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High Temperature Superconductor Magnet for FFAG Accelerators

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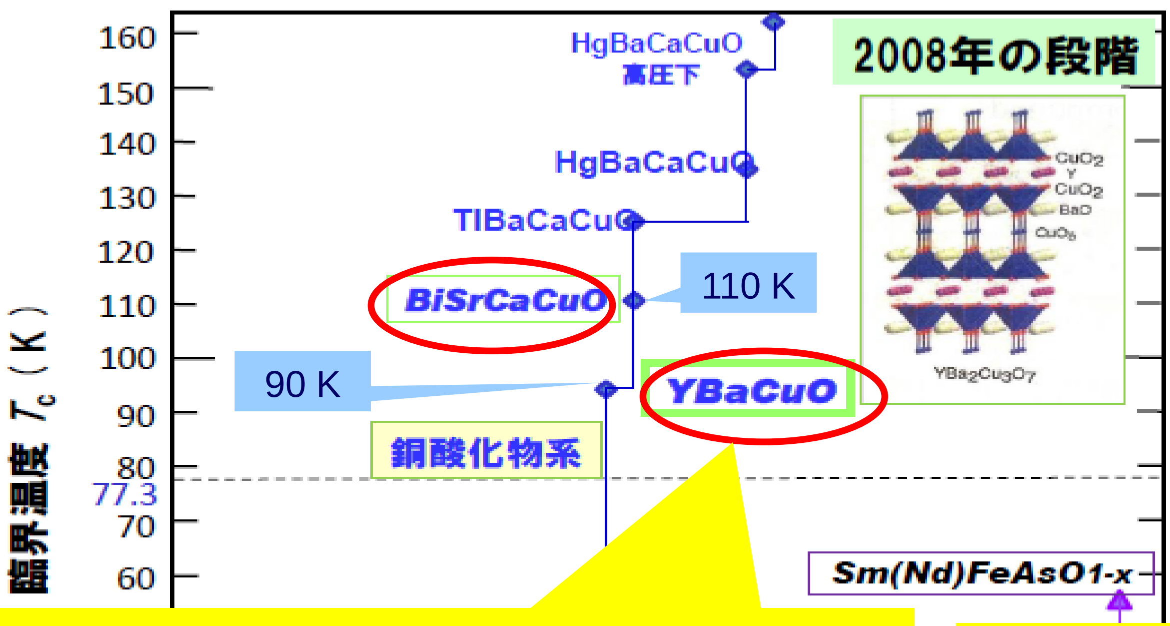
Outline

- Potentials of high temperature superconductors (HTS) for accelerator magnets
- Outline of R&D project for fundamental technology of HTS accelerator magnets
- Some topical results on the key issues in R&D

Potentials of HTS
for accelerator magnets

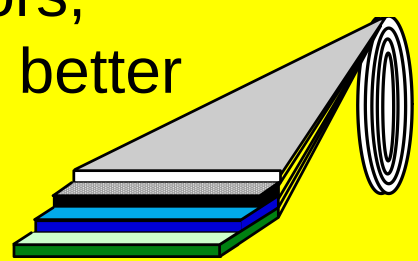
Historical evolution of critical temperature of superconductors



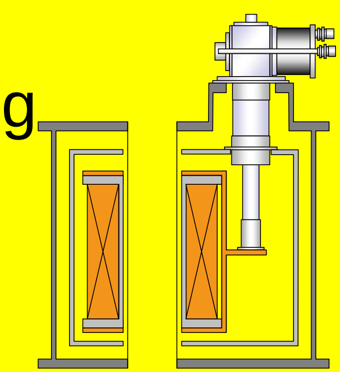
How to cool?

- Cryogen:
  - LHe: 4.2 K
  - LN_2: 77 K
- Cryocooler
  - ~ 4 K – 40 K

We focus on RE-123 coated conductors, because of their better performance in magnetic fields.



We focus on conduction cooling using cryo-cooler because of easy operation.



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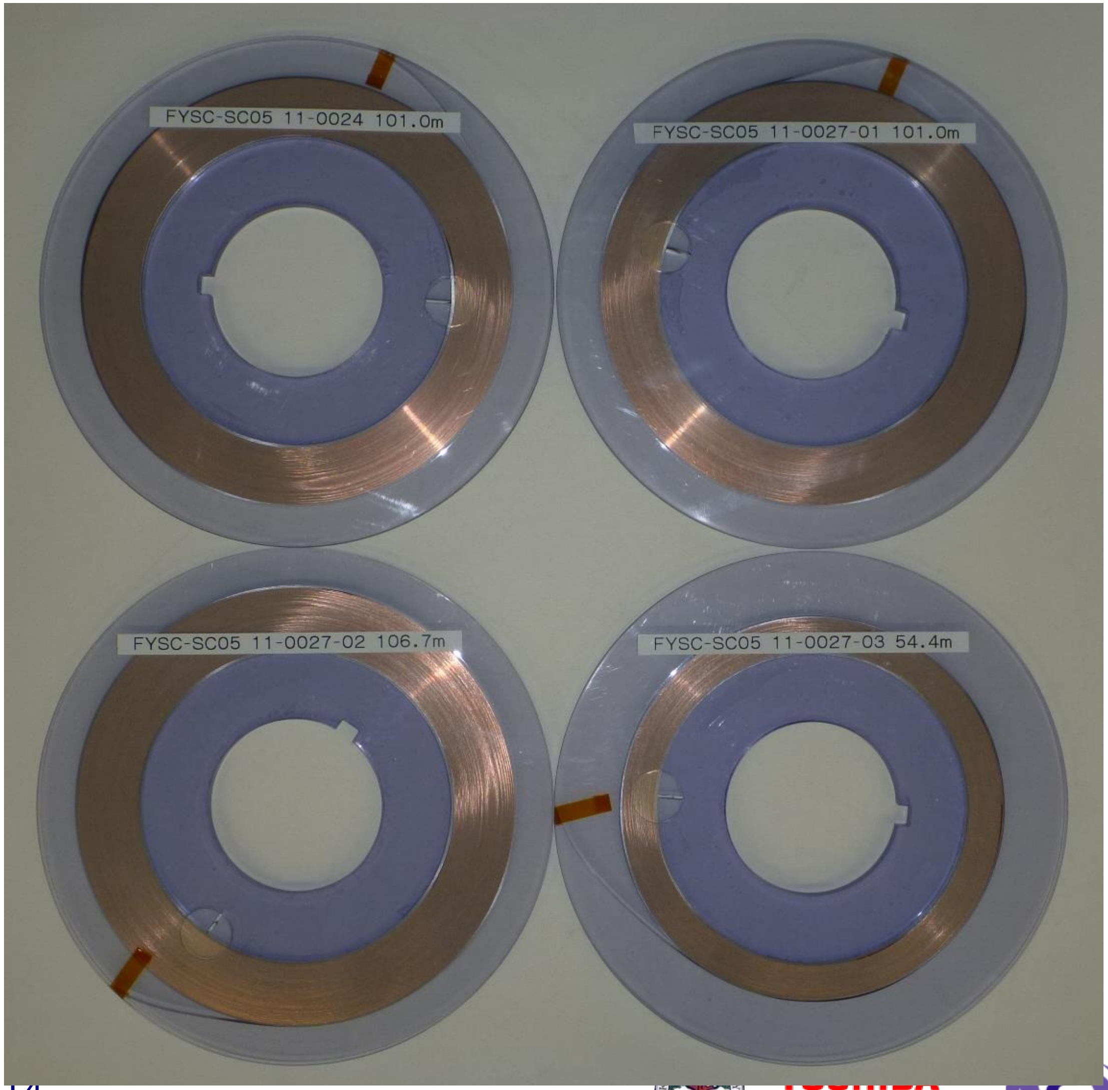
Coated conductors are commercially available now!



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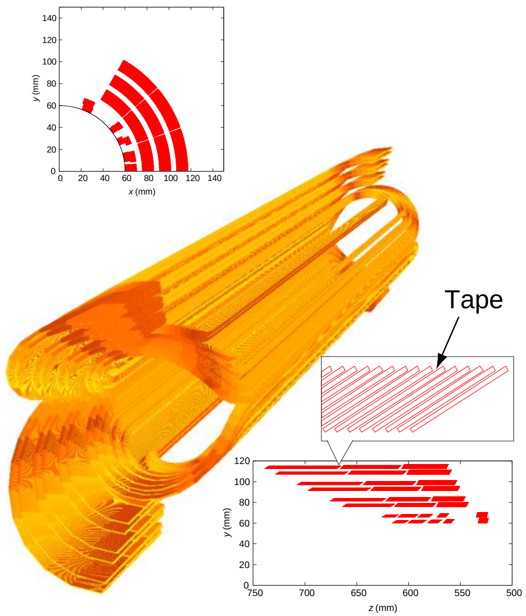
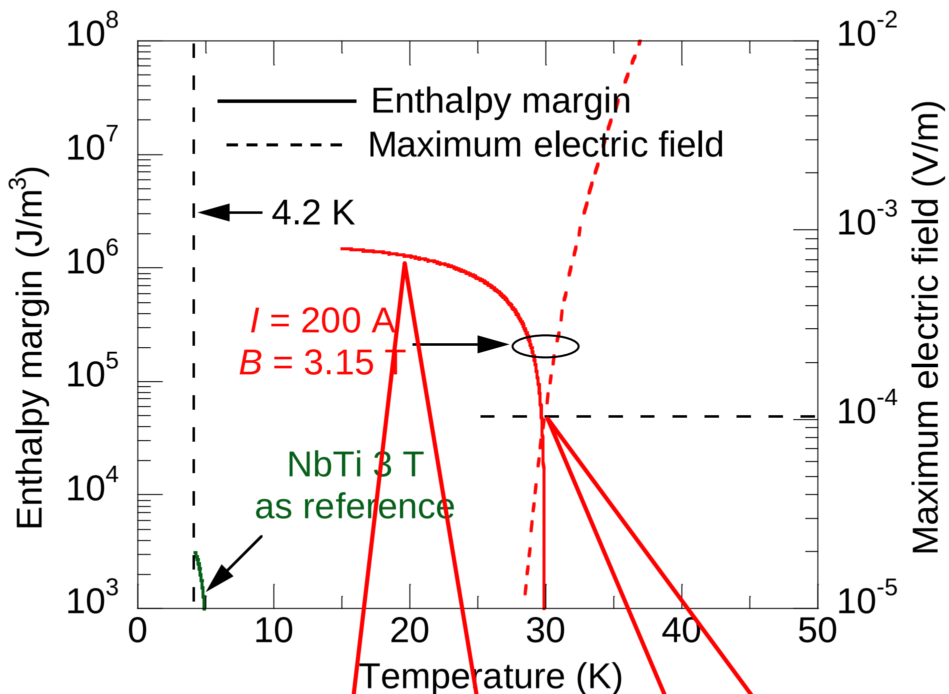
Tolerance against thermal disturbance – Advantage of HTS –



Dipole magnet
(3.15 T @ 200 A)

NbTi operated at 4.2 K transits to normal with 10^3 J/m^3 of energy, i.e., reaching 6 K

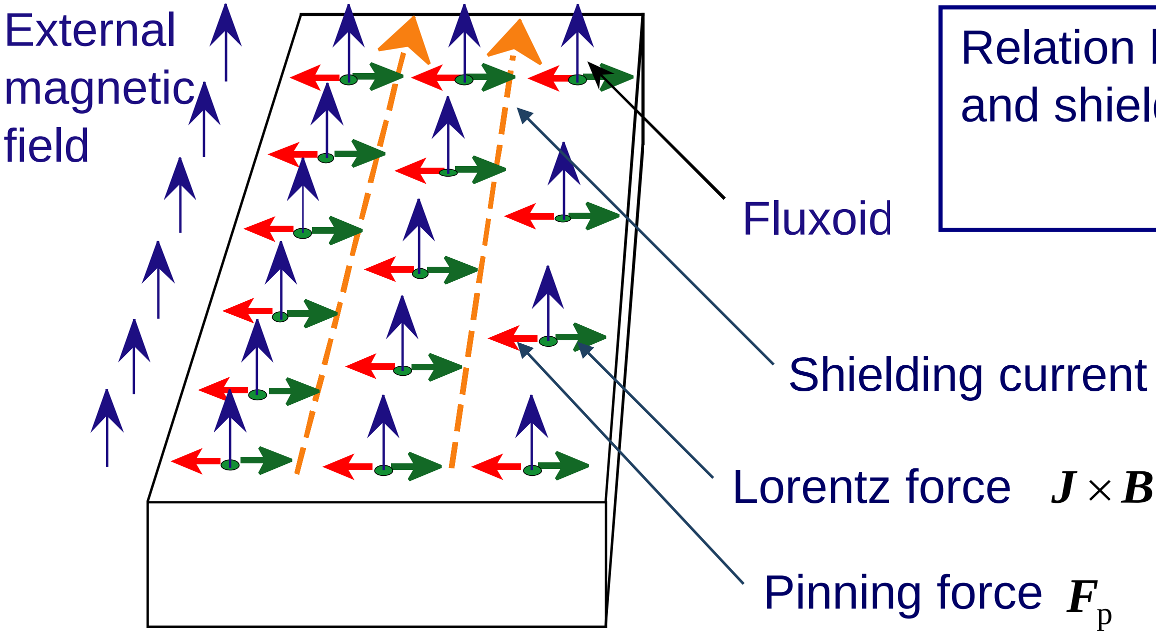


If operated at 20 K, 10^6 J/m^3 of energy is required to transit to normal, i.e., reaching 30 K.

When increasing temperature, normal voltage appears around 30 K

N. Amemiya, FFAG'14

Ac losses in mixed state of type-II superconductors – Compatibility of FFAG accelerators with SC –



Relation between magnetic flux density and shielding current density

$$\nabla \times \boldsymbol{B} = \mu_0 \boldsymbol{J}$$

Mixed state of type-II superconductor

When external magnetic field or transport current changes, magnetic flux distribution changes.

Fluxoids are moved by Lorentz force against pinning force.

Lorentz force makes some work. The energy dissipated in this process is ac loss.

R&D project for fundamental technology of HTS accelerator magnets

Outline 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, Toshiba, KEK, NIRS (National Institute of Radiological Sciences), 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 (S-Innovation) Program by JST

Key issues in R&D

- HTS magnet design which is compatible with accelerator design
- Winding technology for negative-bend coils and 3D shape coils to realize the designed magnets
- Tape magnetization which affects the field quality of magnets

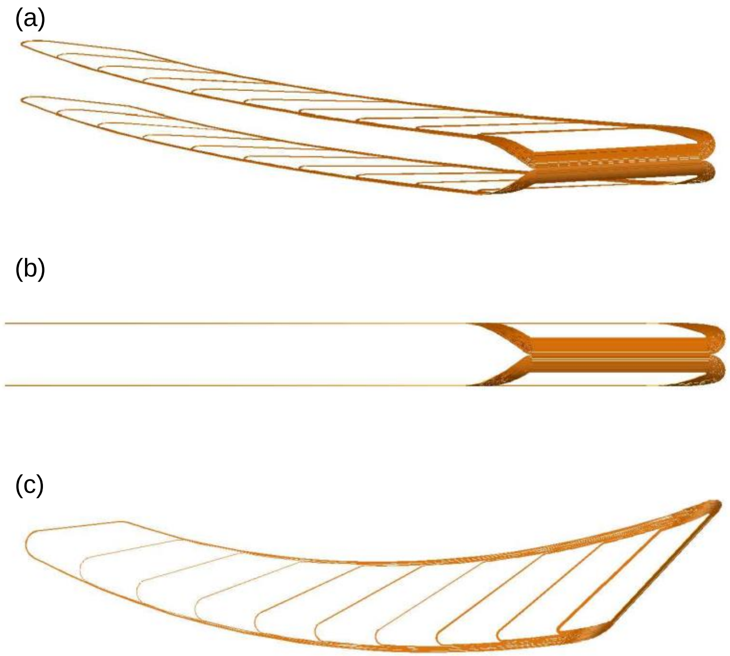
Magnet design

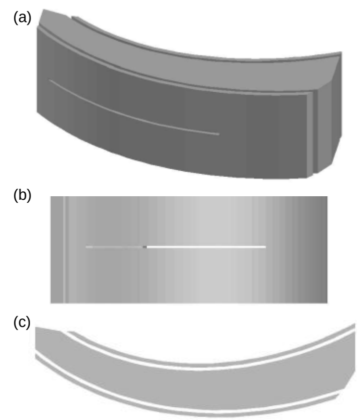
Spiral sector FFAG accelerator for carbon cancer therapy

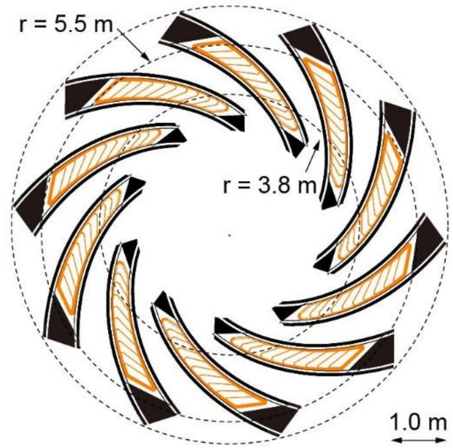
Radial magnetic field distribution $B(r) = B_0 \left(r / R_0 \right)^k$

FFAG accelerator: strong focusing with dc magnet	
Type	Spiral sector
Purpose	Carbon cancer therapy
Particle	C^{+6}
Energy	40 - 400 MeV/u
Major radius	4.65 m
Average orbit radius	3.8 – 5.5 m
Field index (k value)	5.7
Integrated field at *r* = 5.5 m	3.98 T·m
Spiral angle	58.4 deg
Number of cell	10
Packing factor	0.5

Conceptual view of coil and iron yoke







- Radial profile is provided by ladder shape coils. $B(r) = B_0 (r/R_0)^k$
- Field with spiral angle is provided by coils and irons with negative bend

Preliminary estimation

Weight of iron ~ 60 t; stored energy ~ 2 – 3 MJ; B @ conductor ~ 7 – 8 T

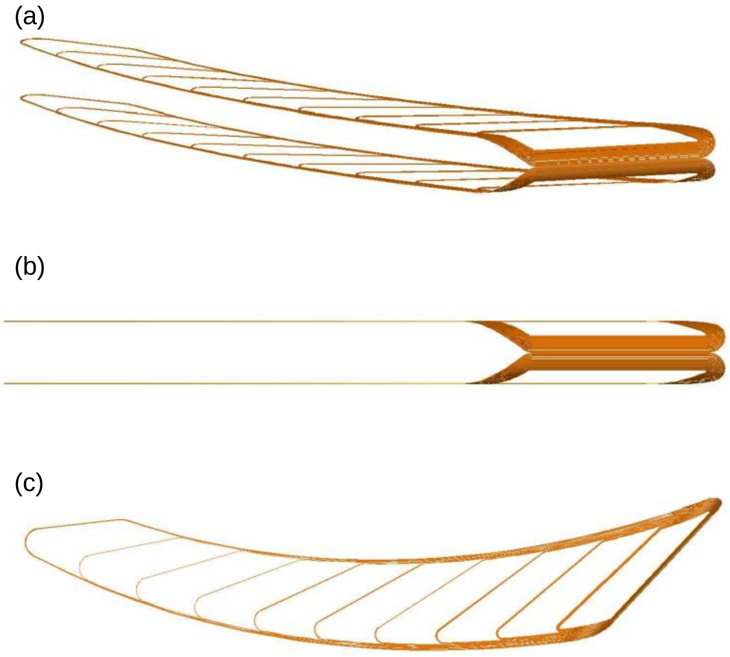
Alternative design with flat coils

Magnet with deformed pancake coils with negative bend	
Number of coils per pole	24
Inner / outer radius of coil assembly	3.5 m / 6.15 m
Inner height of coil assembly	0.3 m (±0.15 m)
Outer radius of magnet (iron yoke)	7.31 m
Number of turns	2040 with 500 A
Conductor length	26 km with 500 A

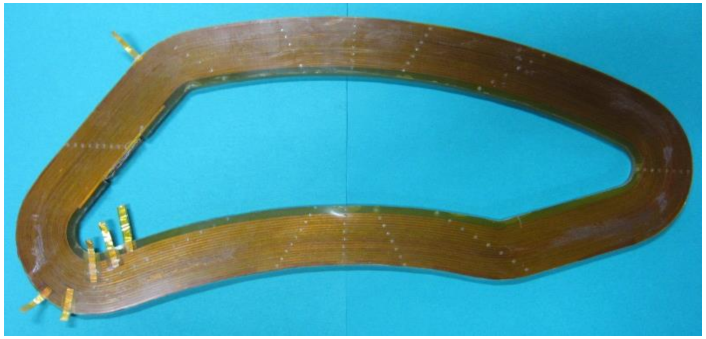
Winding technology R&D

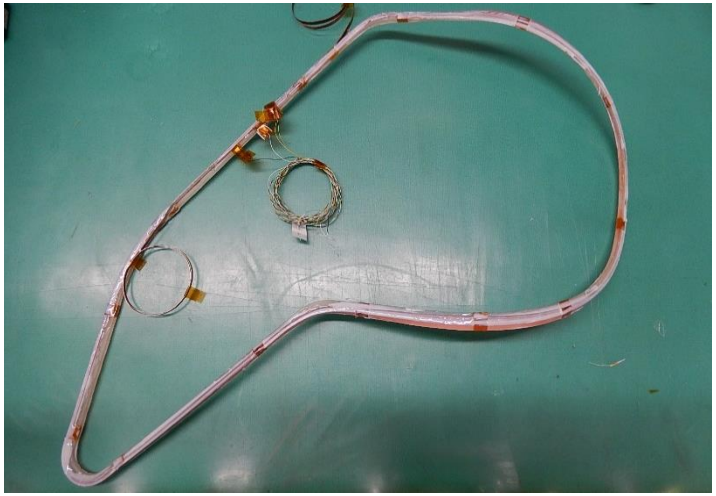
What we need are …

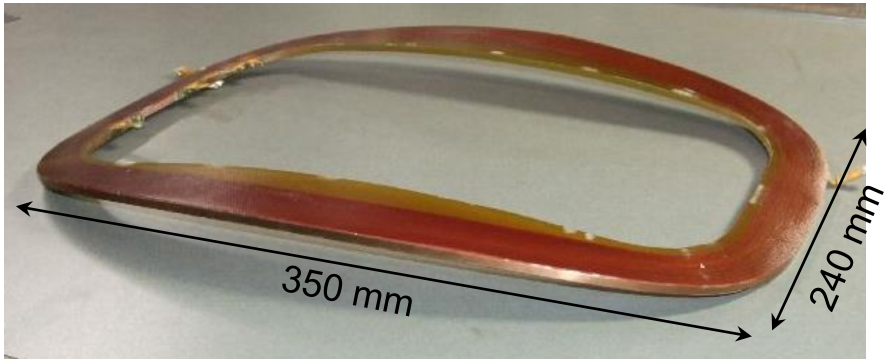
- Winding technology for negative-bend coils
- Winding technology for 3D coils



Examples of results of test winding







Magnetization of coated conductors and field quality

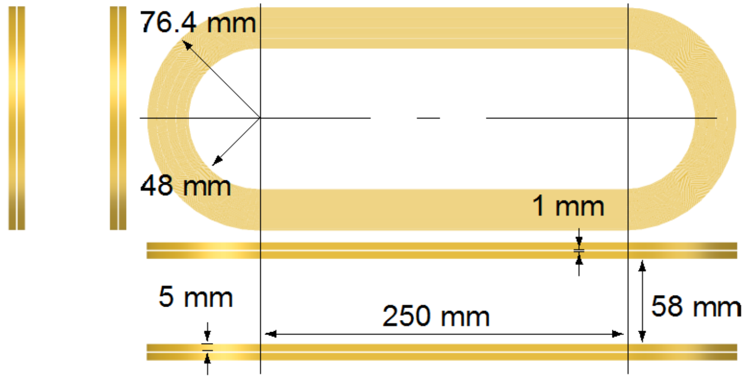
Tape magnetization

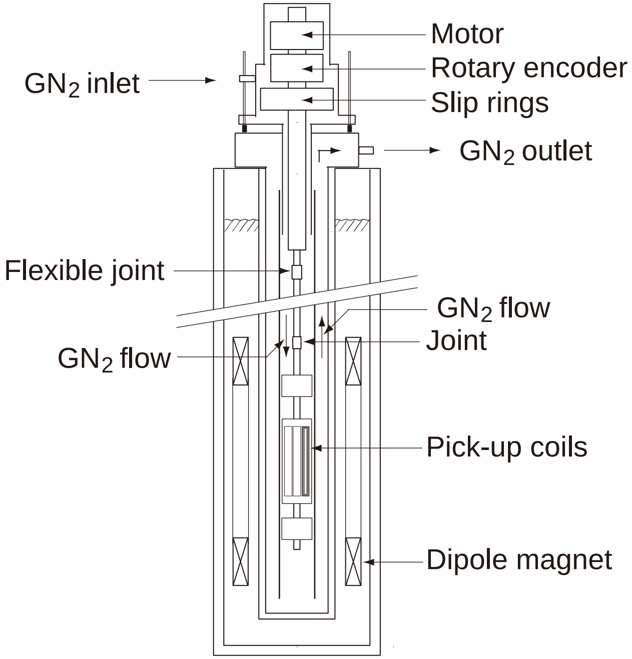
One of the concerns in coated conductor is

large magnetization caused by its tape shape, because it deteriorates the field quality of magnets.

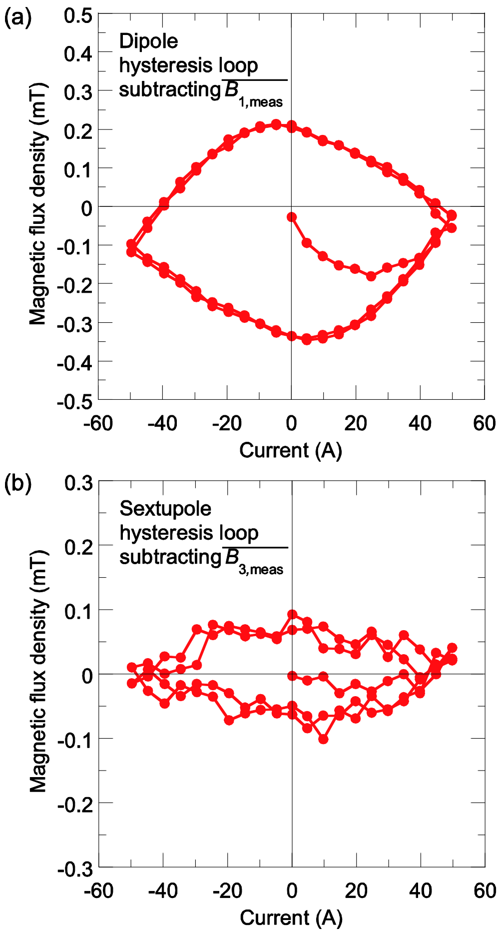
(required error < 10^{-3} – 10^{-4})

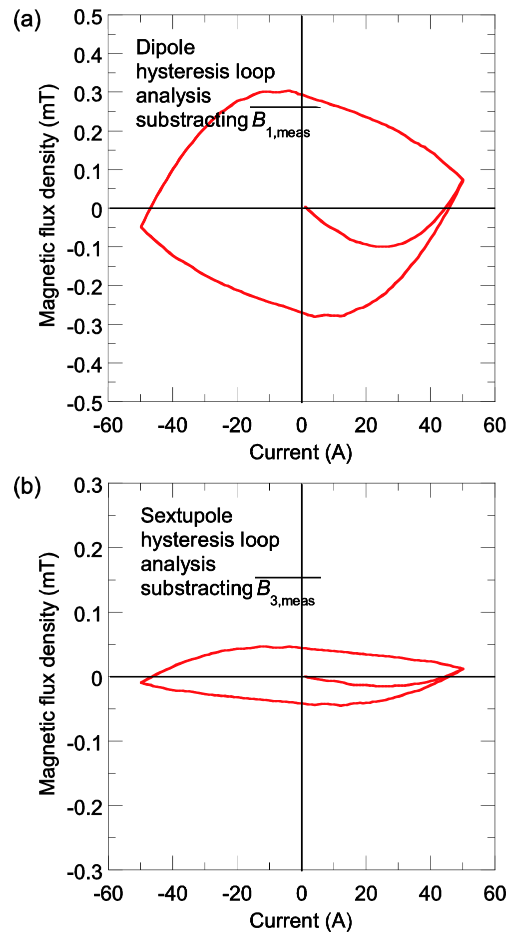
Dipole magnet RTC4-F comprising race-track coils

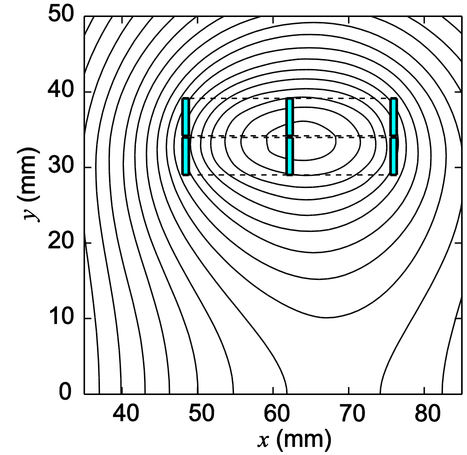


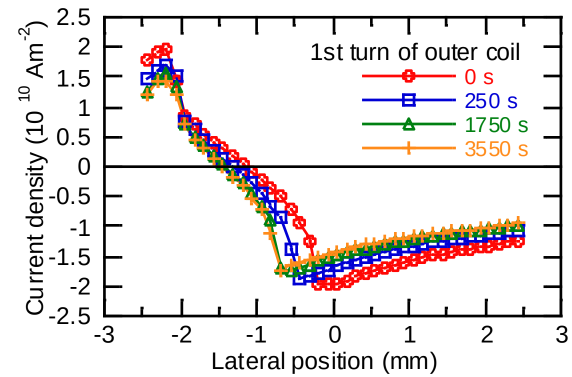


Measured dipole and sextupole components and comparision with numerical results









Summary
– pros and cons of SC magnets (HTS magnets) –

- pros
  - high magnetic field: not limited by iron saturation
  - large working space with high magnetic field
  - small operating cost (electricity, CO_2 emission)
- cons
  - cooling: complicated system and maintenance
  - quench: reliability issue
  - large initial cost