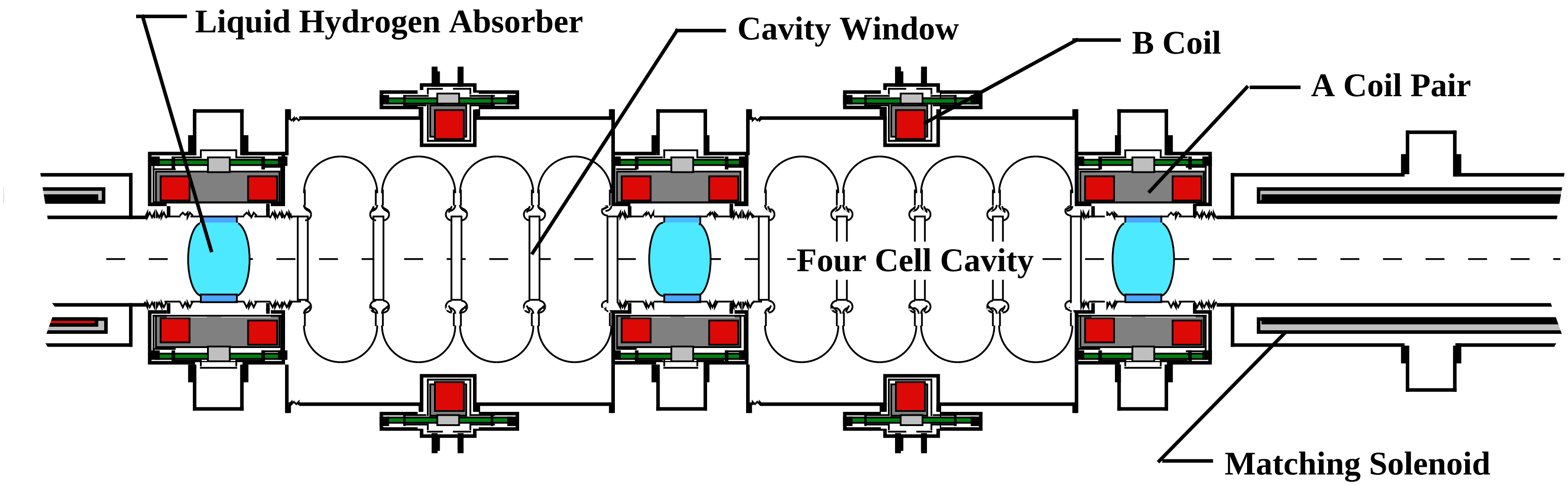
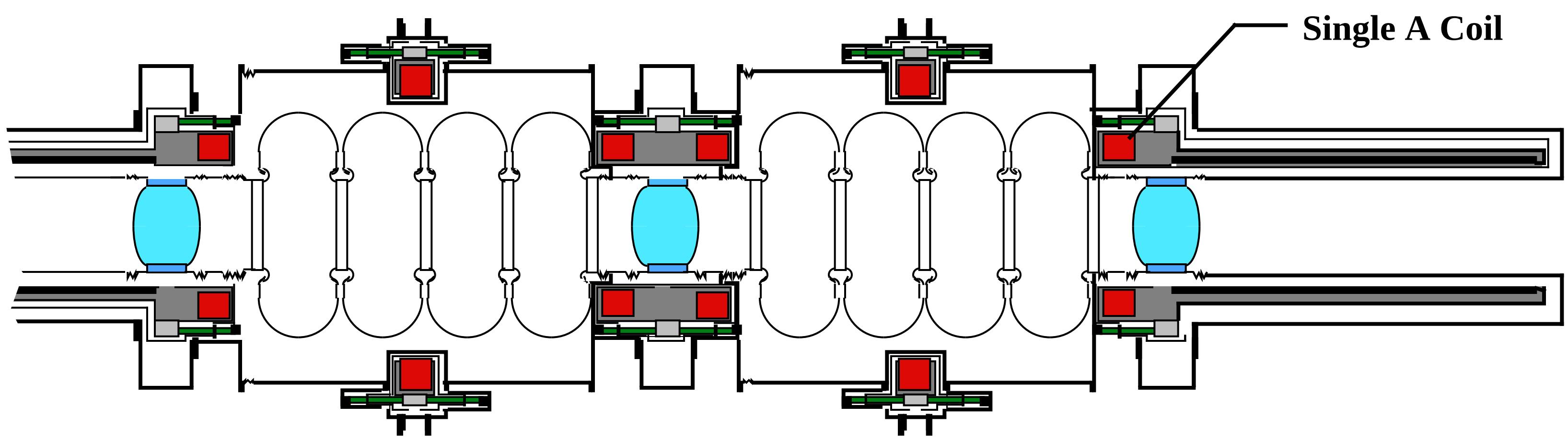
Optimized Cooling Channel Solenoids for the International Muon Cooling Experiment

Michael A. Green
Lawrence Berkeley National Laboratory
Berkeley CA 94720, USA

2.75 m Long Cooling Cell Options with 201.25 MHz Cavities



Triple Flip Option with 2 Cavities and 3 Absorbers



Single Flip Option with 2 Cavities and 3 Absorbers

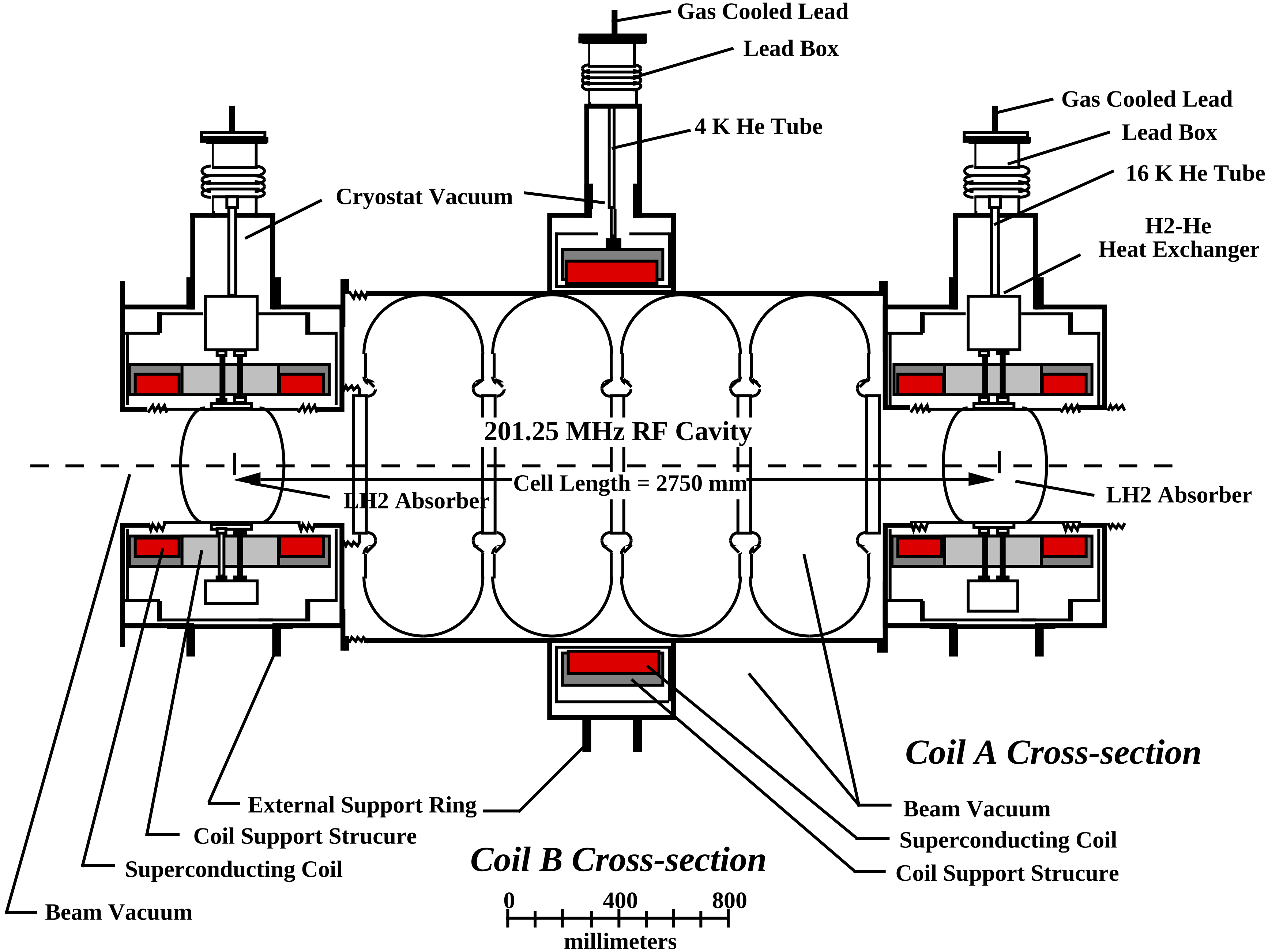
Arguments in Favor of Reduced Flip Coil Size

- Reducing the diameter of the flip coils reduces the amount of radial flux passing between the coils and thus reduces the peak magnetic induction in the coils.
- For a given on axis gradient reduced sized flip coils require fewer ampere turns to achieve the same on axis gradient. The combination of lower current and lower radial field mean the force pushing the coils apart is greatly reduced.
- A lower force pushing the coils apart means that material on the outside of the coils can carry this force. The coil package can be fabricated around the muon absorber.
- Muon cooling performance appears to be improved.
- The fabrication cost of the magnet is reduced.

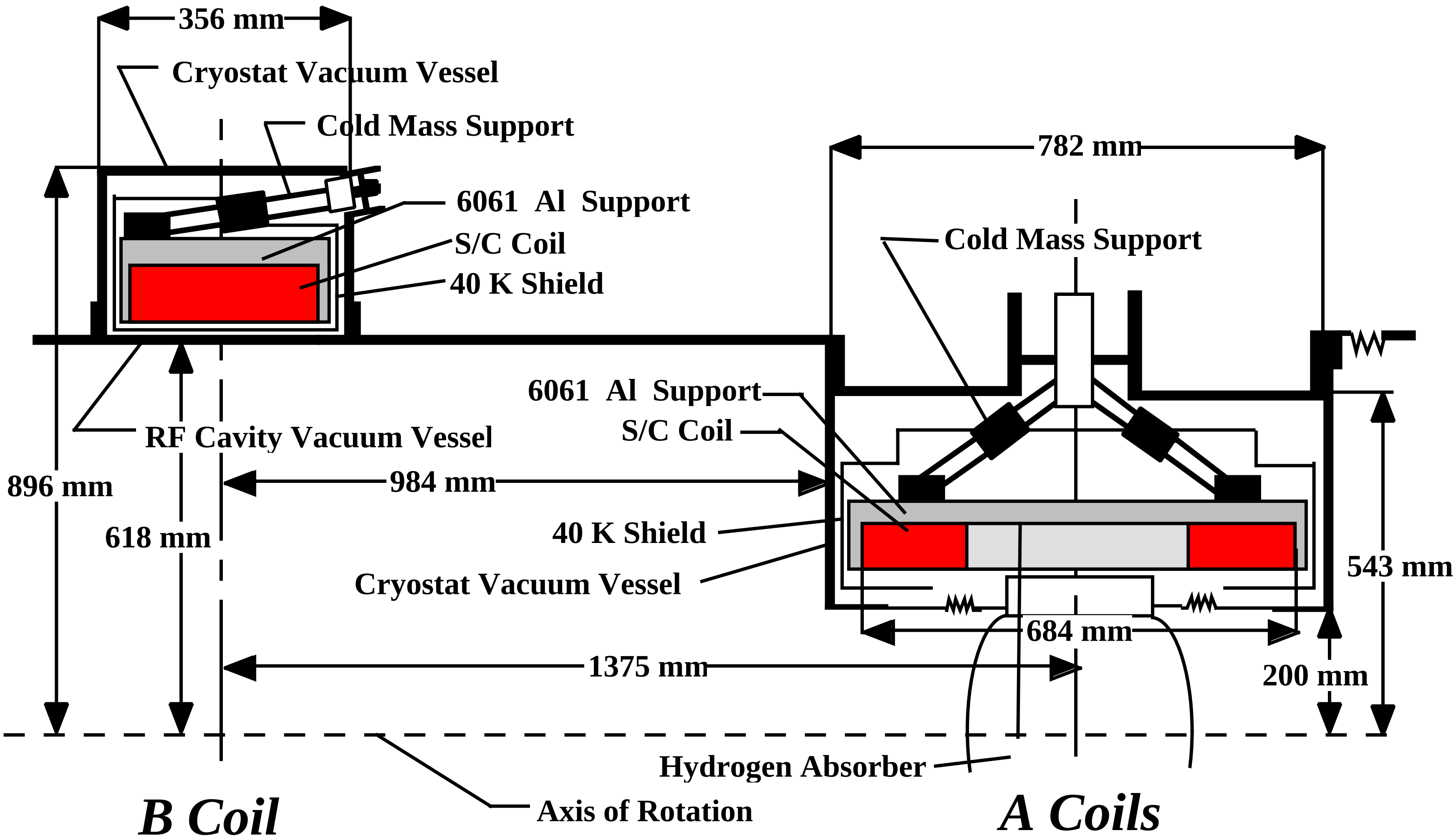
Arguments in Favor of Reducing the Coupling Coil Size

- Reduced size coupling coils cost less to fabricate.
- One can reduce the size of the coils by putting them between RF cavity cells. This does not appear to work because the muons do not stay captured in the channel.
- One can reduce the size of the coils around the cavity by making them thinner and reducing the inside diameter so that the coil fits around the cavity with a small clearance.
- The number of ampere turns in the coupling coils does not change very much as they are made smaller. Smaller coils do have a lower stored energy and a lower fabrication cost.

2.75 m Long Cooling Cell with Reduced Sized Magnets



Reduced Sized Solenoid Magnets for a Quarter Section of a 2.75 meter Long Muon Cooling Cell



Old and New 2.75-m Cooling Cell Magnet Parameters

Parameter	New	Old
Maximum Space for the Cavity (mm)	1968	1966
Number of Cavities per Cooling Cell	4	4
A Magnet Cryostat Length (mm)	356	283
B Magnet Cryostat Length (mm)	782	784
Coil Inside Diameter of the A Magnet (mm)	518	788
Coil Inside Diameter of the B Magnet (mm)	1313	1480
Warm Aperture Diameter of the A Magnet (mm)	400	650
Warm Aperture Diameter of the B Magnet (mm)	1236	1390
Maximum Diameter of Absorber (mm)	676	650
Maximum Cell Stored Energy (MJ)	5.7	13.2
A Coil Maximum Current Density (A mm^{-2})	119	119
B Coil Maximum Current Density (A mm^{-2})	96	96
Maximum Design Warm to Cold Force (MN)	0.316	0.774
Maximum Force Pushing A Coils Apart (MN)	0.696	3.224

Advantages of the Reduced Sized Cooling Channel Coils

Parameter Compared	Old	New
Stored Energy Per Cell (MJ)	13.2	5.8
Maximum Cold to Warm Force (kN)	774	316
Force between A Coil Pair (kN)	3224	696
Cooling Solenoid Cost (M$)	~3.5	~2.0

The reduced size magnet design has lower warm to cold forces. This means that a more concentional cold mass support system can be used for both magnets.

Because the force between the A coils is greatly reduced. The A magnet set can be fabricated around the muon absorber. The structure can be welded.

The net magnetic moment of both muon cooling channels is zero. The channel with reduced sized coils has a lower stray field 5 meters from the coils.

Smaller coils translate to lower stored energy and low magnet fabrication cost.

Controlling dB/dt during a Quench

- The minimum allowable rate of coil current change during a quench is proportional to the current density in the windings squared. Windings that have a matrix current density of 100 A mm^{-2} must have a current decay time constant of 10 seconds or less.
- The field decay time constant can be larger than the current decay time constant when a secondary circuit is used as part of the quench protection system for the coils.
- In practical terms, the dB/dt for the cooling solenoids will be about 1 T/s. The radial component of magnetic flux change produces the largest forces on the cavities, the cavity windows, and the thin windows of the absorber.

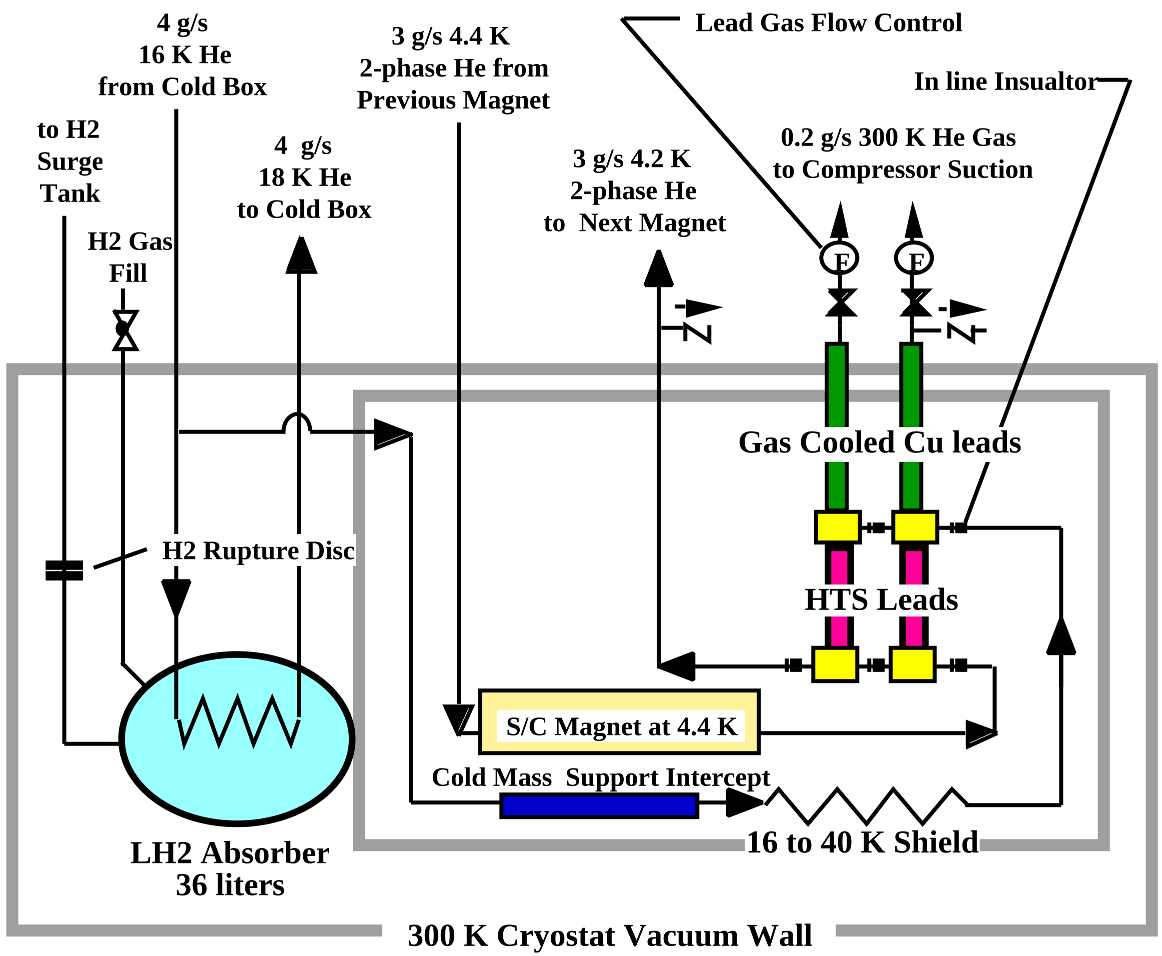
Heat Load and Refrigeration per Cooling Cell

Superconducting Magnets	Heat Load (W)
Cold Mass Supports	2.40
Thermal Radiation	0.60
Bayonet Joints, Piping, and Wires	0.20
HTS Current Leads	2.40
Total at 4.4 K Load to Magnet	5.60
Cold Mass Supports	22.0
Thermal Radiation	5.6
Bayonet Joints, Piping, and Wires	2.7
Total at 16 K Load to Magnet Shield	30.4
Mass Flow 16 K gas for Shield and Leads	~0. 4 g/s
Liquid Hydrogen Absorber	
Bayonet Joints, Piping and Wires	1.4
Thermal Radiation to Windows (ε = 0.15)	16.9
Hydrogen Re-circulation Heater	~5
Heating from the Beam	~10
Total at 16 K Load to Absorber	33.3
Equivalent 4.4K Refrigeration per Cell	~25

Does the New Design Change Refrigeration?

- The total refrigeration load into the absorber is not affected much by a change in the superconducting coil diameter.
- The total refrigeration into the coils is reduced because the absorber becomes part of the coil shield and smaller coils have a lower cold mass support and radiation heat leak.
- The size and cost of the refrigeration system is affected by the fluid in the absorbers. Liquid helium absorbers require larger refrigerators than liquid hydrogen absorbers. To first order, the cooling of the magnets is not affected by the fluid in the absorber.

Muon Cooling Refrigeration System Schematic



Power Supply and Quench Protection Issues

- The reduced stored energy per cell means that all of the coils in that cell can be hooked up in series. The two coupling coils and three flip coil pairs can be hooked in series provided the coil support structure is made from aluminum. This allows the coil support structure to behave as a shorted secondary. The entire coil string is quench protected using quench back from the support structure.
- The inter-coil cold to warm forces can be reduced below the their maximum value.
- Small power supplies can be used to tune individual coils in the muon cooling channel.

Concluding Comments

- Reducing the size of the 2.75-m cell level 2 study channel magnets is an attractive thing to do. The coupling magnets can not be located between the cavity cells. Reducing the coupling coil diameter around the cavities does make sense from a muon acceptance standpoint. The reduced diameter coupling magnet coil must be thinner and longer.
- Reduced size muon cooling solenoids have lower inter-coil forces. This means that a conventional cold mass support system can be used. The field flip coils can be supported from the outside. The field flip coils can be assembled around the absorber with an outer shell that supports the inter-coil forces. The warm bore diameter of the field flip solenoid can be a little larger than the absorber thin window diameter.
- All of the cooling channel solenoids can be powered in series. Trickle supplies can be used to tune the coils in the muon cooling channel. The string of muon cooling solenoids can be protected through quench back from the solenoid coil support structure.