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Forced two-phase helium cooling scheme for Mu2e Transport Solenoid

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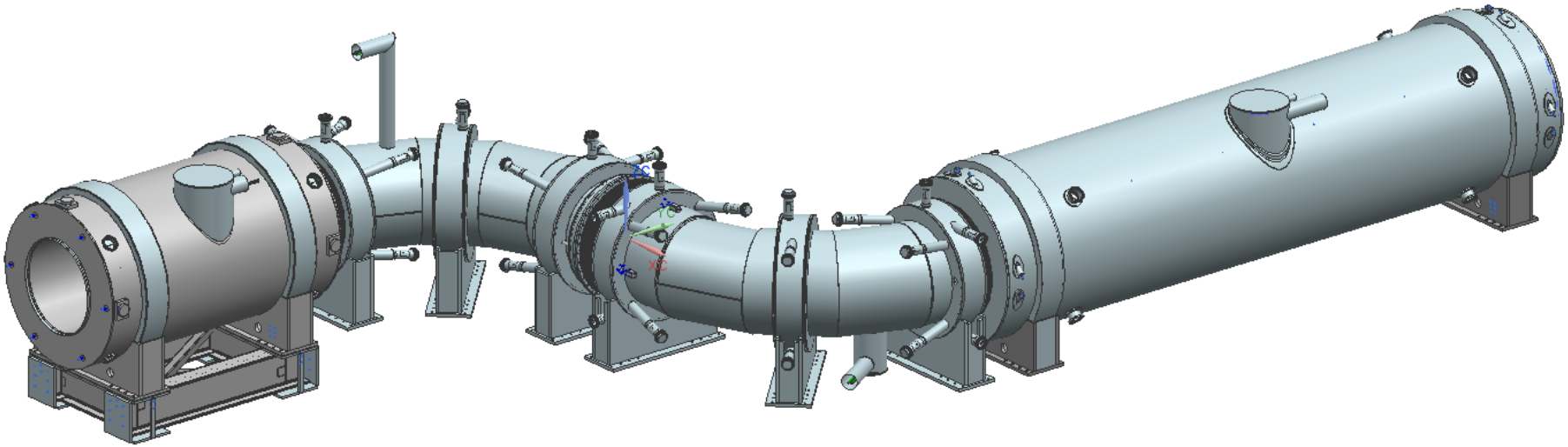
Experimental hall layout

Production Solenoid (PS)

Transport Solenoid (TS)

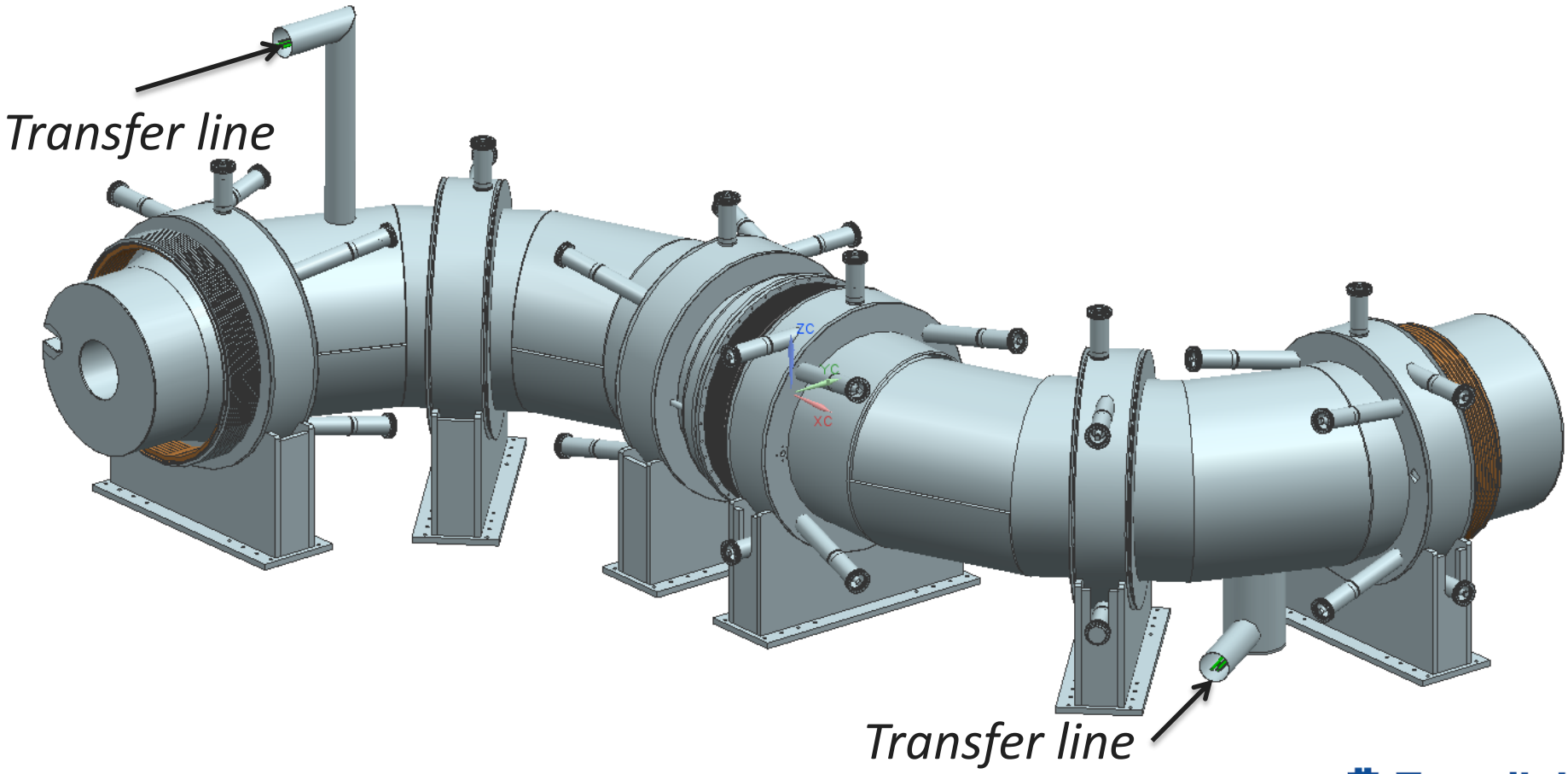
Detector Solenoid (DS)



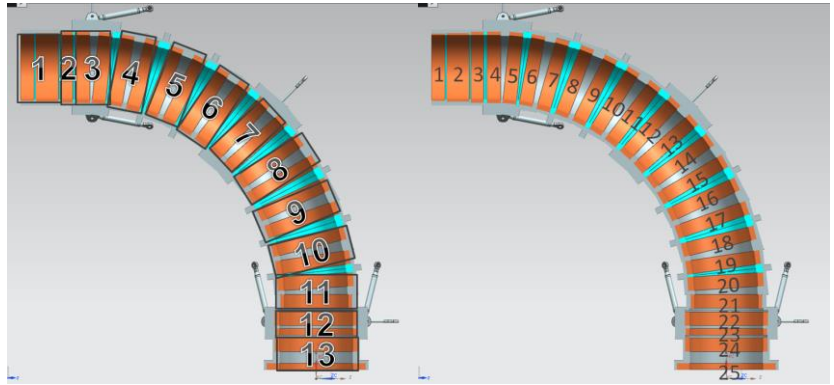
TS layout

Transport Solenoid Upstream (TS-u)

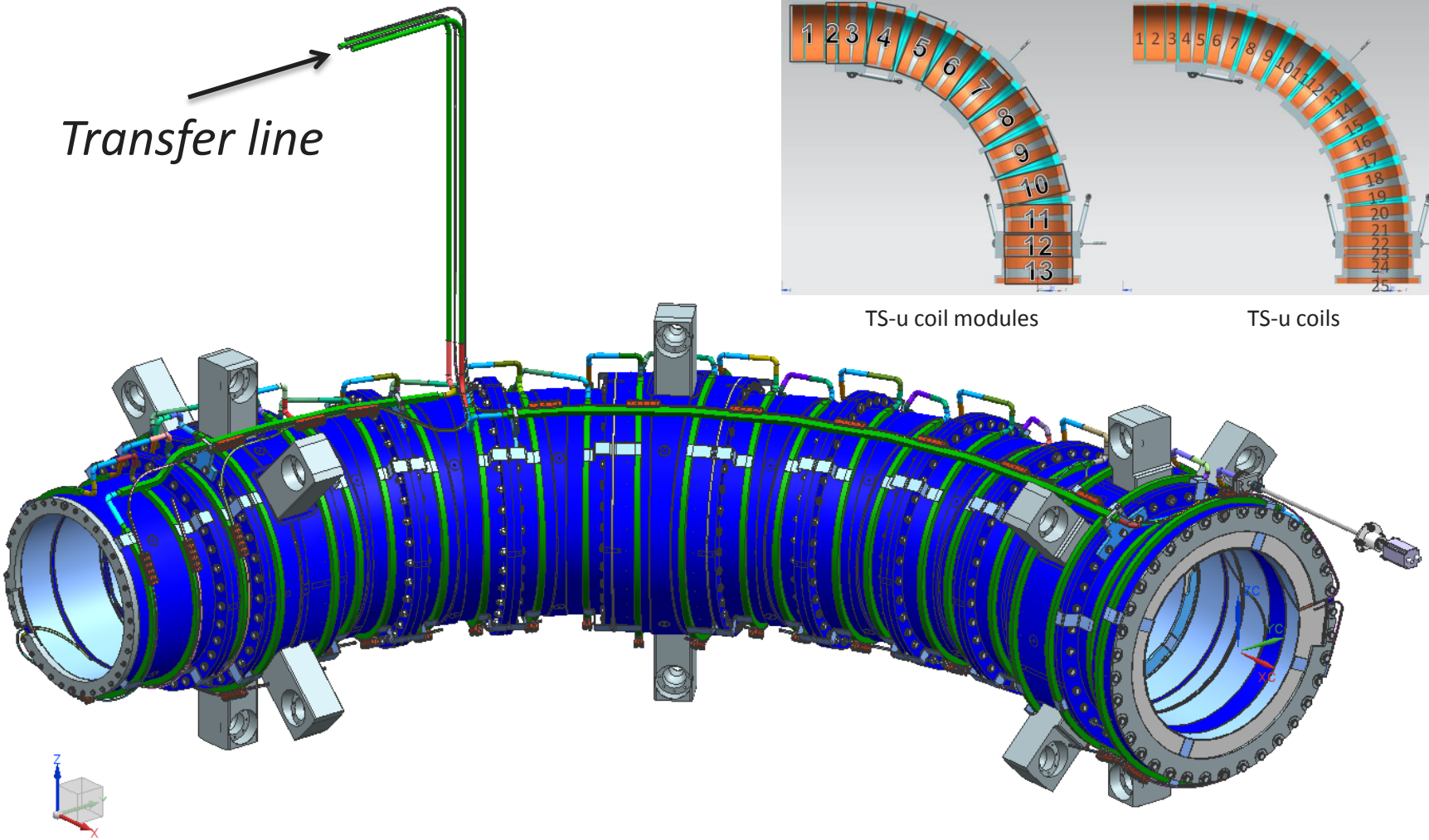
Transport Solenoid Downstream (TS-d)



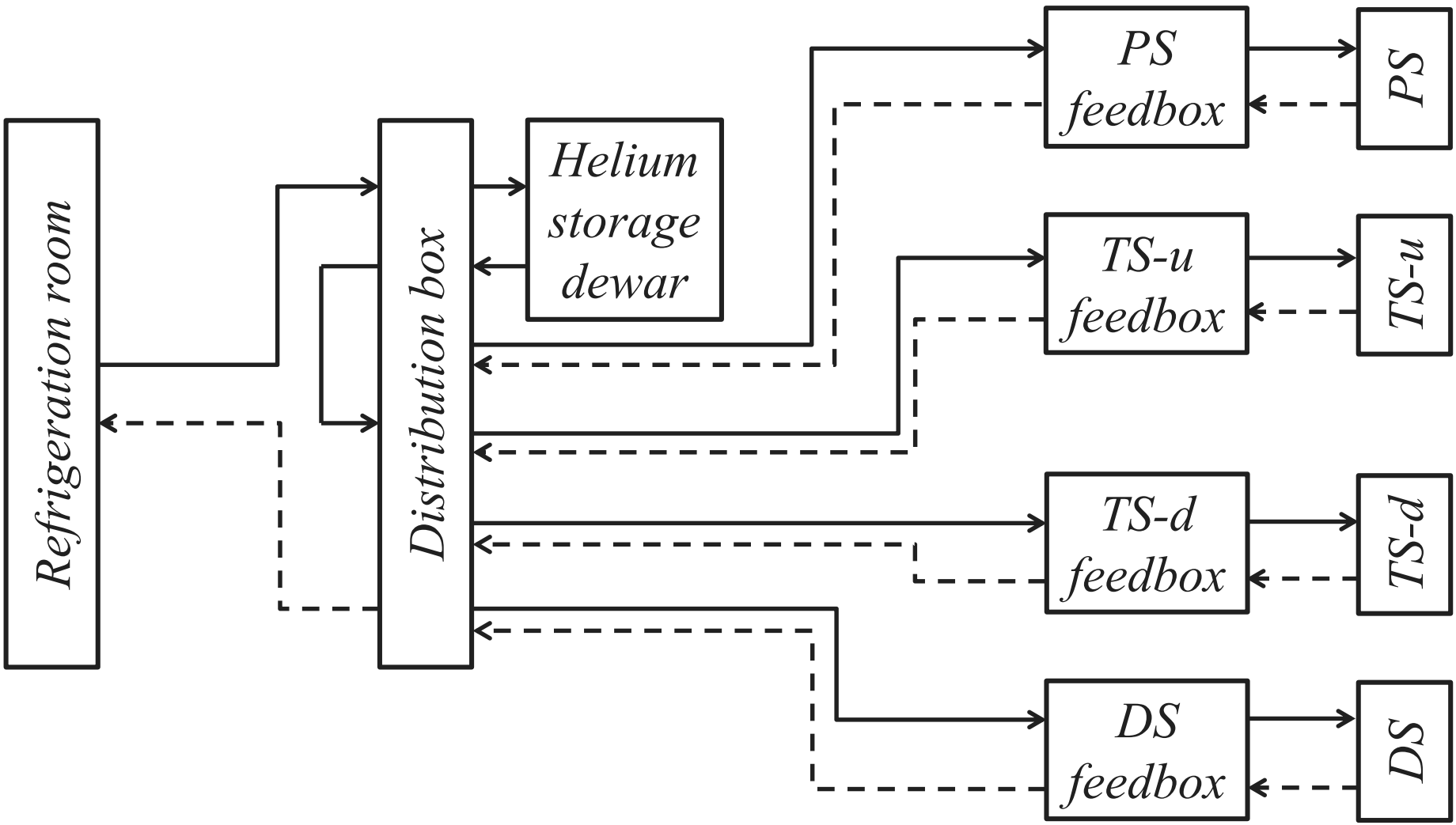
TS-u with vacuum shield removed



TS-u coil modules TS-u coils

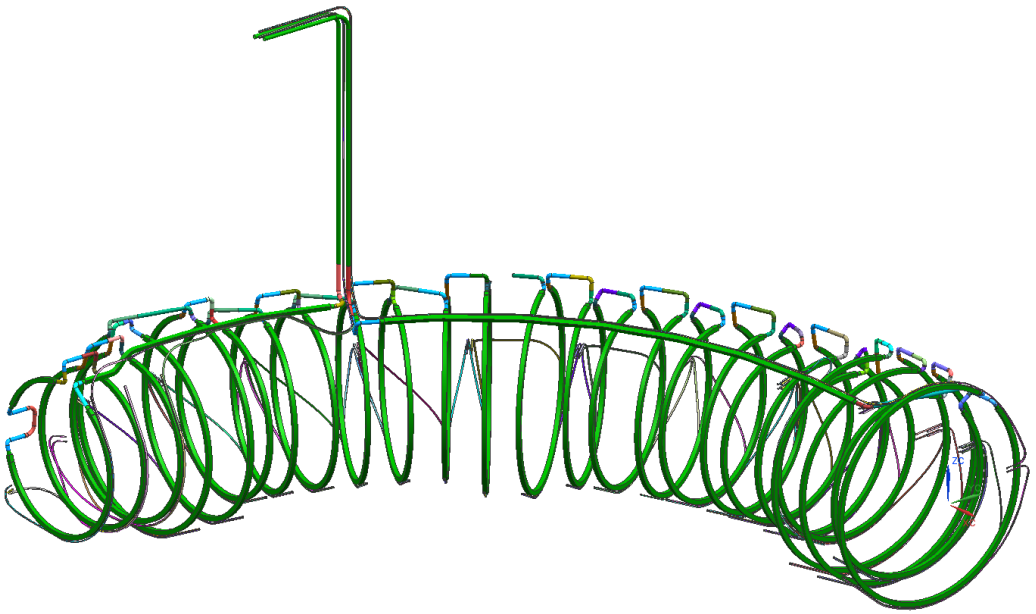


Generalized helium flow schematic for Mu2e



TS-u He cooling lines

- ΔZ ~5 m from feedbox to solenoids
- Transfer line length from feedboxes ~25 m
- TS-u nearly identical to TS-d
  - 0.875 in tube ID
  - 25x cooling coils
    - 18x Ø1m rings
    - 7x Ø1.25m rings
  - Total tubing length in TS-u ≈ 105 m
  - 103x 90° bends
    - r/d ≈ 1.14



Calculation inlet conditions

- Inlet conditions at the TS feedboxes
  - Saturated liquid helium
  - 4.77 K
  - 9 gm/sec
- Heat loads
  - Transfer line: 14 W
  - TS-u heat loads:

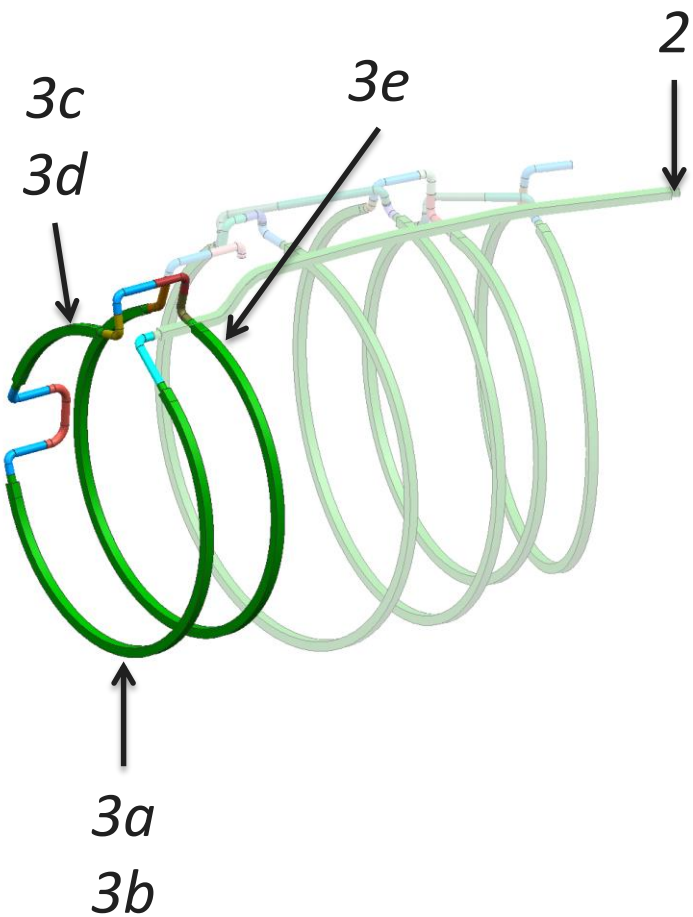
Support section	Coils	Heat (W)			
		Radiation	Dynamic load	Support load	Total
	25-24	0.51	0.00	0.00	0.51
3	23-22	0.48	0.00	9.20	9.68
	21-14	2.11	0.00	0.00	2.11
2	13-12	0.60	0.00	3.60	4.20
	11-6	1.56	0.00	0.00	1.56
1	5-4	0.52	0.00	9.20	9.72
	3-1	0.76	0.05	0.00	0.81
				Σ	28.59

MAX heat load

Equations used

- Pressure drop
  - Horizontal flow
    - Rane T et al. 2011 Improved correlations for computations of liquid helium two phase flow in cryogenic transfer lines, *Cryogenics* **51** 27-33
  - Vertical upwards flow
    - Fridel correlation
      - Thome J 2004 *Engineering databook III* Wolverine Tube Inc.
    - Found to yield more conservative estimates as compared to:
      - Khalil A 1978 Cryogenic two-phase flow characteristics of helium I in vertical tubes (doctoral dissertation) *University of Wisconsin-Madison*
  - Vertical downwards flow
    - Rane equation used for pressure drop
    - Downwards flow static head addition not included

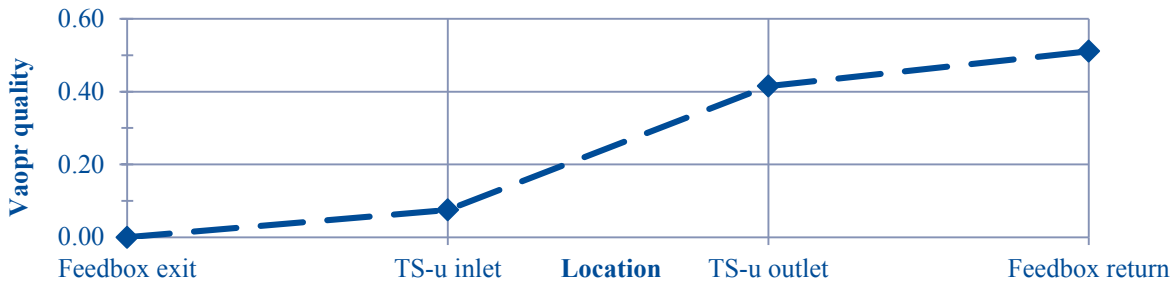
Calculation methodology

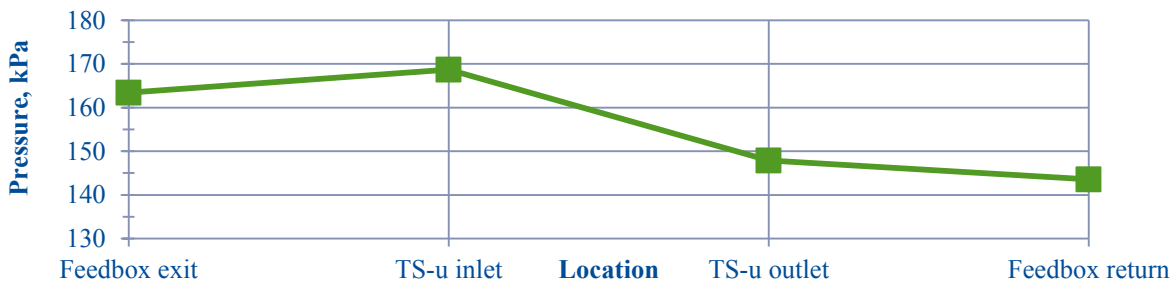


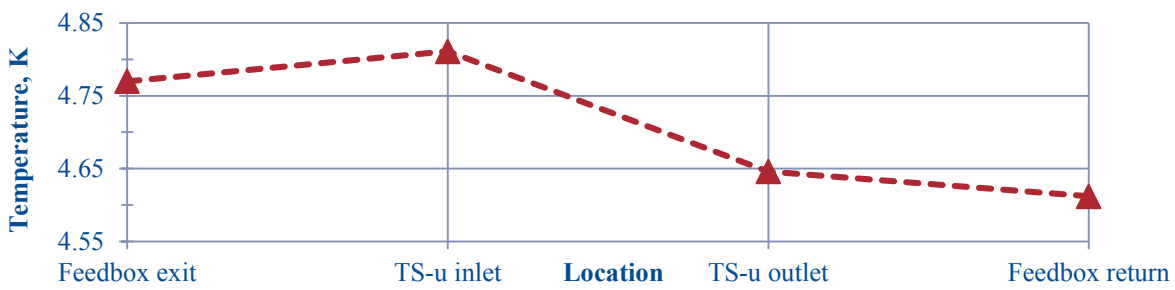
1. Start with known inlet conditions at feedboxes
2. Calculate properties at TS inlet knowing heat input and pressure drop of transfer lines
3. Inside TS
   a) Use “vertical downwards flow” equations from “equations” slide to determine conditions at the bottom of coil #1
   b) Re-calculate He properties
   c) Use “vertical upwards flow” equations from “equations” slide to determine conditions at the top of coil #1
   d) Re-calculate He properties
   e) Repeat procedure for coils 2 – 25, not recovering static head addition in vertical upwards flow segments
4. Calculate properties back at feedboxes using same inputs as in step 2

Results

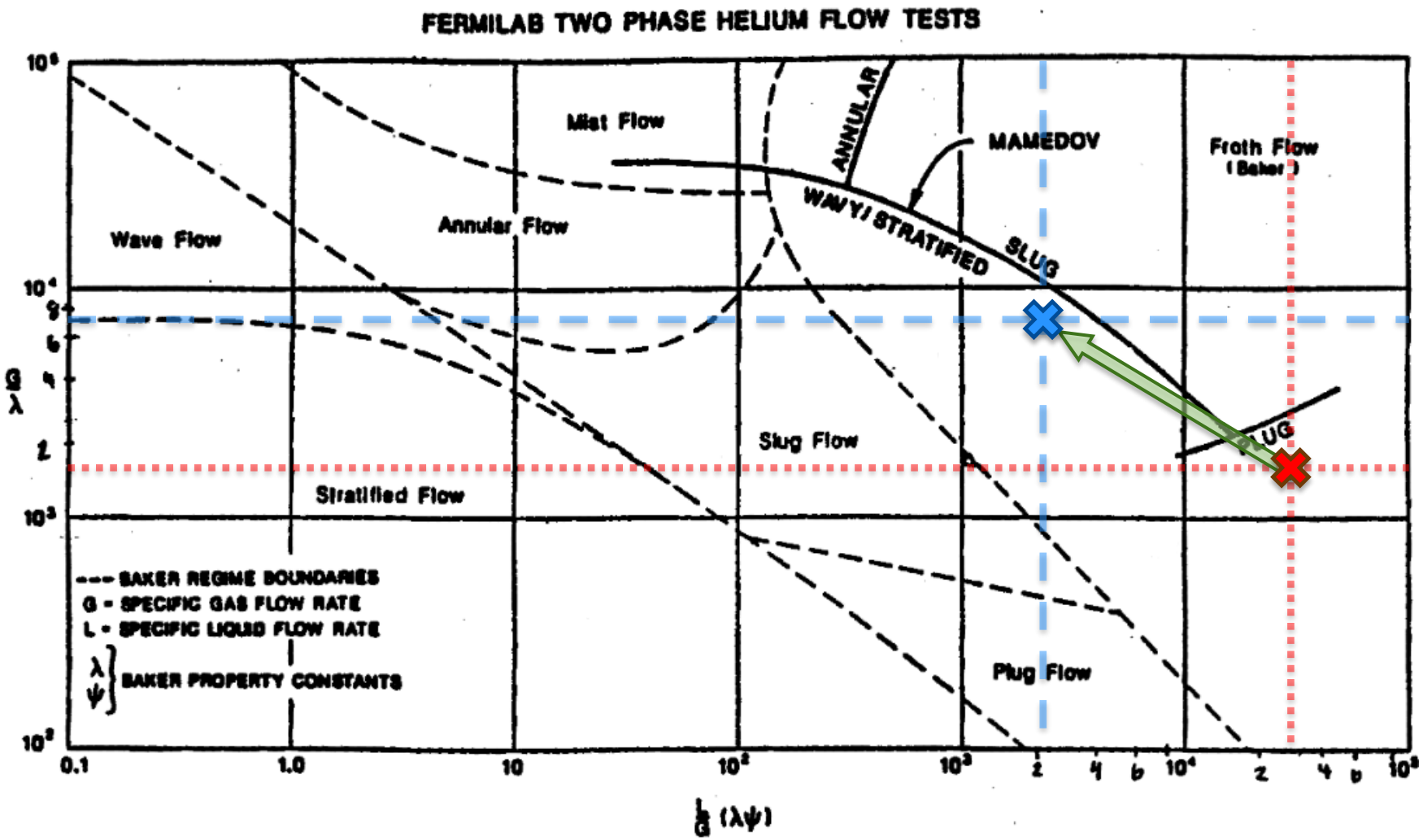
TSU coil	Temperature (K)
1	4.82
2	4.81
3	4.81
4	4.80
5	4.79
6	4.78
7	4.78
8	4.77
9	4.76
10	4.76
11	4.75
12	4.75
13	4.74
14	4.73
15	4.73
16	4.72
17	4.72
18	4.71
19	4.70
20	4.69
21	4.69
22	4.68
23	4.68
24	4.67
25	4.67







TSU inlet and outlet – horizontal flow regime map



J. C. Theilacker, C. H. Rode, *An investigation into flow regimes for two-phase helium flow*, Presented at the Cryogenic Engineering Conference, St. Charles, Illinois, June 14-18, 1987

Pros/cons of using a two-phase cooling scheme

ADVANTAGES:

- Lower mass flow rate
  - Avoids the use of a circulation pump (~$200 k)
- Nearly isothermal magnet cooling
- Less refrigeration load when compared to single phase cooling scheme
- Beneficial when design heat load is exceeded

DISADVANTAGES:

- Available literature for upwards flow pressure drop
- Flow separation concerns
- Need for complex engineering analysis
- “Garden-hose” effect

Disadvantage: “Garden-hose” effect

- Long-period pressure and temperature oscillations seen in two-phase helium flow
- Why the name “garden-hose”?
  - Imagine a coiled garden hose half full of water hanging from a horizontal peg
  - When purging the hose of water, addition pressure is required to force the water out of the hose due to the various heads of water in each of the loops
    - Also causes pressure oscillations as liquid slugs exit the hose
- May be related to “hydrodynamic slugging”
- Observed experimentally in:

1) Green M 1980 *The TPC magnet cryogenic system* LBNL Paper LBL-10552M
2) Green M et al. 1979 Forced two-phase helium cooling of large superconducting magnets *Advances in Cryogenic Engineering* **25** p 420-30
3) Haruyama T et al. 1988 Pressure drop in forced two phase cooling of the large thin superconducting solenoid *Advances in Cryogenic Engineering* **33** 543-9
4) Green M et al. 1978 A large high current density superconducting solenoid for the time projection chamber experiment *Presented at the International Cryogenic Engineering Conference 7* London, England
5) Haruyama T et al. 1994 Cryogenic characteristics of a large thin superconducting solenoidal magnet cooled by forced two-phase helium *Cryogenics* **34** 647-50

http://cmapspublic.ihmc.us/rid=1JDJB9Z7J-10YPJTV-1PDD/garden%20hose.jpg

“Garden-hose” (GH) effect in literature

- An approximation to GH pressure drop is given in Equation (1)
  - $\Delta P_{GH} = \frac{0.8x_{exit}}{2}\left[(\rho_l - \rho_g)\big|_{inlet} + (\rho_l - \rho_g)\big|_{outlet}\right] dNgcos\theta$ (1); from Reference 1
  - When TS conditions are applied, $\Delta P_{GH} \approx 7$ kPa (less than the contribution from not recovering static head on the downwards flow segments)

Nomenclature:

x_exit	exit steam quality
ρ_l	liquid density
ρ_g	vapor density
d	coil diameter
N	number of coils
g	acceleration due to gravity
$cos\theta$	equal to 1 for vertical flow

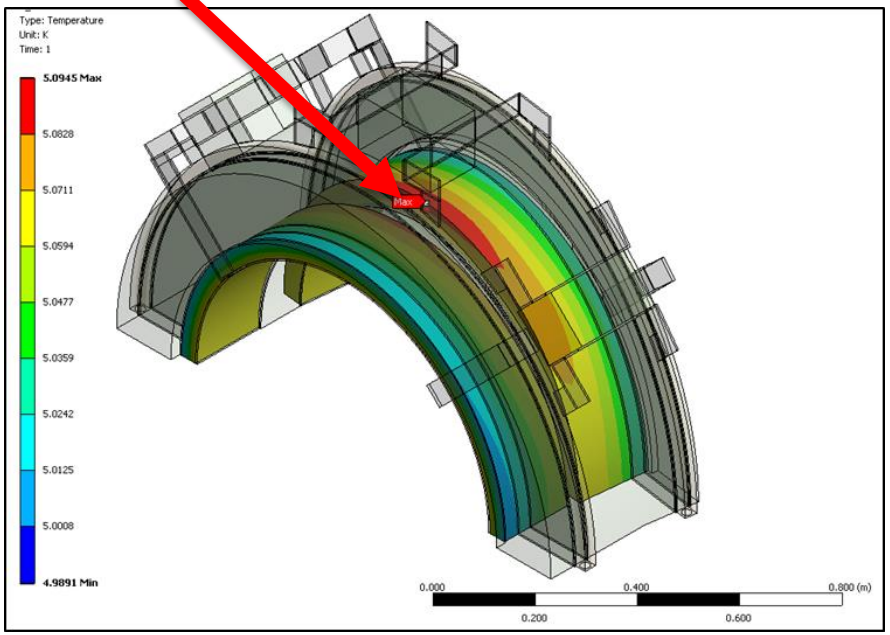
“Garden-hose” pressure drops seen in literature

Ref.	Coil ID (mm)	Coil diameter (m)	Number of coils	Flow rate (gm/sec)	Pressure drop (kPa)	GH pressure oscillation (kPa)	GH oscillation period (sec)	Notes
1	15.1	Main coil: 2.21 Comp. coils: 0.35	Main coil: 52 Comp. coils: 45	12	17.2 (predicted)	Peak to valley equal to total GH Δp	30	---
2	16.6	0.9	160	4 to 5	20.0 (measured) 24.0 (predicted)	20.0 peak to peak	30	When these parameters are inserted to the TS calculation, Δp is 4x higher
3	18	2.9	N/A	8 to 20	1.9 to 3.9 (measured) 1.0 to 3.9 (predicted)	Not observed	N/A	150 m piping length arranged in a serpentine Homogeneous flow model for predicted pressure drop
4	15	2.2	192 turns 64 active turns	12	30.4 (predicted)	20.3 (predicted)	30	Test performed on 1 m diameter test coil, with 20.3 kPa of pressure drop observed
5	25	3.8	N/A	5 to 11	1.1 to 3.0	1.7 peak to peak differential pressure	5 to 6	64 m piping length arranged in a serpentine Coil temperature increases by 10 mK due to GH effect

Coil temperature simulations with and without "garden-hose" effect

5.095 K MAX

Conductor critical temperature: 6.70 K



Steady-state two phase simulation parameters:

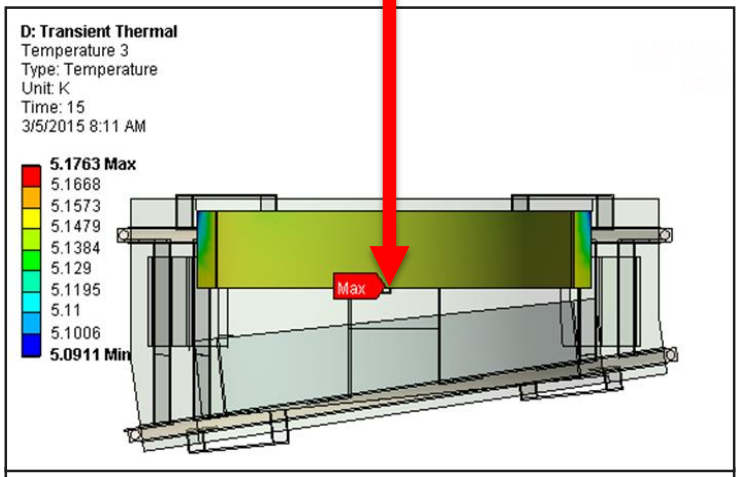
TSU support section #1

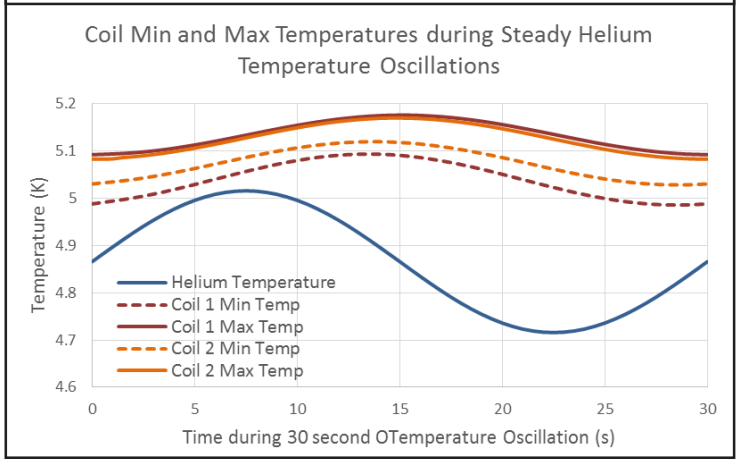
1.5x heat load from "Input conditions" slide

Fluid temperature: 4.809 K

Convection coefficient: 1264 ($^{W}/_{m^2K}$)

5.176 K MAX





"Garden-hose" simulation additional parameters:

Fluid temperature oscillation: +0.200 K, -0.100 K

Oscillation period: 30 seconds

Thank you