Development of a New RF Accelerating Cavity Loaded with Magnetic Alloy Cores Cooled by a Chemically Inert Liquid for Stabilizing and Enhancing the Performance of J-PARC Ring Accelerator

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目的とアウトライン

目的： 世界最高強度の陽子ビームシンクロトロン用加速構造を開発する。

J-PARC（世界最高強度の陽子ビーム加速器）
・ビーム増強に対応できる新型加速構造が必要。
・現行加速構造に改良が必要。

→ 現行加速構造に代わる加速構造を新たに開発する。

アウトライン

1． 新型加速構造開発の要求
  物理側からの要求
  加速器側からの要求

2． RCSの概要及び、加速構造の構成

3． 座屈の原因究明

4． 新型加速構造の設計

5． プロトタイプ構造の製作

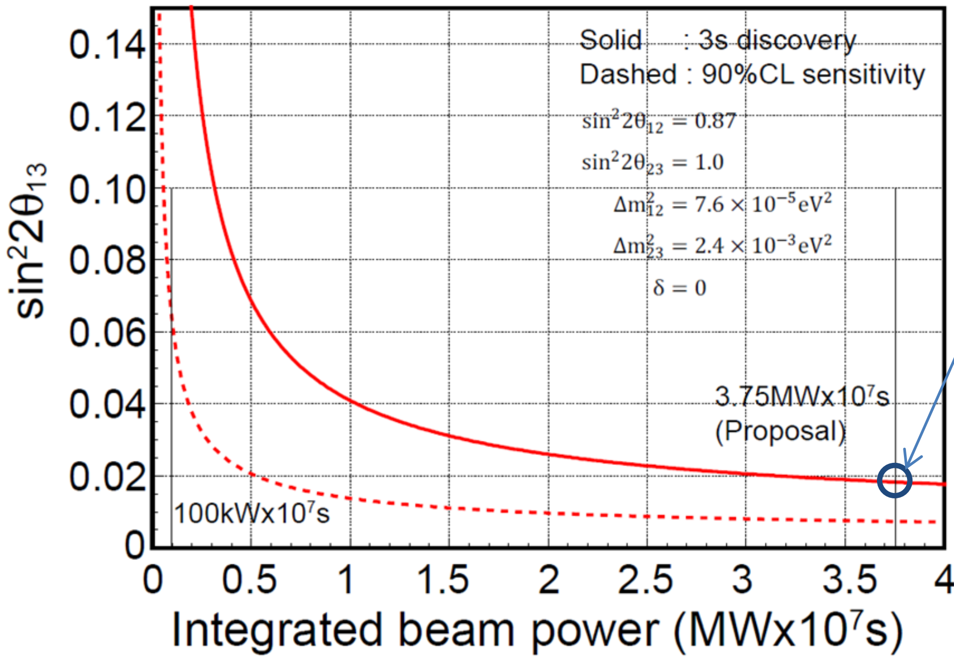
6． 性能試験

7． 結論

Physics goals and requirements for the accelerator system

T2K (from Tokai to Kamioka) is the most important experiment.
"Discovery of $\nu_\mu \rightarrow \nu_e$ oscillation"

Very competitive	NOvA, Double CHOOZ, Daya Bay



$\sin^2 2\theta_{13} > 0.018$ is the condition for the discovery.

3750[kWx10^{7}s]

0.75[MW] for 10^7[s/year] (116 days/year) is necessary to discover in 5 years

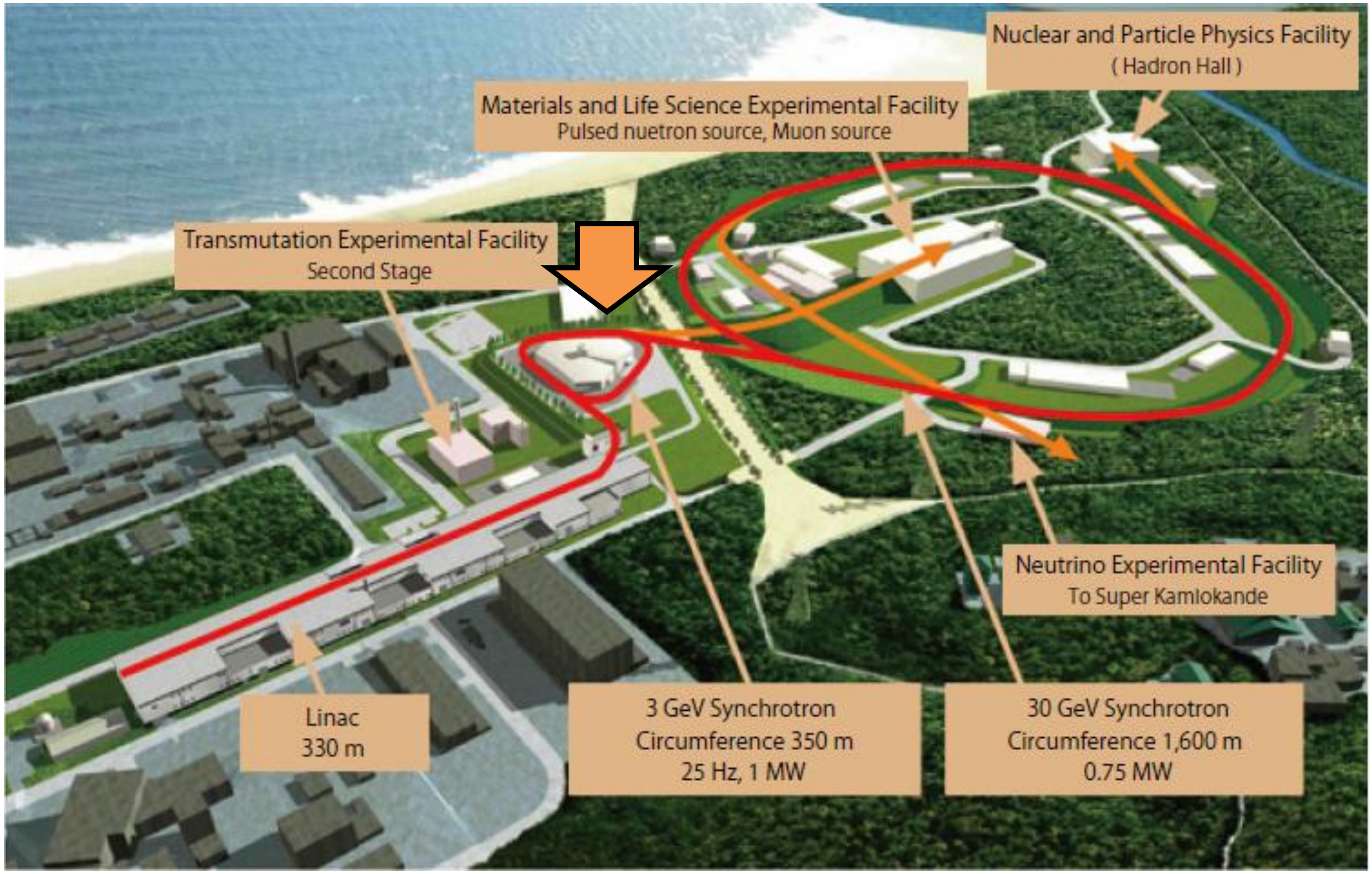
Present power 0.11[MW]

T. Kobayashi

The enhancement of the beam is crucial.

Research background arises from the aspect of the accelerating cavity

Accelerator complex



The accelerating cavity in 3 GeV synchrotron (RCS) has problems.

1. Magnetic alloy cores in the accelerating cavity got buckled.

Shunt impedance decreases.
Accelerating gradient decreases.

2. The coolant (water) corrodes the cores.

The core is covered with the waterproof coating.
The coating prevents thermal radiation.
The coating has glass-transition temperature of ~100℃.

limits the maximum temperature of the core

A new cavity overcoming these issues is necessary

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2．　RCSの概要及び、加速構造の構成
　RCSの概要
　FINEMETコア
　RCS加速構造

3．　座屈の原因究明

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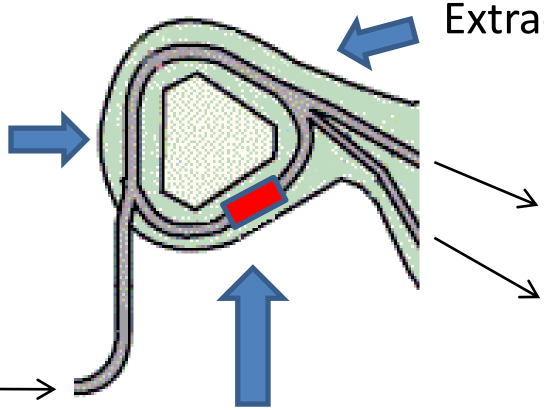
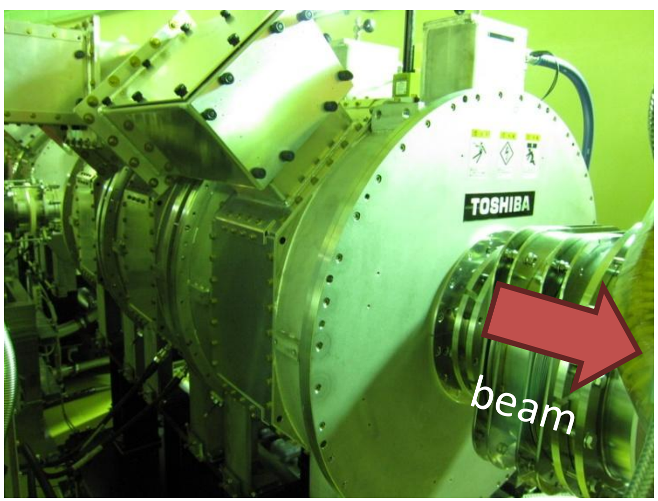
Rapid-Cycling Synchrotron (RCS)



Acceleration
11 accelerating cavities



Circumference	348.333 [m]
Injection energy	181 [MeV]
Extraction energy	3.0 [GeV]
Repetition rate	25 [Hz]

FINEMET core

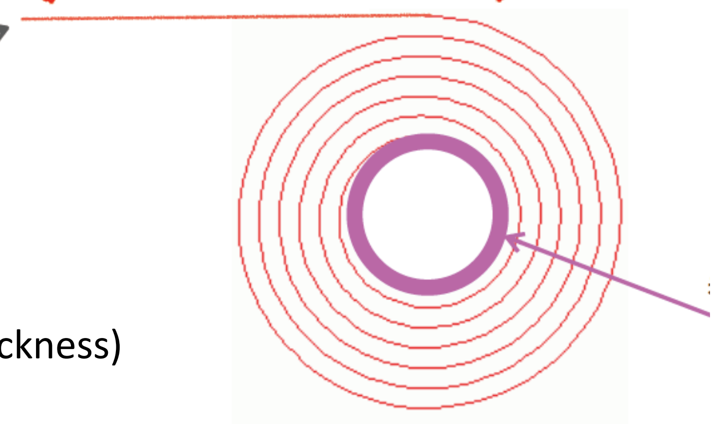
tension

Thin ribbon reduces the eddy current

Ribbon of magnetic alloy
(18μm thickness, 35mm width)

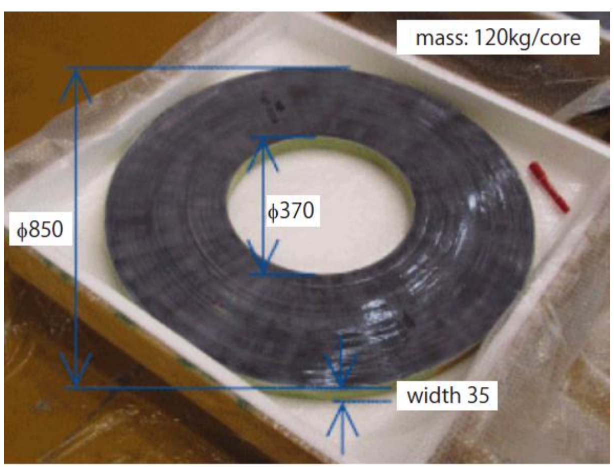
Silica is painted on one surface
(2μm thickness)

insulator



Collar

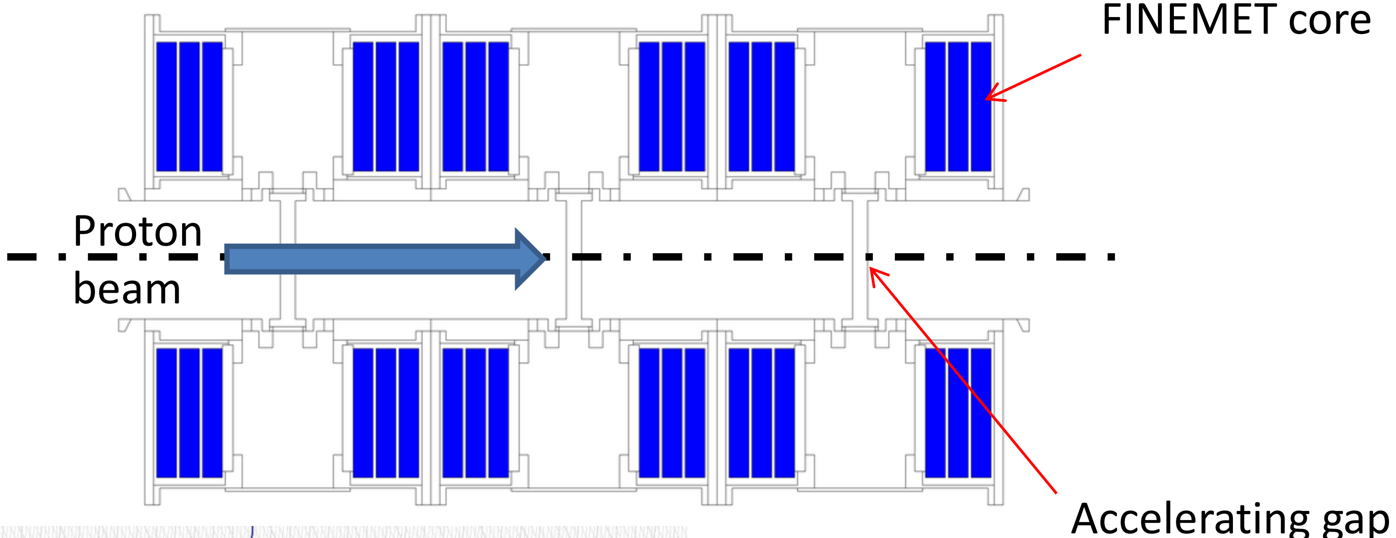
Ribbon of magnetic alloy is wound into a toroidal core

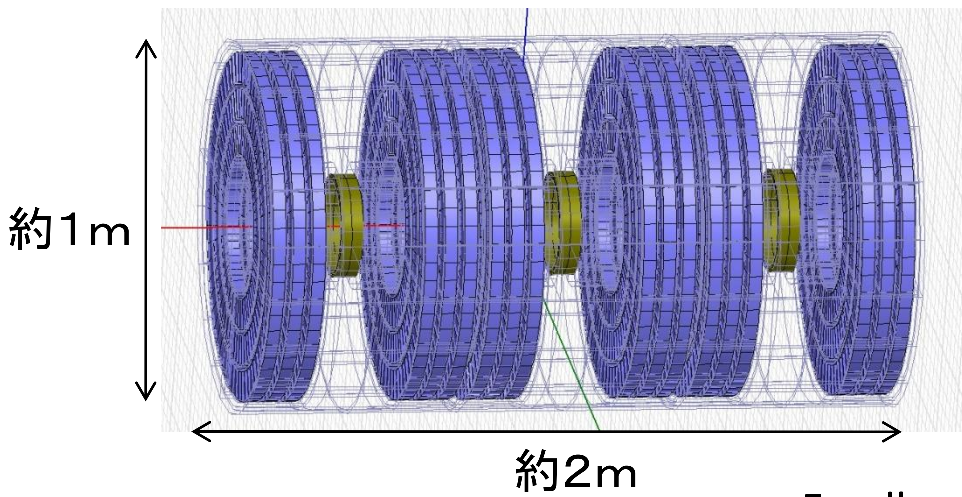


	FINEMET (FT-3M)	Ni-Zn ferrite
Relative permeability (1MHz)	2400	500
Saturation magnetic flux density [T]	1.2	0.4
Curie temperature [˚C]	570	200
Thermal conductivity [W/m/K]	7.1	6

Accelerating cavity in RCS

The cross-section of the RCS cavity





Structure	λ/4-wave coaxial
Accelerating gradient	15 [kV/gap]
Frequency	1.23 – 1.67 [MHz]
Q of cavity	~2
Q of core	0.6

Feedback system is not necessary because of the low Q

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   - RCSの概要
   - FINEMETコア
   - RCS加速構造

3. 座屈の原因究明
   - RCSコアの座屈現象
   - FINEMETコアの熱伝導率測定
   - 熱応力シミュレーション
   - 圧縮試験

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Buckling of RCS core

26 FINEMET cores out of 90 in total were buckled.

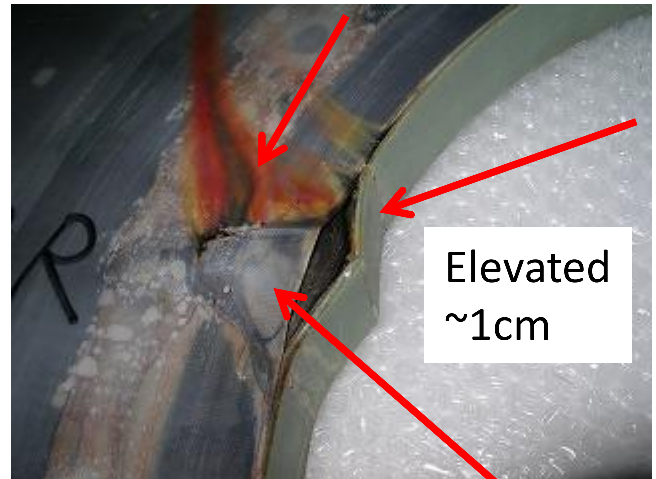
M. Nomura, IPAC'10

Power loss: 6 [kW/core]

rust

Glass epoxy

G-10 collar



Waterproof coating

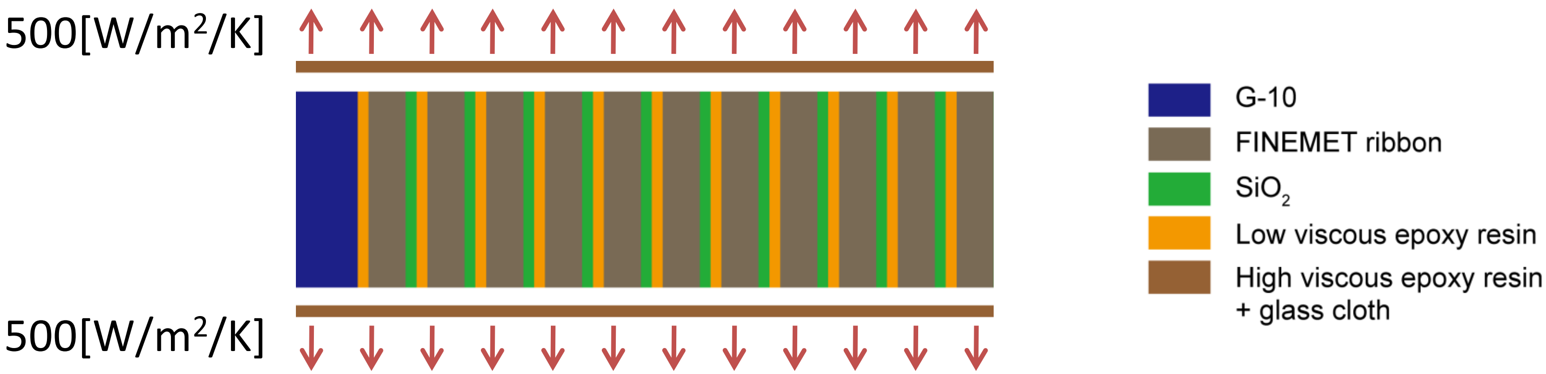
The coating comes off ➡ Cooling efficiency decrease

The cause was identified by means of the simulation and the experiment.

Simulation for thermal stress

Compression test

Properties of materials for the simulation



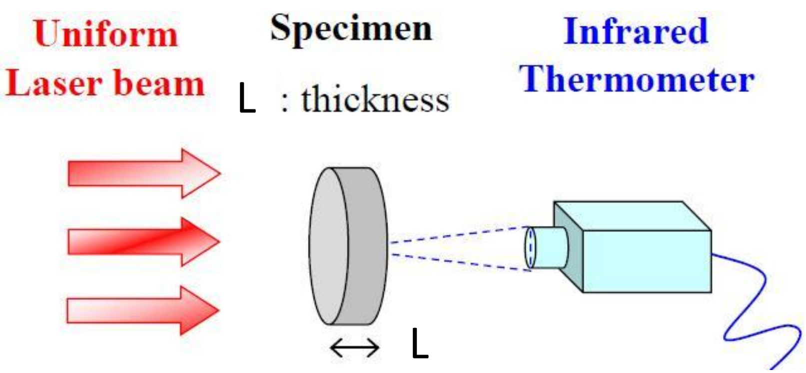
Schematic view of the cross-section of the core

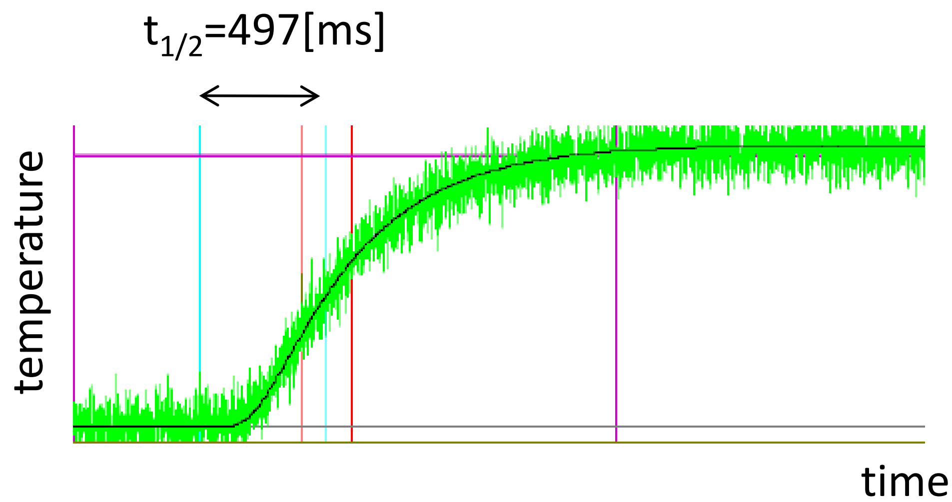
	FINEMET	Epoxy resin	G-10
Young's ratio [GPa]	200	3.2	7.8
Poisson's ratio	0.32	0.34	0.32
Coefficient of thermal expansion [10^{-6}/K]	10.6	60	Radial: 23 Circumferential: 7 Beam direction: 7
Thermal conductivity [W/m/K]	Radial: 0.6 Circumferential: 7.1 Beam direction: 7.1	0.2	Radial: 0.4 Circumferential: 0.8 Beam direction: 0.8

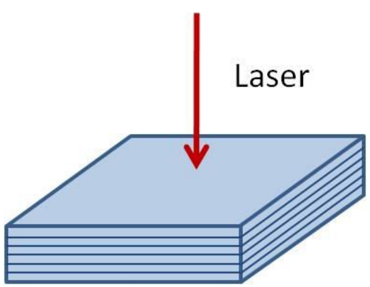
Legend (cell colours): Ref. Hitachi Metal (FINEMET mechanical and thermal expansion values); Ref. プラスチック基複合材料を知る辞典 (Epoxy resin and G-10 values); Measure (FINEMET thermal conductivity)

Measurement of the thermal conductivity of the core

Laser flash method

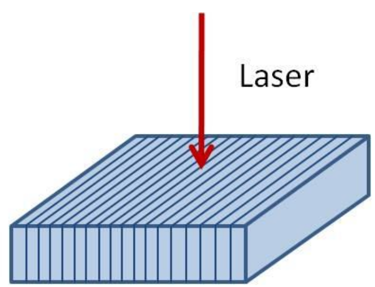






Normal to layers

0.6[W/m/K]



Along to layers

7.1[W/m/K]

Coefficient of thermal diffusion

$$\alpha = \frac{1.38L^2}{\pi^2 t_{1/2}}$$

L: thickness [cm]

C: specific heat [cal/g/˚C]

D: density [g/cm^3]

Thermal conductivity

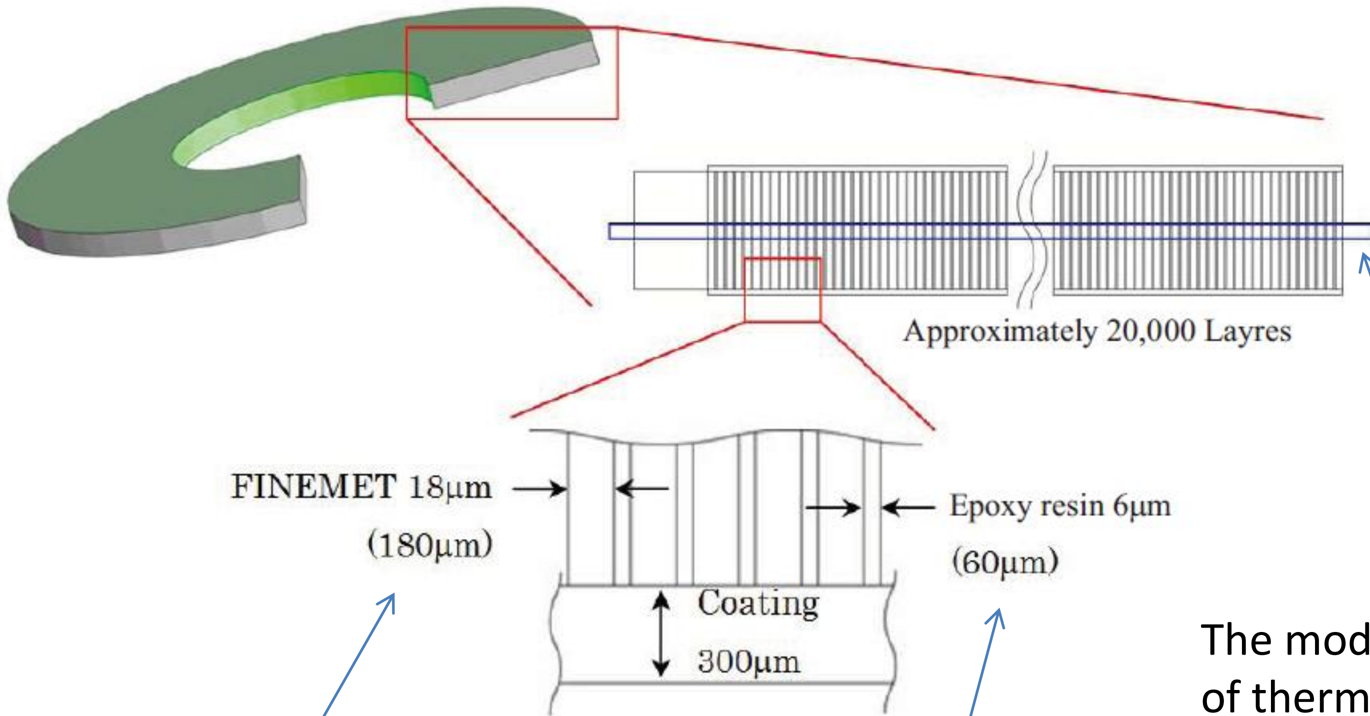
$$\lambda = \alpha C D$$

Specific heat

0.50[J/kg/K]

(measured value)

Model for the calculation



The model for the calculation of thermal stress (2,0000 layers)

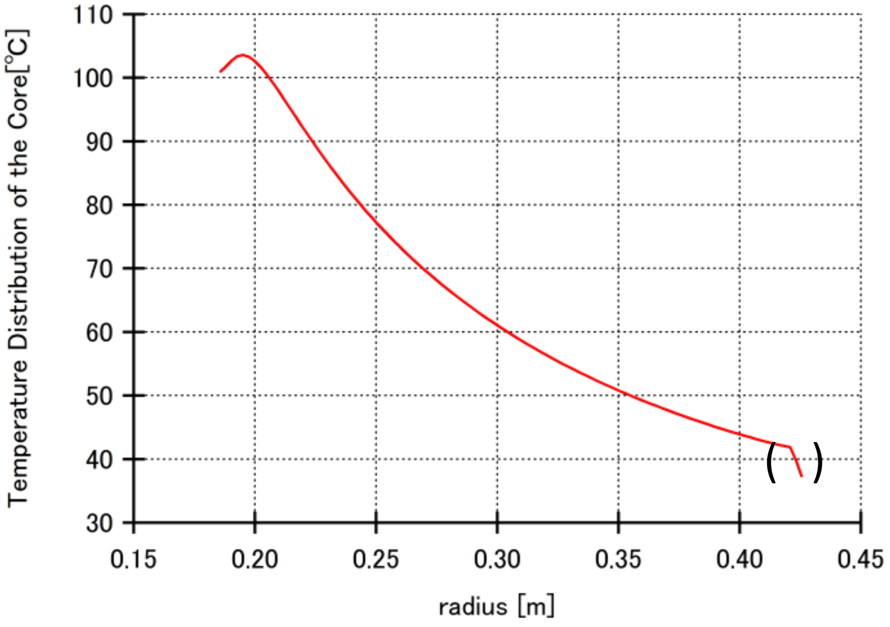
The model of 2,000 layer was used for the calculation of temperature.

Calculation for temperature in the core

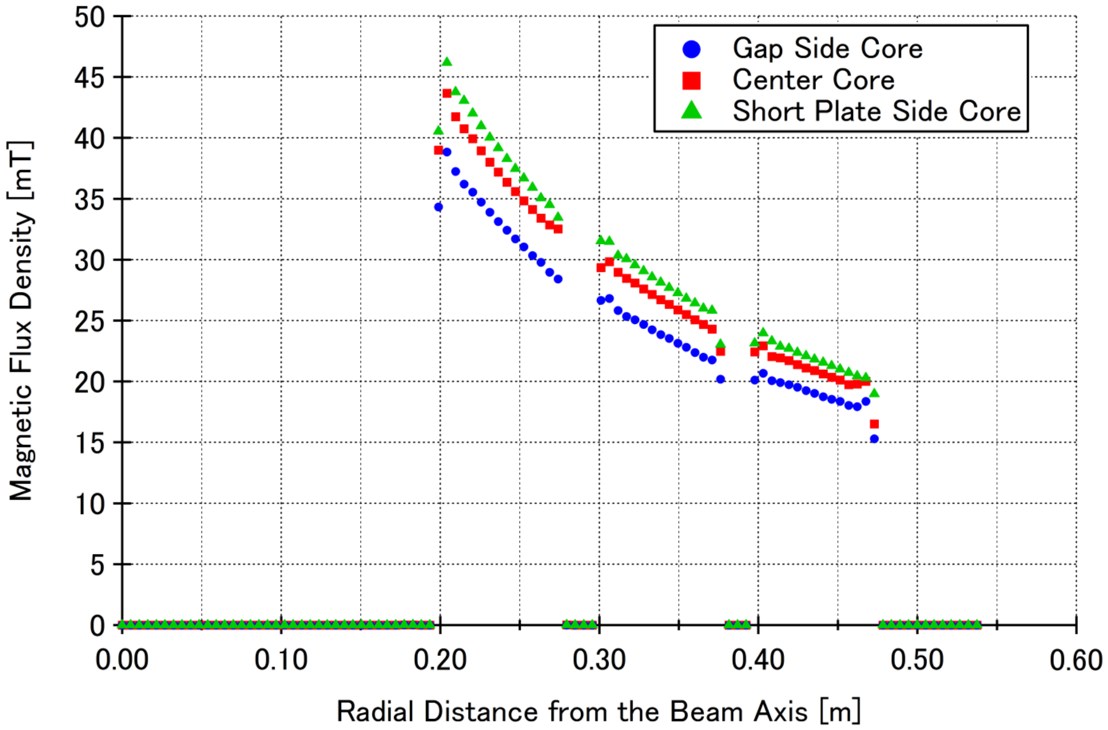
Magnetic-flux-density: 1/r distribution
Power loss: $1/r^2$ distribution

normalized with 6kW

Distribution of temperature



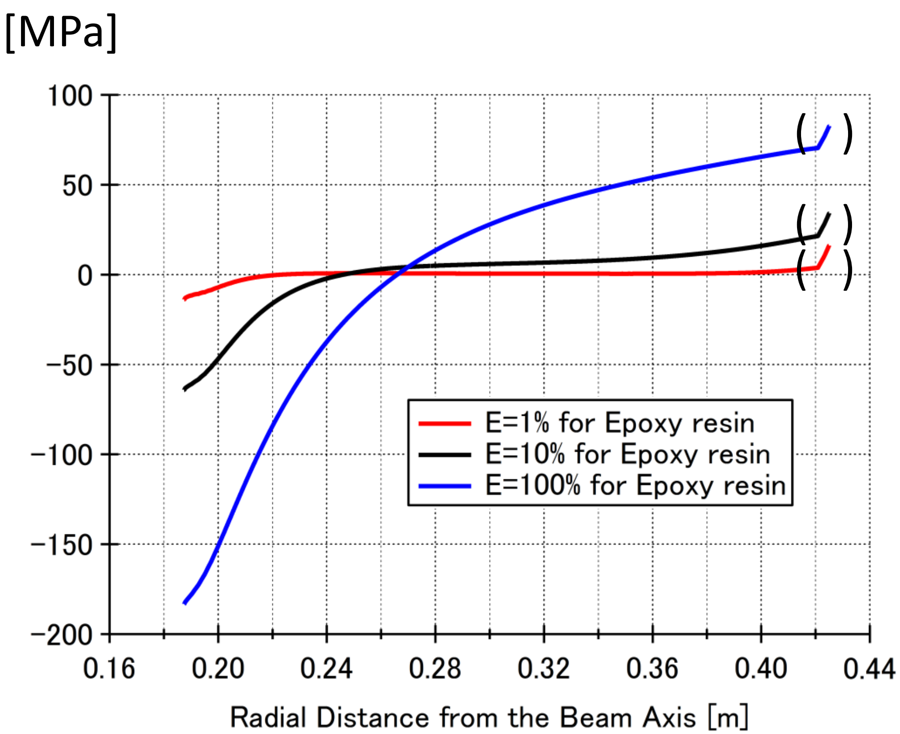
磁束密度分布



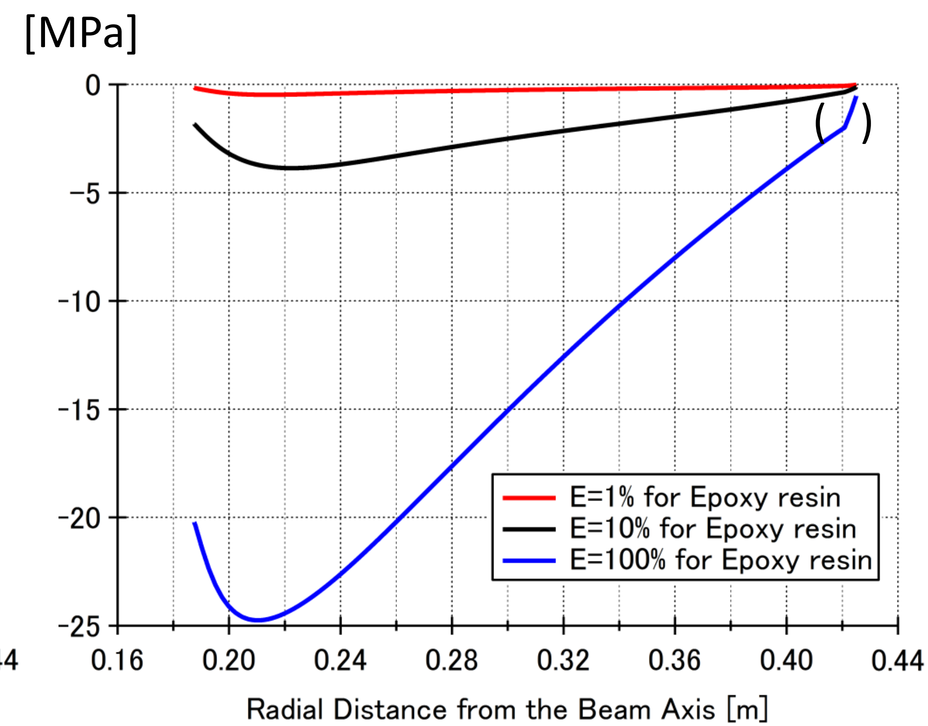
Gap Side Core
Center Core
Short Plate Side Core
Magnetic Flux Density [mT]
Radial Distance from the Beam Axis [m]
0
5
10
15
20
25
30
35
40
45
50
0.00
0.10
0.20
0.30
0.40
0.50
0.60

Circumferential components of the thermal stress

応力は周方向にかかる。



FINEMET



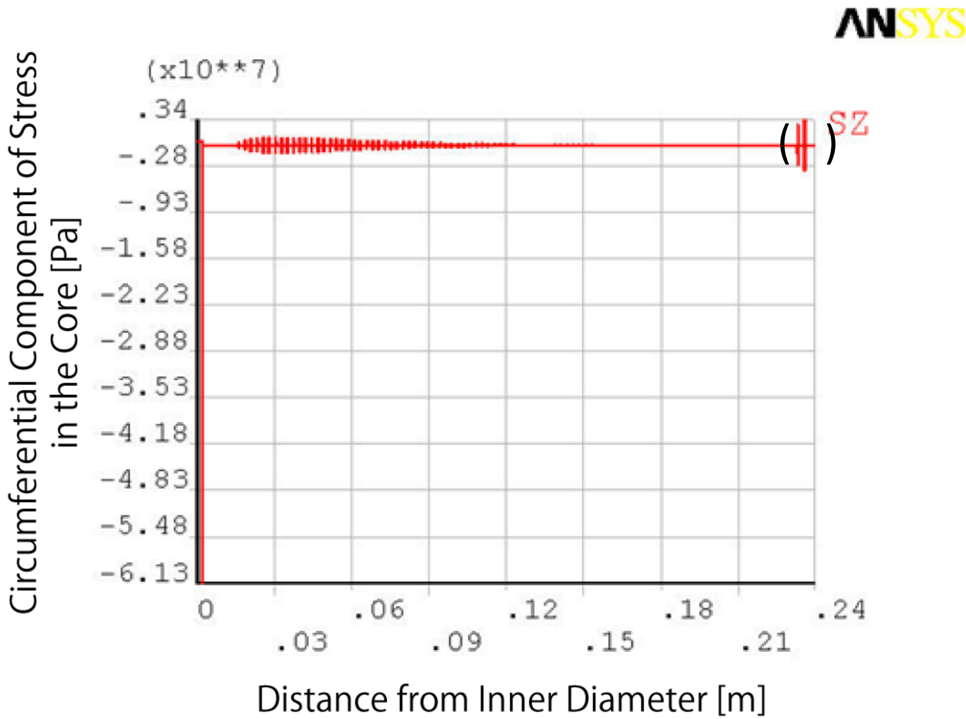
Epoxy resin

Young's ratio of the Epoxy resin decreases.
(Filling ratio of the Epoxy resin decreases.) → Thermal stress decreases.

The core without impregnation is adopted.

Contact simulation

Model with no epoxy resin



Approximately 1MPa (maximum)

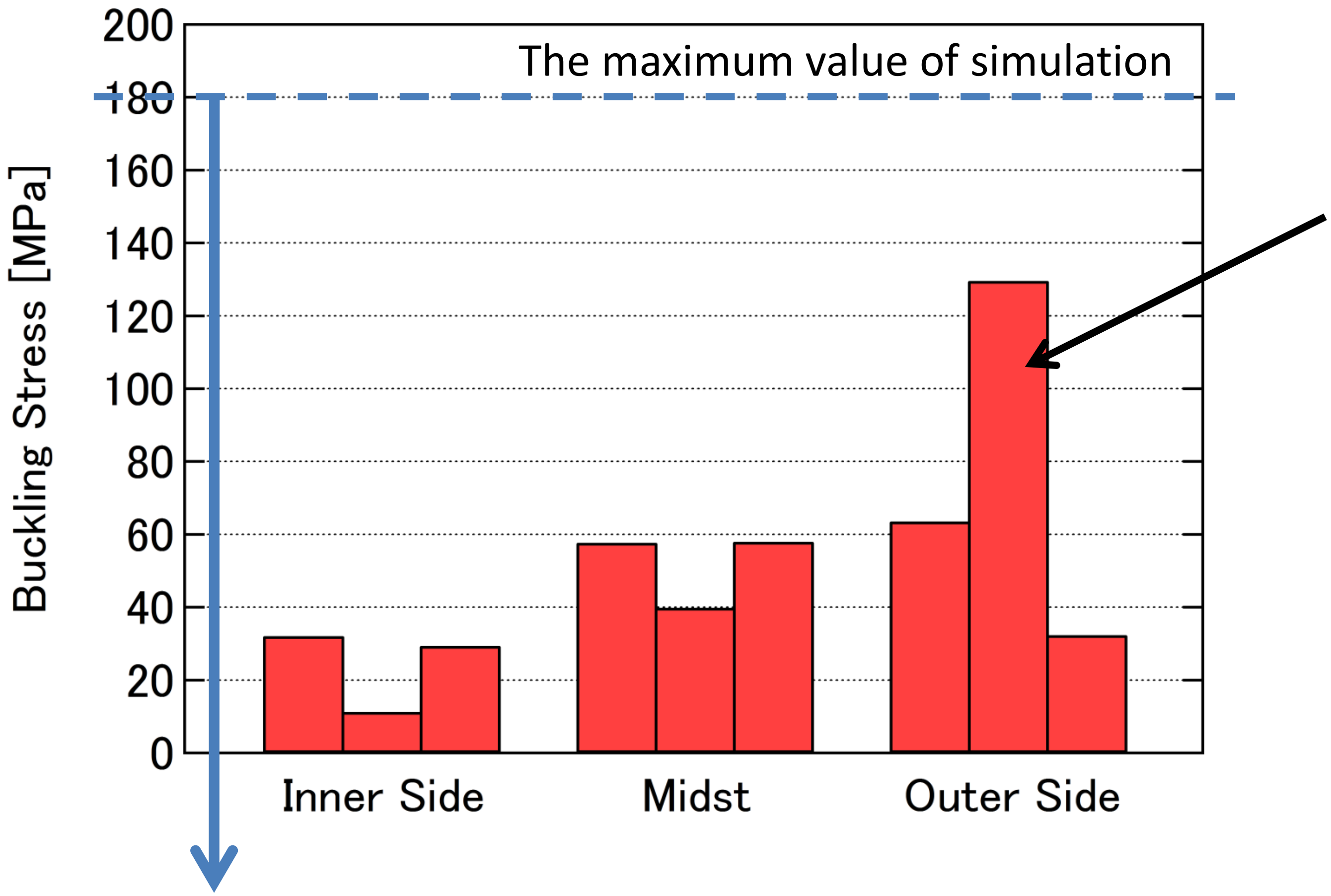
The thermal stress is 2 orders smaller than that of the presently installed core.

Compression test

Fatigue-testing-system

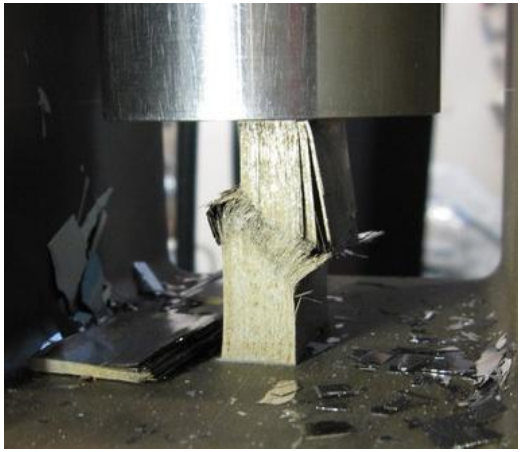
Jig for the compression test

The result of compression test

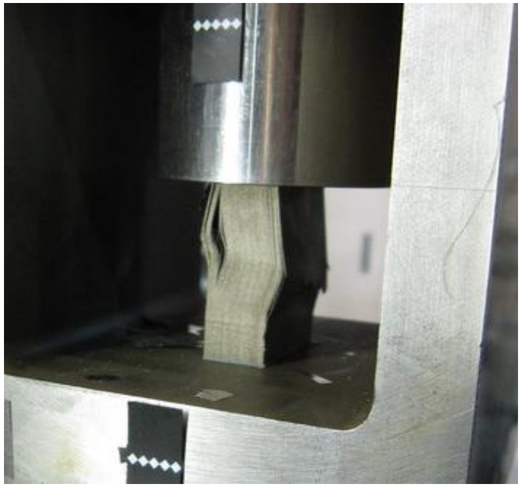


Bucklings appear below 180MPa

Thermal stress is the cause of the buckling.

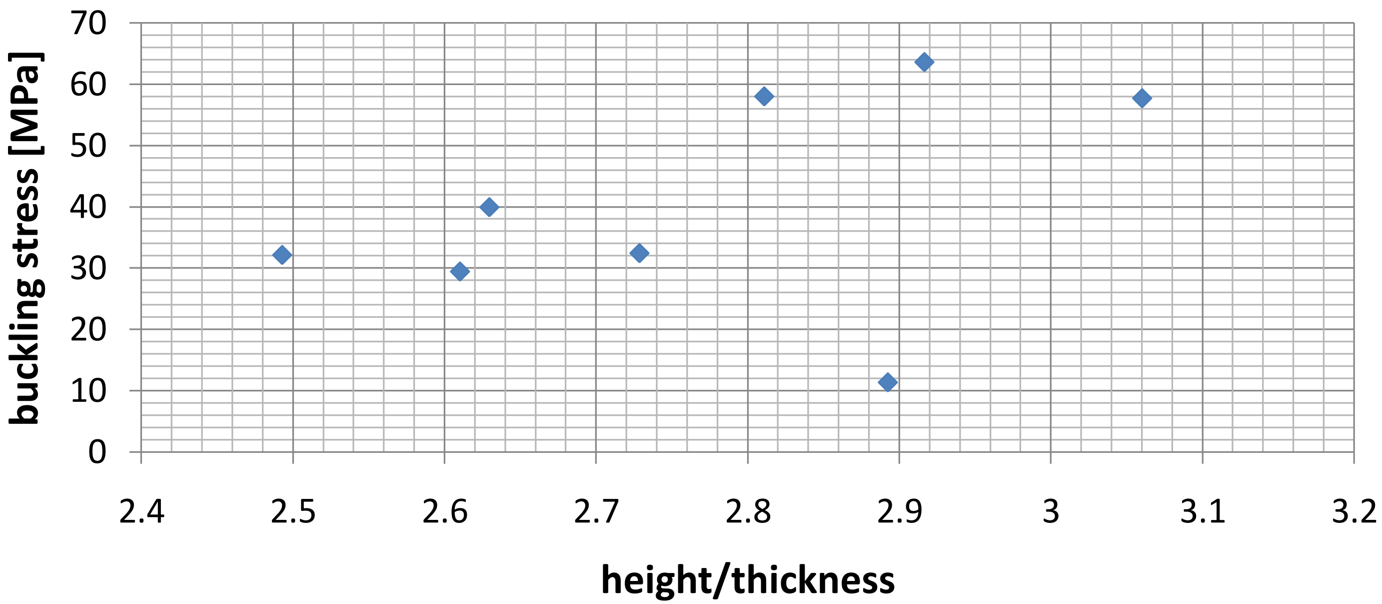


Sheared sample



Buckled sample

Size of sample



Ratio between height and thickness does not relate to the buckling stress.

まとめ

・熱応力シミュレーション　最大180MPa
・圧縮試験　180MPa以下で座屈

熱応力が座屈の原因であることを突き止めた。

熱応力の緩和には含浸無しのコアが効果的である。

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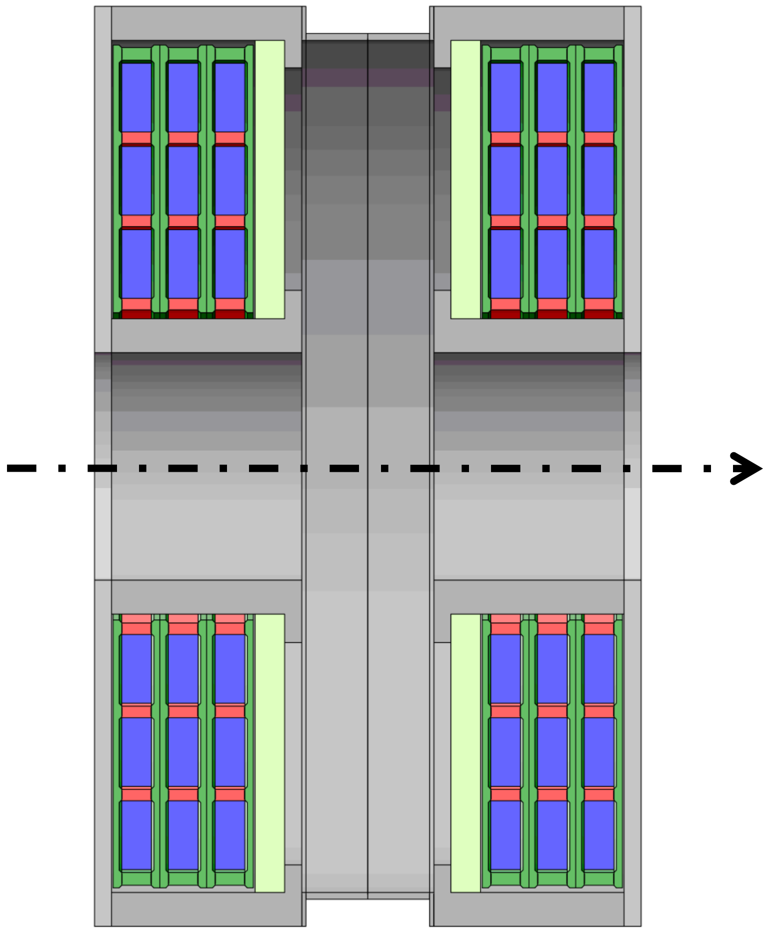
3. 座屈の原因究明
   - RCSコアの座屈現象
   - FINEMETコアの熱伝導率測定
   - 熱応力シミュレーション
   - 圧縮試験

4. 新型加速構造の設計
   - コアモジュール
   - 不活性液体
   - G-10材の膨潤試験
   - コア表面の摩耗試験
   - RF設計
   - 流路設計
   - ½流路試験

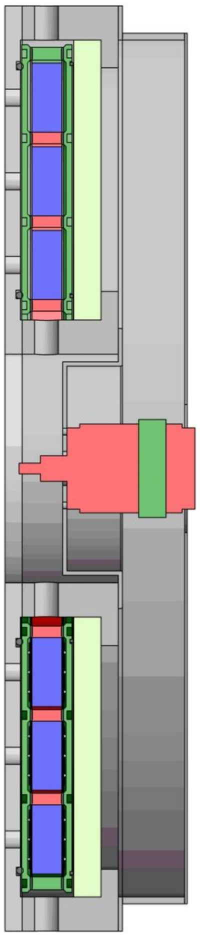
5. プロトタイプ構造の製作

6. 性能試験

7. 結論



One gap structure of
the new cavity
(6 core modules)



The prototype cavity
(one core module)

Two problems on RCS cavity

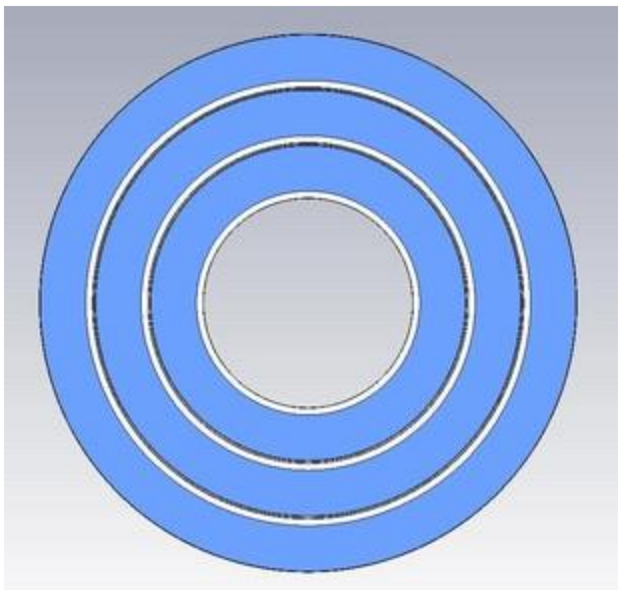
1. Magnetic alloy cores in the cavity got buckled.
2. The coolant (water) corrodes the cores.

Solutions

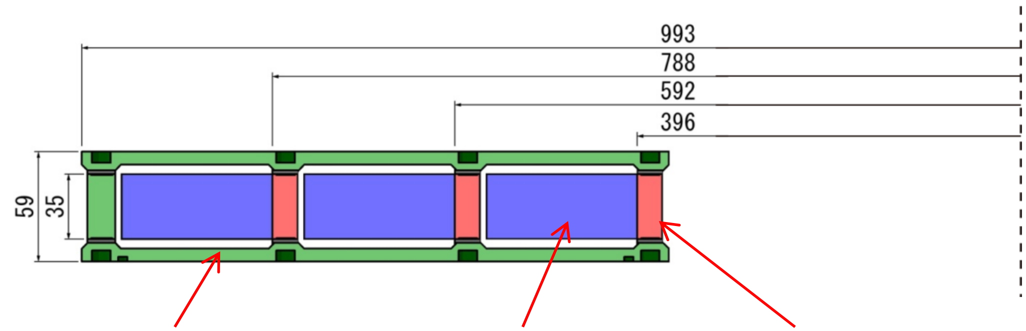
１．熱応力緩和のためにコアをエポキシ含浸しない。
２．不活性の液体を用いる。

Core module

The core is separated into three.



Core module



Advantages of the separation

1. Winding efficiency becomes better.
2. Differentiating structural and functional materials

Advantages of the raw core

1. Release of the thermal stress

   It is able to release the thermal stress and prevent the buckling.
2. Self cleaning and healing

   It is expected seeds of spark are removed by the coolant.

Chemically inert liquid

1. FINEMET core without impregnation is used.
2. Fluorinert is used as a coolant.

FINEMET is a Fe-based magnetic alloy. ➡ FINEMET can be corroded.

	FC-3283 (Sumitomo 3M FC-3283)	Normal paraffin (ENEOS Glade L)	Novec (Sumitomo 3M HFE-7300)	Water
Chemical formula	$(C_3F_7)N_3$	$C_{11}H_{24}$, $C_{12}H_{26}$	$C_6F_{13}OCH_3$	H_2O
Boiling point[˚C]	128	190-210	98	100
Flash point[˚C]	-	71	-	-
Density[kg/m³]	1780	751	1660	992.215
Dynamic viscosity[m²/s]	0.59×10^{-6}	1.36×10^{-6}	0.7×10^{-6}	0.6580×10^{-6}
Specific heat[J/kg/K]	1076	2180	1137	4192
Thermal conductivity[W/m/K]	0.0624	0.126	0.062	0.628
Breakdown voltage[kV/cm]	170	120	110	>1000
Relative permittivity(1kHz)	1.91	2.0	6.14	81
Electric loss tangent(1kHz)	$<4 \times 10^{-4}$	$\sim 1 \times 10^{-4}$	0.016	0.16
Price[1,000yen/Litter]	~19	~0.5	~5	-

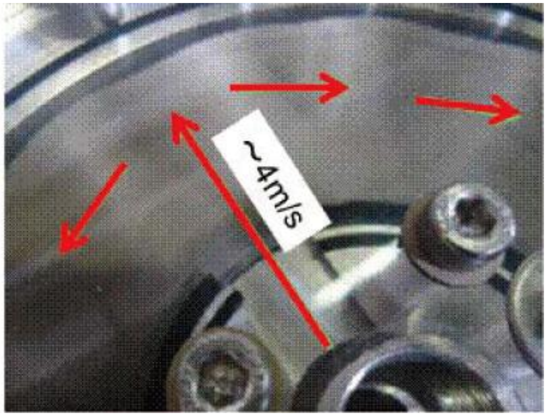
Swelling test for G-10

Samples of G-10 were dipped in Fluorinert for 5 months.

	Before test (18/12/2009)	After test (27/5/2010)	Difference of mass [g]
G-10 sample No. 1	41.98	41.98	0.00
G-10 sample No. 2	43.31	43.32	0.01
G-10 sample No. 3	43.27	43.28	0.01

Appearance, texture and mass did not change. **OK**

Erosion test for the core



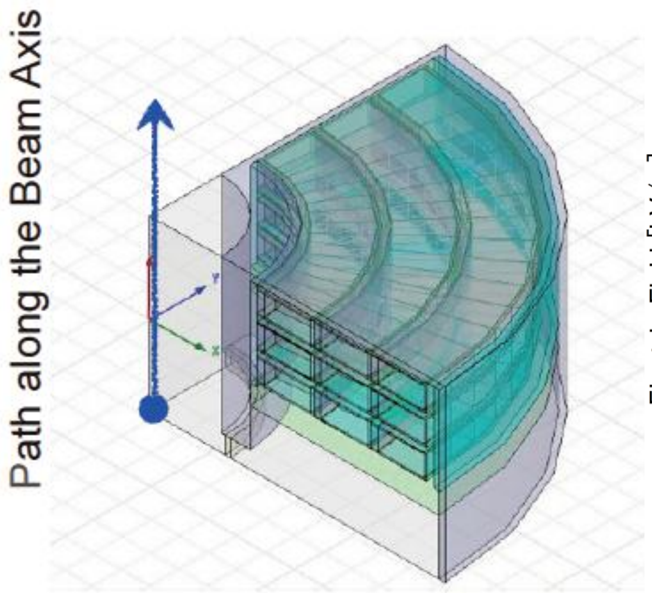
<2m/s in actual operation

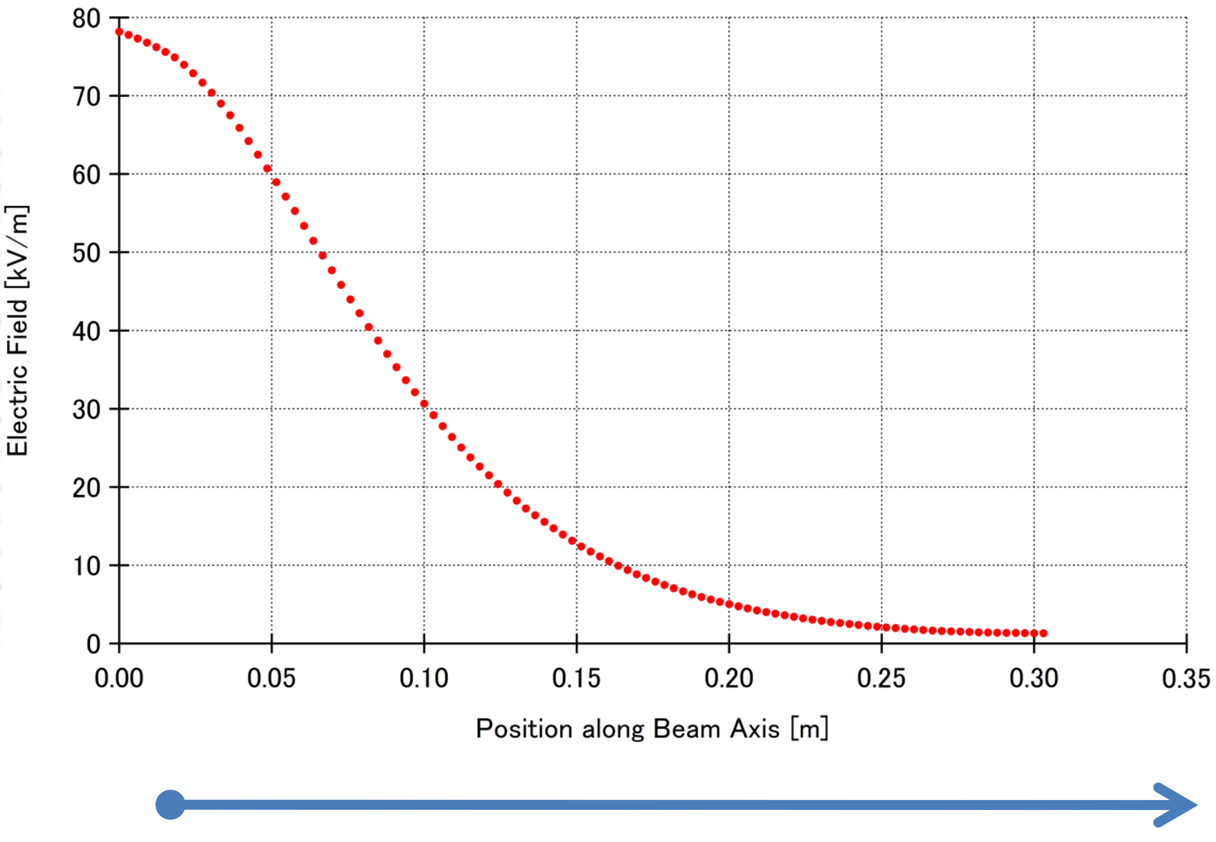
Operated for 2 months

Observed with microscope No defect was seen. **OK**

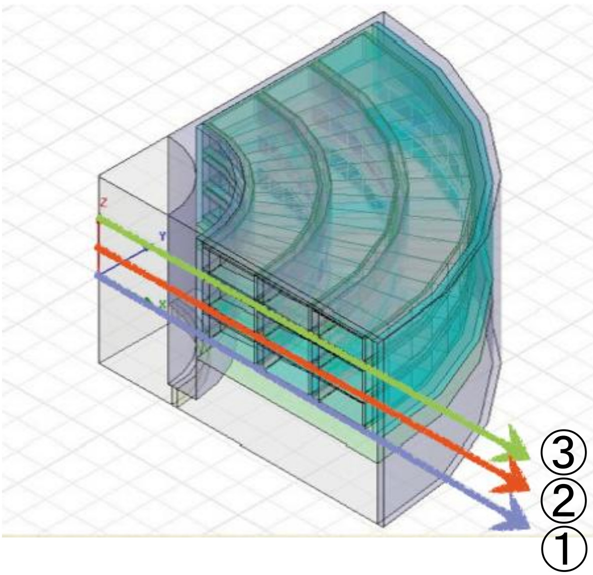
Electric field along the beam axis

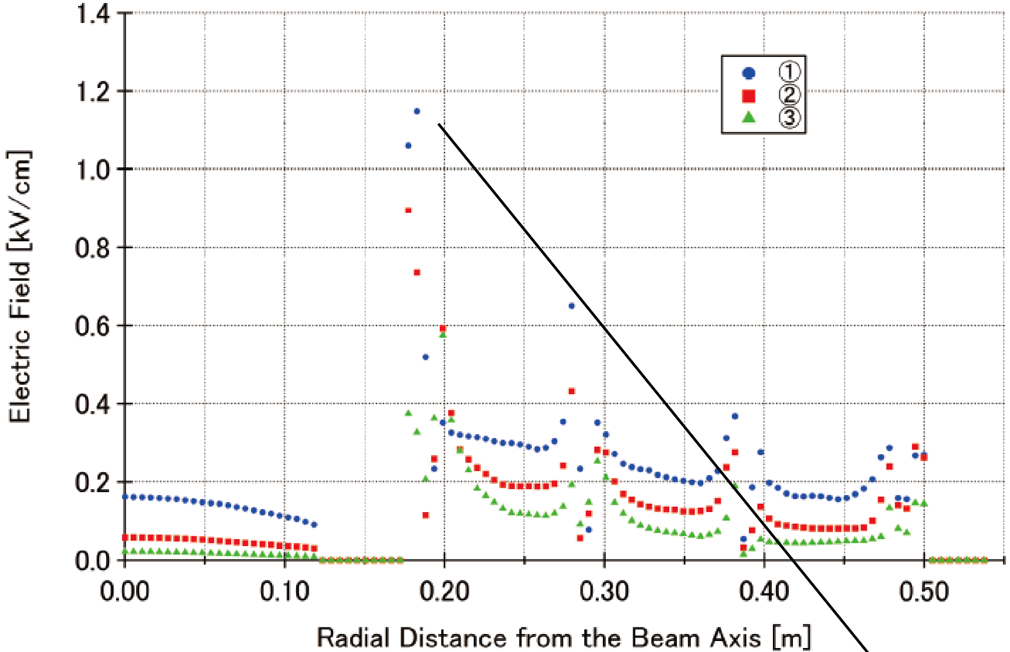
The electric field is normalized with 15kV/gap (design value).





Electric field on the surfaces of the cores

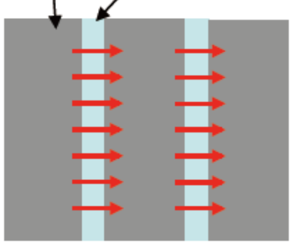




1.2×4=4.8kV/cm

FINEMET 75%

Insulator and Fluorinert 25%



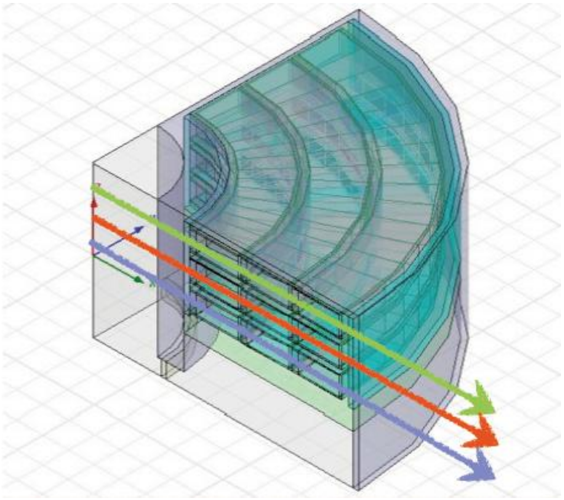
Actual structure of core

→ E field should be multiplied factor 4.

	Fluorinert	Silica	G-10
Dielectric strength [kV/cm]	170	600	220

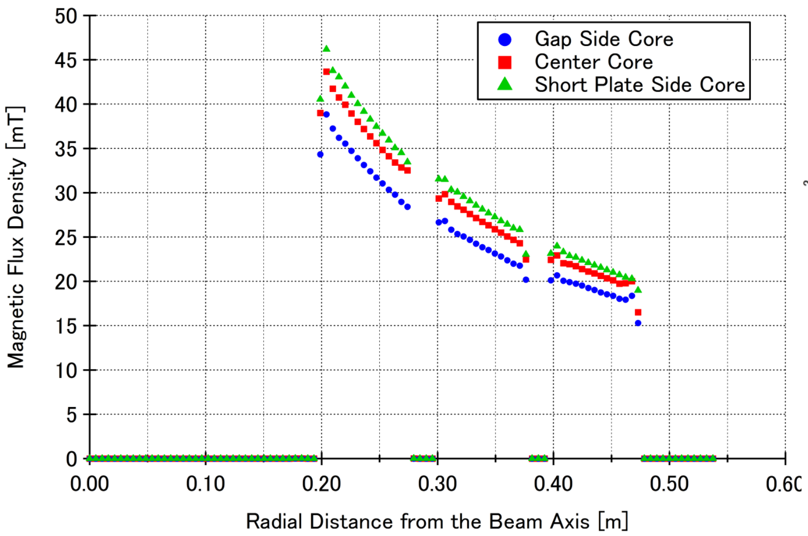
No discharge **OK**

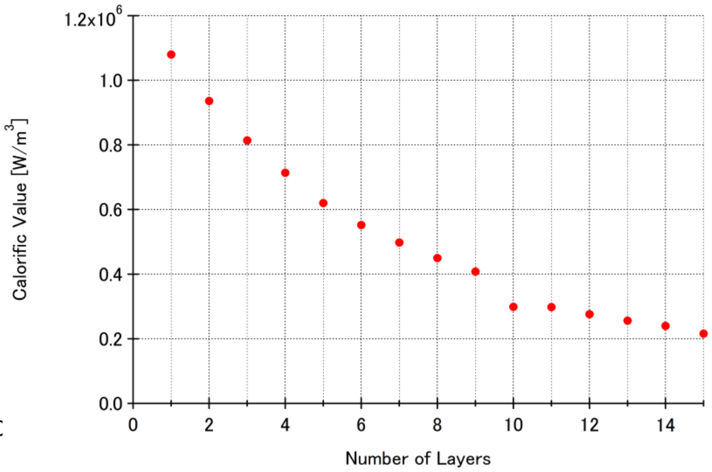
Magnetic-flux-density along the radial direction



Magnetic-flux-density: 1/r distribution
Power loss: $1/r^2$ distribution

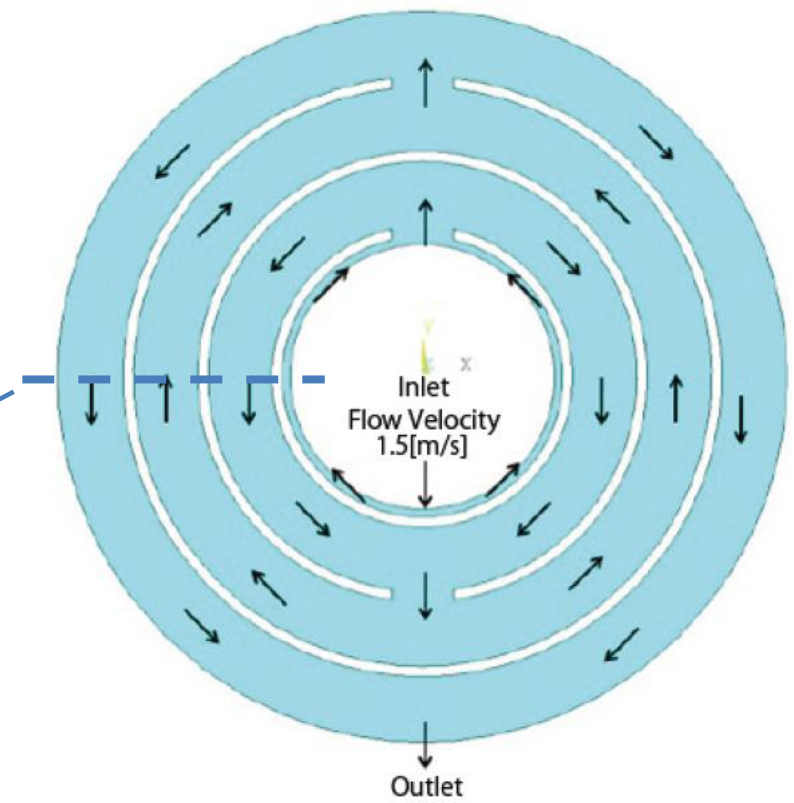
normalized with 6kW



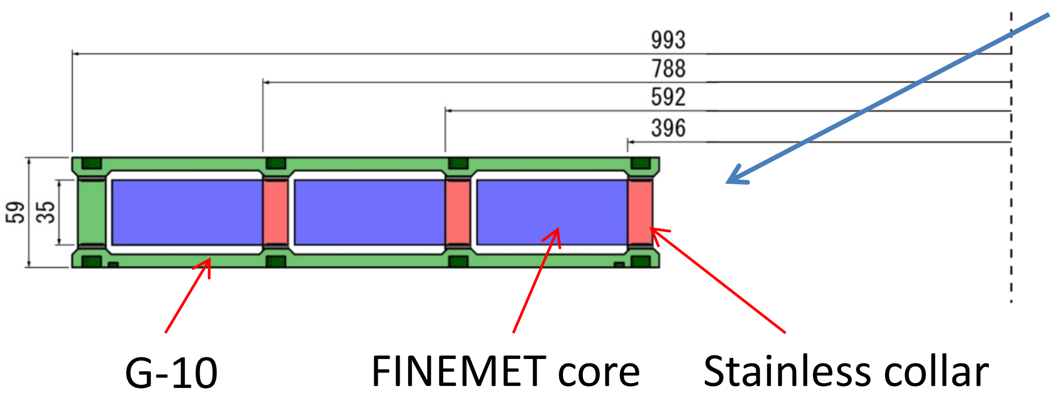


Power loss

Schematic view of the flow channel



Cross-section of the flow channel

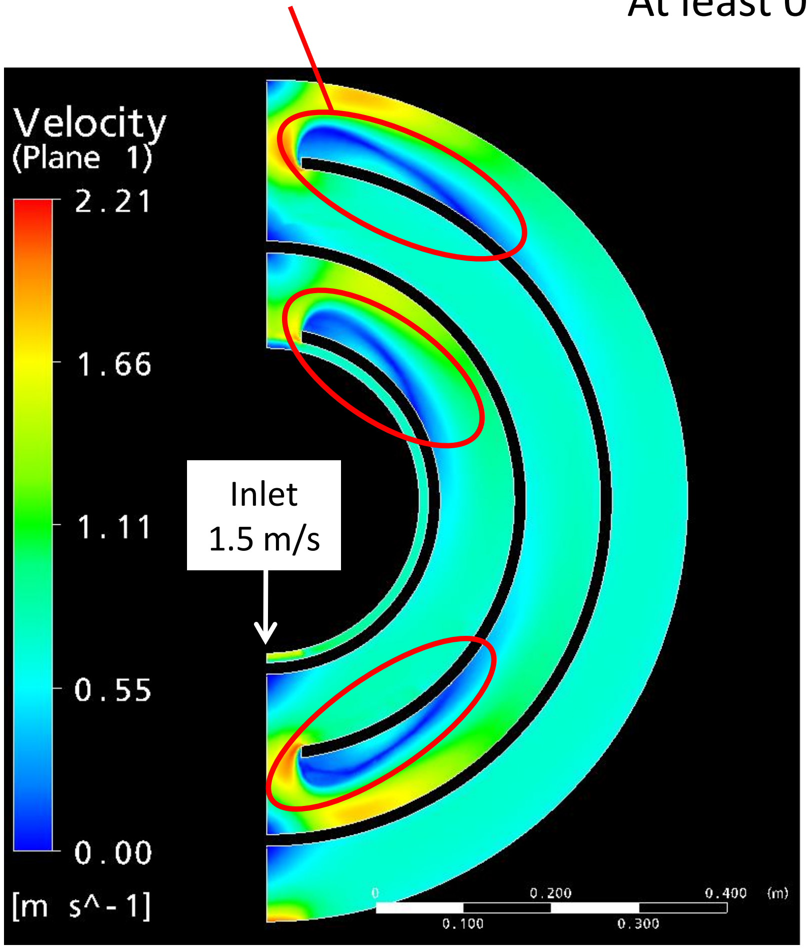


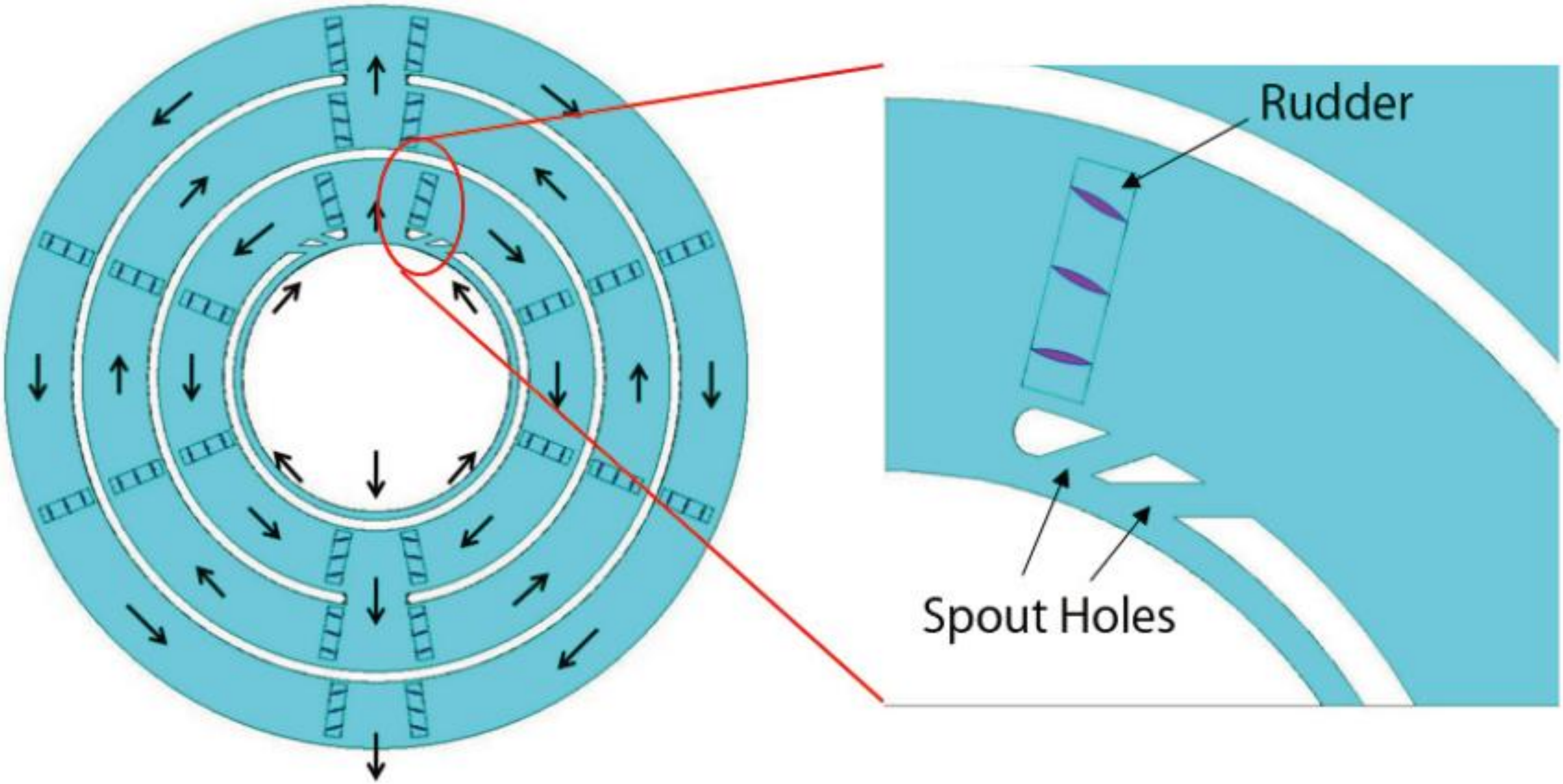
	Cross-section of the flow channel	Flow rate per core module	Velocity of the flow	Reynolds number	Heat transfer coefficient
Real machine	3mm × 81mm	44 L/min	0.75 m/s	6300	750W/m^2/K
prototype	5mm × 81mm	83 L/min	0.85 m/s	11600	750W/m^2/K

Velocity of Fluorinert

stagnation

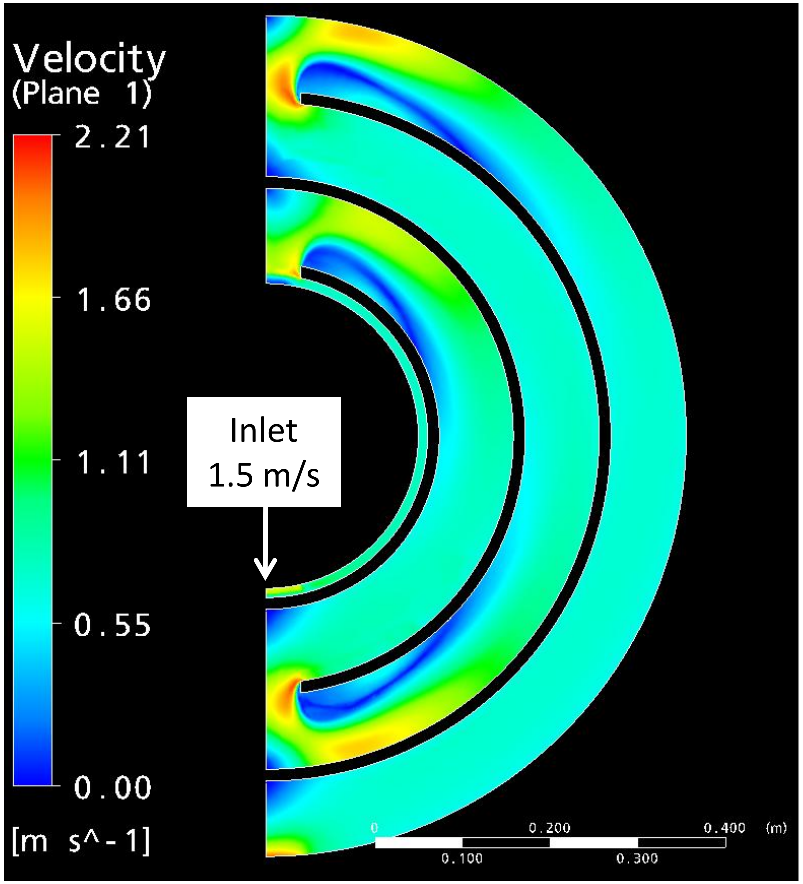
At least 0.33m/s is needed

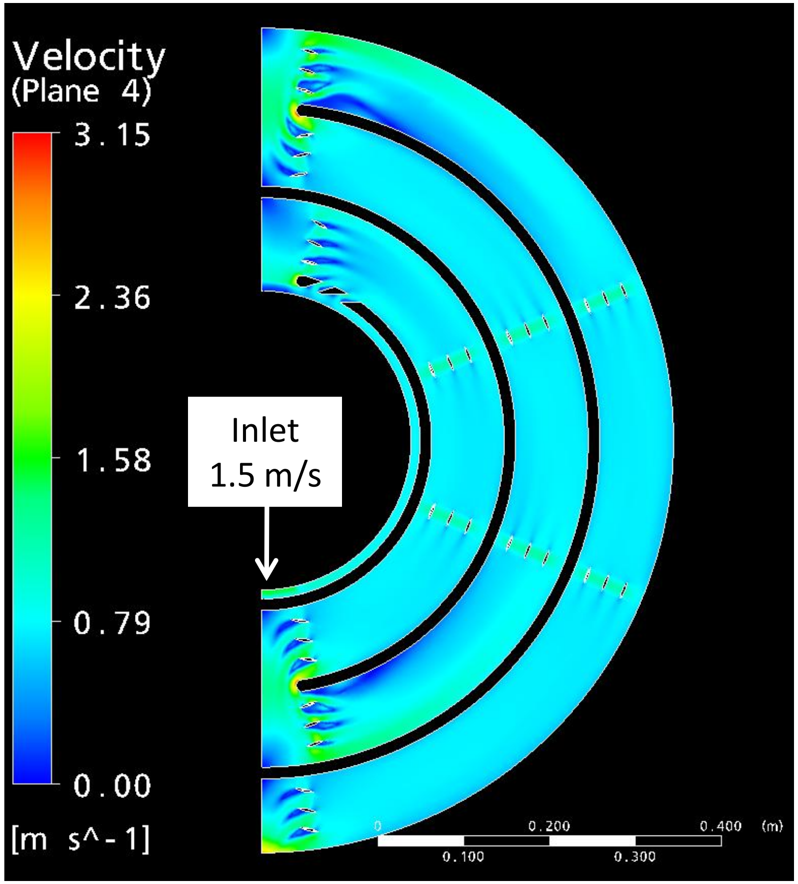




Each rudder is optimized.

Improvement of the flow

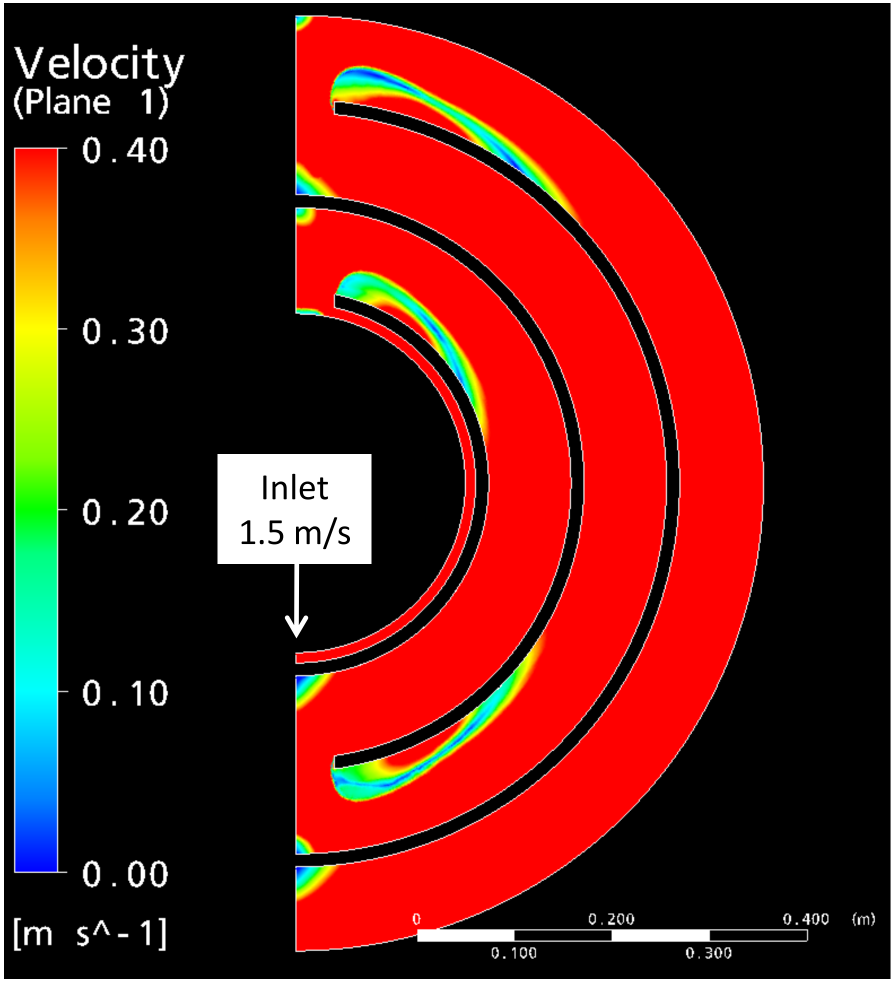


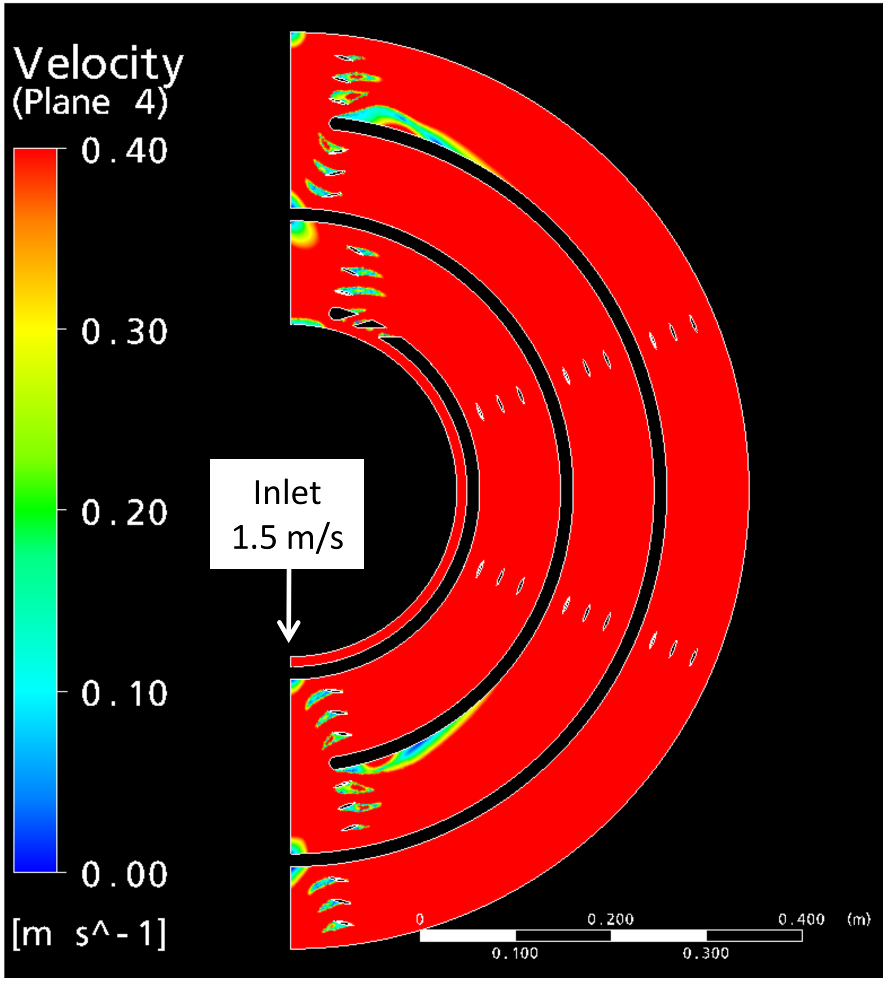


With rudders and spout holes

Critical velocity is 0.33[m/s].

Velocity of Fluorinert (max. of the contour is 0.4[m/s])



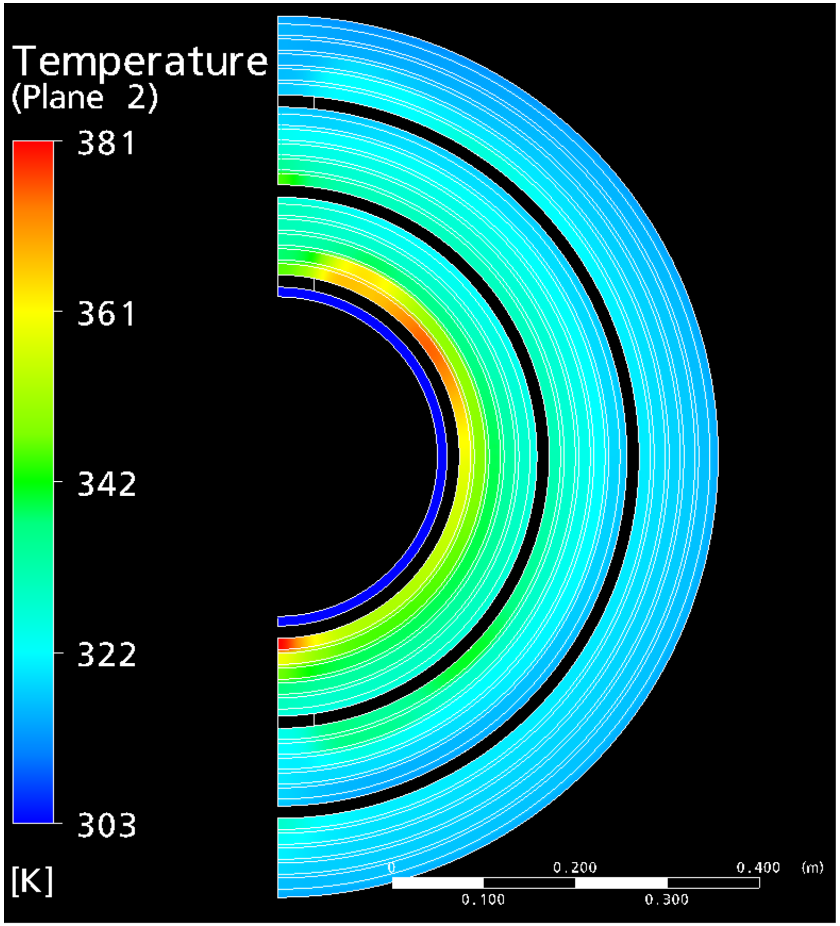


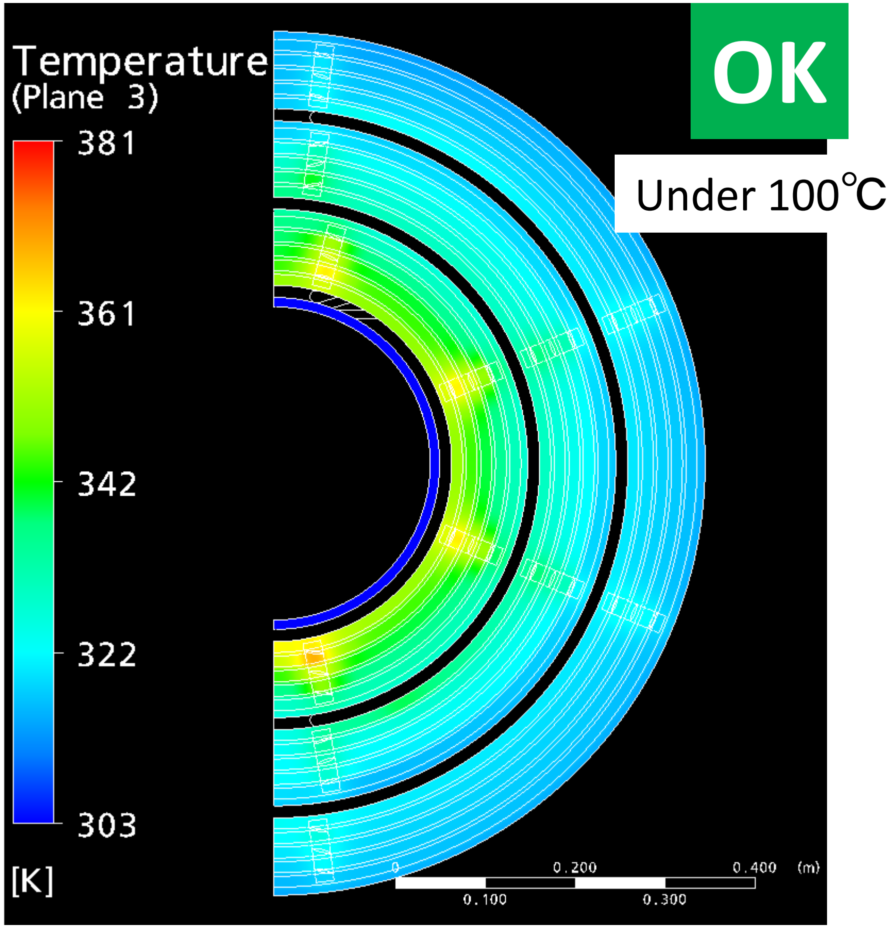
With rudders and spout holes

Half sized flow channel

Temperature at the center of the core

Rudders are defined as insulators
and touch with cores





With rudders and spout holes

まとめ

開発の基本となるアイデア

1. コアモジュール
   生コア
   径方向3分割

2. 冷媒としてフロリナートを採用（乱流）

予備試験

3. G-10の膨潤試験 → 変化はみられない。

4. コア表面の摩耗試験 → 摩耗はみられない。

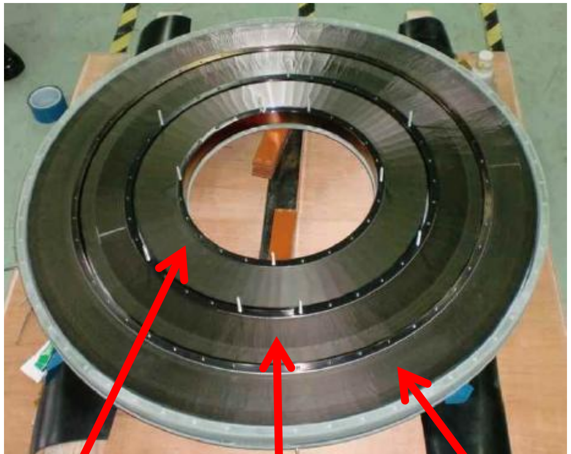
加速構造の設計

5. RF設計 → 放電の無いRF構造を設計できた。

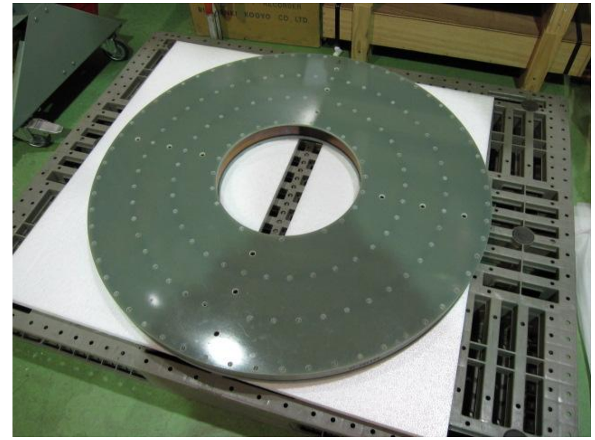
6. 流路設計 → 淀みを消して、コア内温度を100℃以下に抑える流路を設計できた。

アウトライン

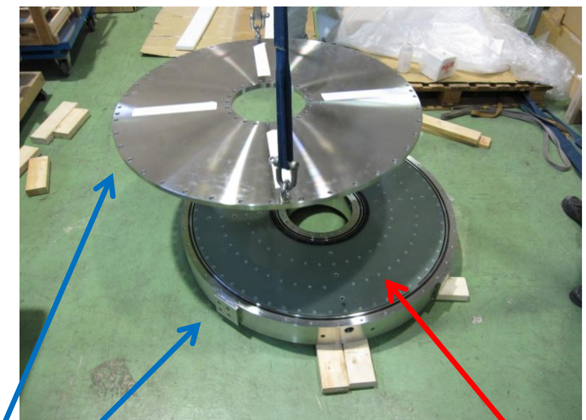
1. 新型加速構造開発の要求
2. RCSの概要及び、加速構造の構成
3. 座屈の原因究明
4. 新型加速構造の設計
   - コアモジュール
   - 不活性液体
   - G-10材の膨潤試験
   - コア表面の摩耗試験
   - RF設計
   - 流路設計
   - ½流路試験
5. プロトタイプ構造の製作
   - プロトタイプ構造の組立
   - Test Facility
6. 性能試験
7. 結論



Small core Middle core Large core



Unifying with G-10 plates



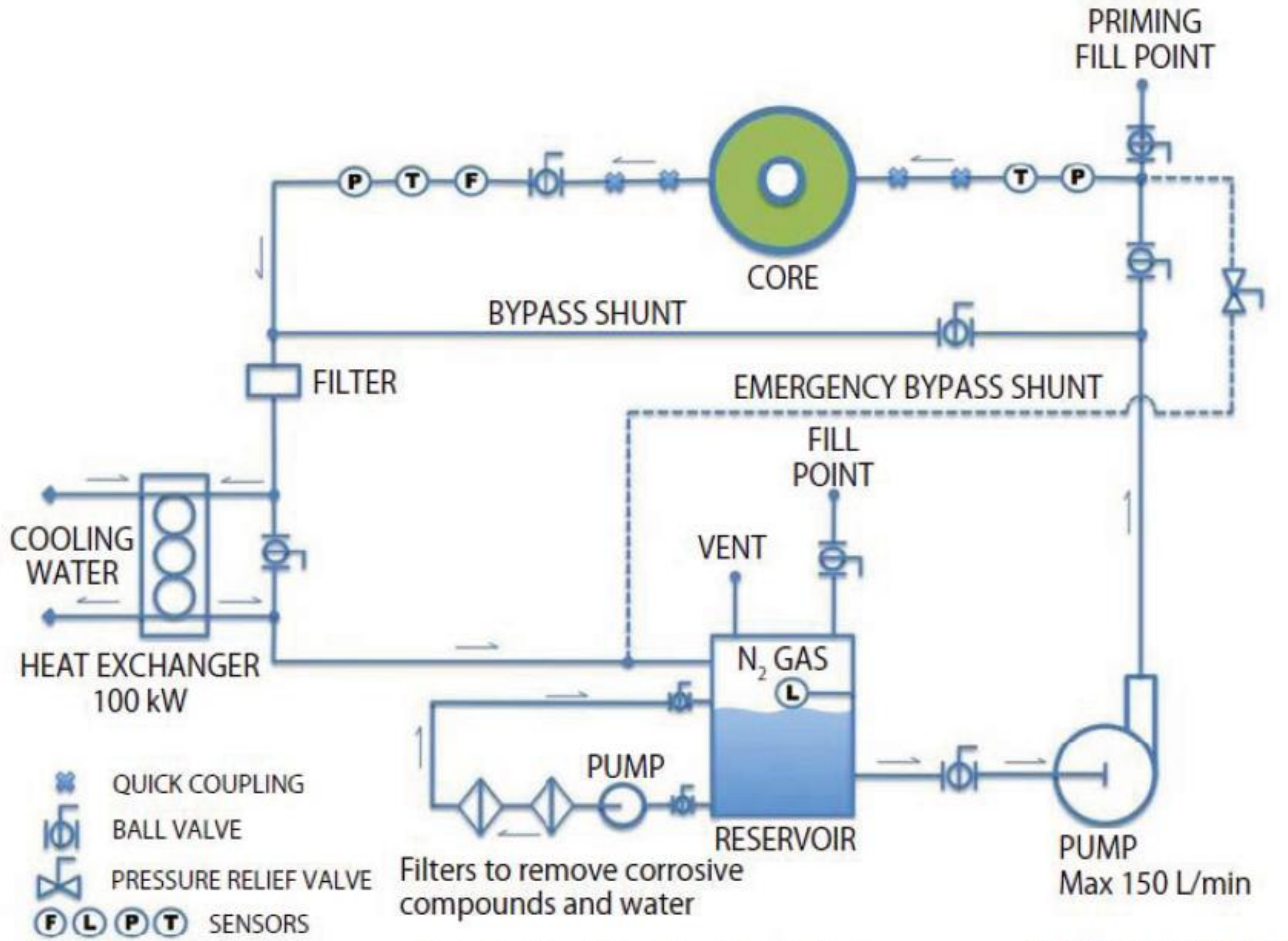
Tank (stainless) Core module

Pressuring with nitrogen gas

- EPDM (Ethylene Propylene Diene Monomer) rubber is used as the sealant.
- Brass plugs are used.
  The tank is made of stainless. The difference of materials avoids sticking.
  Fluorinert doesn’t corrode brass.
- Airtightness was examined with N_2 gas before pouring Fluorinert. (2[atm])

Test facility

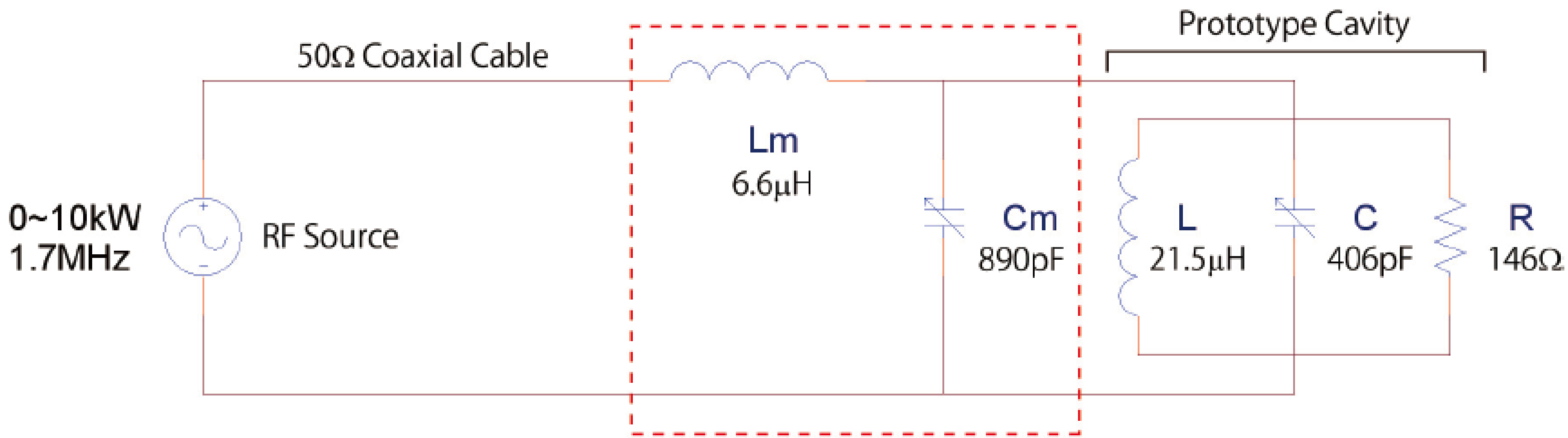
RF source
- ➢Semiconductor
- ➢Max. 10kW
- ➢0.8 – 3 MHz

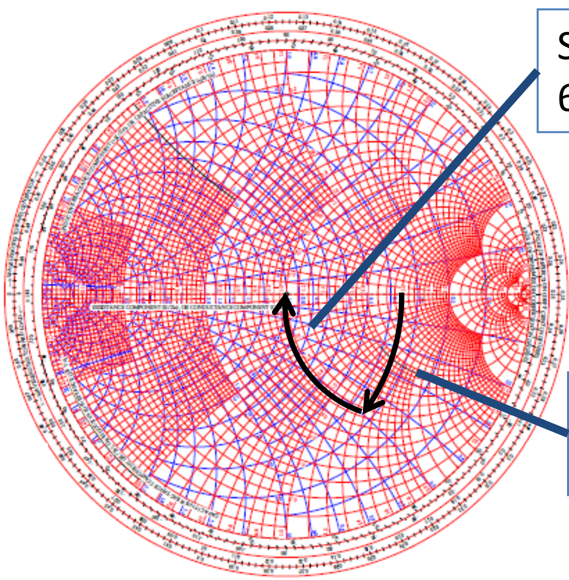


Schematic of Core Cooling System

Interlock system
- ➢Flow rate
- ➢Temperature at inlet

Matching element

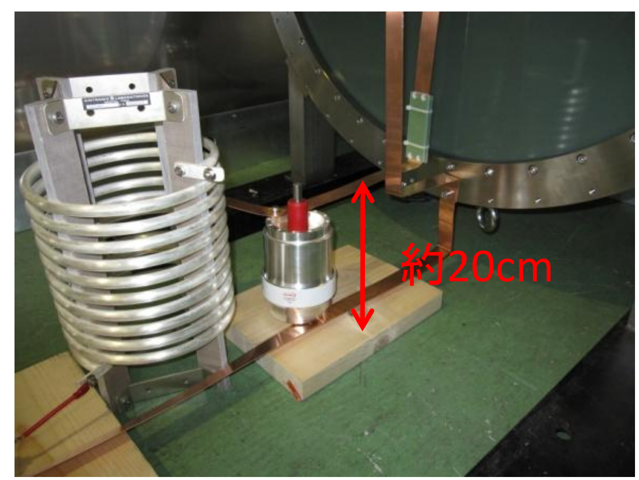




Series inductor
6.6μH

Parallel capacitor
890pF

Immittance chart



OK

VSWR=2.7 → 1.1
（反射率46%→6%）

アウトライン

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６．　性能試験
- 共振周波数調整
- Ｑ値測定
- フロリナート温度上昇測定
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- コア表面温度測定
- 熱伝達係数測定

７．　結論

Tune of resonance frequency

Adjusted to tune to 1.7MHz

measurement simulation

Prototype cavity

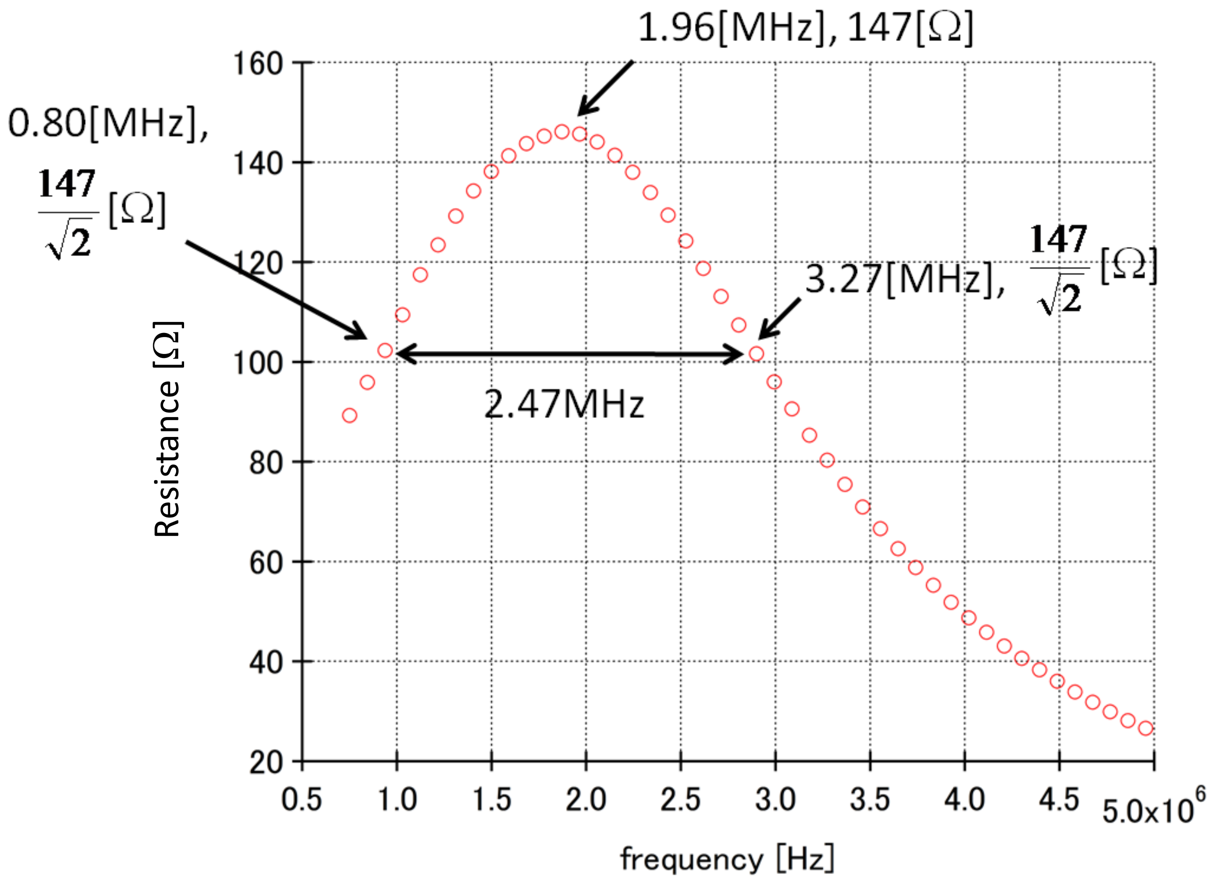
Variable capacitor 406 pF ⟷ 400 pF

Matching element

Aluminum shield

Q factor

Real part of the impedance of the prototype cavity



$$Q = \frac{1.96}{2.47} = 0.8$$

Presently installed RCS cavity
Q=0.6

OK

Temperature rise of Fluorinert

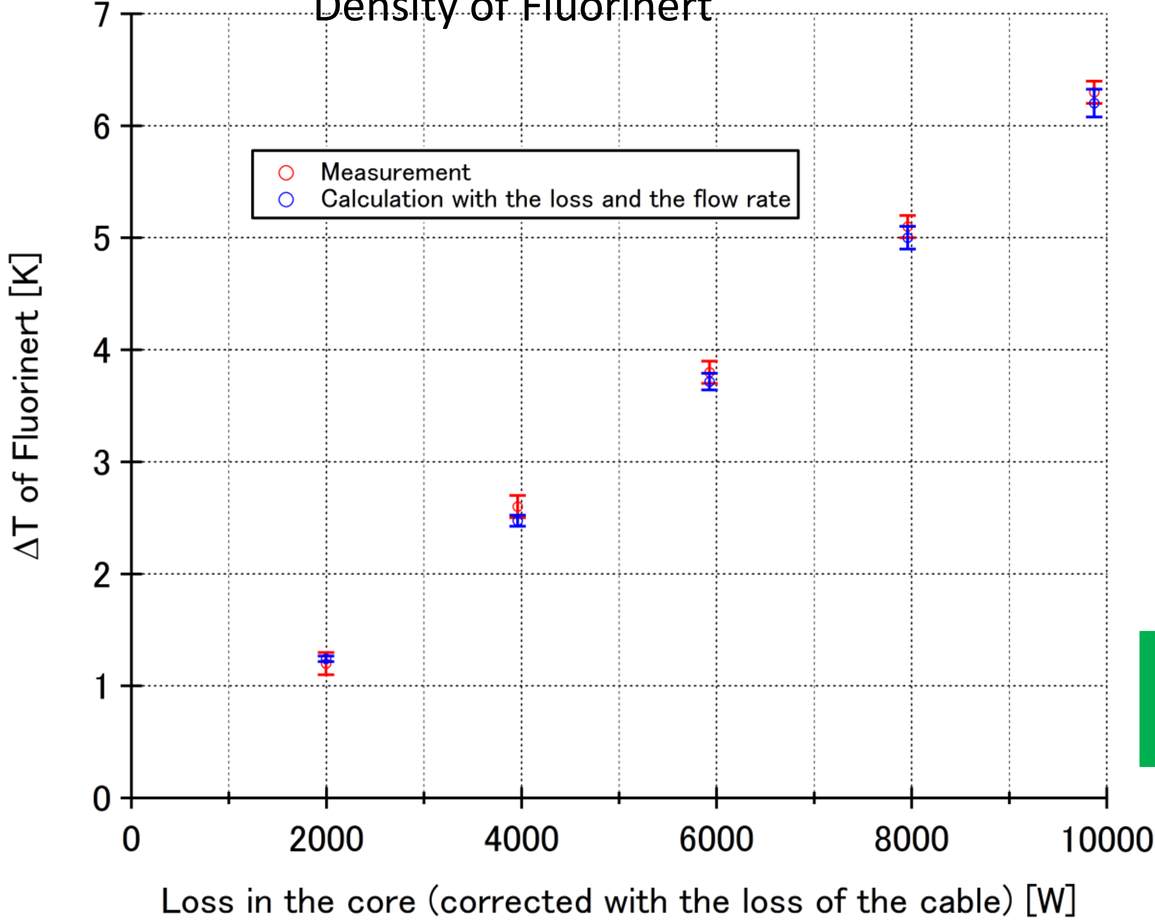
$$\Delta T = \frac{P[\mathrm{W}]}{L[\mathrm{m^3/s}]\times\rho[\mathrm{kg/m^3}]\times C[\mathrm{J/kg/K}]}$$

Power loss

Flow rate

Density of Fluorinert

Specific heat of Fluorinert

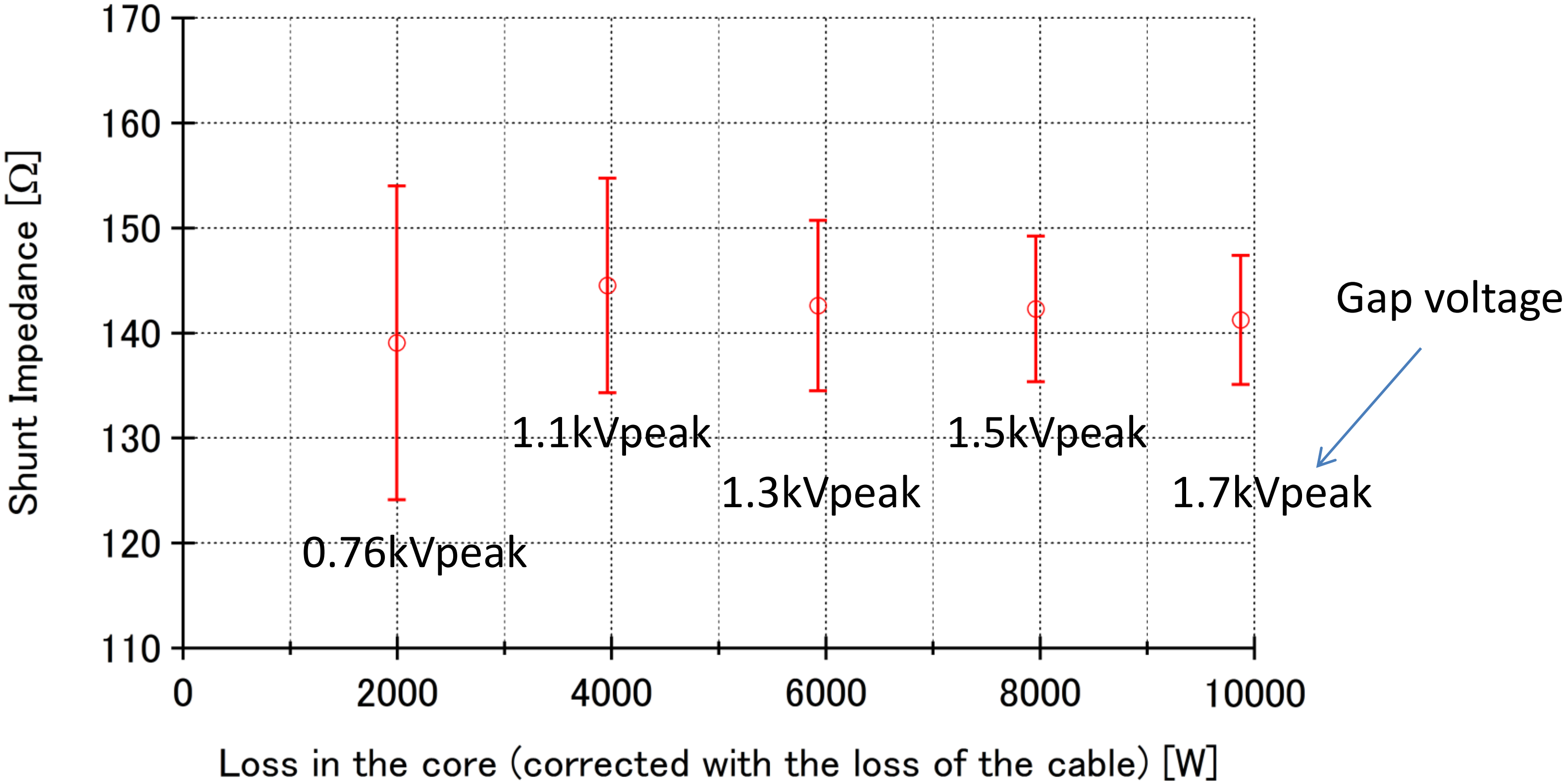


Flow rate
50L/min

OK

Shunt impedance

$$R_p = \frac{V^2}{2P}$$



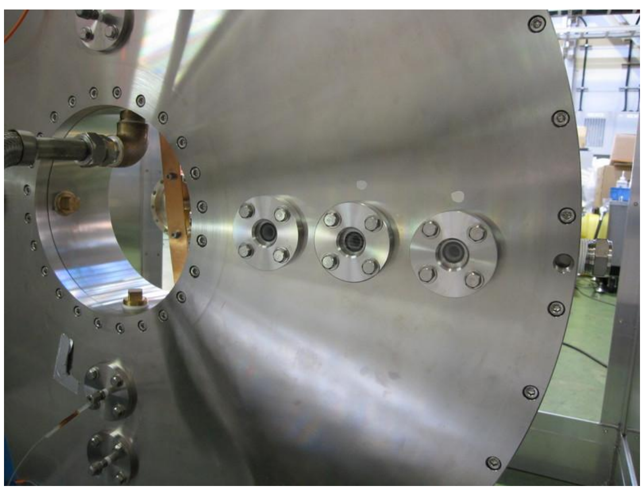
No degradation was seen at high power.

OK

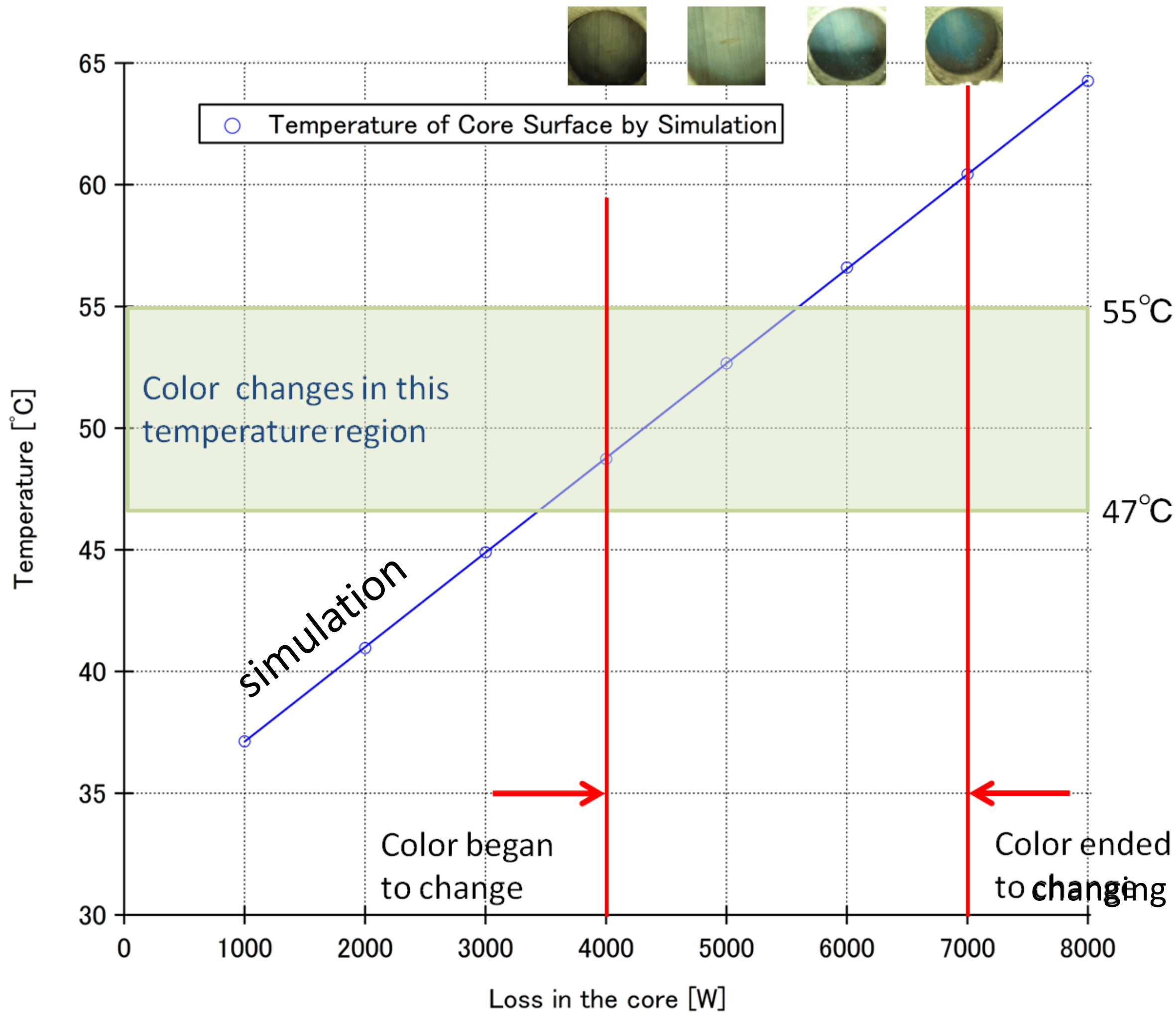
Temperature on the surface of the small core

OK

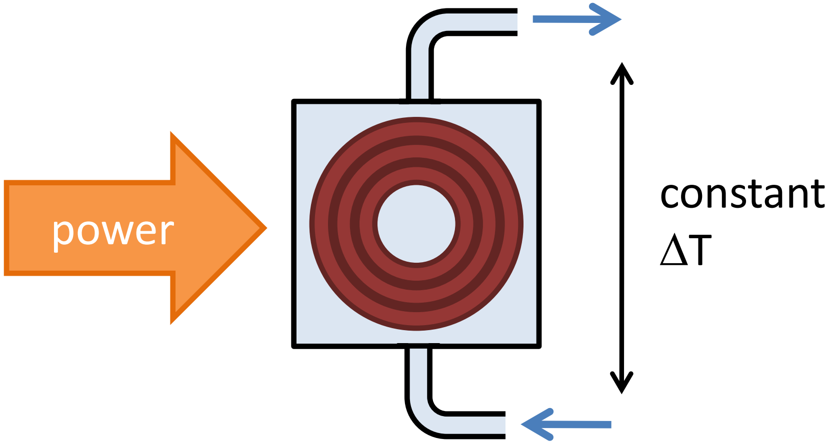
Thermo paint

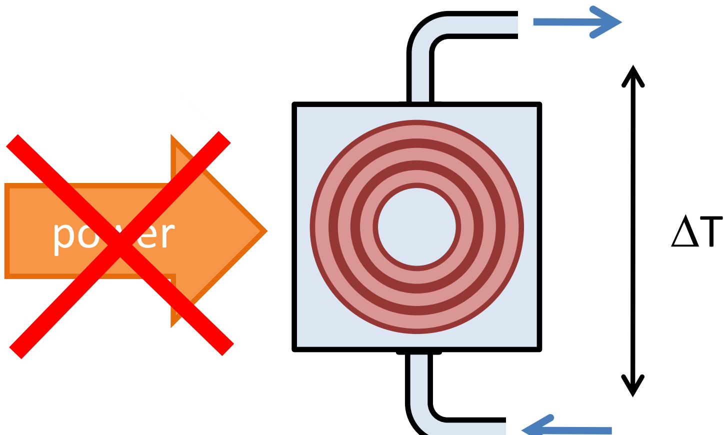


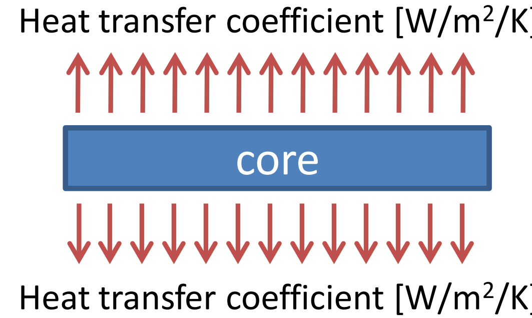
View ports

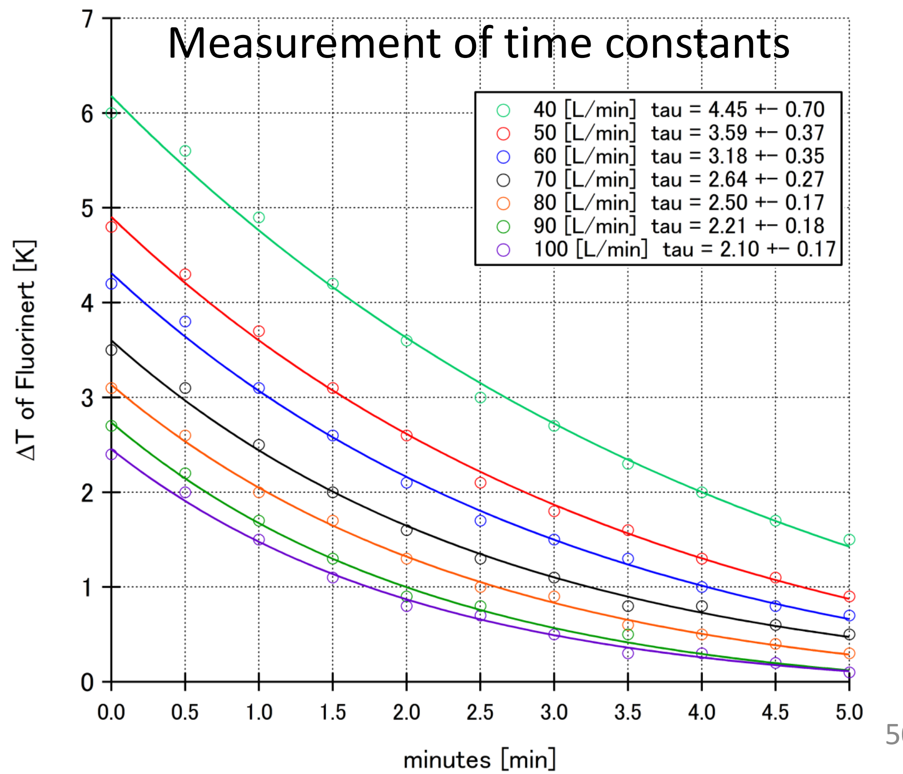


Measurement of heat transfer coefficient

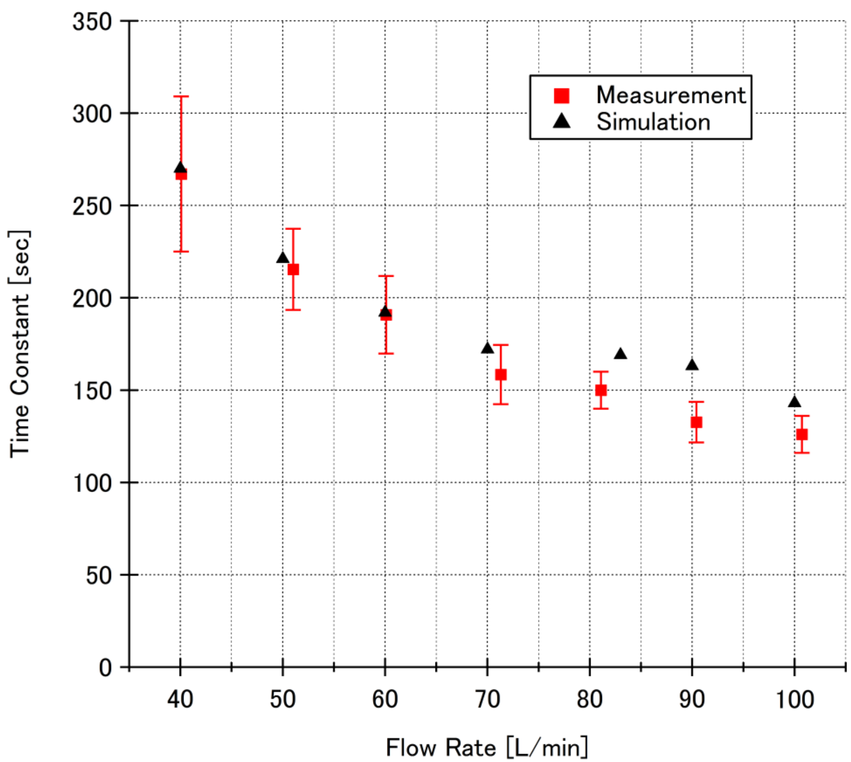




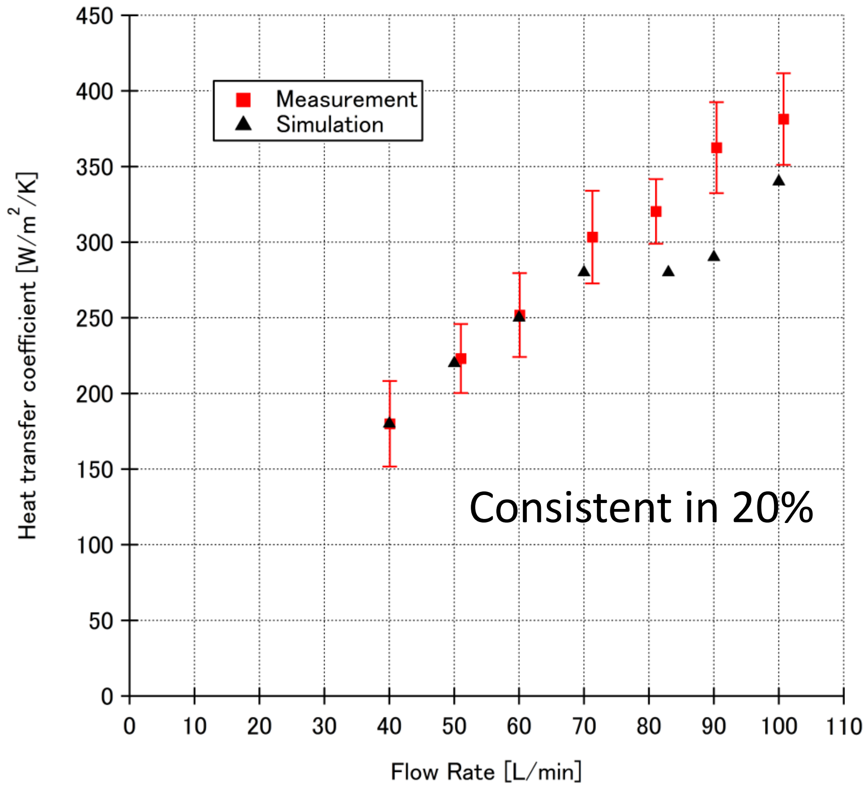




Measurement of the heat transfer coefficient



Time constant



Heat transfer coefficient

$$h = \frac{\rho V C}{\tau A}$$

h: heat transfer coefficient

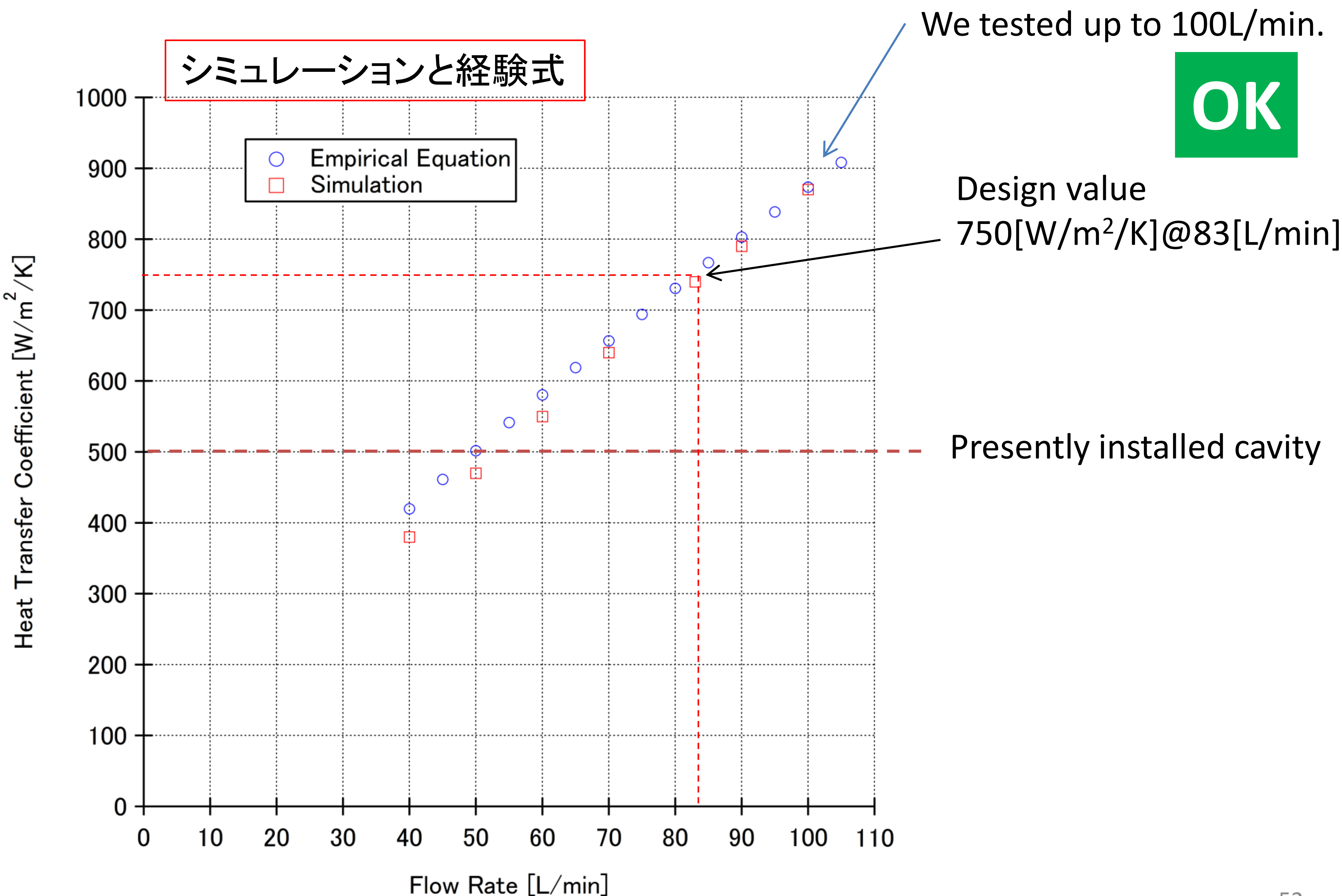
ρ: density of the core

V: volume of the core

A: area of the surface of the core

τ: time constant

Heat transfer coefficient on the surface of the core



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   - 熱伝達係数測定

   加速構造としての性能（共振周波数調整、Q値測定、シャントインピーダンス測定）

   冷却性能（コア表面温度測定、熱伝達係数測定）

7. 結論

Conclusions

Issues to be solved

1. New cavity for beam enhancement is needed.
2. Presently installed cavities need to be improved.

In order to solve these problems

Identify the cause of the buckling problem

1. Simulation of the thermal stress
2. Compression test

The cause is thermal stress
No impregnation is better.

Development of a new cavity

Features
1. "Raw" and "Radially separated" cores
2. Turbulent flow of Fluorinert

Prototype cavity was developed and performance test was carried out.

Conclusions

Development of the prototype cavity

One core module

Measured properties

1. Resonance frequency: 1.7 MHz
2. Shunt impedance: 146 Ω
3. Q factor: 0.8

4. Heat transfer coefficient: 750 $W/m^2/K$ @ 83 L/min
5. The cavity works stably with 10 kW/core module.

(6kW/core for the presently installed cavity)

- **The cavity has enough performance for J-PARC RCS.**
- **This is the first development of the cavity loaded with magnetic alloy cores, which is able to be operated stably with the large input power of 10[kW] per core.**

自分がやっていないこと

- RF計算のためのコアのマクロ媒質モデル構築（長谷川さん・亀田さん）
- 方向舵と噴出孔の最適化（高橋君）
- 半導体増幅器の設計・製作（サムウエイ）
- フロリナート循環システムの設計・製作(大洋バルブ)

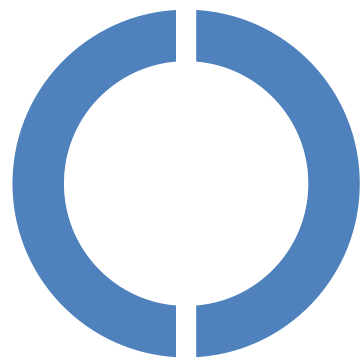
Future plans

1. Breakdown test

Pulse
Max. Voltage: 10kV
Width: >200ns
Rise time: <60ns

2. New cavity for MR

The core is separated into three.
The core is cooled by Fluorinert.



Cut core

The cutting method for the raw core should be established.

3. Evaporative-cooling-system

Three problems to be solved

- Shock waves
- E fields concentrating on bubbles
- The system to stabilize the pressure inside the cavity

The end of the slides