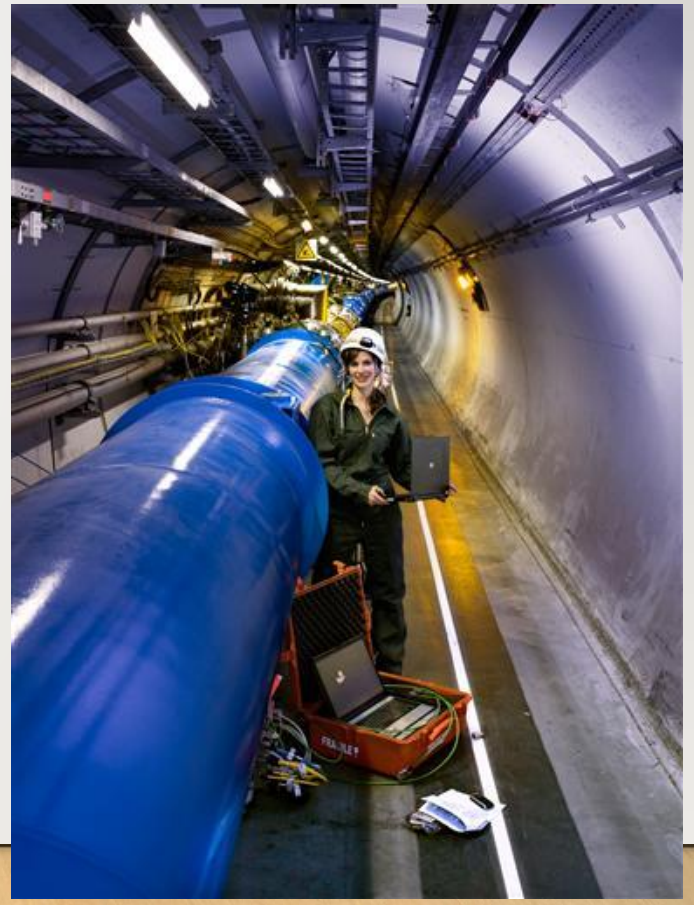
# Superconducting Magnets for Accelerator Science

TORU OGITSU, KEK

CERN LHC

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# Item

- Introduction：Accelerator and Magnet
- Superconducting Magnet for Accelerator
  - Collider・Large Accelerators
  - Light Source・Medical・Small Accelerators
- Future Possibilities
- Summary

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# 4 Particle Accelerator?

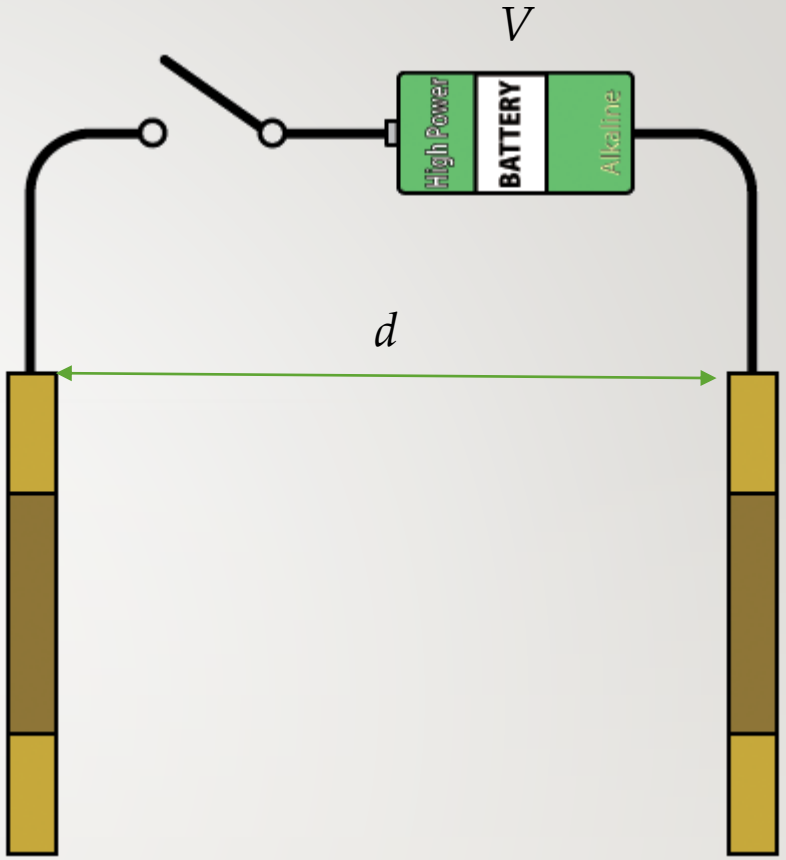
- Accelerate Charged Particle by
- By Electric Field

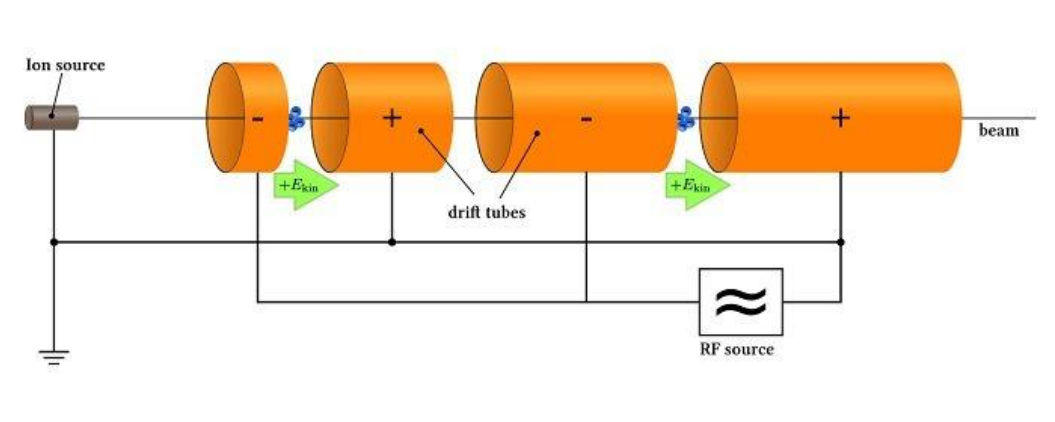
$$F = q \times E$$

$F$: Force

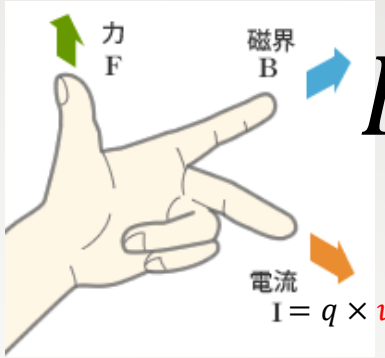
$q$: Charge

$E$: $Electric\ Field (E=V/d)$



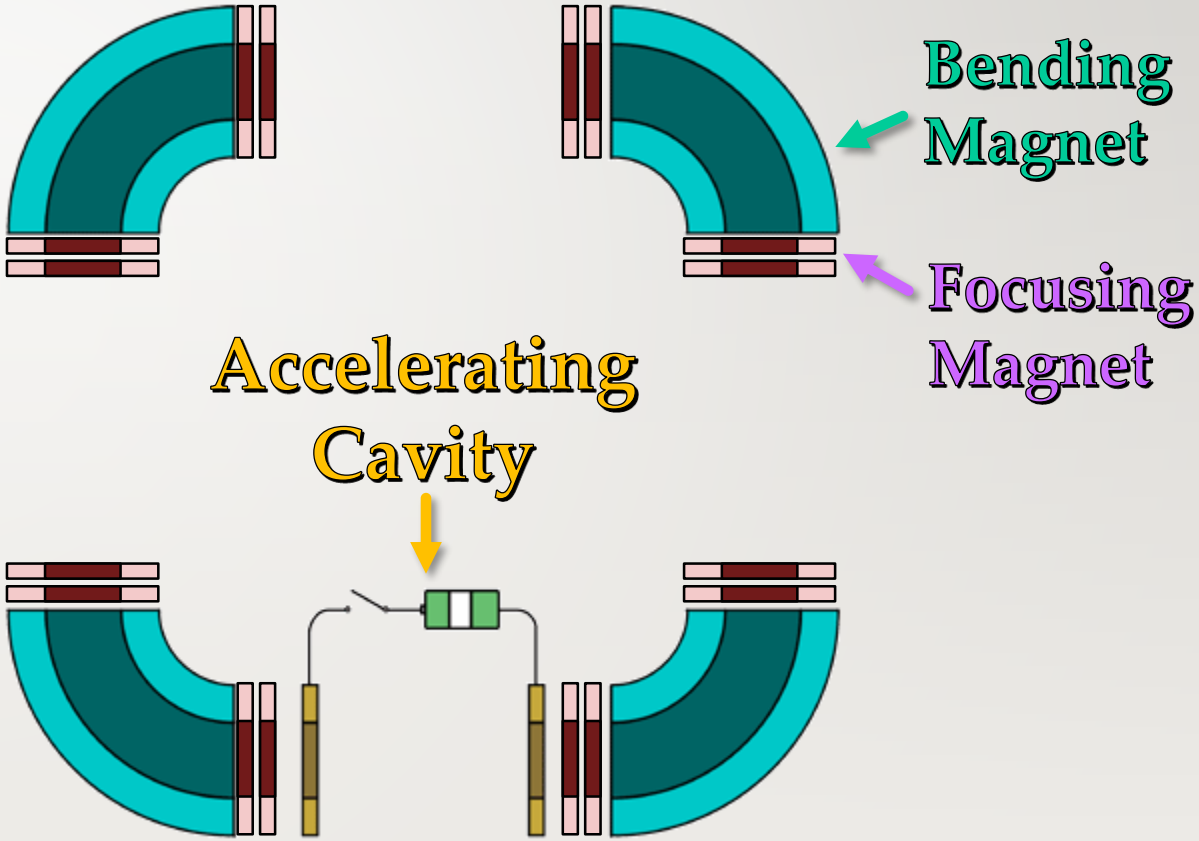
# 5 Synchrotron




$$F = q \times v \times B \qquad \frac{m \times v \times v}{r}$$

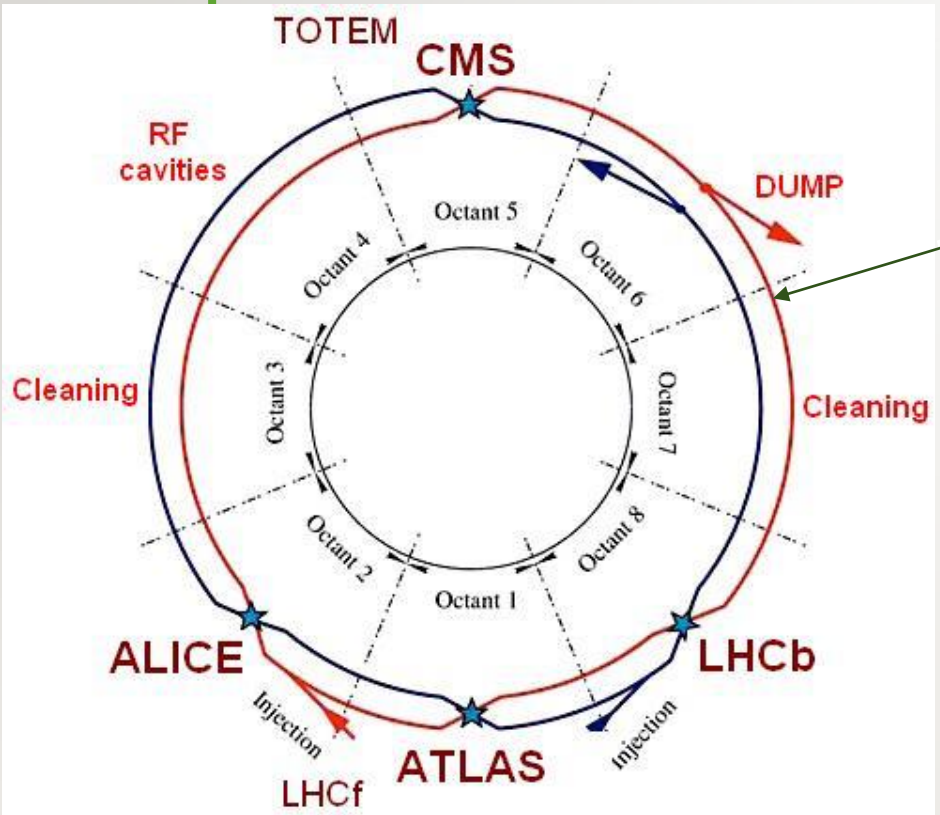
- Confine Charged Particle in Circular Orbit
- Re-use Accelerating Electric Field
- Change Magnetic Field According to Particle Momentum

$$r = \frac{m}{q} \times \frac{v}{B} = \frac{p}{qB}$$




$Br = \frac{p}{q}$ : rigidity

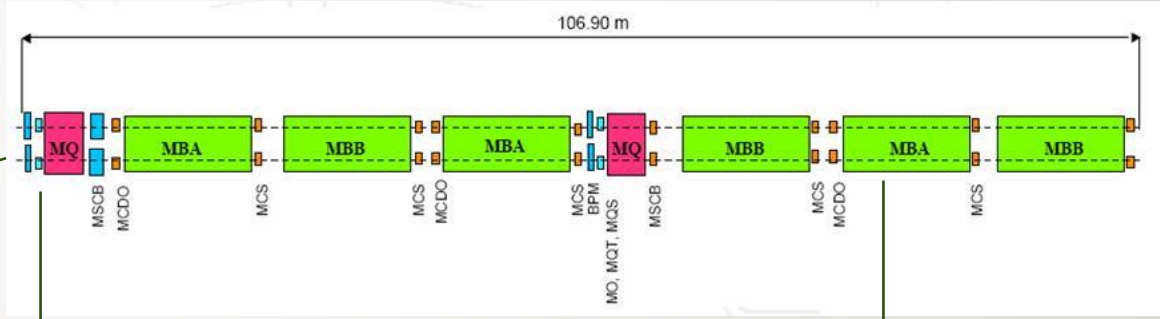
# LHC: Large Hadron Collider



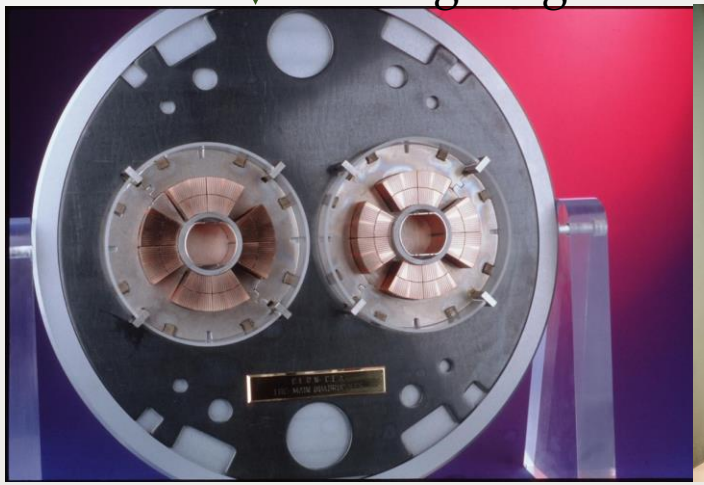

8 of 2.45 km arc+ 8 of 545 m straight section

23 cell per arc

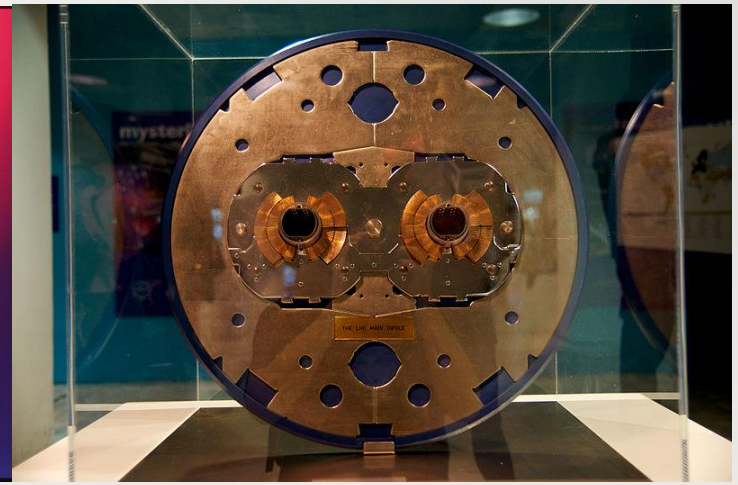
1 Cell: 6 Bending Magnet + 1 Focusing Magnet + 1 Defocusing Magnet




Focusing Magnet



Bending Magnet

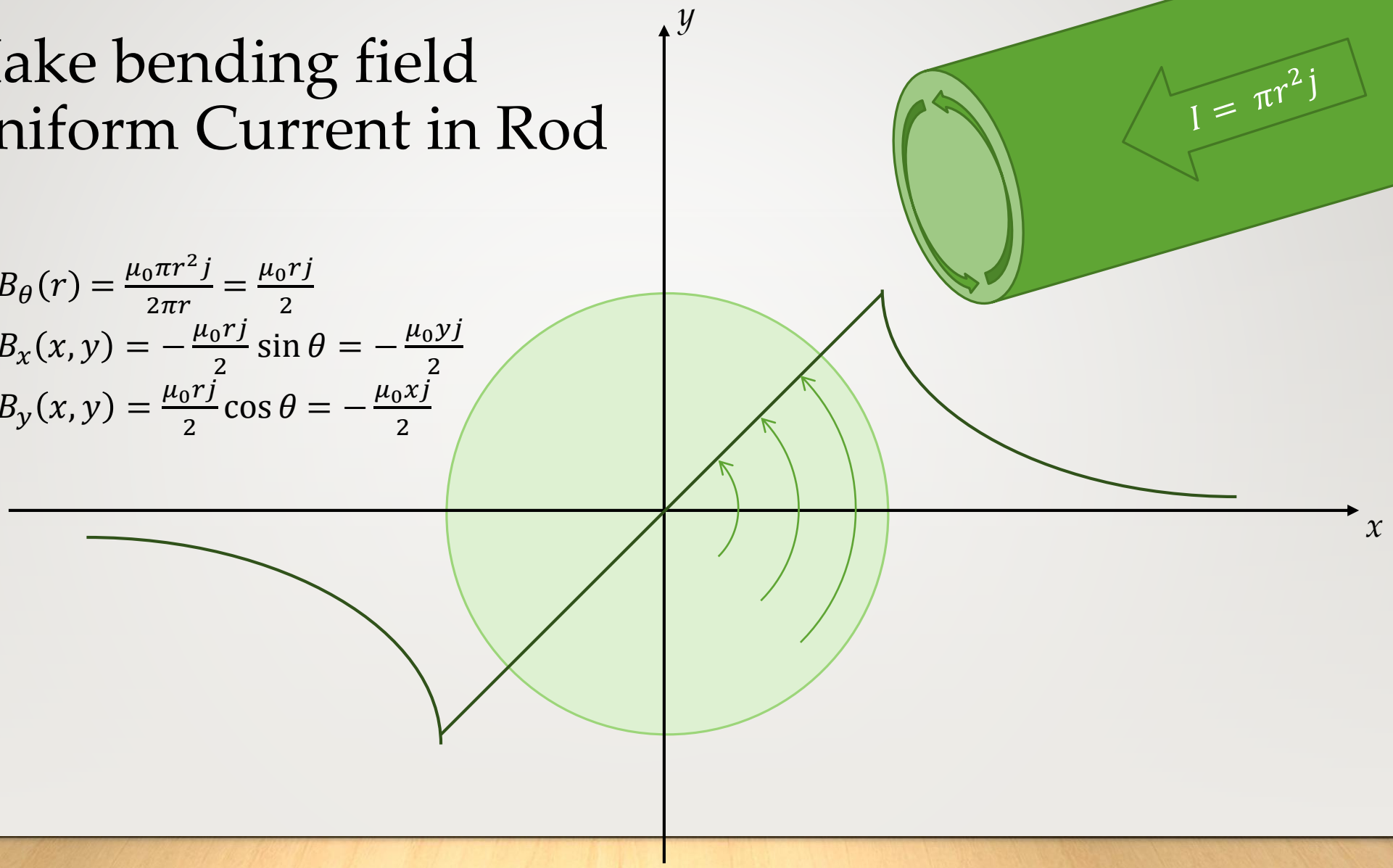


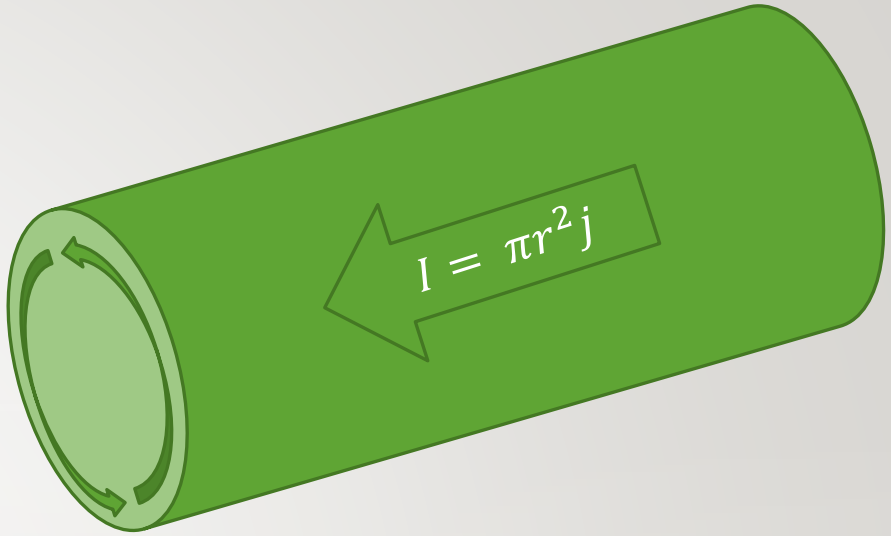
# 7 Make bending field Uniform Current in Rod

$$B_\theta(r) = \frac{\mu_0 \pi r^2 j}{2\pi r} = \frac{\mu_0 r j}{2}$$

$$B_x(x,y) = -\frac{\mu_0 r j}{2}\sin\theta = -\frac{\mu_0 y j}{2}$$

$$B_y(x,y) = \frac{\mu_0 r j}{2}\cos\theta = -\frac{\mu_0 x j}{2}$$



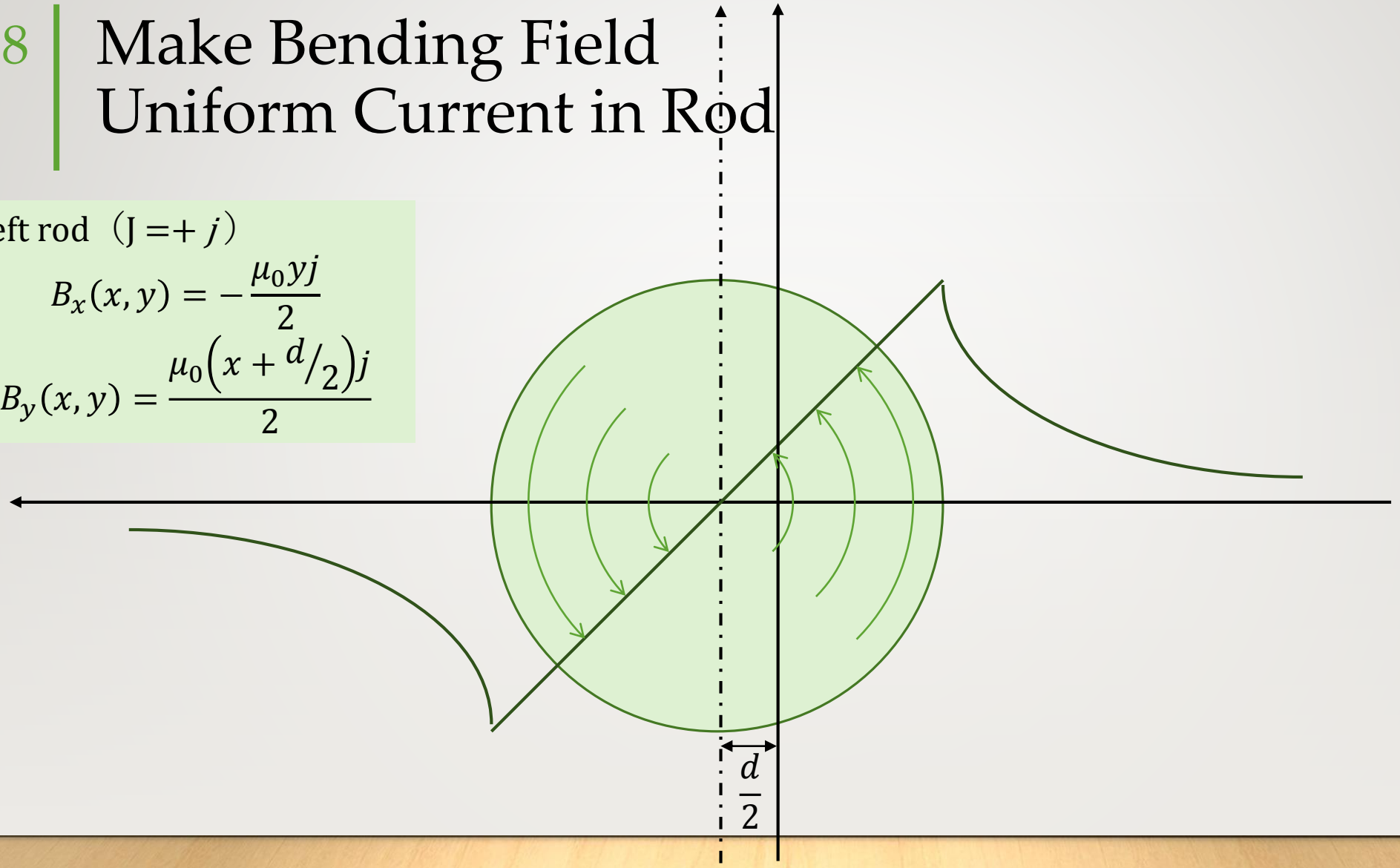



# 8 Make Bending Field Uniform Current in Rod

Left rod（J =+ $j$）

$$B_x(x,y) = -\frac{\mu_0 y j}{2}$$

$$B_y(x,y) = \frac{\mu_0\left(x + {}^{d}/_{2}\right)j}{2}$$



# 9 Make Bending Field Two current rod

Left rod（J =+ $j$）

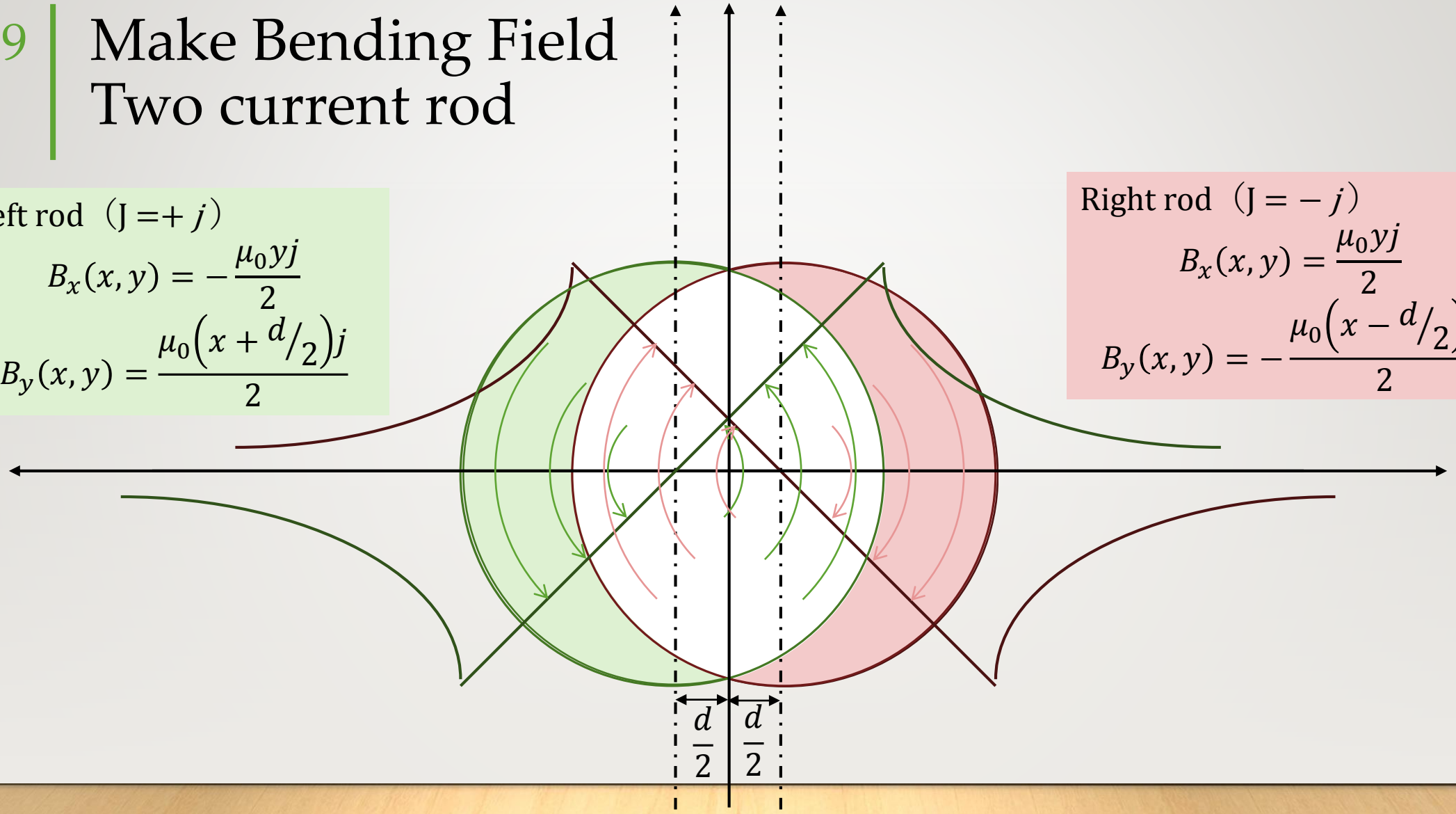
$$B_x(x,y) = -\frac{\mu_0 y j}{2}$$

$$B_y(x,y) = \frac{\mu_0\left(x + {}^{d}/_{2}\right)j}{2}$$

Right rod（J = − $j$）

$$B_x(x,y) = \frac{\mu_0 y j}{2}$$

$$B_y(x,y) = -\frac{\mu_0\left(x - {}^{d}/_{2}\right)j}{2}$$



# 10 Make Bending Field Uniform Field

Overlay area（J =0）

$$B_x(x,y) = 0$$

$$B_y(x,y) = \frac{\mu_0 j d}{2}$$

Left rod（J =+ $j$）

$$B_x(x,y) = -\frac{\mu_0 y j}{2}$$

$$B_y(x,y) = \frac{\mu_0\left(x + {}^{d}/_{2}\right)j}{2}$$

Right rod（J = − $j$）

$$B_x(x,y) = \frac{\mu_0 y j}{2}$$

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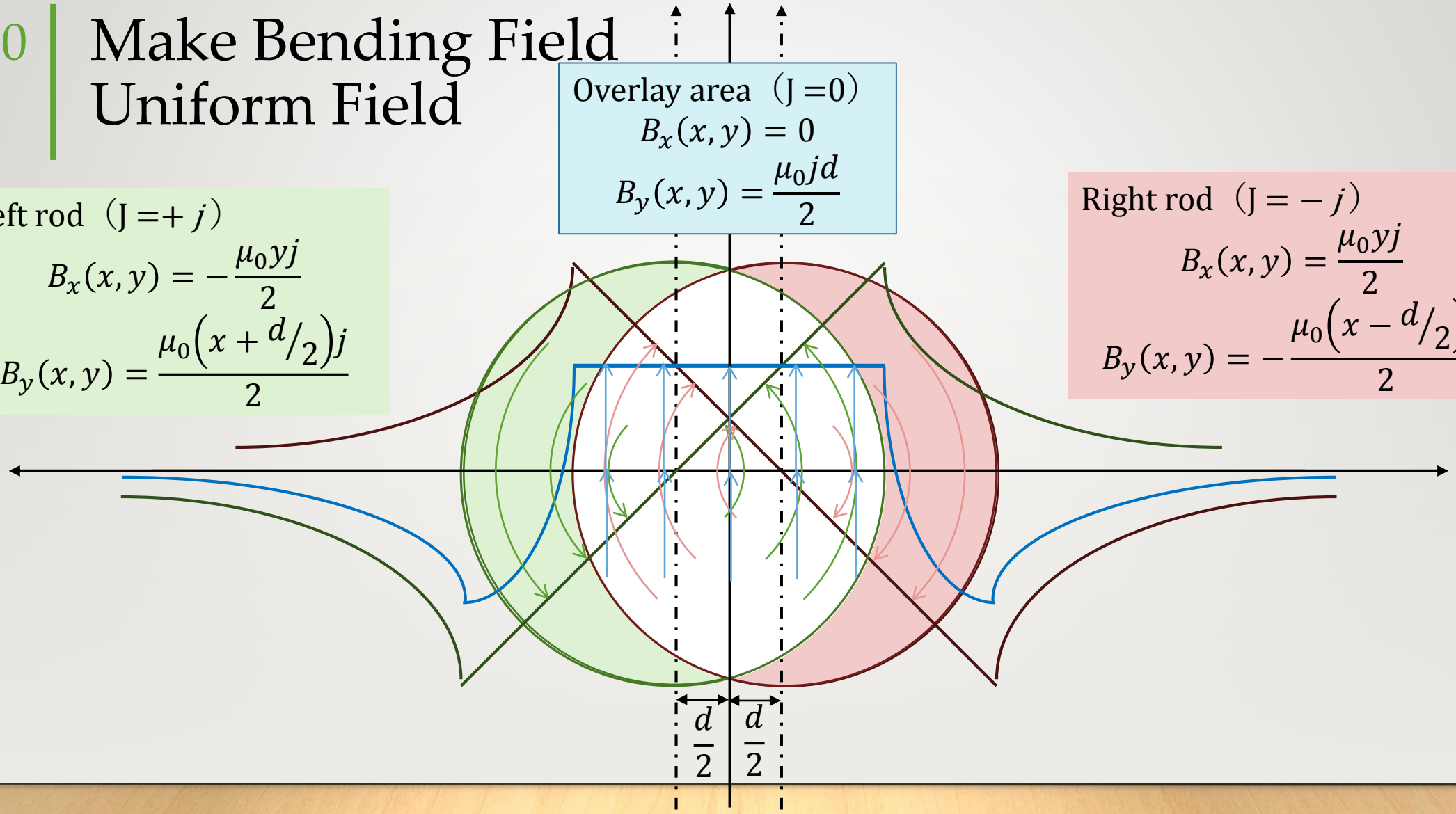


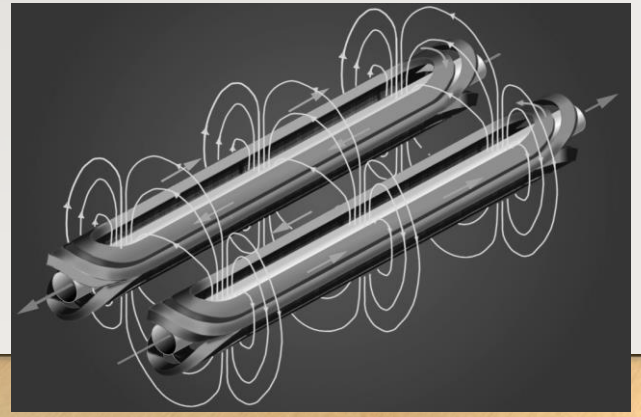
# Make Bending Field
# LHC Bending Magnet

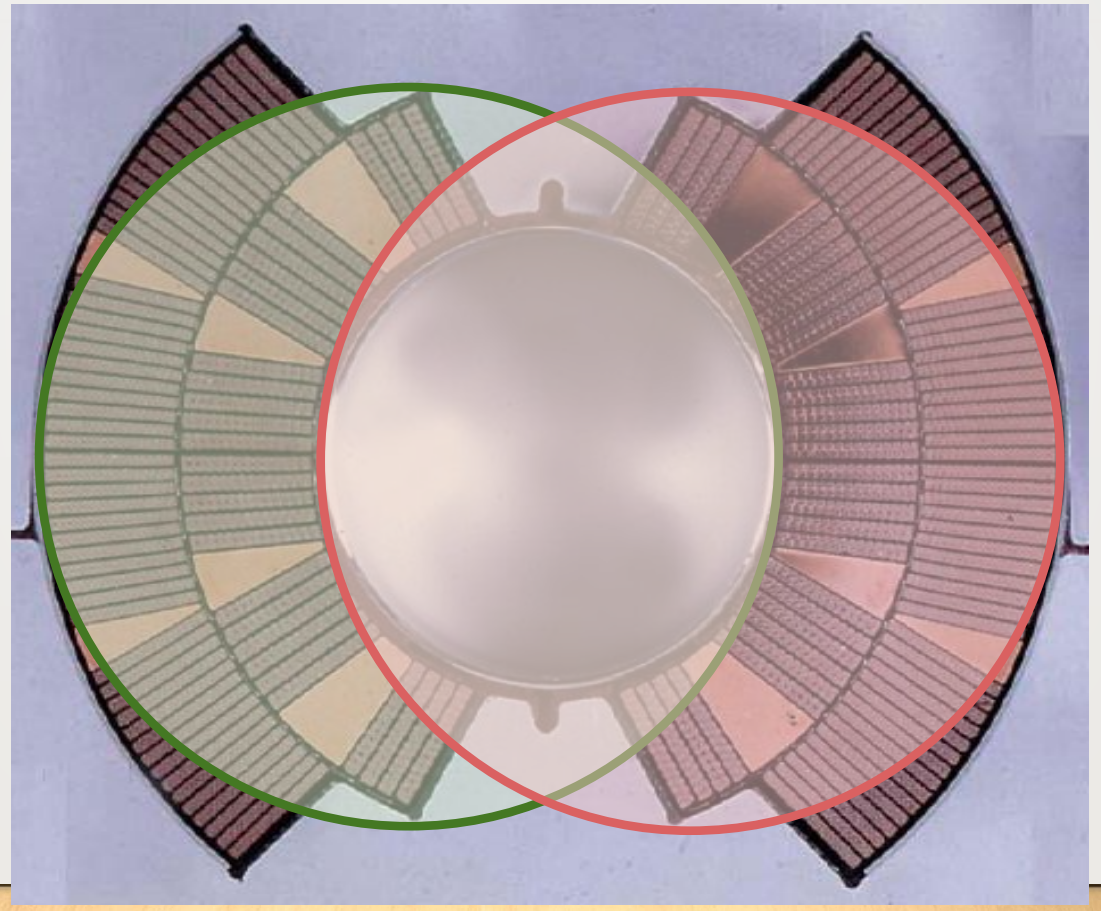
$$B_y(x,y) = \frac{\mu_0 j d}{2}$$

$j = 400\ \mathrm{A/mm^2}$

$d = 3\ \mathrm{cm}$

$B_y = 8.3\ \mathrm{T}$





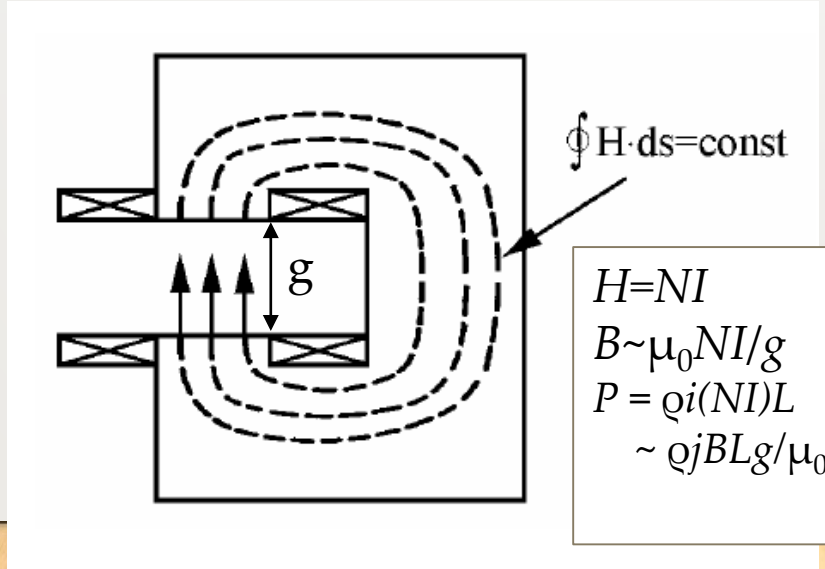
Actual Coil

Inner Cable
Width：15.1 mm
Thickness：1.9 mm
Turn no.：15*2
J：400 A/mm$^2$

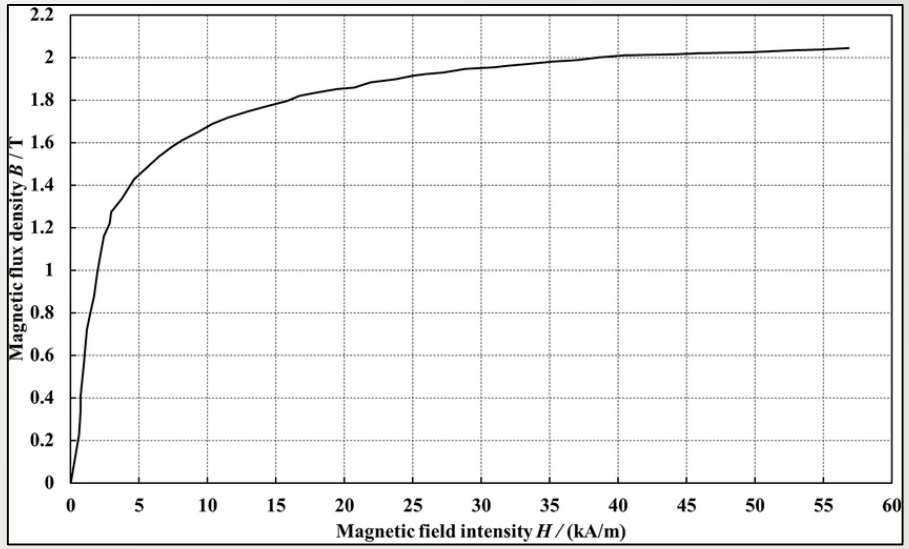
Outer Cable
Width：15.1 mm
Thickness：1.48 mm
Turn no.：26*2
J：520 A/mm$^2$

# Normal conducting magnet?

- Joule Heating：$W = VI = RI^2$ → Limit actual current density：10 A/mm$^2$
- 1/40 of J：40 times larger coil? Noway.
- Real normal conducting magnet: Use iron yoke magnet circuit
- Iron saturation: limit field to 2 T




$H=NI$
$B \sim \mu_0 NI/g$
$P = \varrho i(NI)L$
$\sim \varrho jBLg/\mu_0$




LHC by normal conducting
Need 5 times larger size
10 times more energy consumption

0.05(gap)*0.1(width)*1(length)m & 2T ~ 15kW (@ 10A/mm$^2$) ～ 7kW/Tm

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# 14 円型加速器と超伝導の歴史

- 1895 Crookes tube: first electron accelerator
- 1911 Discovery of Superconductivity
- 1930 Cockcroft & Walton circuit: first radioactive decay
- 1931  Cyclotron (Lawrence)
- 1933 Discovery of Meissner effect
- 1947 Electron Synchrotron
- 1952 Proton Synchrotron
- 1957 BCS theory, Type II superconductor
- 1961 6T Superconducting Magnet
- 1983 Superconducting Synchrotron TEVATRON

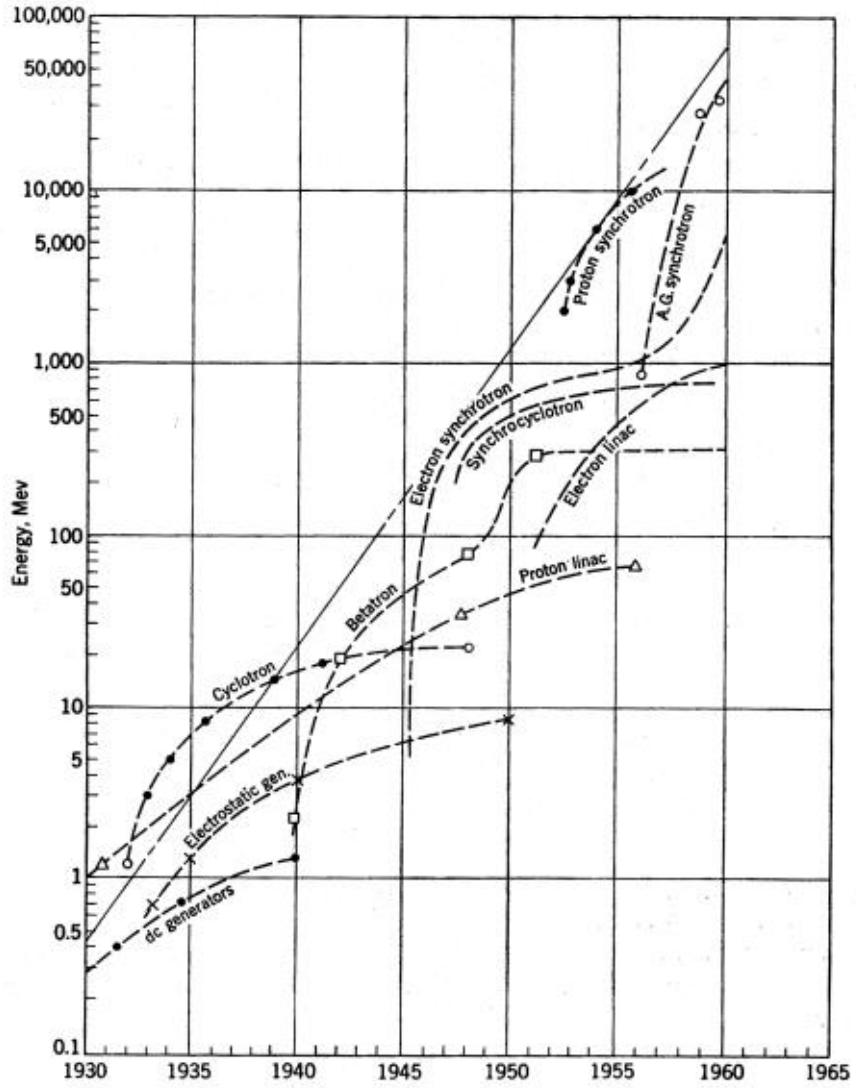
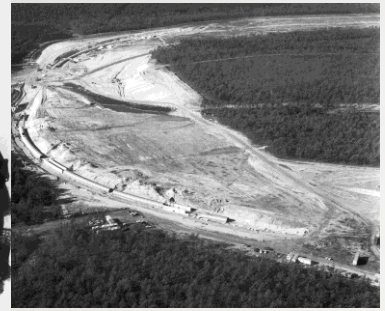



**Fig. 1-1.** Energies achieved by accelerators from 1930 to 1960. The linear envelope of the individual curves shows an average tenfold increase in energy every six years.

**PARTICLE ACCELERATORS by M. Stanley Livingston and John P. Blewett, 1962, p. 6.**

# Superconducting Collider: BNL vs FNAL



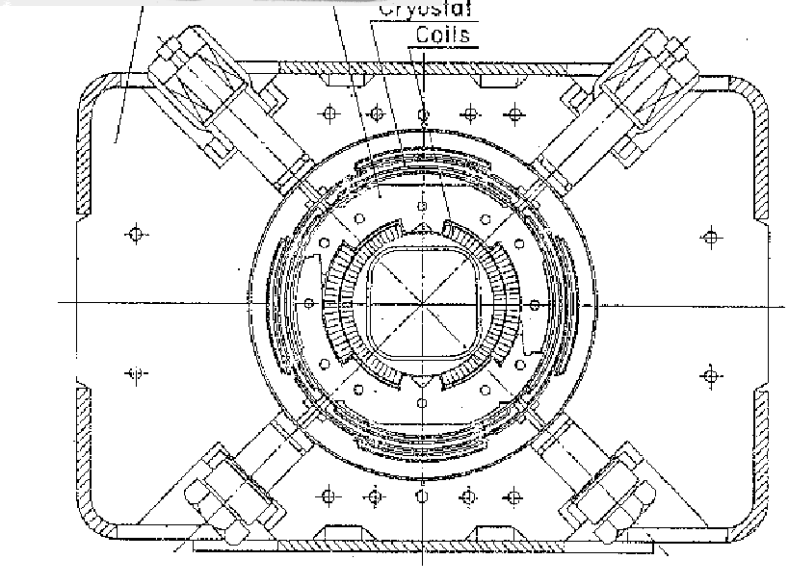
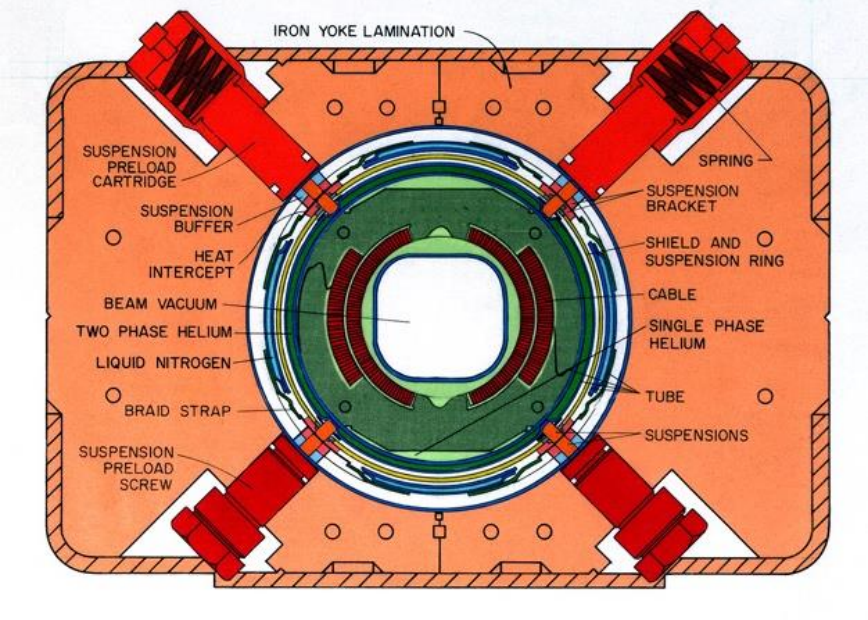



図４－１　Tevatron 用２極電磁石の断面

1970 ~ early 1980s
Strong competition
Between 2 US Lab.

winner



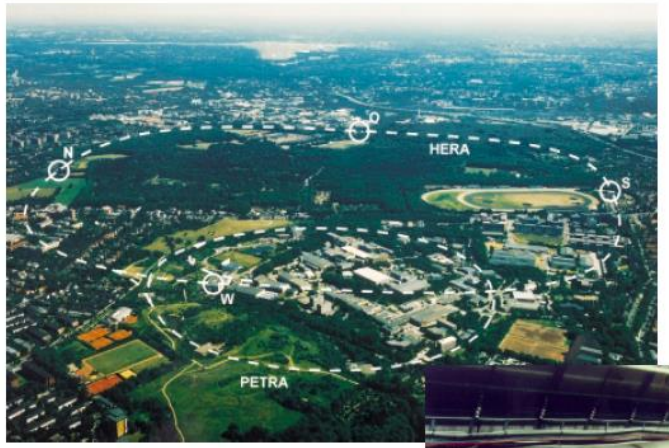

ISABELLE/CBA (BNL) 3.8km, 400GeV

(Magnet: 5.28T)

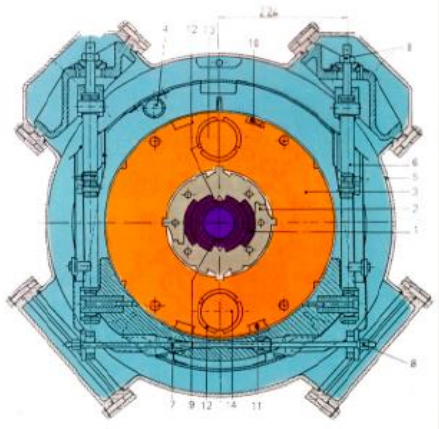
**TEVATRON(FNAL): 6.3km, 1TeV**

**(Magnet: 4.4T, 6.1m, 774台)**

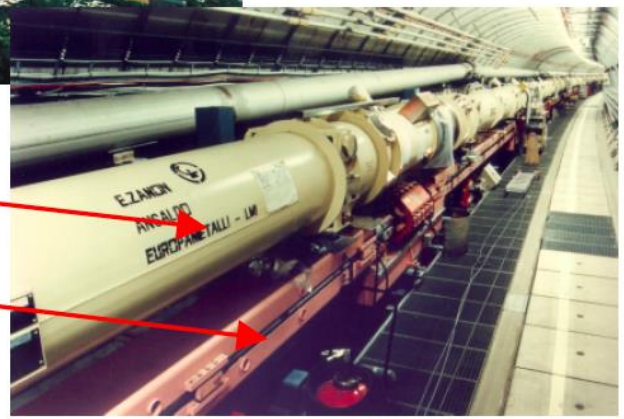
# Superconducting Collider HERAとRHIC




Aerial View of DESY



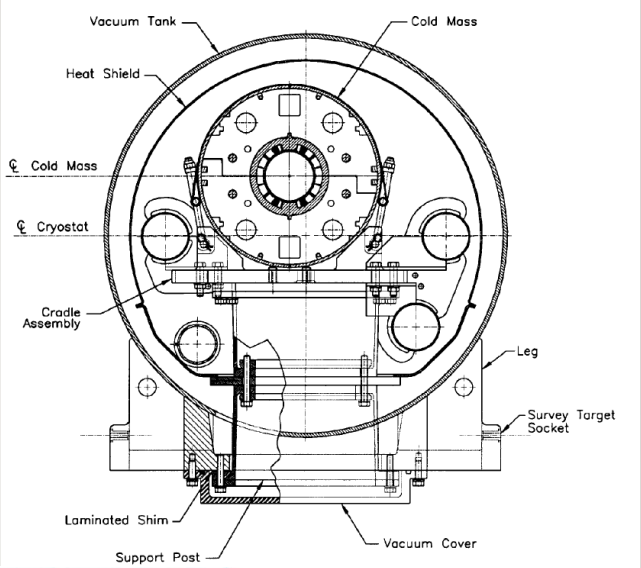
HERA Tunnel



Superconducting p-Ring

Normal e-Ring

1992年：DESY/HERA: 6.3km (4.7T, 8.8m, 416台)



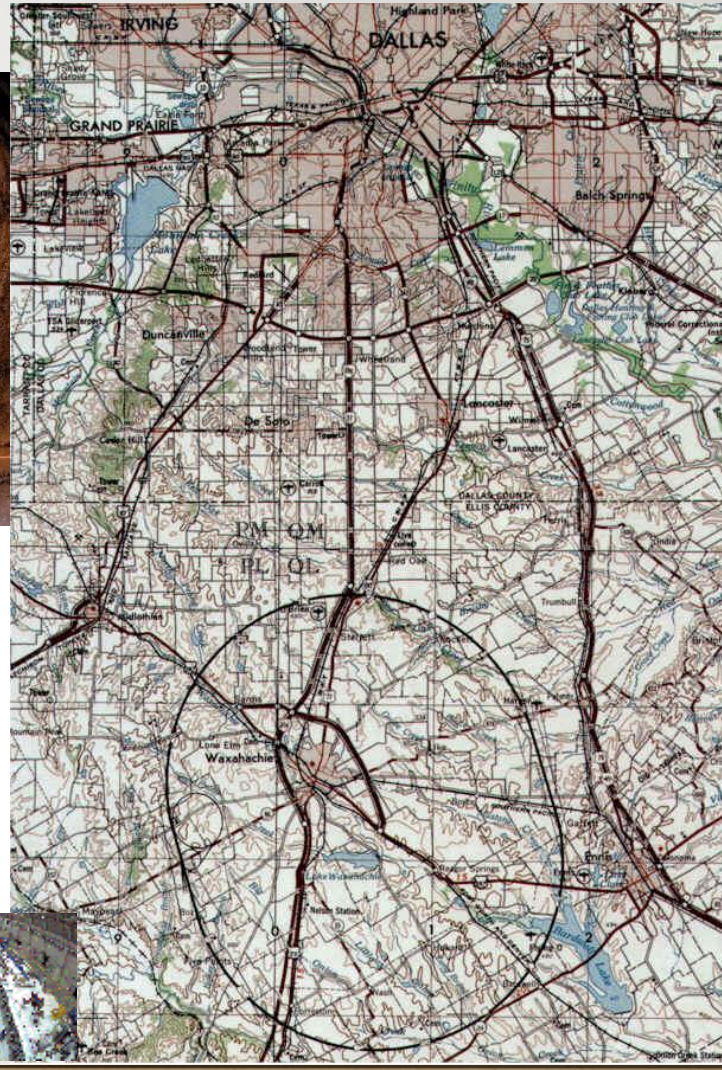

BNL Aerial View

RHIC Tunnel

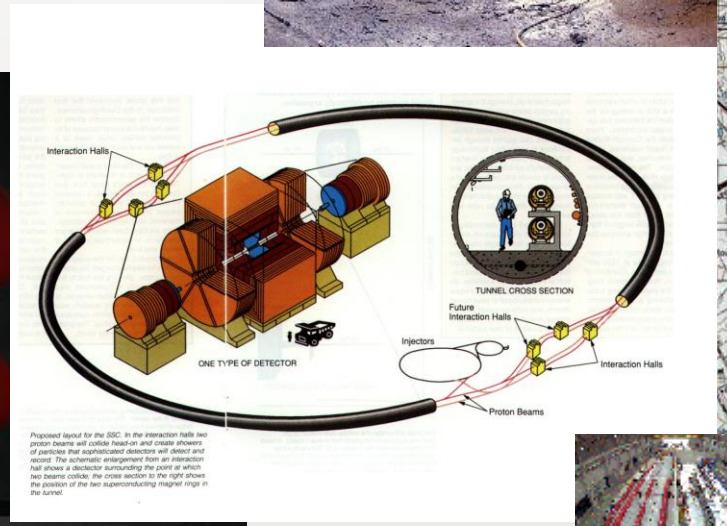
1998年：BNL/RHIC: 3.8km (3.5T, 9.7m, 288台)

# Superconducting Super Collider Tragedy of SSC

- **1988 Start construction > 1993 Canceled**
- **Fail to control budget: 4.4B$ → 12B$**
- **2B$ already spent**

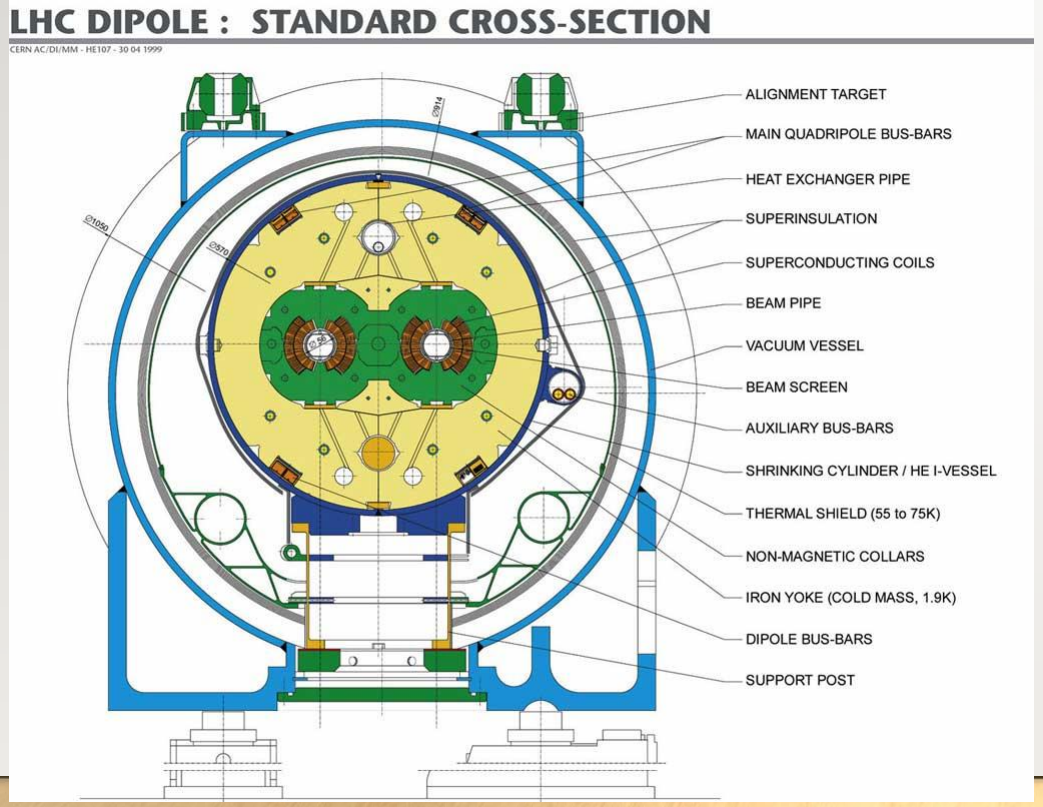


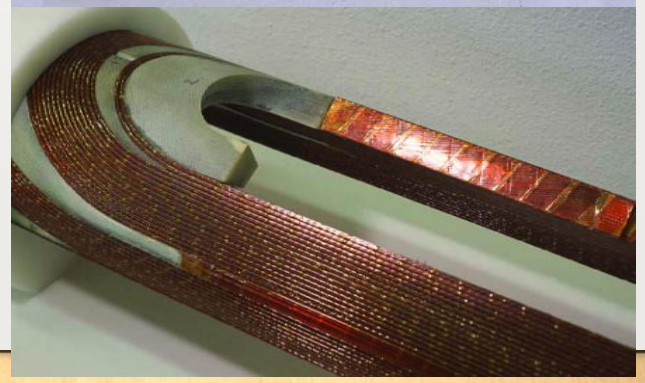


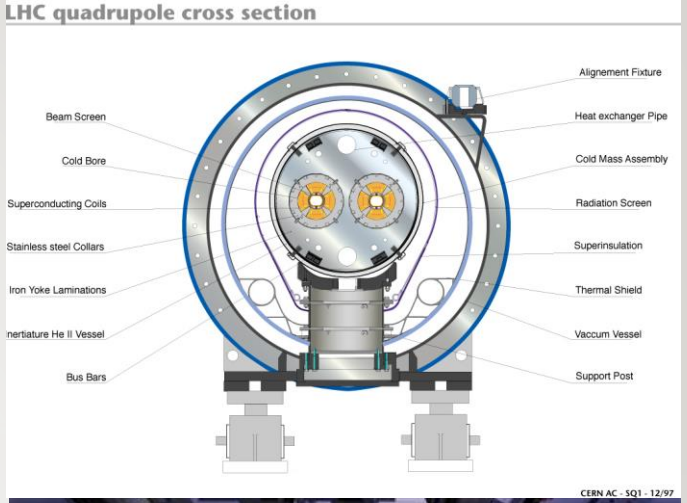


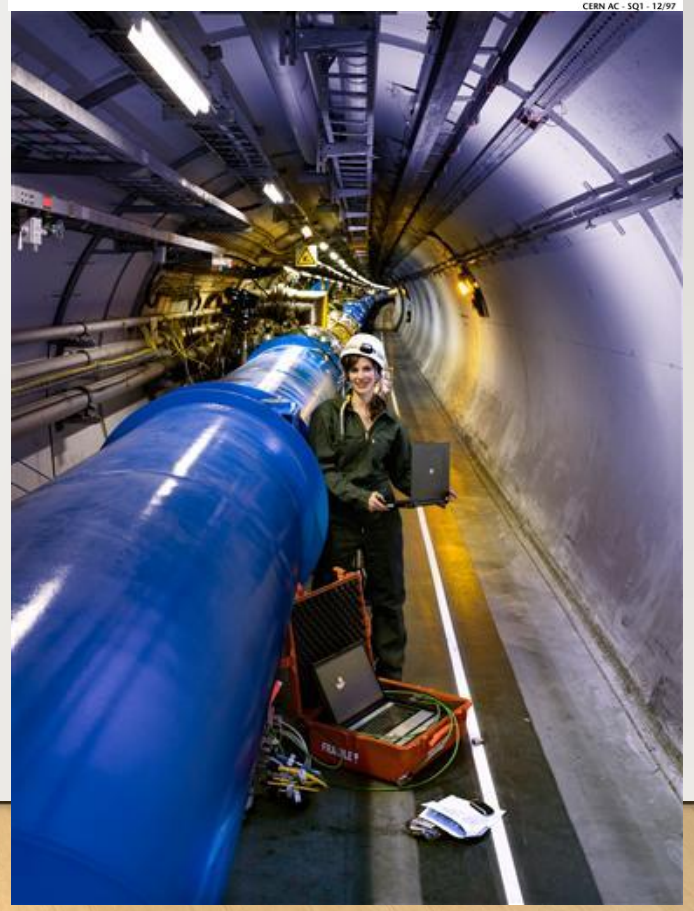

"Contrary to all the hype, the **SSC will not cure cancer**, will no provide a solution to the problem of male-pattern baldness, and will not guarantee a World Series victory for the Chicago Cubs". Congress Man Sherwood Boehlert

# Large Hadron Collider LHC



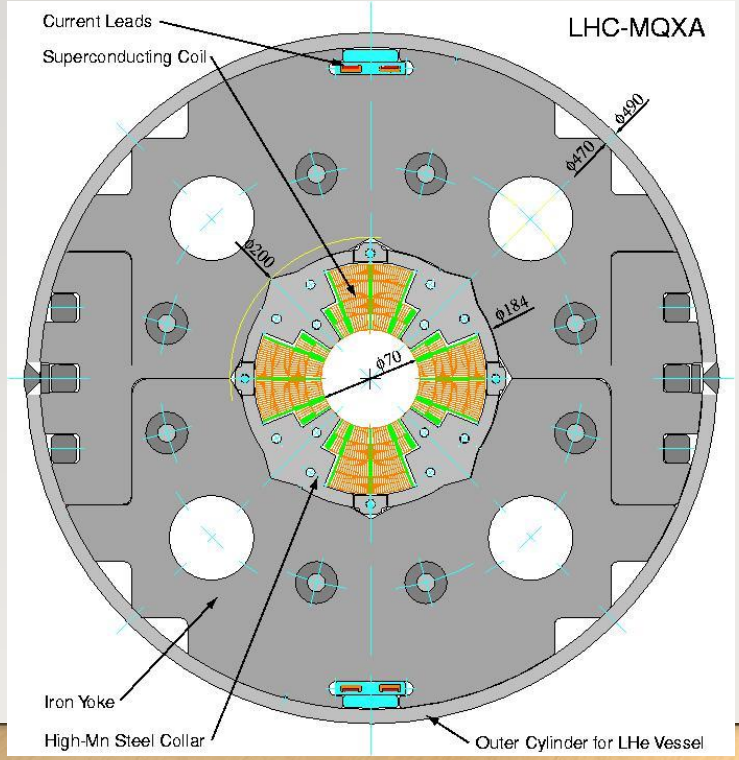


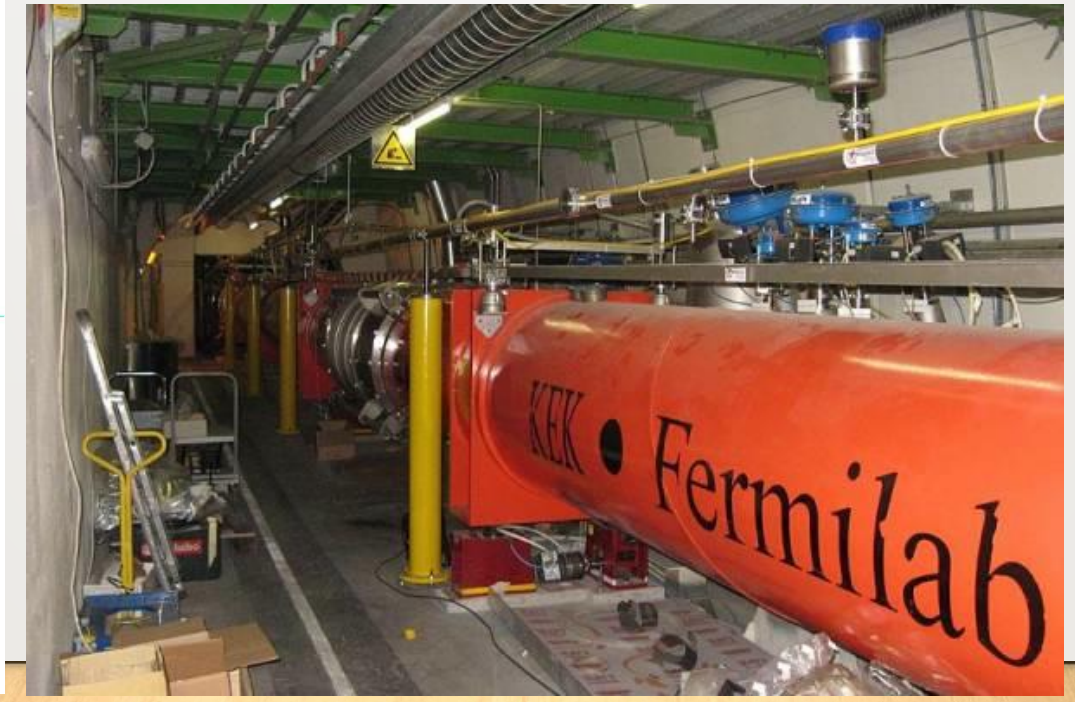



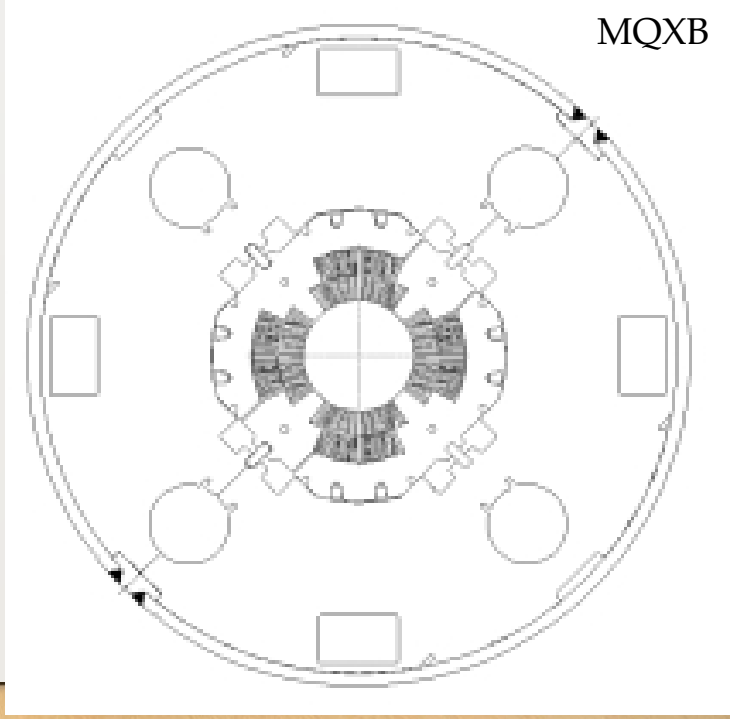
**2008年：CERN/LHC: 26.7km (8.3T, 14.2m, 1232台)**

# LHC International Collaboration MQXA and MQXB

- Focus Beam at Interaction region
  - Japan and US collaborating together to contribute LHC

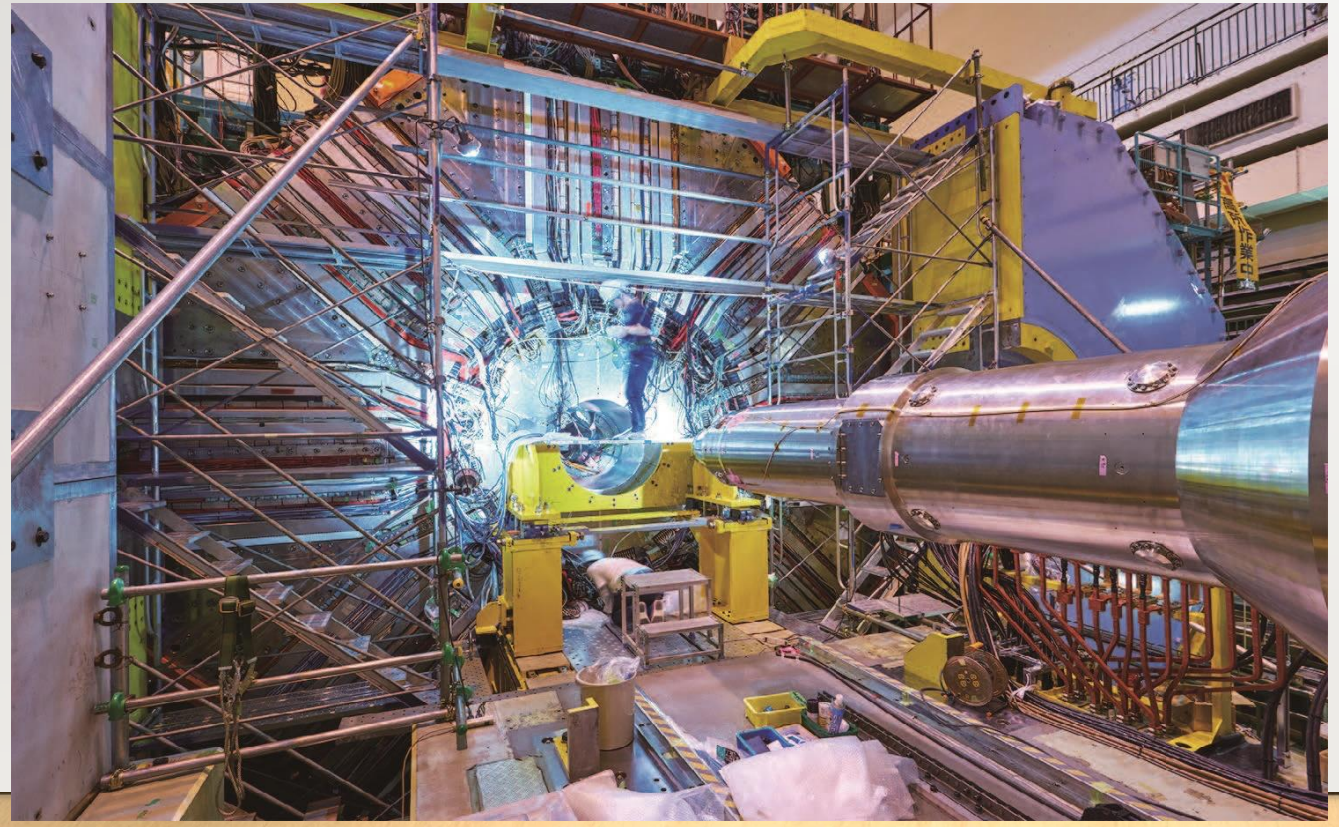


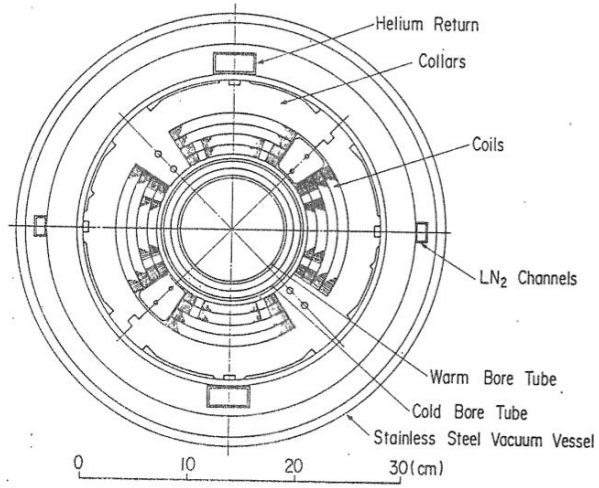
# Electron Positron Colliders TRISTAN, KEKB, S-KEKB

Interaction Region Superconducting Magnet

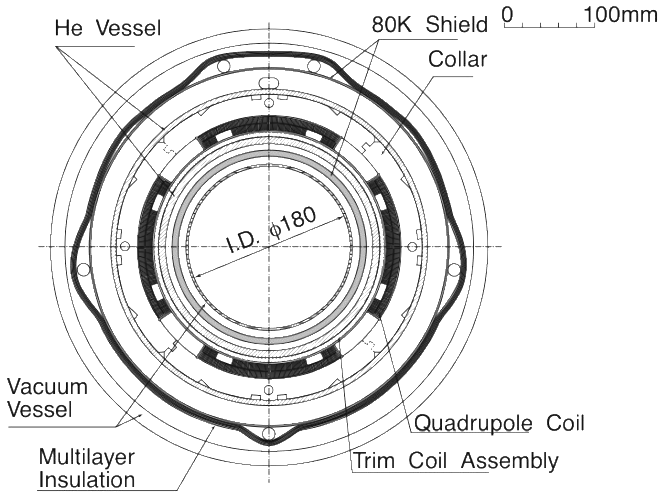


SuperKEKB Interaction Region Superconducting Magnet

b) TRISTAN QCS(70T/m, 4.5K)

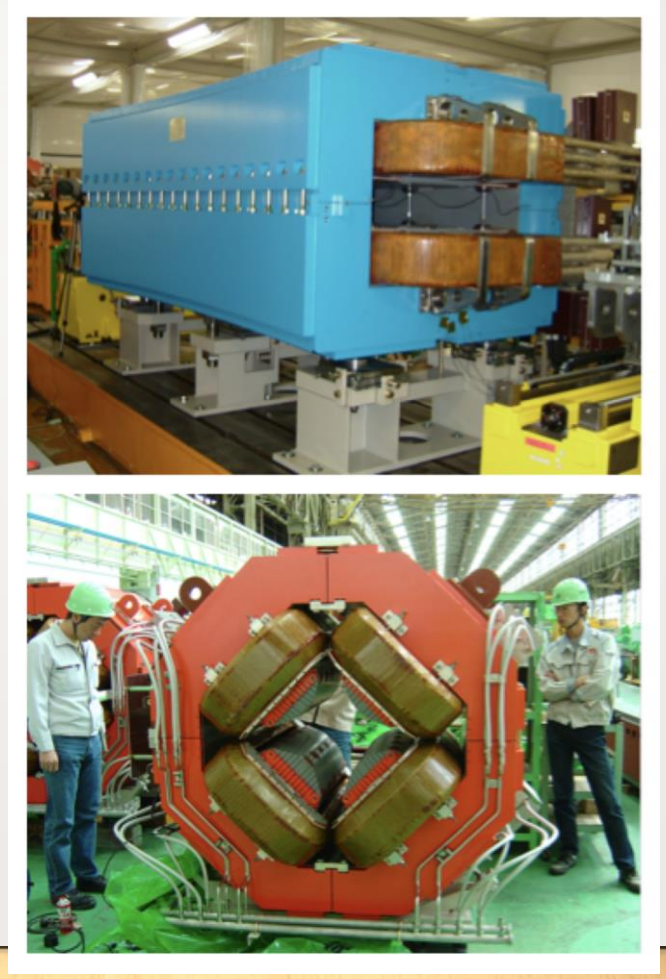



c) KEK-B QCS(22T/m, 4.5K)



# High Power Accelerator J-PARC

- J-PARC: Extraction Machine
  - Rapid cycle operation: dificult for Superconducting Magnet
    - AC loss
  - J-PARC RCS (3GeV 1MW)：25 Hz
  - J-PARC MR (30GeV 1MW): ~1 Hz
- Beam Line after extraction
  - fixed energy = fixed field
  - J-PARC Neutrino Facility

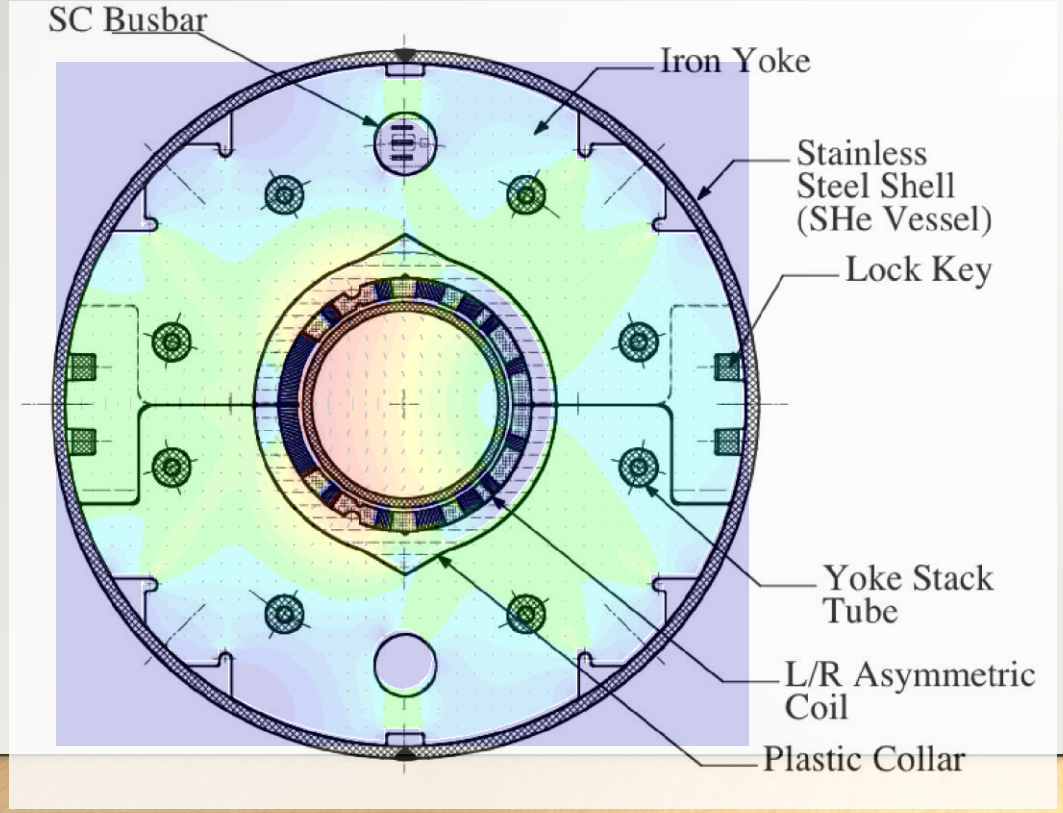


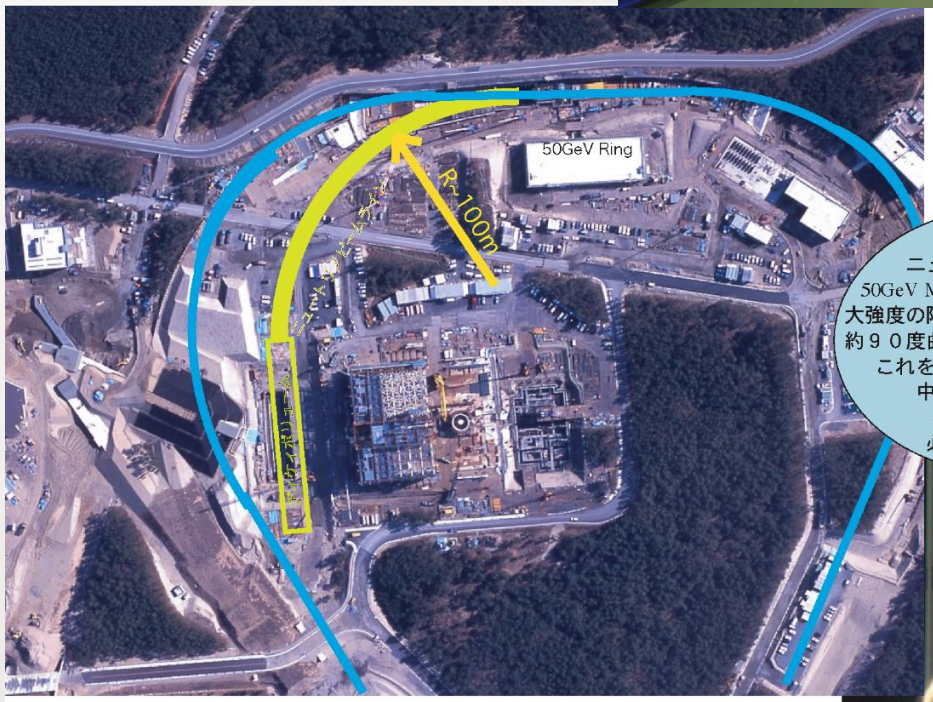
J-PARC RCS Magnets

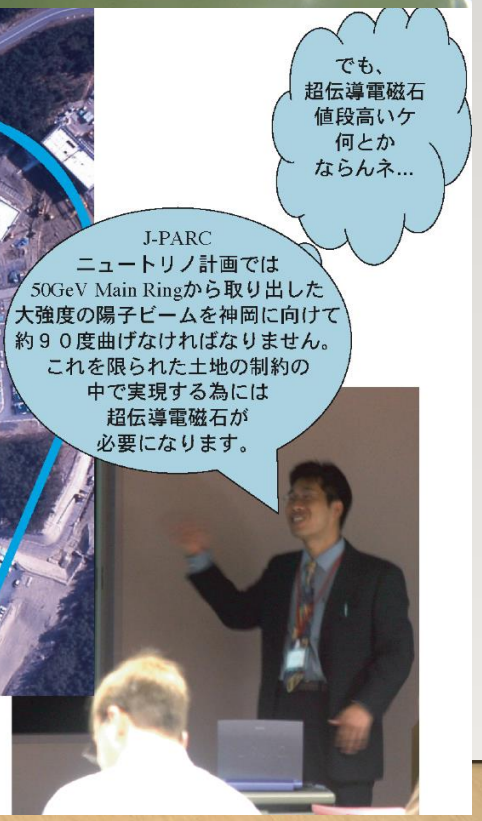
J-PARC MR Magnets

# J-PARC Neutrino Facility

- Need SC magnet to save space.



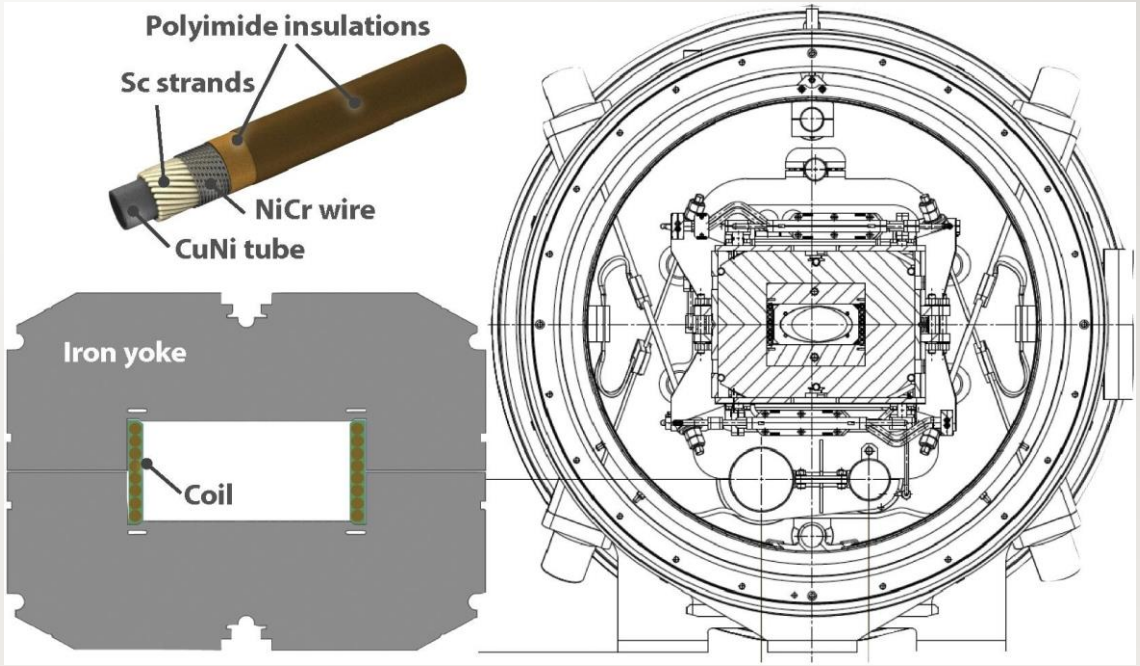




Combined function magnet (2.6T+19T/m, 28 SCFM) optimize schedule and budget

# High Power Accelerator
# TEVATRON, GSI SIS100, RIKEN SRC

- TEVATRON (800GeV ~70kW)
  - Originaly exraction machine
  - ZEBRA cable: AC loss
  - Not very fast cycle: 1 min
- GSI SIS100 (30GeV ~100kW)
  - Superferic; 1.9T, 1Hz(4T/s)
- RIKEN SRC (0.4GeV 80kW)
  - Largest cyclotron
  - DC Operation
  - Energy limitation




GSI SIS100 Main Dipole Magnet

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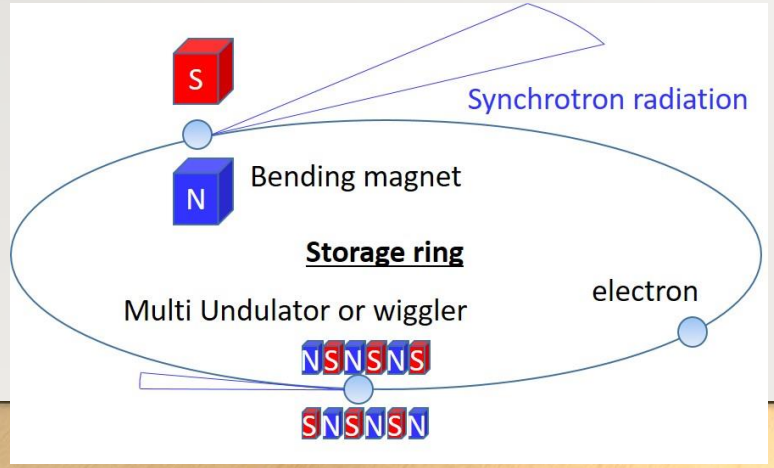
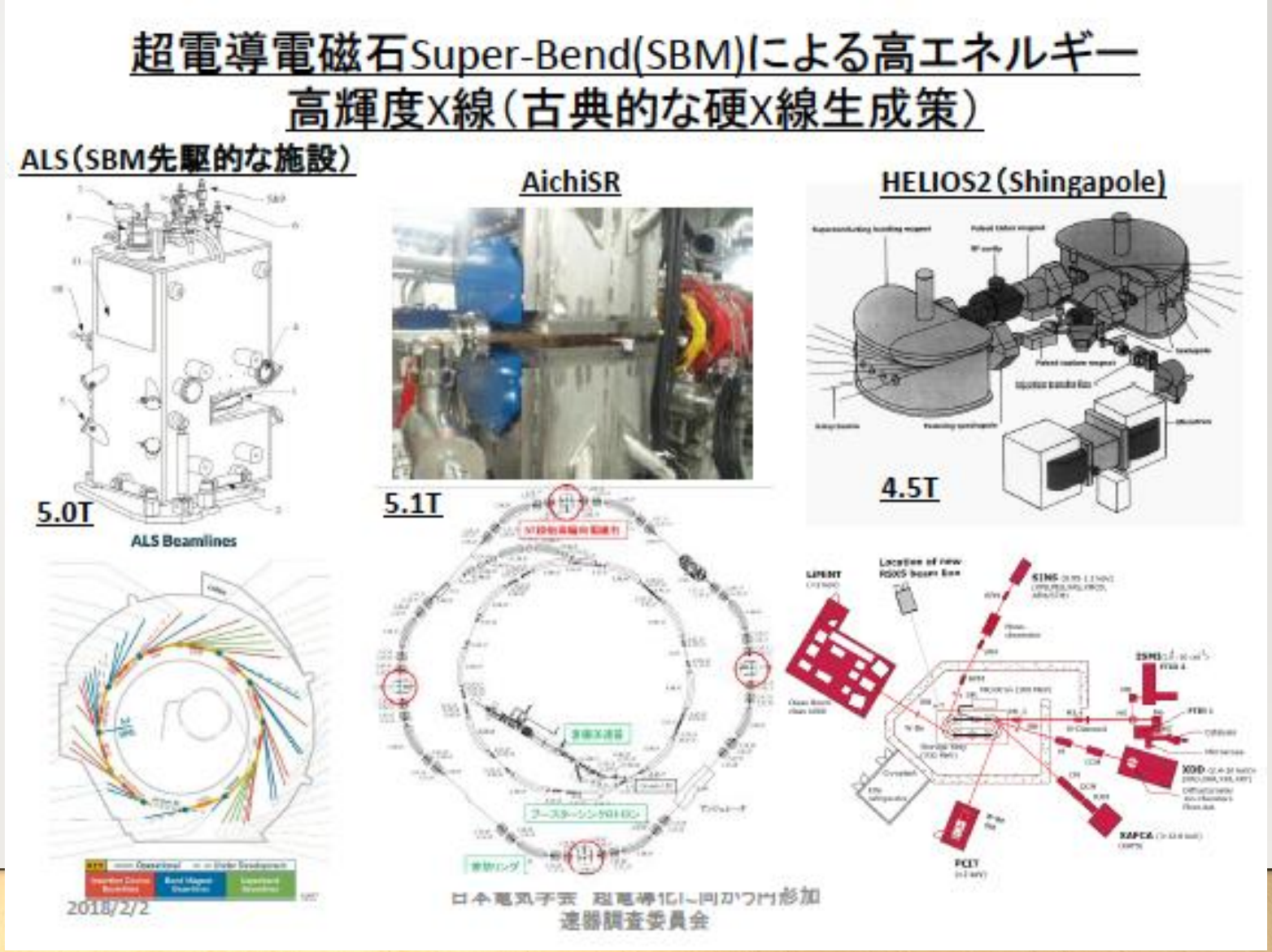
# Synchrotron Light Source

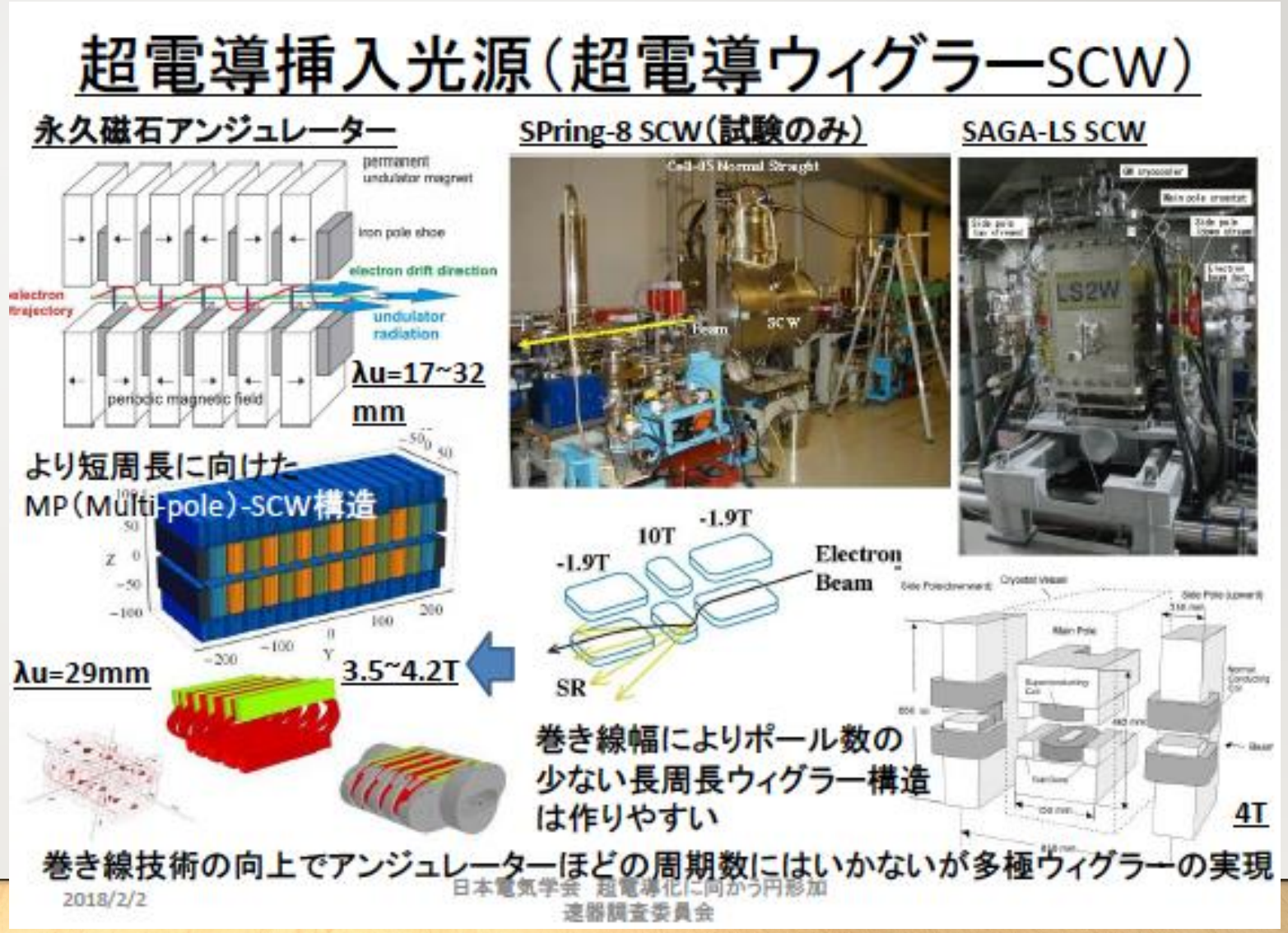
- Super-Bend
- Traditional



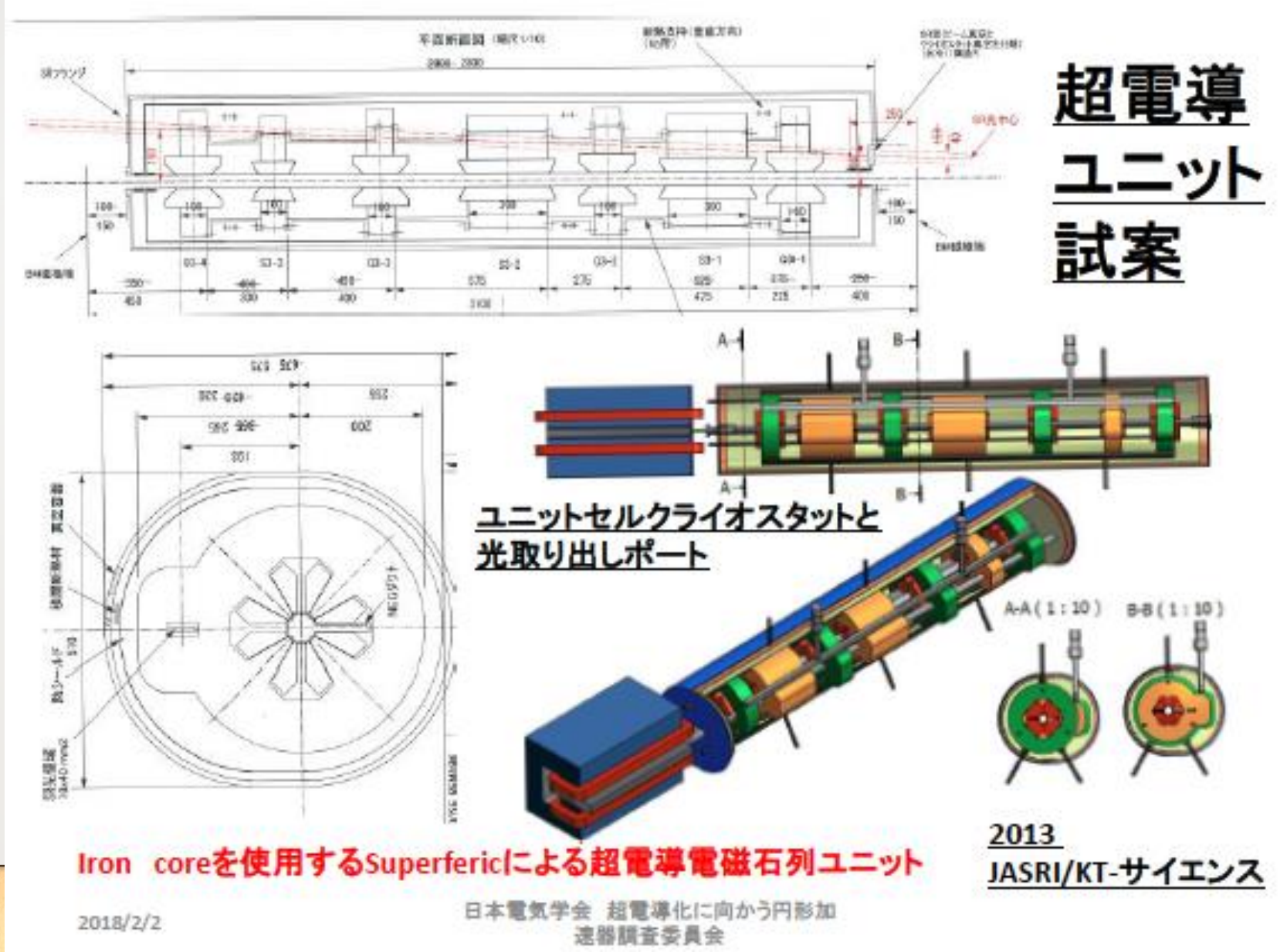
# Synchrotron Light Source

- Wiggler
- High Field Wiggler by Superconducting Magnets



# Synchrotron Light Source

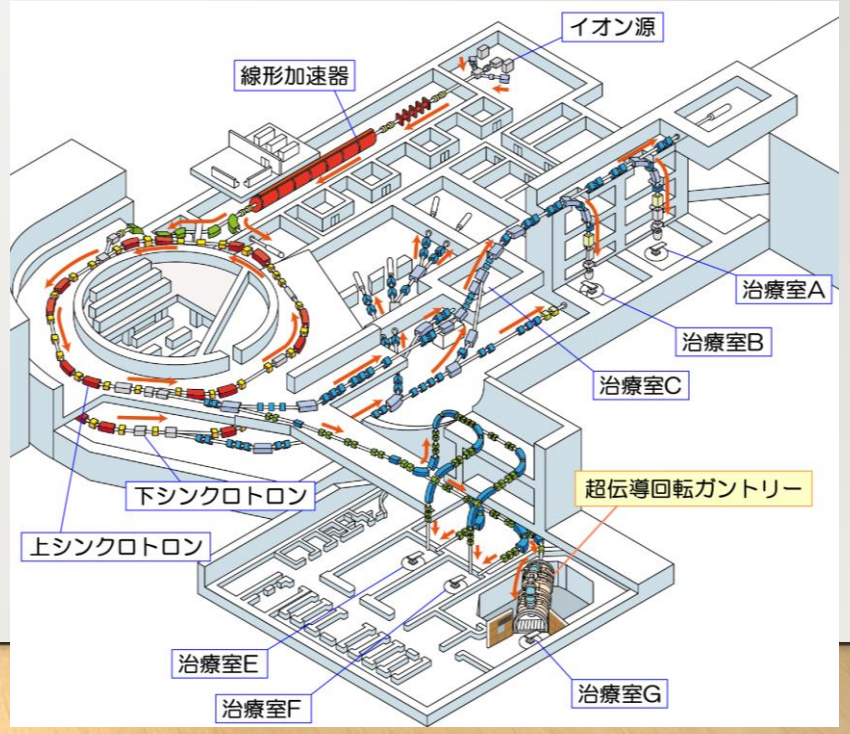
- High Field Focusing Magnets



# Medical Synchrotron for Carbon Therapy

- Extraction type synchrotron
  - Normal conducting magnets

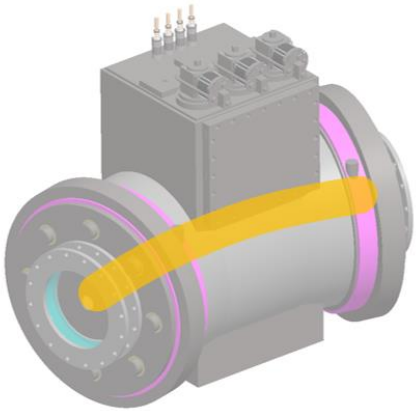
世界初の重イオン加速器治療を行なったLBNLのBevalac




放医研のHIMAC

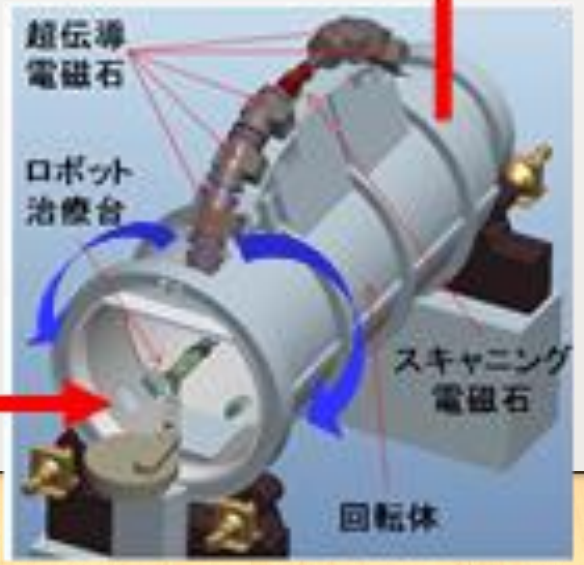
# Medical Synchrotron for Carbon Superconducting Gantry

To reduce size and weight



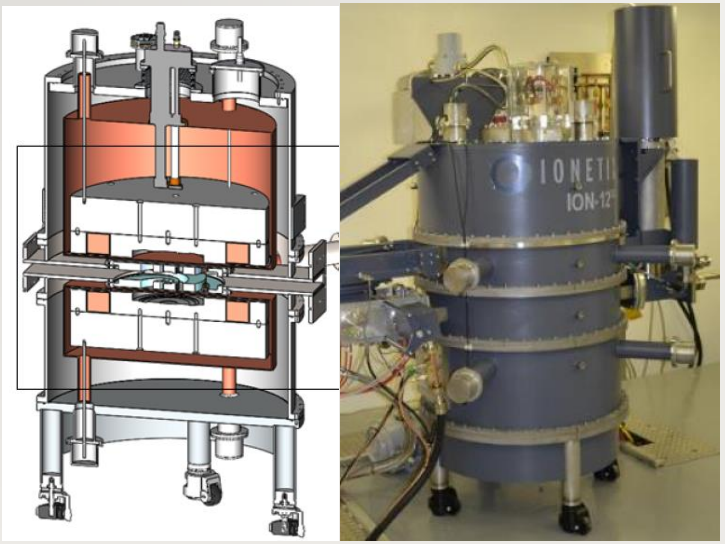
ガントリー用超電導コイルのイメージ
(オレンジの部分)

実際の超電導コイル

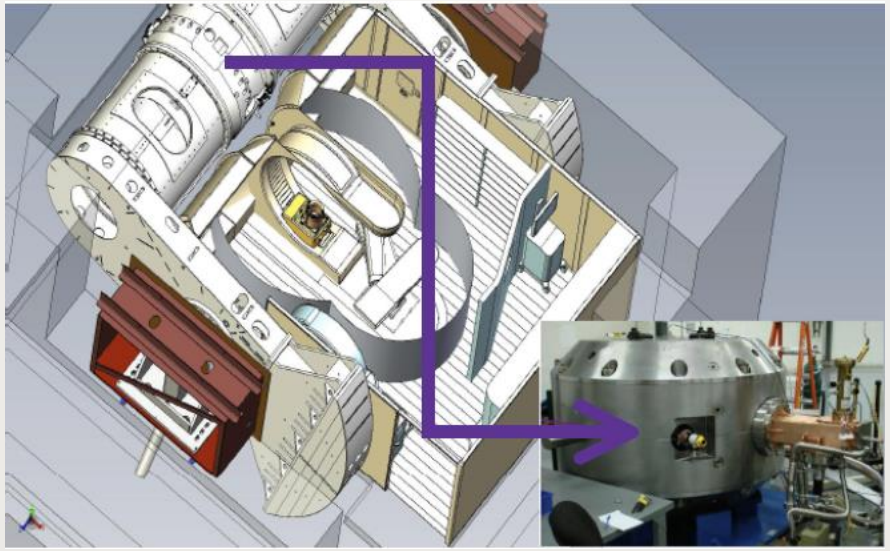



# Small Accelerator Superconducting Cyclotron

- DC operation: good for superconducting magnet
- High Field = smaller size
  - Smaller beam separation: larger beam loss




Cyclotron to produce radioactive material at the University of Michigan

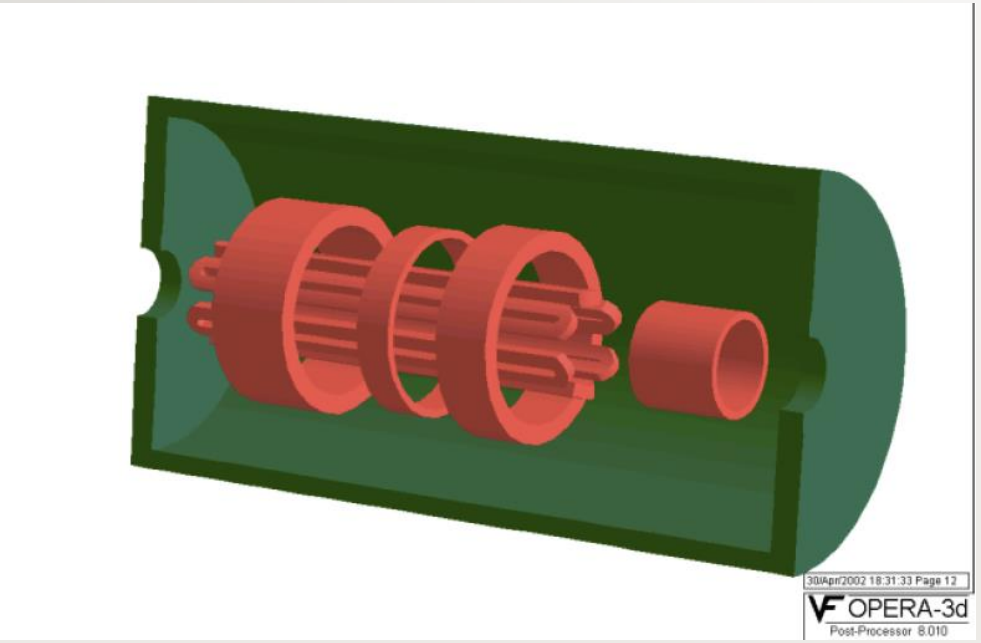


Superconducting Cyclotron for Proton Therapy Mevion S250

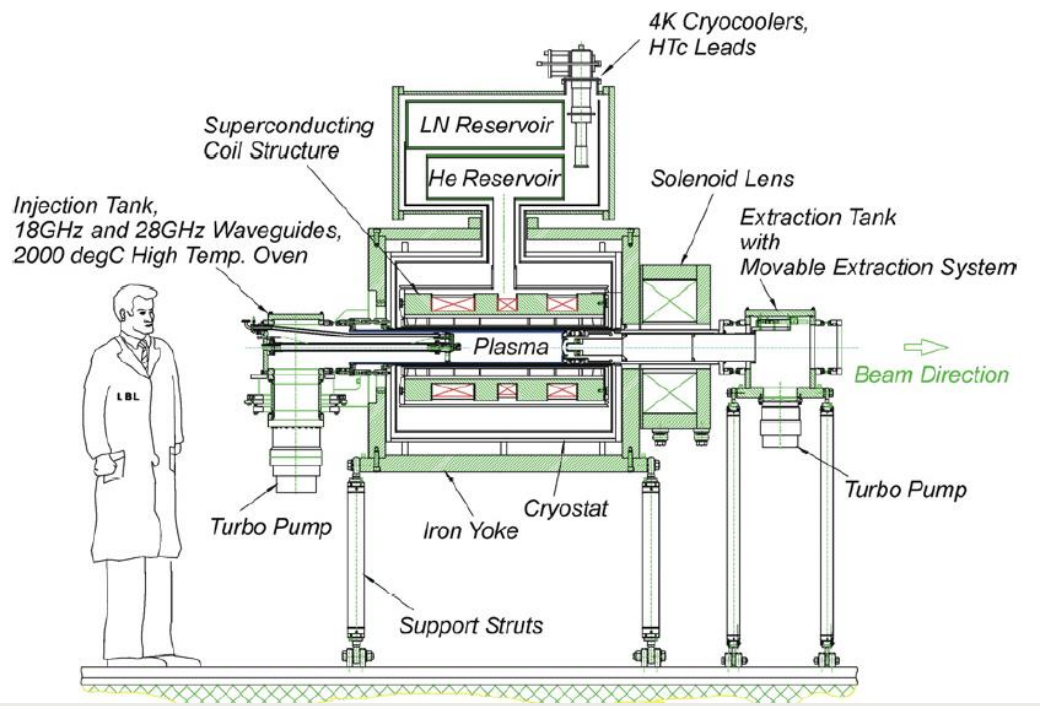
Superconducting Cyclotron for Proton Therapy by IBA

# Small Accelerator Application
# ECR Iron Source

- Trap plasma via strong solenoid field with sextupole field




GyroSERSE Solenoid and Sextupole coil by OPERA-3D

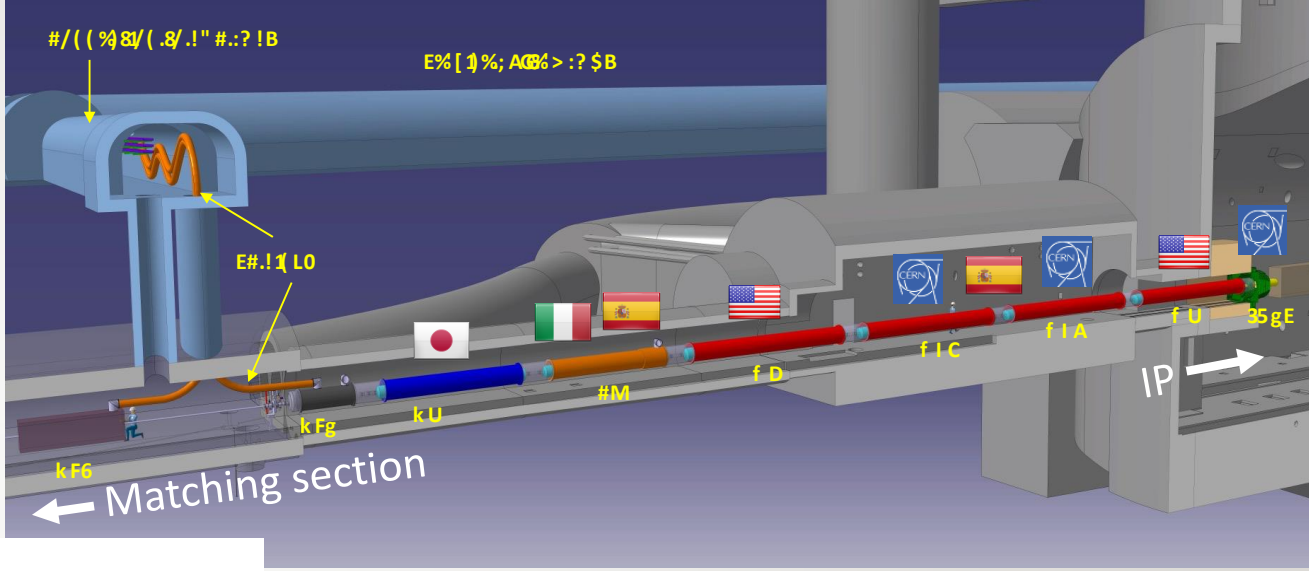


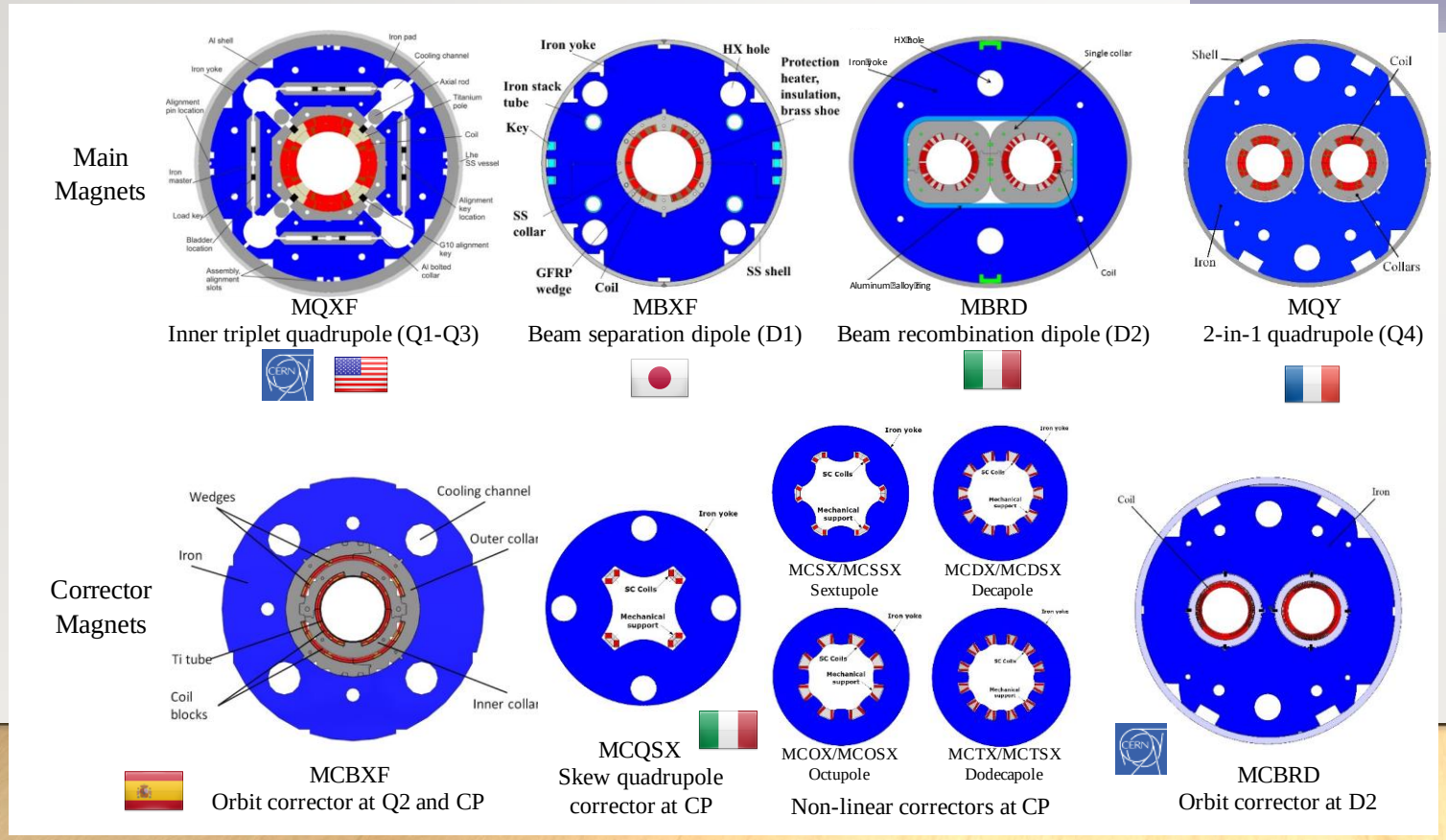

VENUS Iron Source at LBNL

# Item

- Introduction：Accelerator and Magnet
- Superconducting Magnet for Accelerator
  - Collider・Large Accelerators
  - Light Source・Medical・Small Accelerators
- Future Possibilities
- Summary

# Future Reality HL-LHC

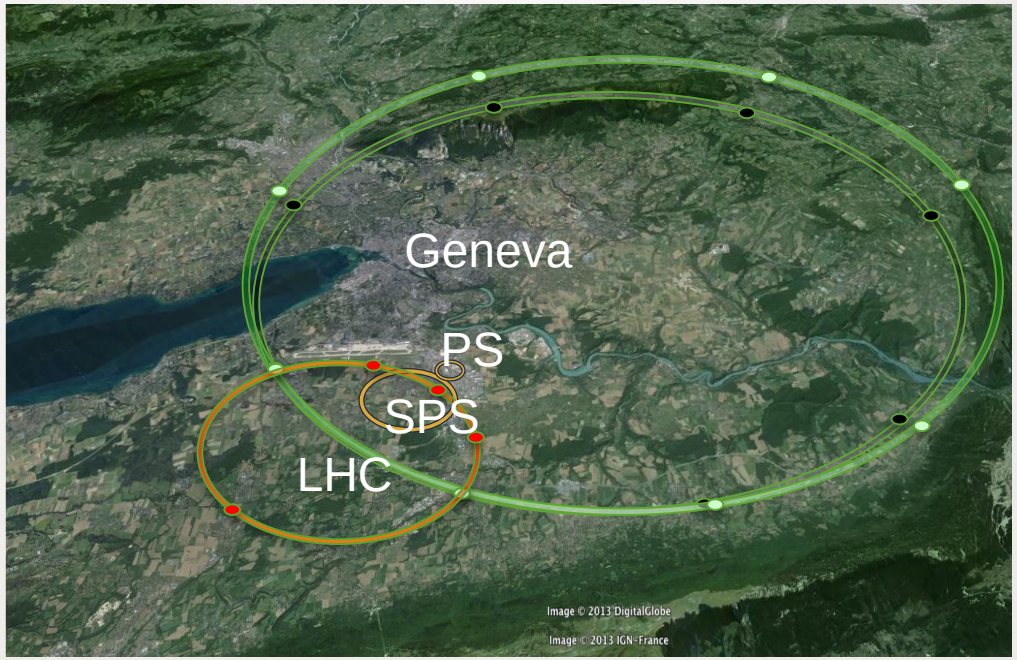


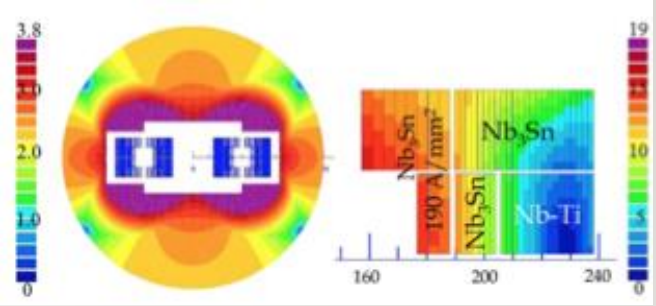



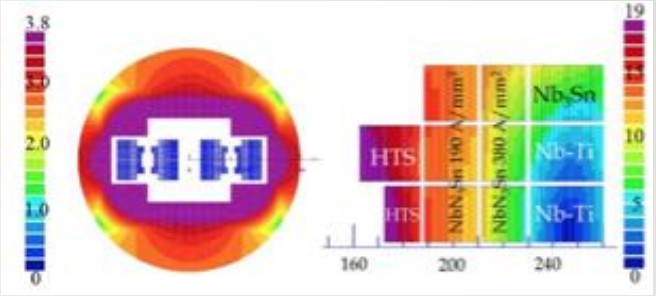

- Upgrade Interaction region
  - Smaller beam size
    - Higher Field Focusing Magnets ($Nb_3Sn$)
  - Club Cavity
  - Higher Field Beam Separation Dipole
  - Increase Luminosity

# Future Possibilities
# Future Circular Collider：FCC at CERN

Future Circular Collider (FCC)
Future 100 TeV Machine
At around CERN
100km ring with 16T $Nb_3Sn$
Or 20T with 20T HTS




FCC-hh
80 km, **20 T**
100 TeV (c.o.m.)

FCC-hh
100 km, **16 T**
100 TeV (c.o.m.)

# Future Possibilities: SPPC at China

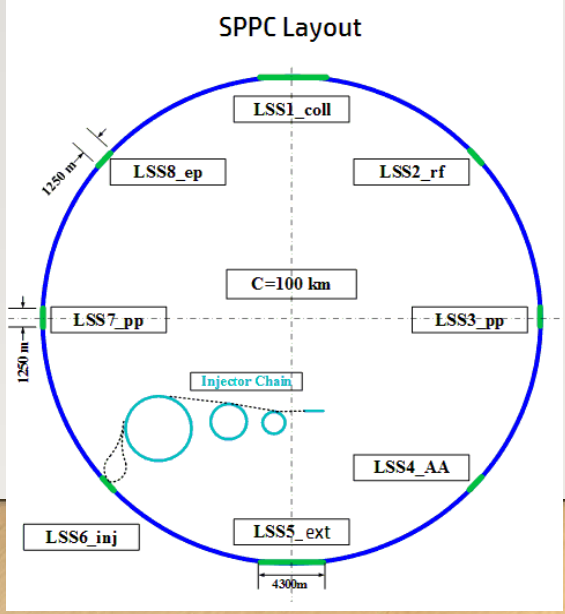
*SPPC*

- ***100** km in circumference*
- *C.M. energy 70-150 (Upgrading) TeV*
- *Timeline*

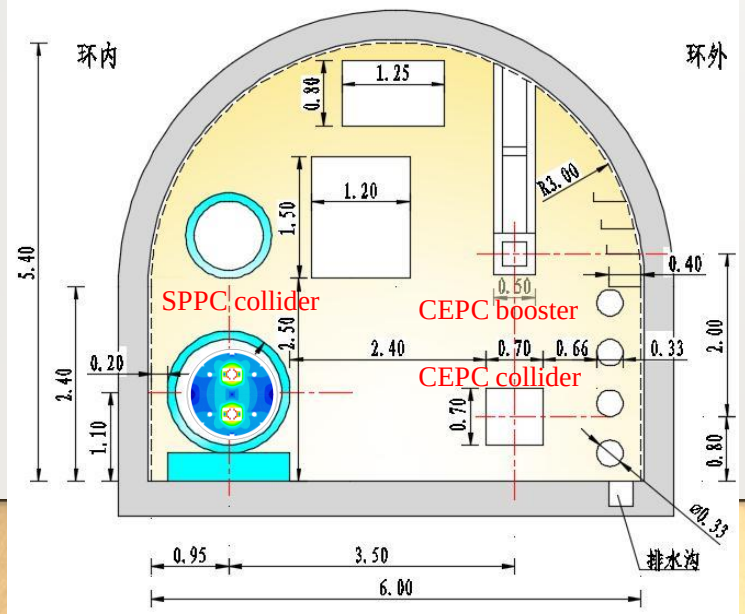
  *Pre-study: 2013-2020*
  *R&D: 2020-2030*
  *Eng. Design: 2030-2035*
  ***Construction: 2035-2042***

***Main dipoles*** $E[GeV] = 0.3 \times B[T] \times \rho[m]$

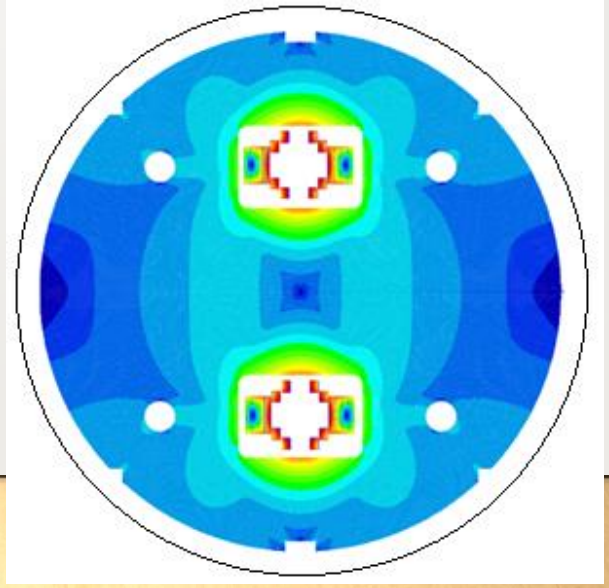
- *Field strength: 12~24 (Upgrading) Tesla*
- *Aperture diameter: 40~50 mm*
- *Field quality: $10^{-4}$ at the 2/3 aperture radius*
- *Outer diameter: 650-900 mm in a 1.5 m cryostat*
- *Tunnel cross section: 6 m wide and 5.4 m high*

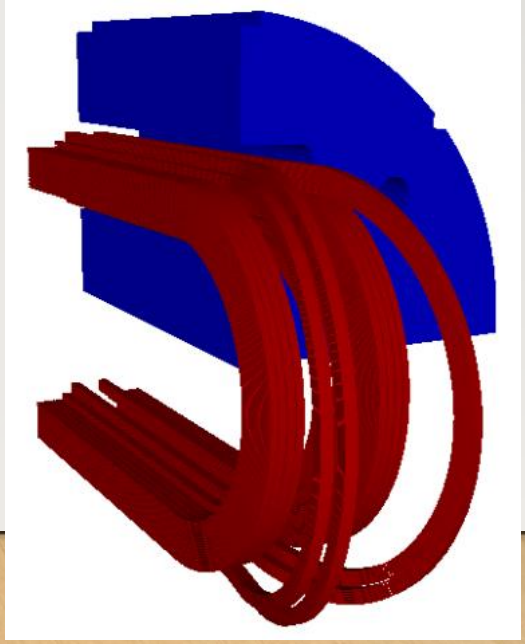



6-m Tunnel for CEPC-SPPC



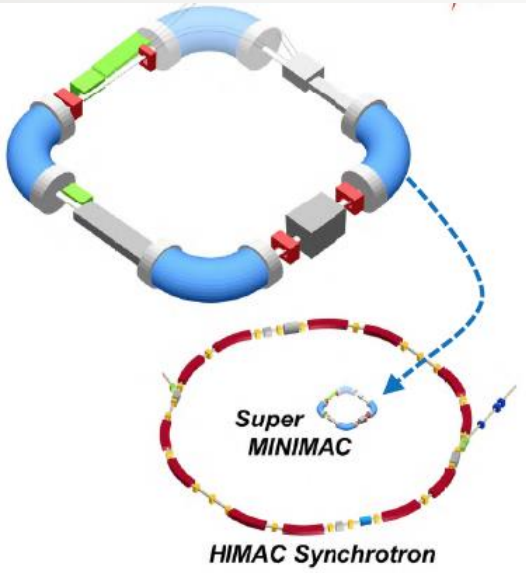

Conceptual design of the SPPC 12-T magnet with IBS and common coil configuration

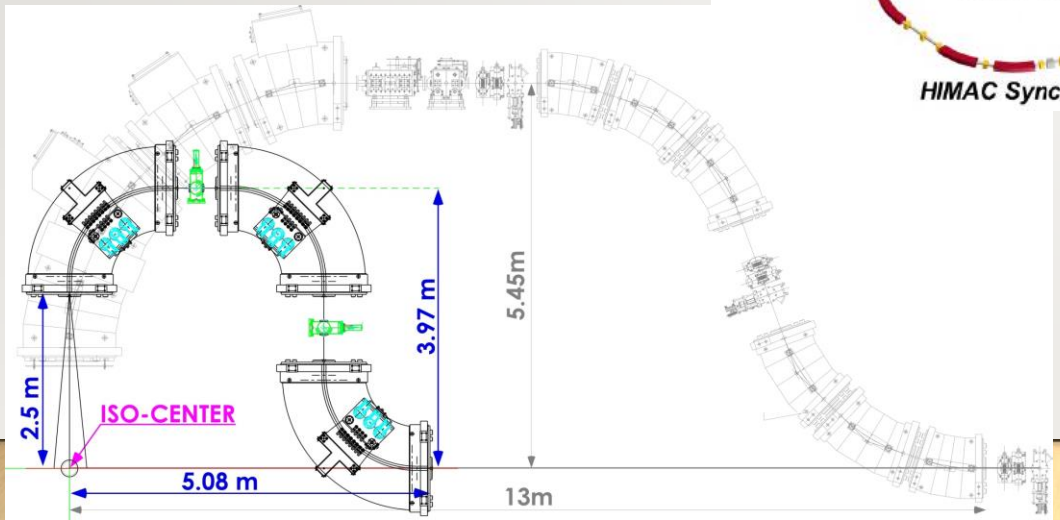


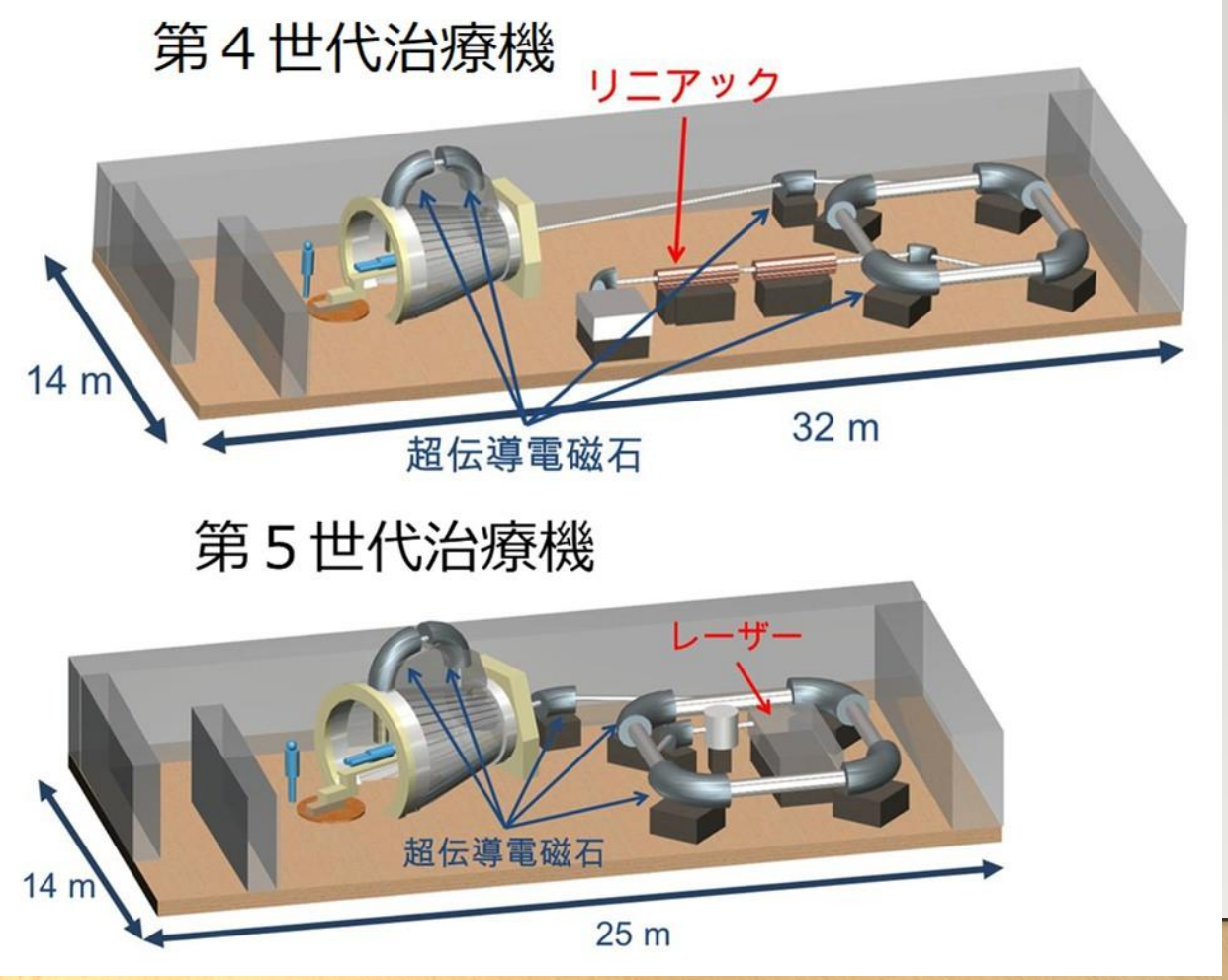


# Future Possibilities: Medical Accelerator Carbon Therapy

- Smaller Accelerator with SCM

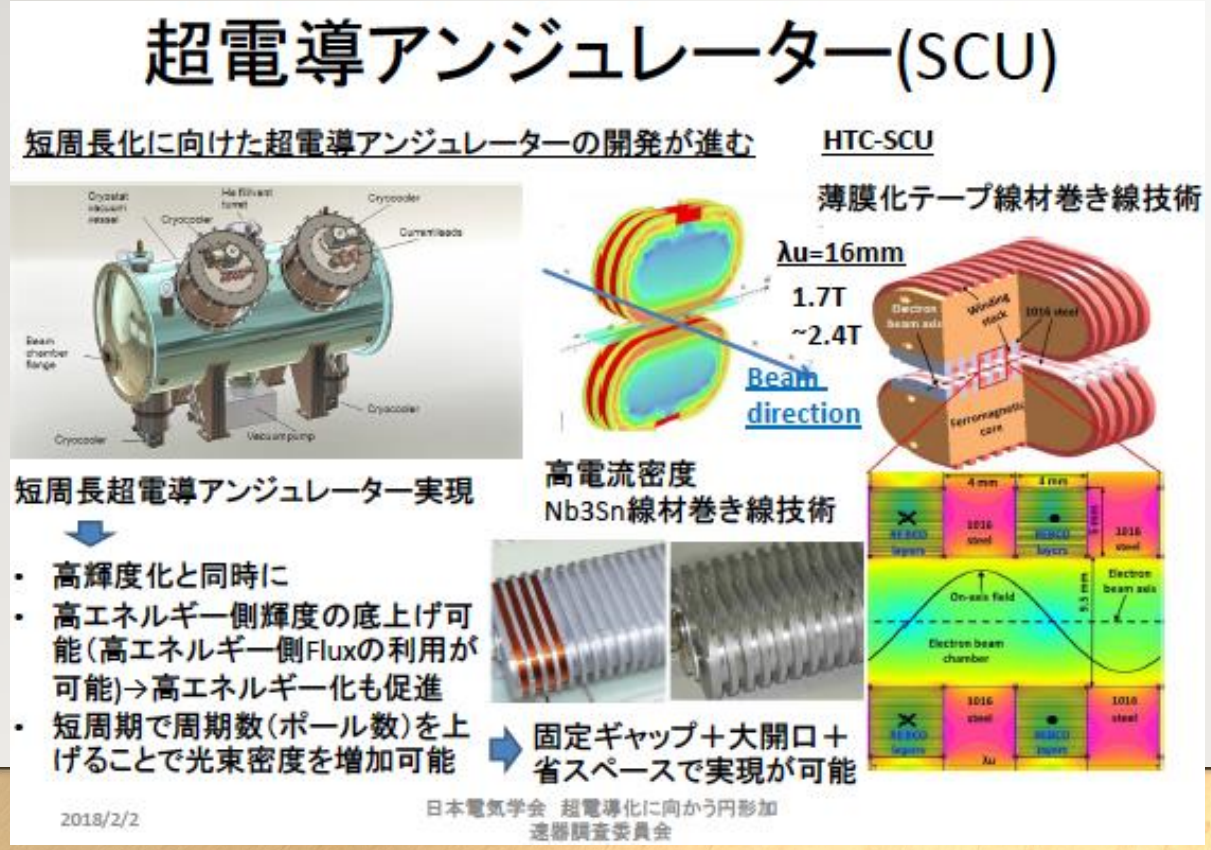


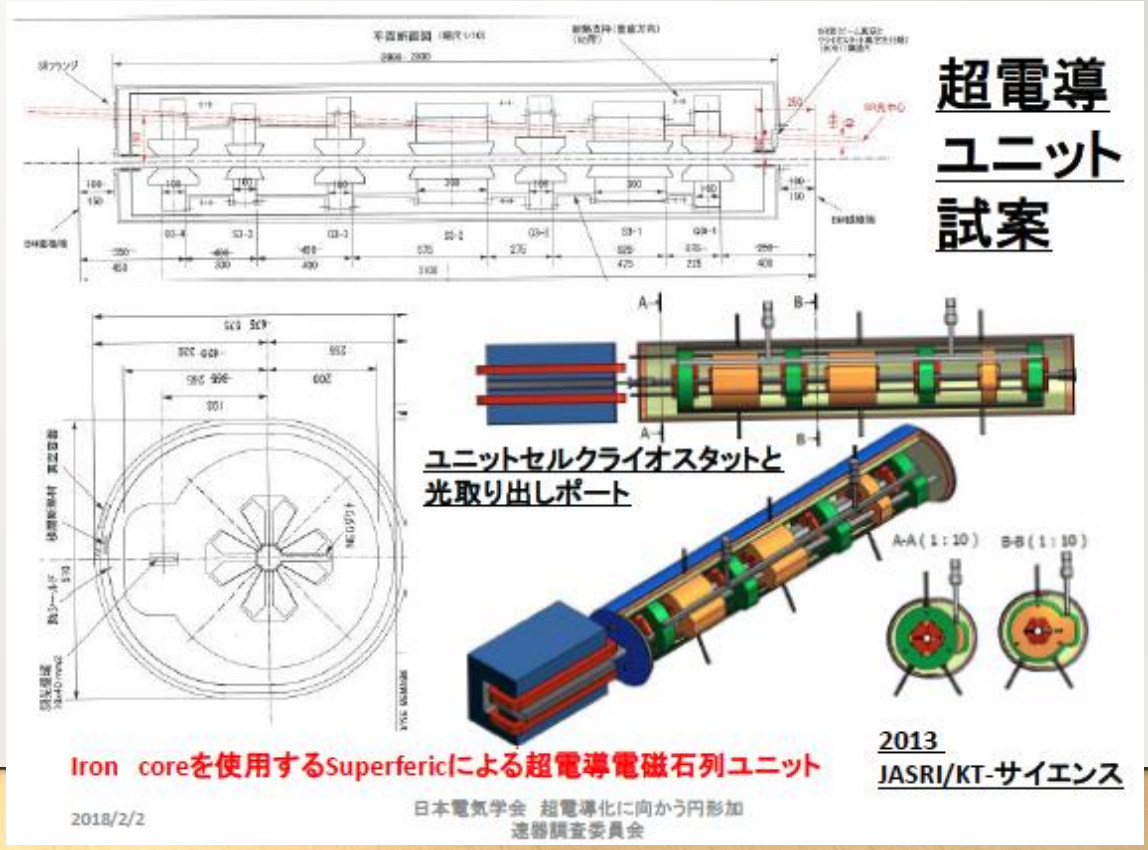



# Future Possibilities
# Synchrotron Light Source

- Superconducting Undulator or Superconducting Focusing Magnets



# Summary

- Accelerator and Superconducting Magnet: developed simultaneously
- Superconducting Magnet: Good for Slow Repetition Accelerator
  - Good for Collider and Synchrotron Light Source
  - High Field: limited for NbTi needs new technologies A15 or HTS or IBS
- Not used for high repetition accelerators
  - AC loss, error field due to eddy current etc…
  - But there are needs, such as medical acclerators
- Possibilities for new conductor
  - $Nb_3Sn$ or IBS for high field magnet
  - HTS for high field or high temperature
    - High heat load, i.e. high radiation environment, high repetition….
- **In any case cost is important issue: chicken or egg**