Development of the Superconducting Solenoid for the MuHFS Experiment at J-PARC

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Contents

Magnet Parameter

- Requirement for HFS
  - Field: 1.7 T
  - Local Uniformity : < 1ppm
  - Uniform Field Region :
    - Ellipsoid

      (z:300 mm, r:200mm)

- Requirement for g-2
  - Field : 3T
  - Local Uniformity : < 1ppm
  - Uniform Field Region:
    - Cylindrical

      (z: ±10 cm, r:28.3 ~ 33.8 cm)

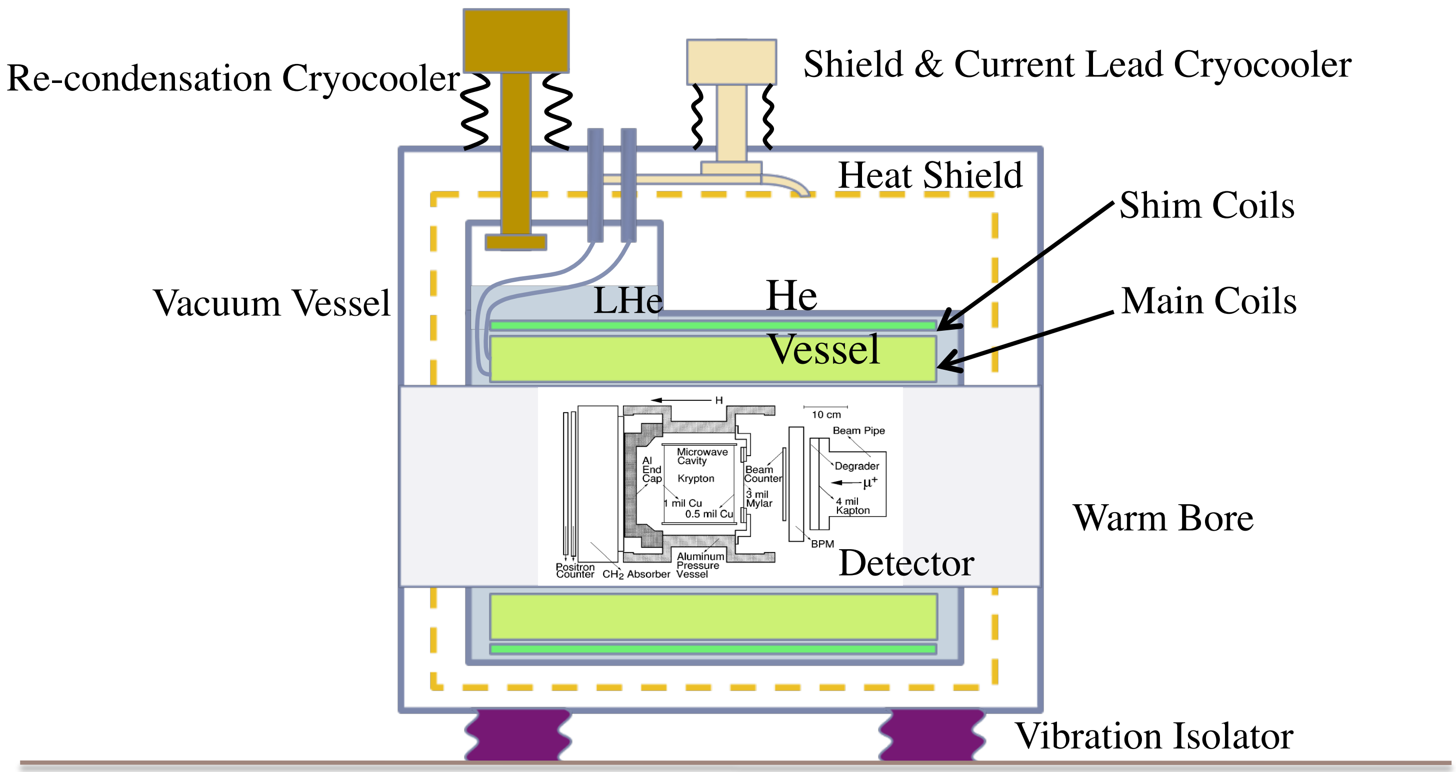
- Future application
  - HFS at higher field ?
  - etc….

- Target
  - Max. Field: 3.4 T
  - Uniform Field Region :
    - Ellipsoid

      (z:300 mm, r:200mm)
  - Local Uniformity : < 1ppm

Schematic View

- Build the magnet system in-house at KEK
- Design => almost the same as MRI magnet
  - Superconducting Solenoid with shim coils
  - cooled by LHe with re-condensation cryocooler
    - for long term operation
  - Operate in persistent current mode
    - for long time stability (0.01~0.1 ppm /h)



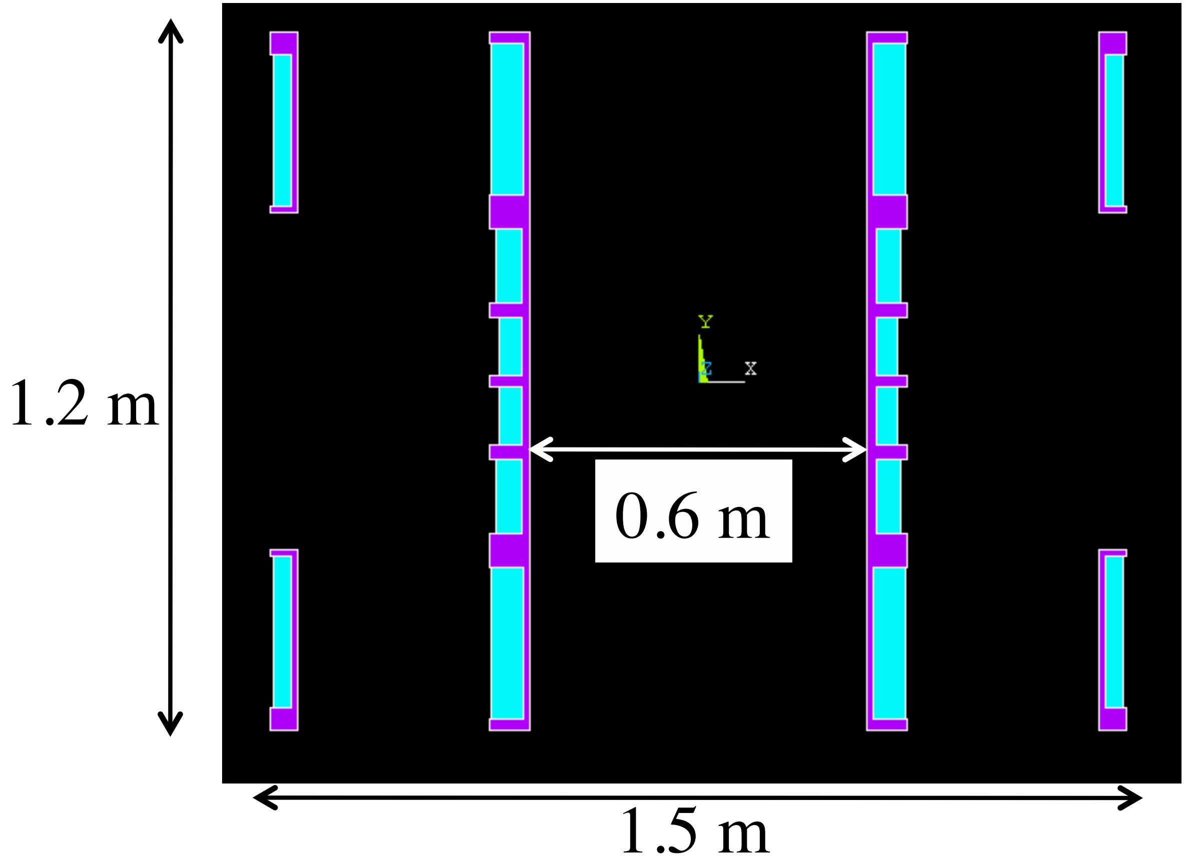
Superconducting Solenoid Design Step

- Magnetic Design
  - Main Coil Configuration finished
  - Shim Coils Configuration on going
- Superconducting Design
  - Superconducting Strand Parameters finished
- Cryogenic Design
  - Heat Load Estimation finished
  - Re-condensation Cryocooler on going
- Mechanical Design on going
- Others
  - Field Monitoring System on going
  - Test Coil on going

Main Coil Design

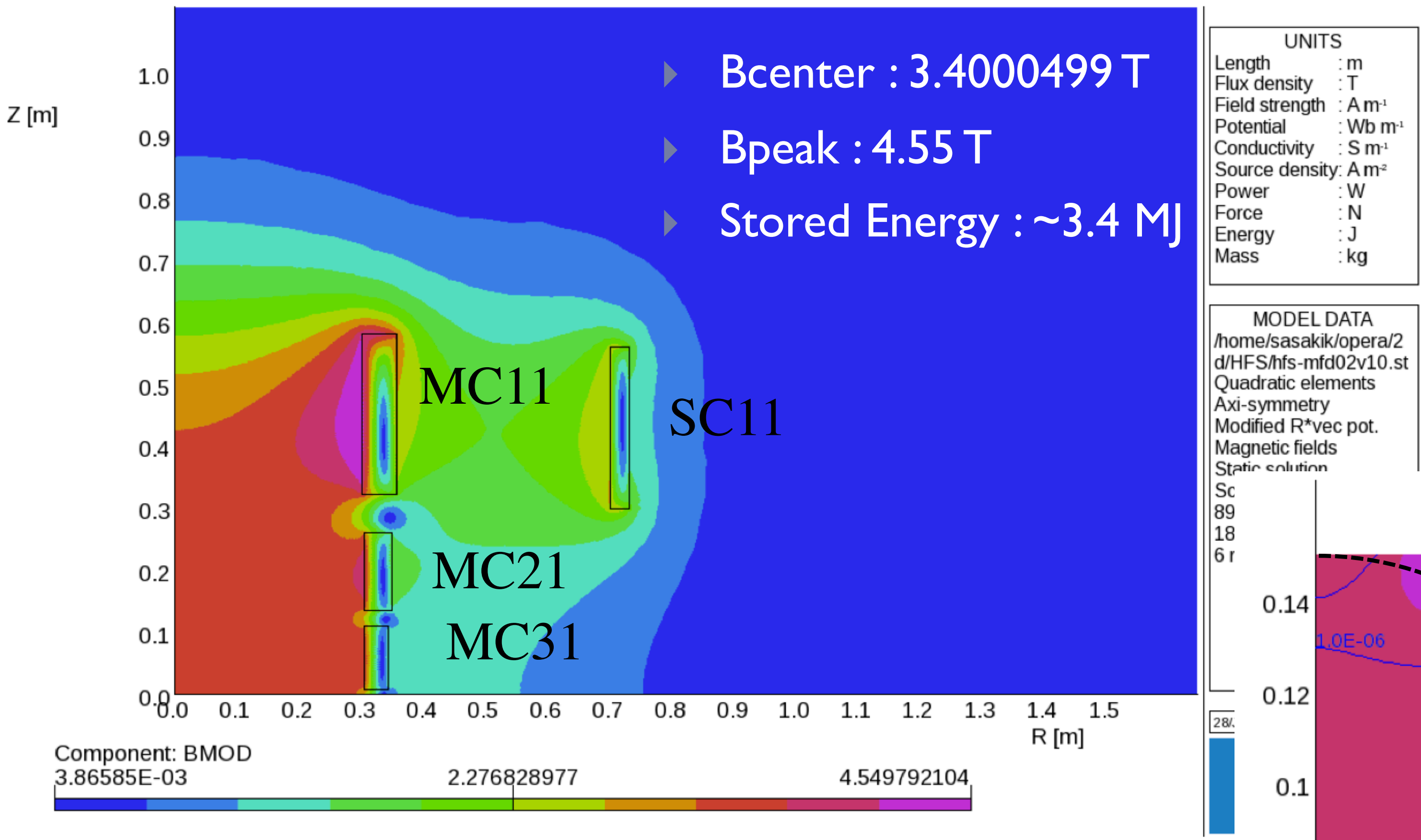
- Optimized
  - Coil Current Density : 1.1e8 A/m^2
  - 6 main coils and 2 shielding coils

	Bottom Left R	Bottom Left Z	Top Right R	Top Right Z
MC11	0.3	0.321439	0.356258	0.580432
MC12	0.3	−0.321439	0.356258	−0.580432
MC21	0.305	0.134763	0.348547	0.260680
MC22	0.305	−0.134763	0.348547	−0.260680
MC31	0.305	0.008939	0.343476	0.110401
MC32	0.305	−0.008939	0.343476	−0.110401
SC11	0.7	0.3	0.73	0.56
SC12	0.7	−0.3	0.73	−0.56



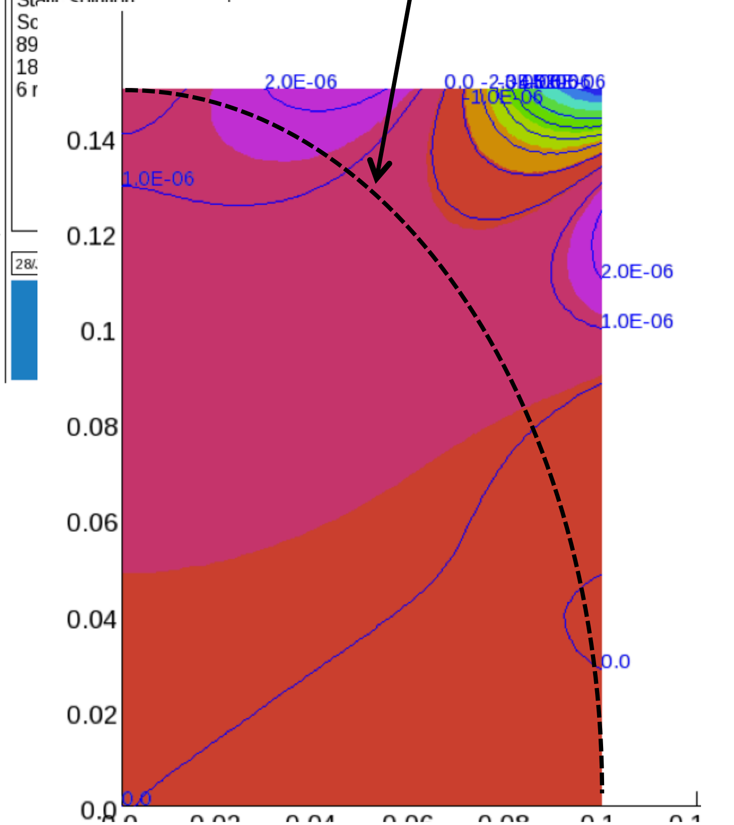
Ideal coil size
w/o shim coils

Magnetic Field by Opera 2d



- Bcenter : 3.4000499 T
- Bpeak : 4.55 T
- Stored Energy : ~3.4 MJ

Ellipsoidal region



In the Ideal coil size

- Error field from magnet center (T)
  - 2e-6 T = 2/3.4 = 0.588 ppm

Contents

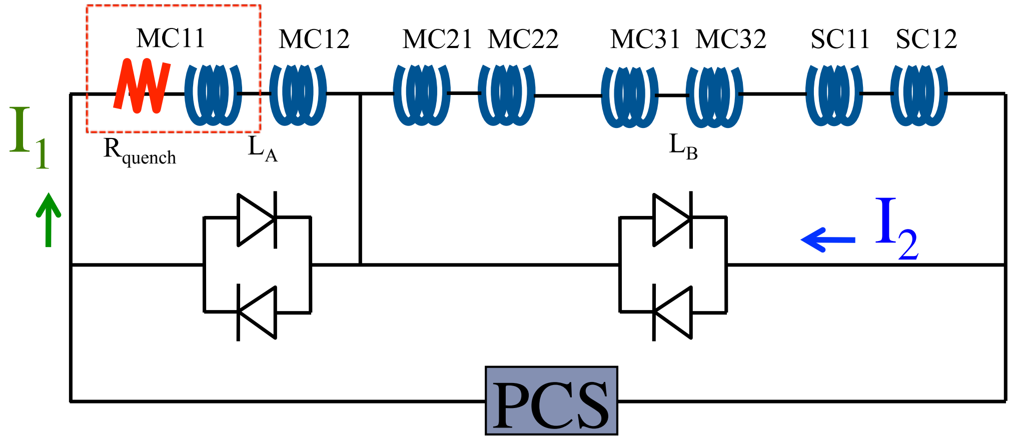
- Magnet
  - Main Coil Design
  - Quench Protection Study
  - Error Field Study
  - Cryogenic Design
  - Mechanical Design
- Field Monitoring System
- Summary

Quench Protection Study

- To decide the parameters of superconducting cable
  - Quench simulation
  - evaluate Peak Temperature and Peak Voltage in the coil

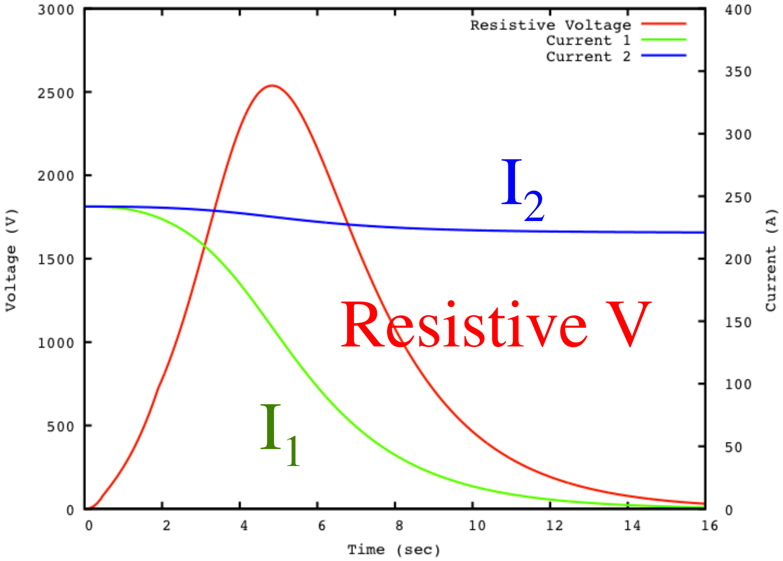
- Strand parameters for the calculation
  - ϕ 1.5(1.6) mm; Insulation thick. : 50 um ; Cu/Sc:6; -> L = 147.2 H
  - ϕ 1.9(2.0) mm; Insulation thick. : 50 um ; Cu/Sc:6; -> L = 62.9 H

- Assume simple condition
  - Adiabatic
  - AC loss is neglected
  - Forward V of Diode : 5V
  - Quench starts on MC11

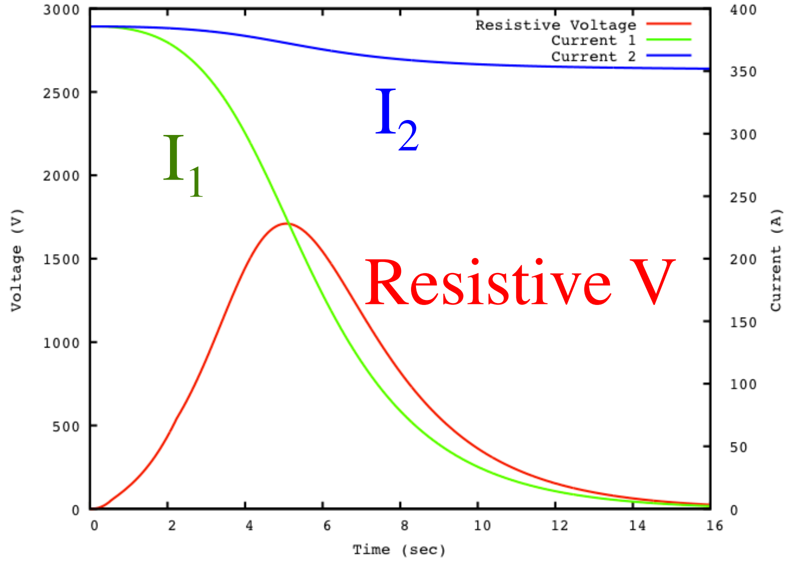


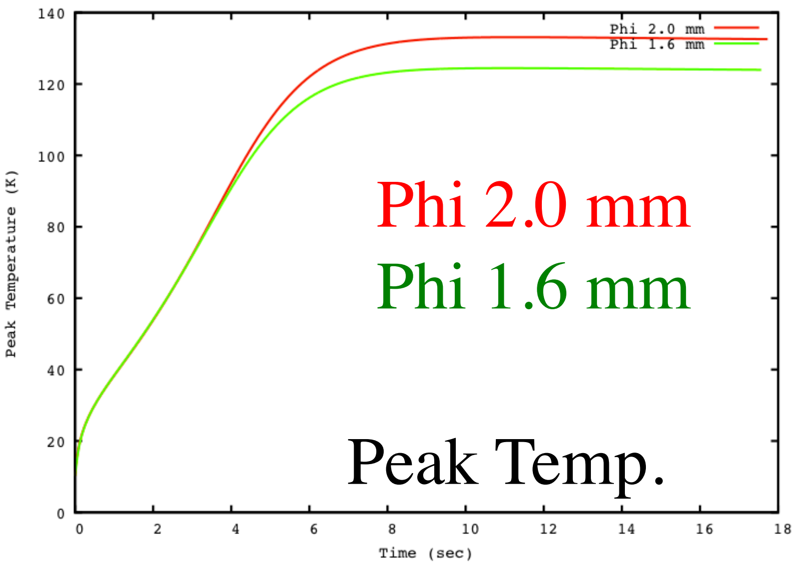
1.6 mm & 2.0 mm Results

- 1.6 mm:



- 2.0 mm:





- Peak Temperature: both OK
  - 1.6mm : ~123 K, 2.0 mm : ~132 K
- Peak Voltage :
  - 1.6 mm : 2500 V > 2.0 mm :~1600V

Lower voltage is preferable : <u>ϕ2.0 mm</u>

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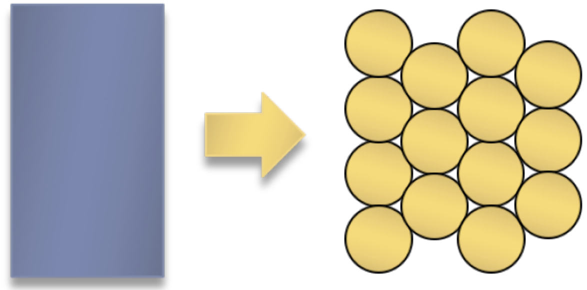
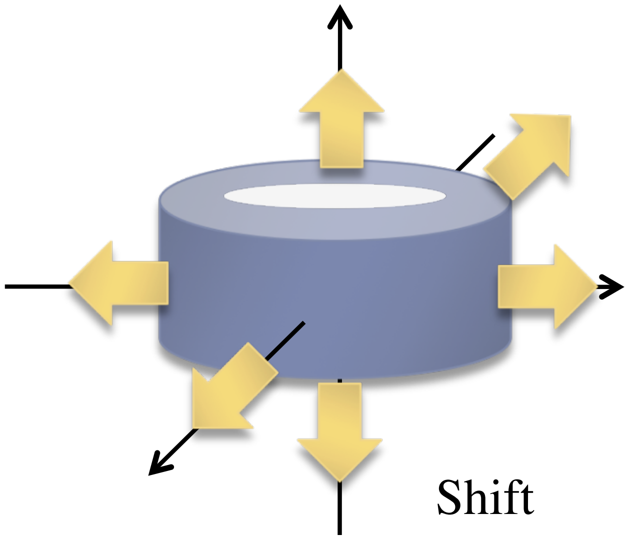
Error Field Study

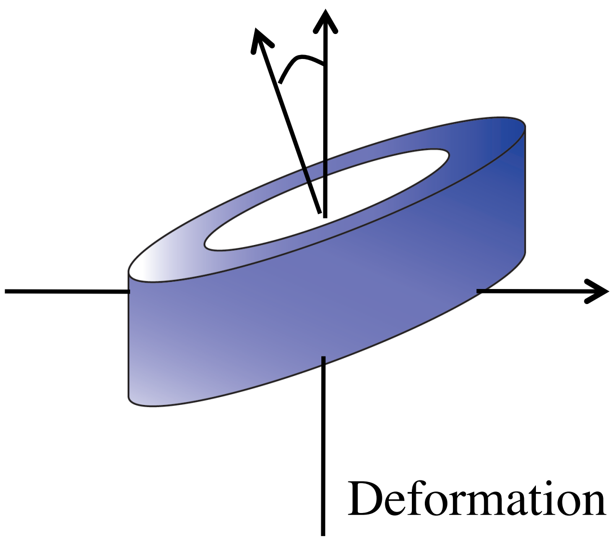
- Evaluated the error field caused by the inaccuracy of the actual winding and structure
  - Non-uniform Current Distribution
  - Position error
  - Deformation
  - Rotation



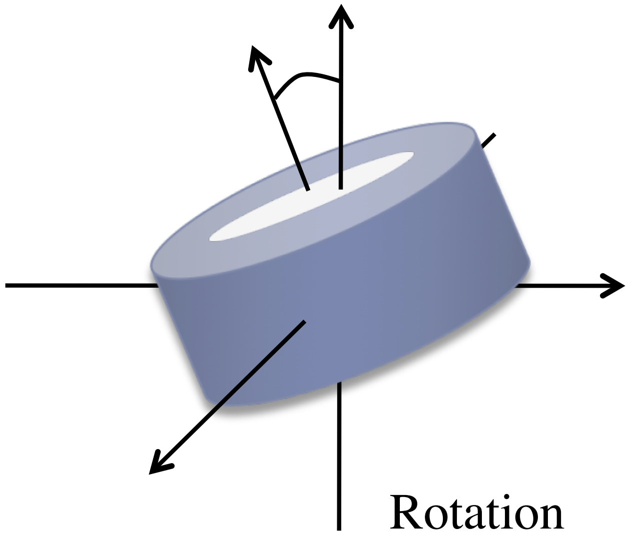
Non-uniform current



Shift



Deformation



Rotation

Estimated Error Field

- Peak Error Field by actual winding : ± 2 ppm
- Peak Error Field (ppm / 0.1 mm, ppm/ 0.1mrad)

	Shift			Deformation	Rotation
	x	y	z		
MC11	−7.7	7.7	−38.7	−1.7	2.1
MC21	−0.3	0.3	45.0	−4.2	−10.6
MC31	10.4	−10.4	332.3	−1.5	−14.0
SC11	0.2	−0.2	0.1	1.2	1.1

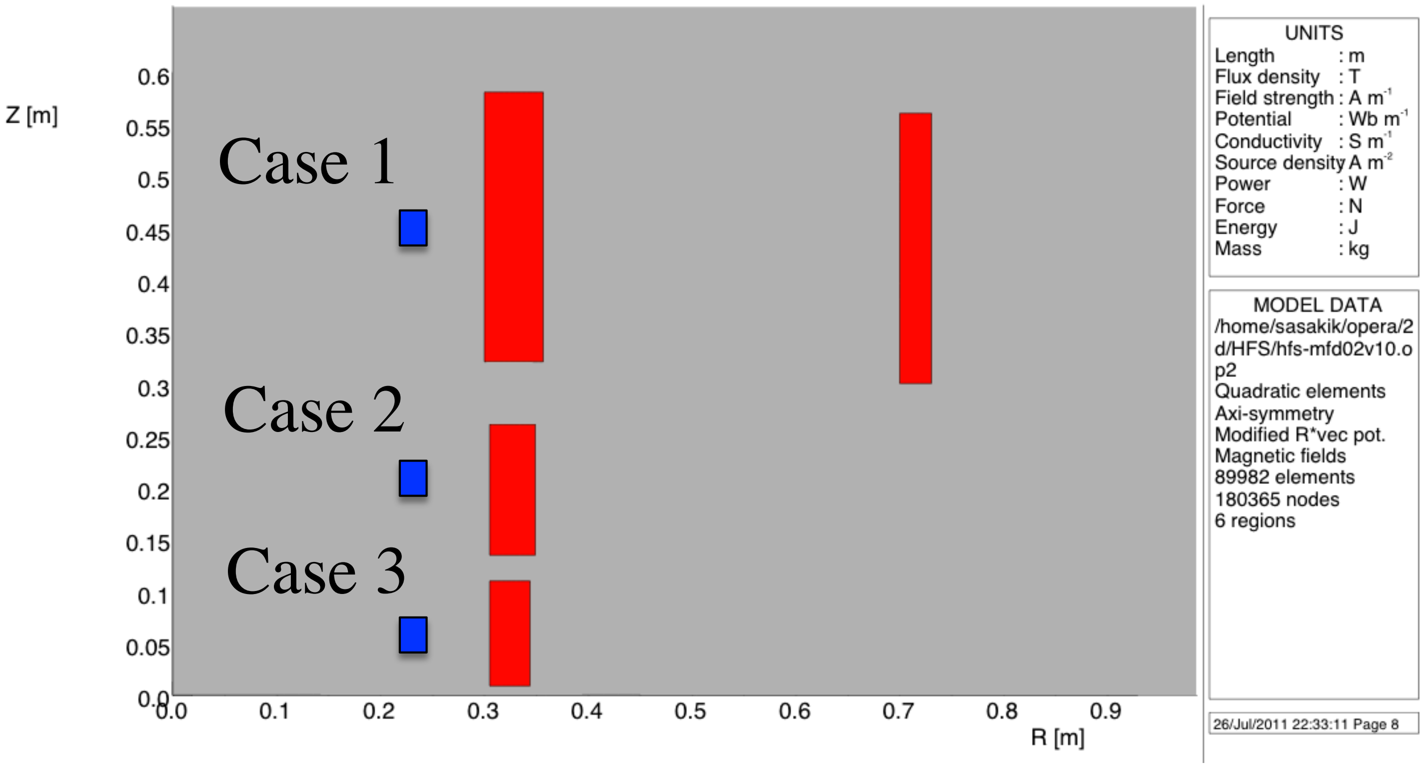
Manufacturing Tolerance : 0.1 mm, 0.1 mrad -> 338 ppm

probably inevitable

•Rough correction -> Iron shim
•Fine correction -> Superconducting Shim Coils

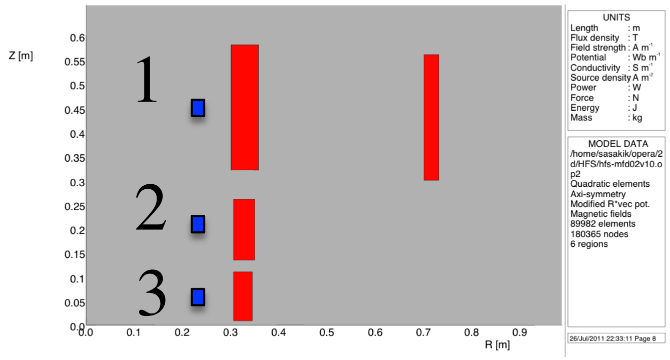
Field Correction by Iron Shim

- Estimated the correction power of Iron shim
  - Ring shape
    - Inner radius 0.42 mm; Cross section:10mm x 20 mm



Field Correction by Iron Shim

Shim Position	(ppm)	z^1	z^2	z^3	z^4
		A_2^0	A_3^0	A_4^0	A_5^0
Case 1; z=0.47	521	968	1351	349	−5341
Case 2; z=0.18	−91109	−2597	−24598	−90106	−119578
Case 3; z=0.06	465921	−16303	13989	467519	1053708



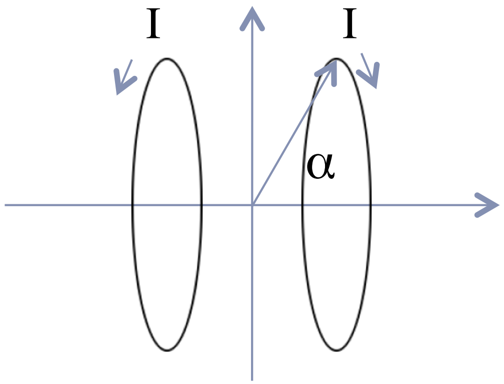
- Spherical harmonics expansion
  - Polar Coordinate

$$B_z(r,\theta,\varphi) = \sum_{n=1}^{\infty}\sum_{m=0}^{n-1} r^{n-1}(n+m)\mathrm{P}_{n-1}^{m}(u)(A_n^m \cos m\varphi + B_n^m \sin m\varphi)$$

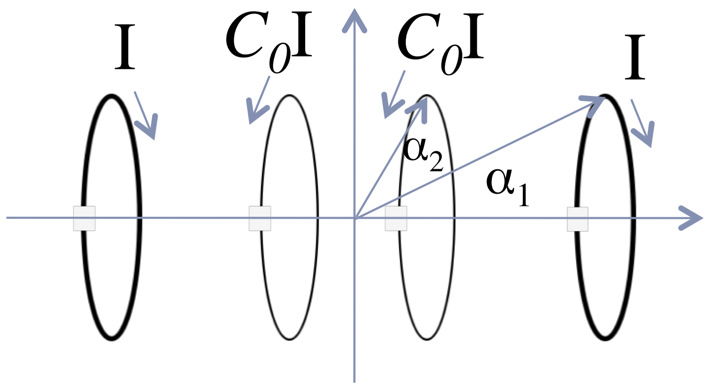
where, $u = \cos\theta$

Superconducting Shim Coil ~ Zonal Coil Model

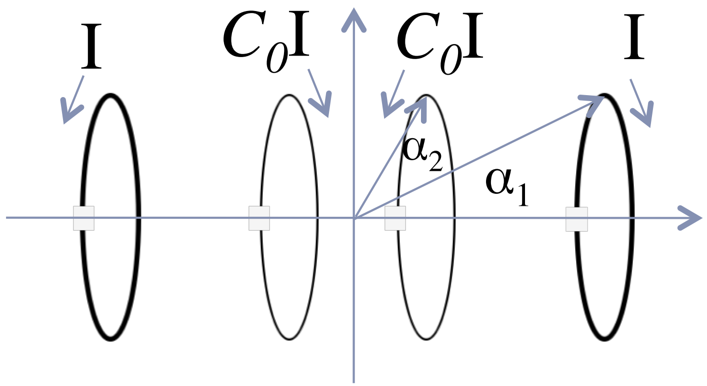
- Assume ideal circular current
  - n=1 (z^1 coil)



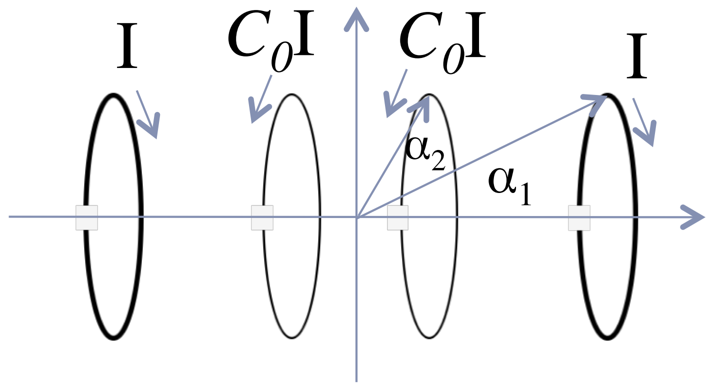
  - n=2 (z^2 coil)



  - n=3 (z^3 coil)



  - n=4 (z^4 coil)



Zonal shim coils could be composed of 2 or 4 circular currents

Zonal Shim coil ~ harmonic coefficient

$$B_z = A_1^0 + 2A_2^0 z + 3A_3^0 z^2 + 4A_4^0 z^3 + \cdots$$

- Bz on z axis generated by circular currents in radius of 0.4 m

	z1	z2	z3	z4	(z4)
No. of Coil	2	4	4	4	4
α_1	49.1066°	40.0889°	33.8782°	29.3385°	53.7222°
α_2	-	73.4273°	62.0404°	53.7222°	77.9187°
C_0	-	0.3033	0.2809	0.2245	0.5603
Length in Z	0.693 m	0.950 m	1.192 m	1.423 m	0.587 m
$A_1^0(z^0)$	0	0	0	0	0
$2A_2^0(z^1)$	5.036e-6	0	0	0	0
$3A_3^0(z^2)$	0	10.5698e-6	0	0	0
$4A_4^0(z^3)$	0	0	19.4982e-6	0	0
$5A_5^0(z^4)$	0	0	0	19.0557e-6	-114.652e-6
$6A_6^0(z^5)$	-100.95e-6	0	0	0	0
$7A_7^0(z^6)$	0	-265.06e-6	0	0	0

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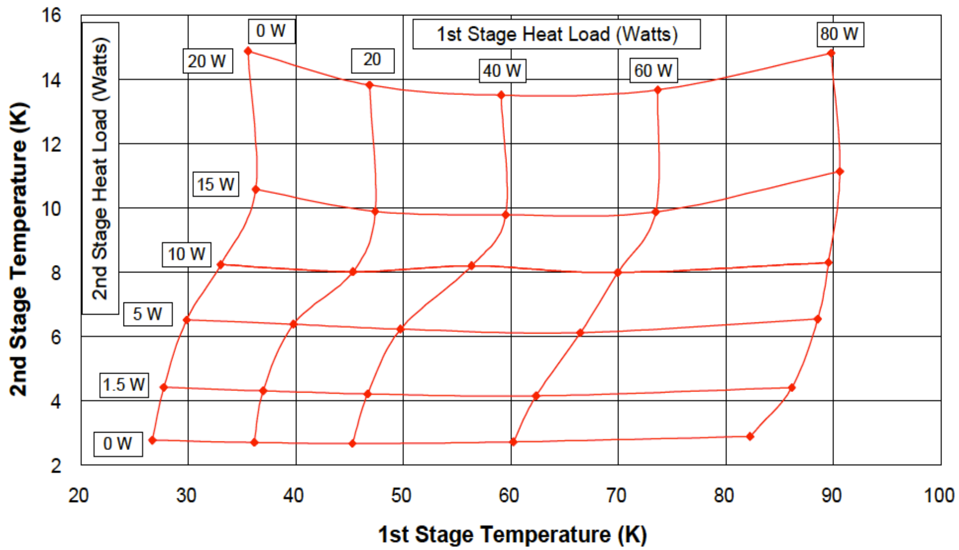
  - Mechanical Design
- Field Monitoring System
- Summary

Cryogenic Design

- Heat Load Estimation
  - Conductive Heat
    - Coil Support Rod
    - Current Leads
  - Radiation Heat

Cooling Capacity Curve of GM Cryocooler



•Total Heat Load

	No. of GM cooler	He vessel	Thermal shield
Case 1	1	1.77 W	75.24 W
Case 2	2	0.62 W	78.63 W

One GM cryocooler -> no enough margin

Two 2-stage GM cryocoolers

Contents

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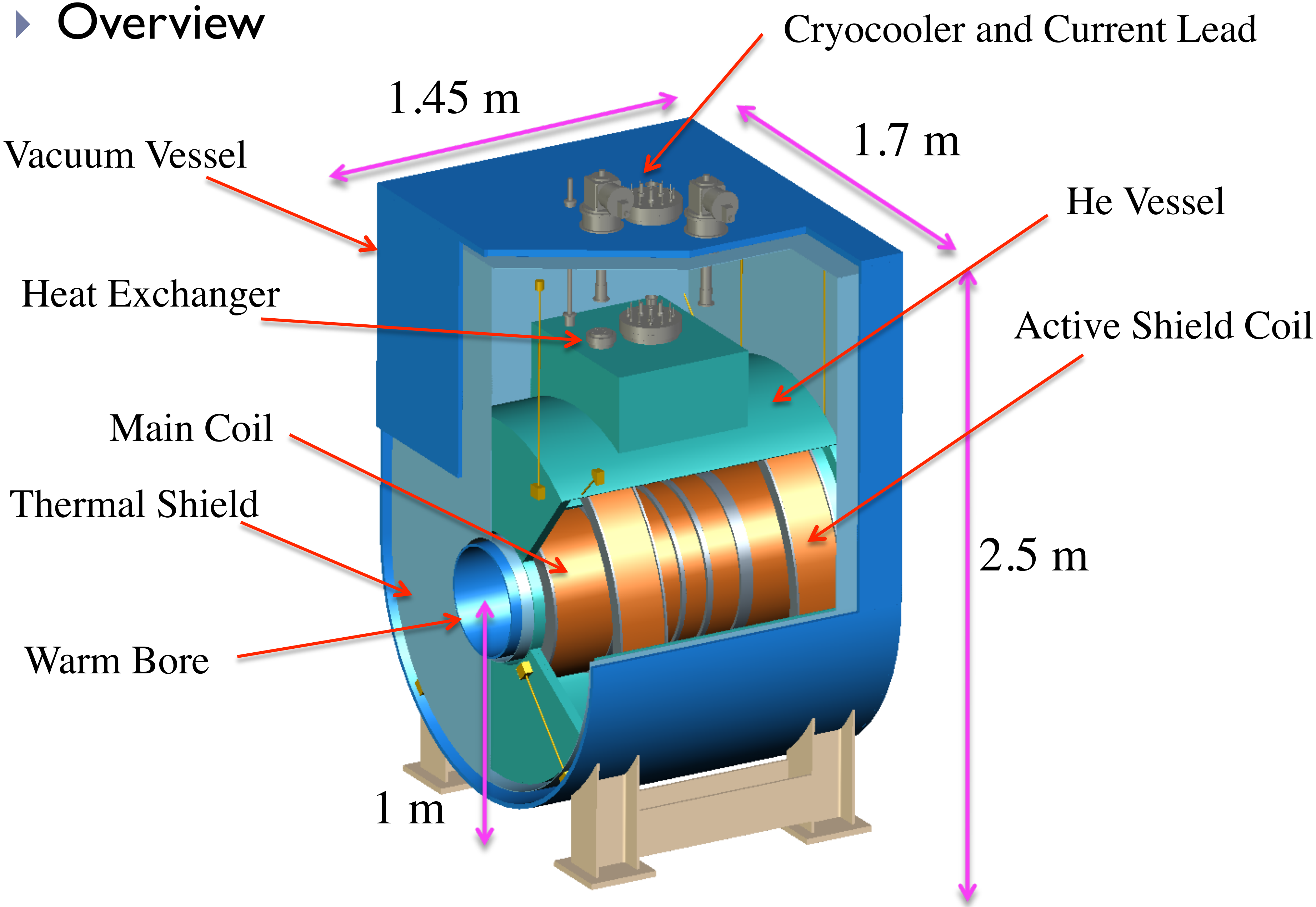
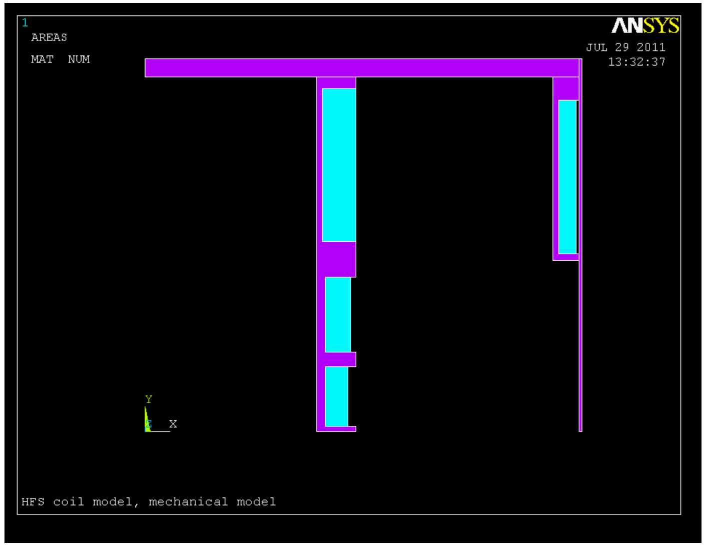
Mechanical Design

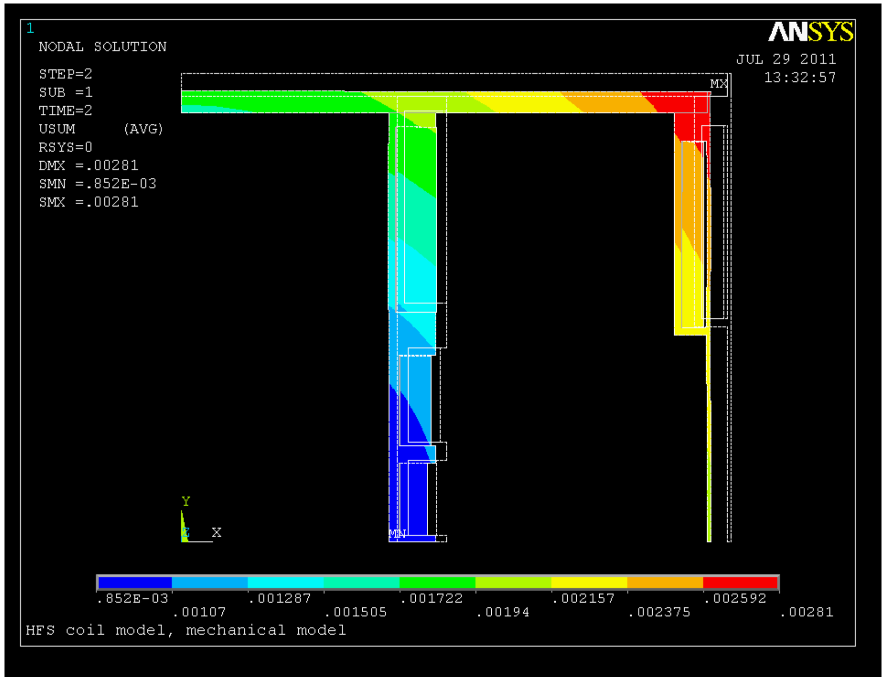
- **Overview**



Mechanical Design ~ Coil Bobbin Design

- For the precise magnet design
  - must consider coil deformation
    - Winding tension
      - 100 ~ 500 um depending on the tension
    - Thermal contraction during cooling
      - ~ 2.8 mm at a maximum
    - Hoop stress during excitation
      - 27 ~ 30 MPa

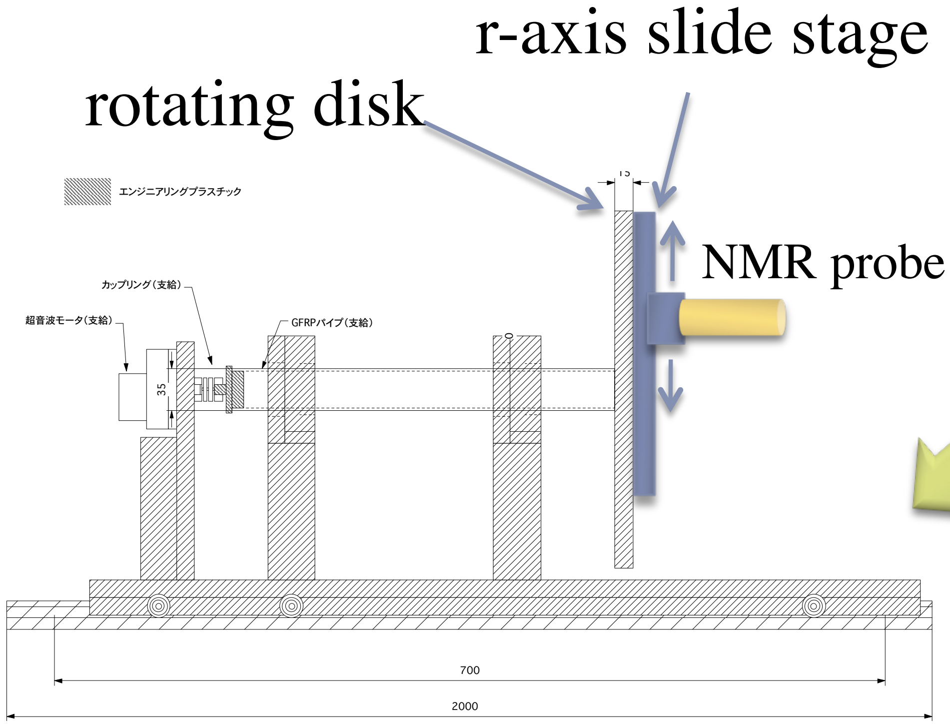


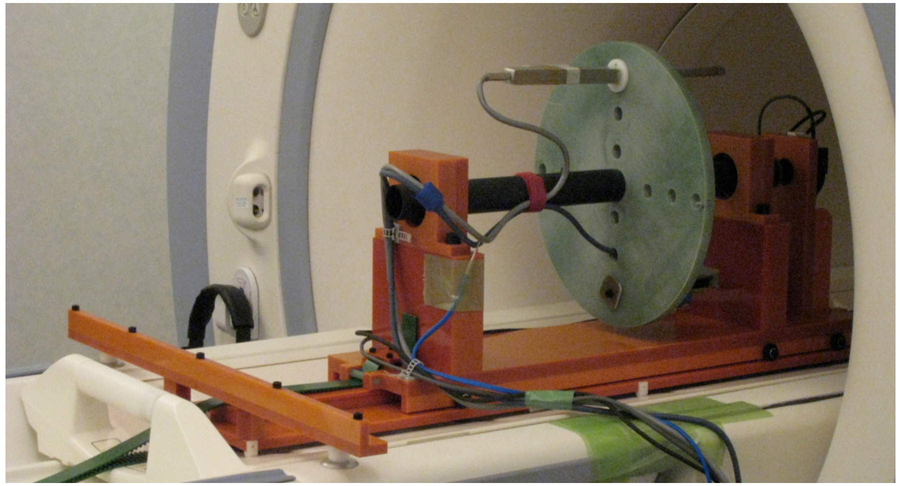


Contents

Precise Field Monitoring System

- NMR probe
- Require 3-axis moving stage (r, θ , z)
  - built the prototype stage

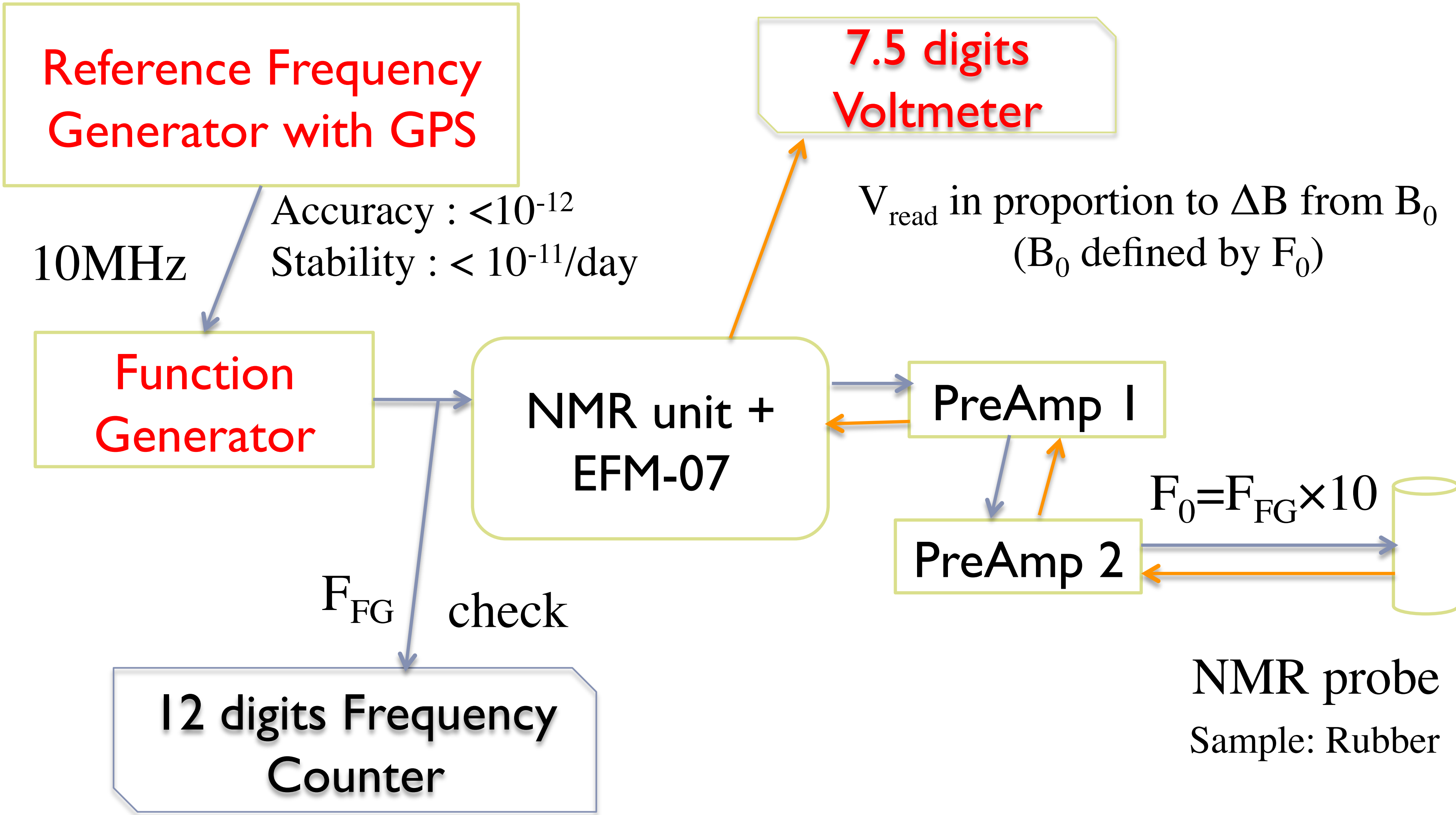




2-axis moving stage (θ, z)

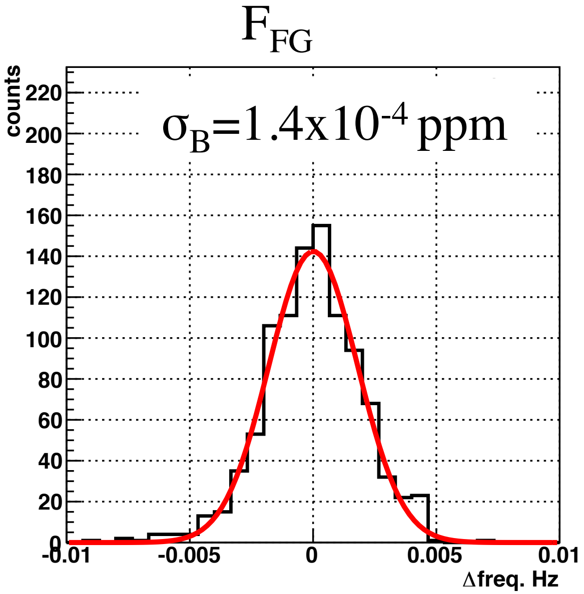
NMR system ~ Connection Diagram

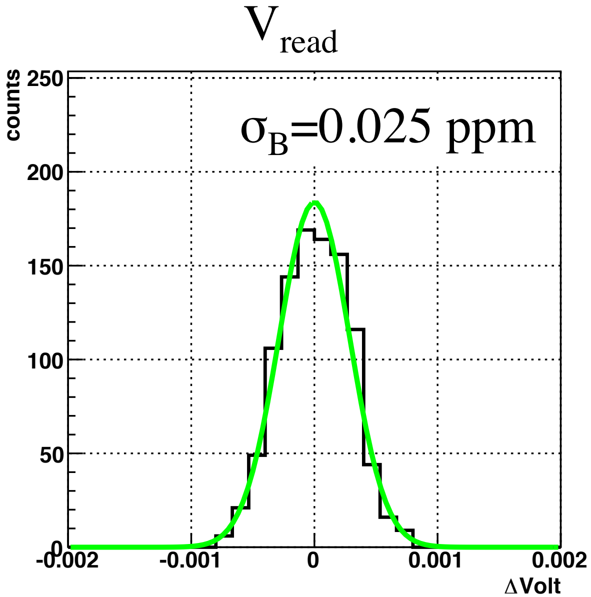
- In order to achieve the high stability and accuracy
  - the frequency of the RF signal to the NMR sample has to be stabilized.



Stability of NMR system in 3T magnet test

- Input Frequency : 12,771,271.534 Hz (~ 2.9996145 T)





- RF signal of the function generator seems to be highly stabilized due to the reference frequency generator.

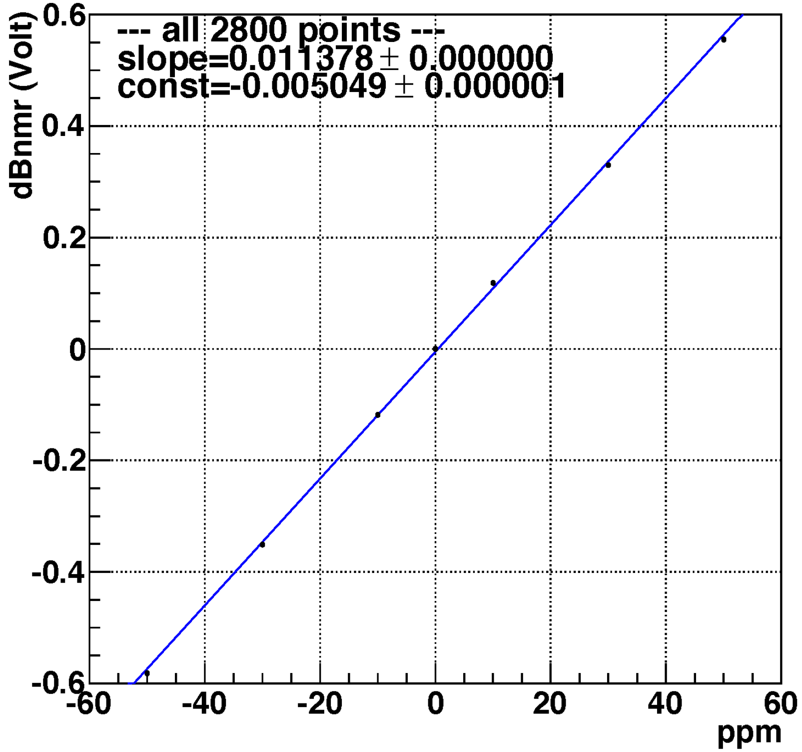
- Deviation of the output voltage is larger than input RF signal.
  - Measurement error of voltmeter.
  - Signal modulation in the NMR unit and the pre amps.

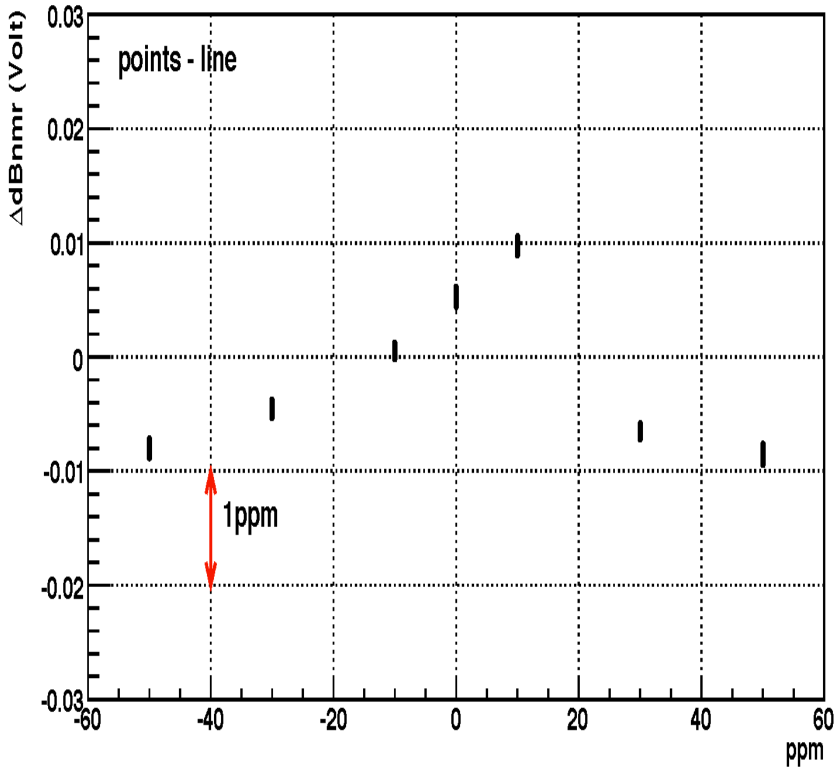
To decrease the noise -> New NMR unit
RF signal could inputs directly into the NMR probe

Accuracy of NMR system

- The output voltage "must" be linear with the input frequency, when the field is measured at a fixed point.

Correlation between ΔV and ΔF





- Error from the linear regression line : ± 1 ppm
- NMR unit might have any problem in the electrical circuit.

-> In the next test, we will investigate the reasons in more detail.

Summary ~ Plan

- Magnet design :
  - Many design steps are steadily proceeded in parallel
    - Main Coil Design : Ideal coil geometry was obtained
      - 6 main coils and 2 active shield coils
    - Quench Protection Study
      - Strand Diameter : ϕ2 mm, Cu/Sc = 6
    - Error Field Study
      - Manufacturing Tolerance : 0.1 mm, 0.1 mrad -> 338 ppm
    - Mechanical Design
      - on going
    - Cryogenic Design
      - Estimated heat load -> Two GM cryocoolers are required
  - Field Monitoring System
    - developing the moving stage
    - try to improve the stability and accuracy

Next step

- Test coil winding
  - in this summer
- Shim coil design
  - practical design of zonal shim coils
  - design tesseral shim coil
- Field Monitoring System
  - upgrade the moving and NMR system

Magnet system will be ready in the end of March, 2013