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# A Static Packed Bed Target

Tristan Davenne, Otto Caretta, Peter Loveridge

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# Summary

**Why consider a packed bed as a high power target?**

- Surface to volume ratio through out target enables significant heat removal with reasonable target temperature
- Small target segments result in low thermal stress and also low inertial stress (stress waves and excited natural frequencies)
- Structural integrity not dependant on target material

**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 available

**A couple of relevant papers:**

- A helium gas cooled stationary granular target (Pugnat & Sievers) 2002
- The “Sphere Dump” – A new low-cost high-power beam dump concept (Walz & Lucas) 1969

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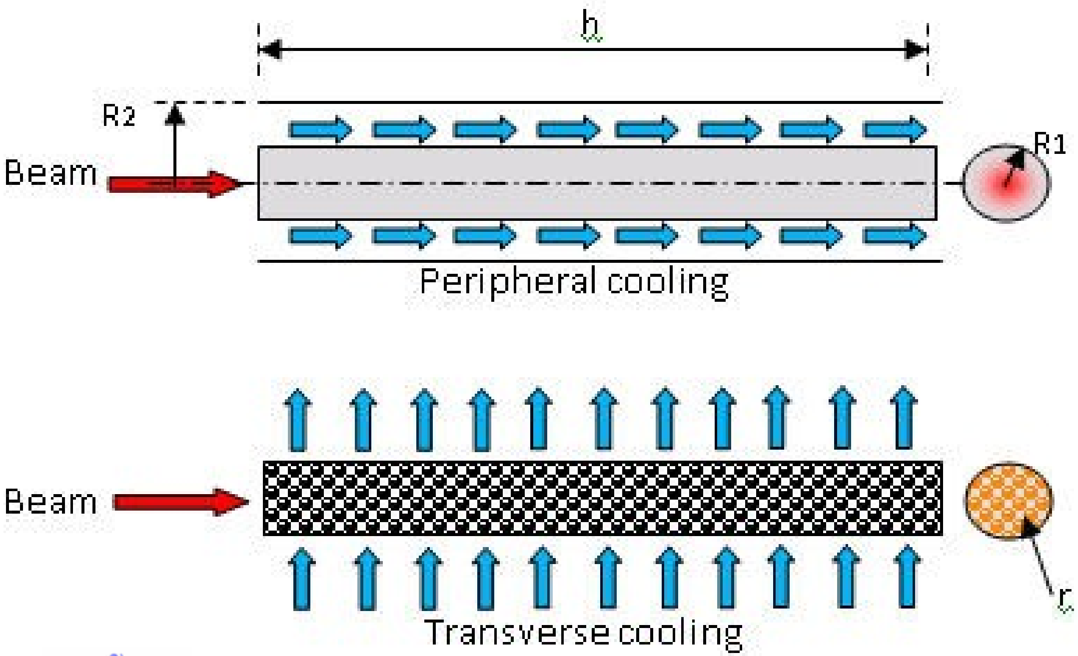
# Solid target vs. Ideal Packed Bed Configuration






Example Comparison (h=0.78m, $R_1$=12mm, $R_2$=25mm, r=1.5mm, Q=1.5e9W/m$^3$, k=200W/mK)

| **Target→** | **Solid Target** | **Packed Bed Sphere** |
|---|---|---|
| Radial temperature difference (Thermal stress ) | $3R1^2Q/16k$ =202.5K | $QR1^2/6k$ =3K |
| Inertial Stress | Significant (stress waves due to rapid heating and stress oscillation due to off centre beam) | Small (stress waves small due to fast expansion time, off centre beam not a problem due to segmentation) |
| Surface area for heat exchange | $2\pi R1h$=0.058m$^2$ | $\pi R1^2h/(4/3\ \pi r^3)*4\ \pi r^2$=0.71m$^2$ |
| Flow area | $\pi(R2^2\text{-}R1^2)$ = 1.5e-3m$^2$ | R1h/2 =4.68e-3m$^2$ |

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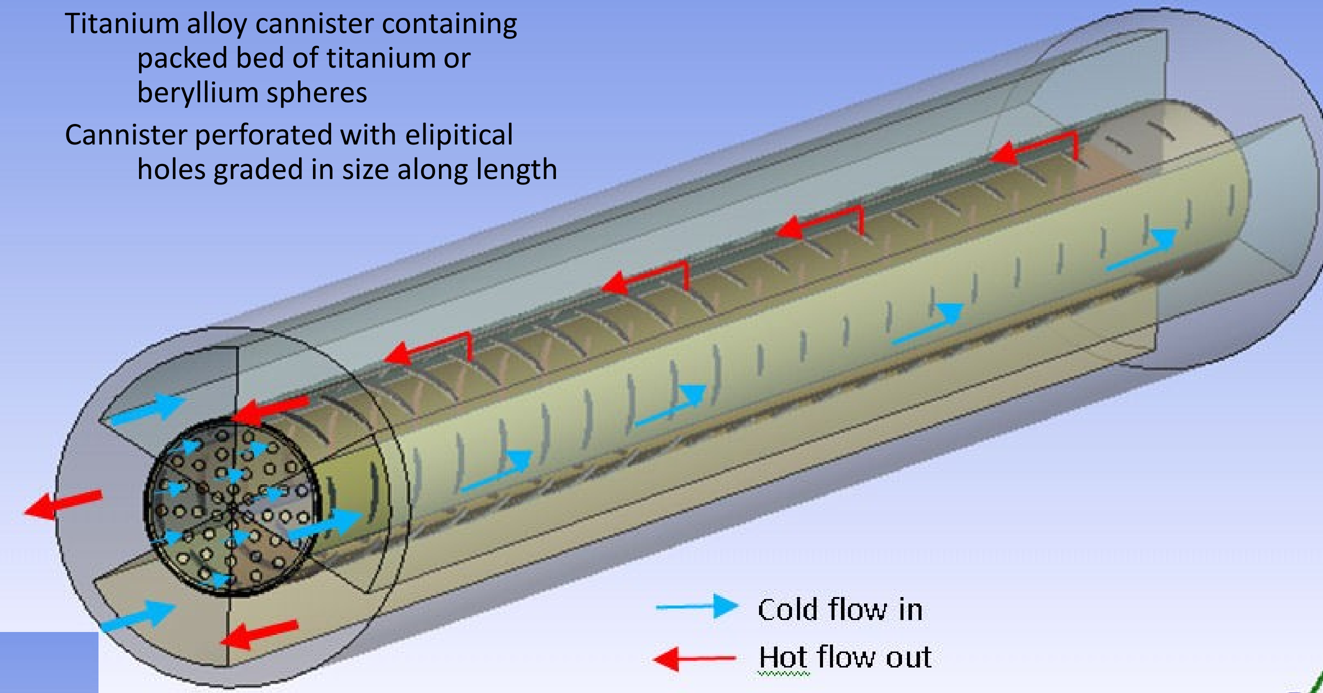
# Packed Bed Target Concept for Euronu (or other high power beams)

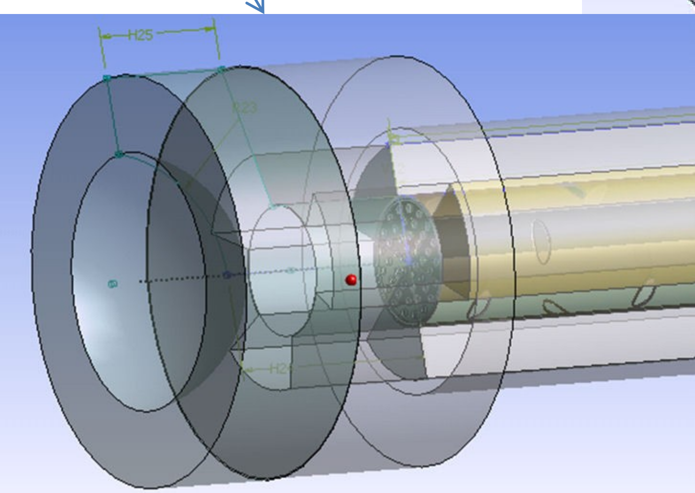
Titanium alloy cannister containing packed bed of titanium or beryllium spheres

Cannister perforated with elipitical holes graded in size along length

Packed bed cannister in parallel flow configuration




Packed bed target front end



**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 : Beryllium or <u>Titanium</u>
Coolant = Helium at 10 bar pressure

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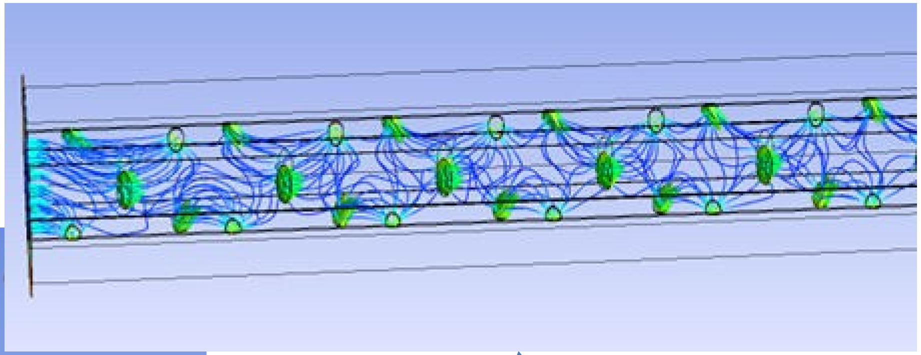
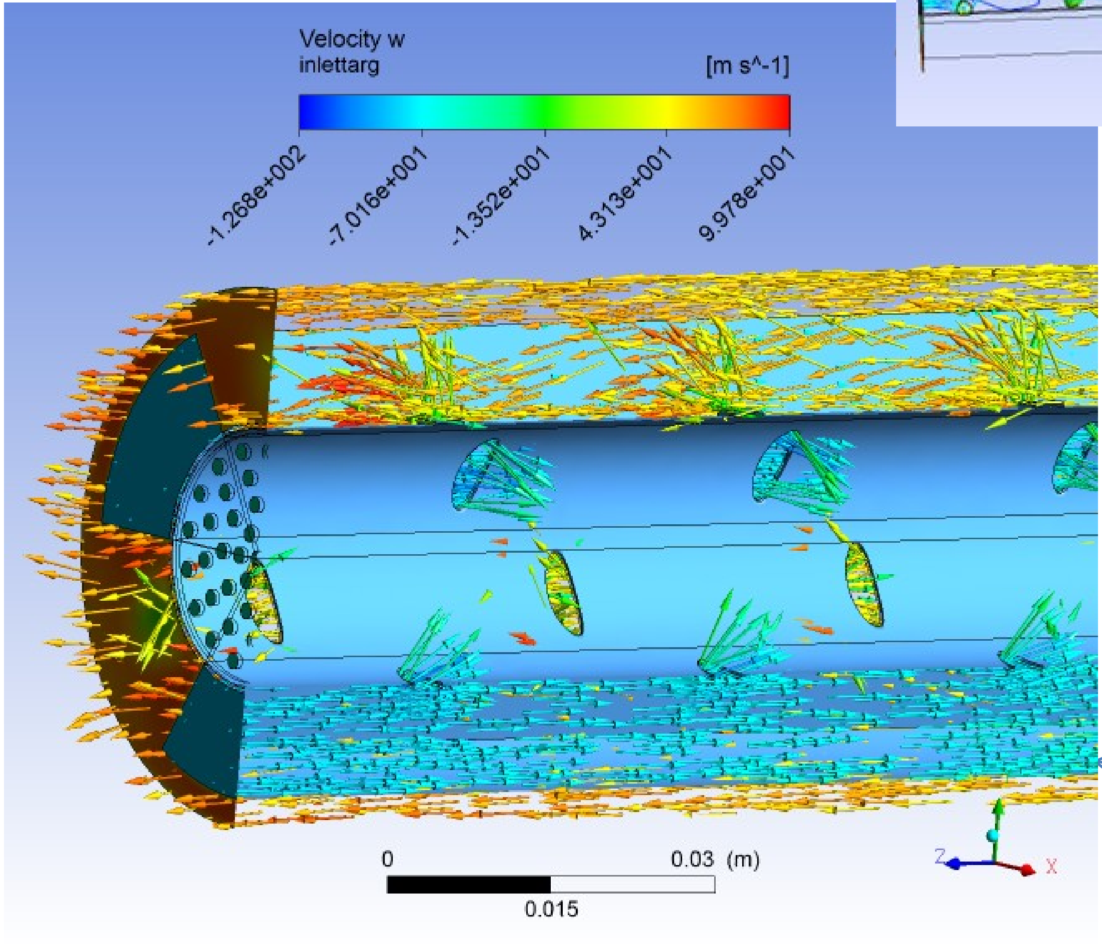
# Packed Bed Model
# (FLUKA + CFX v13)






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

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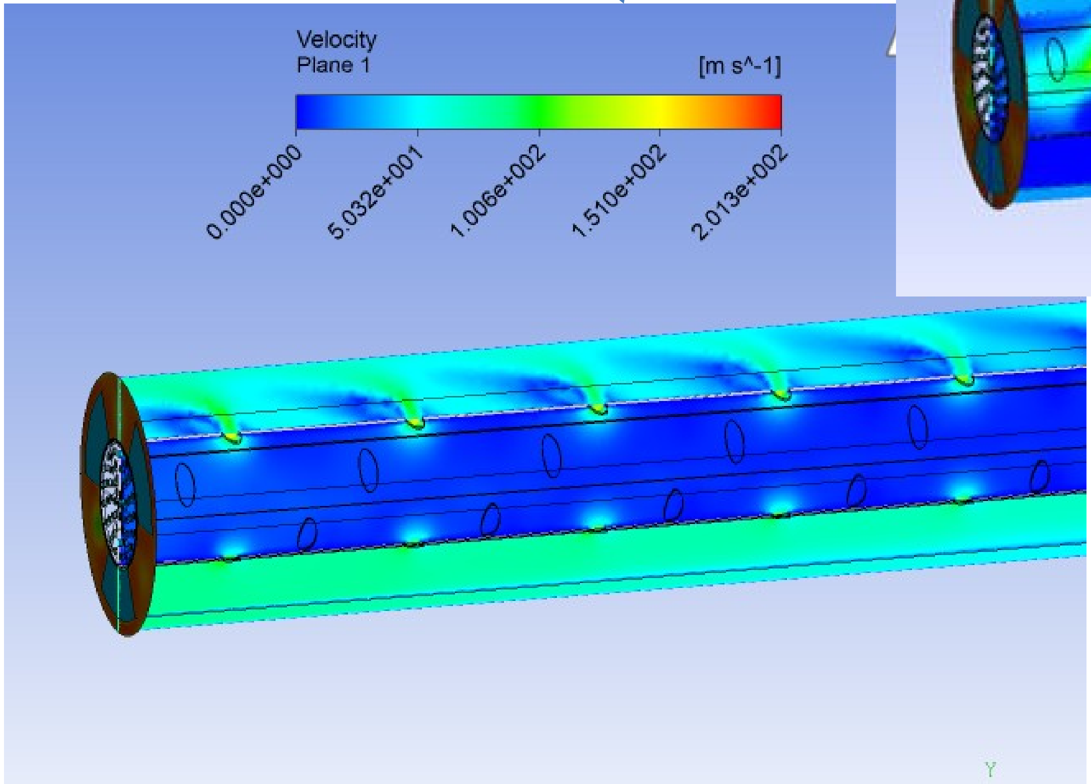
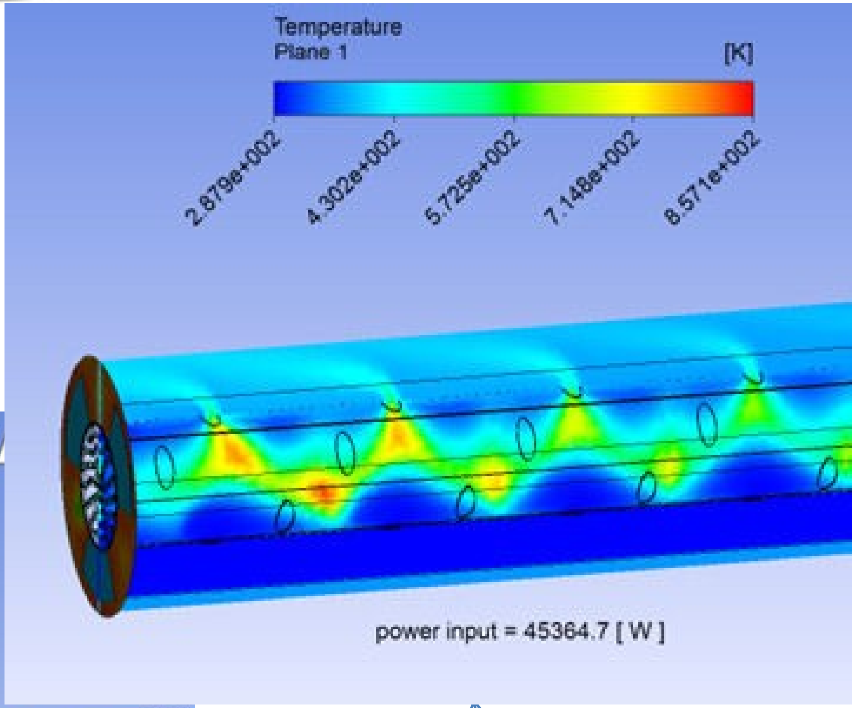
# Helium Flow

<u>Helium Velocity</u>

Maximum flow velocity = 202m/s

Maximum Mach Number < 0.2




<u>Helium Gas Temperature</u>

Total helium mass flow = 93 grams/s

Maximum Helium temperature = 857K =584°C

Helium average outlet Temperature = 109°C

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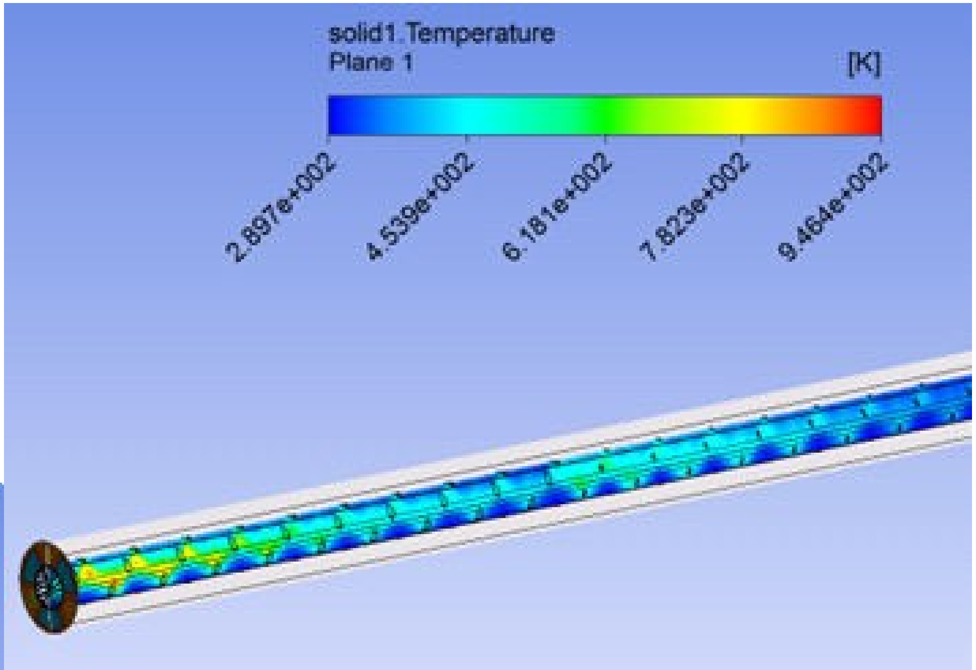
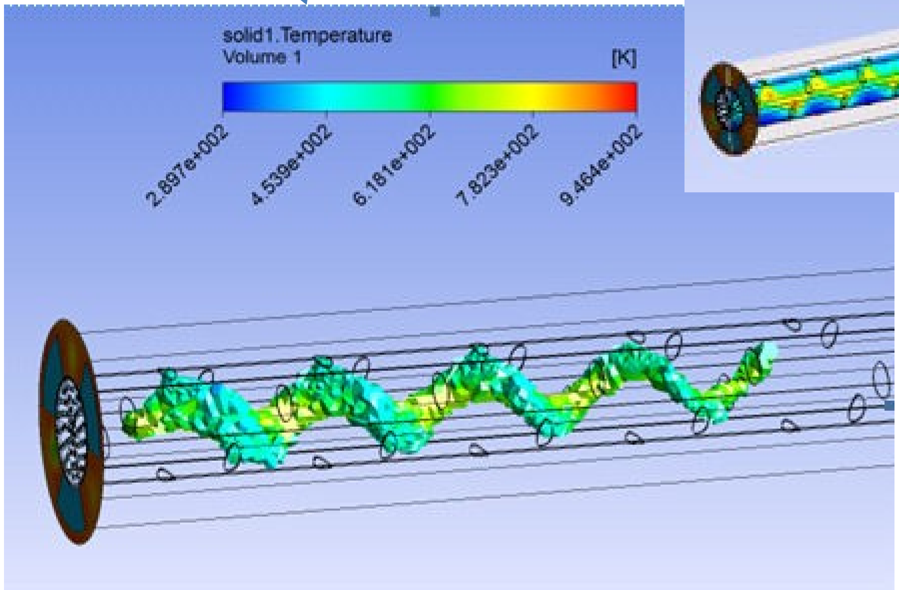
# Packed Bed




<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)

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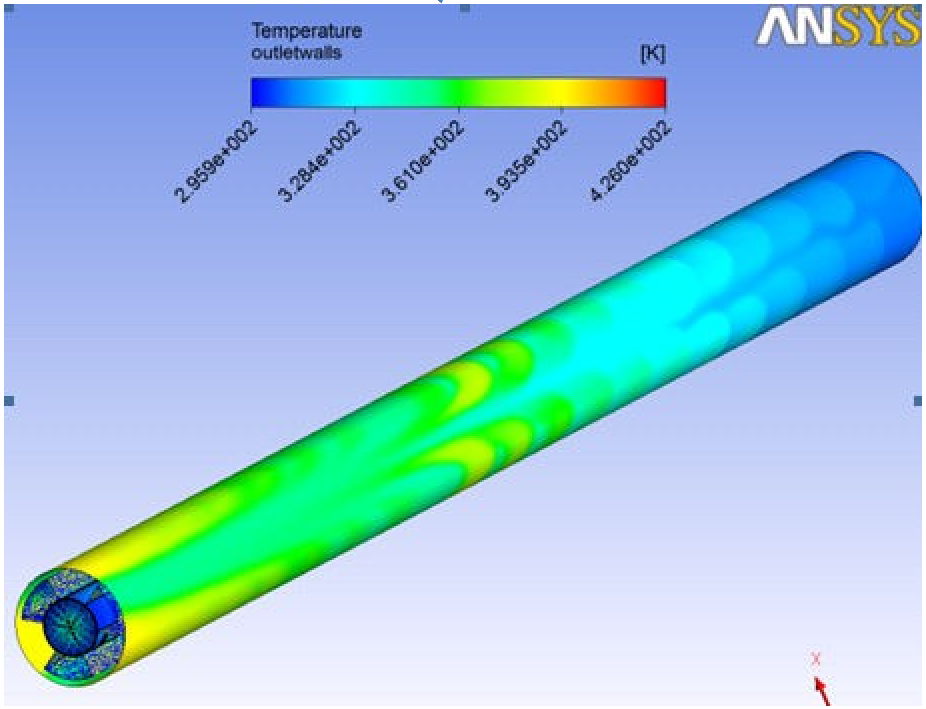
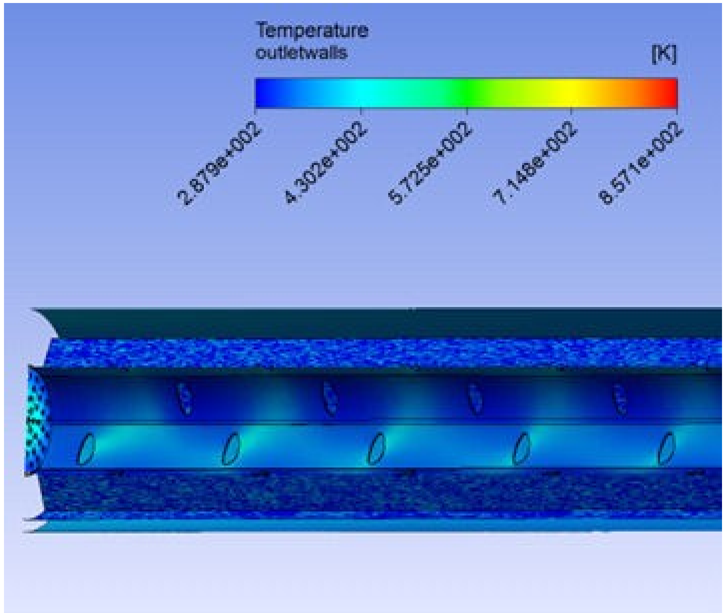
# Cannister components

<u>Outer Can Surface Temp</u>

Almost Symmetric Temperature contours

Maximum surface Temperature = 426K = 153°C




<u>Internal Temperatures</u>

All components made from Ti-6Al-4V

Maximum cannister temperature ≈ 600K = 327°C

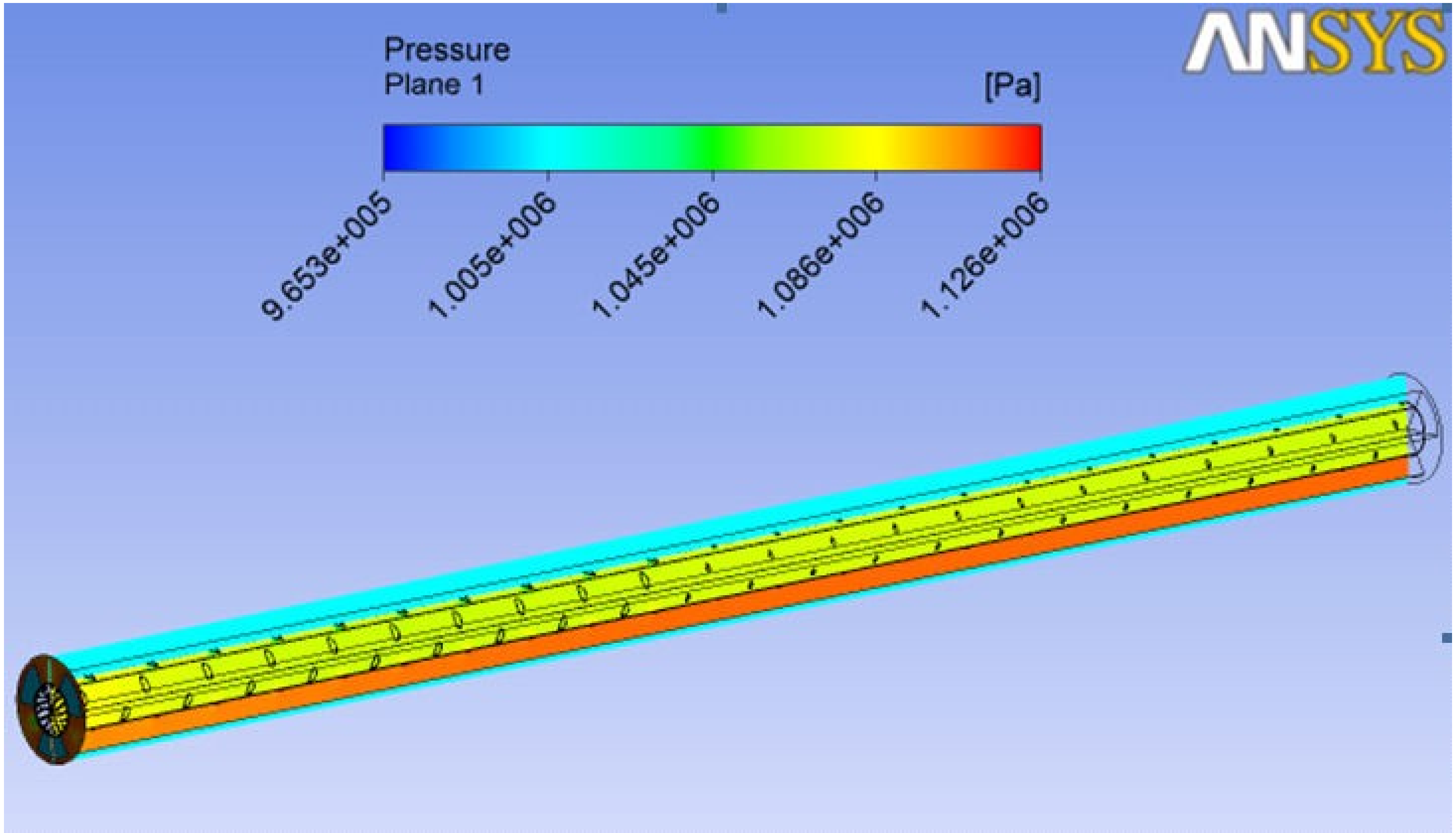
# Pressure Drop

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

Helium outlet pressure = 10bar

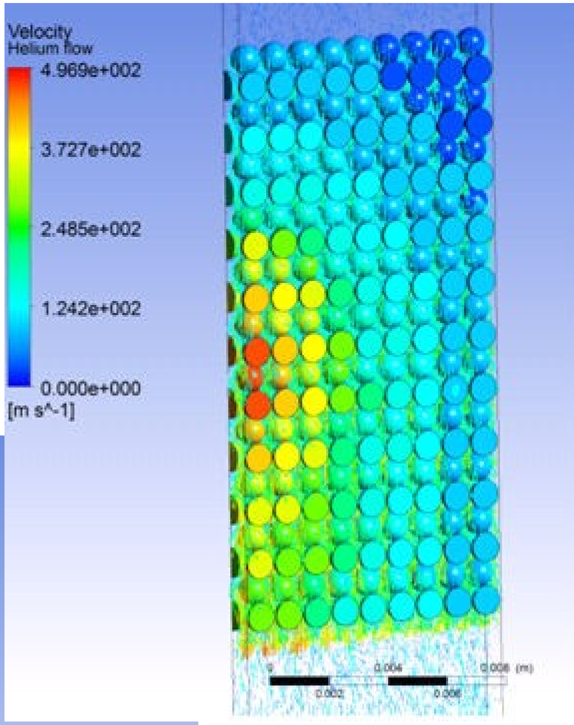
Helium inlet pressure  = 11.2bar

Majority of pressure drop across holes and not across packed bed

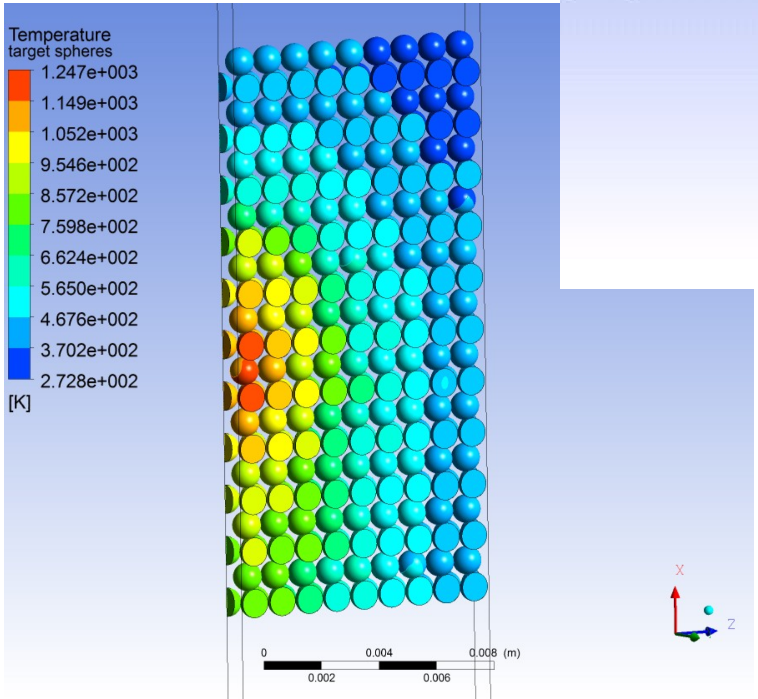


# How much power can a packed bed target dissipate???

Pugnat & Sievers considered a packed bed as a neutrino factory target with 4MW proton beam with some analytical expressions, they calculated maximum helium and tantalum temp as 585°C and 731°C respectively for a single target and less for a quadruple target concept




Some quick FLUKA-CFD analysis:
Consider a 300mm long 20mm diameter packed bed of 1mm diameter tungsten spheres with incident 4MW 14GeV proton beam
Mass flow for modelled slice of target = 1.72g/s
Total Mass flow for 300mm long target =516g/s
Inlet pressure = 11.7bar, outlet pressure = 10bar
Inlet density = 2kg/m3
Maximum Helium velocity = 497m/s
Maximum Mach number = 0.33
Average outlet temperature = 544K=271°C
Maximum tungsten temperature = 1247K=974°C
Heat to helium for slice= 2418W
Heat to helium for complete target = 725kW

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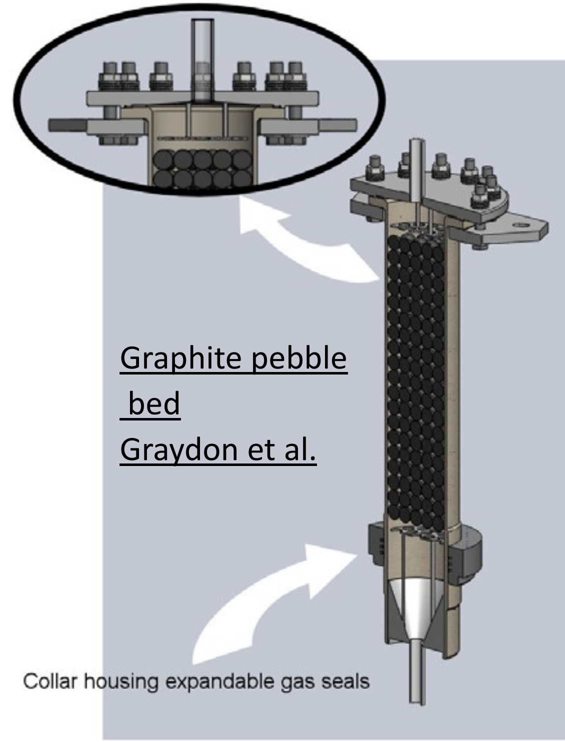
# Packed Bed Testing




## Induction Heating

Packed bed placed in an alternating magnetic field.

Eddy currents induced in metallic spheres.

Resultant Joule heating provides internal heating of spheres.


References of interest:

"Particle to fluid heat transfer in water fluidized systems" Holman et al.
Used 30kW induction heater to investigate heat transfer from steel and lead spheres down to 1/16 inch diameter

"Fluid-particle heat transfer in packed beds" Baumeister et al.
Induction heating of air cooled 3/8 inch steel spheres

"Development of a Forced-Convection Liquid-Fluoride-Salt Test Loop"
Graydon et al. ORNL
Induction heating of 3cm diameter graphite spheres and rods, 30kHz supply providing 200kW to the spheres (1.2kW per sphere)

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# Conclusions

A Packed Bed Targets have the following characteristics

- Large surface area for heat transfer
- Coolant able to access areas with highest energy deposition
- Inherently small thermal stress
- Minimal inertial stresses (stress waves due to rapid heating + off axis beam induced oscillations)
- Potential heat removal rates at the hundreds of kiloWatt level
- Pressurised cooling gas required at high power levels to keep velocity and pressure drop down
- Bulk density lower than solid density

From a thermal and engineering point of view a packed bed seems like a reasonable concept design to put forward for Euronu where stress levels in a traditional solid target design look concerningly high.

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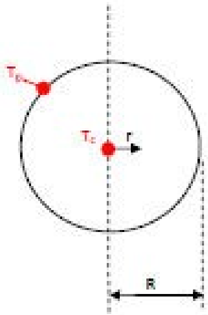
# Temperature and stress in a uniformly heated sphere

## 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]




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

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

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

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

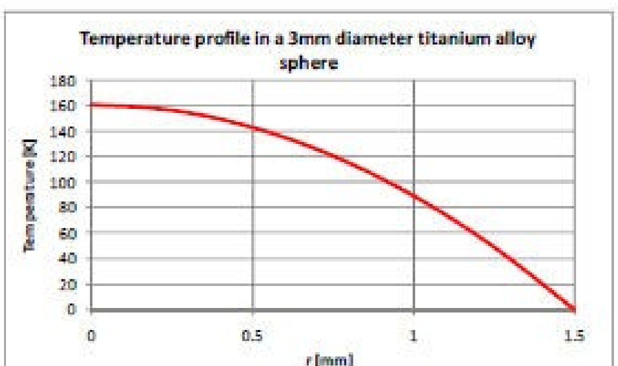
$$T = T_0 + \frac{Q}{6k}(R^2 - r^2)$$ temperature as a function of r

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:

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

Where $E$ is elastic modulus, $\alpha$ is linear expansion coefficient, and $\nu$ 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: $\sigma_{VM} = \frac{E\alpha Q r^2}{15k(1-\nu)}$

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

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