Normal and Superconducting magnet for FFAG

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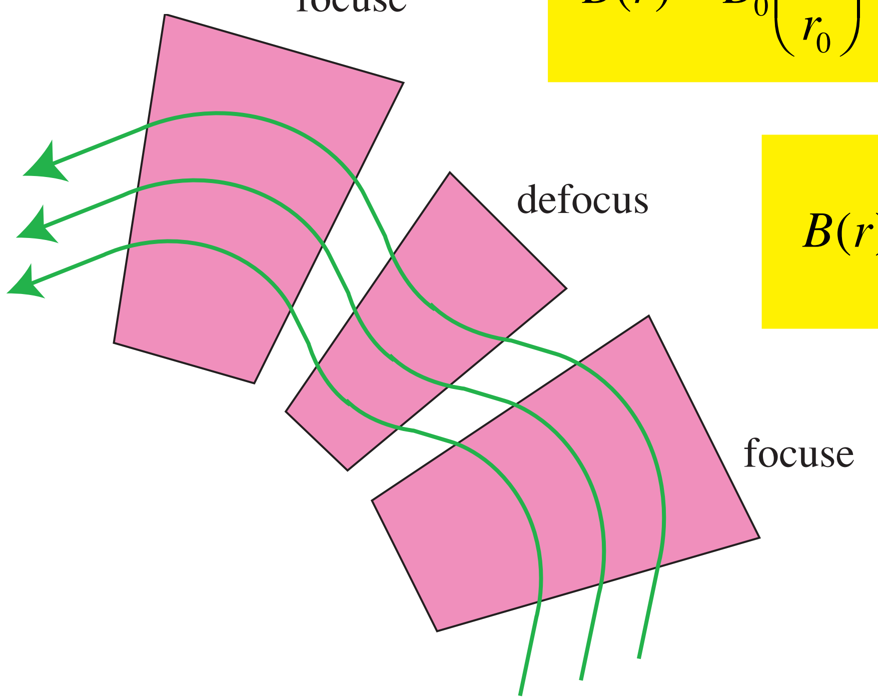
Magnet design for FFAG accelerator

Required magnetic field for FFAG : $B(r,\theta) = B_0\left(\frac{r}{r_0}\right)^k F(\theta - h\ln\frac{r}{r_0})$

Radial sector type FFAG:



$$B(r) = B_0\left(\frac{r}{r_0}\right)^k$$

$$B(r) = -B_0\left(\frac{r}{r_0}\right)^k$$

How to be realized this field ?

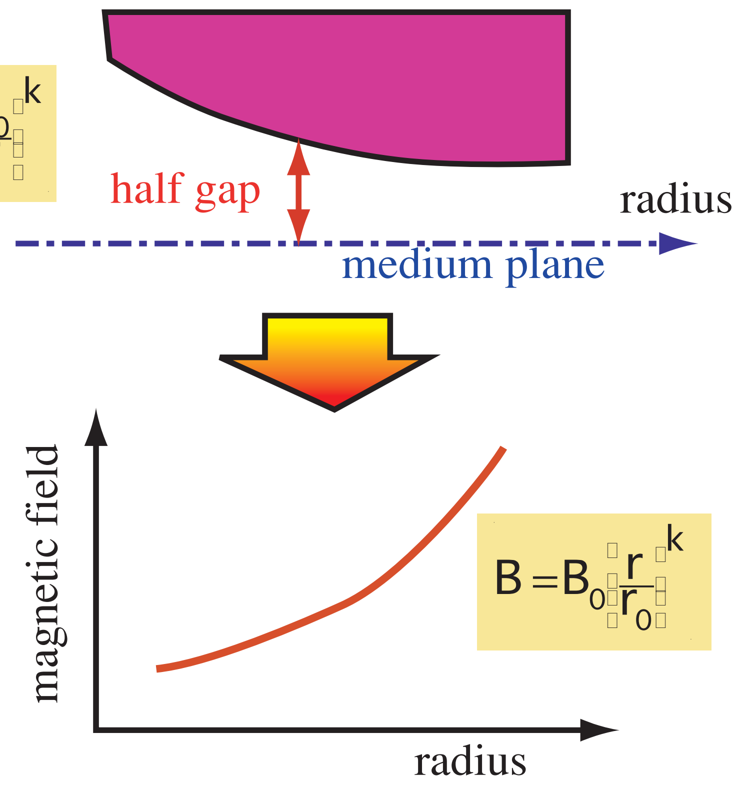
(1) iron pole shape

(2) current distribution

METHOD-1 : Iron pole shape type

The magnetic field is realized by changing the gap space !

for example : PoP-FFAG, & 150MeV-FFAG



$$G = G_0 \left(\frac{r_0}{r}\right)^k$$

$$B = B_0 \left(\frac{r}{r_0}\right)^k$$

merit & demerit

merit:

- easy to design
- easy to operate

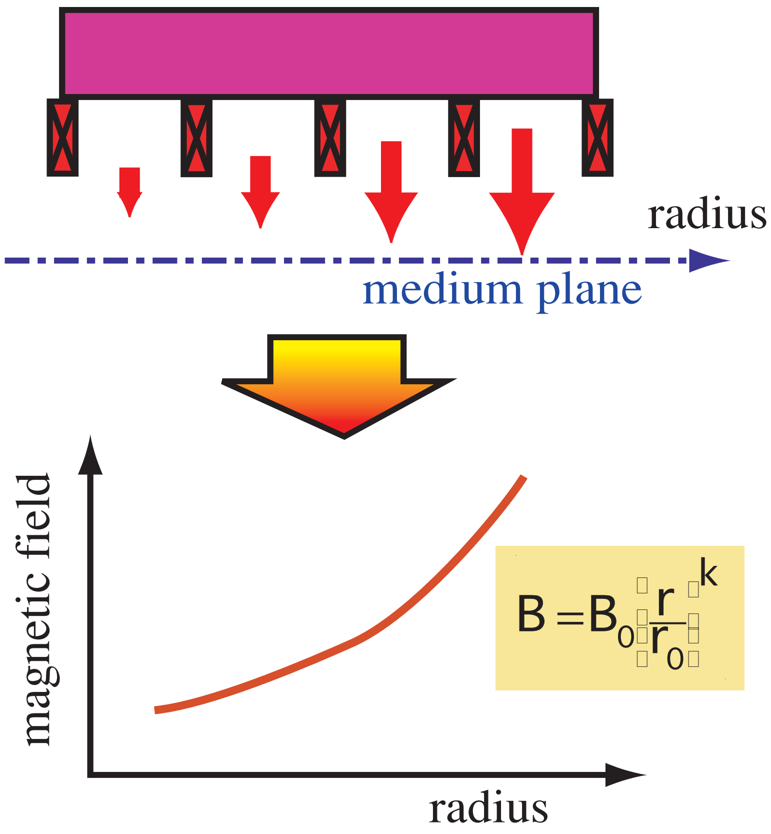
demerit

- impossible to change the k-value
- difficult to make the long pole magnet
  (<= fringing field on the pole edge)
- difficult to make the high field magnet
  (<= saturation in the pole iron)

This method may not be suitable for the neutrino factory base on the FFAG accelerator.

METHOD-2: current distribution type

The magnetic fields are produced by the current distribution !



merit vs. demerit

merit:

- possible to change the k-value !
- possible to make the long pole magnet !
- possible to make the high filed magnet !

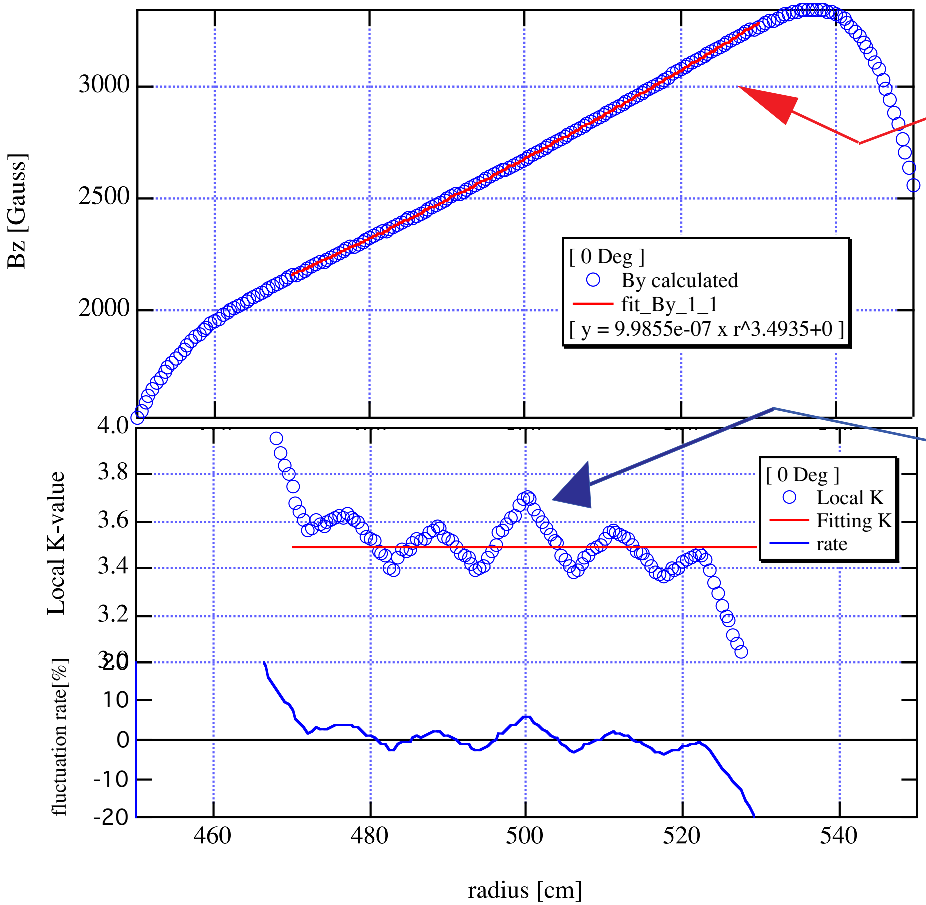
demerit

- not easy to design conpare to pole shaple method
  (<= find the nice sets of coil configuration)
- not simple to operate
  (<= different currents are supplied to each coil)

Fitting k-value & local k-value

The indicator of the field quality => fitting k-value & local k-value !

typical results of the field calculated by the current distribution type magnet



k_fitting fit : y=a(r)^b

(with Levenberg-Marqurdt algorizm)

$$k\_local = \frac{\Delta B}{\Delta r}\frac{r}{B}$$

$$B = B_0\left(\frac{r}{r_0}\right)^k$$

$$\frac{\Delta B}{\Delta r} = k\frac{B_0}{r_0}\left(\frac{r}{r_0}\right)^{k-1}$$

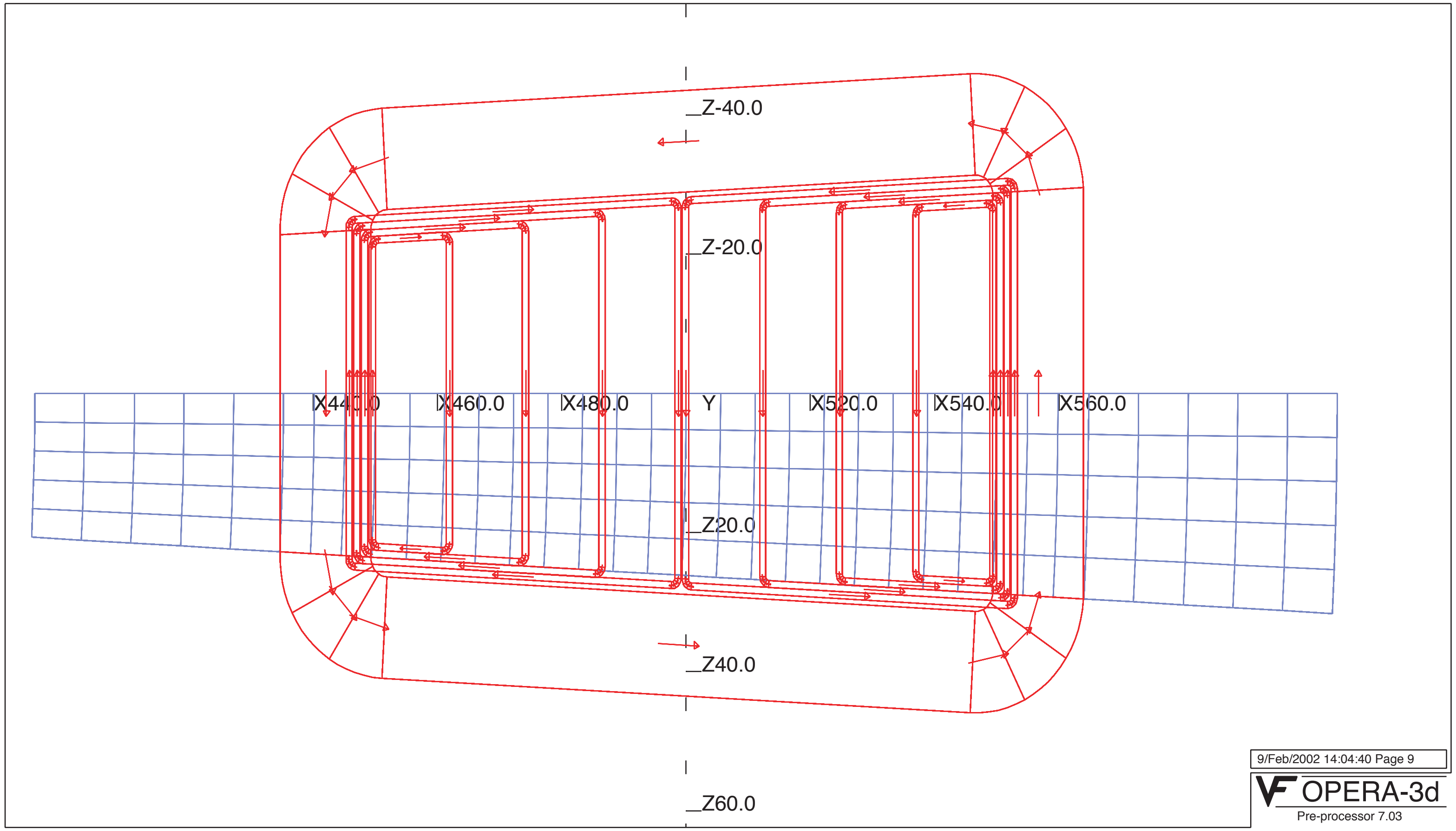
$$= k\frac{B_0}{r_0}\left(\frac{r}{r_0}\right)^{k}\frac{r_0}{r}$$

$$= k\frac{B_0}{r}\frac{B}{B_0}$$

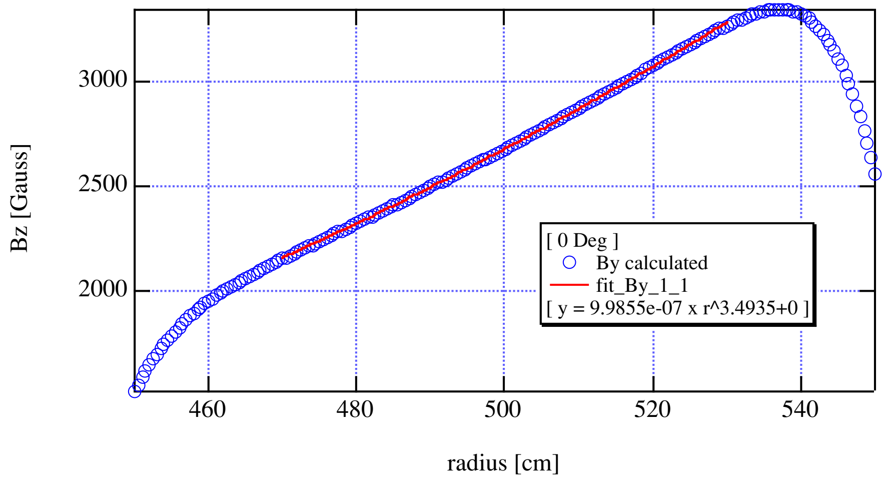
$$= k\frac{B}{r}$$

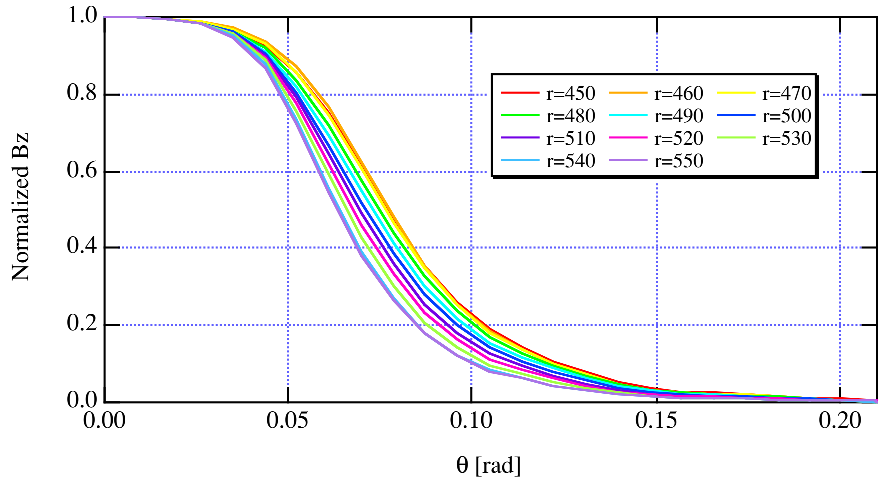
The field quality is judged by the ratio of the local k-value to the fitting k-value !

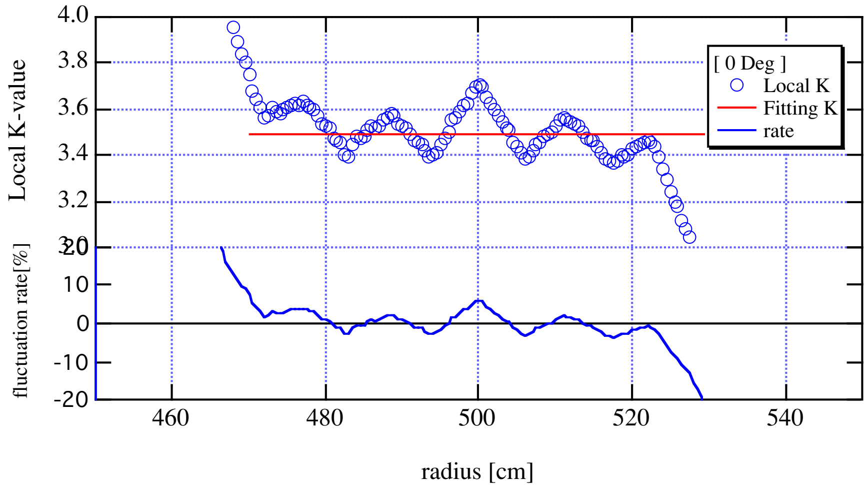
Magnet design 3 (with current distribution type)

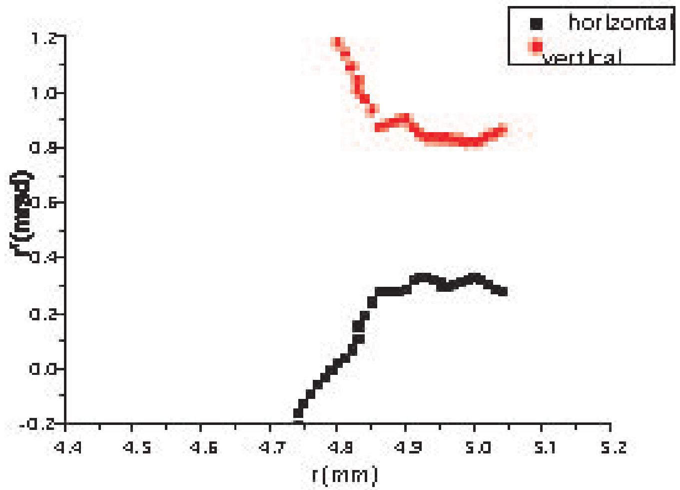


Magnet design 3 (with current distribution type)



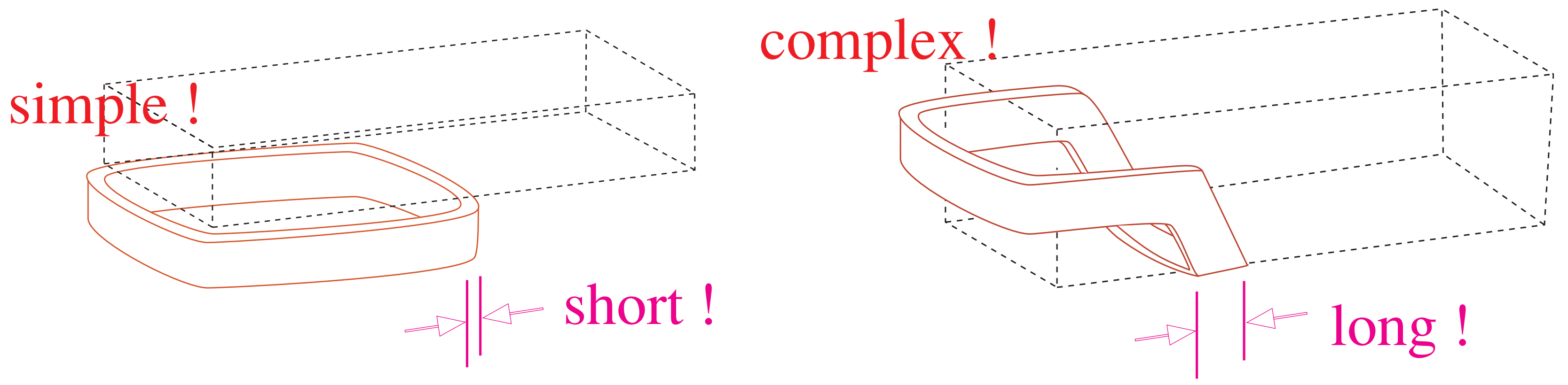




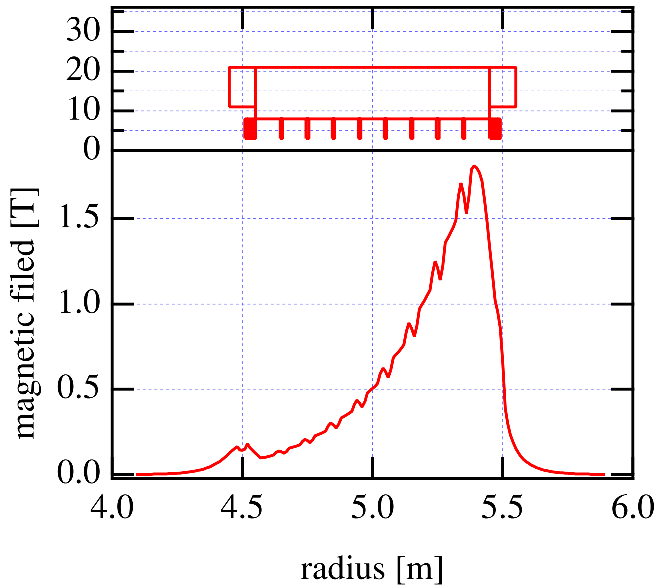


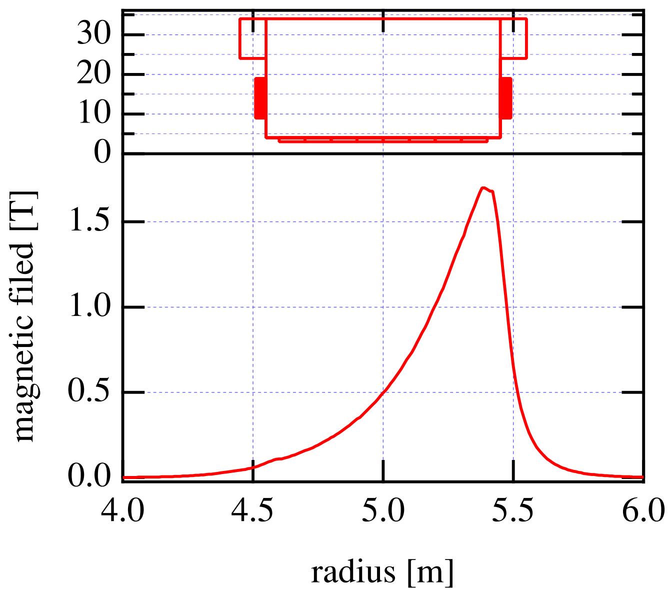
Magnet design 4 (with current distribution type)

race track coils or wind frame coils ?

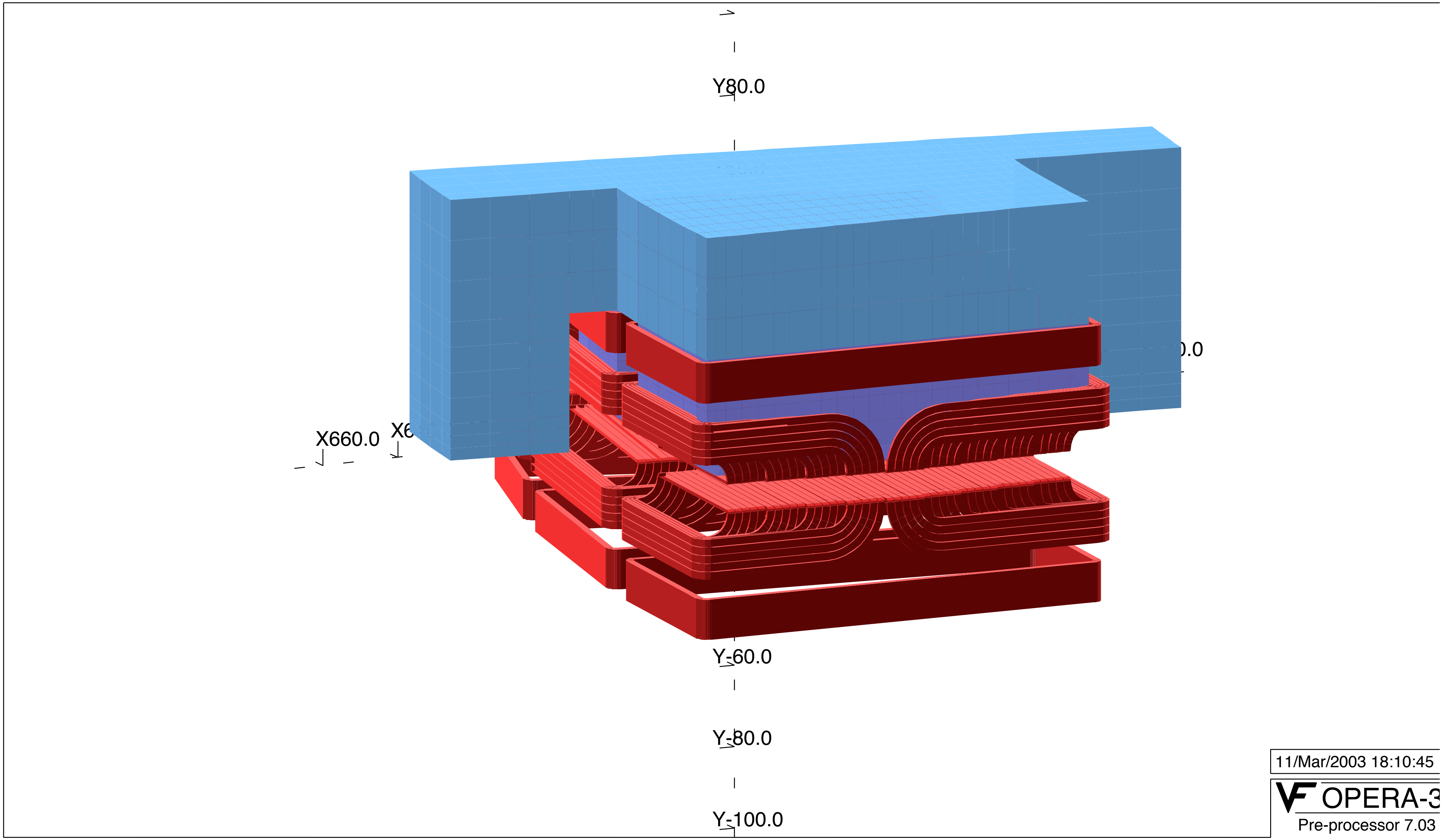


if small gap size (half gap = 3cm) ....



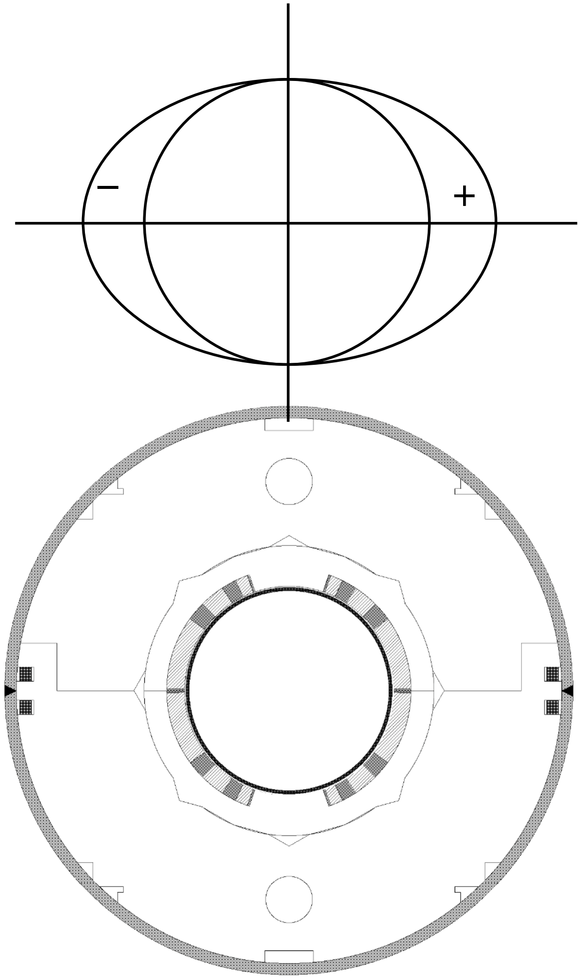


Magnet design 4 (with current distribution type)



Conventional SC magnets for Accelerator

- Cosine theta design
  - For example: Dipole
  - Cos(nθ) > 2n-pole magnet
- Well established for
  - Dipole, Quadrupole
    - ~ 8T ~5cm aperture
    - ~5T ~20cm aperture
  - Higher order coils
    - Smaller coils but some are combined with larger main coil



What to do with FFAG field?

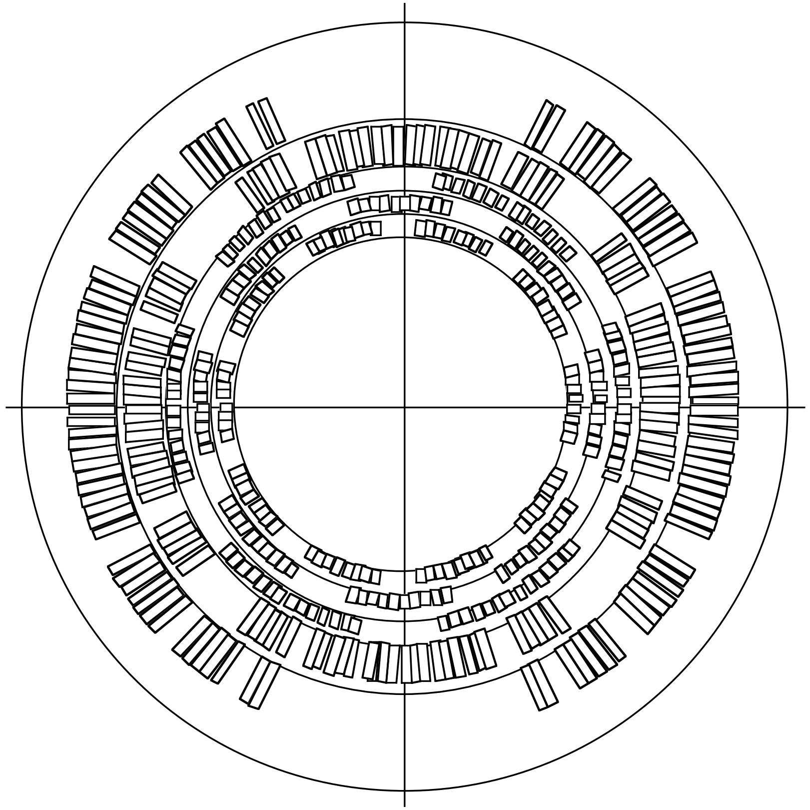
What about combination of multipole fields

$$B(r) = B_0 \left(\frac{r}{r_0} \right)^k$$

$$= B_0 + \frac{k}{r_0} B_0 r + \frac{k(k-1)}{2! r_0^{\ 2}} B_0 r^2 + \frac{k(k-1)(k-2)}{3! r_0^{\ 3}} B_0 r^3 + \ldots$$

Combined Multipole Coil?

- Can change B_0 and k in wide range within the conductor limit.
- Can even change the field profile.
- Isn't it too complicated?
  - Magnetic force?
  - Can be expensive...



Let’s make it SIMPLE!

Required current distribution

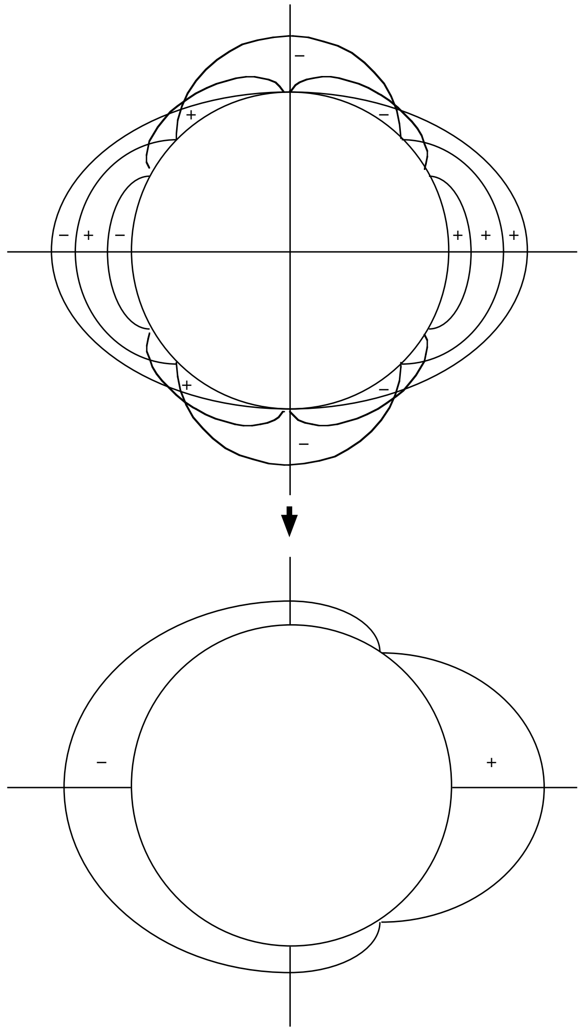
□

Sum of all cosine theta current

□

Asymmetric Coil

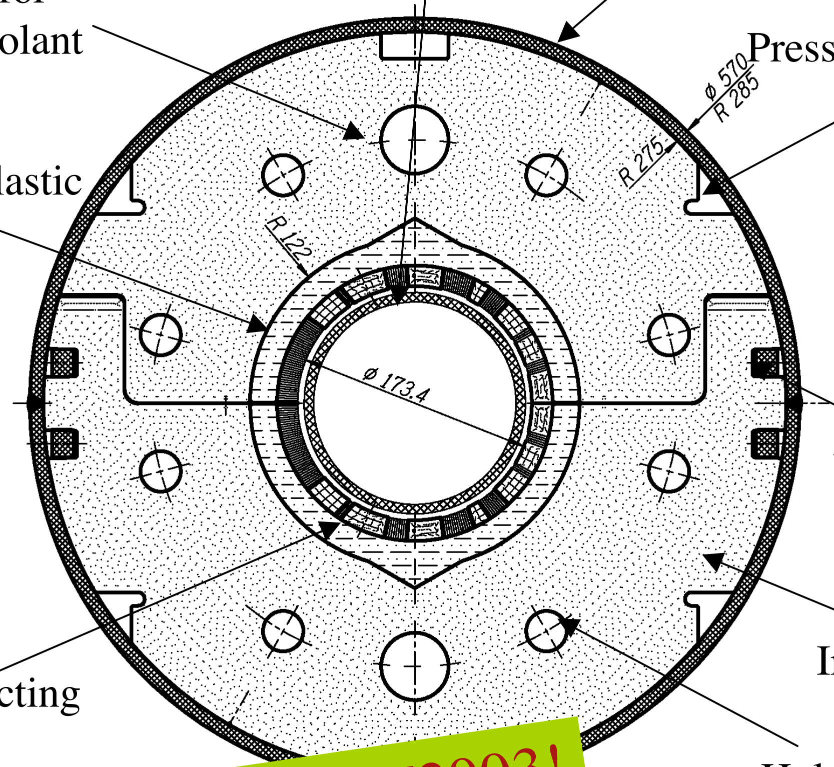
Need R&D!



Example of Asymmetric Coil

J-PARC Neutrino CF-SC Magnet

- **Dipole Field**
  - **~2.6 T**
- **Quad. Field**
  - **~18.5 T/m**
- **Op. Current**
  - **~7kA**
- **Op. Margin**
  - **~70%**
- **Inductance**
  - **~15mH**
- **Field Quality**
  - **<10^{-3} @ 5 cm**
- **Cable**
  - **LHC Dipole outer cable**



Prototype Development in FY2003!

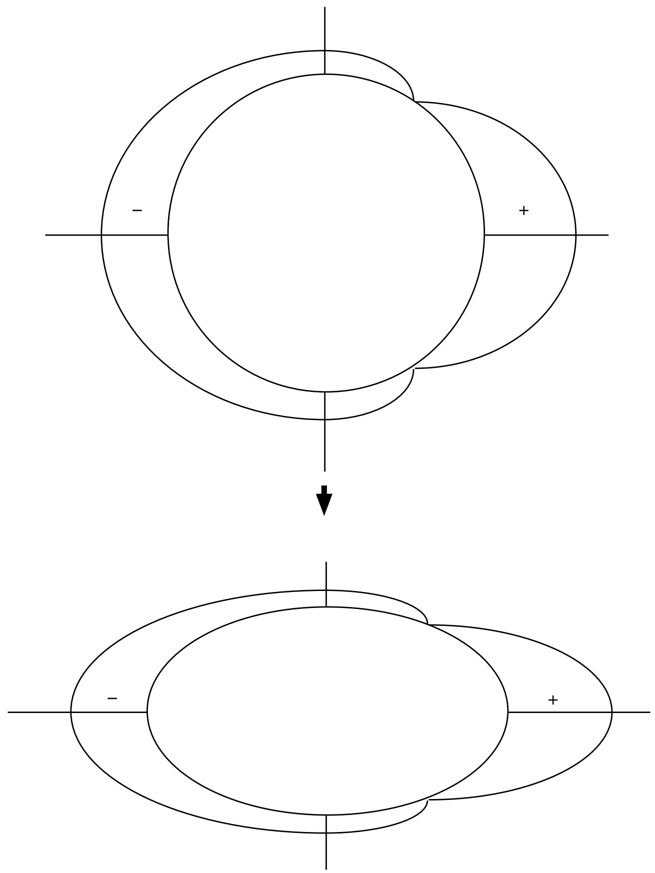
Elliptic Structure

- Round Asymmetric Coil
  - May be Feasible!
- But, large beam excursion
  - Requires large aperture
  - Large Stored Energy
    - Difficult to protect
  - More superconductor
    - More money

⇓

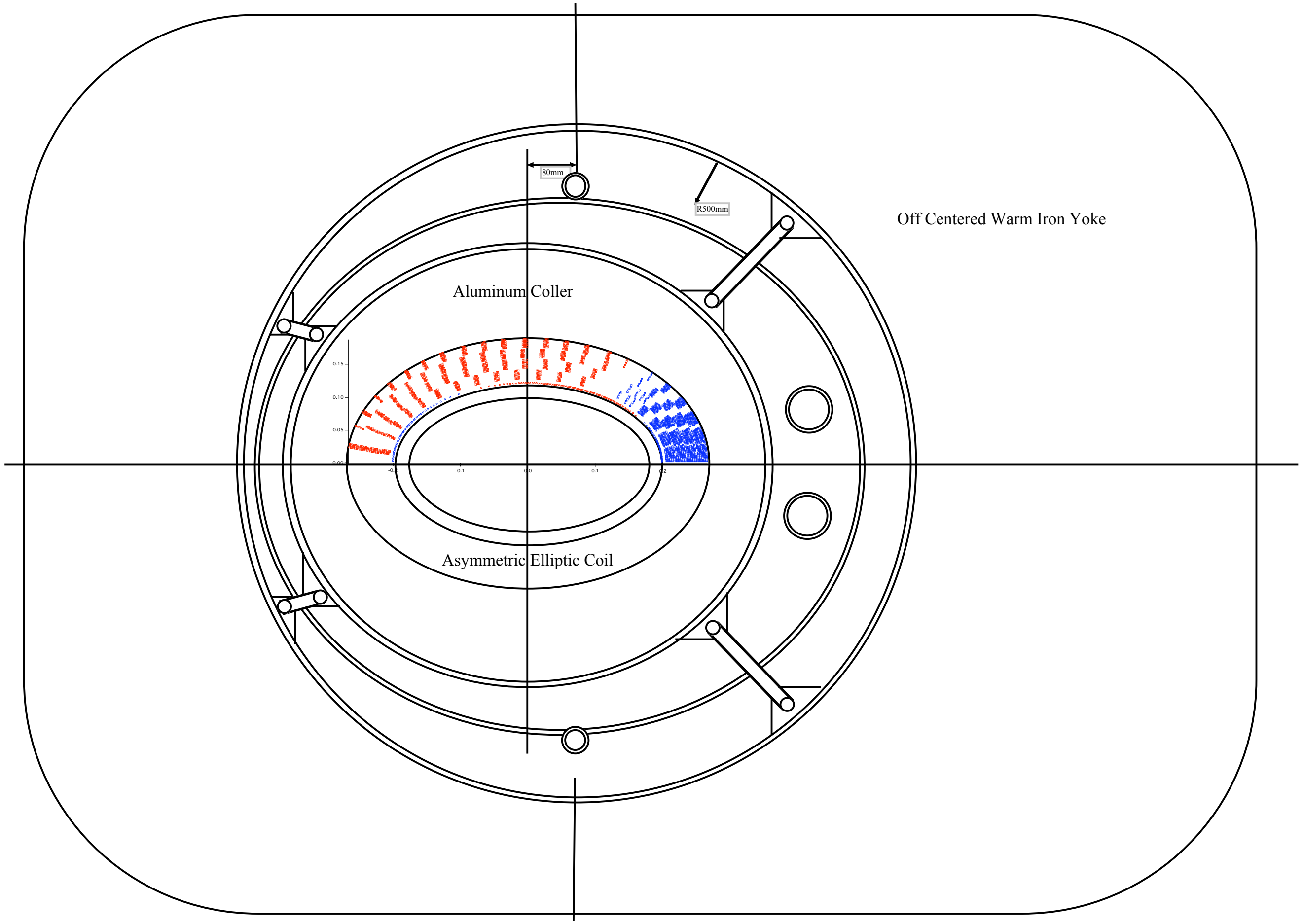
Elliptic Structure

Need R&D as well



Reference Design 1a

- B_0=6.0T, r_0=120m, k=450, beam excursion 0.18m



1. Main Coil
   - Asymmetric & Elliptic
   - Rutherford Cable~ 2X15mm
   - Operation Current ~6.8kA
   - Stored Energy: ~1MJ/m
2. Corrector Coil
   - Wind & glue (BNL)
   - ~10A/delta-K
3. Collar
   - Pre-stress ~90MPa
   - Horizontal EMF ~ 3.9 MN
   - Aluminum collar to gain pre-stress during cool down
4. Iron Yoke
   - Off centered yoke for EMF balance
   - Warm Iron

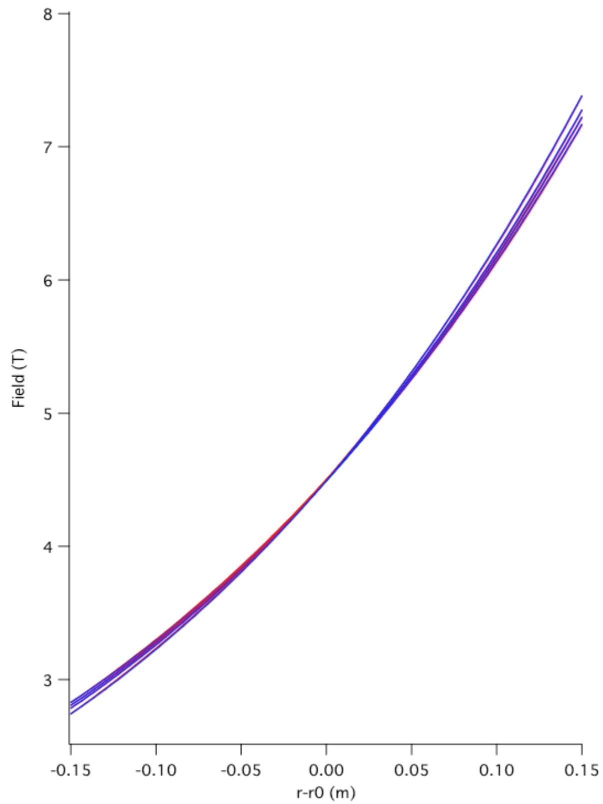
K corrector

- K correction?
  - Does it need to be wide range?
  - If not, first order correction

$$B(r,k+\Delta k) = B_0\left(\frac{r}{r_0}\right)^{k+\Delta k}$$

$$\sim B(r,k) + \frac{dB(r,k)}{dk}\Delta k$$

$$\sim B_0\left(\frac{r}{r_0}\right)^{k} + \boxed{B_0\left(\frac{r}{r_0}\right)^{k}\ln\left(\frac{r}{r_0}\right)\Delta k}$$

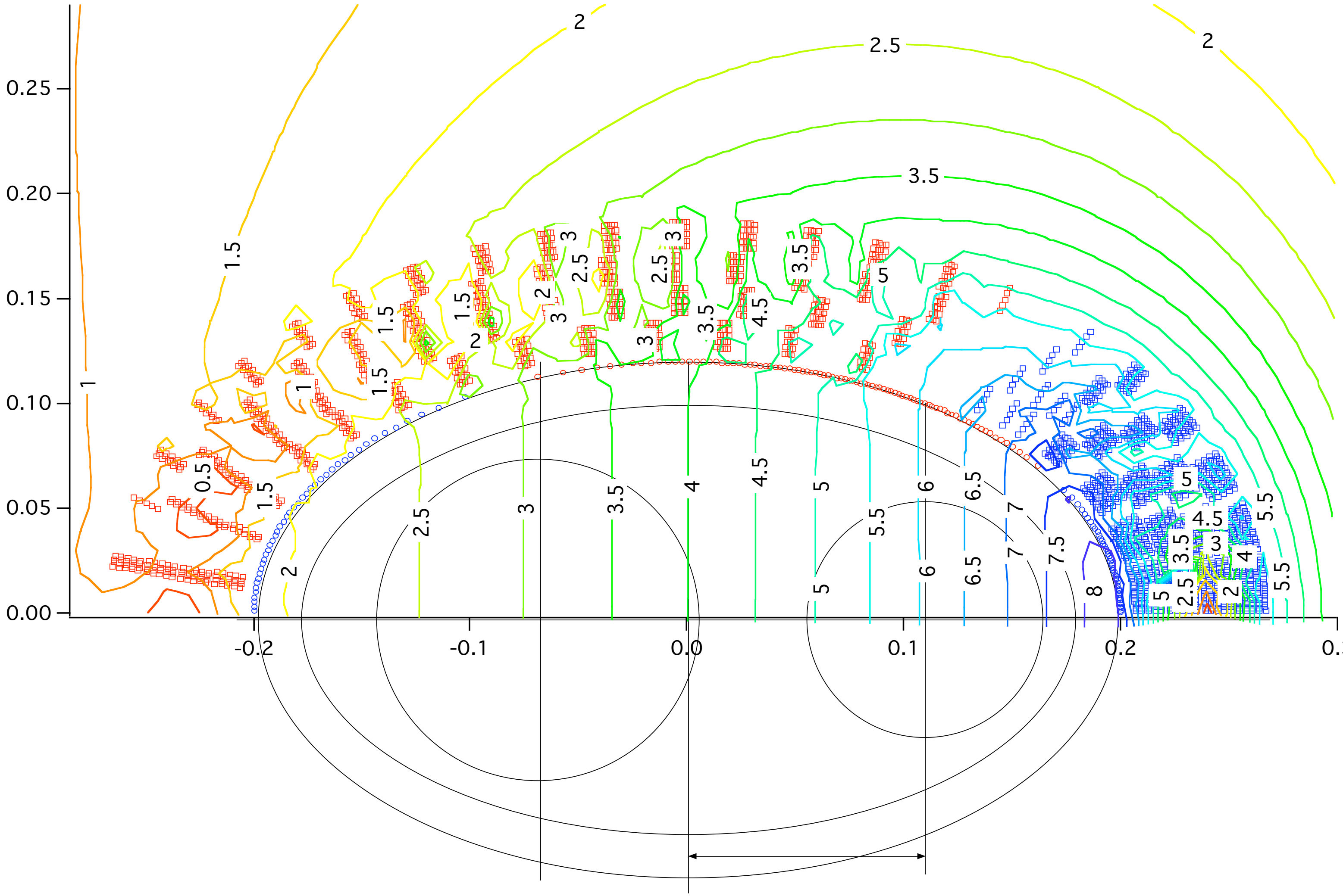


$B_0 = 4.5$, $r_0 = 200$, $k = 620$, $\Delta k = 10, 20, 40$
Red lines represent definite equation, while
Blue lines represent first order approximation.

Current distribution can be derived using the same method as that of main coil

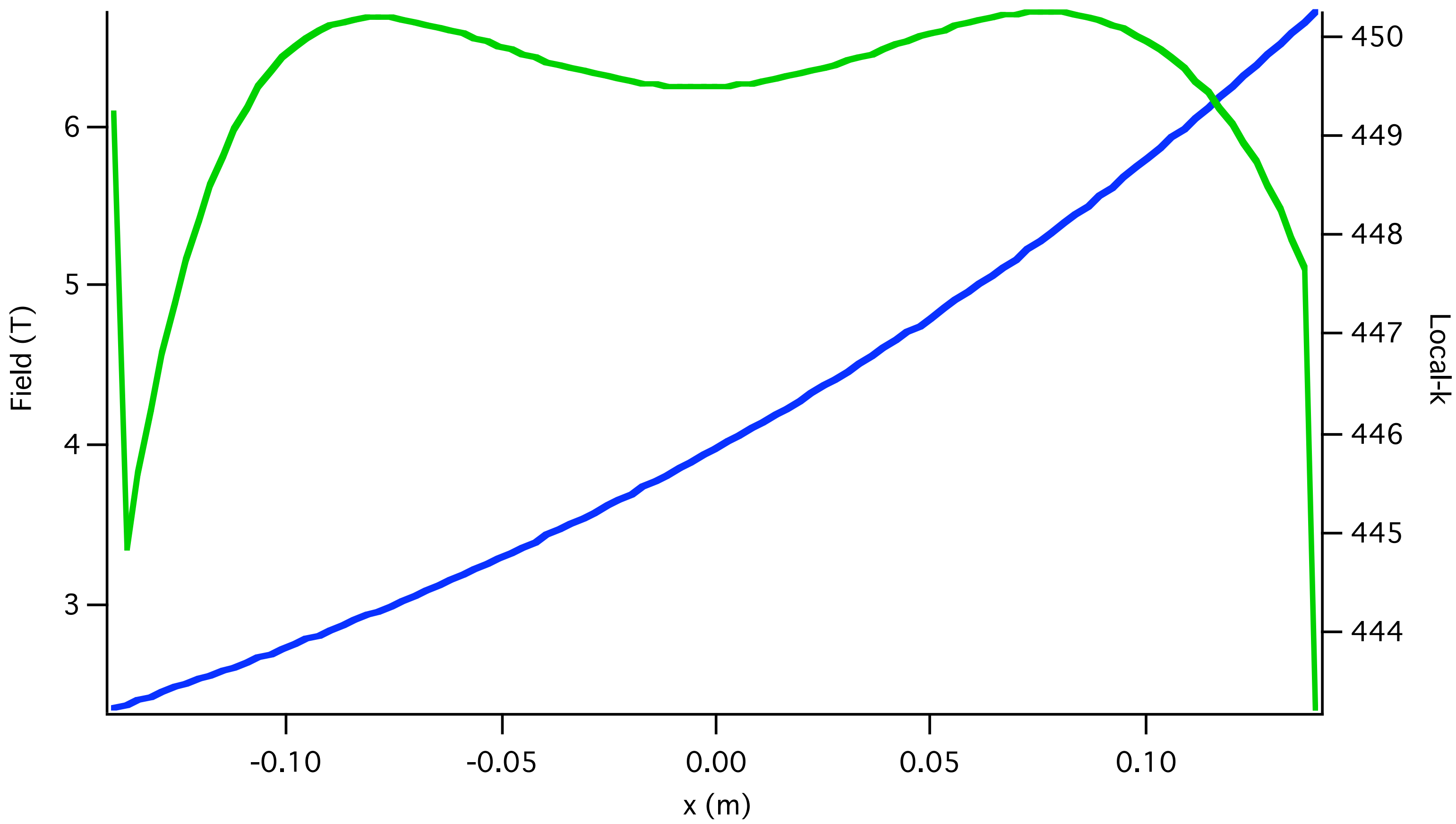
Reference Design 1a

Field Map & Beam Aperture

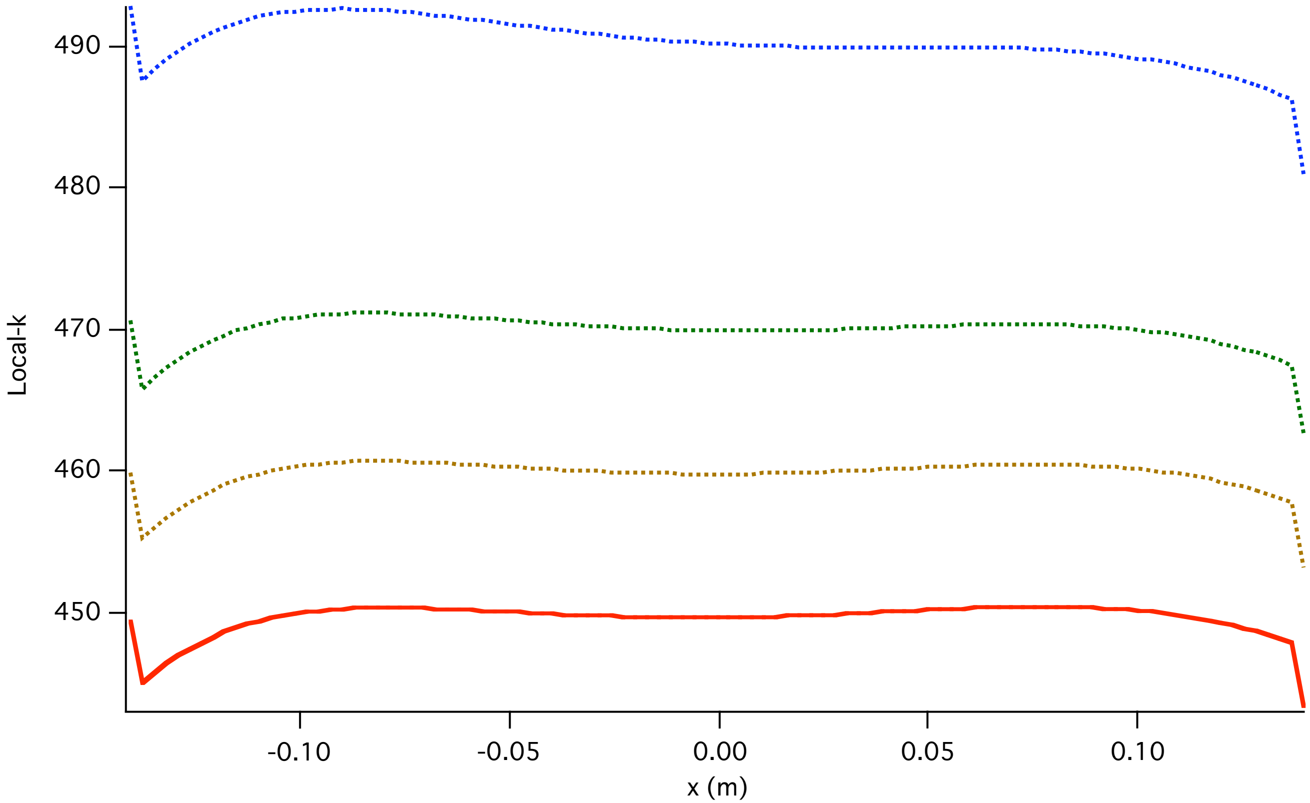


Reference Design 1a

Field quality of main coil



Reference Design 1a
k corrector



Works fine up to Δk ~ ±20

SUMMARY

Normalconducting magnet:

-pole shape type

-distribution current type

Superconducting magnet:

-Asymmetric Elliptical Coil

-First Order Delta-K Correction Coil

Issues to be studied

-3d end design

-Detailed mechanical analysis