

2012年度中国人留学生研究奨励賞受賞者紹介

九州大学ー物質・材料研究機構連係大学院
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「強磁場発生用超伝導磁気レンズの開発」

受賞者略歴

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2003-2007年 北京科技大学(学士)
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2012年12月21日(金) 東京大学山上会館

研究成果

- 様々な超伝導材料で効果を確認
- 作動条件(温度、磁場)を変えて検証
- 形状、スリット、配置など磁気レンズの形状を検討し最適な形状を導出
- 磁気レンズを組み込んだ超伝導磁石を開発

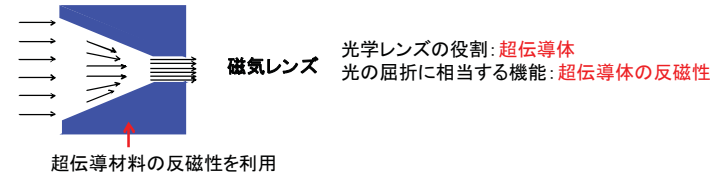
評価すべき点

- 冷媒、冷凍機、超伝導材料、磁石等の新たな技術の理解や装置の操作を習得
- 超伝導材料、実験条件等の研究方針がよく整理され、一つ一つが丁寧に行われた
- 約2年半で、誌上发表5件(筆頭5件)、口頭発表7件(筆頭5件)の研究成果の活発な外部発信
- 磁気レンズを組み込んだ超伝導磁石製作において、構想、設計、超伝導コイル巻線、磁石評価を自ら行った

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磁気レンズとは？

磁気レンズ: 光学レンズが光を集めるように、磁束を集める機能



研究課題

- 最適な超伝導材料
- 最適な作動条件(温度、磁場など)
- 最適な磁気レンズの形状
- 磁気レンズを組み込んだ装置(磁石)の開発

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強磁場発生用超伝導磁気レンズの開発



九州大学大学院 工学府材料物性工学専攻
先端ナノ材料工学専攻
物質・材料研究機構 超伝導線材ユニット
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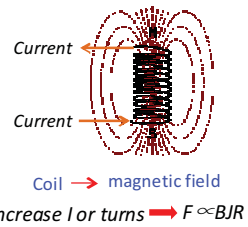
意義と目的



NMR 930 MHz 21.9 T @NIMS

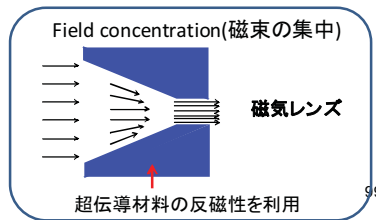
高磁場の使用

- Physics
- Material
- Chemistry
- Health



Disadvantages

1. Large magnet size
2. Mechanical stability
3. High cooling cost
4. Energy consumption



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コンテンツ

- ① 超伝導の背景と超伝導磁気レンズの原理
- ② 積層したNbTi磁気レンズ
- ③ MgB₂超伝導磁気レンズ
- ④ GdBCO超伝導磁気レンズ
- ⑤ 小型強磁場発生装置
- ⑥ まとめ

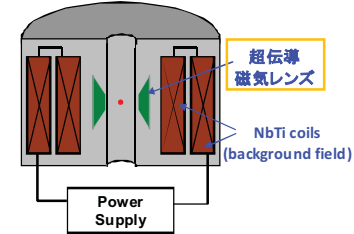
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意義と目的

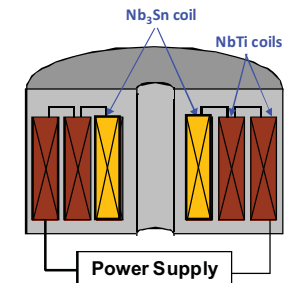
Compact high field magnet
(小型強磁場発生装置)

superconducting magnet + magnetic lens

Goal: concentrated field > 10 T (background field ≈ 6 T)



Conventional 10T
superconducting magnet



Advantages:

- 1.Compact, inexpensive
- 2.Easy fabrication
- 3.Non-source, energy saving
- 4.High field gradient


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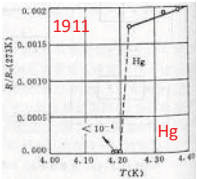
コンテンツ

- ① **超伝導の背景と超伝導磁気レンズの原理**
- ② 積層したNbTi磁気レンズ
- ③ MgB₂超伝導磁気レンズ
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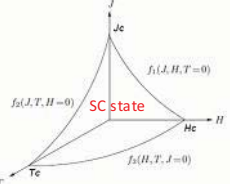
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Superconductivity(超伝導)


H.K. Onnes 




1911




SC state




MRI



NMR



Accelerator



Power Cable

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Diamagnetism of superconductor

超伝導材料の反磁性

$T < T_c$

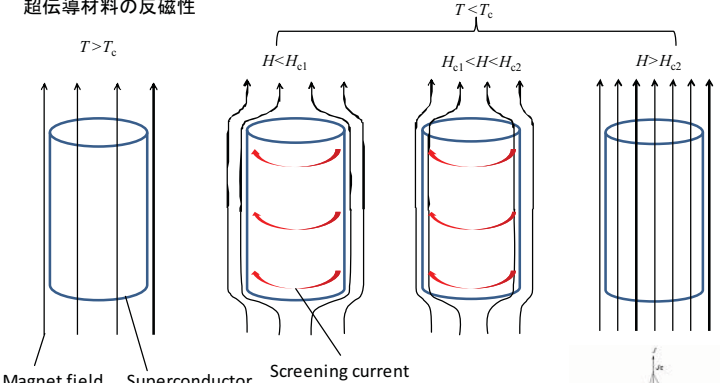
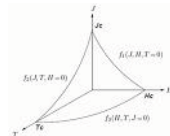
$T > T_c$

$H < H_{c1}$

$H_{c1} < H < H_{c2}$

$H > H_{c2}$

Magnet field Superconductor Screening current

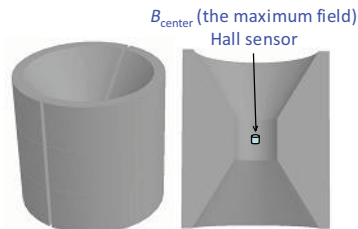



What is Magnetic Lens(磁気レンズ)

A field concentrator using the **diamagnetism of superconductor** and **hollow conical shape**.

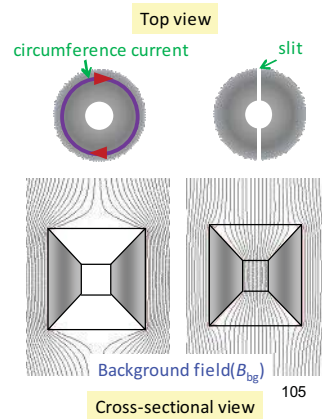
Slit: to suppress the shielding current.

Principle: change the distribution of flux density.



Magnetic Lens

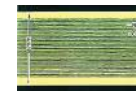
$$\text{Concentration ratio } (r_{con}) = \frac{\Delta B_{center}}{\Delta B_{bg}}$$



Candidate Materials (候補材料)

Magnet-grade SC: NbTi, Nb₃Sn, MgB₂, Bi2212, Bi2223, and REBCO

1 NbTi Multilayer Sheet



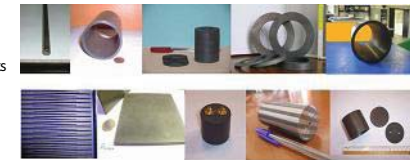
Specification of NbTi sheets (Nippon Steel Co.)

Thickness	1 mm
Copper ratio	1.36
Layer No.	NbTi 30
	Nb 60
	Cu 31

2 MgB₂ Bulk

Advantages:

Easy to produce a large-scale, high-density bulks
Cheap raw materials (Mg and B)
Operations without Liquid He (> 4.2 K)



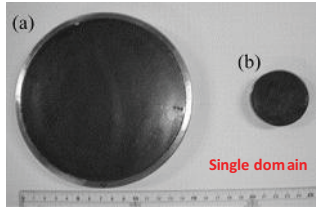
Mg-Reactive Liquid Infiltration (Mg-RLI)

EDISON Spa. Italy



Candidate Materials (候補材料)

3 Large grain (RE)BCO bulk (Nd, Sm, Gd, Y)



Top seeded melt growth processing (TSMG)

High upper critical field and current density

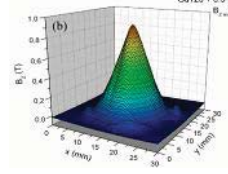
(1) Levitation:
bearings or flywheels



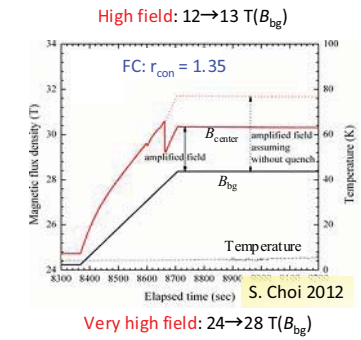
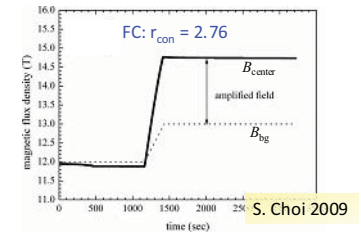
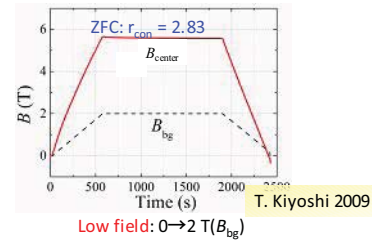
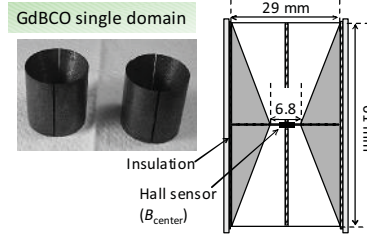
(2) Current-carrying:
current lead or current limiter



(3) Bulk magnet:
Superconducting permanent magnet



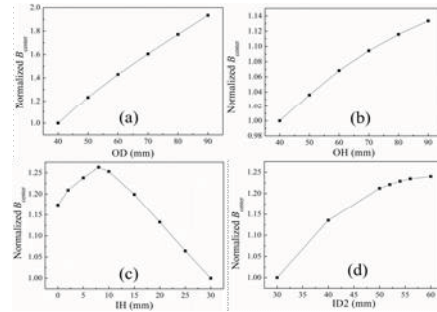
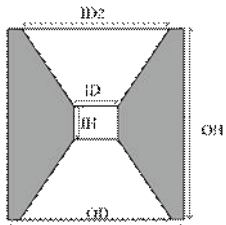
GdBCO Lens



Geometric Optimization (形状最適化)

OPREA-3D (TOSCA): $\mu_r = 1 \times 10^{100}$

Perfect diamagnetism model



	ID (mm)	OD (mm)	OH (mm)	IH (mm)	ID2 (mm)
(a)	20	Variable	60	20	OD-10
(b)	20	60	Variable	20	50
(c)	20	60	60	Variable	50
(d)	20	60	60	20	Variable

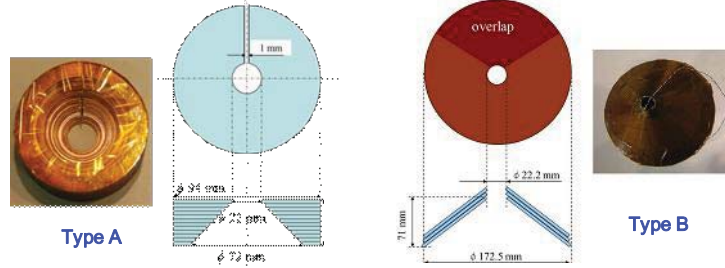
Final dimension: ID2=50, OD=58, OH=60, IH=10 mm

コンテンツ

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- ③ MgB₂超伝導磁気レンズ
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- ⑥ まとめ

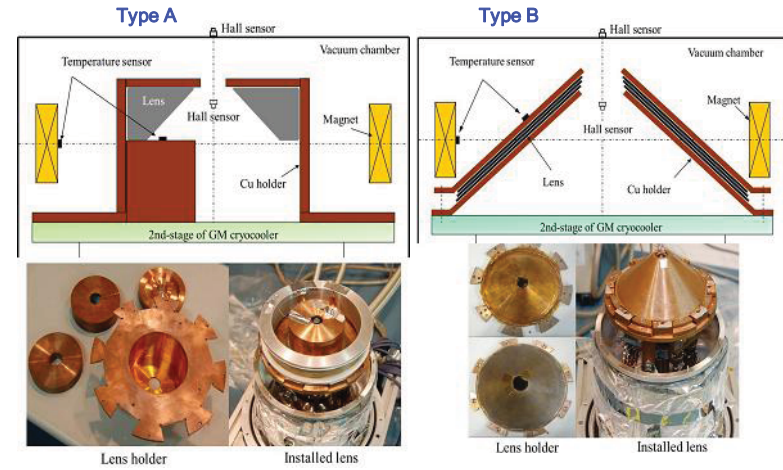
NbTi磁気レンズ

Geometric effect on magnetic lens

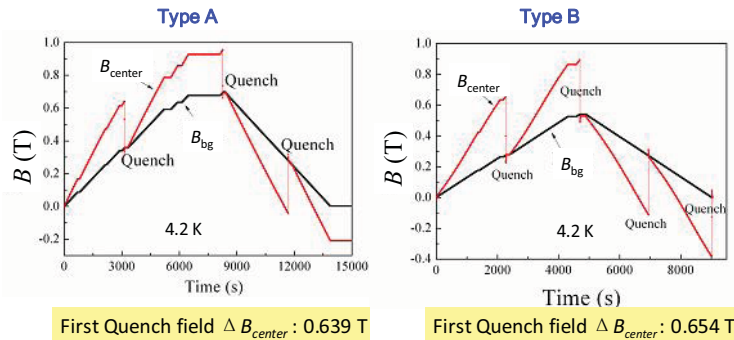


	Height (mm)	Inner diameter (mm)	Outer diameter (mm)	Specifications
A	1	22-72	94	Slits aligned; no insulation between rings
	2	22-72	94	Slits aligned; insulation between rings
	3	22-72	94	Each slit rotated by 90°; insulation between rings
B	1	22.2	172.5	Three cones stacked
	2	71	172.5	One NbTi cone sandwiched between two copper cones

Experiment setup (実験装置)



Results (実験結果)



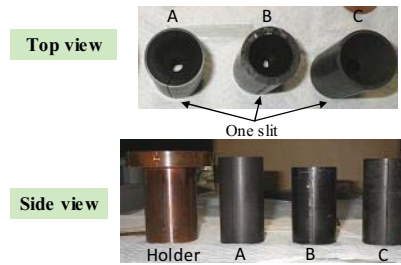
$$\frac{\Delta B_{center}}{\Delta B_{bg}} \text{ Concentration ratio: } 1.8$$

$$\text{Concentration ratio: } 2.4$$

Quench: an abnormal termination of superconductivity

MgB₂磁気レンズ

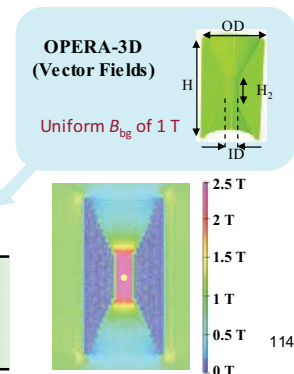
Starting material effect on magnetic lens



Name	OD	H	ID	H ₂	Remarks
A	29.0	57.0	7.0	14.9	B _{cryst} < 100 μm
B	29.2	50.1	7.0	15.3	B _{cryst} < 38 μm + C block 4% wt.
C	29.2	55.0	7.0	15.1	B _{cryst} < 38 μm

Numerical calculation

Steady-state Analysis
relative permeability: 1×10⁻¹⁰⁰

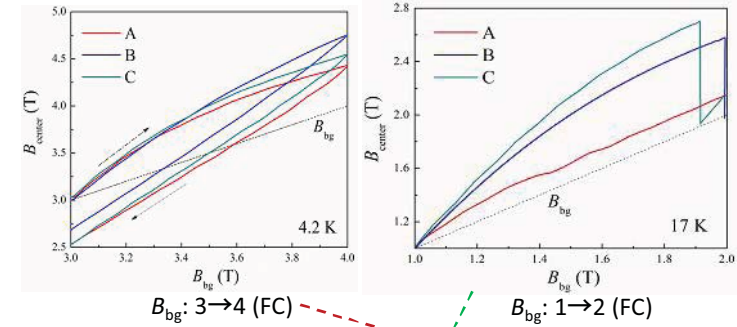


Experiment apparatus (実験装置)



Measurement system

Results (実験結果)



	J_c (A/mm ²)			
	(10 K, 0 T)	(20 K, 0 T)	(10 K, 2 T)	(4.2 K, 3 T)
A	1720	1150	350	220
B	1830	925	500	400
C	2870	1980	500	230

Concentration performance is affected by the starting material.

	T_c (K)	Manuf. cost	Field range@4.2K
NbTi	9.2	low	Quenched below 1 T
MgB ₂	39	very low	< 5 T
GdBCO	~90	high	

NbTi has stable performance and potential for large-scale application. However, it only can be used at 4 K and is easy to quench.

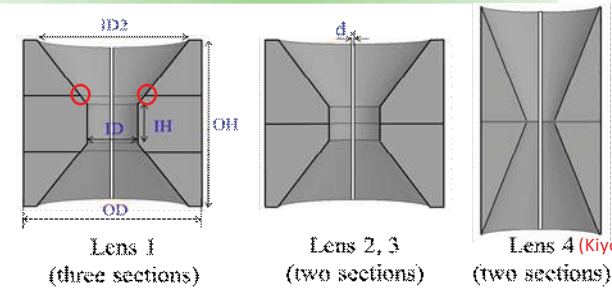
Bulk MgB₂ which shows better mechanical properties, has potential for magnetic lens if J_c is improved in the future.



Bulk GdBCO

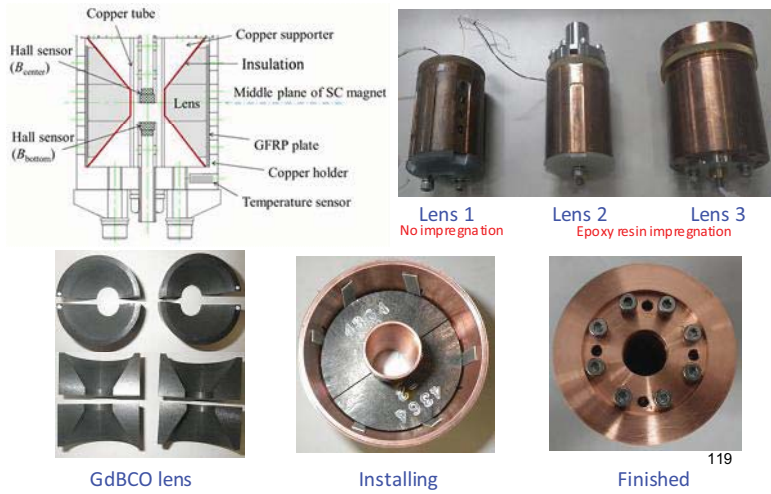
GdBCO磁気レンズ

Goal: required large inner-diameter for the compact magnet

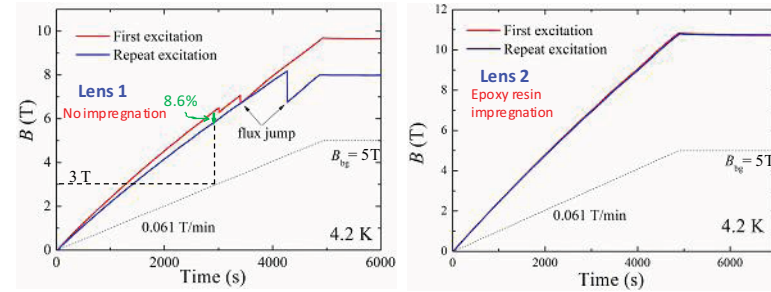


	ID(mm)	OD(mm)	OH(mm)	IH(mm)	ID2(mm)	d(mm)	r_{con} (Cal)	Remark
1	12	42	39	9	36	1	2.56	No impregnation
2	12	42	40	8	36	0.8	2.62	Epoxy resin impregnation
3	20	58	60	10	50	1.6	2.3	Epoxy resin impregnation Final lens
4	6.8	29	60			0.5	3.33	Epoxy resin impregnation

GdBCO磁気レンズ組み立て



Reproducibility(再現性)

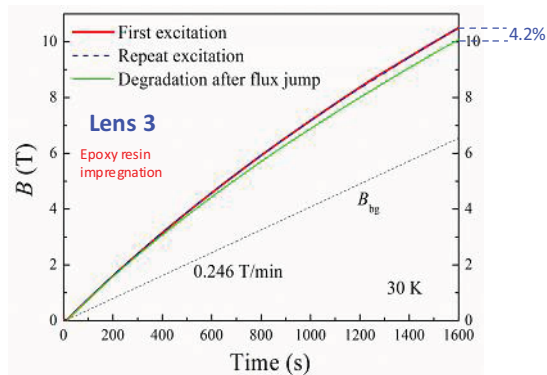


Lens 1 degraded 8.6% at $B_{bg} = 3$ T in LHe (before flux jump).
 Lens 2 has stable performance after impregnation.
 Epoxy resin impregnation is benefit for mechanical and thermal stability.

Flux jump: magnetothermal instability, partial quench

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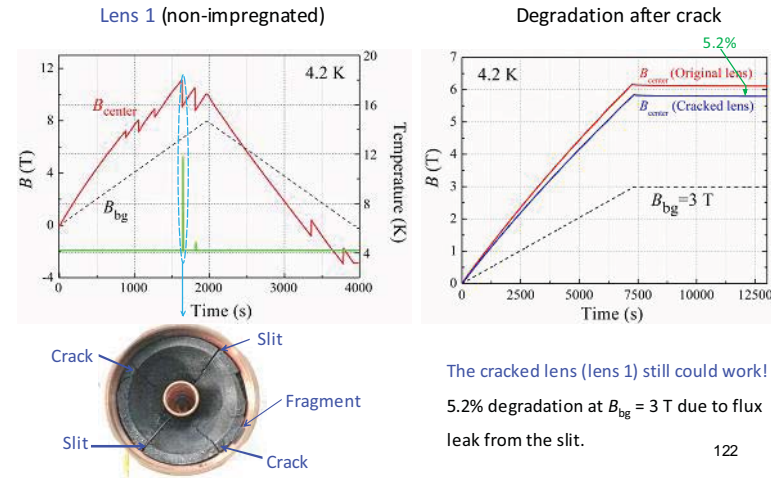
Reproducibility(再現性)



GdBCO lens has stable reproducibility after impregnation.
 However, several flux jumps induced the degradation.

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Crack(クラックによる劣化)

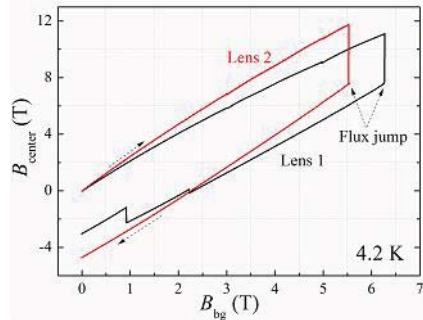


The cracked lens (lens 1) still could work!
 5.2% degradation at $B_{bg} = 3$ T due to flux leak from the slit.

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Limitation(制限)

Magneto-thermal instability at low temperature (4.2 K)

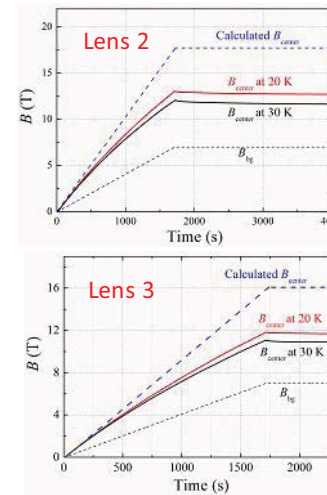


	Flux jump field(B_{center})	r_{con}
Cracked Lens 1	11.10	1.77
Lens 2	11.76	2.13

Strong flux jump occurred when $B_{center} > 11$ T

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レンズ効果の温度依存性



Background field: 0→7 T

Temp.	Highest concentrated field		Efficiency	
	B_{center} measured	B_{center} calculate		
Lens 2	20 K	13.04	18.34	71.1%
	30 K	12.06	18.34	65.76%
Lens 3	20 K	11.82	16.1	73.42%
	30 K	11.06	16.1	68.69%

Efficiency decreased with the increase of temperature determined by the J_c behavior.

Flux jump was suppressed resulting from the increase of thermal conductivity and specific heat at high temperature.

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コンテンツ

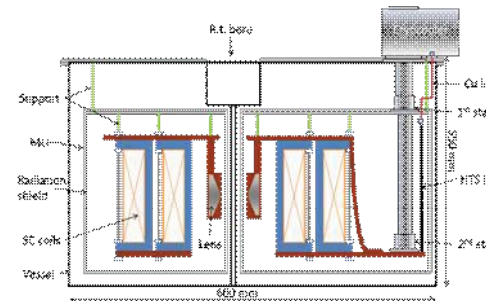
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- ⑥ まとめ

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Compact high-field magnet system

小型強磁場発生装置

小型超伝導マグネット + 磁気レンズ



NbTi coils: 7 T @108 A



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まとめ

To implement a compact high field magnet above 10 T, superconducting magnetic lenses, the novel device for field concentration were studied in this thesis.

The concentration field above 10 T were achieved by the improved GdBCO lens.

GdBCO lens with epoxy resin impregnation exhibited a stable performance to against the mechanical and thermal disturbance. The magnetic properties could satisfy the requirement of the compact magnet.

NbTi laminating lens and MgB_2 bulk were also tested as a candidate. We studied the shape effect on NbTi lens and MgB_2 lenses with different starting materials.

Magnetic lens is antipated to use extremely high field, neutron scattering and pulsed field.

Acknowledgement :

本研究はKakenhi科研費(Grant No. 20656015, No. 2236039)の助成を受け実施されたものです。

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Thanks for your attention

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