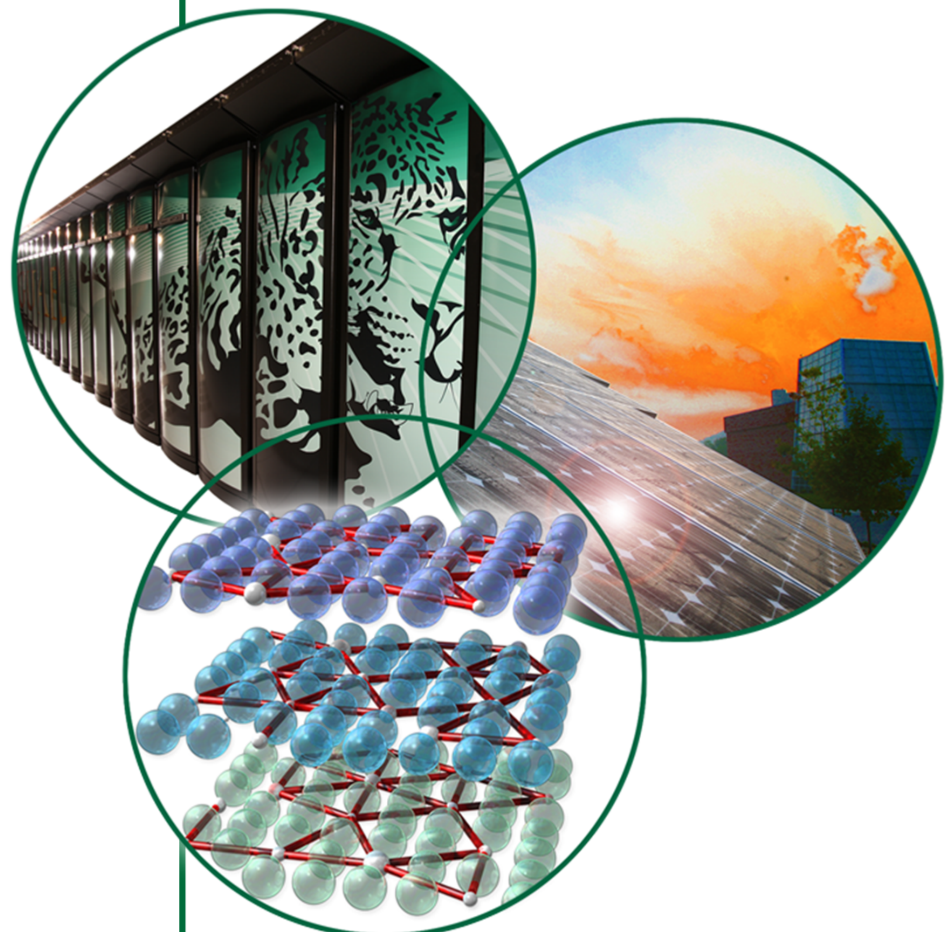
Neutrino Factory Mercury Vessel: Initial Cooling Calculations



V. Graves

Target Studies

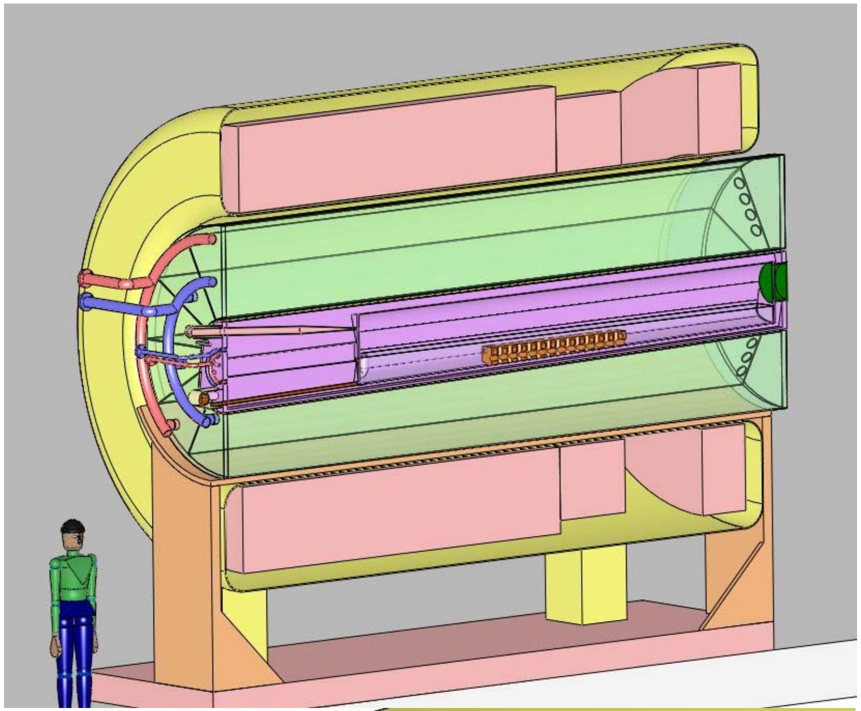
Nov 15, 2012

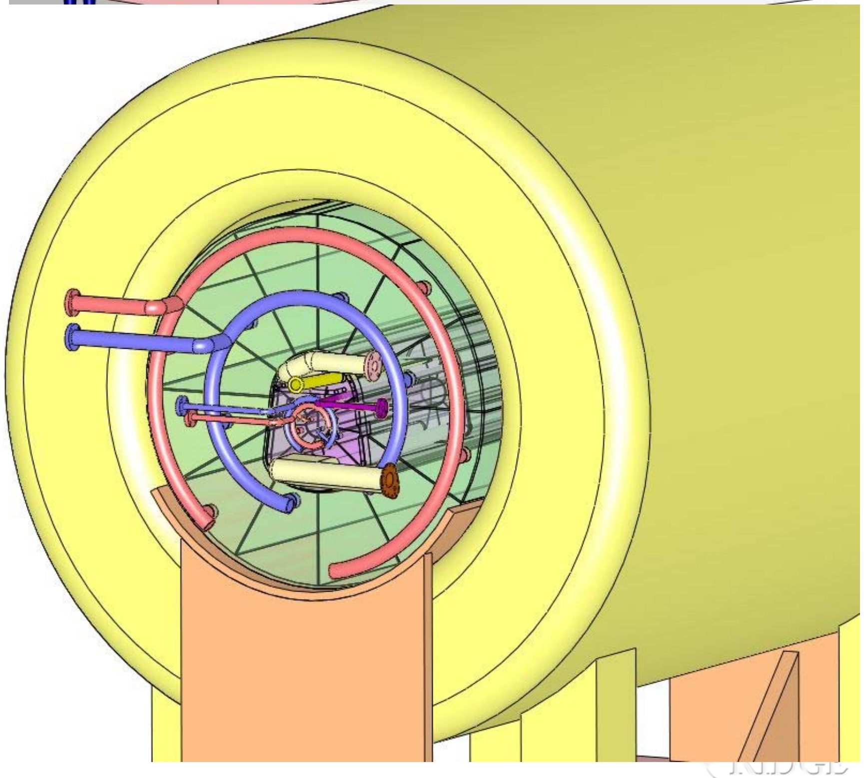
U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Target System Review

- Current mechanical concept incorporates independent mercury and shielding modules
- Separates functionality, provides double mercury containment, simplifies design and remote handling
- Each vessel assumed to be cooled with Helium
  - Shielding vessel filled with tungsten beads
  - Mercury vessel cooling chambers empty
- Purpose: take an initial look at the cooling issues





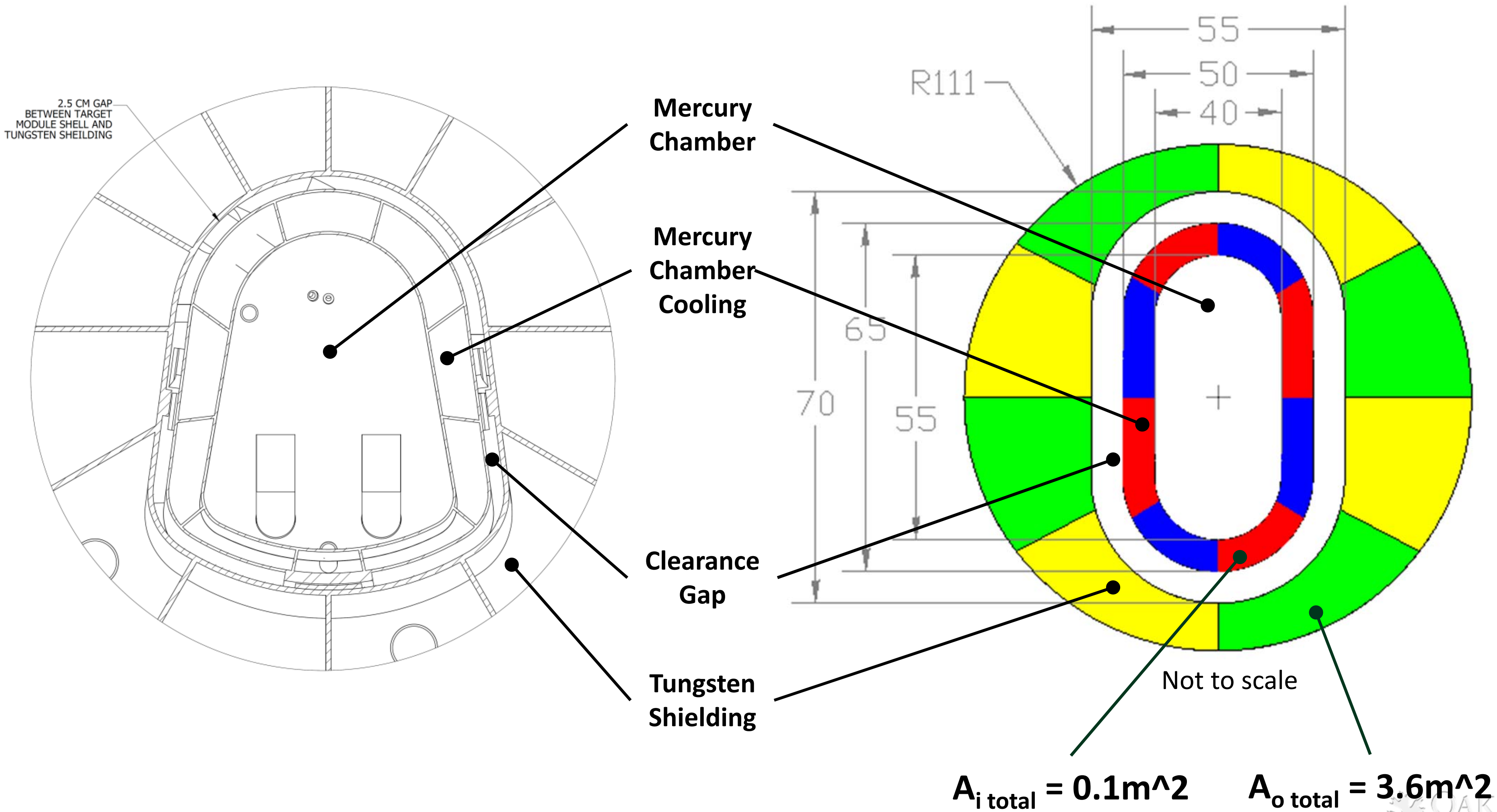
Helium Properties @ 20C

Property	Value	Unit
Density (ρ)	0.16674	kg/m^3
Dynamic Viscosity (μ)	1.9561E-5	kg/m-s
Kinematic Viscosity (ν)	1.1731E-4	m^2/s
Specific heat (Cp)	5193	J/kg-K
Conductivity (k)	0.14786	W/m-K
Prandtl number	0.68700	
Thermal Diffusivity (κ)	1.7120E-4	m^2/s
Thermal Expansion Coefficient (α)	3.4112E-3	1/K

http://www.mhtl.uwaterloo.ca/old/onlinetools/airprop/airprop.html

Analysis Model Simplification

- **First-order cooling analysis based on simplified geometry model**
- **Break inner and outer regions into supply/return channels of equal areas within each region**



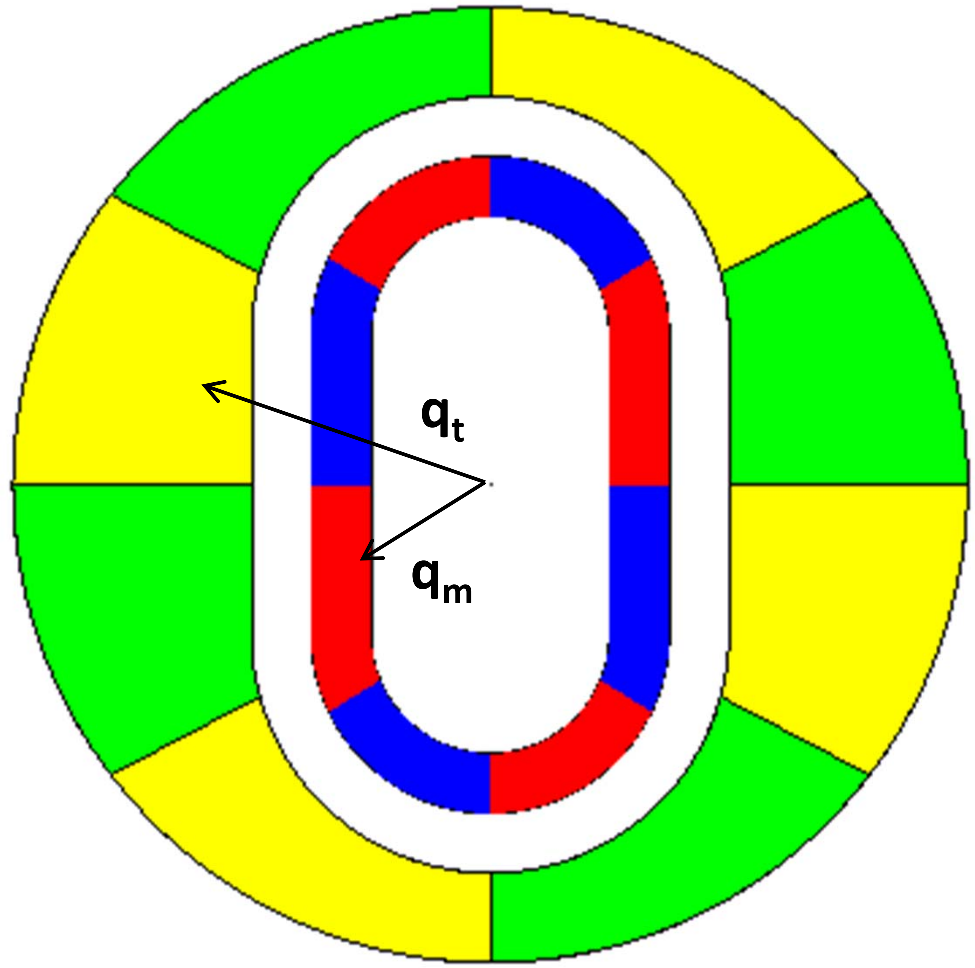
Helium Mass Flow Rates

$$q = \dot{m} C_p \Delta T$$

- **Assumptions**
  - **q_t = 1.5 MW**
  - **q_m = 0.5 MW**
  - **ρ = 0.16674 kg/m^3**
  - **C_p = 5193 J/kg-K**
  - **Helium ΔT <= 100C**
  - **Helium velocity <= 100 m/s**

$$\dot{m}_t = \frac{1.5E6}{5193*100} \approx 3 kg/s$$

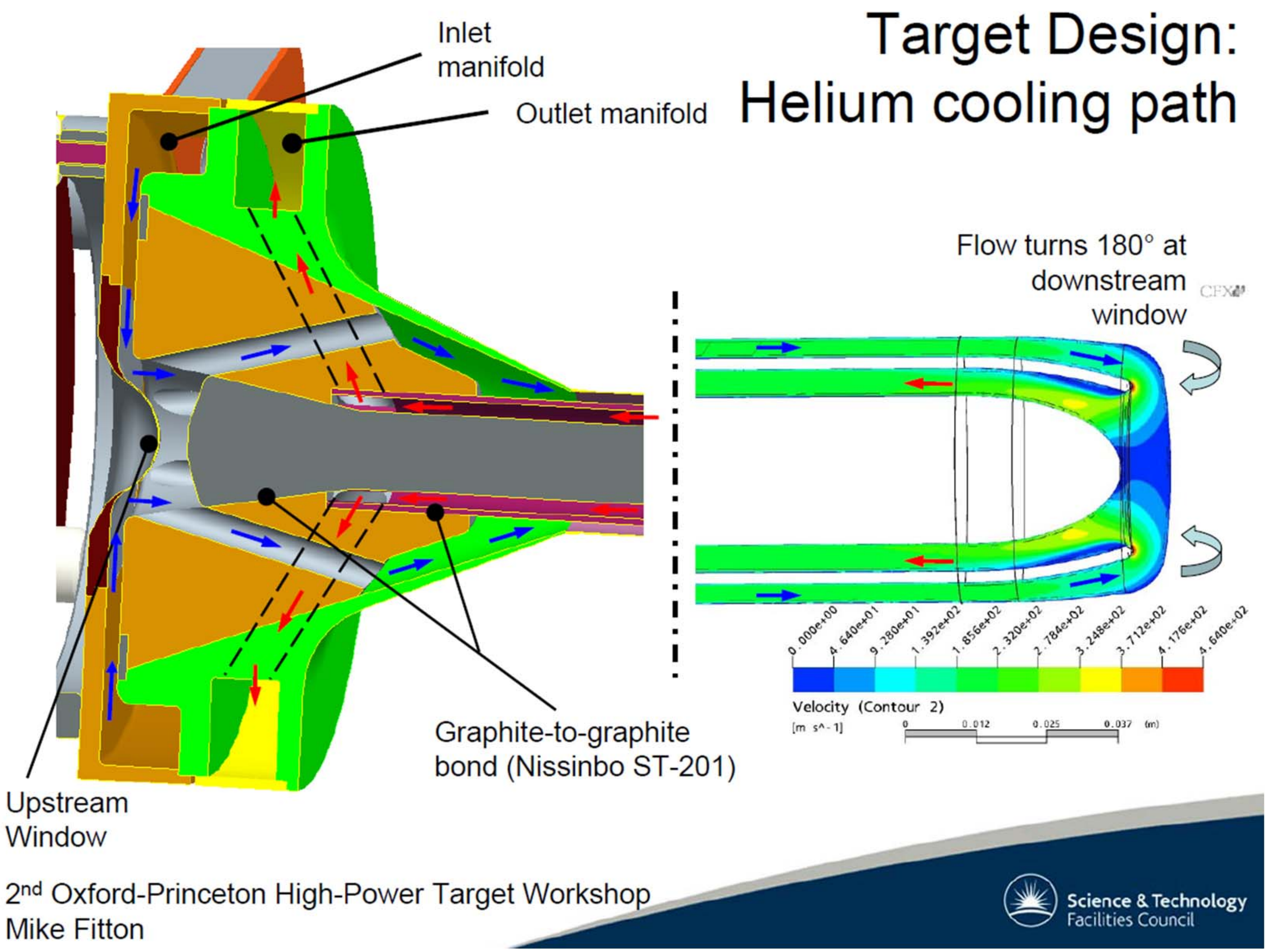
$$\dot{m}_m = \frac{0.5E6}{5193*100} \approx 1 kg/s$$



1kgHe @ STP = 6 m^3

T2K Target Design

- **Required flow rate 32 g/s**
- **Minimize dP (max 0.8 bar) due to high flow rate (avg = 200 m/s)**



Mercury Vessel Calculations

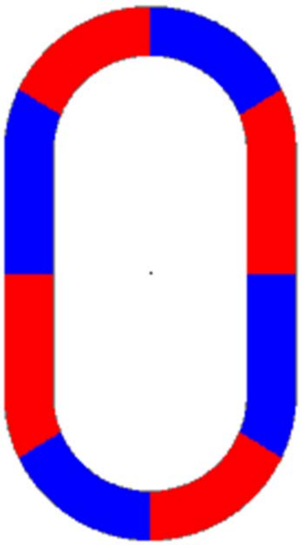
- **Mercury cooling chamber empty (only Helium)**
- **Assume 4 cooling paths (8 chambers)**

$$\dot{m} = \frac{\dot{m}_m}{4} = 0.25\,kg/s$$

$$A = \frac{\dot{m}}{\rho V} = \frac{0.25}{0.16674 \times 100} = 0.015m^2$$

$$8A = 0.12m^2$$

$$A_i = 0.1m^2$$



Helium Supply Channels - Blue

Helium Return Channels - Red

- **Area may be adequate, but asymmetric heating may be problem**
- **Pressure drop through system needs to be calculated**

Tungsten Shielding Vessel Calculations

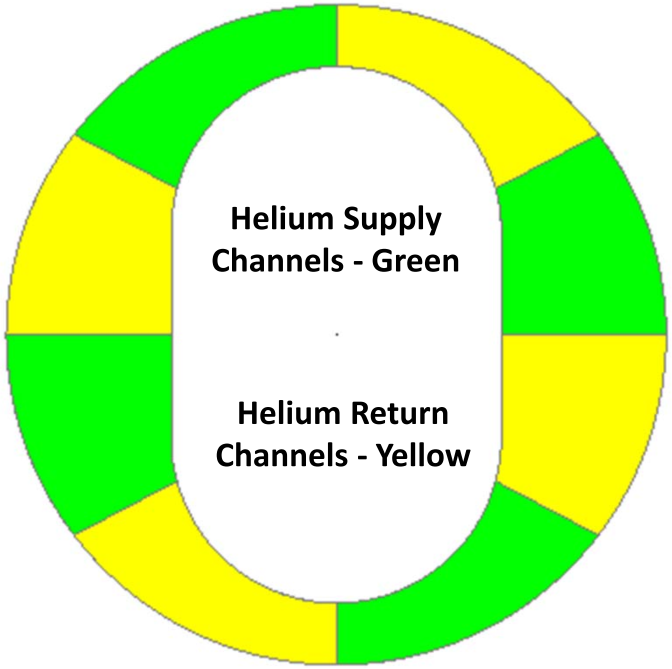
- **Shielding vessel cooling chamber not empty (Tungsten spheres)**
- **Assume 4 cooling paths (8 chambers)**

$$\dot{m} = \frac{\dot{m}_t}{4} = 0.75\,kg/s$$

$$A = \frac{\dot{m}}{\rho V} = \frac{0.75}{0.16674 \times 100} = 0.045 m^2$$

$$8A = 0.36 m^2$$

$$A_o = 3.6 m^2$$



- **Area adequate, may reduce helium velocity**
- **Pressure drop through spheres must be reviewed**

Tungsten Shielding Vessel Pressure Drop

- **Ergun Equation gives pressure drop through fixed beds of uniformly sized solids**

$$\frac{\Delta P}{L} = \left(\frac{\Delta P}{L}\right)_{viscous} + \left(\frac{\Delta P}{L}\right)_{kinetic}$$

$$\frac{\Delta P}{L} = 150\frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{\mu u_0}{(\phi_s d_p)^2} + 1.75\frac{1-\varepsilon}{\varepsilon^3}\frac{\rho u_0{}^2}{\phi_s d_p}$$

$\Delta P =$ *pressure drop*

$L =$ *bed length*

$\mu =$ *fluid viscosity*

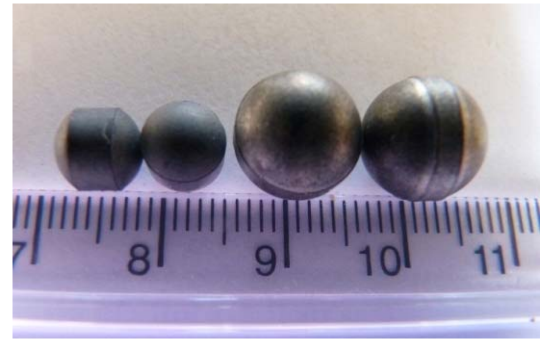
$\varepsilon =$ *particle void fraction*

$u_0 =$ *superficial fluid velocity*

$\phi_s =$ *particle sphericity* $= 1$

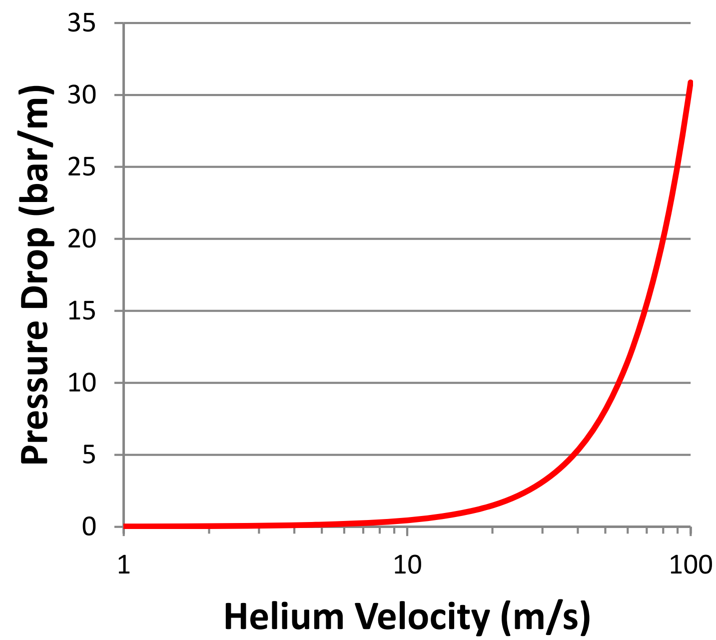
$d_p =$ *particle diameter*

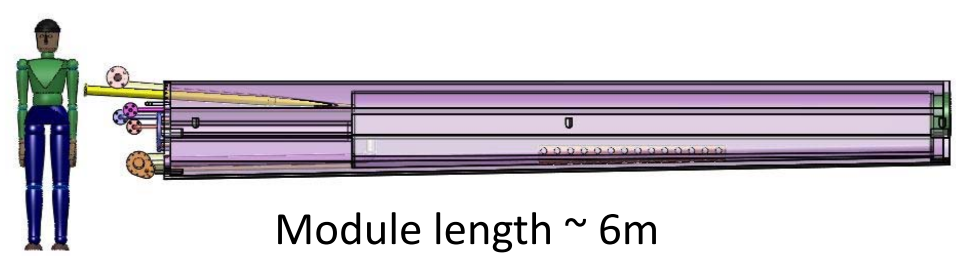
Pressure Drop Results



http://www.hep.princeton.edu/~mcdonald/mumu/target/weggel/W&WC_spheres.pdf

- **Assumptions**
  - **$\varepsilon = 0.4$**
  - **d_p = 1 cm**
- **Results indicate He pressure ~180 bar required**
- **100m/s velocity results in large amounts of stored energy within system**
- **Implies we need to limit He velocity to ~ 10 m/s**
  - **Requires 10X more flow area**
  - **Space is available**
  - **If need 1 s to recool the He in a heat exchanger, need 3 kg, volume = 18 m^3**

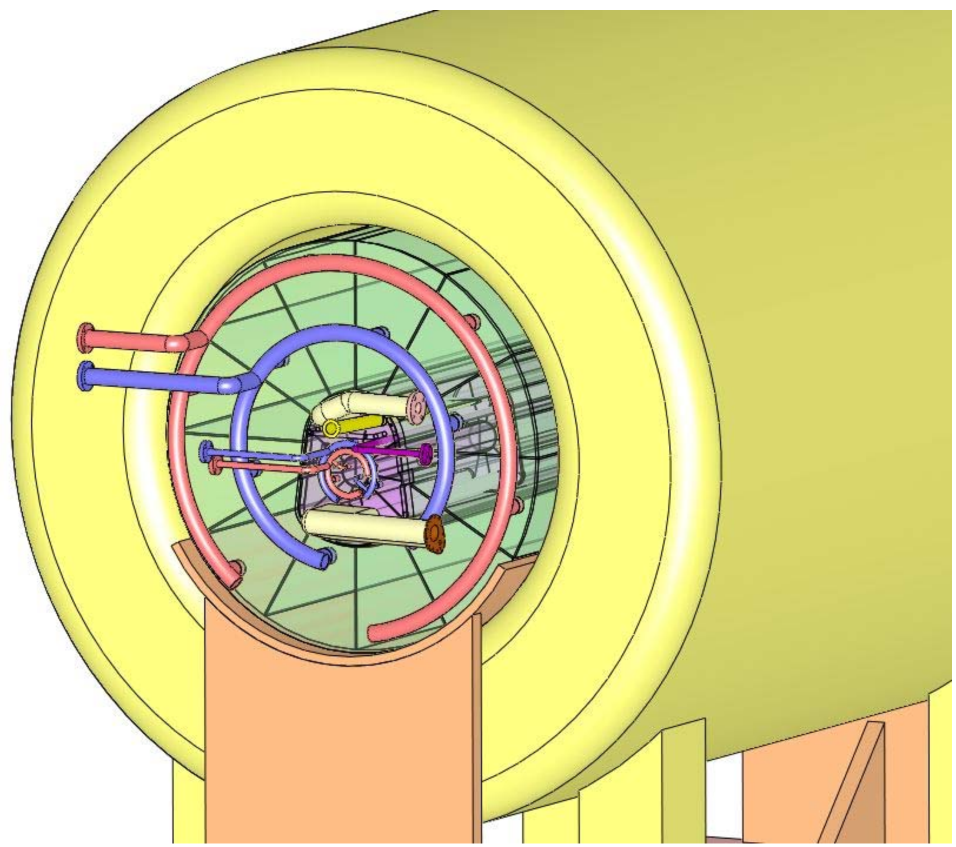




Module length ~ 6m

Mechanical Complexities

- **Non-equally distributed energy deposition**
- **Complicated cooling channel geometries**
- **Flow control hardware likely to increase space requirements**
- **Implement two helium systems (one for mercury cooling, one for tungsten)?**



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Summary

- **Mercury Module now provides double-wall mercury containment with no leak path into tungsten cooling channels**
- **Helium cooling of the mercury and shielding vessels is not straightforward**
- **Initial calculations performed based on guesses for energy deposition and very simple geometry model**