BNL-101766-2013-CP

Magnet Design and Simulation

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Presented at the Facility for Rare Isotope Beams (FRIB)
Michigan State University, 22 August 2013

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Outline

2d complex potentials

Single/Combined function magnet --- iron-dominated
coil-dominated

Opera-2d usage (eddy current heating, multipole)

Rogowski contours

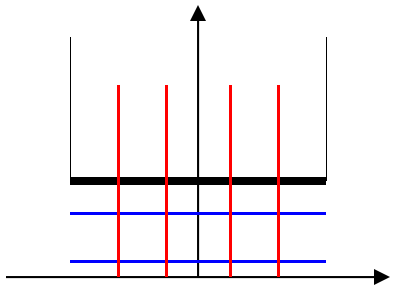
Magneto-static shimming; coil-shimming; SC shielding

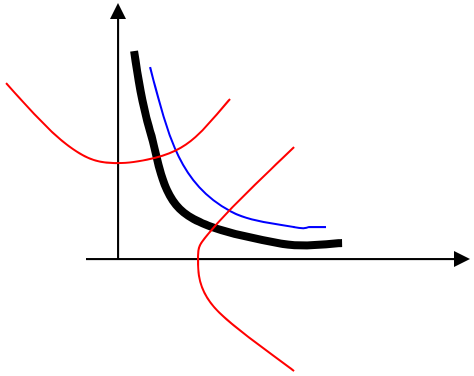
Large detector-magnet simulation

2d Multipole Expansion of Complex Potential --- ($z = x + i\,y$)

$$F(z) = A(x,y) + i\,V(x,y) = \Xi\, C_n (z - z_o)^n = \Xi\, C_n\, \mathbf{(x+iy)^n}$$

	A(x,y) = const (Flux lines) Real	V(x,y) = const (Equal scalar pot lines) Imaginary
n=1	x	y
n=2	$x^2 - y^2$	$2xy$
n=3	$x^3 - 3xy^2$	$3x^2y - y^3$
n=4	…… (Ref. Poisson/Superfish Manual)	





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Separate (Single) function magnet

Iron-dominated -- choose a equal scalar potential line

Coil-dominated – K1 cosθ, K2 cos(2θ), … on a circular aperture;

Combined function magnet

Iron-dominated -- work out a combined scalar potential line with certain ratios:

$$Y + (2\ m\ )X\ Y = \text{constant} = Gap/2$$ (Half-Gap at X=0)

→ $$\boxed{Y(x) = (Gap/2)^* (1+ G/Bo^*X)}$$ (For large Ro)

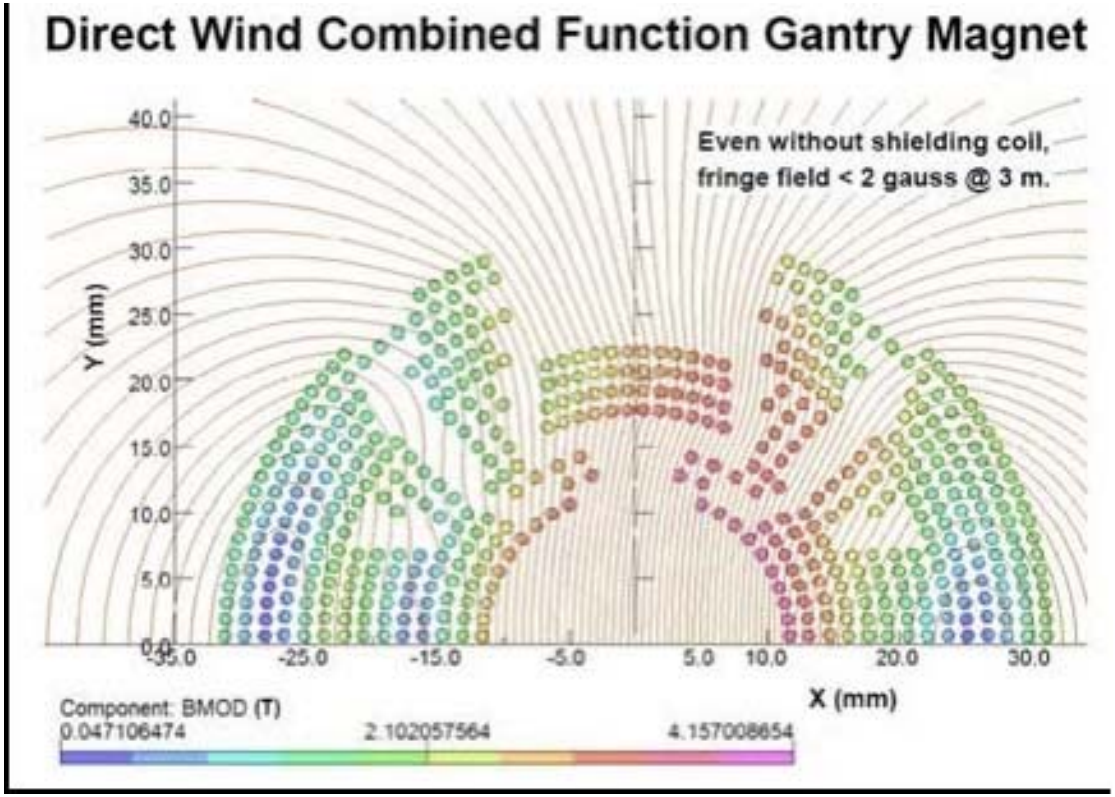
G = gradient (T/m); Bo = dipole (T) (given by lattice design)

-> Try in Opera-2d; check harmonics;
-> Modify gradient G; get a new Y(x) curve…

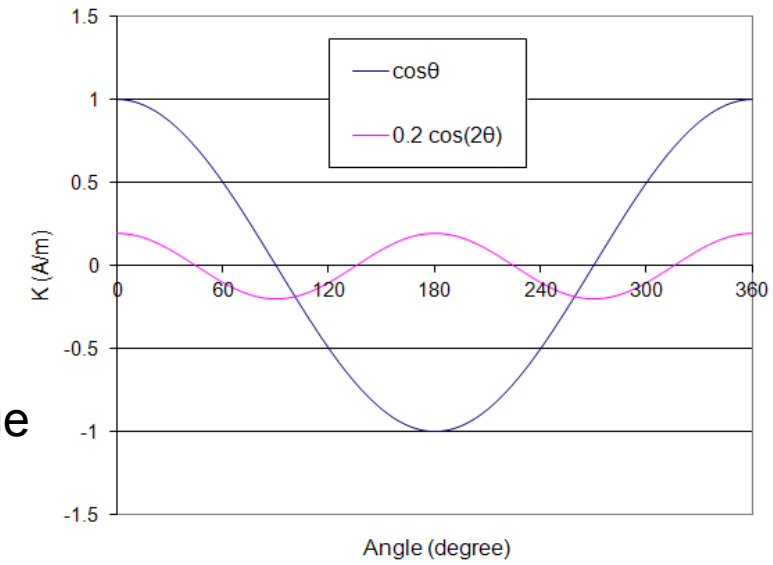
Combined function magnet --- **If Coil-dominated**?

Method (A) Simply superimpose cosθ and cos2θ distributions on a circle

(many people do this; but not efficient, because of current cancellations.)



Current cancellations occur around 180 degree, and 90, 270 degree. In SC cases, it results in larger cold Mass and inductance (larger voltage during quenches).



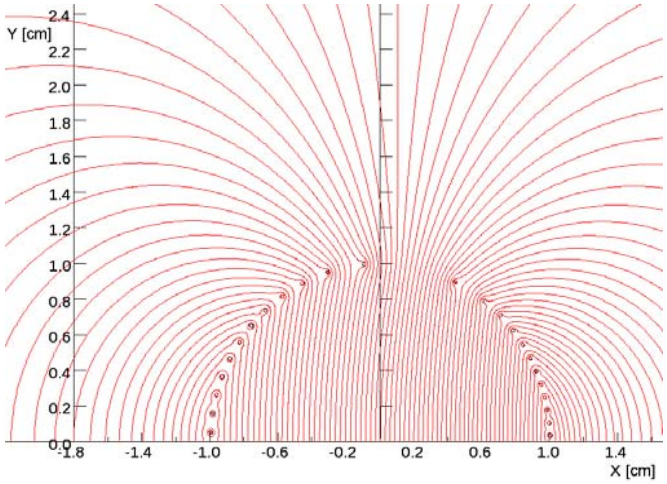
(Cont. Coil-dominated)

Method (B) Calculate combined current distributions by using 2d potential theory; then **Preliminary conductor centers can be precisely computed and positioned.**

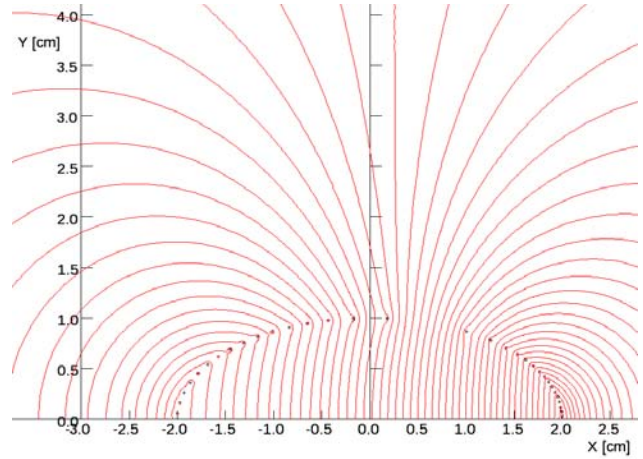
F. Krienen, D. Loomba, W. Meng, “Development of Non-ferrous Superconducting Magnets”, Proceedings of PAC91, p.2474. See also BNL/AGS Muon g-2 Note No.63, November 10, 1990.

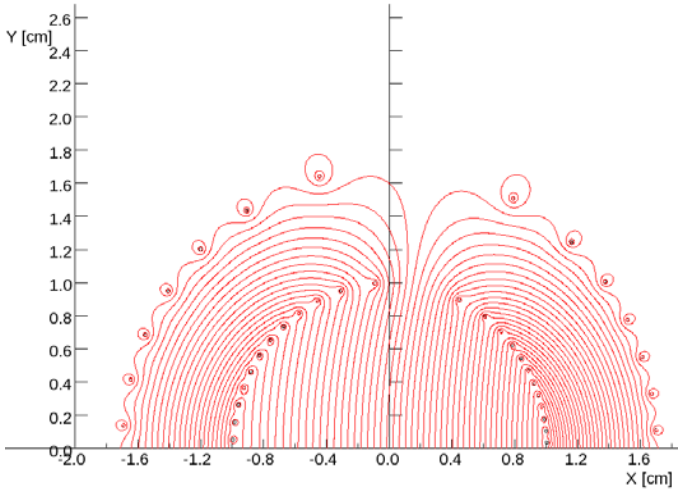
W. Meng **“Coil-dominated Combined Function Design”**, **NIM A 715 (2013) 39-47**

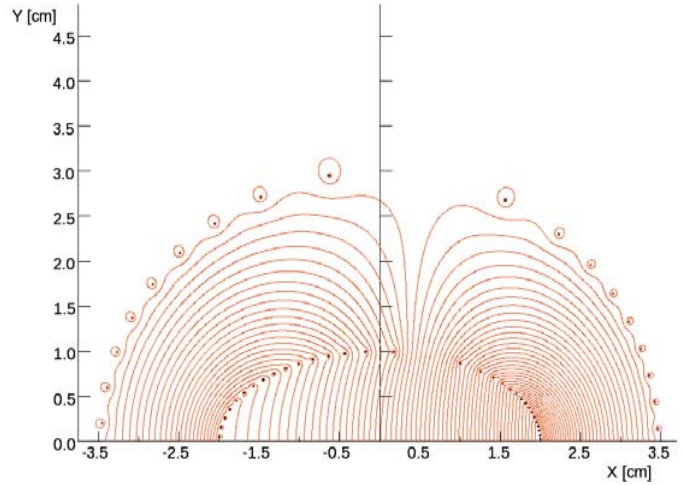
Circular Aperture



Elliptical Aperture







Design Steps (coil-dominated combined function magnet) ---

(1) Lay out potentials inside & outside of aperture (circle/ellipse)

(2) Compute the scalar potential jumps (sudden changes) across the current boundaries (circle/ellipse)

$$\nabla V = - \mathbf{B} \qquad \mathbf{n} \times (\mathbf{H}_2 - \mathbf{H}_1) = \mathbf{K}$$ [Jackson (I-20)]

Current Boundary: $\mathbf{K = dV/ds}$

(3) Compute the positions of each individual conductor (preliminary current center) based on the derived equations

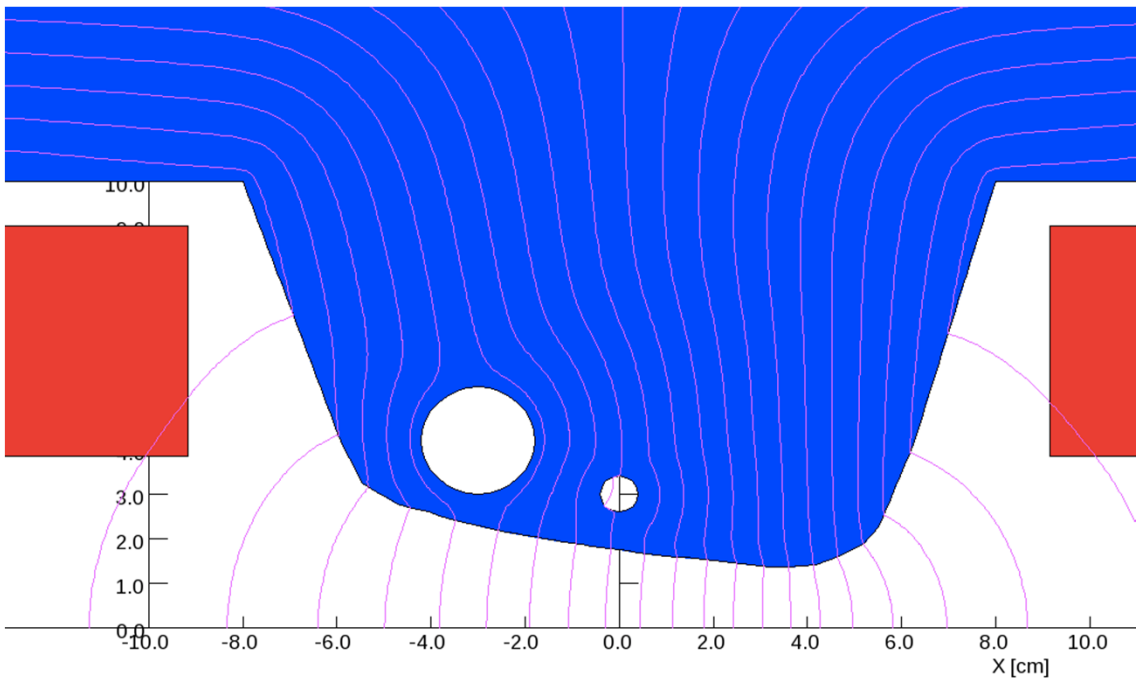
(4) Use Opera-2d to check the flux plot and field quality (E-3 level)

In all cases, current per wire = 1 A; R=1 cm (circular case); a=2, b=1 cm (elliptical case). It will be easy to scale up.

About 2d Simulation ---

Most accelerator magnets have uniform cross-sections; it is very useful to optimize first in 2d, then check it and finalize it in 3d.

(Ex. Balance the saturation levels in ramped combined function magnet, in order to keep the n-value (quadupole to dipole ratio) constant during ramp)

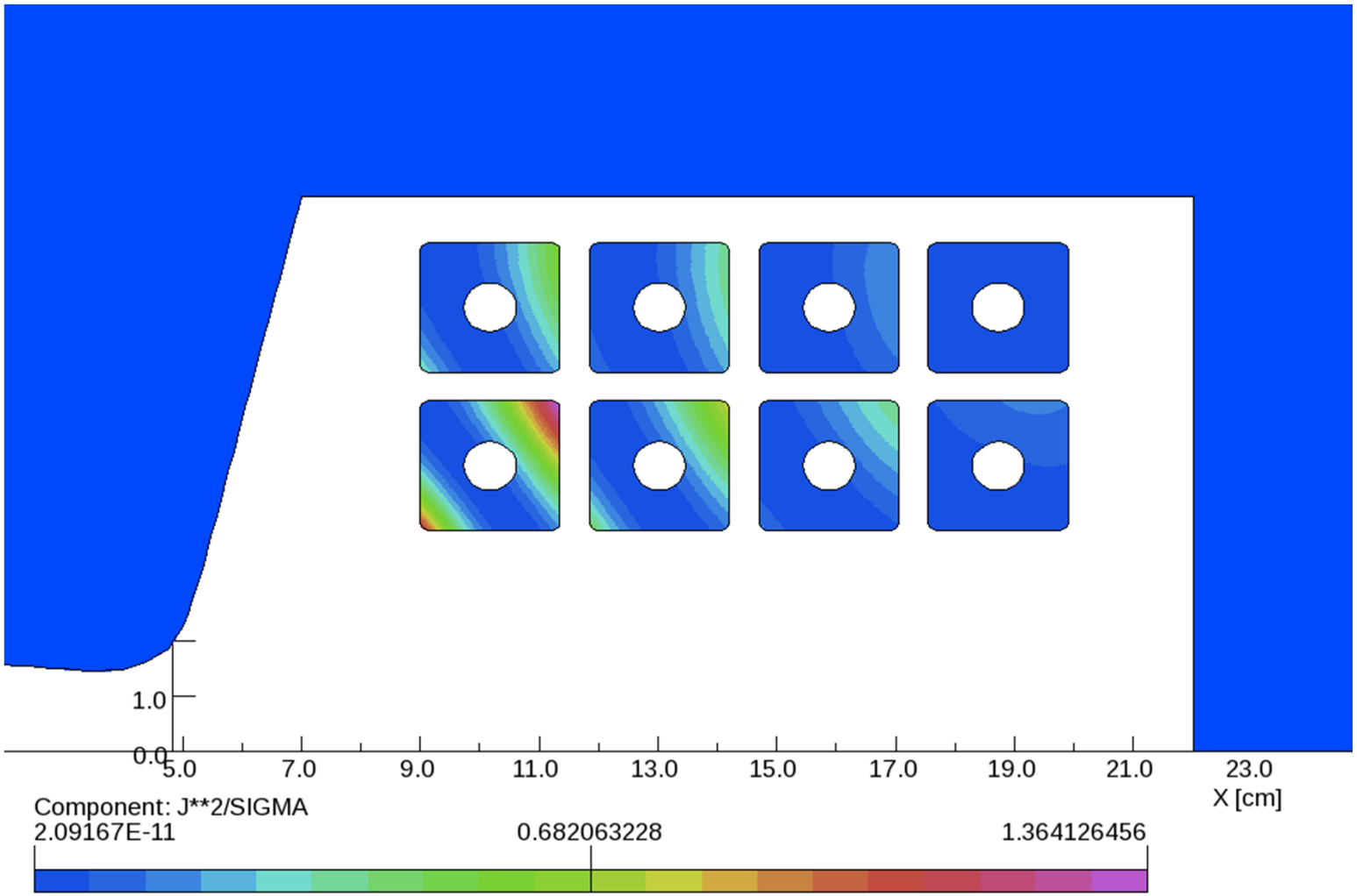


(Slots work as well as holes)

Ref. Yoshihisa Iwashita et al, Japan J. Appl. Phys. Vol. 38 (1999) pp.895-897

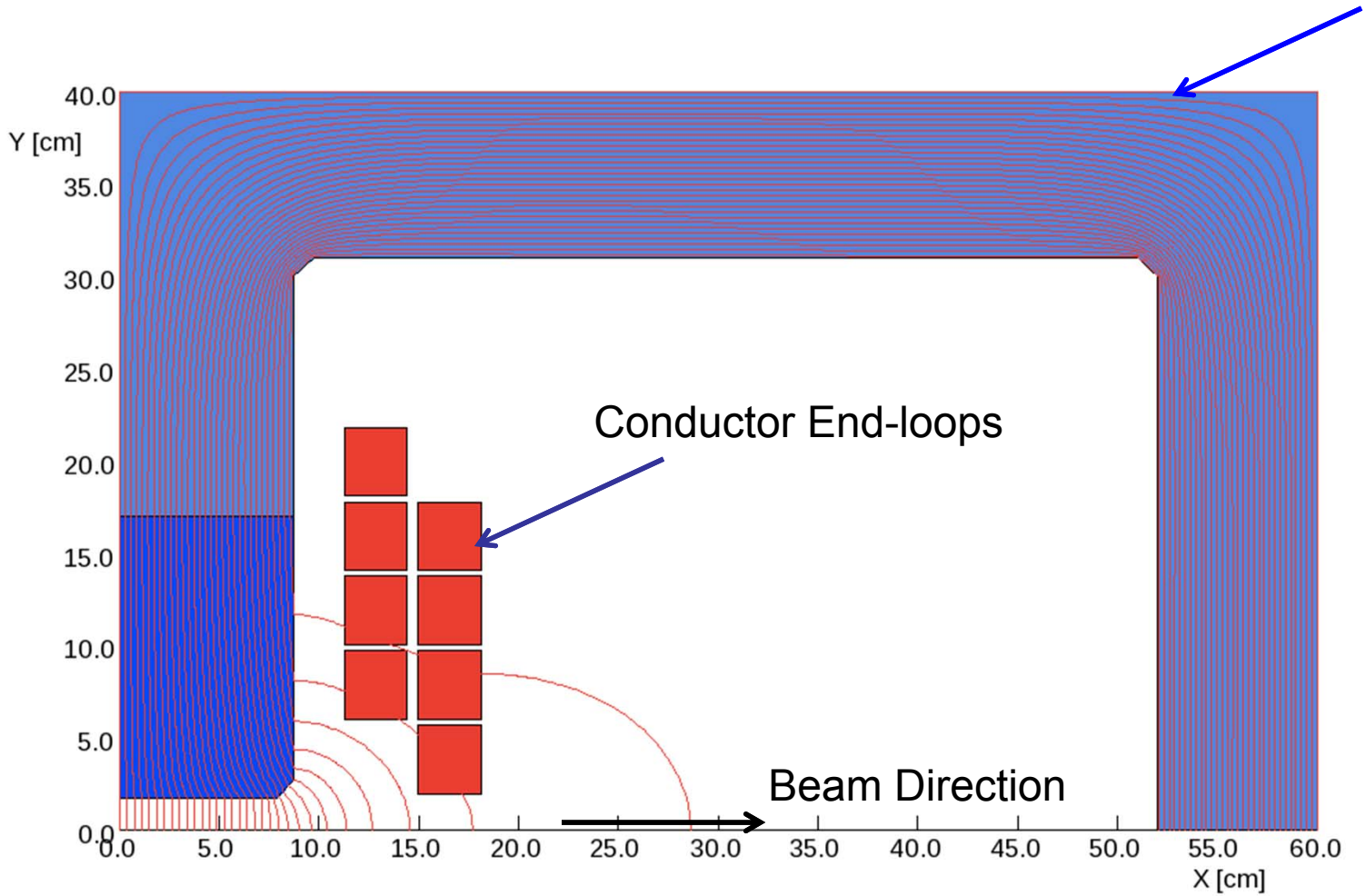
Opera-2d (AC steady state, Transient) solvers are very useful fir eddy current simulation in conductors

Ex. Power losses in the coils (including driving current and eddy current)



Power = Integral (J**2/σ) ds (watt/cm)

Ex. Use 2d to simulate “3d” end-effect by setting equivalent magnetic path



Adjust the thickness & permeability in this path to match the main field,
This model can be used to study the fringe field and end coil heating (if in AC case)
(Ref. Poisson/Superfish Users Guide)

A. Chao & M. Tigner: "Handbook of Accelerator Physics and Engineering" p. 397 equation (9) can be used for eddy current heating power on metal vacuum chambers, or on Recipes coating on ceramic chamber.

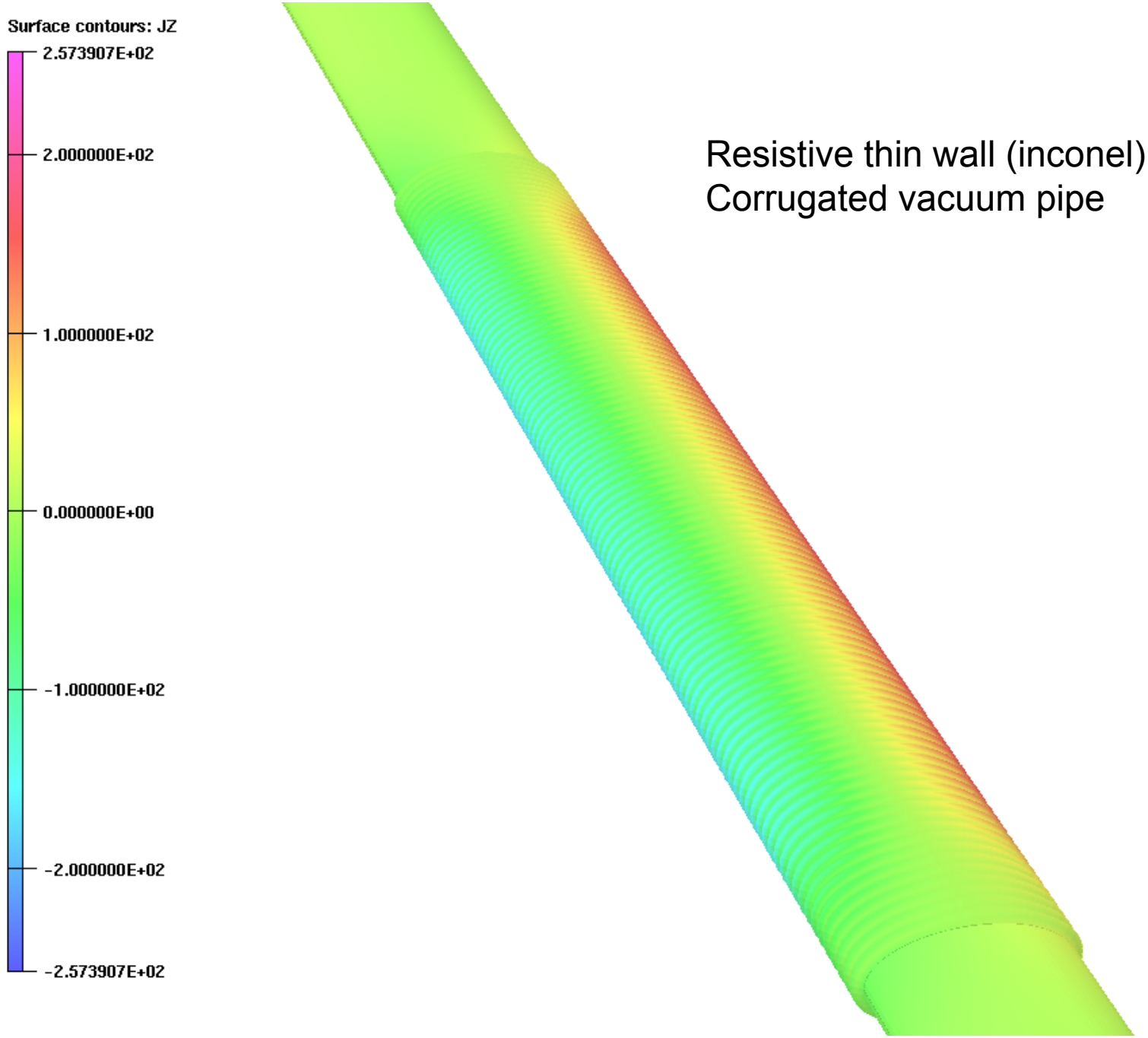
This equation was for "half-sine" wave field.

If the field is sine-wave, a factor of 2 must be applied.
The Opera-2d results agrees with it very well for circular pipe case.

If the pipe cross-section is elliptical, then this equation has to be modified;
Also, Opera-2d is a good tool to simulate it.

If the pipe is "corrugated" like a bellow, Opera-3d result shows that the power loss is about the same as a smooth pipe with the same thickness.

For a corrugated vacuum chamber, we can simplify it as a smooth chamber (with the same thickness) to perform eddy current heating calculation and eddy current multipole analysis.

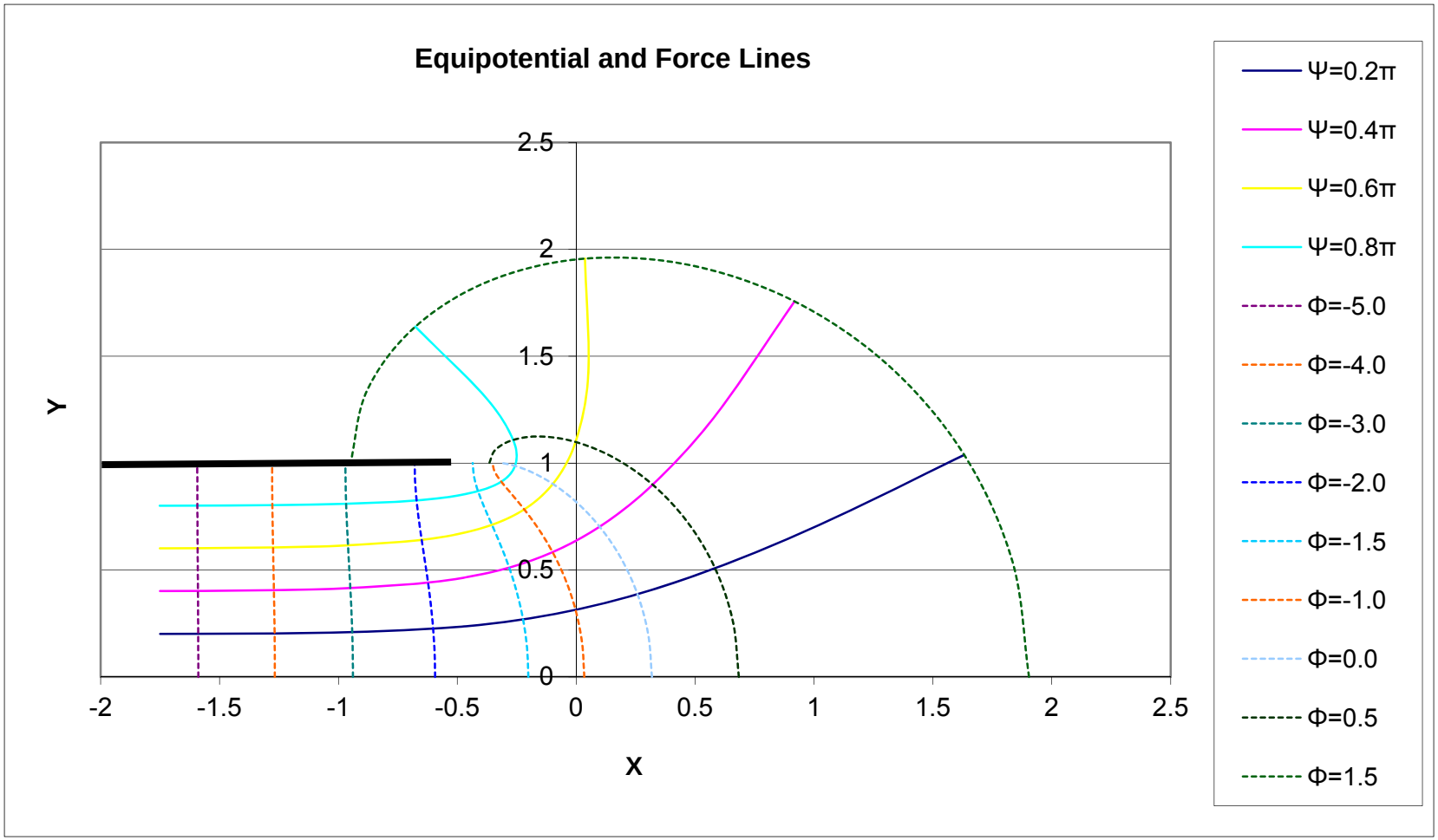


Resistive thin wall (inconel)
Corrugated vacuum pipe

About Rogowski Contour

Electro-static Case –

A pair of charged parallel plates (Electro-static)



Maxwell (1900)

$X = (a/\pi)\,(\phi + e^{\psi}\cos\psi)$

$Y = (a/\pi)\,(\psi + e^{\phi}\sin\psi)$

Ψ = constant (equal-potential lines)

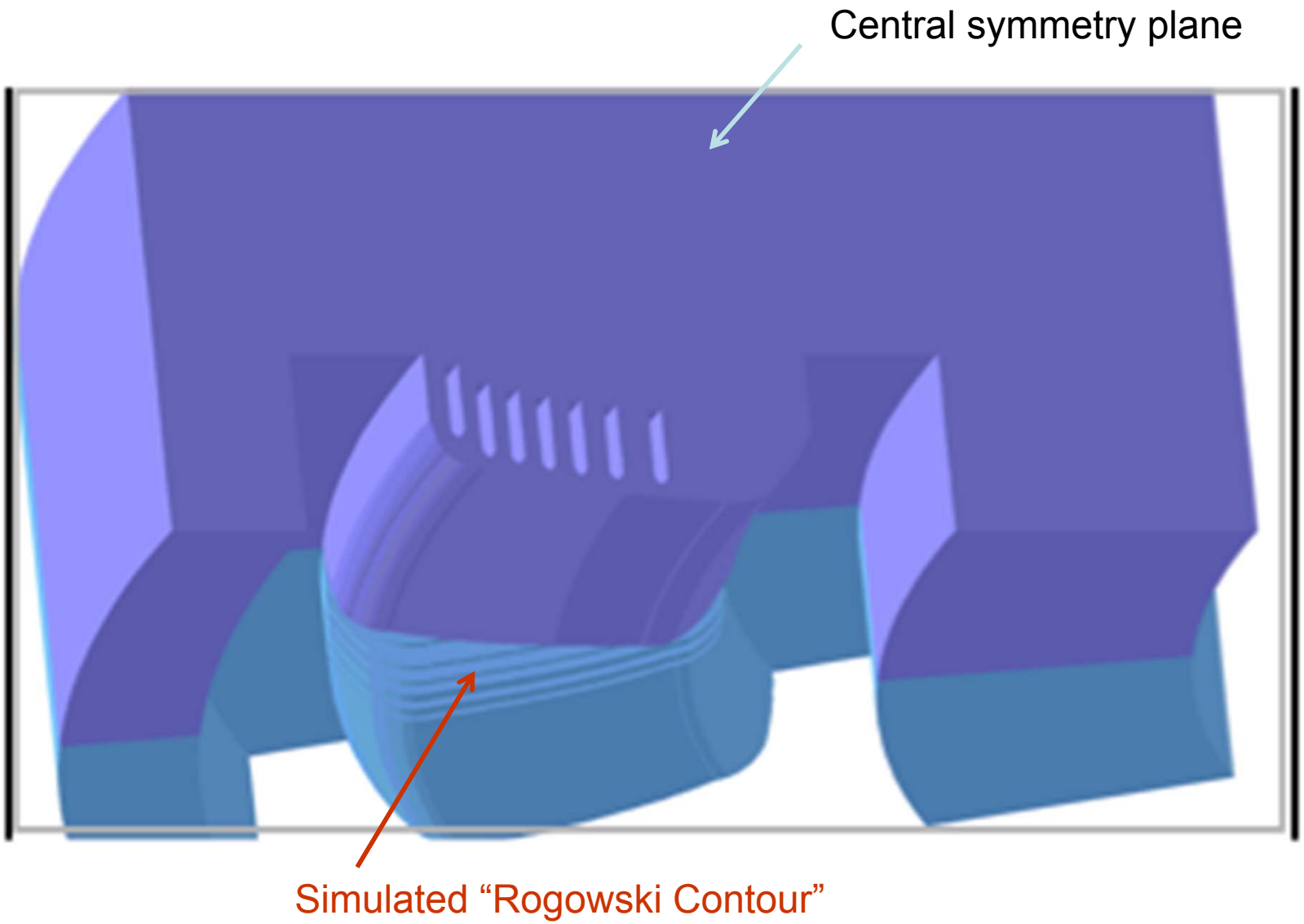
Φ = constant (E-flux lines)

Rogowski (1923)

If $\psi \leq 0.5\,\pi$, then the E field strength near the edge is equal to center. (high voltage breakdown won't happen at edges)

This can be applied on magnet end shape design, to reduce the local saturation in DC magnet (chamfers), or to keep magnetic effective length unchanged during circling in AC magnet.

Ref. Chao & Tigner "Handbook of Accelerator Physics and Engineering", p.440 (by F.E. Mills)



Ref. Akira Noda et al, “Development of compact proton accelerator facility dedicated For cancer therapy”, APAC 98.

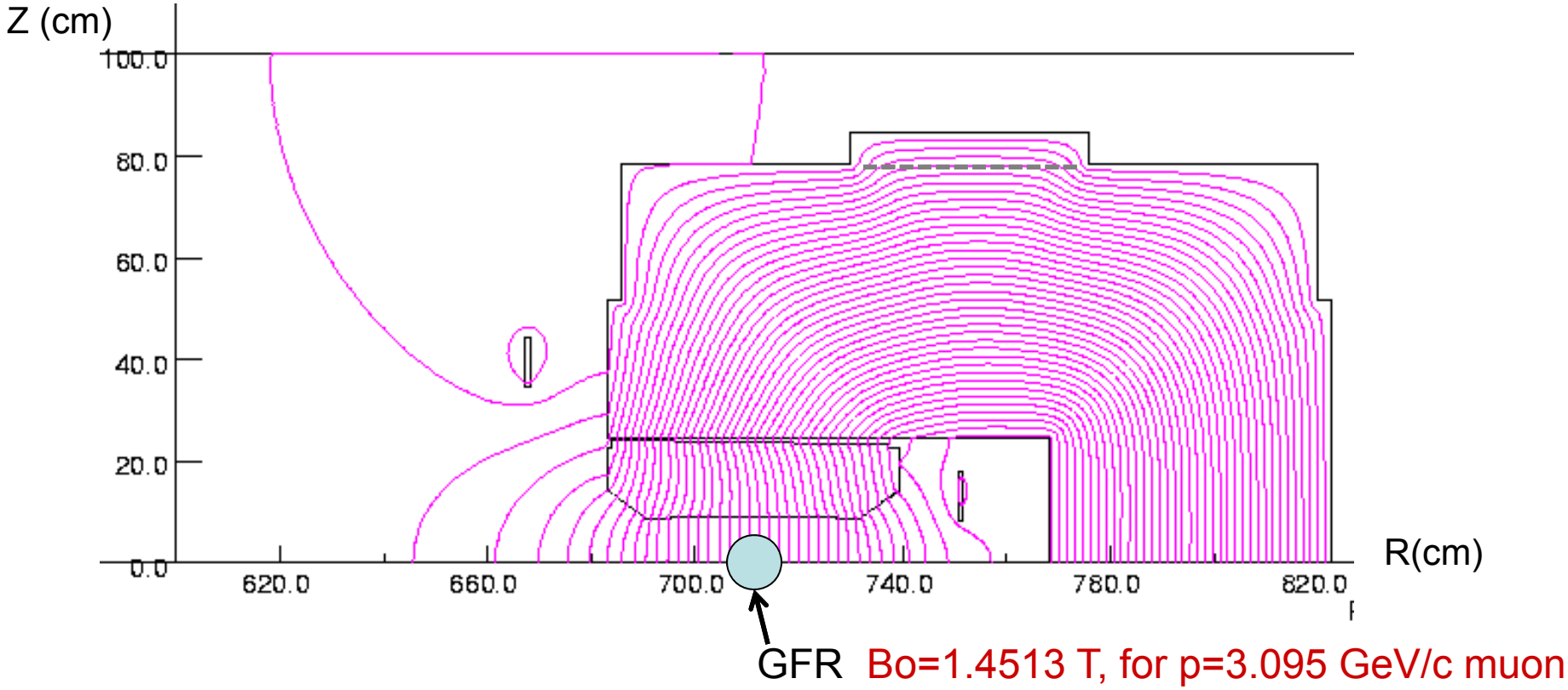
Shimming Tools --- Good example: requirement $\int (dB/B)dl \le 1\,ppm$

Dipole correction: top/bottom plates adjustments; wedge translation (for b1)

Quad correction: tilt pole angle, tapered wedge angle machining (for b2 ~ r)

Sextupole correction: pole chamfers, edge shims width/thickness (for b3 ~ r^2)

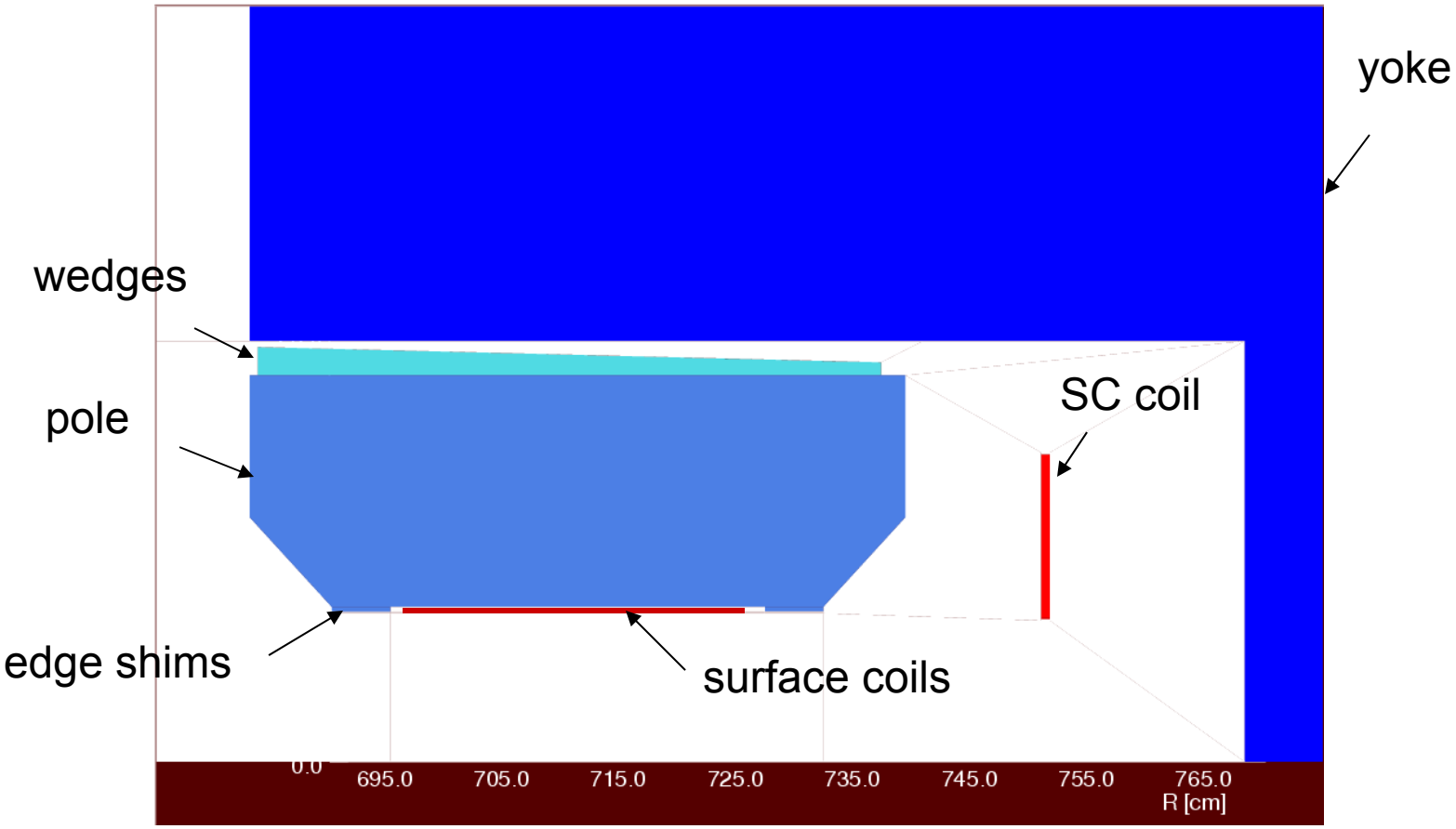
…… and more: azimuthal correction, surface coils fine tuning ...



SC Storage Ring for BNL Muon g-2 Experiment (E821) 1997-2001

Built-in Shimming Tools --- Good example (cont.)

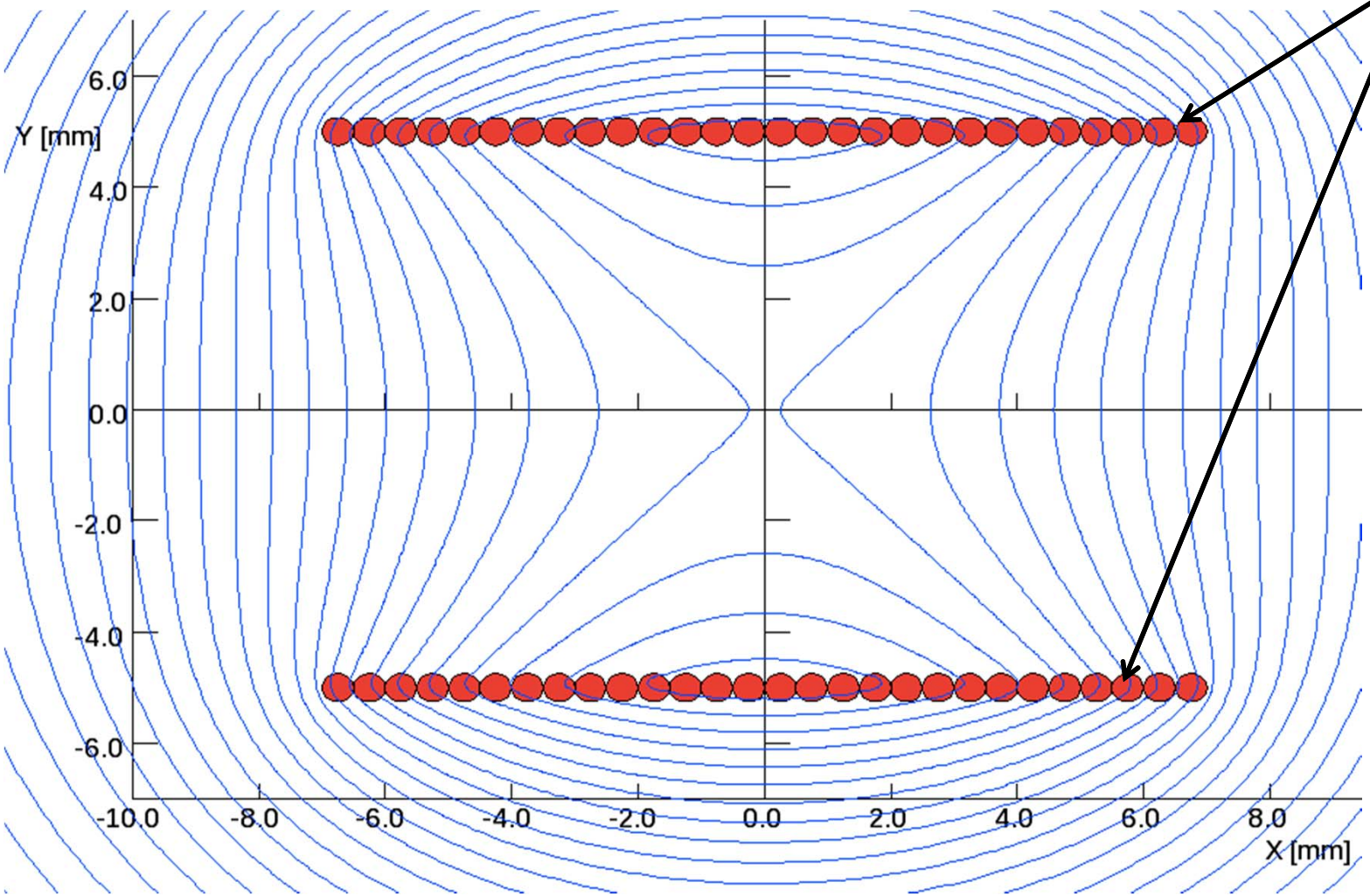
Ref. G.T.Danby et al "The Brookhaven muon storage ring magnet" NIM A 457 (2001) 151-174



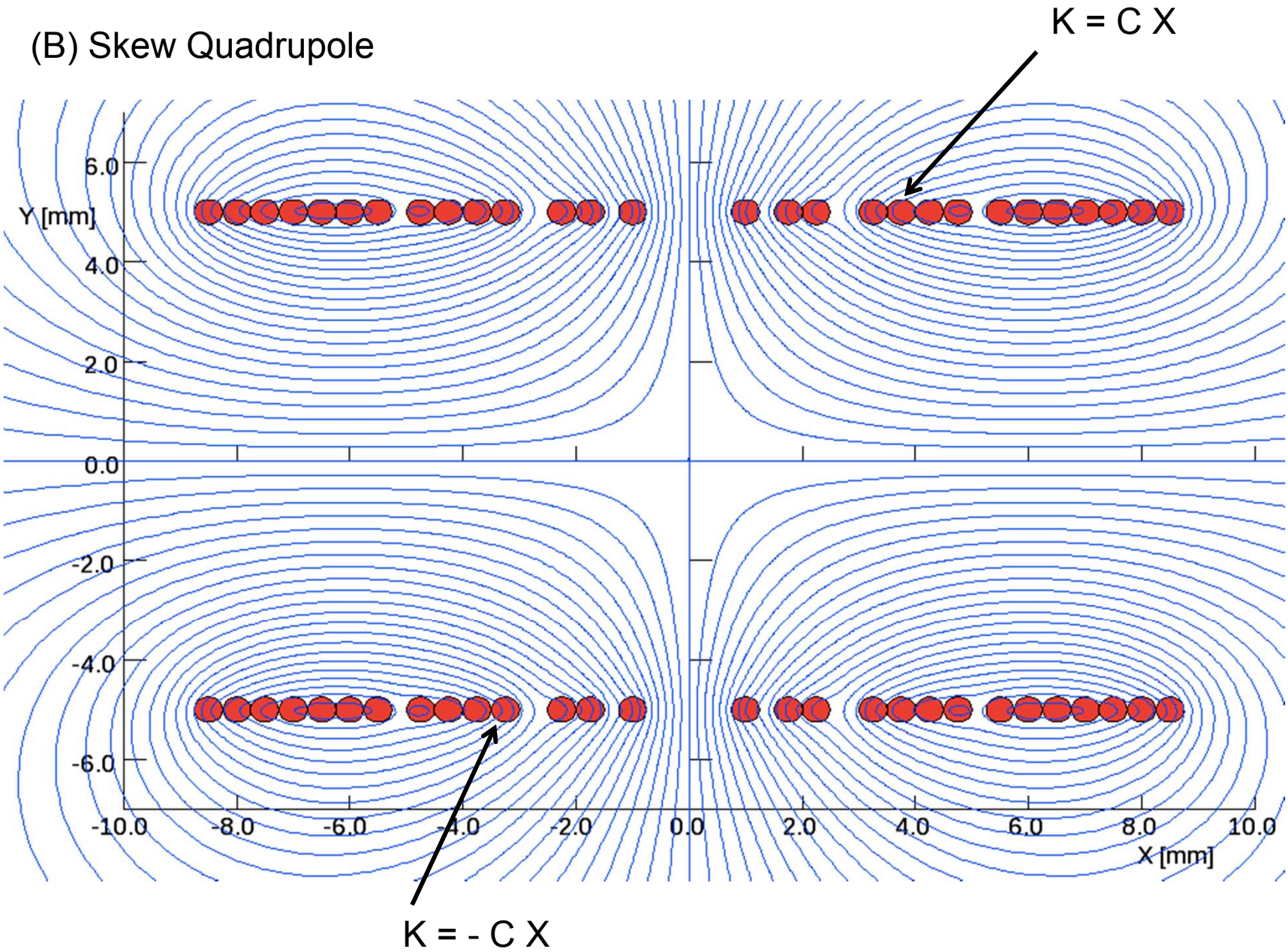
Surface Coils (applied on Y= +/- Half-gap) ---

(A) Normal Quadrupole

K = C



(B) Skew Quadrupole



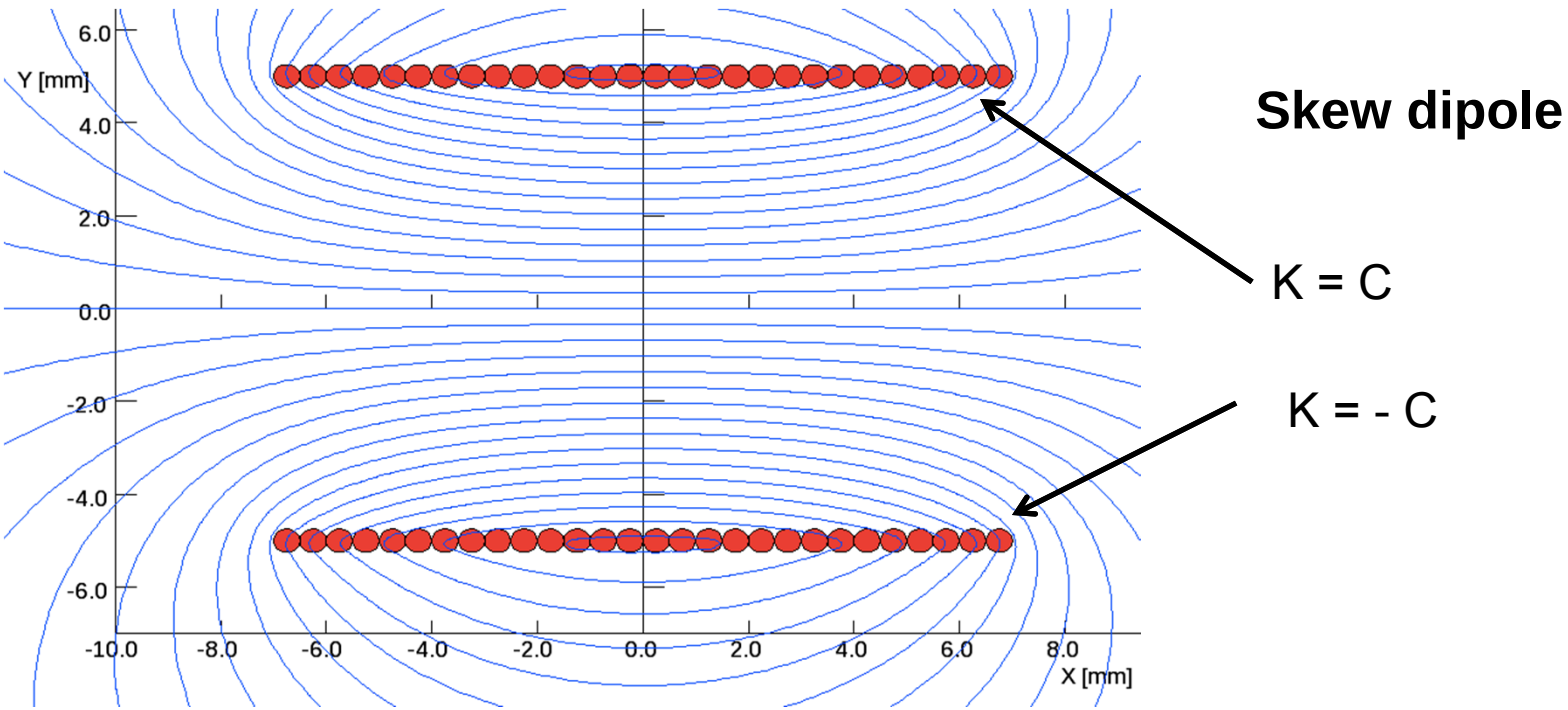
Cautious (surface coils):

(a) Pay attention on influence from adjacent magnetic materials

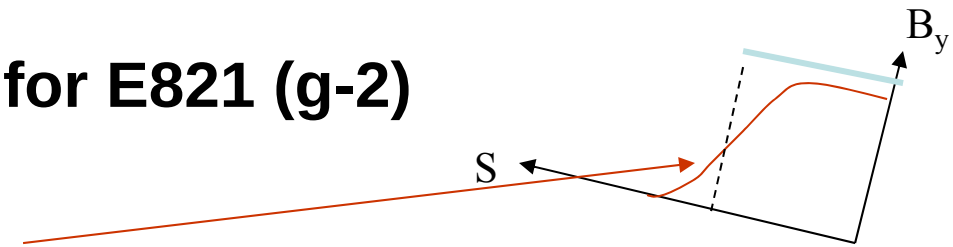
(b) For normal components n = 1, 3, … coils will present significant impurity:

n=1 – dipole coil creates significant sextupole component;

n=3 – sextupole coil create significant dipole component

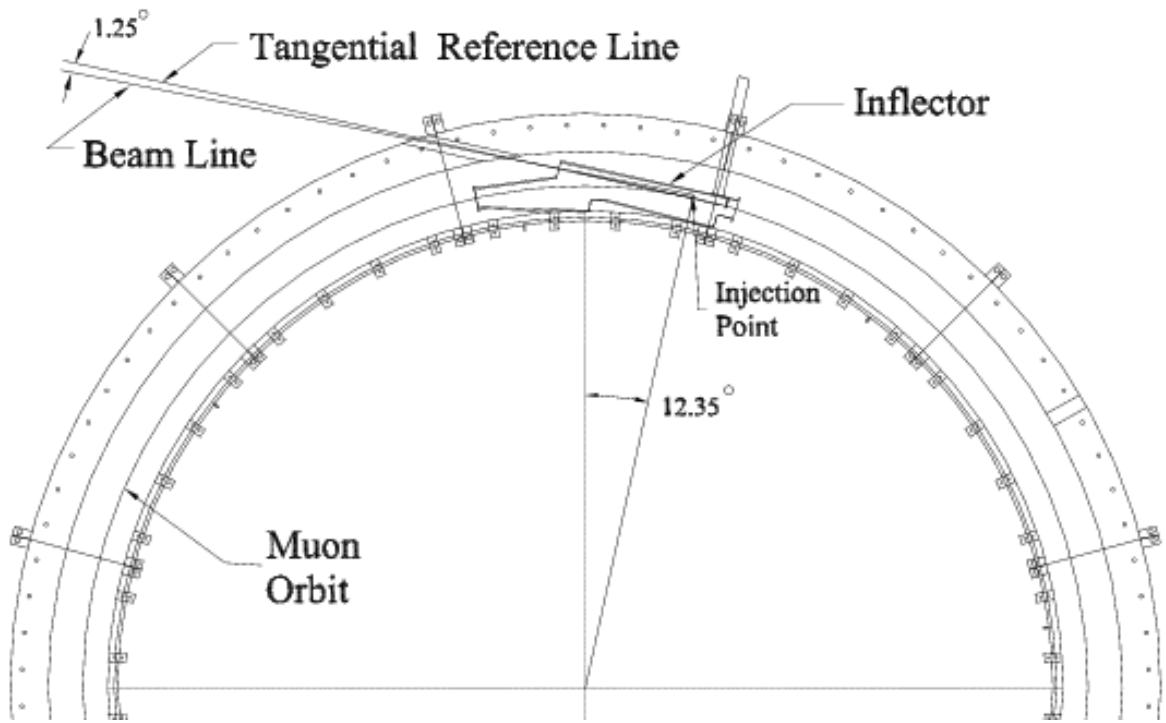


SC Inflector for E821 (g-2)



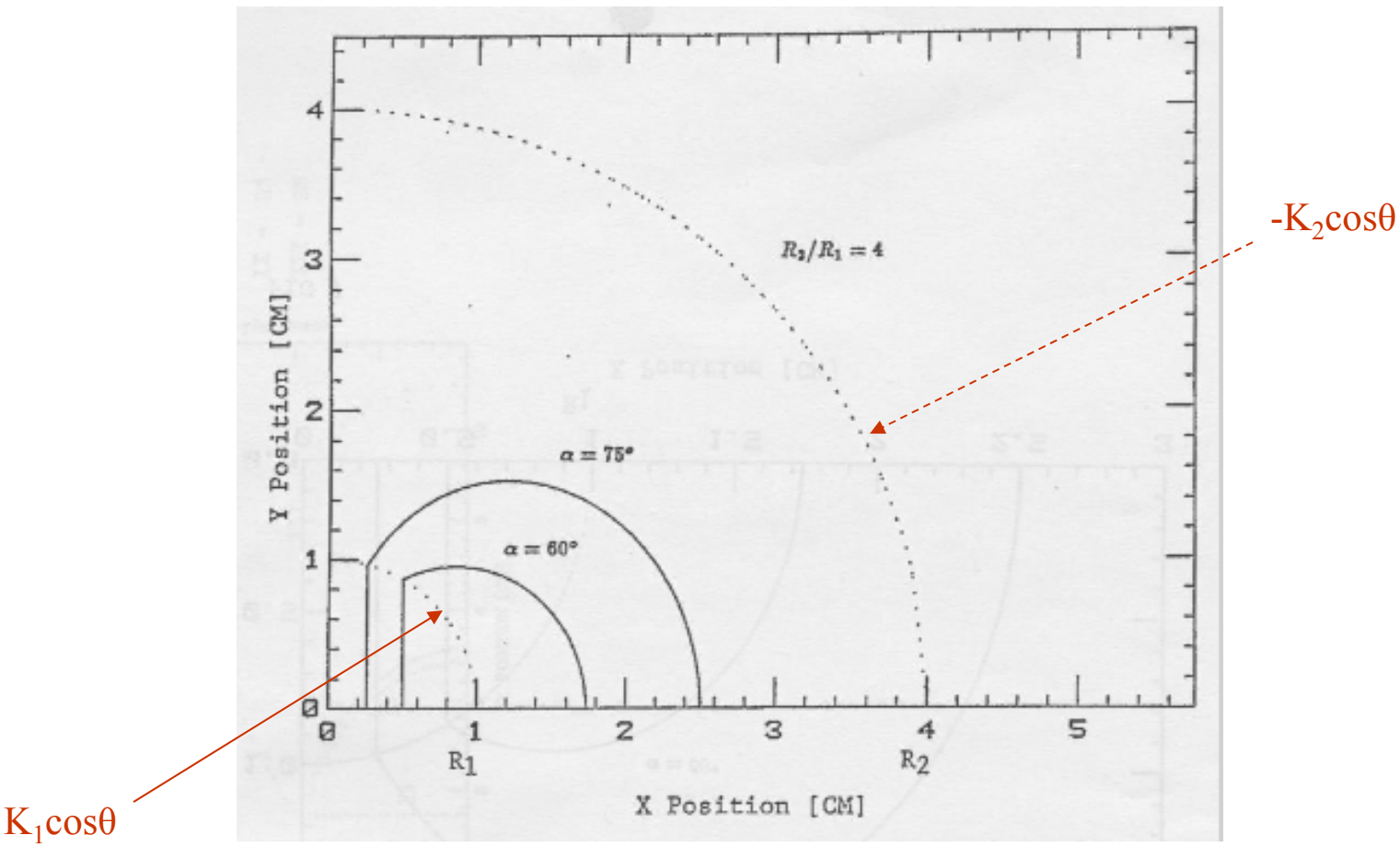
In order to cancel 2.55 T-m Fringe field from storage ring,

Bo = 1.5 Tesla
L= 1.7 m
Low Tc NbTi SC septum magnet

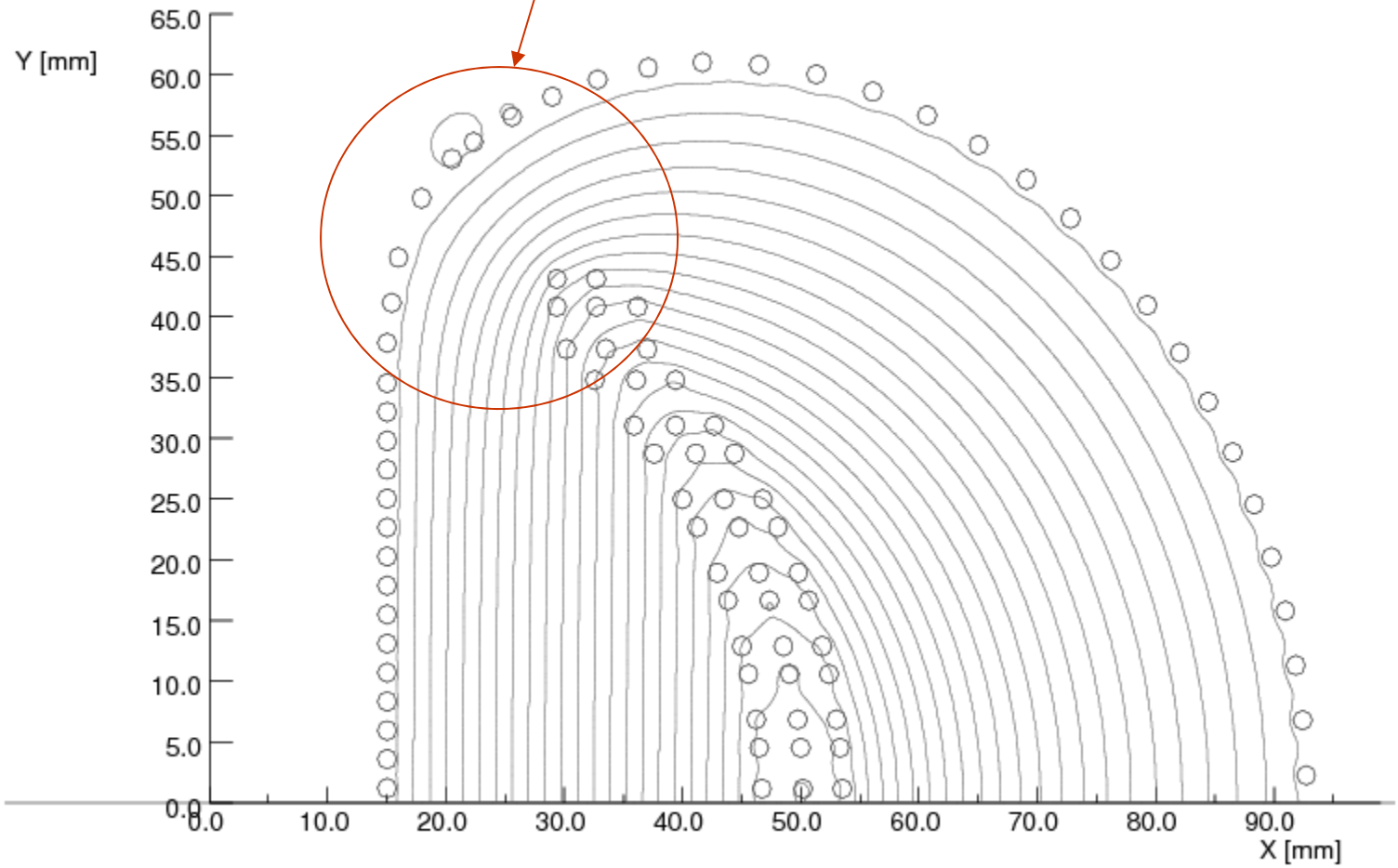


How to eliminate Fringe Field?

Double cosθ Distribution and Truncation along
Vector-potential lines --- Frank Krienen (NIM A283(1989)5)

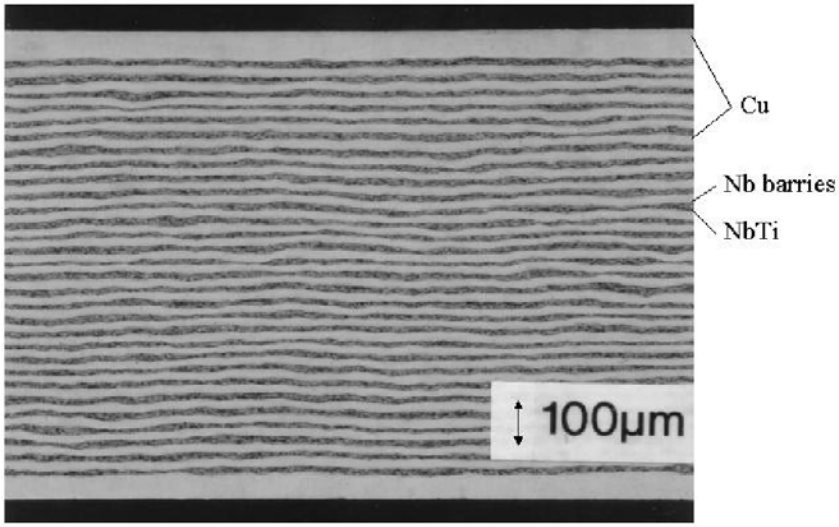


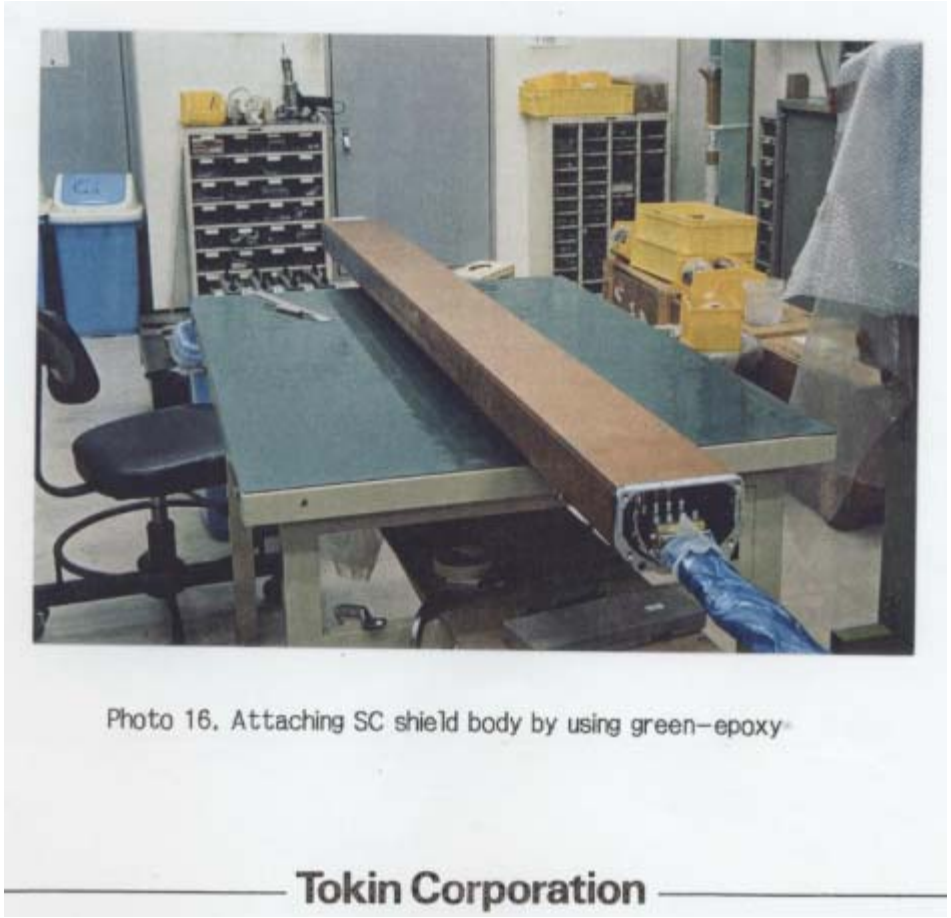
Conductor positions were modified to avoid technical difficulties



However, residual fringe field still exists ……

Multilayer SC Sheet





Nippon Steel Corporation
Advanced Technology Research Lab

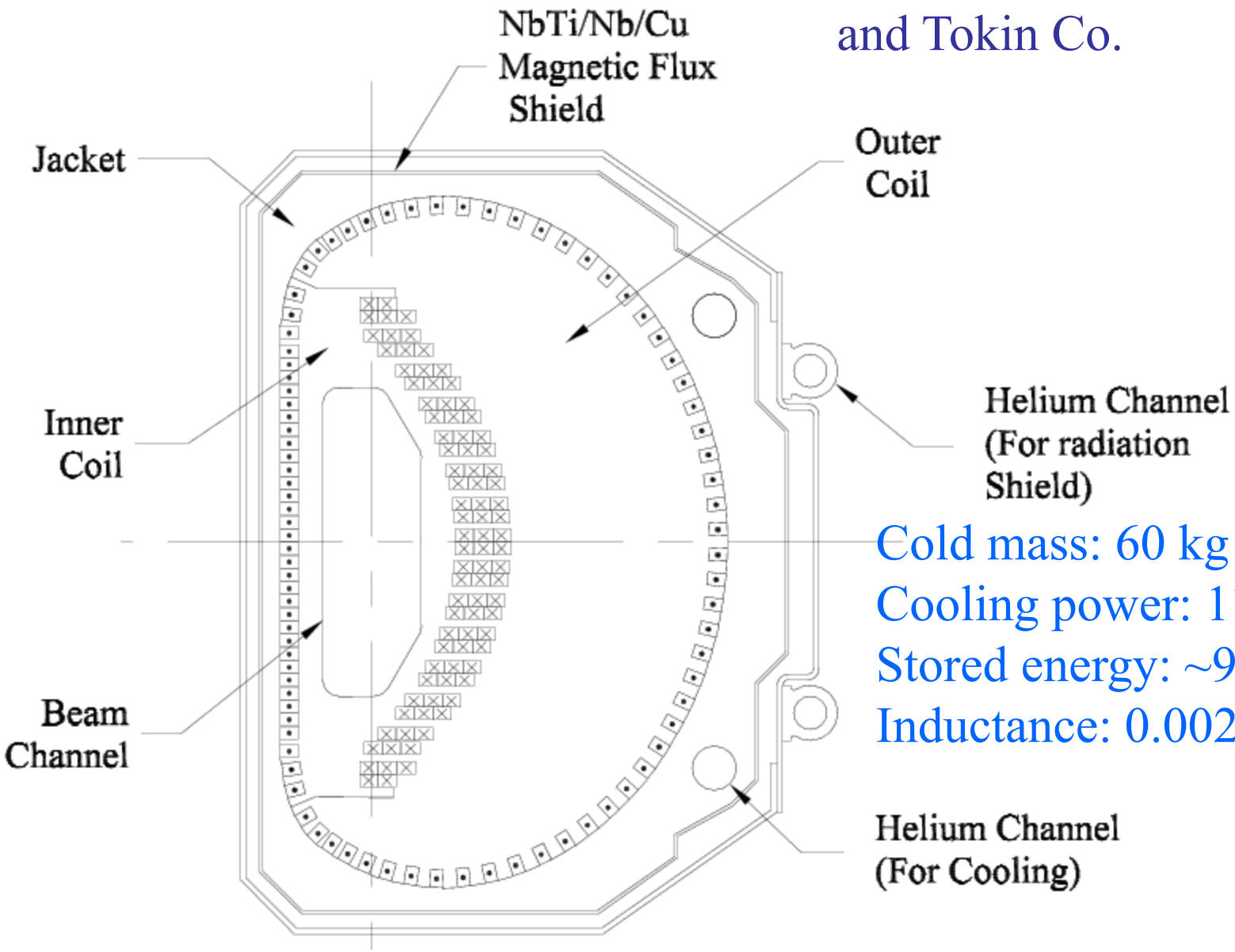
Dr. Ikuo Itoh

$Jc > 1200\ A/mm^2$
@1.5 T, 4.2 K, H ⊥ NbTi layer

$$B = \mu_0 Jc\ d$$

(d = Total thickness of NbTi layers)

Prof. Akira Yamamoto (KEK) and Tokin Co.



Cold mass: 60 kg
Cooling power: 11 W
Stored energy: ~9000 J
Inductance: 0.002 H

Working Procedure --

(1)

Main magnet powered
Flux penetrating
Inflector stays "warm"
Un-powered

(2)

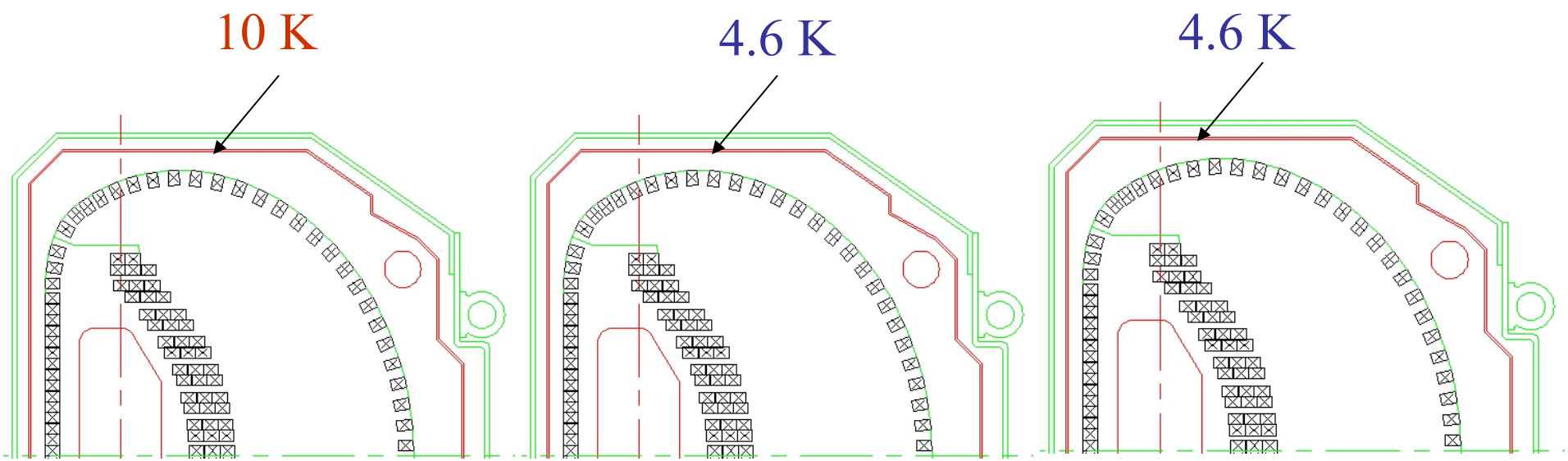
Main magnet stable

Cool down inflector

Main flux are trapped
by the SC shield

(3)

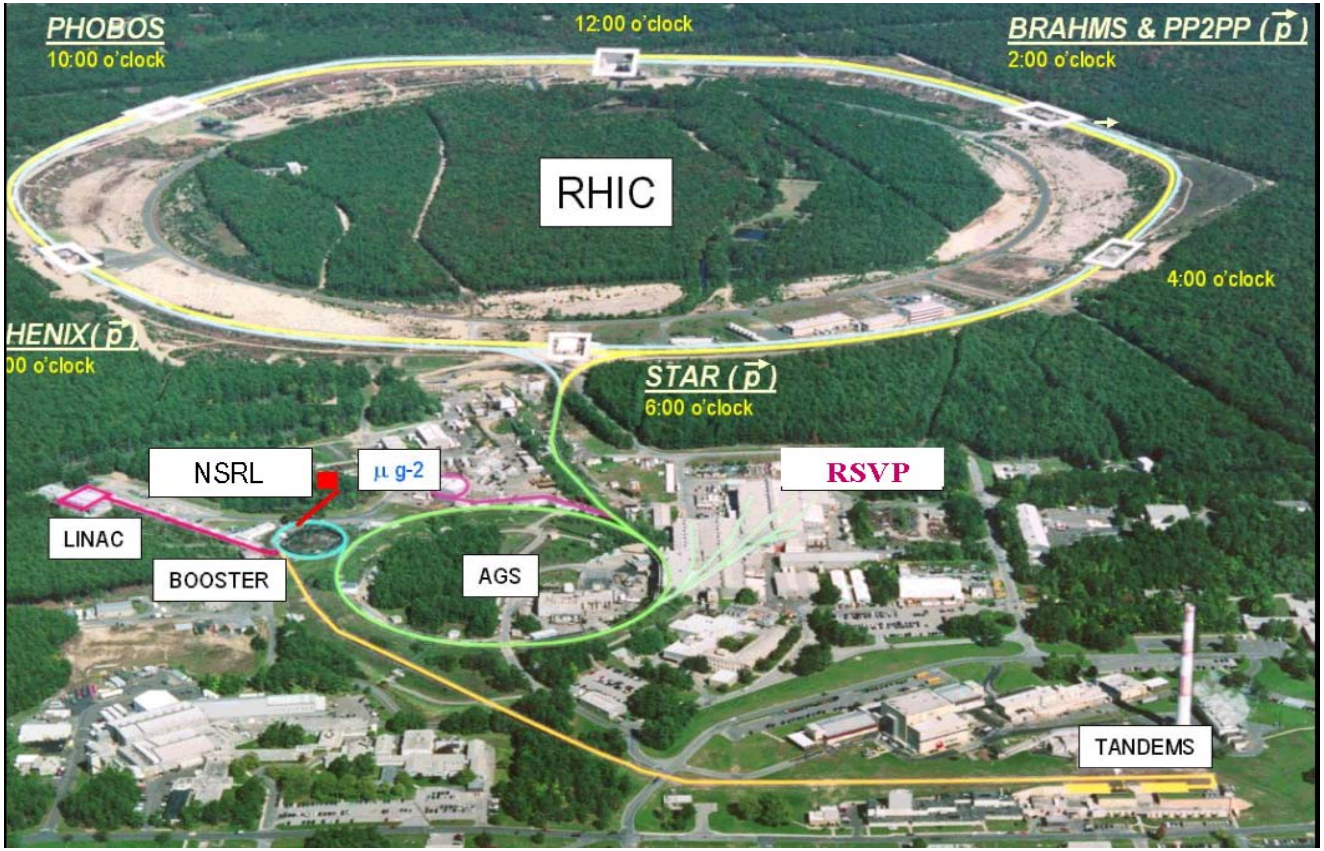
Power Inflector slowly
(Io → 2850 A; 2 A/sec)
Main flux are trapped
Fringe flux are blocked
by the SC shield



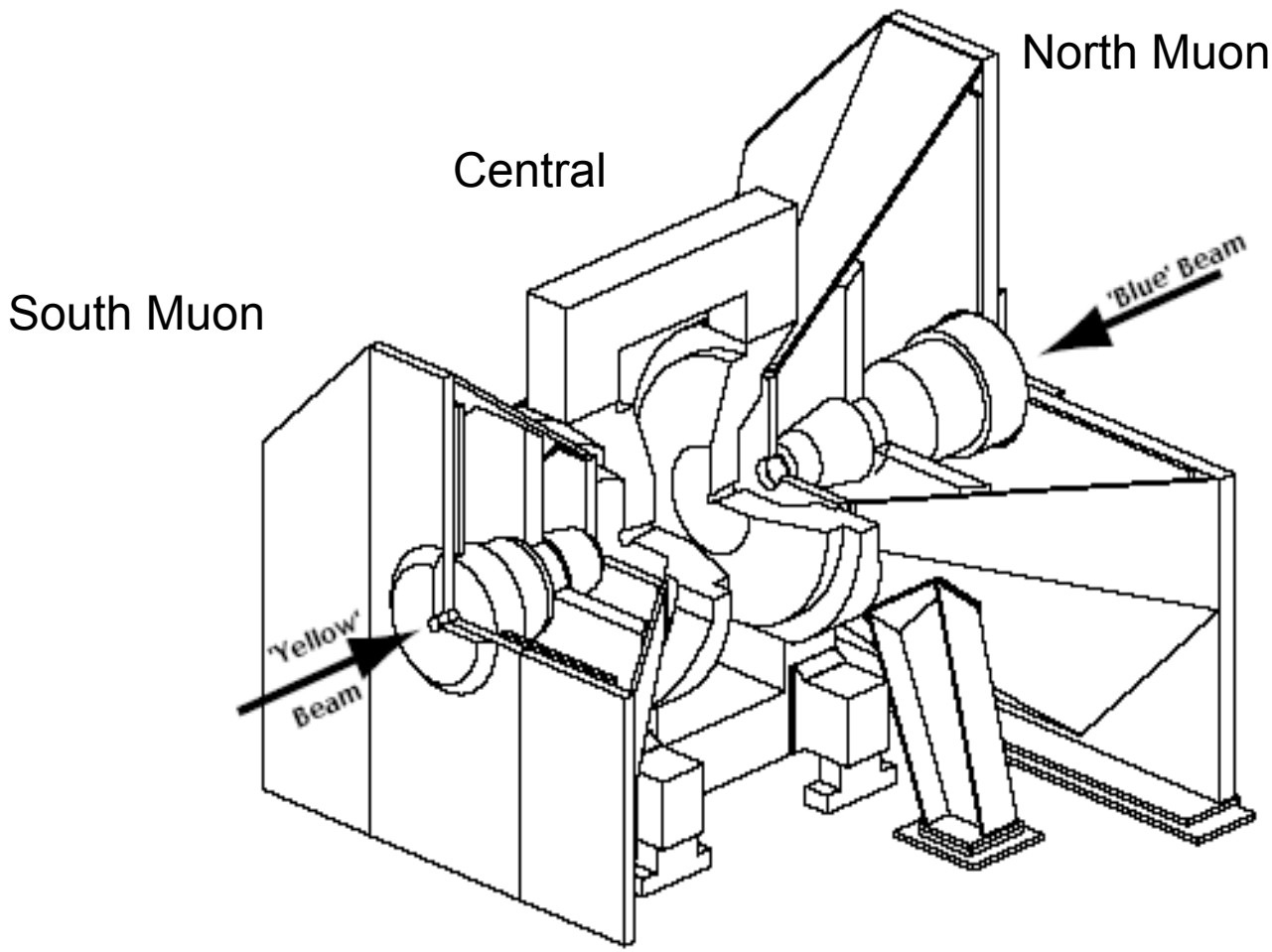
Simulations are quite useful in following situations:

(1) Some magnets are not accessible for measurement (either the bore region is occupied by sensitive equipment, or the magnet is highly radioactive)

(2) Some detector magnets are too big to measure.

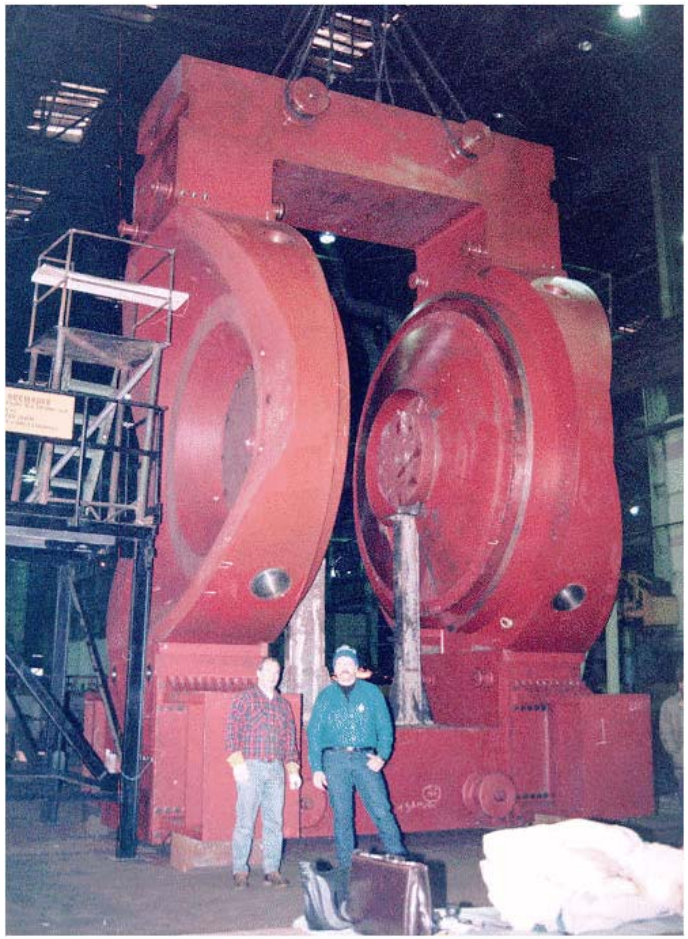


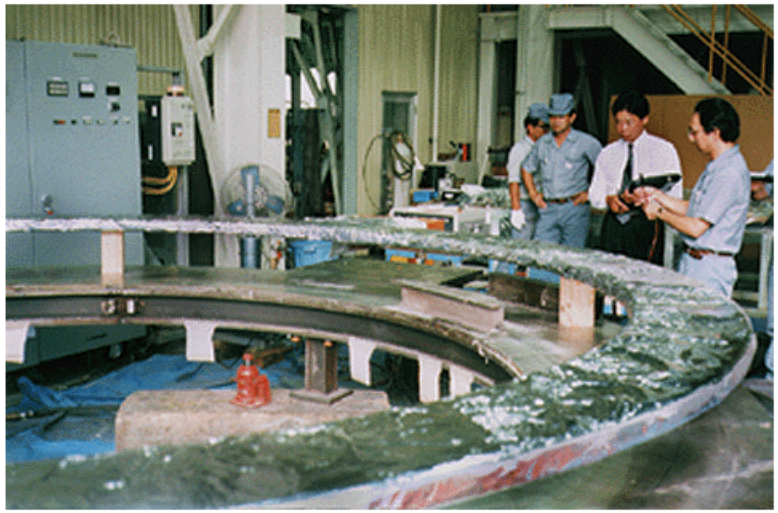
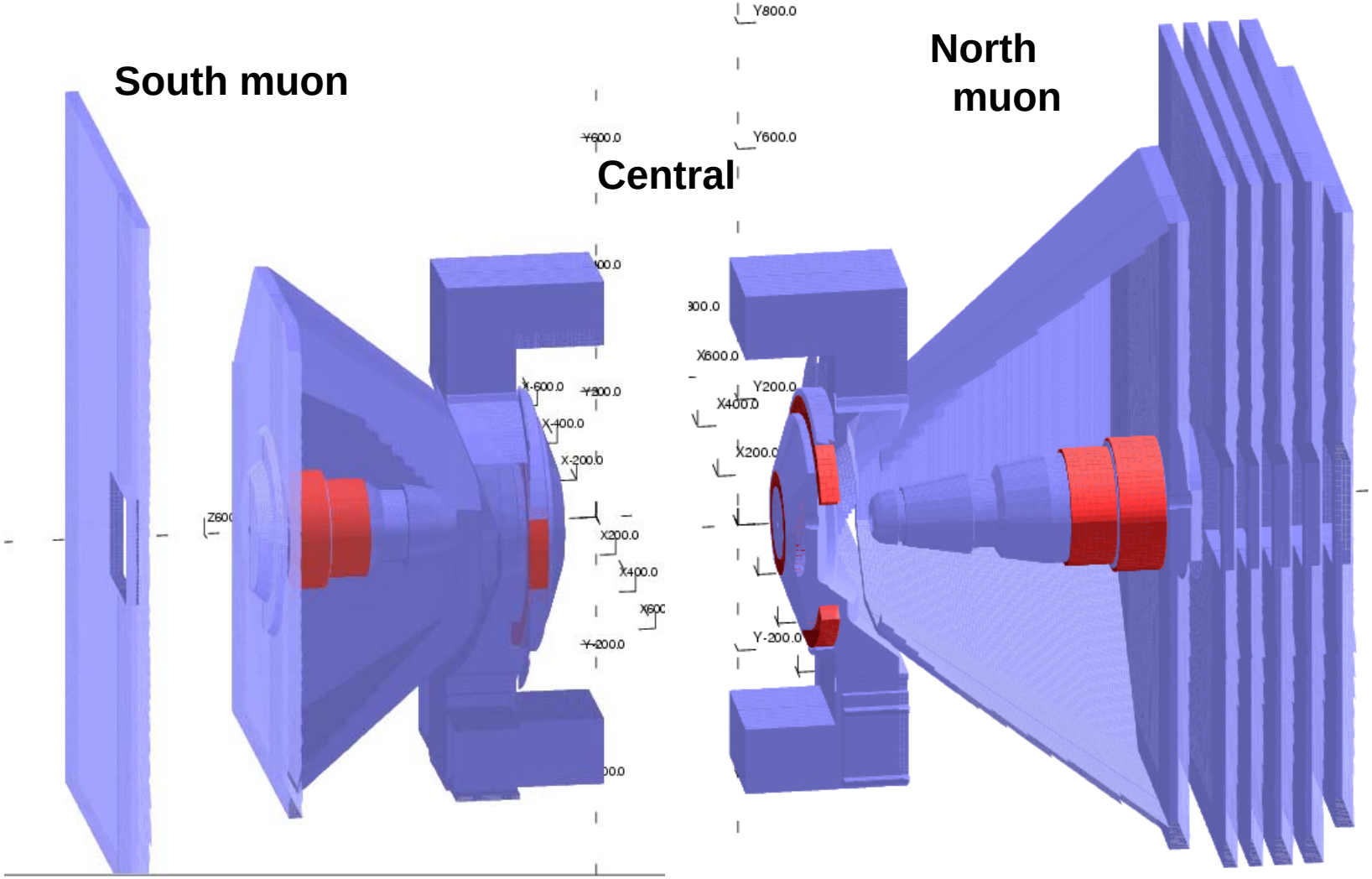
PHENIX (all 3 Magnets)



Overall size
10 m (H)
10 m (W)
20 m (L)
Ctr. B=0.49 T

PHENIX Central Magnet & Coils





Opera Models for PHENIX Magnets