An Analytical Approach to Designing a Thermosiphon Cooling System for Large Scale Superconducting Magnets

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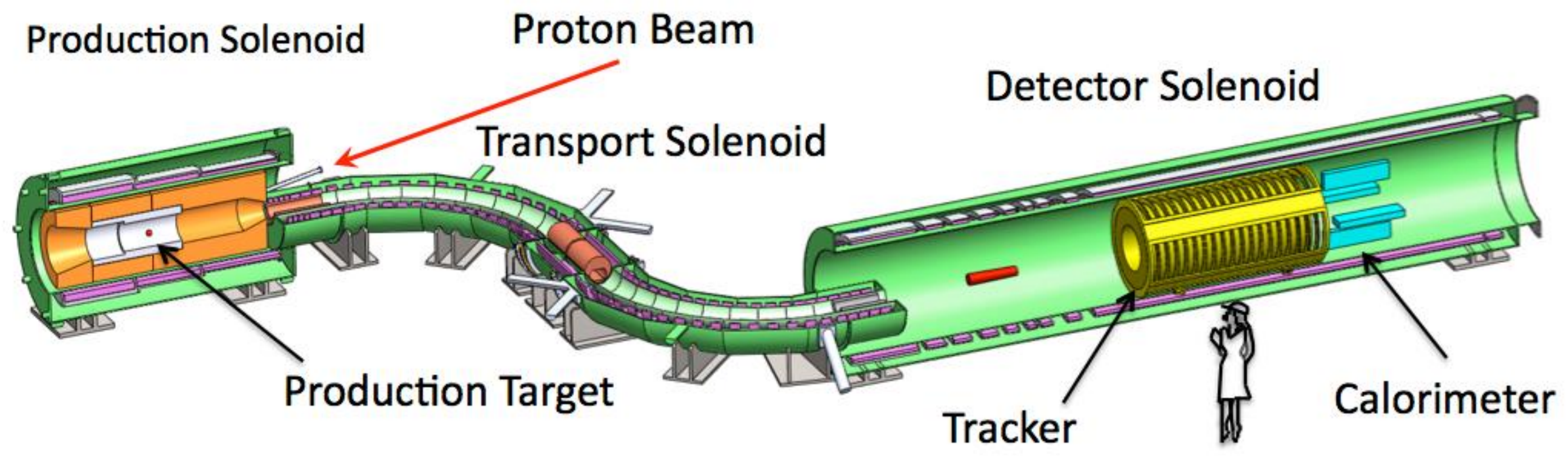
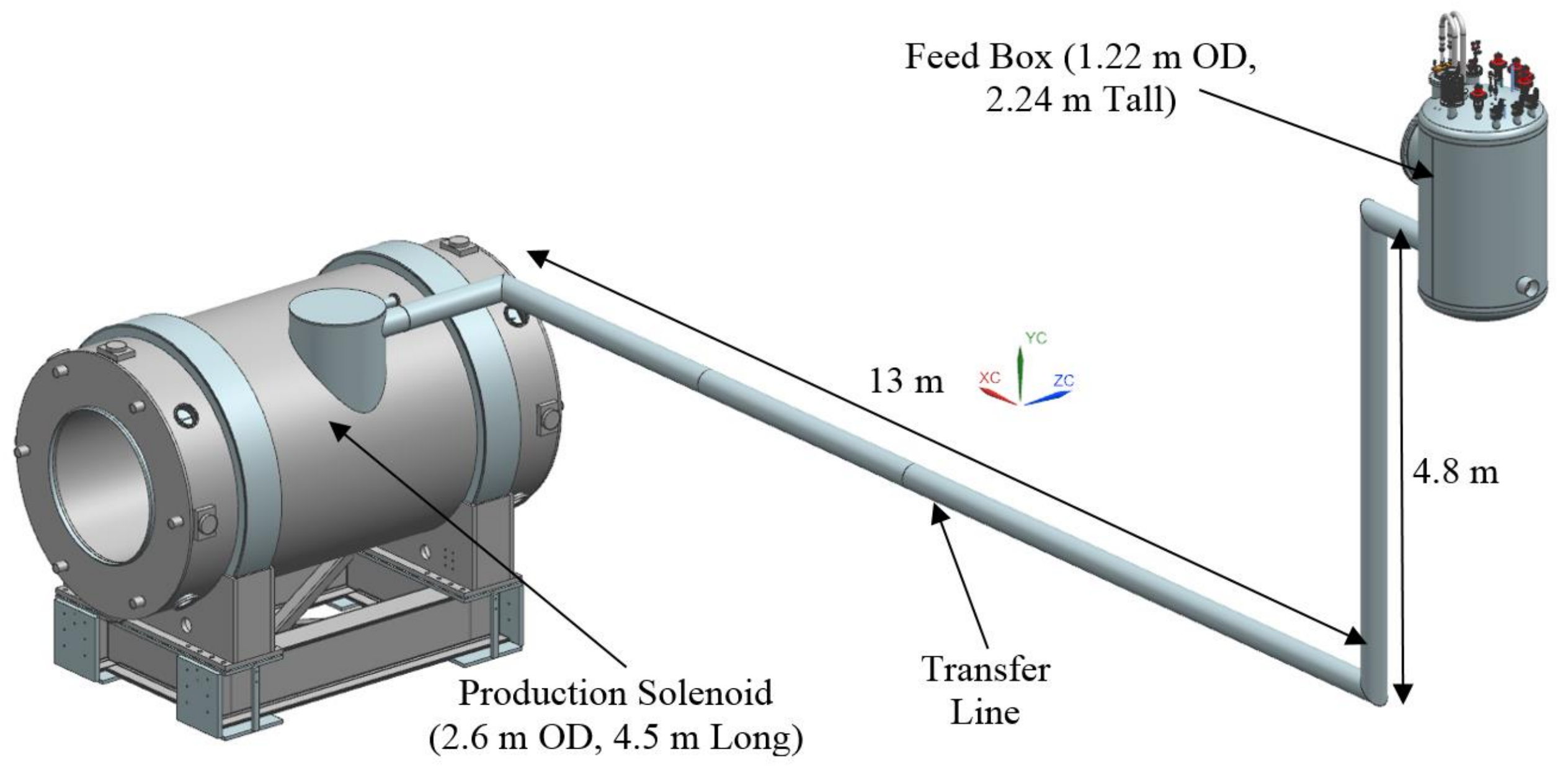
Introduction

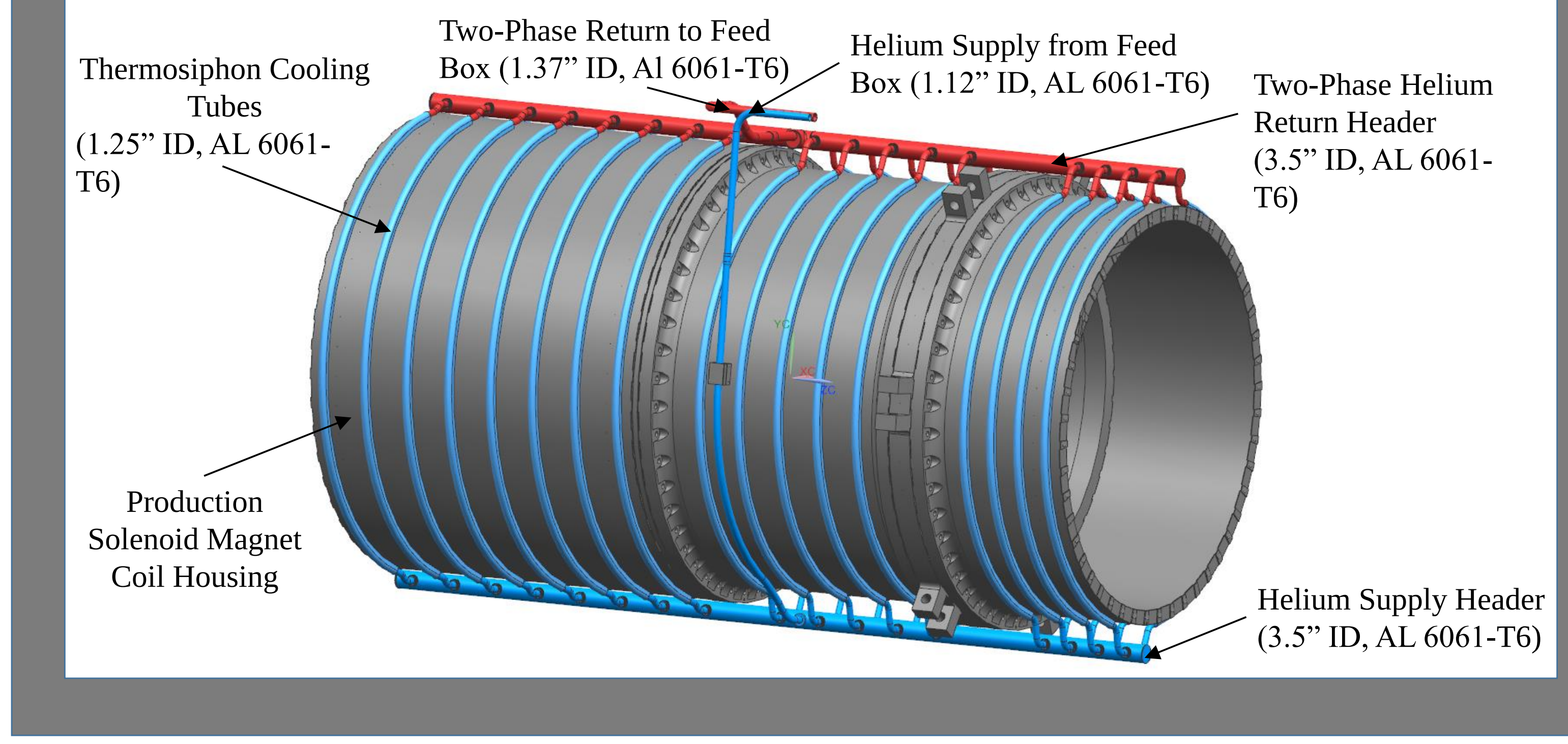
The Mu2e experiment at Fermilab employs four large superconducting magnets, namely, the Production Solenoid, the Transport Solenoid Upstream, the Transport Solenoid Downstream and the Detector Solenoid.



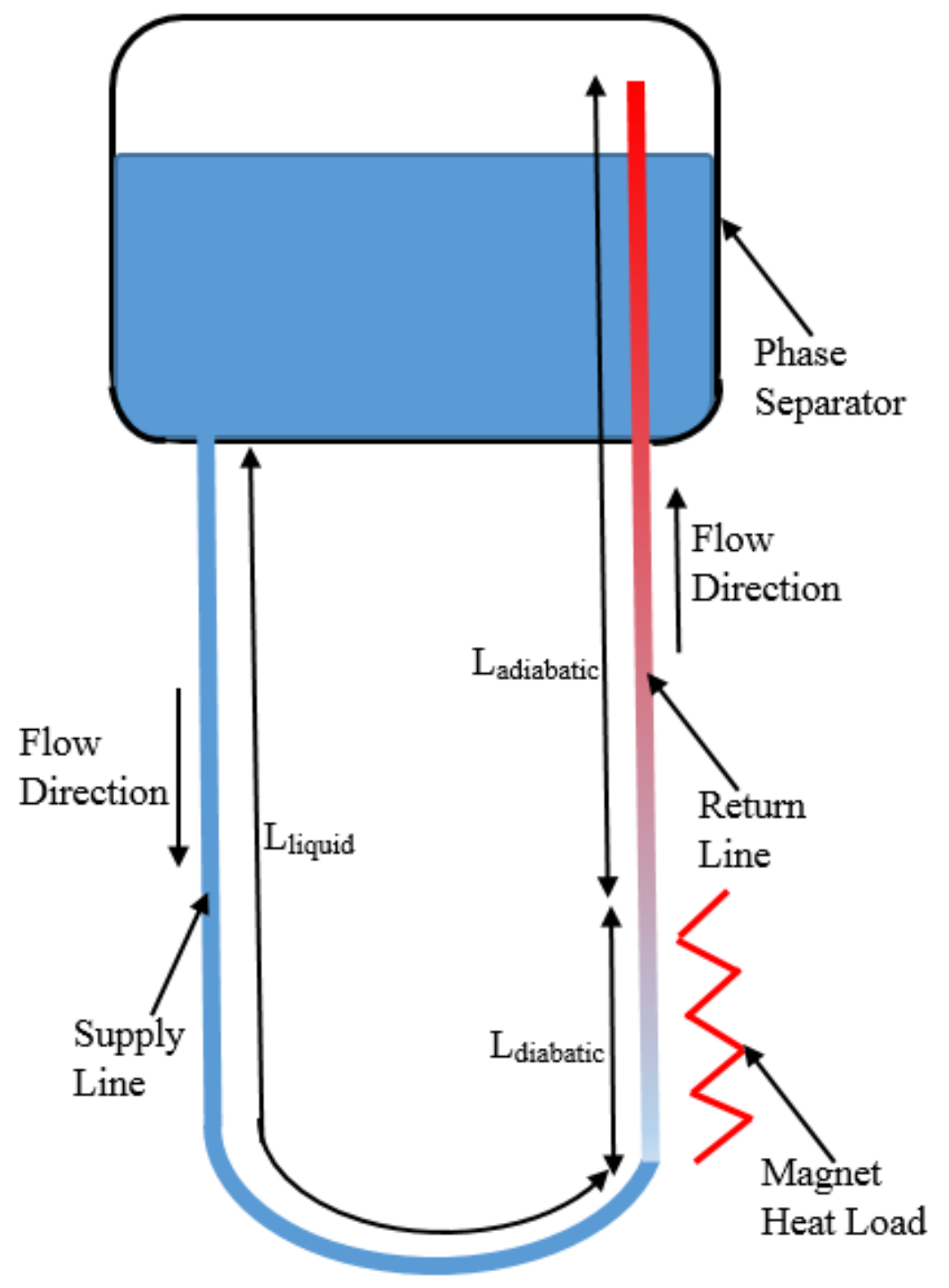
Thermosiphon Cooling Scheme for Mu2e



Saturated liquid helium at 4.7 K is supplied from the phase separator contained within the feed box to the magnet via the transfer line.



Thermosiphon Design



$$\Delta P_{tot} = \Delta P_{static} + \Delta P_{momemtum} + \Delta P_{friction} + \Delta P_{minor} = 0$$

$$\Delta P_{static} = \rho_L g H - g\int_0^H \rho(z)\,dz$$

$$\Delta P_{momentum} = G^2\left(\frac{1}{\rho_G} - \frac{1}{\rho_L}\right)(x_{ex} - x_{in}) \quad \text{(Homogeneous)}$$

$$\Delta P_{momentum} = G^2\left\{\left[\frac{(1-x_{ex})^2}{\rho_L(1-\varepsilon)} + \frac{{x_{ex}}^2}{\rho_G.\varepsilon}\right] - \left[\frac{(1-x_{in})^2}{\rho_L(1-\varepsilon)} + \frac{{x_{in}}^2}{\rho_G.\varepsilon}\right]\right\} \quad \text{(Separated)}$$

$$\Delta P_{friction\_1p} = f\,\frac{G^2 L_{liquid}}{2\rho_L D_h}$$

$$\Delta P_{friction\_2p} = f\,\frac{G^2(L_{diabatic} + L_{adiabatic})}{2\rho_L D_h}\,\emptyset_l^2(x_{ex})$$

$$\Delta P_{minor} = (\text{entry} + \text{exit})\text{losses}$$

Equation Solver Block

$$\boxed{m\_dot_{tot}\cdot X = m\_dot_v}$$

$$\boxed{\left(\Delta P_{mom}(m\_dot_{tot}, X, \varepsilon) + \Delta P_{ftp}(m\_dot_{tot}, X) + \Delta P_{fsp}(m\_dot_{tot}) + \Delta P_{minor}(m\_dot_{tot}, X)\right) = \Delta P_l - \Delta P_{static}(\varepsilon)}$$

$$\boxed{m\_dot_{tot} - m\_dot_L = m\_dot_v}$$

$$\boxed{\varepsilon = \frac{x}{\rho_G}\left[\left[1 + 0.2(1-x)\left(\frac{g d_o \rho_L^2}{G^2}\right)^{0.25}\right]\left(\frac{x}{\rho_G} + \frac{1-x}{\rho_L}\right) + \frac{1.18(1-x)\left[g\sigma(\rho_L - \rho_G)\right]^{0.25}}{G^2 \rho_L^{0.5}}\right]^{-1}} \quad \text{(Separated)}$$

$$\boxed{\varepsilon = \frac{1}{1 + \left[\frac{(1-X)}{X}\cdot\frac{\rho_G}{\rho_L}\right]}} \quad \text{(Homogeneous)}$$

$$\boxed{v := \text{Find}\left(m\_dot_{tot}\cdot\frac{s}{kg}, X, m\_dot_L\cdot\frac{s}{kg}, \varepsilon\right)}$$

Input Parameters for Production Solenoid

Parameters	Value
Magnet Heat Load per unit area (W/m²)	**147**
Total Head on Supply Side (m)	**7.23**
Single Phase Line ID (mm)	**28**
Two-Phase Line ID (mm)	**36**
Single Phase Line Length (m)	**29**
Two Phase Line Length (m)	**36**

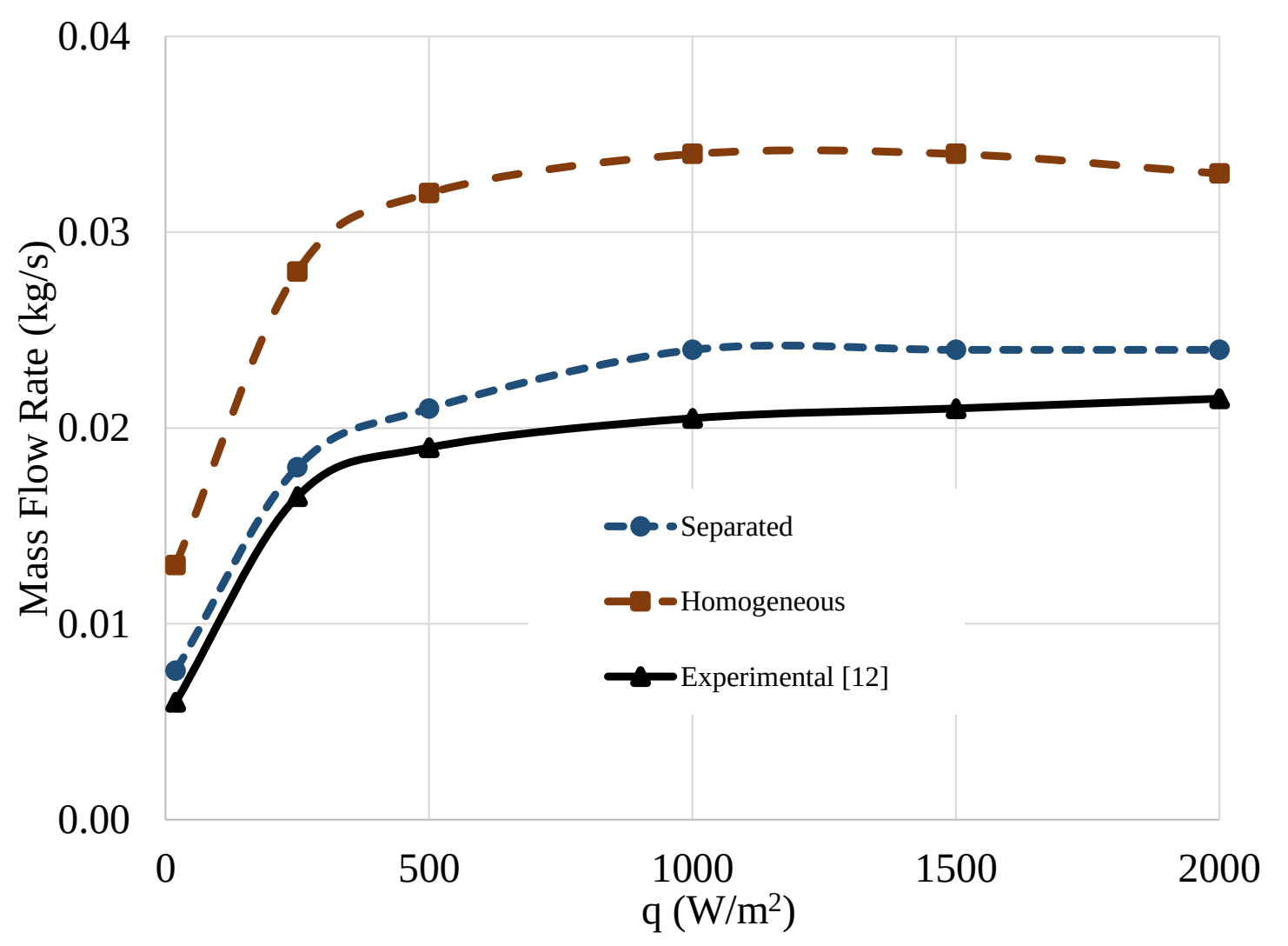
Results

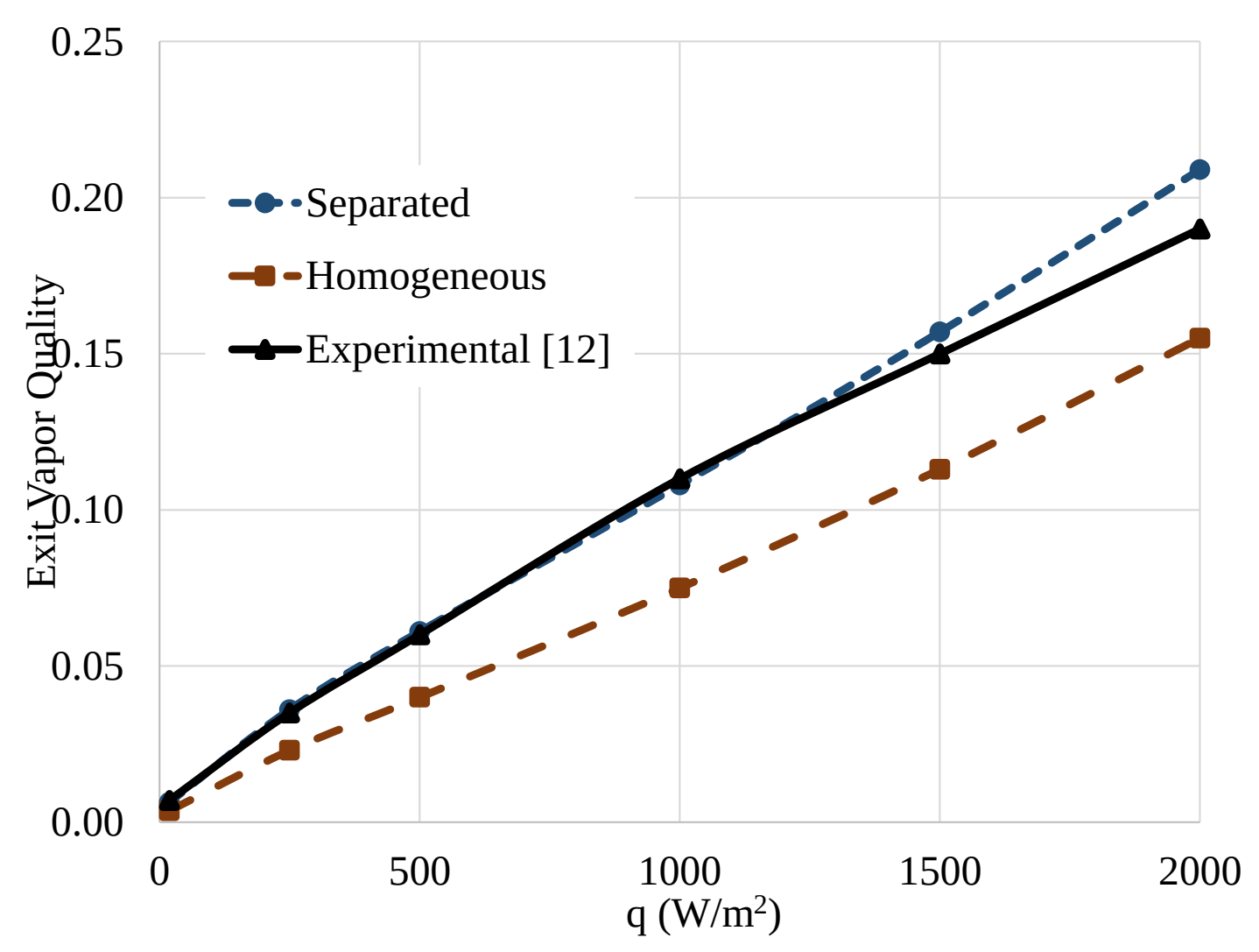
Production Solenoid Thermosiphon Results

Parameter	Separated Flow Model	Homogeneous Flow Model
Total Mass Flow Rate (kg/s)	0.068	0.07
Exit Vapour Quality (%)	6.6	6.4
Liquid Mass Flow Rate (kg/s)	0.063	0.065
Void Fraction	0.189	0.225
Slip Ratio	1.285	1

Model Validation

The design approach was validated by applying the design parameters of the experimental set up described in the paper by B. Baudouy, "Heat and Mass Transfer in Two-Phase He I Thermosiphon Flow" . The separated flow model was able to predict the experimental results with good accuracy up to a exit vapor quality of 10 – 15 %.





Conclusions

An analytical approach to designing a thermosiphon cooling system has been demonstrated. The separated flow model agrees well with experimental results. Although, the homogeneous model does not agree very well with experimental results. We believe that the separated flow model may be used to design thermosiphon cooling schemes accurately up to about 10-15 % exit vapor quality as seen from the comparison plots.

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