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RCNP
大阪大学 核物理研究センター

HTS Magnets for Accelerator Applications

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Outline

1. Introduction
2. High Temperature Superconducting (HTS) wire
3. Development of HTS magnets at RCNP

   Models:

   - ECR mirror coil
   - Scanning magnet
   - Superferic dipole magnet with bana-shaped coil

   Magnets for practical use:

   - UCN polarizer
   - Beam line switching magnet

   design and performance

   hysteresis loss of HTS coil
4. Summary

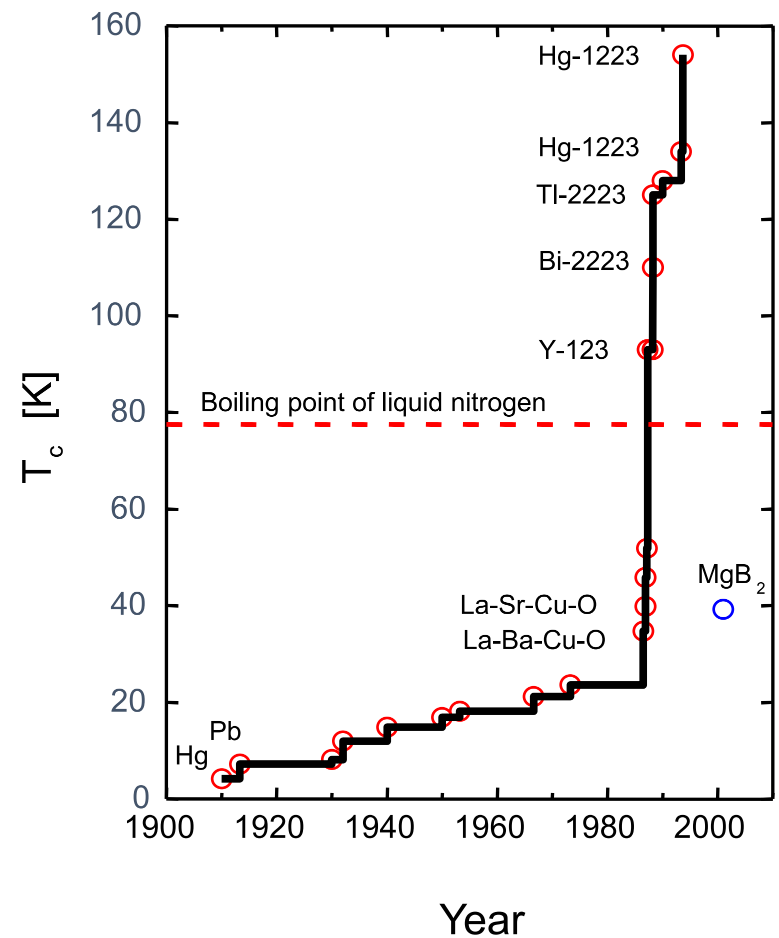
Motivations to develop HTS magnets

- Compact system
  - Beam line, Gantry for particle therapy, Accelerators
- Low power consumption system
- Advantages over LTS system
  - No liquid helium is required
  - Cooled by conduction to cryo-coolers
  - Operating temperature can be 20 K or higher
    - Cryogenic components become simpler
    - Cooling power of refrigerators is much larger
    - Temperature range for superconductivity is wider
    - AC and pulsed magnets may be possible.

HTS materials

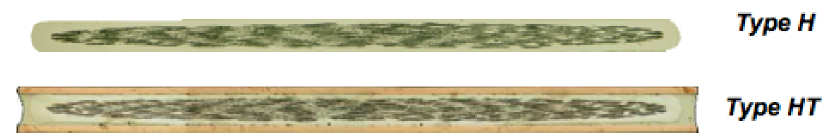
- 1986: discovery of $(La_{1-x}Ba_x)_2CuO_4$
  J.G. Bednorz and K.A. Müller
- Significant effort went into the development of new and improved conductor materials.
- Two wires are commercially available, which are long over km.
  1st generation HTS wires (T_C = 110 K)
  $Bi_2Sr_2Ca_2Cu_3O_{10}$ (Bi-2223)
  2nd generation HTS wires (T_C = 95 K)
  $YBa_2Cu_3O_7$ (REBCO / Y-123)
- Many prototype devices using HTS wires have been developed so far.

History of transition temperature of HTS materials



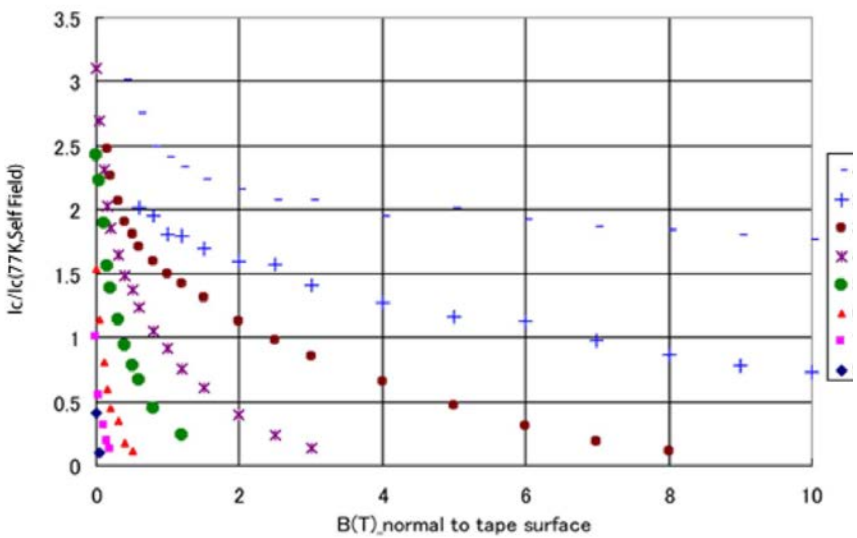
1st generation HTS wire

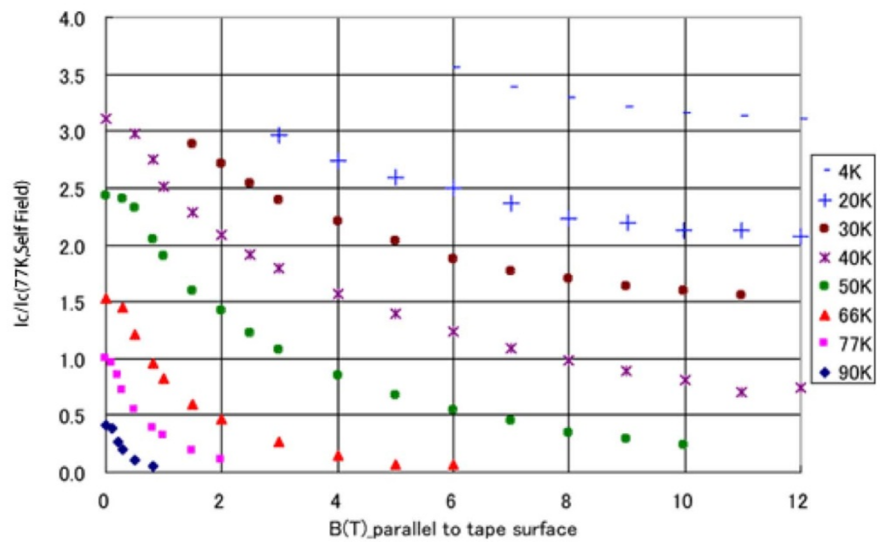
- Wire consists of a flexible composite in a silver alloy matrix with a thin stainless steel (or copper alloy) lamination that provides mechanical stability and transient thermal conductivity.
- Wire is in thin tape-form approximately 4mm wide and 0.3mm thick.



$Bi_2Sr_2Ca_2Cu_3O_x$ (Bi-2223)

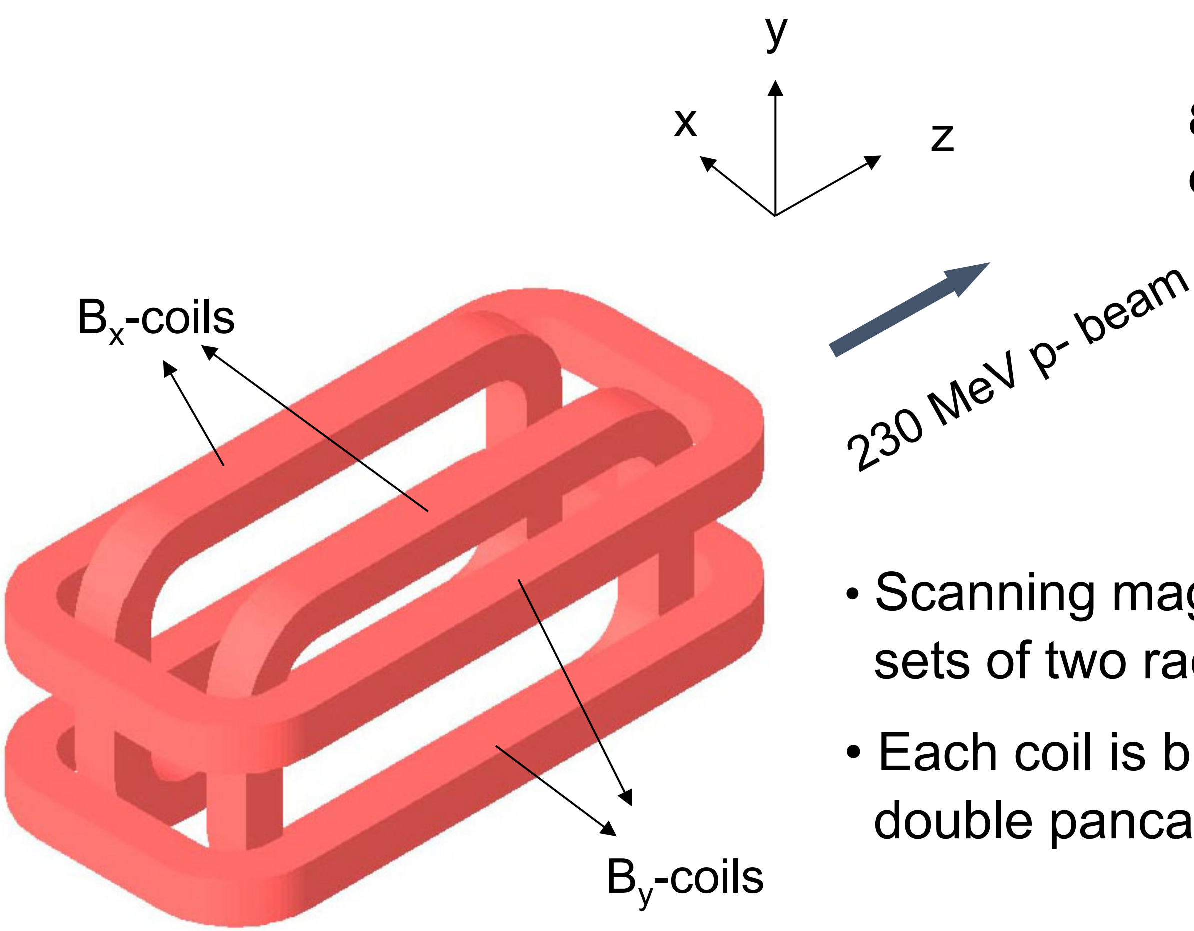
(Sumitomo Electric Industries, Ltd.)





Critical current depends on the operating temperature and the strength and direction of magnetic field on the tape surface. They are scaled by Ic at 77K and with self field.

A scanning magnet

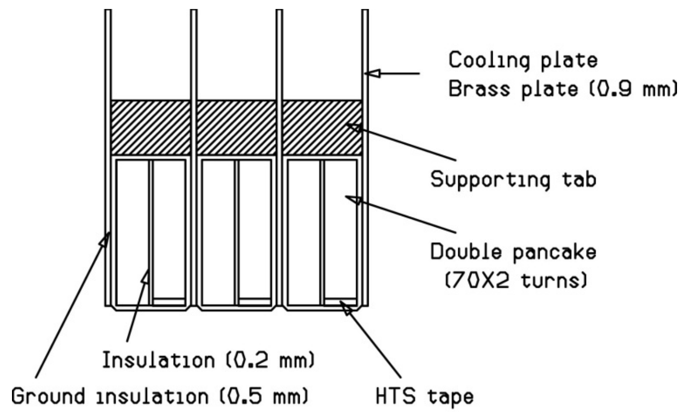


80 mrad deflection

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

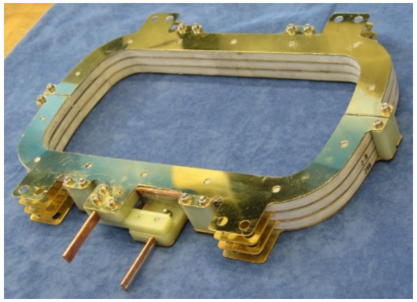
Structure and Design parameters

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.



Assembled one B_x coil.

AC losses in superconducting magnet

- Q_H: hysteresis losses (in the superconductor)

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

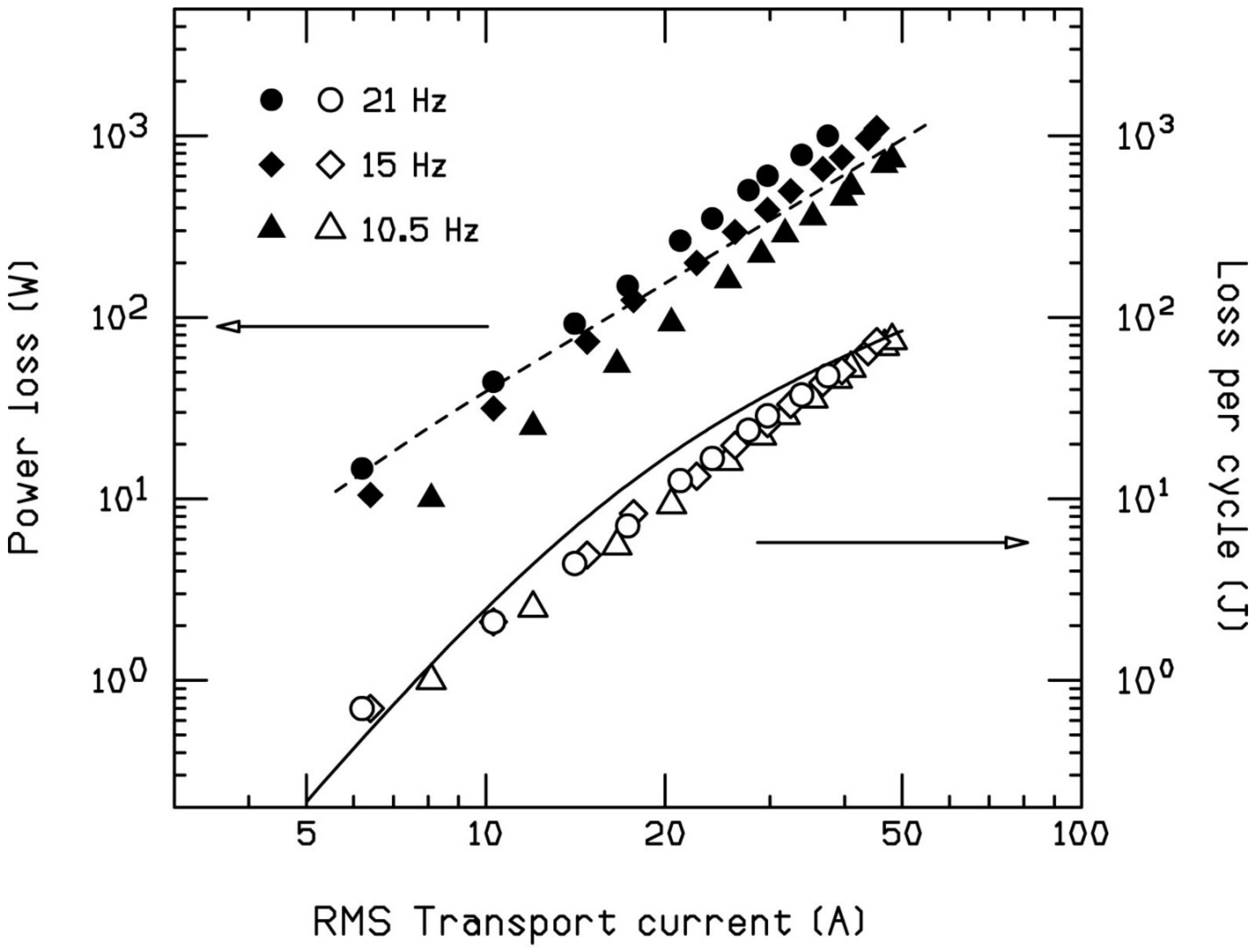
- Q_C: coupling losses (between filaments)
- Q_E: eddy current losses in the metallic
  sheath/substrate and supporting structures
- Q_D: dynamic resistance losses caused by the flux flow
- Q_R: current sharing in metallic sheath (I>Ic)

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 coils in both experimental and theoretical points of view.

AC losses at 20 K
Comparison with calculations



Loss per cycle

Data $\propto I^{2.4}$

Independent on *f*

- - - - - - - - -

FEM results at 15 Hz

$\propto f \cdot I^2$

———————

by Brandt et *al*.,

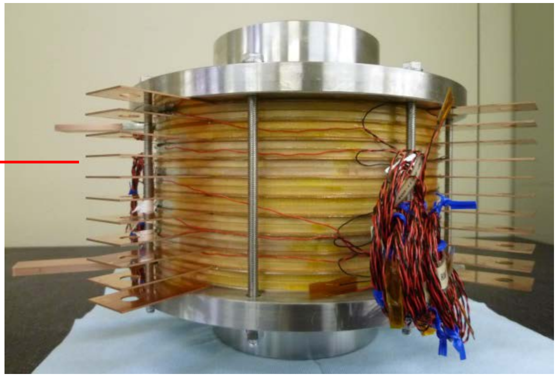
Normalized at 50 A

Ultra Cold Neutron polarizer

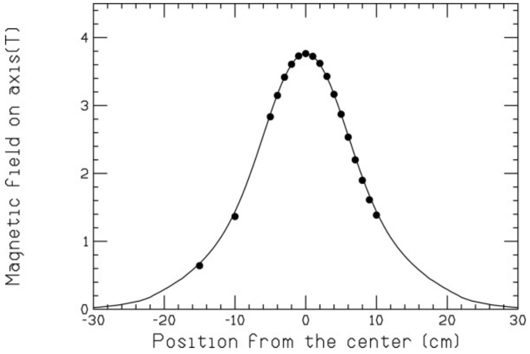
Coil	Inner diameter	131.5 mm
	Outer diameter	213 mm
	Length	105 mm
	Number of DP	10
	Number of turns	2800
	Total length of wire	1530 m
	Inductance	1 H
	Weight	30 kg
Magnet	Operating Temperature	20 K
	Rated current	200 A
	Field at the center	3.5 T
Cryostat	Cooling power	35 W at 45 K 0.9 W at 4 K
	Temperature of the shield	60 K

3.5 T is required to polarize 210 neV UCN

12 K



Coil on the bobbin



Magnetic field on the axis

Structure in the thermal shield

Ultra Cold Neutron polarizer

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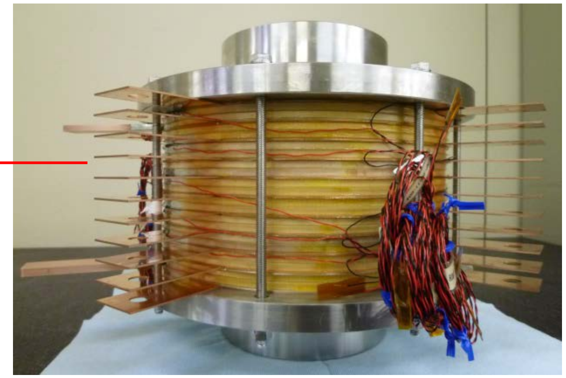
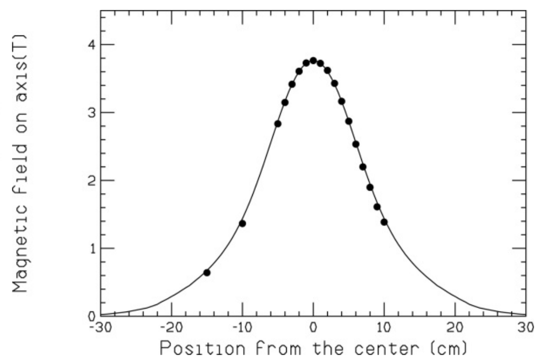


Coil on the bobbin

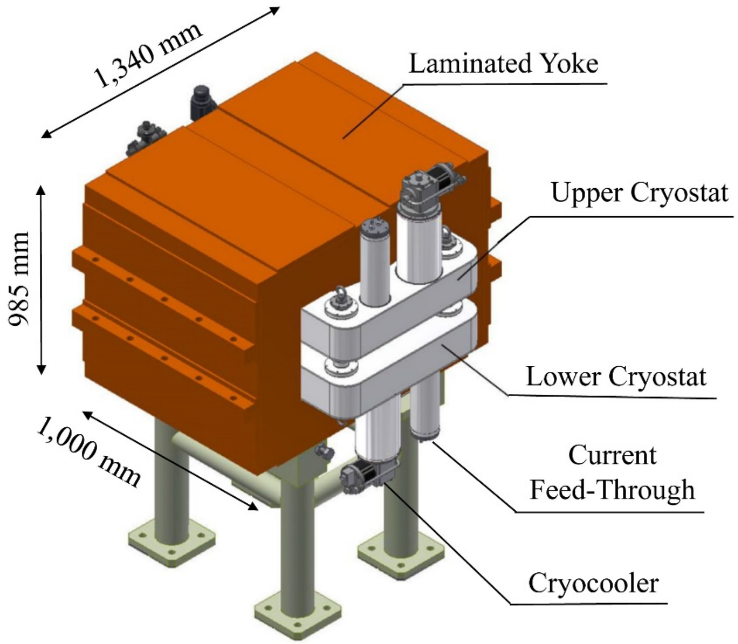


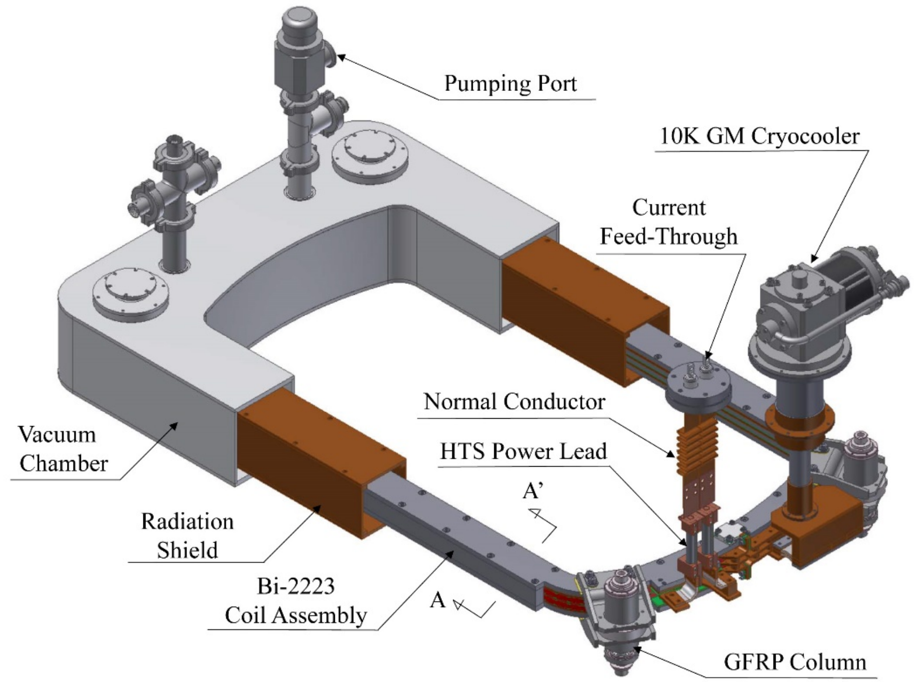
Magnetic field on the axis

Structure in the thermal shield

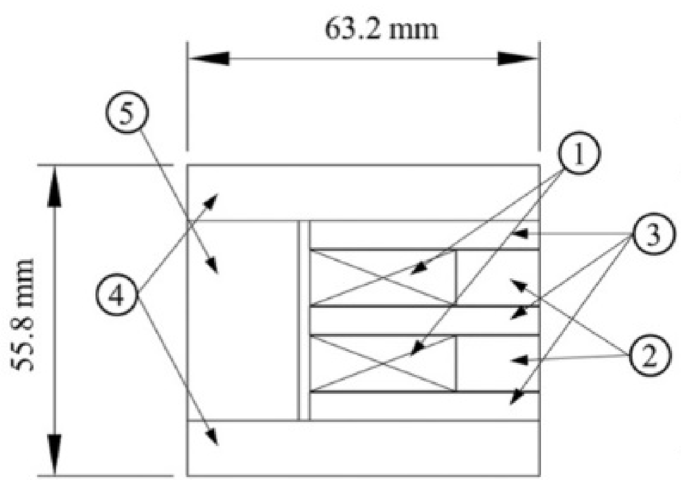
UCN was successfully polarized.
Polarization is higher than 90 %.
Polarizer has been transported to TRIUMF already,
and is used for neutron EDM project at TRIUMF.

Dipole magnet for beamline switching





A-A' Cross Section



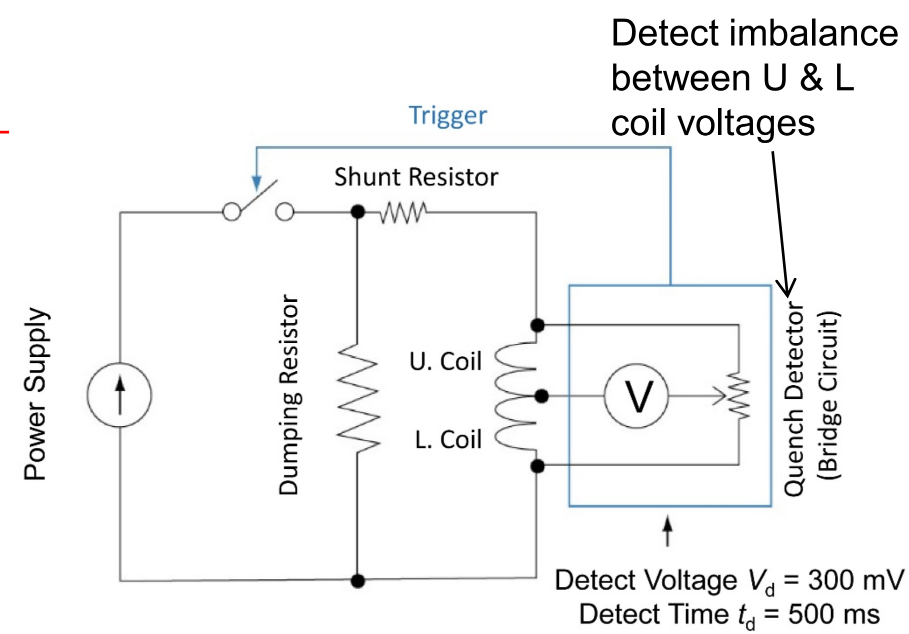
No.	Description	Material
1	Bi-2223 DPC	
2	Winding Frame	Stainless Steel
3	Cooling Plate	Copper
4	Reinforcing Plate	Stainless Steel
5	Reinforcing Bar	Stainless Steel

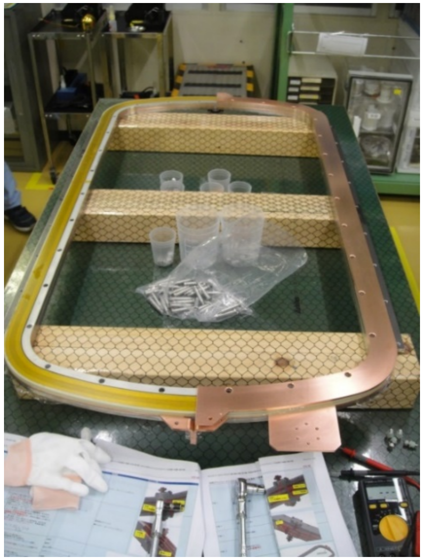
Specifications of the SW magnet

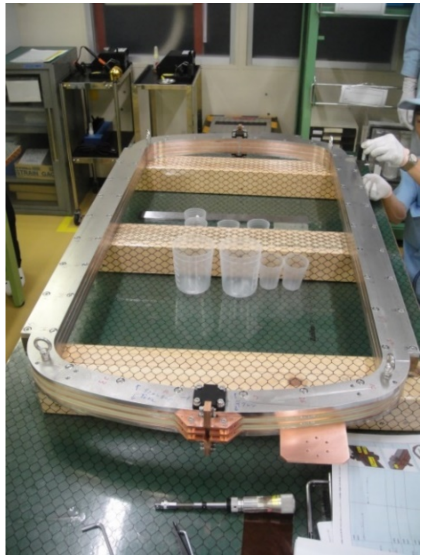
Maximum magnetic field	1.6 T
Fastest switching time	10 s
Bi-2223 wire	DI-BSCCO type HT-CA (Sumitomo Electric Industries, Ltd.)
Number of total turns	512 turns
2-stage 10 K GM cryo-cooler	SRDK-408S2 (Sumitomo Heavy Industries, Ltd.)
Cooling	Conduction cooling
Cooling power	1st stage: 40 W at 45 K (Radiation 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
Maximum operating current	200 A
Maximum ramping speed	20 A/s
Stored energy	45.5 kJ

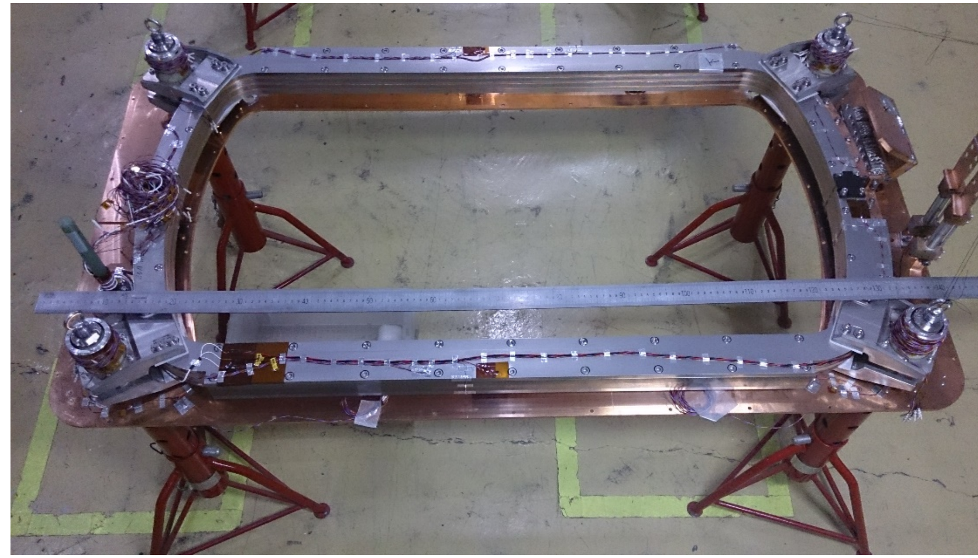
Quench detect and protect circuit

Loss in the wire 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.

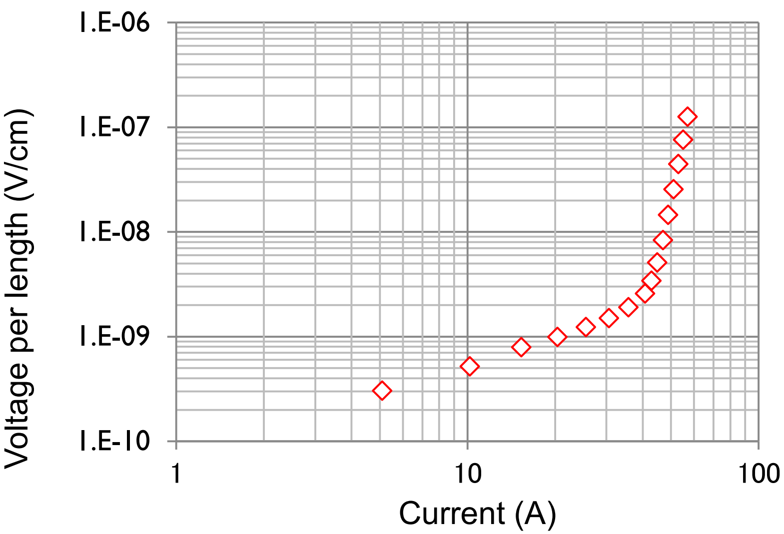




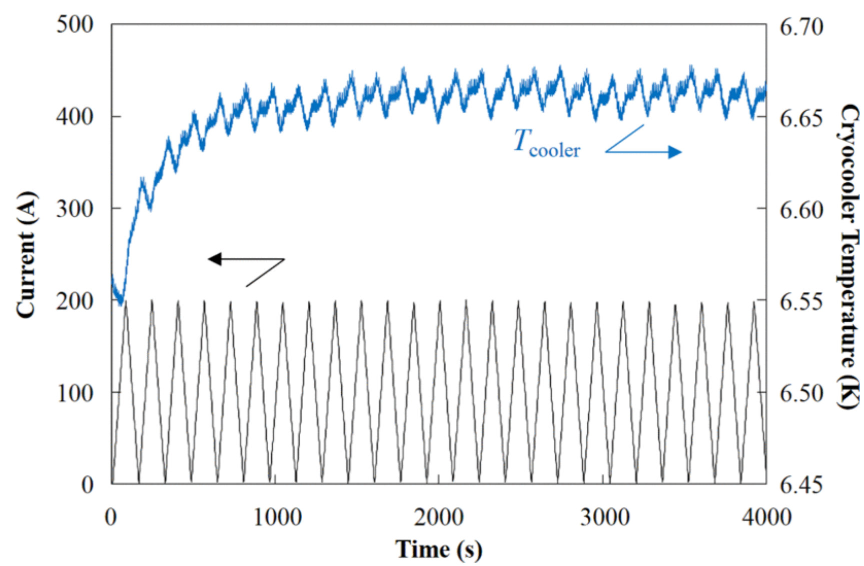




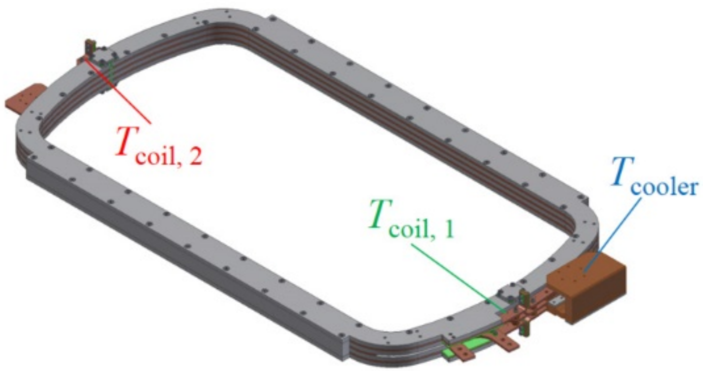
I_c measurement at 77 K

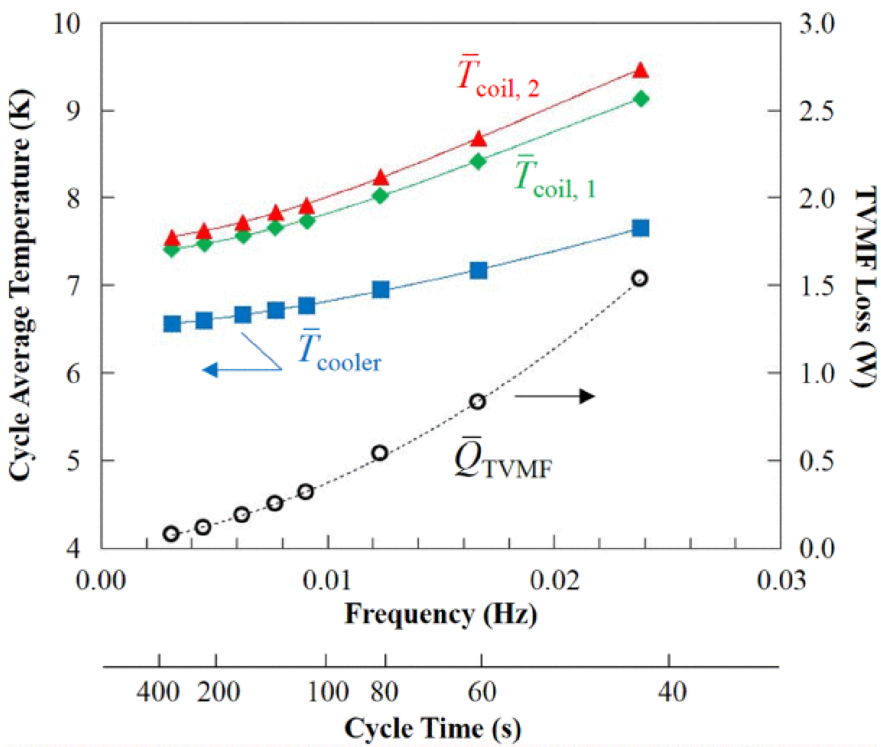


Cryo-cooler temperature measured during triangular wave excitation with a cycle time of 160 s.

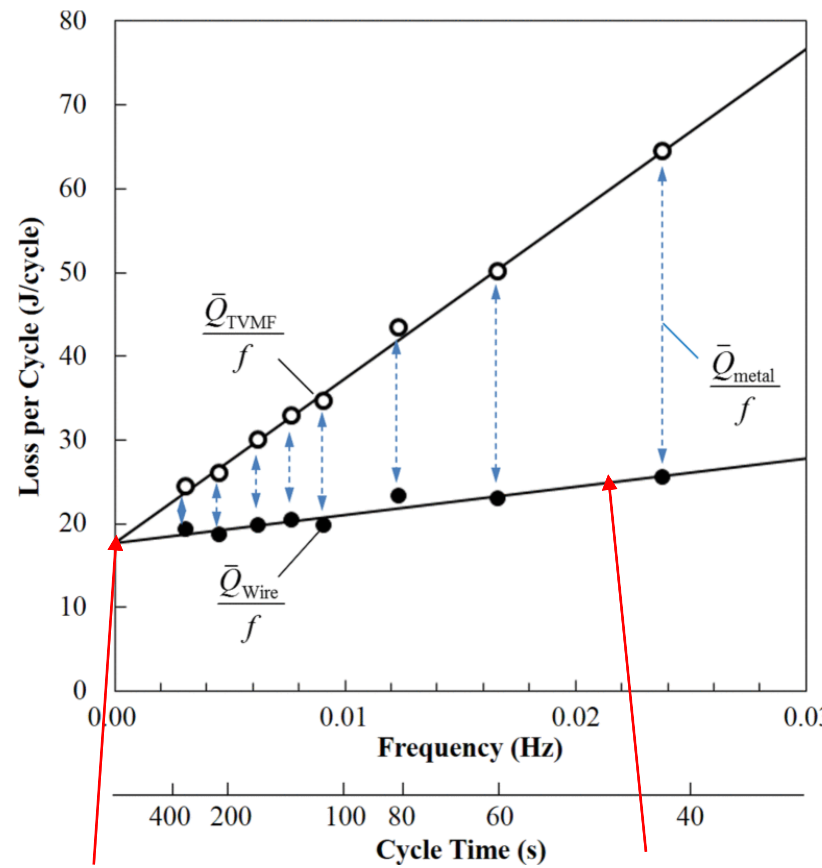


Time-varying magnetic field losses





Triangular wave excitation between 0 A and 200 A



Hysteresis loss
= 17.7 (Joule/cycle)

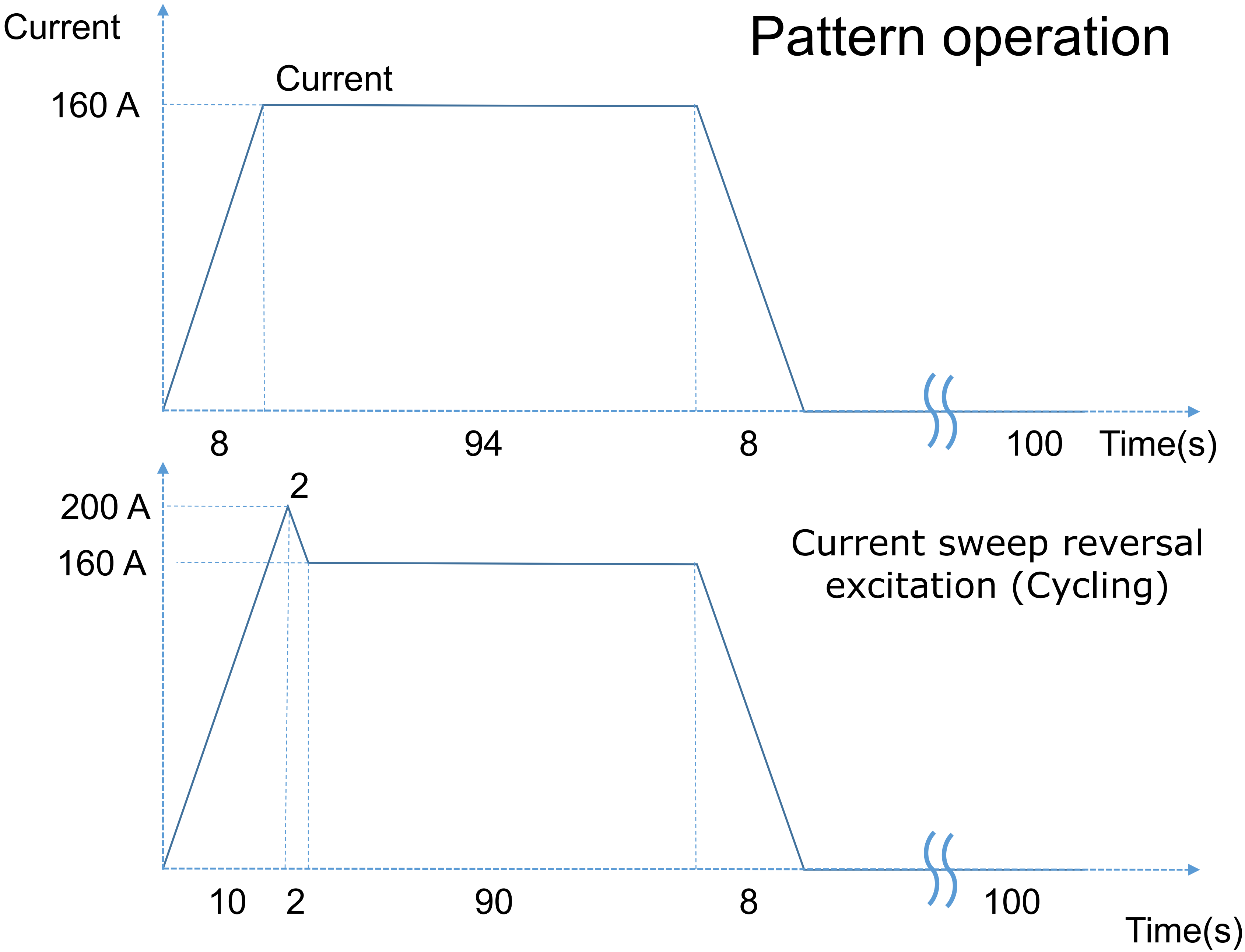
f dependent:
Coupling loss

$$Q_{wire} = Q_{TVMF} - Q_{metal} = Q_{TVMF} - \frac{0.163}{0.01^2} f^2$$

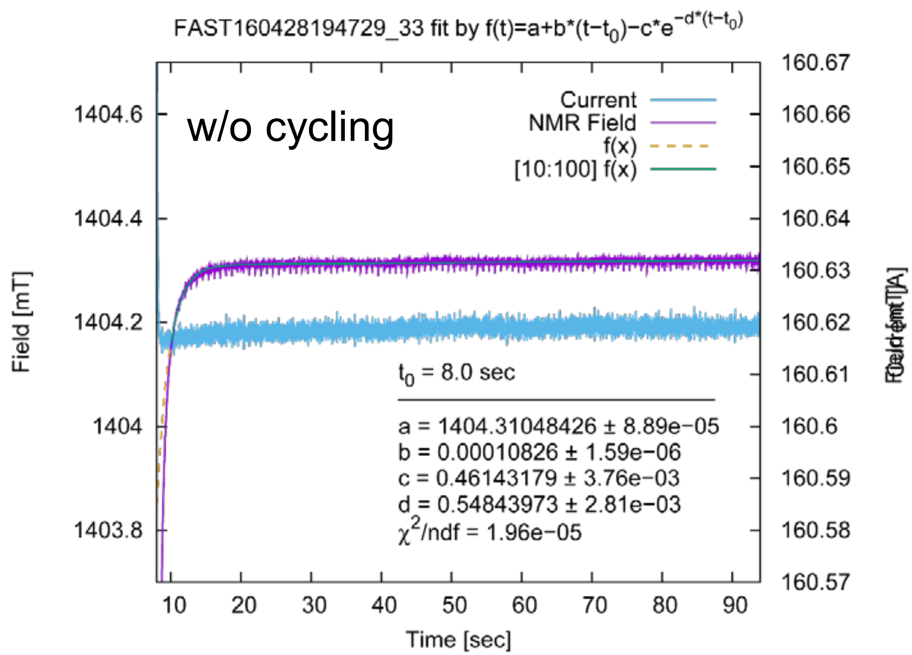
Eddy current loss of
metallic components
estimated by JMAG code

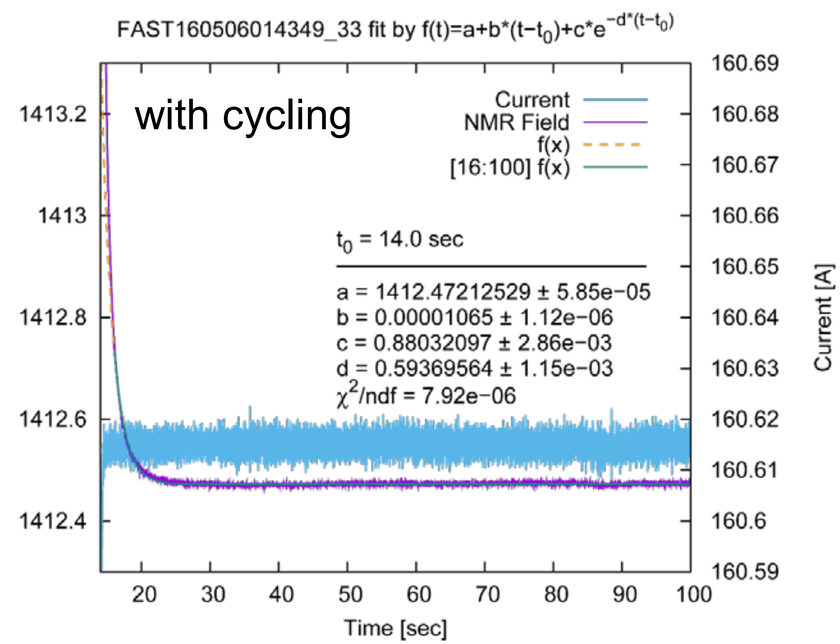
J.Yoshida et al., IEEE, vol. 27 No. 4 (2017)

Pattern operation



Current sweep reversal excitation (Cycling)



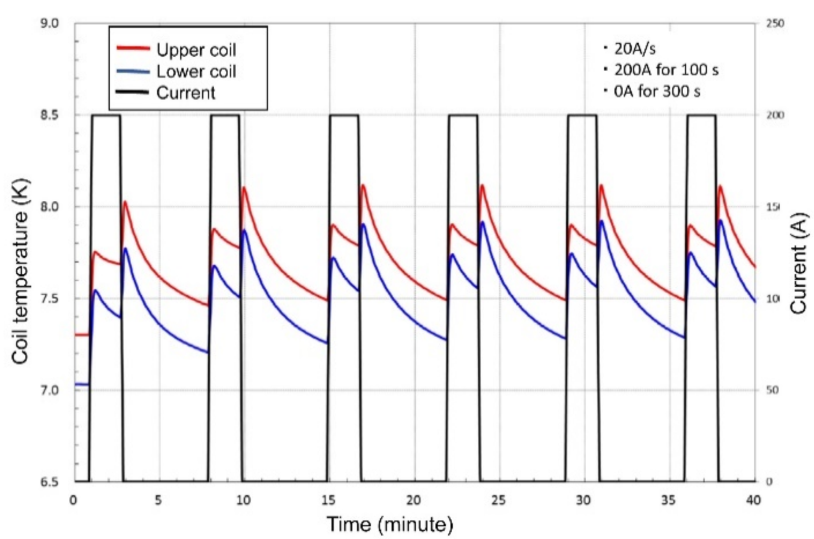


Field drift

$$b = 1.08 \times 10^{-4}\ (\mathrm{mT/s})$$

Field drift

$$b = 1.07 \times 10^{-5}\ (\mathrm{mT/s})$$



Coil temperature during a pattern operation of the switching magnet

Summary and perspectives

Development of HTS magnets at RCNP

- for compact and low power consumption system
  (e.g. next generation particle therapy facilities)
- As prototypes, toy-model, a scanning and a dipole magnets were fabricated.
- For practical use, a UCN polarizer and a switching magnet were constructed.
- Performance tests were performed with DC, AC and pulsed currents.
- AC losses were measured by electrical or calorimetric method.
- Hysteresis losses of wire are several tens Joule/cycle.
- Hysteresis loss is expected to be smaller for 2nd generation (Y-123/REBCO) wire.
- Feasibility study of HTS cyclotrons is continued and conceptual design has been started at RCNP.

Collaborators

RCNP: M. Fukuda, T. Yorita, H. Ueda, J. Nakagawa,
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Thank you for your attention