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Multi-pole components of magnetic field in small dipole magnets wound with coated conductors

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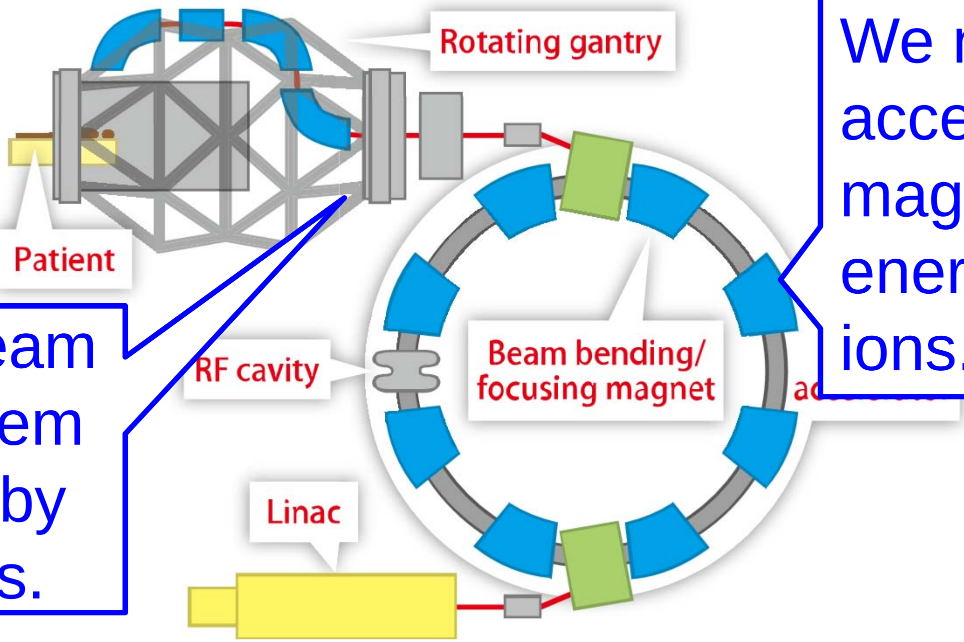
Outline

- Overview of an R&D project for fundamental technologies for accelerator magnets using coated conductors
- Influence of tape magnetization of multi-pole components of magnetic field (field harmonics)
  - Liquid N_2 cooled magnet
  - Cryo-cooler cooled magnet
  - A simulation of practical scale magnet

Overview of the project

Expected future application of accelerators using HTS magnets

Accelerator system for carbon cancer therapy



We need a beam transport system to the patient by using magnets.

We need a circular accelerator using magnets to energize carbon ions.

What do we expect to HTS?

- Size reduction: 20 m to 10 m Dia., for example.
- Less power consumption (several million USD per year)
- While keeping better reliability and easier operation as compared to LTS.

Overview of the project

Name of project	Challenge to functional, efficient, and compact accelerator system using high T_c superconductors
Objective	•R&D of fundamental technologies for accelerator magnets using coated conductors •Constructing and testing prototype magnet
Future applications	•Carbon caner therapy •Accelerator-driven subcritical reactor
Participating institutions	Kyoto University (PM: Amemiya), Toshiba, KEK, NIRS, JAEA
Period	Stage I: 01/2010 – 03/2012 Stage II: 04/2012 – 03/2016 Stage III: 04/2016 – 03/2019
Funding program	Strategic Promotion of Innovative Research and Development Program by JST

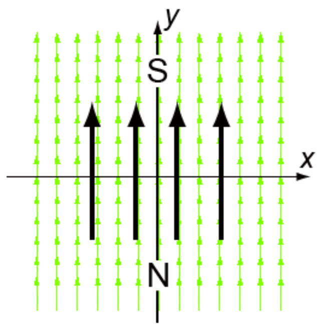
Influence of tape magnetization of multi-pole components of magnetic field (field harmonics)

Tape magnetization

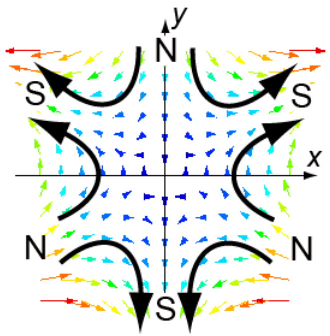
One of the concerns in the applications of coated conductors to accelerator magnets is ***large magnetization caused by its tape shape***, because it could deteriorate the field quality of magnets (required error < 10^{-3} – 10^{-4}).

Objective:

To clarify the influence of tape magnetization on magnetic field harmonics in a small dipole magnets



Dipole

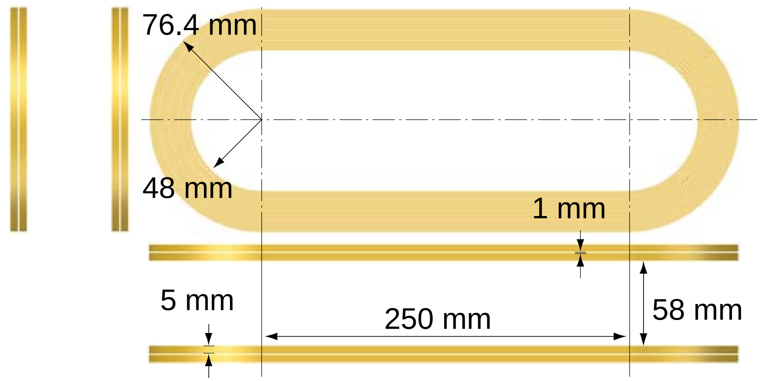


Sextupole

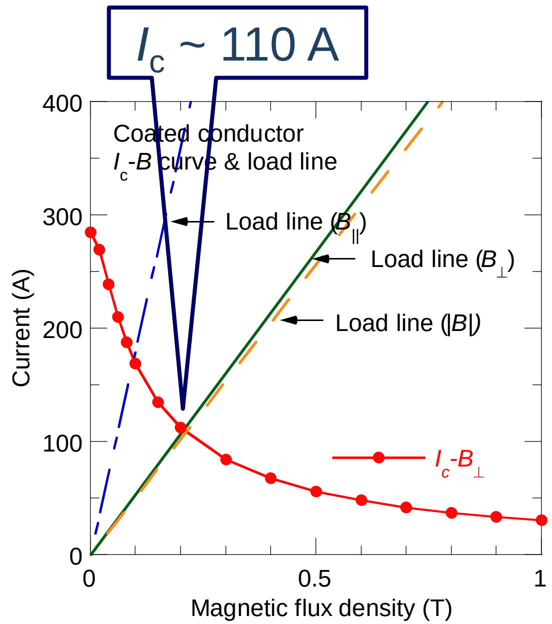
Liquid N_2 cooled magnet

Dipole magnet RTC4-F comprising race-track coils

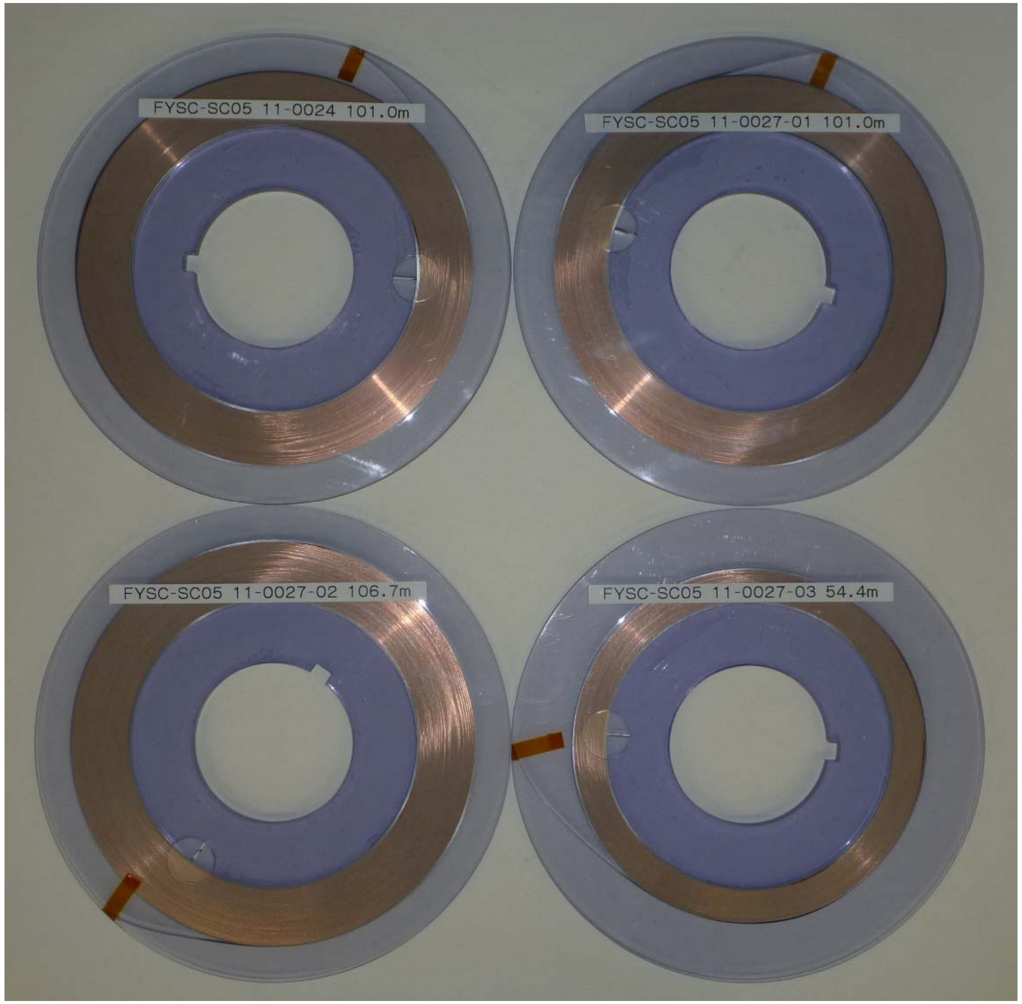
Coated conductor	Fujikura (FYSC-SC05)
Superconductor	GdBCO
Width × thickness	5 mm × 0.2 mm
Stabilizer	0.1 mm – thick copper
Critical current	270 A – 298 A



Shape of coils	Single pancake race-track
Number of coils	4
Length of straight section	250 mm
Inner radius at coil end	48 mm
Outer radius at coil end	76.4 mm
Coil separation	58 mm
Number of turns	83 turn/coil
Length of conductor	74 m/coil

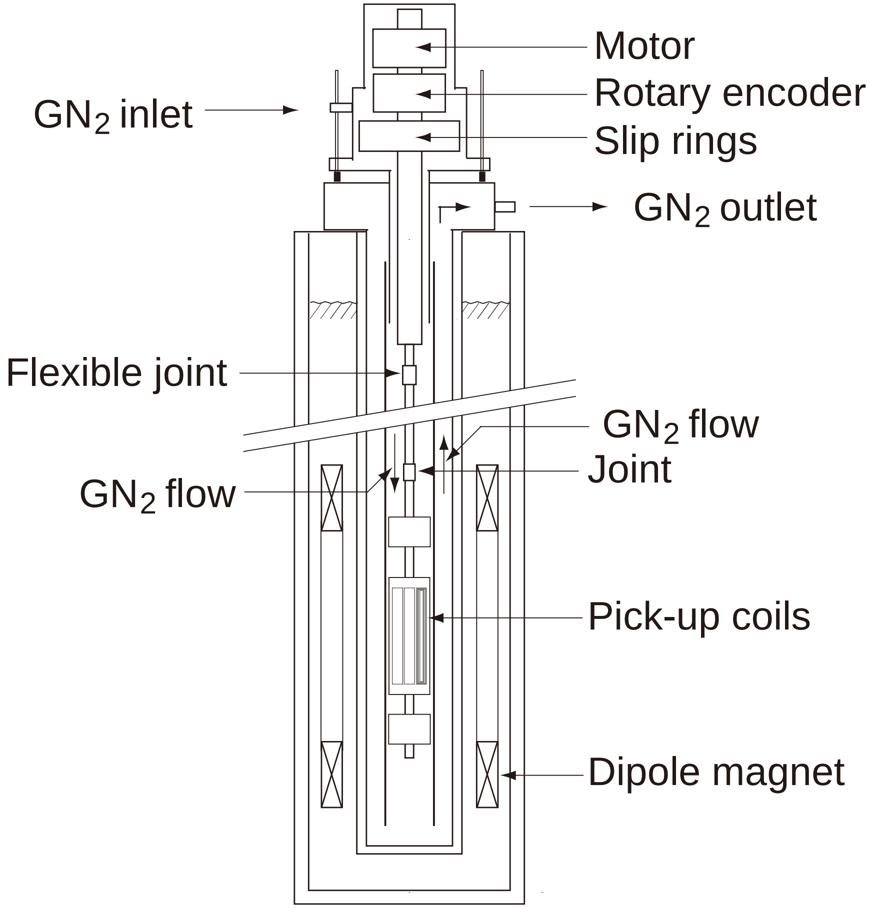


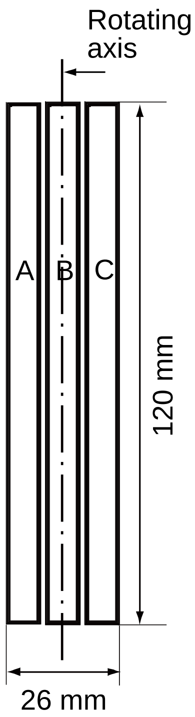
350 m coated conductor by Fujikura



Lot No.	Length	I_c
11-0024	101.0 m	298 A
11-0027-01	101.0 m	292 A
11-0027-02	106.7 m	282 A
11-0027-03	54.4 m	270 A

Experimental set-up





- A and B are connected in series so as to cancel the dipole (pick-up coil S).
- C is used independently to detect all harmonics (pick-up coil R).

All experiments were done in LN_2.

□ Normalization

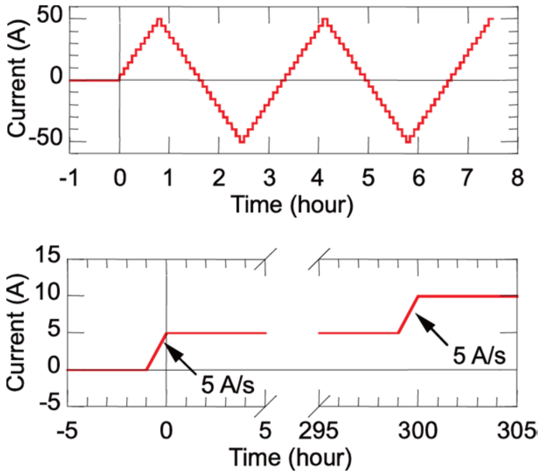
$$\text{Multi-pole coefficient} = \frac{B_n}{B_{1,\mathrm{u}}(I_{\mathrm{meas}})}$$

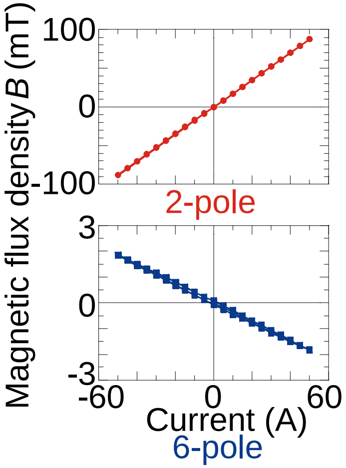
□ Field error caused by error in dimension etc.

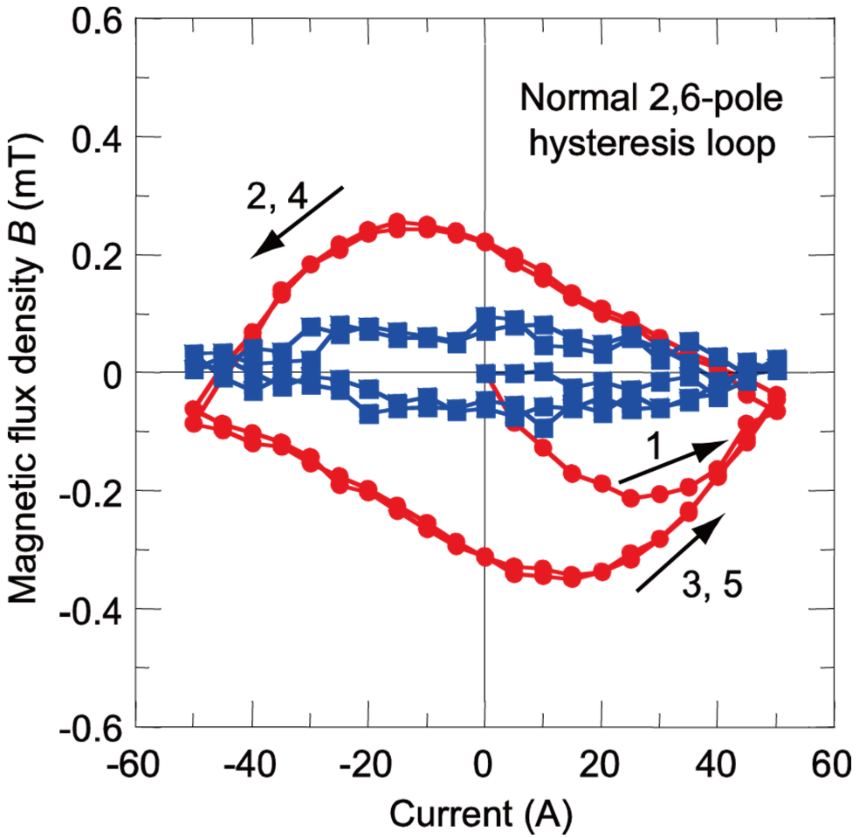
Multi-pole	2 A @RT	Measured	Sd.	Designed
2	3.444 mT	9785×10^{-4}	4.4×10^{-4}	10000×10^{-4}
4	-0.014 mT	40.9×10^{-4}	30.1×10^{-4}	–
6	-0.081 mT	-228.7×10^{-4}	14.4×10^{-4}	-7.0×10^{-4}
8	-0.037 mT	55.5×10^{-4}	72.6×10^{-4}	–
10	-0.387 mT	-1106×10^{-4}	93.3×10^{-4}	-157.9×10^{-4}

Objective: clarifying the influence of tape magnetization rather than the winding accuracy

Hysteresis loop measurements



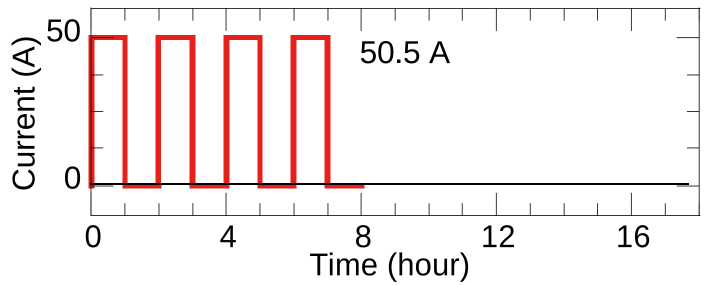




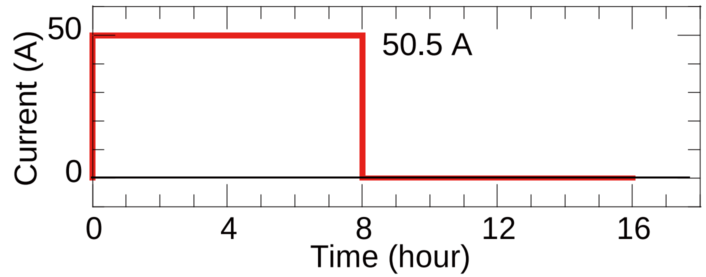
pole	Magnetic flux density at 50 A	Residual magnetic flux density
2	87.788 mT	0.266 mT
4	-0.166 mT	0.003 mT
6	-1.834 mT	0.068 mT
8	0.346 mT	0.017 mT
10	-8.848 mT	0.116 mT

Patterns of excitations

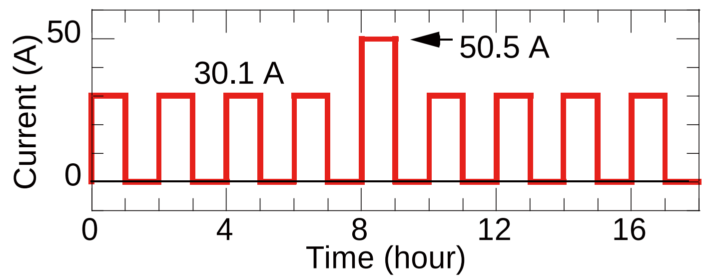
Repeated (50 A, 1 h) – excitations



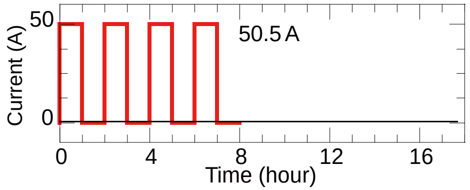
(50 A, 8 h) – excitations

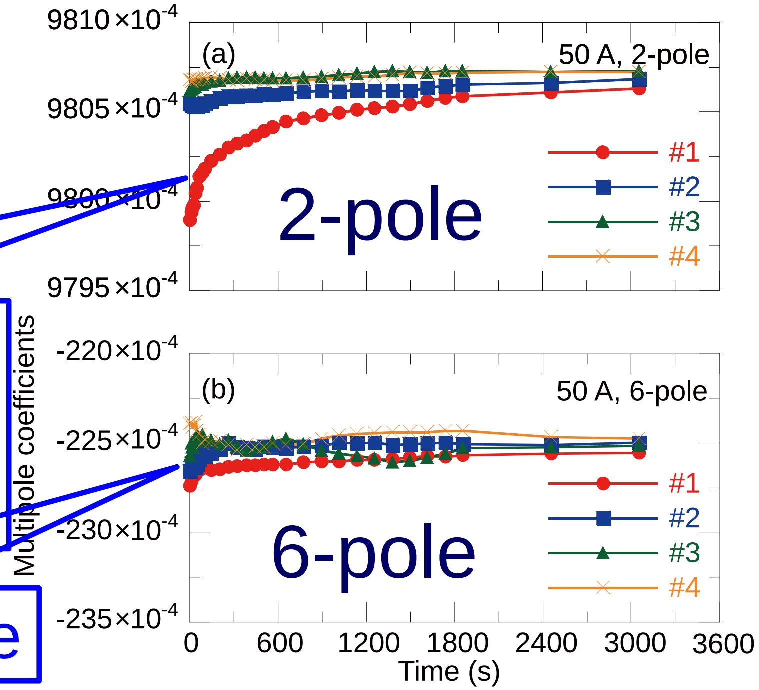


Repeated (30 A, 1 h) – excitations
with a (50 A, 1h) – excitation



Repeated (50 A, 1 h) – excitations

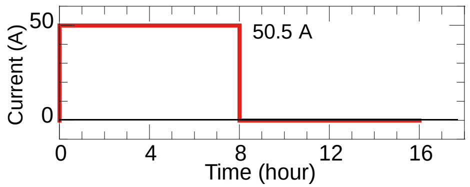


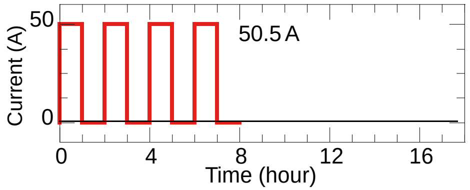


Larger drift in the 1st excitation; stable and reproducible in the 2nd, 3rd, and 4th excitations

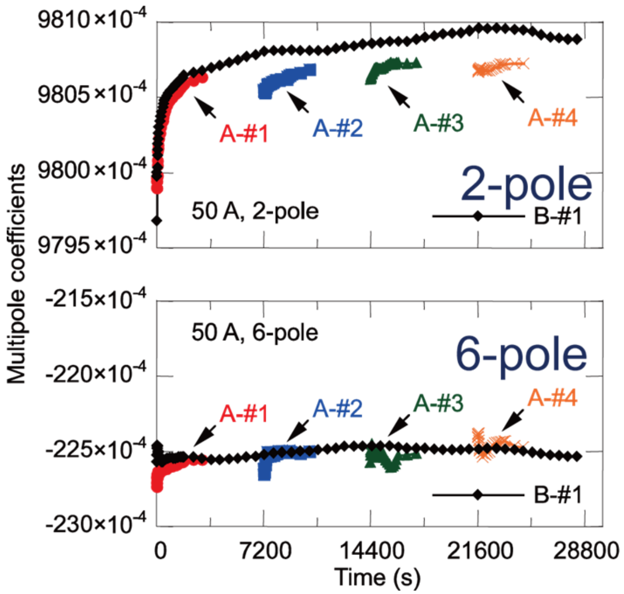
Smaller drift in sextupole

(50 A, 8 h) – excitations

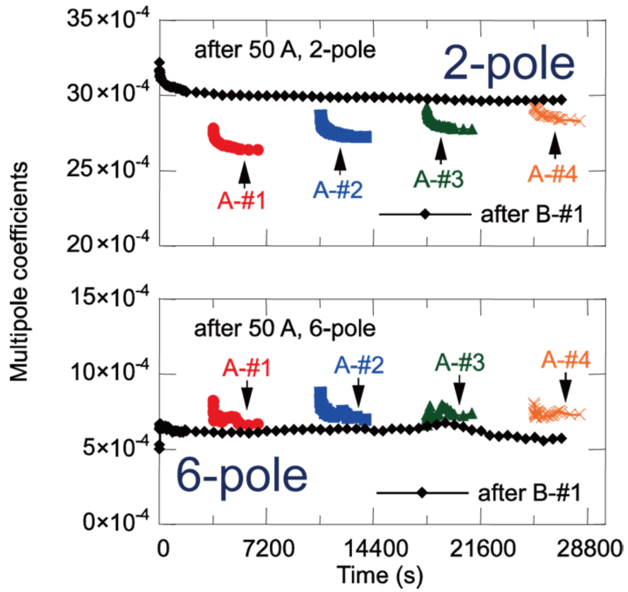




	2-pole	6-pole
Drift in 8 hours	4.8×10^{-4}	1.3×10^{-4}

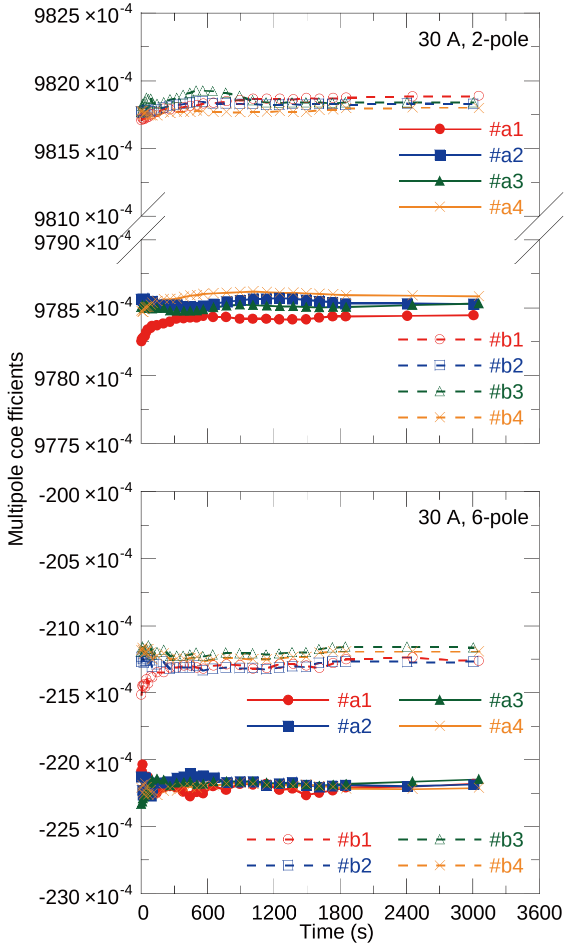


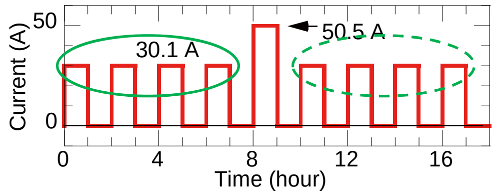
Excited

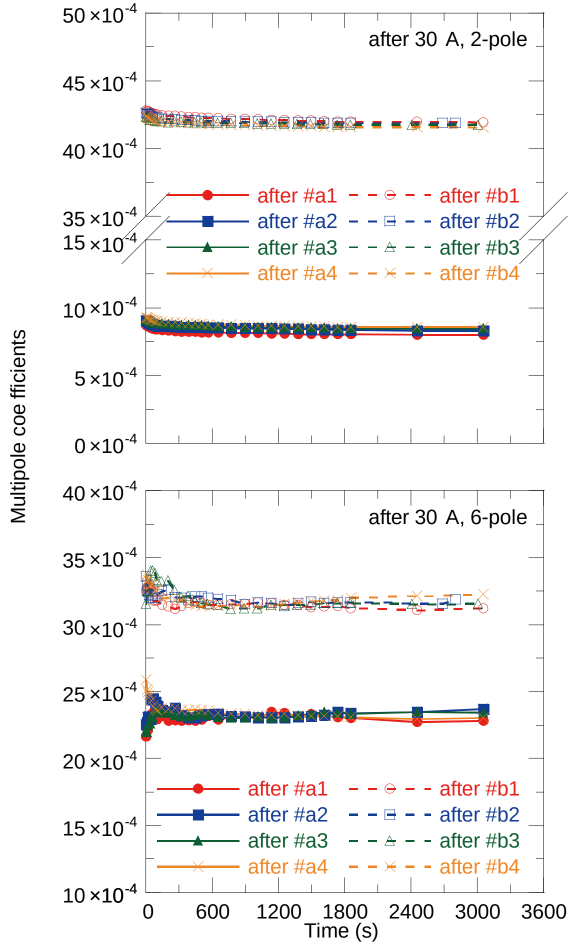


Shut down (residual field)

Influence of 50 A – excitation between 30 A - excitations





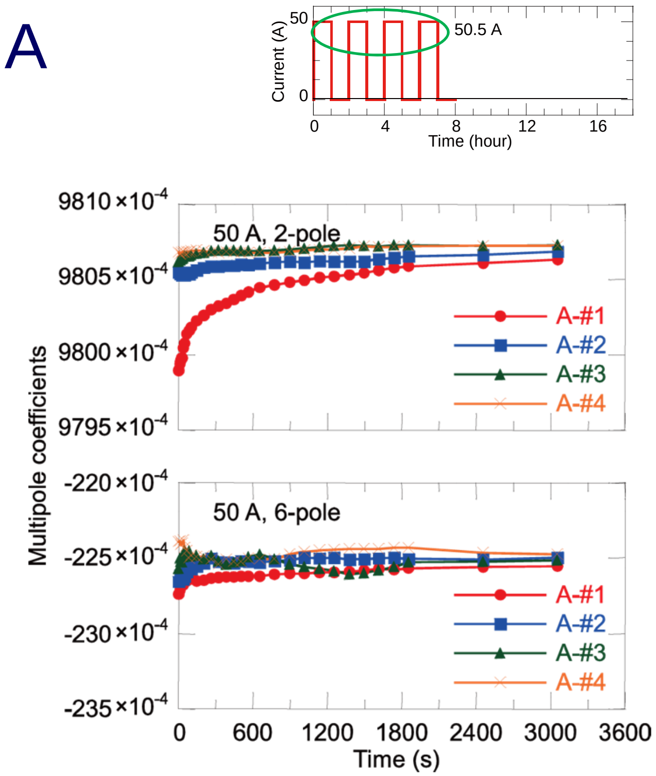


Excited

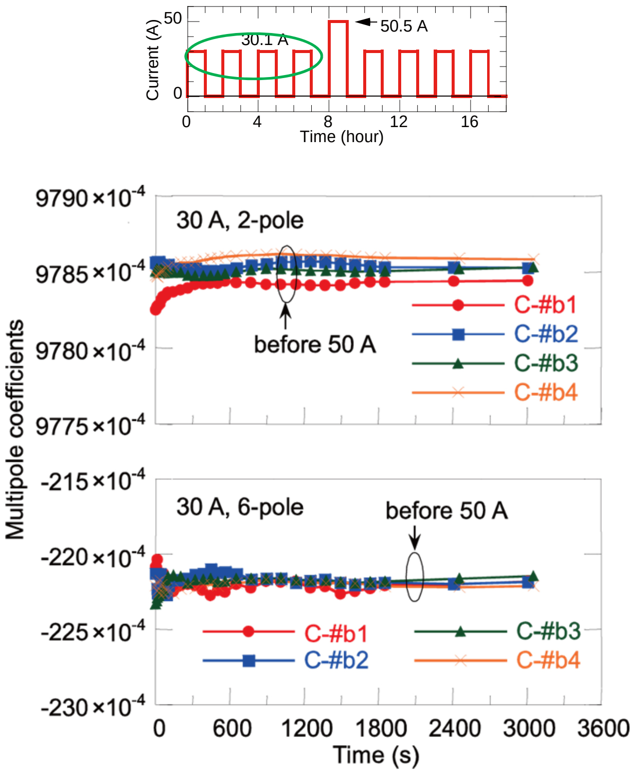
Shut down

Influence of current

50 A



30 A



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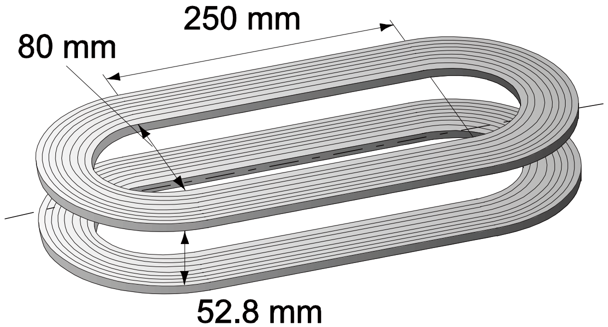
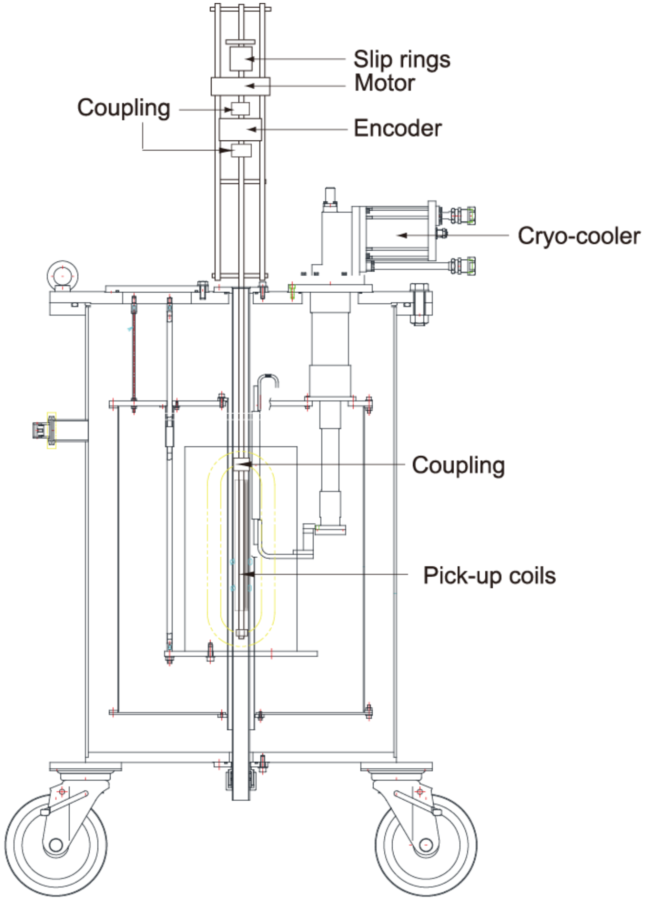
Cryo-cooler cooled magnet

Experimental setup



Shape of coil	Single-pancake racetrack
Number of coils	2
Coil separation	52.8 mm
Length of straight section	250 mm
Inner radius of coil end	40.0 mm
Outer radius of coil end	66.0 mm
Number of turns	77.5 turn/coil
Length of tape	63 m/coil



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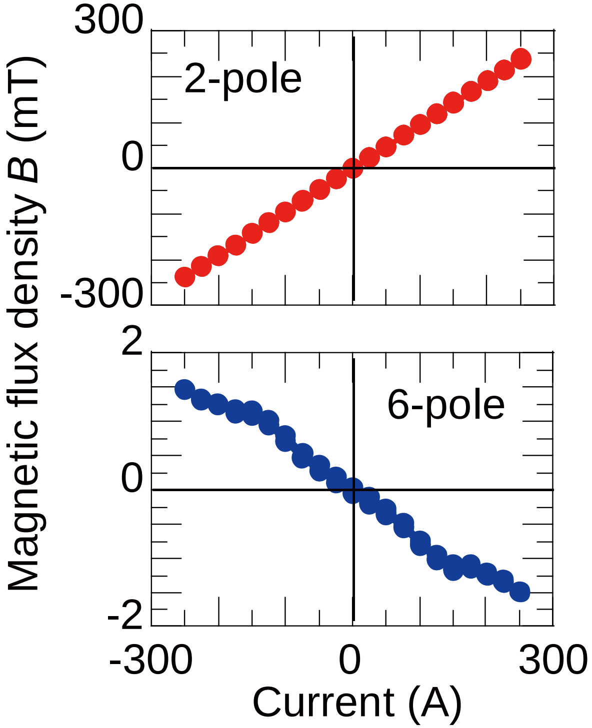
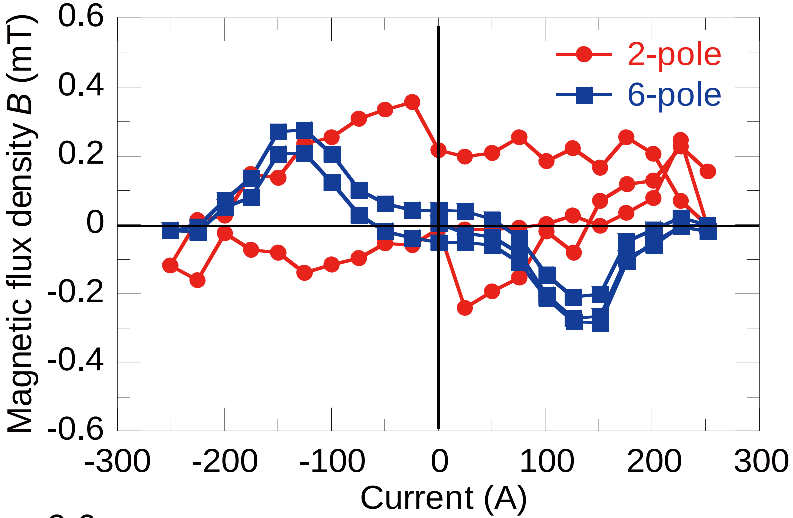
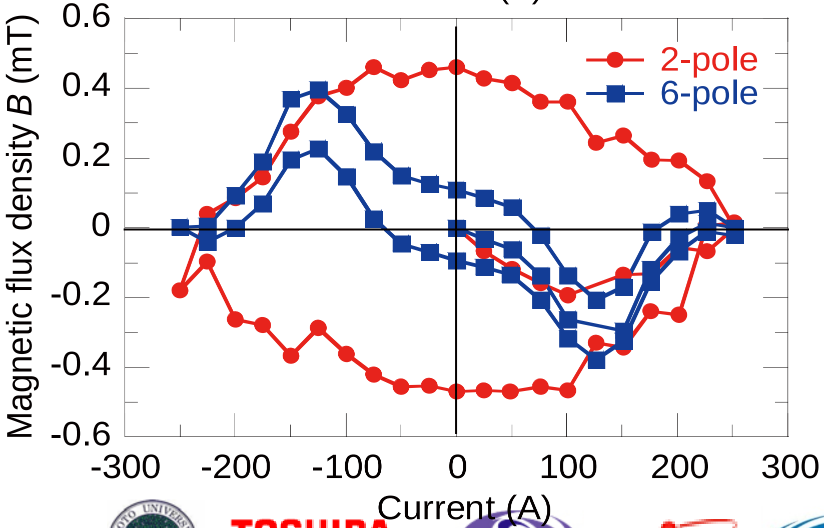
Hysteresis loop of dipole and sextupole components



10 K



30 K



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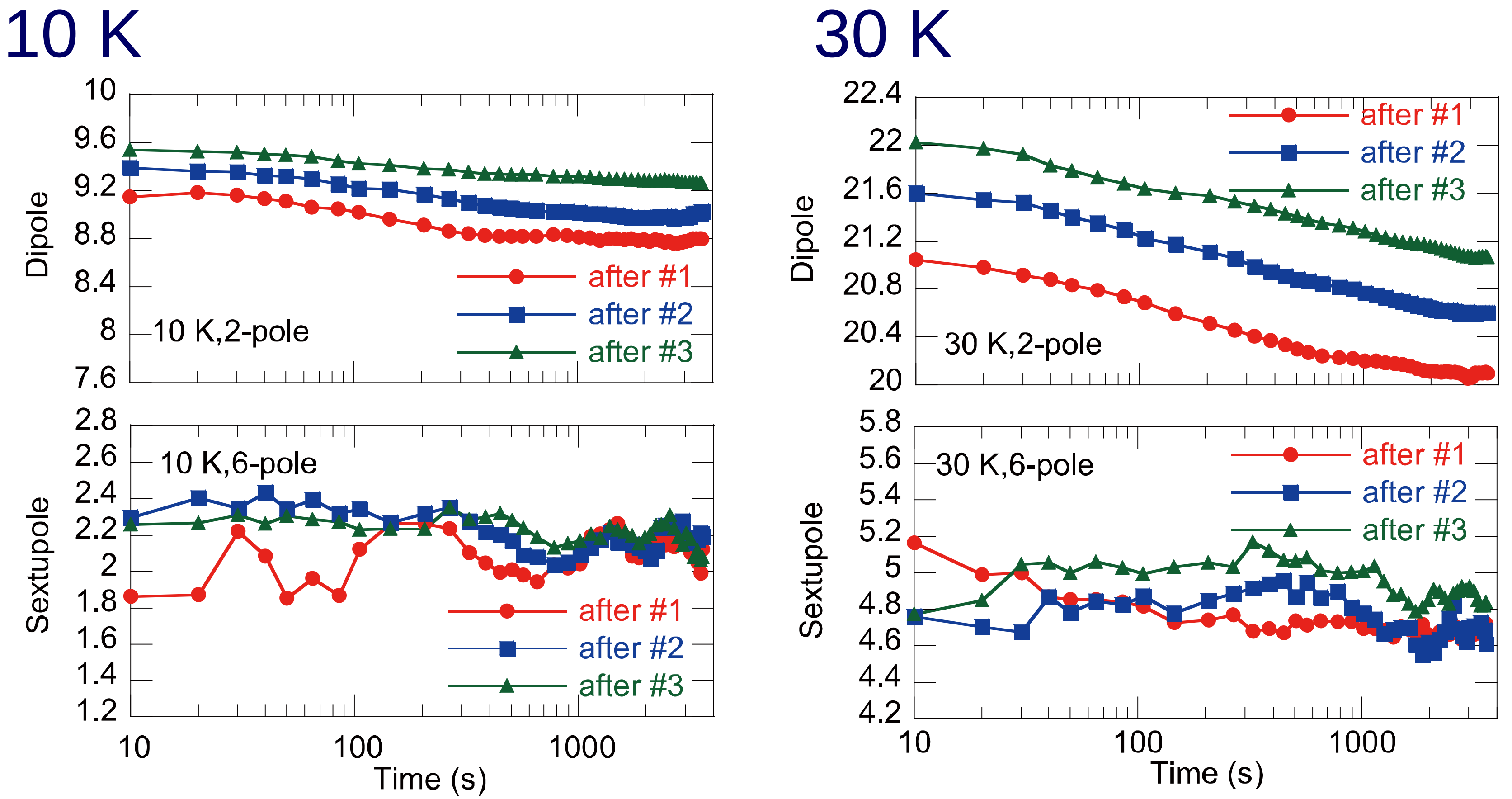
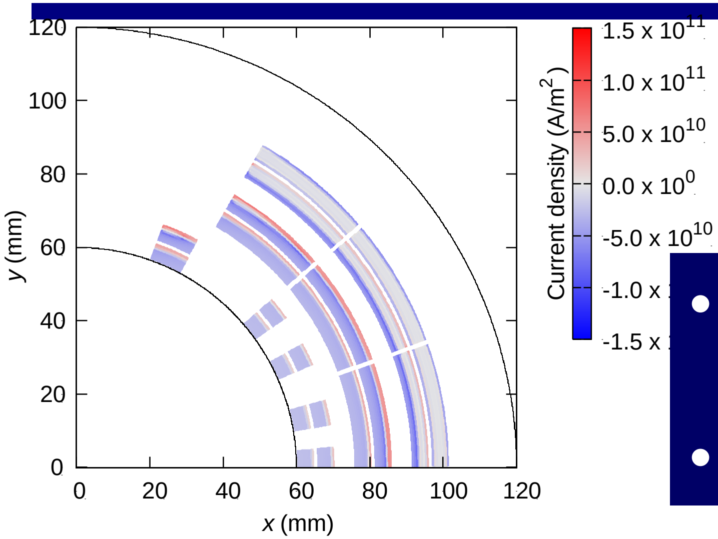
Drifts of residual magnetic fields



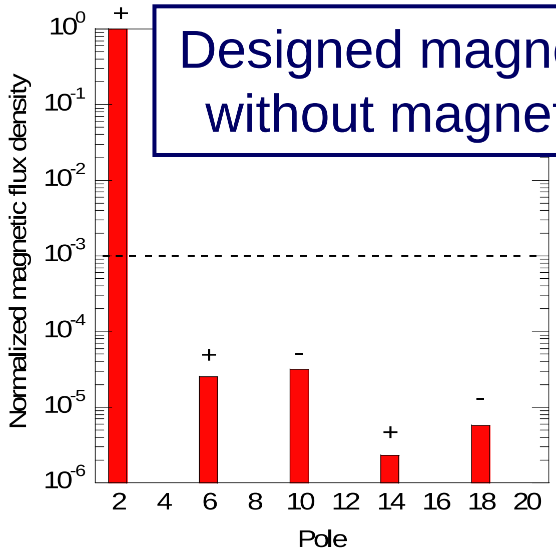
A simulation of practical scale magnet

What will happen in real magnets?

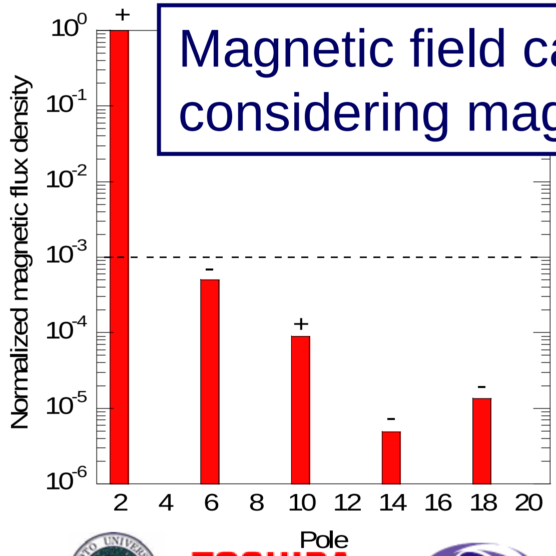


A 3 T large bore cosine-theta magnet for beam line of carbon cancer therapy

- Even when considering magnetization, higher harmonics coefficients < 10^{-3}
- Influence of magnetization < 10^{-3}



Designed magnetic field without magnetization



Magnetic field calculated considering magnetization

N. Amemiya, CHATS-AS 2013 (11/10/13)

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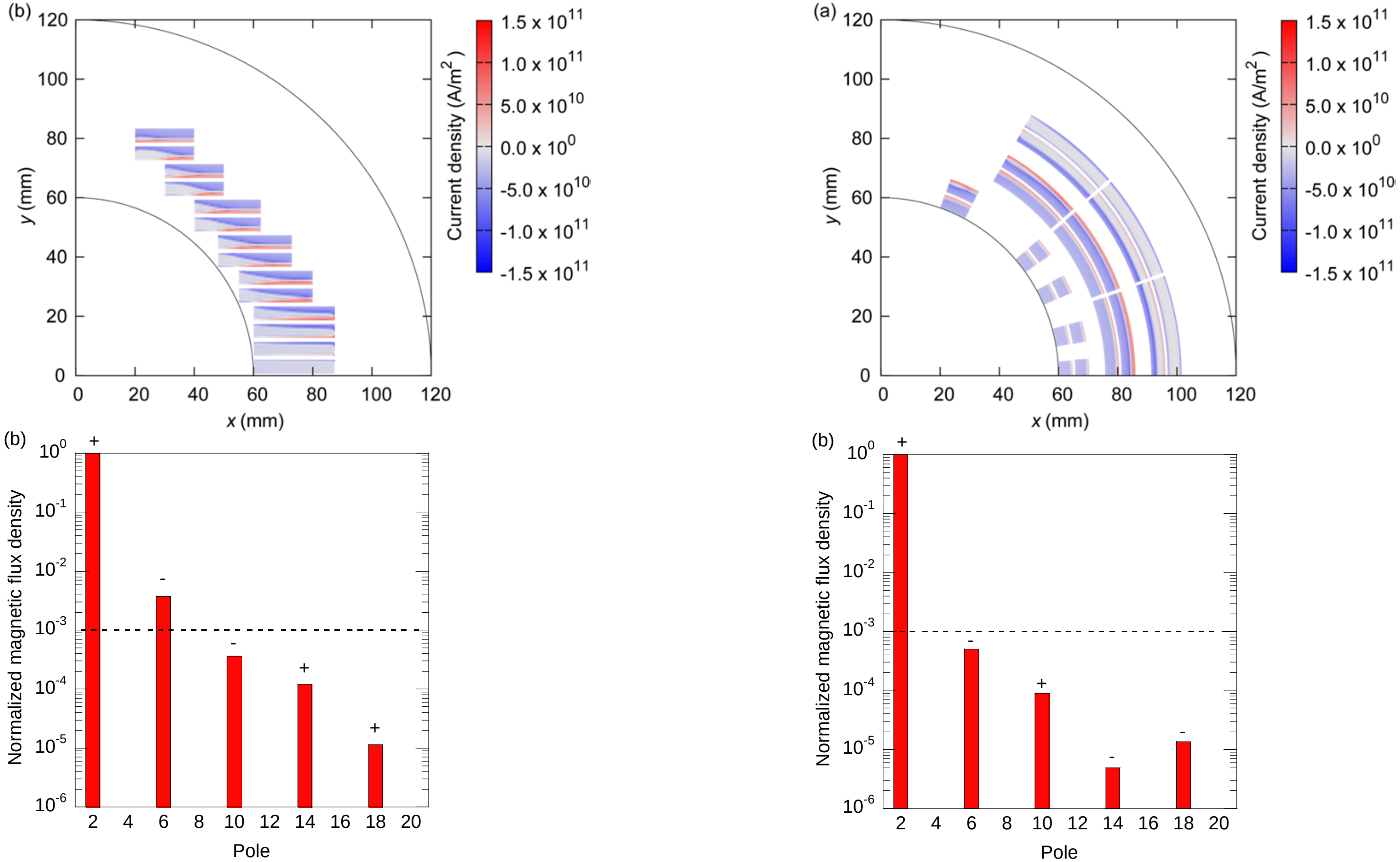
Influence of magnet configurations



Summary

- Multi-pole components of magnetic field were measured and calculated.
- Calculations qualitatively agree with experiments.
- Future plan includes
  - More detailed experiments with cryo-cooler cooled magnet
  - More detailed modelling