Superconducting Magnets for Particle Accelerators

Toru Ogitsu

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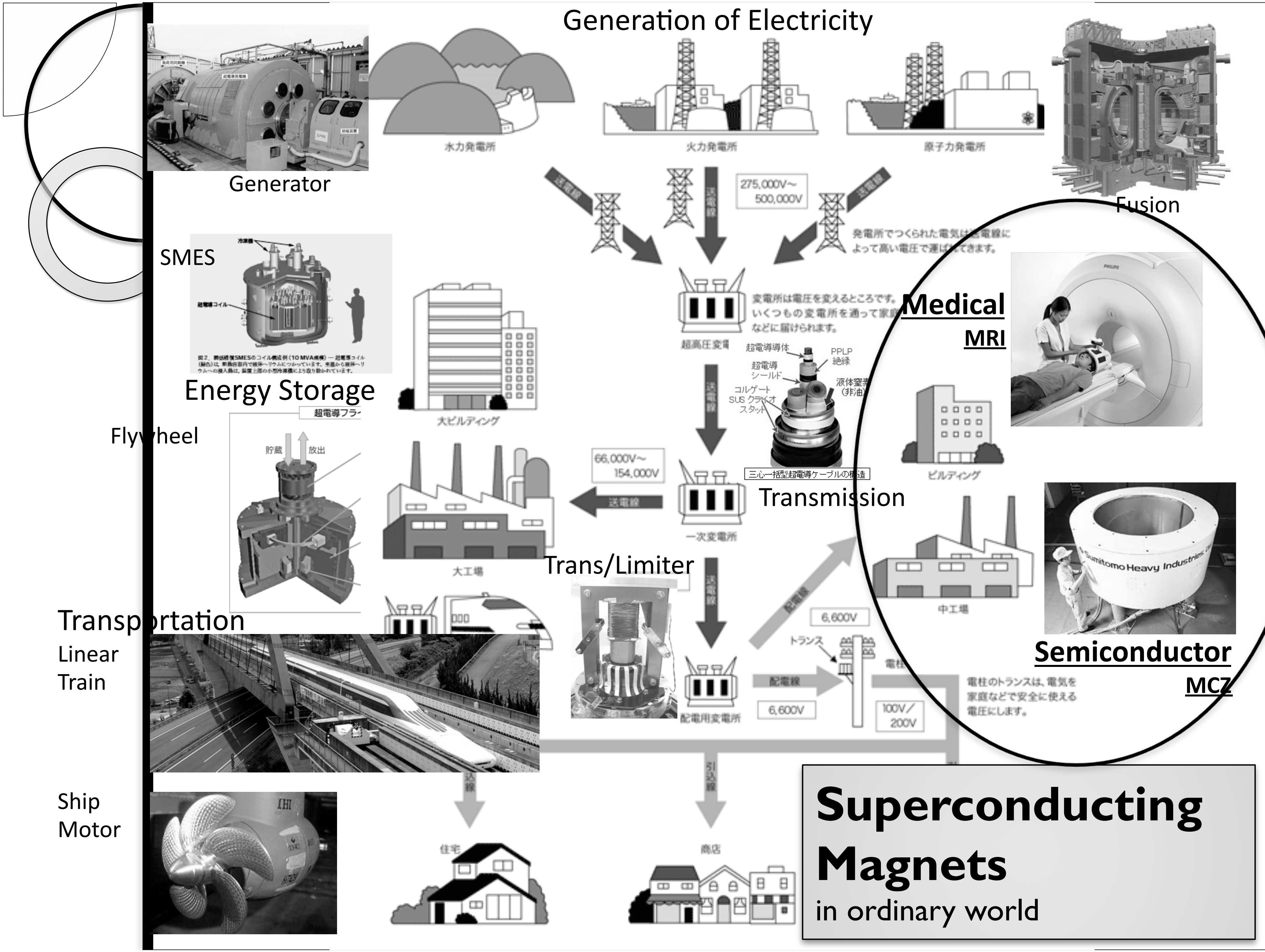
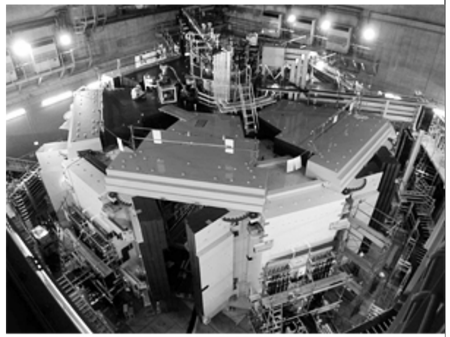
Introduction



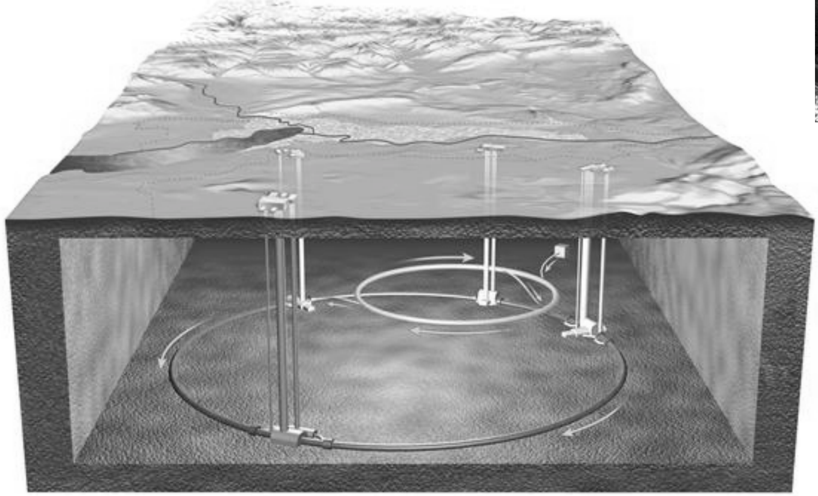
Generation of Electricity
Generator
水力発電所
火力発電所
原子力発電所
Fusion
275,000V～
500,000V
送電線
SMES
Energy Storage
Flywheel
大ビルディング
超高圧変電所
Medical
MRI
超電導導体
PPLP
絶縁
三心一括型超電導ケーブルの構造
ビルディング
66,000V～
154,000V
Transmission
一次変電所
大工場
Trans/Limiter
中工場
Semiconductor
MCZ
Sumitomo Heavy Industries
6,600V
配電線
トランス
配電用変電所
100V／
200V
Transportation
Linear
Train
Ship
Motor
IHI
住宅
商店
Superconducting
Magnets
in ordinary world

SC Magnets in Accelerators



Superconducting
Ring
Cyclotron
RIKEN
Japan

EU CERN/LHC

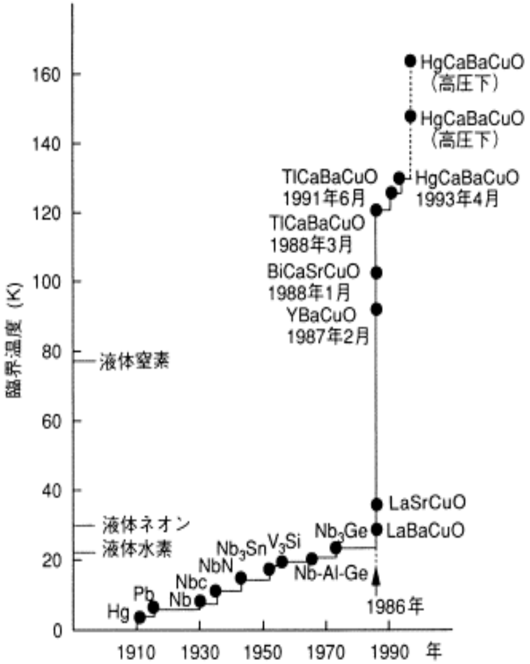


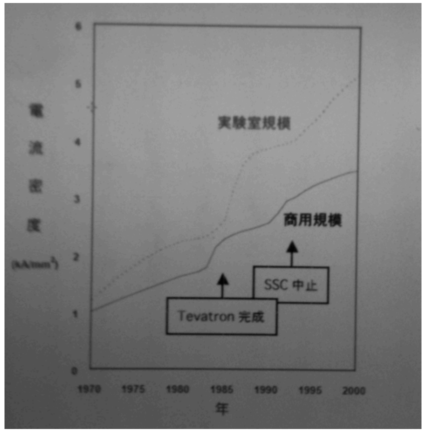
Japan
J-PARC
Neutrino
Beamline

USA FNAL/Tevatron

Advances of Superconductivity and Particle Accelerators

1908	Liquid Helium (K. Onnes)
1911	Superconductivity (Hg：K. Onnes)
1933	Meissner Effect (W.Meissner)
1957	BCS Theory (J.Bardeen L.Cooper J.Schrieffer)
1965	First International Symposium of Magnet Technology (SLAC)
1970	Industrialization of NbTi Composite Conductor
1977	**FNAL/Tevatron prototype magnet**
1979	**Industrialization of MRI Magnet**
1983	**FNAL/Tevatron: 6.3km (4.4T, 6.1m, 774)**
1986	High Tc Superconductor (K.Muller, J. Bednorz)
1988	SC Tokamak （TORE SUPRA）
1989	SC Cavity (KEK/TRISTAN)
1990~	Industrialization of MCZ Magnet
1992	DESY/HERA: 6.3km (4.7T, 8.8m, 416)
1993	SSC Cancel: 87.1km (6.6T, 15.8/13.3m, 7956/504)
1998	BNL/RHIC: 3.8km (3.5T, 9.7m, 288)
2001	MgB_2 (J.Akimitsu)
2008	CERN/LHC: 26.7km (8.3T, 14.2m, 1232)

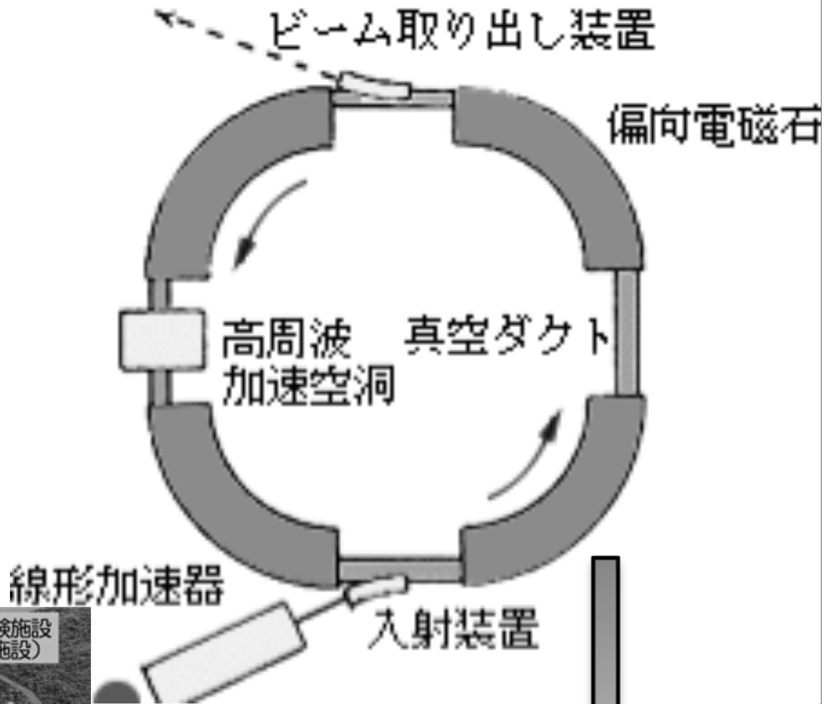


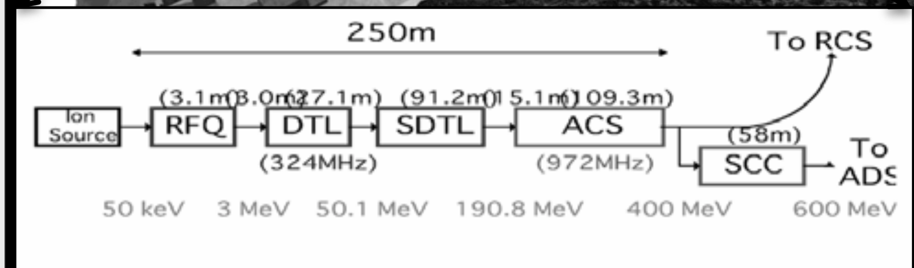


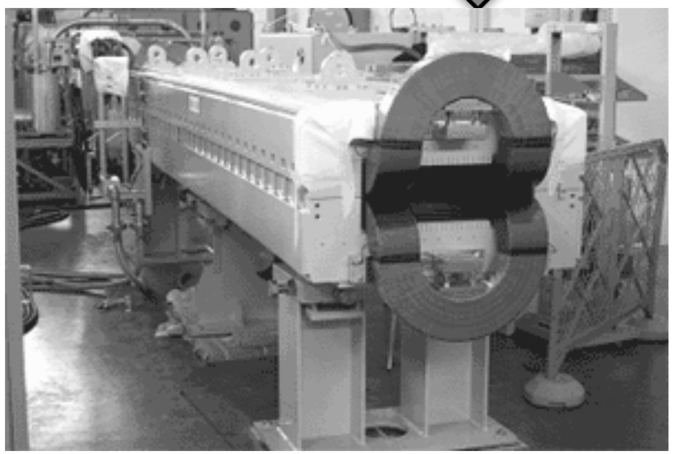
Synchrotron Magnets

Accelerator Magnets

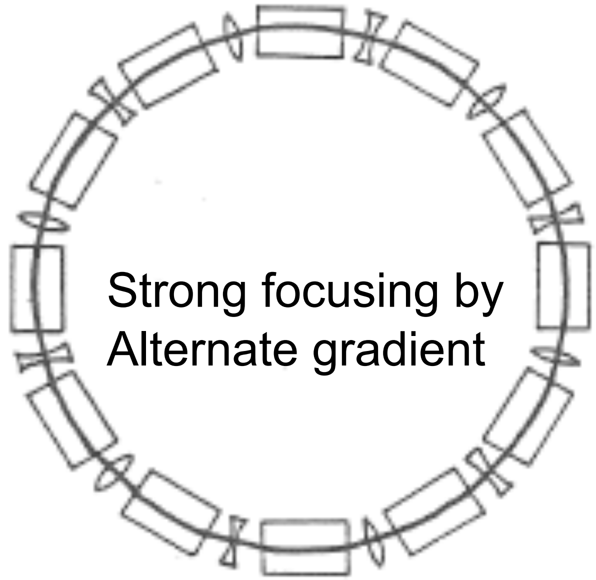
Magnet is used to make economical accelerator



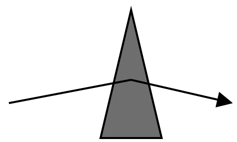


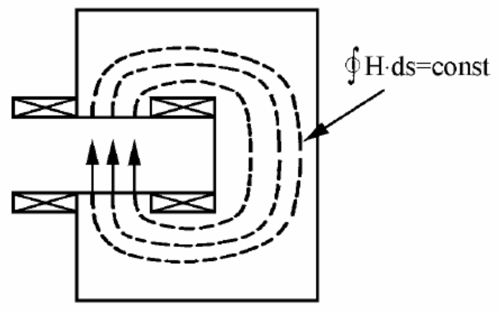


Magnets for Synchrotron

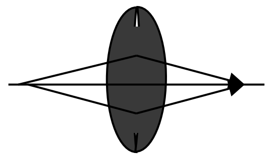


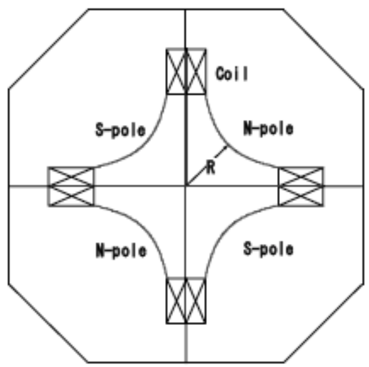
- Magnet
  - Transport beam in confined orbit
- Required Magnet
  - Bending
    - Dipole Magnet





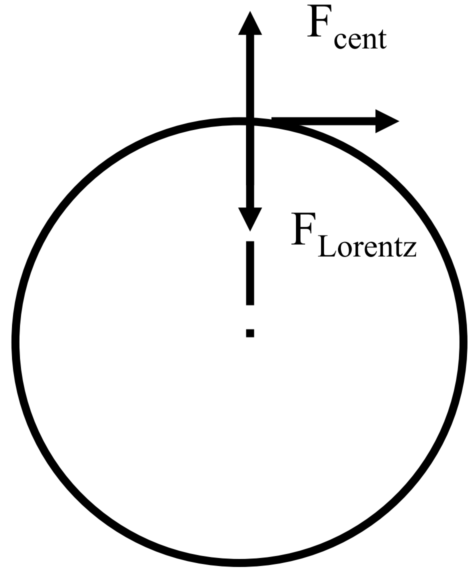
  - Focusing
    - Quadrupole Magnet



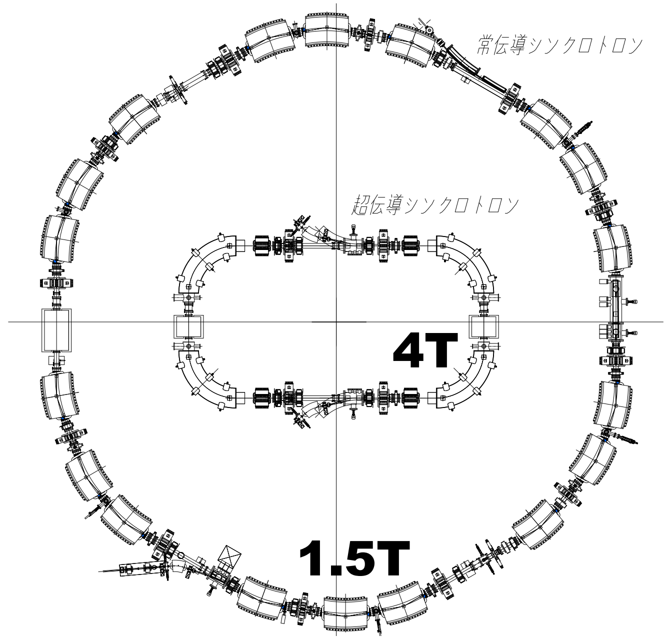


  - Correction
    - 6,8,10…pole magnet

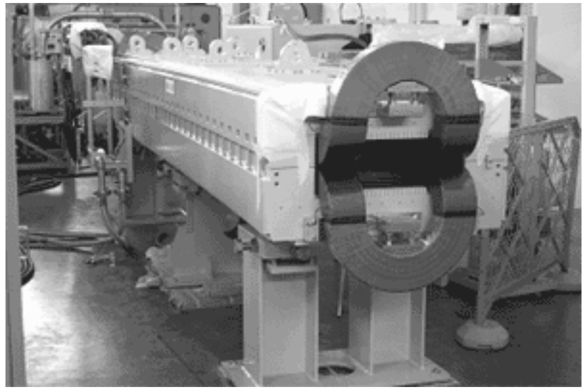
Why Superconducting Magnets
-High Field Magnets-



- **Beam orbit in Magnetic Field**
  - Lorentz Force
    - $\mathbf{F_{Lorentz} = q\ [E + (v \times B)]}$
  - Centrifugal Force
    - $\mathbf{F_{cent} = m \bullet v^2 / \rho \quad = p \bullet v / \rho}$
- **Beam Orbit**
  - $p \bullet v_\phi / \rho = q \bullet v_\phi \bullet B_y$ → $\mathbf{p = q \bullet B_y \bullet \rho}$
- **Toward Energy Frontier**
  - Larger Circumference
  - and/or Higher Field
- **High Field Magnet**
  - Normal Conducting Magnet
    - Current Density Limitation < 10 A/mm^2
    - Iron Yoke is inevitable
    - Saturation of Iron <2 Tesla
  - Superconducting Magnet
    - Coil Current Density < 500 A/mm^2
    - Field creation by current distribution
    - Tevatron 4.5 Tesla
    - LHC 8.4 Tesla



Why Superconducting Magnet -Power Consumption-



- Normal Conducting Magnet
  - to produce Magnetic Field
    - $B \sim \mu_0 NI/g$ (*NI*: Coil Ampere Turn, *g*: Iron Gap)
  - Power Consumption
    - $P = \rho i(NI)L \sim \rho iBLg/\mu_0$ (*i*: Current Density, *L*: Conductor Length / turn)
      - 0.1(gap)*0.2(width)*1(length)m & 1.5T ~ 45kW (@ 10A/mm^2)
  - **~30 kW/ Tm (@ 10cm aperture)**

- Superconducting Magnet
  - power for refrigerator
    - Heat load to cryo-mass * 1000~2000
  - **~1 kW/Tm (@ 4.2K 4T)**
- **S** is **an order** better than **N**

Two dimensional field and multipole

- **Synchrotron Magnets**
  - Straight section ~ 2D
  - End; integral field –> 2D
- **Maxell Eq.**
  - **div B** = 0, **rot B** = μ_0 J
  - @ J = 0
  - **div B** = 0, **rot B** = 0
- **Potentials, A, Φ**
  - **B = rot A**, **B** = -grad Φ
  - with 2D assumption
  - $dA_x/dz = dA_y/dz = d\Phi/dz = 0$

    $Bx = dA_z/dy = - d\Phi/dx$

    $By = - dA_z/dx = - d\Phi/dy$

    $Bz = - d\Phi/dz = 0$

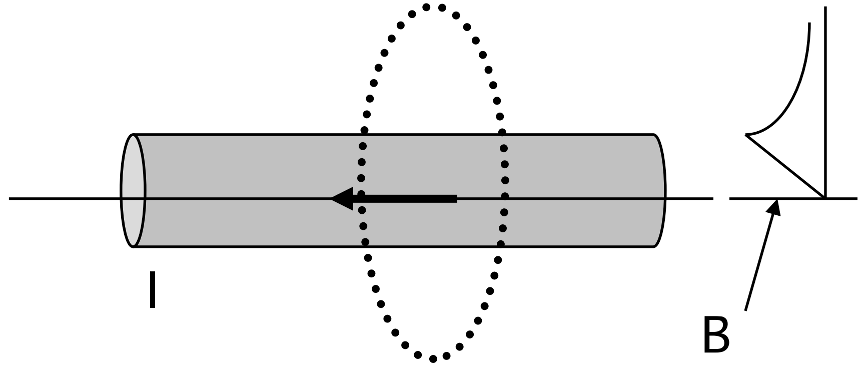
- Az, Φ: Cauchy-Riemann
  - $\mathbf{F}(\mathbf{z}) = A_z(x,y) + i\,\Phi(x,y)$
  - $\mathbf{F}(\mathbf{z}) = \Sigma\, \mathbf{c_n}\, (x + iy)^{\mathbf{n}}$
  - $d\mathbf{F}(\mathbf{z})/d\mathbf{z} = -B_y - iB_x$

  → $\mathbf{B} = B_y + i\,B_x = -\Sigma\, n \bullet \mathbf{c}_n \bullet \mathbf{z}^{n-1}$
- $-n \bullet c_n = \mathbf{C}_n = B_n + iA_n$

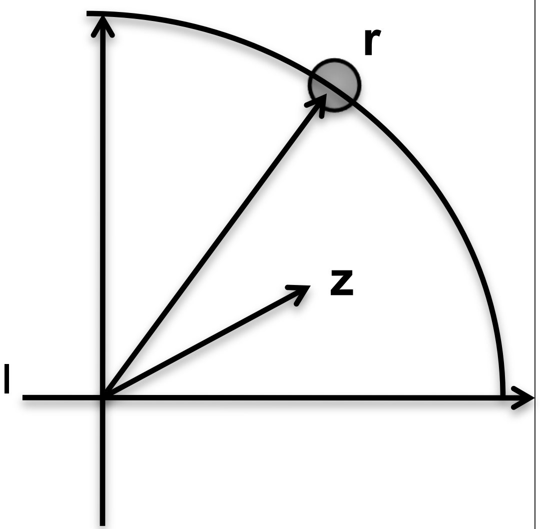
$$\mathbf{B} = \sum_{n=1}^{\infty} \mathbf{C}_n \mathbf{z}^{n-1} = \sum_{n=1}^{\infty} (B_n + iA_n)\mathbf{z}^{n-1}$$

  - Bn: normal 2 n-pole
  - An: skew 2 n-pole

Current Line with Infinite Length

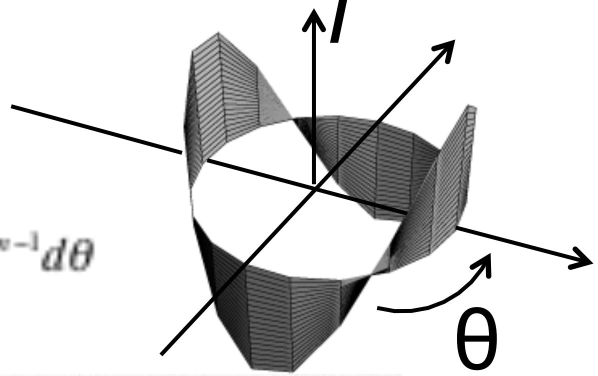


- Maxell EQ.
  - rot B = $\mu_0 \cdot J$
- In side (r<a)
  - $2\pi r B = \mu_0 \pi r^2 J$
  - $B_r = (1/2) \cdot \mu_0 \cdot r \cdot J$
- Out side (r>a)
  - $2\pi r B_r = \mu_0 \pi a^2 J$
  - $B_r = (1/2) \cdot \mu_0 \cdot a^2 \cdot J \cdot 1/r = (\mu_0/2\pi r) \cdot I$
- current@$\mathbf{r}=r_x+ir_y$; $z=x+iy$; $|\mathbf{r}|>|\mathbf{z}|$
  - $\mathbf{B}(\mathbf{z}) = \mu_0 I/2\pi(\mathbf{z}-\mathbf{r}) = \Sigma -\mu_0 I/2\pi\mathbf{r}\ (\mathbf{z}/\mathbf{r})^{n-1}$



How to make field for accelerator

- Cos θ Magnets



$$I(r,\theta) = I_0\cos(m\theta)$$

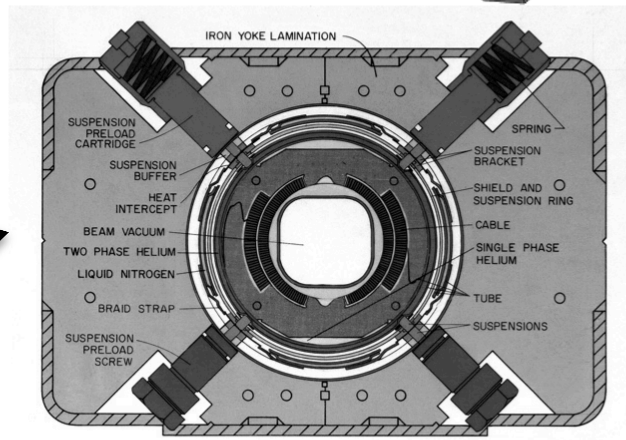
$$\mathbf{B}(\mathbf{z}) = \int_{\theta=0}^{2\pi}\sum_{n=1}^{\infty} -\frac{\mu_0 I_0\cos(m\theta)}{2\pi} r^{-n}[\cos(n\theta) - i\sin(n\theta)]\mathbf{z}^{n-1}d\theta$$

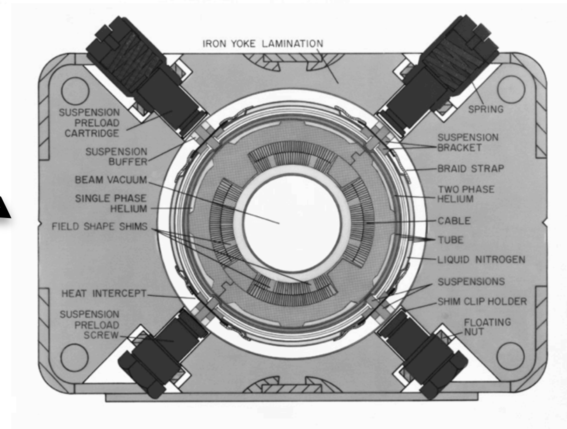
$$= \begin{cases} 0 & n \neq m \\ -\frac{\mu_0 I_0}{2r^n}\mathbf{z}^{n-1} & n = m \end{cases}$$

n = 1: dipole

n = 2: quadrupole

n = 3: sextupole





Biggest requirement:

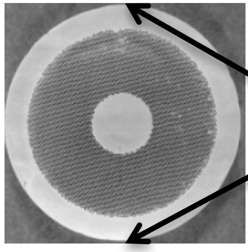
Field Quality: 10^{-4}

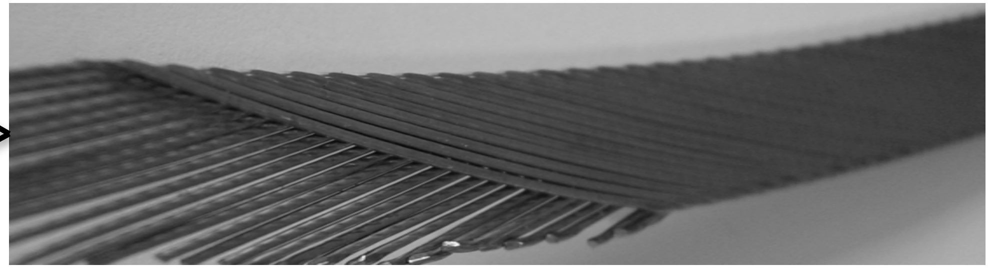
Construction Accuracy: 50 μm

Various Ele-Mag effects

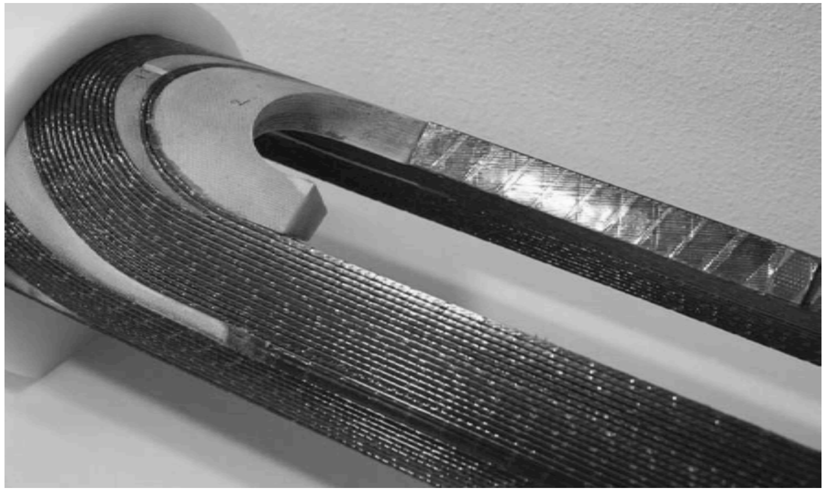
SC Accelerator Magnet
Coil Structure

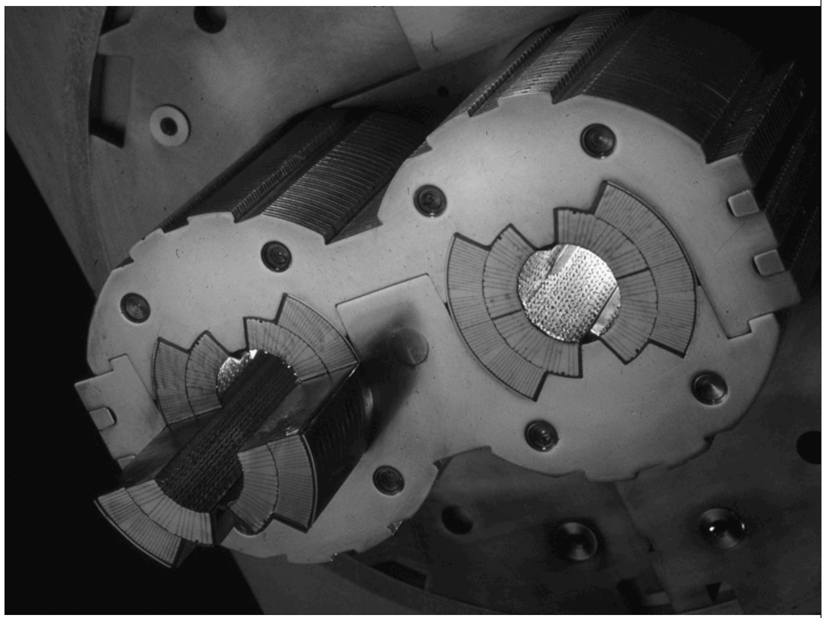
- Rutherford Cable





- Saddle Shape Coil





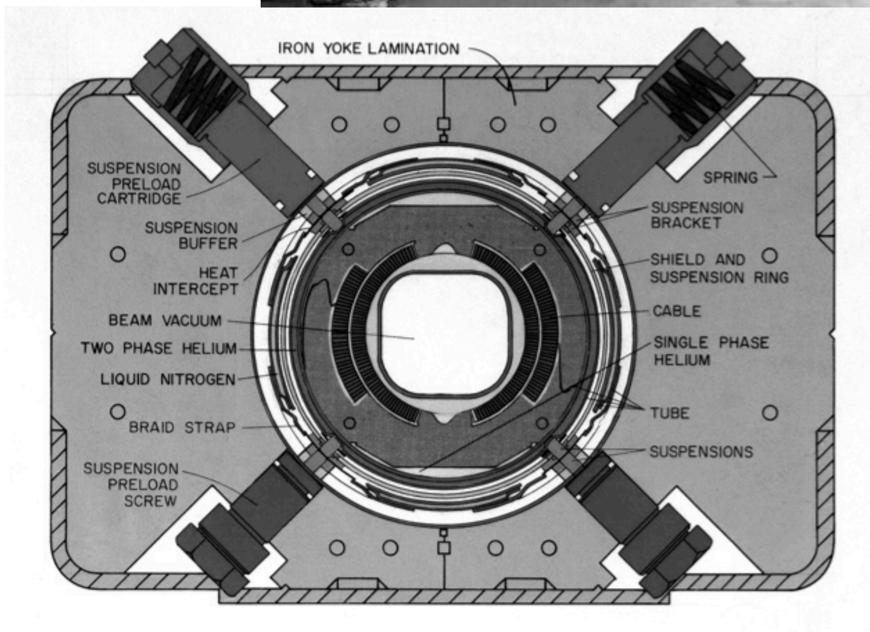
- Collared Coil Structure

SCM Accererators
Tevatron

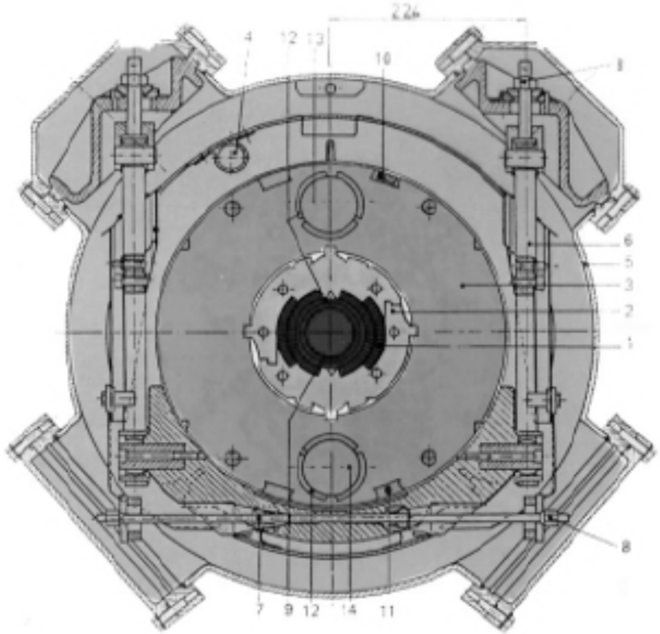
- Energy Doubler (1TeV)
  - Higher Field Magnet 4.4T
- Energy Saver
  - ~1/2 Overall Power Saving

Tunnel is given (main ring)
SCMs are installed in the same tunnel
main ring (normal conducting) is used as injector, but reduce energy from 400 GeV to 150 GeV
Overall energy saving ~ ½

Warm Iron Magnet
Mis-alignment of iron to coil
= unwanted field harmonics



SCM Accererators
HERA



HERA Dipole
Cold Iron to eliminate
iron-coil mis-alignment

Aerial View of DESY

HERA Tunnel

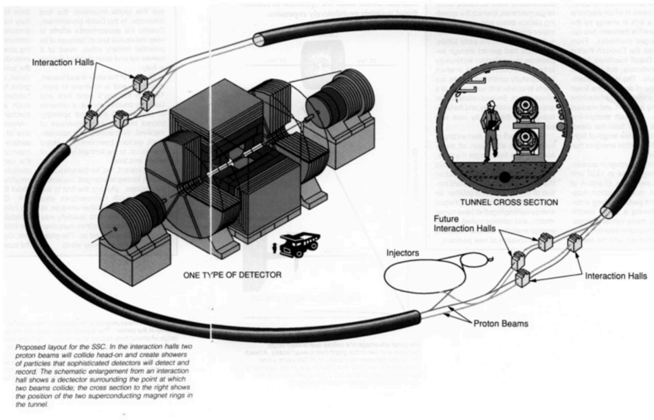
Superconducting p-Ring

Normal e-Ring

"The p-ring was easier to maintain, because no water in tunnel"
Holger Lierl@DESY

SCM Accererators

Superconducting Super Collider

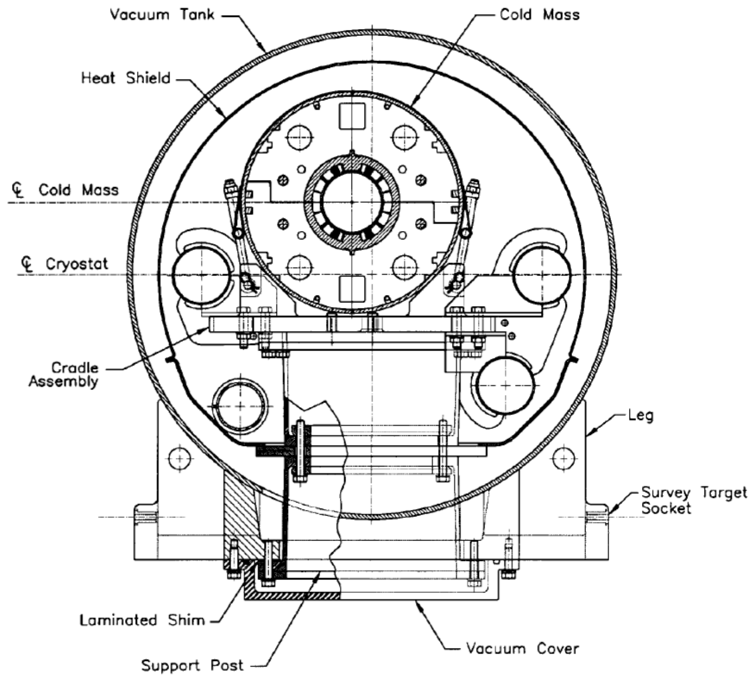


- Try to reach high energy: 20 TeV
  - Huge Circumference 87.1 km
  - High Field 6.6 T

Cancel by 1993
Fail to control cost
4.4B$→~12B$
2B$ already invested

SCM Acererators RHIC

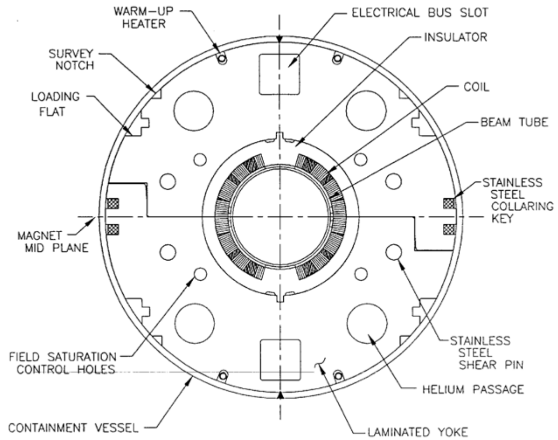
- Given tunnel 3.8 km
- Medium field 3.5 T



Yoke Collar Structure
Plastic Collar
Low Cost

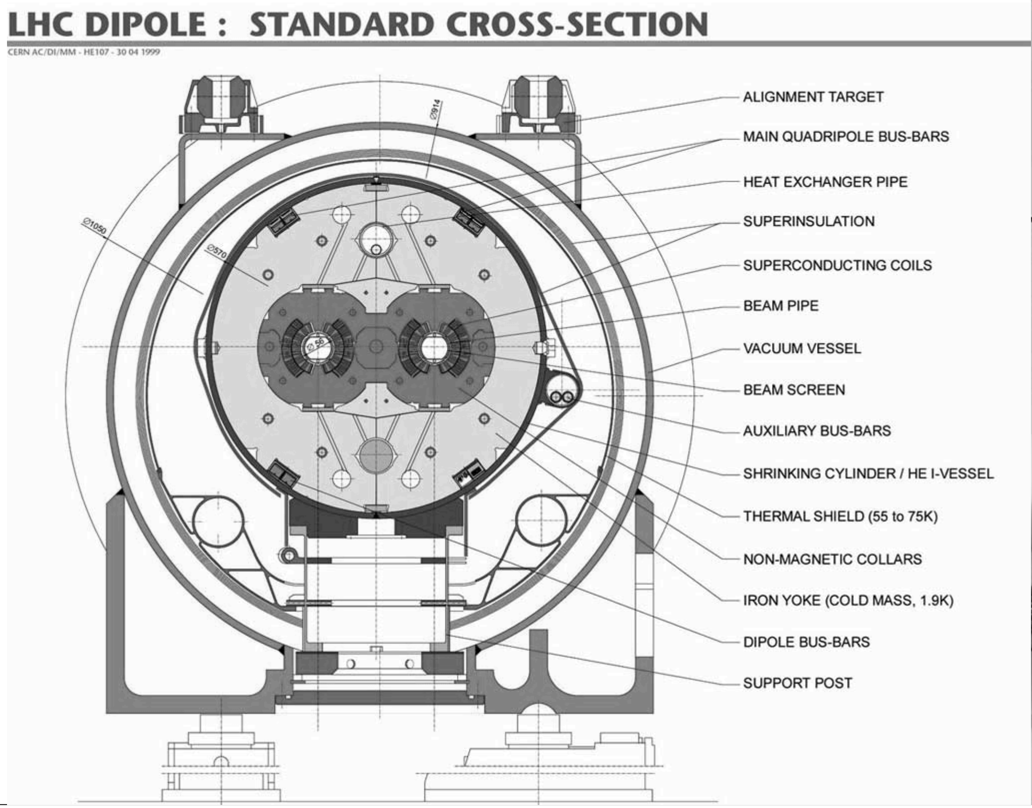
BNL Aerial View

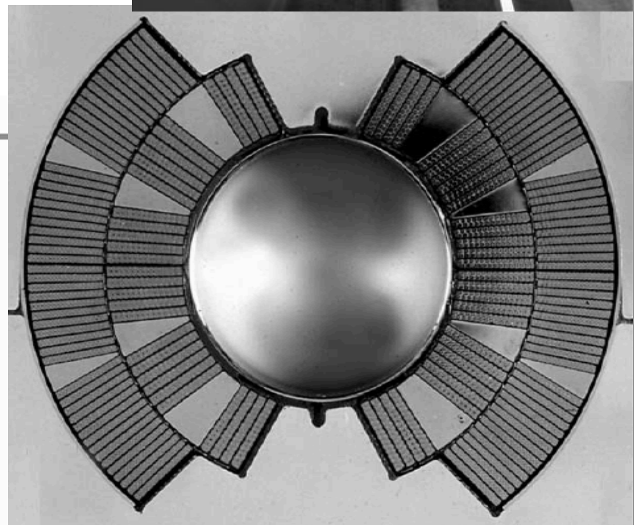
RHIC Tunnel

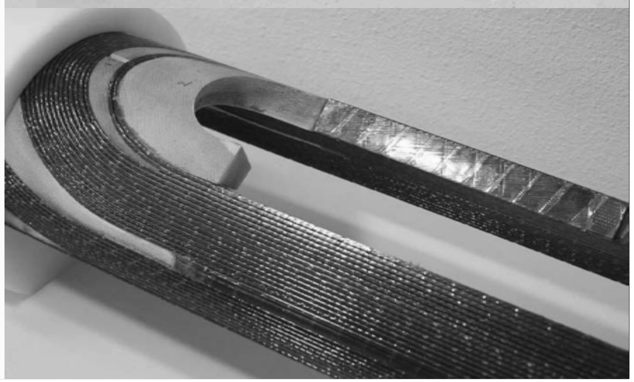


SCM Accererators
Large Hadron Collider

- Try to reach high energy 7 TeV
  - with given tunnel (LEP 26.7 km)
  - with very high field 8.3 T

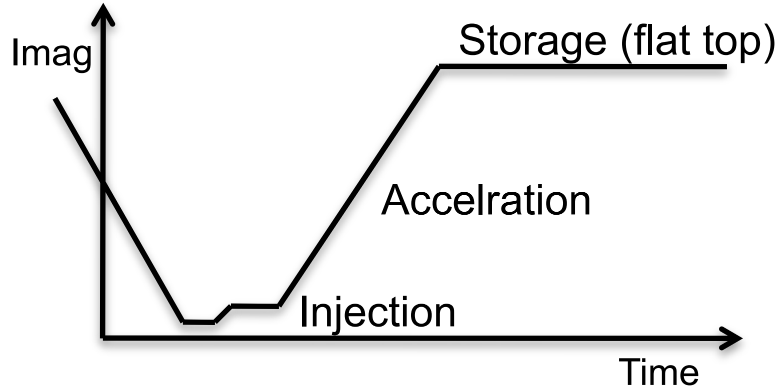




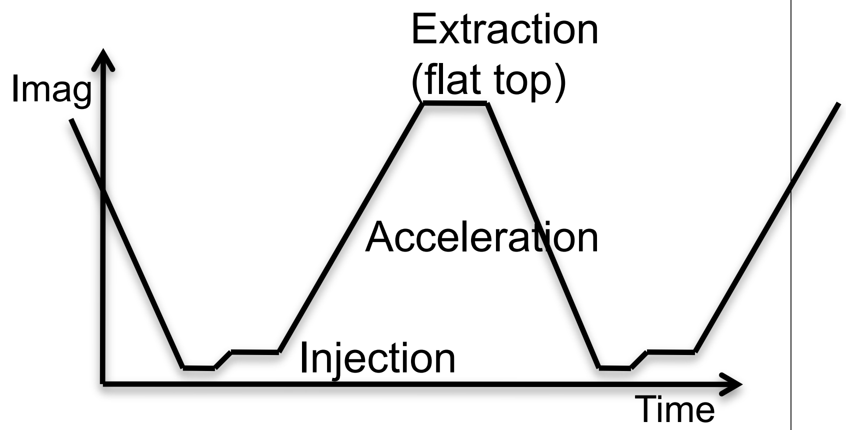


Synchrotron Operation

- Storage Ring
  - Collider, Photon Factory
  - Slow Operation Cycle



- Extraction Machine
  - Injector, Fixed Target
  - Fast Operation Cycle



Field Quality of SC Magnet during operation cycle I

- Superconductor Magnetization
  - Hysteresis
  - Allowed pole
    - 6, 10, ...

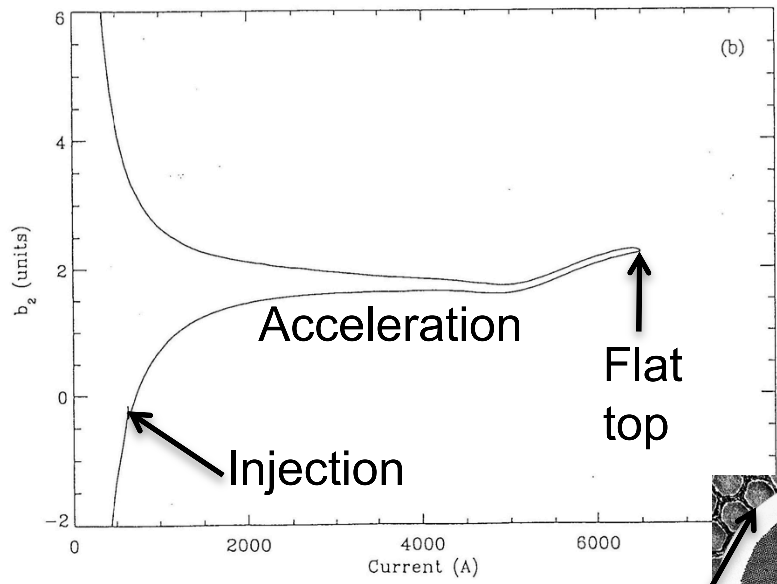
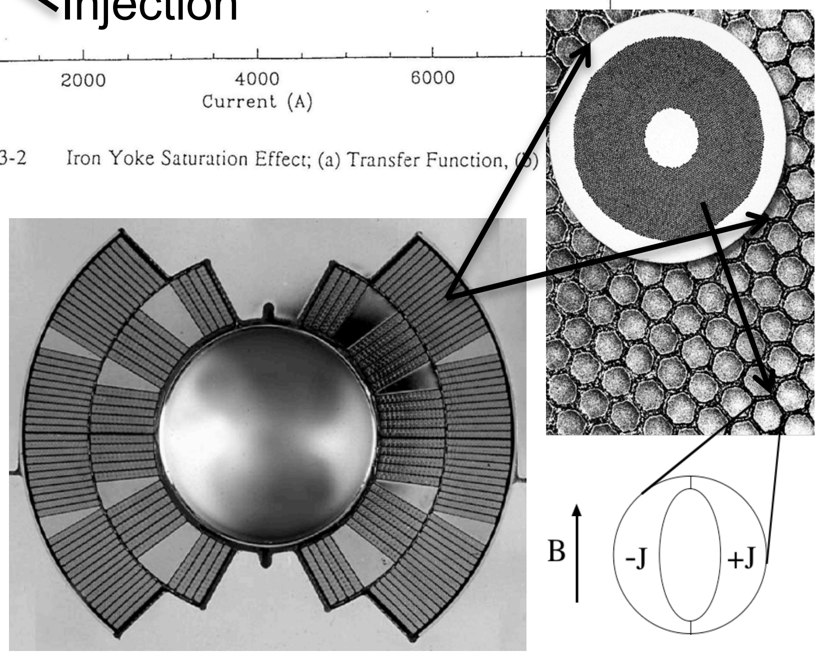


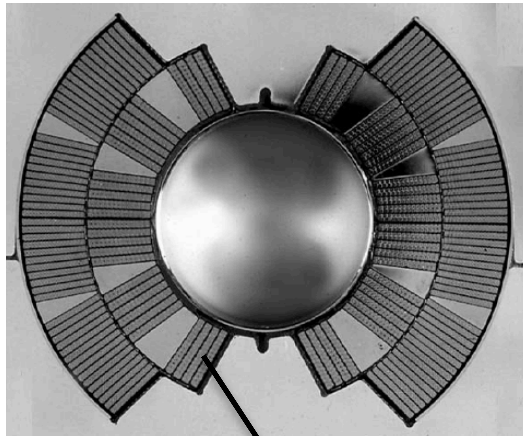
Figure 3-2 Iron Yoke Saturation Effect; (a) Transfer Function, (b)

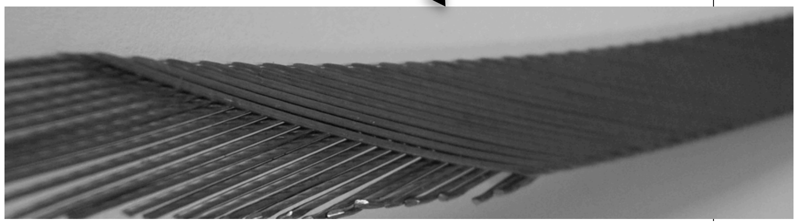
- Observation
  - Found in TEVATRON
  - Confirmation by Computation at HERA

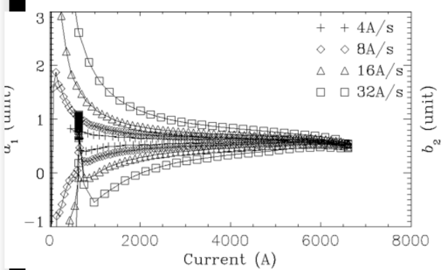


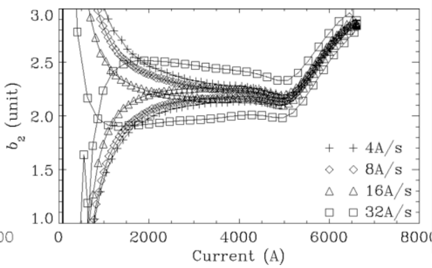
Field Quality of SC Magnet during operation cycle 2

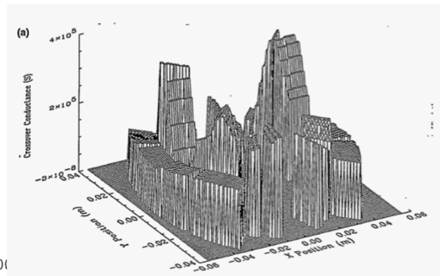
- Cable Coupling Current
  - Current ramp dependence
  - Un-allowed pole
- Observation
  - SSC dipole
    - Confirmed by
      - Computation model
      - Inter-strand resistance measurement
      - Quench localization by quench antenna

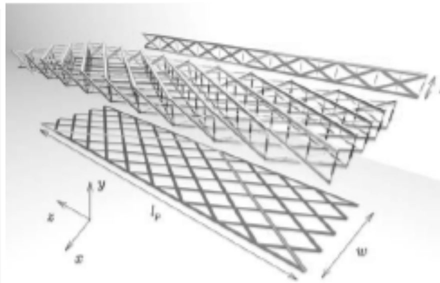






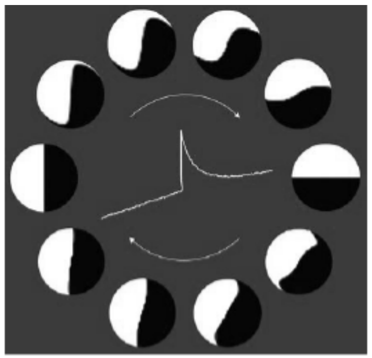






Field Quality of SC Magnet during operation cycle 3

- Superconductor Magnetization time decay at injection
- Observation
  - Time decay found in TEVATRON
  - Current redistribution in cable strand found in HERA
  - Full simulation by CERN (LHC)



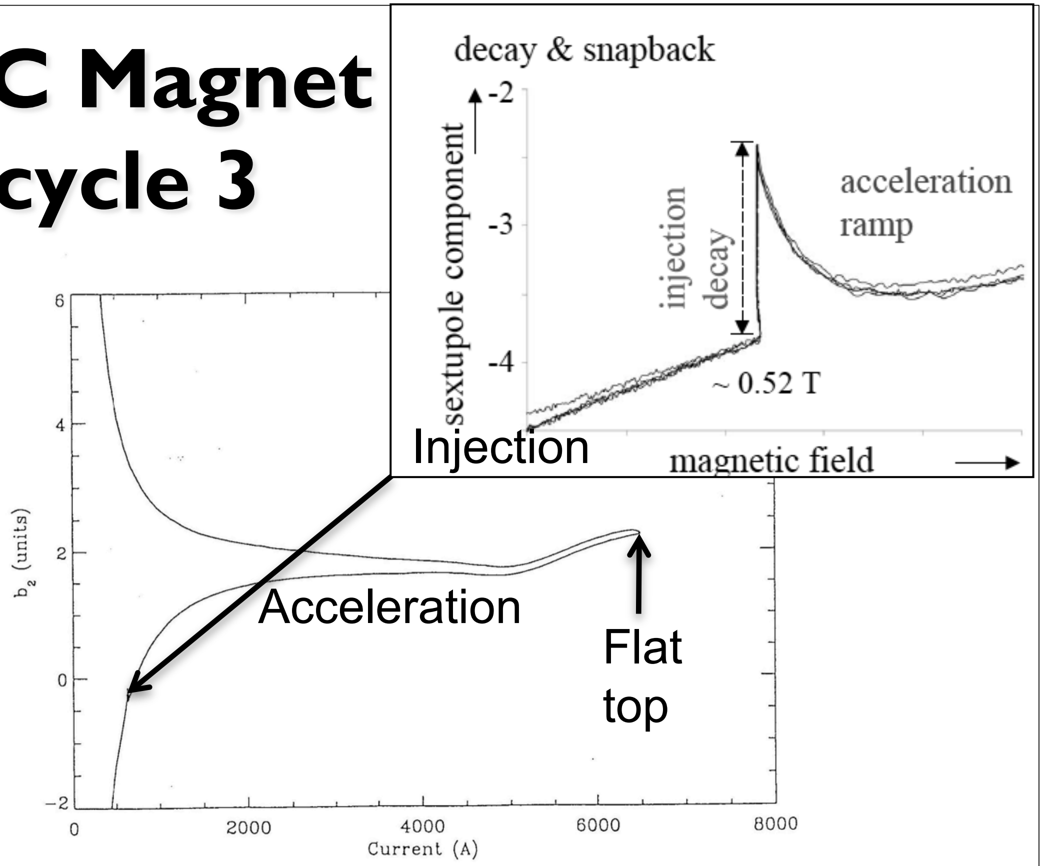
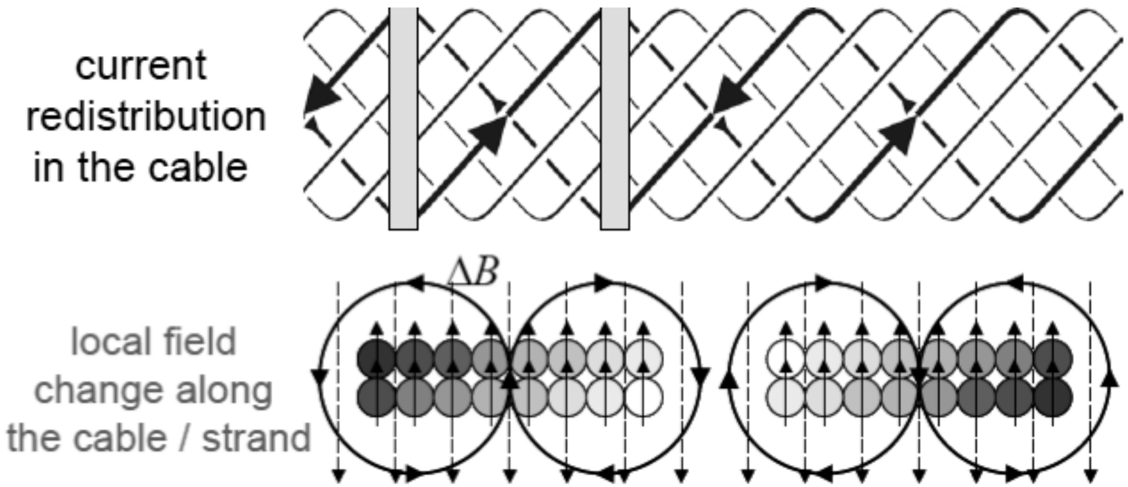


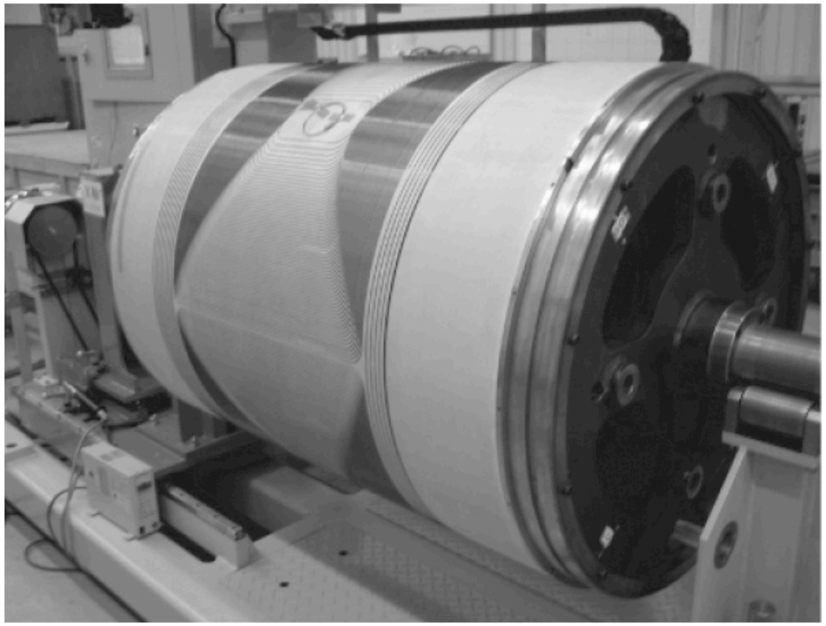
Figure 3-2 Iron Yoke Saturation Effect; (a) Transfer Function, (b) b_2



SC Synchrotron Magnets

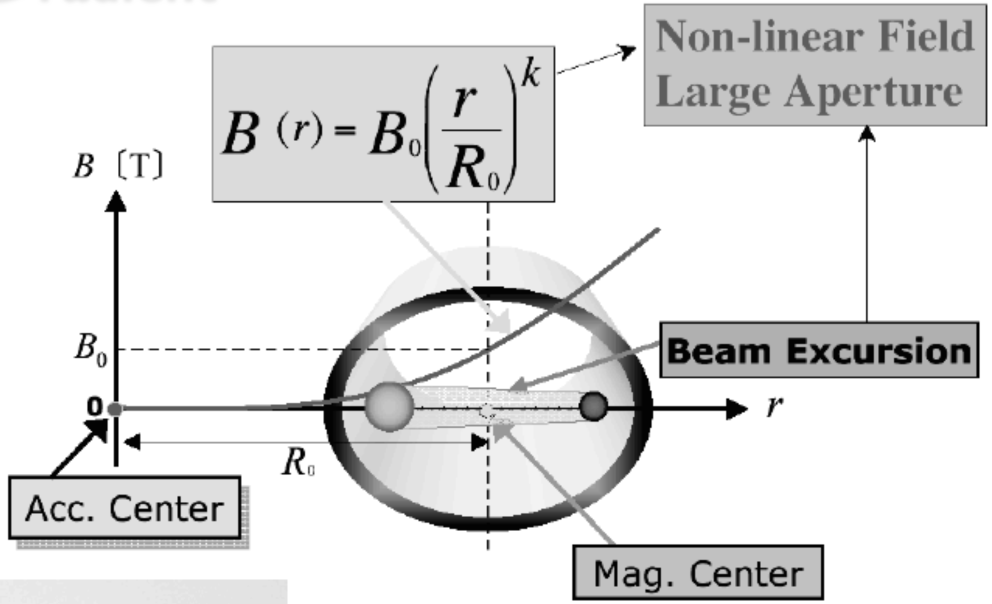
- Developed extensively for large colliders
- Long history of fighting against various electro-magnetic effects associated with operation cycle
  - limit field quality to 10-4 level
  - AC loss issues
- In DC SC Magnet such as MRI
  - very high field quality sub-ppm
  - very low loss GM cryo-cooler refrigeration
- Preference: DC accelerator magnets

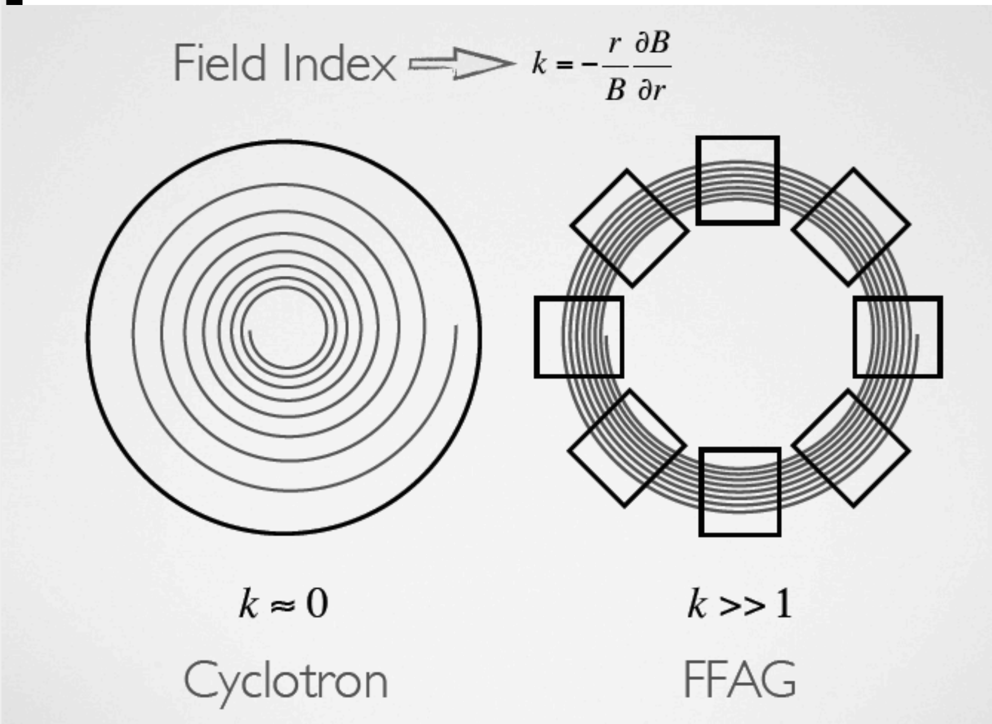
FFAG Magnets



FixedFieldAlternateGradient

- DC Magnet
- Strong focusing





- DC operation
- Big aperture
  - than synchrotron
  - smaller than cyclotron
- Fits to superconducting magnet application

What to do with FFAG field?

What about combination of multipole fields

$$B = B_0\left(\frac{r}{R_0}\right)^k = B_0\left(\frac{R_0 + x}{R_0}\right)^k$$

$$= B_0\left\{1 + r_0\frac{k}{R_0}\frac{x}{r_0} + r_0^2\frac{k\,(k-1)}{2!R_0^2}\left(\frac{x}{r_0}\right)^2 + \cdots\right\}$$

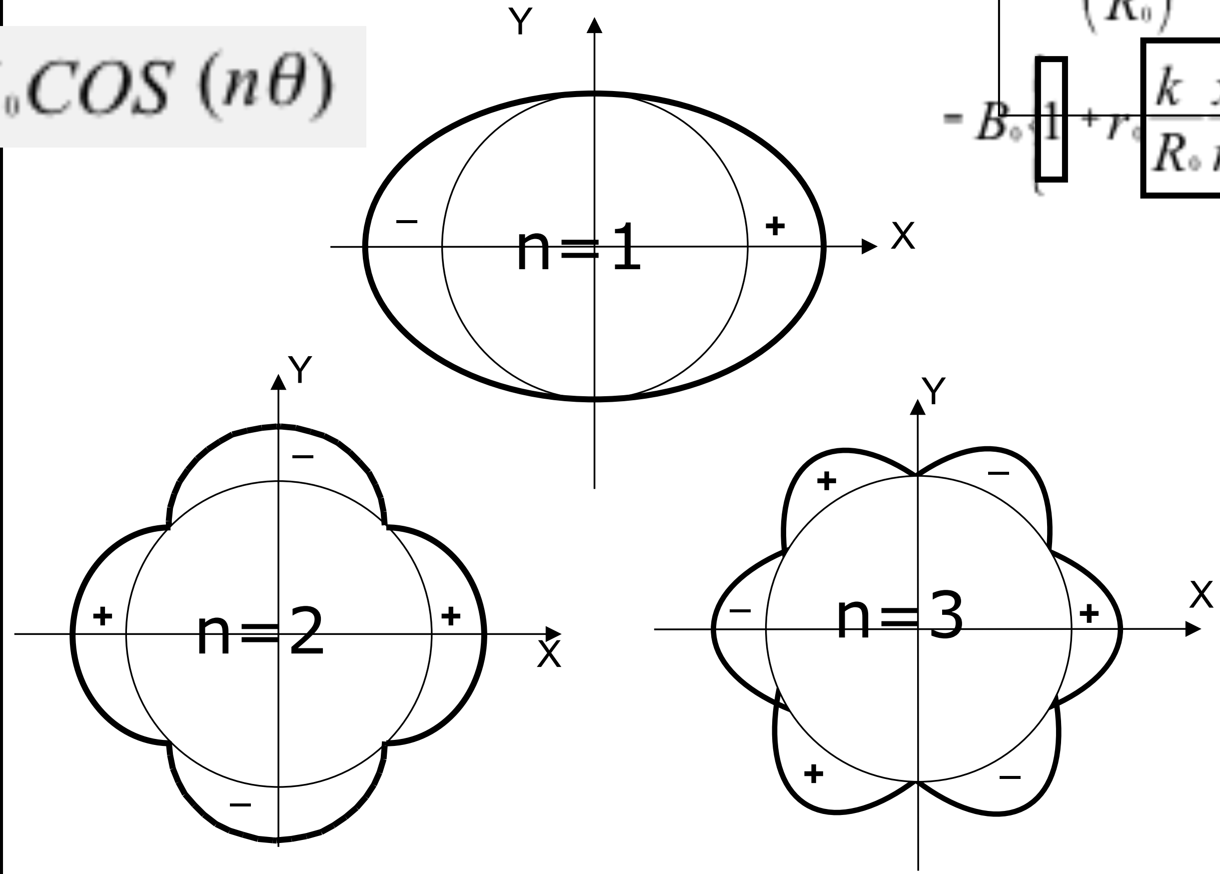
qualification of the field quality: local-k

$$local\_k = \frac{\Delta B}{\Delta r}\frac{r}{B}$$

Current distribution

$$I = I_0 COS\,(n\theta)$$

$$B = B_0\left(\frac{r}{R_0}\right)^k = B_0\left\{1 + r_0\frac{k}{R_0}\frac{x}{r_0} + r_0^2\frac{k\,(k-1)}{2!R_0^2}\left(\frac{x}{r_0}\right)^2 + \cdots\right\}$$



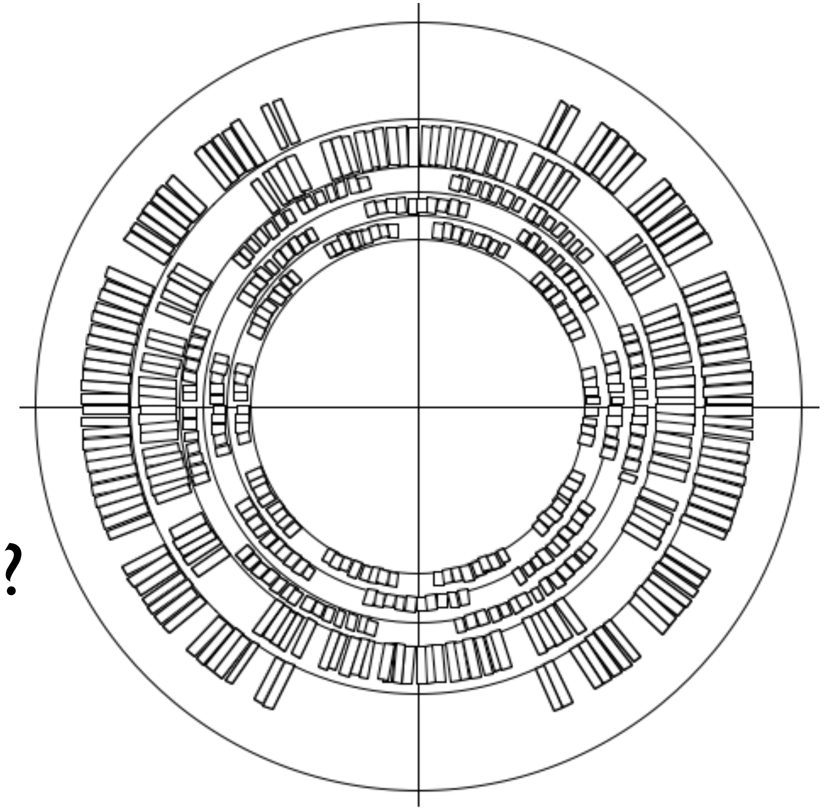
n=4
and more…

Multi layer coil?

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

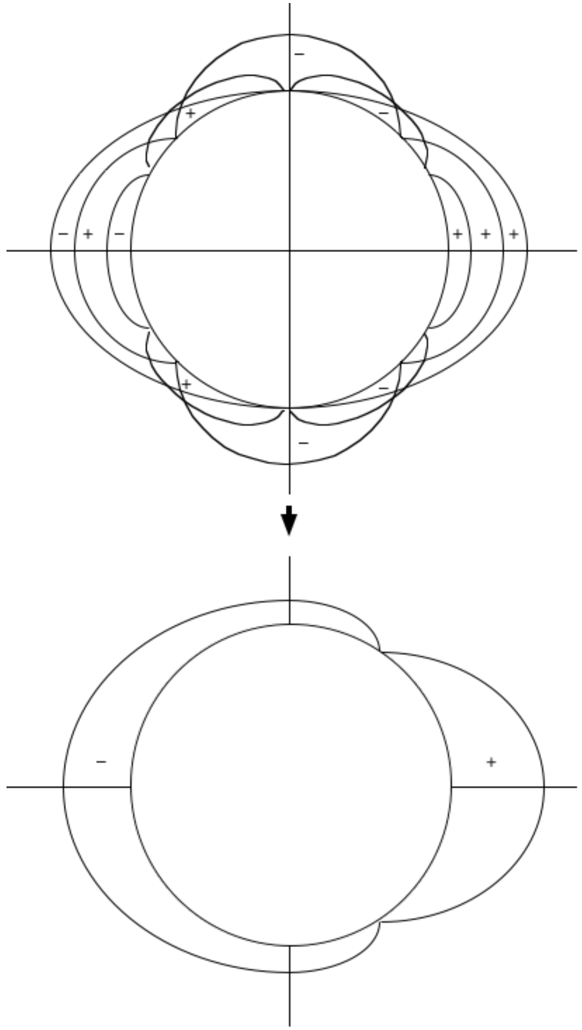
⇓

Sum of all cosine theta current

⇓

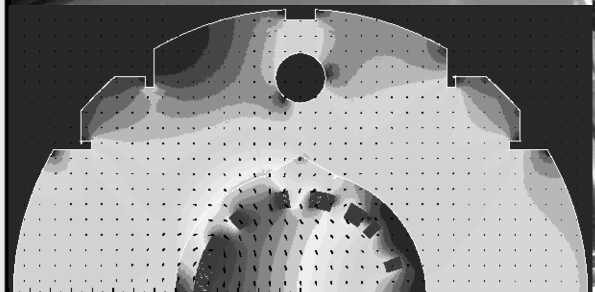
Asymmetric Coil

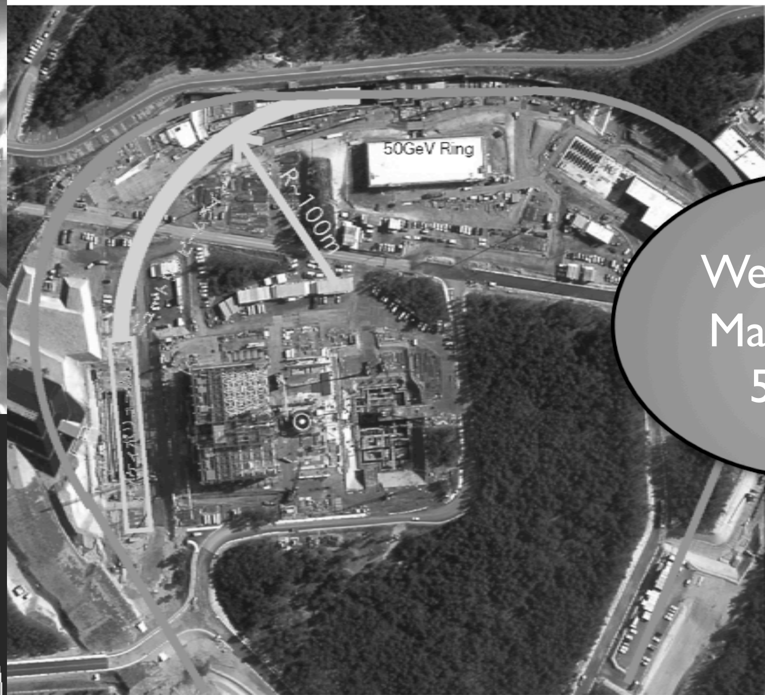
Need R&D!



SCM Beam Line
Neutrino Beam Line at J-PARC

- Space for tunnel is limited
- needed to accommodate 50 GeV

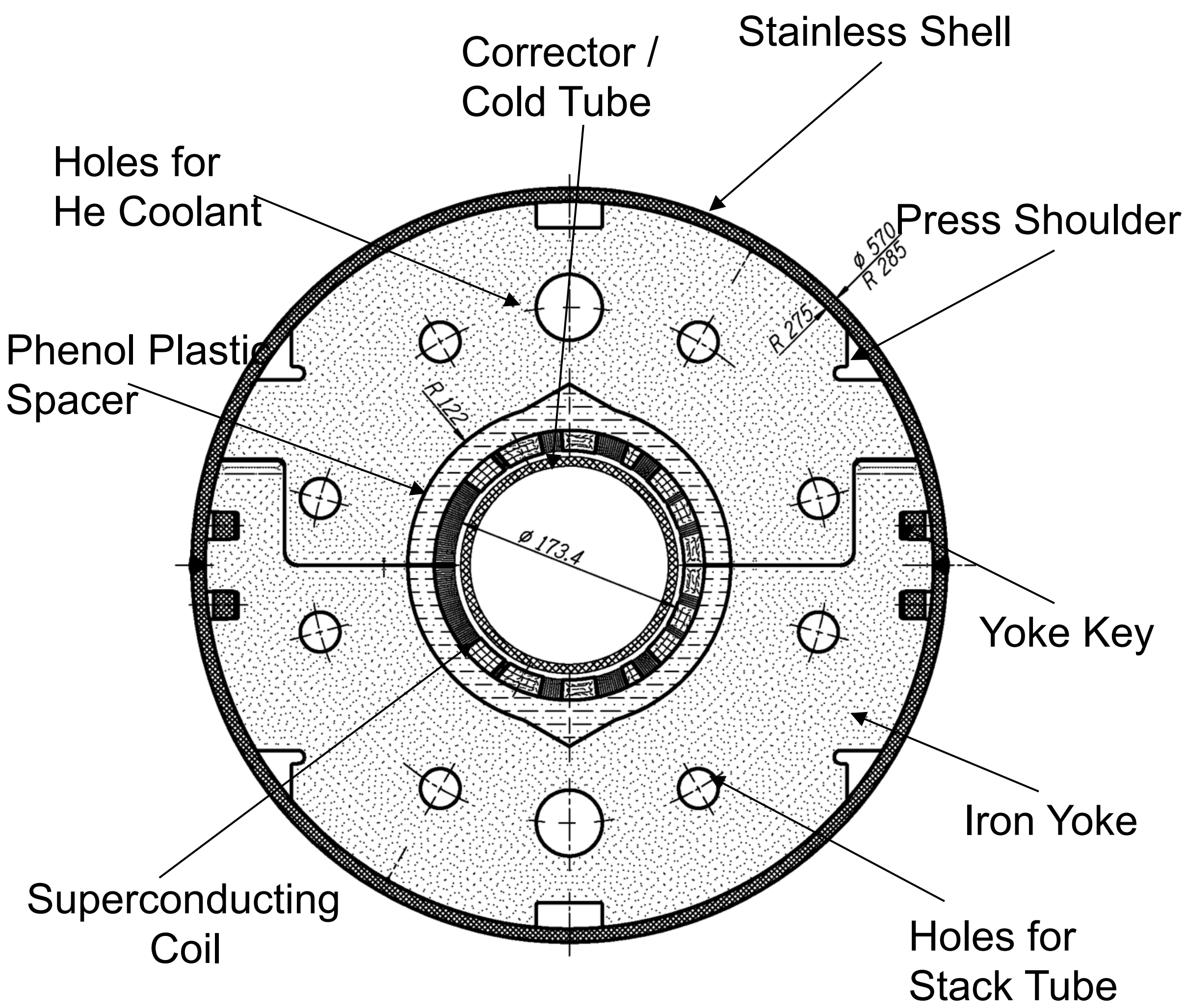




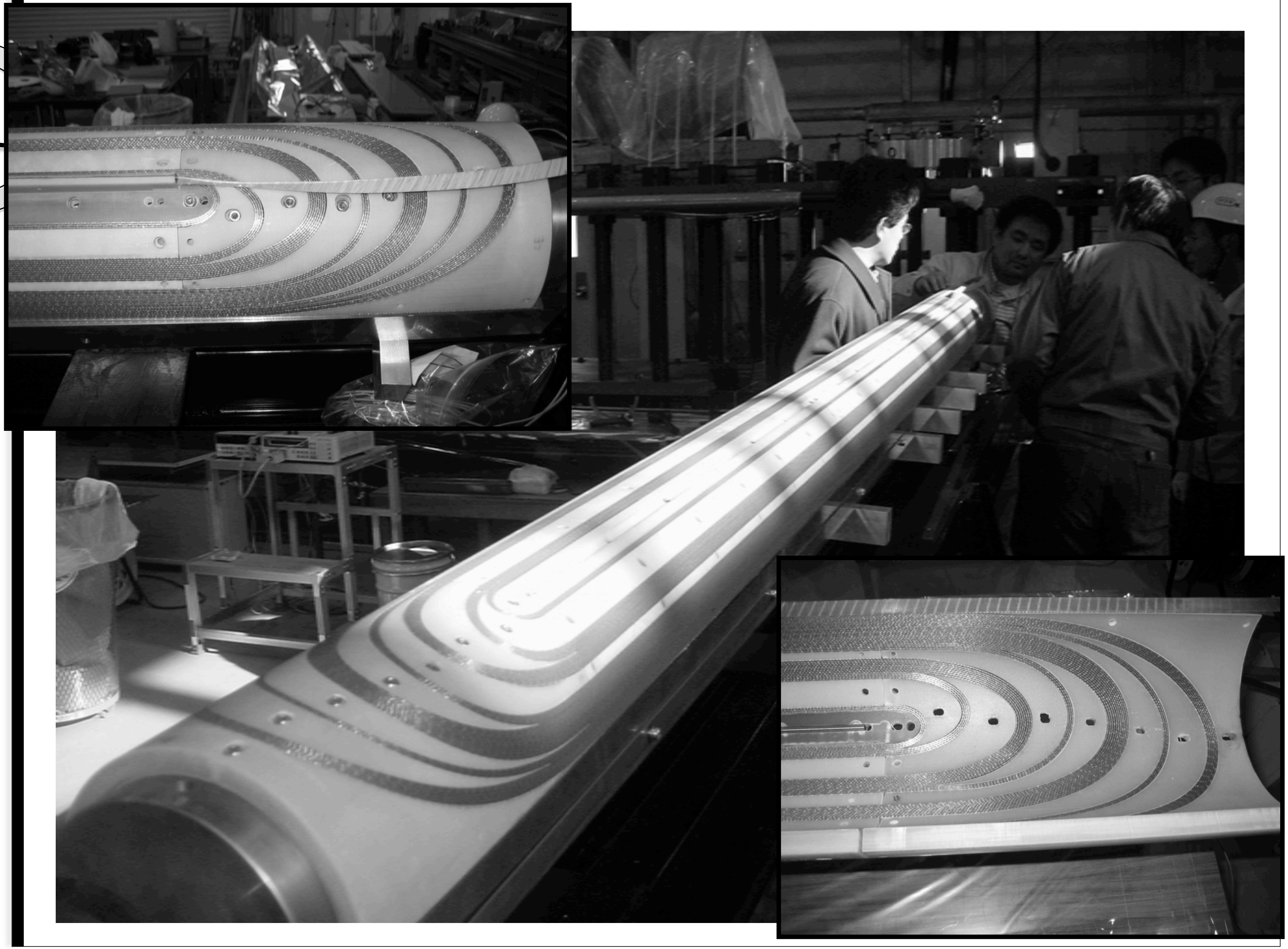
SC Combined Function Magnet for cost saver
(Structure similar to RHIC, LHC common parts, etc)

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**



The Asymetric Coil



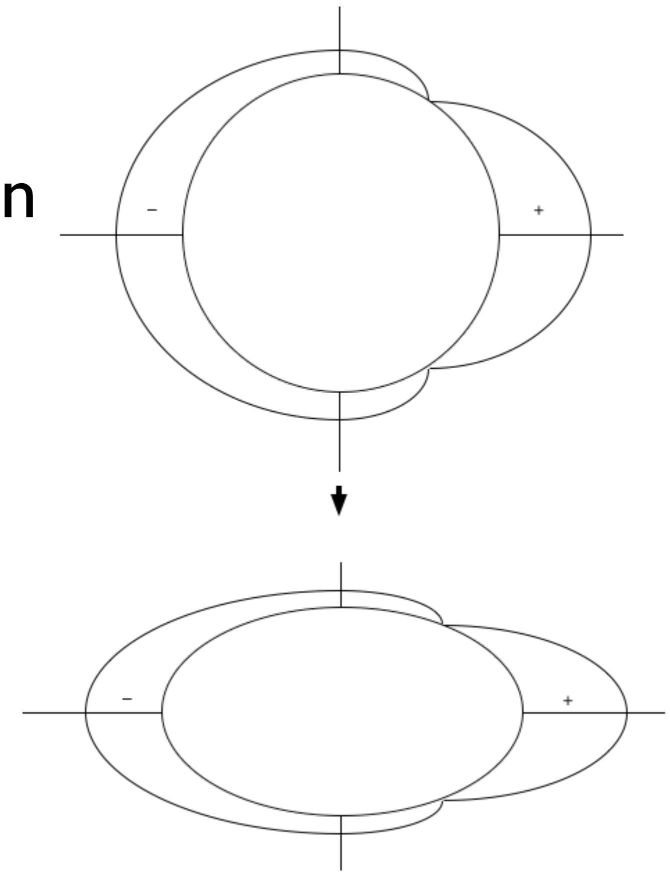
Elliptic Structure

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

⇓

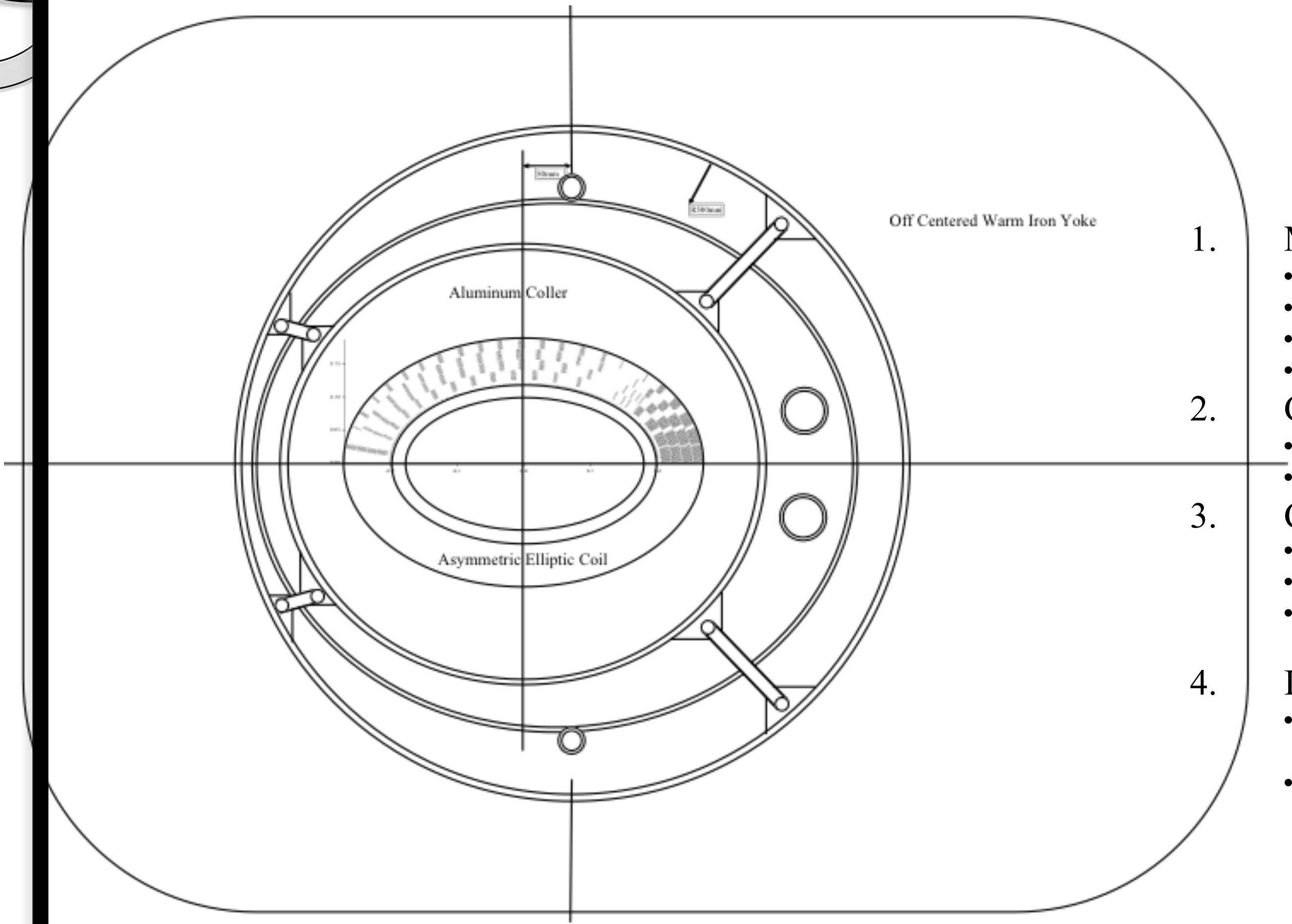
Elliptic Structure

Need more R&D



FFAG Reference Design

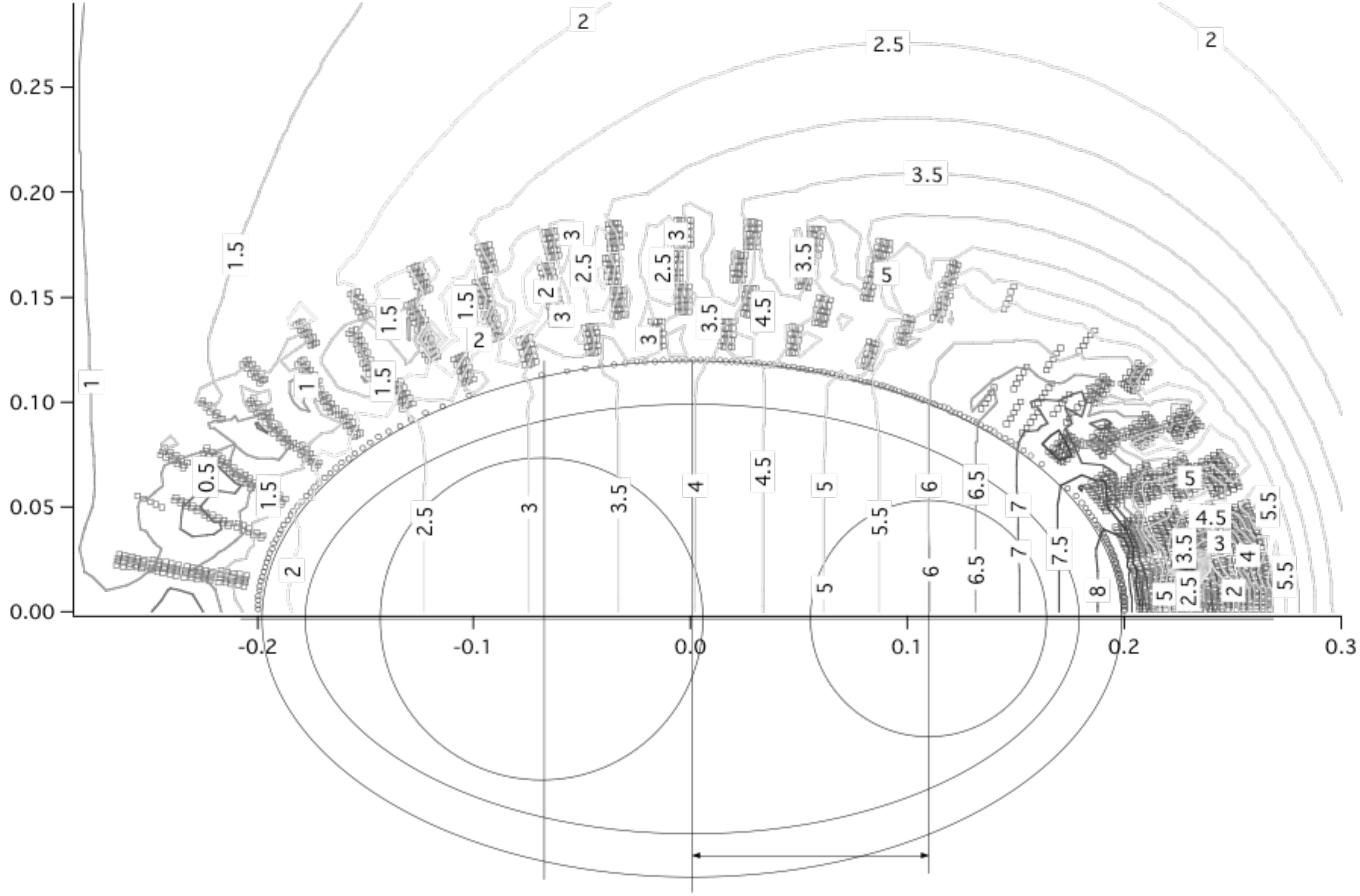
- B_0=6.0T, r_0=120m, k=450, beam excursion 0.18m



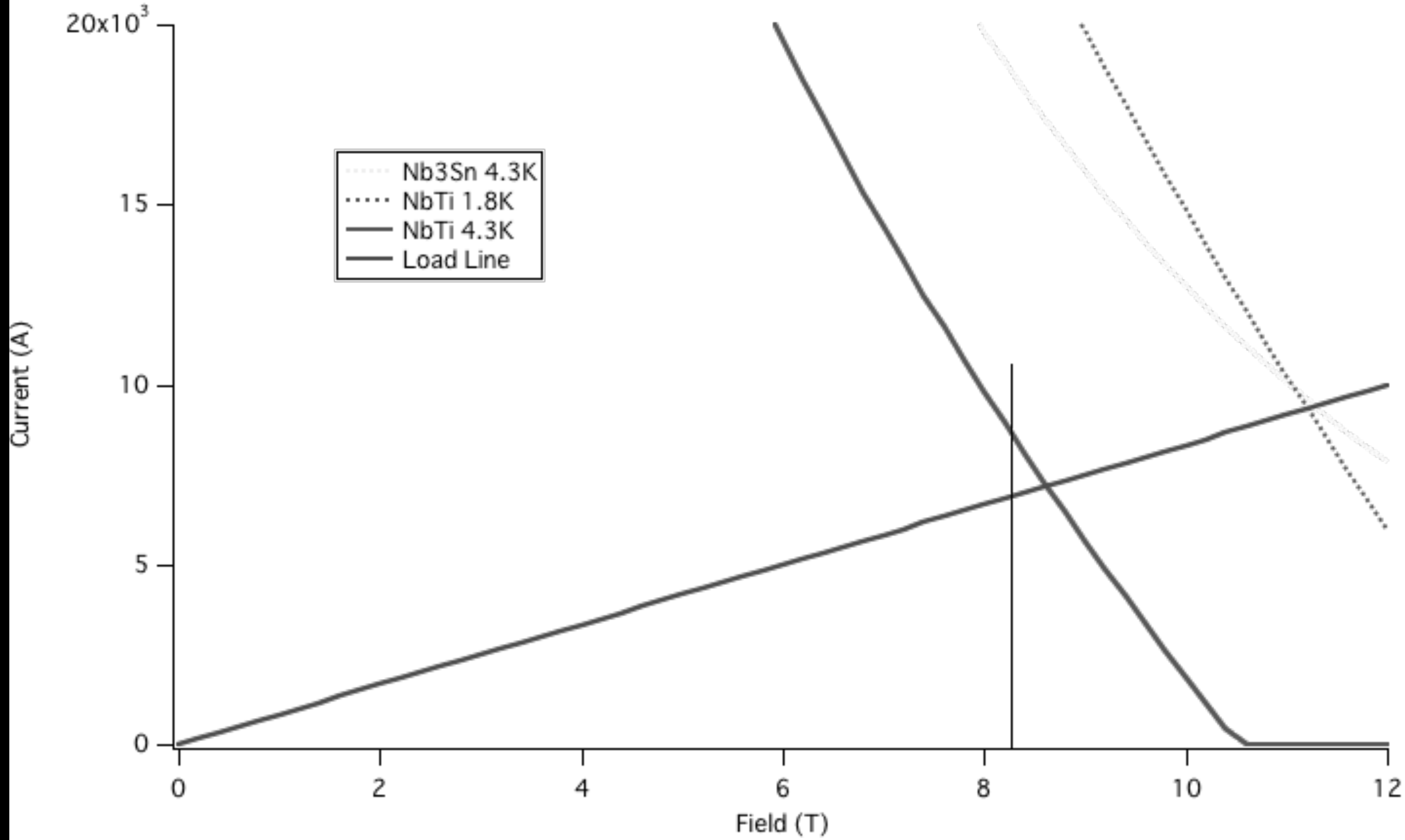
1. Main Coil
   - Asymmetric & Elliptic
   - Rutherford Cable~ 2X15mm
   - Operation Current ~6.8kA
   - Stored Energy: ~1MJ/m
2. Corrector Coil
   - Wind & glue (BNL)
   - ~10A/delta-K
3. Collar
   - Pre-stress ~90MPa
   - Horizontal EMF ~ 3.9 MN
   - Aluminum collar to gain pre-stress during cool down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

FFAG Reference Design

Field Map & Beam Aperture

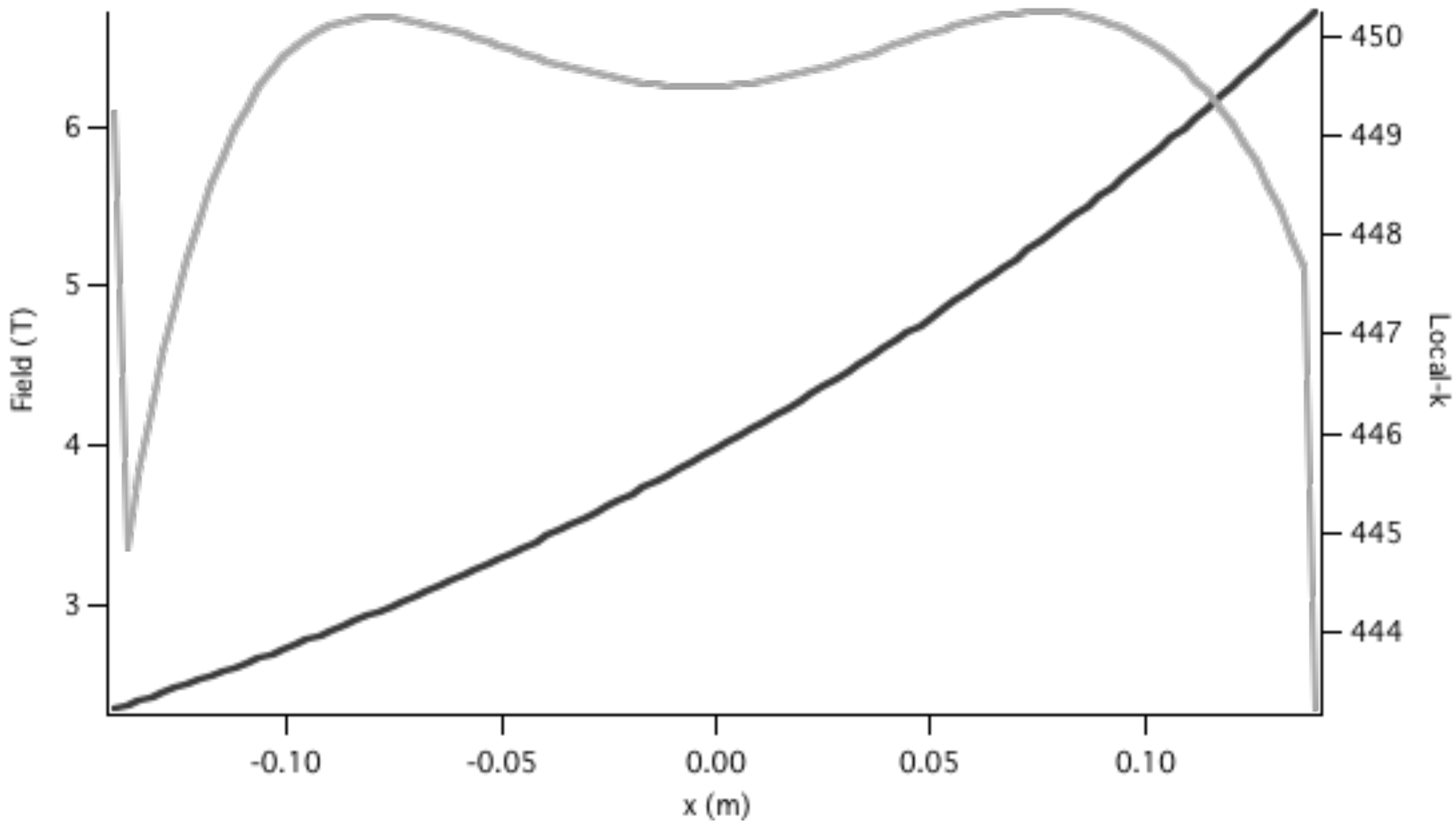


FFAG Reference Design
Operation Margin



FFAG Reference Design

Field quality of main coil



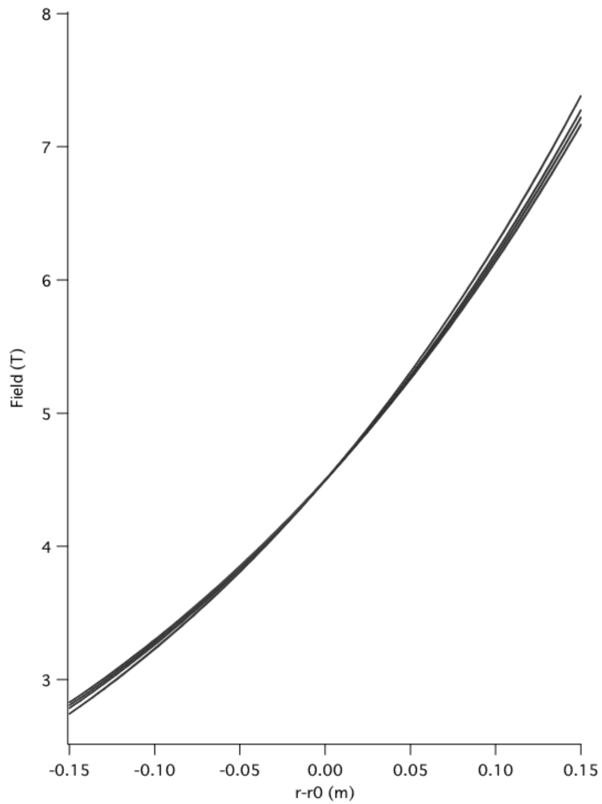
K corrector

- 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, δk = 10, 20, 40
Red lines represent definite equation, while
Blue lines represent first order approximation.

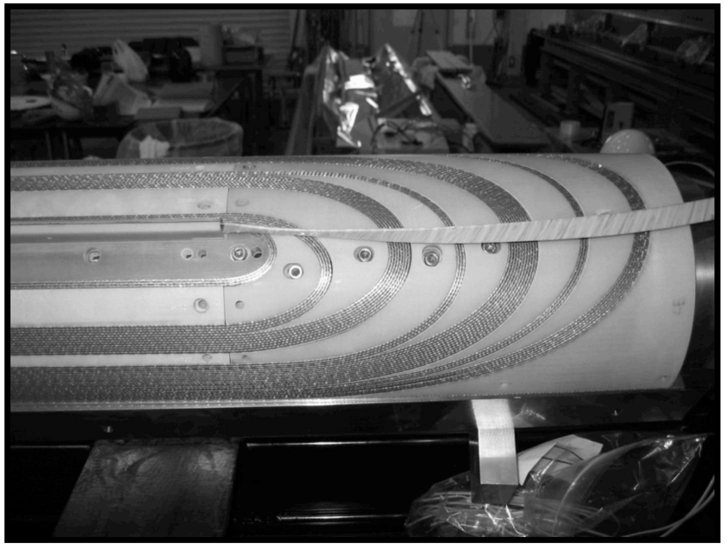
Current distribution can be derived using the same method as that of main coil

2D Magnetic Design

- Summary
  - Extension of cos(nθ) coil
  - Asymmetric Elliptic Coil
  - Warm Off Centered Yoke
  - First Order Delta-k Correction Coil
- Issues to be studied
  - 3d end design
  - Coupling between main and corrector coil

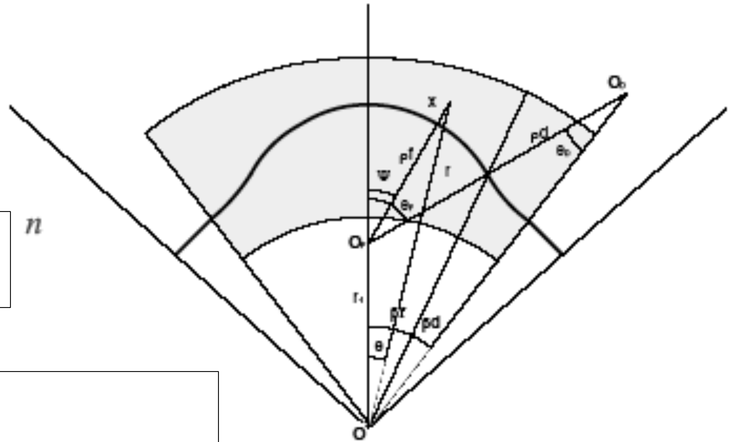
3D design STUDY

- For conventional SCM
  - 3D design is optimized such that integral field quality is good.

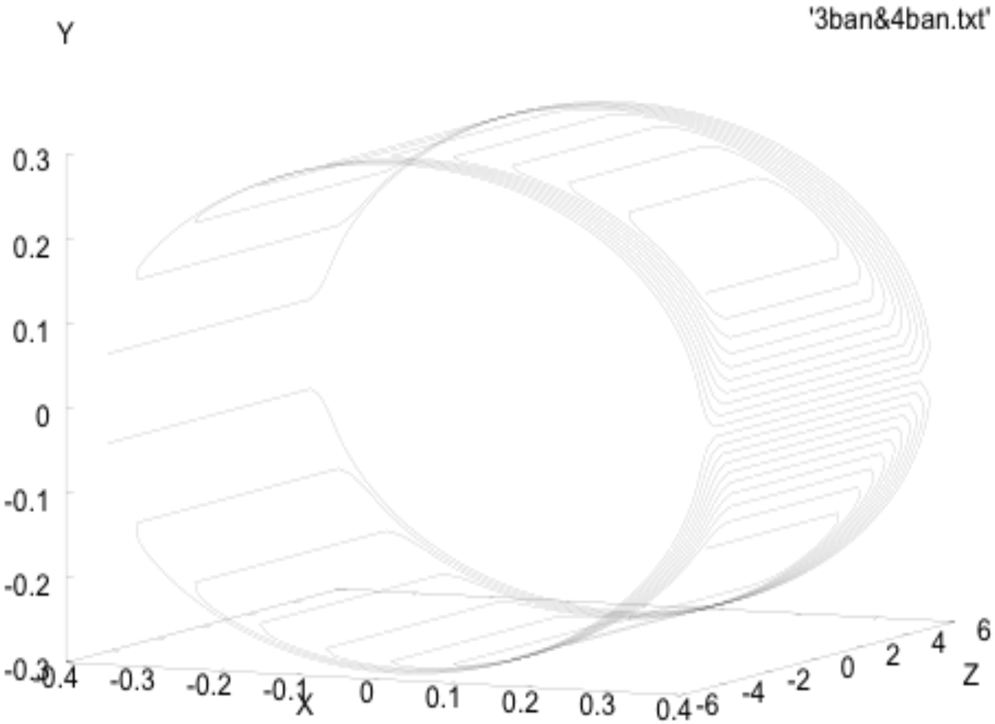


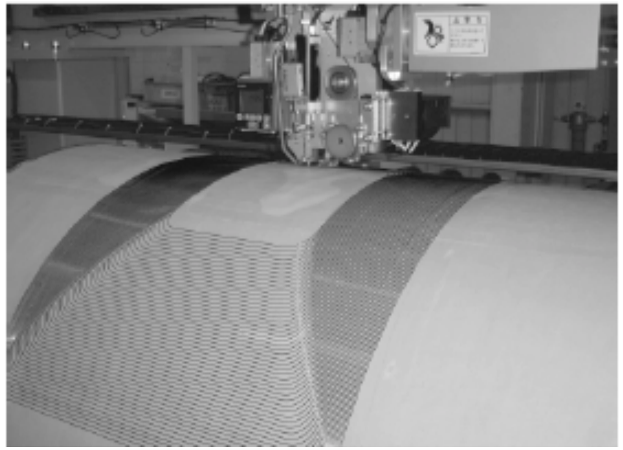
- For FFAG magnet
  - Not only integral but also local field quality may be needed

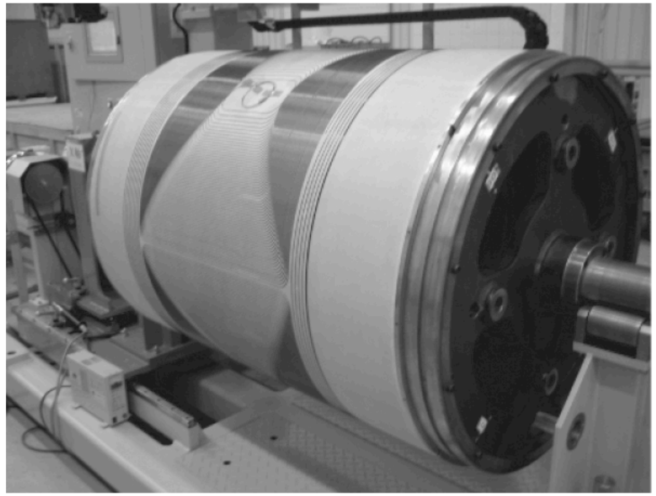
$$B(r,\theta) = B_0\left(\frac{r}{R_0}\right)^k F(\theta)$$



3 D design STUDY
Saddle Shape Winding







Combination of 2 coils for 1 layer

Con

Integral field is not optimized (can be corrected)

Pro

Smaller end structure

3 D design STUDY
Single Winding

Single coil construct 1 layer

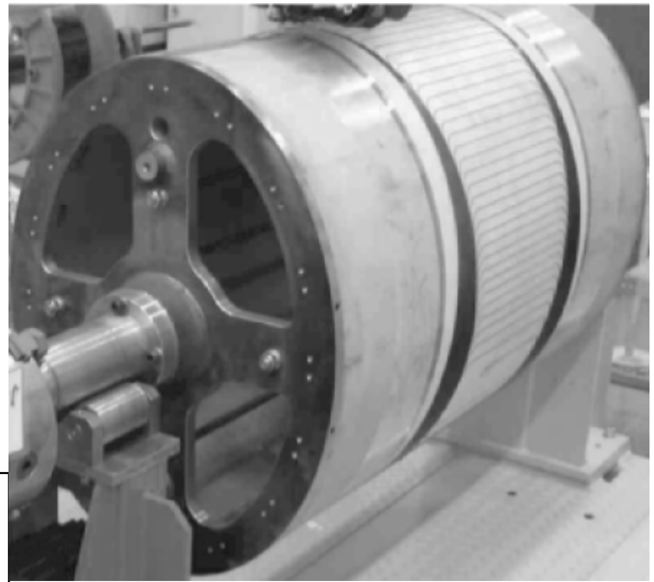
Pro

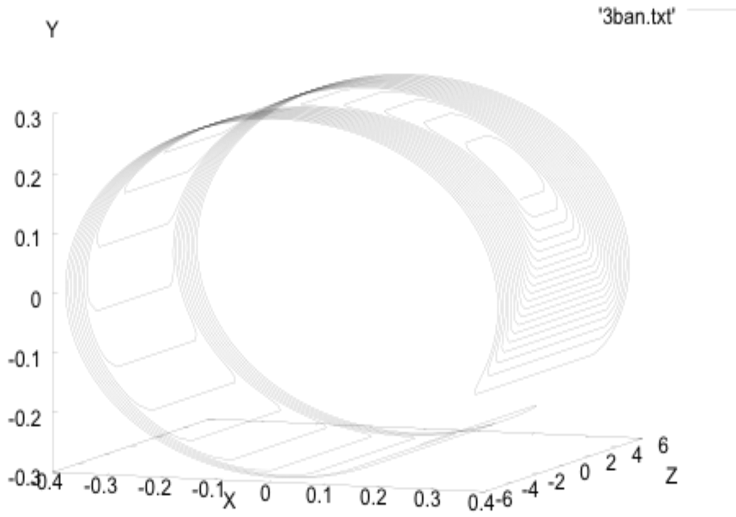
Integral field is optimized

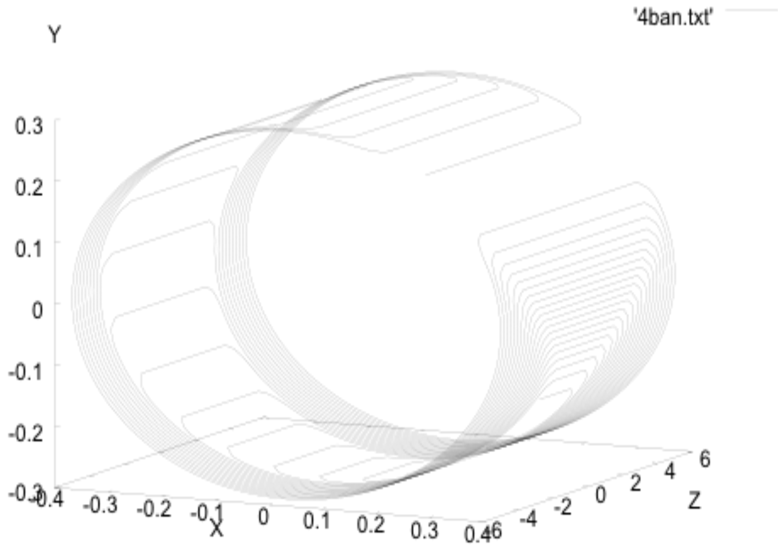
Con

Larger end structure

Need two layers

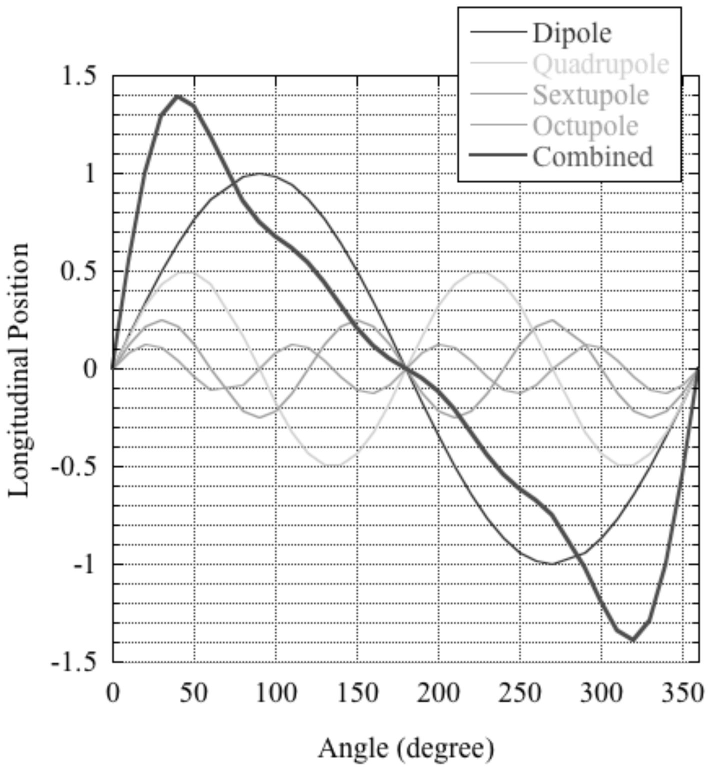






3D DESIGN STUDY
Titled Solenoid

- Integral field optimized
- Fits to short magnet
- Effective current density is small



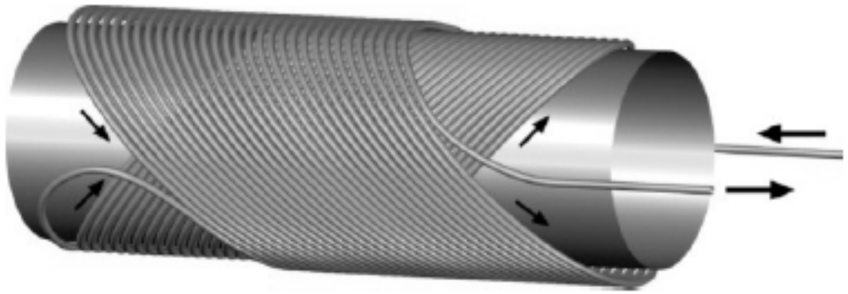


Figure 2. Example of a 2-layer winding used to form a DH dipole magnet

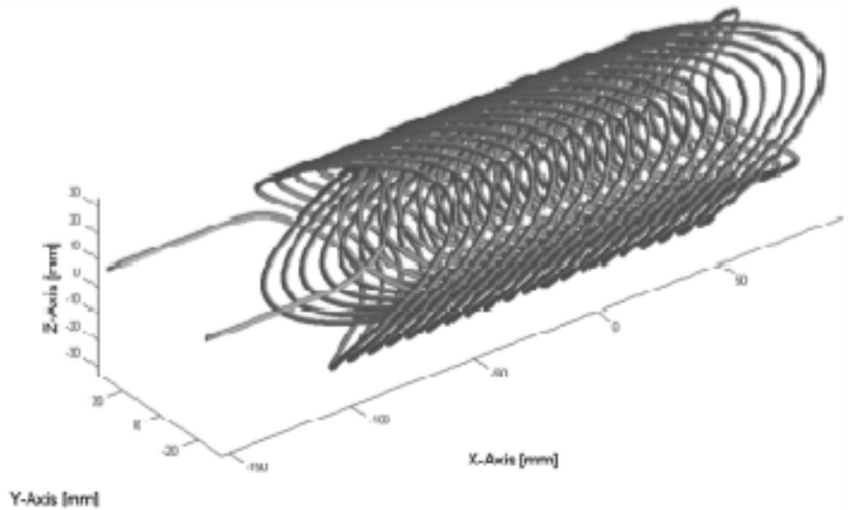


Figure 4. Quadrupole DH magnet

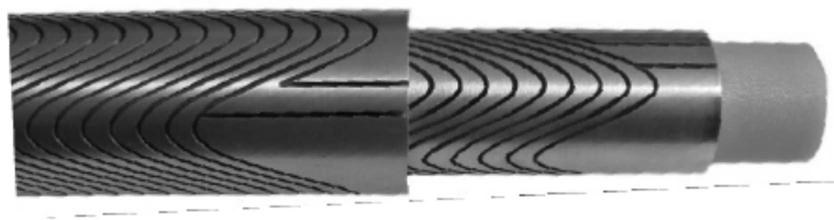
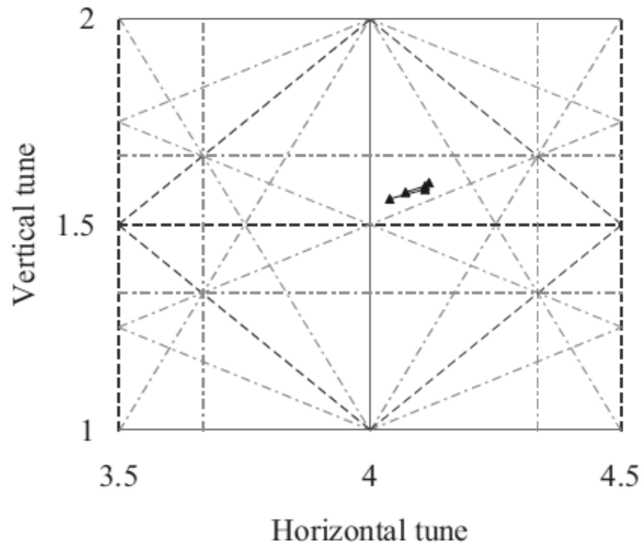


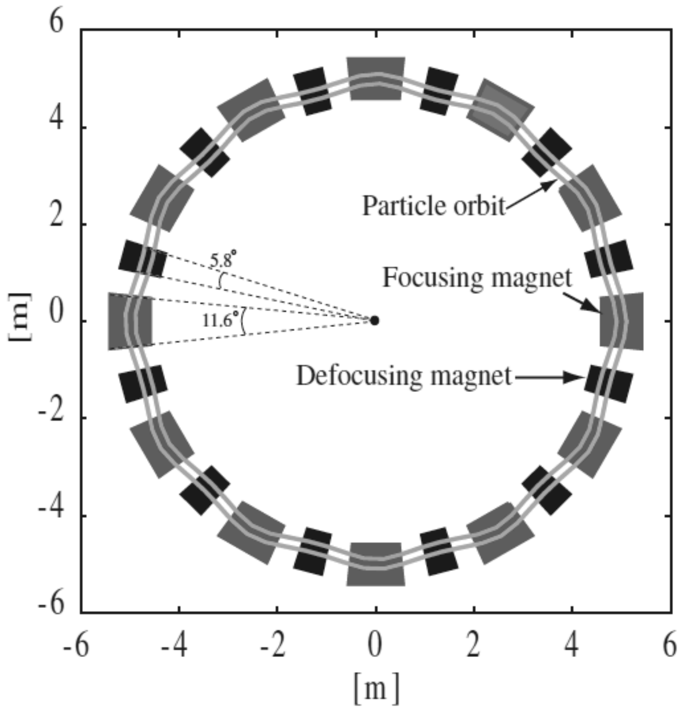
Figure 5. Two concentric cylinders of a DDH coil in a sextupole configuration

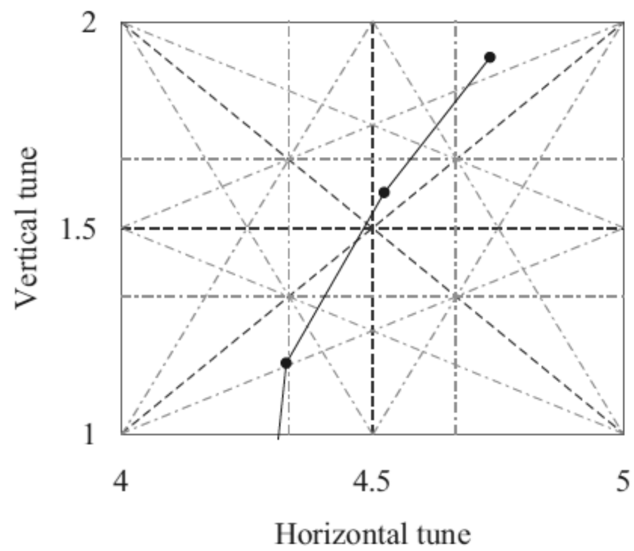
Real Design

- 2D design
- 3D design
- Field Map
- Tracking



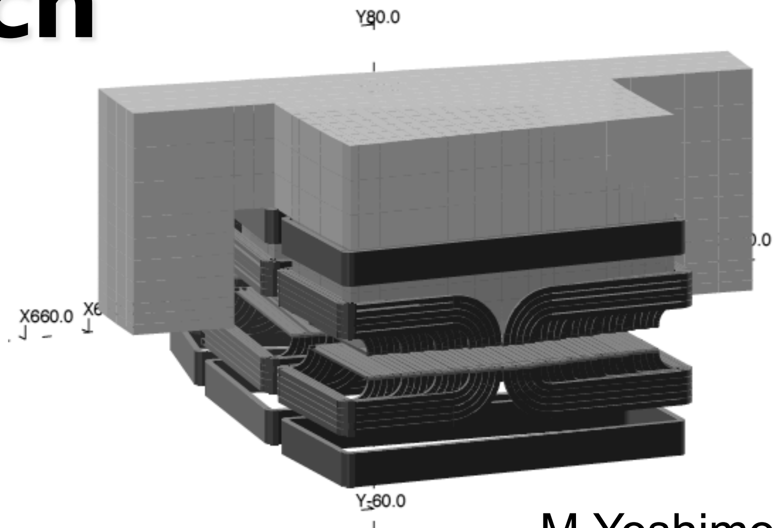
(a) Saddle shaped coil



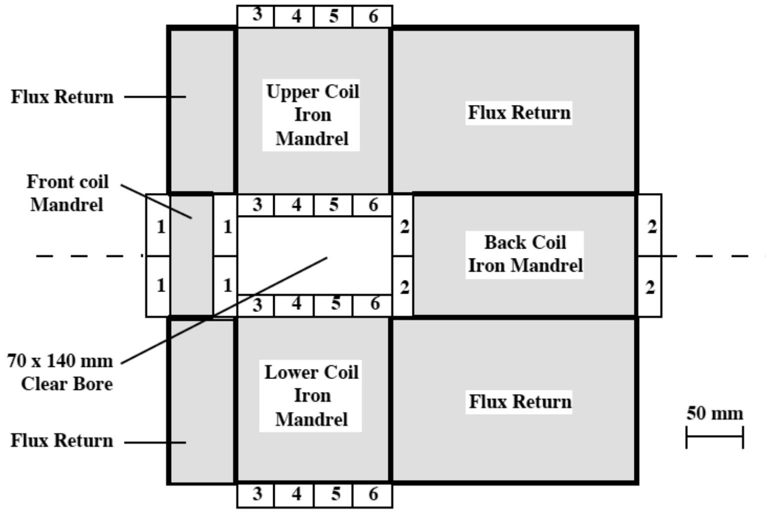


SC FFAG Magnets Other approach

- Superferic
  - Use normal conducting design
  - replace coil by SC
  - Iron saturation
- Pole face winding
  - correct iron saturation

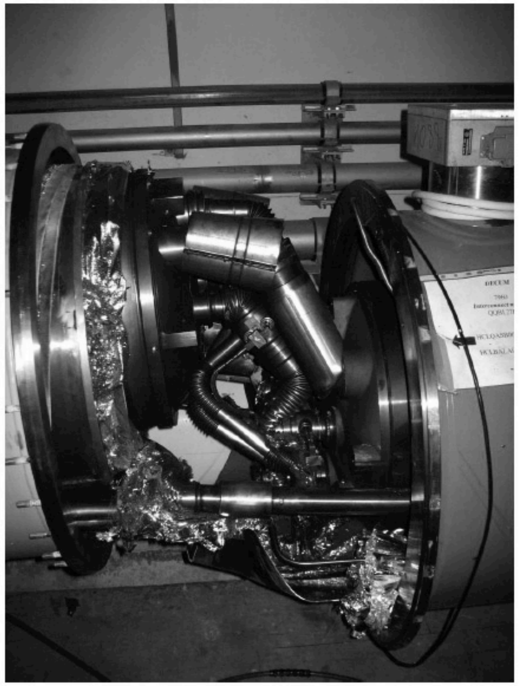


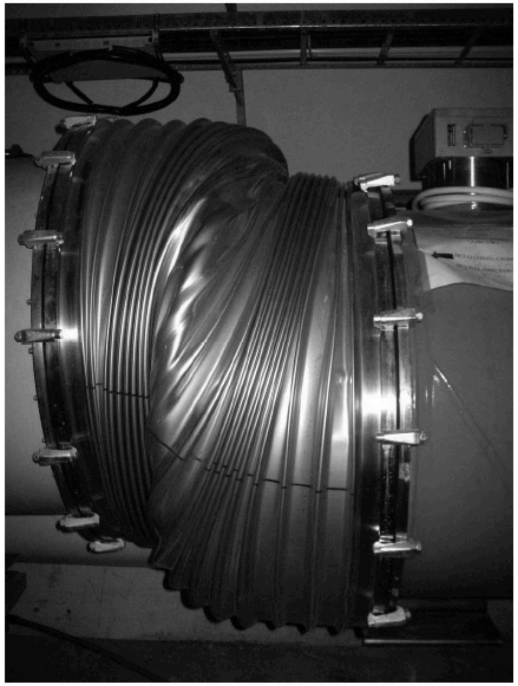
M.Yoshimoto et.al.



M.A. Green

Quench Protection

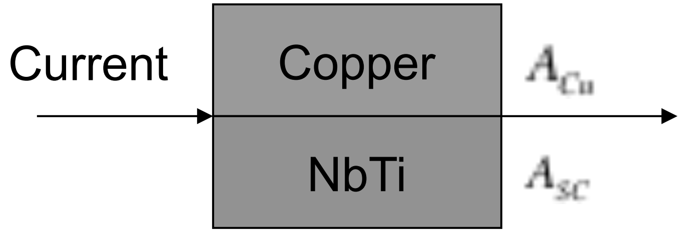




Quench Protection

- SC Magnet
  - J > $100 A/mm^2$
  - Quench

    = Rapid temperature rise
- MIITs



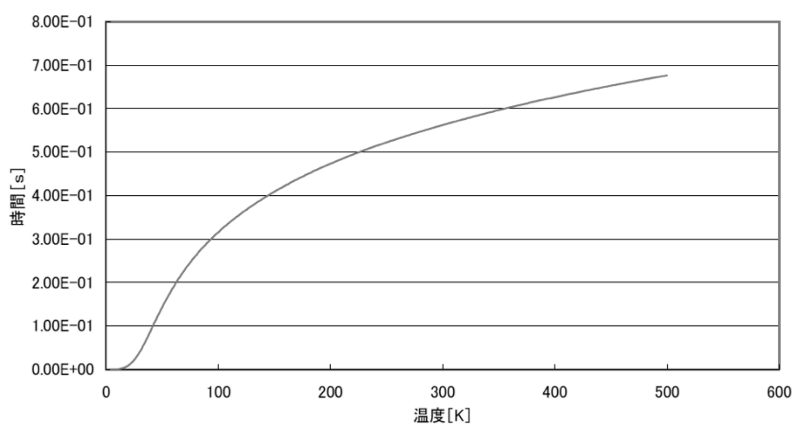
$$R = \rho_{Cu} l / A_{Cu}$$

$$G = I^2 \rho_{Cu} l / A_{Cu}$$
$$= \Delta H$$
$$= (C_{p-Cu} A_{Cu} + C_{p-SC} A_{SC}) l \Delta T$$

$$\int_{t_{quench}}^{t_{end}} I^2 dt$$

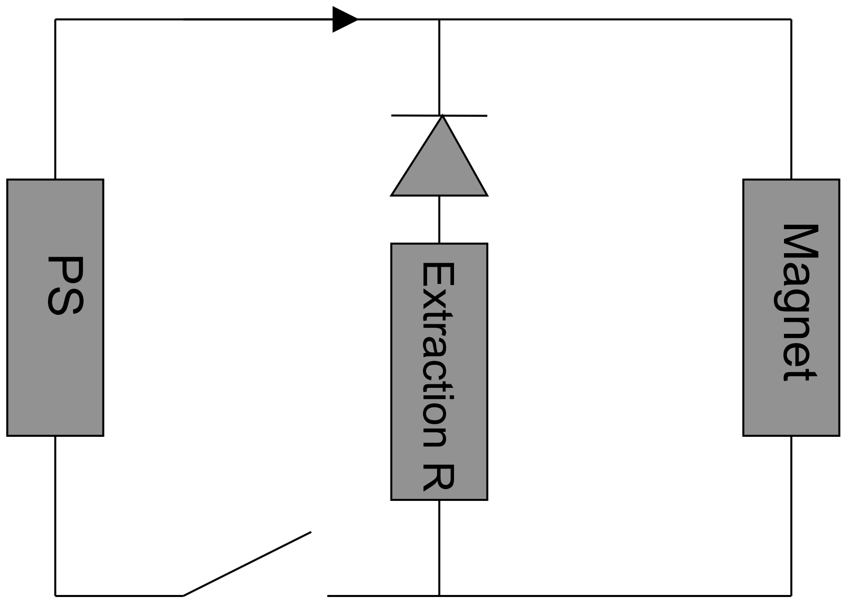
$$= \int_{T_0}^{T_{max}} \frac{C_{pCu} A_{Cu} + C_{pSC} A_{SC}}{\rho_{Cu} / A_{Cu}} dT$$

- $MIITs/I^2 = t$
- Need to shut down current as soon as possible

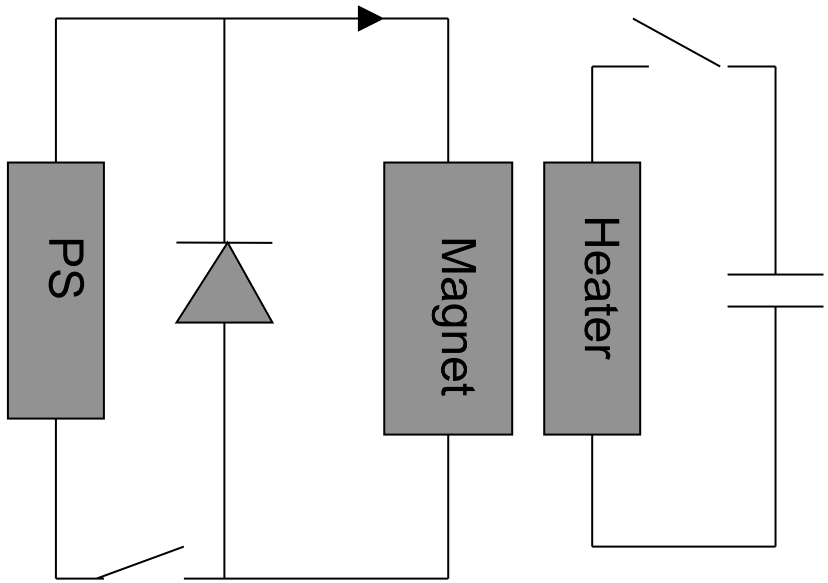


Protection Circuit

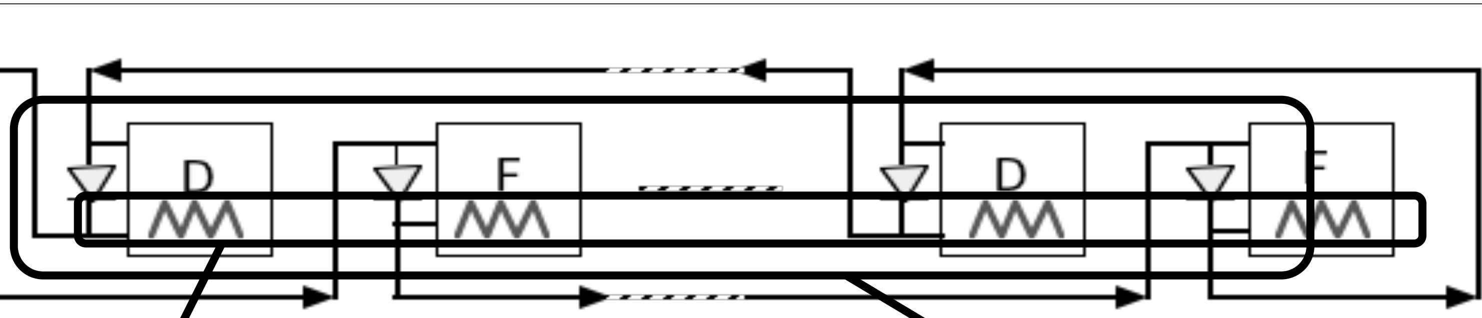
- Extract Magnet Energy by External Resistor
  - External Energy Extraction
  - =less load to cryogenics
  - High voltage
    - Large inductance?

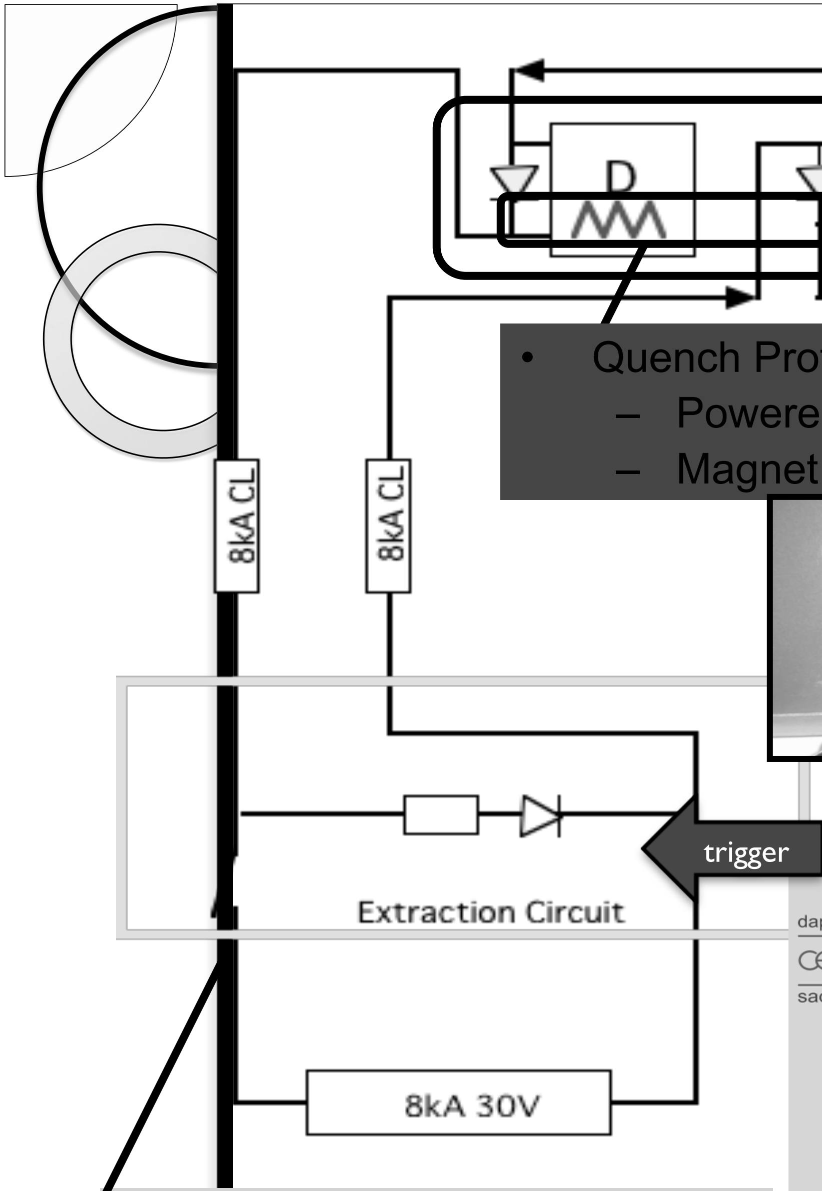


- Quench Heater
  - Internal Energy Spread
  - = higher load to cryogenics
  - Voltage spread in coil
    - good for large system

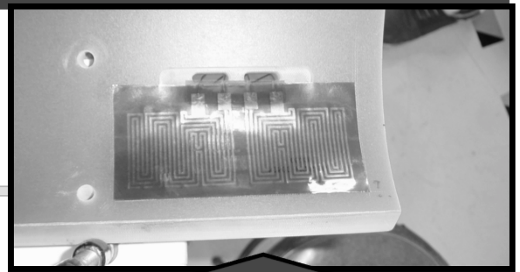


Protection Circuit for Accelerator String

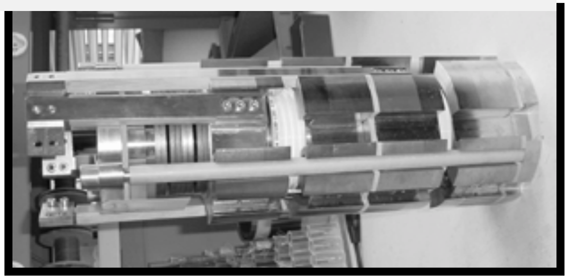




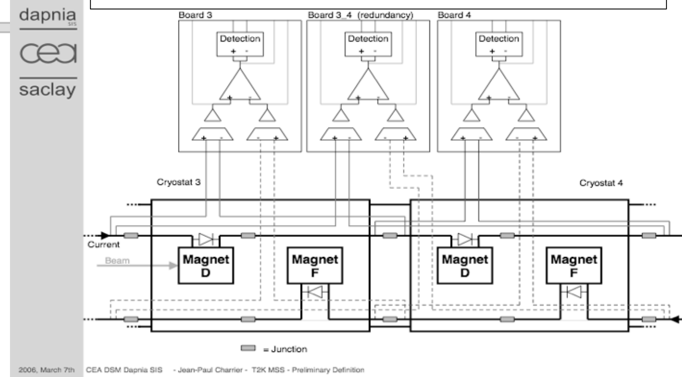
- Quench Protection Heater
  - Powered by Capacitor Bank
  - Magnet Current τ≈1 sec

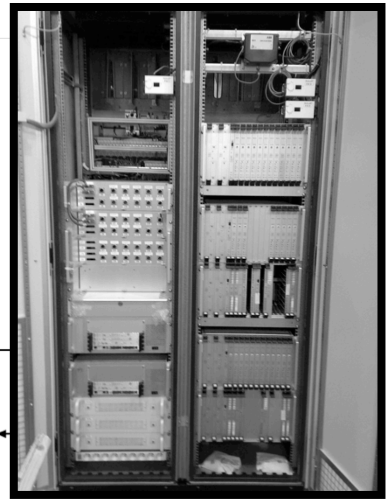


- Cold Diode
  - Turn On Voltage: 6V
  - Forward Voltage: 1V



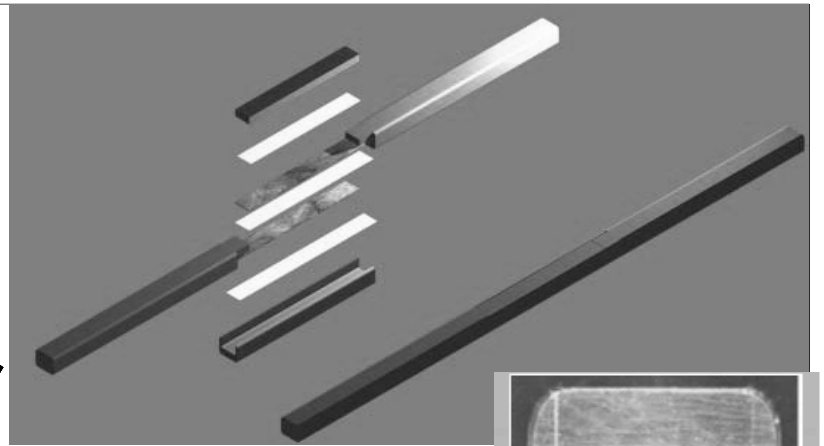
- Quench Detector

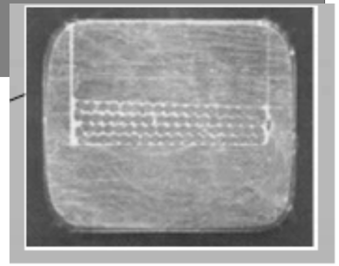




- Dump Circuit
  - Protect Cold Diodes and SC Bus Bars
  - Time Constant: 20 sec

The LHC Incident



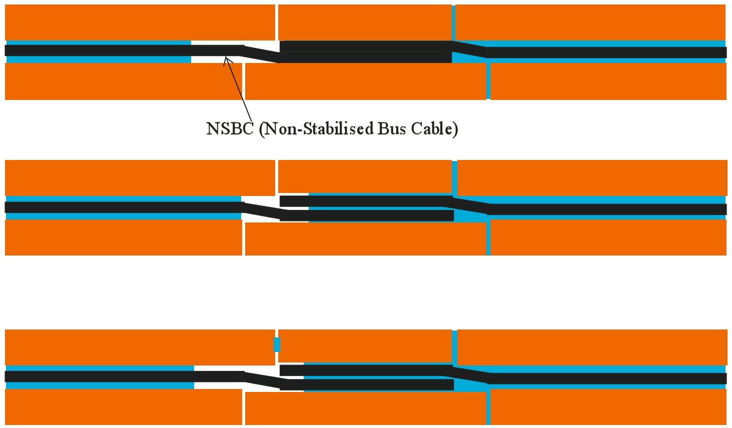


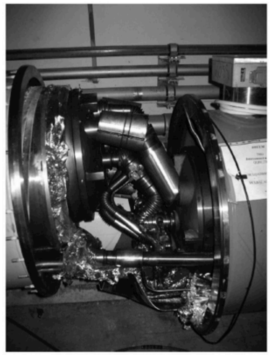
- Cause
  - Bad joint on Cu stabilizer
  - Not Enough Detection System
  - Huge Stored Energy
- Ring is recovered
  - not for full operation
  - Needs extensive repair

Defect B:
Soldered splice with
outside void and/or
lack of bonding

Defect C:
Badly soldered splice
(R>0.3 nΩ) with *inside*
void and/or lack of bonding

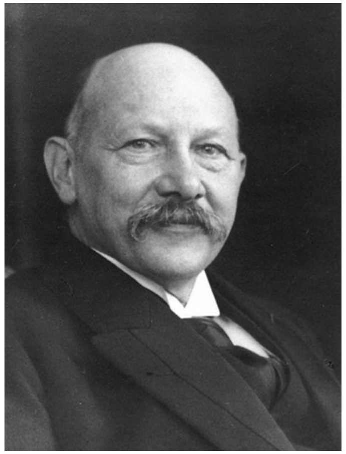
Defect D:
Splice with void and/or
lack of bonding and
small amount of SnAg
in vertical gap





Summary

- Superconductivity
  - Found by **Heike Kamerlingh Onnes**
- Superconducting Magnet
  - First large application: TEVATRON
- Now used extensively in many Accelerators
- What's NEXT??
  - Synchrotron Magnets
    - High Field by A15; LHC IR upgrade
    - High Ramp Rate by NbTi; GSI, LHC injector upgrade etc
  - Limitations of known technologies
    - NbTi; 6T@4.2K, 9T@1.8T for practical use
- **Time for new innovation**
  - FFAG
    - Medical Applications, ADSR, Muon Source, etc....
    - Neutrino Factory, Muon Collider, etc...
  - New material
    - MgB_2, BSCCO, YBCO, etc.....



Who's next
YOU?