THB03

Developments of HTS Magnets for Accelerators

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Outline

1. *Introduction*
2. Design and performance of HTS magnets

   Prototype magnets

   · A mirror coil for an ECR ion source

   · Two sets of race track coils for a scanning magnet

   · A 3T super-ferric dipole magnet having a negative curvature

   Magnets for practical use

   · A cylindrical magnet to polarized 210 neV UltraCold Neutrons

   · A dipole magnet for beamline switching (time sharing)
3. Summary

Motivations to develop HTS magnets

- Compact system
    - Accelerators, Beam line, Gantry for particle therapy
        - Low power consumption system
- Advantages over LTS system
    - No liquid helium is required
    - Operating temperature is around 20 K
        - Cryogenic components for cooling are simpler
        - Cooling power of a cryocooler is much larger
        - Temperature range for superconductivity is wider
        - and AC or pulsed current operation may be possible
        - by conduction cooling

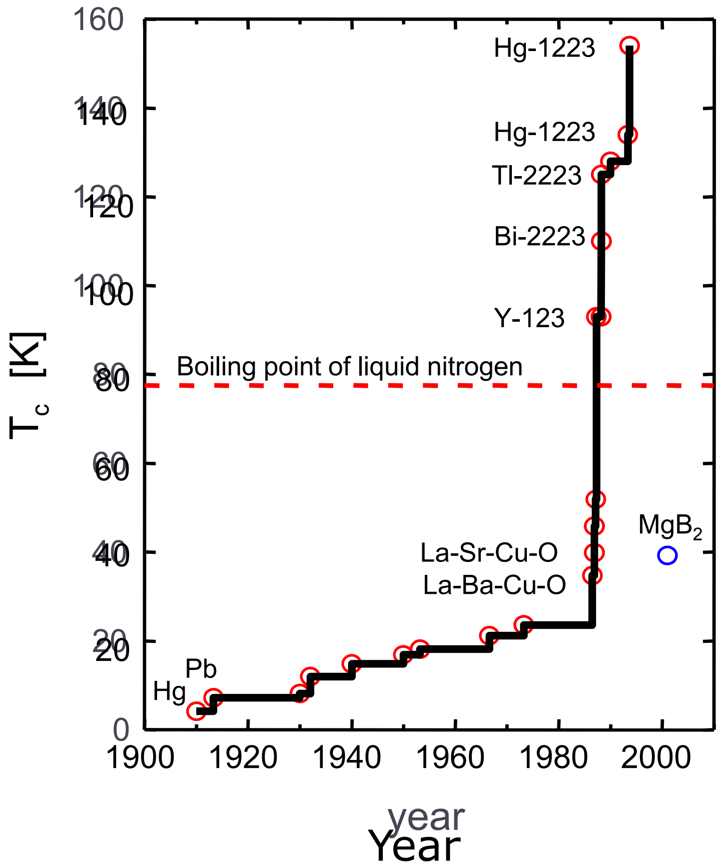
Cu-oxide HTS materials

- 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 wires (T_C = 110 K)
  $Bi_2Sr_2Ca_2Cu_3O_{10}$ (Bi-2223)

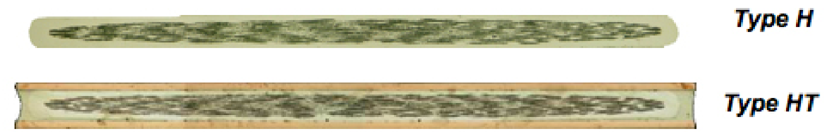
  2nd generation HTS wires (T_C = 95 K)
  $YBa_2Cu_3O_7$ (YBCO / Y-123)
- Although many prototype devices using HTS wires have been developed, so far there have been limited applications to accelerators and beam line facilities.

History of transition temperature



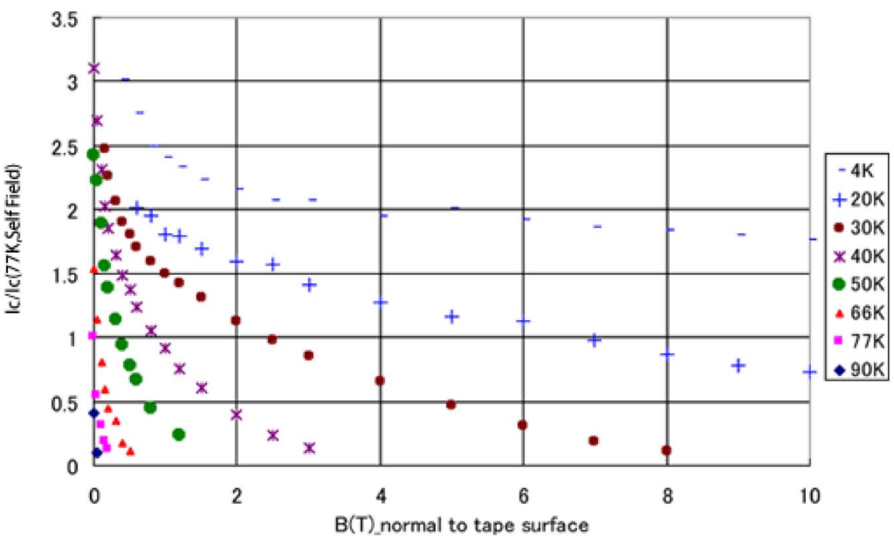
1^{st} generation HTS wire

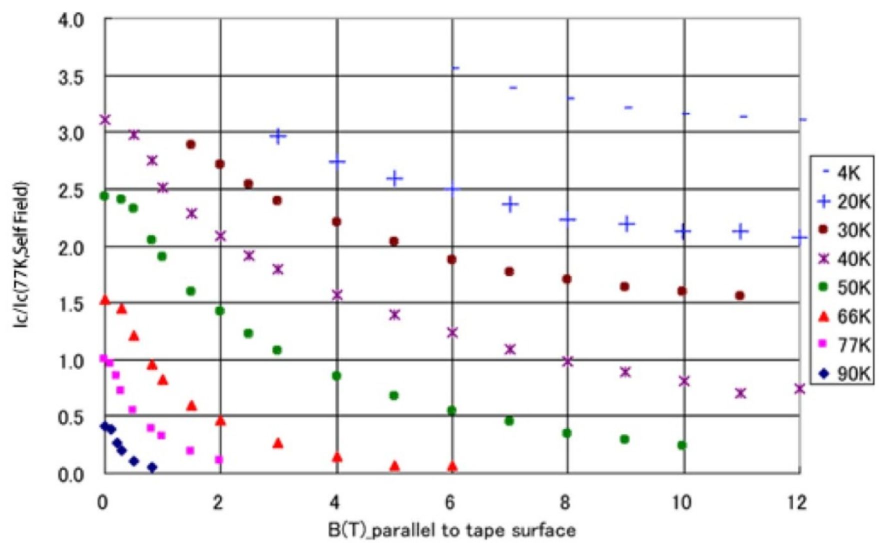
- Wire consists of a flexible composite of in a silver alloy matrix with a thin stainless steel (or copper alloy) lamination that provides mechanical stability and transient thermal conductivity.
- Wire is in thin tape-form approximately 4mm wide and 0.3mm thick.



$Bi_2Sr_2Ca_2Cu_3O_x$ (Bi-2223)

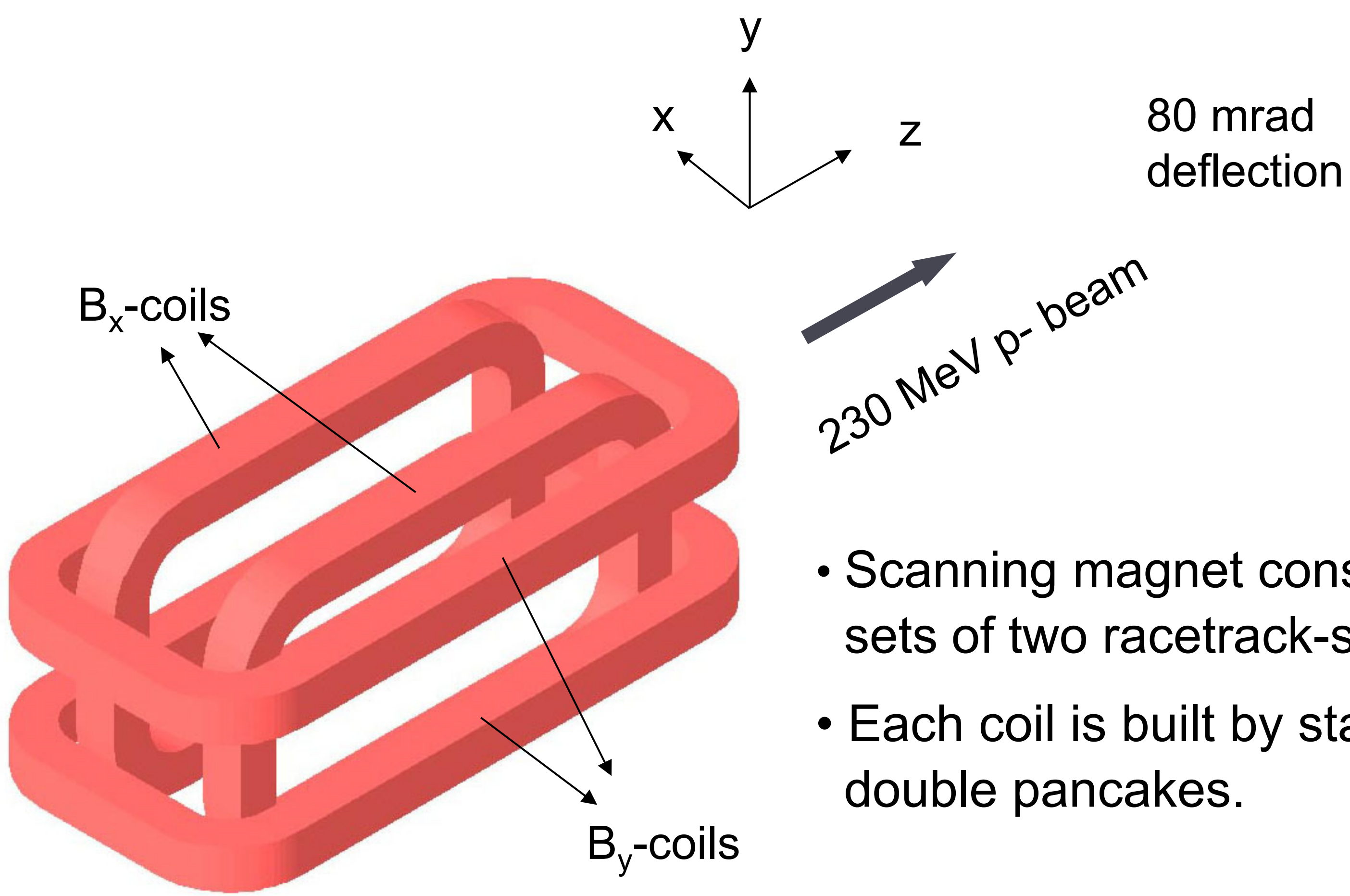
(Sumitomo Electric Industries, Ltd.)





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.

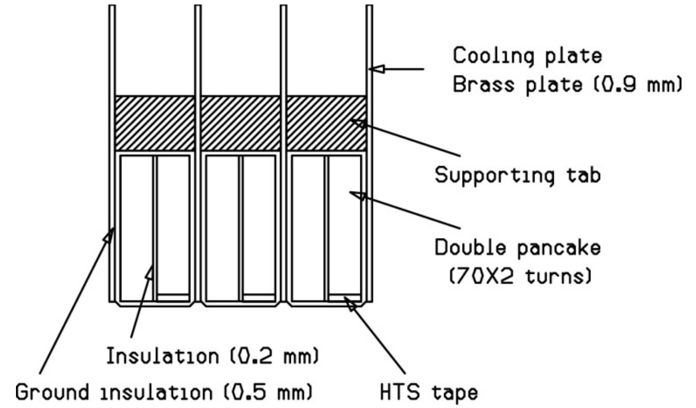
A scanning magnet



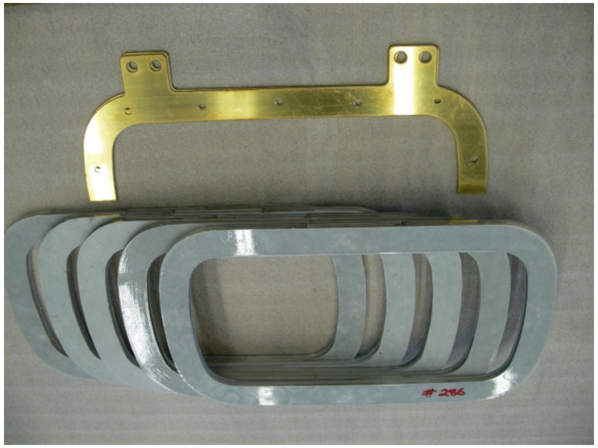
- Scanning magnet consists of two sets of two racetrack-shaped coils.
- Each coil is built by stacking three double pancakes.

Structure and Design parameters

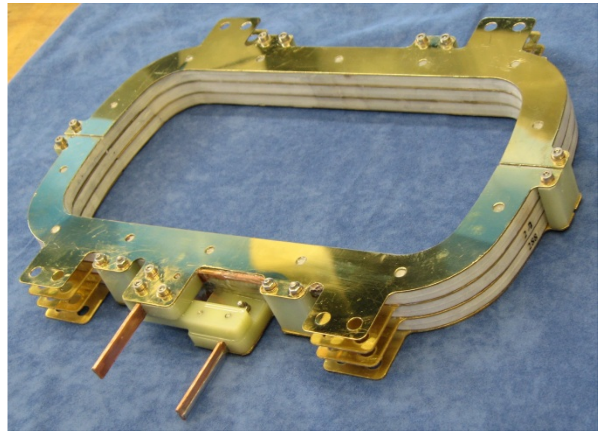
Coils	Inner size	B_x: 150 mm × 300 mm, B_y: 150 mm × 380 mm
	Cross section	30 mm × 30 mm
	Separation	70 mm
	Max. field	0.6 T
	Superconductor	Bi-2223/Ag alloy wire
	Total length	B_x: 412 m × 2, B_y: 460 m × 2
	Number of turns	420 × 2 coils for both B_x and B_y
	Winding construction	3 double pancakes/coil
	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



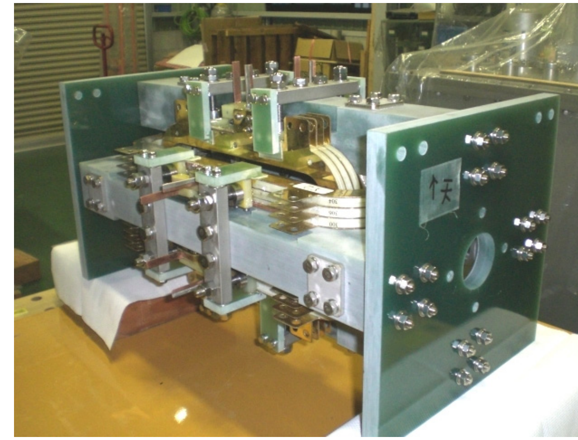
- Ic of the HTS wire over the full length was measured at 77K in a 10m pitch and was 125-140A.
- 0.2mm thick layer insulation is put in the middle of each double pancake.
- Double pancale is covered with a 0.5mm thick ground insulation.
- Four 0.9 mm thick brass plates are fixed to a coil with epoxy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



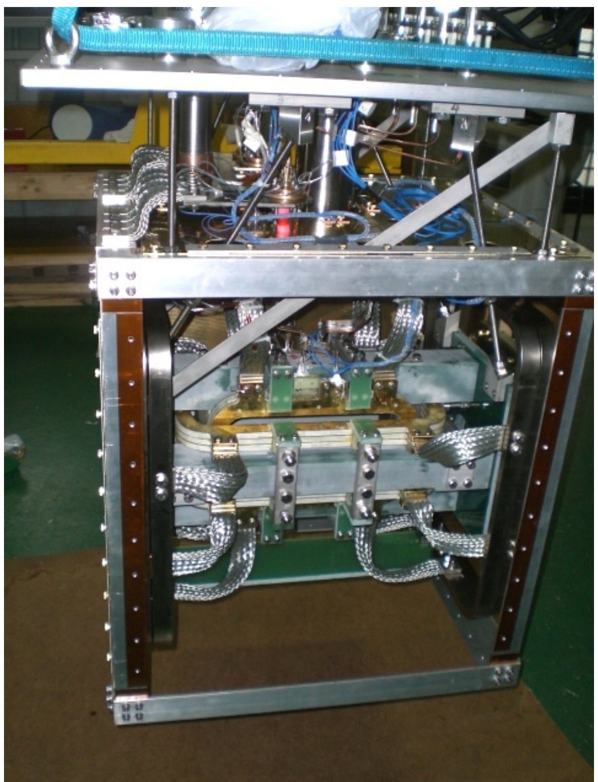
Double pancakes and cooling plates.



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: hysteresis losses (in the superconductor)

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

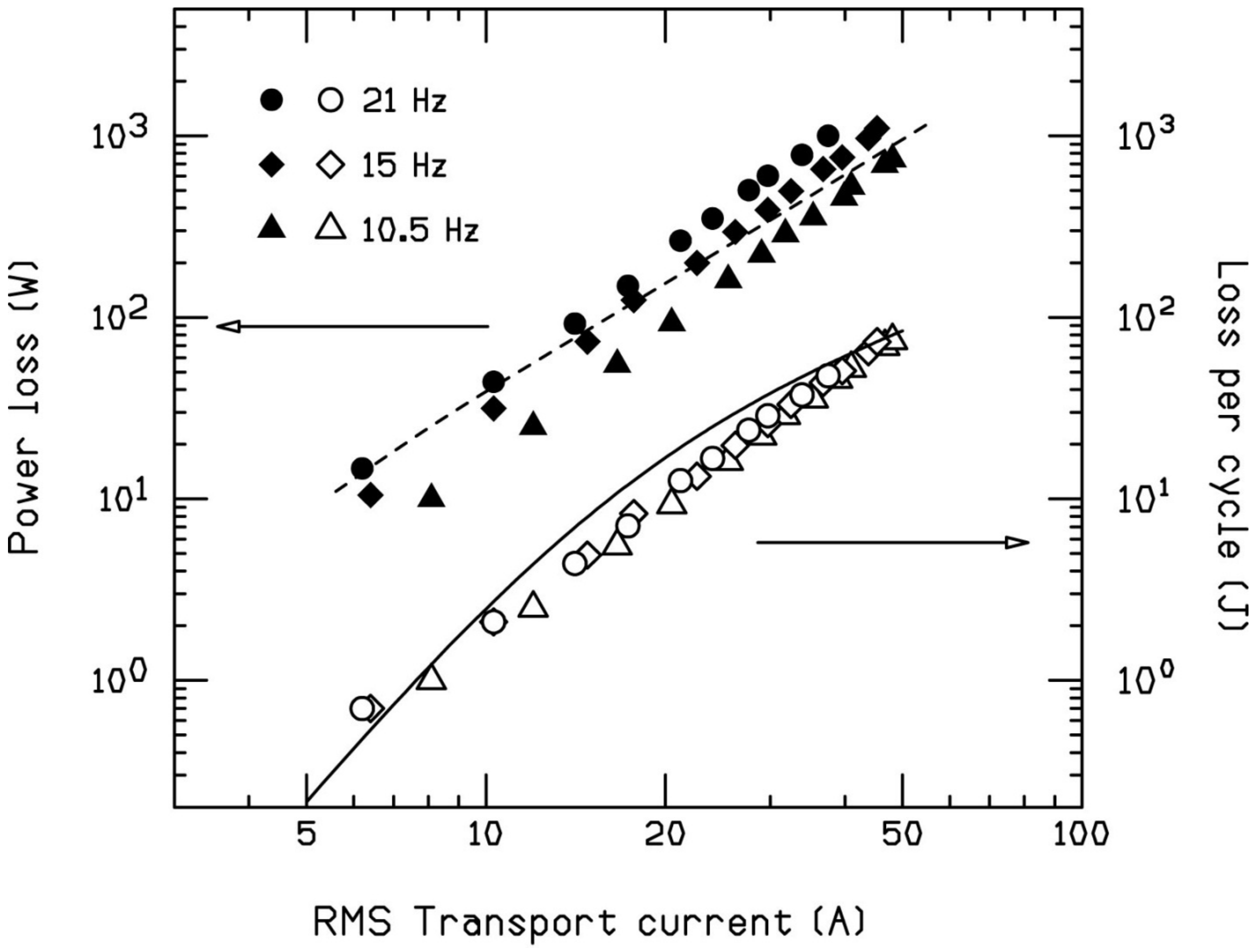
- Q_E: eddy current losses in the metallic sheath/substrate and supporting structures
- Q_D: dynamic resistance losses caused by the flux flow
- Q_C: coupling losses (between filaments)
- Q_R: current sharing in metallic sheath (I>Ic)

AC losses per cycle of HTS conductors

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

So far studies have been limited to such simple structures as tapes, cables and simple coils in both experimental and theoretical points of view.

AC losses at 20 K
Comparison with calculations



Loss per cycle

Data $\propto I^{2.4}$

FEM results at 15 Hz

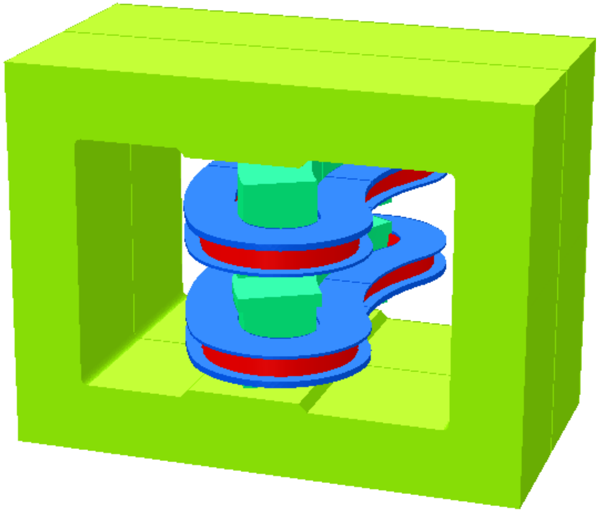
$\propto f \cdot I^2$

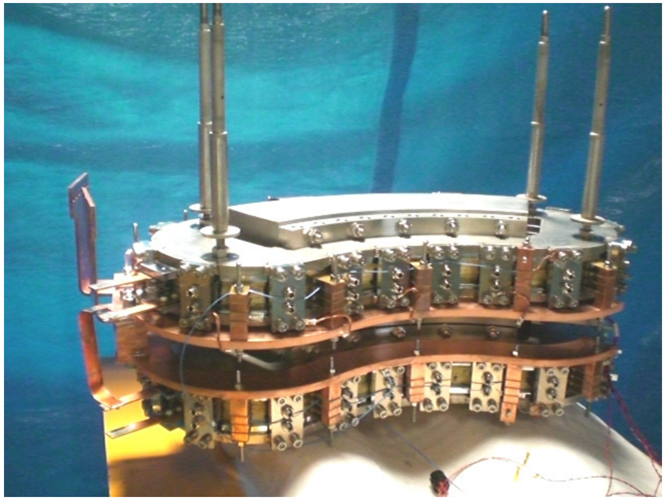
by Brandt et *al*.,

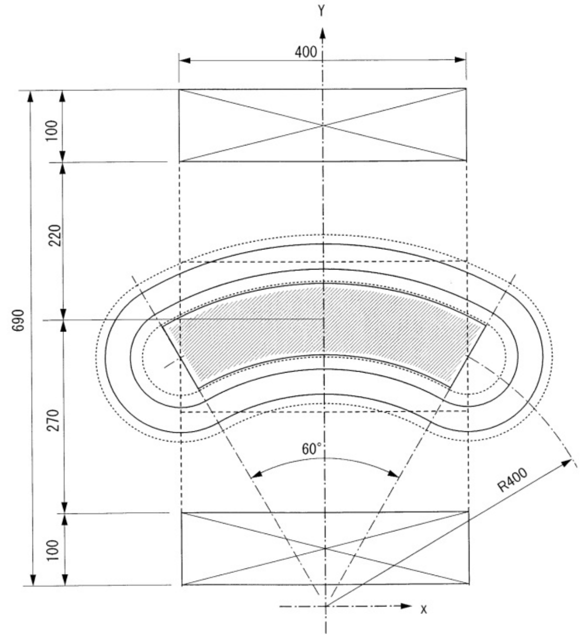
Normalized at 50 A

Specifications of a toy-model dipole magnet

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







Specifications of HTS coils for the dipole magnet

Wire：DI-BISCCO Type-HT(SS20)

4.6 mm × 0.36 mm

12.5 μm polyimide（Half wrap）

Winding：600 turns × 2 coils

Inductance: 0.7 H

Operating temperature：20 K

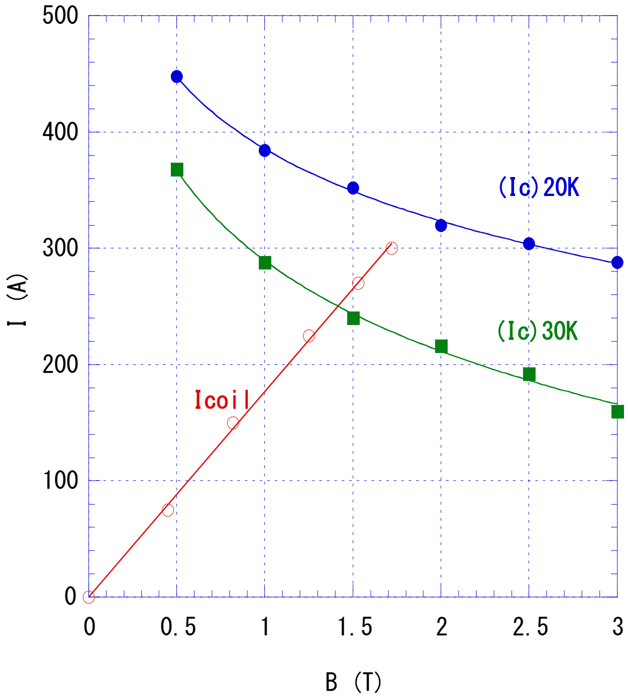
Critical current (measured at 77 K)：

Wire：160 ~ 178 A

Double pancake：60 ~ 70 A

Coil：47 A、51 A

No degradation was observed after winding.



Critical current of wire and the load line of a coil

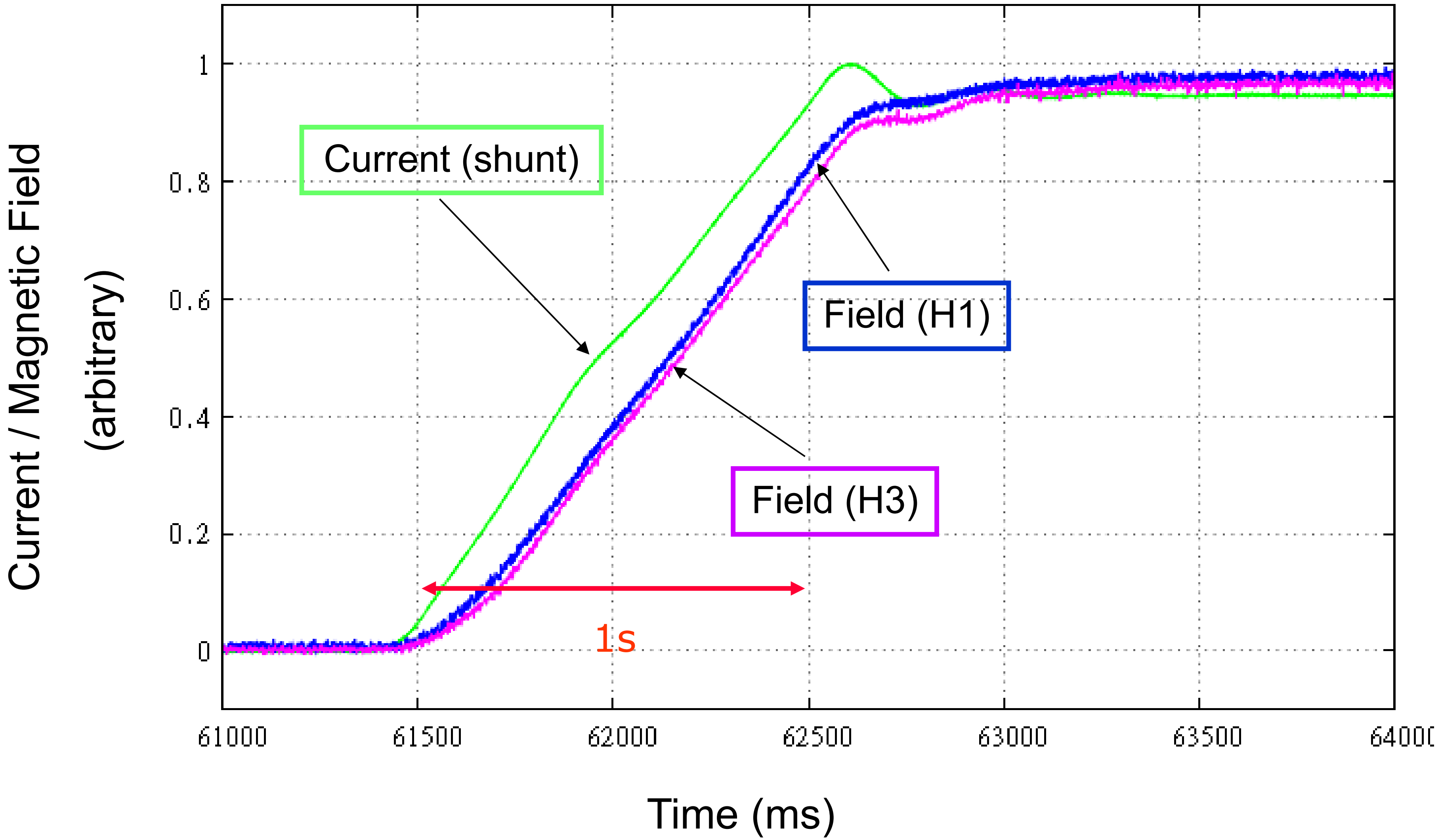
Double pancake (DP) was wound with applying tensile stress.

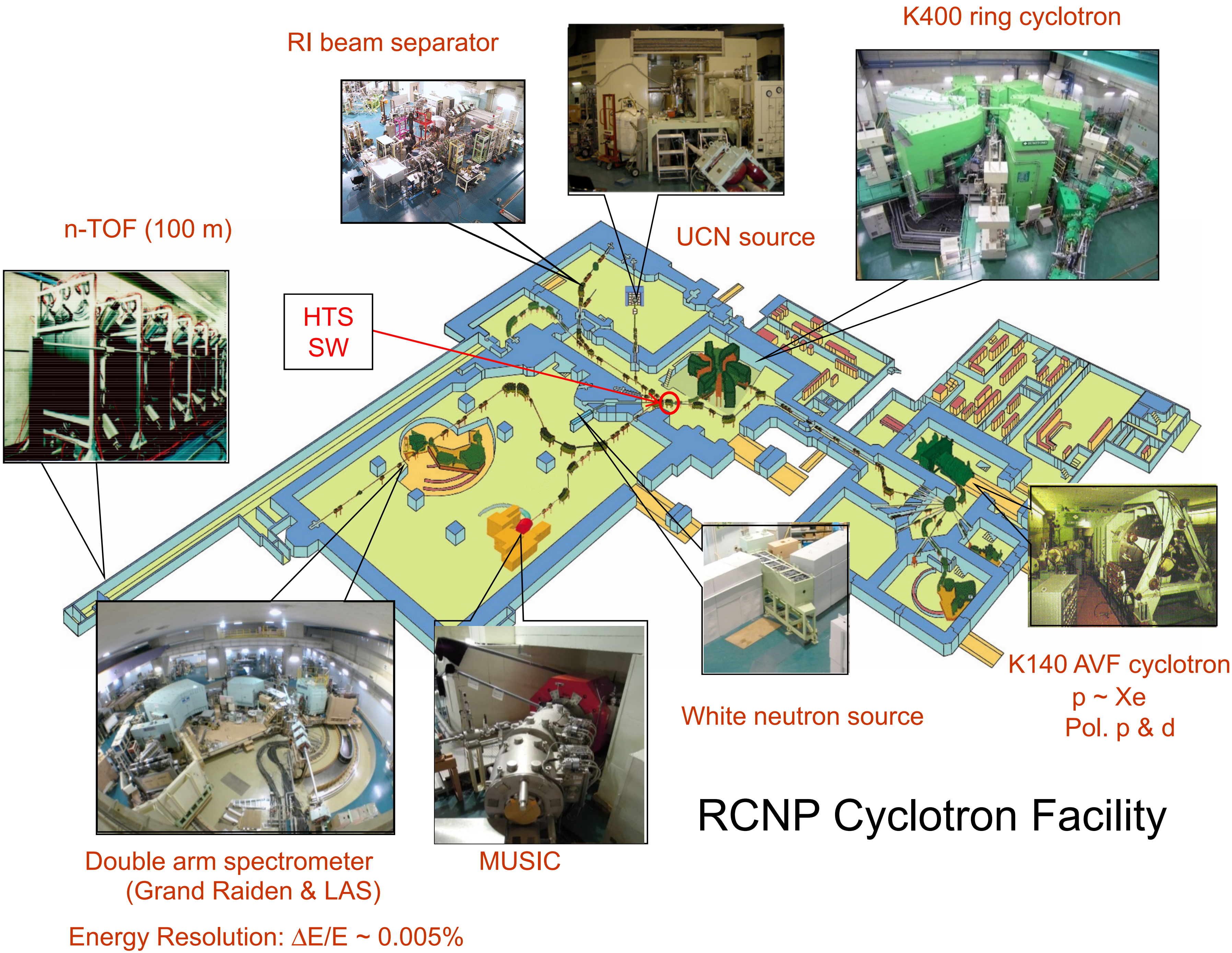
Each DP was impregnated with epoxy resin in vacuum.

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

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

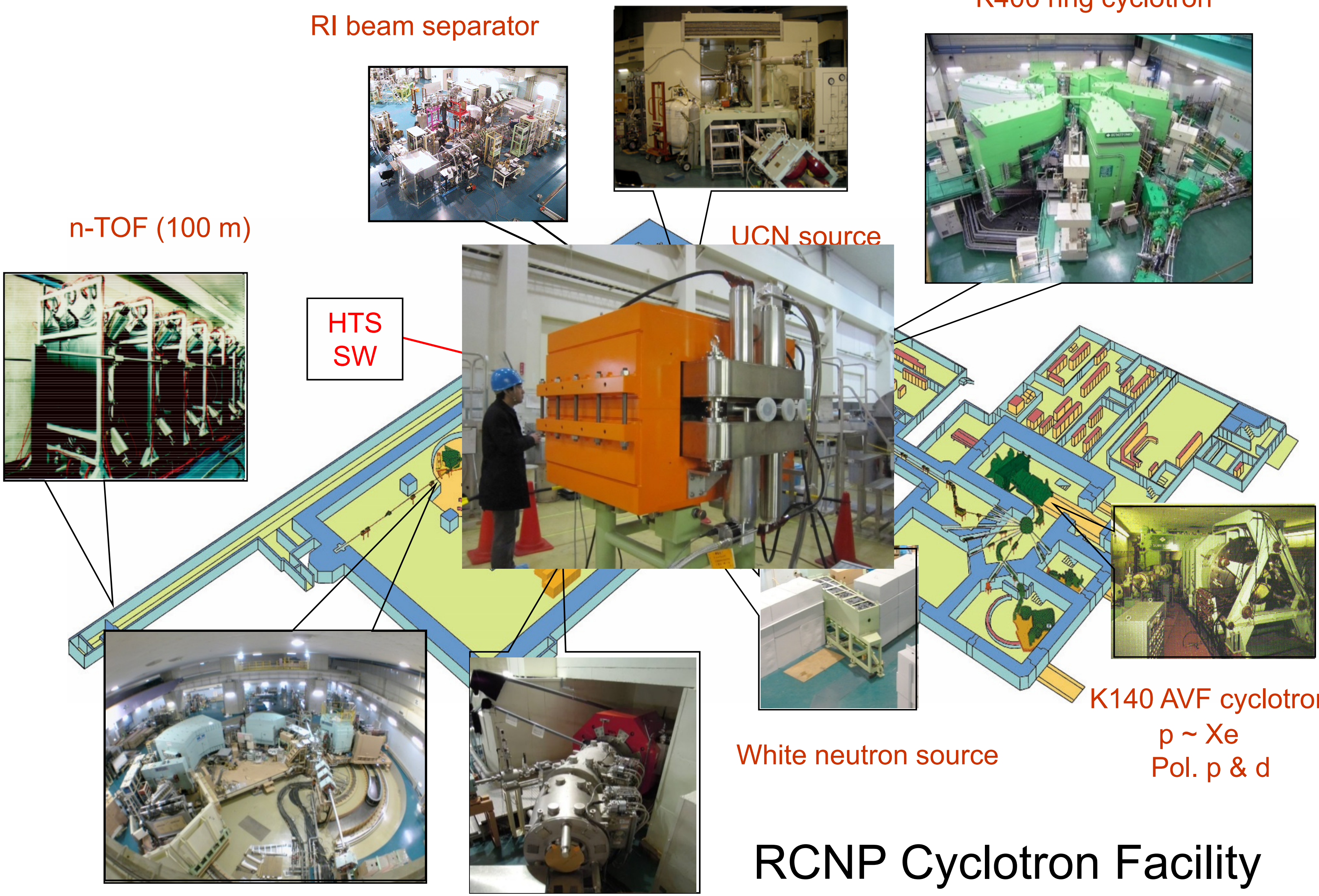
Excitation by pulsed current



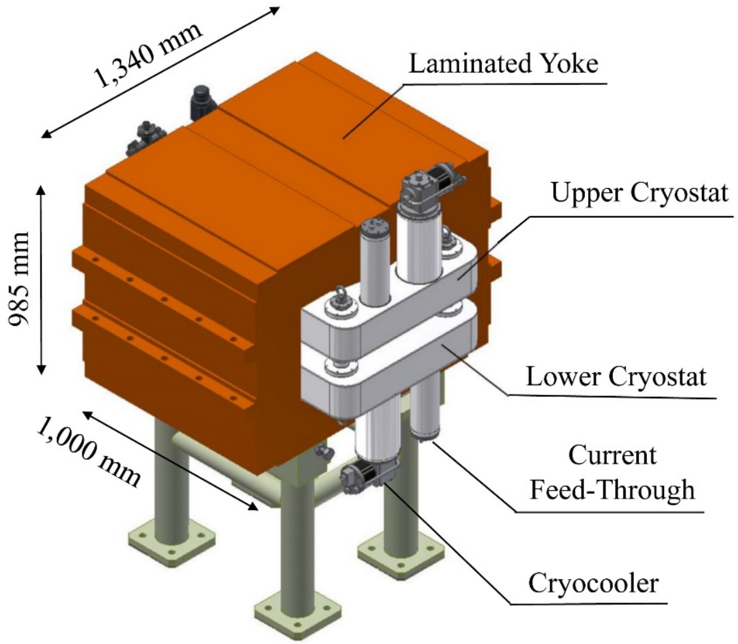


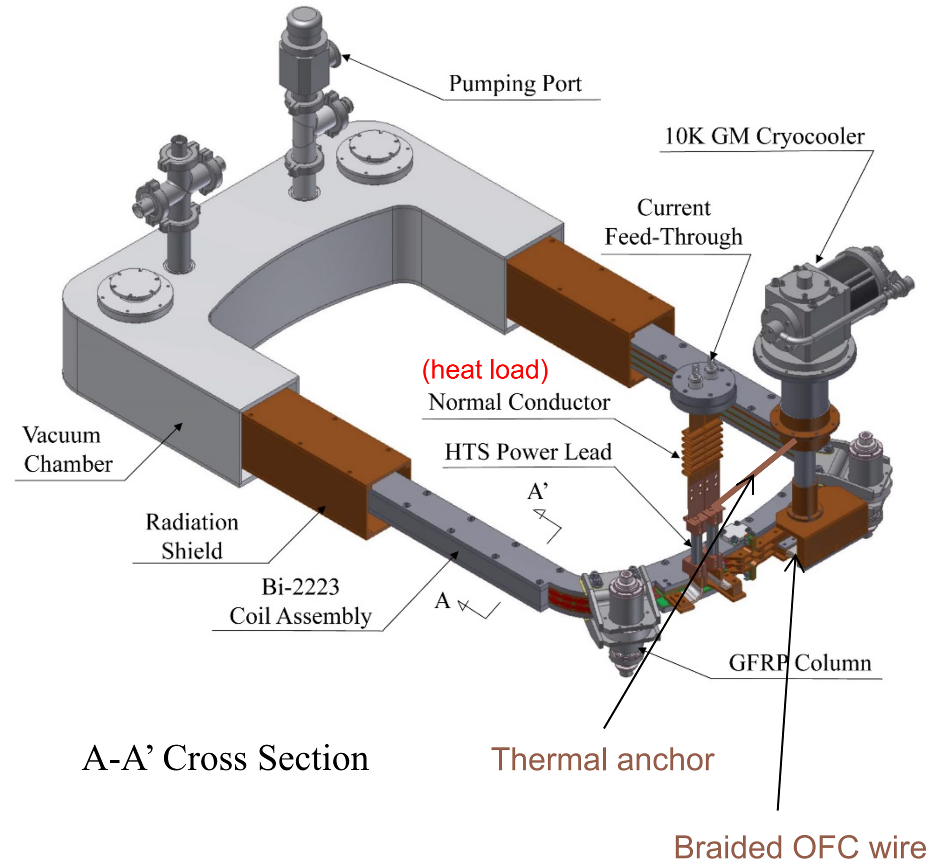
RCNP Cyclotron Facility

RCNP Cyclotron Facility

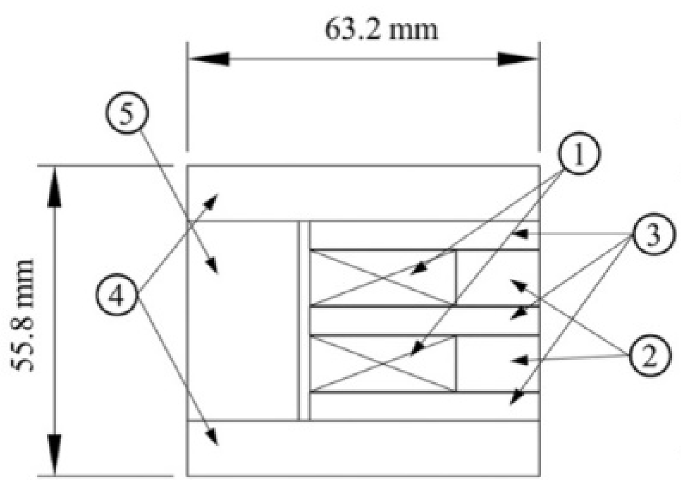


Dipole magnet for beamline switching





A-A' Cross Section



No.	Description	Material
1	Bi-2223 DPC	
2	Winding Frame	Stainless Steel
3	Cooling Plate	Copper
4	Reinforcing Plate	Stainless Steel
5	Reinforcing Bar	Stainless Steel

Specifications of the SW magnet

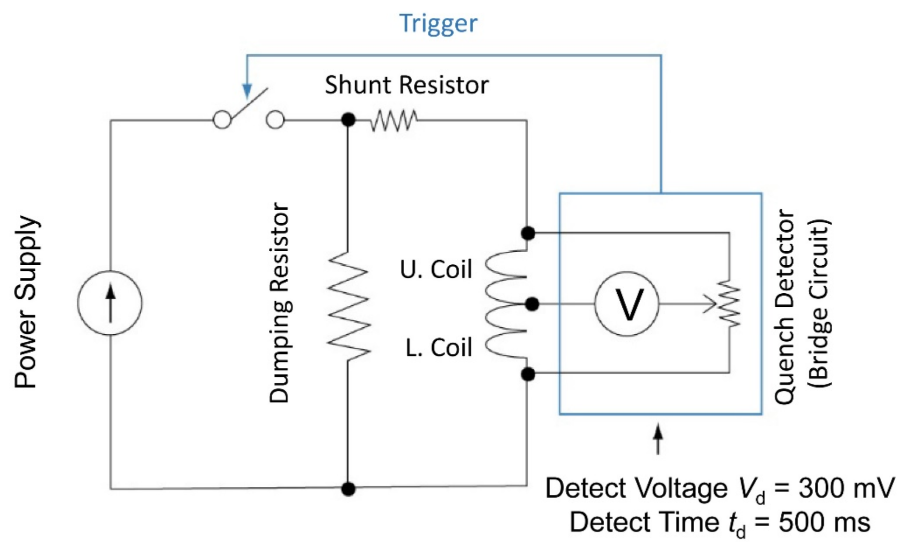
Maximum magnetic field	1.6 T
Fastest switching time 10 s	
Bi-223 wire	DI-BSCCO type HT-CA (Sumitomo Electric Industries, Ltd.)
Number of turns	512 turns
2-stage 10 K GM cryocooler	SRDK-408S2 (Sumitomo Heavy Industries, Ltd.)
Cooling	Conduction cooling
Cooling power	1st stage: 40 W at 45 K (Radiation shield, Thermal anchor to Cu conductor) 2nd stage: 6.3 W at 10 K (Coil assembly)
Peak perpendicular field	0.8 T
Coil temperature	< 20 K
Critical current	330 A at 20 K
Stored energy	45.5 kJ

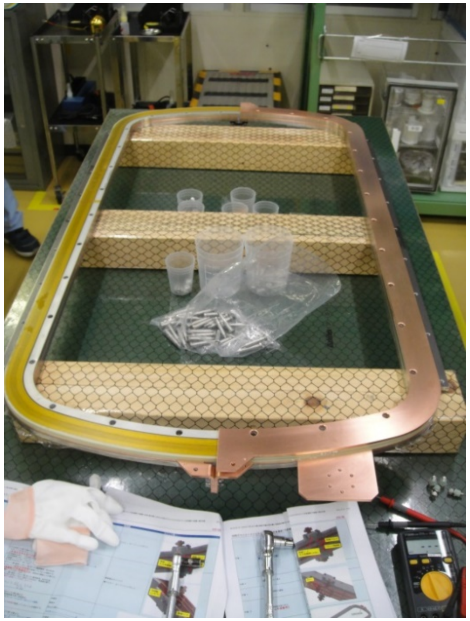
Quench detect and protect circuit

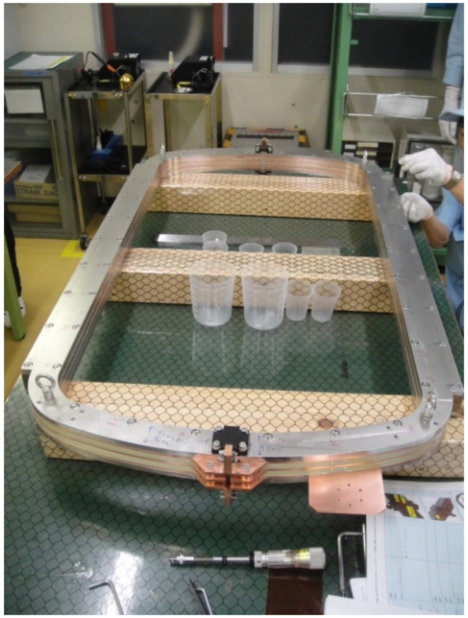
Normal zone propagating velocity (NZPV)
LTS: a several 10–100 m/s
HST: a several cm/s

It is difficult to detect a quench in HTS coils by voltage pick-up method.

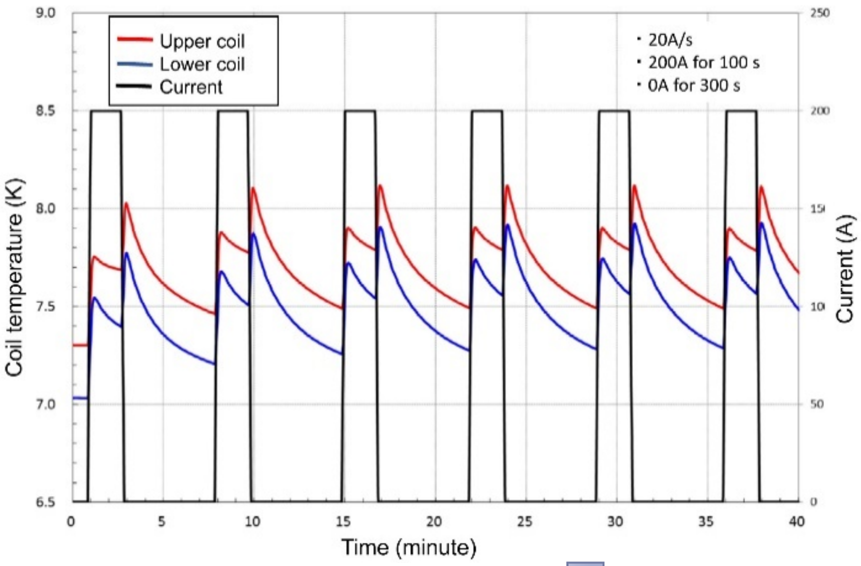
Imbalance voltage between the upper and lower coil is measured by a bridge circuit.

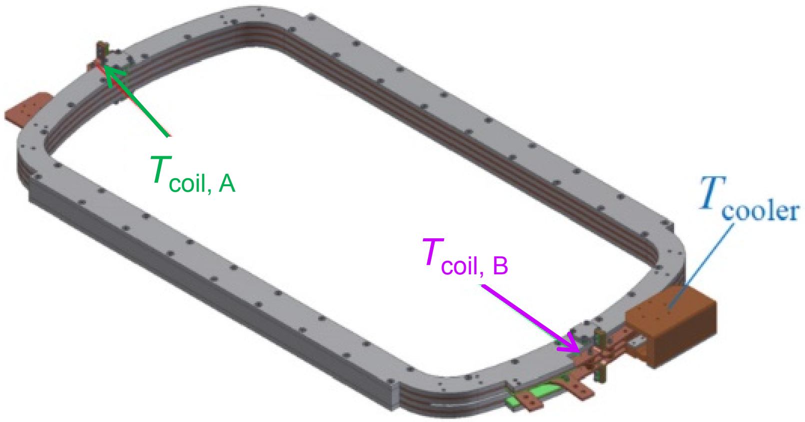




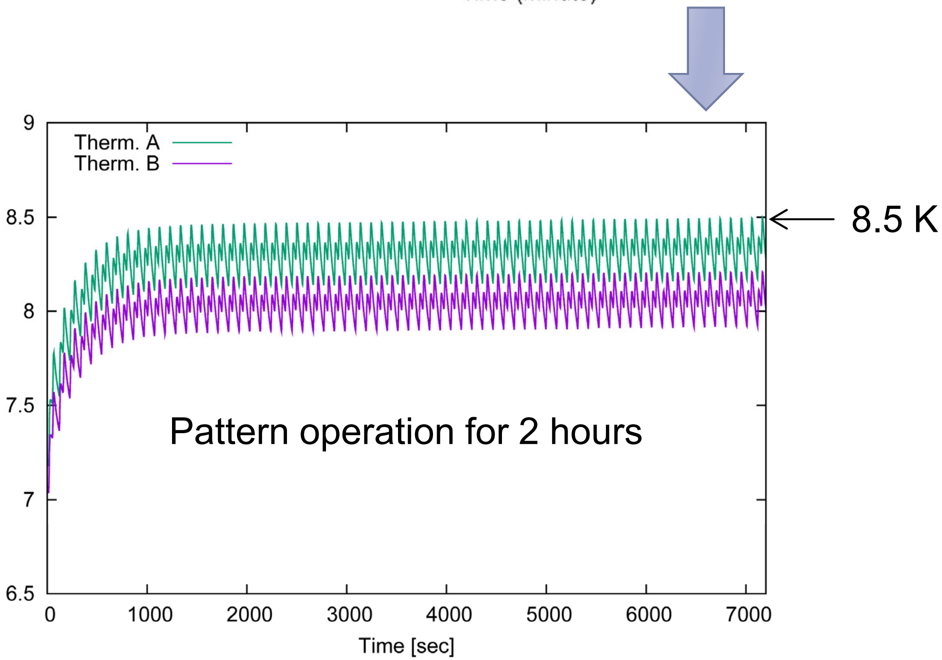


Coil temperature during a pattern operation of the switching magnet

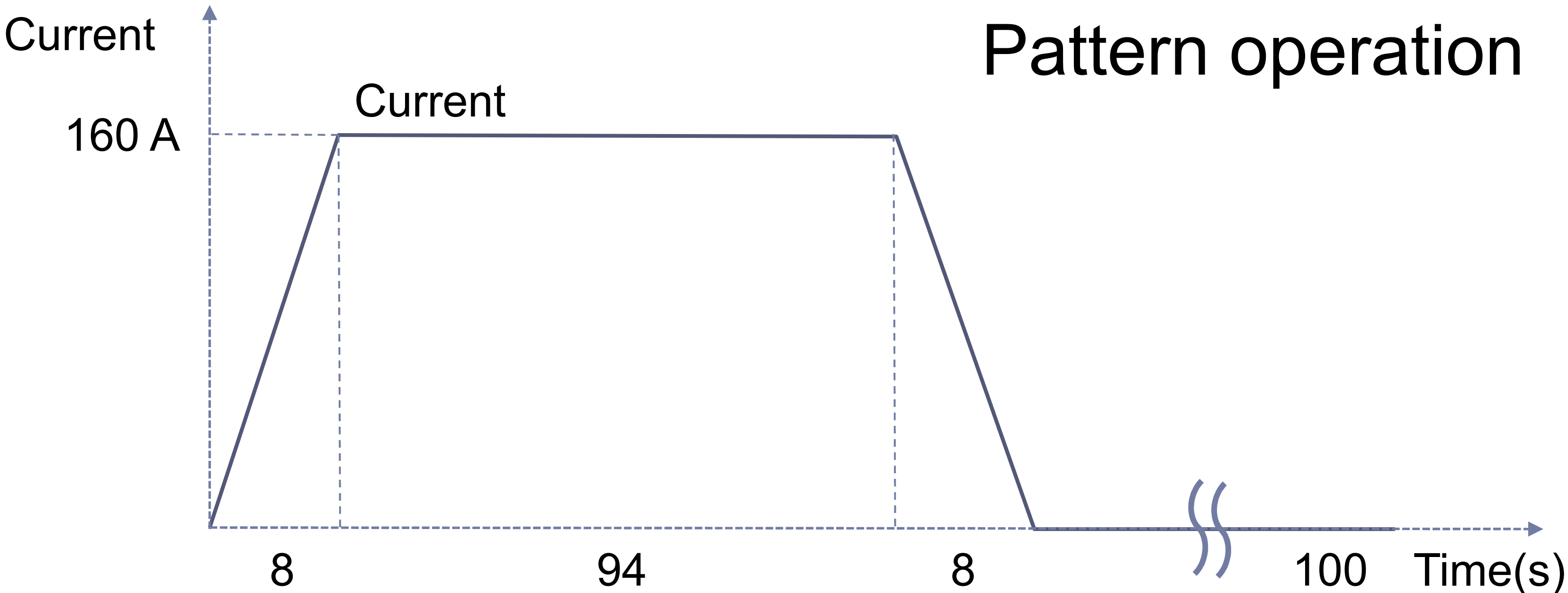


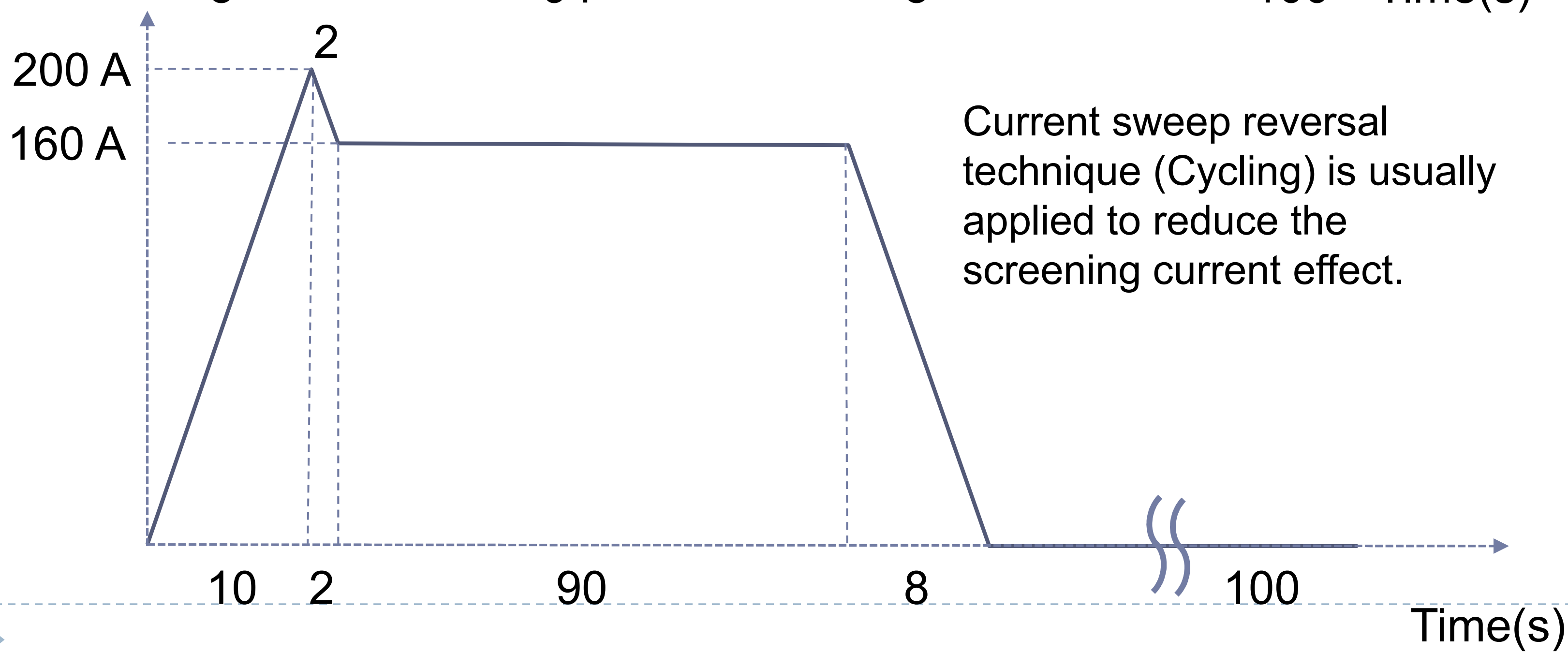


Coil temperature is measured with cernox sensors at 2 positions, near the cryocooler and far from it.



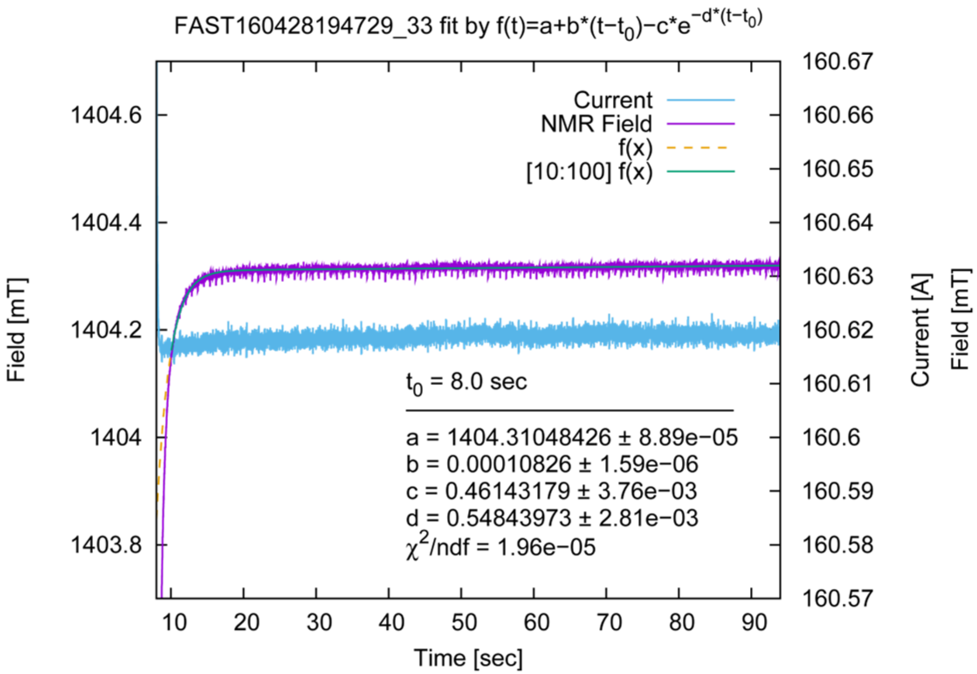
Pattern operation





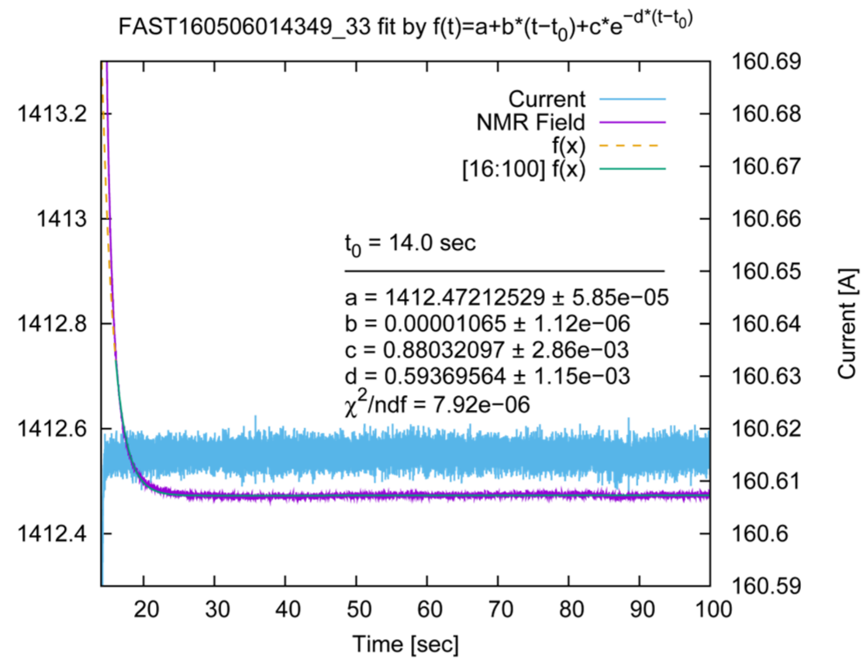
Current sweep reversal technique (Cycling) is usually applied to reduce the screening current effect.

w/o cycling



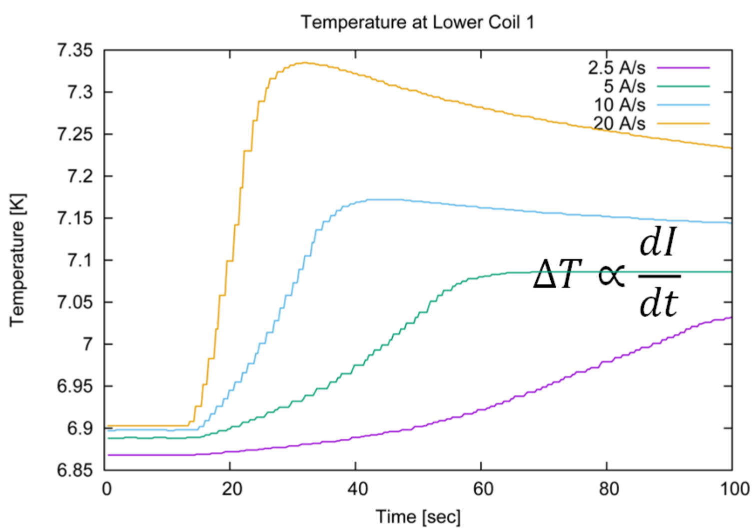
b=1.0x10^{-4} mT/s

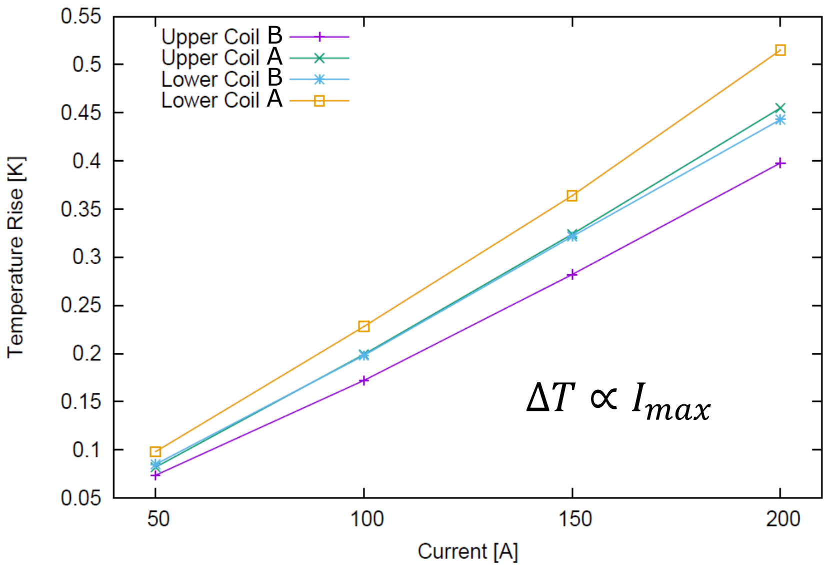
w/ cycling

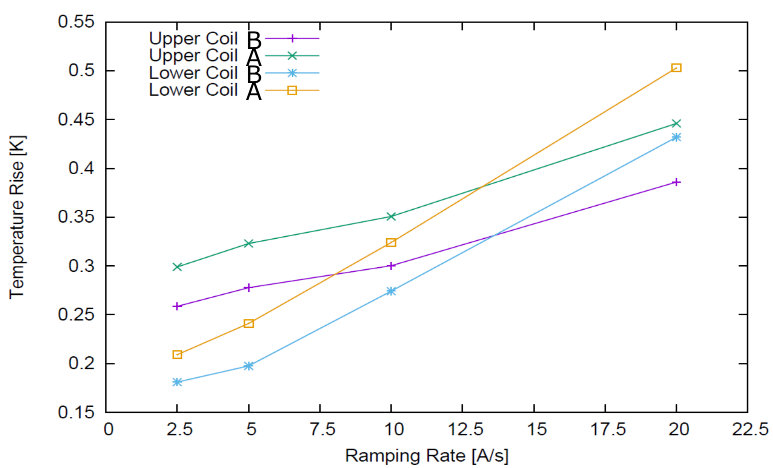


b=1.0x10^{-5} mT/s

Ramping rate dependence of the temperature rise (I_{max} = 200 A)







- Main AC loss is the hysteresis loss by screening current.
- Effects of the screening current on the magnetic field is expected to be small in the present structure.

Summary and perspectives

- Development of HTS magnets at RCNP
  - Three prototype magnets were fabricated.
  - For practical use, a UCN polarizer and a beamline switching magnet have been constructed.
  - Performance tests were performed with DC, AC and pulsed currents.
  - The switching magnet will be installed in the beamline by the end of this year.
  - At RCNP, feasibility study of HTS cyclotrons is continued and conceptual design has been started.

Collaborators

RCNP: M. Fukuda, T. Yorita, J. Nakagawa, N. Izumi,
T. Saito, H. Tamura, Y. Yasuda, K. Kamakura,
N. Hamatani, S. Hara

Okayama U.: H. Ueda

Tohoku U.: Y. Sakemi

Kyushu U.: T. Wakasa

NIRS: K. Noda

KT Science: T. Kawaguchi

SHI: J. Yoshida, T. Morie, A. Hashimoto, H. Mitsubori,
Y. Mikami, K. Watazawa

Thank you for your attention