Thu-Mo-Po2.07-01 [41]

Design of a Tabletop Liquid-Helium-Free, Persistent-Mode 1.5-T/90-mm MgB2 "Finger" MRI Magnet for Osteoporosis Screening

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OUTLINE

- Introduction – MIT 1.5 T ***Finger*** MRI Project
- Preliminary Studies at the MIT FBML/PSFC

  : Small-scale Prototype and Superconducting Joints
- Final Design Report

  : SN_2-cooled, Shielded, 1.5-T/90-mm MgB_2 Magnet

  : Active Shielded Gradient Coils
- Conclusion

LHe-Free Tabletop 1.5-T "Finger" MRI For Osteoporosis Screening

REQUIREMENT

Compact, Affordable *Osteoporosis Screening* MRI

Francis Bitter Magnet Laboratory

Design, construction, test of *LHe-Free, iron-Shielded, persistent* 1.5-T/90-mm MgB_2 magnet.

Gradient coil design confirm and fabrication.

MRI system assembly.

Athinoula A. Martinos Center For Biomedical Imaging

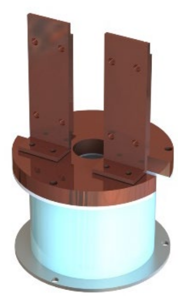
Active-shield gradient coil design

MRI spectroscopy, amplifiers, power supplies

System testing with phantom and specimen

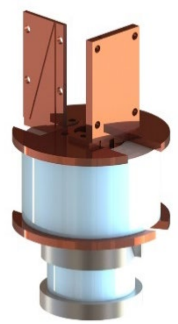
Preliminary Researches at MIT

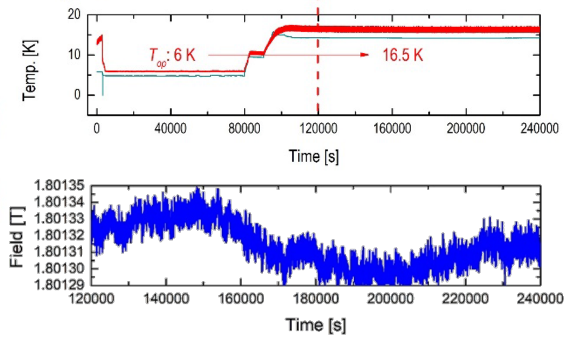
❑ Small-scale MgB2 magnets



(2017)

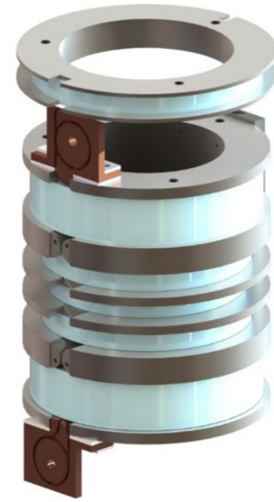
SN_2-cooled single coil with use of 76-m MgB_2 wire





(2018)

SN_2-cooled persistent two-coil magnet with 86-m MgB_2 wire



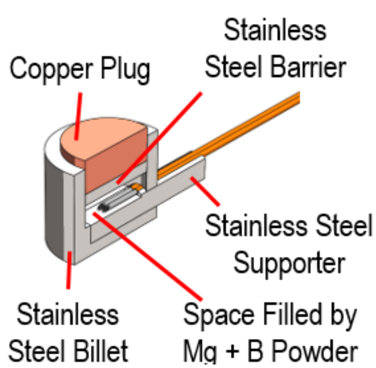
Construction, operation details to be presented:

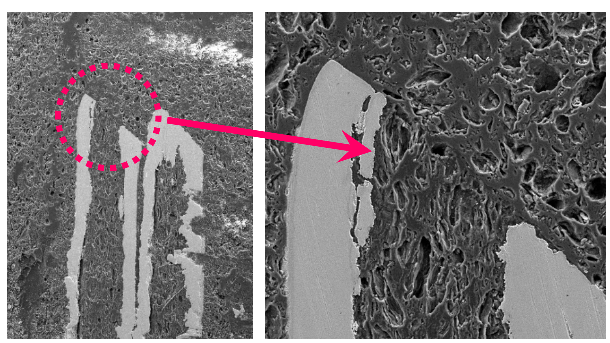
Tue-Mo-Or9-05

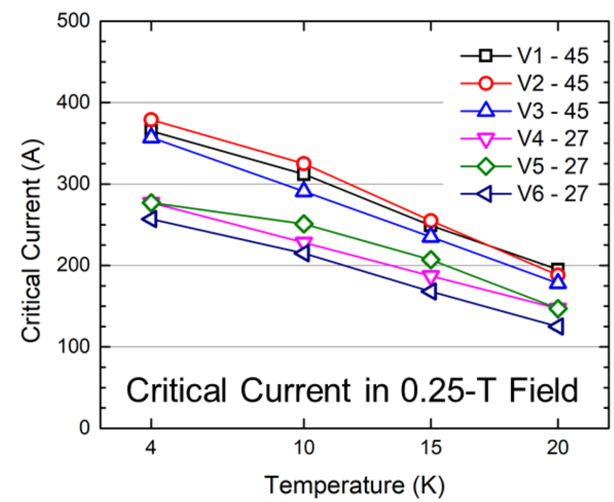
(2019)

SN_2-cooled persistent 5-Coil MRI-field quality 1.5T/(RT)54mm magnet with 580-m MgB_2 wire

❑ Superconducting joint technique





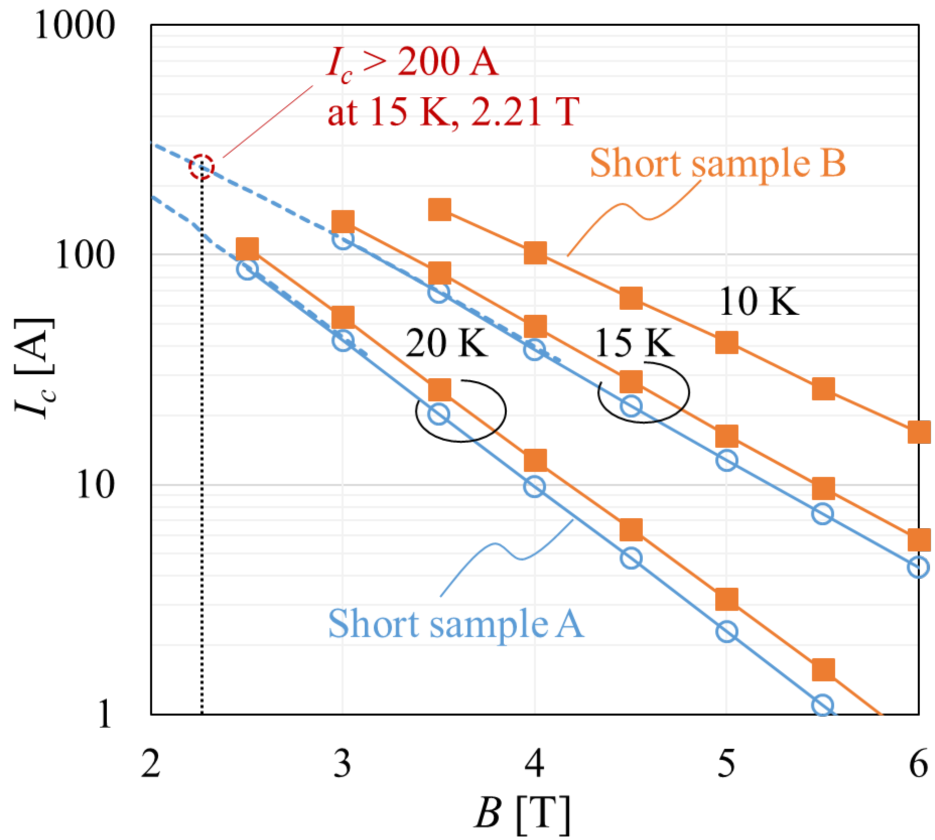


Design Requirement and MgB_2 Wire

Field Intensity	[T]	1.5
Magnet Bore	[mm]	>90
Region of Interest, (DSV)	[mm]	25
Homogeneity (Peak-to-Peak)	[ppm]	<5
Temporal Stability	[ppm/hr]	<0.1
Radial 5-Gauss Fringe Field Radius	[m]	<0.5
Operating Temperature	[K]	10 – 15
Time 10 ➔ 15 K in SN_2 (cooler off)*	[hr]	>5

*To Eliminate cryo-cooler vibration during scanning

Total length (Unit length)	1,400 (m)
Diameter	Bare 0.64-0.65 (mm) w/insulation 0.74-0.78 (mm)
Insulation	T-glass (typically 0.06 mm^t)
Cross-section	-
Heat treatment	600 ℃ 12 hr
Ic	117 A at 15 K, 3 T > 200 A at 15 K, 2 T
N-index	30 at 20 K, 3 T (> 30 at 15 K, 2 T)



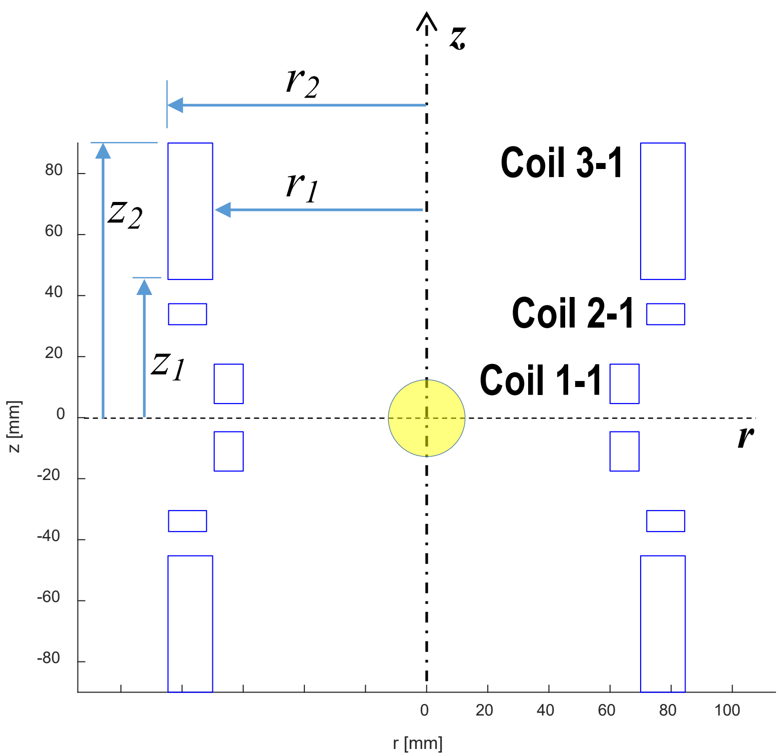
Magnet Design: Method

- ❑ Unshielded 6-coil design optimization by use of *genetic algorithms with **simulated annealing***
  - Cost function is evaluated with different weight parameters: B0 (**1.35 T**), homogeneity (**<5 ppm**), length (<**1.4 km**).
  - Find the **lowest function value** within the magnet **size confinement**.
- ❑ Re-optimization with **an iron-shield** using 2D FEM
  - Parameter: B0 (**1.5 T**), fringe field (5-gauss at **0.5-m** radius)
- ❑ Refine design using 3D FEM model with more detailed shapes of magnet taken into account.
- ❑ From cooled-down/energized dimensions to **RT dimensions** for manufacture.

Limit: Heat treatment inducing irreversible deformation, maybe occurred in MgB_2, is ignored.

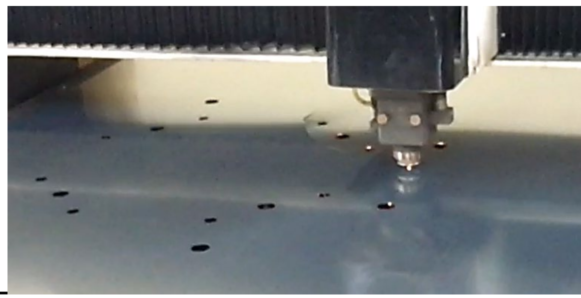
Magnet Design: Main Coil

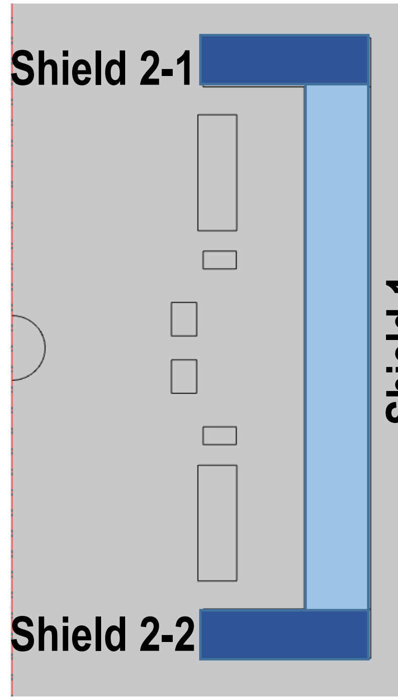
- Wire dimension from actual winding practice.
- Cooled-down, energized coil dimension.

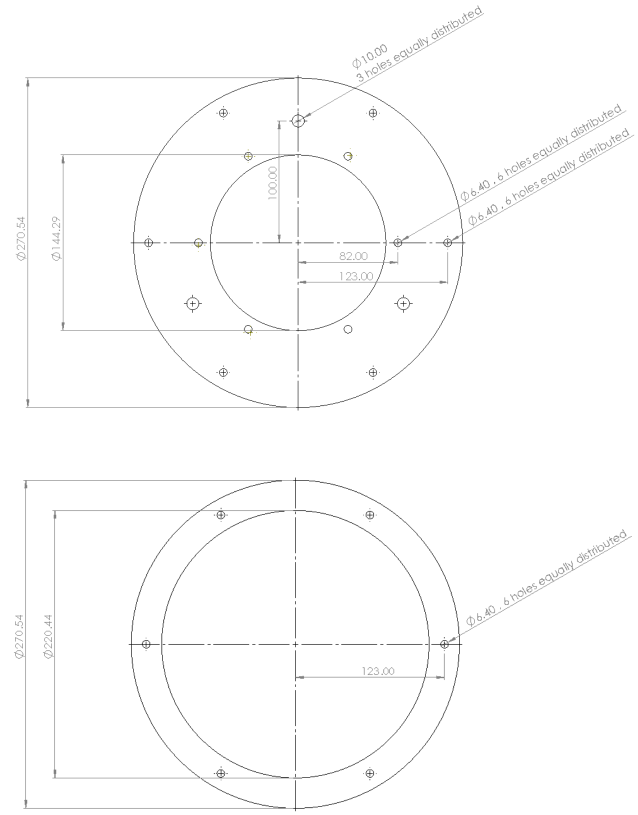


Mid-plane symmetry	**Coil 1-1**	**Coil 2-1**	**Coil 3-1**
Wire (insulated) dimension	**0.86 mm × 0.73 mm**		
$2r_1$; $2r_2$ [mm]	**120.00; 138.98**	**144.00; 168.82**	**140.00; 169.20**
z_1; z_2 [mm]	**4.62; 17.52**	**30.46; 37.34**	**45.28; 90.00**
# turns/layer; # layers	15; 13	8; 17	52; 20
Total length [m]	1,303		
I_{op} [A]	105		
Center field [T]	**1.33**		
Max field [T]	1.55	1.25	1.88
σ_{hoop} (EM only) [MPa]	16	15	22
Total inductance [mH]	619 (Stored energy: 3.4 kJ)		
Homogeneity @ 25-mm DSV [ppm]	**1400**		
5-gauss line [m]	(Radial) **1.01**; (Axial) 1.28		

Magnet Design: Iron-Shield

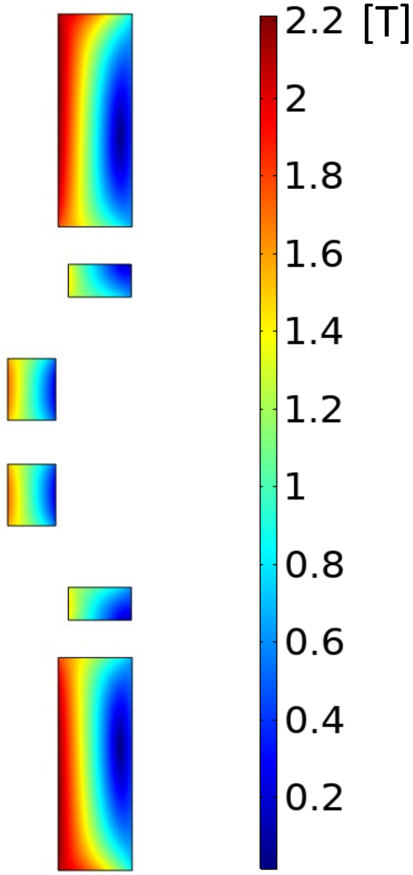
	Shield 1	Shield 2-1
Material	0.5-mm thick Silicon Steel NGO 50PN1300	
$2r_1$; $2r_2$ [mm]	220; 270	144; 270
z_1; z_2 [mm]	-100.80; 100.80	100.80; 119.76
Stack #	404	2× 38
Cutting Method	Laser Cut 	



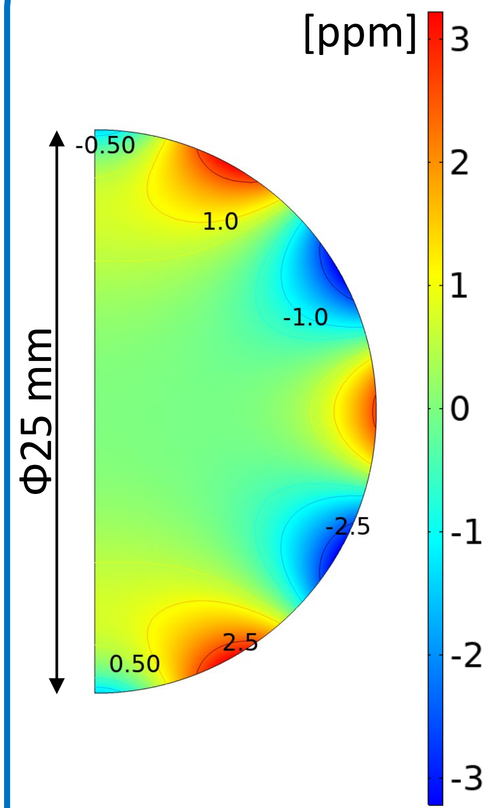


Mid-plane symmetry	Coil 1-1	Coil 2-1	Coil 3-1
Center field [T]	1.33 → **1.5**		
Max field [T]	1.73	1.45	**2.21**
σ_{hoop} (energ. only) [MPa]	17.4	17	26
Total inductance [mH]	720 (Stored energy: **3.97 kJ**)		
Homogeneity @ 25-mm DSV [ppm]	1400 → **6.4**		
Sensitivity with 0.1 mm error [ppm]	570	210	630
5-gauss line [m]	(Radial) 1.01 → **0.48**; (Axial) 0.69		

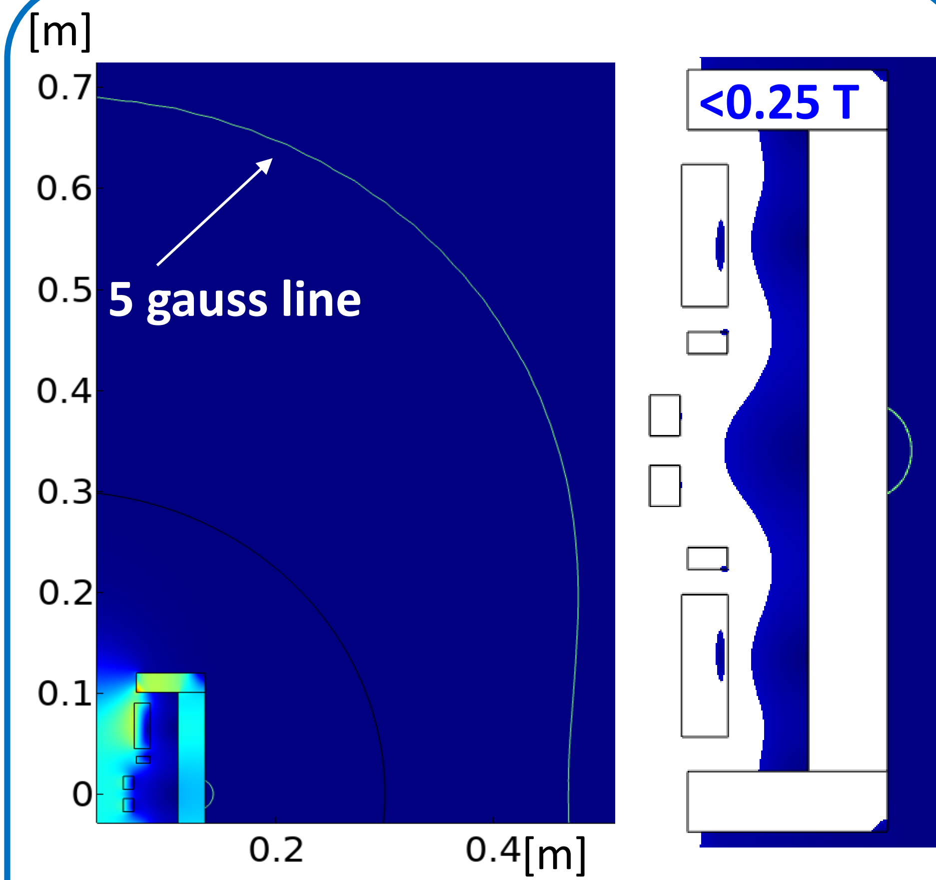
Magnet Design: Analysis Results



Field distribution
in coil sections
Max. **2.22 T**



Homogeneity
in 25-mm DSV
6.5 ppm

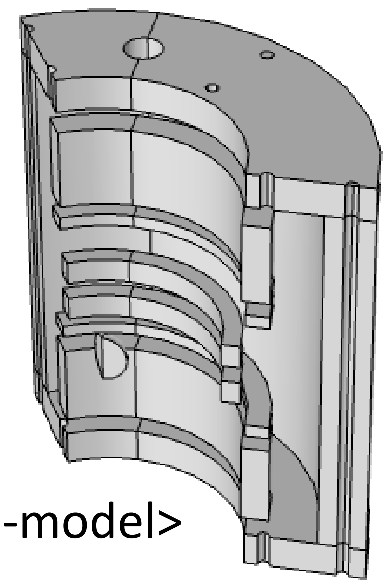


Radial 5-gauss line, **0.48 m**

Low field region **<0.25 T**
for the joint location

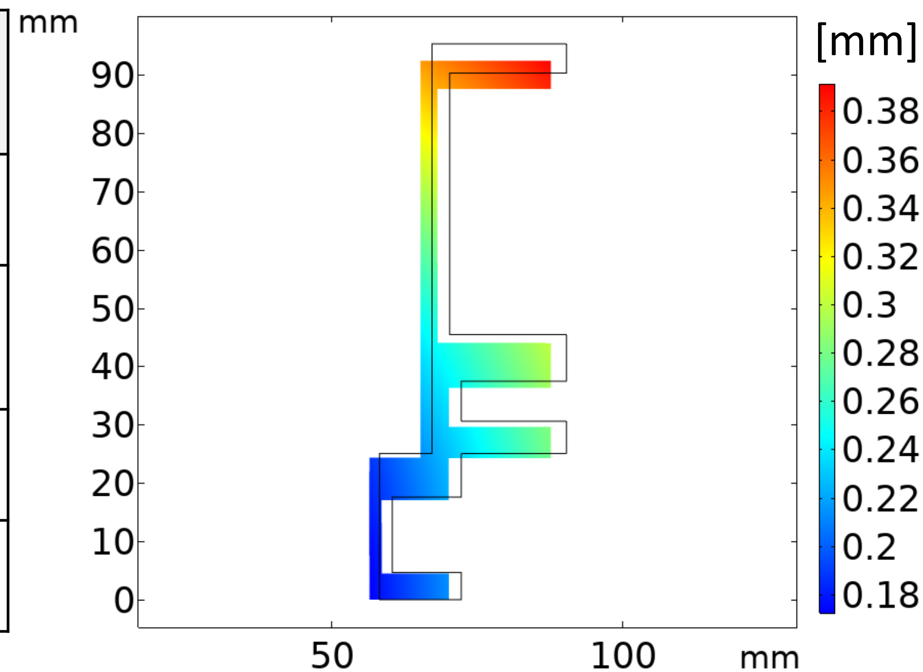
Magnet Design: Manufacture Dimension

- Refine design with considering holes of an iron shield.
- RT dimension for manufacture determined by
  Thermal contraction (Major) and
  Deformation (Minor) by energization.



<3D-model>

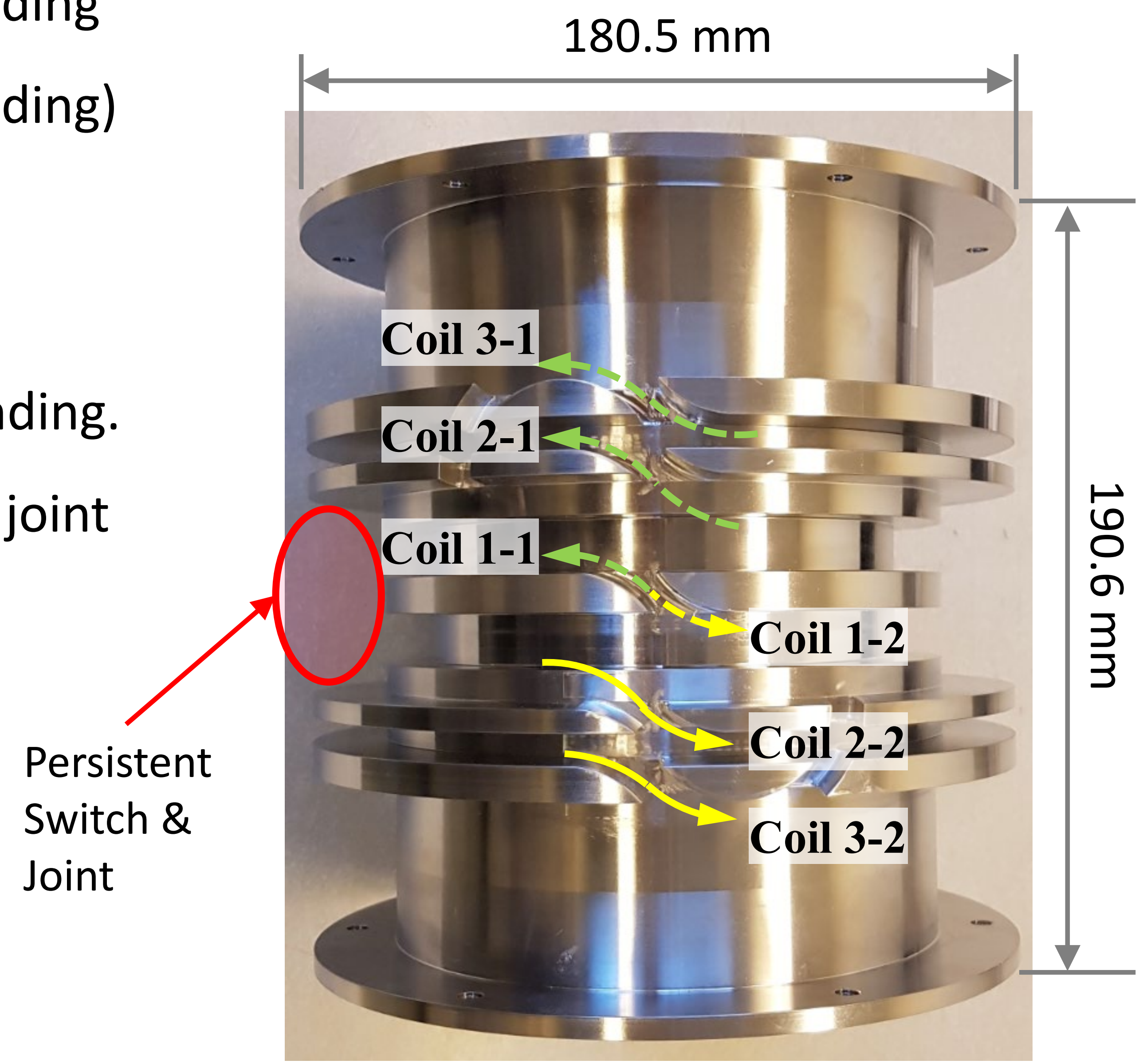
Mid-plane symmetry	Coil 1-1	Coil 2-1	Coil 3-1
$\Delta 2r_1$ [mm]	**0.74**	**0.43**	**0.41**
Δz_1; Δz_2 [mm]	**0.01; 0.05**	**0.09; 0.12**	**0.14; 0.27**
# turns/layer	15	8	52
# layers	13	17	20



<Displacement>

Magnet Design: Former and Winding

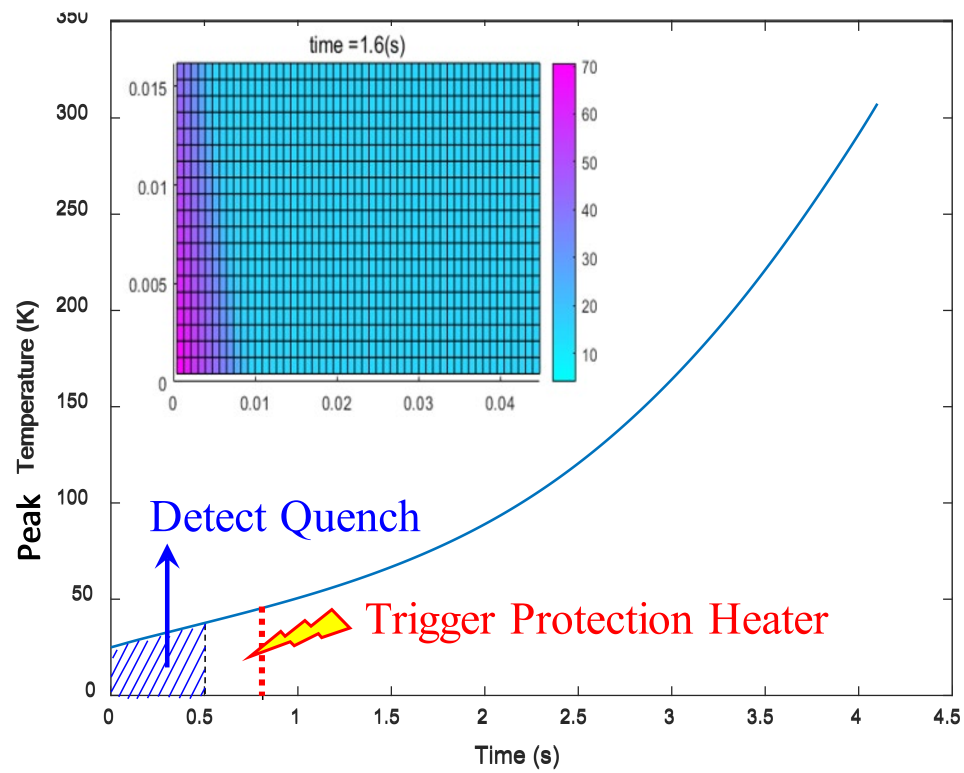
- Former made of Stainless Steel 304L with **≤10 μm** manufacturing tolerance.
- Continuous solenoid winding (like double pancake winding) to have **one joint.**
- Persistent Switch **non-inductive bifilar** winding.
- Place a superconducting joint at **<0.25 T region.**



Quench Protection Design

- When local hot spot (1 inner most turn) in Coil 3 quenched, the peak temperature rise goes up to 300 K in 4 seconds.

Operation Current [A]	105
T_{op} **[T]**	15
Representative T_c **@ Operation [T]**	20
Representative NZPV [m/s]	0.5
Non-Sc / SC	1.5

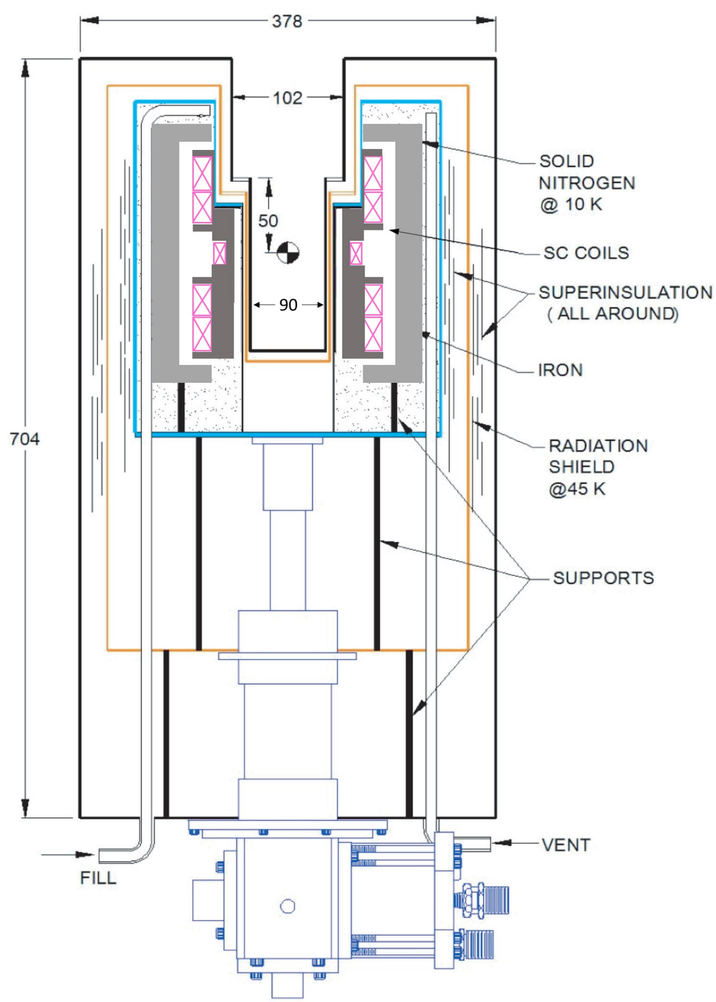


- **Active protection** required.
  - Detect in ***0.5 s***.
  - Trigger the quench heater in ***0.3 s*** to suppress the maximum temperature rise below **200 K**.

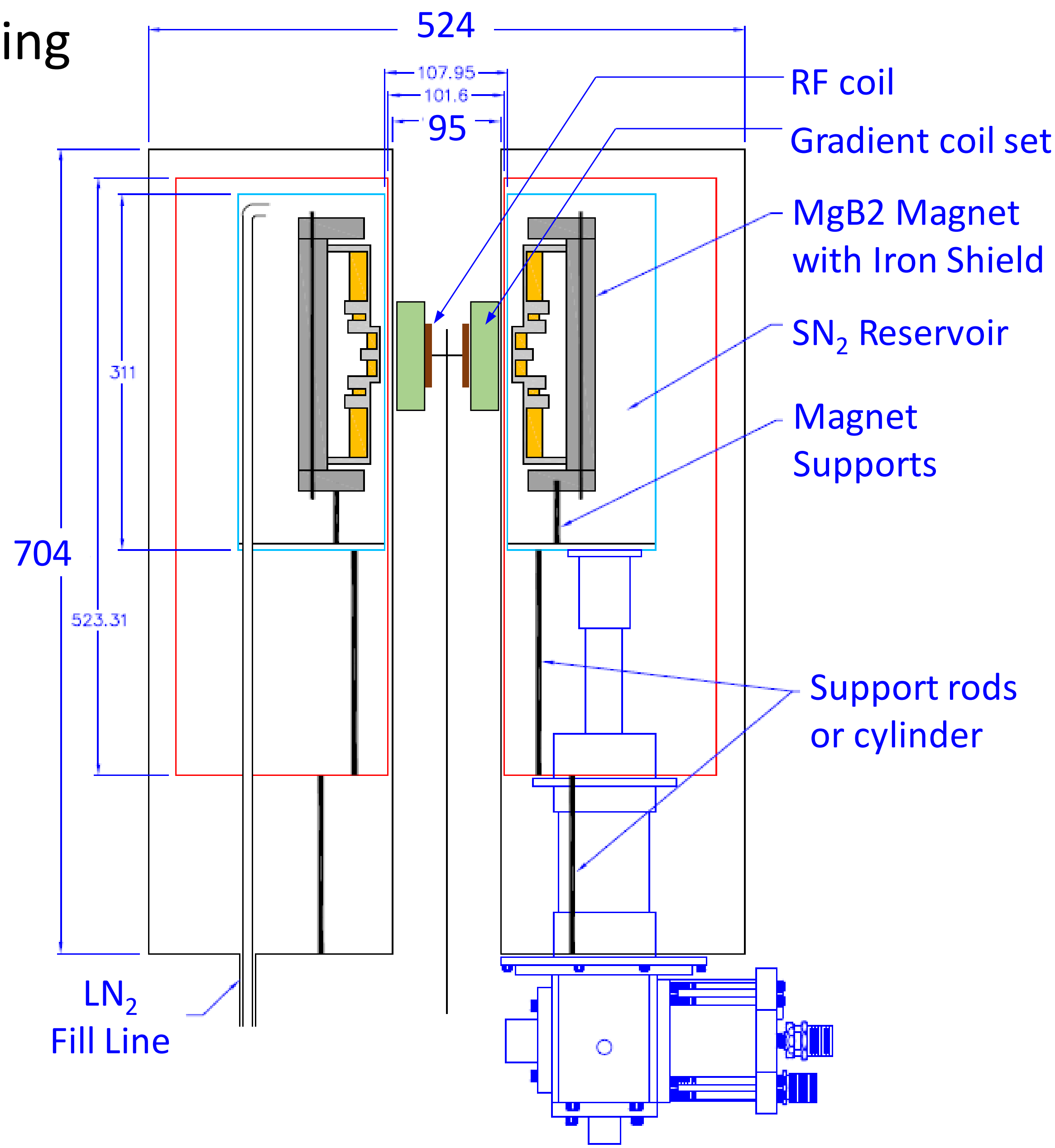
  (to be determined after further analysis and tests)

SN_2-Cooling Cryostat Design

- Key Changes
  - Open bore for gradient coil wiring
  - O.D. 378 ➔ 523 mm
  - Bore size: 102/90) ➔ 95 mm

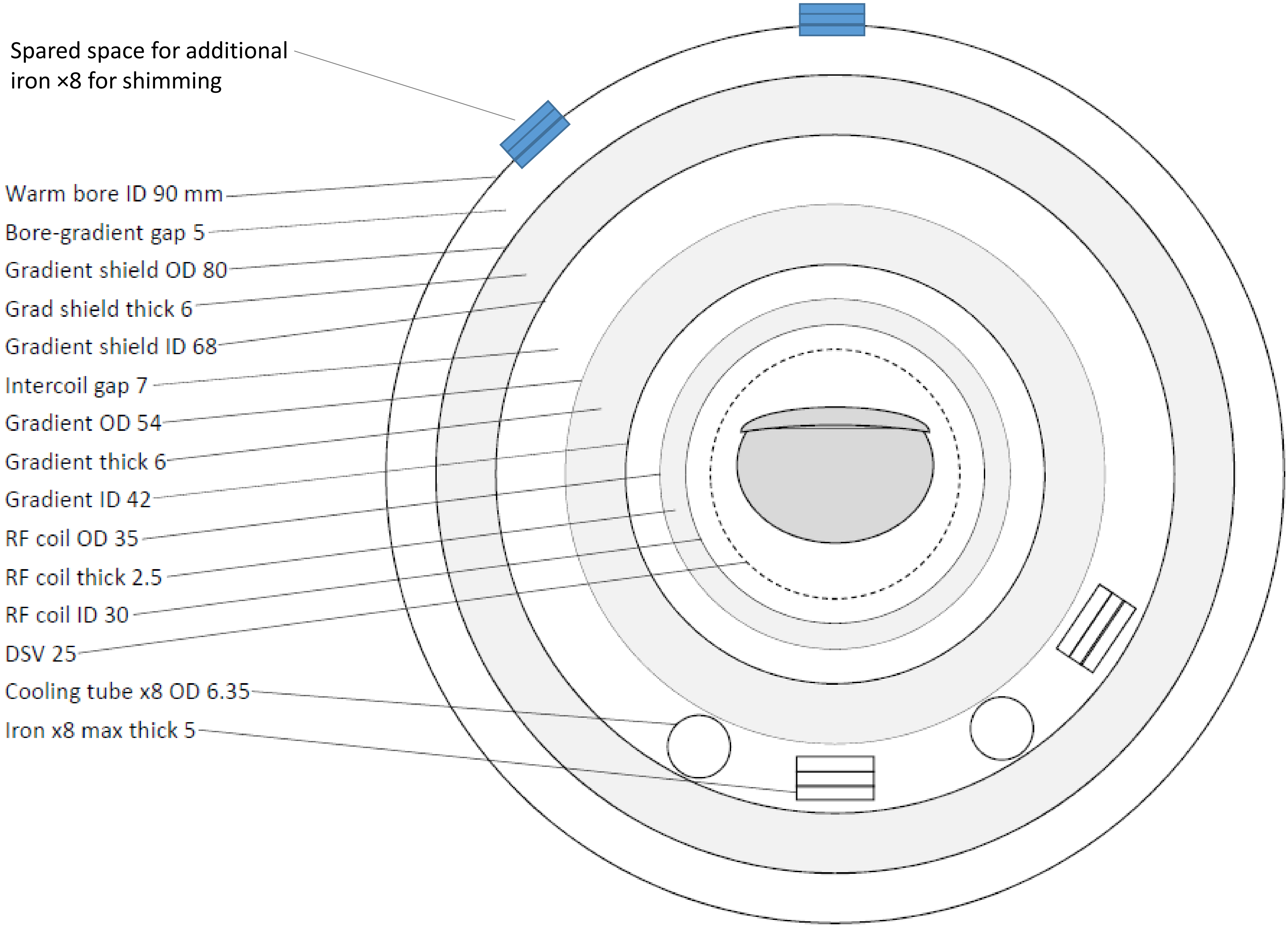


<1st Design, 2017>



<Final Concept Design, 2019>

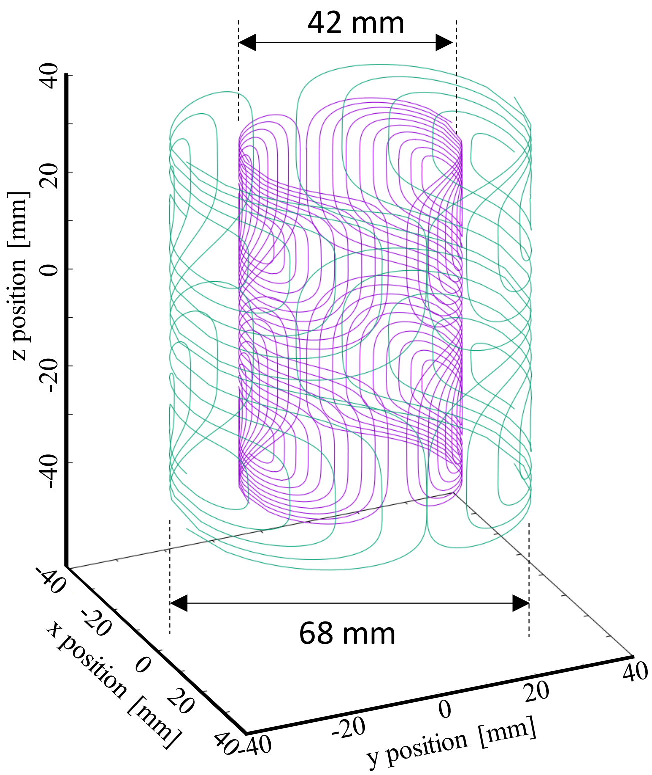
Magnet Bore Design



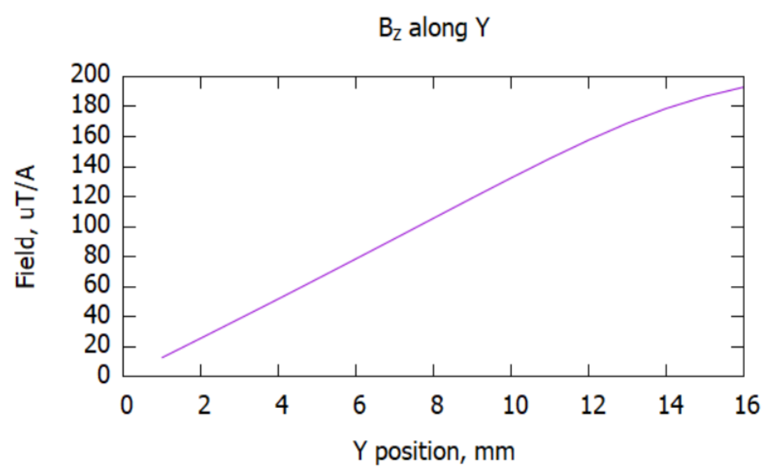
Gradient Coil 1st-Cut Design

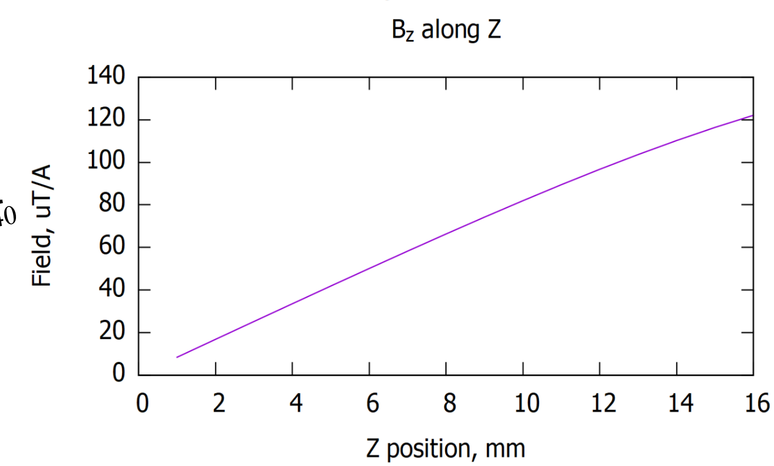
- Computation based on the Biot-Savart formula in octant space (Symmetry).
- Wire path optimization (Nonlinear least squares problem):
  Levenberg-Marquardt Algorithm (LMA) with conformity weighting
  (Target Fields, Stray Field, Power Dissipation and Self-Inductance).

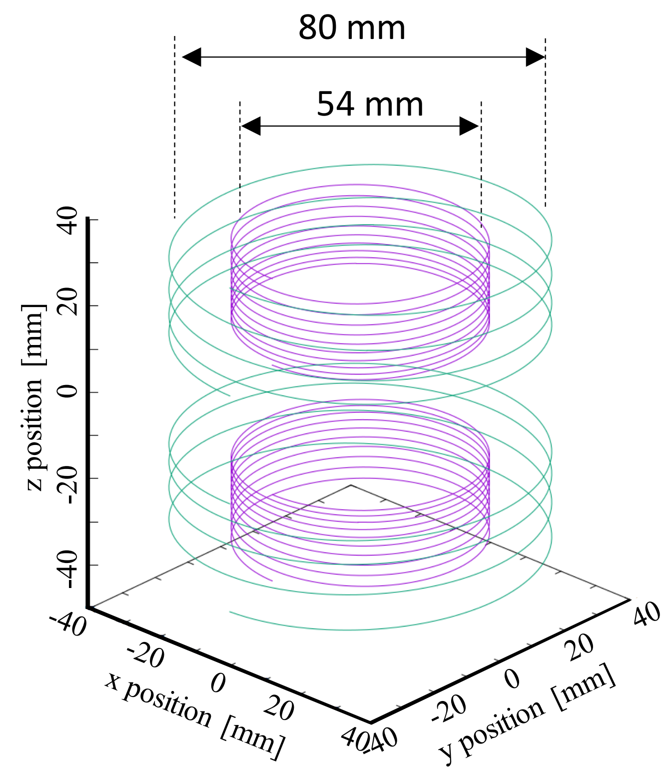
Limit: Dynamic Effect (eddy-currents in nearby metals), Finite Wire Dimension are not taken into account.



Gradient Strength 13.2 mT/m/A
Wire length 7.25 meters







Gradient Strength 8.22 mT/m/A
Wire length 5.40 m

Conclusion

- Design results of 1.5-T "Finger" MRI Magnet (final) and Gradient coils (1st-Cut) are presented.

- Active protection method will applied for reliable operation, although MgB_2 is immune to quench.

- We will complete:
  - SN_2-cooled Persistent 1.5-T MgB_2 Magnet Construction in 2019 and Operation in 2020.
  - Tabletop Osteoporosis MRI Demonstration in 2020.

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