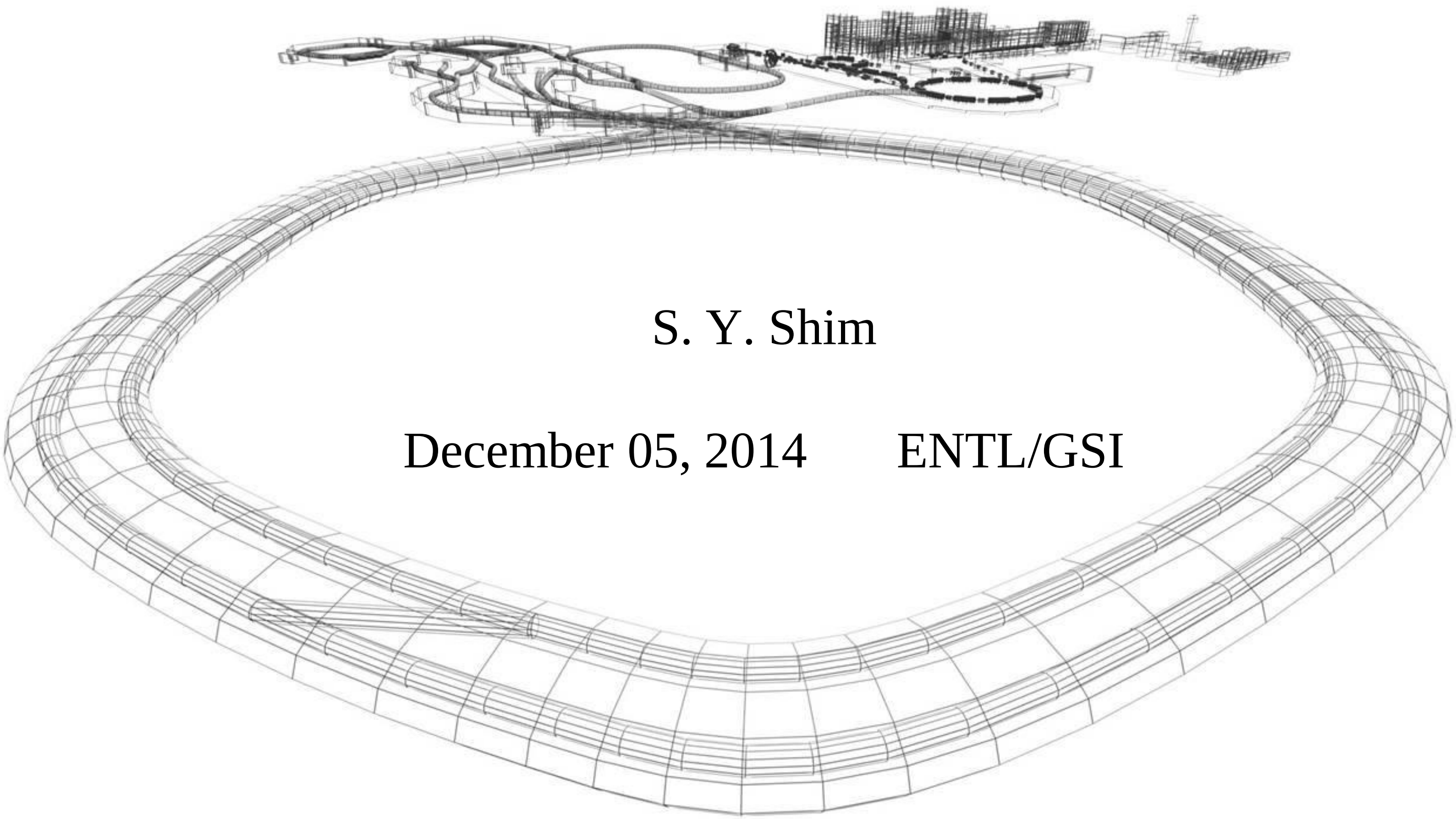
Influence of Driving Current Ripple on CR Dipole Magnetic Field



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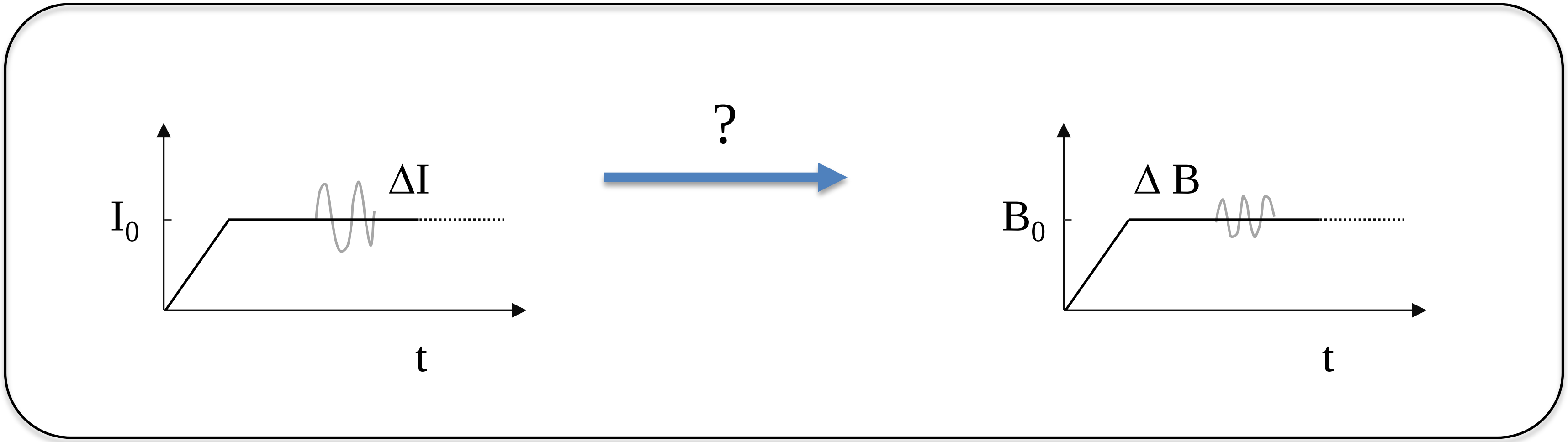
Motivation

- The driving current unstability was reported considering the CR magnets circuit. And it may give a change of magnetic field.
- Therefore, we need to clarify the relation between rippling current and corresponding magnetic field.
- The proportional ratio α can be expressed by following relation.

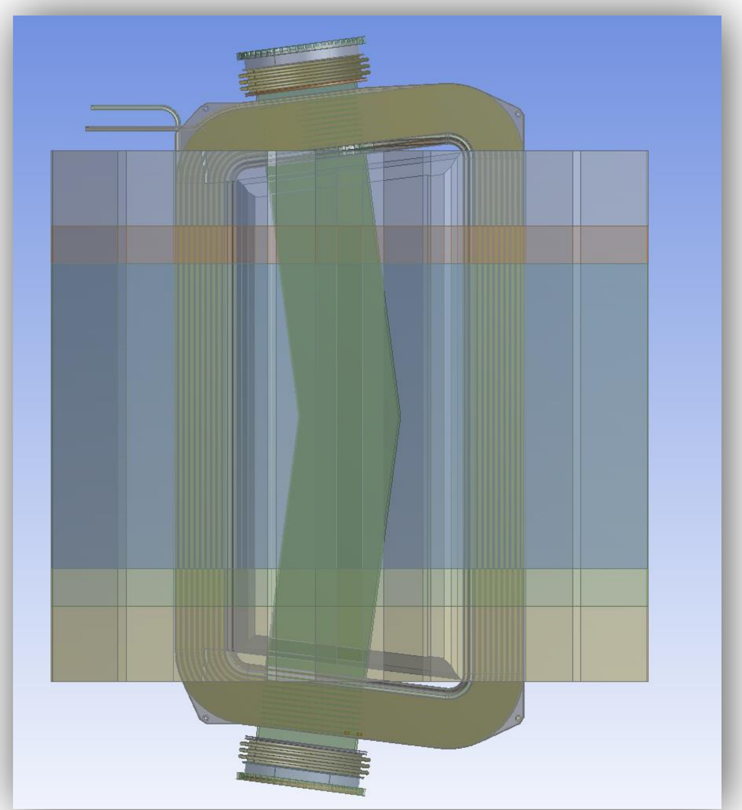
$$\frac{\Delta B}{B_0} = \alpha \frac{\Delta I}{I_0}$$

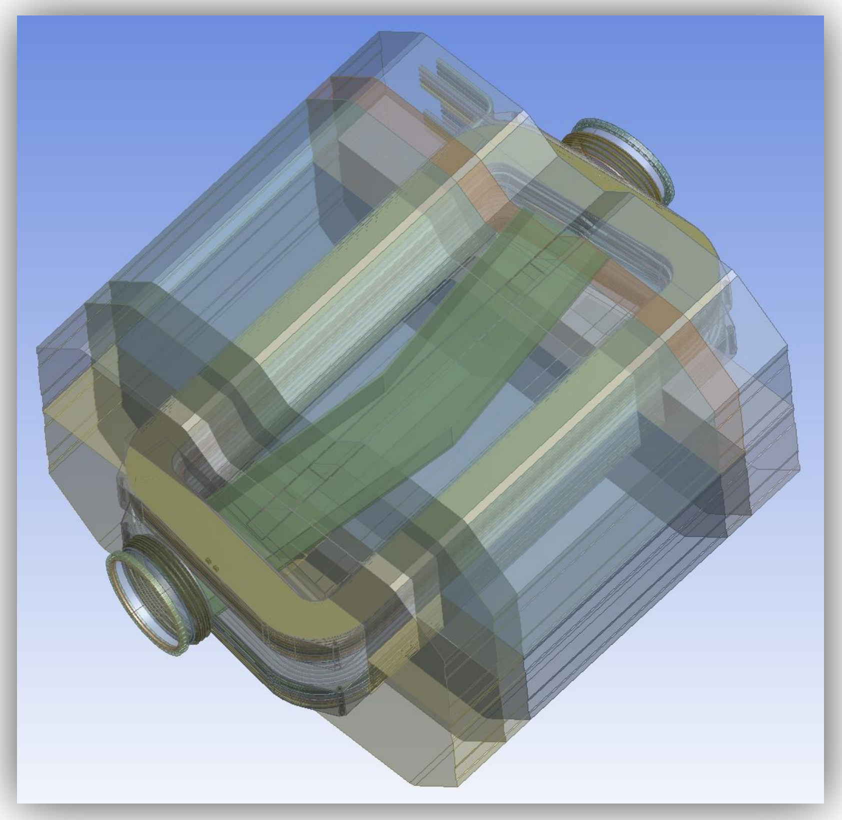


Parametric Condition

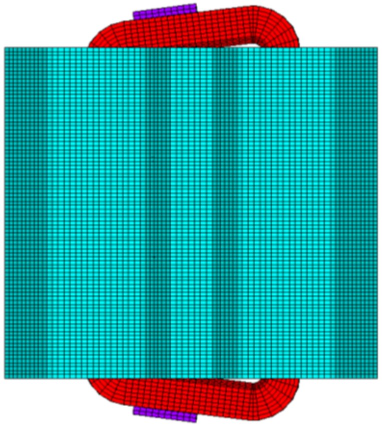
- The α depends on not only frequency but also I_0 and ΔI.
- The frequency range of rippling current is 10 ~ 10 kHz.
- The maximum amplitude of current ripple is assumed to be $\Delta I_{max}/I_0 = 10^{-4}$.
- The desired field stability is $\Delta B_{max}/B_0 \cong 10^{-6}$.
- The operation field for Collect Ring is B_0 = 1.6 T and corresponding applied current I_0 is about 1.4 kA.

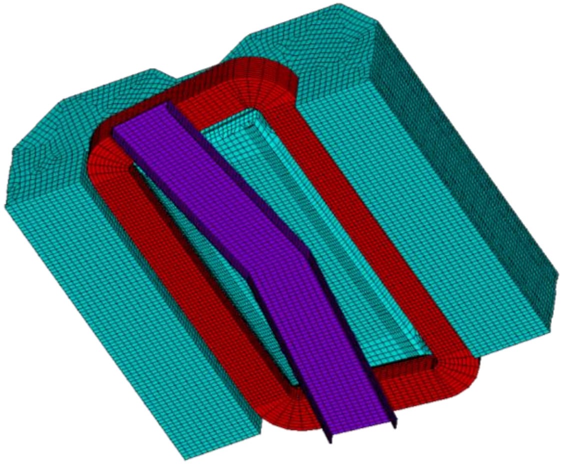
Geometry of CR dipole magnet

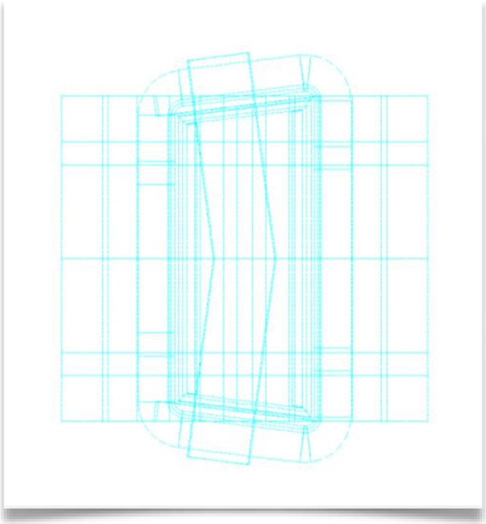


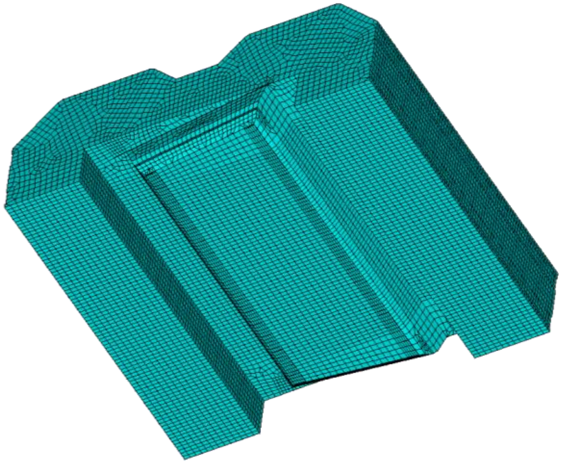


FE model

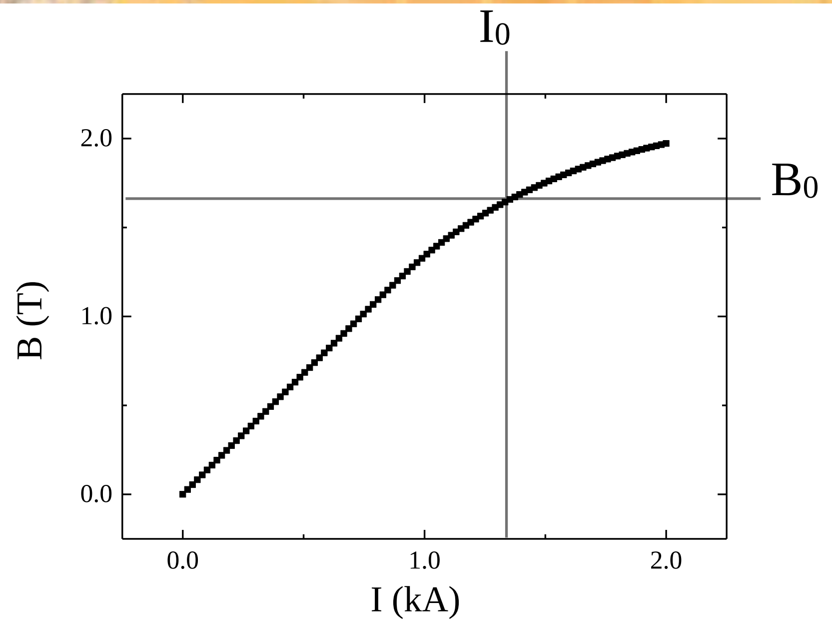


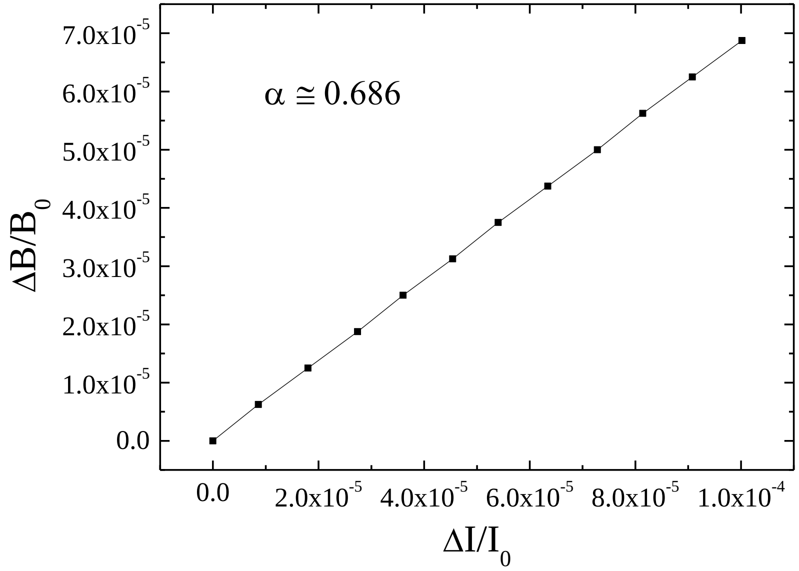






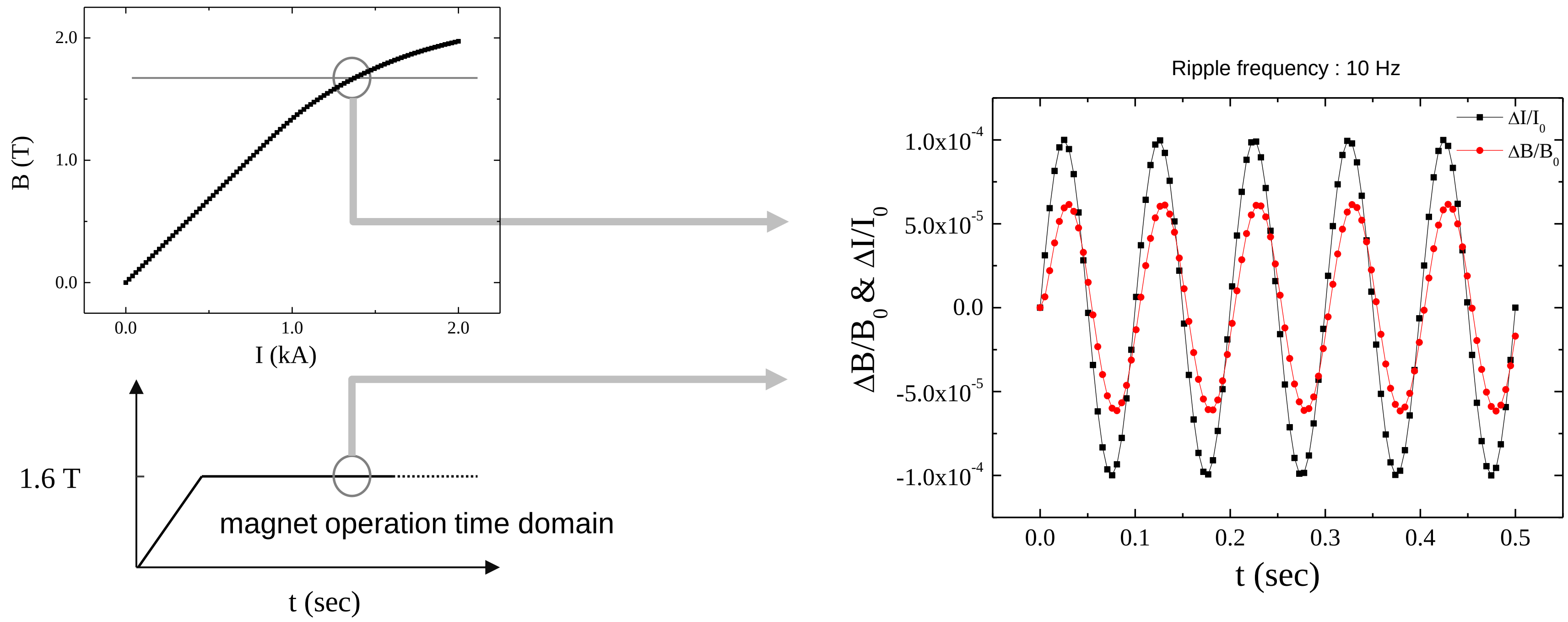
DC Property





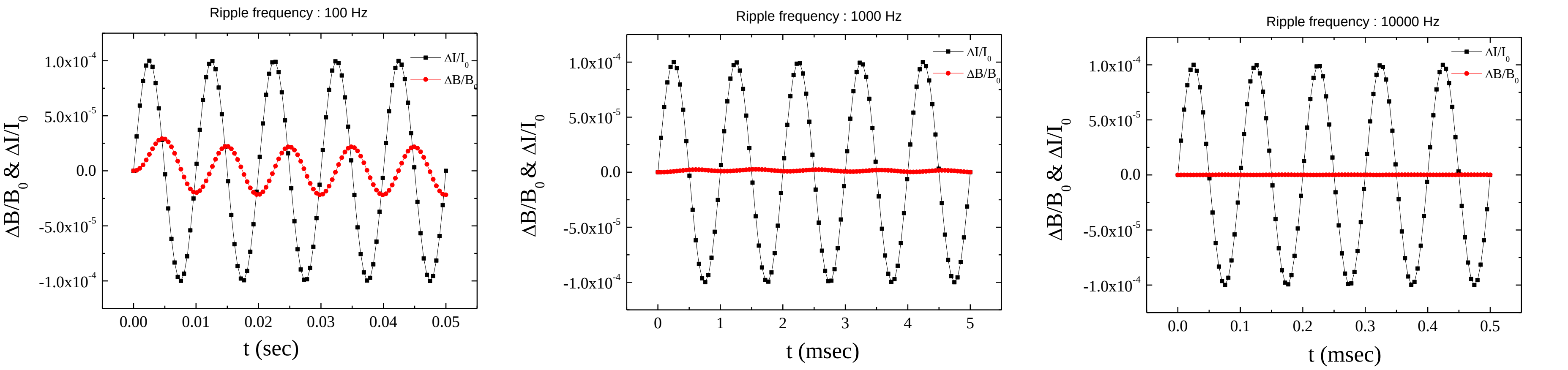
- This result shows field operation property as a function of DC current.
- It enables us to estimate the maximum α as a reference value to interpret the results of AC ripple effect.
- The DC proportional parameter α is 0.686.
- This curve depends on material property and is shown in Appendix 1.

Current Ripple Effect 1



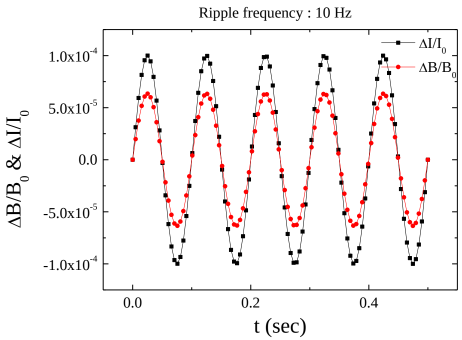
- The current ripple is produced in the range of 10 ~ 10 kHz at the reference field 1.6 T.
- The corresponding α value is similar to that of DC current in 10 Hz.
- The result of higher frequency is shown in the next slide.

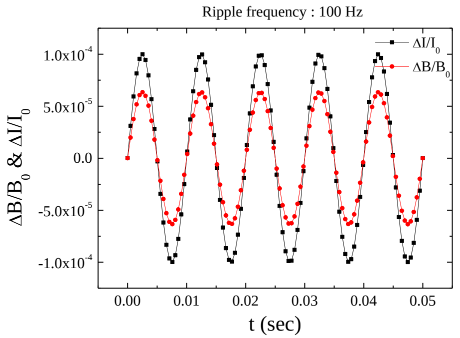
Current Ripple Effect 2

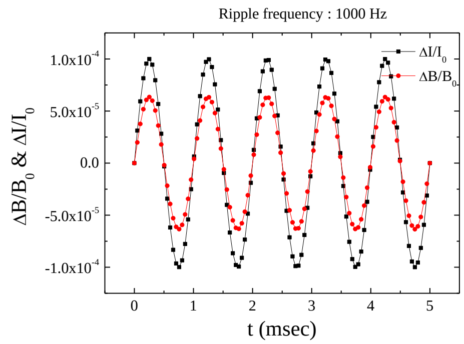


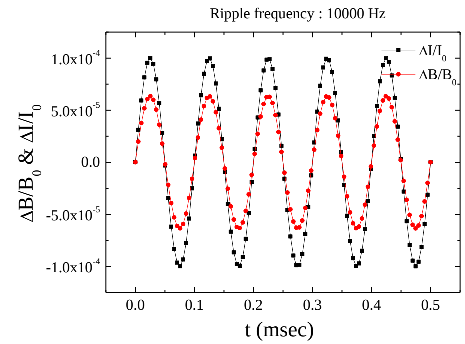
- The amplitude of field response is decreased by increasing ripple frequency.
- The reason of this field amplitude decreasing is secondary field by eddy current on the beam chamber. And it is confirmed by comparative simulation with and without beam chamber.

Without beam chamber



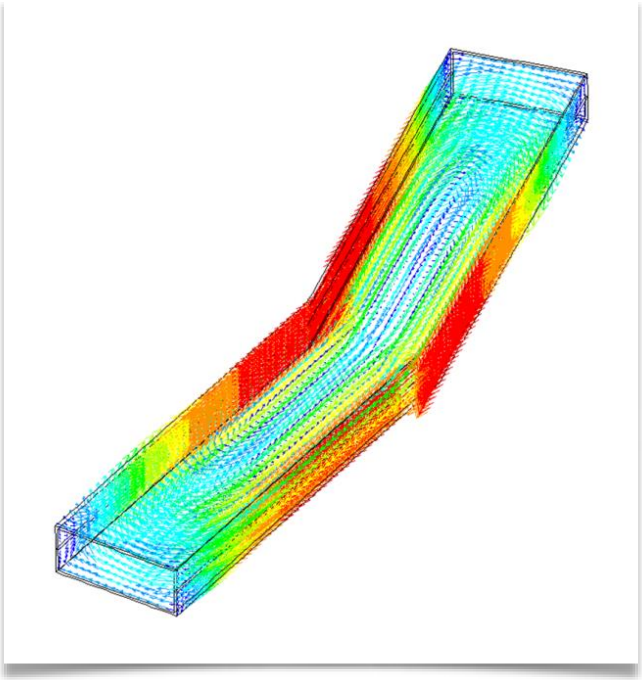




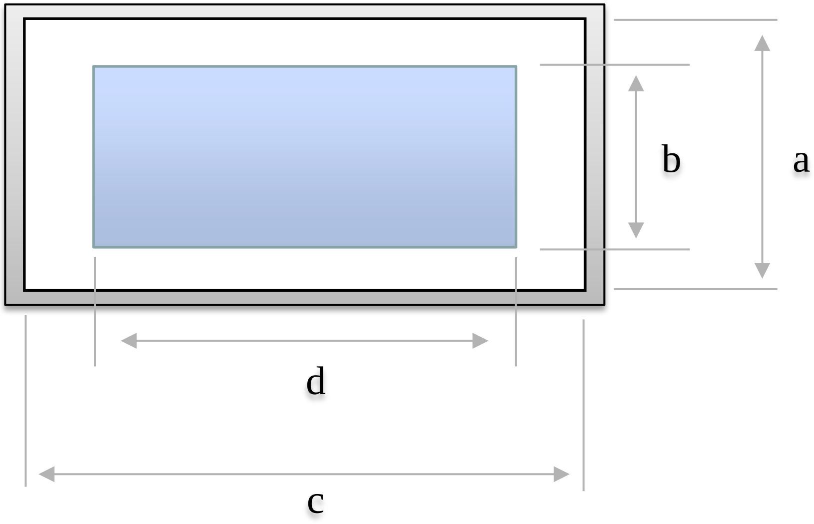


- The results are from the simulation without beam chamber.
- There is no frequency dependence of $\Delta B/B_0$ without beam chamber.
- The secondary field by eddy current on the beam chamber is the origin of the high frequency shielding.

Space for average calculation

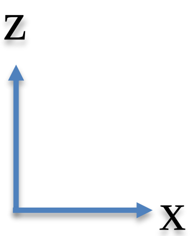


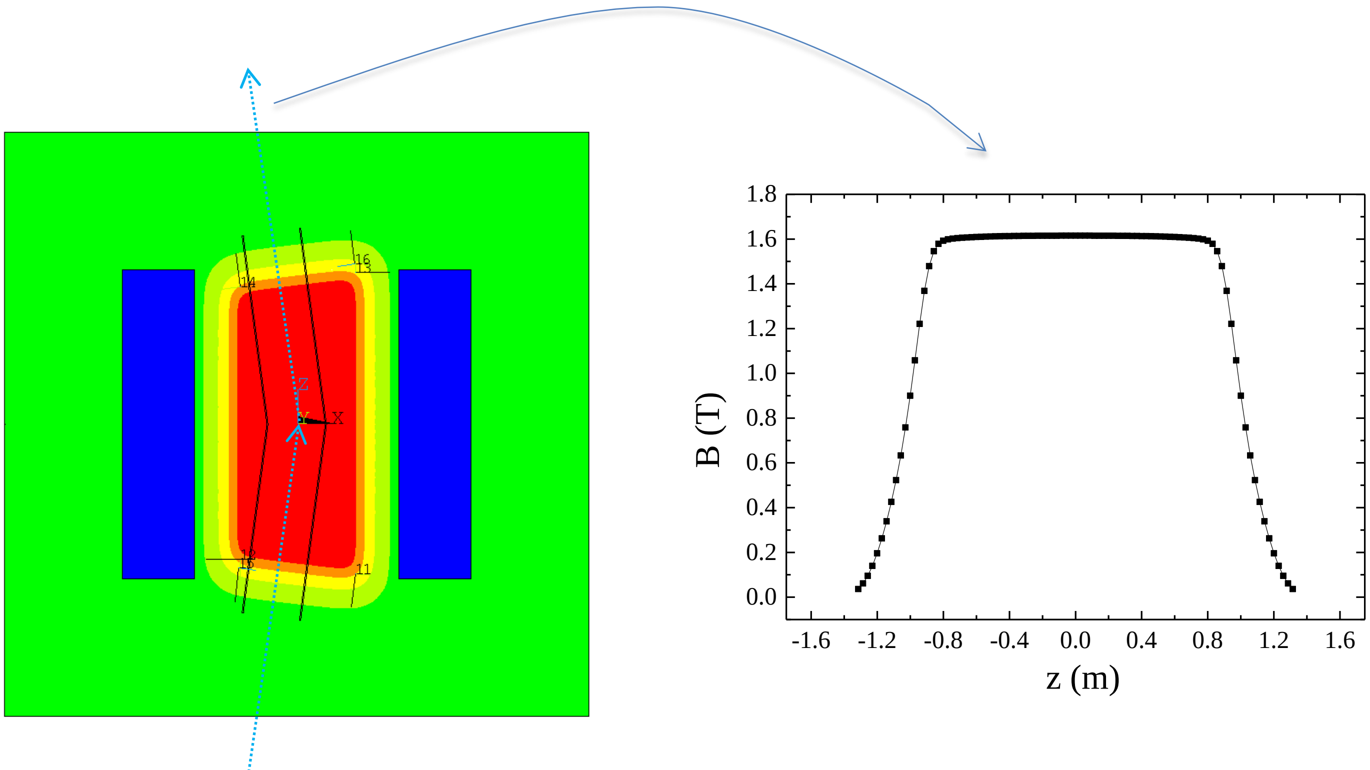
Eddy current density profile.



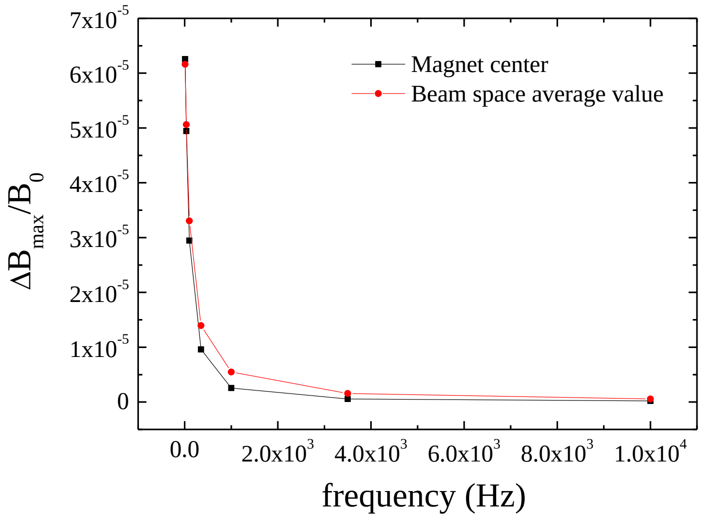
The ratio of area for finding average α is b/a = 6/10, d/c = 11/15

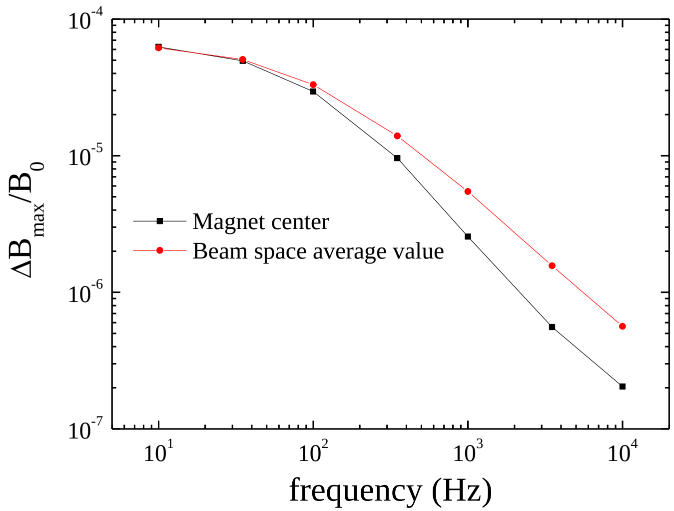
Static field profile on beam axis





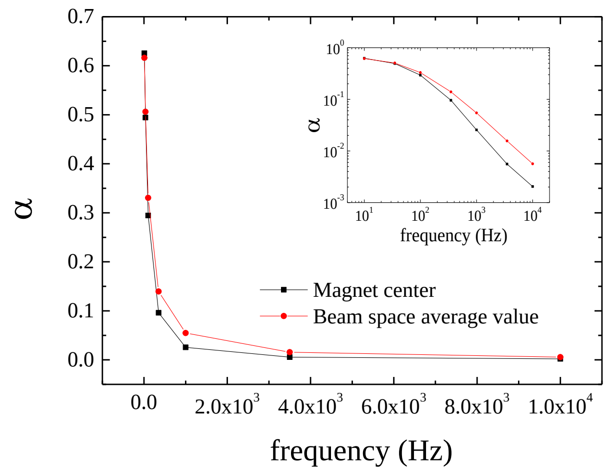
$\Delta B/B_0$ according to Ripple Frequency

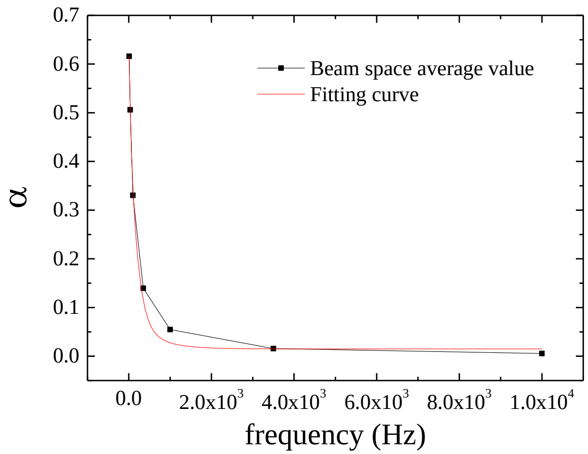




- The figures show the $\Delta B_{max}/B_0$ as a function of current ripple frequency.
- The $\Delta B/B_0$ has a rapid decreasing with increasing frequency in the low frequency region.

Proportional Variable $\alpha(f)$





- We can estimate functional expression with curve fitting procedure and the result shown below.

$$\frac{\Delta B}{B_0} = \alpha(f)\frac{\Delta I}{I_0} \longrightarrow \alpha(f) \cong a + b \times c^f$$

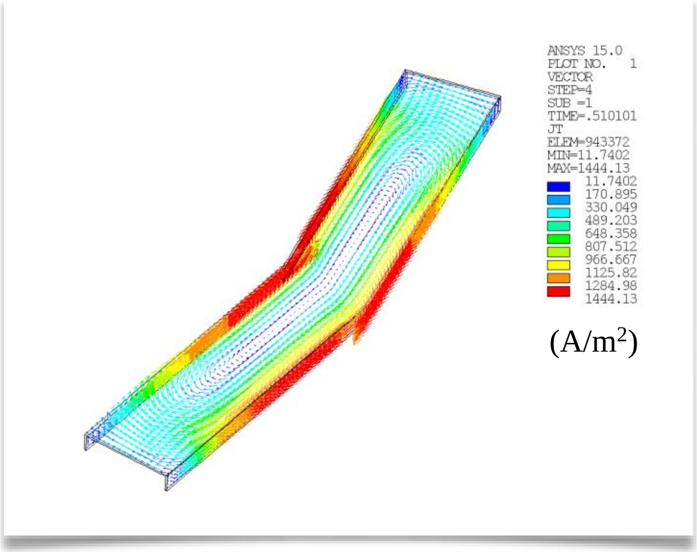
$$a \cong 0.015$$

$$b \cong 0.65$$

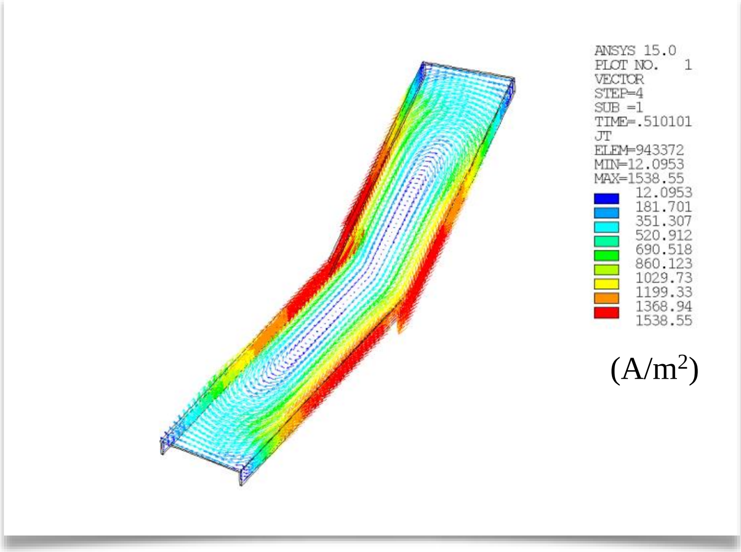
$$c \cong 0.99205$$

- The α is close to the value of DC result with decreasing *f* down to zero.
- The α is less than 1.0×10^{-2} with frequency of higher than ~ 2 kHz and ~ 5 kHz at the center of magnet and considered beam space, respectively.

Beam chamber resistivity



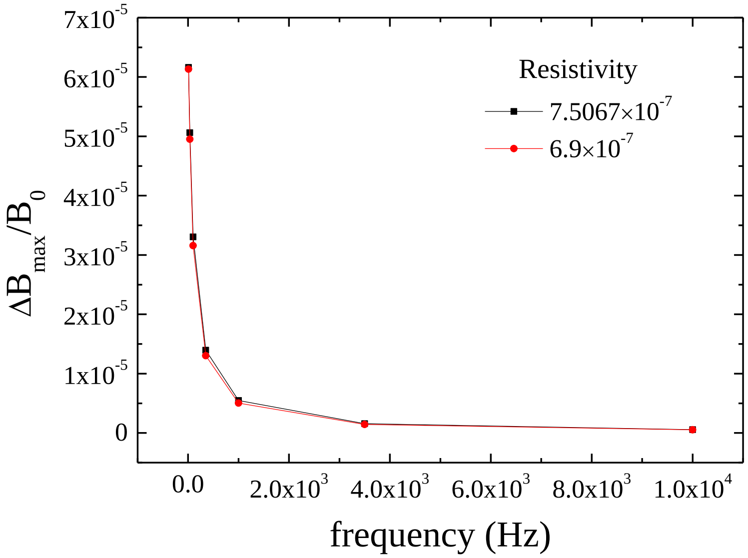
$\rho_{ref} = 7.5067 \times 10^{-7}\ \Omega m$

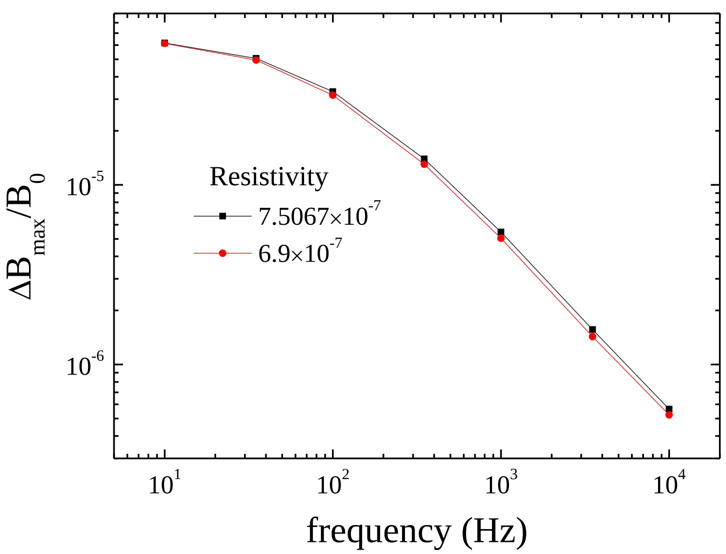


$\rho = 6.9 \times 10^{-7}\ \Omega m$

- The field shield effect is due to the eddy current in the beam chamber. Therefore, the resistivity of the beam chamber can be a parameter which can affect magnetic field ripple.
- To get more reasonable interpretation for this simulation, additional calculation has been done with another low resistivity of $6.9 \times 10^{-7}\ \Omega m$.

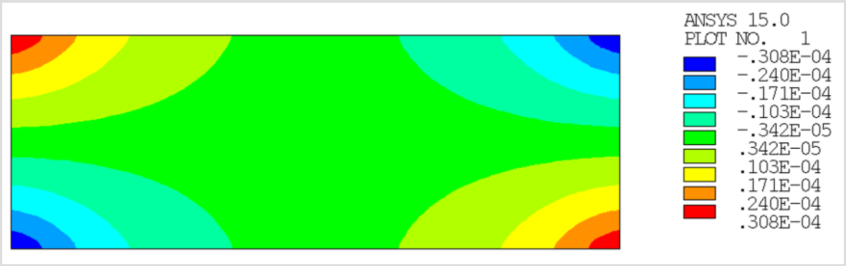
Resistivity effect



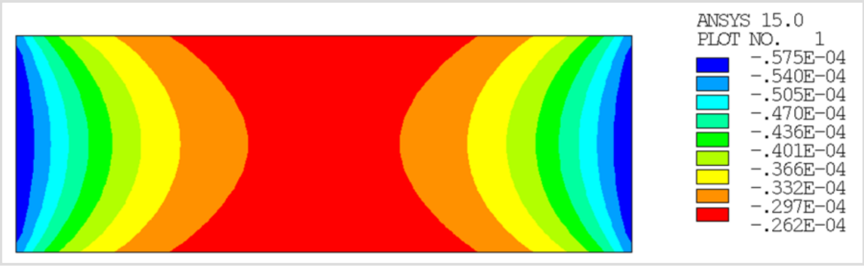


- Δf is ~ 400 Hz at $\Delta B_{max}/B_0 = 10^{-6}$.

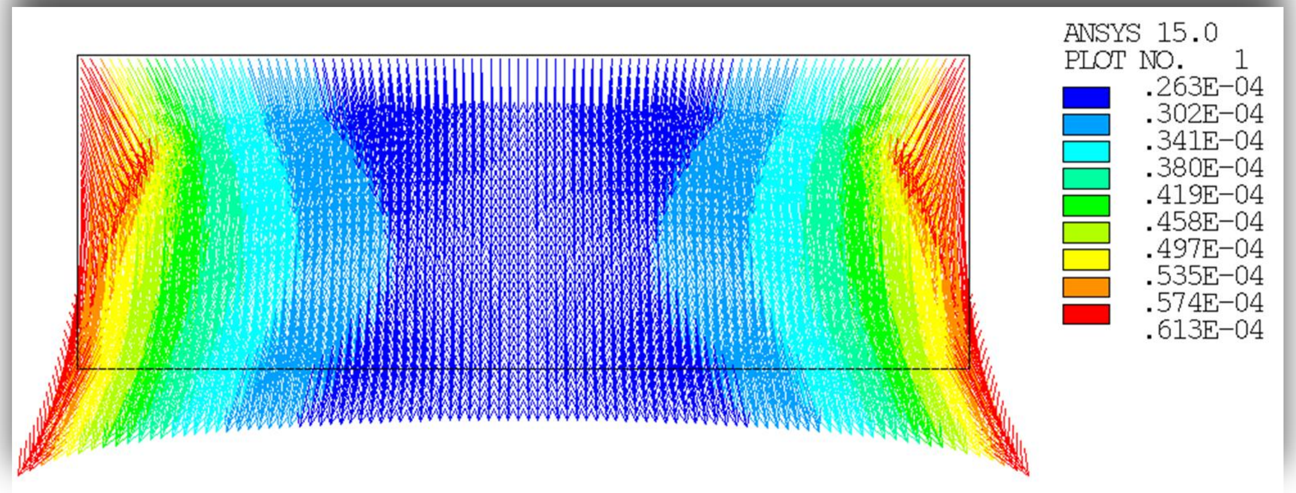
Eddy current induced magnetic field inside beam chamber - 10 kHz



B_x



B_y

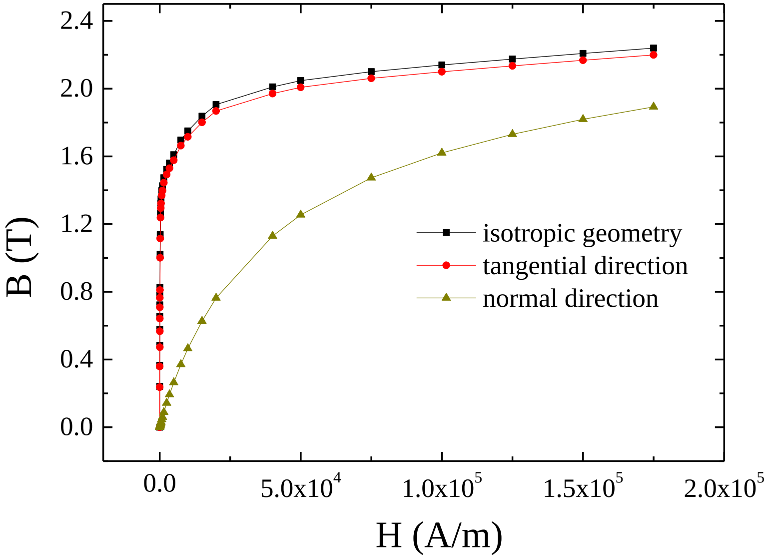


unit : Tesla

Summary & Conclusion

- To find the current ripple effect on magnetic field, the variable α is needed to be clarified.
- The α variable reaches to 10^{-2} around 2 kHz and 5.5 kHz around the center of magnet and beam space, respectively.
- The reason of this field shielding effect is the magnetic field by eddy current in beam chamber.
- The eddy current on the rectangular shaped beam chamber generates not only dipole but also all other higher odd-number multipoles. The eddy current density is ~ 25 times lower than that of SIS100 dipole beam chamber. Even though the different geometry and eddy current profile, we can expect negligibly small higher odd-number multipoles.
- Result of resistivity dependence can be used for the practical interpretation after having confirmation of real material parameters of CR dipole construction.

Appendix 1 - Material property



$$\mu_n = \frac{\mu_0 \mu}{p\mu_0 + (1-p)\mu}$$

$$\mu_t = p\mu + (1-p)\mu_0$$

- μ_n and μ_t is magnetic permeability of laminated material with normal and tangential direction, respectively.
- The 98 % packing factor, p = 0.98, is considered for this simulation.
- We can produce FE model which has laminated yoke property with un-laminated iron yoke FE model after applying this curve.