RCNP
大阪大学 核物理研究センター

TUOAC02

Development of HTS magnets

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Outline

1. Introduction
2. High Temperature Superconducting (HTS) wires
3. Development of HTS magnets

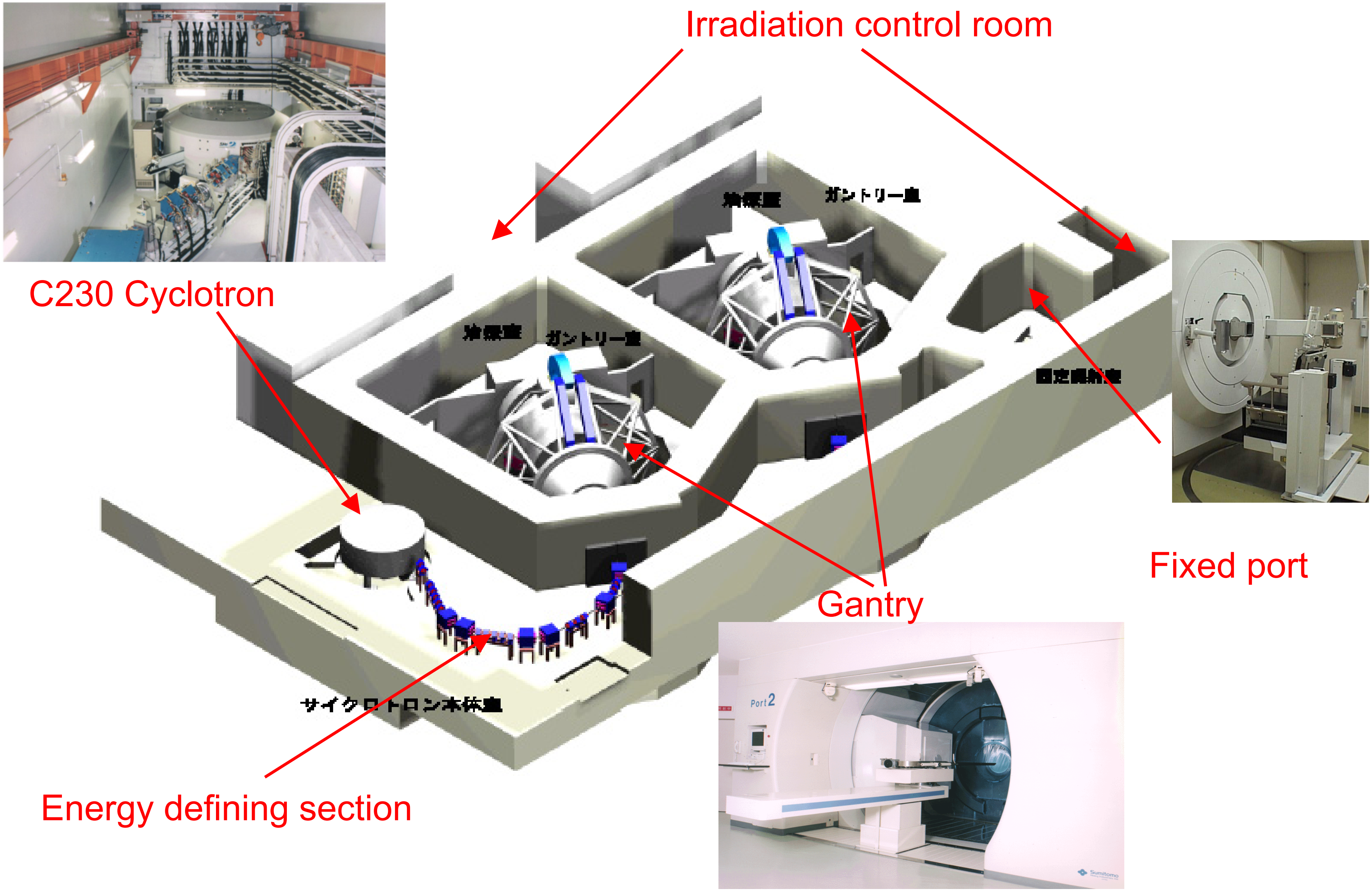
   Scanning magnet

   Dipole magnet
4. Summary

Motivations to develop HTS magnets

- Compact devices
    - Beam line, Gantry for particle therapy, Accelerators
- Low power consumption system
- Advantages over LTS system
    - No liquid helium is necessary
    - Operating temperature is 20K or higher
        - Cryogenic components for cooling are simpler
        - Cooling power of refrigerators is much larger
        - Temperature range for superconductivity is wider
            - Possible AC magnets and pulsed magnets

The National Cancer Center (Kashiwa, Chiba)



Irradiation control room

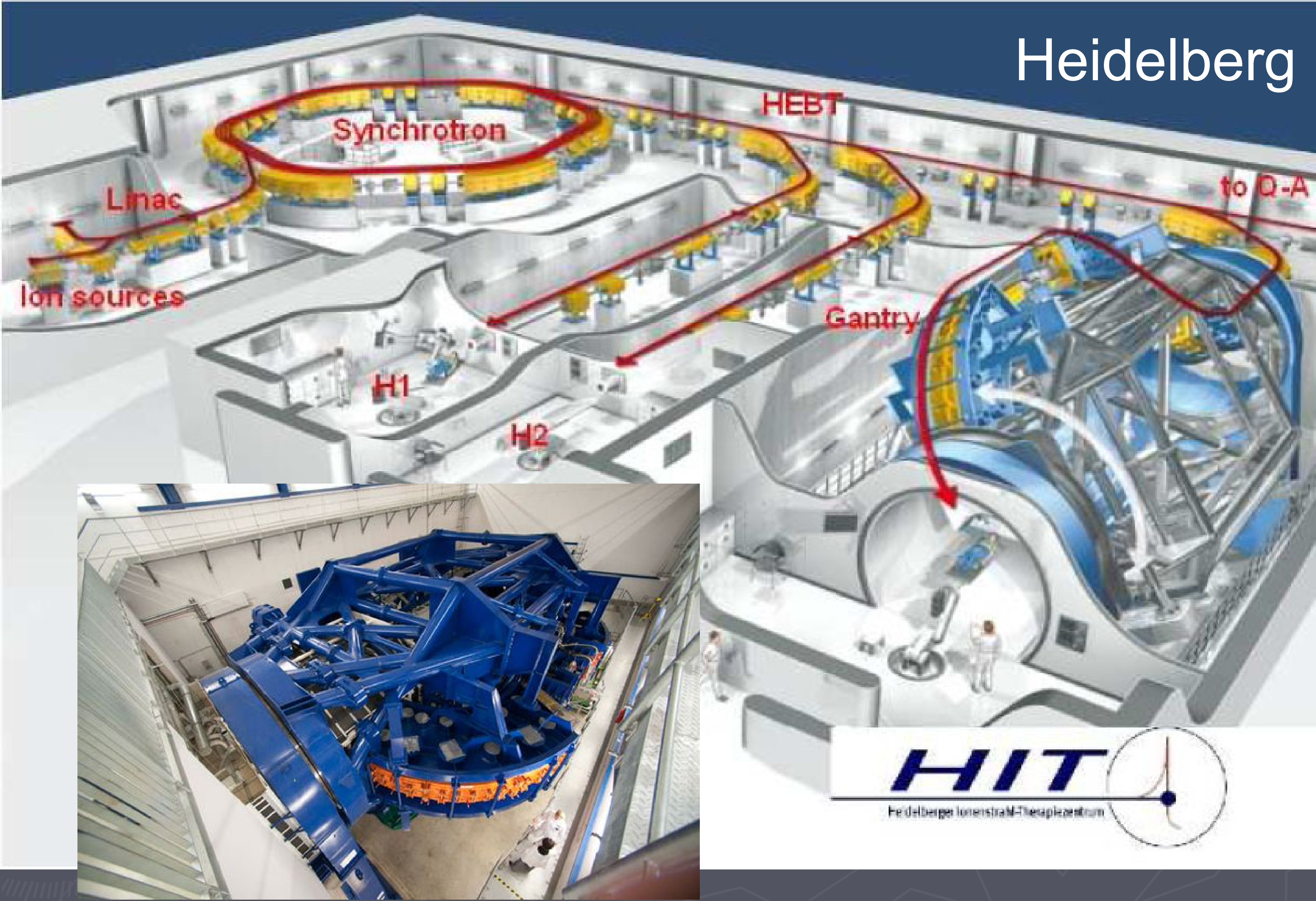
C230 Cyclotron

Fixed port

Gantry

Energy defining section

Heidelberg



Gantry: Diameter =13m, Length = 25m, Weight of rotating parts = 570t

Motivations to develop HTS magnets

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  - Beam line, Gantry for particle therapy, Accelerators
- Low power consuming system
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    - Cryogenic components for cooling are simpler
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    - Temperature margin for superconductivity is larger
      - AC magnets and pulsed magnets

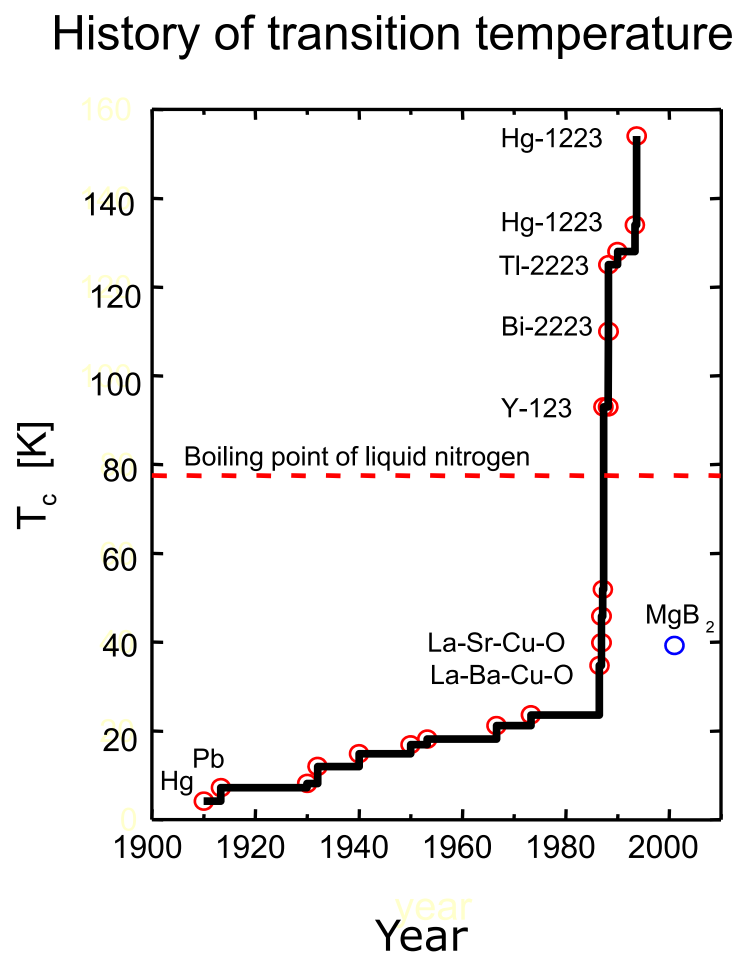
Cu-oxide HTS materials

- 1986: discovery of $(La_{1-x}Ba_x)_2CuO_4$
  J.G. Bednorz and K.A. Müller
- Significant effort went into the development of new and improved conductor materials.
- It became possible to manufacture long HTS wires over km.

1st generation HTS wire (T$_C$ = 110 K)
$Bi_2Sr_2Ca_2Cu_3O_{10}$ (Bi2223)

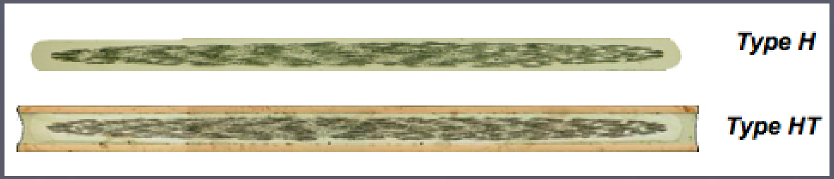
2nd generation HTS wires (T$_C$ = 95 K)
$YBa_2Cu_3O_7$ (YBCO / Y-123)

- Although many prototype devices using HTS wires have been developed, so far there have been limited applications to accelerators and beam line devices.


History of transition temperature

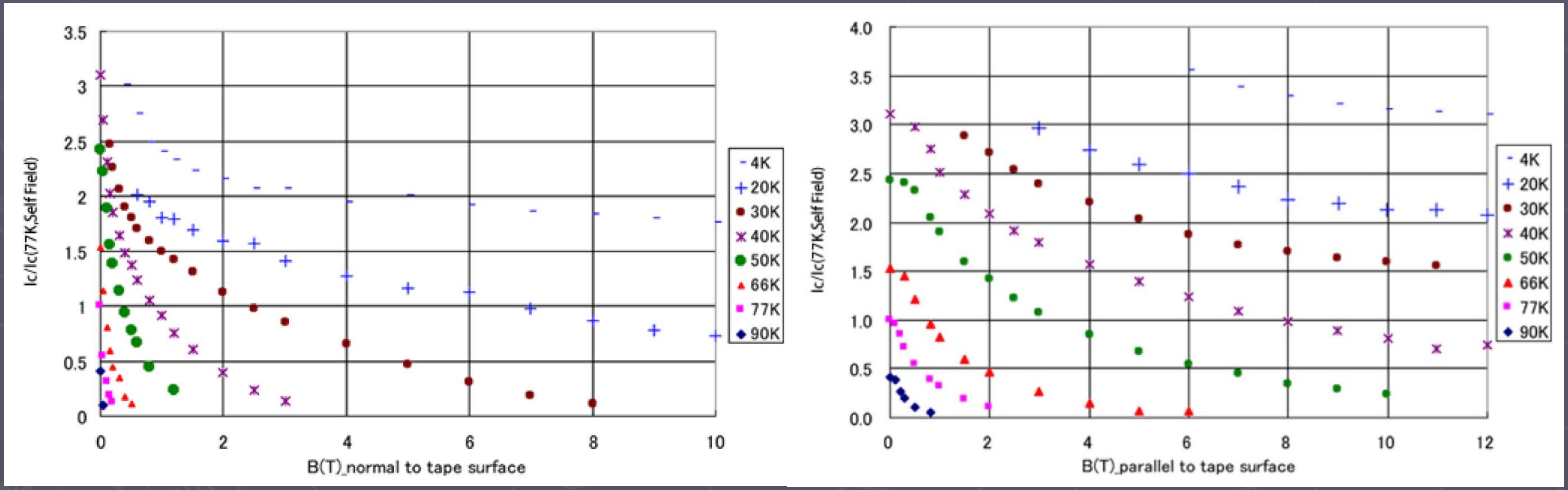
First-generation HTS wire

- Wire consists of a flexible composite of filaments in a silver alloy that provides mechanical stability and transient thermal conductivity.
- Wire is in thin tape-form approximately 4mm wide and 0.3mm thick.



$Bi_2Sr_2Ca_2Cu_3O_x$（Bi-2223）

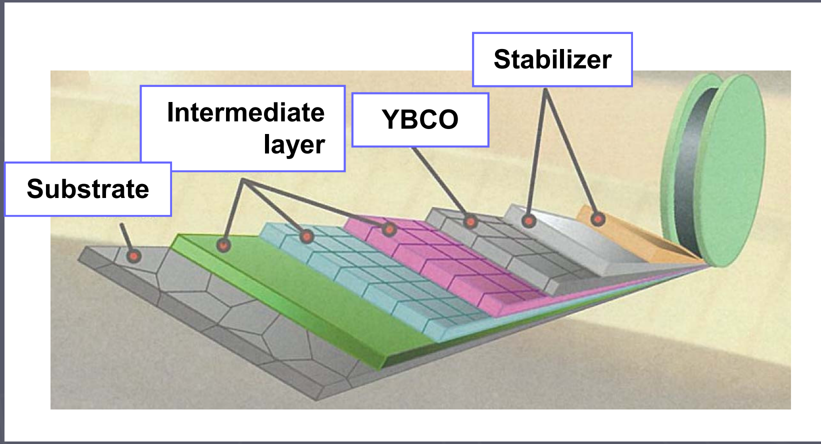
(Sumitomo Electric Industries, Ltd.)



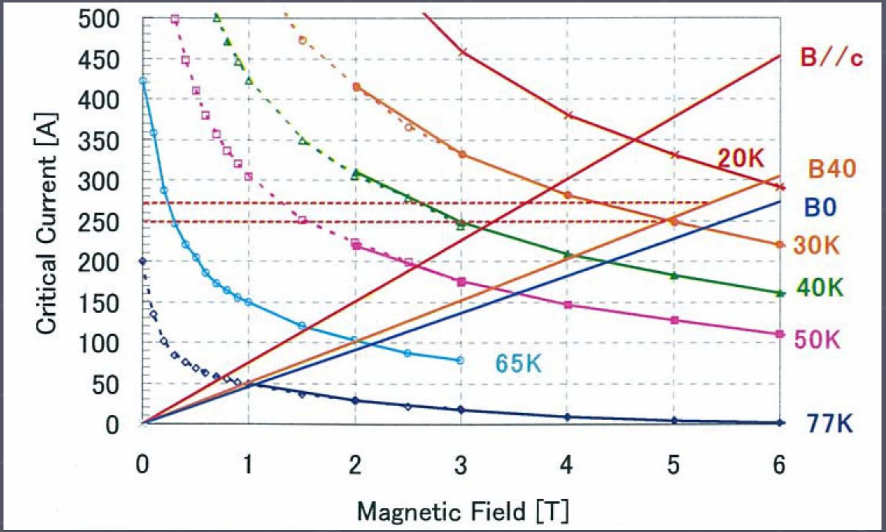
Critical current depends on the operating temperature and the strength and direction of magnetic field on the tape surface. It is scaled by Ic at 77K and self-field.

Second-generation HTS wire

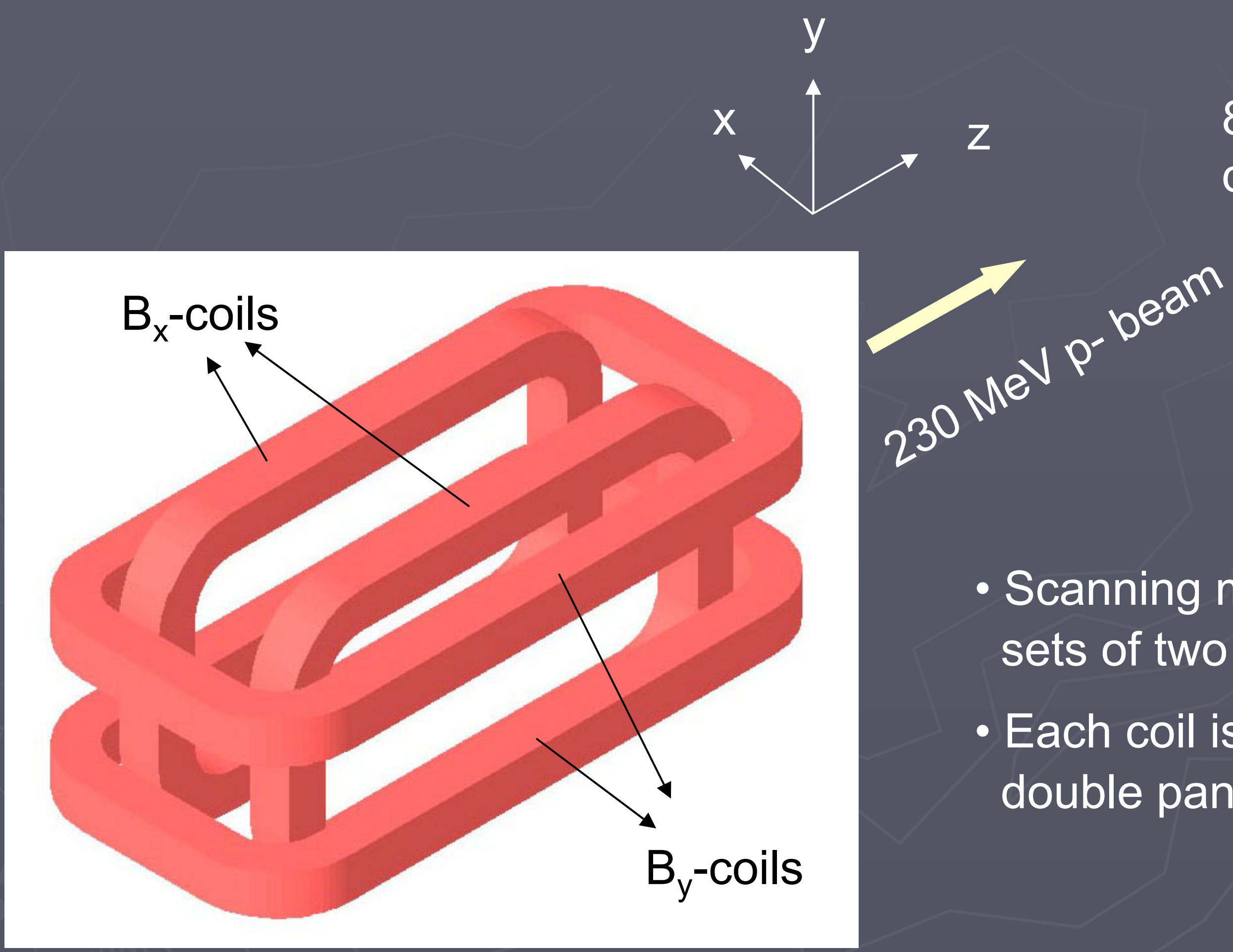
- Intermediate layer and superconducting layer are formed on a substrate, and a silver layer is formed to protect the superconducting layer. Copper tape is laminated on the YBCO tape to prevent burnout from over current.
- Tape is 5-10mm wide and the YBCO layer is 0.5-10μm thick.
- Higher performance is expected over the fist-generation wire in future.
- They are under development by many industries all over the world.



$YBa_2Cu_3O_7$（YBCO）
(Fujikura, Ltd.)



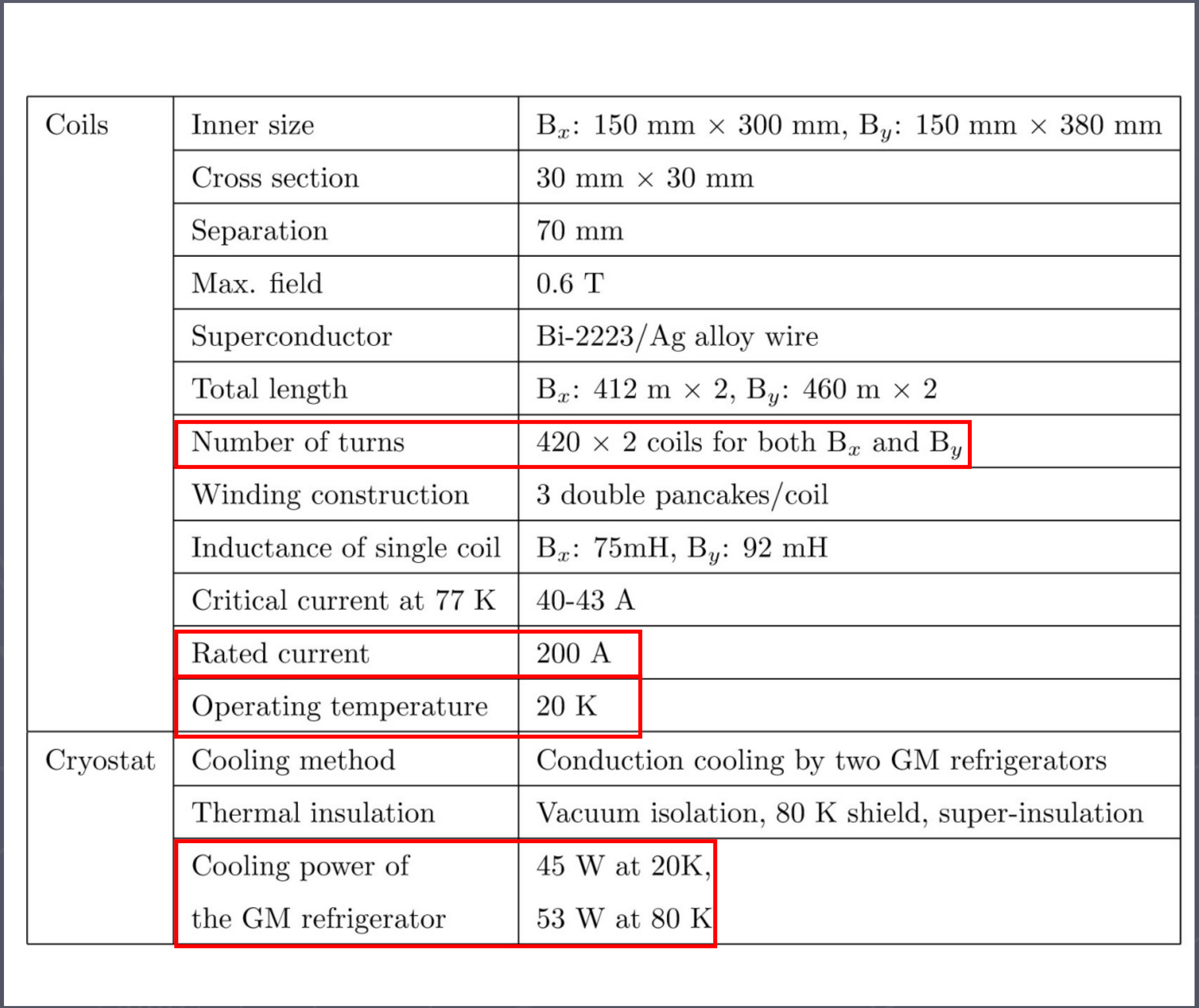
A scanning magnet



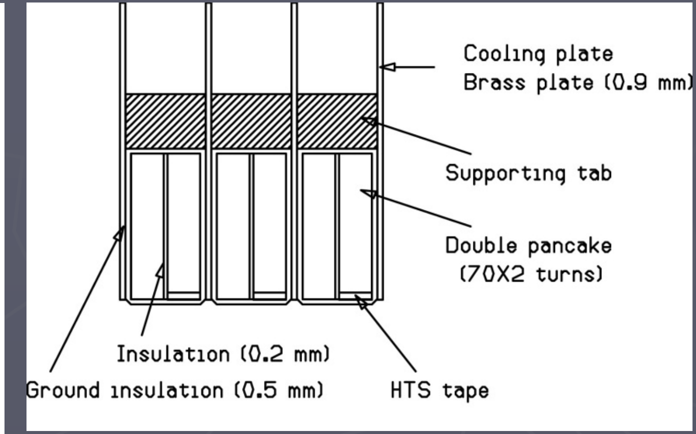
80 mrad deflection

- Scanning magnet consists of two sets of two racetrack coils.
- Each coil is built by stacking three double pancakes.

Structure and Design parameters

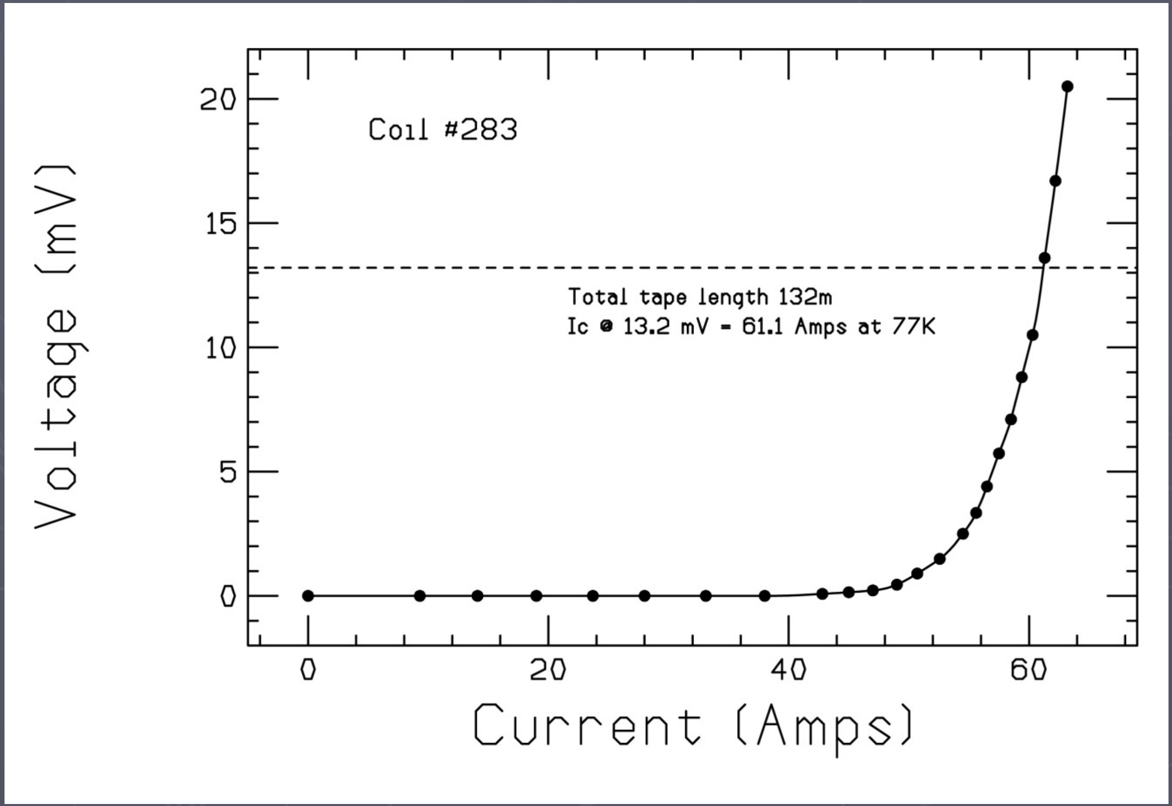


Coils	Inner size	B_x: 150 mm × 300 mm, B_y: 150 mm × 380 mm
	Cross section	30 mm × 30 mm
	Separation	70 mm
	Max. field	0.6 T
	Superconductor	Bi-2223/Ag alloy wire
	Total length	B_x: 412 m × 2, B_y: 460 m × 2
	Number of turns	420 × 2 coils for both B_x and B_y
	Winding construction	3 double pancakes/coil
	Inductance of single coil	B_x: 75mH, B_y: 92 mH
	Critical current at 77 K	40-43 A
	Rated current	200 A
	Operating temperature	20 K
Cryostat	Cooling method	Conduction cooling by two GM refrigerators
	Thermal insulation	Vacuum isolation, 80 K shield, super-insulation
	Cooling power of the GM refrigerator	45 W at 20K, 53 W at 80 K

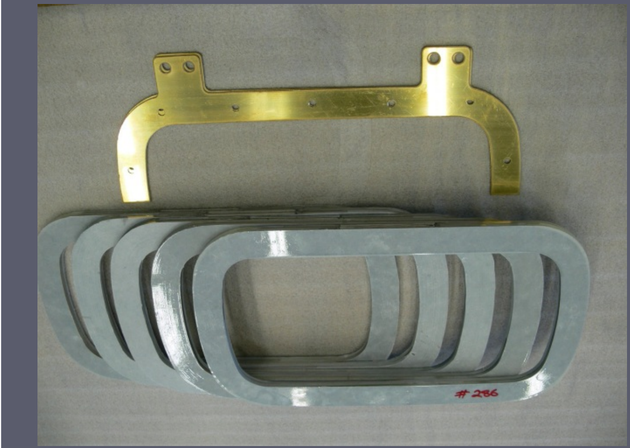


- Ic of the HTS wire over the full length was measured at 77K in a 10m pitch and was 125-140A.
- 0.2mm thick layer insulation is put in the middle of each double pancake.
- Double pancake is covered with a 0.5mm thick ground insulation.
- Four 0.9 mm thick brass cooling plates are fixed to a coil with epoxy resin.

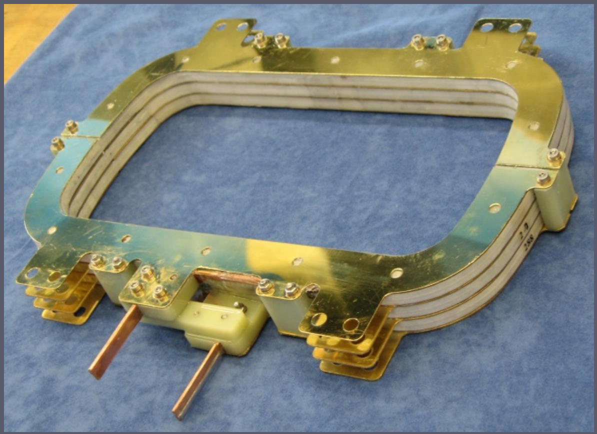
Measured critical current (I_c) of double pancakes and four coils at 77 K



Coil No.	Length (m)	I_c (A)
278	132	56.1
280	132	57.0
283	132	61.1
285	132	58.0
286	132	62.2
288	132	57.4
290	162	60.6
296	162	58.7
298	162	59.8
300	162	60.5
304	162	61.1
306	162	59.0
Bx_1	396	40.8
Bx_2	396	41.1
By_1	486	42.7
By_2	486	42.9

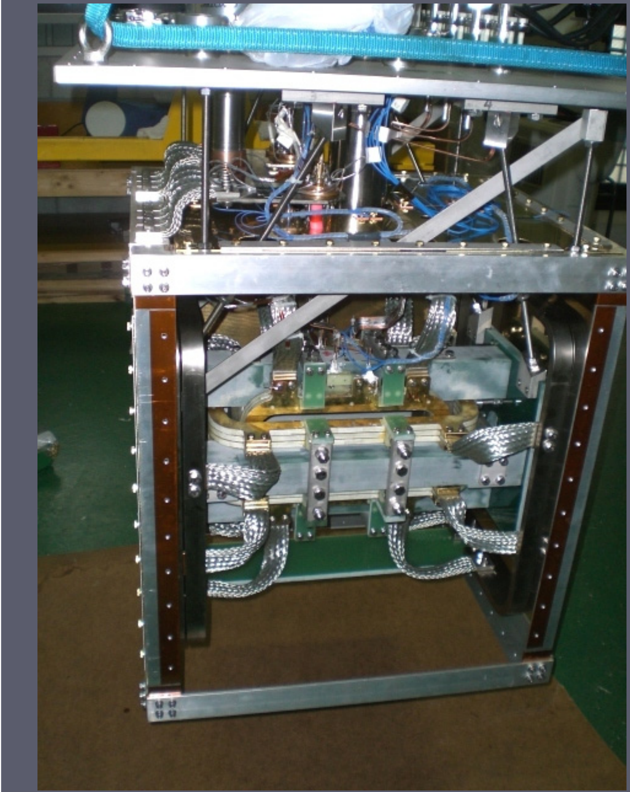


Double pancakes and cooling plates.



Single assembled B_x coil.

Assembled scanning magnet.



Connection to GM refrigerators.

Thermal shield.

Installation into the cryostat.

AC losses in superconducting wire

- Q_H: hysteretic losses (in the superconductor)

$$Q_{\mathrm{H}} = \oint P\,dt = -\mu_0 \oint dt \oint \mathbf{M}\,d\mathbf{H} = \oint dt \int_V (\mathbf{i}\cdot\mathbf{E})\,dV$$

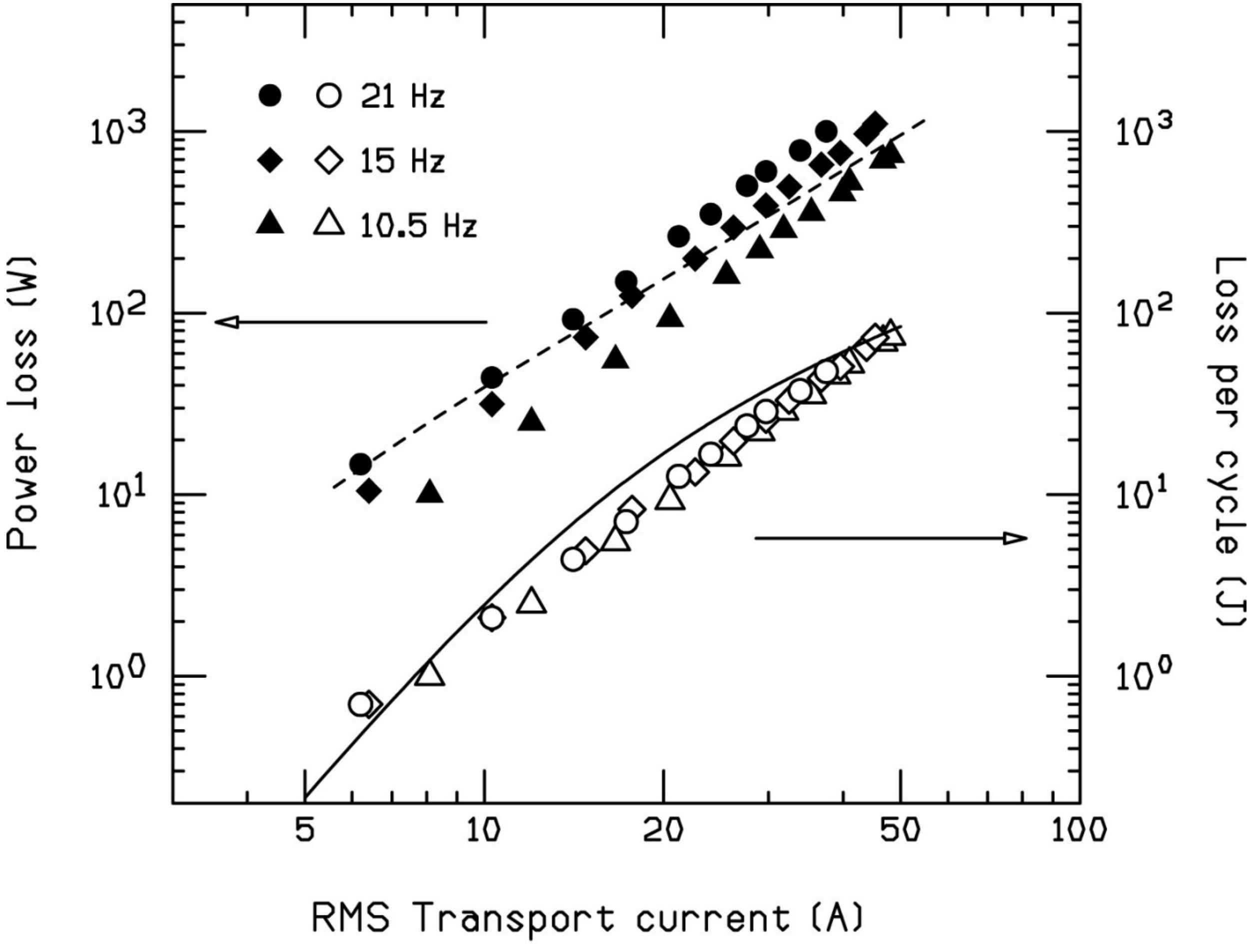
- Q_D: dynamic resistance losses caused by the flux flow
- Q_C: coupling losses (between filaments)
- Q_E: eddy current losses in the metallic sheath/substrate and supporting structures
- Q_R: current sharing in metallic sheath (I>Ic)

AC losses per cycle of HTS conductors

- $Q_H \propto I^{3-4}$
- $Q_D \propto I^2$
- $Q_C \propto f \cdot I^2$
- $Q_E \propto f \cdot I^2$
- $Q_R \propto I^2$

So far studies have been limited to such simple structures as tapes, cables and simple shape coils both experimentally and theoretically.

AC losses in two Bx coils at 20 K
Comparison with calculations



Loss per cycle

Data $\propto I^{2.4}$

- - - - - - - - -

FEM results at 15 Hz

$\propto f \cdot I^2$

———————

by Brandt et *al*.,

Normalized at 50 A

Specification of HTS coils for the dipole magnet

Wire：DI-BISCCO Type-HT(SS20)

4.6mm × 0.36mm

12.5μm polyimide（Half wrap）

Winding：600 turns × 2 coils

Inductance: 0.7H

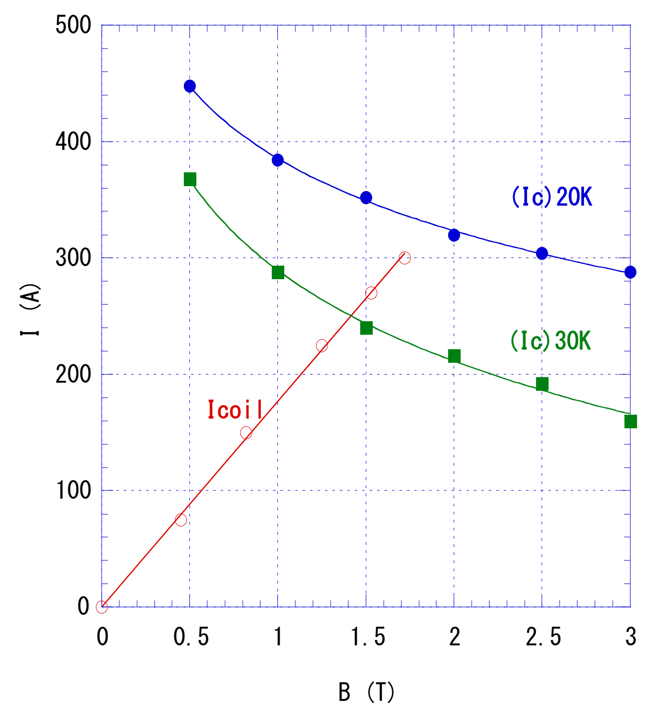
Operating temperature：20K

Critical current (measured at 77K)：

Wire：160 ~ 178A

Double pancake：60 ~ 70A

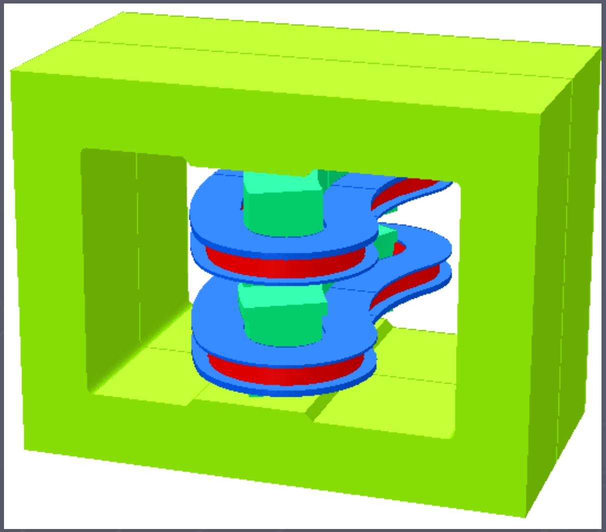
Coil：47A、51A

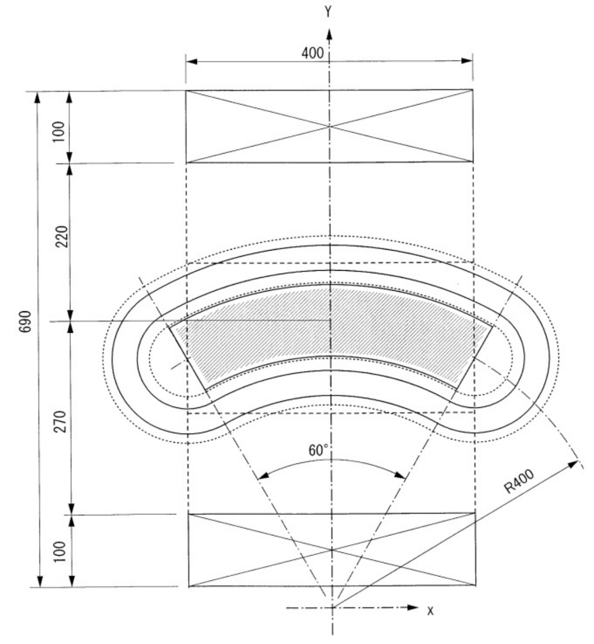


Critical current of wire and the load line of a coil

Specification of the dipole magnet

- Orbit radius : 400 mm
- Deflection angle : 60 deg.
- Pole gap : 30 mm
- Cold pole structure
- Laminated pole and yoke for pulsed operation





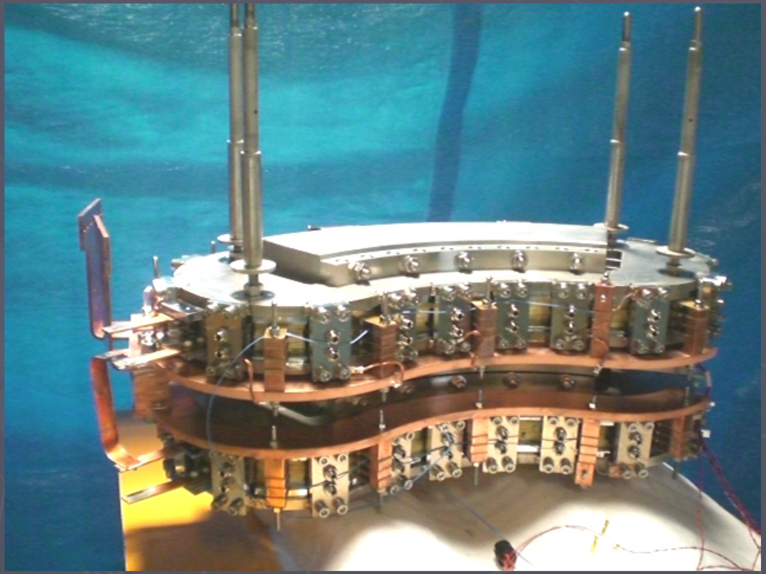
Double pancake (DP) was wound applying tensile stress.

Each DP was impregnated with epoxy resin in vacuum.

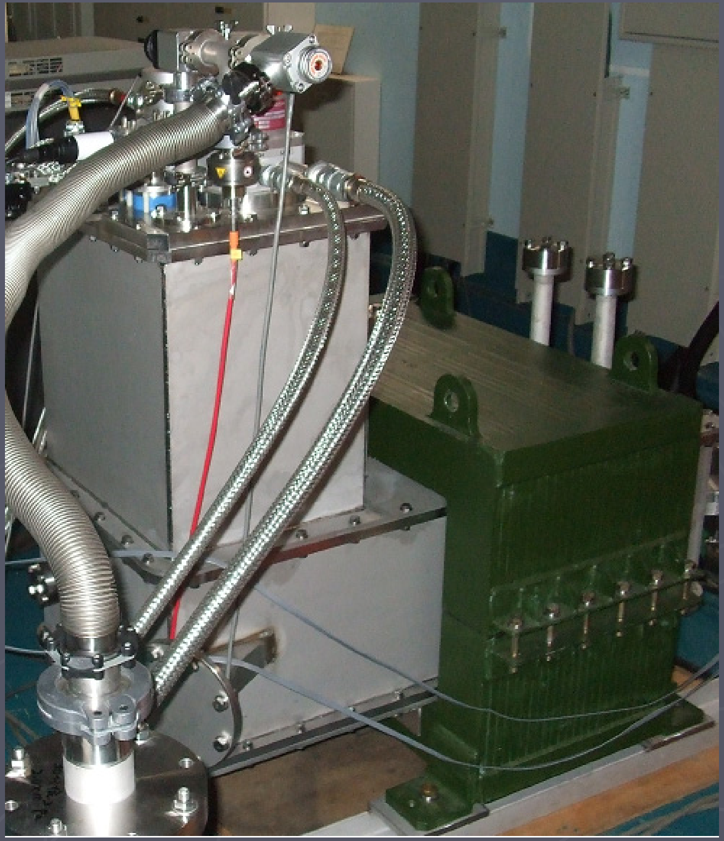
Three DP and cooling plates are stacked and fixed with epoxy resin in vacuum.

9mm and 4.5mm thick iron plates were put on outside and inside of a coil, respectively.

- Coils are fixed to poles to bear the electromagnetic expansion force of 112,000 N/m.
- Poles are formed by stacking 2.3mm thick carbon steel plates.
- Coils and poles weigh 56 and 90kg, respectively. Total weight of the cold mass is 250kg.

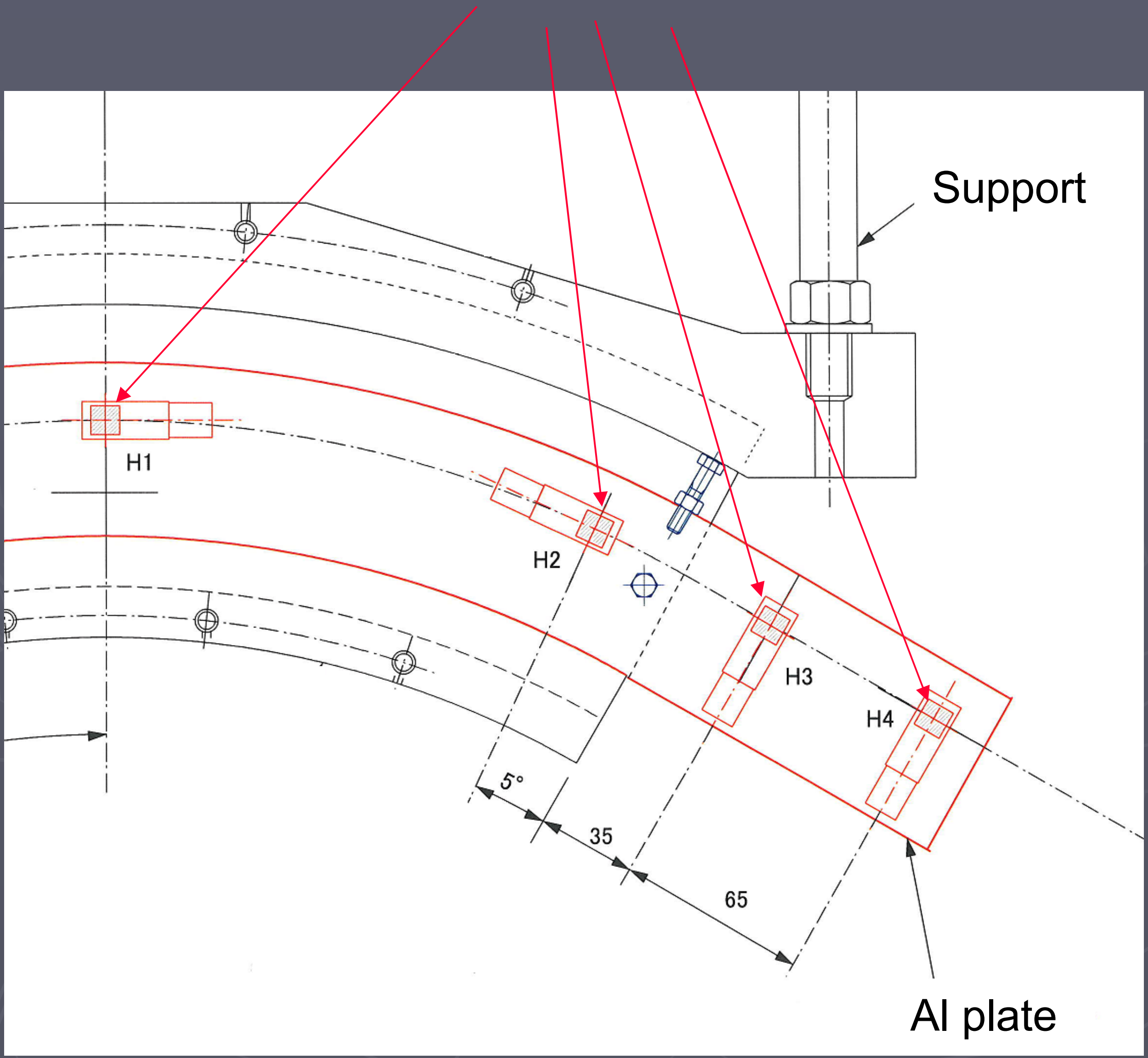


Cold mass

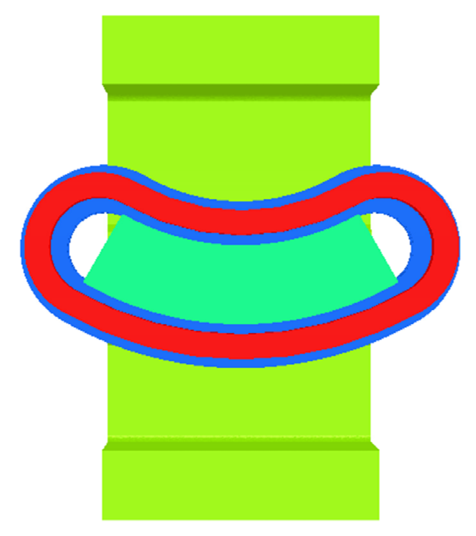


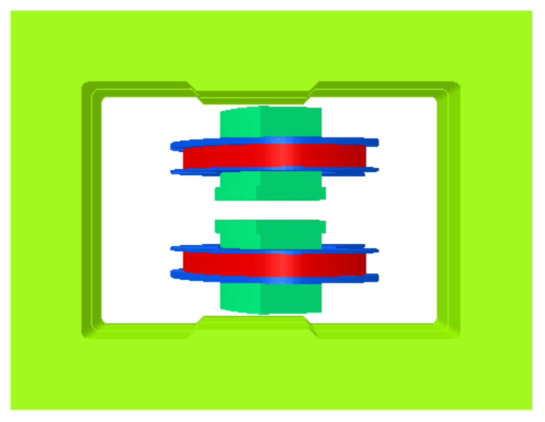
Assembled dipole magnet

Hall probes

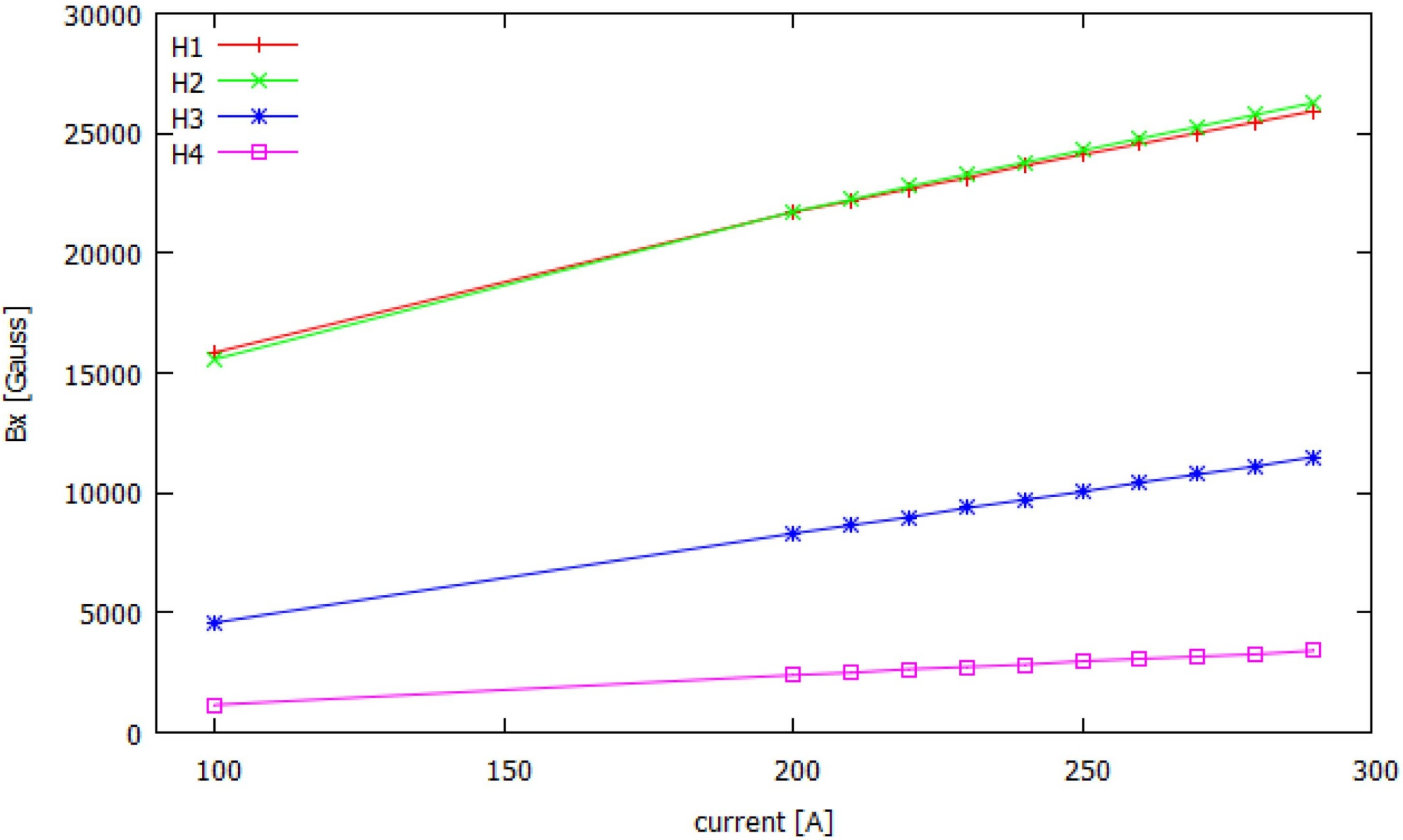

Support

Al plate

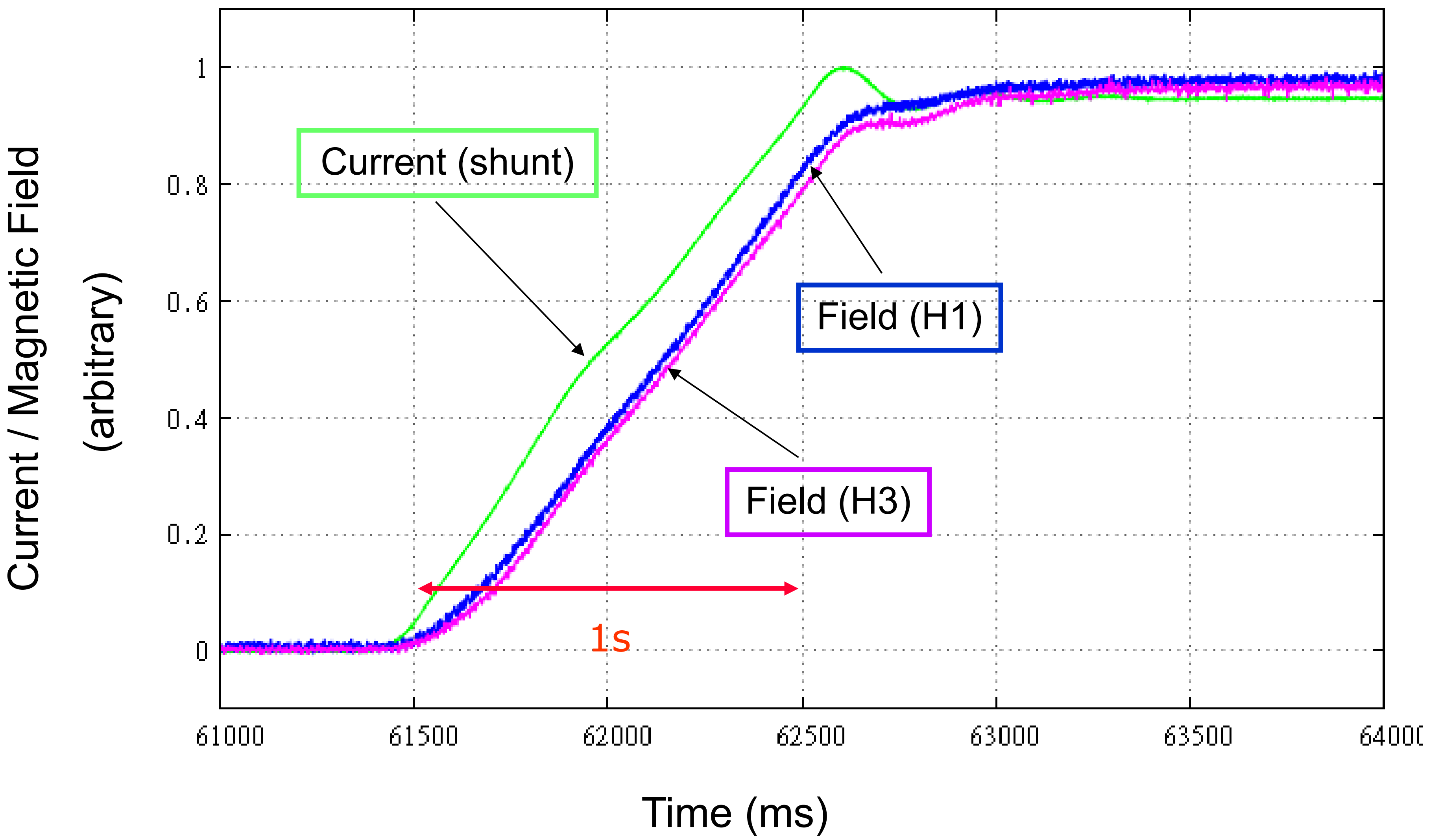




Excitation by DC currents



Excitation by pulsed current (100A/s)



Summary and perspectives

- Next generation particle therapy facilities
  - Both compact accelerators and compact gantries are indispensable.
- Development of HTS magnets at RCNP
  - Scanning magnet and a dipole magnet were fabricated.
  - Performance tests are ongoing with DC, AC and pulsed currents.
  - Presently available HTS wires have relatively large hysteretic losses. Does YBCO show better performance?
  - Feasibility study of HTS cyclotrons is continued and conceptual design work has been started.
  - UCN polarizer (solenoid) is under construction with HTS wire, which is used for the neutron electric dipole moment (EDM) measurements..

Collaborators

RCNP: M. Fukuda, T. Yorita, H. Ueda、J. Nakagawa,
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KT Science: T. Kawaguchi

Thank you for your attention