Solenoid Magnet System

Outline

- Introduction
- Scope
- Key Design issues
- Conclusions

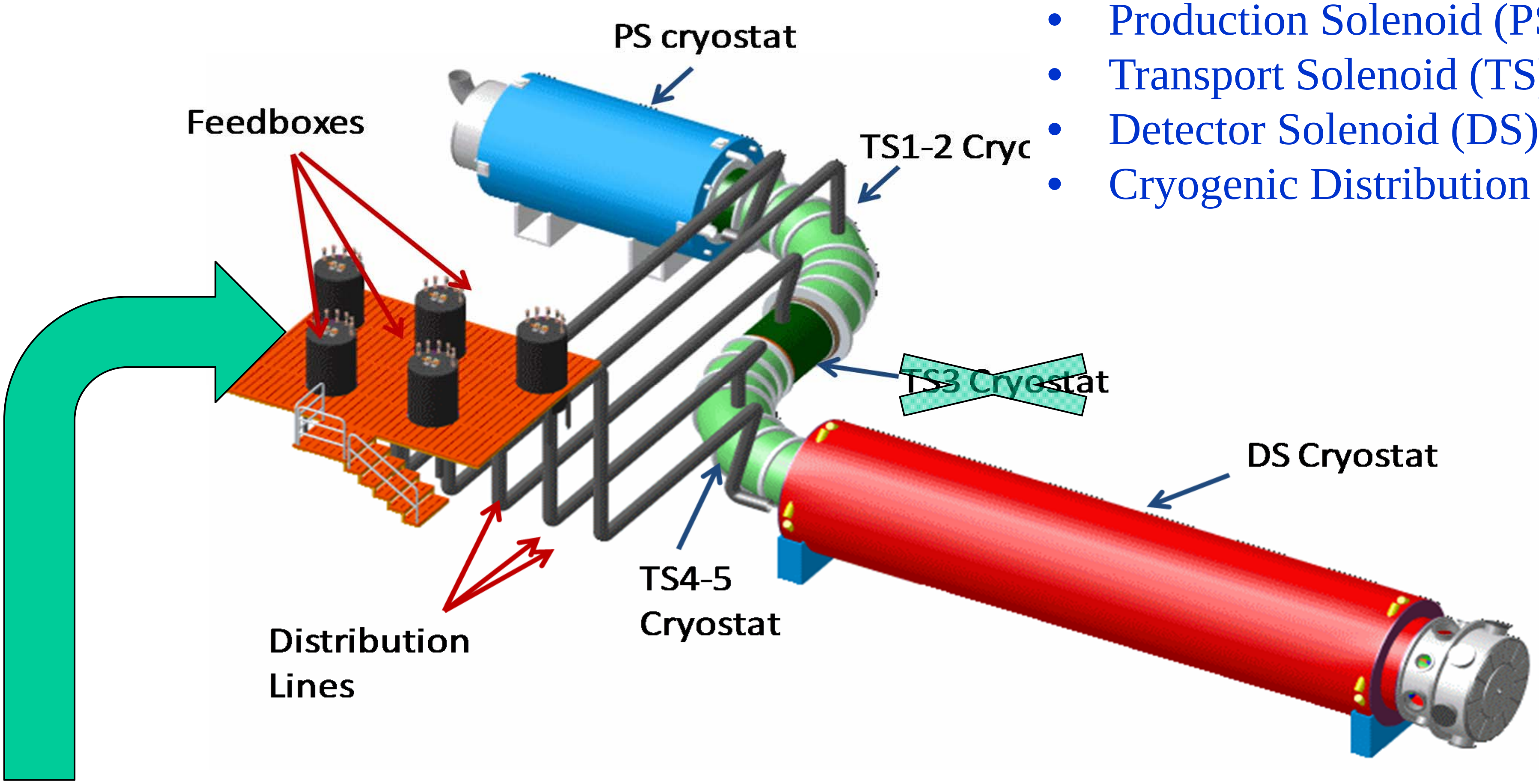
RESMM'12

February 13, 2011

Michael Lamm
For the Mu2e Solenoids

L2 Solenoid

- Production Solenoid (PS)
- Transport Solenoid (TS)
- Detector Solenoid (DS)
- Cryogenic Distribution



- Power Supply/Quench Protection
- Cryoplant (actually off project)

- Field Mapping
- Ancillary Equipment
- Insulating vacuum
- Installation and commissioning

Design Specifications

- Field quality
  - Monotonic axial gradients in transport straight sections
  - Field uniformity in spectrometer
- Quench margin and stability
  - 1.5 K in temperature, 30-35% in Jc along load line, stability (TBD)
  - Stabilizer resistivity, conductor heat capacity, thermal conductivity
- Fits within the cryogenic budget
  - 1 Satellite refrigerator steady state
  - 1-2 Additional refrigerators for cooldown/quench recovery
- Limited radiation damage
  - Superconductor and insulation secondary to stabilizer degradation
  - RRR reductions and annealing compatible with planned thermal cycles
  - Frequency of thermal cycles (for radiation repair) coincides with expected accelerator and/or cryogenic operation cycles

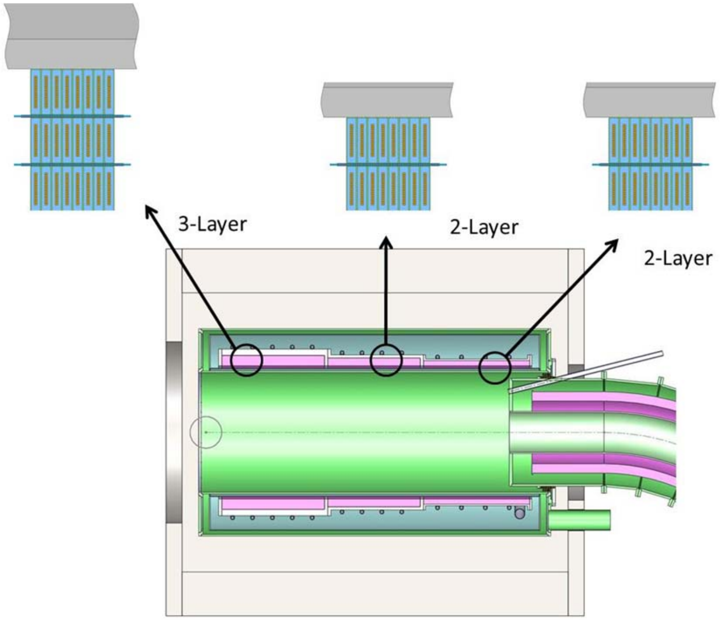
Cost and Time Considerations

- Cost is a major factor
  - Raw materials for both magnet and shields
  - Pool of vendors capable of building large-complex magnets
  - Simplified infrastructure with commonality to rest of muon campus
- Time Constraints
  - Magnets are on the critical path for most of project life.
  - Present Schedule
    - June 2012: Prototype conductor order (1 year lead time)
    - June 2013:
      - Place order for conductor production run
      - Place contract for magnet fabrication

Argues for using proven technologies

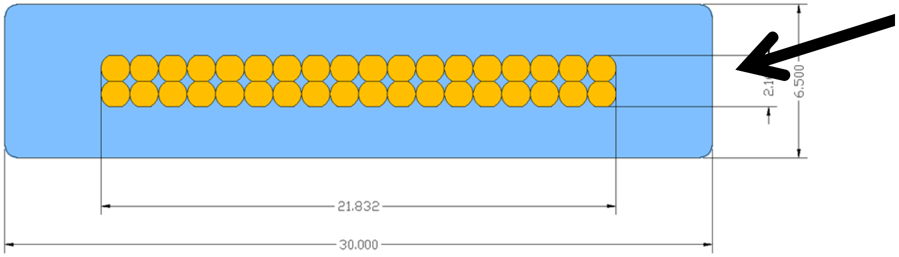
PS Baseline Design

4-5T➔ 2.5 T Axial Gradient



Gradient made by 3 axial coils same turn density but increase # of layers (3,2,2 layers)

- Wound on individual bobbins
- I operation ~9kA
- Trim power supply to adjust matching to TS
- Indirect Cooling (Thermal Siphon)



Aluminum stabilized NbTi

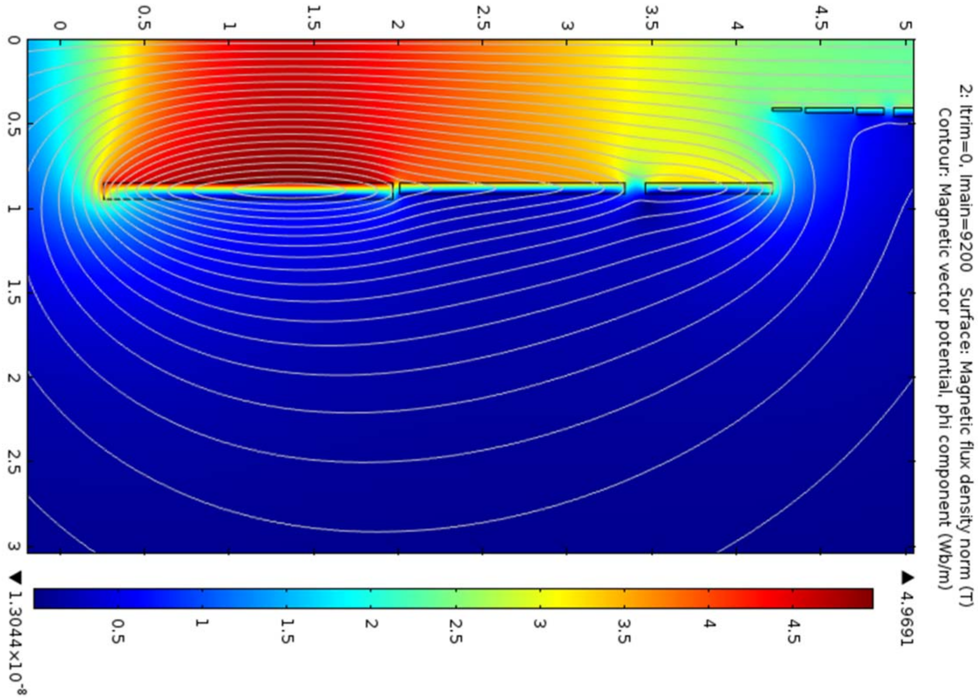
- reduce weight and nuclear heating
- Special high strength/high conductivity aluminum needed (like ATLAS Central Solenoid)

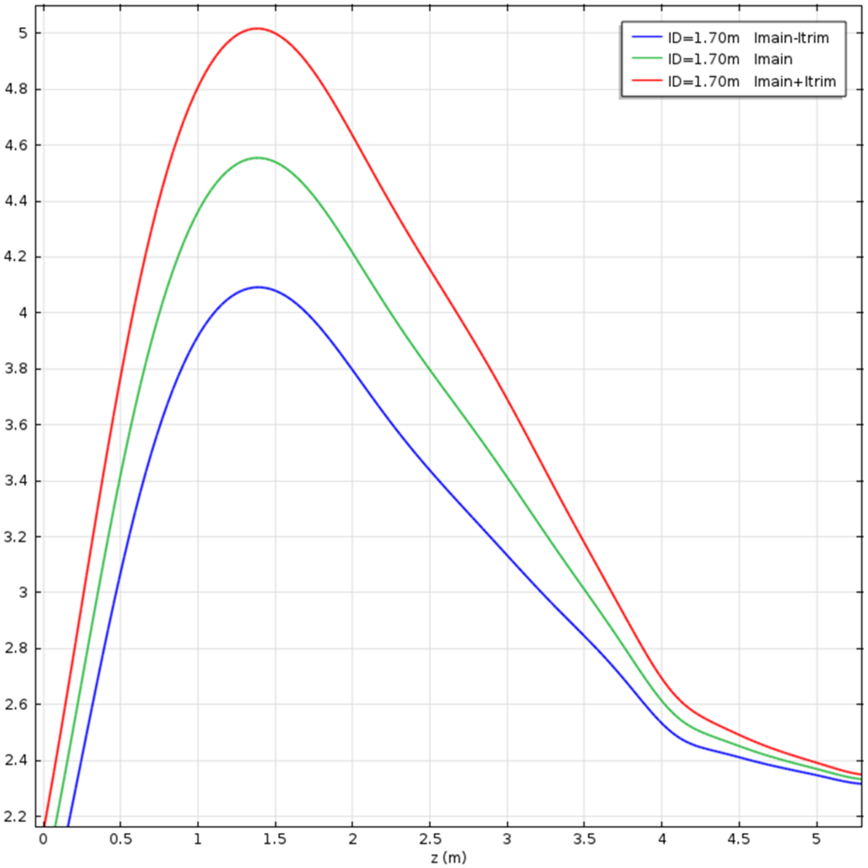
Vadim Kashikhin, task leader

See Next Presentation

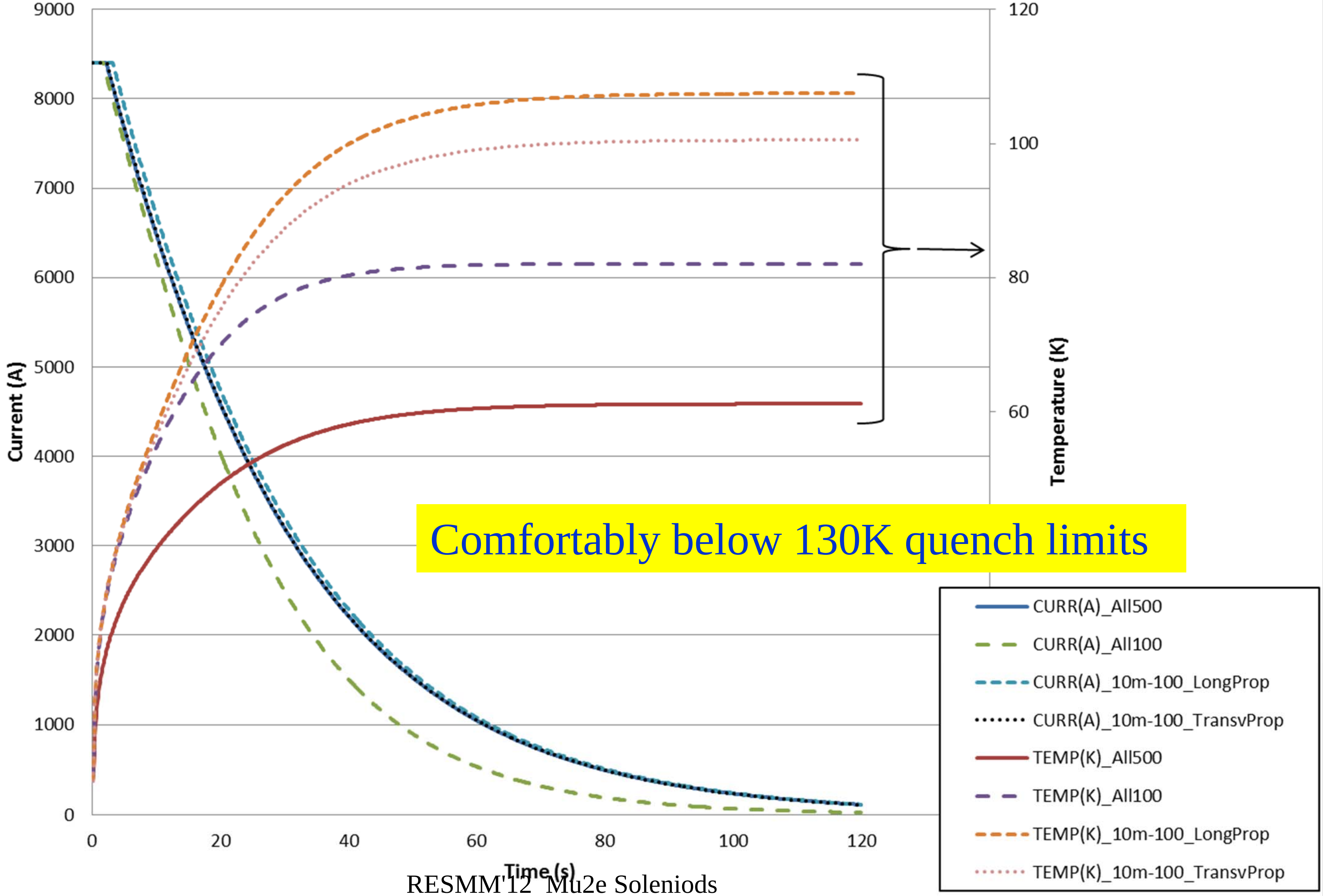
3-2-2 magnet design

Gradient Uniformity meets field spec.





PS Quench Studies

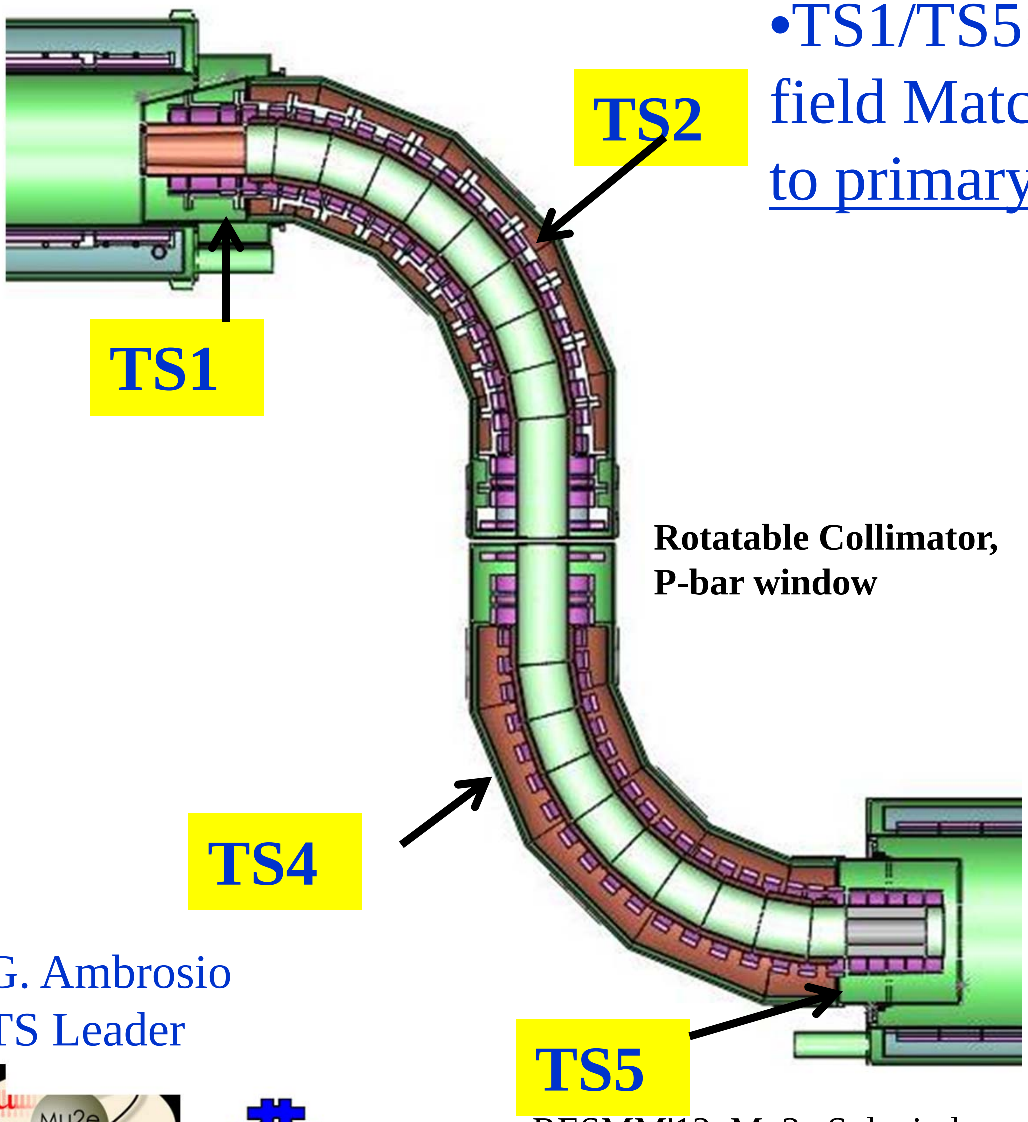


Comfortably below 130K quench limits

Quench Stability

- Is magnet stable against quenches caused by expected mechanical motion?
    - Motion of strand within cable
    - Motion of cable within epoxy
    - Epoxy Cracks
- Difficult to predict from first principles
    - Comparison to successful magnet of similar design
    - Scale with properties of material elements
    - Important material attributes:
        - Thermal conductivity
        - Resistivity at operational fields
        - Heat capacity
- This will be covered in the next talk….

New baseline Transport Solenoid

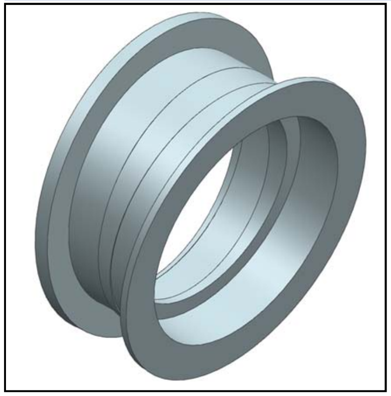


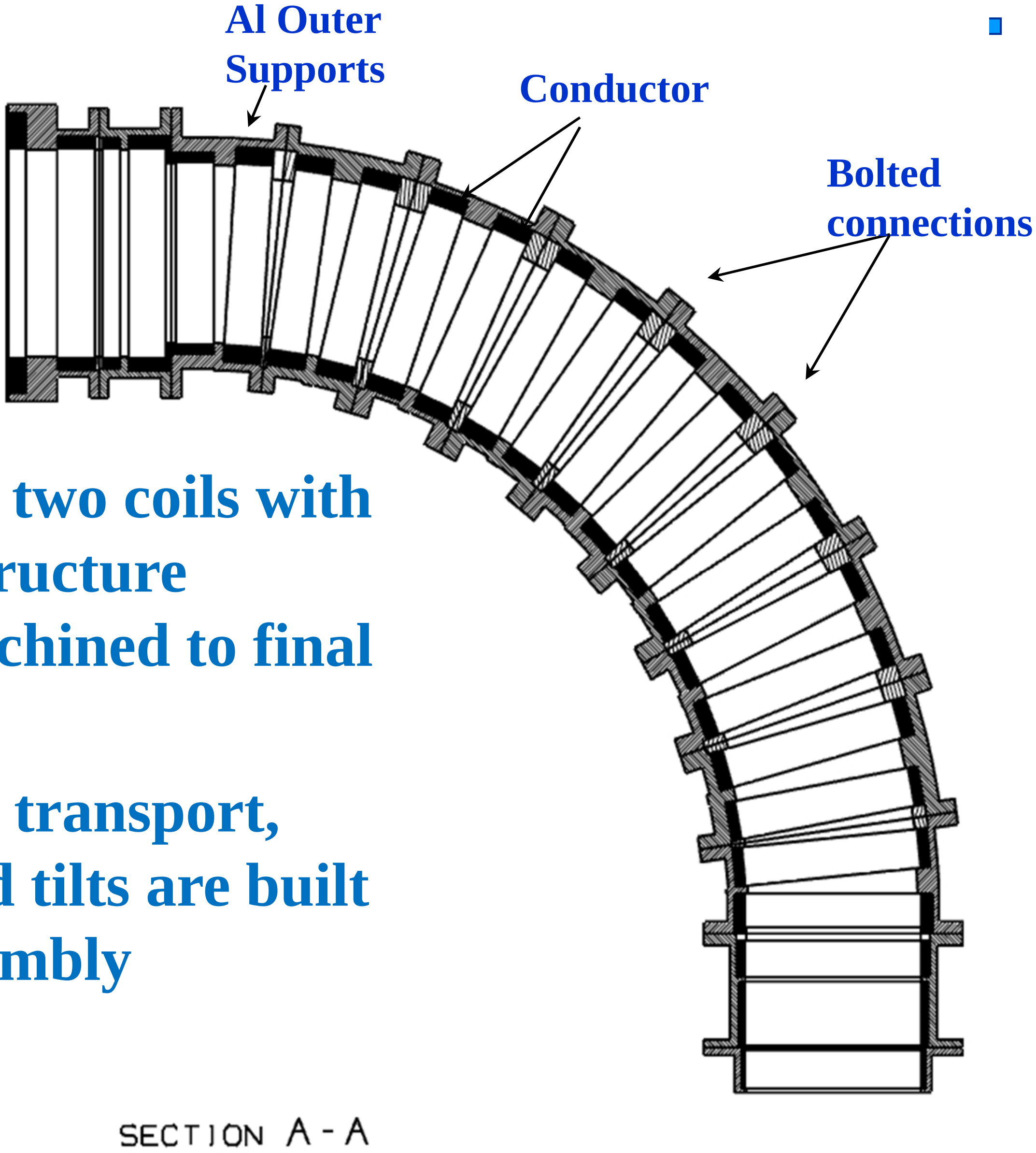
Rotatable Collimator,
P-bar window

- TS1/TS5: Negative axial gradient and field Matching to PS/TS TS1 subject to primary target radiation
- TS2/TS4: Horizontal tilt to compensate for horizontal drift
- TS3: ➔ TS3U, TS3D. Wider coils to compensate for gap
- Two cryostats: TSU, TSD
- New coil fabrication proposed

G. Ambrosio
TS Leader

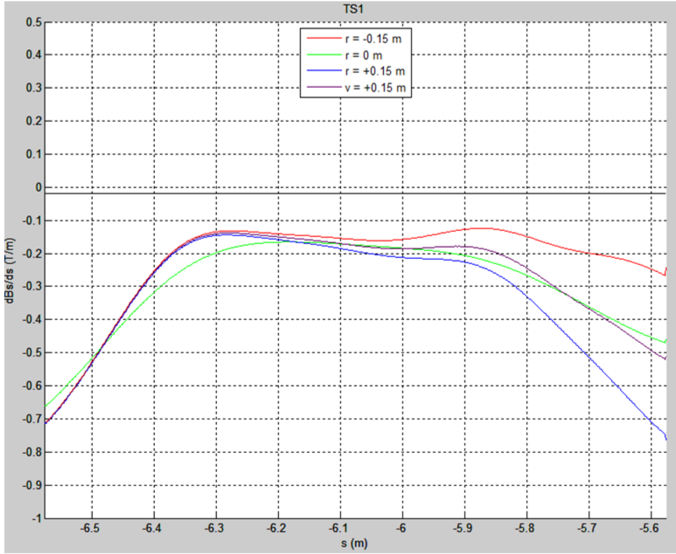
Coil Fabrication

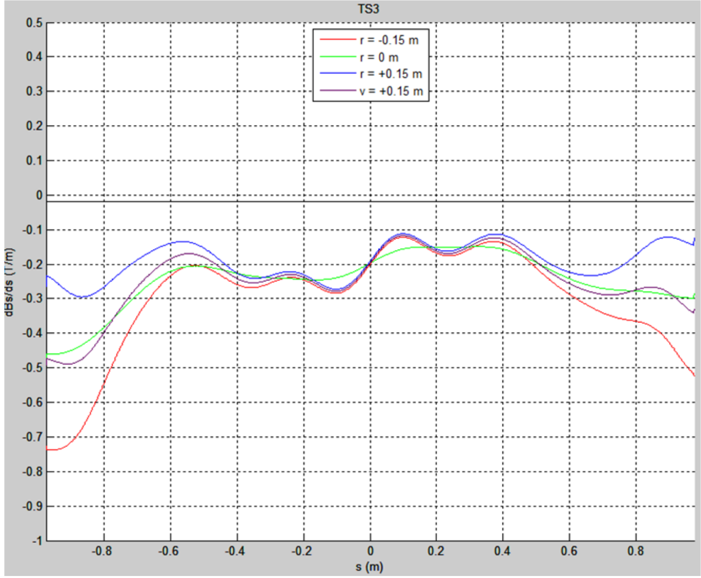




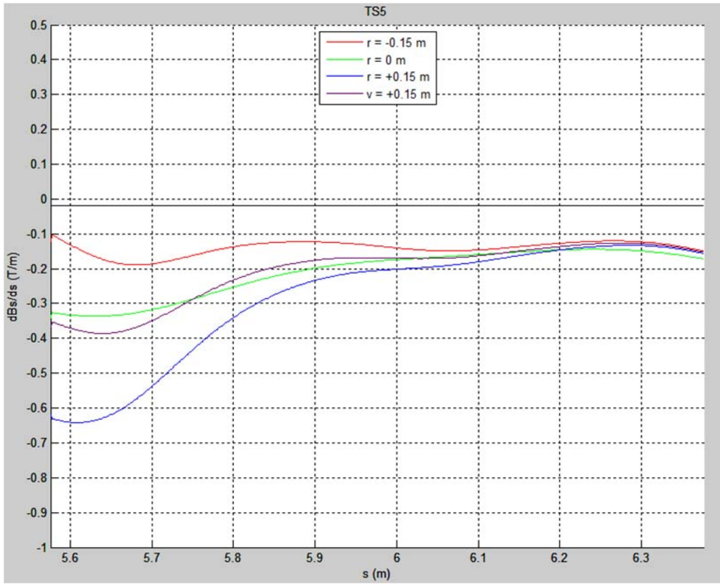
- **Fabrication unit consists of two coils with outer support aluminum structure**
- **Forged aluminum ring, machined to final shape**
    - **Placement of coil in transport, including bends and tilts are built into outer shell assembly**

TS field quality

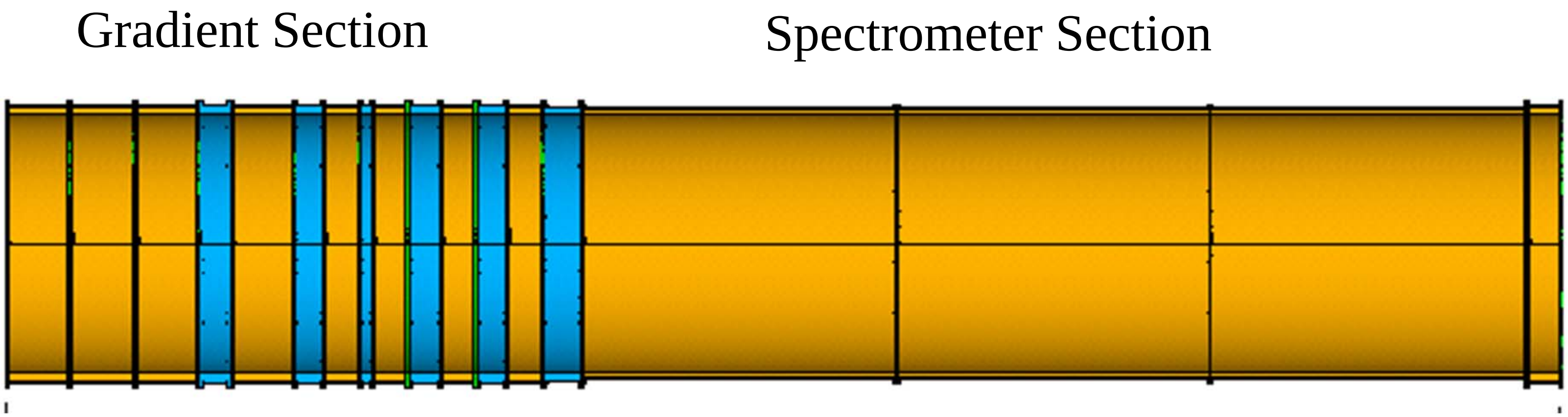




- Negative Gradient in all straight sections
- Smooth transitions between magnet elements
- Design focus: sensitivity to conductor placement on meeting specs.



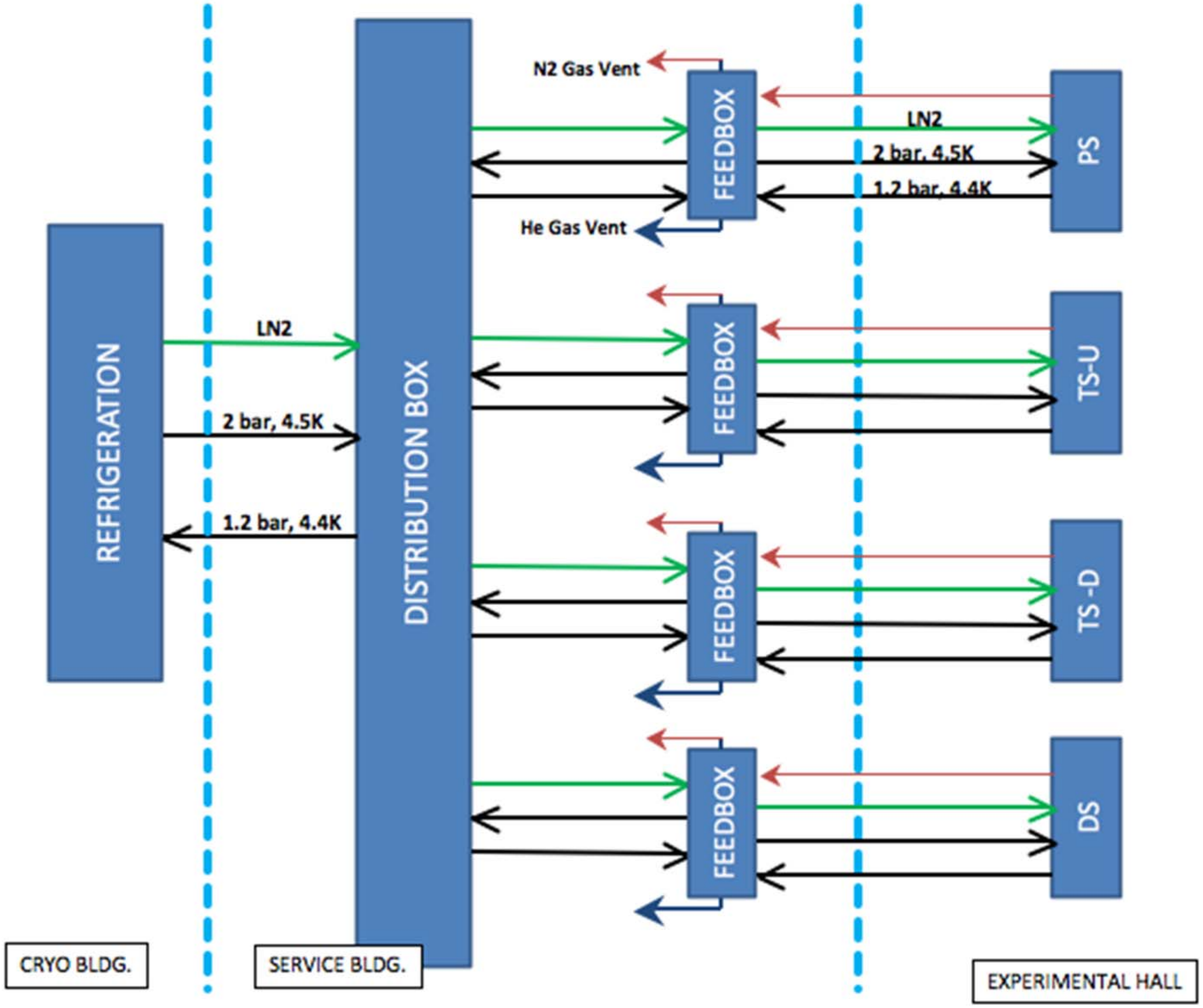
DS Baseline



- **Gradient section: 2 layer coils**
  - Gradient accomplished by use of spacers
- **Spectrometer: 3 <u>Single Layer</u> Coils ➔ shorter coils, greatly reduced conductor volume**
- **Relaxed calorimeter field requirements➔ shorten spectrometer**
- **<u>No significant materials issues with respect to radiation damage</u>**

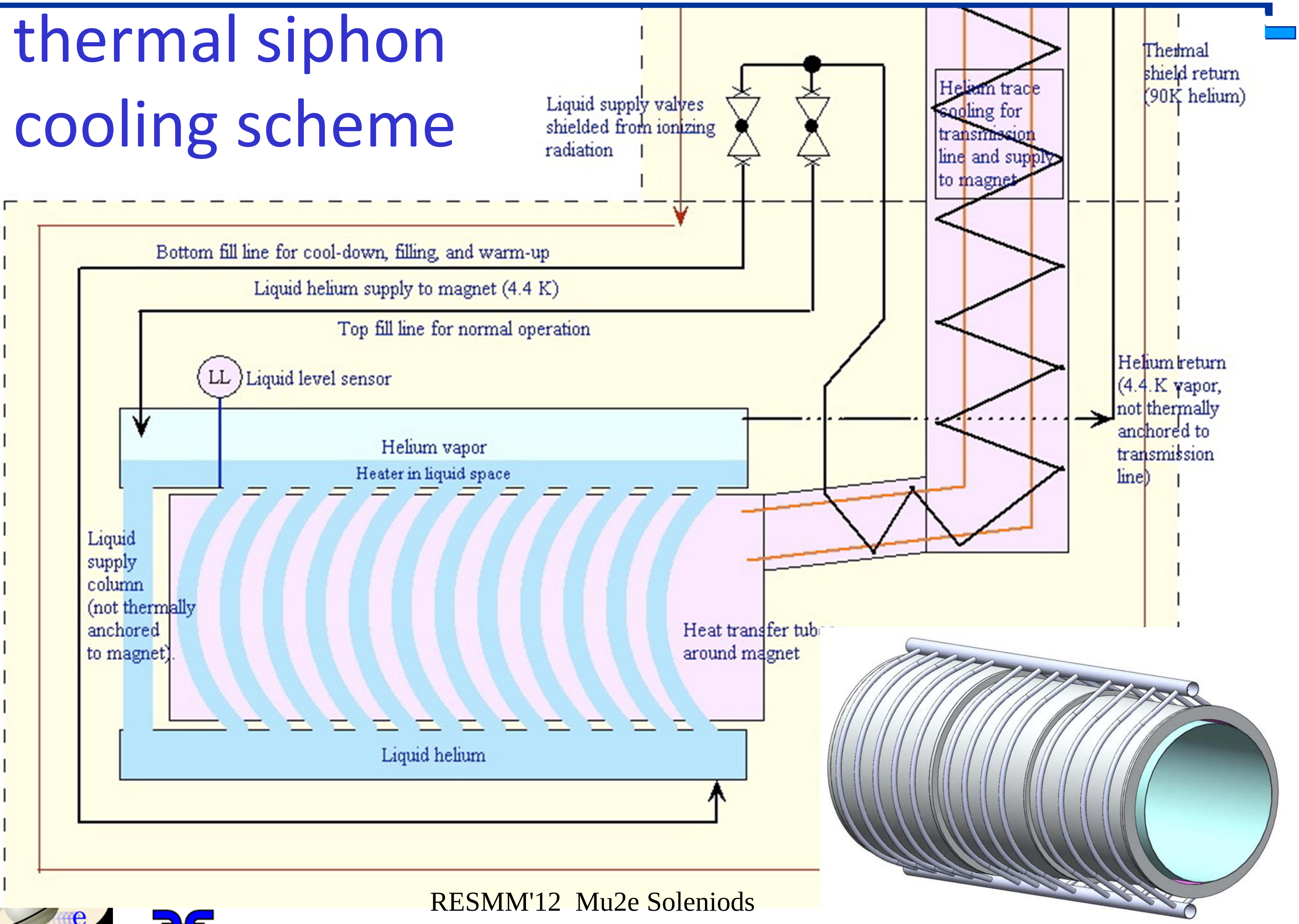
R. Ostojic
DS Leader

Cryogenic Distribution Scope



T. Peterson

Production solenoid thermal siphon cooling scheme



Thermal Siphon vs. Forced Flow

- Present baseline
  - Thermal Siphon for PS
  - Forced flow for TS and DS
- Advantages to Thermal Siphon
  - Maintain lowest temperature at magnet
  - Simple, passive→ cost effective for both design, fabrication and operation
- Advantage to Forced Flow
  - Can tie together circuits that are not well thermally coupled; less sensitive to geometric constraints (might be better for TS)
  - Less passive → more control

Refrigeration loads at 4.5 K

- **For cooling entirely with thermal siphons**
  - Total heat load at 4.5 K (which equals the refrigeration load) is 230 W
  - Total 4.5 K helium flow rate is 12 grams/sec
- **For cooling PS with thermal siphon and others with forced flow**
  - Total refrigeration load (which is circulating pump heat plus the transfer and magnet heat loads) = 350 W
  - Peak helium temperature (assuming 50 grams/sec circulating flow and a 4.50 K inlet temperature) = 4.68 K.

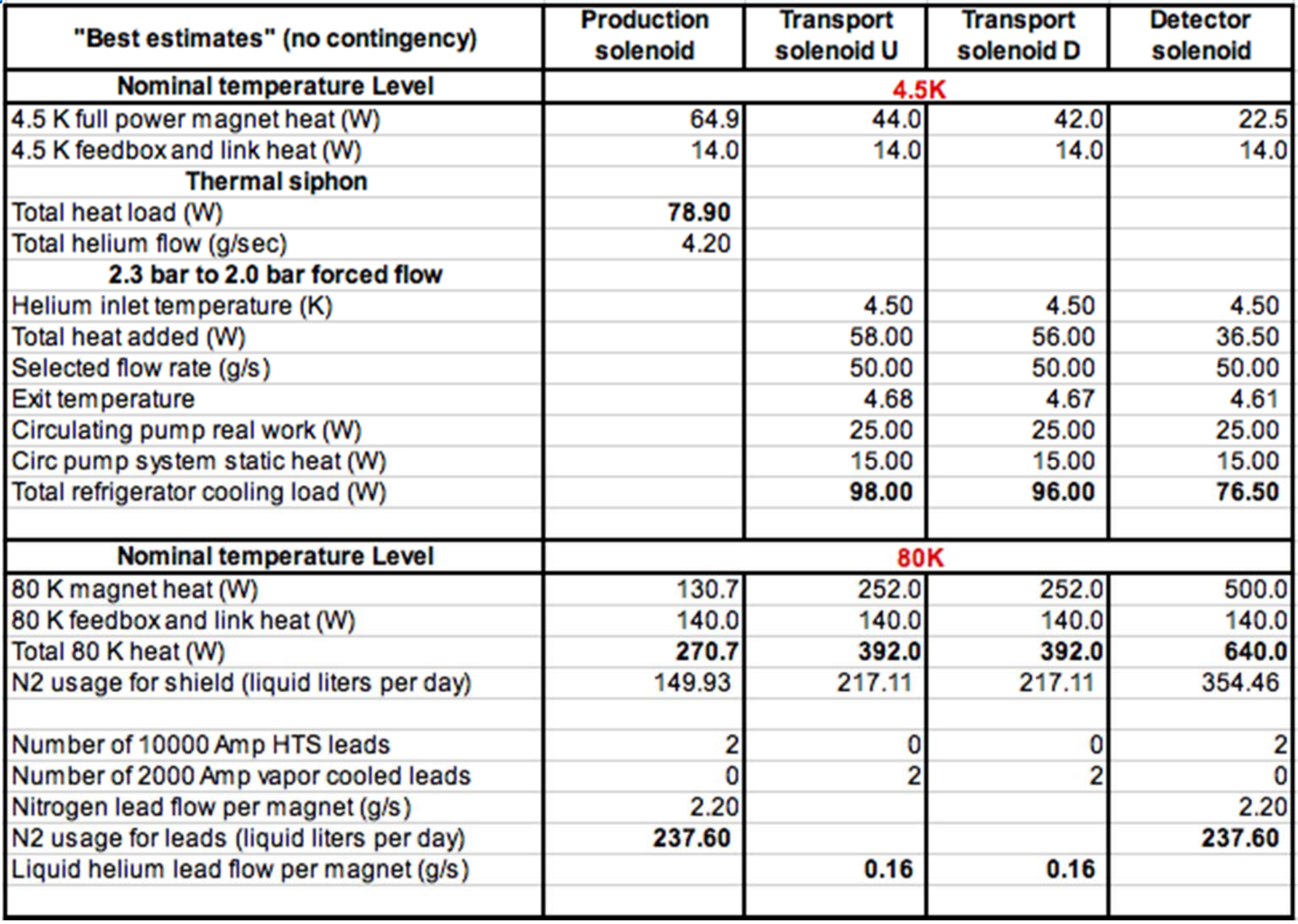
Cool-down and Warm-up

- **First look – Production Solenoid. Treat as simply 11.8 metric tons of aluminum for thermal energy estimate**
  - Start at 300 K and cool to 80 K by means of the same heat exchanger system used for thermal shield cooling
  - Then cool to 5 K by means of one satellite refrigerator running in liquefier mode (getting warm gas back)
- **Result**
  - Time from 300 K to 80 K is about 18 hours
  - Time from 80 K to 5 K is about 26 hours
- **Conclusion**
  - Assuming no constraints due to thermal stresses (no delta-T constraints) for the 80 K portion of the cool-down, one could cool the 11.8 ton PS solenoid in about 2 days.
  - This is just a rough estimate, but it seems reasonable considering that we cooled multi-ton SSC and LHC cold iron magnets at MTF in a day.
- **In reality, we may have some constraints so as not to thermally stress the magnet, resulting in a time of more like 4 – 7 days.**
- **Warm up time back to ~273K is comparable**

Conclusion

- Present design meets mu2e experiment requirements
- Radiation studies (presented in related talks) show that magnet temperature will not exceed 5K.
- Warm up to repair radiation damage: >1 between thermal cycles
  - Time for warm up/cool down 1-2 weeks
  - Consistent with reasonable expectations for accelerator operations
- **At 300 kGy/year,**
  - Damage to epoxy and superconductor ➔ > 20 year life time

Heat and flow estimates



"Best estimates" (no contingency)	**Production solenoid**	**Transport solenoid U**	**Transport solenoid D**	**Detector solenoid**
Nominal temperature Level	4.5K			
4.5 K full power magnet heat (W)	64.9	44.0	42.0	22.5
4.5 K feedbox and link heat (W)	14.0	14.0	14.0	14.0
Thermal siphon				
Total heat load (W)	**78.90**			
Total helium flow (g/sec)	4.20			
2.3 bar to 2.0 bar forced flow				
Helium inlet temperature (K)		4.50	4.50	4.50
Total heat added (W)		58.00	56.00	36.50
Selected flow rate (g/s)		50.00	50.00	50.00
Exit temperature		4.68	4.67	4.61
Circulating pump real work (W)		25.00	25.00	25.00
Circ pump system static heat (W)		15.00	15.00	15.00
Total refrigerator cooling load (W)		**98.00**	**96.00**	**76.50**
Nominal temperature Level	80K			
80 K magnet heat (W)	130.7	252.0	252.0	500.0
80 K feedbox and link heat (W)	140.0	140.0	140.0	140.0
Total 80 K heat (W)	**270.7**	**392.0**	**392.0**	**640.0**
N2 usage for shield (liquid liters per day)	149.93	217.11	217.11	354.46
Number of 10000 Amp HTS leads	2	0	0	2
Number of 2000 Amp vapor cooled leads	0	2	2	0
Nitrogen lead flow per magnet (g/s)	2.20			2.20
N2 usage for leads (liquid liters per day)	**237.60**			**237.60**
Liquid helium lead flow per magnet (g/s)		**0.16**	**0.16**	

Heat budget is <	420.0	W
Total 4.5 K heat =	**349.4**	**W**
Total heat / budget =	0.83	

Properties of Al and Cu

Compare Aluminum and Copper properties at 5K

Aluminum	Thermal conductivity W/(m*K)					Electrical resistivity nOhm*m			
T = 5 K	B = 0 T	1 T	2 T	3 T		B = 0 T	1 T	2 T	3 T
RRR = 100	487	419	415	412					
RRR = 200	959	727	713	707		0.167	0.208	0.212	0.215
RRR = 400	1907	1168	1132	1117		0.069	0.11	0.114	0.117
RRR = 600	2861	1468	1412	1387					
Copper	Thermal conductivity W/(m*K)					Electrical resistivity nOhm*m			
T = 5 K	B = 0 T	1 T	2 T	3 T		B = 0 T	1 T	2 T	3 T
RRR = 50	375	326	293	267					
RRR = 100	749	576	481	415		0.153	0.193	0.233	0.273
RRR = 150	1122	775	611	509					
RRR = 200	1494	936	707	574		0.077	0.117	0.157	0.197

Data from MATPRO:

L. Rossi, M. Sorbi, "MATPRO: a Computer Library of Material Property at Cryogenic Temperature"
INFN/TC-02/02 and CARE-Note-2005-018-HHH