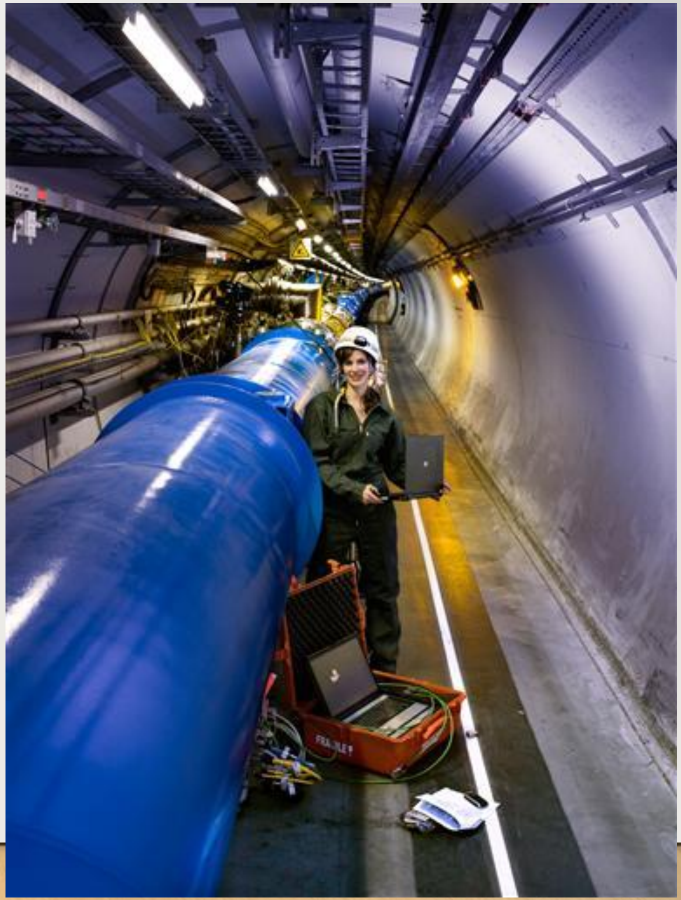
1

# Superconducting Magnets for Accelerator Science

CERN LHC

# Item

- Accelerator & Superconducting Magnet
- Superconducting Magnets for Hadron Colliders
- Superconducting magnet applications in various accelerators
- Summary

# Item

- **Accelerator & Superconducting Magnet**
- Superconducting Magnets for Hadron Colliders
- Superconducting magnet applications in various accelerators
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4

# Accelerator？

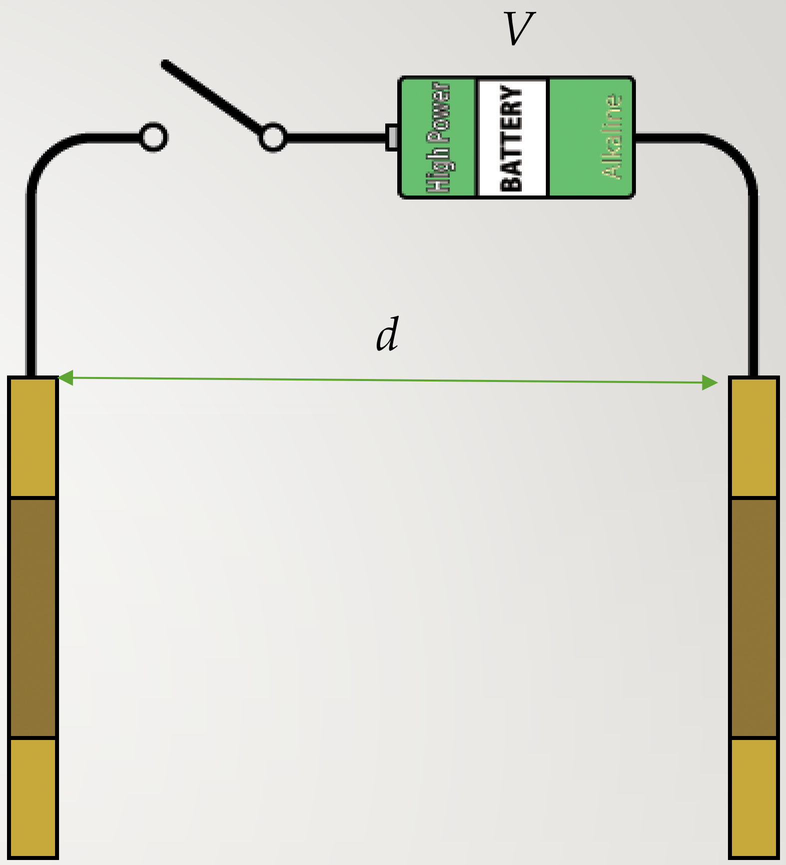
- Accelerate Charged Particle

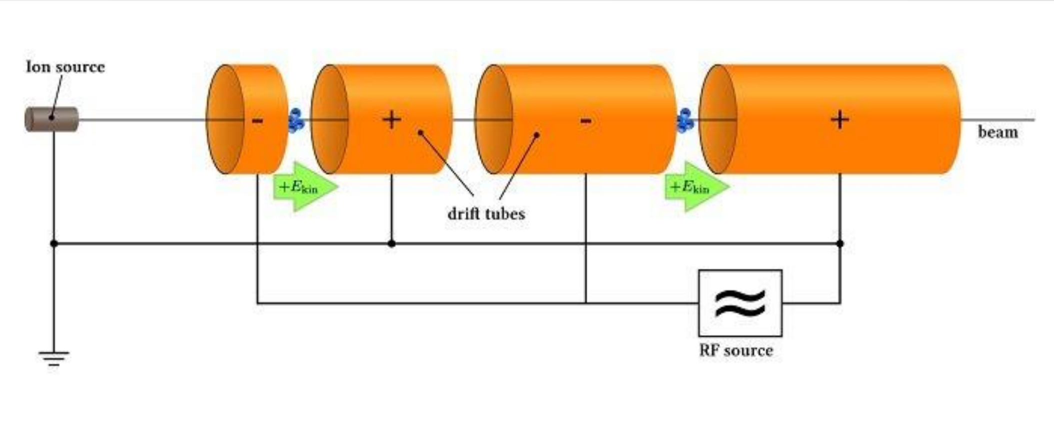
$$F = q \times E$$

$F$:力

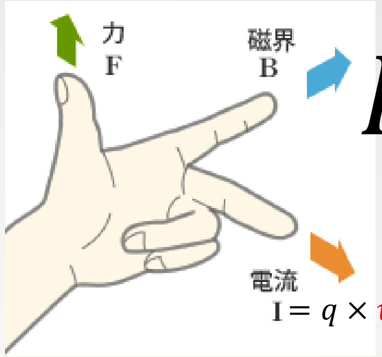
$q$: Charge

$E$: *Electric Field*（$E=V/d$）



# 5 Ring Accelerator Synchrotron

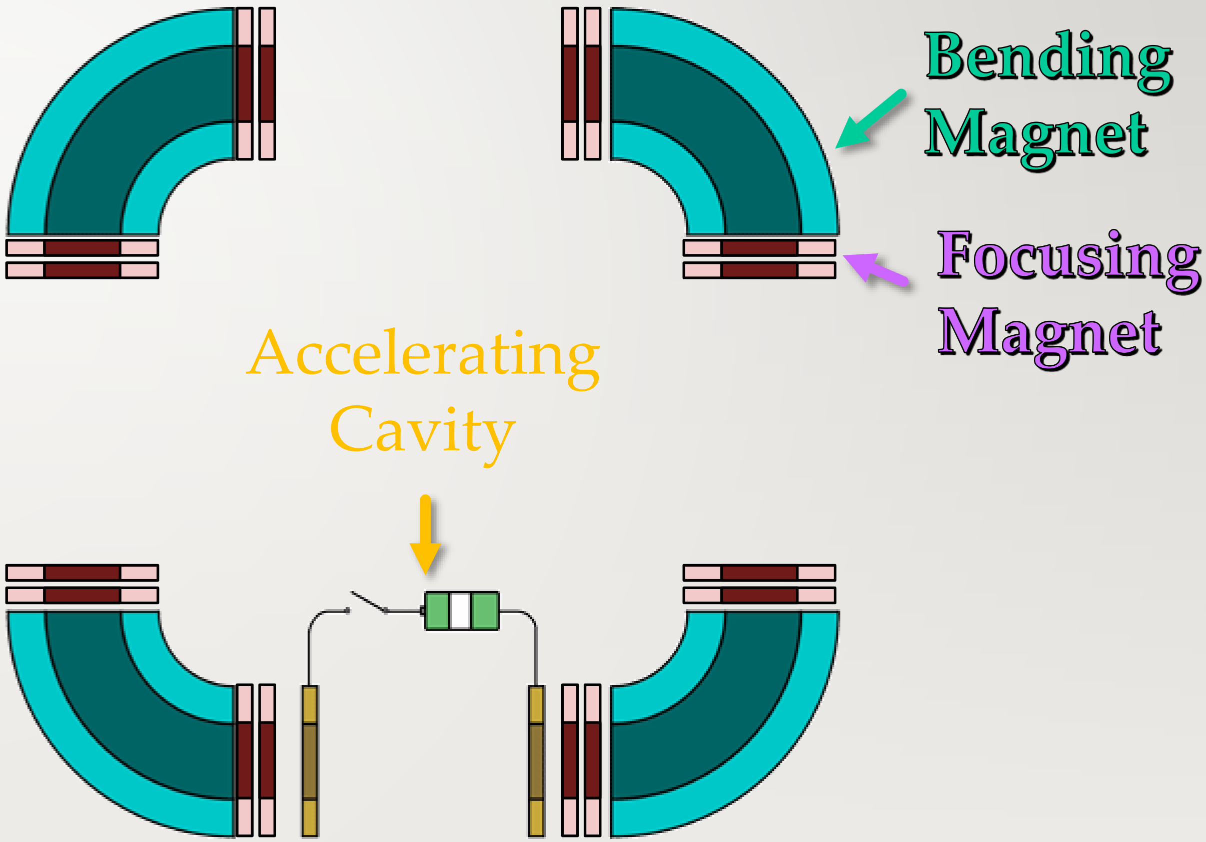



$$F = q \times v \times B = \frac{m \times v \times v}{r}$$

EM Force 遠心力

Bent Beam by Magnetic Field

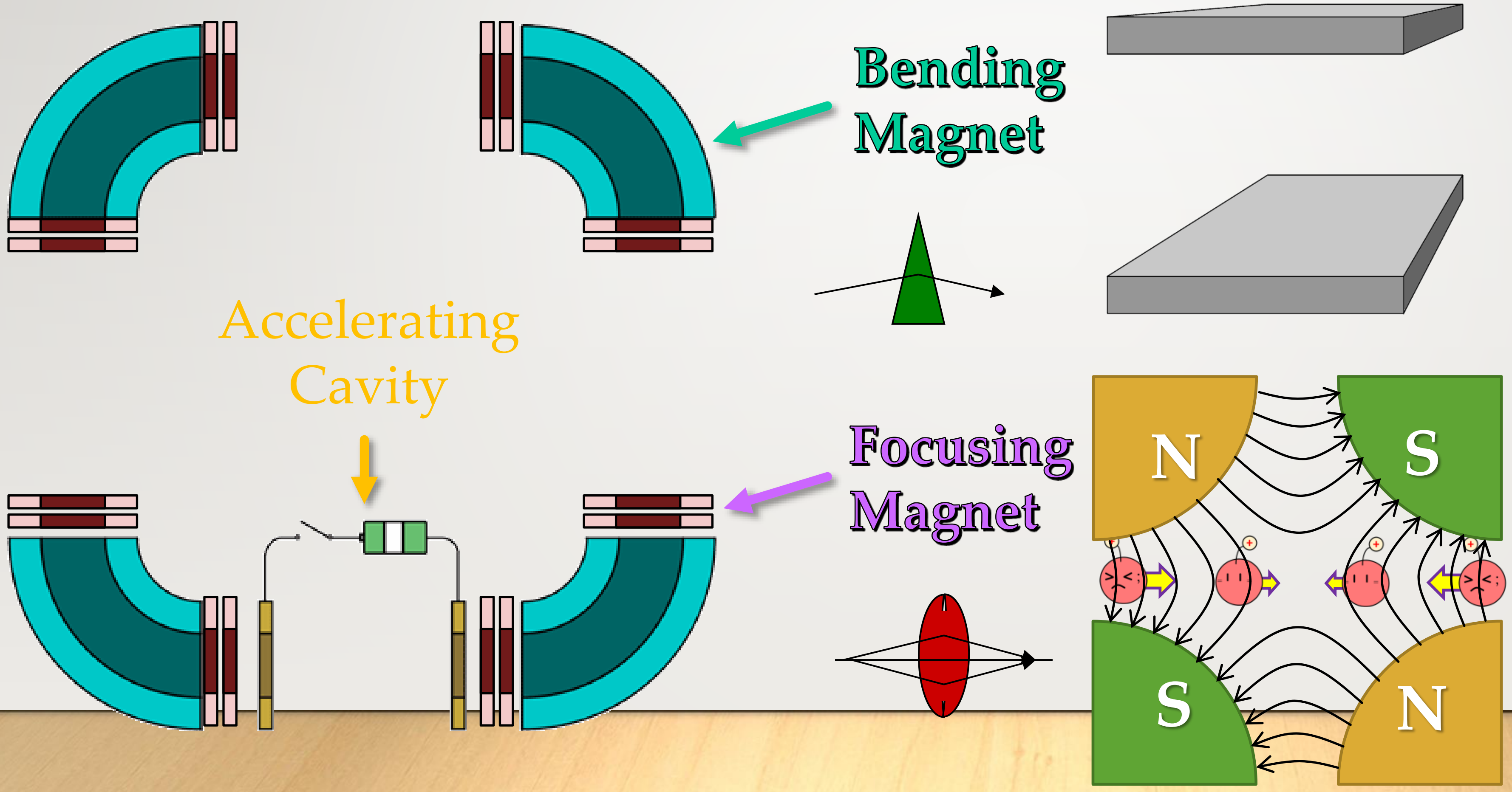
- Ring Orbit by Magnetic Field
- Reuse Accelerator Cavity
- Stronger B Field for Higher Energy




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

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

# 6 Magnets for Synchrotron




- Bending Magnet
  - Normal Dipole
  - Bend Beam
  - Uniform Field

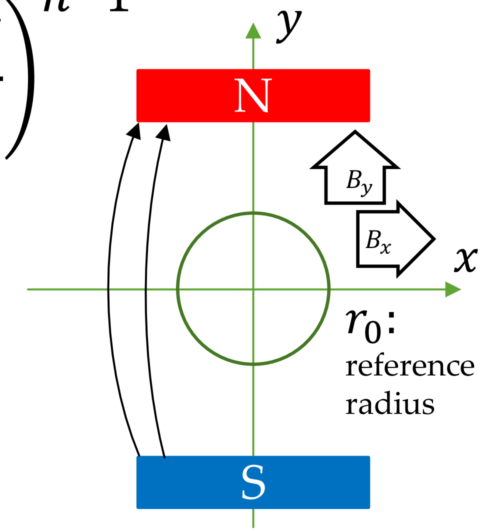
- Focusing Magnet
  - Normal Quadrupole
  - Focus Beam
  - Gradient Field

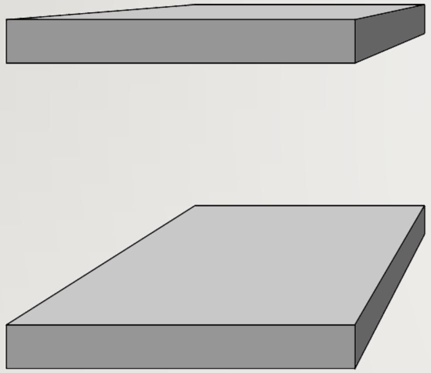
7

# Multipole Field

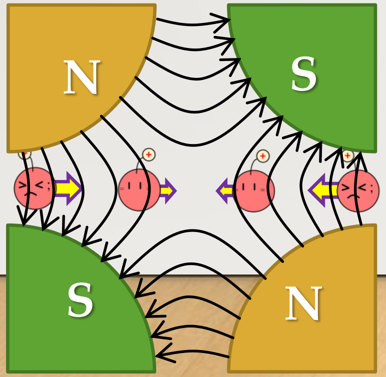
$$B_y + iB_x = \sum_{n=1}^{\infty} (B_n + iA_n)\left(\frac{x+iy}{r_0}\right)^{n-1}$$

$B_n$: Normal 2n-pole、
$A_n$: Skew 2n-pole



Normal Dipole
$B_1$=const. (zero otherwise)
$B_y=B_1$
$B_x=0$
Uniform Field

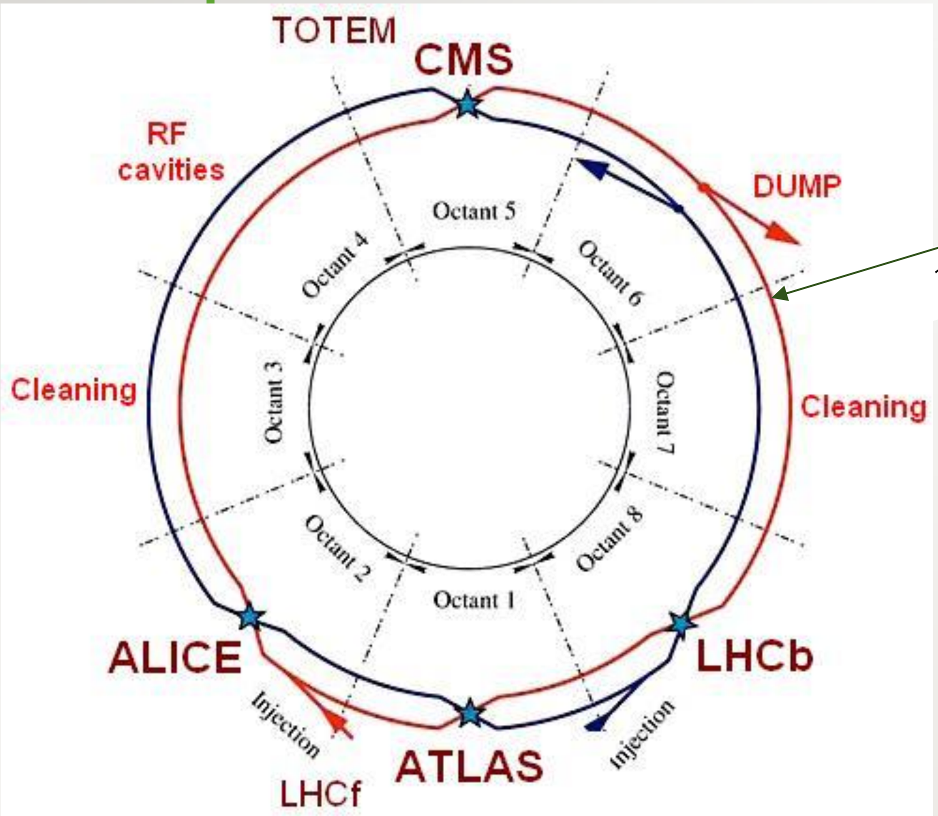



Normal Quadrupole
$B_2=G_0$=const. (zero otherwise)
$B_y+iB_x=G_0/r_0(x+iy)$, $G_0/r_0=g_0$
$B_y=g_0x$
$B_x=g_0y$
Uniform Gradient Field

2n-pole field
$B_n=K_n$=const. (zero otherwise)
$B_y+iB_x=K_n/r_0^n(x+iy)^n$
On $x$-axis ($y$=0)
$B_y=K_n(x/r_0)^n$

$$B_y = \sum_{n=1} B_n\left({}^{x}/{}_{r_0}\right)^n$$

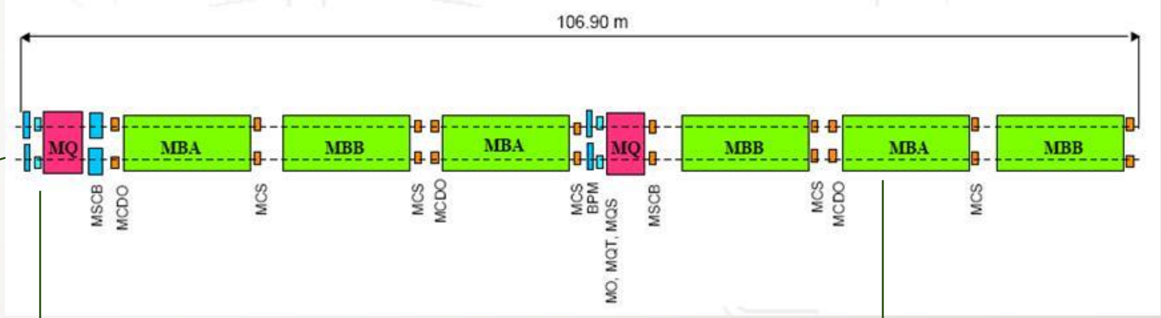
# LHC: Large Hadron Collider



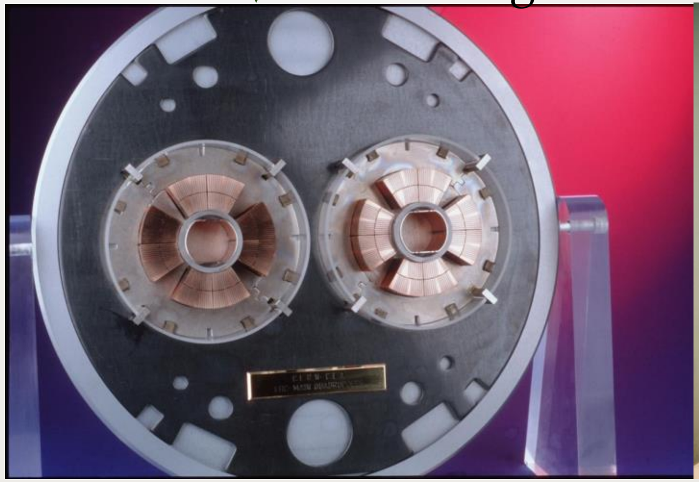

8 x 2.45 km arc,  8 x 545 m straight section

1 arc = 23 cell

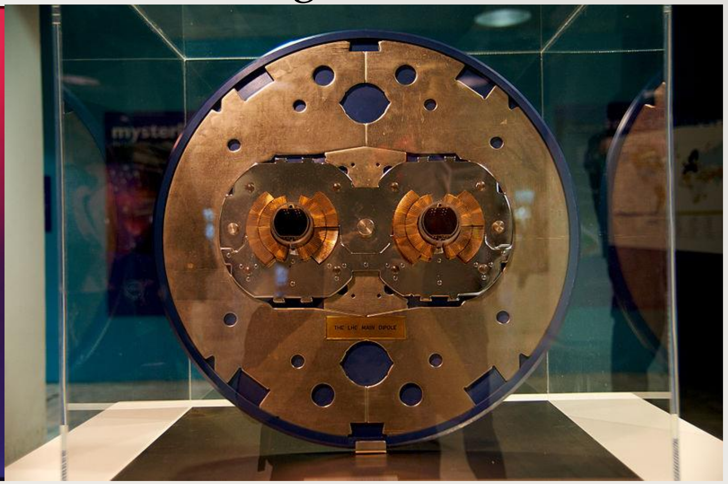
1 cell：BM 6 + FM 1 + DFM 1




F or DF Magnet

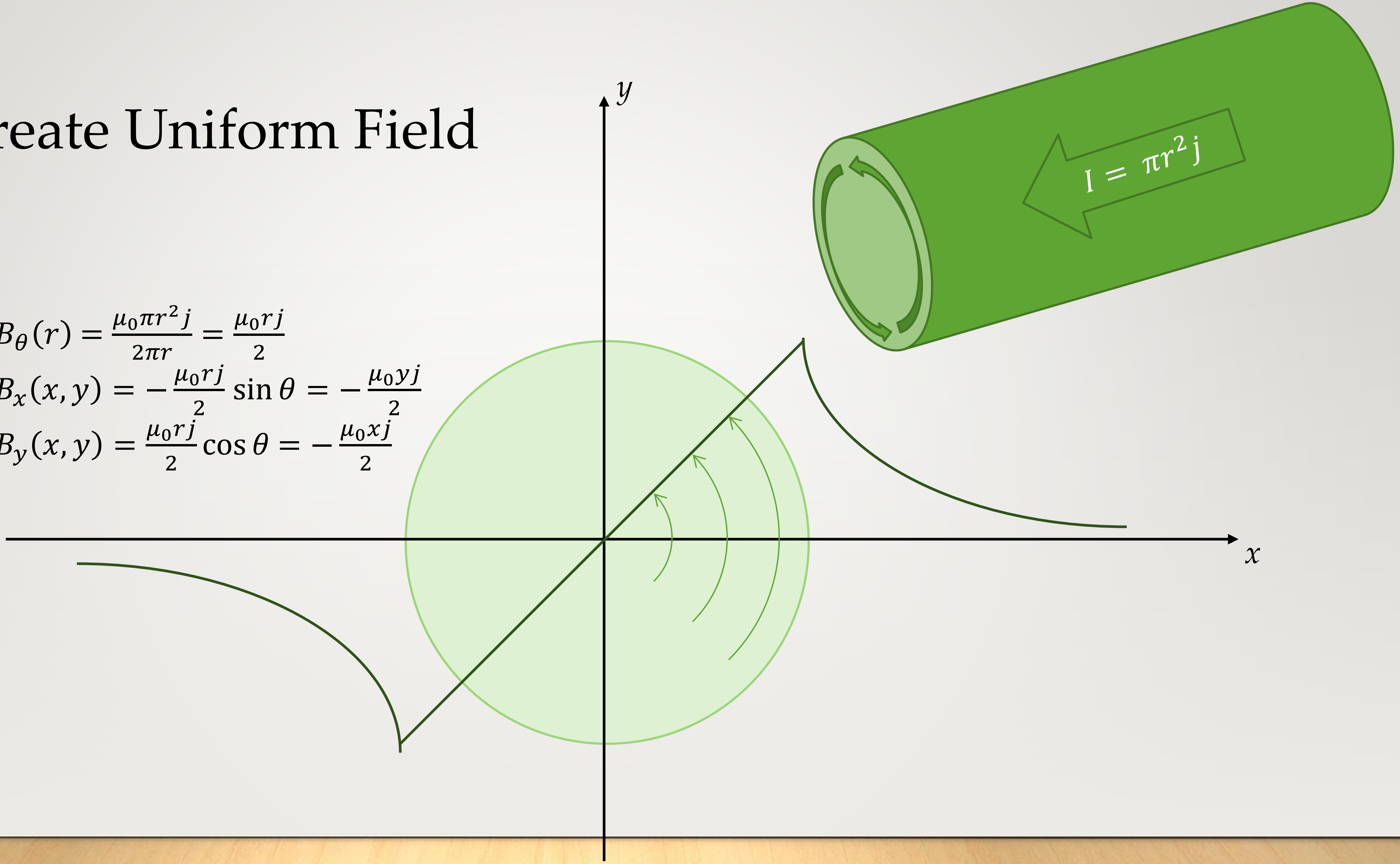


B Magnet



# 9 Create Uniform Field

$$B_\theta(r) = \frac{\mu_0 \pi r^2 j}{2\pi r} = \frac{\mu_0 r j}{2}$$
$$B_x(x,y) = -\frac{\mu_0 r j}{2}\sin\theta = -\frac{\mu_0 y j}{2}$$
$$B_y(x,y) = \frac{\mu_0 r j}{2}\cos\theta = -\frac{\mu_0 x j}{2}$$



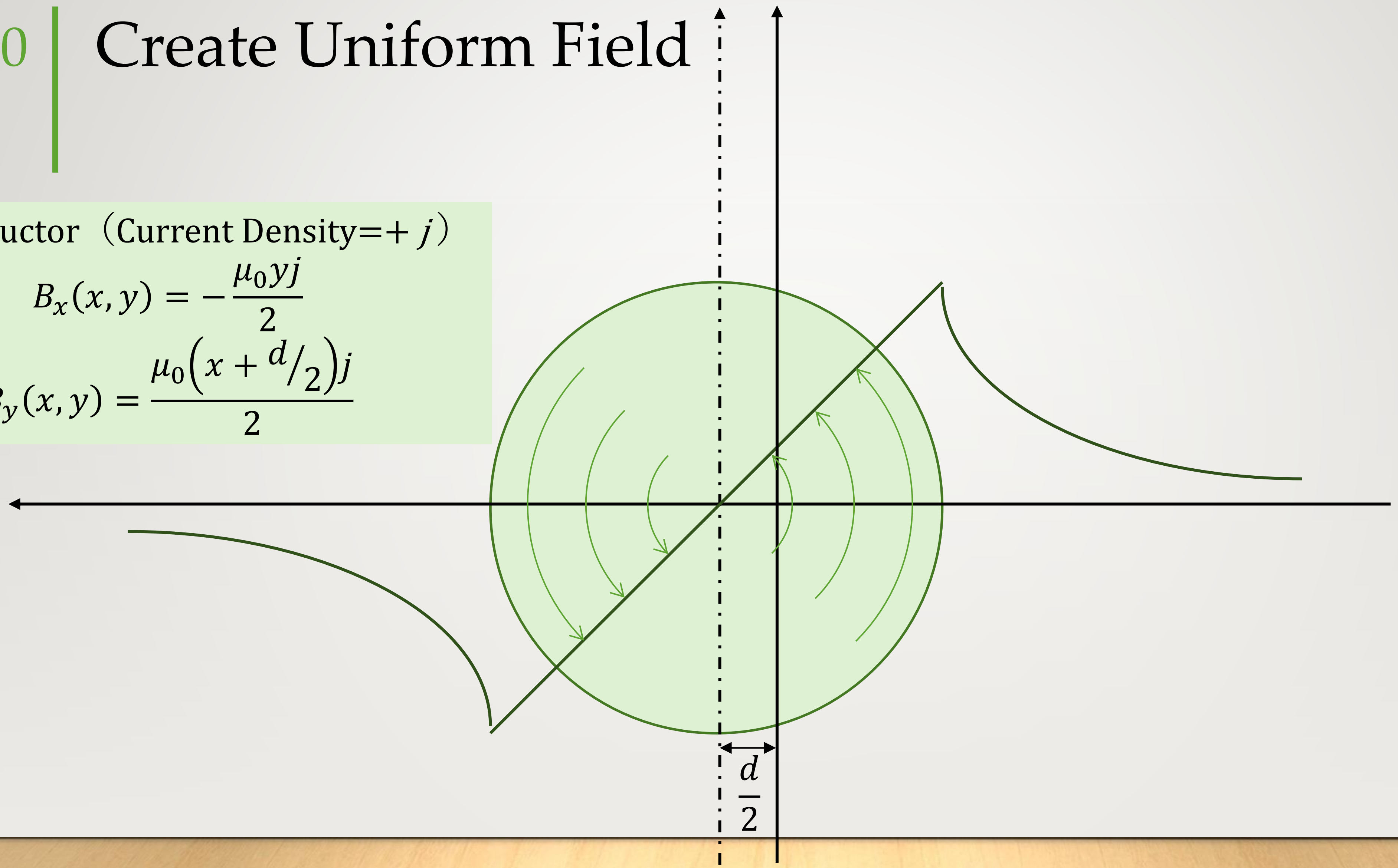
10

# Create Uniform Field

Left conductor（Current Density=+ $j$）

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

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



# 11 | Create Uniform Field

Left Conductor（Current Density=+ $j$）

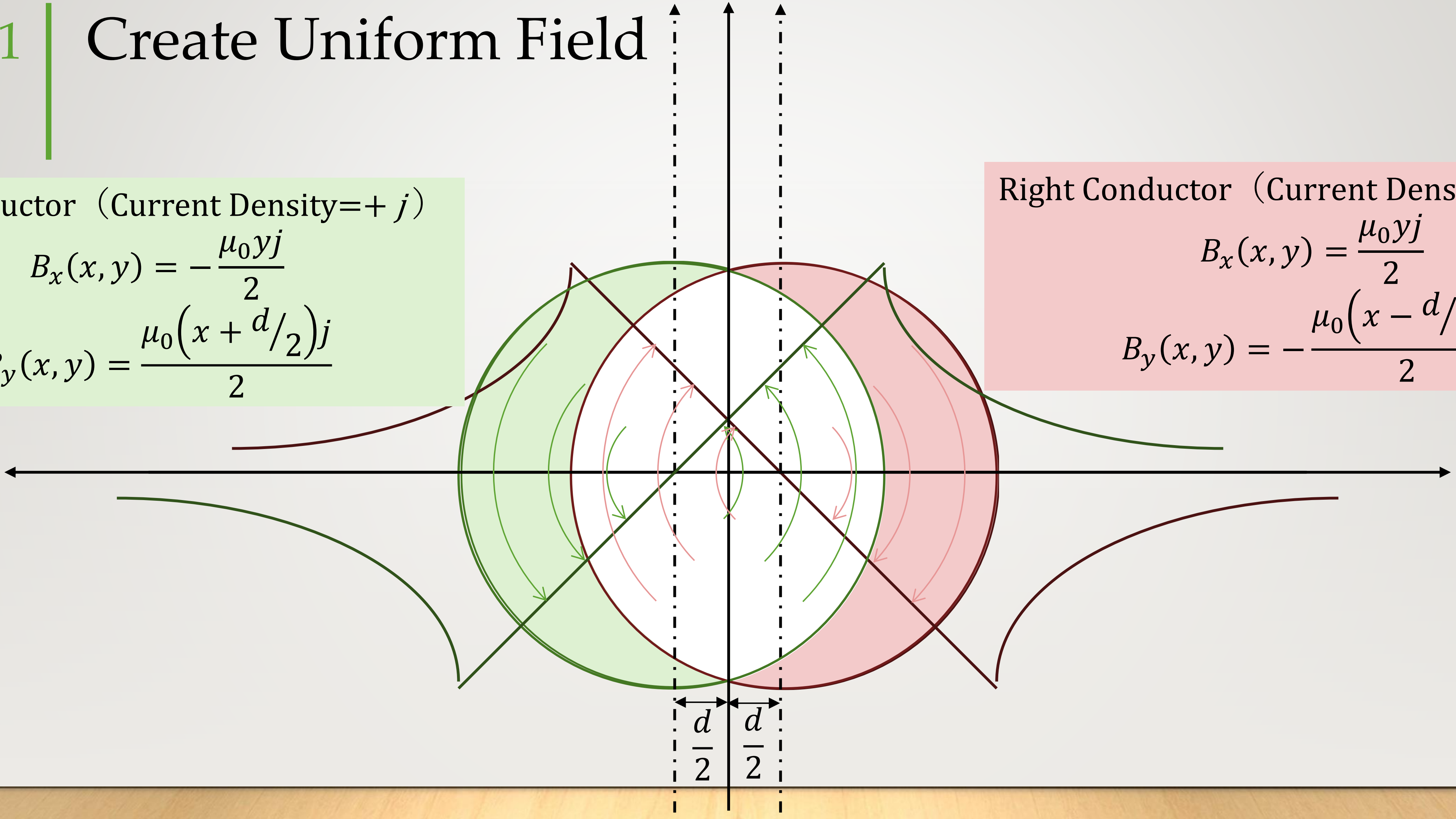
$$B_x(x,y) = -\frac{\mu_0 y j}{2}$$

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

Right Conductor（Current Density = − $j$）

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

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



# Create Uniform Field

Center（Current Density=0）

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

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

Left Conductor（Current Density=+ $j$）

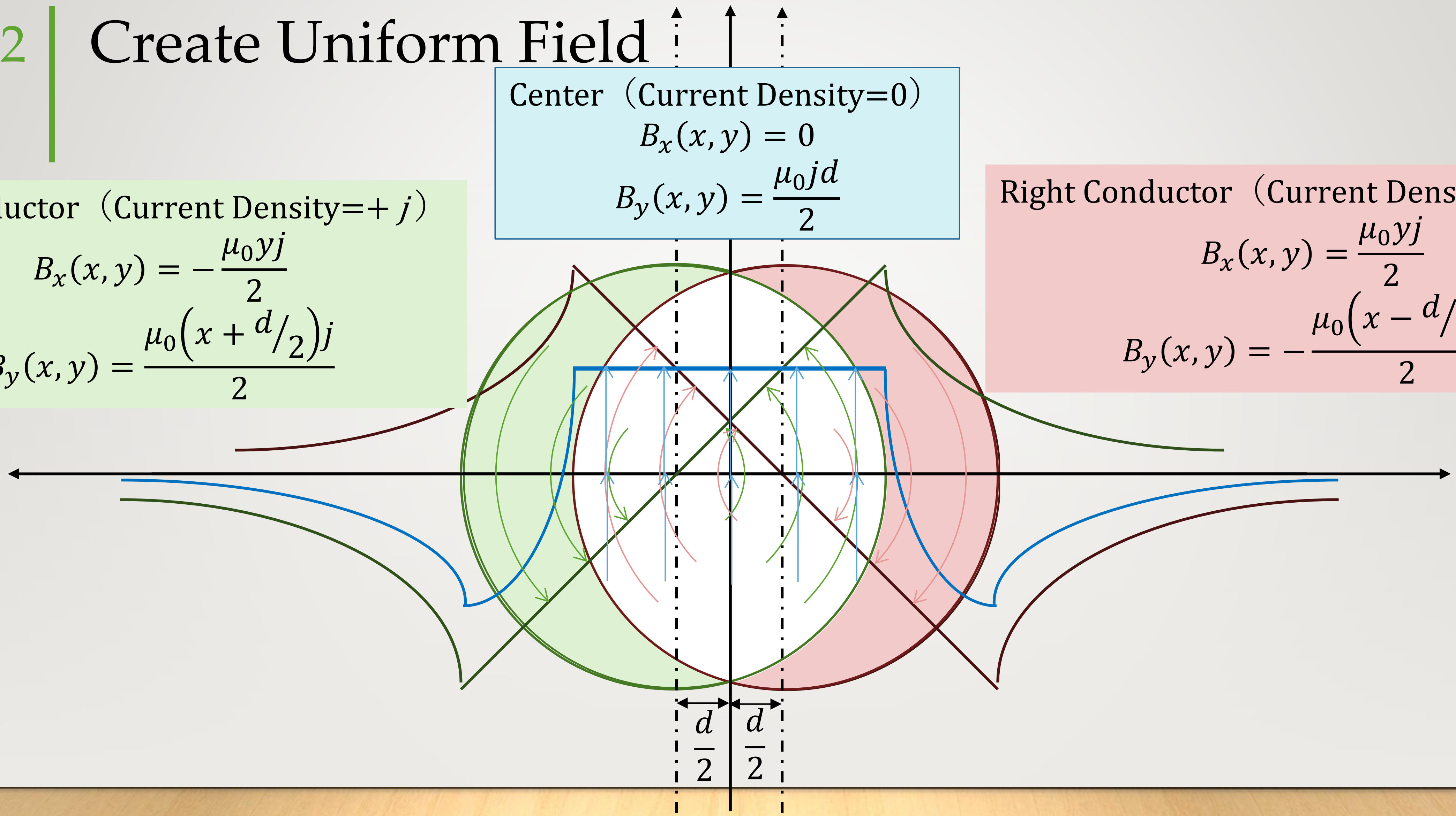
$$B_x(x,y) = -\frac{\mu_0 y j}{2}$$

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

Right Conductor（Current Density = − $j$）

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

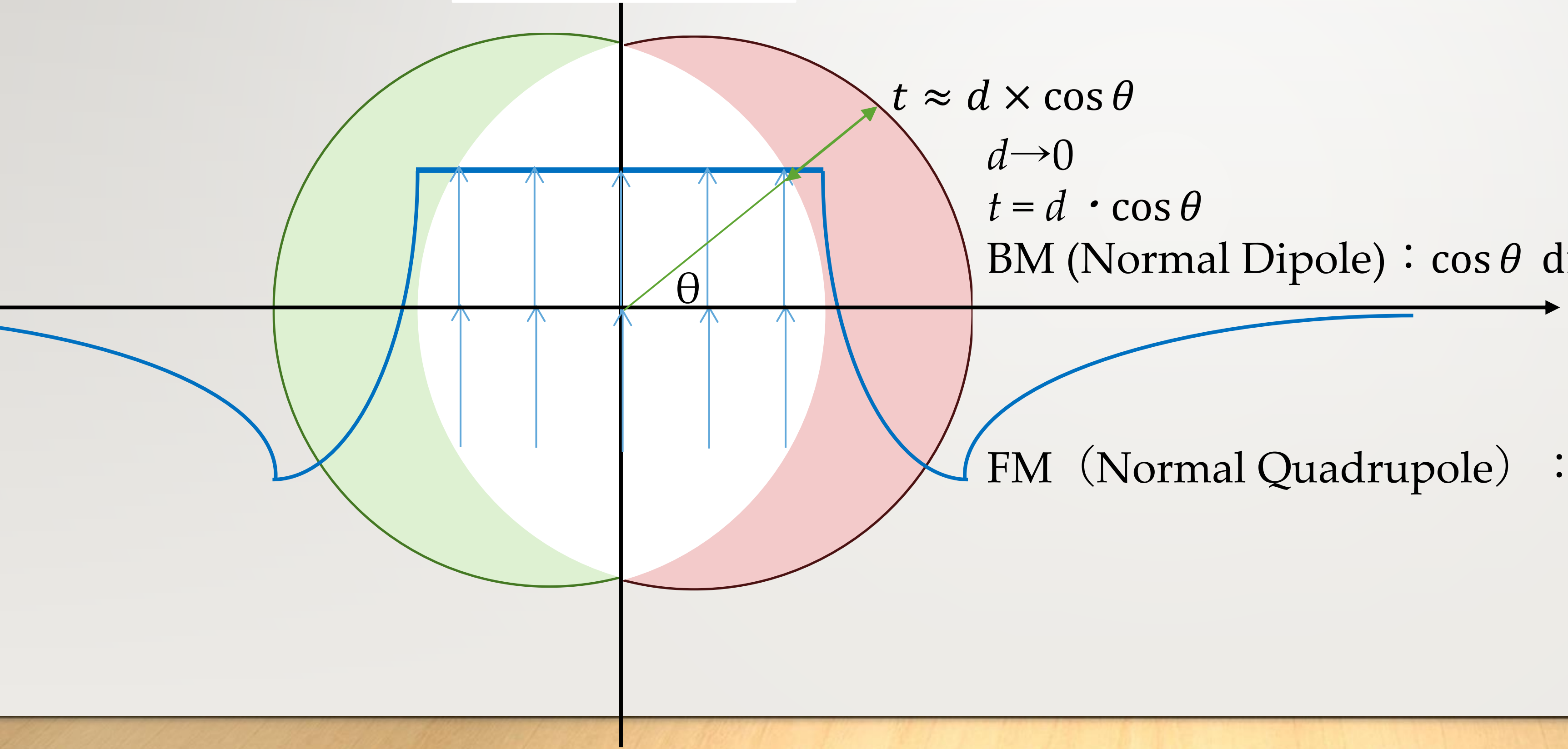
$$B_y(x,y) = -\frac{\mu_0\left(x - {}^{d}/_{2}\right)j}{2}$$



# Cosθ coil

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

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



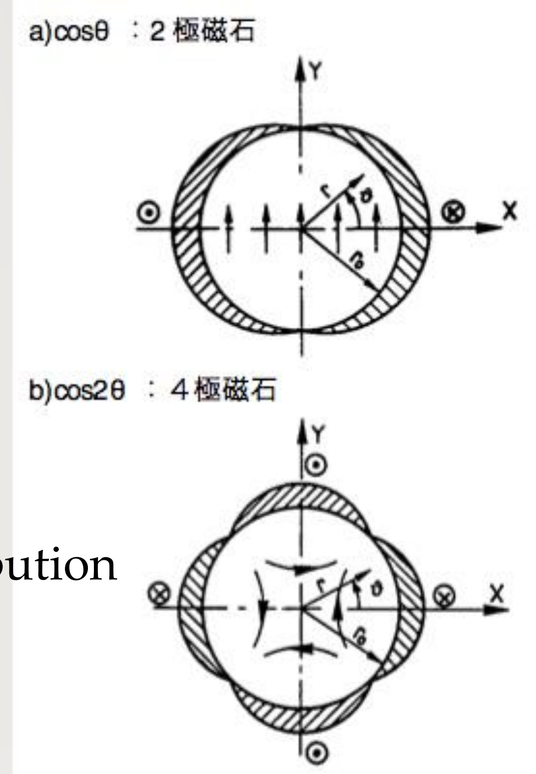

$t \approx d \times \cos\theta$

$d \rightarrow 0$

$t = d \cdot \cos\theta$

BM (Normal Dipole)：$\cos\theta$ distribution

FM（Normal Quadrupole）：$\cos 2\theta$ Distribution



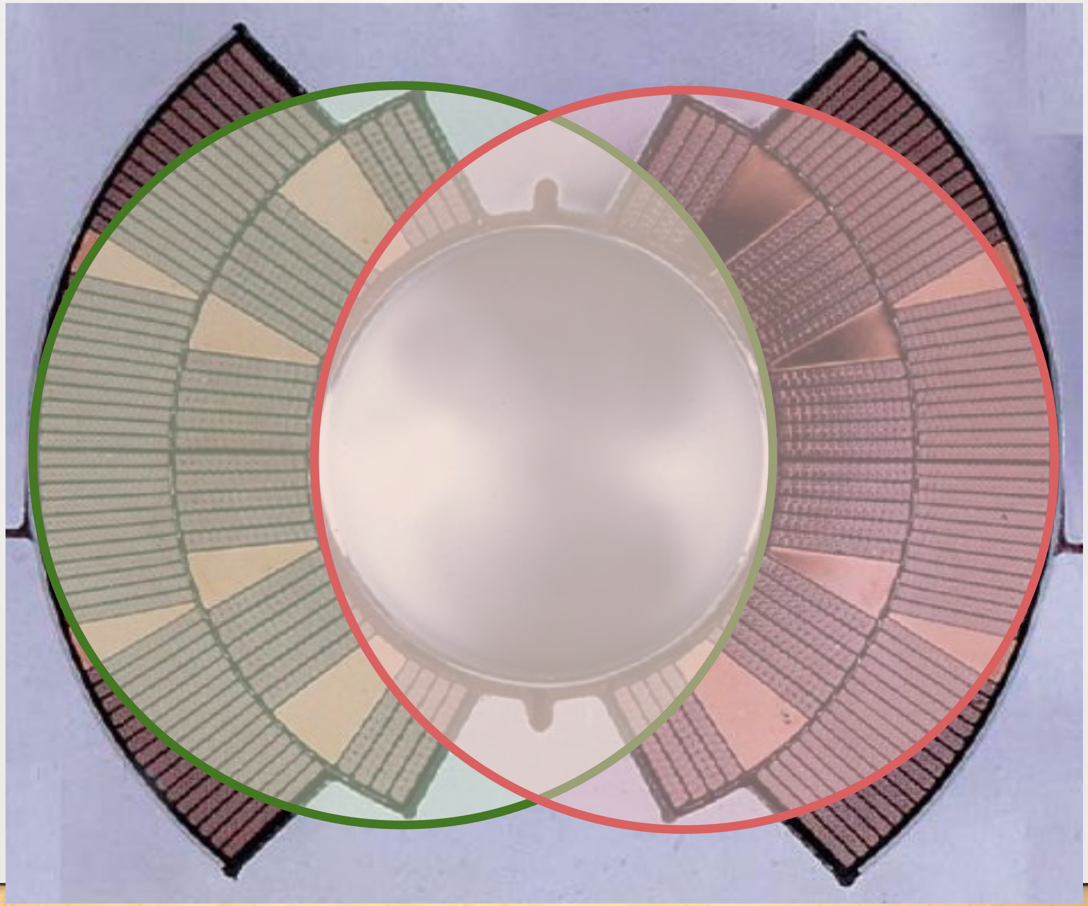
# Create Uniform Field：LHC Dipole

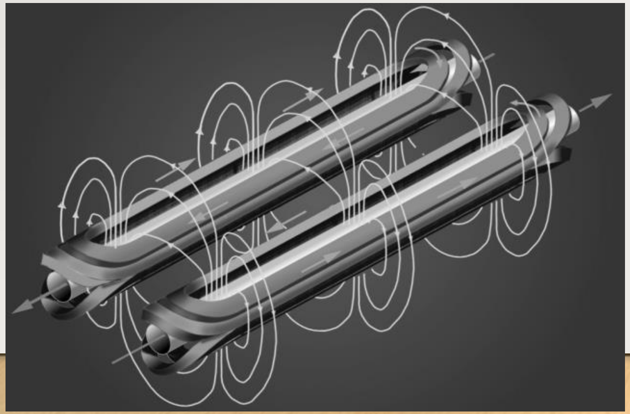
$$B_y(x,y) = \frac{\mu_0 j d}{2}$$

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

$d = 3\ \mathrm{cm}$

$B_y = 8.3\ \mathrm{T}$





Actual Coil

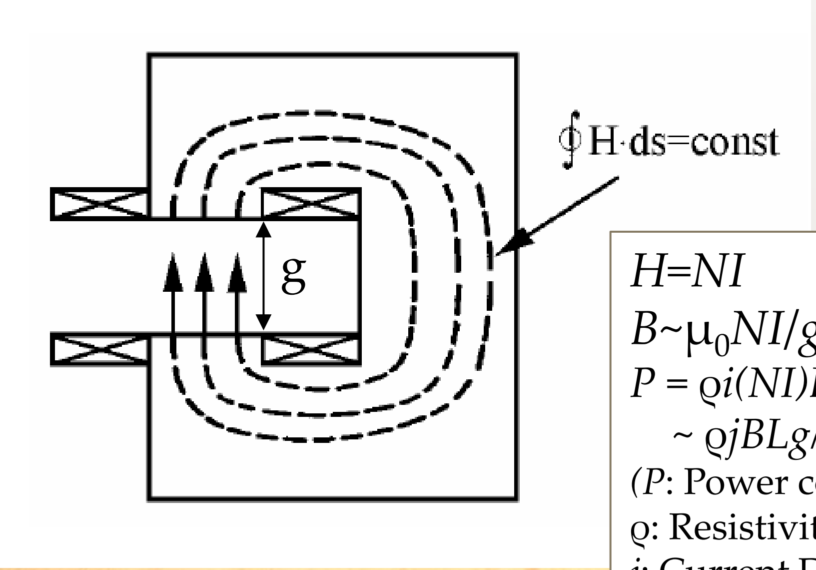
Inner Cable
Width：15.1 mm
Thickness：1.9 mm
Turn Number：15*2
Current Density：400 A/mm$^2$

Outer Cable
Width：15.1 mm
Thickness：1.48 mm
Turn Number：26*2
Current Density：520 A/mm$^2$

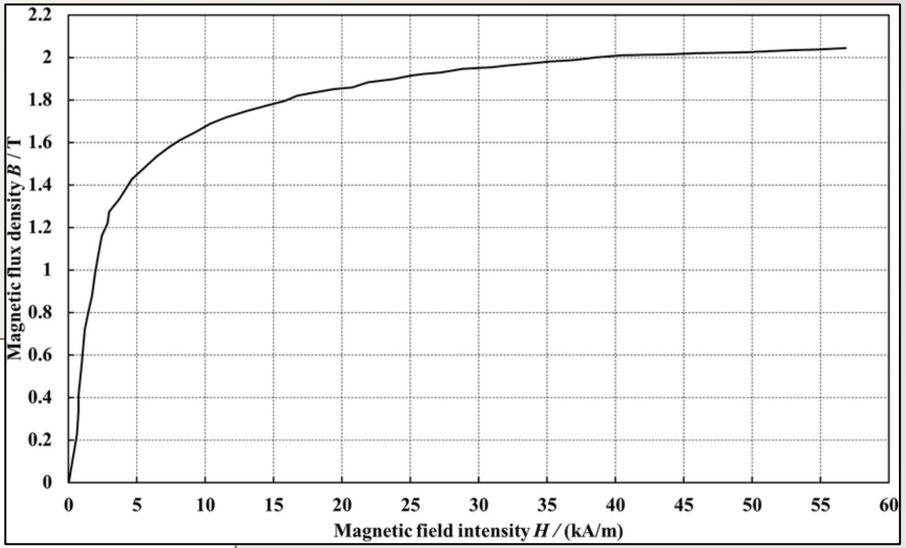
Power consumption：total LHC: 120MW ～ 600W/Tm

# 15 Normal Conducting Magnet

- Ohmic Heating：$W = VI = RI^2$ → Cooling limitation：10 A/mm$^2$
- 1/40 of Superconductor：40 times large coil?：Not real
- Real normal magnet：Magnetic circuit with Iron Yoke
- Iron Saturation：2 T limit




$H=NI$
$B \sim \mu_0 NI/g$
$P = \varrho i(NI)L$
$\sim \varrho jBLg/\mu_0$
($P$: Power consumption、
$\varrho$: Resistivity
$j$: Current Density,
$L$: Conductor length / turn)




LHC with Normal Magnet
4 times large accelerator
10 times large Power Cons.

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

# Item

- Accelerator & Superconducting Magnet
- **Superconducting Magnets for Hadron Colliders**
  - **History**
  - On going
  - Future
- Superconducting magnet applications in various accelerators
- Summary

# History of Accelerator and Superconductivity

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)

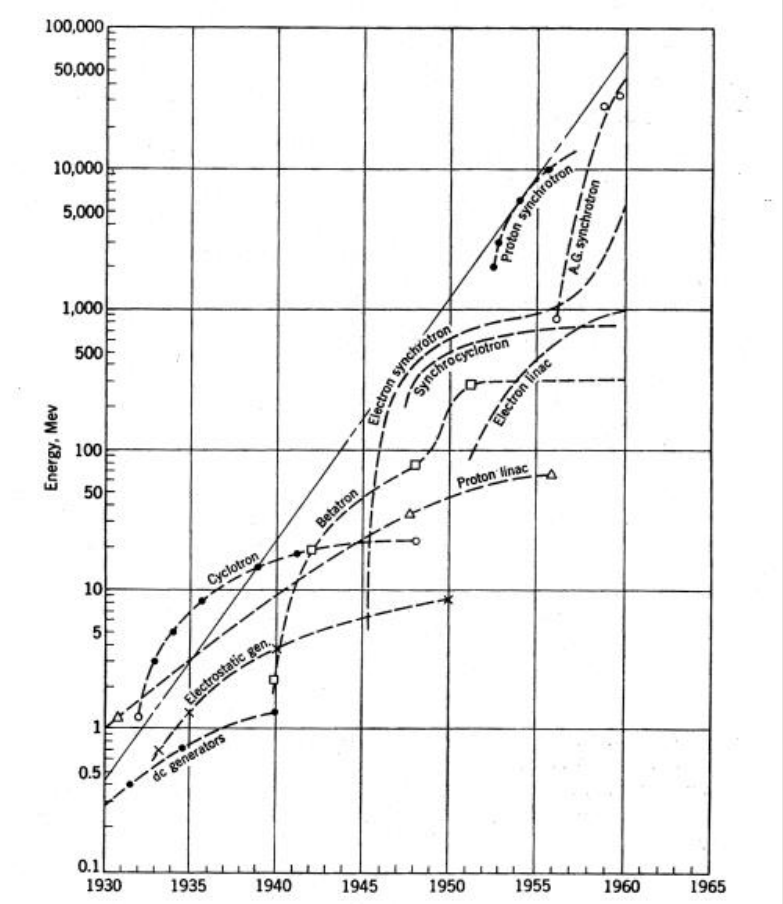
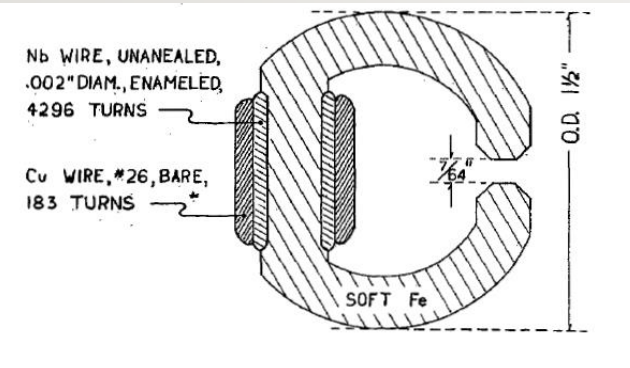



**Fig. 1-1.** Energies achieved by accelerators from 1930 to 1960. The linear envelope of the individual curves shows an average tenfold increase in energy every six years.

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

# History of Superconducting Magnet Early Days（1960s）

- 初めての磁石
  - 1954 G. Yntema 0.71 T

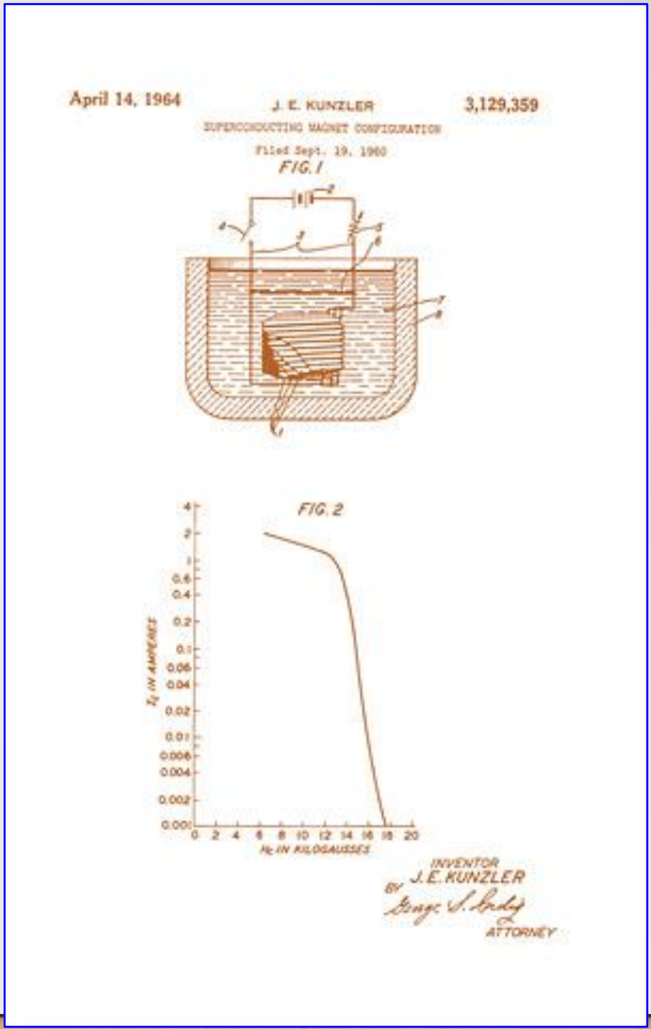



Electromagnet with superconducting niobium windings, horizontal cross-section. Magnet constructed at University of Illinois in 1954.

- 1961 MIT Conference
  - J.E.Kunzler (Bell Lab.): $Nb_3Sn$ 6.8T　Win!
  - J.Hulm (Westinghouse): NbZr 6T　！

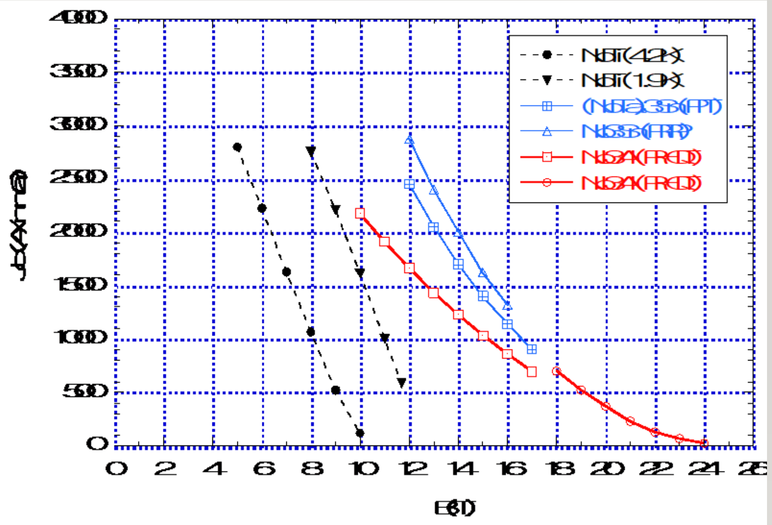
Kunzler:10T $Nb_3Sn$ Magnet
Win 2 case of scotti！
But Bell lab. stop SCM R&D

**J. Hulm: NbTi !**

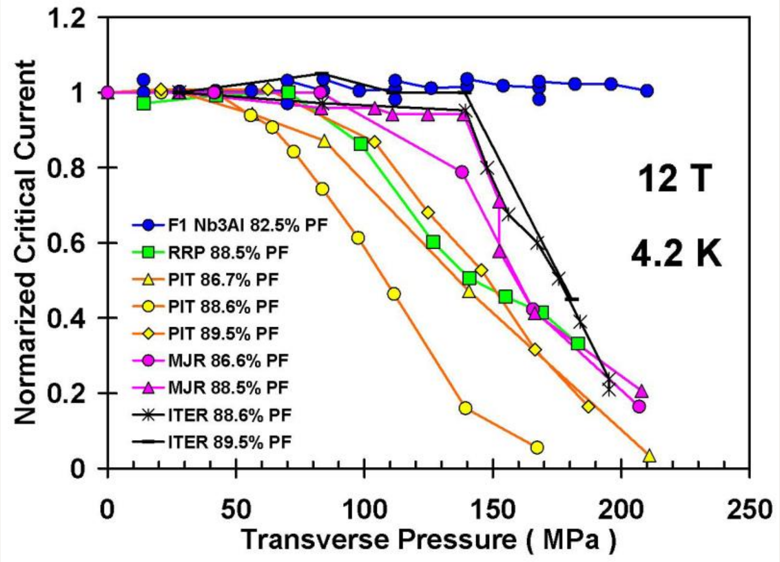



Kunzlerによる最初の特許

# NbTi (Alloy) vs $Nb_3Sn$ (Compound)



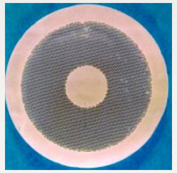

- Jc : $Nb_3Sn$ is better
- Mechanical Property
  - NbTi: Alloy → Ductile → Easier to wind coil
  - $Nb_3Sn$: Brittle → Difficult to wind coil
- Below 8T
  - **NbTi**

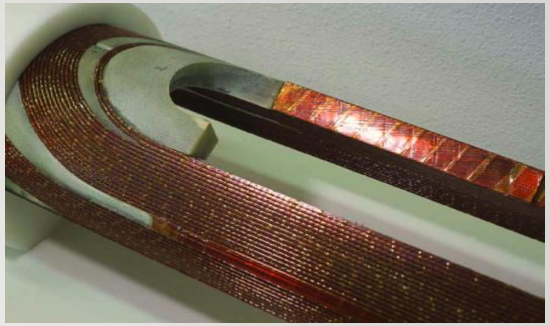


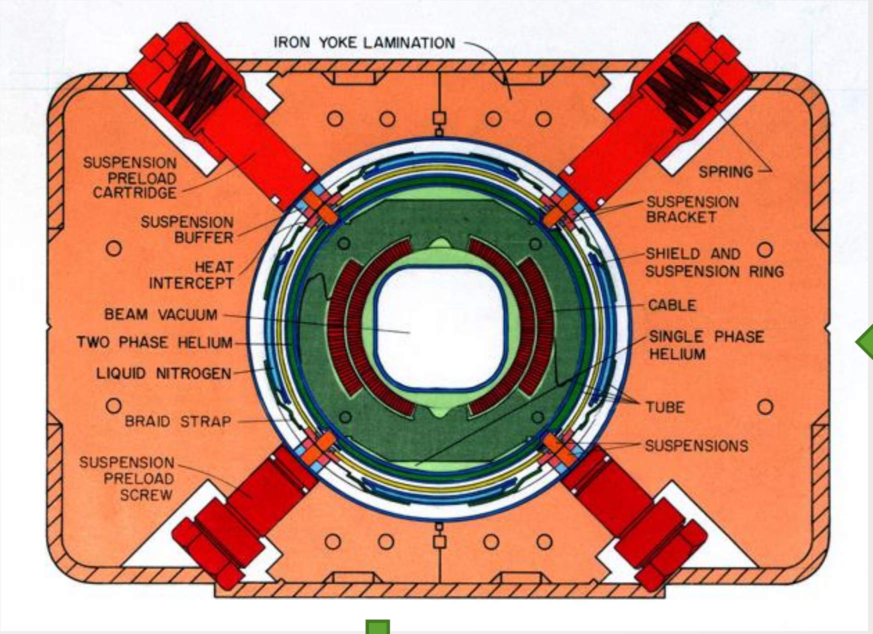
# TEVATRON

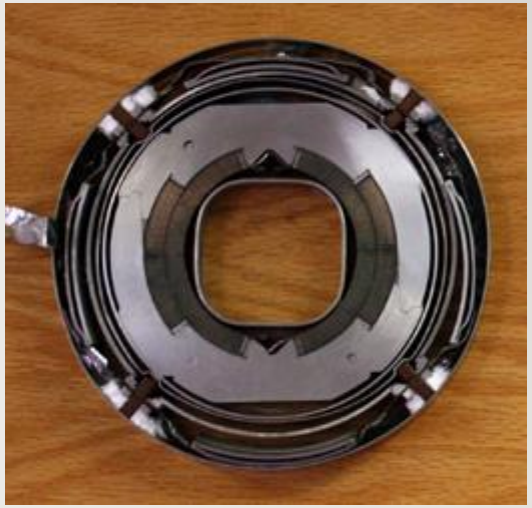
- Energy Doubler (1TeV)
  - Higher Field Magnet 4.3 T
- Energy Saver
  - ~1/2 Overall Power Saving

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





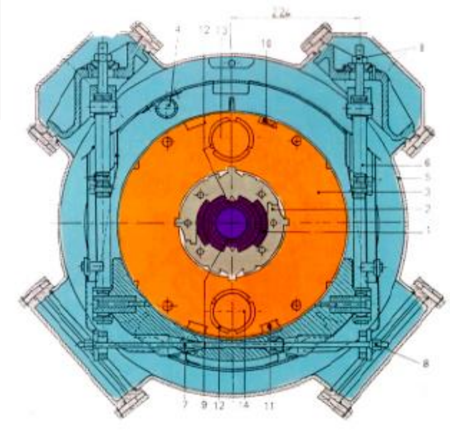


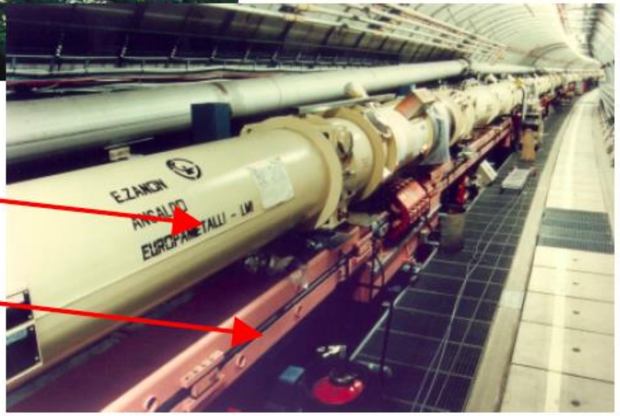
21

# Accelerator Superconducting Magnet: HERA & RHIC


Aerial View of DESY



HERA Tunnel

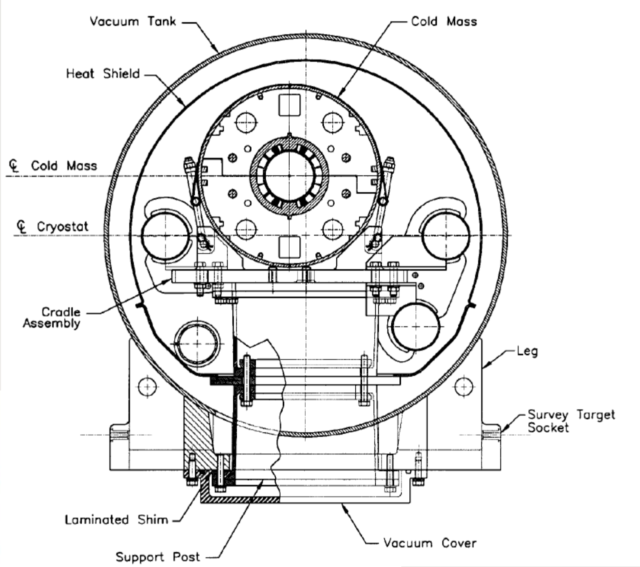


Superconducting p-Ring

Normal e-Ring

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

BNL Aerial View

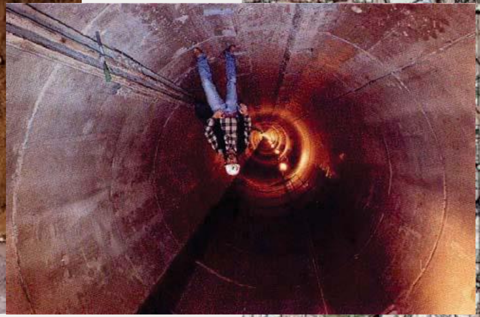


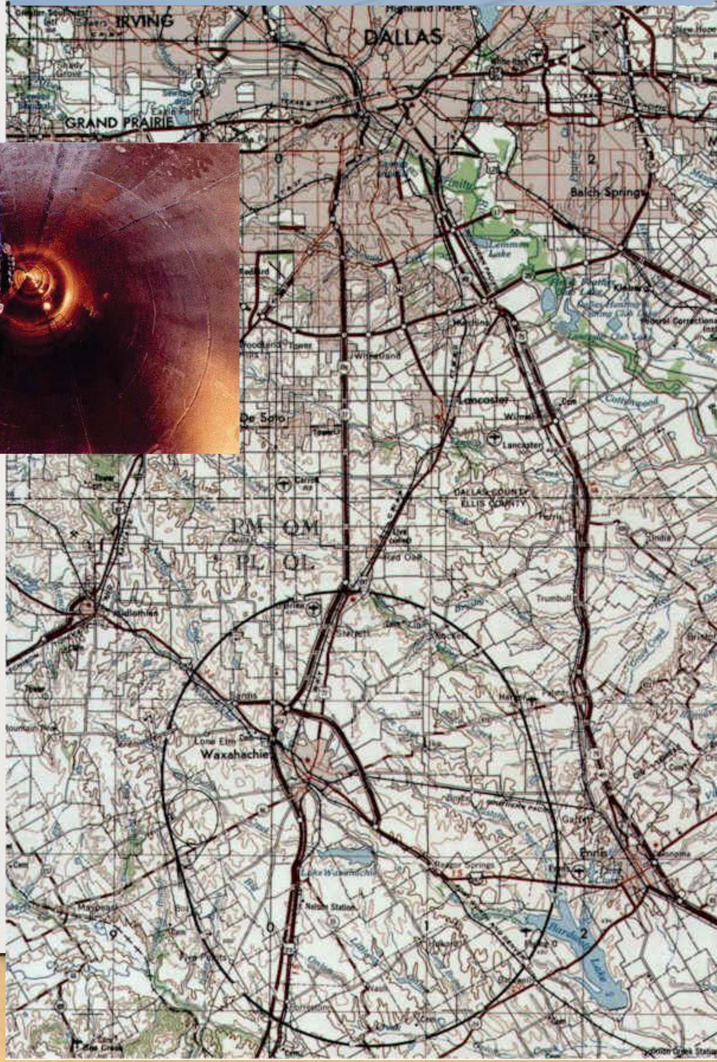

RHIC Tunnel

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

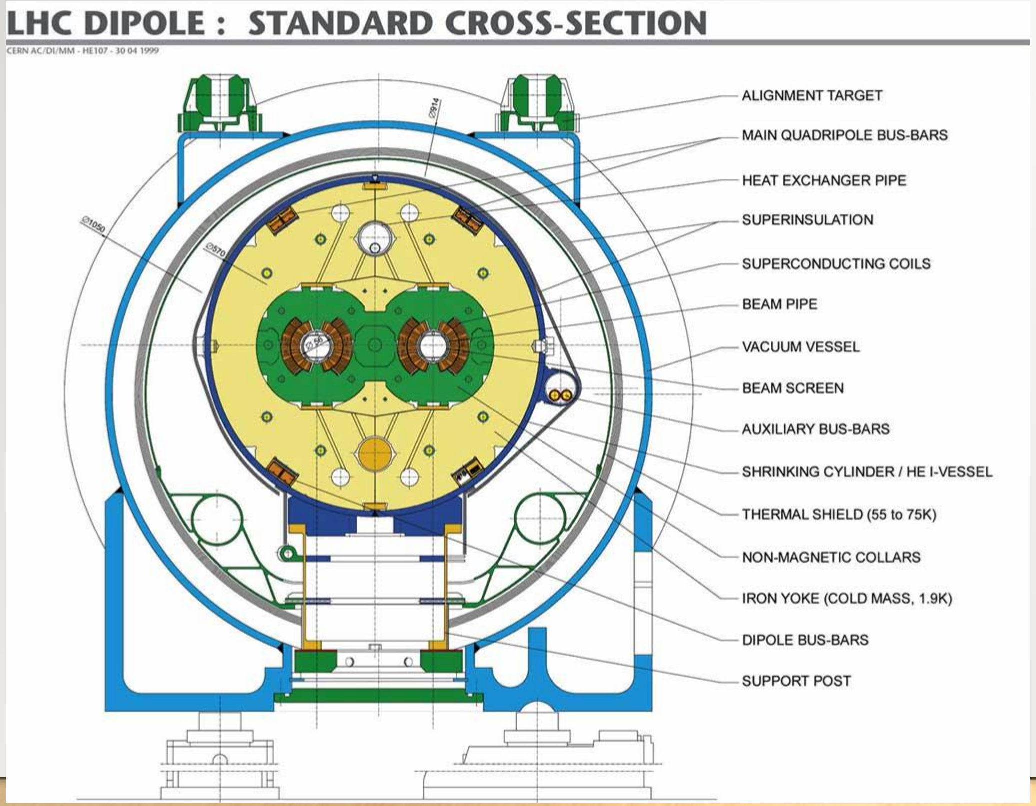
# Accelerator Superconducting Magnet: Superconducting Super Collider

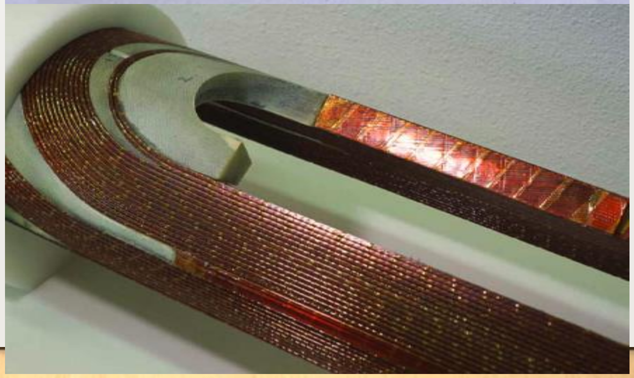
- **Start in 1988 > Terminated in 1993**
- **Fail to control budget 4.4B$→12B$**
- **2B$ already used**

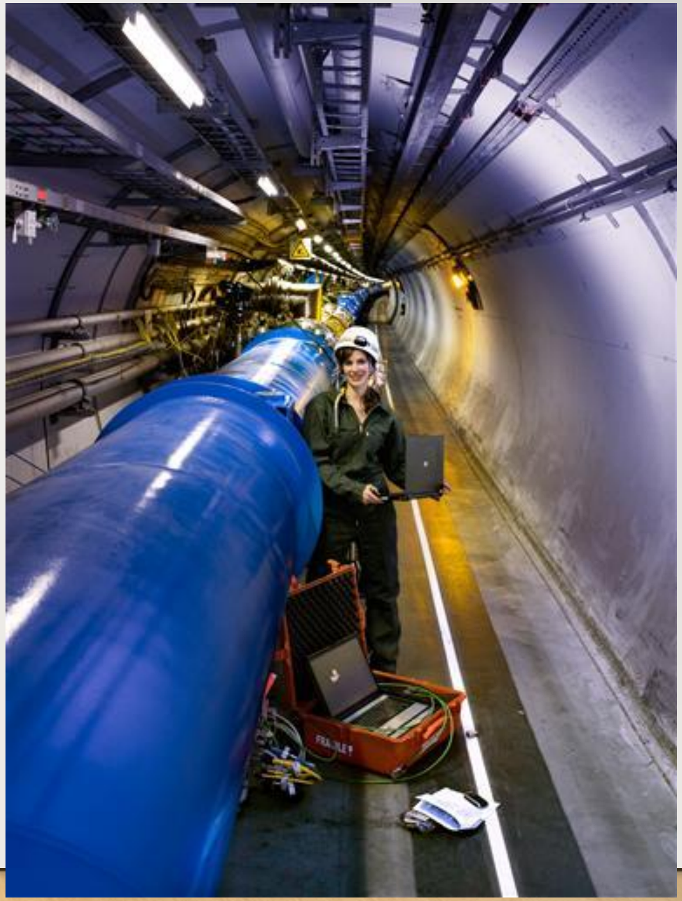





# Accelerator Superconducting Magnet: LHC



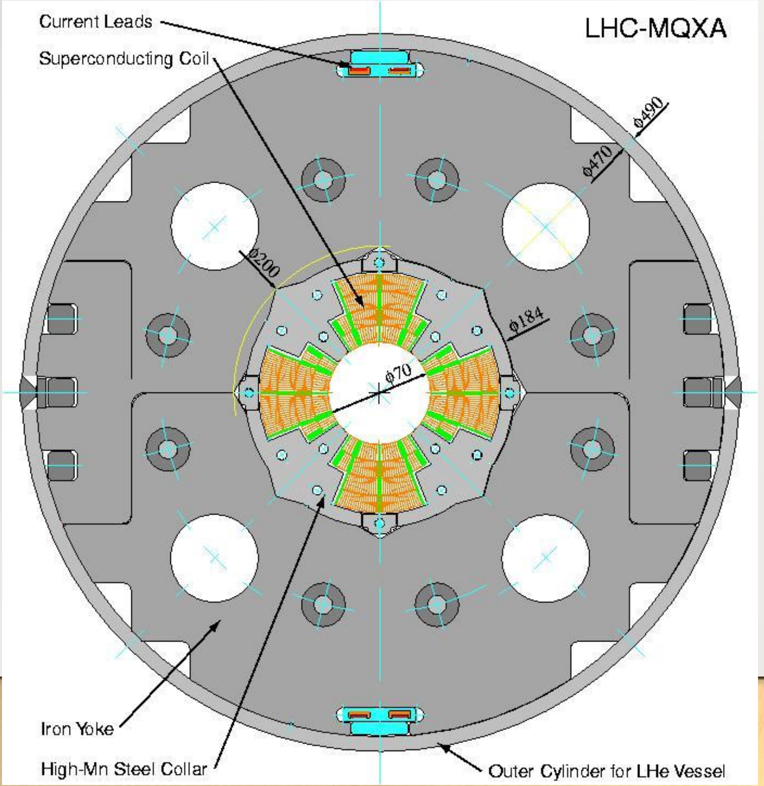



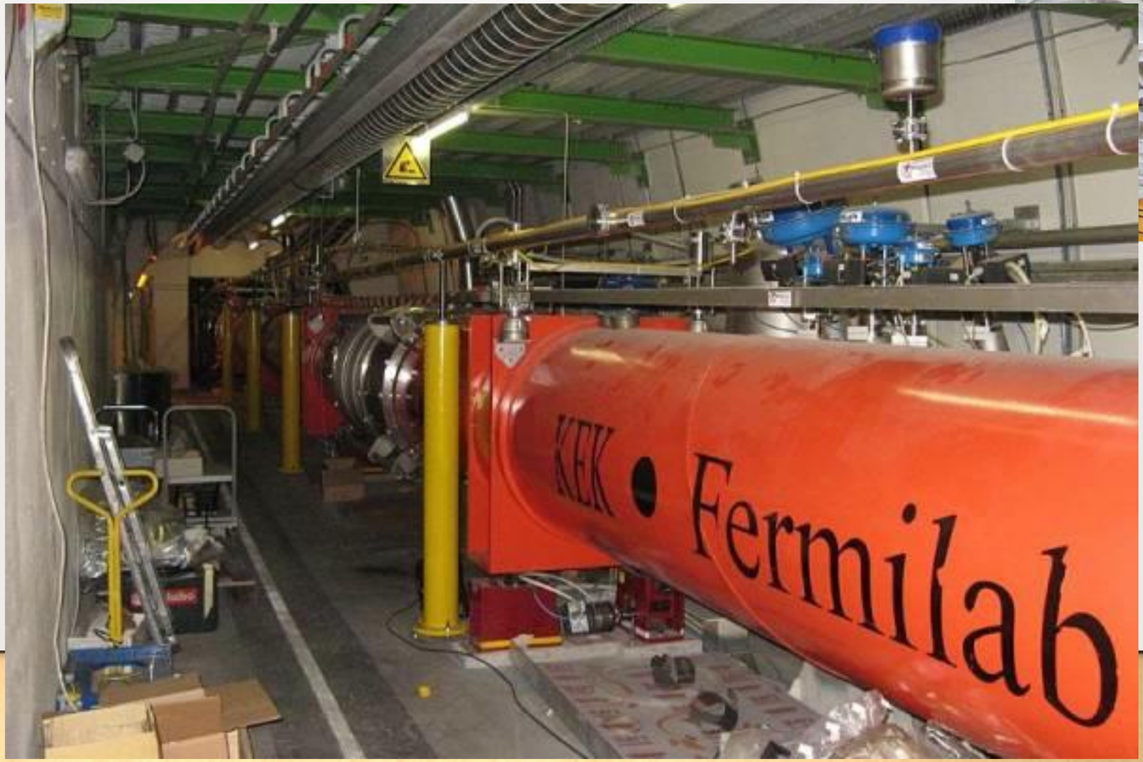


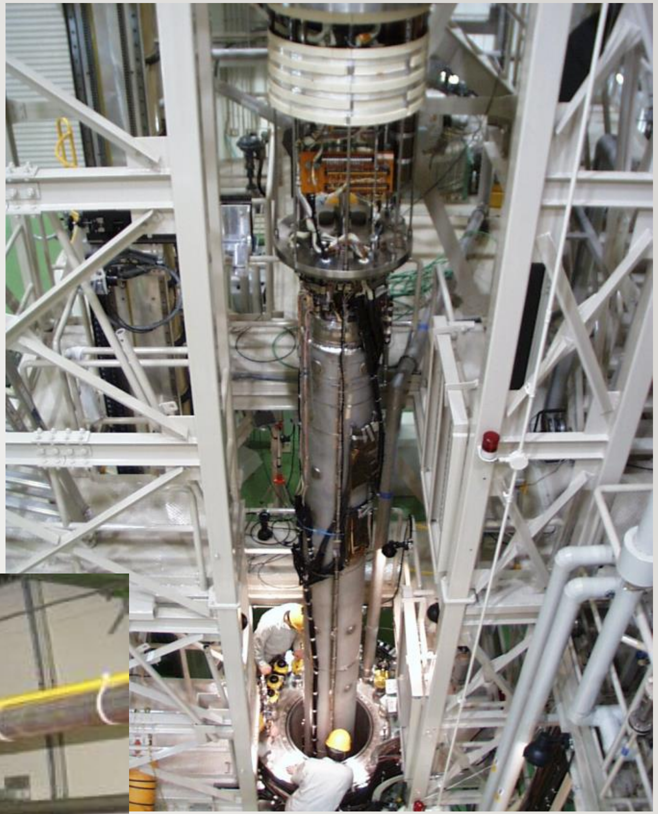
**2008 : CERN/LHC: 26.7km (8.3T, 14.2m, 1232 Magnets)**

# Japanese Contribution to LHC MQXA: Interaction Quadrupole

- Focus Beam at Interaction Region (Increase Luminosity)
  - Field Gradient 280T/m, Maximum Field 8.7 T



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  - History
  - **On going**
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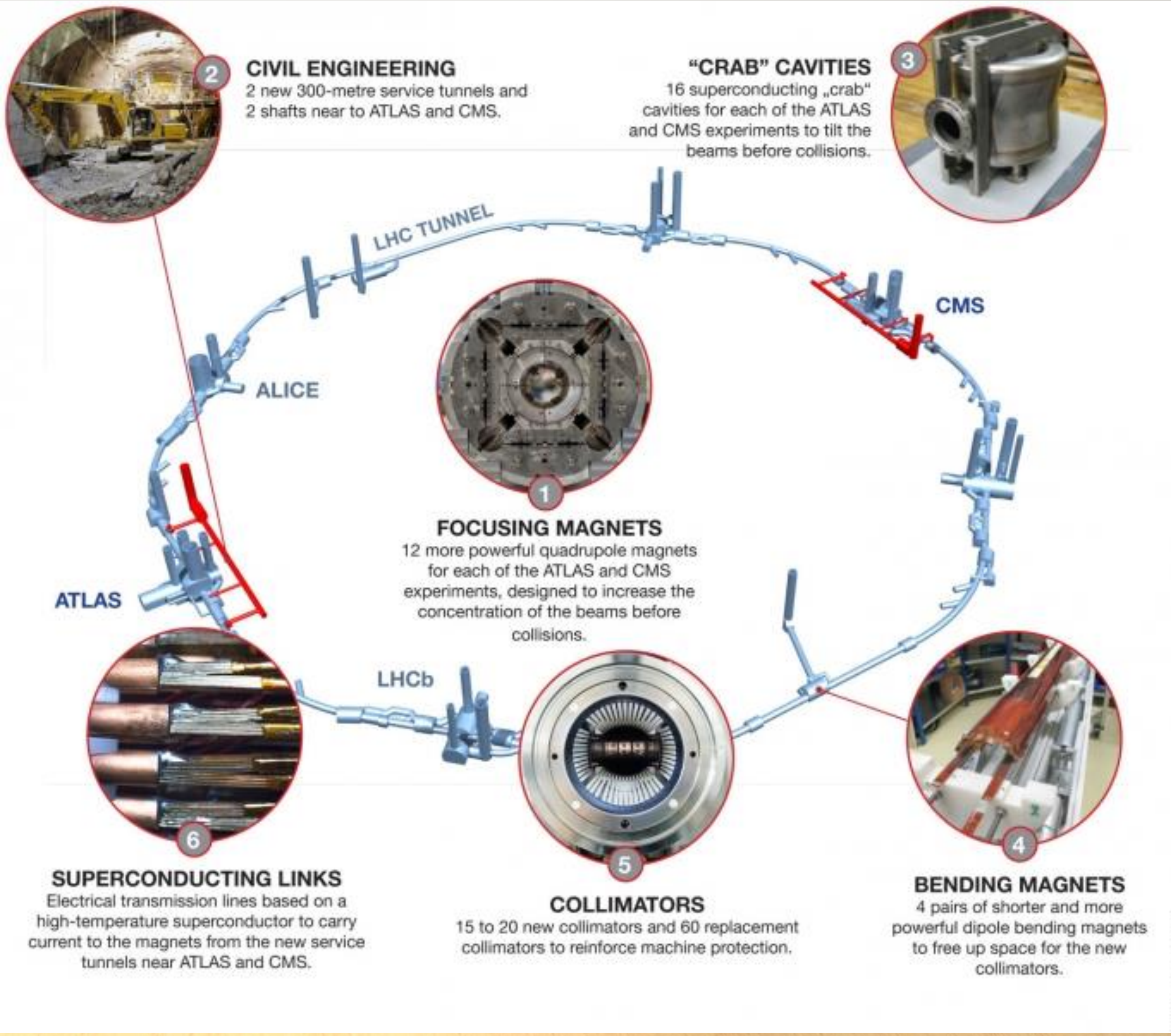
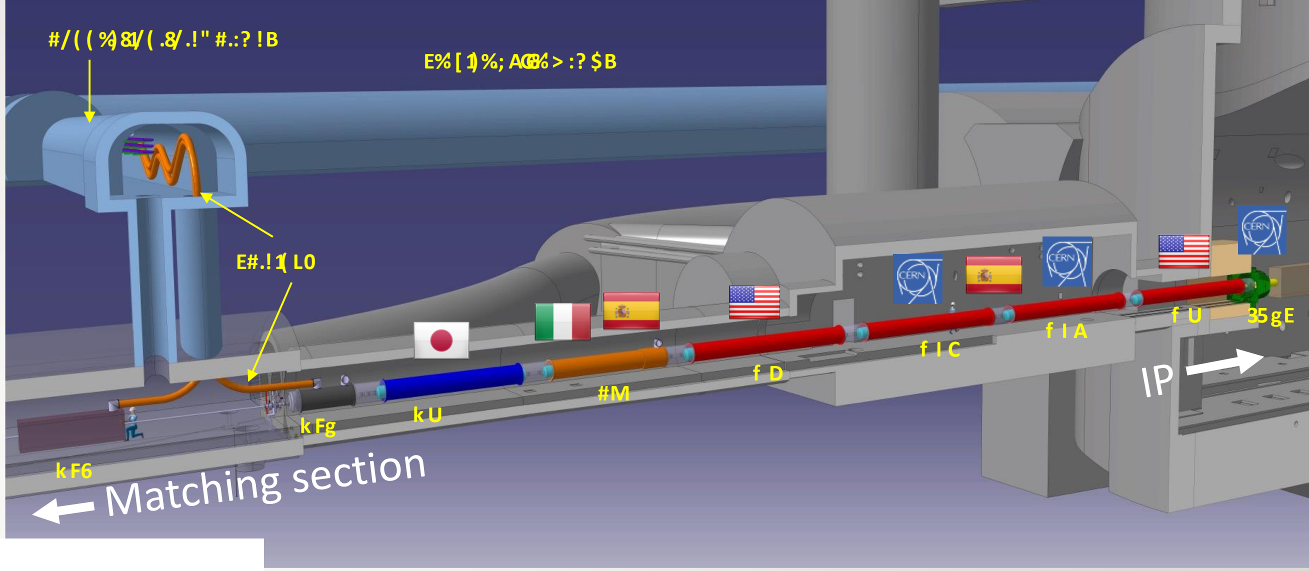
# On going HL-LHC

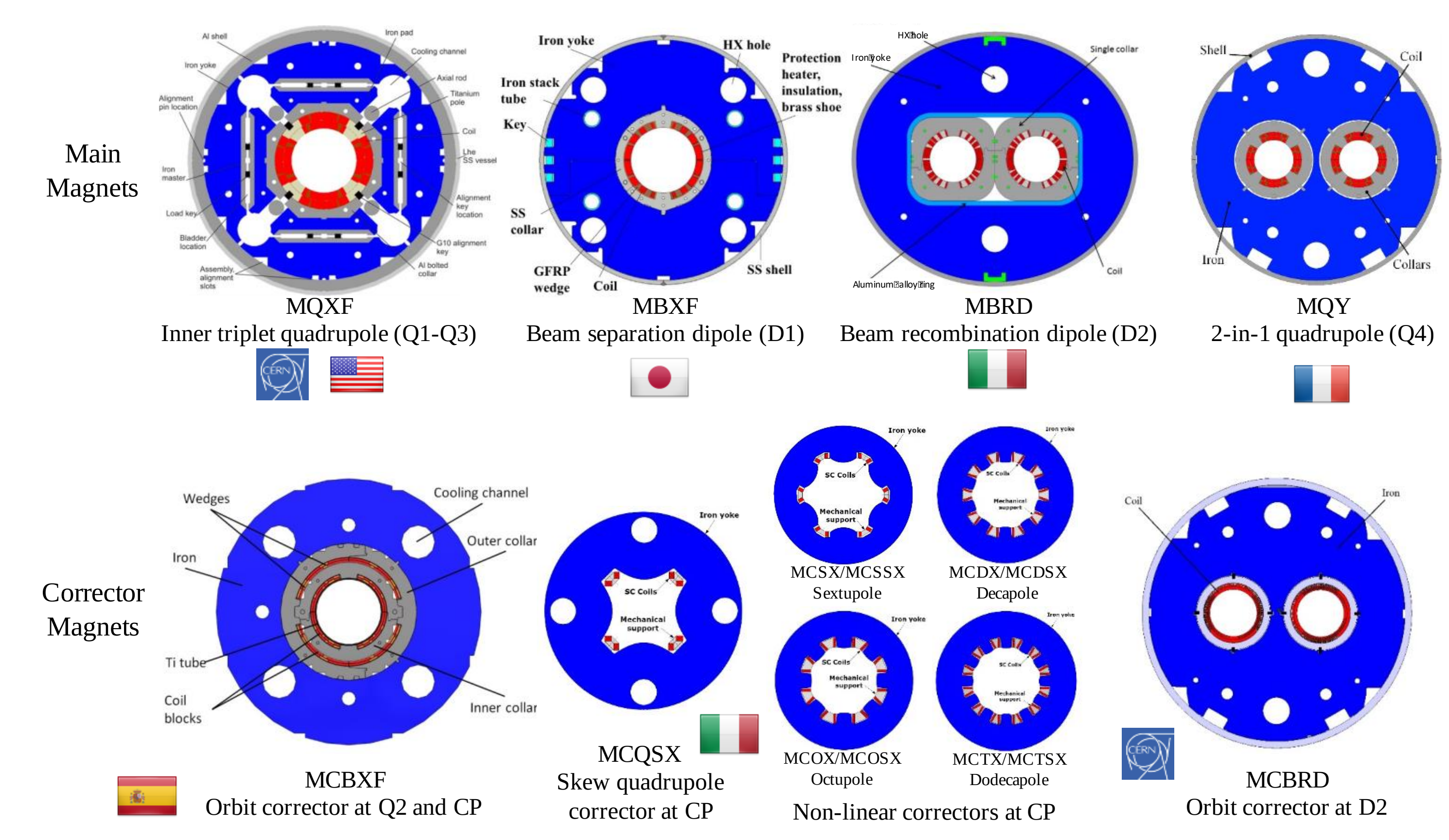
- High Luminosity LHC
- Increase Collision Statistics
- More detailed physics



27

# On going HL-LHC

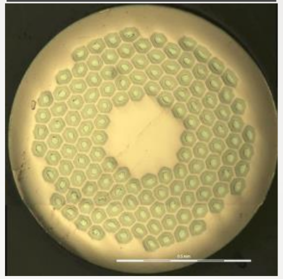


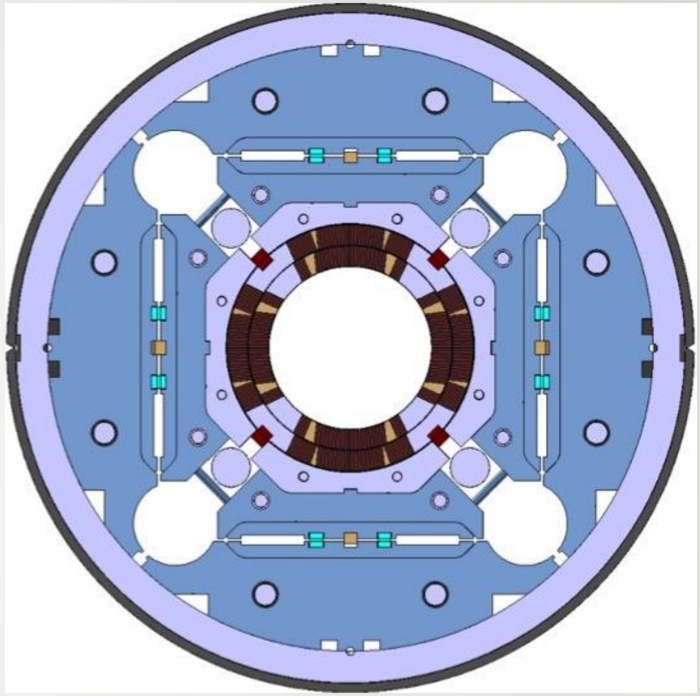

- Interaction Region Upgrade
  - Smaller beam size at IR
    - Quadrupole upgrade by $Nb_3Sn$
  - Crab cavity
  - Beam separation magnet upgrade
    - NbTi superconducting magnet
  - Luminosity Upgrade

# IR Quadrupole Upgrade Higher Field by $Nb_3Sn$

OST RRP strand, 132/169

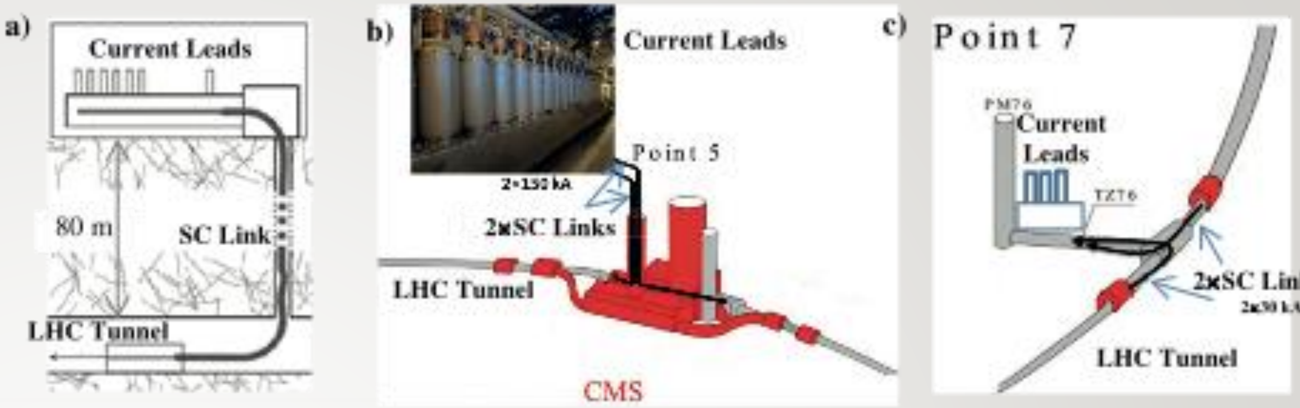


- $Nb_3Sn$: maximum field 11.4T
- Wind and React to handle brittle superconductor

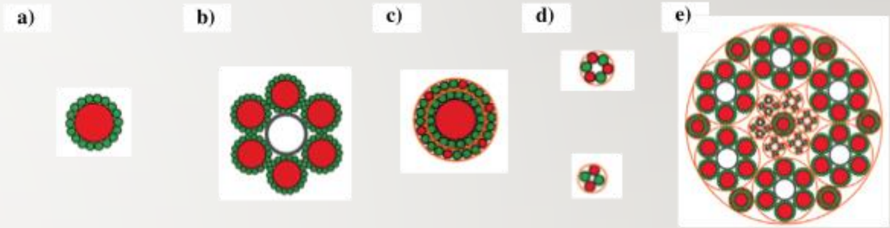


29

# Superconducting Transmission Line




- Transmission line system for HL-LHC.
- Default $MgB_2$
- Option HTS

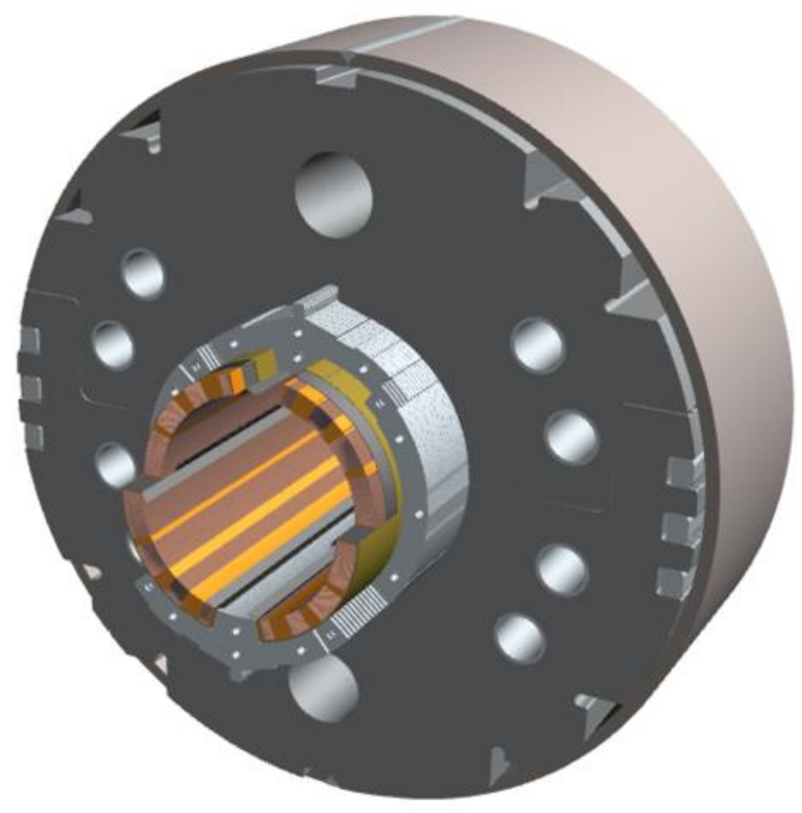




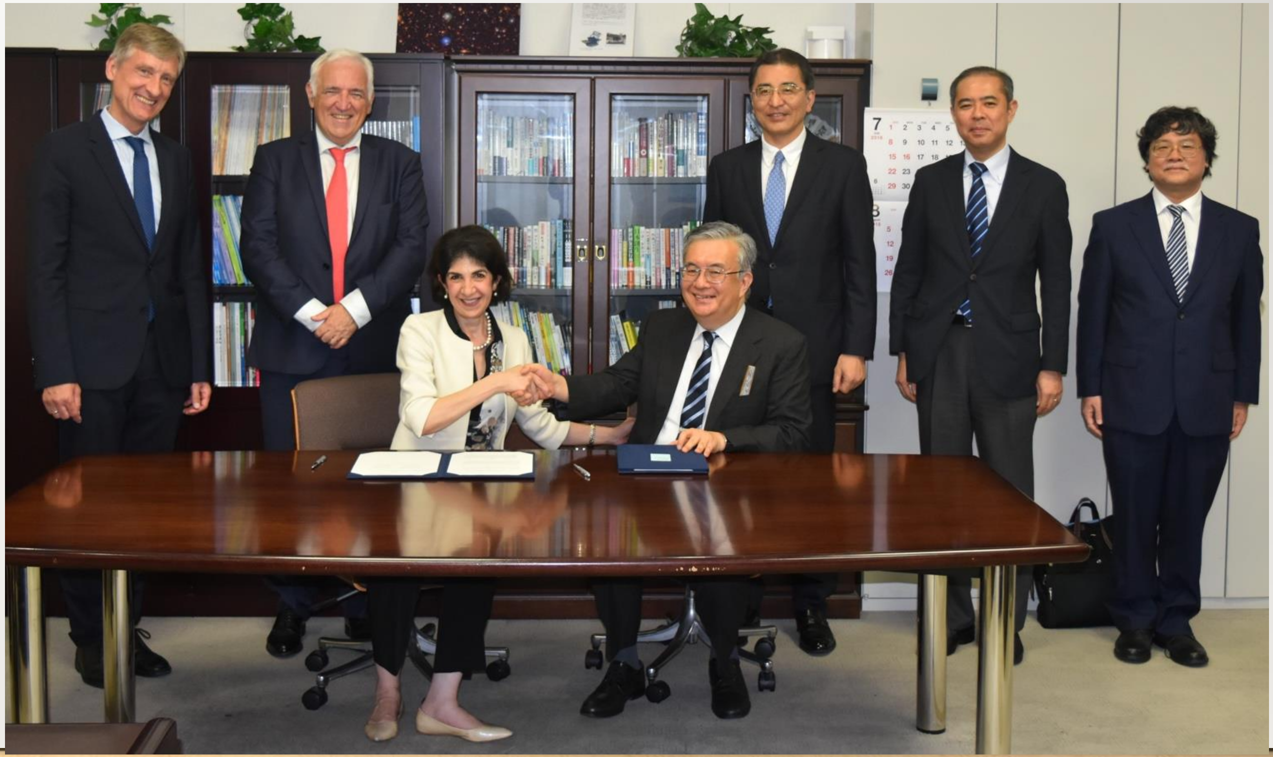
"Development of superconducting links for the Large Hadron Collider machine," A. Ballarino, *Supercond. Sci. Technol.* 27, 2014, 044024.

# Beam Separation Dipole Upgrade KEK Contribution

- Large Aperture 150mm, 6T Dipole



HL-LHC D1 Magnet



Sigh of MOU between CERN and KEK

# Item

- Accelerator & Superconducting Magnet
- **Superconducting Magnets for Hadron Colliders**
  - History
  - On going
  - **Future**
- Superconducting magnet applications in various accelerators
- Summary

# Major High Field Accelerator Magnet Program in the World

## EU HFM

## High Field Magnets Program

## US-MDP

## IHEP-CAS

# HFM

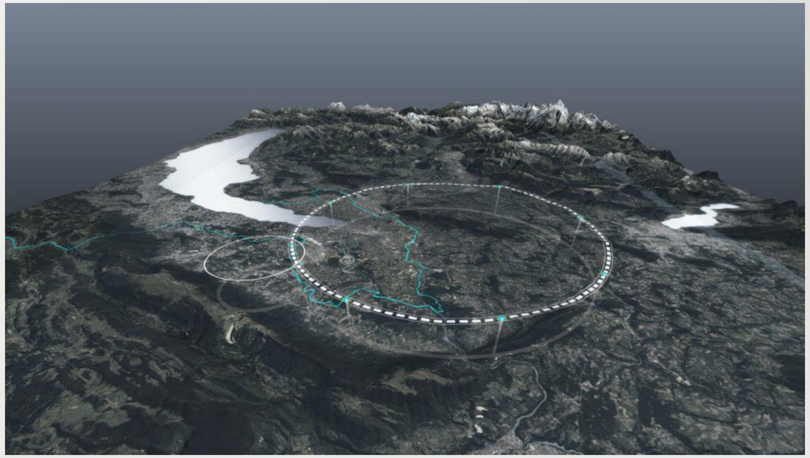
High Field Magnets
Programme

# Updated FCC-hh baseline: 14 T

- The new targets for FCC-hh in $Nb_3Sn$ allow reaching 85 TeV with 83% filling factor, and improved HL-LHC conductor (see also ESSP document 247 page 533-546 )
- The magnet is at 80% of short sample, and 14 T makes several aspects less critical
    - Stress limits <150 MPa rather than <200 MPa, protection is less demanding, conductor is available
    - lling factor could allow 90 TeV c.o.m (G. Perez Segurana talk at FCC week)

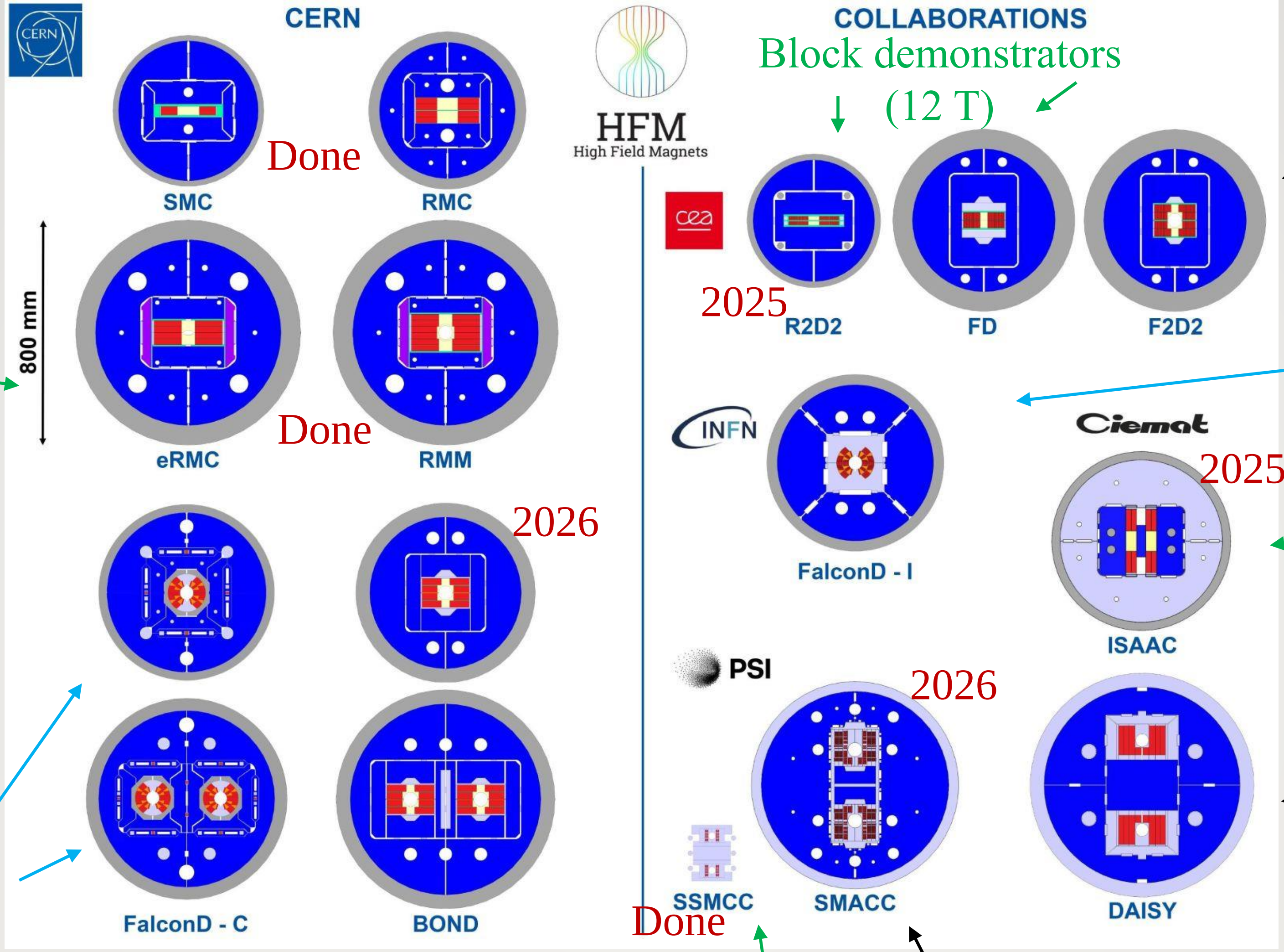
| FCC-hh parameters | CDR 2019 | 2024-$Nb_3Sn$ |
|---|---|---|
| **Dipole field (T)** | **16.0** | **14.0** |
| Temperature (K) | 1.9 | 1.9 |
| Tunnel length (km) | 100 | 90.7 |
| Arc length (km) | 82.0 | 76.9 |
| Arc filling factor (adim) | 0.80 | 0.83 |
| Energy c.o.m (TeV) | 100 | 85 |
| Non Cu jc 16 T 4.2 K | 1500 | 1200 |
| Loadline margin | 86% | 80% |


7-m-long $Nb_3Sn$ magnets for HL-LHC



FCC layout and evolution of parameters

# HFM $Nb_3Sn$ zoo




Block demonstrators (>14 T)

Done

Done

2026

Cosθ 12 T option

Block 14 T

Block demonstrators (12 T)

2025

Block 14 T current grading

Cosθ 12 T option

2025

Common coil Demonstrator (12 T)

2026

Common coil 14 T

Done

SMCC demonstrator (5 T)

Stress managed Common coil 14 T

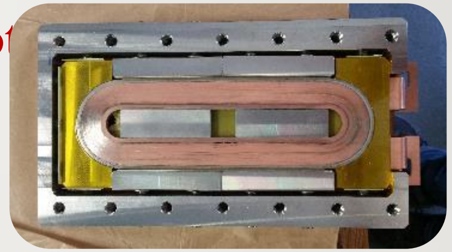

P. Greenaway, “A zed and two noughts” (1985, Channel four films)

# The HTS path

- HFM also includes as a R&D target dipoles based on HTS in the 14 -20 T range, that could operate at higher temperatures and at fields >15 T
  - HTS has a huge potential and a large momentum from the fusion community
  - Even though high field solenoids have been successfully built, many challenges have still to be solved for the applications to high field dipoles
    - Is the 20 T target still valid for FCC-hh? 120 TeV means 4 times more synchrot TeV rs), ar ritical

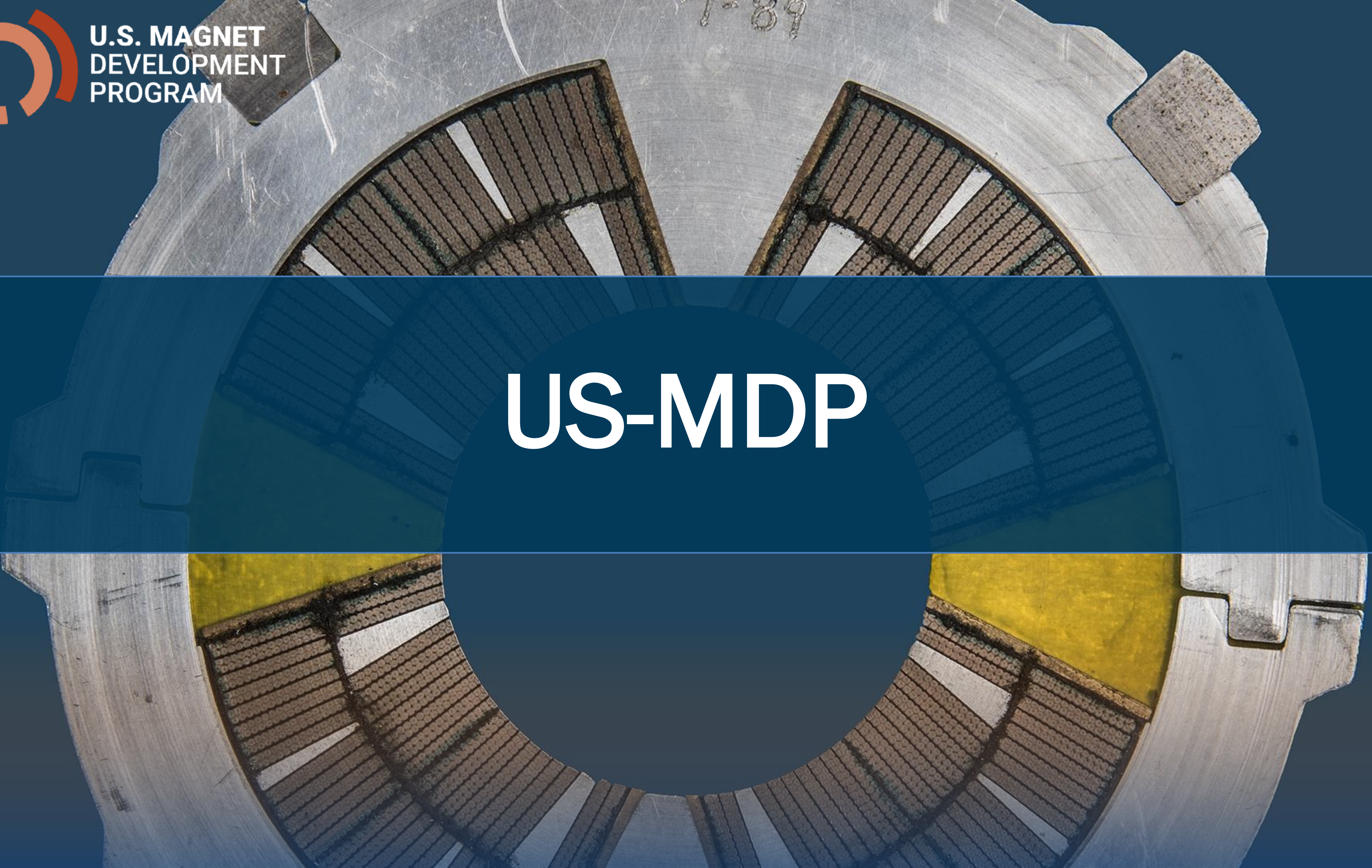
| FCC-hh parameters | 2024-Nb$_3$Sn | 2024-HTS |
|---|---|---|
| **Dipole field (T)** | **14.0** | **14-20** |
| Temperature (K) | 1.9 | 4.5-20 |
| Tunnel length (km) | 90.7 | 90.7 |
| Energy c.o.m (TeV) | 85 | 85-120 |
| Non Cu jc 16 T 4.2 K | 1200 | TBD |
| Loadline margin | 80% | TBD |


HTS tape developed in ARIES and Bruker


MI racetrack coil [T. Lecrevisse, et al. ]

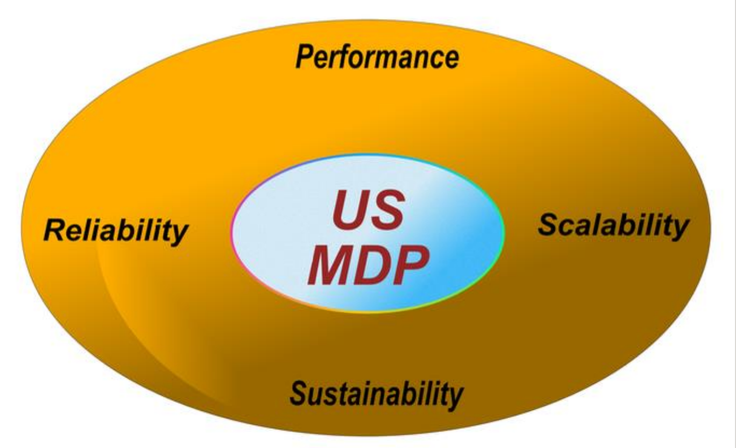

ReBCO racetracks [A. Ballarino, et al.]

U.S. MAGNET DEVELOPMENT PROGRAM

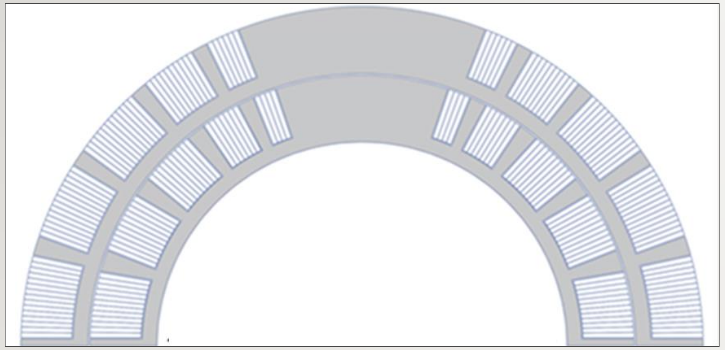


# US-MDP

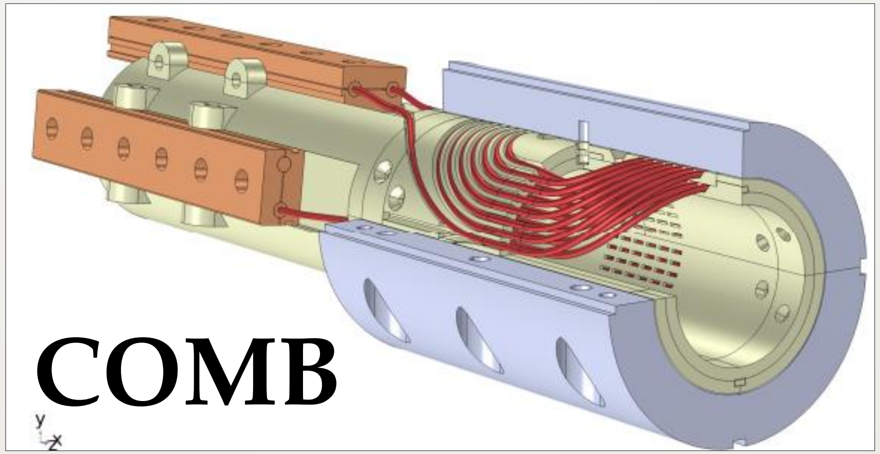
# US-MDP

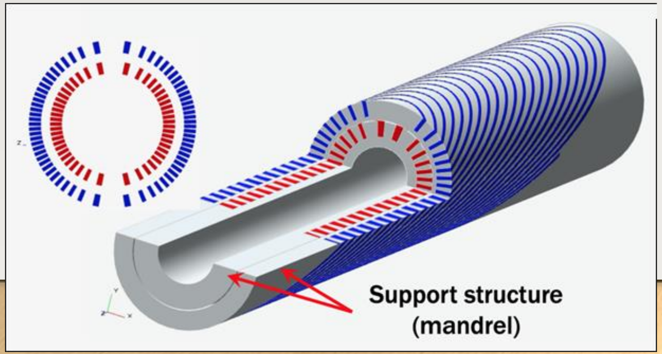



Large Aperture $Nb_3Sn$ + HTS inserts

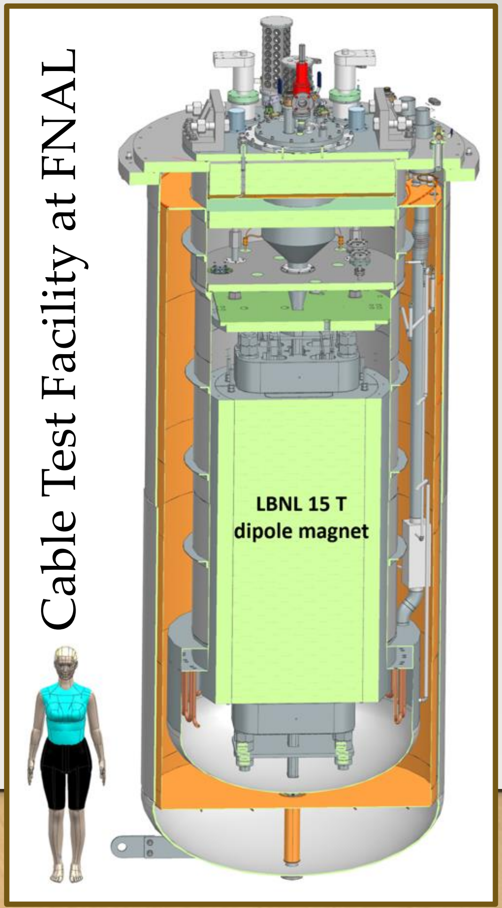


SMCT



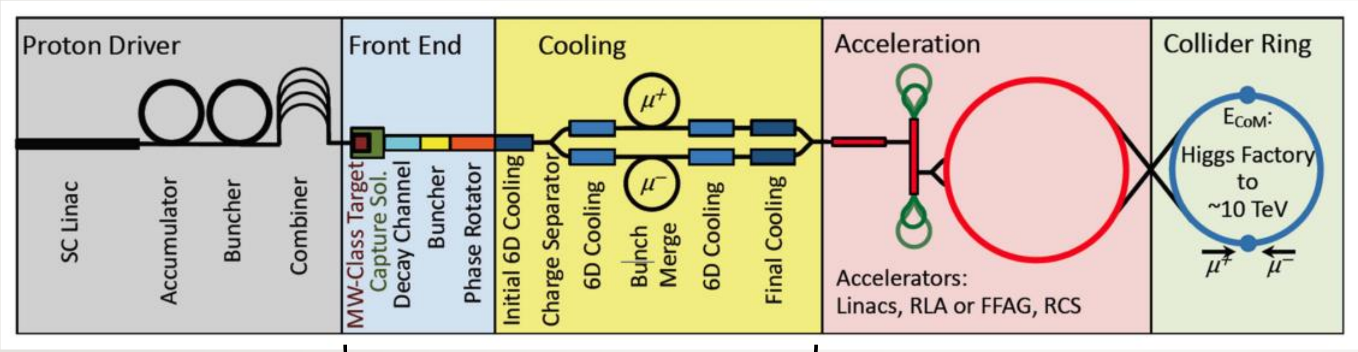





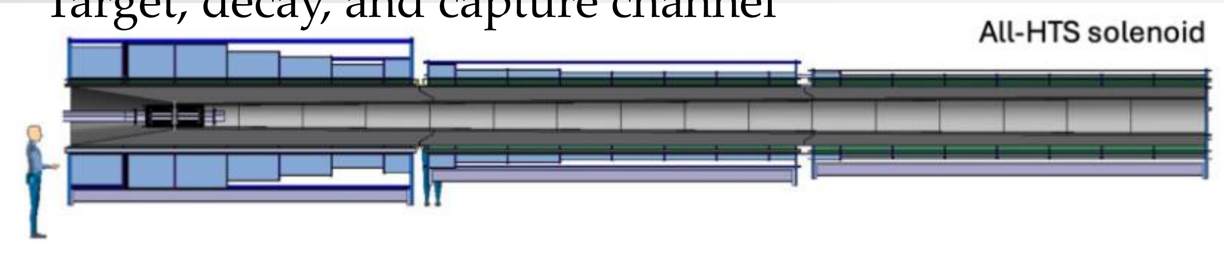


# HF Solenoid Motivation: Muon Collider

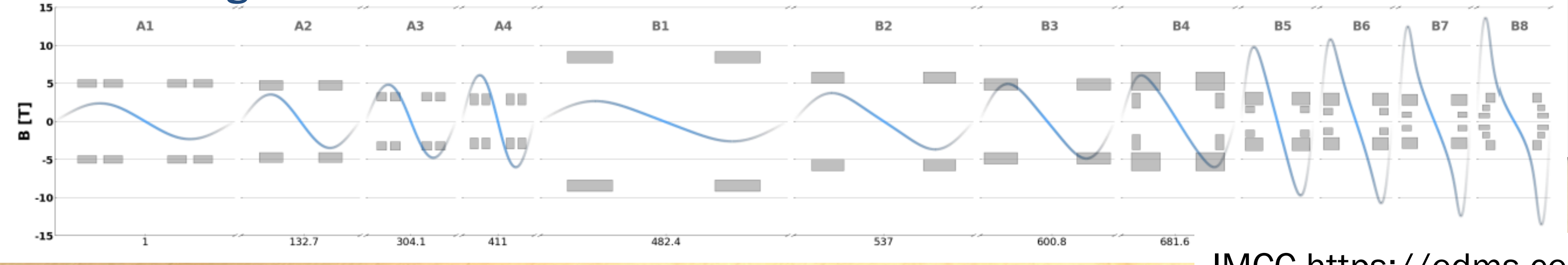
IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 34, NO. 5, AUGUST 2024



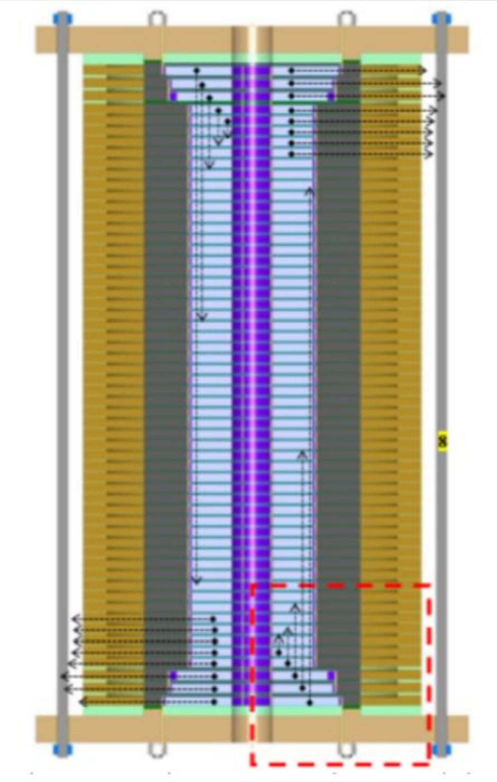

Target, decay, and capture channel




## 6D cooling channel




## Final cooling channel



IMCC https://edms.cern.ch/document/3284682/1

# High Field Magnet R&D
# for the High Energy Particle Accelerators
# at IHEP-CAS

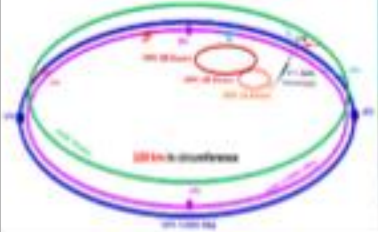
Qingjin XU
for the Superconducting Magnet Group
Accelerator Division, IHEP-CAS
Feb 2025, CERN

中国科学院
CHINESE ACADEMY OF SCIENCES

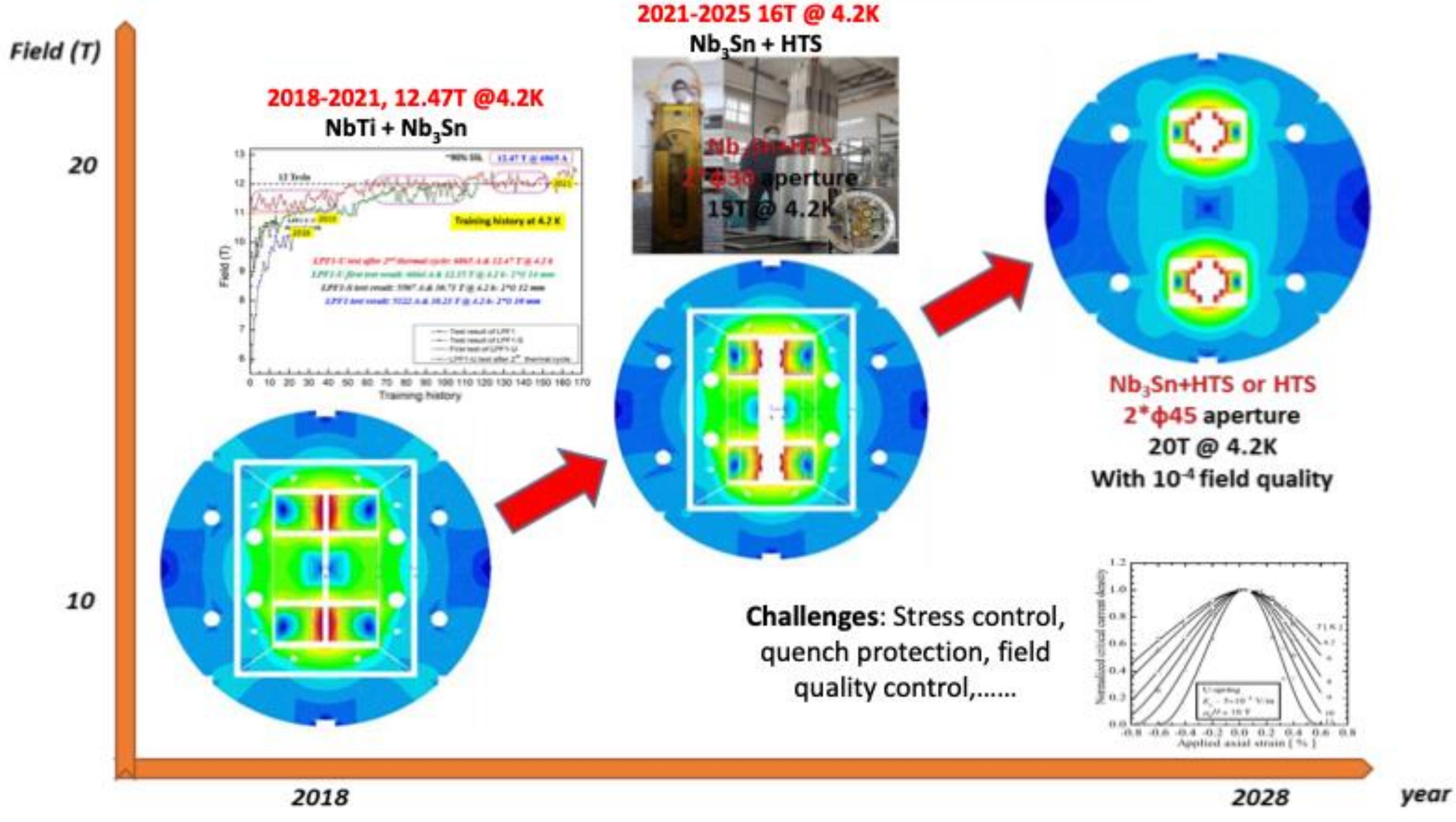
中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

# Design Scope for Next-generation Accelerators

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

| | | |
|---|---|---|
| **High Energy Circular Colliders for next decades** | **SPPC**   | **FCC**  |
| **Proposed institution** | **IHEP-CAS, China** | **CERN, Europe** |
| **Proposed dates** | **2012** | **2013** |
| **Site of the project** | **China** | **Europe** |
| **Baseline technology** | **IBS baseline 20~24 T to reach 125-150 TeV, $Nb_3Sn$+REBCO as options** | **$Nb_3Sn$ 16 T to reach 100 TeV** |
| **Timeline** | **Construction at 2040s** | **Construction at 2050-60s** |
| **Cost** | **/** | **/** |

# Roadmap of the High Field Magnet R&D at IHEP



# Item

- Accelerator & Superconducting Magnet
- Superconducting Magnets for Hadron Colliders
- **Superconducting magnet applications in various accelerators**
- Summary

# Superconducting magnet applications in various accelerators

- Lepton colliders
- Synchrotron radiation facilities
- Proton extraction synchrotron
- Medical synchrotron
- Cyclotron
- Ion source, klystron
- Detector magnets

# Superconducting magnet applications in various accelerators

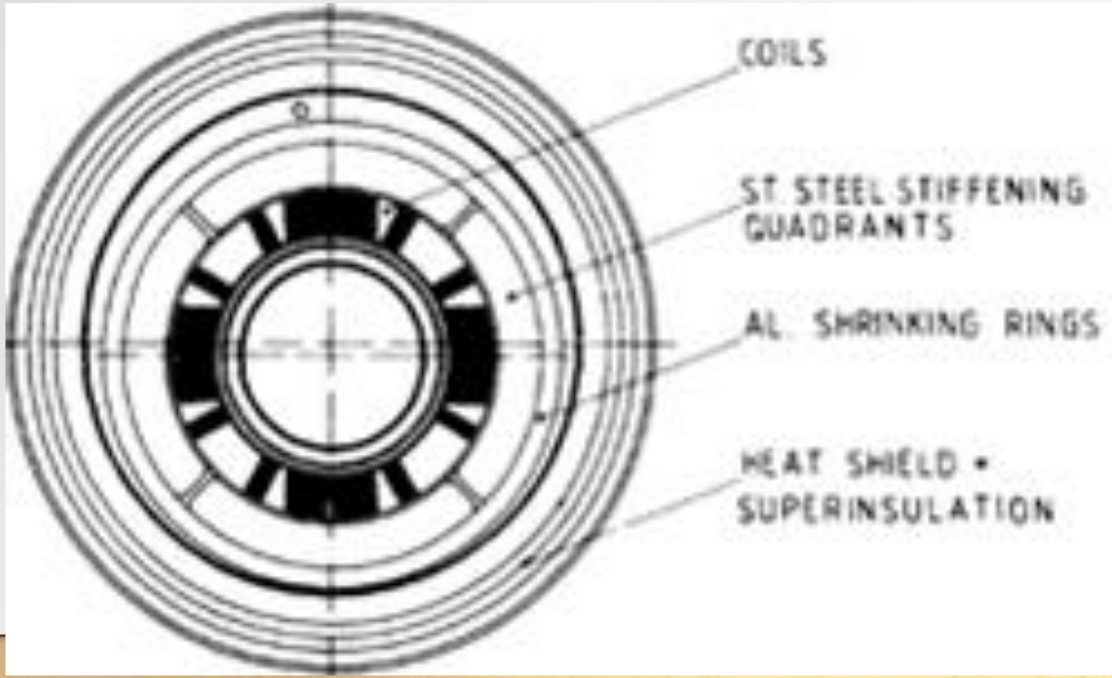
- **Lepton colliders**
- Synchrotron radiation facilities
- Proton extraction synchrotron
- Medical synchrotron
- Cyclotron
- Ion source, klystron
- Detector magnets

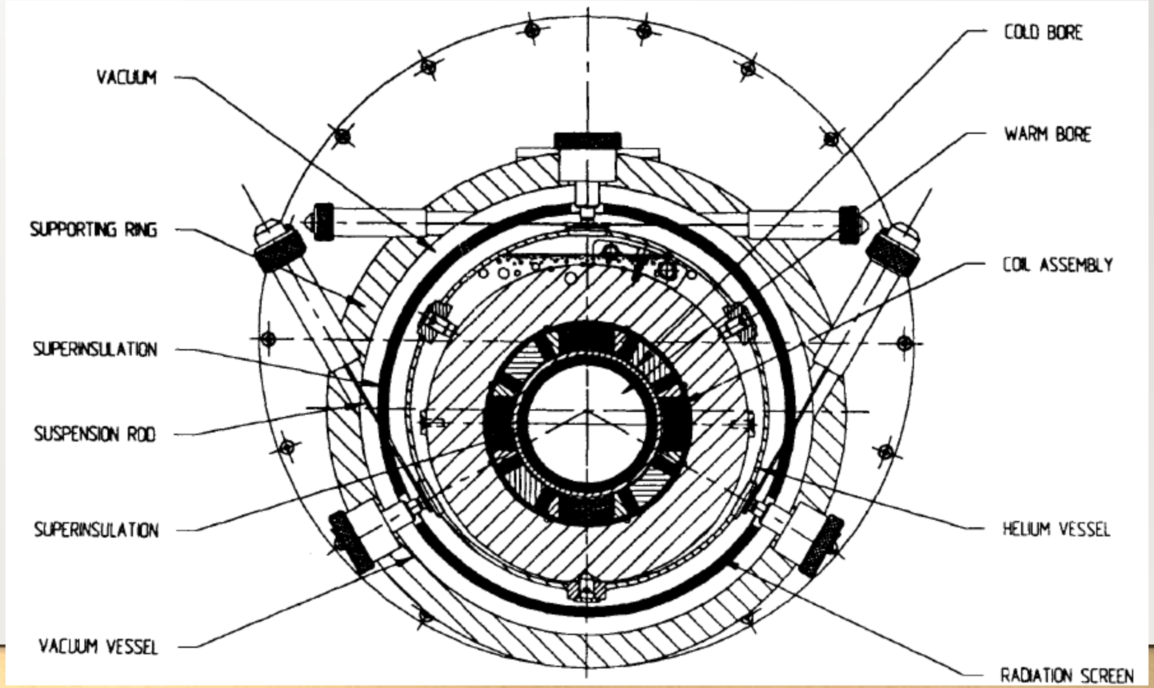
# LEP and LEP2

- LEP: electron positron collider at CERN
- 27 km circumference
- Superconducting magnets for interaction region: focusing quadrupole magnets

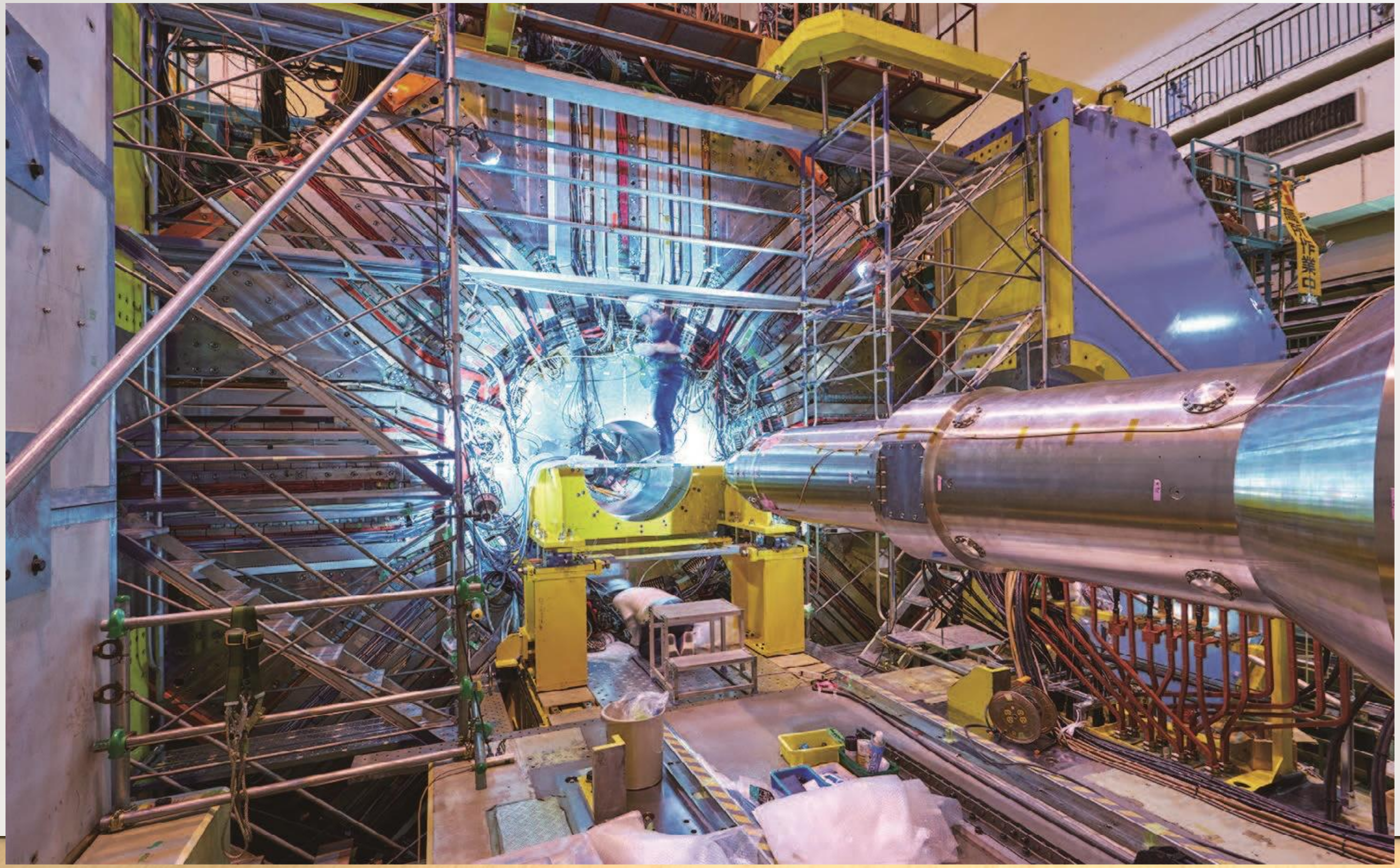
LEP AND LEP2 IR QUADRUPOLE PARAMETERS.

| Parameter | LEP | LEP2 |
|---|---|---|
| $G_{nom}$ (T/m) | 21.7 | 76.37 |
| Coil ID (mm) | 130 | 50 |



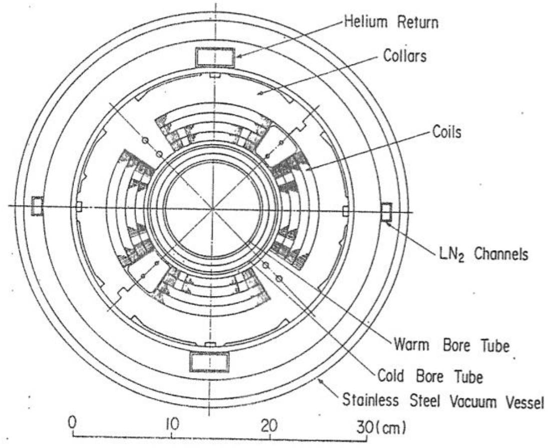



# KEK Lepton colliders and SC Magnets TRISTAN, KEKB, S-KEKB

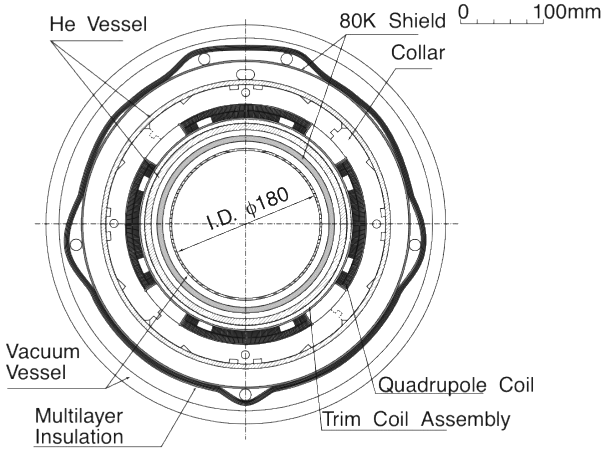


SuperKEKB Quadrupole magnet at Collision point

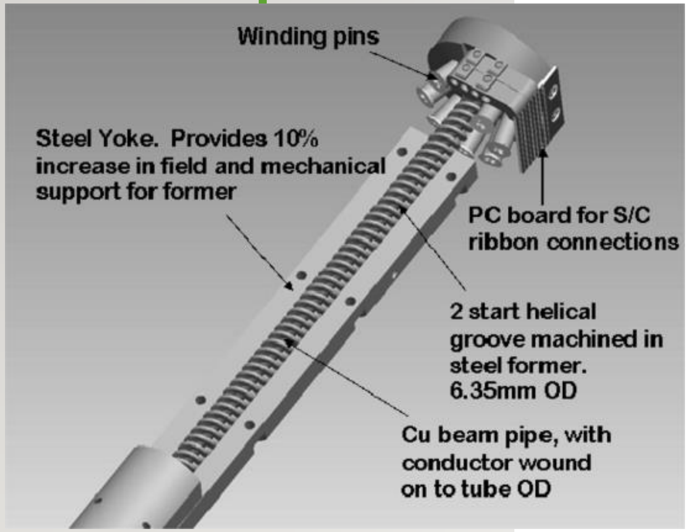
b) TRISTAN QCS(70T/m, 4.5K)



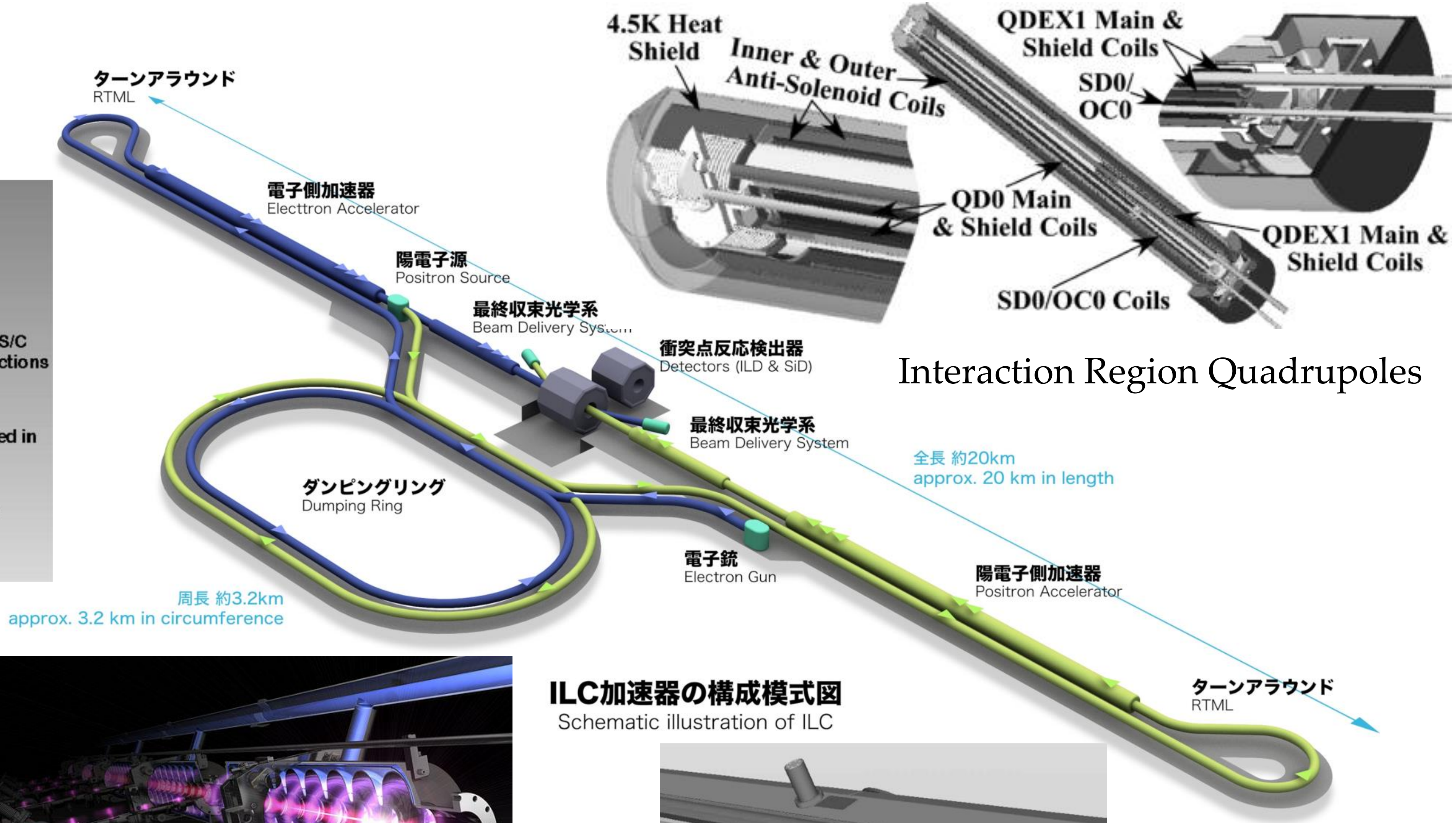

c) KEK-B QCS(22T/m, 4.5K)



# ILC Magnets

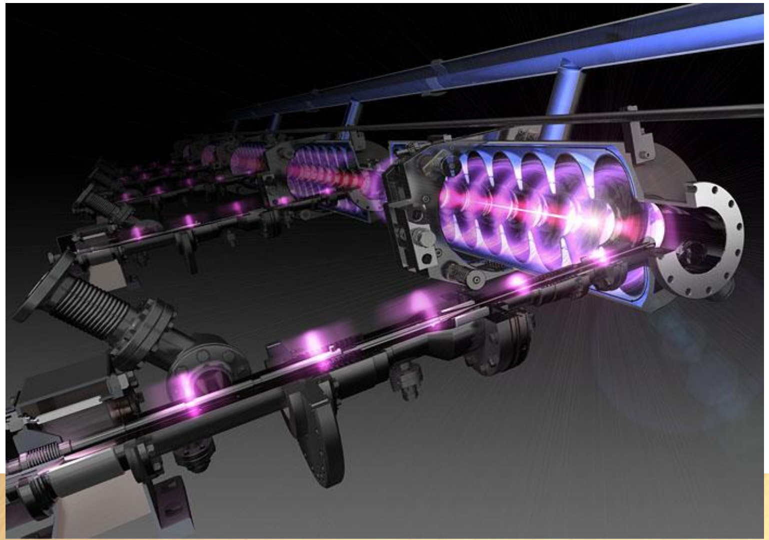


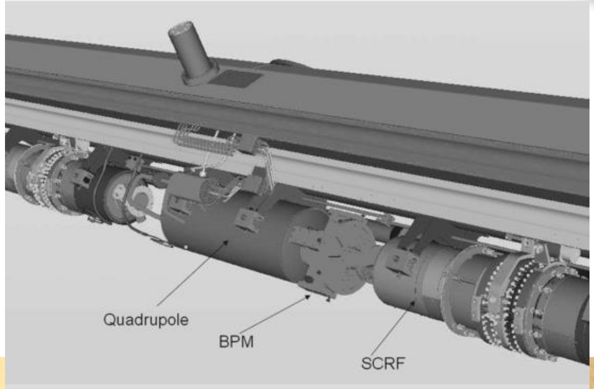

Undulator




Interaction Region Quadrupoles

ILC magnets
Low field



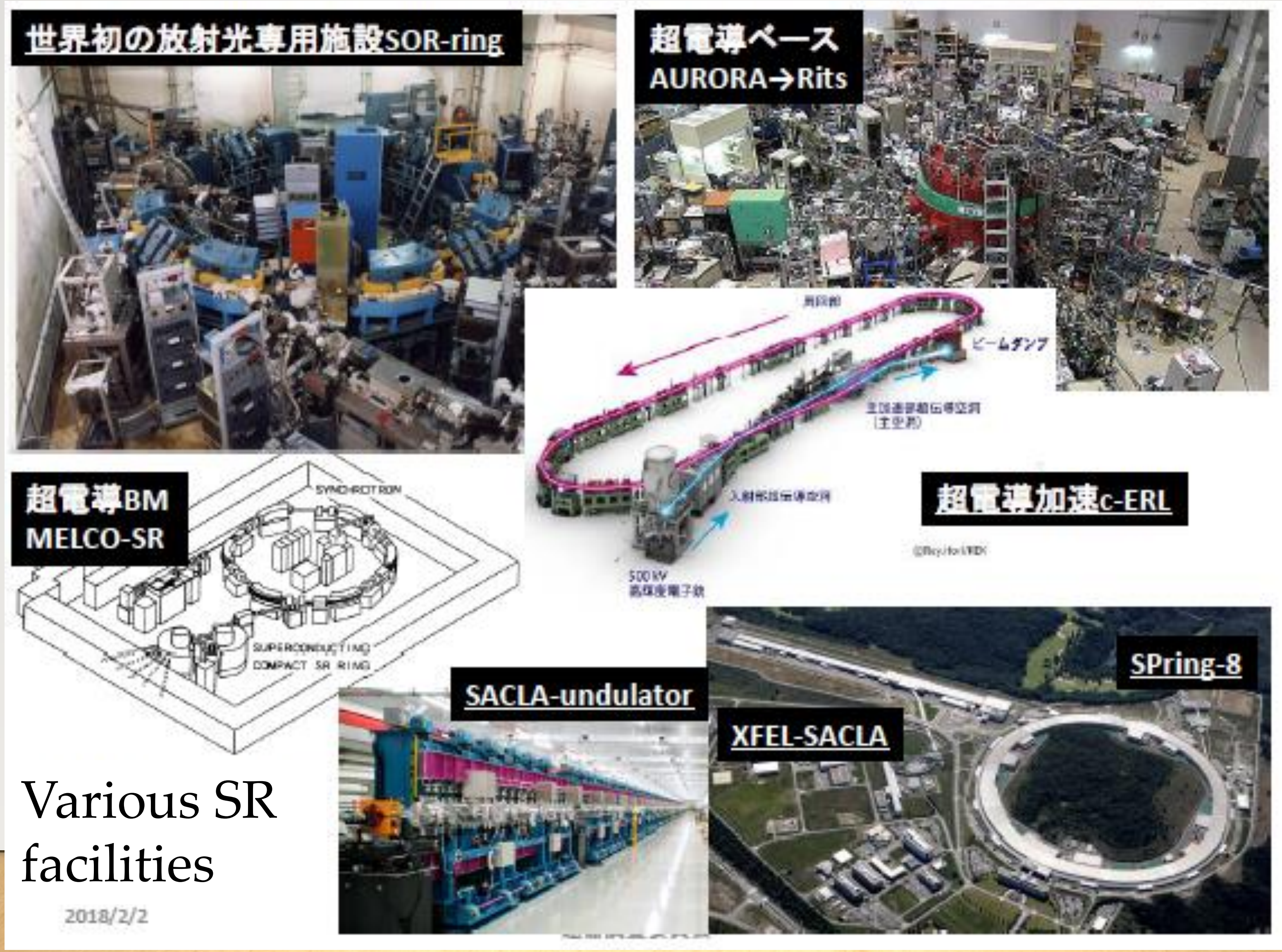



Acceleration Region Quadrupoles

# Superconducting magnet applications in various accelerators

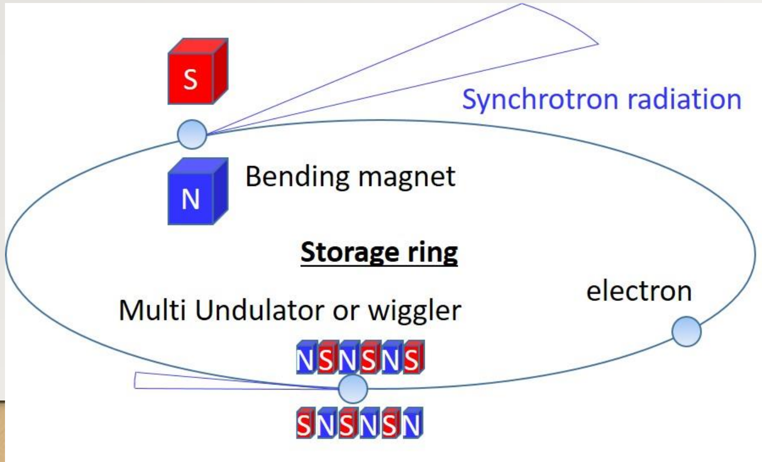
- Lepton colliders
- **Synchrotron radiation facilities**
- Proton extraction synchrotron
- Medical synchrotron
- Cyclotron
- Ion source, klystron
- Detector magnets

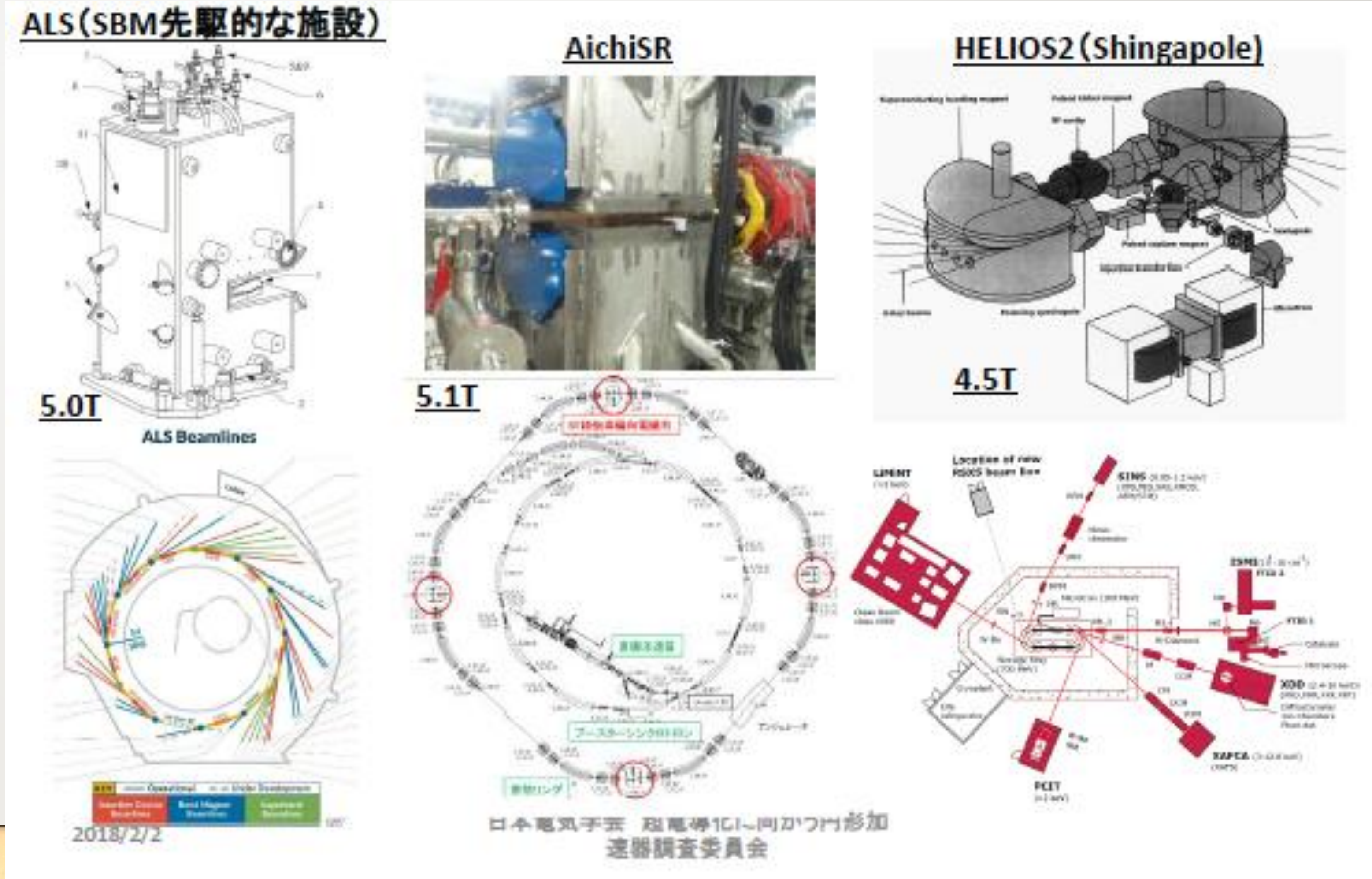
# Synchrotron radiation facilities



# SR facilities

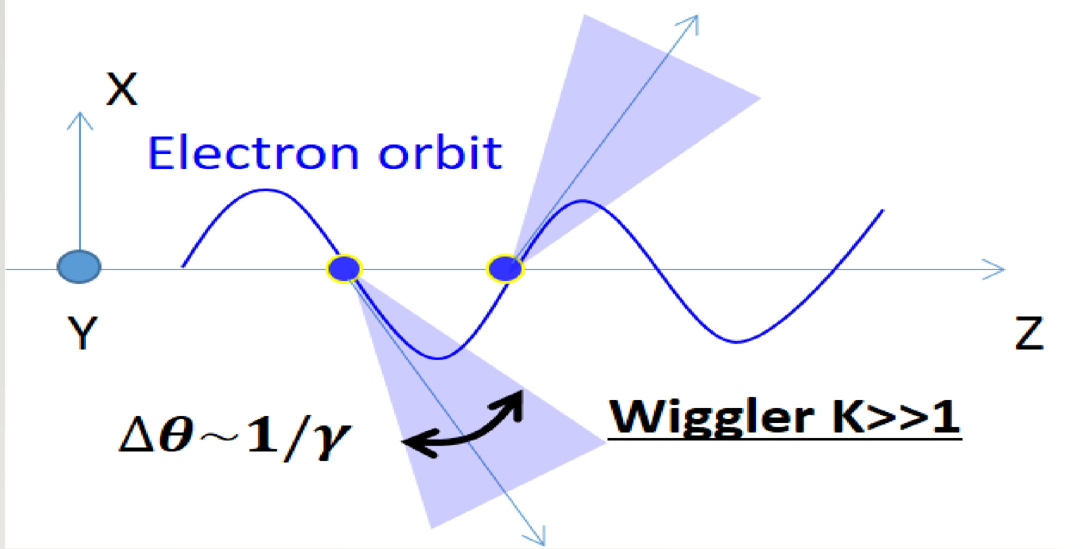
- Super-Bend
- Traditional usage

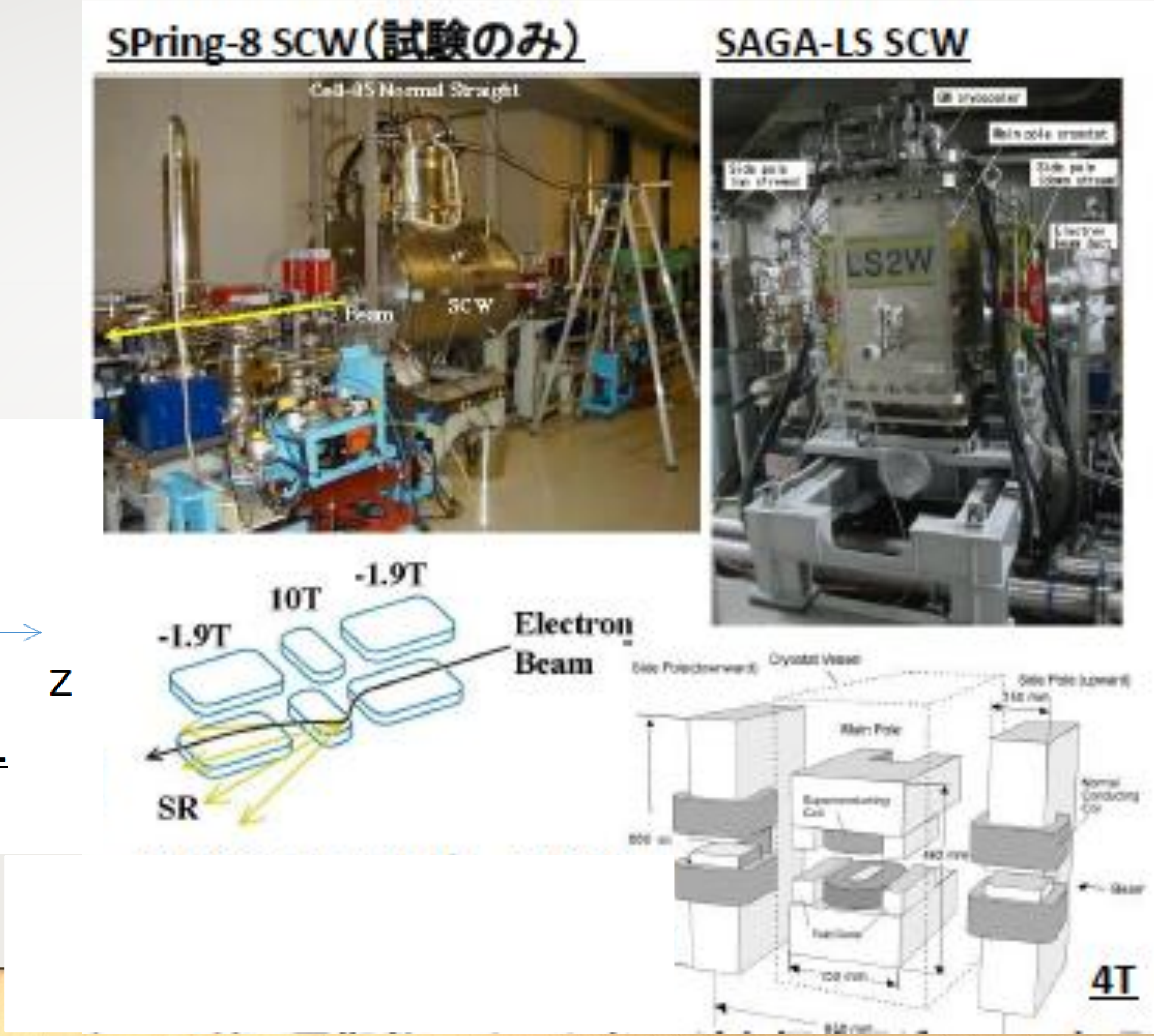


# SR facilities

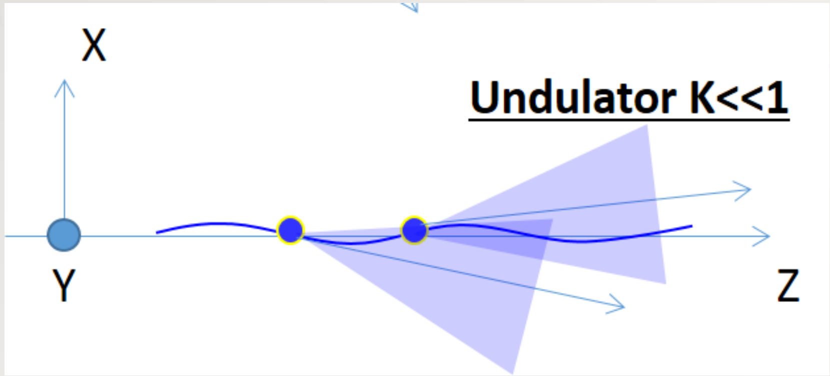
- Wiggler

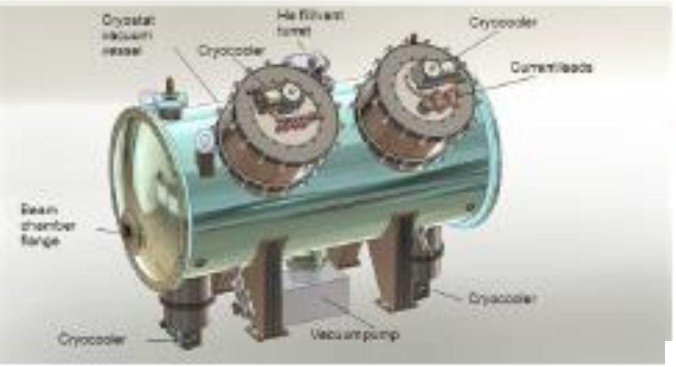


# SR facilities

- Superconducting undulator



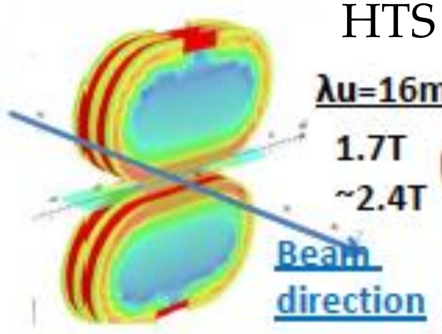



Shorter period

Higher brightness

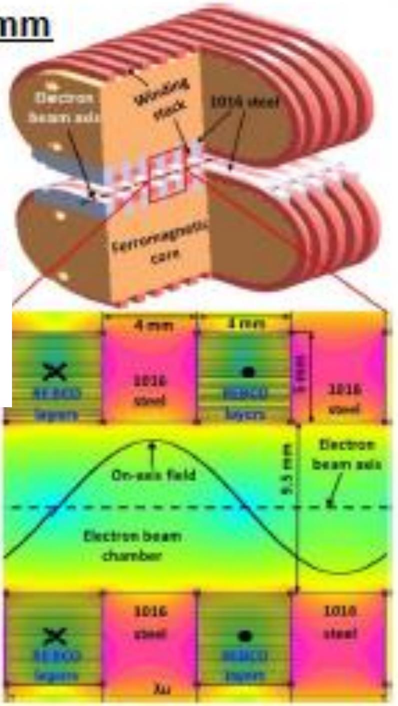
Higher energy

Large fixed aperture




$Nb_3Sn$ high current density coil

HTS tape conductor coil

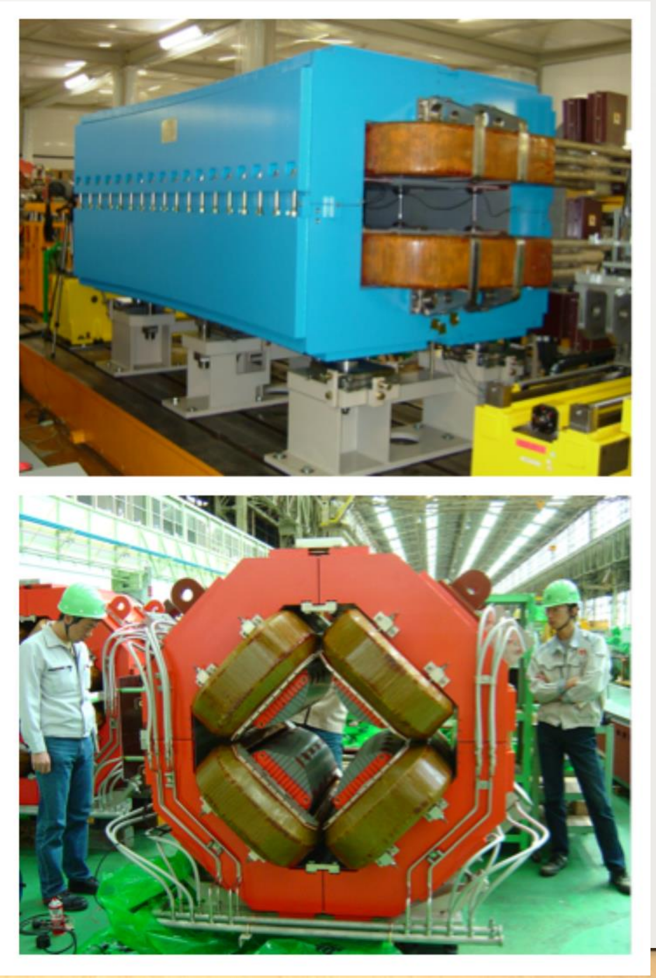


# Superconducting magnet applications in various accelerators

- Lepton colliders
- Synchrotron radiation facilities
- **Proton extraction synchrotron**
- Medical synchrotron
- Cyclotron
- Ion source, klystron
- Detector magnets

# Proton extraction accelerators
# J-PARC

- J-PARC: extraction machine
  - Rapid cycle synchrotron
  - J-PARC RCS (3GeV 1MW)：25 Hz
  - J-PARC MR (30GeV 1MW): ~1 Hz
  - Not suitable for superconducting magnets
- After extraction: constant beam energy = constant magnetic field: good for superconducting magnet
  - J-PARC neutrino beam line

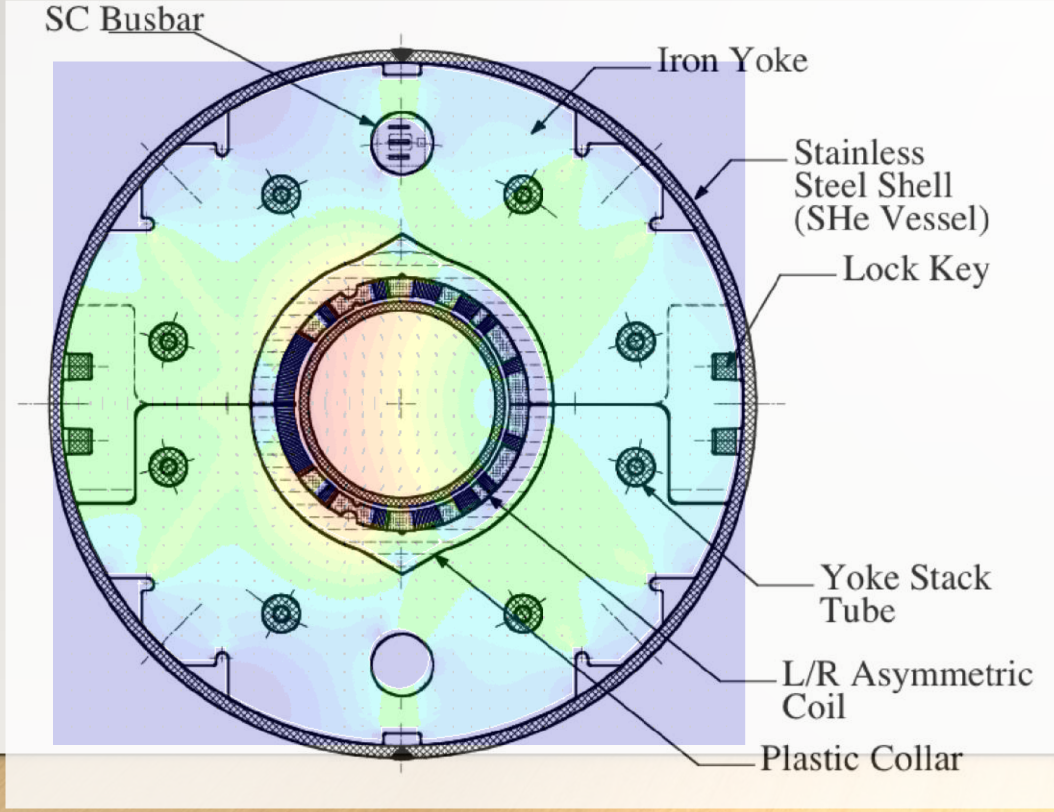


J-PARC RCS Magnets

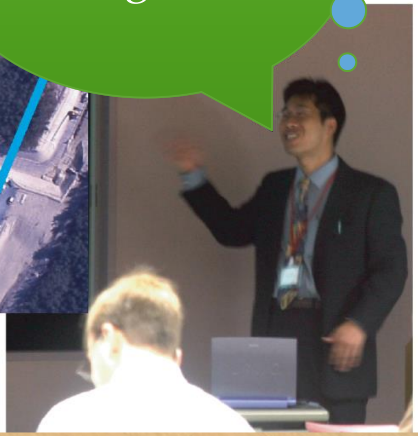
J-PARC MR Magnets

# Japanese Accelerators and SC Magnets
# J-PARC Neutrino Facility

- Neutrino Facility needed SC magnets due to space limitation



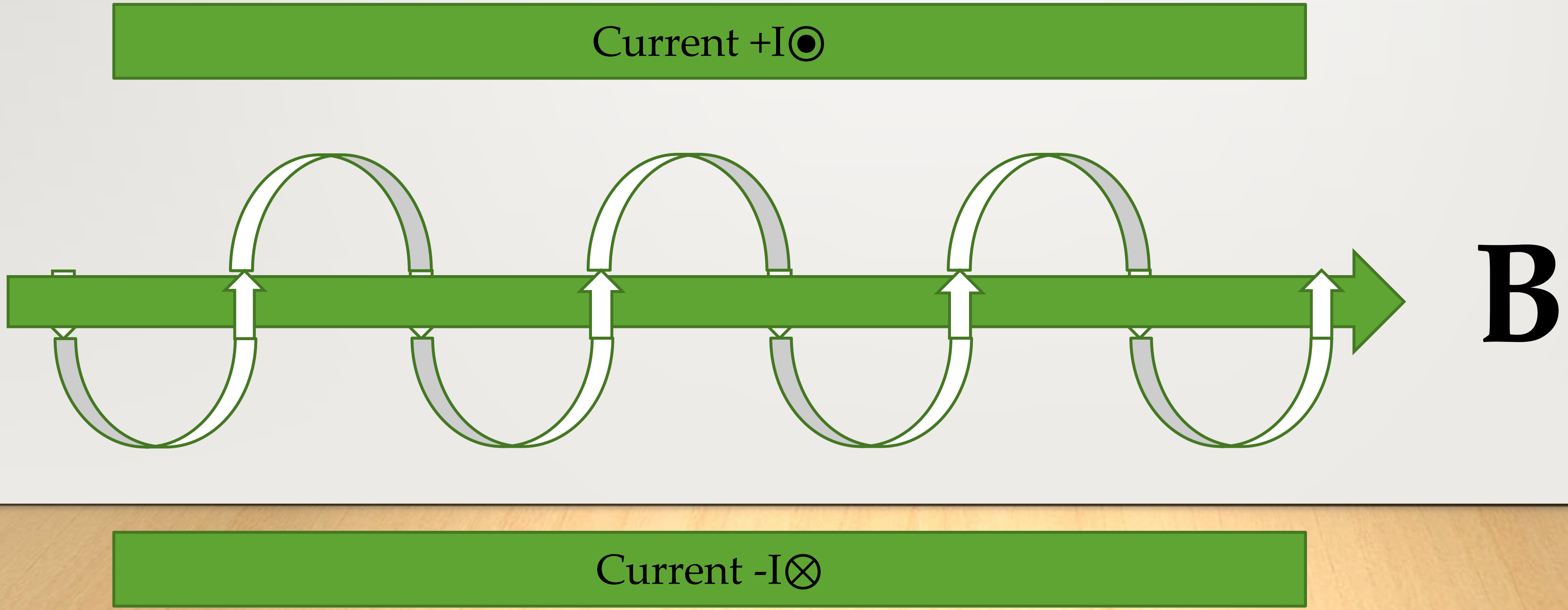




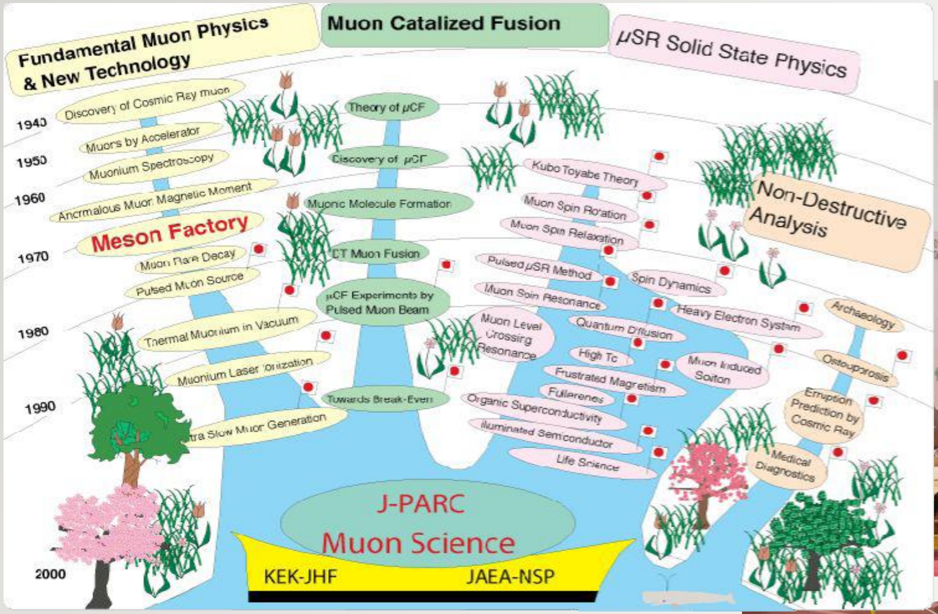

Combined Function Magnet Beam Line（2.6T+19T/m, 28 Magnets）Optimize Cost and Schedule

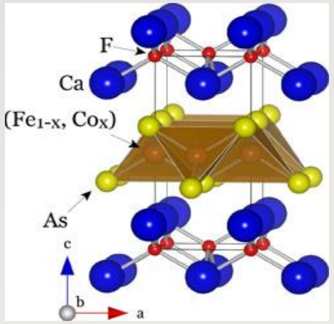
# Muon Capture and Trasportation

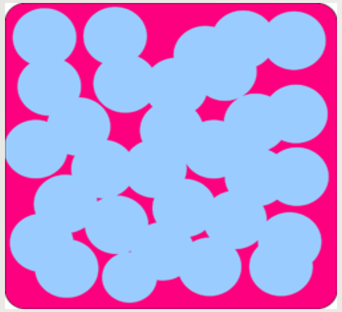
- Muon at J-PARC MLF: Low Energy (low momentum)
  - Trap Muon in helical orbit (cyclotron motion)
  - Use solenoid magnet



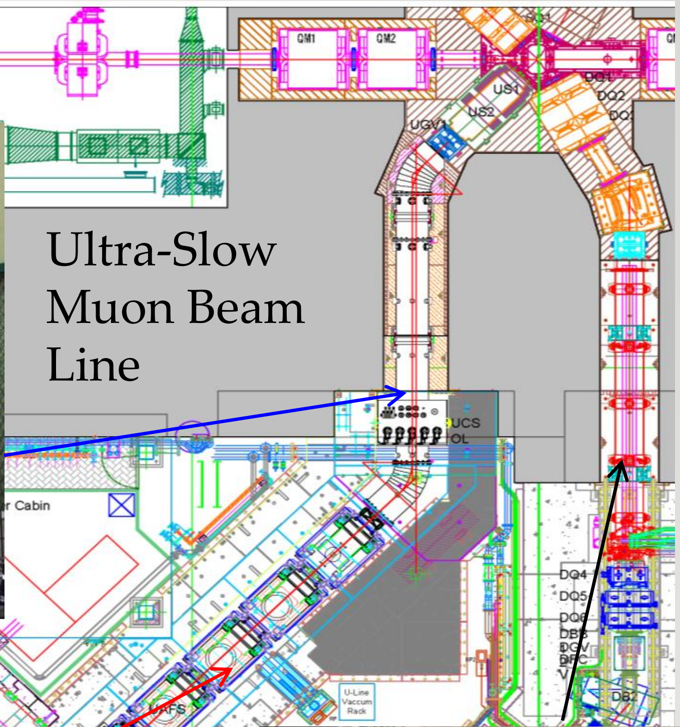
# SC Solenoids in MLF Muon Science Facility



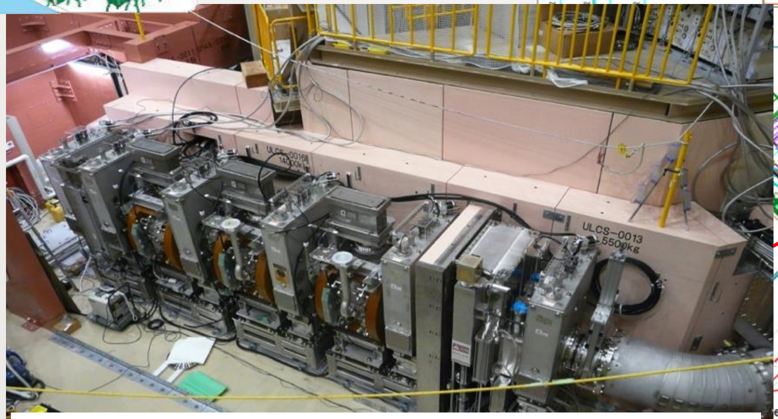



Superconducting Curved Solenoid




Ultra-Slow Muon Beam Line

Decay Muon Beam Line



Superconducting Focusing Solenoids

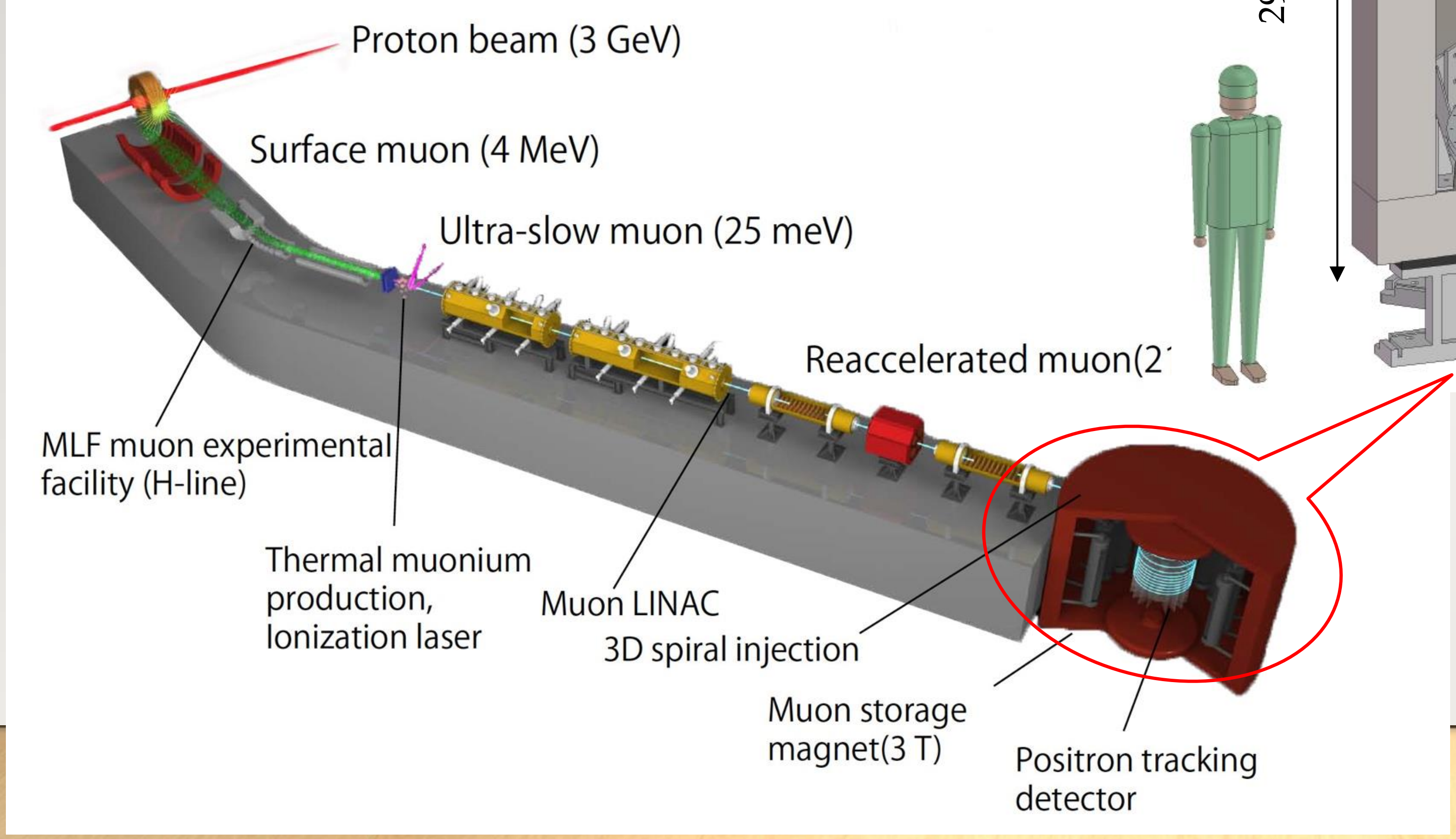
Superconducting Solenoid

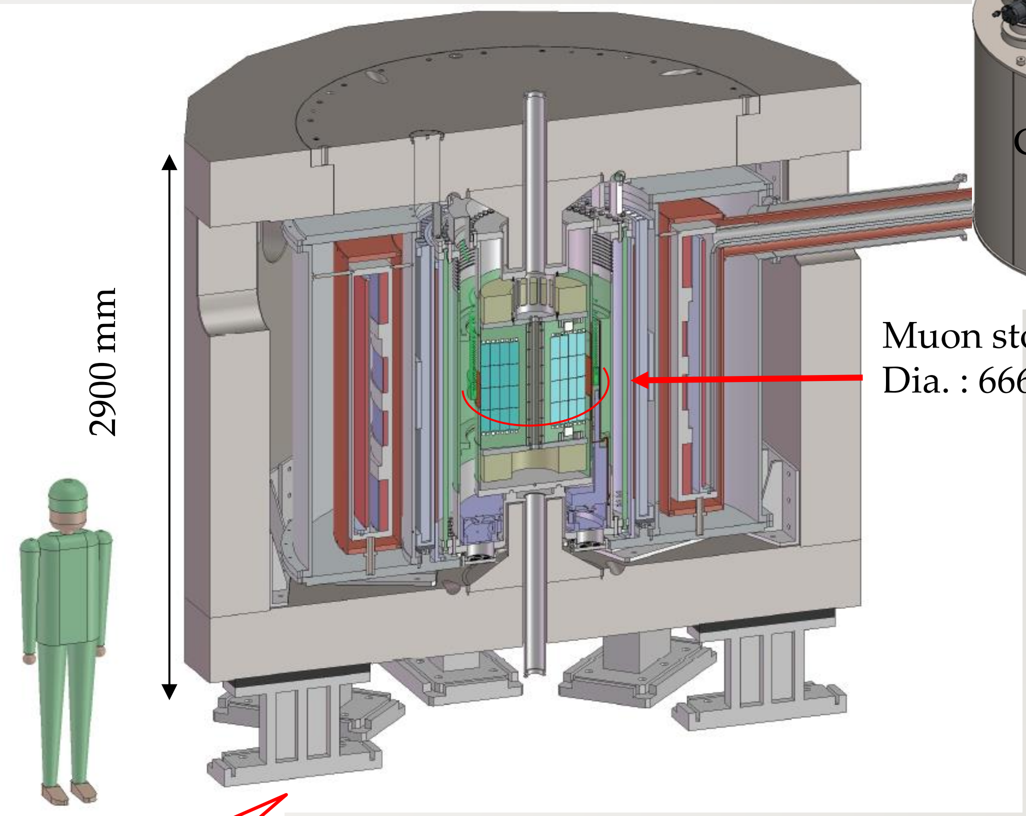
http://legacy.kek.jp/newskek/2009/julaug/CFCAF.html

Institute of Materials Structure Science, KEK
Muon Science Laboratory

# J-PARC g-2/EDM

Very high precision solenoid (sub-ppm) for Muon storage: measure muon g-2 and EDM



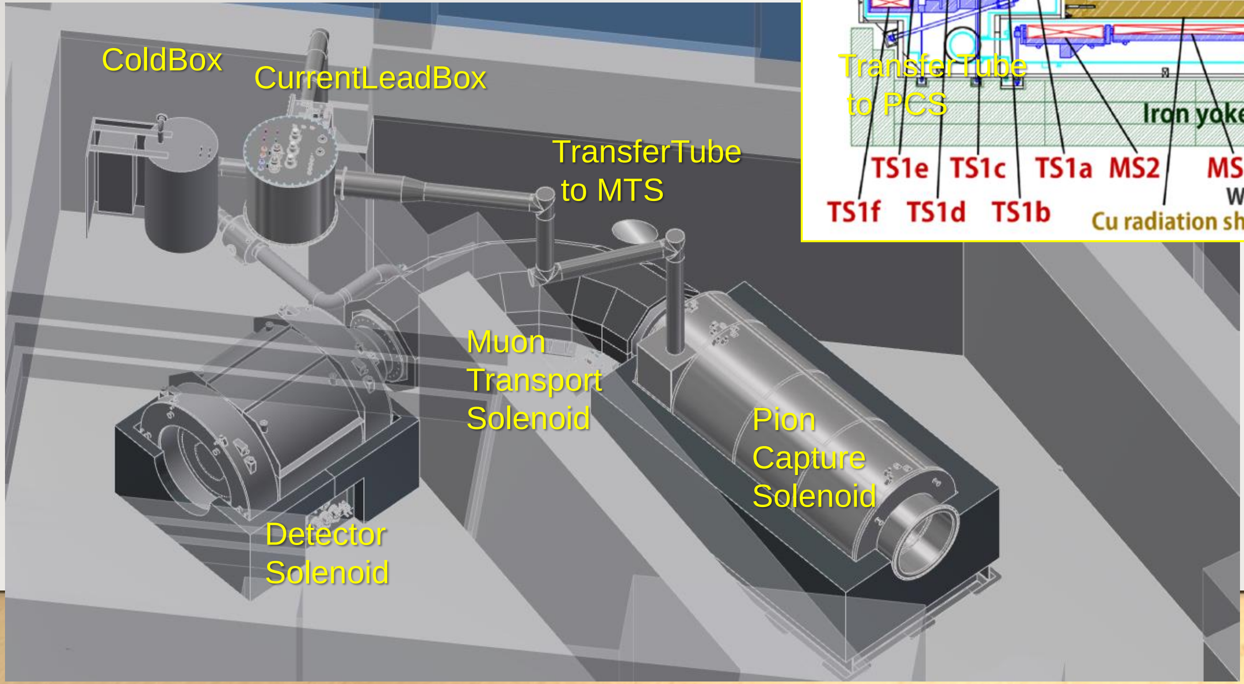


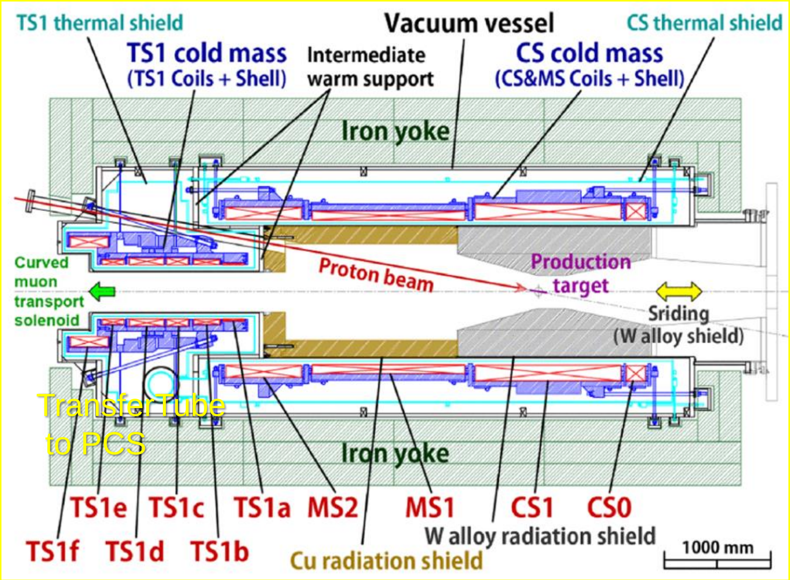
Muon storage orbit
Dia. : 666 mm

NMR probe system R&D

# COMET at J-PARC

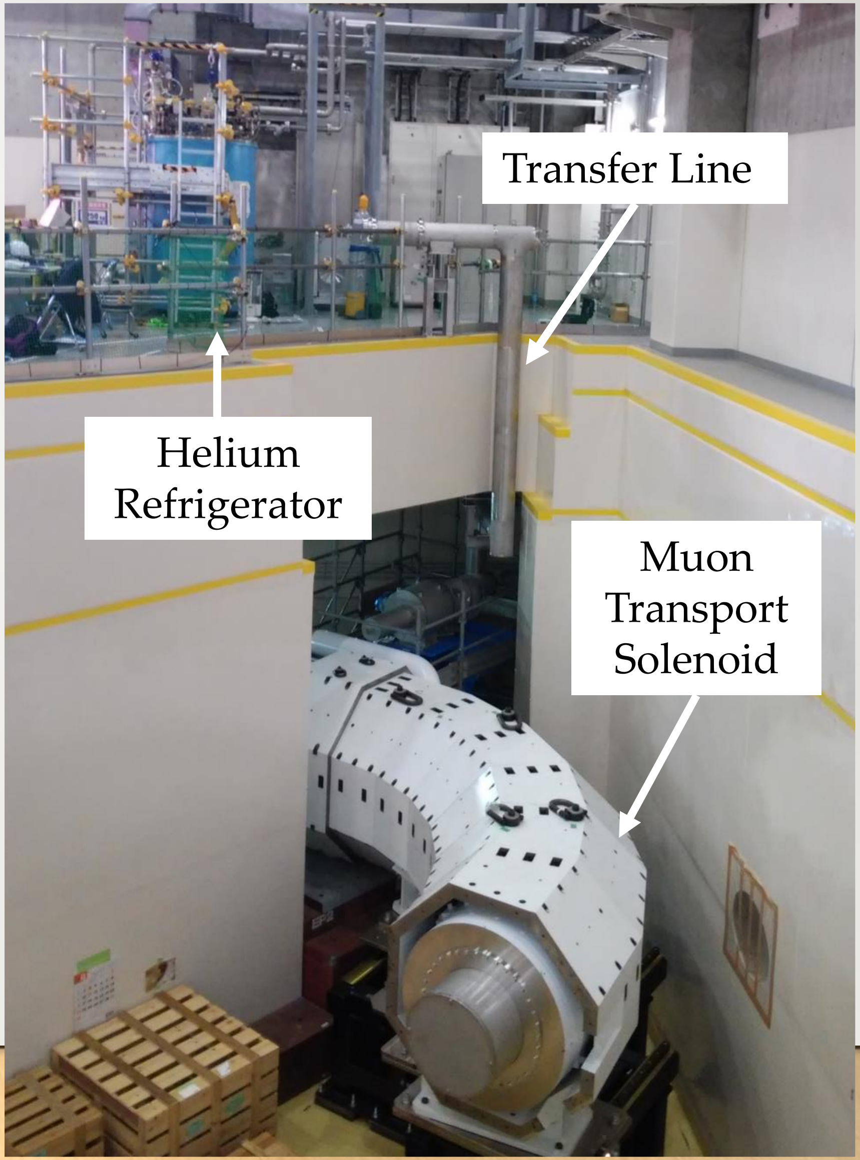
Muon production solenoid
Capture muon and pion with large solenoid



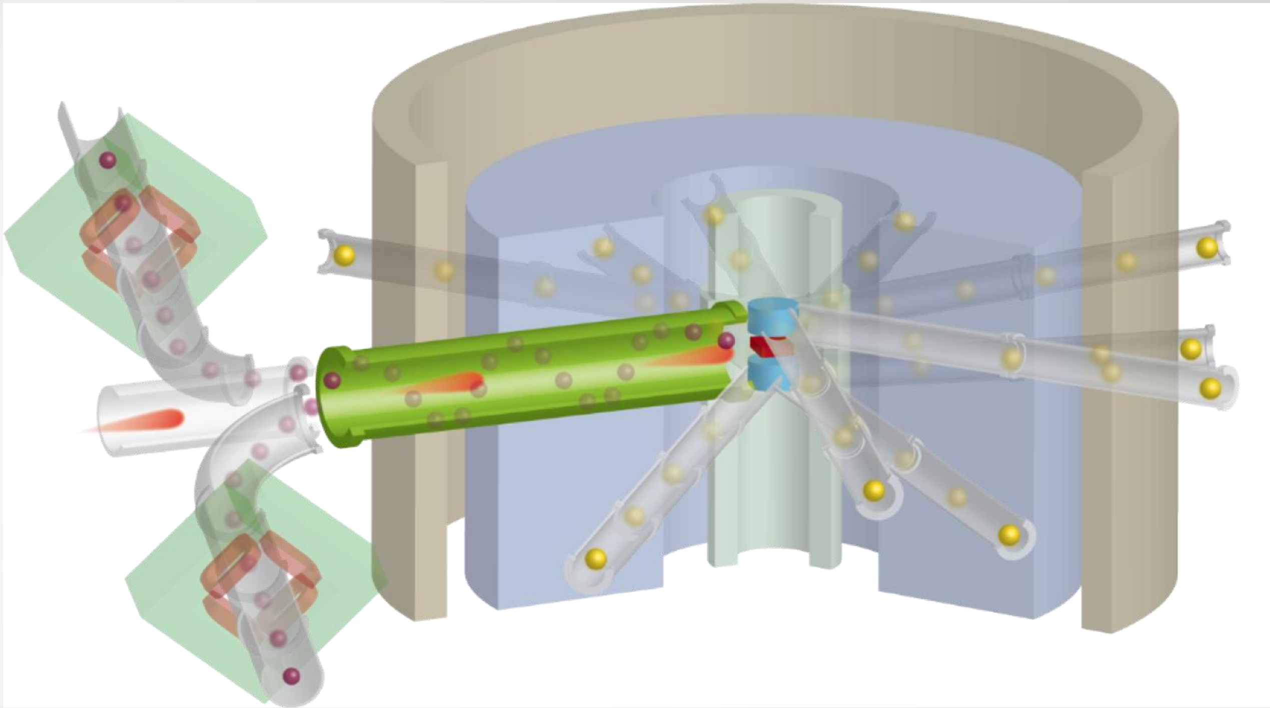




## Support to J-PARC Projects

COMET SC Magnet System: Helium Transfer Line to Muon Transport Solenoid is under construction.

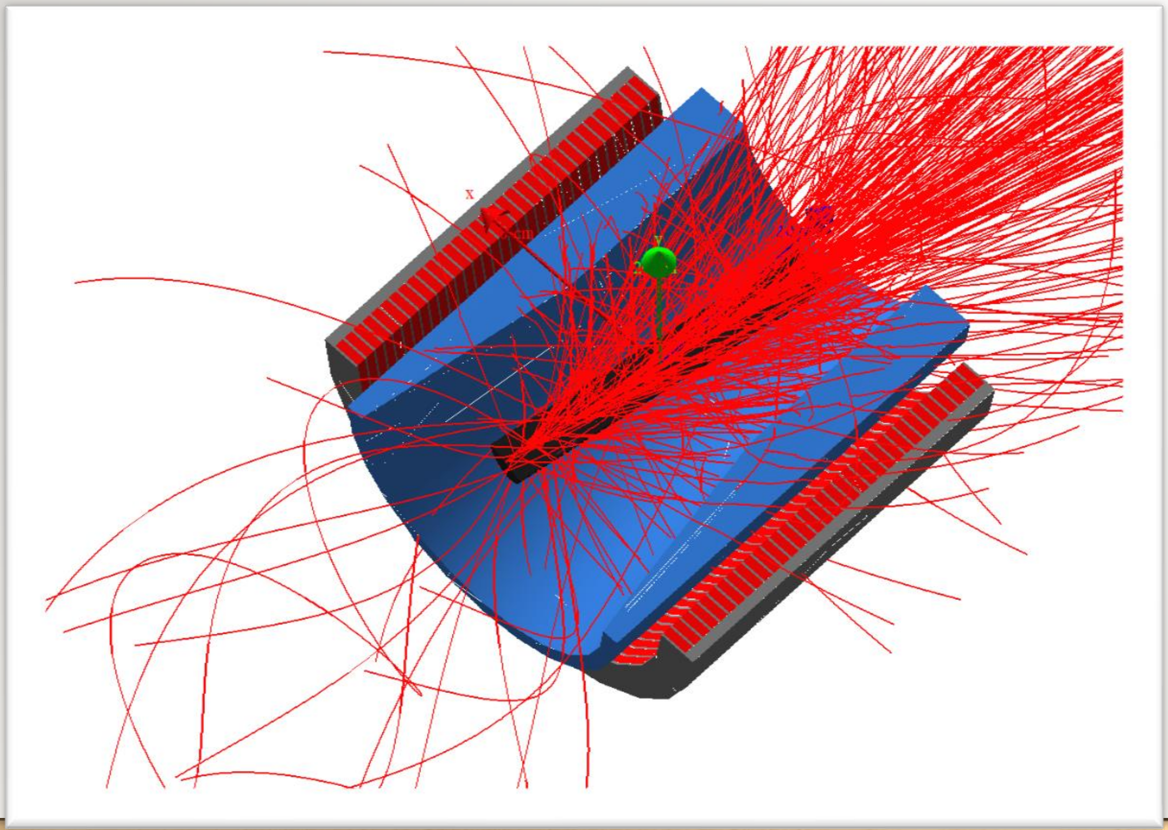


# J-PARC MLF Second Target



MLF Second Target

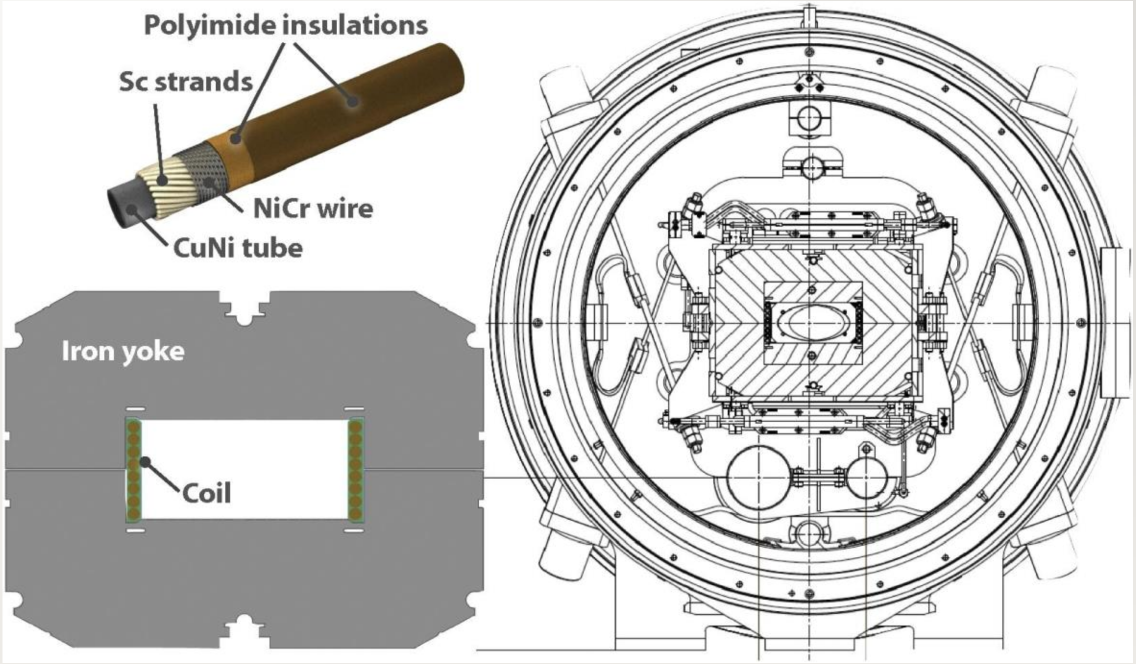
- Utilize HTS to sustain high radiation environment



Secondary Particle Capture Solenoid

# Other Extraction Synchrotron TEVATRON, GSI SIS100

- TEVATRON (800GeV ~70kW)
  Originally extraction machine
  - Various AC loss reduction method such as ZEBRA cable
  - Operation Cycle: ~ 1 min
- GSI SIS100 (30GeV ~100kW)
  - Superferic: 1.9T, 1Hz(4T/s)




GSI SIS100 Main Dipole Magnet

# Superconducting magnet applications in various accelerators

- Lepton colliders
- Synchrotron radiation facilities
- Proton extraction synchrotron
- **Medical synchrotron**
- Cyclotron
- Ion source, klystron
- Detector magnets

# Superconducting magnet applications in various accelerators

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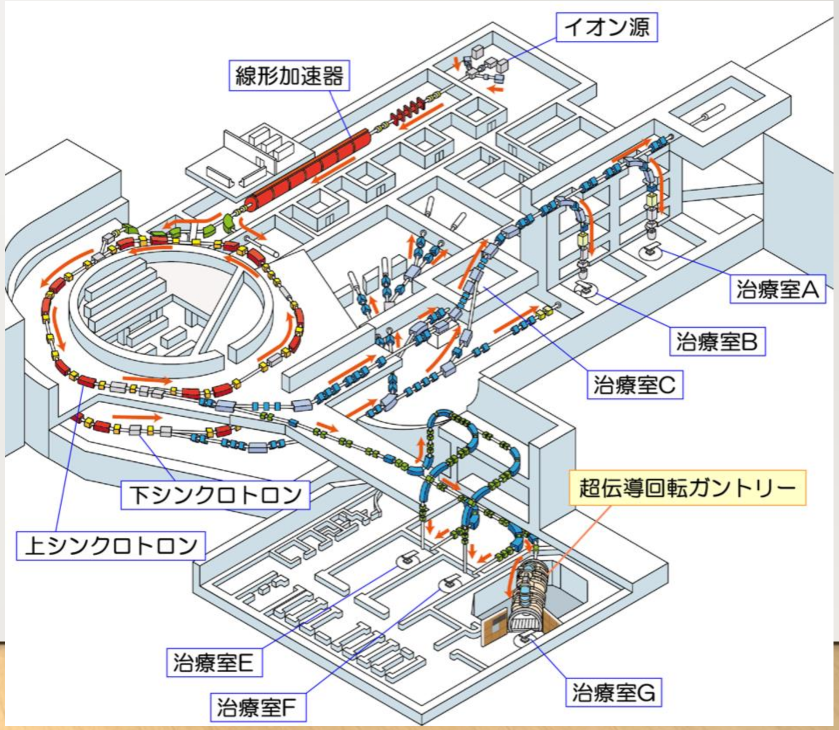
# Medical Accelerator

- Synchrotron for heavy ion accelerator
  - Synchrotron: enables energy scan
  - Need rapid cycle: difficult for superconducting magnets

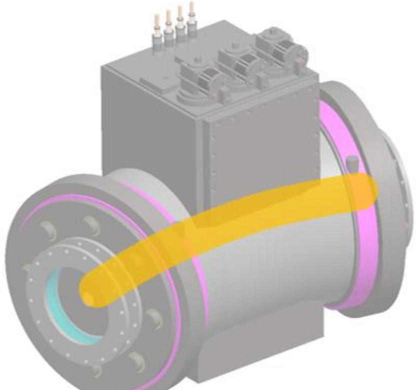
LBNL Bevalac

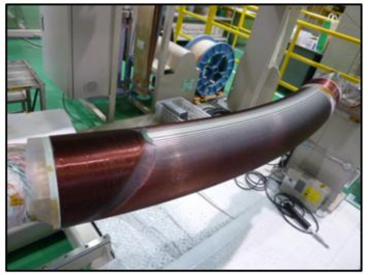


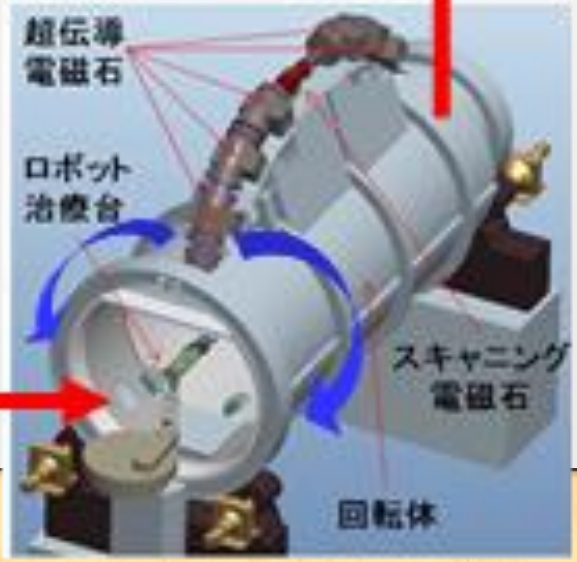

QST HIMAC

# Medical Accelerator Superconducting Gantry

Compact and light weight with superconducting magnet

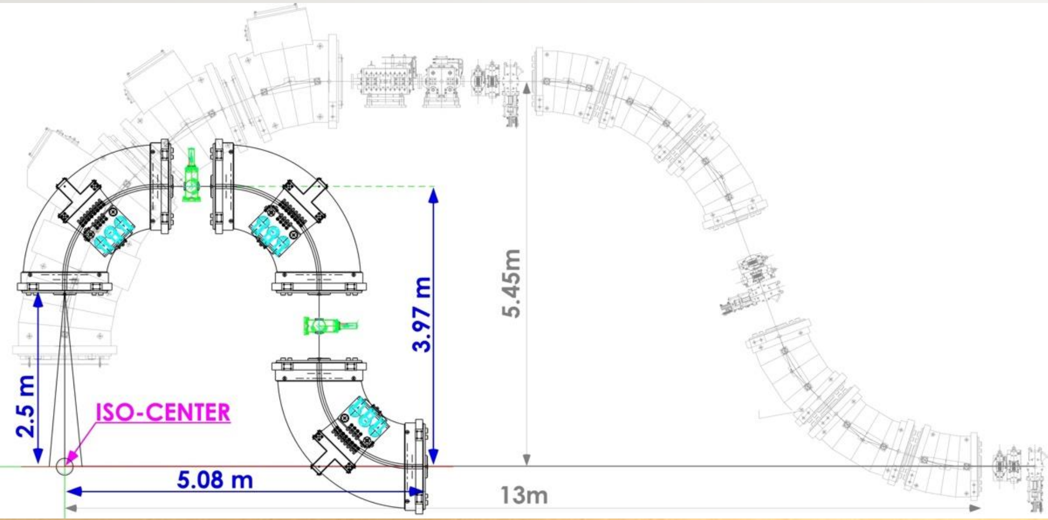

ガントリー用超電導コイルのイメージ
(オレンジの部分)


実際の超電導コイル

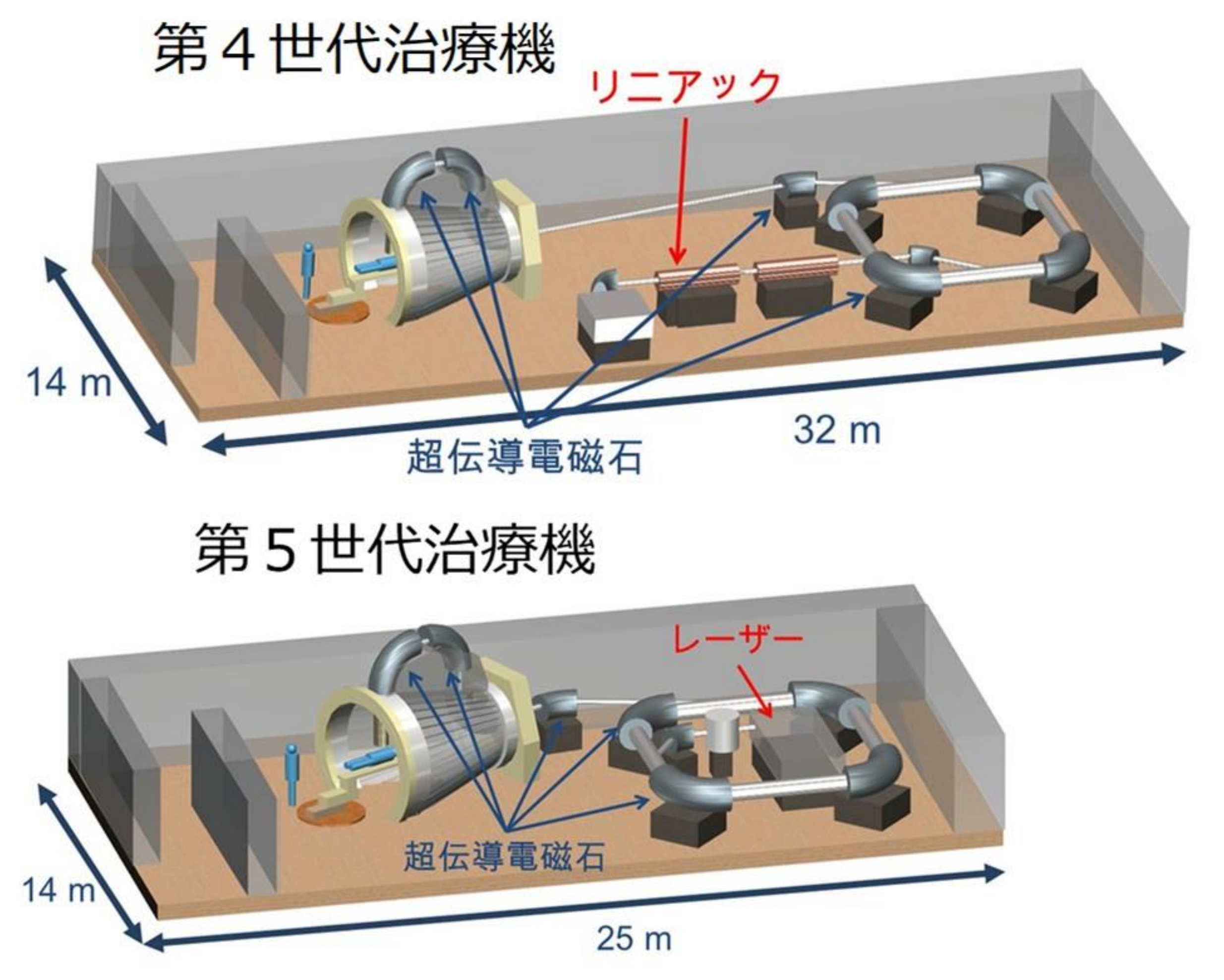



# Medical synchrotron
# Future prospect

- Superconducting synchrotron for more compact machine
- Fast ramp rate magnet R&D




High field gantry



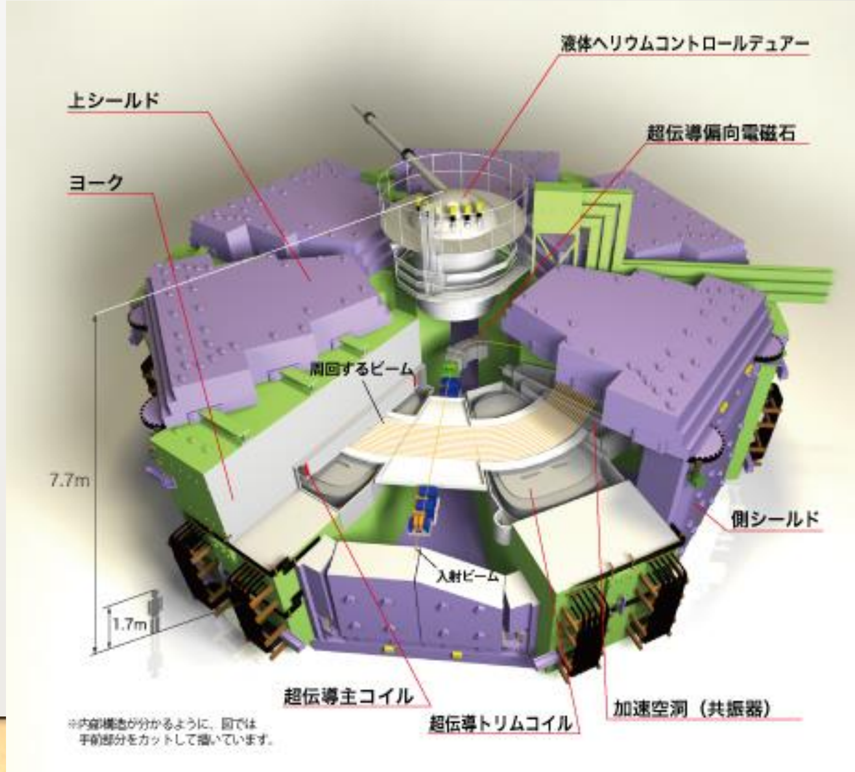

Future medical synchrotron

# Superconducting magnet applications in various accelerators

- Lepton colliders
- Synchrotron radiation facilities
- Proton extraction synchrotron
- Medical synchrotron
- **Cyclotron**
- Ion source, klystron
- Detector magnets

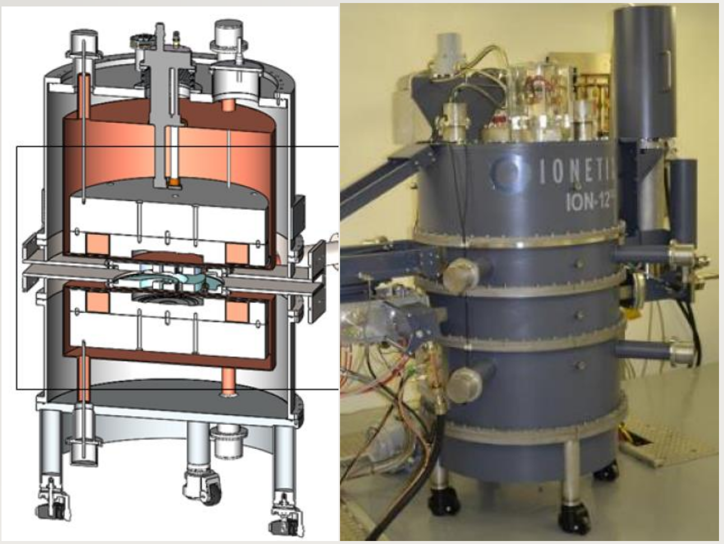
# RIKEN SRC

- World largest superconducting ring cyclotron

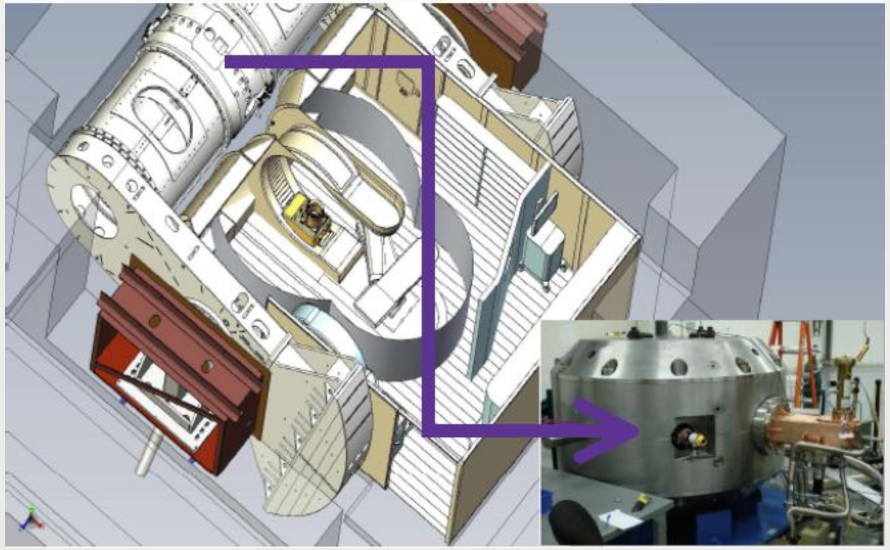



# Small Cyclotrons

- DC operation: good for superconducting magnets
- High field magnet for compact accelerator



Beta Installation at the University of Michigan



Mevion S250 Medical synchro-cycrotron

IBA synchro-cycrotron

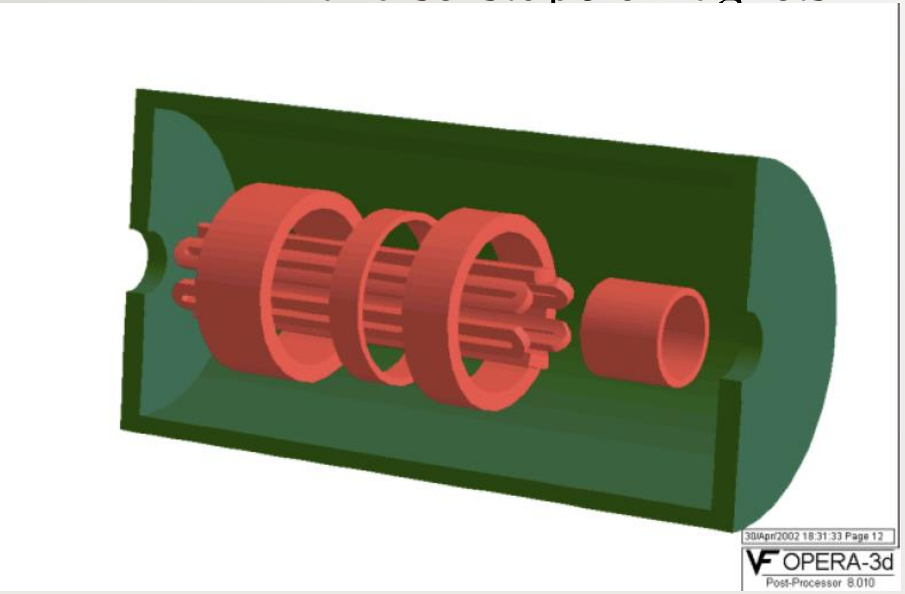
# Superconducting magnet applications in various accelerators

- Lepton colliders
- Synchrotron radiation facilities
- Proton extraction synchrotron
- Medical synchrotron
- Cyclotron
- **Ion source, klystron**
- Detector magnets

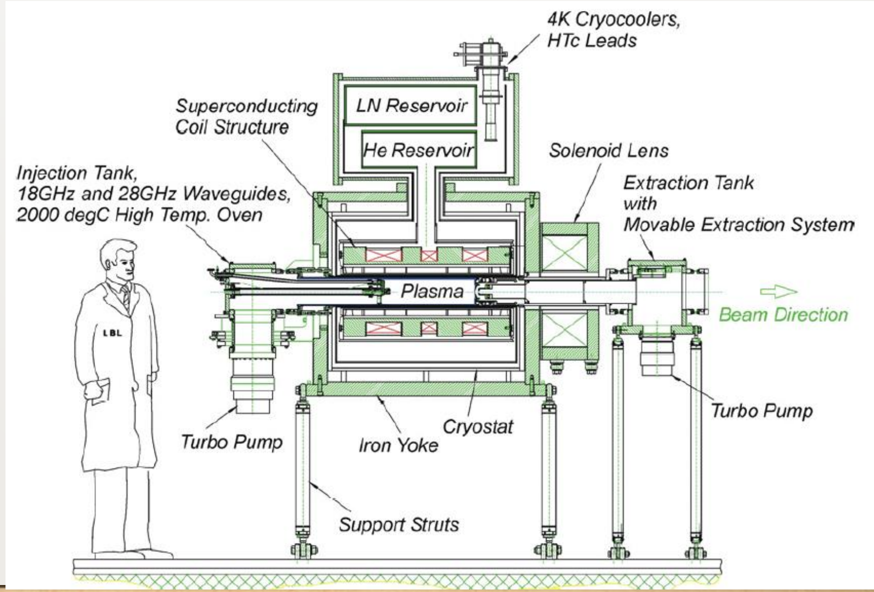
72

# Small applications
# ECR Ion source 、 Klystron

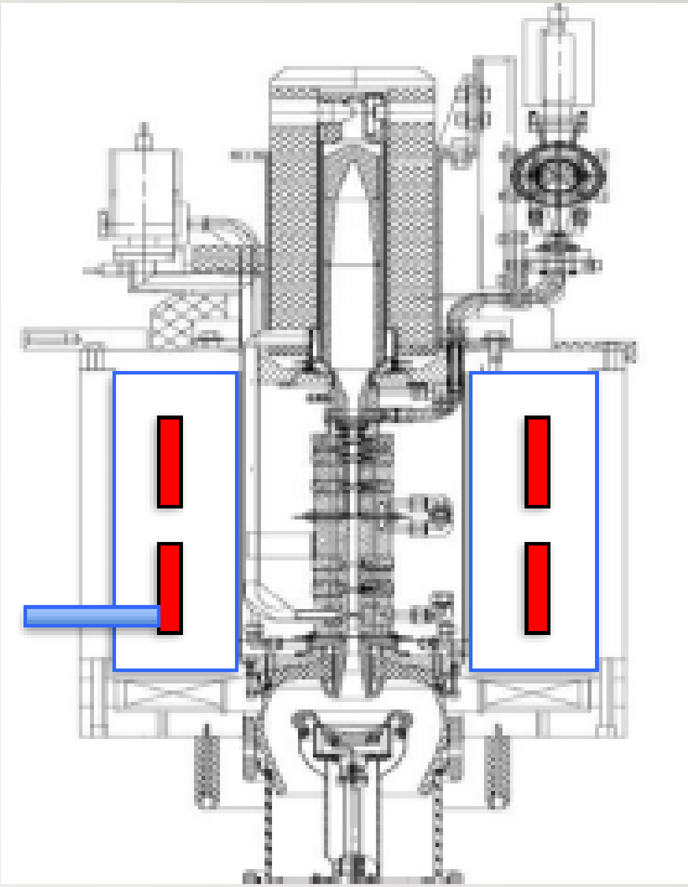
- High intensity ion source
  - Focusing superconducting magnet with solenoid and sexstupole magnets




GyroSERSE OPERA-3D model




Berkeley VENUS Ion Source



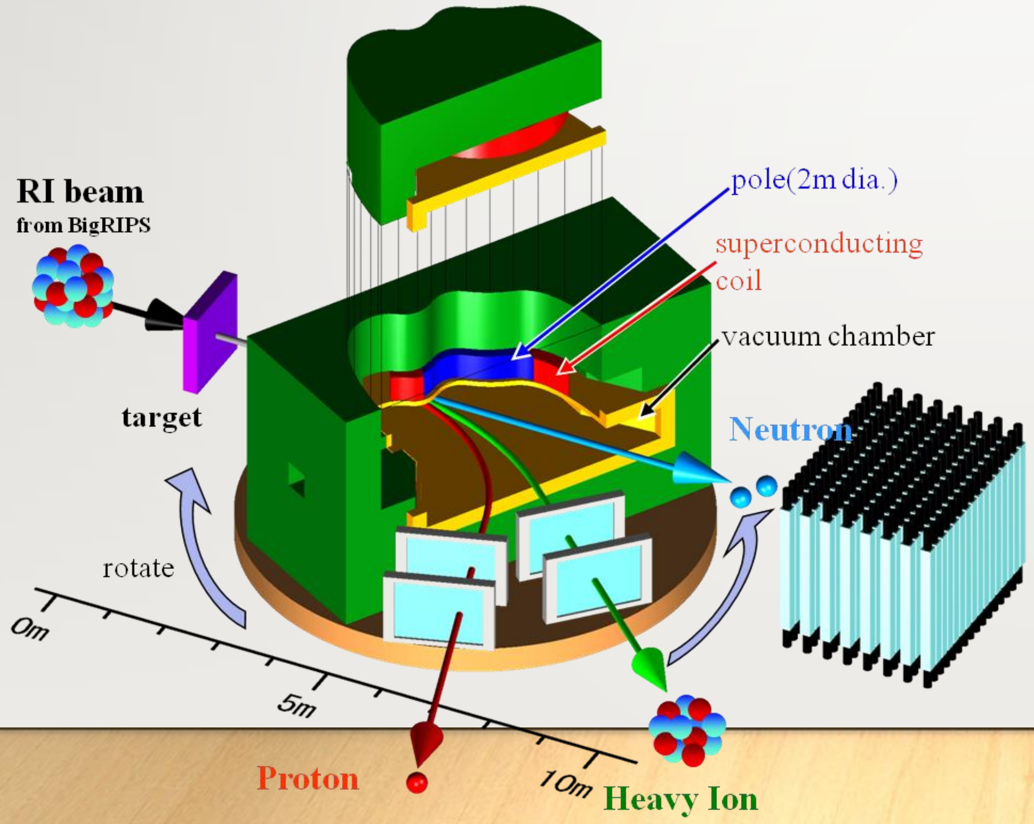
CERN CLIC Klystron foucusing solenoid

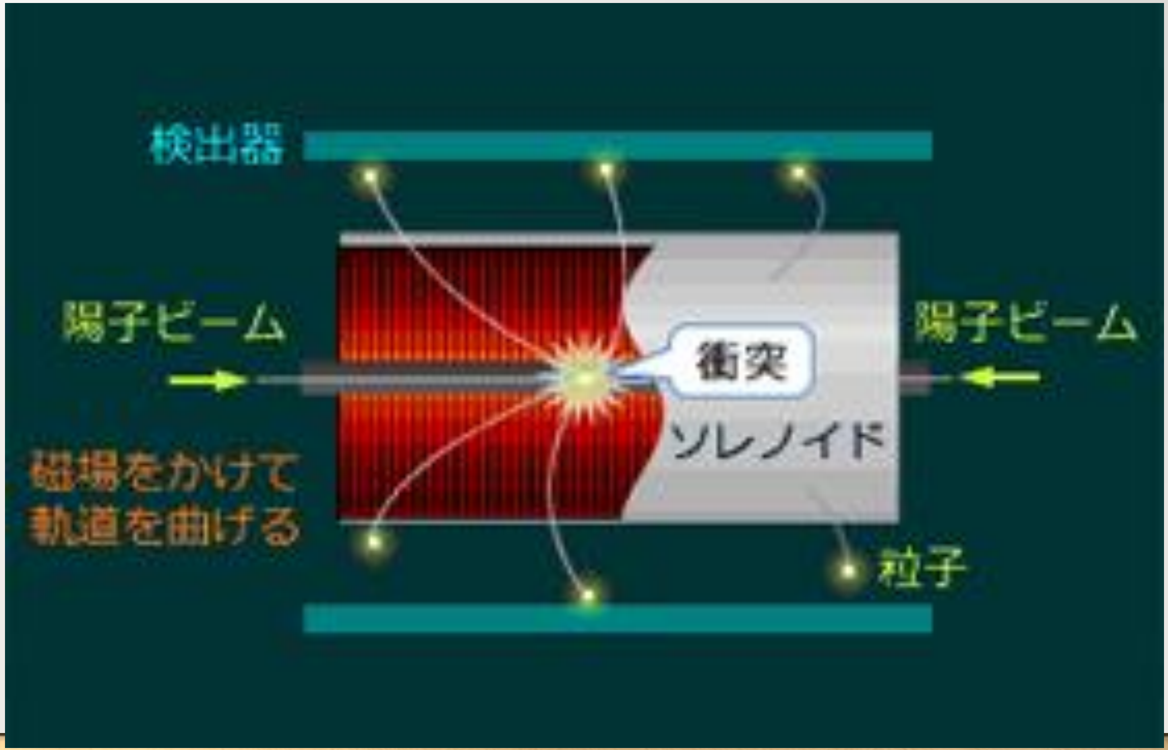
# Superconducting magnet applications in various accelerators

- Lepton colliders
- Synchrotron radiation facilities
- Proton extraction synchrotron
- Medical synchrotron
- Cyclotron
- Ion source, klystron
- **Detector magnets**

# Detector magnets
# Spectrometer, Thin solenoid, Toroid

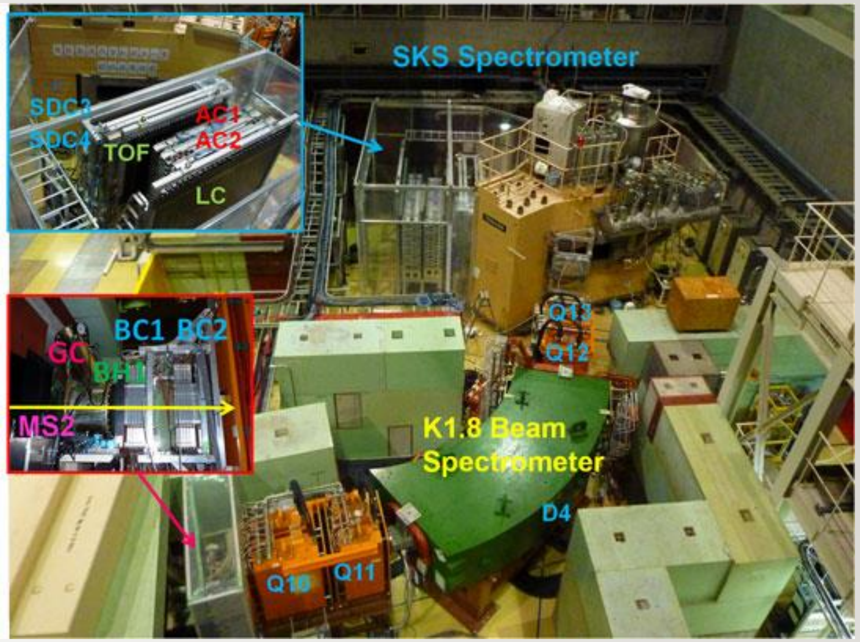
- Identify particle momentum and charge



# Detector Magnets
# Spectrometer

RIKEN　SAMURAI



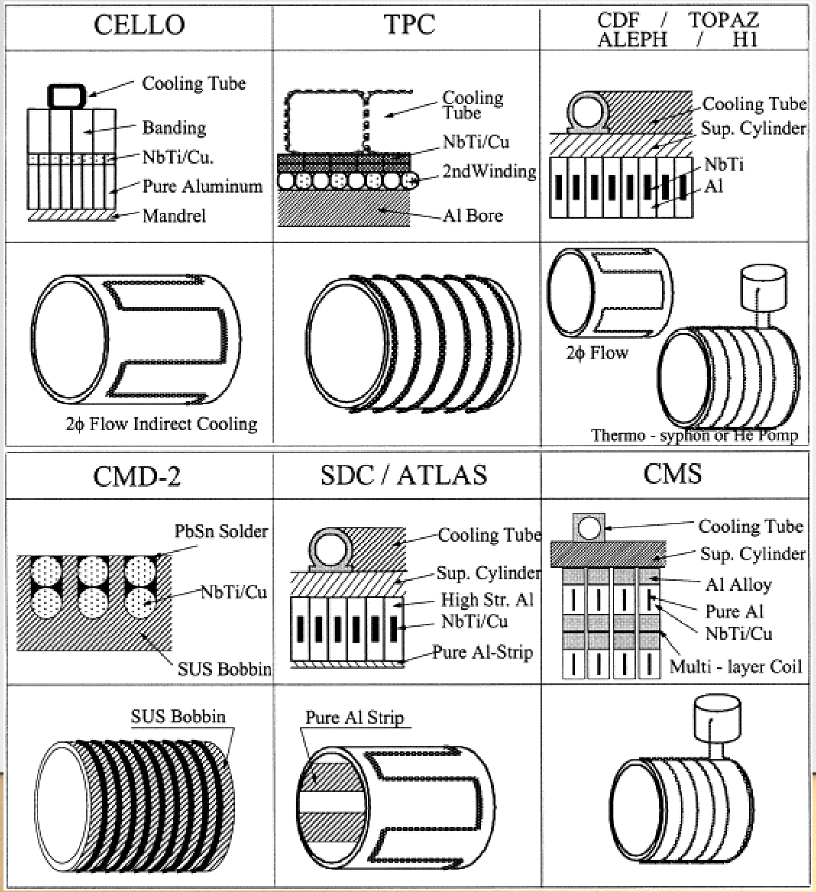

J-PARC SKS

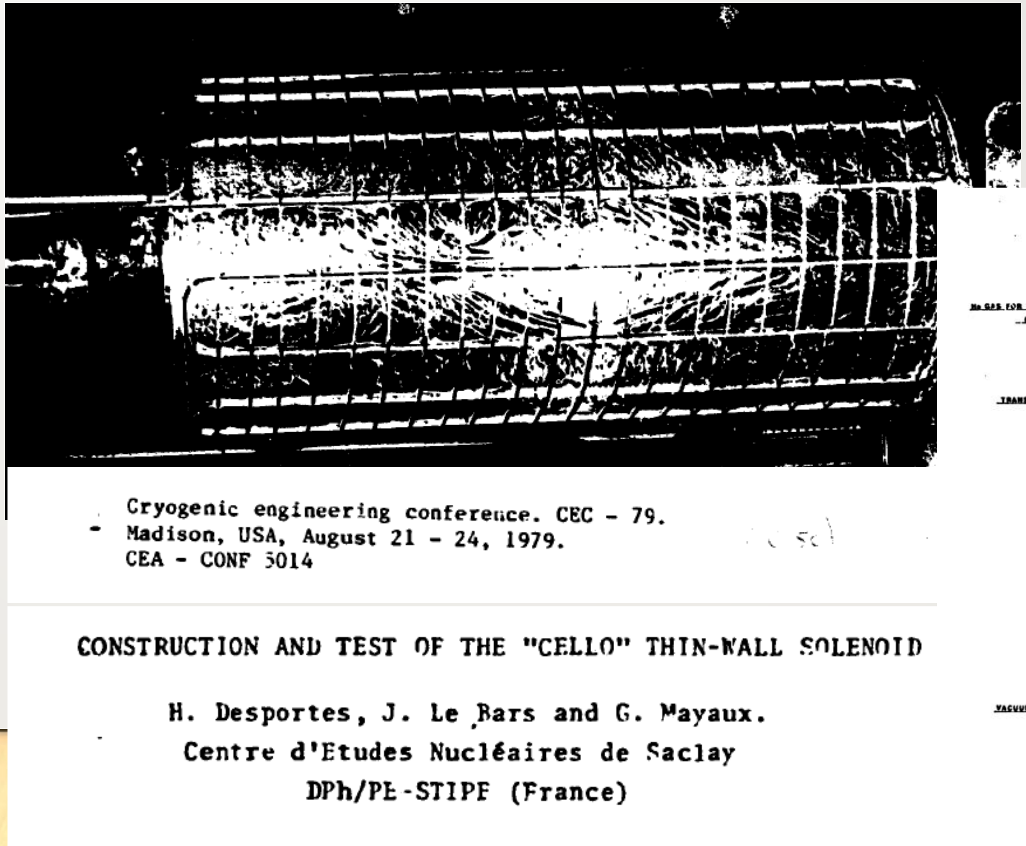
超伝導化されたBENKEI
BENKEI rebuilt as a superconducting analyzing magnet.

KEK BENKEI

# Detector magnet
# Thin solenoid

- Use aluminum stabilized conductor to realize particle transparency

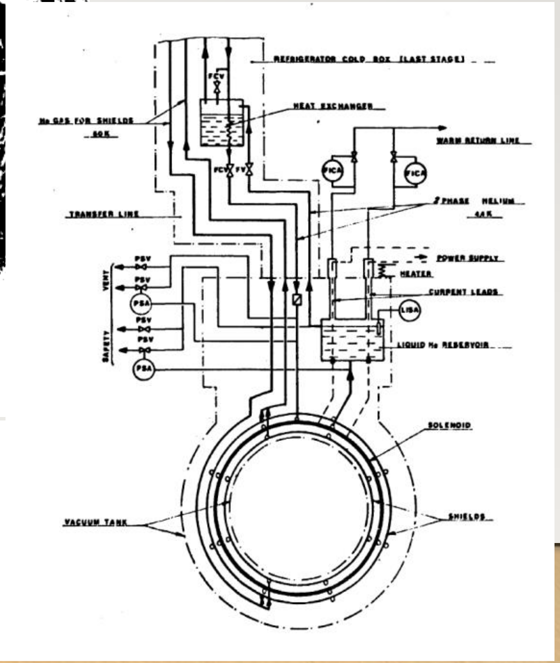


Cryogenic engineering conference. CEC - 79.
Madison, USA, August 21 - 24, 1979.
CEA - CONF 5014

CONSTRUCTION AND TEST OF THE "CELLO" THIN-WALL SOLENOID

H. Desportes, J. Le Bars and G. Mayaux.
Centre d'Etudes Nucléaires de Saclay
DPh/PE-STIPE (France)



# Detector magnet
# Thin solenoid

- CDF solenoid:
  - FNAL TEVATRON

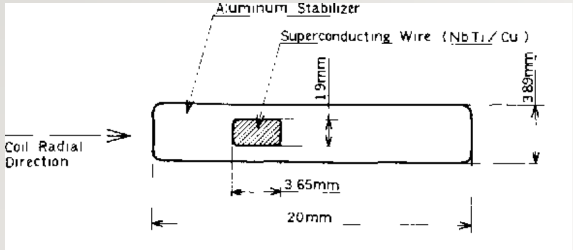
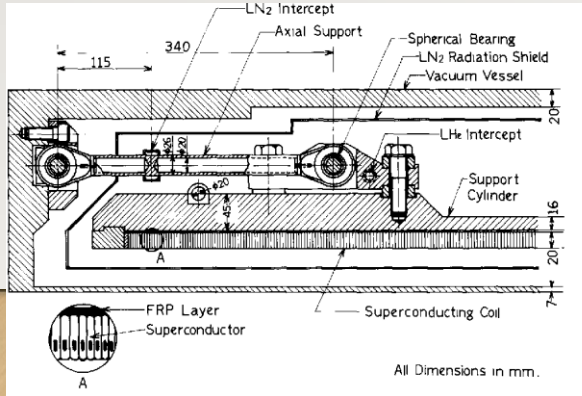
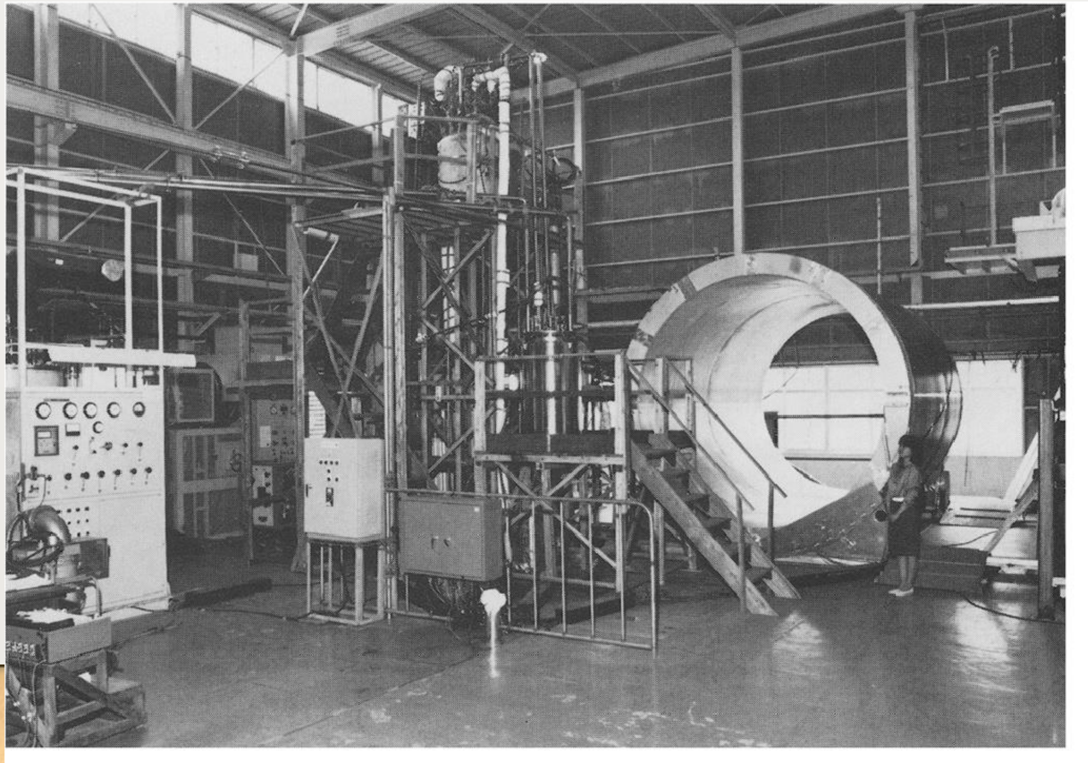
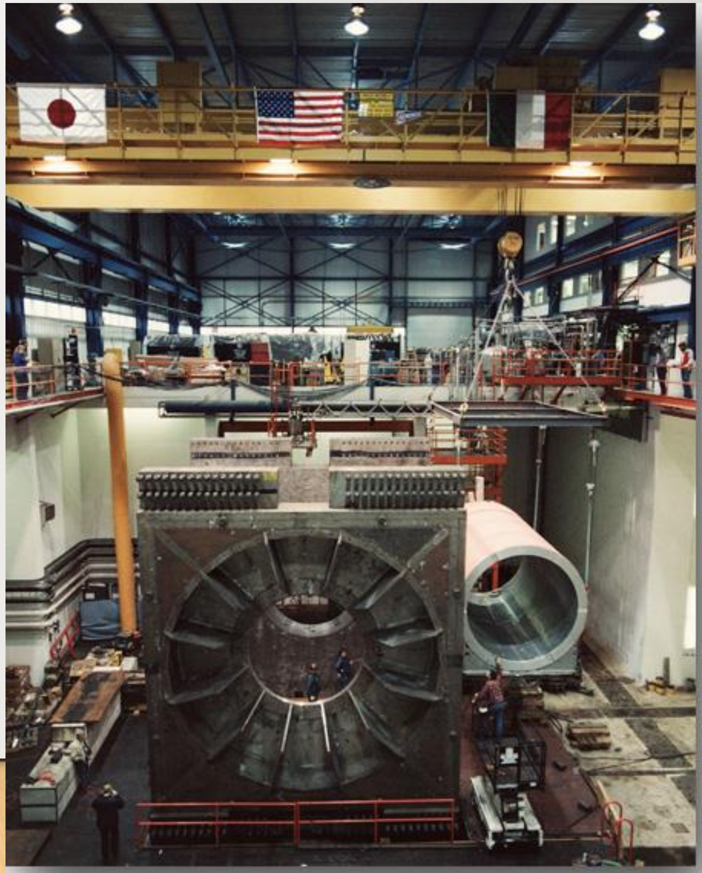



Fig. 3. Schematic diagram of the conductor cross section. Th





# Detector magnet
# Thin solenoid

- Japanese solenoids

TOPAZ: TRISTAN

VENUS: TRISTAN

BELLE: KEKB

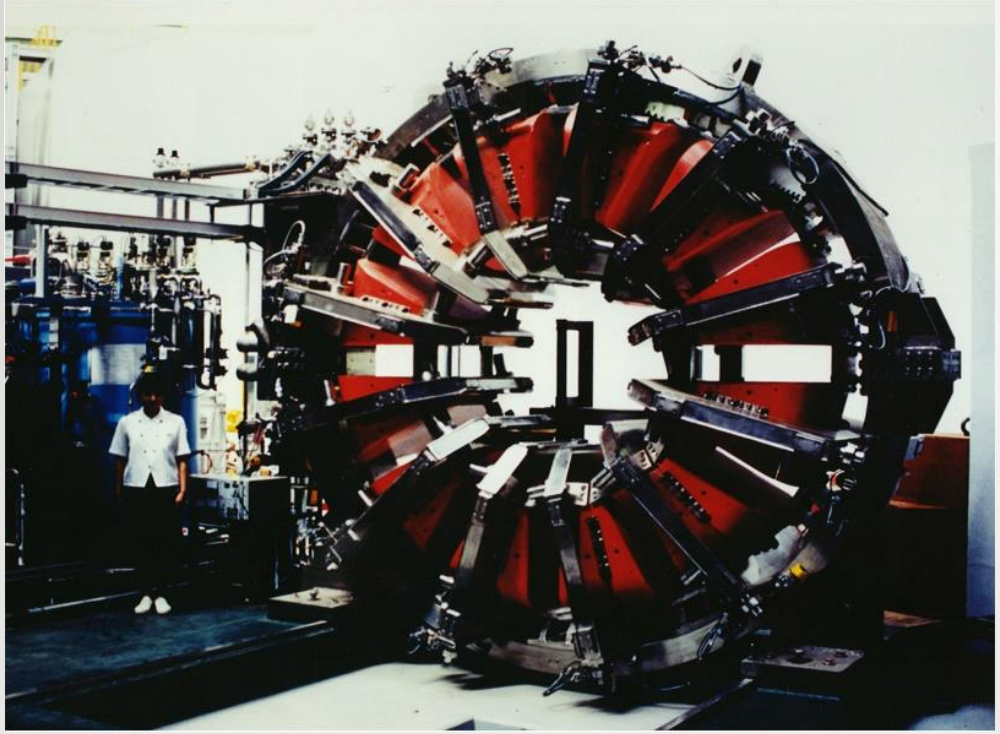
# Detector magnets
# Thin solenoid

- LHC

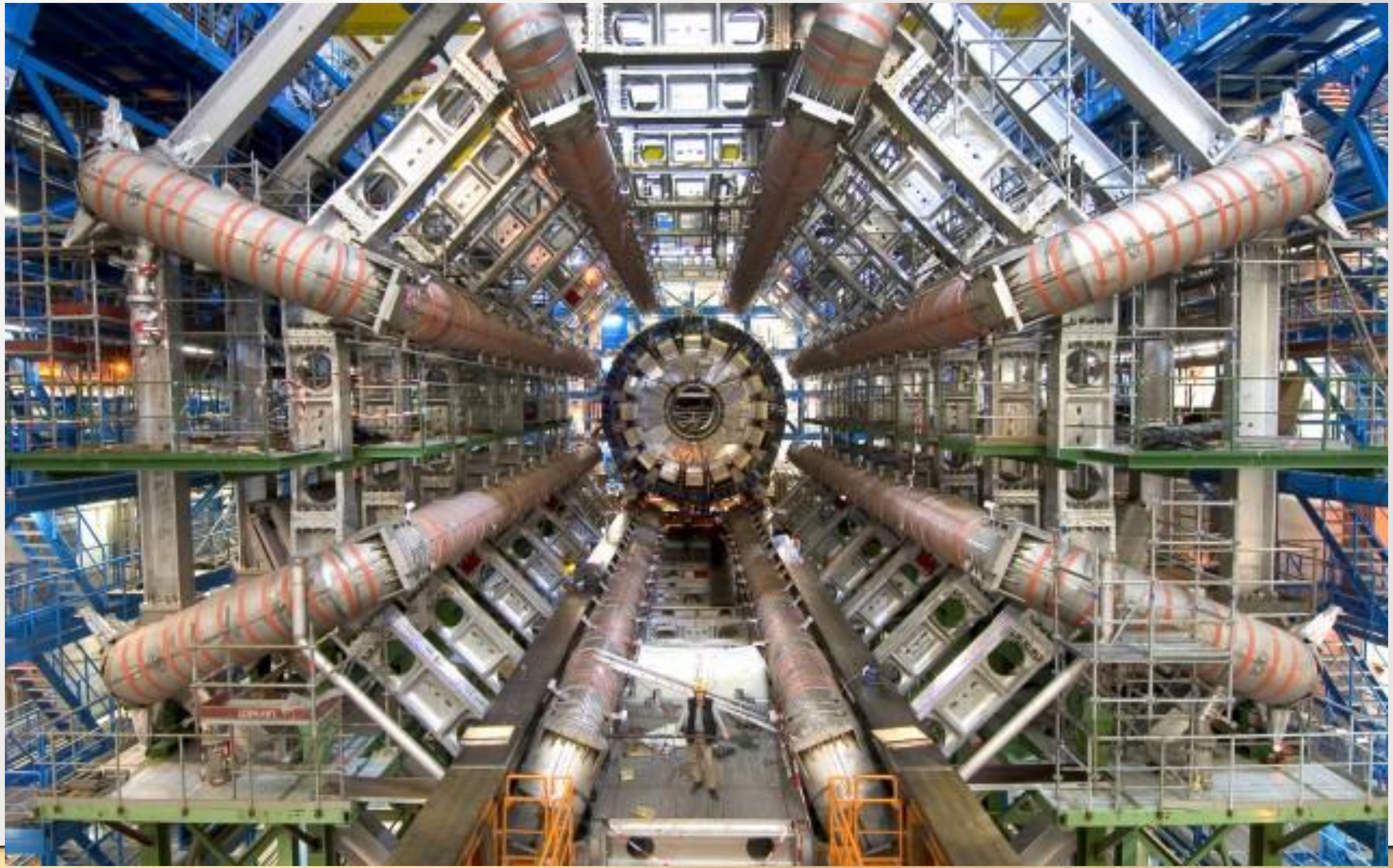
ATLAS solenoid

CMS solenoid

# Detector magnets
Toroid



J-PARC TREC



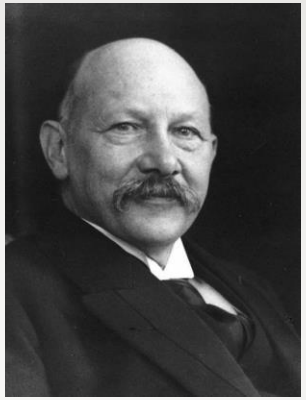
LHC ATLAS TOROID

# Item

- Accelerator & Magnet
- Superconducting Accelerator Magnet
- Superconductivity
- Superconducting Magnets for Hadron Colliders
- Superconducting magnet applications in various accelerators
- **Summary**

# Summary

- SC Magnet and Accelerator
- Developed supplementary
- Reached to NbTi limit
- Higher Field by $Nb_3Sn$ (or IBS?)
  - FCC world wide development
- HTS (High Temperature Superconductor)
  - Still very expensive
  - Needs special usage
    - High Radiation
    - High Filed above 20 T
- **Game Change = New Chance!**



Kamerlingh Onnes
Find Superconductivity

Alvin Tollestrup
TEVATRON Magnet

Who's next YOU?