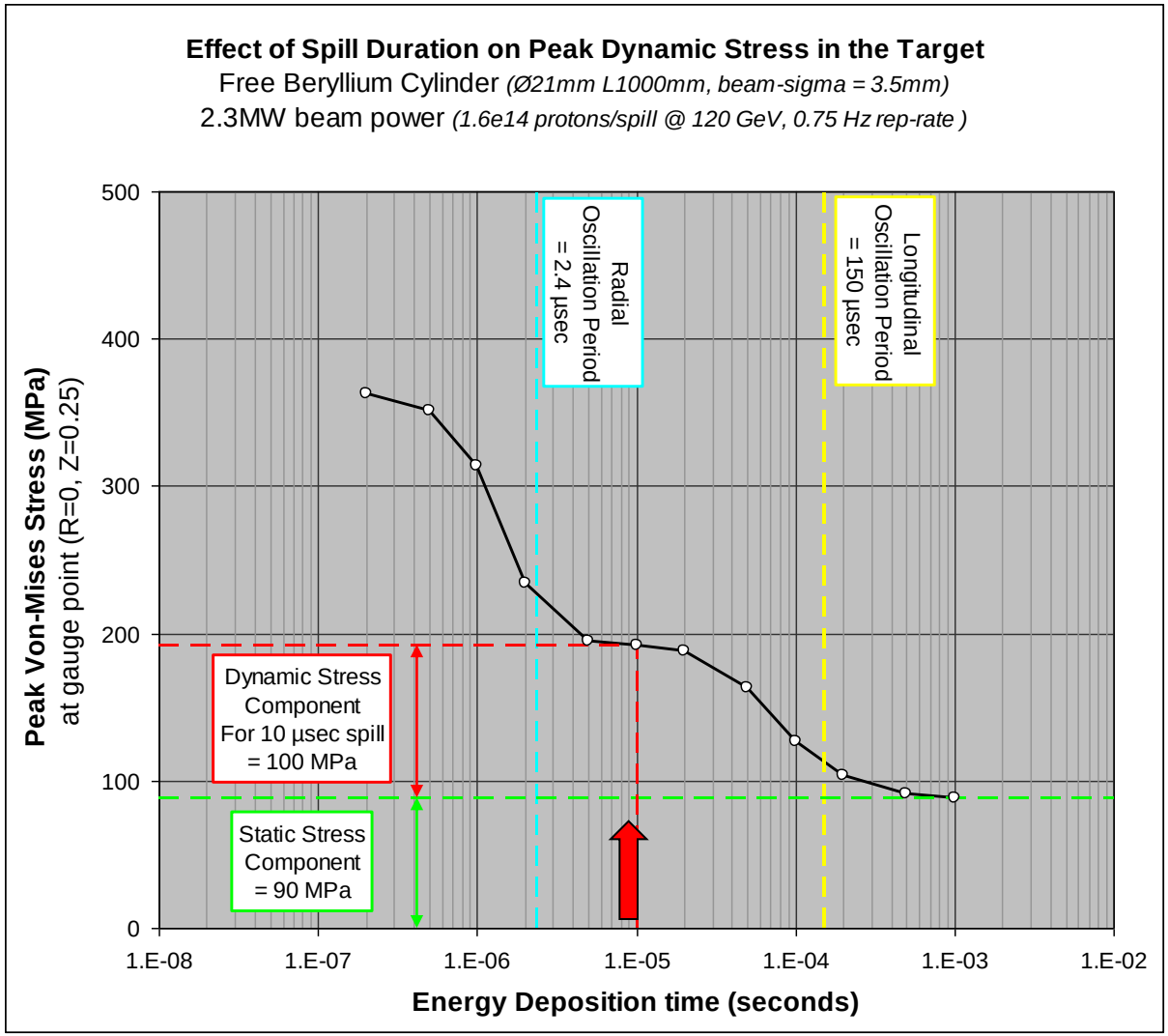

Effect of Spill Duration on Peak Dynamic Stress in the T2K Target
Cantelevered Graphite Cylinder (Ø26mm L900mm, beam-sigma = 4.24mm)
0.75MW beam power (3.3e14 protons/spill @ 30 GeV, 0.4735Hz rep-rate)
Material Properties @ 400°C
Peak Von-Mises Stress (MPa)
10
8
6
4
2
0
1.E-08
1.E-07
1.E-06
1.E-05
1.E-04
1.E-03
1.E-02
1.E-01
Energy Deposition time (seconds)
Radial Oscillation Period = 16 µsec
Longitudinal Oscillation Period = 1.4 msec
Dynamic Stress Component For 4.2 µsec spill = 5.4 MPa
Static Stress Component = 2.4 MPa
Stress wave magnitude determined by $t_{spill} < t_{radial\ period}$

LBNE study: Combined target and horn inner conductor (a la K2K)



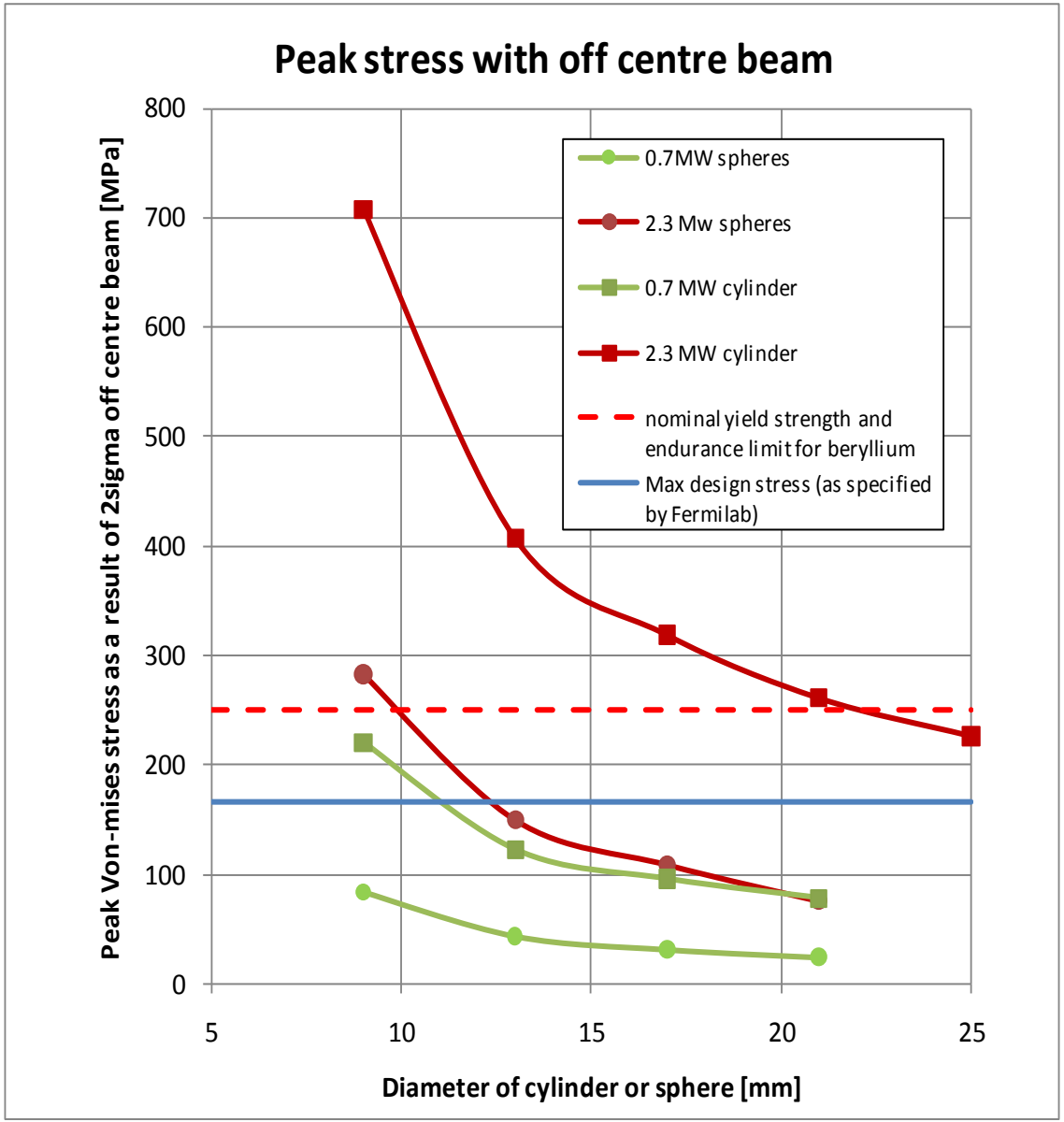
LBNE study: Stress-Waves in Be rod

- "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

Effects of accidental 2σ off-centre beam on 'violin mode' stress waves in simply supported target rod



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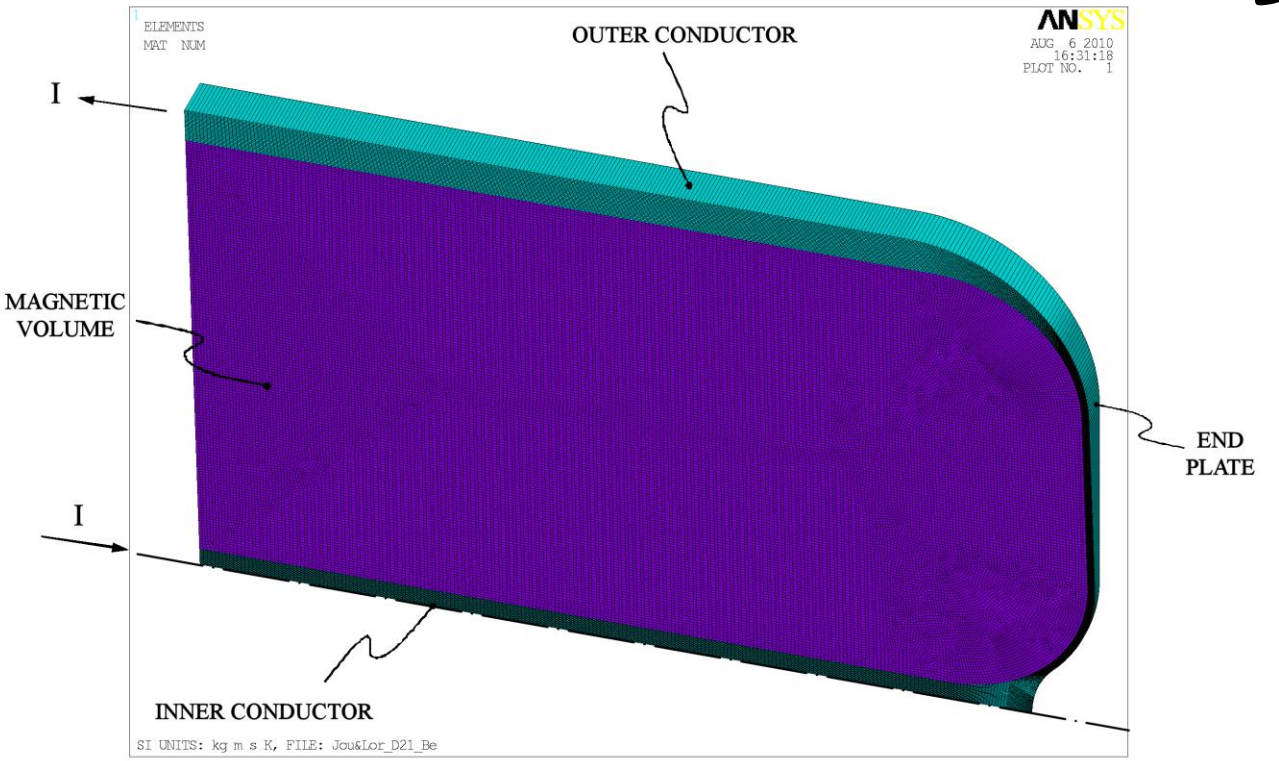
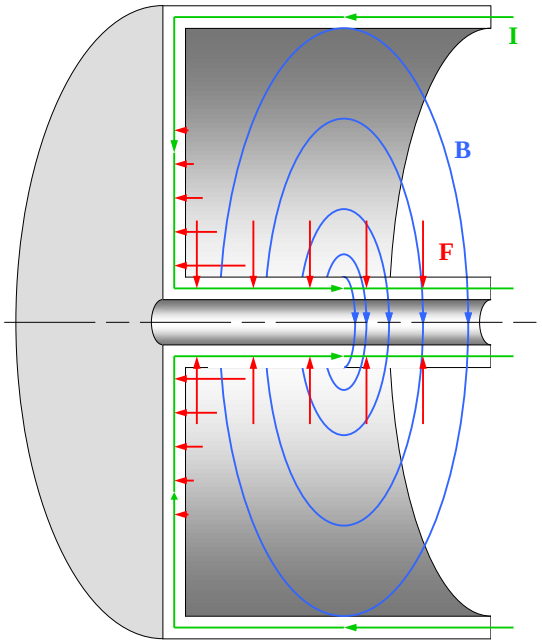
Lorentz forces on horn inner conductor



Longitudinal force in inner conductor

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



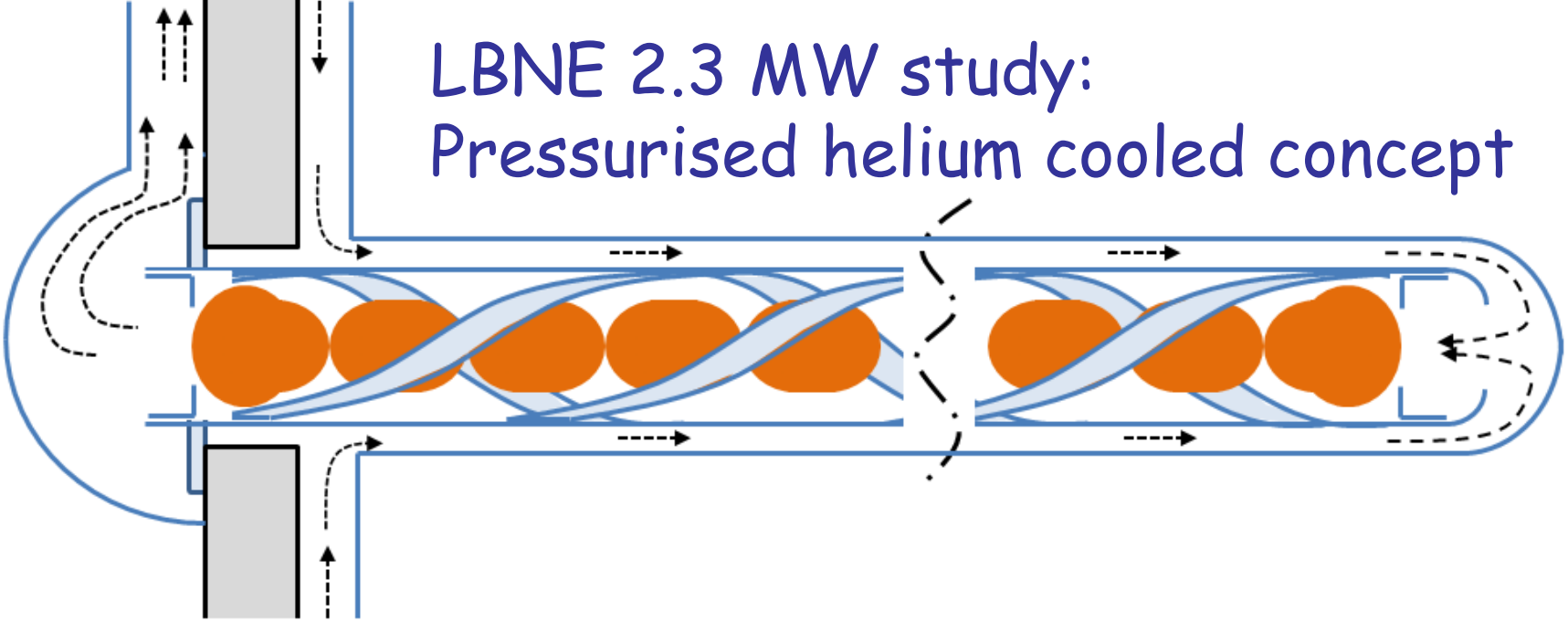
As target/inner conductor size decreases:

- Longitudinal force increases
- Cross sectional area decreases
- 'Double whammy' effect on stress

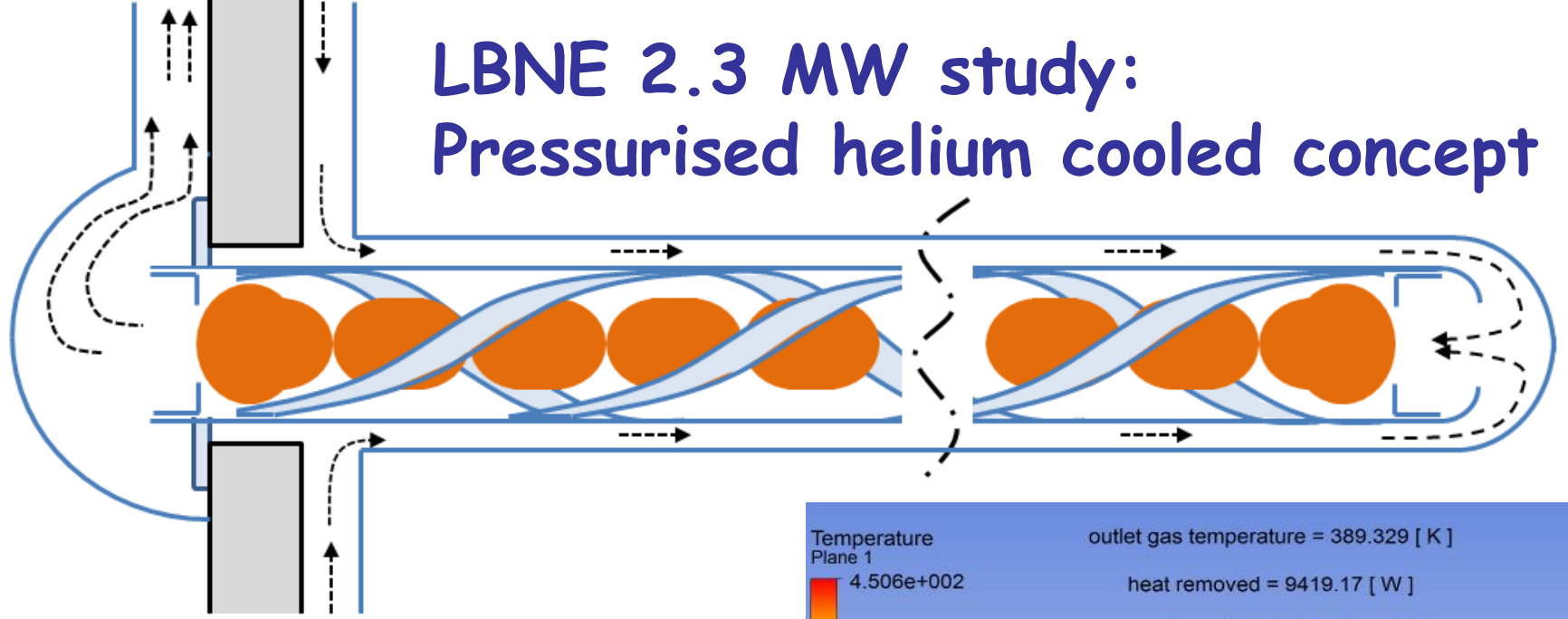
Conclusions on combined target/horn IC

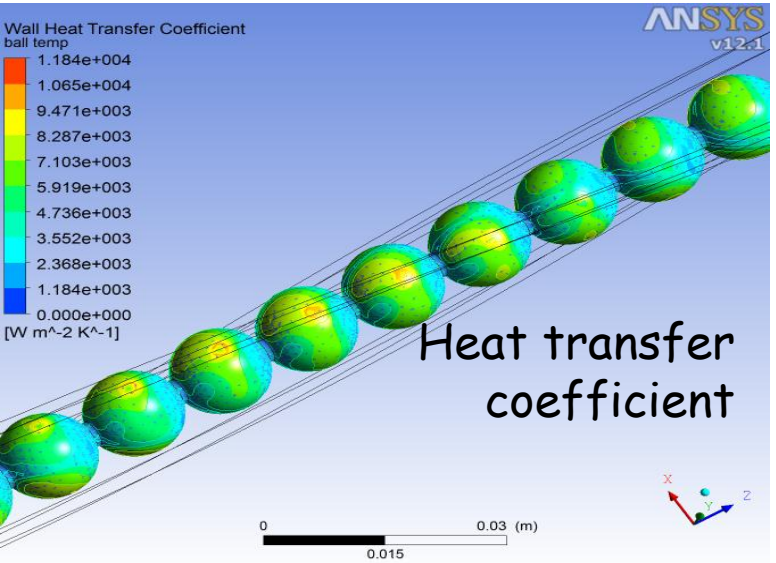
- Very simple design concept
- But complex, combined horn current pulse and beam pulse effects
- Need to reduce longitudinal Lorentz stresses requires target diameter to be larger than desired for optimum pion yield
- Effects of off-centre beam 'violin modes' problematic, in combination with longitudinal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

LBNE 2.3 MW study: Pressurised helium cooled concept

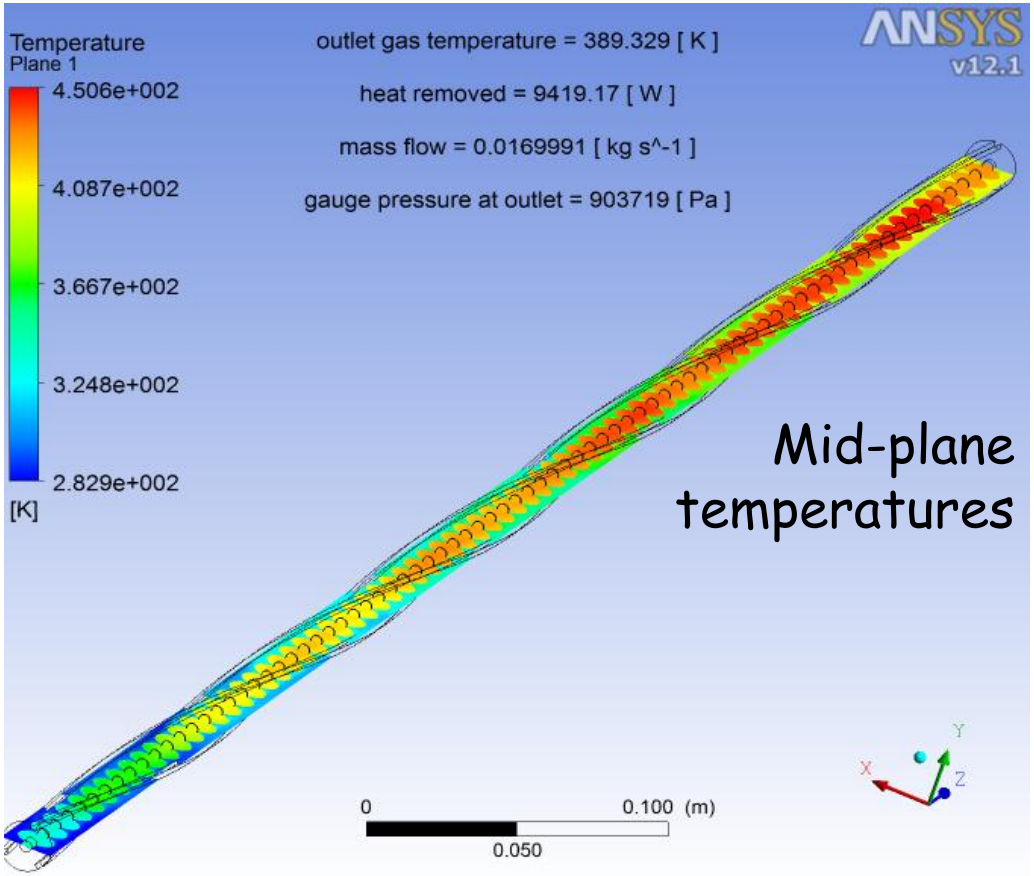


LBNE 2.3 MW study: Pressurised helium cooled concept





Heat transfer coefficient



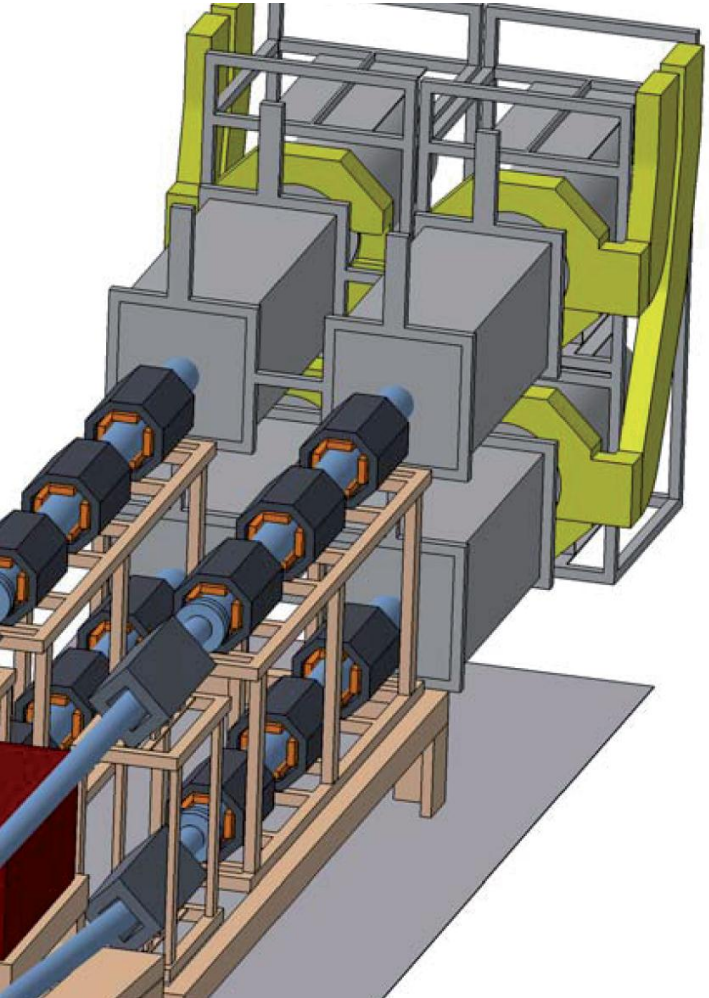
Mid-plane temperatures

Otto Caretta & Tristan Davenne

LBNE 2.3 MW study: Pressurised helium cooled concept

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

EURONu Super Beam study using HP SPL -> Frejus



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

⇒ 4 x 12.5 Hz operation using beam splitter

Beam parameters used:

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

Why consider a packed bed target?

- Small target segments result in low thermal stress and also low inertial stress (stress waves and excited natural frequencies)
- Not sensitive to off centre beam
- Structural integrity not dependant on target material
- High surface to volume ratio throughout target enables significant heat removal while maintaining reasonable target temperature, (particularly suited to 'low' energy beam and high energy density)

Points to note

- Lends itself to gas cooling
- High power designs require pressurised gas
- Bulk density lower than material density (approx factor of 2) may result in a reduction in yield compared to a solid target made of the same material.
- Suitable alternative materials with higher density may be preferred
- Outstanding question over wear due to relative motion of segments with a pulsed beam

Some relevant papers:

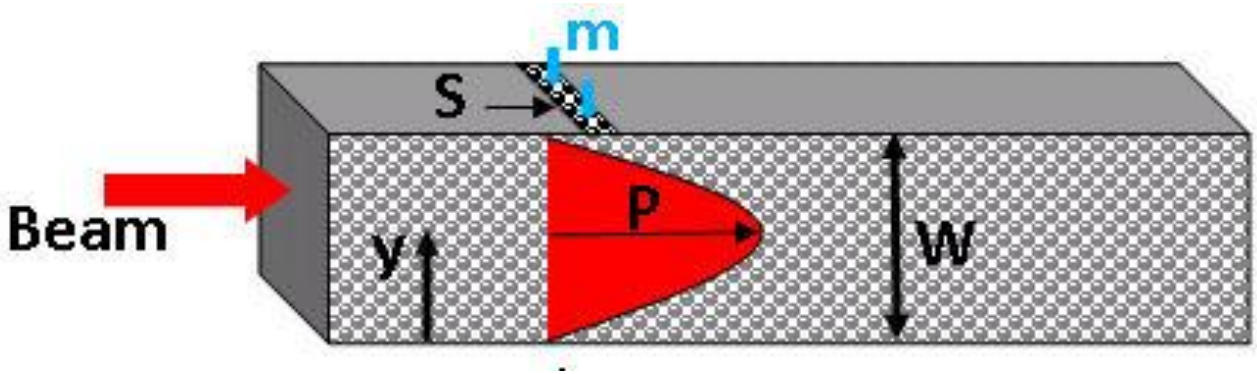
- A helium gas cooled stationary granular target (Pugnat & Sievers) 2002
- Conceptual Designs for a Spallation Neutron Target Constructed of a Helium-Cooled, Packed Bed of Tungsten Particles (Ammerman et al.)
- The "Sphere Dump" – A new low-cost high-power beam dump concept (Walz & Lucas) 1969

Where does a Packed Bed Target fit?

Beam Power →	≈1MW	4MW+?	?
Solid Peripherally cooled Target	Packed Bed or segmented Target	Flowing Target - powder jet, mercury jet	
Simple, well proven	A bit more complex, less experience	Much harder, very complex	

Limiting factors		
Heat Transfer Area Thermal and Inertial Stress Off axis beam	Helium Pressure Radiation damage Window components	Reliability Complexity Development Time

Simple packed bed target model

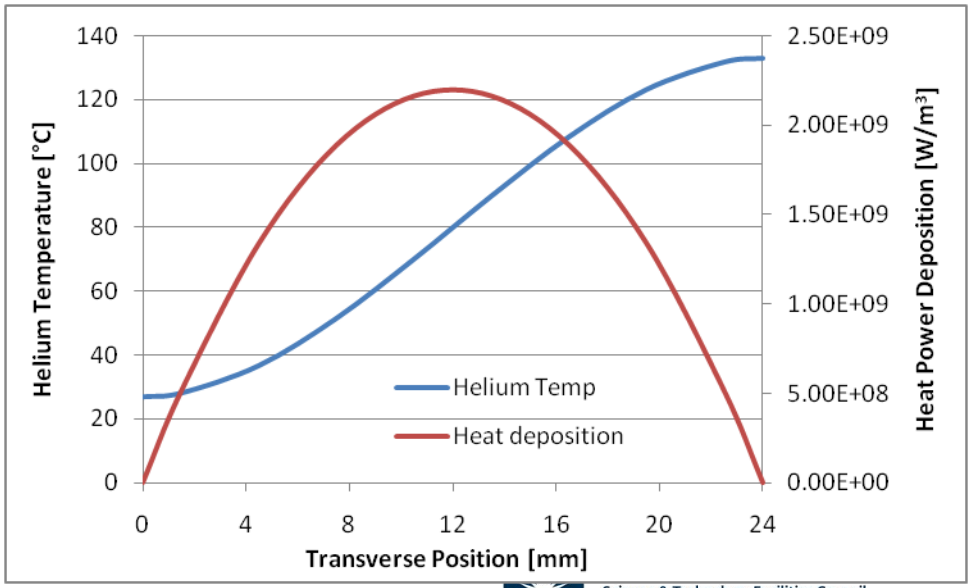


Assume parabolic energy deposition profile

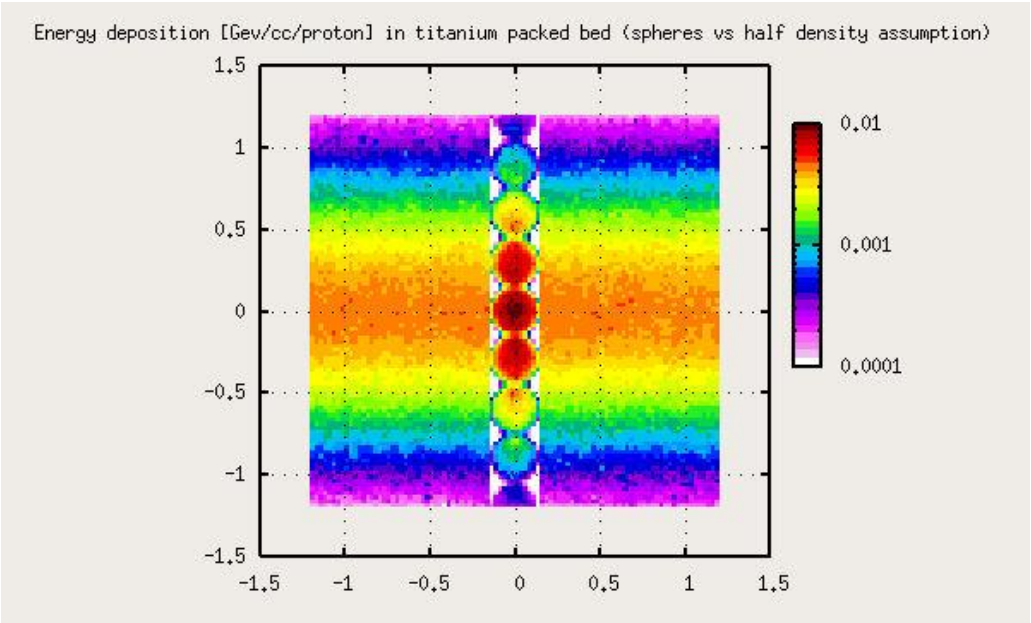
$$Q = 4P\left(\frac{y}{W} - \frac{y^2}{W^2}\right)$$

Obtain gas temperature as a function of transverse position

$$T_g(y) = \int_0^y \frac{SQ}{mCp}\,dy = \frac{4SP}{mCp}\left(\frac{y^2}{2W} - \frac{y^3}{3W^2}\right)$$

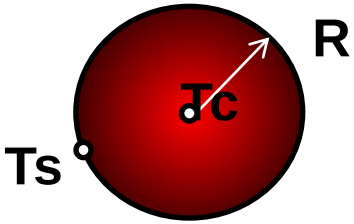


Energy Deposition calculated from FLUKA for 1 MW 4.5 GeV beam



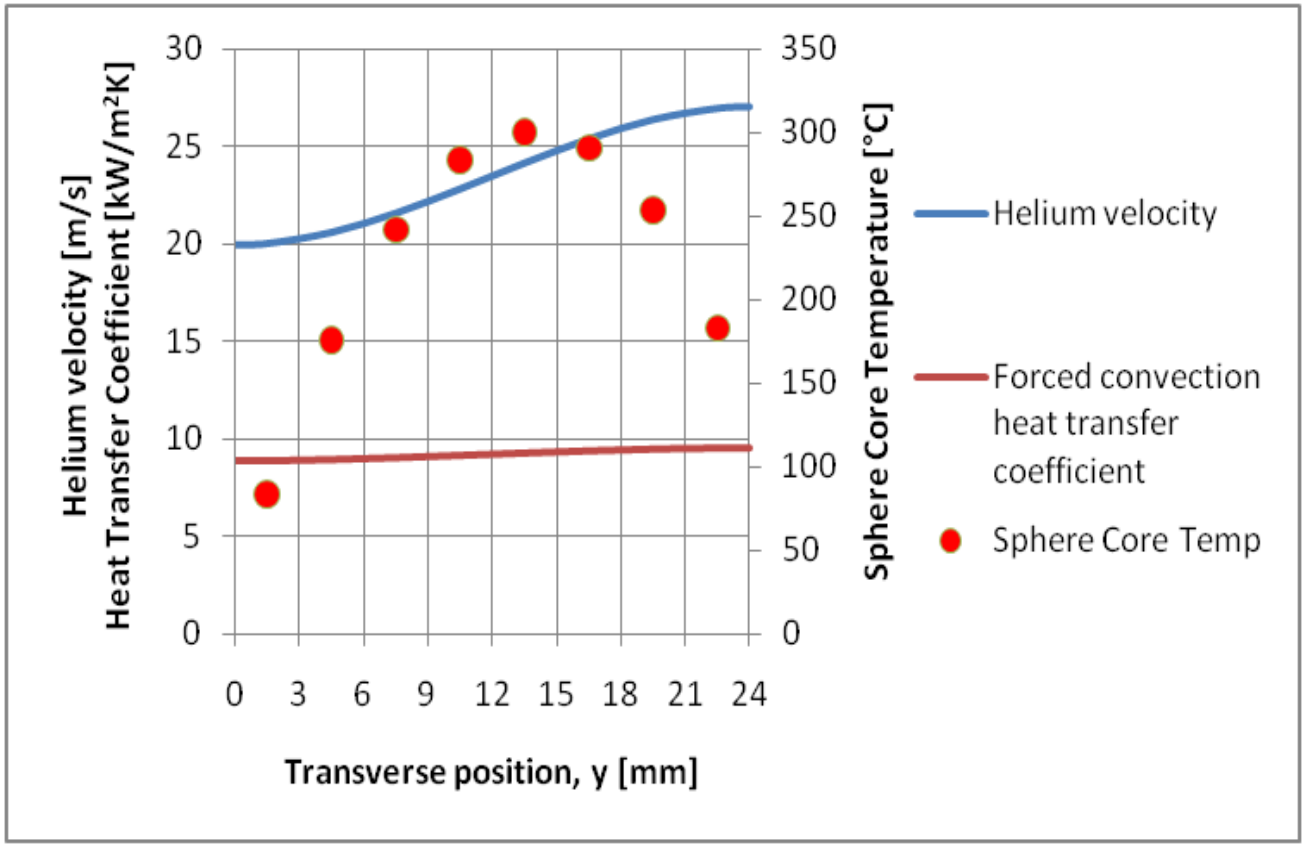
FLUKA compound model used to determine energy deposited in target material

Temperature profile a function of energy deposition, Q, radius and thermal conductivity, k



$$T_c = T_s + \frac{2Q(y)R^2}{6k}$$

Sphere Temperature for 3mm Ti6Al4V spheres

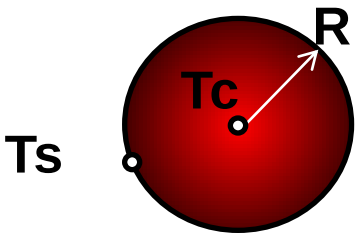


Empirical Nusselt number correlation for heat transfer in packed bed (Achenbach et al.)

$$Nu = \frac{hd}{k_g} = \left[(1.18Re^{0.58})^4 + (0.23Re^{0.75})^4\right]^{0.25}$$

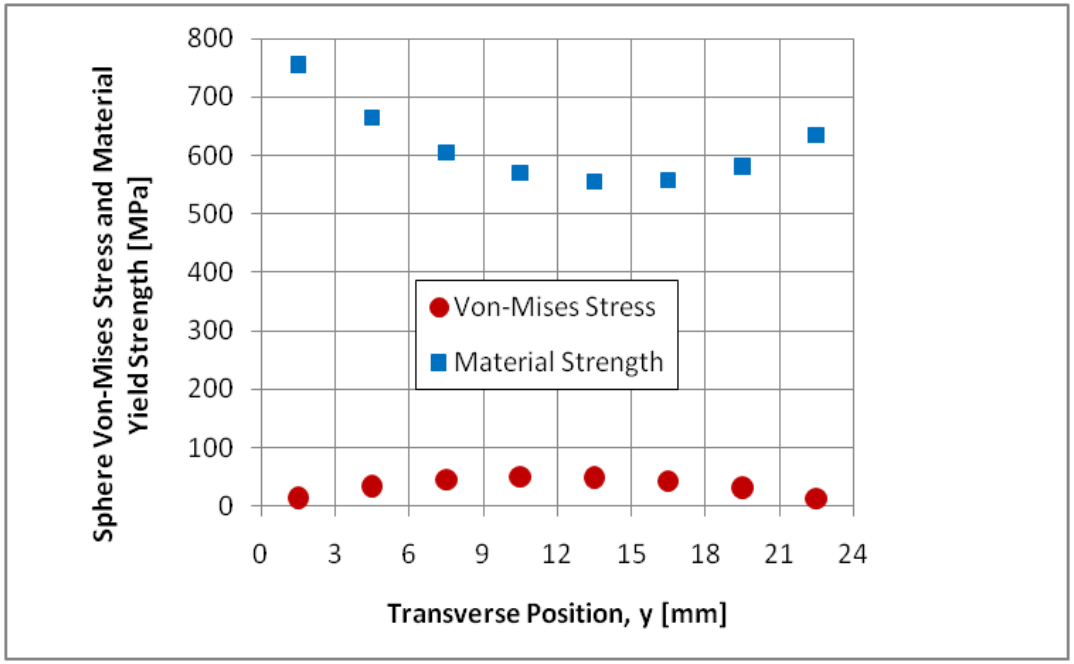
Sphere core temperature is seen to depend on gas temperature and energy deposition, variation in thermal conductivity with temperature is also accounted for.

Sphere Stress: Steady state thermal component



$$\sigma_{VMmax} = \frac{2E\alpha QR^2}{15k(1-\nu)}$$

Low temperature gradient
-> Low stress



NB Long pulse (600 μs)
+ Small particle size
-> low inertial stress

Results Summary for EUROnu

24mm wide cannister packed with 3mm diameter Ti6Al4V spheres.

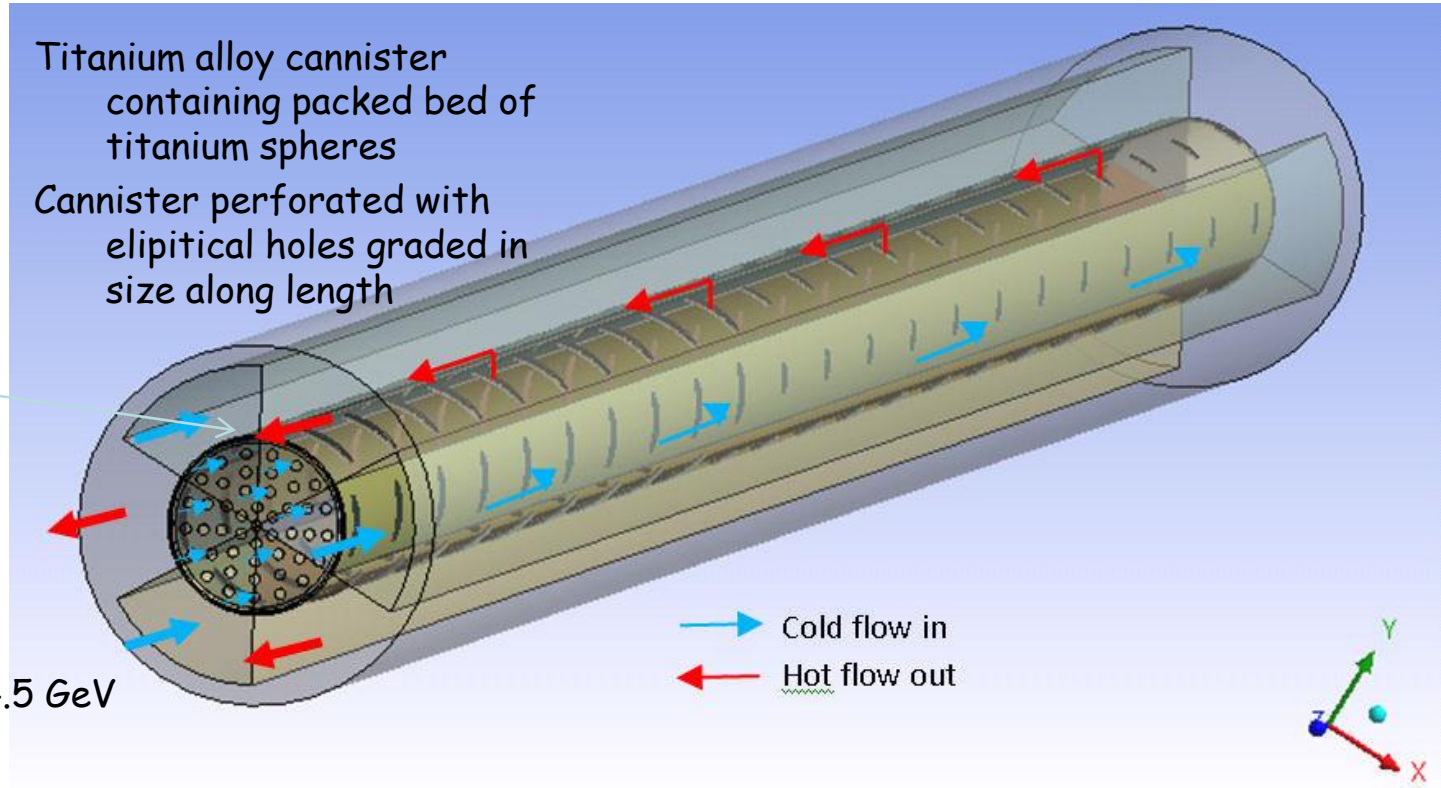
INPUTS									LIMITING FACTORS				
Beam Energy	Beam Sigma	Beam Power	Maximum Power Deposition	Target Width	Sphere diameter	Sphere Material	Helium Pressure	Flow rate per unit surface	Maximum Helium Temperature	Sphere Core Temperature	Max Sphere VM stress	yield stress/ max VM stress	Pressure Drop
4.5GeV	4mm	1MW	2.2e9W/m3	24mm	3mm	Ti6Al4V	10bar	50 kg/s per m^2	133°C	296°C	49MPa	11.7	0.45bar
4.5GeV	4mm	1.33MW	2.9e9W/m3	24mm	3mm	Ti6Al4V	10bar	66 kg/s per m2	133°C	331°C	65MPa	8.7	0.73bar
4.5GeV	4mm	4MW	8.8e9W/m3	24mm	3mm	Ti6Al4V	10bar	133 kg/s per m2	200°C	650°C	116MPa	3.8	2.8bar
4.5GeV	4mm	4MW	8.8e9W/m3	24mm	3mm	Ti6Al4V	20bar	200 kg/s per m2	133°C	557°C	140MPa	3.2	3.4bar
4.5GeV	4mm	4MW	8.8e9W/m3	24mm	3mm	Ti6Al4V	20bar	133 kg/s per m2	200°C	650°C	116MPa	3.8	1.4bar

1.3MW looks reasonable

4MW more challenging but does not look impossible

How to achieve symmetrical transverse flow?

Packed Bed Target Concept



Model Parameters

Proton Beam Energy = 4.5 GeV

Beam Power = 1 MW

Beam sigma = 4 mm

Packed Bed radius = 12 mm

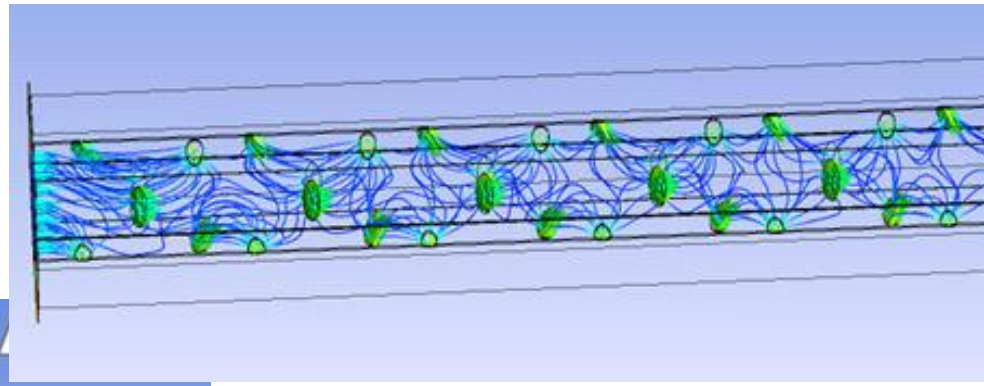
Packed Bed Length = 780 mm

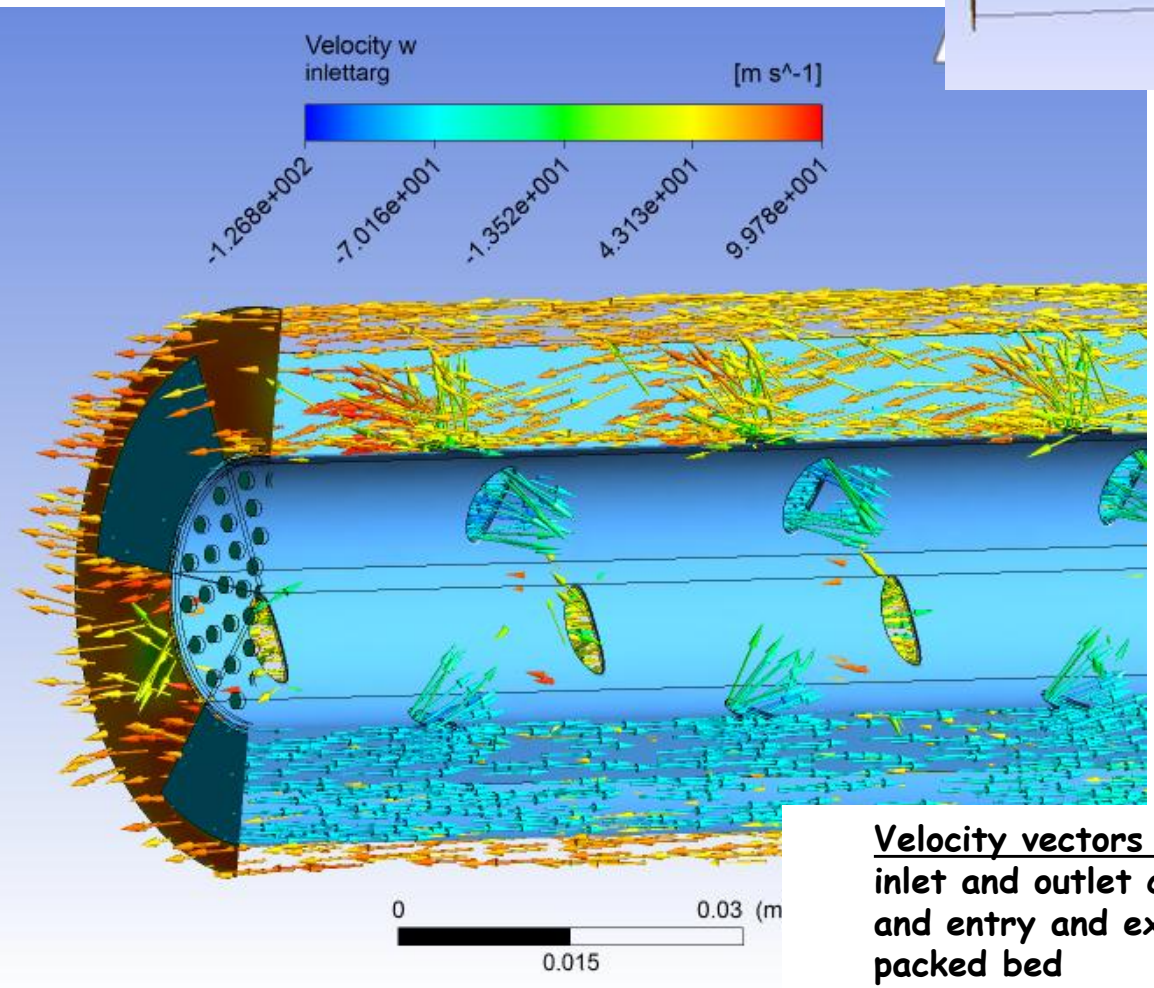
Packed Bed sphere diameter = 3 mm

Packed Bed sphere material : Titanium

Coolant = Helium at 10 bar pressure

Packed Bed Model (FLUKA + CFX v13)



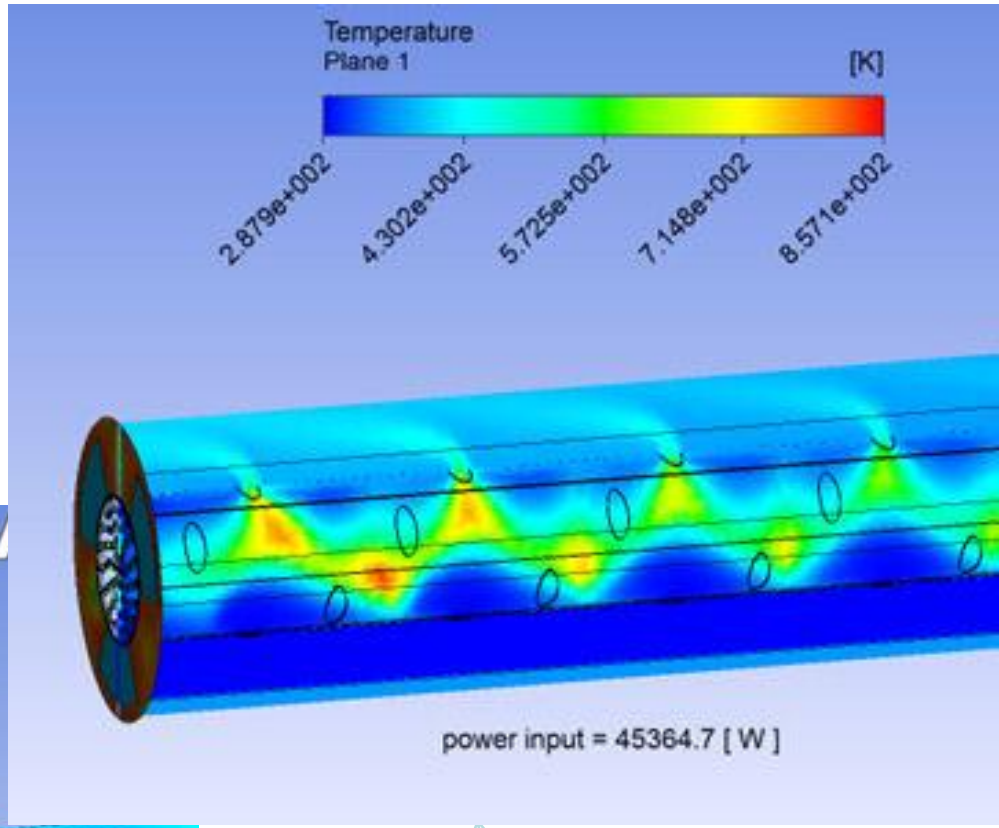


Streamlines in packed bed

- 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

Velocity vectors showing inlet and outlet channels and entry and exit from packed bed

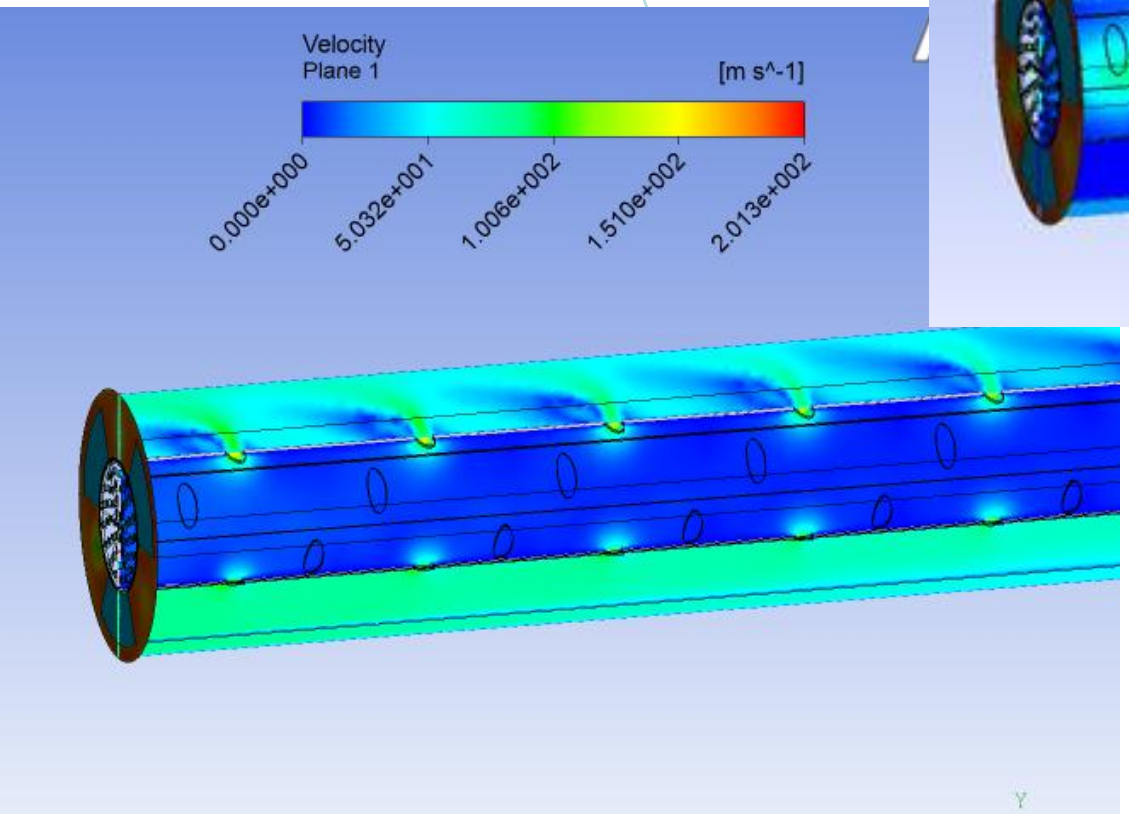
Helium Flow



Helium Velocity

Maximum flow velocity = 202m/s

Maximum Mach Number < 0.2



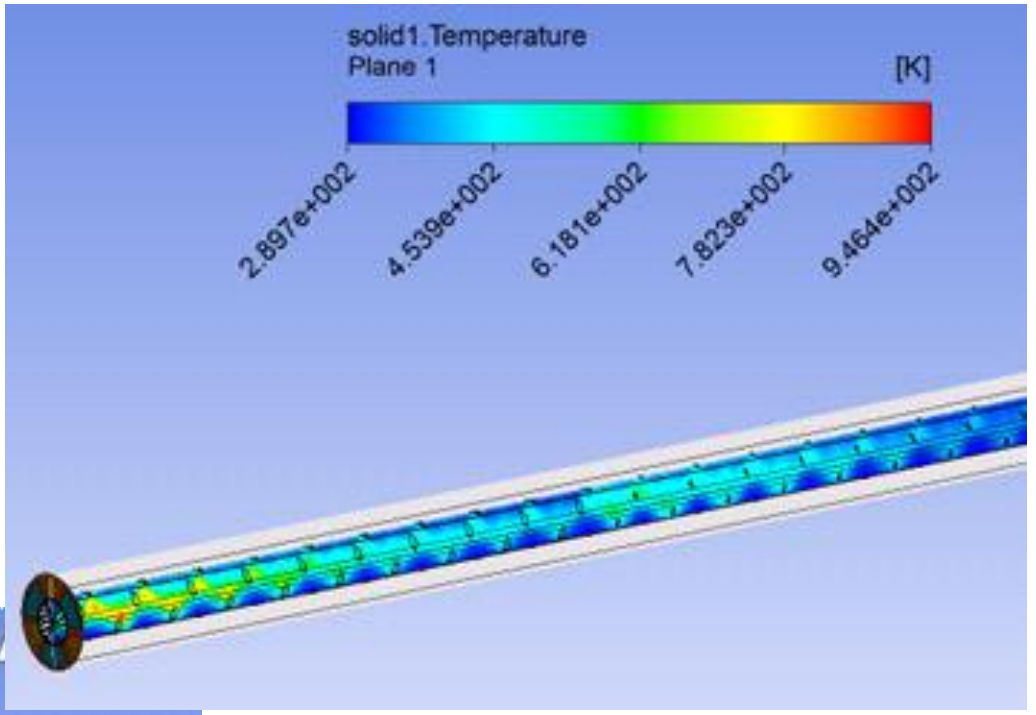
Helium Gas Temperature

Total helium mass flow = 93 grams/s

Maximum Helium temperature = 857K = 584°C

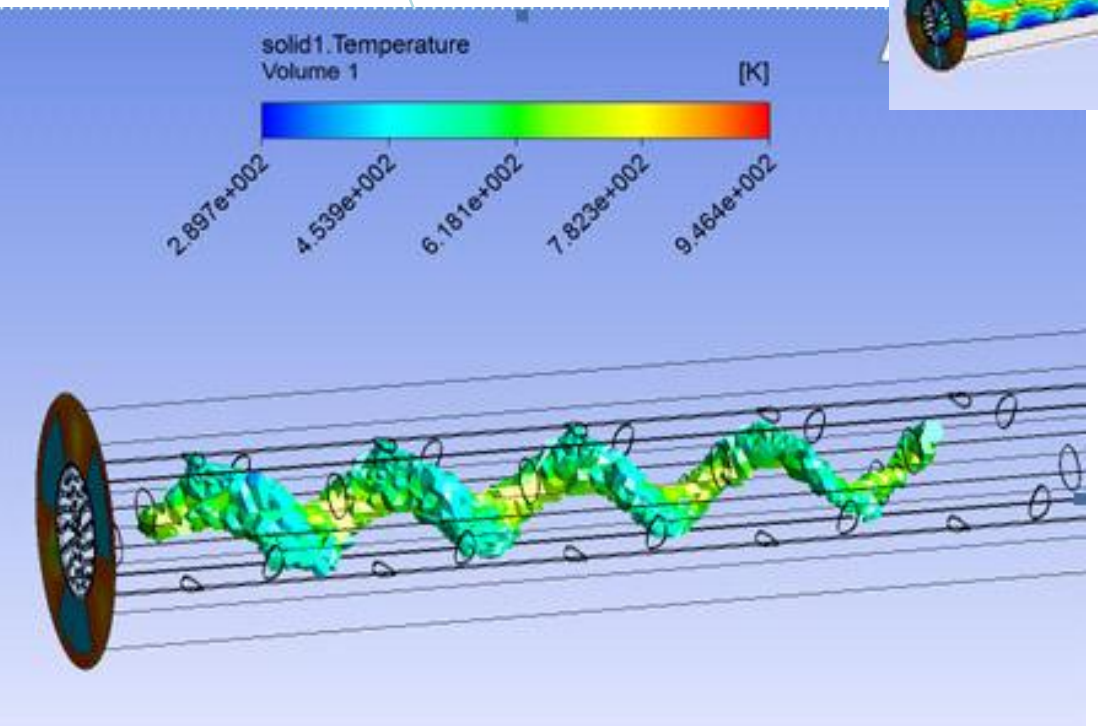
Helium average outlet Temperature = 109°C

Titanium spheres



<u>High Temperature region</u>

Highest temperature Spheres occur near outlet holes due to the gas leaving the cannister being at its hottest



<u>Titanium temperature contours</u>

Maximum titanium temperature = 946K =673°C (N.B. Melting temp =1668°C)

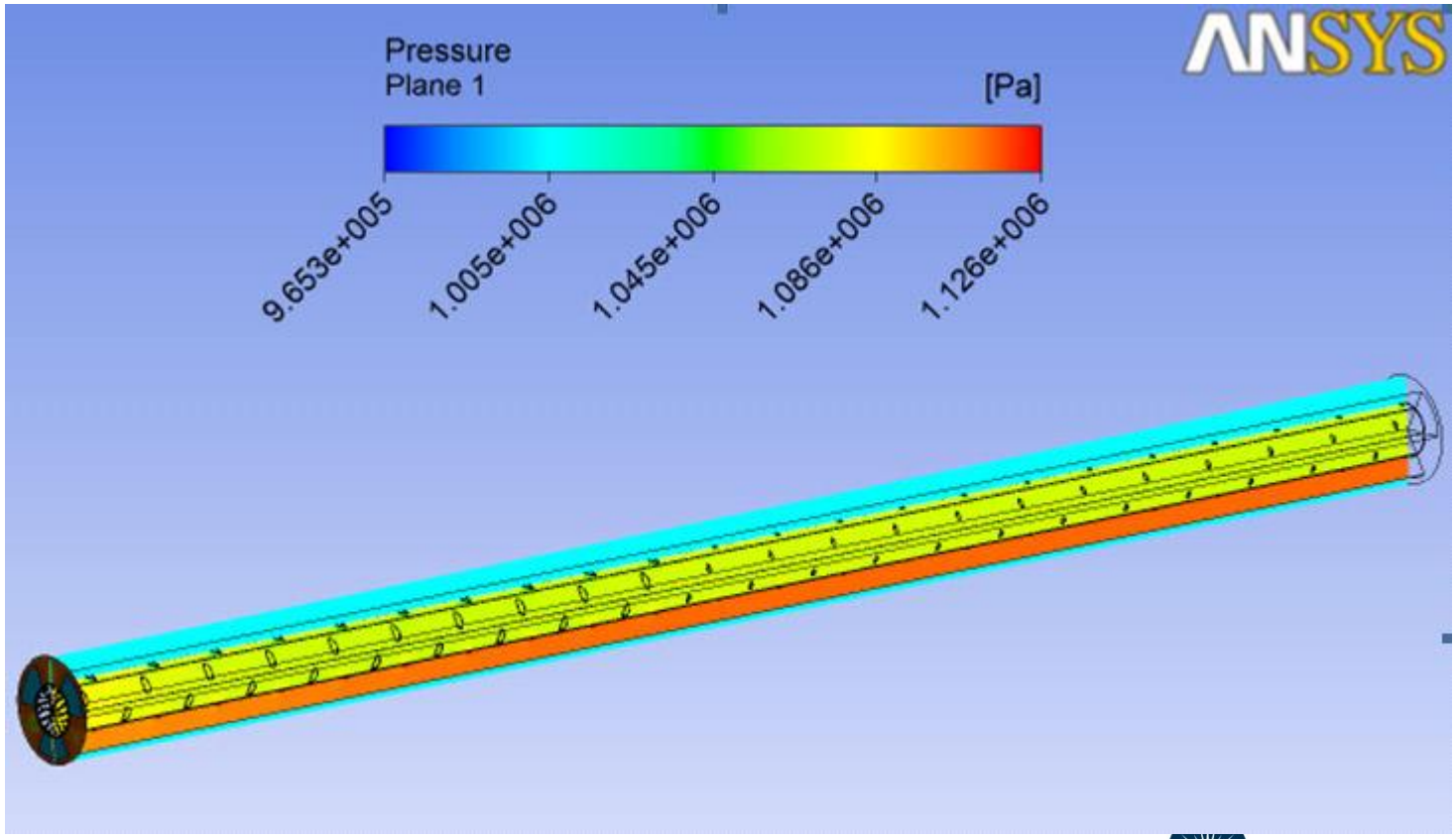
Pressure Drop

<u>Pressure contours on a section midway through target</u>

Helium outlet pressure = 10bar

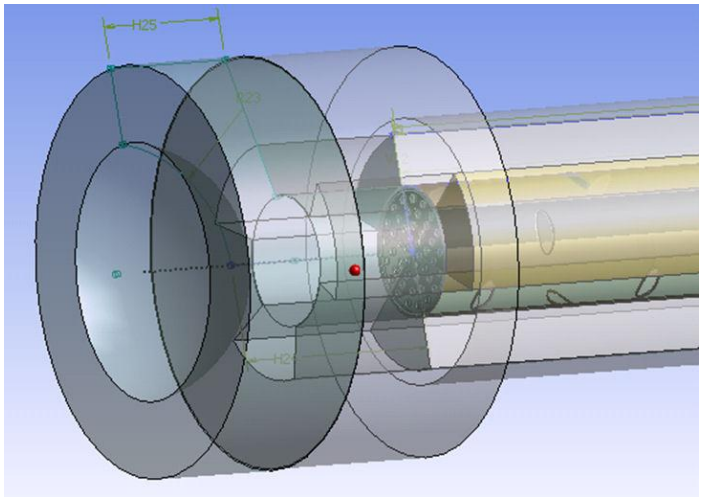
Helium inlet pressure = 11.2bar

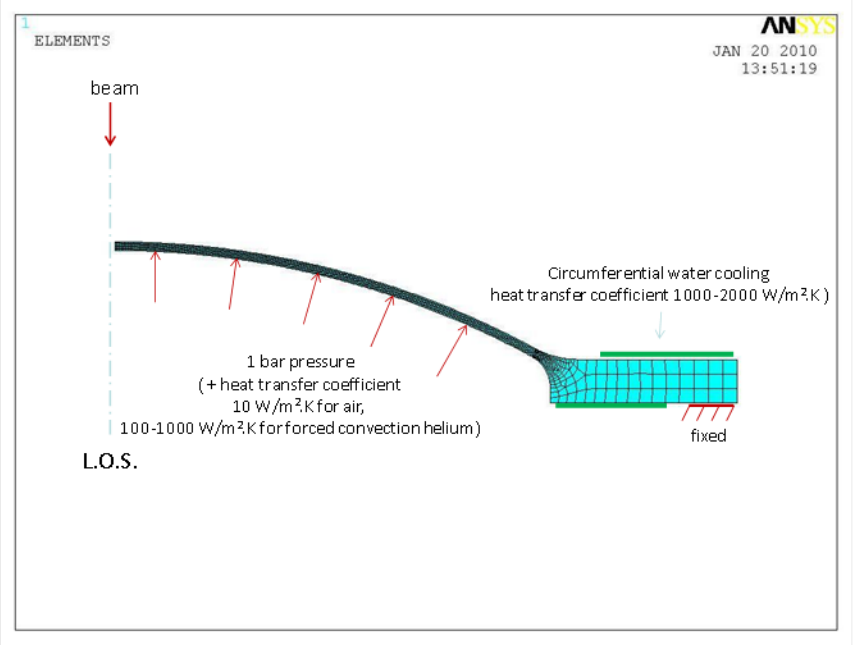
Majority of pressure drop across holes and not across packed bed



Target Beam Window

- Beam enters the target cannister through a beam window which separates target coolant from target station helium
- Beryllium is a candidate material for the window
- Peripheral or surface cooling look to be feasible options
- Static and inertial stresses result from beam heating are manageable
- Pressure stresses can be dealt with by having a hemispherical window design





Packed Bed Testing

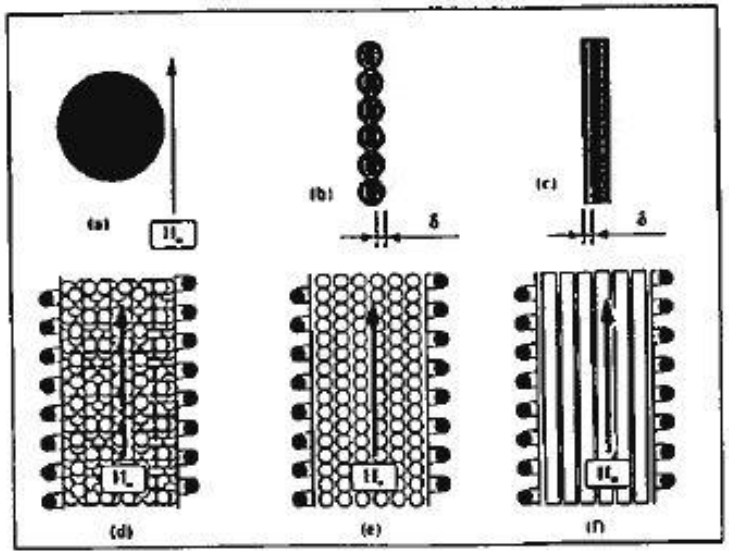


Figure 3 — (a) Path of the eddy currents at the surface of a sphere; (b): sectional view of eddy currents in a well-ordered pile of spheres; (c): sectional view of eddy currents in a cylinder; (d): analogy between a randomly-packed bed; (e): regular piles of particles; (f): a bundle of cylinders.

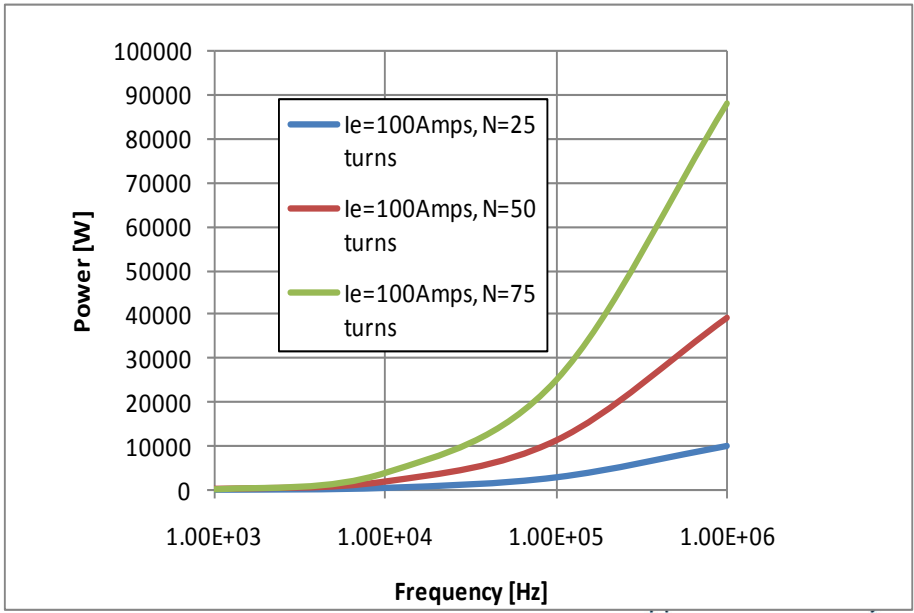
$$R_{eq\,packed\,bed} = 4(1-\epsilon)\left(\pi^2 R^2 N^2 / r_s L\right)\left(\sqrt{10^{-7}\mu_R f/\sigma}\right)F$$

Induction Heating

Packed bed placed in an alternating magnetic field.

Eddy currents induced in conductive spheres.

Resultant Joule heating provides internal heating of spheres.



Packed bed induction heating theory

Duquenne et al.

Conclusions for SPL Super Beam target

- A packed bed target has been adopted as the baseline target design for the EUROnu superbeam. It offers:
  - Inherently low steady state and inertial stress as well as tolerance to off-centre beams.
  - A potential design up to 4MW beam power while the more conventional solid target is limited to less than 1MW beam power.
- A CFD model of a packed bed target concept for 1MW beam power indicates the feasibility of such a target.
- Stress in window components, containment vessel, required operating pressure and radiation damage may be the limiting factors for a packed bed target, however heat dissipation is less of a problem.
- Vibration levels and relative motion and wear between spheres is as yet an unknown and so an in-beam test would be useful.
- Induction heating offers potential for an offline test of the heat transfer and pressure drop characteristics of a packed bed design.

General conclusions: 'Divide and Rule' for greater power

Dividing material generally favoured since:

- Better heat transfer
- Lower static thermal stresses
- Lower dynamic stresses from intense beam pulses (NB benefit depends on target dimensions/beam pulse length)

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

http://www.hep.utexas.edu/VietNus2012/

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Viet Nus 2012 Workshop

Toward CP Violation In Neutrino Oscillations

Qui Nhon, Vietnam Dec 17-22, 2012

Viet Nus 2012
'Beam Challenges' working group topics

- Are there any modifications to existing beams which can be carried out to aid in the delivery of useful information?
- Is there a way to reduce NC background?
- Are there particular neutrino energies which are easier to deliver?
- Is there an advantage to a lower energy WBB?

- Registration is open!

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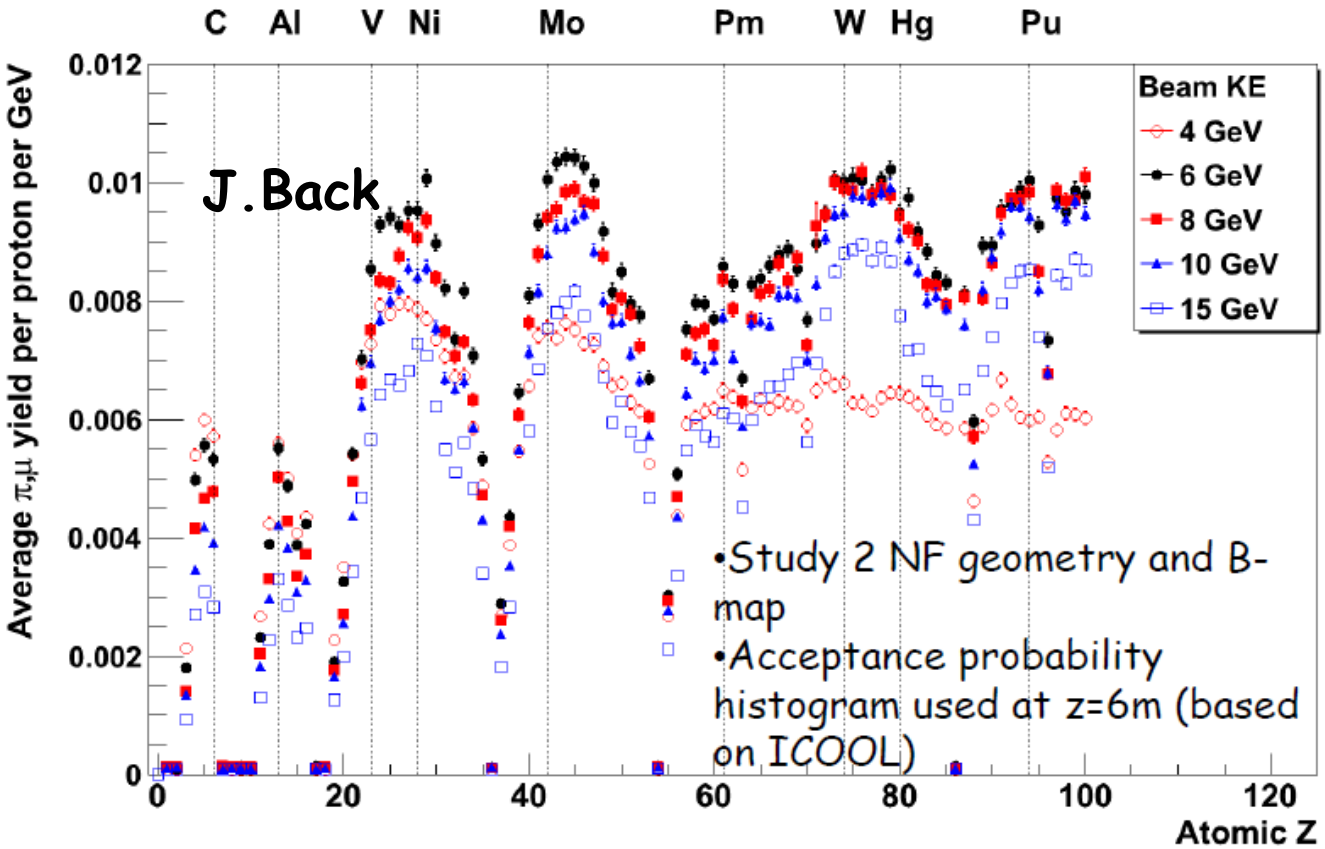
Qui Nhon, Vietnam Dec 17-22, 2012

Packed Bed Target for a neutrino factory?

- A titanium packed bed offers a potential design to dissipate the heat load from a 4MW 4.5GeV proton beam.
- The neutrino factory baseline beam pulse has a challenging 2ns pulse length.
- Some evidence to suggest a low density neutrino factory target would offer comparable physics performance.



Temperature and stress in a uniformly heated sphere

Temperature profile inside a sphere with uniform heat deposition

1D problem (uniform energy deposition and surface temperature)

r= radial position [m]

T_c = core temperature [K]

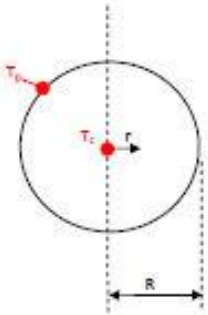
T_0 = surface temperature [K]

Q = heat load per unit volume [W/m^3]

q(r)= heat flux as a function of r [W]

R=radius of sphere [m]

k=thermal conductivity of sphere [W/mK]



$$q(r) = Q\tfrac{4}{3}\pi r^3$$

$$q(r) = -kA\frac{dT}{dr} = -4\pi r^2 k\frac{dT}{dr}$$

$$T = \int -\frac{Qr}{3k}dr \quad \rightarrow \quad T = -\frac{Qr^2}{6k} + C$$

Applying boundary conditions T=To at r=R and T=Tc at r=0 gives

$$T = T_0 + \frac{Q}{6k}(R^2 - r^2)$$ temperature as a function of r

and

$$\Delta T = T_c - T_0 = \frac{QR^2}{6k}$$

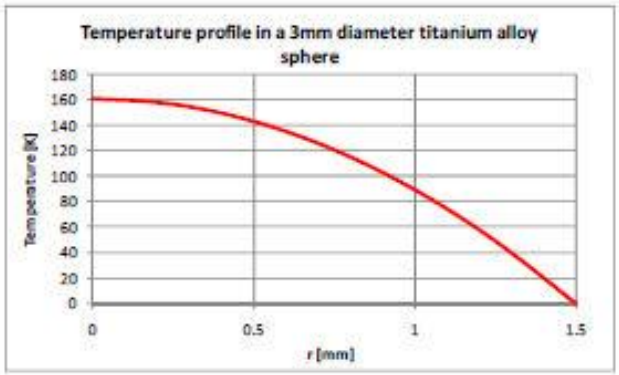
Example for titanium alloy

k=7.2 W/mK

R=1.5 mm

Q=3.1e9 W/m^3

ΔT=161.5 K



Stress distribution inside a sphere with uniform heat deposition

In general form, the radial and azimuthal thermal-stress components inside a sphere where the temperature varies as a function of radius are given by:

$$\sigma_r = \frac{2E\alpha}{(1-\nu)}\left(\frac{1}{R^3}\int_0^R Tr^2dr - \frac{1}{r^3}\int_0^r Tr^2dr\right) \qquad \sigma_\theta = \frac{E\alpha}{(1-\nu)}\left(\frac{1}{r^3}\int_0^r Tr^2dr + \frac{2}{R^3}\int_0^R Tr^2dr - T\right)$$

Where E is elastic modulus, α is linear expansion coefficient, and ν is poisson ratio. In Tristan's case (above) recall that the temperature distribution was:

$$T = T_0 + \frac{Q(R^2 - r^2)}{6k}$$

Substituting and performing the integration yields the radial and azimuthal thermal-stress components as a function of radius for this particular case:

$$\sigma_r = \frac{E\alpha Q(r^2 - R^2)}{15k(1-\nu)} \qquad \sigma_\theta = \frac{E\alpha Q(2r^2 - R^2)}{15k(1-\nu)}$$

The Equivalent Von-Mises Stress comes from:

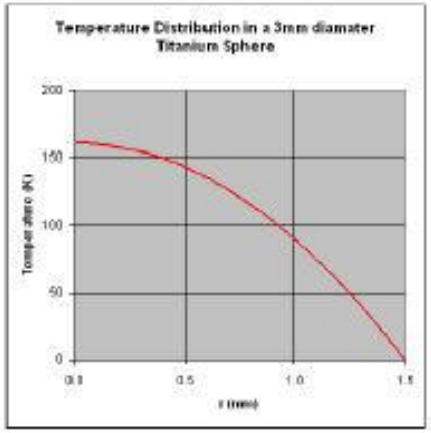
$$2\sigma_{VM}^2 = (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2$$

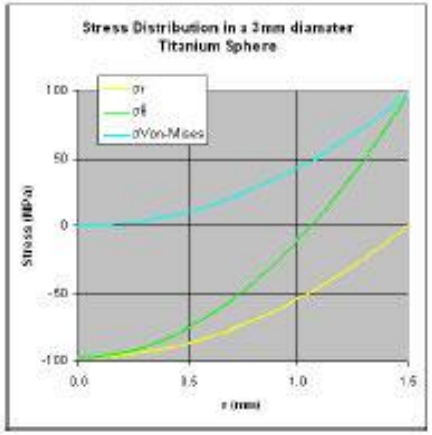
In this case leading to: $\sigma_{VM} = |\sigma_\theta - \sigma_r|$

The Von-Mises stress as a function of radius is then: $\sigma_{VM} = \dfrac{E\alpha Q r^2}{15k(1-\nu)}$

It is at a maximum at the outer radius where $r = R$. So: $\sigma_{VM\,max} = \dfrac{E\alpha Q R^2}{15k(1-\nu)}$

Taking E = 114 GPa, α = 8.7e-6 /°C, ν = 0.34, gives $\sigma_{VM\,max}$ = 97 MPa





Packed Bed Notes

The Ergun equation, relates the friction factor in a packed column as a function to the Reynolds number:

$$f_p = \frac{150}{Gr_p} + 1.7555$$

where fp and Grp are defined as

$$f_p = \frac{\Delta p}{L}\frac{D_p}{\rho V_s^2}\left(\frac{\epsilon^3}{1-\epsilon}\right) \qquad Gr_p = \frac{D_p V_s \rho}{(1-\epsilon)\mu}$$

where: Δp is the pressure drop across the bed,
L is the length of the bed (not the column),
D_p is the equivalent spherical diameter of the packing,
ρ is the density of fluid,
μ is the dynamic viscosity of the fluid,
Vs is the superficial velocity(i.e. the velocity that the fluid would have through the empty tube at the same volumetric flow rate), and
ε is the void fraction of the bed (Bed porosity at any time).

CFX v13 uses two Energy Equations, one for fluid and one for solid with interfacial heat transfer applied as an equivalent source/sink term in each equation.
Overall heat transfer coefficient and interfacial area defined to account for thermal conductivity through solid components of packed bed as well as forced convection between gas and solid.