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Step-current Method for Improving Storage Energy Density of Superconducting Magnet

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Introduction

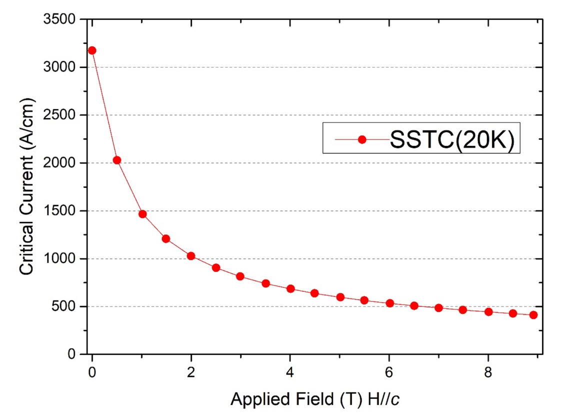
It was observed that superconducting magnets which have been charged with identical current may face the current limitation due to the strong perpendicular magnetic field usually found on the ends of the magnet. In this case, the pancake coils in the interior of the magnet can't get fully used, which has a low utilization rate for the magnet. This paper provides a new method to improve the storage energy density by applying step-currents to pancake coils according to the different perpendicular magnetic fields on different positions. And an iteration method is proposed to obtain the critical currents for each group of pancake coils. Finite element method models of double solenoid magnet and toroid magnet are established. The comparative analysis of the three kinds of magnets with step-current is made and the variation trend such as the perpendicular magnetic field, critical currents, storage energy and mechanical stress are presented.

Conclusion

- The current density of double solenoid magnet could be less than that of single solenoid magnet when two element solenoid magnet is too close.
- The iteration method could reduce calculation time when solving step-currents and obtain accurate results.
- Stress limitation is important for the Step-current method.
- Step-current method increases Energy storage by 32.5%.

Parameters survey

Superconducting Tape



Ic-B characteristics of the type provided by SSTC

$$I_c = 8.286 \times e^{-1.426B} + 4.406 \times e^{-0.1161B} \quad (1)$$

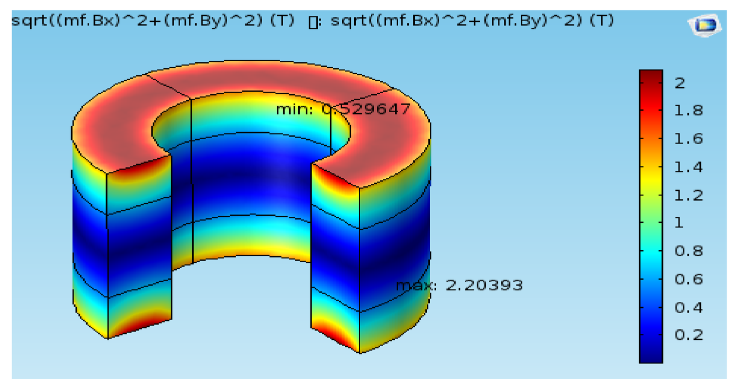
The superconducting tape(SSTC):

- I_c is 100A at 77K, 0T
- Minimum bending radius is 30mm
- Max Stress is 250 Mpa
- Size: 4.8mm x 0.24mm

Single Solenoid Magnet

Tab. I
Parameters of 20H single solenoid magnet

Parameters	Values
Inner radius (mm)	97
Outer radius (mm)	175
Height (mm)	240
Height of a double pancake coil (mm)	10
Number of double pancake coil	24
Safety factor	0.8
Filling coefficient	0.7
Inductance (H)	20
Running temperature (K)	20



Distribution of perpendicular magnetic field

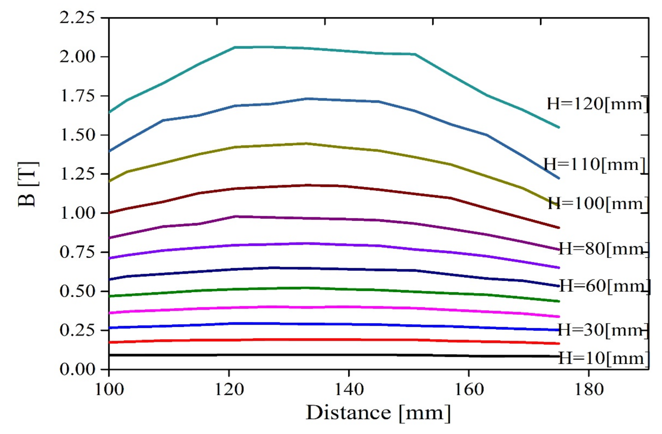
Make unitary processing and gain the excitation curve.

$$I = 1/2.2093B \quad (2)$$

The distribution of perpendicular magnetic field when we apply 100A into the magnet using finite element simulation software COMSOL Multiphysics .

Maximal perpendicular component field appears on the ends of magnet— 2.2093 T.

Critical current is 239.3A combining equation (1) and equation (2).



Changing curve of the perpendicular field in the radial direction

Changing curve on top of 12 double pancake coils.

Distance between adjacent curves is 10mm, showing space between two adjacent ends of coils.

The other coils can suffer currents greater than 293.3A.

Optimization method

Iteration Method

Steps:

1）. obtain the relationship between excitation and currents.

$$\begin{bmatrix} B_1 \\ B_2 \\ \vdots \\ B_i \end{bmatrix} = \begin{bmatrix} K_{11} & K_{21} & \cdots & K_{i1} \\ K_{12} & K_{22} & \cdots & K_{i2} \\ \vdots & \vdots & \vdots & \vdots \\ K_{1i} & K_{2i} & \cdots & K_{ii} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_i \end{bmatrix} \quad (3)$$

i means the number of steps, B_i means the maximum perpendicular magnetic field on the ends of ith group coils, and K_{ij} is the influence coefficient caused by ith current to the ends of jth coils

2）. An initial value of critical step-currents （I_1^0, I_2^0, …, I_i^0 and the initial perpendicular magnetic fields （B_1^0, B_2^0, …, B_i^0) using equation (3).

3）. Substitute into equation (1) to calculate the first-generation critical step-currents （I_1^1, I_2^1, …, I_i^1）

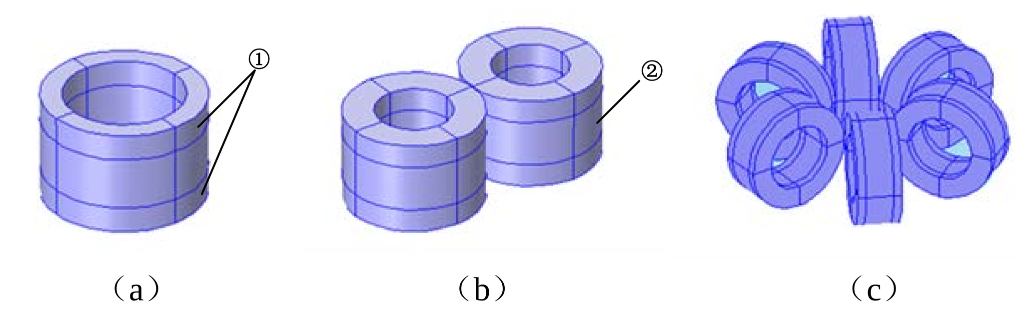
4）. Repeat equation (3) and equation (1) until the error satisfy design requirement （$I_1^{k+1-} I_1^k$）/ $I_1^k \leq 0.005$

Models

Number the 24 double pancake coils, dividing coils which suffer the same field into one group.

Apply the method on double solenoid magnet and 6-toroid magnet.

Two-step-current, i=2



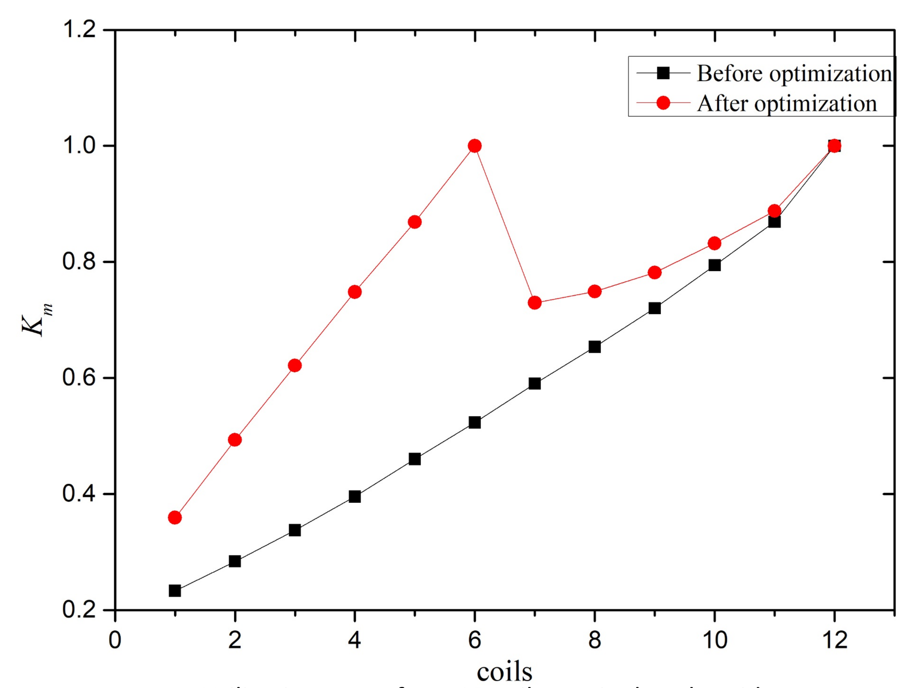
Construction of three models

First part ①: ends of magnet coils　Second part ②: middle coils

（a） ① = 1-6, 19-24　② =7-18
（b） ① = 1-3, 10-12　② =4-9
（c） ① = 1, 4　② =2,3

Result

Utilization Rate



Utilization rate of top 12 coils on single solenoid magnet

$K_m = I_c^k / I_c^i$ （k=1,2,…,12; i=1,2）

I_c^k is critical current of kth coil according to the maximum perpendicular magnetic field on the ends of it.

I_c^i is critical current of ith part.

Make more difference on second part coils than first part coils.

Utilization rate of every coil is improved.

Specification

Tab II
Specification of investigated magnet

Tape of magnet	Before optimization			After optimization(step-currents)		
	Single	Double	Toroid	Single	Double	Toroid
Number of element coils	1	2	6	1	2	6
Inner and outer radius of (mm)	97×175	97×175	97×175	97×175	97×175	97×175
Height of coil (mm)	240	120	40	240	120	40
Distance (mm)	0	176	211.45	0	176	211.45
Critical current (A)	239.3	236.10	293.36	230/314	221/307	277.1/361
Magnetic field ($B_\perp$)(T)	5.274	5.3874	3.64	5.57/3.16	5.98/3.31	4.07/2.39
Inductance (H)	20	14.878	8.7758	20	14.878	8.7758
Stress (MPa)	119	151.64	143.83	242.61	184.82	193.42
Energy （kJ）	572	415	378	758	532	479
Stray field (Gs)	606	135	0.244	687	141	0.2713

Distance : From origin of coordinates to center of element coil.

Stray field is measured at a distance 2m .

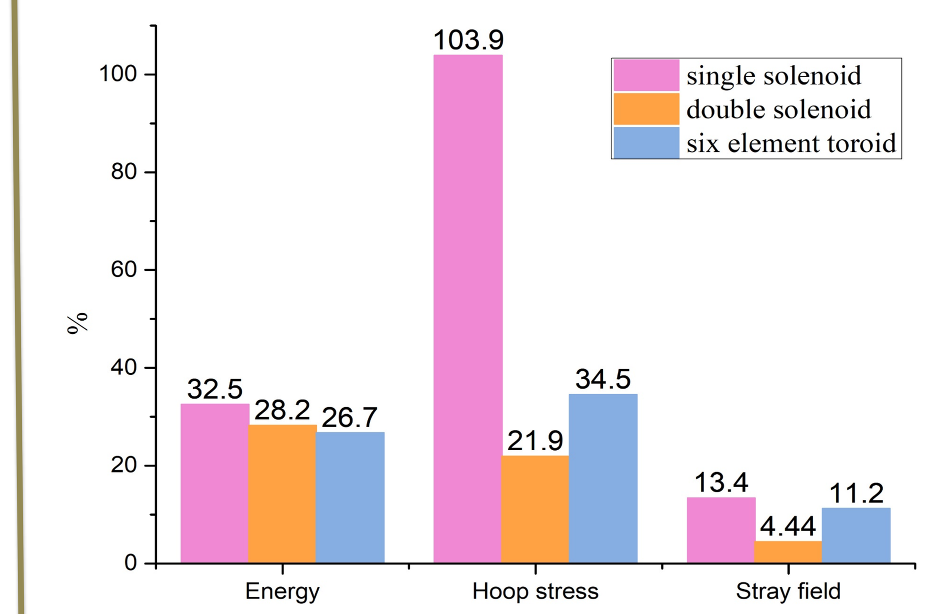
Hoop stress is close.

The inductance changes a lot.

Hoop stress of single solenoid magnet increases significantly.

All of three models increase the energy storage.

Increase



Increasing percentage after optimization

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