



OSAKA  
UNIVERSITY



# Development of HTS magnet system for Skeleton Cyclotron Accelerator - Next Generation Medical Application - - KAKENHI (S) -

S. Noguchi (Hokkaido Univ.)

A. Ishiyama (Waseda Univ.)

H. Ueda (Okayama Univ.)

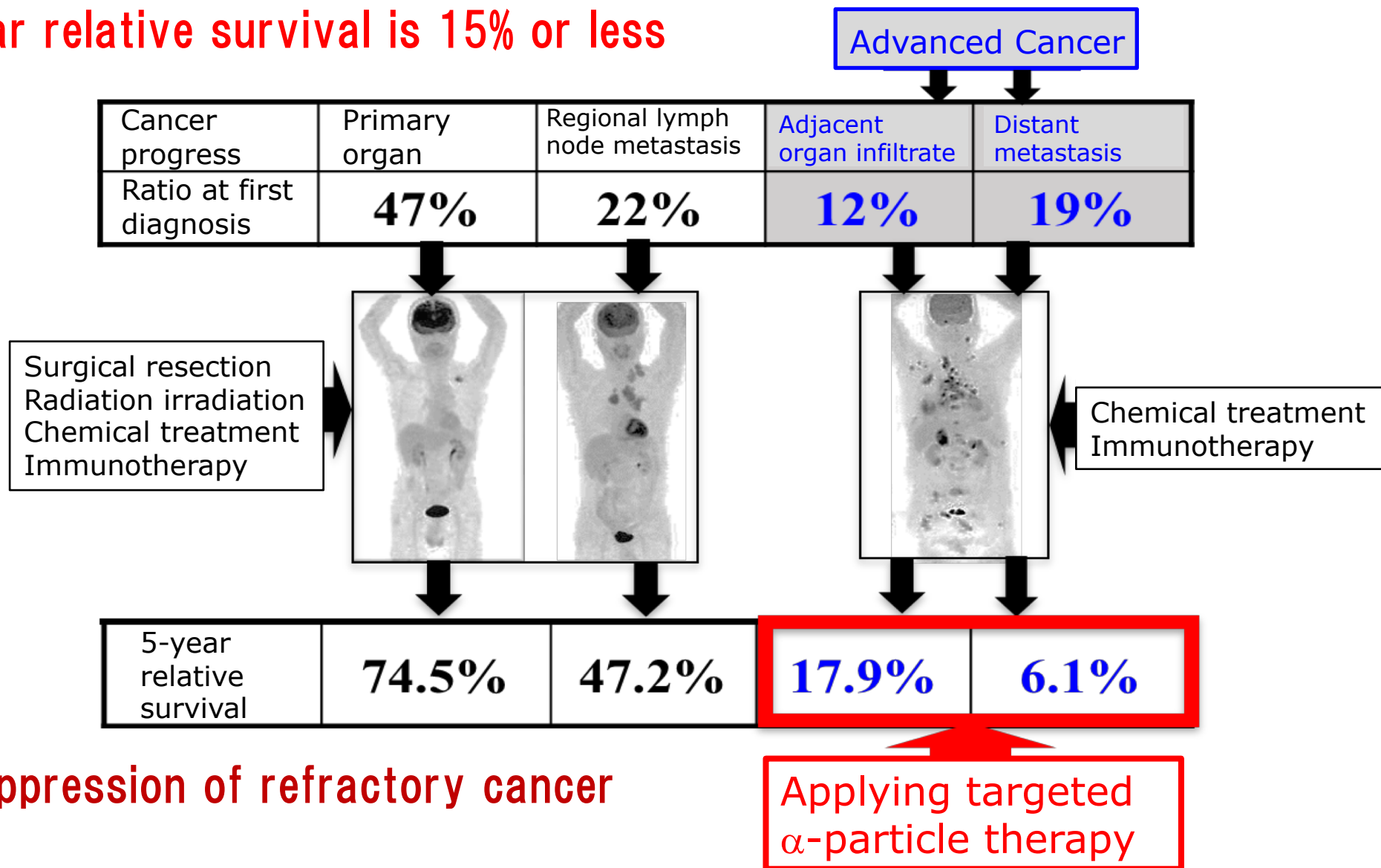
T. Watanabe, S. Nagaya (Chubu Electric Power Co.)

J. Yoshida (Sumitomo Heavy Industries, Ltd.)

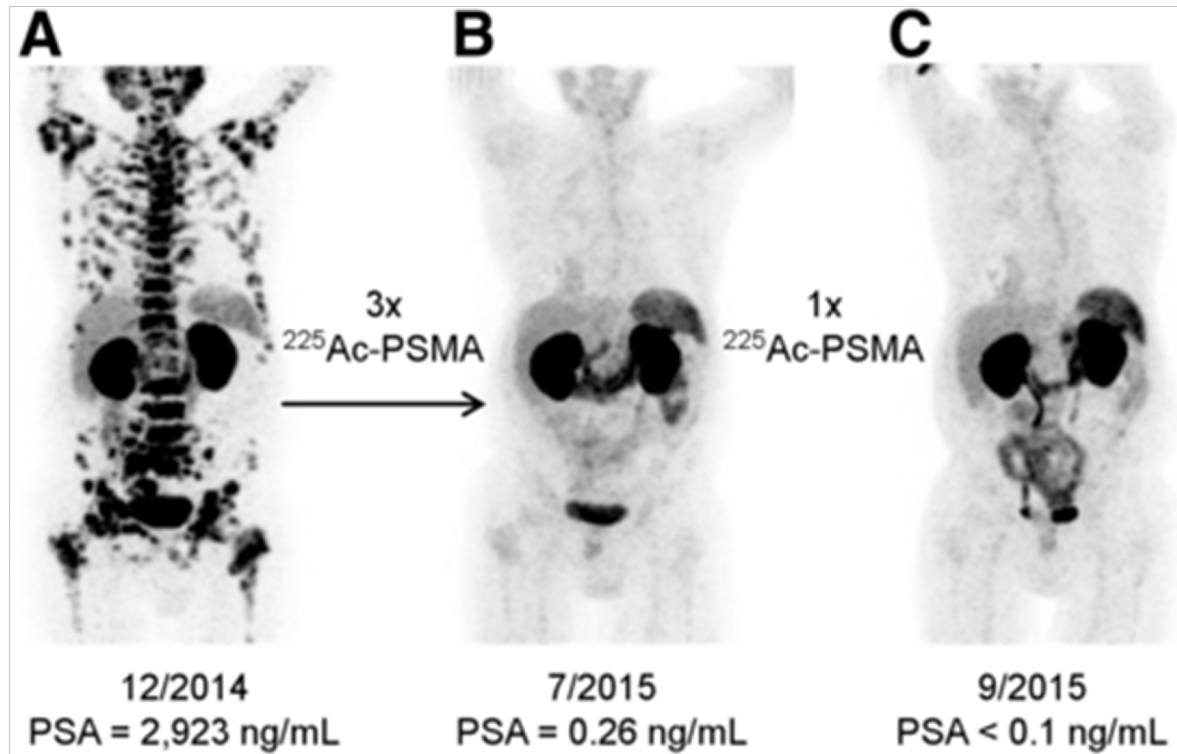
M. Fukuda (Osaka Univ.)

# Targeted $\alpha$ -particle therapy

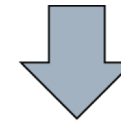
One third of patients are diagnosed as "advanced cancer" at first visit:  
5-year relative survival is 15% or less



# Targeted $\alpha$ -particle therapy



Using  $^{225}\text{Ac}$   $\alpha$ -ray radionuclide



All cancer tissues disappeared.

Kratochwil et al., J Nucl Med. 2016 , 57, 1941-1944.

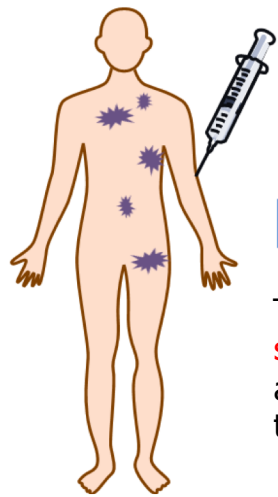
$^{225}\text{Ac}$ -PSMA-617 for PSMA-Targeted  $\alpha$ -Radiation Therapy of Metastatic Castration-Resistant Prostate Cancer.

It is hard to handle  $^{225}\text{Ac}$   $\alpha$ -ray radionuclide due to Japanese law.  
Half-life period: 10 days ( $^{225}\text{Ac}$ ) --> **7.2 hours ( $^{211}\text{At}$ )**



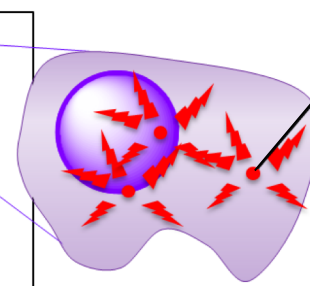
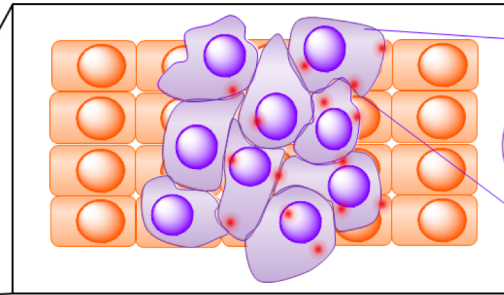
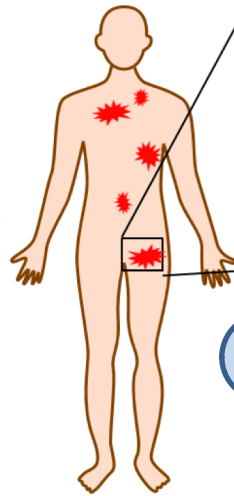
# Challenges to spread targeted $\alpha$ -particle therapy

## Advanced cancer patients



Administering targeting agents containing  $\alpha$ -ray radionuclide,  $^{211}\text{At}$ .

Targeting agents **spontaneously** find and accumulate cancer cells in the body.



$^{211}\text{At}$   
 $\alpha$  radiation  
Destruction of cancer cells

$\alpha$ -ray radiated from  $^{211}\text{At}$  destroys cancer cells

## Merits

- **Short range:** small influence on peripheral organs.
- Short-lived nuclide: **less burden on patients**

## Demerits

- Accelerators are needed to generate  $\alpha$ -ray radionuclide.
- Short-lived nuclide: **Necessary to produce in small areas.**

Compact HTS accelerators are necessary to stably produce  $\alpha$ -ray radionuclide

**HTS Skeleton Cyclotron**





# Magnetic field required for cyclotron accelerator

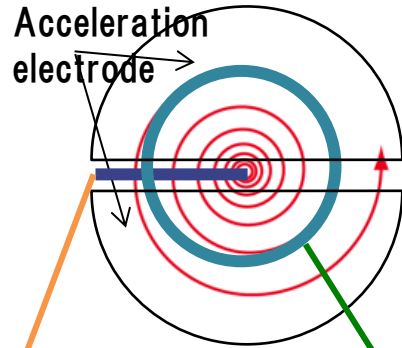
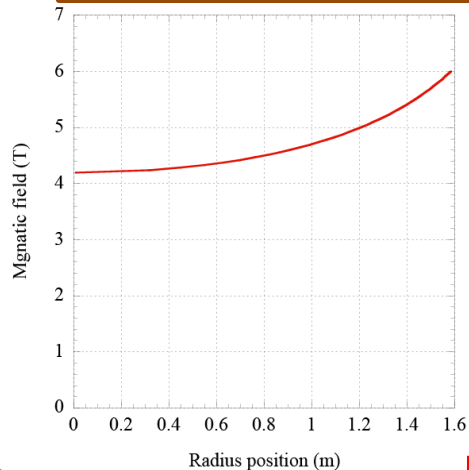
## Isochronism

It takes the same time that particle takes one round.

The orbit radius of accelerated particle is getting larger, and the mass is also getting heavier.

## Isochronous field

Keep isochronism by radially increasing magnetic field



## Beam trajectory stability

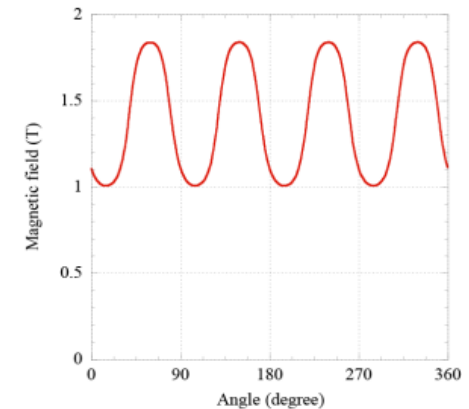
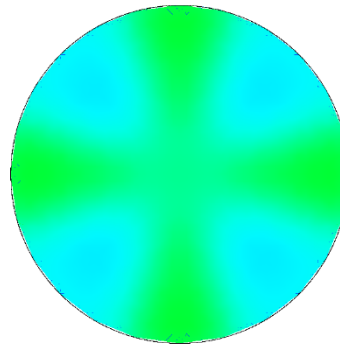
Maintain particles in orbit.

Particles off the mid-plane diverge.

## AVF (Azimuthally Varying Field)

Magnetic field with a periodical strength in the circumferential direction places particles in orbit.

Field distribution on beam acceleration plane

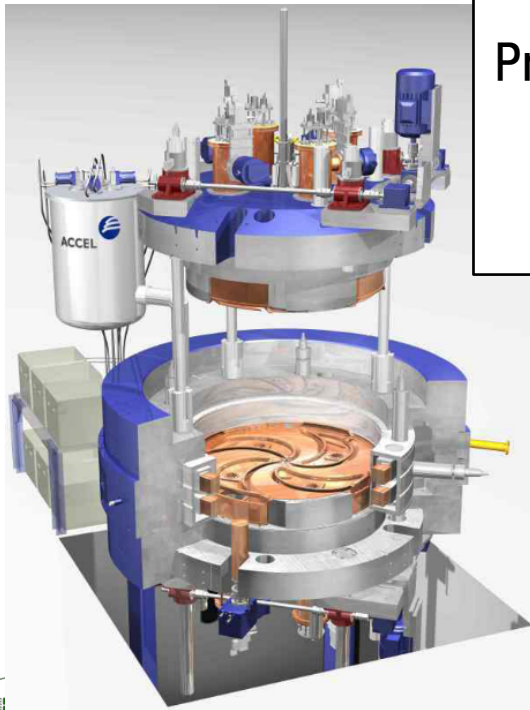
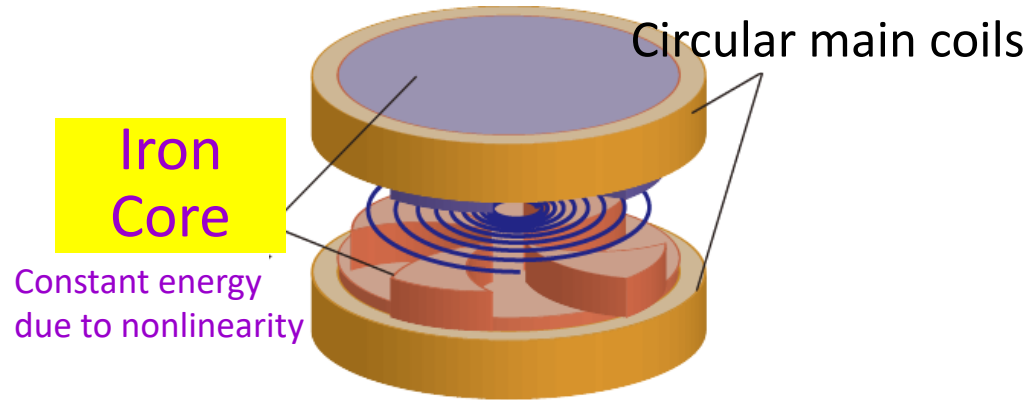


Coil-azimuthal direction

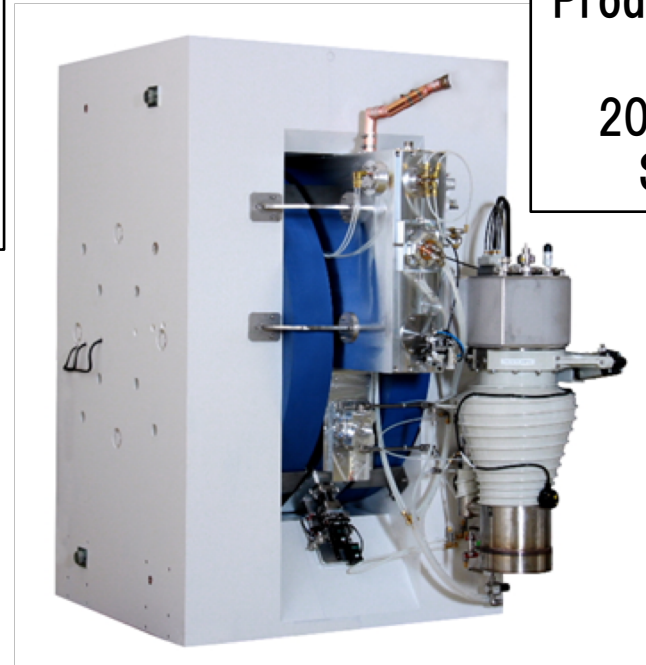
Necessary to generate highly accurate field (0.01-0.1%)



# Conventional AVF cyclotron



**NbTi LTS coils**  
Proton cancer therapy  
(250MeV,  $nA$ )  
PSI(Switzerland),  
RPTC(Germany)



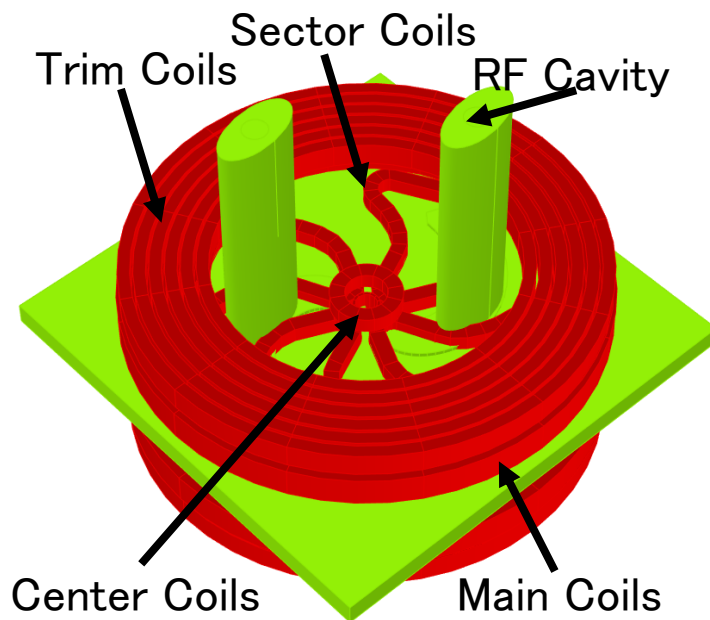
**Cu coil**  
Production of medicine  
for PET  
20MeV,  $\sim 100 \mu A$   
SHI Co. HM-20

# World's First HTS "Skeleton Cyclotron"

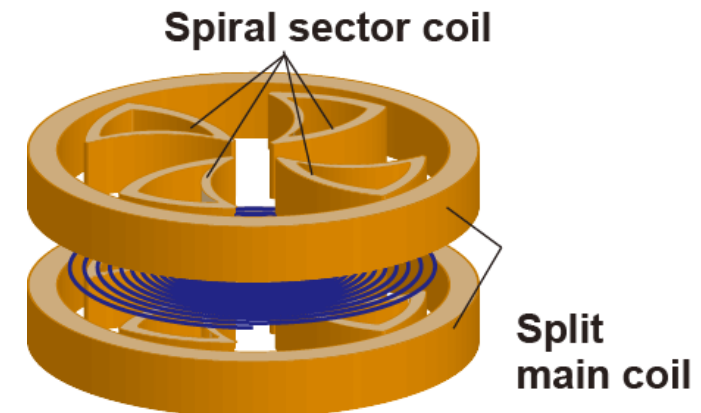
## HTS-SC(HTS Skeleton Cyclotron)

H.Ueda, M.Fukuda, A.Ishiyama, S.Noguchi, S.Nagaya et al.,  
“Conceptual Design of Next Generation HTS Cyclotron”,  
IEEE Trans. on Applied Supercond., Vol.23, No.3,  
4100205, 2013

Only an HTS multi-coil system **without iron core** produces a high magnetic field with high precision necessary for beam acceleration.



Coreless multi-coil



**Compact, lightweight, & high power!**

$^{211}\text{At}$  Mass production (36MeV,  $500\mu\text{A}$ )

# “Skeleton Cyclotron”: variable energy & multi-function

Due to **Iron-Coreless**

Compact, lightweight, and **energy-variable cyclotron accelerator**

1)  $^{211}\text{At}$  Production (targeted  $\alpha$ -particle therapy)

2) RI Production for PET (high output desired)

3) BNCT (Boron Neutron Capture Therapy)

4)  $^{225}\text{Ac}$ , RI Production ( $\alpha$ -ray)

**We are developing an HTS skeleton cyclotron system with the above functions, which can change the field.**

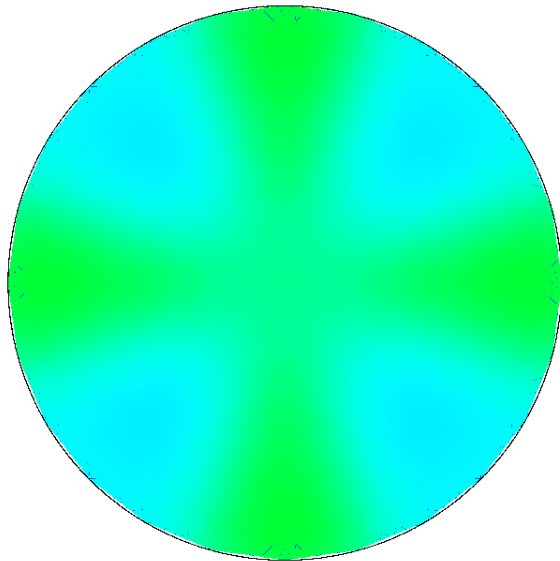


# “Skeleton Cyclotron”: variable energy & multi-function

1)  $^{211}\text{At}$  Production (targeted  $\alpha$ -particle therapy)

Ave. Field: 1.7T

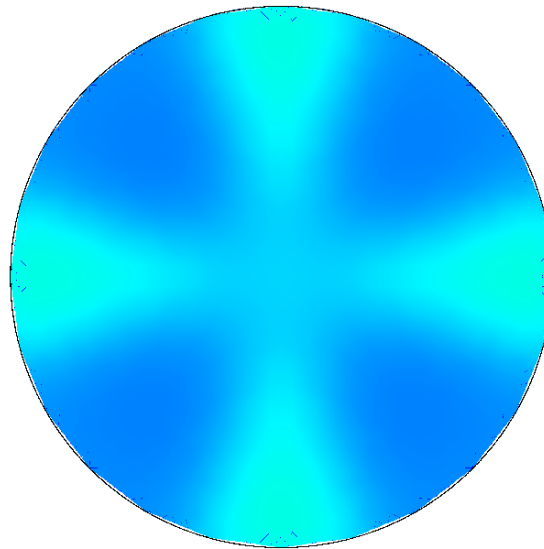
$^4\text{He}^{2+}$



2) RI production for PET

Ave. Field: 1.2T

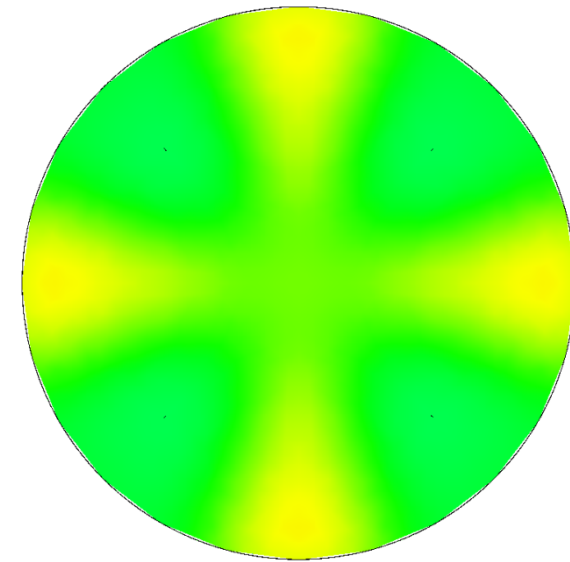
$\text{H}^-$



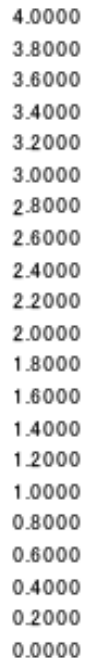
3) BNCT

Ave. Field: 2.6T

$\text{D}^+$



Field (T)



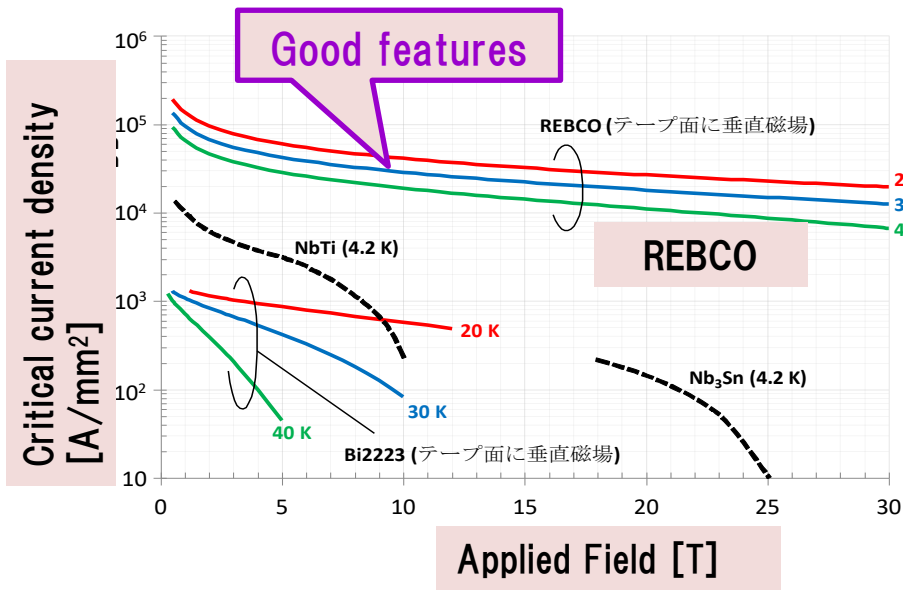
Field distribution on beam acceleration plane

All magnetic fields generated by the same coil system

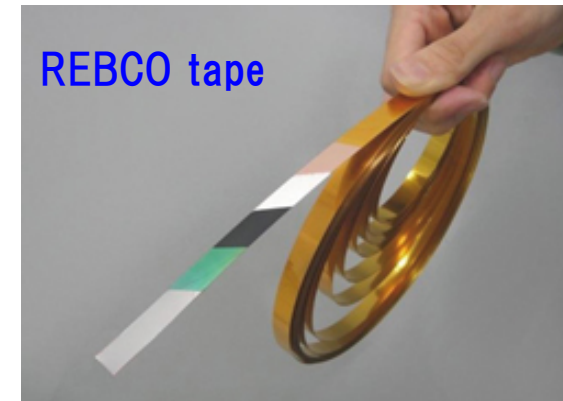


# Required techniques to develop “Skeleton Cyclotron”

1. By utilizing superior properties of REBCO tape as much as possible,



2. by considering the electromagnetic, mechanical, and thermal properties of multi-layer tape structure,



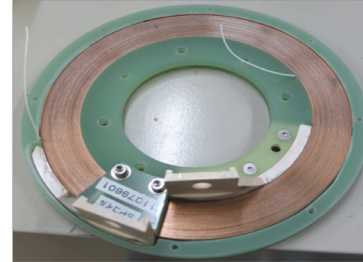
3. To stably operate a multi-coil system consisting of large-size (meter order) circular coils and noncircular coils

4. We'd like to confirm a design method and to develop basic technologies of “Skeleton Cyclotron.”

# HTS magnet technologies

4) **H**igh field & compactness

Optimal design method  
YOROI coil structure+NI winding technique



2) **H**ighly precise field

Reduction of  
screening current

3) **H**igh mechanical  
strength

YOROI coil structure

**5-H**igh  
basic technologies

Antinomy 5)

1) **H**igh thermal stability

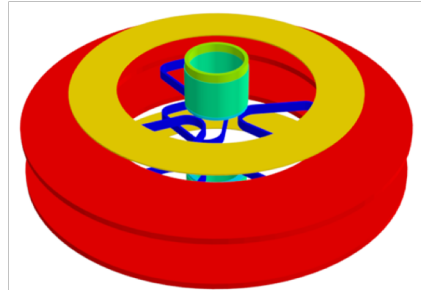
**H**igh current density

No-insulation winding technique

Manufacturing small-size 5-High innovative HTS magnet

For development of REBCO magnet for Skeleton Cyclotron

Small-size HTS  
Skeleton Cyclotron,  
"Baby Cyclotron"

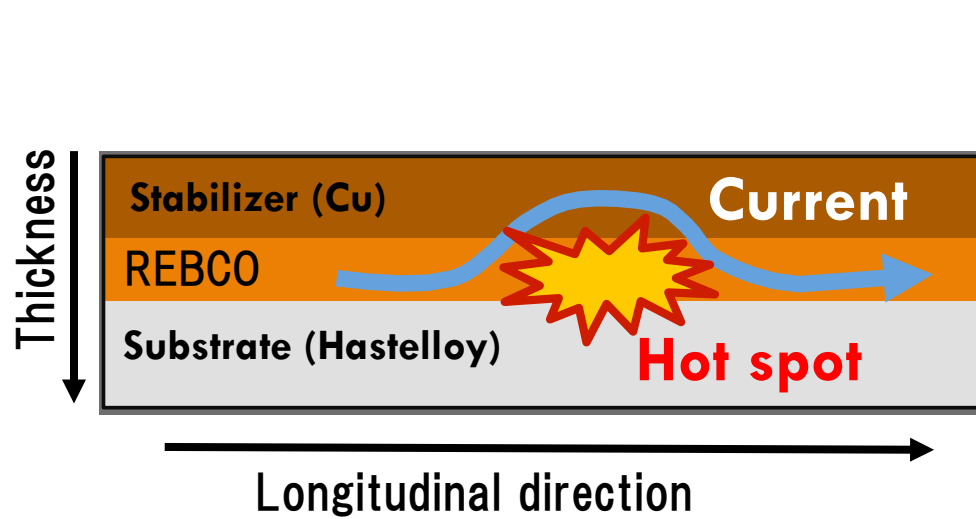


Energy-variable

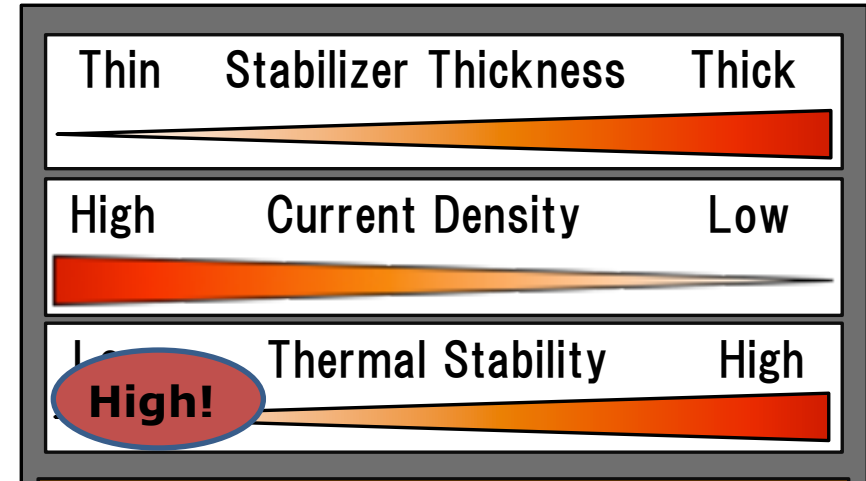




# 1) High current density & High thermal stability (NI winding technique)

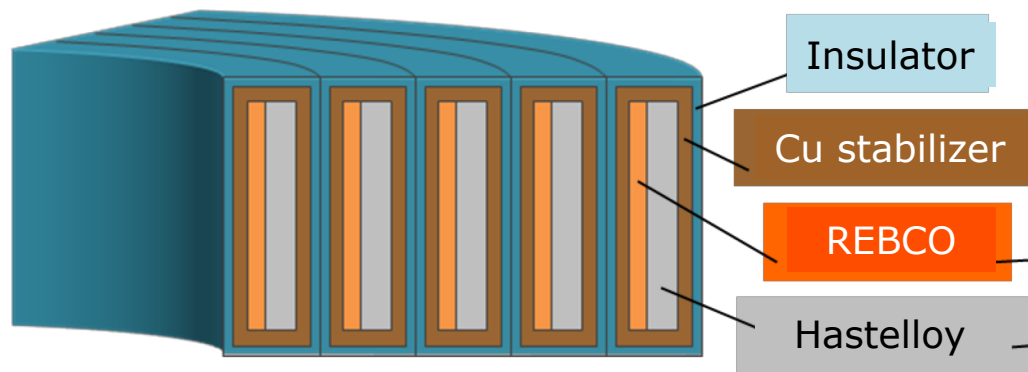


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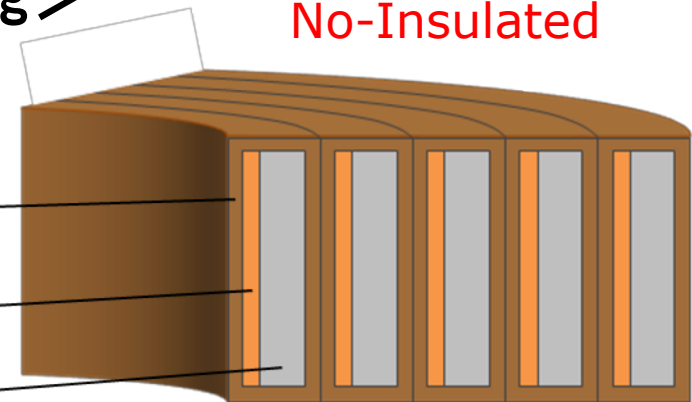


<Pancake winding>

Insulated



No-Insulated



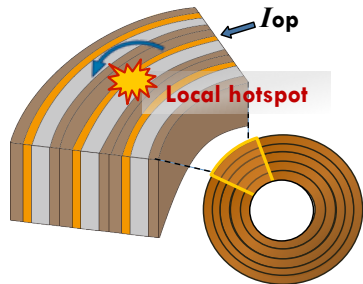
# 1) High current density & High thermal stability (NI winding technique)

Before

Applicable to NI winding technique

## High Thermal Stability

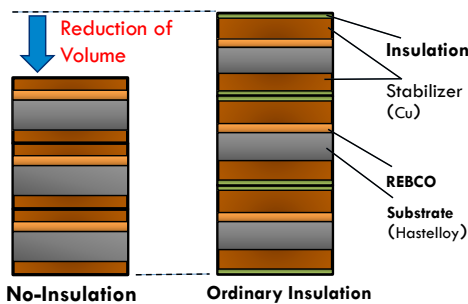
• Self-protection



- Current avoiding a local hotspot
- Dissipating magnetic energy into thermal capacity of a whole coil

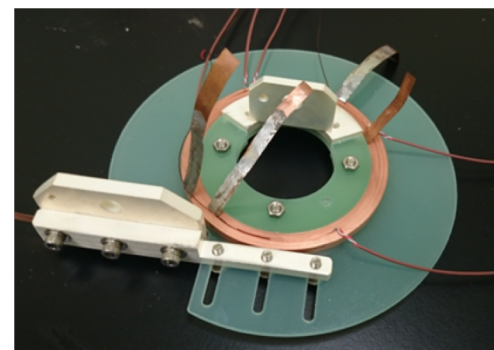
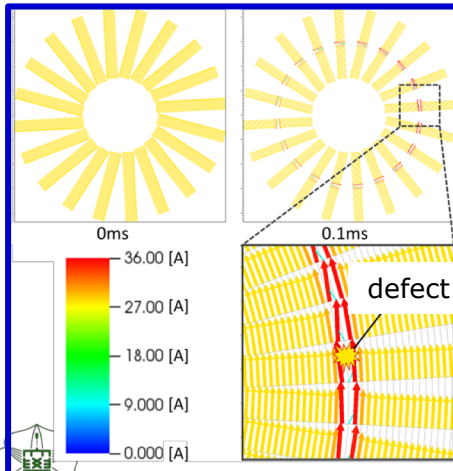
## High Current Density

• To Enhance Engineering Current Density  $J_e$



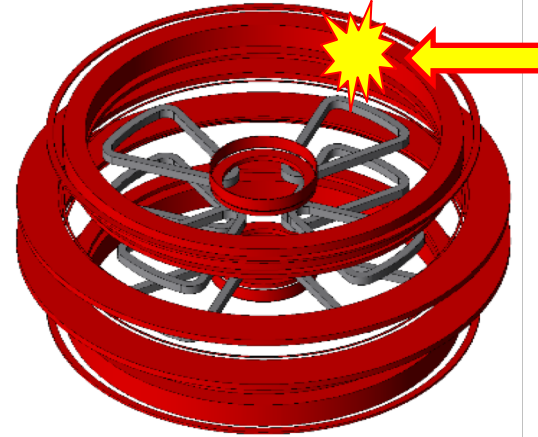
- Winding with no-insulated REBCO tape
- Decrease of stabilizer by sharing it

## Current & thermal coupled analysis



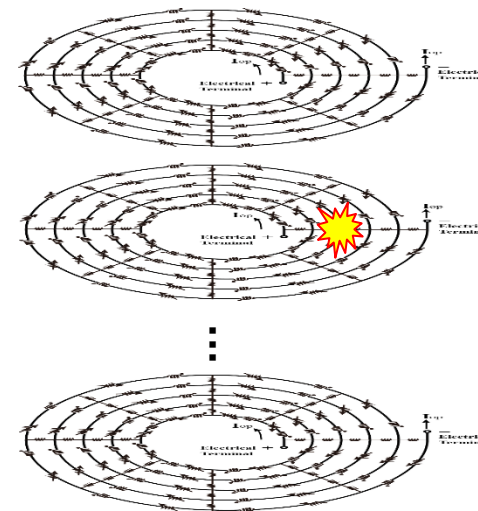
Now

Developing a simulation method to clarify multi-physics behavior coil



Additional currents are induced in the other coils after occurrence of local hot spot.

It is impossible to control the current flow in coils from outside



Experiment & analysis of NI multi-coil

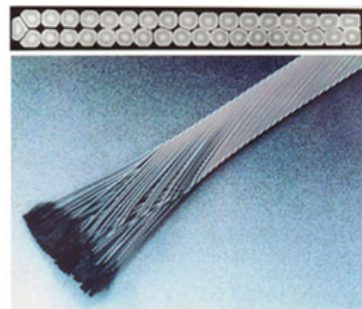
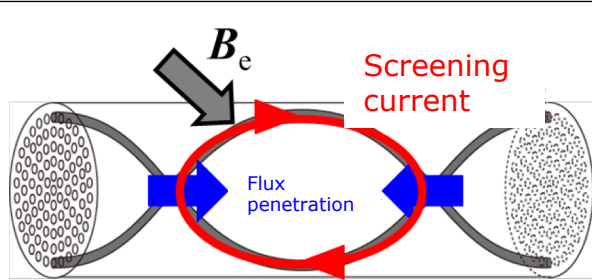
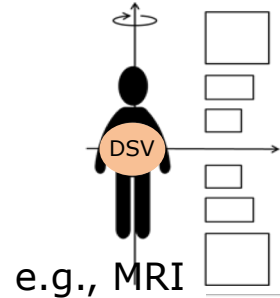


Quench detection & coil protection for NI multi-coil system

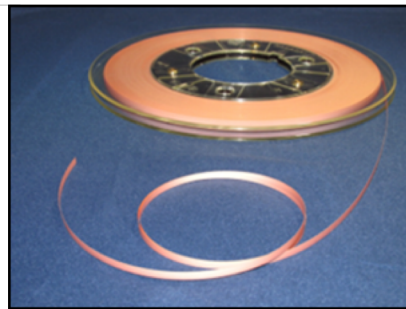
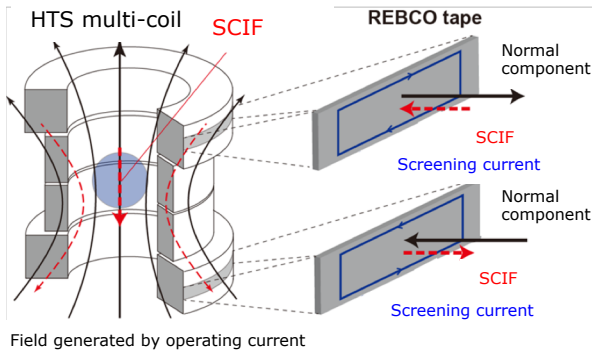
Current, thermal, & stress coupled analysis

## 2) Highly precise magnetic field (screening current-induced field reduction)

A large amount of screening current is induced due to the tape shape of REBCO wires.

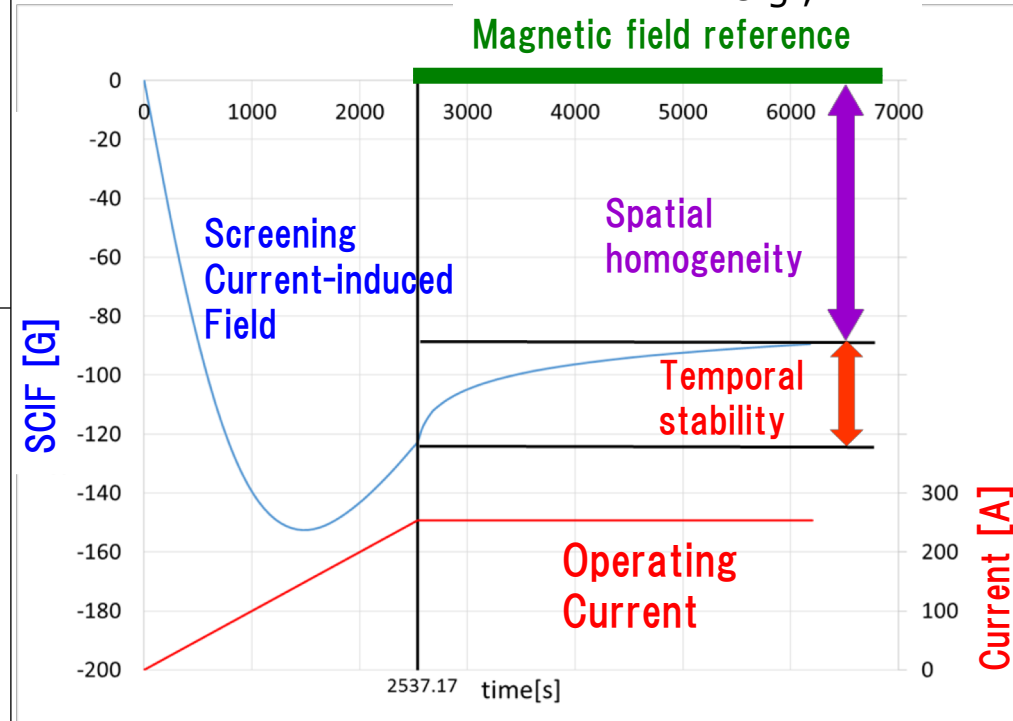


NbTi Rutherford Cond.



REBCO tape wire

Tape : Long constant time



⇒ SCIF largely temporally and spatially changes magnetic field.

It's a problem to be solved to realize variable energy.



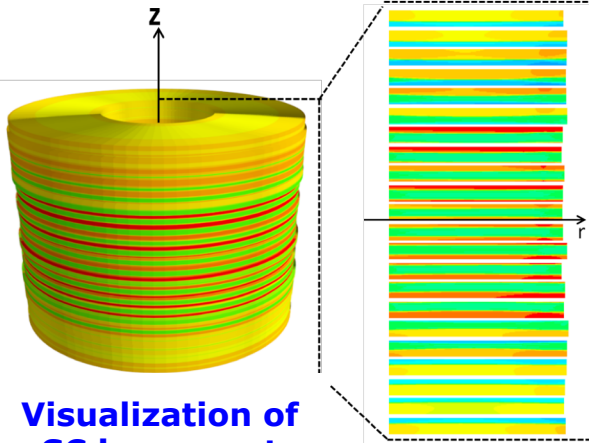
## 2) Highly precise magnetic field (screening current-induced field reduction)

**Before**

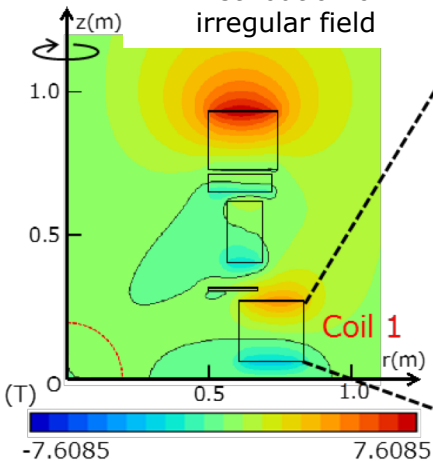


Small magnet  
(22 SPs)

Accurate simulation  
of screening current



Distribution of  
irregular field



**SC distribution**

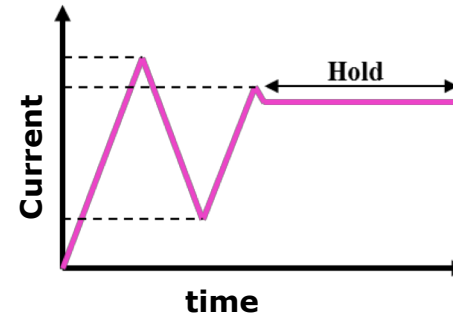
**Zero SC**

Irregular field evaluation of 9.4-T whole-body  
MRI magnet caused by screening currents

**Now**

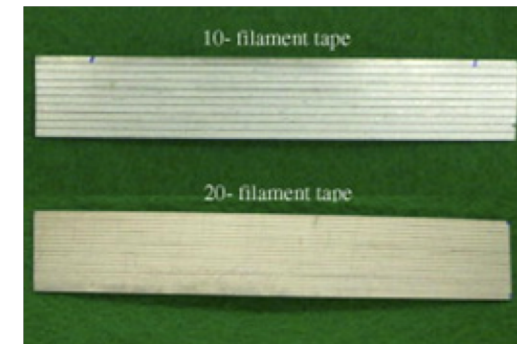
**Reduction methods of SCIF**

**Current control**

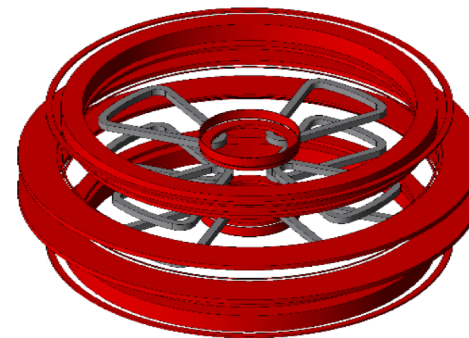


Once operating current  
exceeds target value.  
-> Temporally stable

**Thinning**



REBCO layer is scribed.  
-> Spatially stable



HTS Skeleton Cyclotron magnet

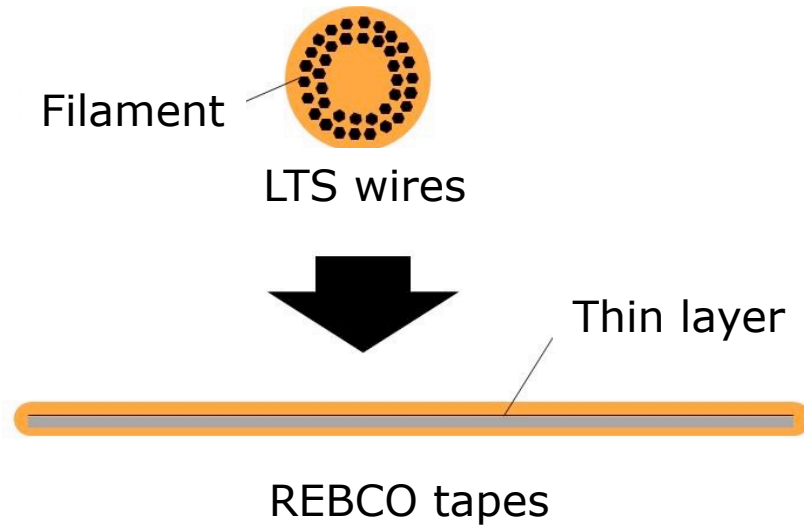
★To generate precise  
magnetic field with error  
of 0.01-0.1% or less, for  
realization of cyclotron.

★Quick response at changing  
energy



# Generation of magnetic field required for cyclotron

Necessary to generate highly accurate field (0.01-0.1%)



For use of cyclotron, it is necessary to rebuild the design and manufacturing technologies which have developed to generate a spatially highly homogeneous and temporally stable magnetic field for conventional MRI, accelerator magnets and so on.

## Causes of irregular field

- ◆ Coil design
- ◆ Coil winding/manufacturing accuracy
- ◆ Coil deformation by cooling
- ◆ Coil deformation by electromagnetic stress
- ◆ Screening current

Evaluation/reduction method of irregular field

Design/make good correction coils (trim coils)





# Conceptual design

## 1. Specifications

Particle	D <sup>+</sup>
Energy	40 MeV
Number of sectors	4
Maximum average magnetic field	2.589 T
Extraction radius	0.5 m

## 2. Radial sector coil for AVF

### 1) Flutter

Flutter is the azimuthal variation of magnetic field.

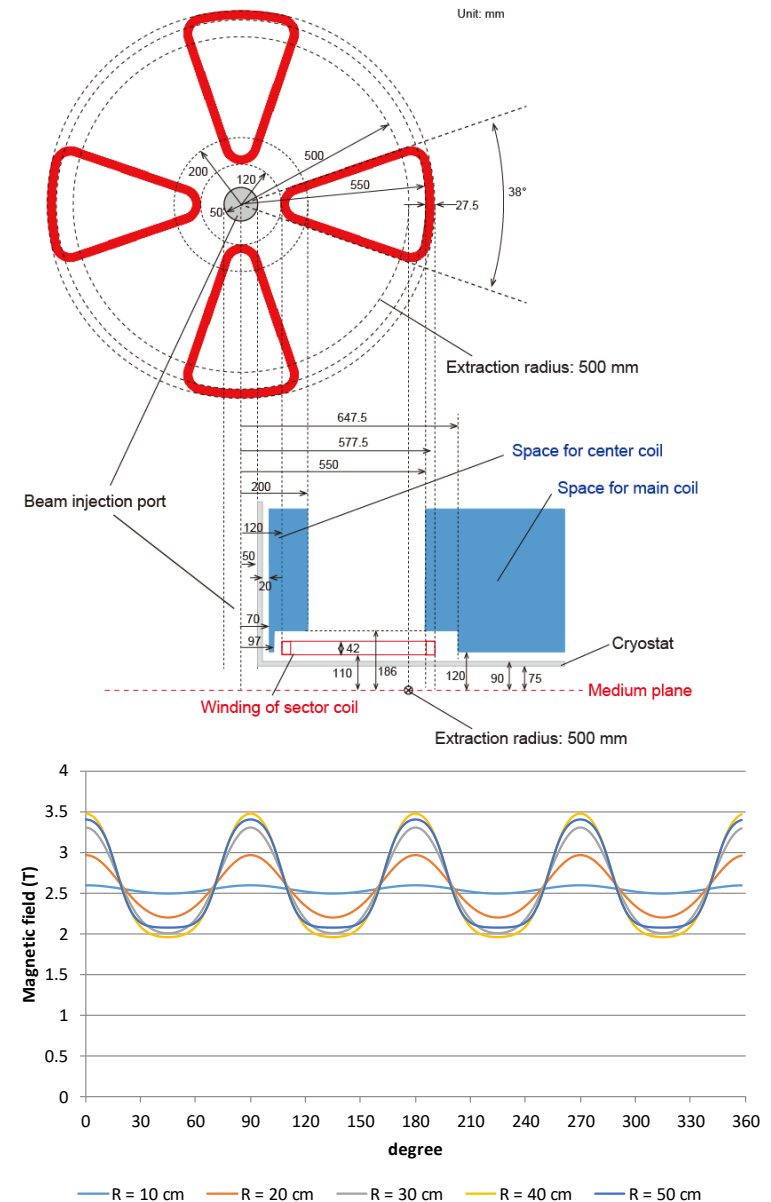
$$F^2 = \frac{\langle B_z^2 \rangle - \langle B_z \rangle^2}{\langle B_z \rangle^2} = 0.04$$

where  $\langle \rangle$  denotes the average over the azimuth.

$$\langle B \rangle = \frac{1}{2\pi} \oint_0^{2\pi} B(r, \theta) d\theta$$

### 2) Span angle

A span angle of a sector coil is 38 degrees to secure a space for the acceleration cavity in valley region.



# Conceptual design

## 3. Main coil for isochronous field

Optimization method: **GA-SA algorithms**

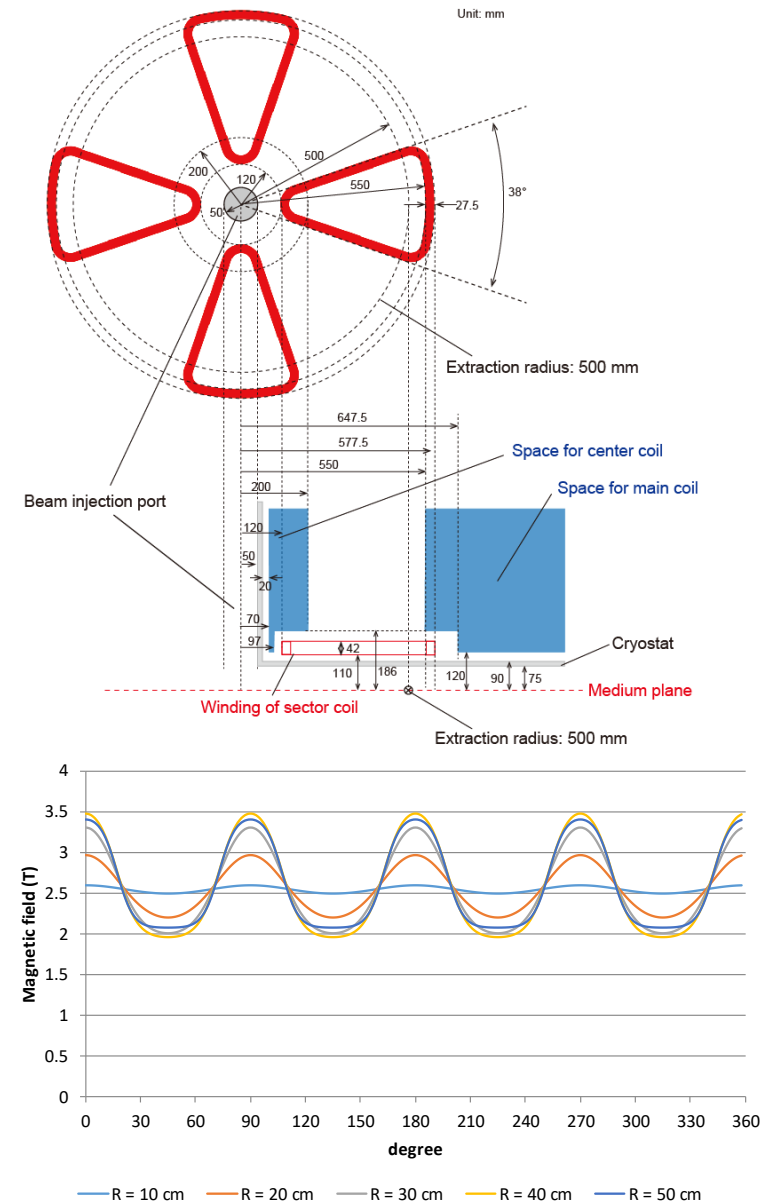
Object function: **Volume minimum**

Design conditions:

1) **REBCO tape** Width = 6 mm, thickness = 0.1 mm  
(including substrate and stabilizer)

Magnetic field and angle dependencies of I-V characteristic are considered.

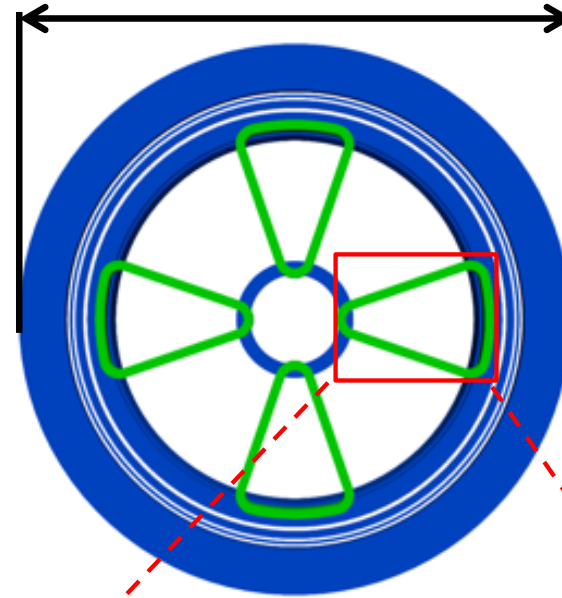
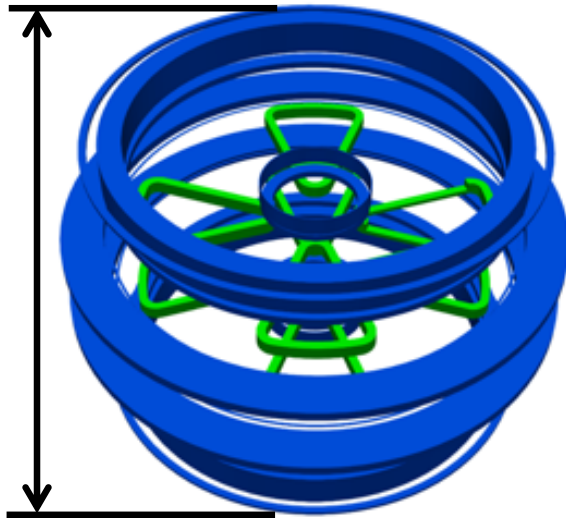
2) **Operating temperature = 30K** (cryocooler-cooled system)



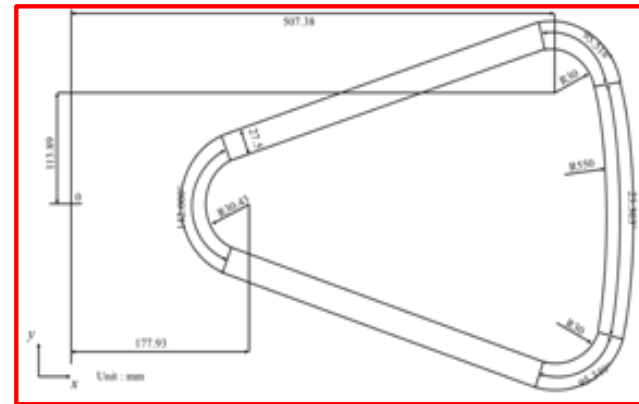
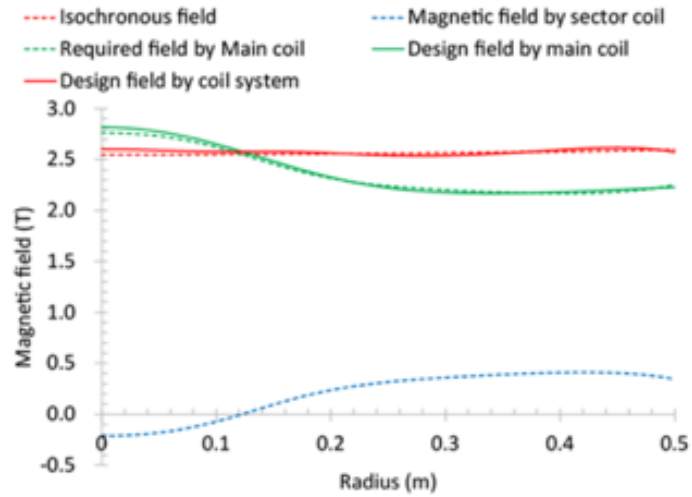


# Conceptual design

#### **4. An example of design**



### ◆ Azimuthal average field of mid-plane



# Summary

- We are developing a new cyclotron accelerator.  
We are now on the stage of REBCO magnet design and fundamental tests.
- As a fundamental test, we are developing a small size REBCO magnet for cyclotron.
  - Proton 50 MeV
  - 30 cm in magnet diameter
  - $\sim 1.6$  T at center field
  - To investigate the feasibility of REBCO magnet further

Thank you!

