Harvard ATRAP Design 2009

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Summary

This report summarizes the coil parameters of the system as built. Information about the design iterations that were necessary to reach this point can be found in the numerous reports presented to Harvard throughout the project.

The manufacturing experience from the octupole test winding has shown that only 4 layers can be stacked up due to the stiffness of the NbTi conductor with low copper content.

The coil configurations for both the octupole and quadrupole coils have been redesigned accordingly, subdividing the coils into 3 subcoils with 4 layers each and accommodating the larger conductor diameter of 0.85 mm (previously 0.80 mm). The radial dimensions of both coils have slightly increased due to the necessary modifications.

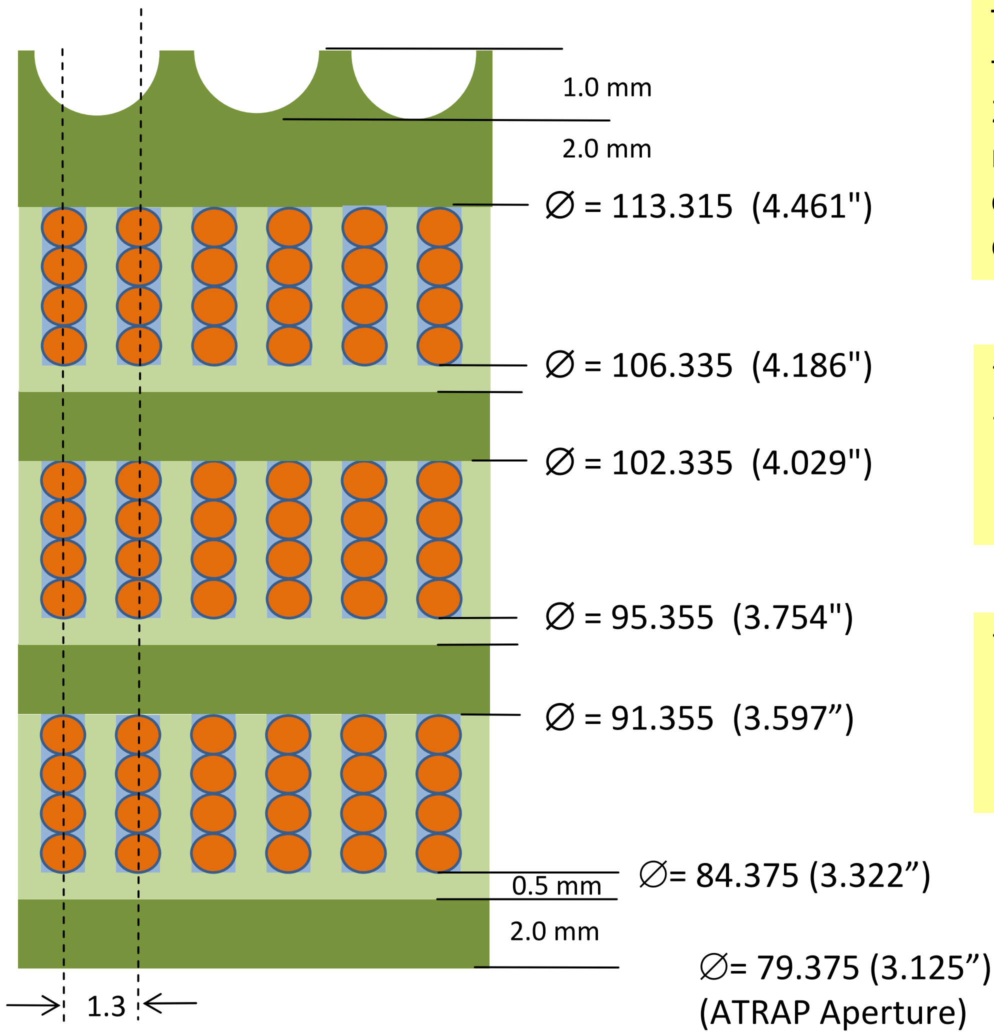
An expected decrease in the octupole and quadrupole fields caused by the radial increases has been corrected by accommodating more turns per layer. The octupole field obtained with the new coil configuration is practically identical to the original configuration.

The coil end conductor spacing has been optimized to give the largest length of the field without compromising/increasing the peak field.

The quadrupole coil has been redesigned and actually shows a slightly improved performance.

Design details of both coils and for the mirror coils as built are shown on the following pages.

Octupole Schematic Coil Layout



The ATRAP beam aperture is 79.375 mm formed by a G-10 tube with a wall thickness of 2 mm. This is followed by a composite with a minimum radial thickness of 0.5 mm (under the conductor support grooves) with radial fiber directions.

The radial gap between subcoils is 2.0 mm thick, consisting of a fiber reinforced overwrap (1.5 mm), followed by 0.5 mm composite with radial fiber directions.

The outer coil containment consists of an overwrap with a total radial thickness of 3 mm. 1-mm deep grooves are cut into this composite to allow for helium flow.

Octupole Radial Subcoil Dimensions

Subcoil-1:	
Number of Layers:	4
Number of Turns:	8
Coil Open Aperture [mm]:	84.375 (3.322")
Coil Outer Diameter [mm]:	91.355 (3.597")
Subcoil-2:	
Number of Layers:	4
Number of Turns:	9
Coil Open Aperture [mm]:	95.355 (3.754")
Coil Outer Diameter [mm]:	102.335 (4.029")
Subcoil-3:	
Number of Layers:	4
Number of Turns:	10
Coil Open Aperture [mm]:	106.335 (4.186")
Coil Outer Diameter [mm]:	113.315 (4.461")

Wire diameter:	0.85 mm
Layer Spacing:	0.88 mm

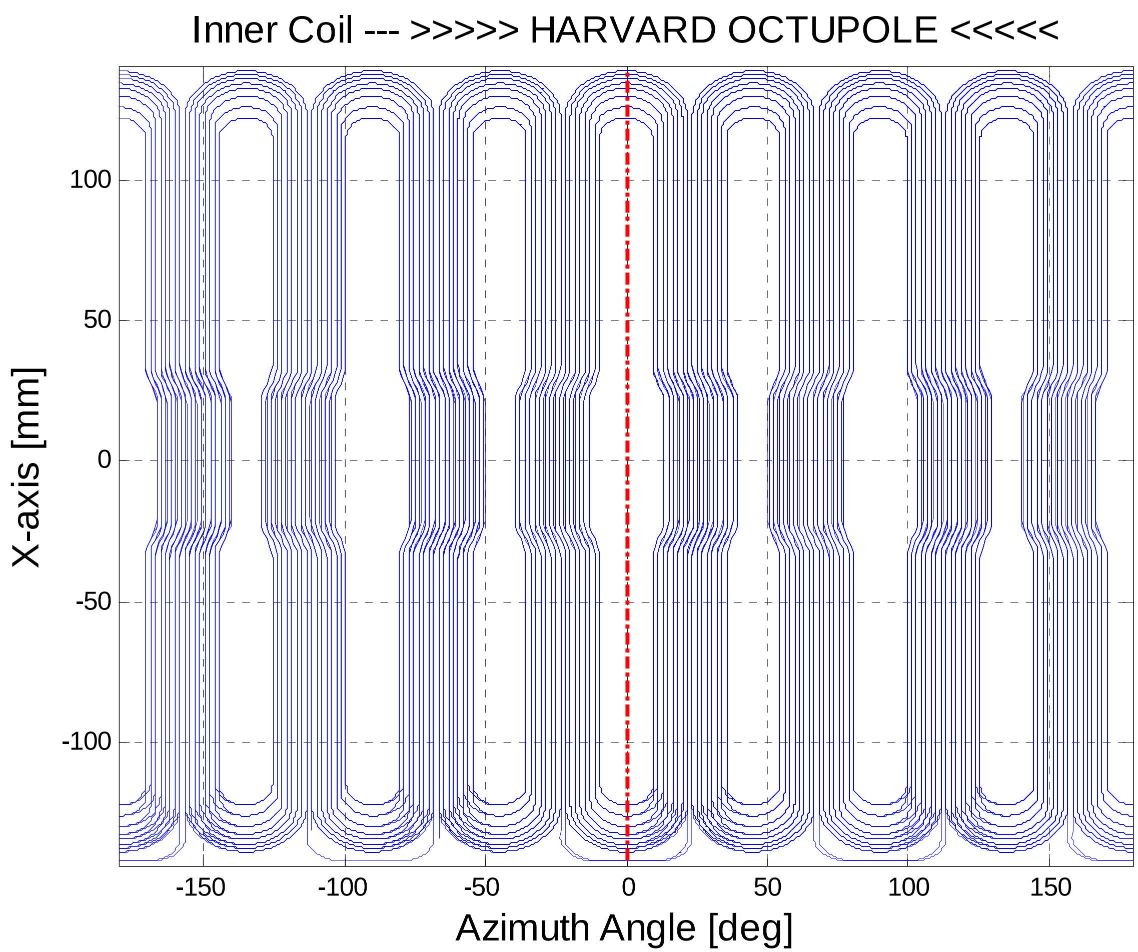
Octupole: Optimized Straight Section Lengths

Optimized Straight Section Lengths:

[245,245,245,244,243,240,235,230,225,220,215]
>>>>> Peak Field at 676.00 A <<<<<
Number of pattern points checked: 25690
BX: -0.11; BY: 2.02; BZ: -1.84; BTot: 2.74 [Tesla]
X: 117.00; [mm] R: 48.10; [mm] Theta: -37.35 [deg]

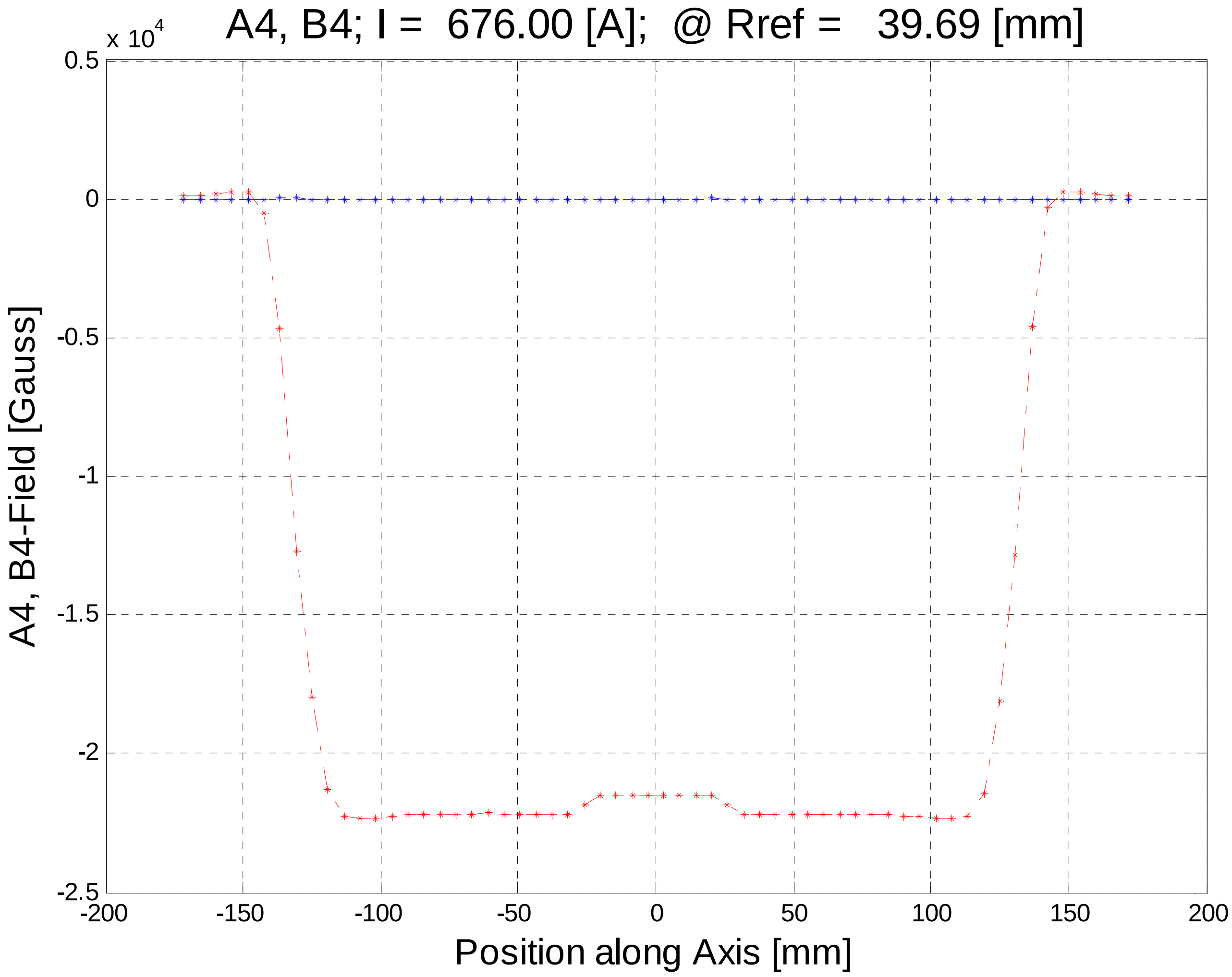
The straight sections of individual turns have been optimized in respect to the peak field in the coil.

Unrolled View with Optimized Coil End Spacing



Same coil end conductor spacing for all 3 subcoils

Octupole Field at Beam Tube Aperture
--- Optimized ---



Octupole Parameters

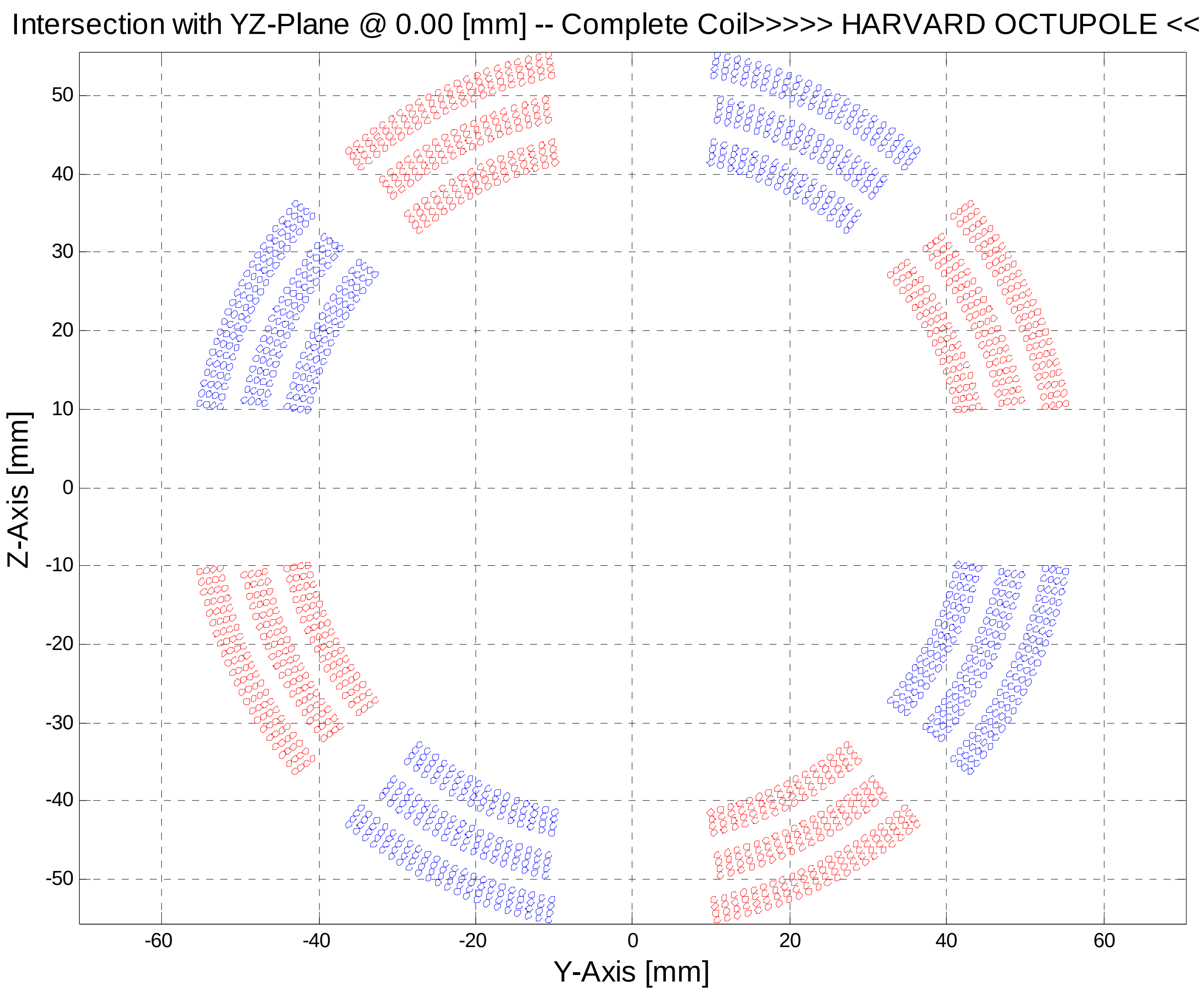
OCTUPOLE						
	Inner Coil		Middle Coil		Outer Coil	
Parameter	**Unit**	**Value**	**Unit**	**Value**	**Unit**	**Value**
Coil ID	mm	84.375	mm	95.355	mm	106.335
Coil OD	mm	91.355	mm	102.335	mm	113.315
Number of Layers		4		4		4
Number of Turns per Subcoil		8		9		10
Beam Tube Aperture	mm	79.375				
Wire Diameter	mm	0.85				
Total Conductor Length	m	493				
Nominal Current	A	676				
Nominal Field at Aperture	Tesla	2.25				
Peak Field	Tesla	2.75				
Current Margin (incl. ext. field)	%	40				
Temperature Margin	K	~1.0				

Cu:SC ratio: 1:1

Current margin based on 1 Tesla superimposed external field

Total Conductor Length: 495 m

Octupole Cross Section



Octupole Resistance and Inductance

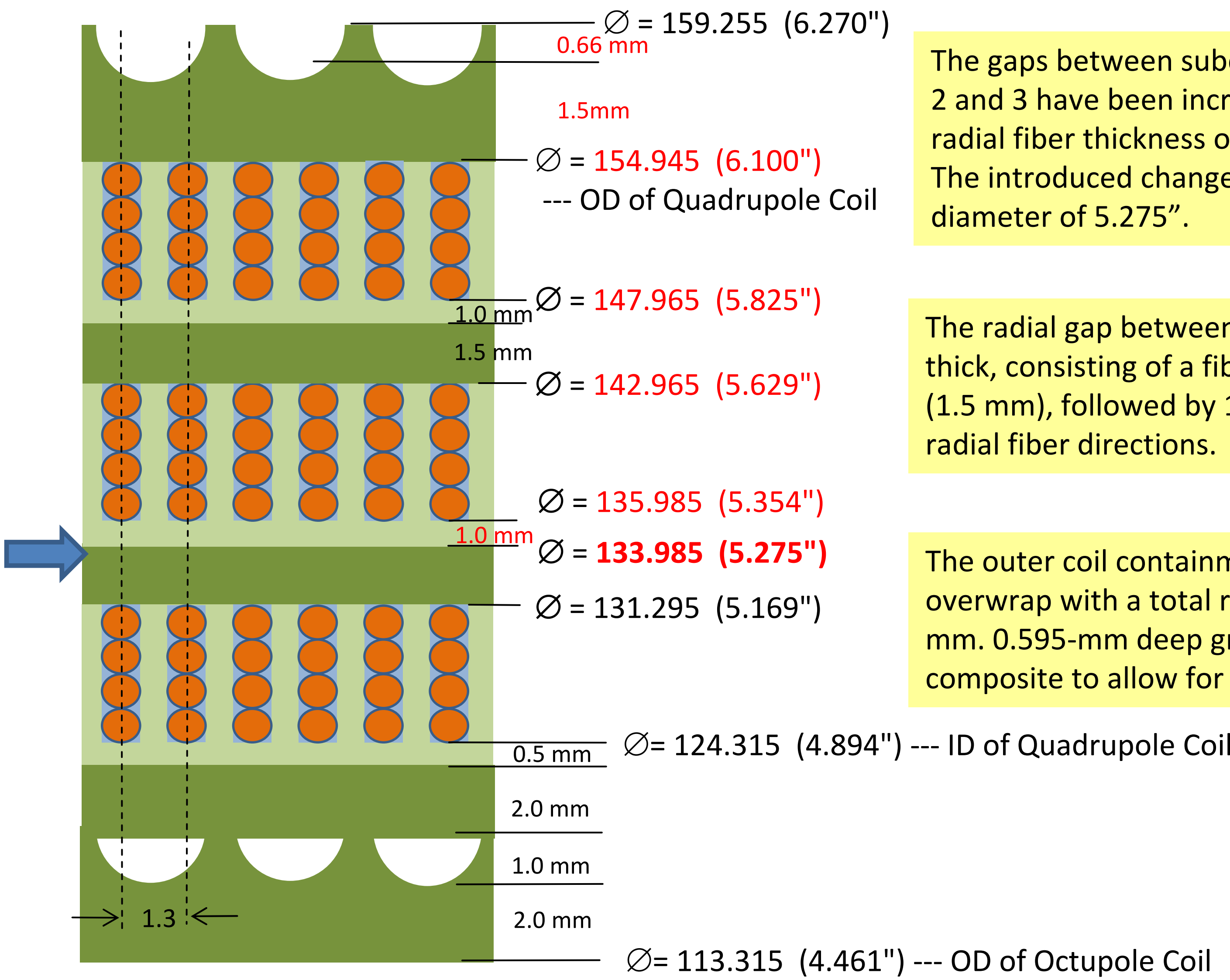
Resistance: 31.4 Ohm (Measured at room temperature)

Inductance:

Monte-Carlo: H = 1.917e-002 [Henry]
Monte-Carlo: H = 1.941e-002 [Henry]
Monte-Carlo: H = 1.923e-002 [Henry]
Monte-Carlo: H = 1.927e-002 [Henry]
Monte-Carlo: H = 1.993e-002 [Henry]
Mean Value = 1.940e-002 Standard Deviation = 3.101e-004 [mm]

Calculated: H = 19.4 mH
Measured: H = 19.5 mH

Modified Quadrupole Coil Layout



The gaps between subcoils 1 and 2 and subcoils 2 and 3 have been increased to accommodate a radial fiber thickness of 1mm instead of 0.5mm. The introduced change starts at measured diameter of 5.275”.

The radial gap between subcoils is 2.5 mm thick, consisting of a fiber reinforced overwrap (1.5 mm), followed by 1.0 mm composite with radial fiber directions.

The outer coil containment consists of an overwrap with a total radial thickness of 2.095 mm. 0.595-mm deep grooves are cut into this composite to allow for helium flow.

Modified Radial Quadrupole Subcoil Dimensions

Subcoil-1:	
Number of Layers:	4
Number of Turns:	28
Coil Open Aperture [mm]:	124.315 (4.894")
Coil Outer Diameter [mm]:	131.295 (5.169")
Subcoil-2:	
Number of Layers:	4
Number of Turns:	30
Coil Open Aperture [mm]:	135.985 (5.354")
Coil Outer Diameter [mm]:	142.965 (5.629")
Subcoil-3:	
Number of Layers:	4
Number of Turns:	32
Coil Open Aperture [mm]:	147.965 (5.825")
Coil Outer Diameter [mm]:	154.945 (6.100")

Wire diameter:	0.85 mm
Layer Spacing:	0.88 mm

Modified Quadrupole Parameters

QUADRUPOLE						
	Inner Coil		Middle Coil		Outer Coil	
Parameter	**Unit**	**Value**	**Unit**	**Value**	**Unit**	**Value**
Coil ID	mm	124.315	mm	135.985	mm	147.965
Coil OD	mm	131.295	mm	142.965	mm	154.945
Number of Layers		4		4		4
Number of Turns per Subcoil		28		31		34
Wire Diameter	mm	0.85				
Total Conductor Length	m	253	m	281	m	309
Nominal Current	A	500				
Nominal Field at Aperture	Tesla	1.95				
Peak Field	Tesla	3.75				
Current Margin (incl. ext. field)	%	20				
Temperature Margin	K	0.5				

Cu:SC ratio: 1:1

Current margin based on 1 Tesla superimposed external field

Total Conductor Length: ~ 843 m

Quadrupole Resistance and Inductance

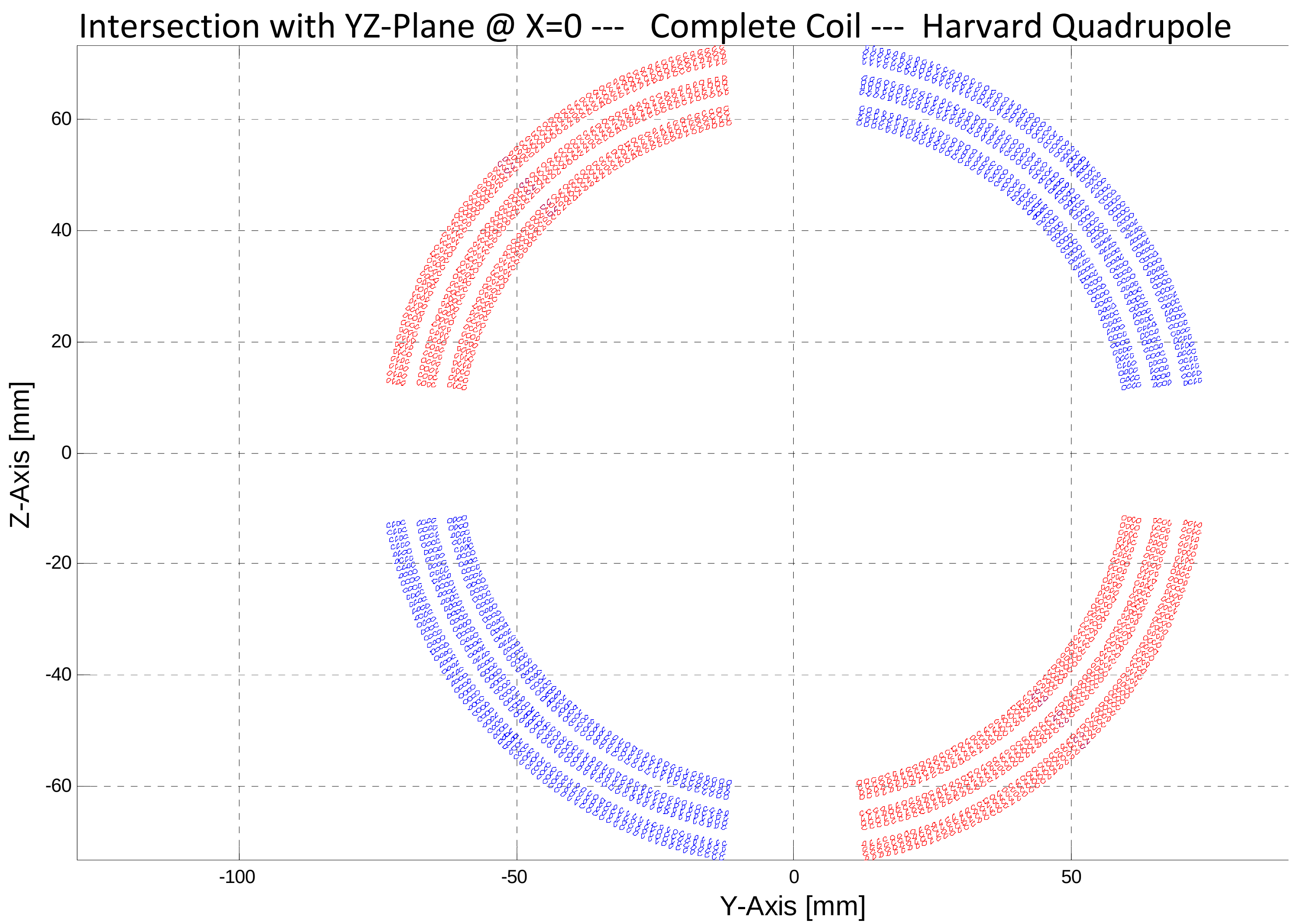
Resistance: 54.1 Ohm (Measured at room temperature)

Inductance:

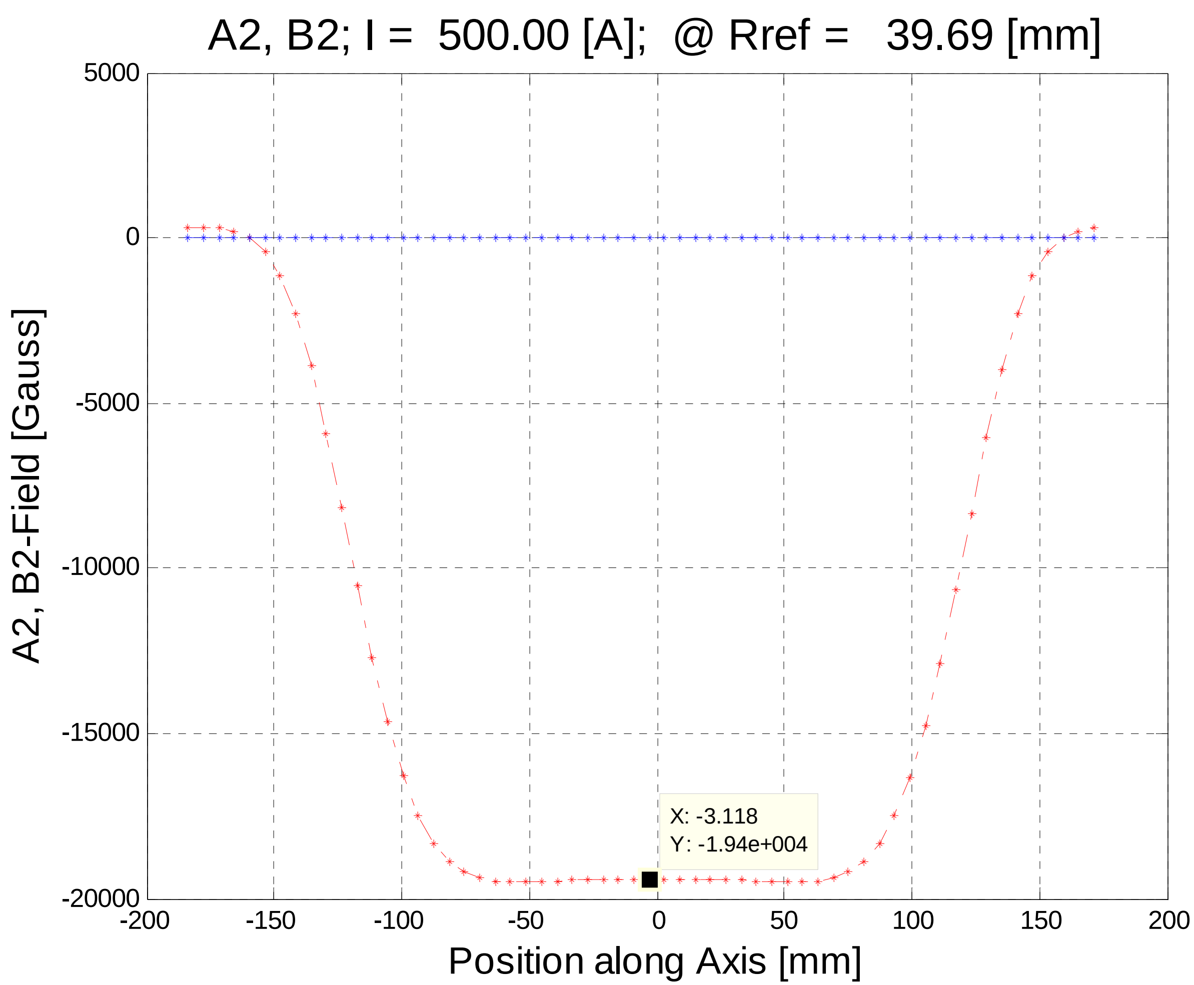
Monte-Carlo: H = 1.121e-001 [Henry]
Monte-Carlo: H = 1.126e-001 [Henry]
Monte-Carlo: H = 1.135e-001 [Henry]
Monte-Carlo: H = 1.141e-001 [Henry]
Monte-Carlo: H = 1.133e-001 [Henry]
Mean Value = 1.131e-001 Standard Deviation = 7.656e-004 [mm]

Calculated: H = 113 mH
Measured: H = 113.1mH

Quadrupole Cross Section



Quadrupole Field at Beam Tube Aperture



Mirror Coils
Original and Modified Design

Tuesday, July 14, 2009

Steve's Parameters
12-Layer Design

---Outer coils---

Inner radius: 85 mm
Outer radius: 99 mm
Axial start: 90 mm
Axial end: 150 mm
Current density: 230 A/mm^2

Total conductor cross section
14*60 = 840 mm^2.
Total Current = 230*840 = **193,200A**

---Inner coils---

Inner radius: 85 mm
Outer radius: 99 mm
Axial start: 32 mm
Axial end: 54 mm
Current density: -198 A/mm^2

Total conductor cross section
14*22= 308 mm^2.
Total Current = 198*308= **60,984 A**

With the above solenoid pairs, the quadrupole coil, and an external uniform axial field of 1 T, I find that the peak field on the outer solenoidal coil is 3.8 T.

Superconductor Parameters for Mirror Solenoids

>>>>> Conductor Description <<<<<

Conductor material:		NbTi
Wire width with varnish [mm]:	1.576	
Wire height with varnish [mm]:	1.052	
Insulation thickness [mm]:		0.035
Wire cross section (metal) [mm2]:	1.476	

Steve's Parameters Implemented

Resulting Winding Parameters: --- Coil 1 -----

Center of Wdg. [mm]:	43.000
Length of Wdg. [mm]:	21.980
Thickness of Wdg. [mm]:	14.448
Inner radius of Wdg. [mm]:	85.000
Outer radius of Wdg. [mm]:	99.448
Number of turns:	14
Number of layers:	12
Transport current:	**-363.0**
Wire length [m]:	98.

Resulting Winding Parameters: --- Coil 2 -----

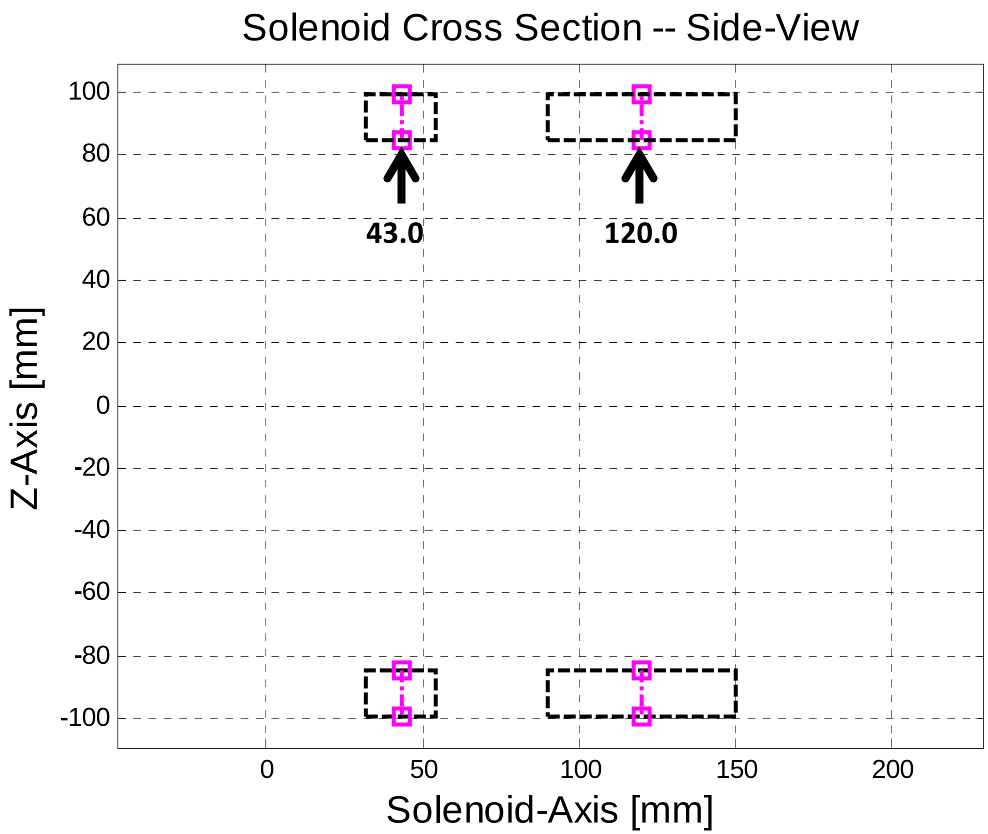
Center of Wdg. [mm]:	120.000
Length of Wdg. [mm]:	59.660
Thickness of Wdg. [mm]:	14.448
Inner radius of Wdg. [mm]:	85.000
Outer radius of Wdg. [mm]:	99.448
Number of turns:	38
Number of layers:	12
Transport current:	**423.0**
Wire length [m]:	265.

Transport currents in wires to match required current densities:

Total # turns: 168
Transport current: 60,984/168= **363 A**

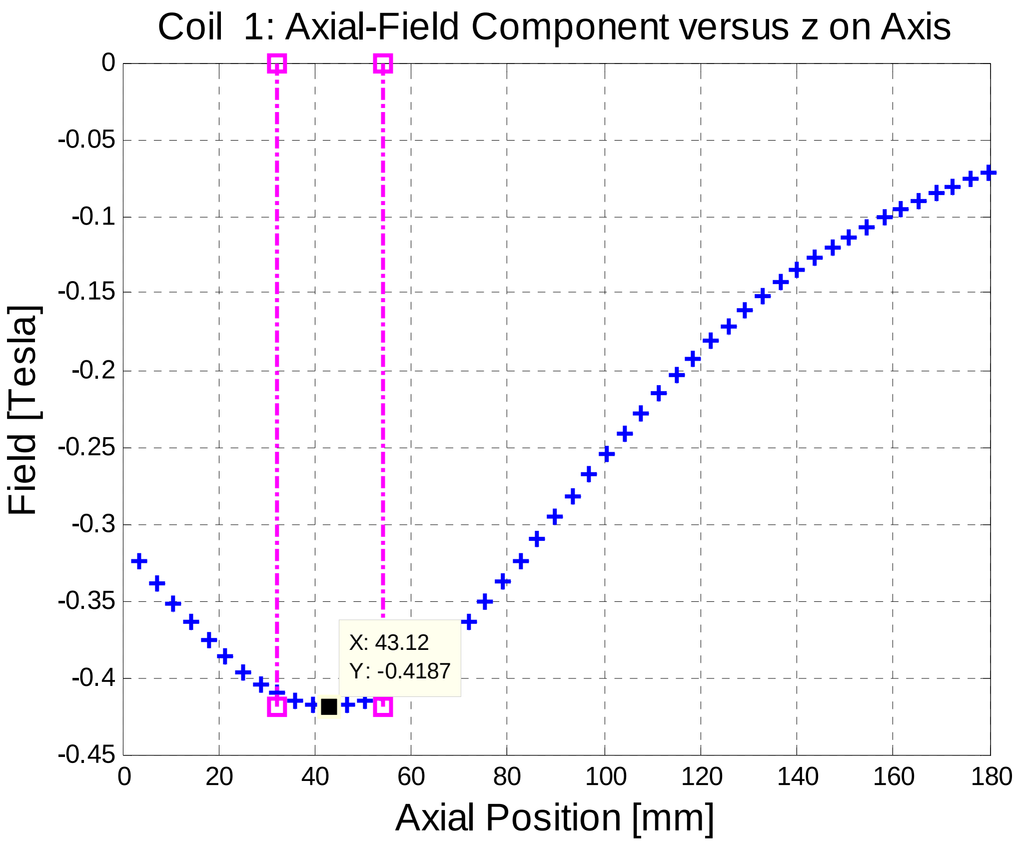
Total # turns: 456
Transport current: 193,200/456 = **423 A**

Solenoid Winding Packages



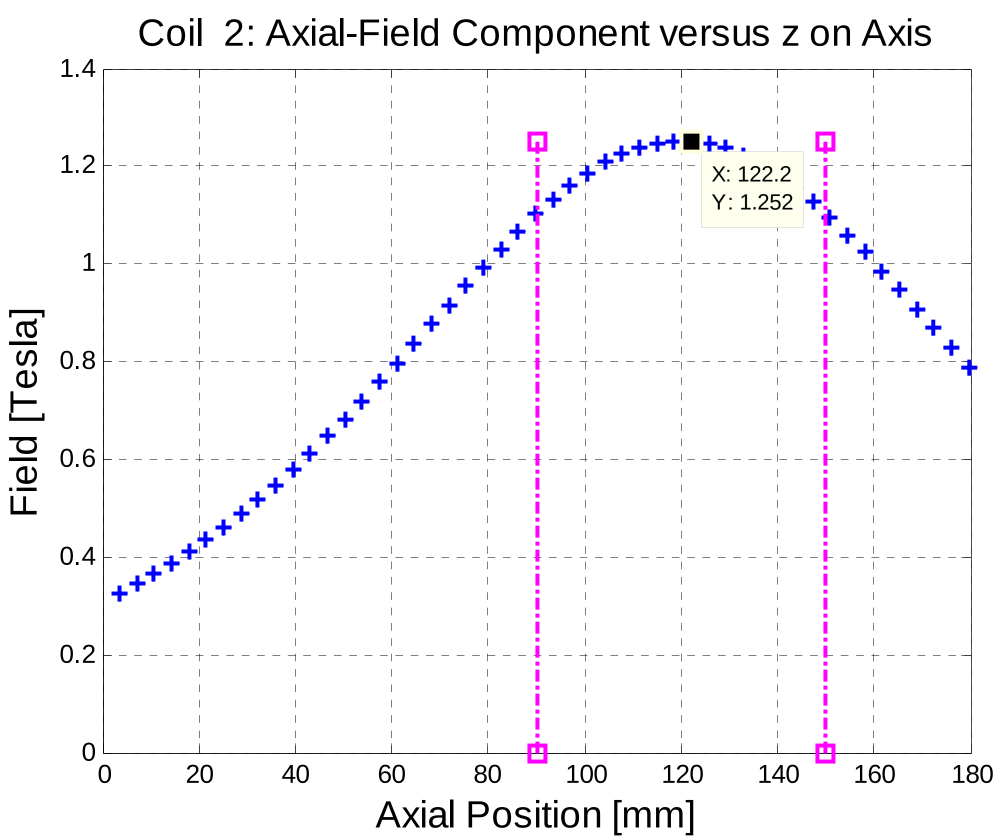
Only one half of the mirror coil system is shown.

Inner Coil Pair
12-Layer Design



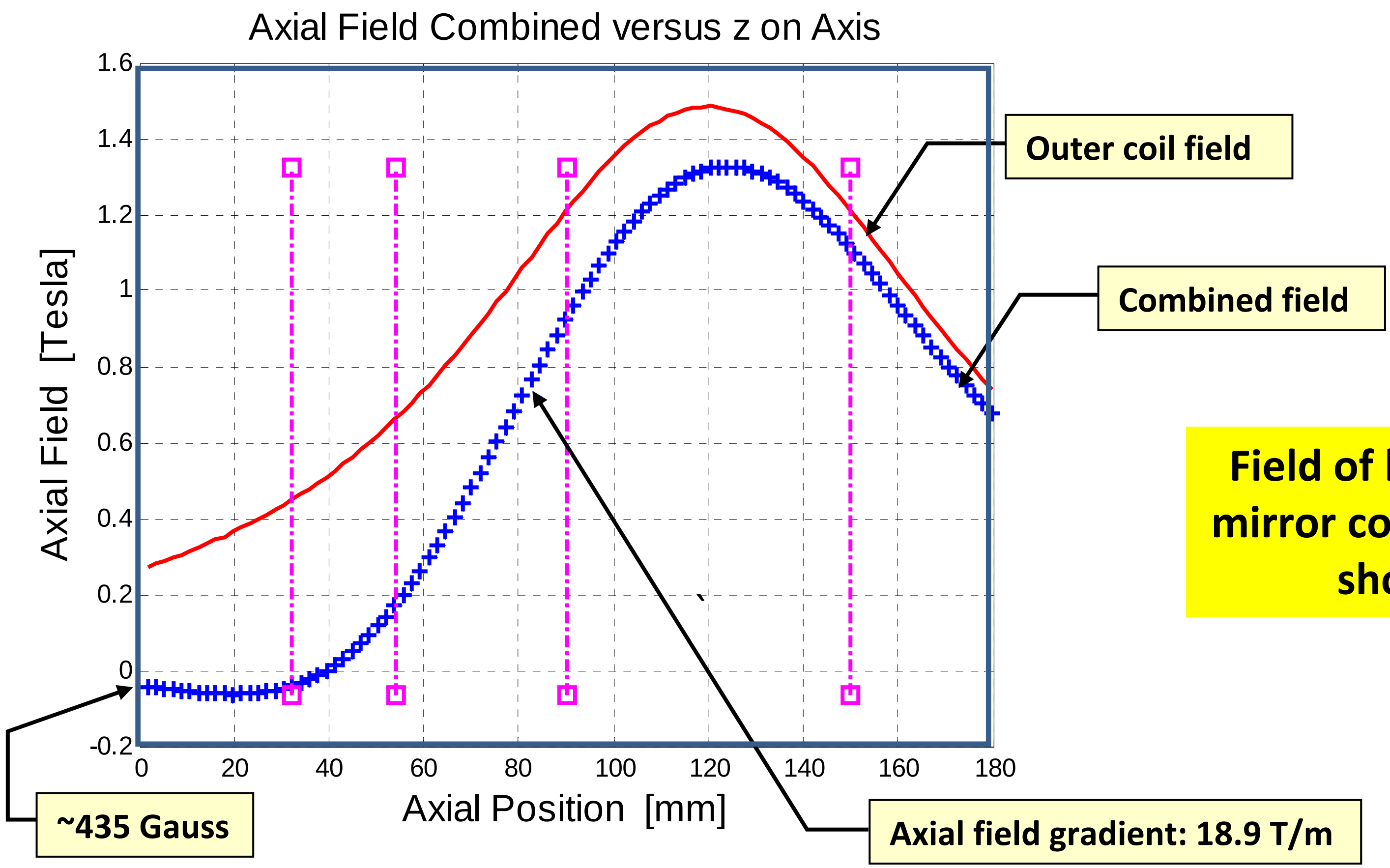
Highest Field on Axis: -0.419 Tesla at -363 A

Outer Coil Pair
12-Layer Design



Highest Field on Axis: 1.252 Tesla at 423 A

Combined Field of Mirror Coil System
12-Layer Design



Field of half of the mirror coil system is shown.

Operational Current Margin of Mirror Coils 12-Layer Design

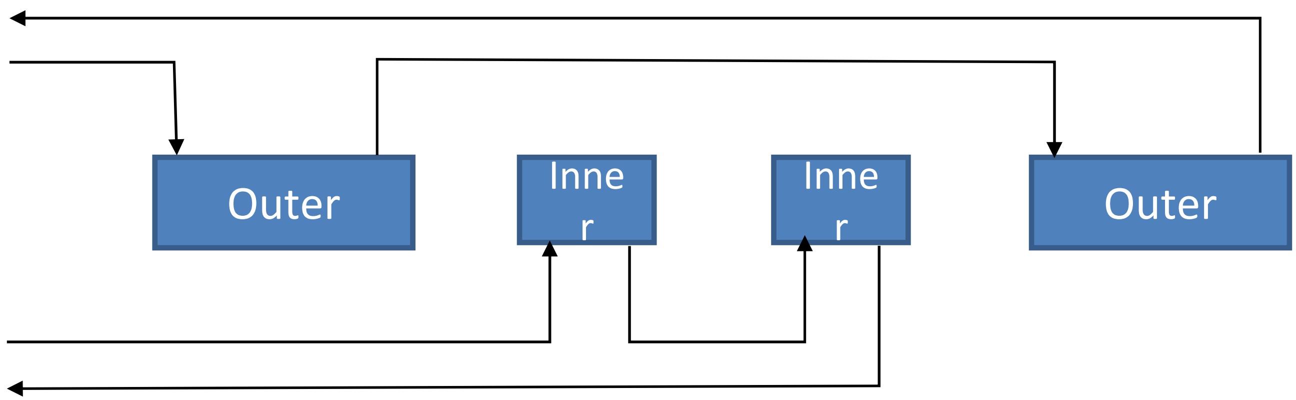
>>>>> Conductor Performance <<<<<:

Conductor material:	NbTi	
Conductor cross section (metal) [mm2]:		1.470
Copper to non-copper ratio:		2.700
SC cross section [mm2]:		0.397
Cu cross section [mm2]:		1.072
Nominal critical current density [A/mm2]:		2500.
Peak/Reference field [Tesla]:		6.0
Operational temperature [K]:		4.30
Resulting critical current density [A/mm2]:		1945.
Resulting critical current [A]:		**772.6**
Coil 1 ------		
Transport current [A]:	< 500	
Coil 2 ------		
Transport current [A]:		< 500

Large operational margin even at peak fields of 6 Tesla and 500 A

Mirror Coil Leads

To facilitate the interconnection of the two inner and two outer mirror coils it is advantageous to have an uneven number of layers. For an even number of layers the start and end are at the same side of the solenoid. Since the two inner coils should be in series and the also the two outer coils, it is easier to have the incoming and outgoing leads at opposite ends as shown in the sketch.



Coil Parameters: 13-Layer Design

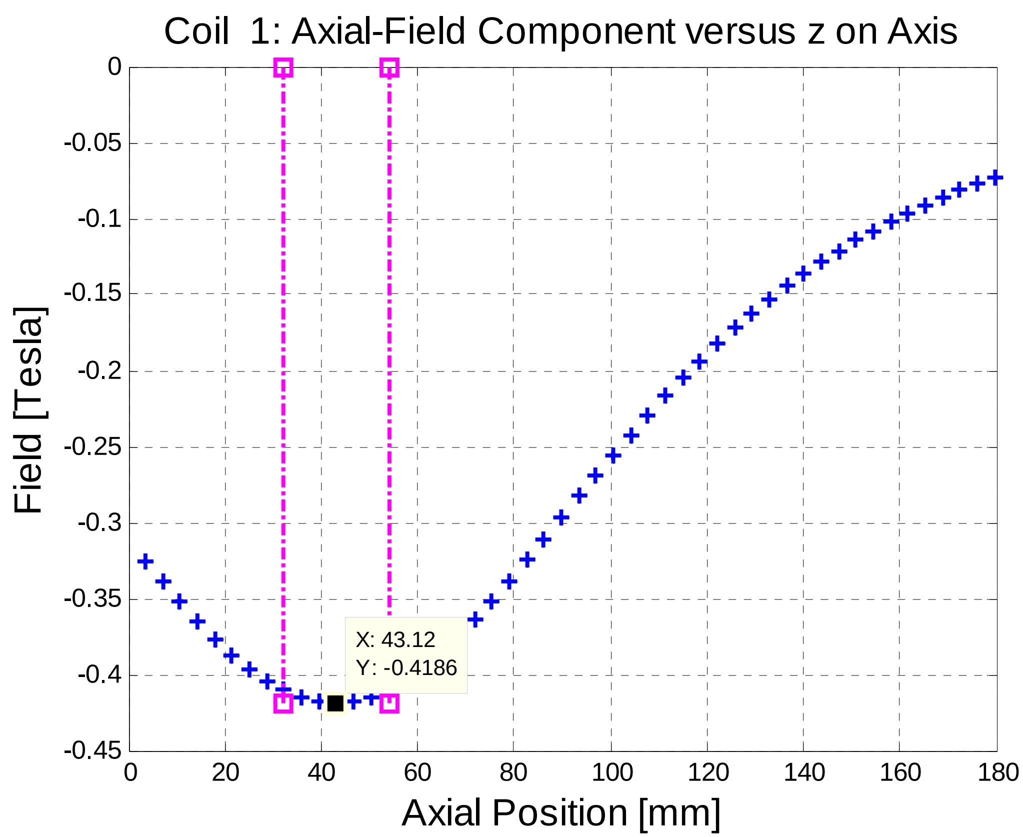
Resulting Winding Parameters: --- Inner Coil Set -----

Center of Wdg. [mm]: 43.000
Length of Wdg. [mm]: 21.980
Thickness of Wdg. [mm]: 15.652
Inner radius of Wdg. [mm]: 83.820
Outer radius of Wdg. [mm]: 99.472
Number of turns: 14
Number of layers: 13
Transport current: -337.000

Resulting Winding Parameters: --- Outer Coil Set -----

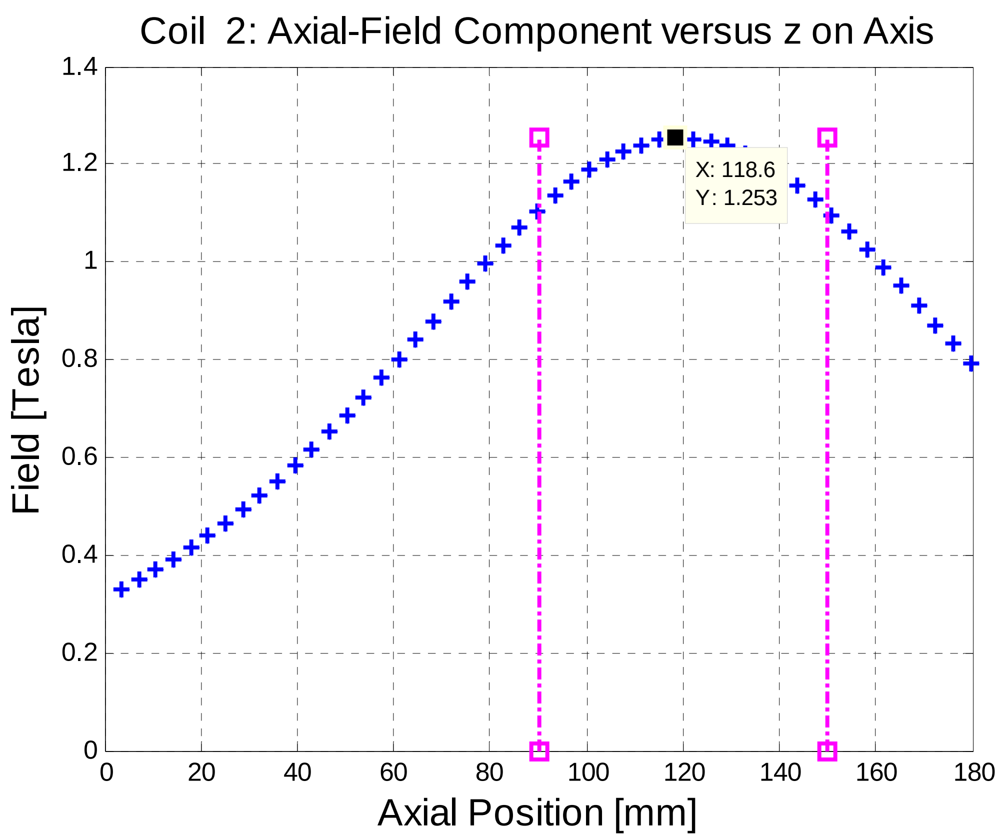
Center of Wdg. [mm]: 120.000
Length of Wdg. [mm]: 59.660
Thickness of Wdg. [mm]: 15.652
Inner radius of Wdg. [mm]: 83. 820
Outer radius of Wdg. [mm]: 99.472
Number of turns: 38
Number of layers: 13
Transport current: 393.000

Inner Coil Pair
13-Layer Design



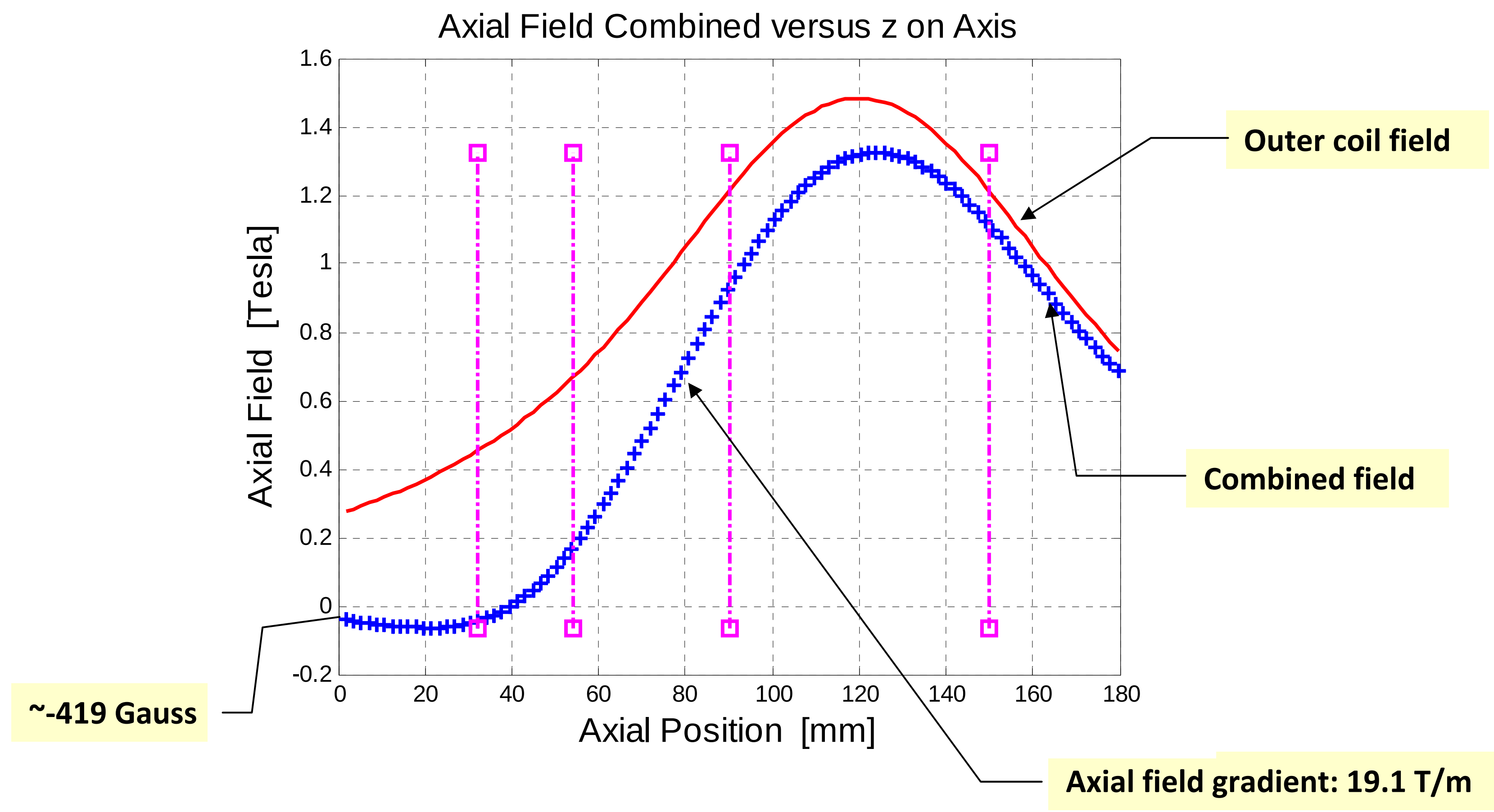
Highest Field on Axis: -0.419 Tesla at -337 A

Outer Coil Pair
13-Layer Design



Highest Field on Axis: 1.253 Tesla at 393 A

Combined Field of Mirror Coil System
13-Layer Design



Summary

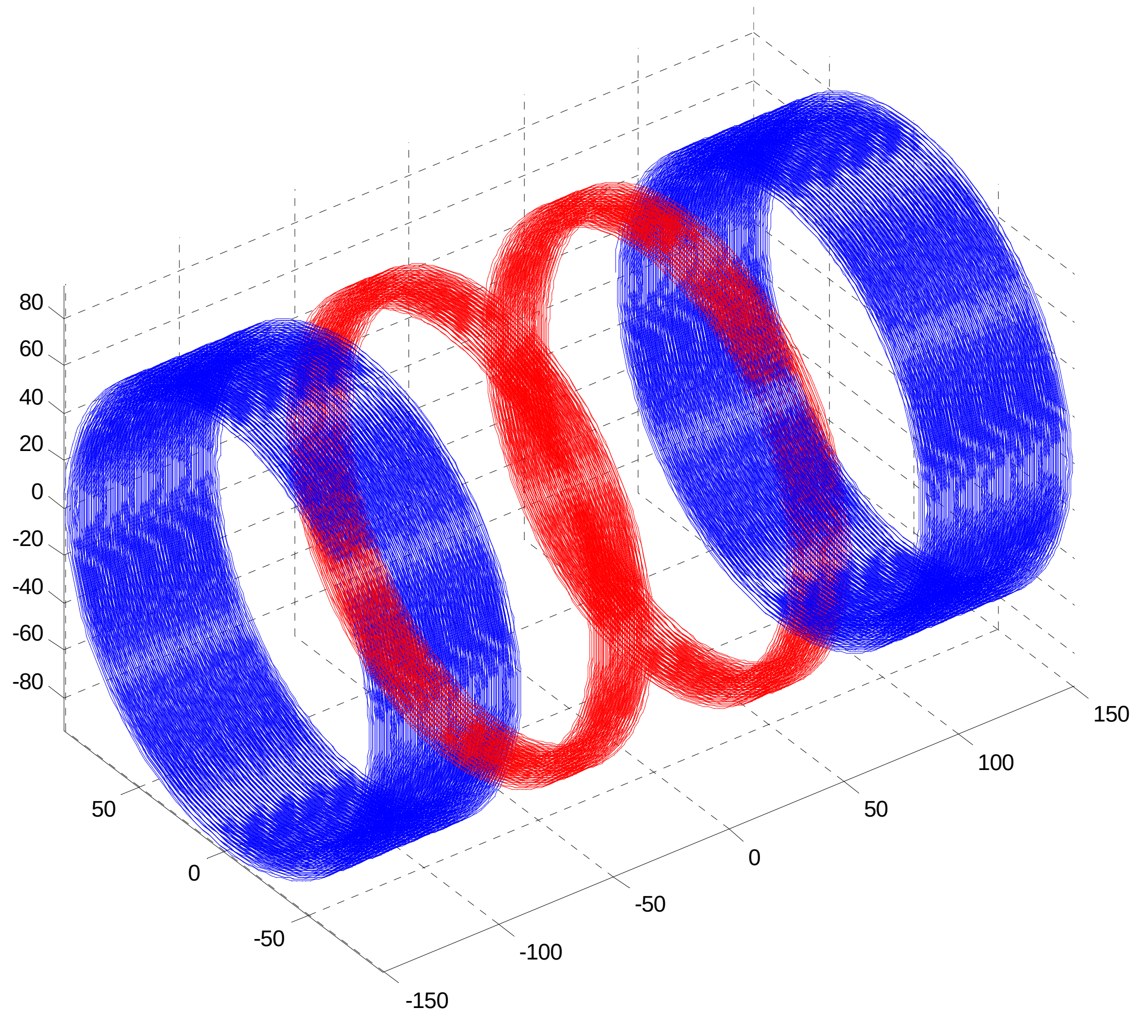
- The mirror coil design has been changed from 12 to 13 layers to facilitate the routing of coil interconnections.
- The nominal currents for both coil sets have been reduced to give the same fields on axis as in the 12-layer design.
- The modified design has slight advantages over the original 12-layer design:
- The operational currents are reduced by about 7%, which will increase the current margin accordingly.
- The field in the center of the magnet system is reduced by a small amount; the highest gradient is slightly increased.

Forces Acting On Mirror Coils

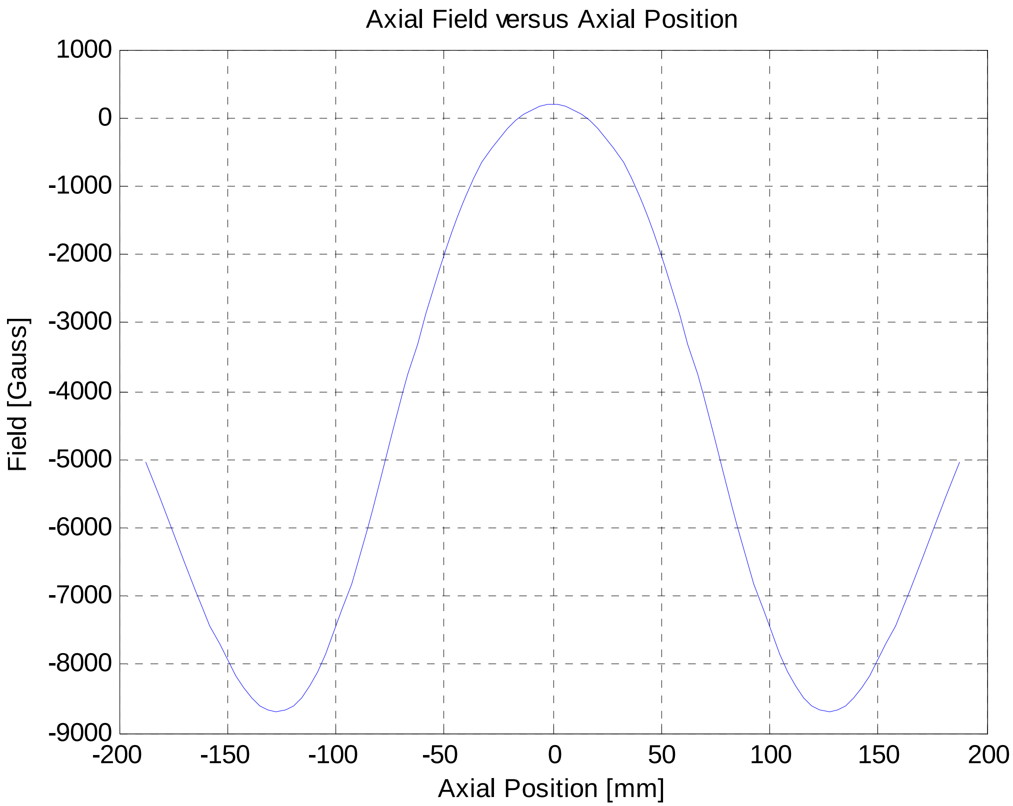
Forces Acting on Mirror Coils

The mirror coil system consists of 2 identical inner coils and 2 outer coils. Details of the coils are given above. The current direction in the series connected inner coils is opposite to the series connected outer coils to minimize the acial field in the center of the magnet system.
The forces acting on the coil system have been estimated in the following way:
In the 1st step the Lorentz forces are calculated between a combined system of the 2 inner coils and 1 outer coil. Since the currents are in opposite direction, the 2 inner coils repel the outer coil.
In the next step the force between the 2 outer coils is calculated, which have equal current direction and attract each other.
The sum of the repulsive force and the attractive force determines the overall performance of the system.

CoilCad Model of Mirror Coil System



Axial Field versus Axial Position



Acting Forces

Force Acting on Right Outer Coil Due to Inner Coils
FX = -8.698e+003   FY = 2.057e-001   FZ = -4.306e+000 [Newton]

Force Acting Between the Two Outer Coils
FX = 1.533e+003   FY = -1.130e-002   FZ = 8.112e-002 [Newton]

Net Force on Outer Coils
FX = -7.165e+003   FY = 1.944e-001   FZ = -4.225e+000 [Newton]

The outer coils are repelled from the inner coils with a force of about 7,200 Newton

Testing and Operation Procedures

The ATRAP magnet system consists of an octupole coil on the inside, a quadrupole coil surrounding the octupole, and a set of mirror coils surrounding the quadrupole. The octupole coil has been cryogenically tested. The test data have been presented to Harvard.

The newly built quadrupole and mirror coils have only been tested at room temperature. As a wire wound magnet based on LTS conductor the quadrupole is expected to show training behavior, and a quench training of the coil needs to be performed.

The mirror coils have large operational margins and are built with a superconductor with large copper to superconductor ratio (2.7:1) . It is therefore expected that these coils reach and exceed their nominal currents without training.

However, the mirror coils should not be operated without a quench detection system and an external dump resistor. If a quench for any reason is occurring, the power supply has to be disconnected to prevent damage of the coil.

Quadrupole Quench Training

The following procedure should be followed during quench training of the quadrupole:

•Attach quench detection system to the quadrupole coil.
•The quadrupole coil is equipped with a voltage tap in the middle of the complete quadrupole winding, subdividing the coil into two halves with (about) equal inductances.
•The quench detection system being used should compare the voltage across both halves of the quadrupole coil.
•The inductances of both halves being about equal, the voltage difference is insensitive to the inductive voltage rise during a current ramp. An observed voltage difference therefore reflects a difference in resistance, which indicates that a quench is developing in one of the two half coils.
•The voltage threshold indicating a quench should be set to 100 mV or less. The AML quench protection system had a noise level during the octupole tests of about ±5 mV.
•To still detect a quench in the very unlikely case that the quench develops simultaneously in both half coils, the total voltage across the quadrupole coil should be independently monitored by the quench detection system. The threshold for this voltage should be set to accommodate the inductive voltage during current ramp plus the noise level. The quadrupole inductance is 0.11 H.
•When a quench is detected the power supply should be disconnected within 50 msec or less.
•A dump resistor parallel to the coil should be used to absorb a major part of the energy stored in the coil.

Installation and Operation

Quench Protection:

- All coils of the ATRAP system should only be operated when monitored by a quench detection system and an external dump resistor in parallel to the coils. If a quench is detected the power supply should be disconnected.
- Before a coil is powered the coil temperature and proper functioning of the quench protection system should be verified.
- In case of a quench in the octupole or quadrupole coil is not necessary to automatically disconnect the mirror coils, since this leads to unnecessary heating of the whole system.
- Only if a quench is detected in a mirror coil, the corresponding power supplies needs to be disconnected and the energy dumped into the connected dump resistor.

Conductor Stabilization between coils and current leads:

- The superconducting connections between the coils and the cryostat current leads have to be stabilized with copper and mechanically supported to avoid any movement of the conductor under the influence of Lorentz forces.
- Sufficient electrical insulation between the two leads of all coils is needed to prevent electrical breakdown. The voltage between any pair of leads during a quench depends on the resistance of the connected dump resistor, and the insulation should be sized accordingly.