A Design Study on No-Insulation HTS 385 MeV/u Isochronous Cyclotron Magnet for Carbon Ion Therapy

Jeonghwan Park[1], Garam Hahn[2], Jeseok Bang[1], Uijong Bong[1],
Kibum Choi[1], Jung Tae Lee[1], and Seungyong Hahn[1]

[1] Department of Electrical and Computer Engineering, Seoul National University
[2] Pohang Accelerator Laboratory, Pohang University of Science and Technology

Magnet Technology Conference 2019 (MT26)
Vancouver, Canada

09/26/2019

Contents

1.1 Former Studies on Carbon Ion Accelerator for Cancer Treatment

- Cyclotron
  - Carbon cyclotron has not been built yet.

(C400, KIRAMS430 designs are presented)

(1) Small space

(2) DC operation: simple control

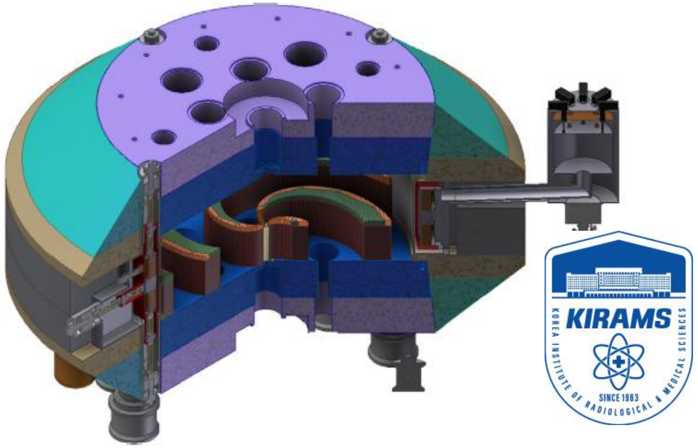
(3) Continous beam

- Synchrotron
  - Several systems are available (HIMAC,HIT…)

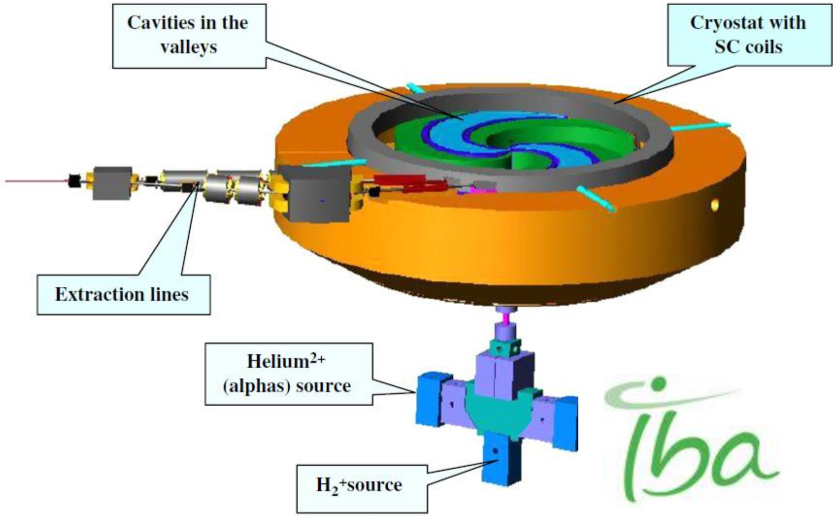
(1) Large space

(2) AC operation: complex control

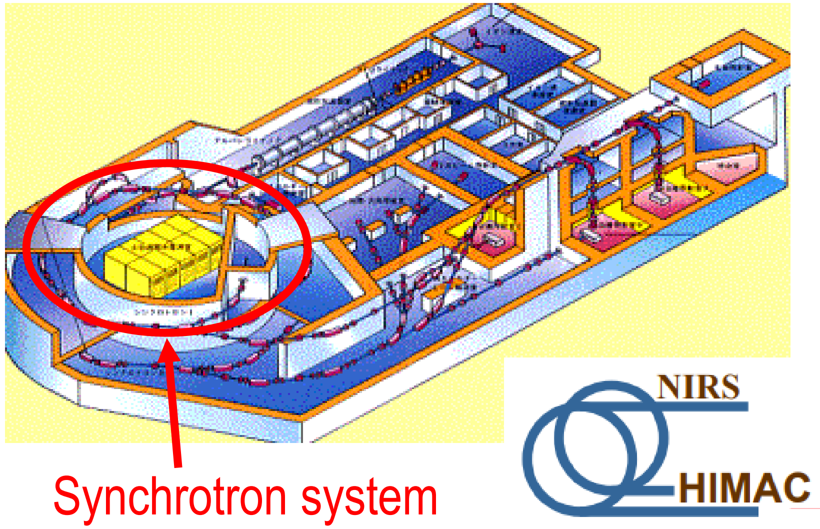
(3) Discontinuous beam



Ref: H. W. kim *et al.*, "Design study of the KIRAMS-430 superconducting cyclotron magnet," *Nucl. Inst. Methods Pys. Res.*, A 823 (2016), 26-31



Ref: Y. Jongen *et al.*, "Compact superconducting cyclotron C 400 for hadron therapy," *Nucl. Inst. Methods Pys. Res.*, A 823 (2010), 47-53



Ref: https://www.nirs.qst.go.jp/ENG/rd/1ban/himac_inf.html

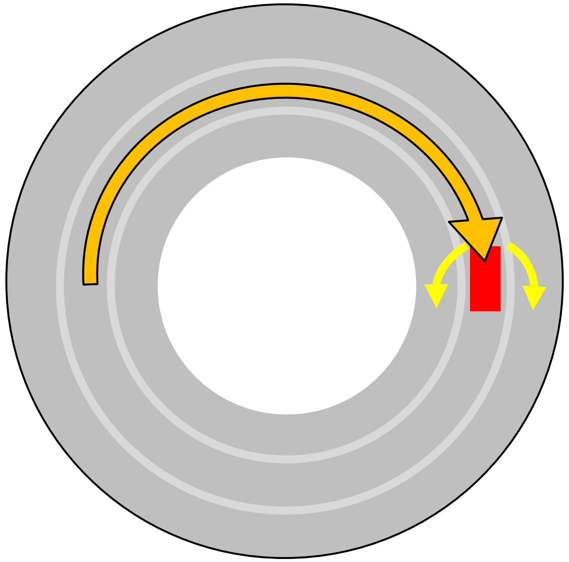
Current systems are constructed (or designed) with Cu (or LTS) technology

1.2 Key Concepts: No Insulation (NI) / Multi-Width (MW) / Cryocooling

- No-Insulation (NI)

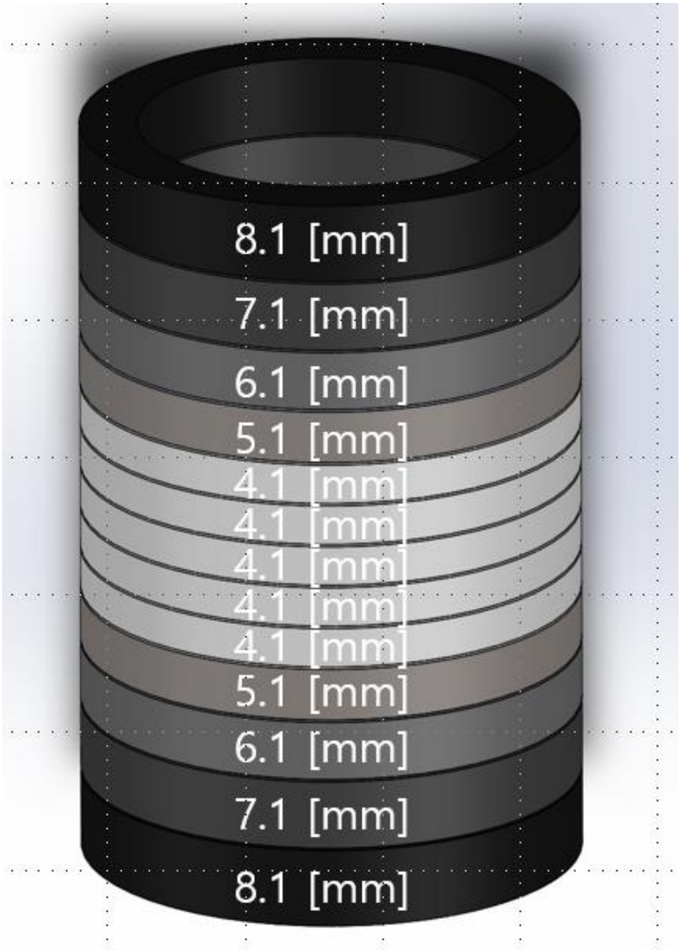
1. Excellent protection
2. High mechanical intensity
3. High current density

NI: "Quench Current Bypass"



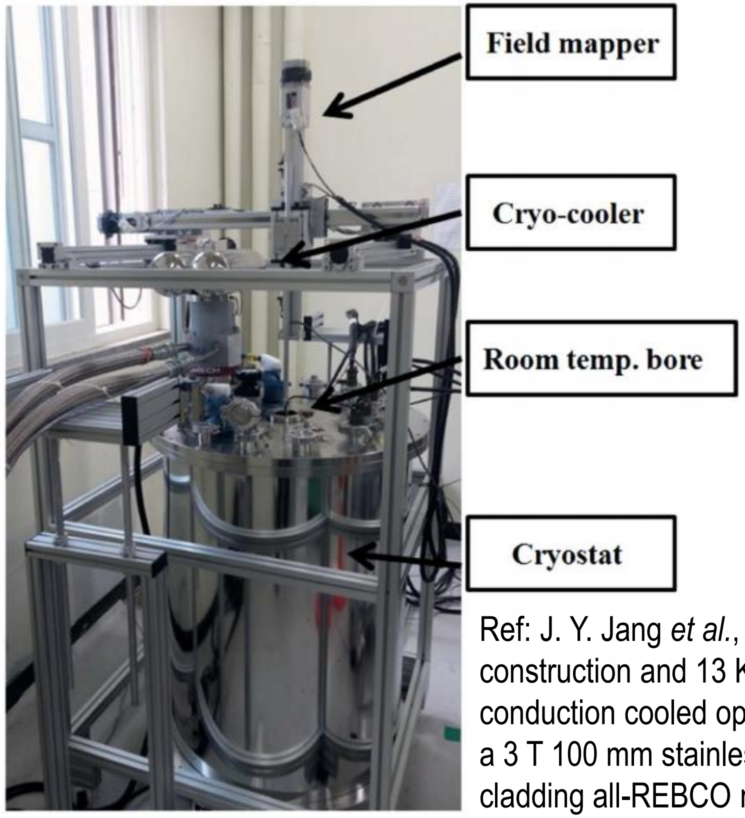
- Multi-Width (MW)

Minimization of conductor usage



- Cryocooling: 20 K operation

1. Helium free cryogenic system
2. >100 stability margin than LTS

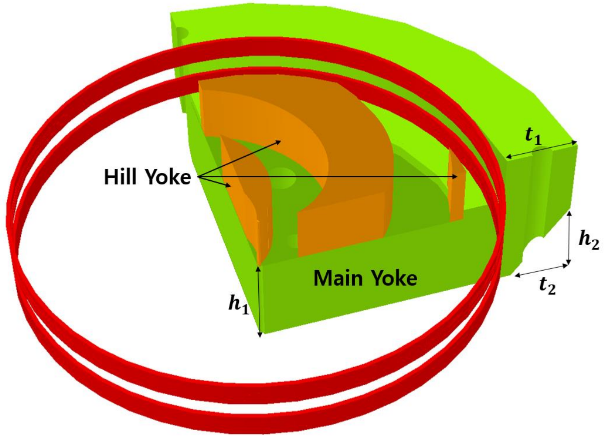


Ref: J. Y. Jang *et al.*, "Design, construction and 13 K conduction cooled operation of a 3 T 100 mm stainless steel cladding all-REBCO magnet," *Supercond. Sci. Technol.*, 30, (2017), 105012

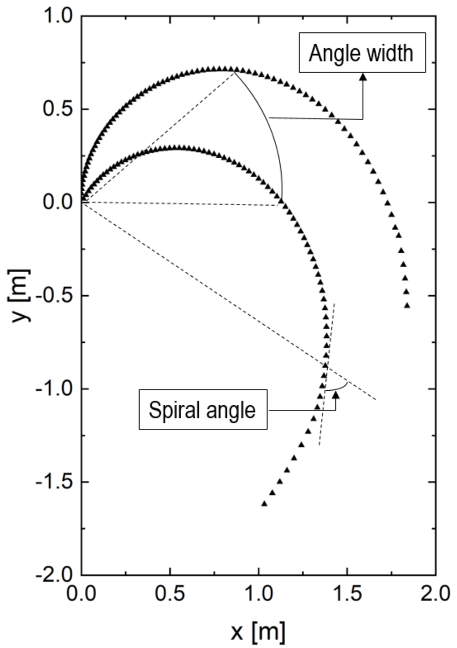
Contents

2.1 Overview Table: Requirements & Physical Constants & Dimension

- 3 Considerations: (A) Cost (B) Performance (C) Reliability



Design Process	Requirements	Physical constants	Dimension
A. Cost	Compactness	Iron Weight	Main Yoke Configuration
1. EM Design		Conductor Length	h_1, h_2, t_1, t_2
B. Peformance	Field Strength	Magnetic Rigidity	Coil Configuration
2. Beam Stability Design	Field Distribution	Isochronous Field	*Iop* *Coil size* *# of dps* *Cowinding*
		AVF	
C. Reliablity	Mechanical Integrity	Mechanical Strain	Hill Yoke Configuration
3. Mechanical Analysis	Operating Scenario	Charging Time	*Spiral angle* *Angle width* *Pole gap*
4. Operation Analysis		Overstress	
	Quench Sencario	Unbalanced Force	
		Temperature Rise	



Analysis from field distribution & coil parameters

Park, Jeong Hwan
<hwan1022@snu.ac.kr>

2.2 Design Process: Design Flowchart

- 7 Steps for Specified Design Process

Design Process

A. Cost

1. EM Design

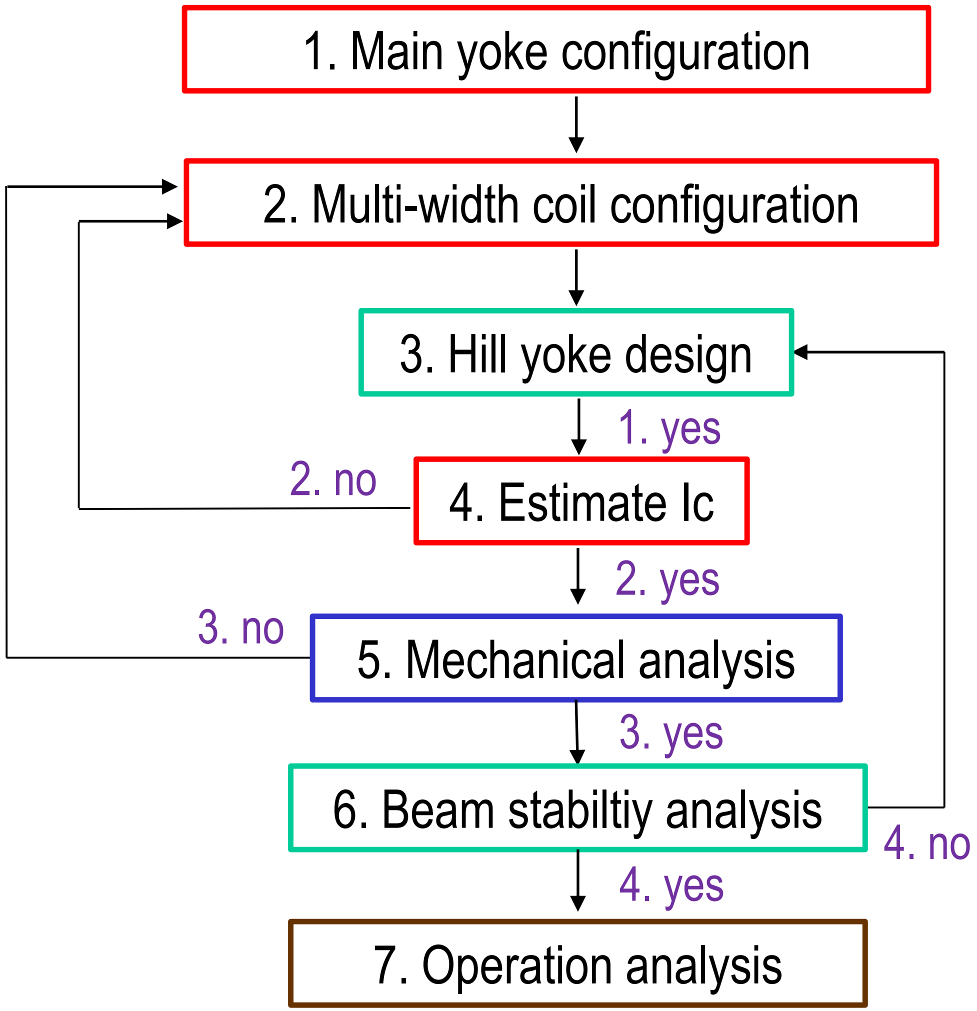
B. Peformance

2. Beam Stability Design

C. Reliablity

3. Mechanical Analysis

4. Operation Analysis



Constraints

1. |Bcal-Biso| < 10 gauss
2. (Iop < 0.8 Ic)
3. Strain < 0.4%
4. Stable beam dynamics

Keywords for each design steps

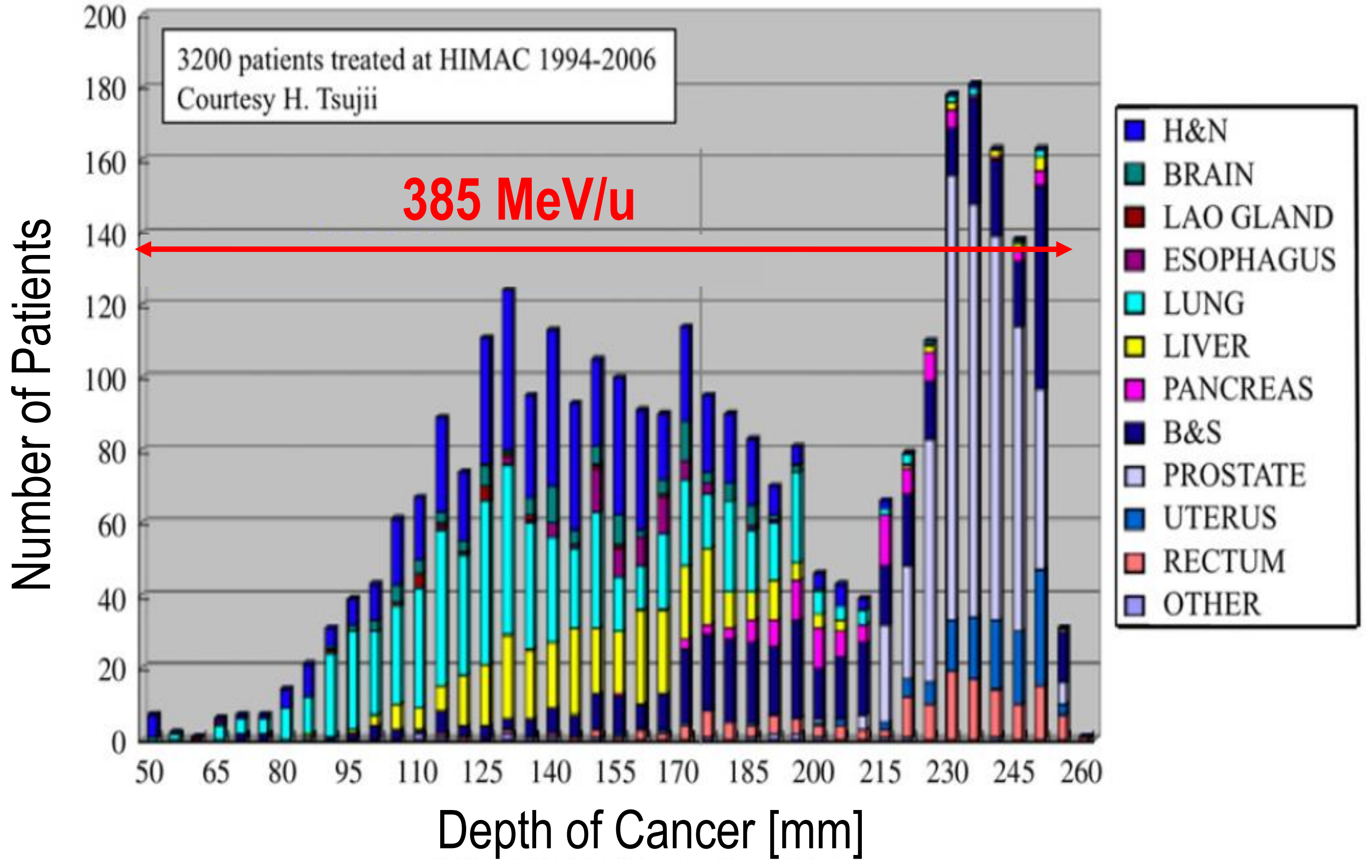
1: Parameter sweep method
2: Gauss-Newton method
3: Isochronous field
4 : $I_c(|B, \theta, 20\ \mathrm{K}|)$
5 : Strain
6 : Tune diagram
7 : Charging delay & quench analysis

Park, Jeong Hwan
<hwan1022@snu.ac.kr>

2.3 Design Target: Extraction Energy of 385 MeV/u

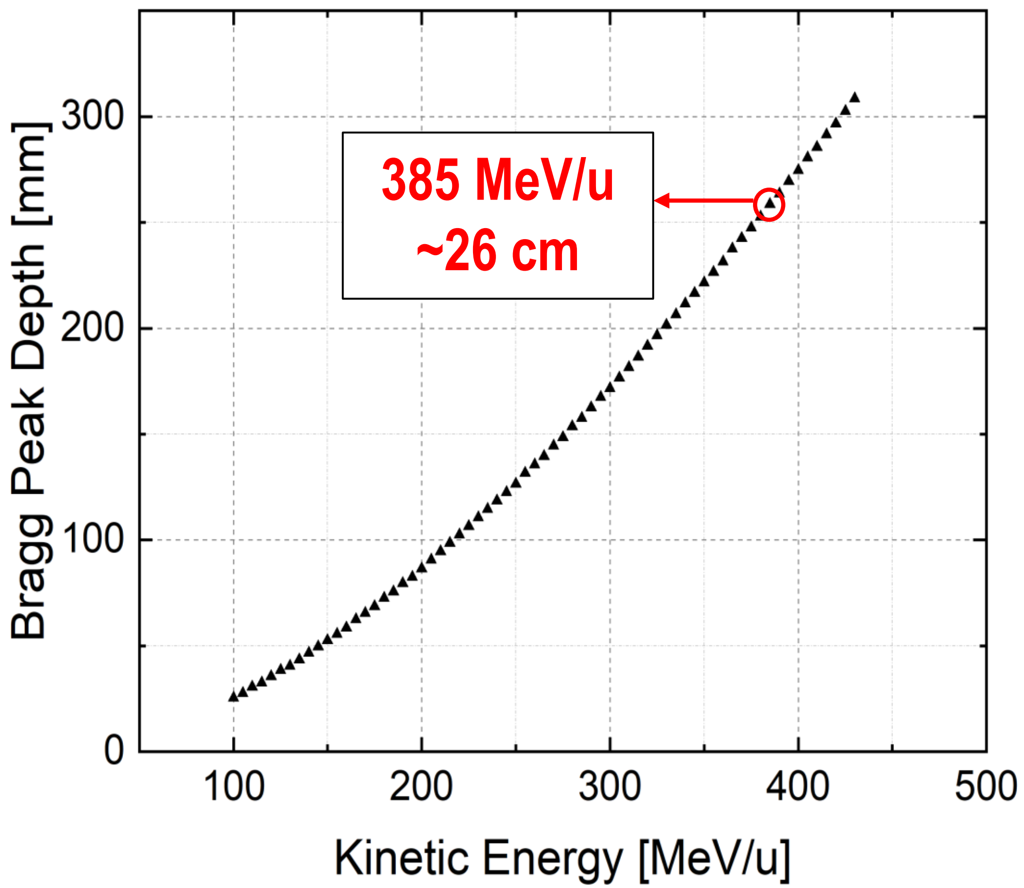
- Why 385 MeV/u? : To treat cancer deep in ~26 cm

□ Depth Distribution of Cancer for Patients at HIMAC



Ref) U. Amaldi *et al.*, "Accelerators for hadrontherapy: from Lawrence cyclotrons to linacs," *Nucl. Inst. Methods Pys. Res.*, A 620 (2010), 563-577

□ GEANT4 Simulation Results



Contents

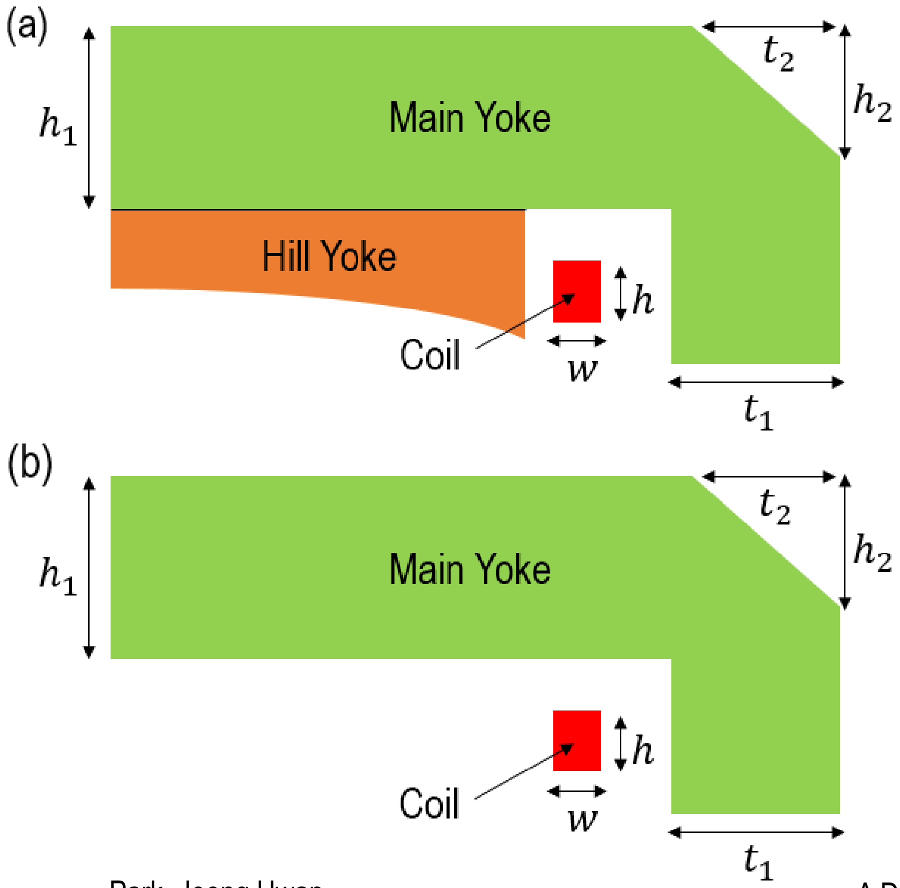
3.1.1 Electomagnetic Design: Parameter Sweep for Main Yoke

■ Main yoke Configuration: Ampere Turn vs. Main Yoke Weight

□ Simplified 2D Axisymmetric Model

$$B_{app}^{3D}(r) = \alpha(r)B_h(r) + \left(1 - \alpha(r)\right)B_v(r)$$

$B_h(r), B_v(r)$: field at (a) and (b) / α: arbitrary hill ratio

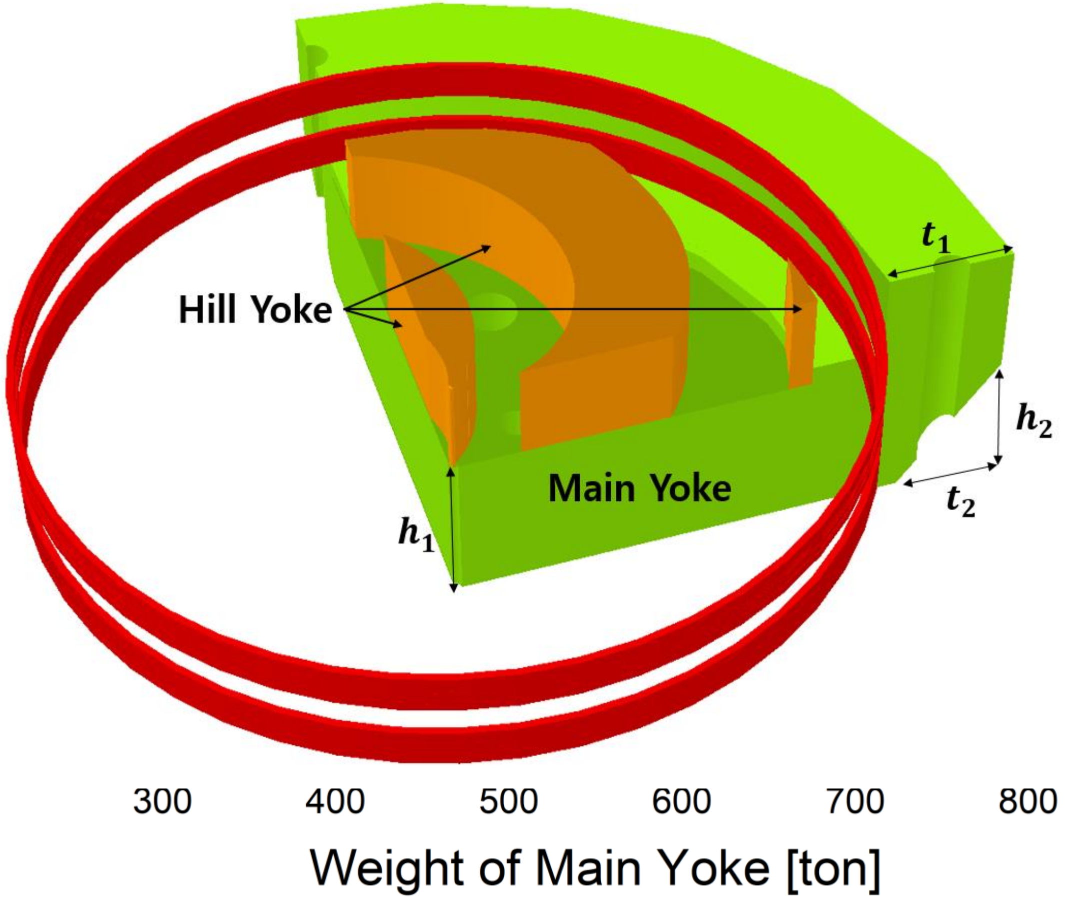


Sweeping Parameters
h_1 : [0.6 0.05 1.2] t_1 : [0.6 0.05 1.0] r : [0.6 0.1 1] (= t_2/t_1= h_2/h_1)
Gauss-Newton Parameters
h, w

□ Gauss-Newton Method

$$f = \sum_{i=1}^{n} \left| B_{app}^{3D}(r_i) - B_{iso}(r_i, h, w) \right|^2$$

where $B_{iso}(r) = \frac{m_0 c}{\ldots}$

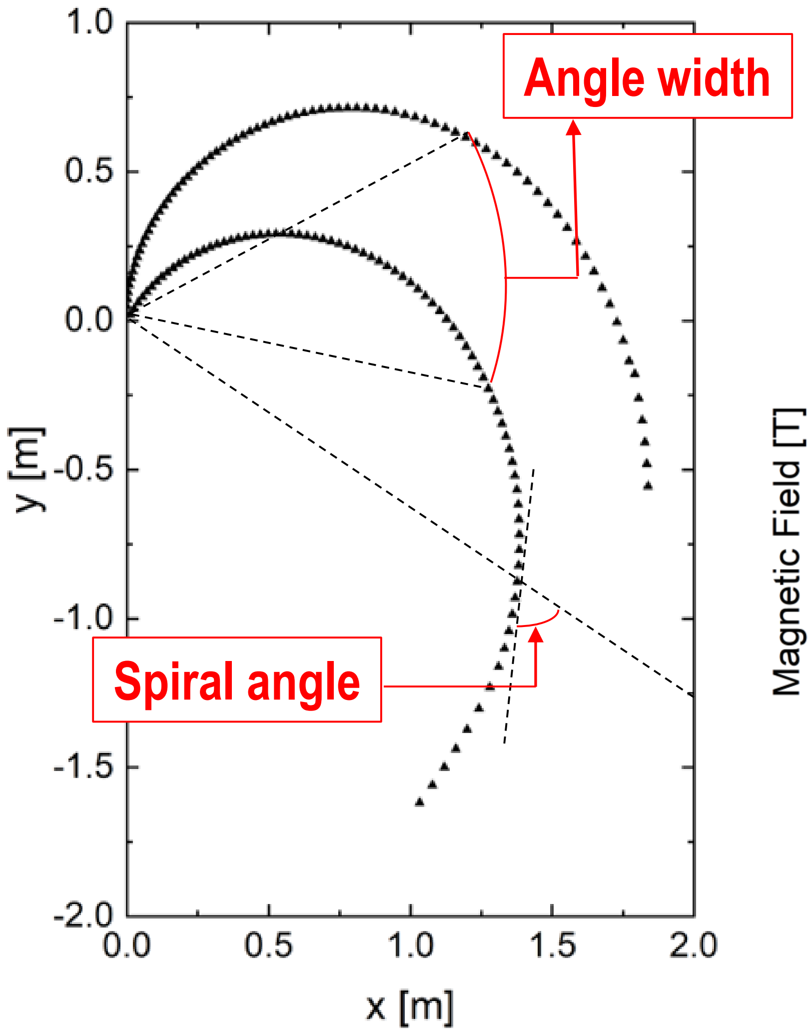


Park, Jeong Hwan
<hwan1022@snu.ac.kr>

3.1.2 Electomagnetic Design: Hill Yoke Design toward Isochronous Field

■ Hill yoke Configuration: Shaped by Controlling Angle Width & Spiral Angle

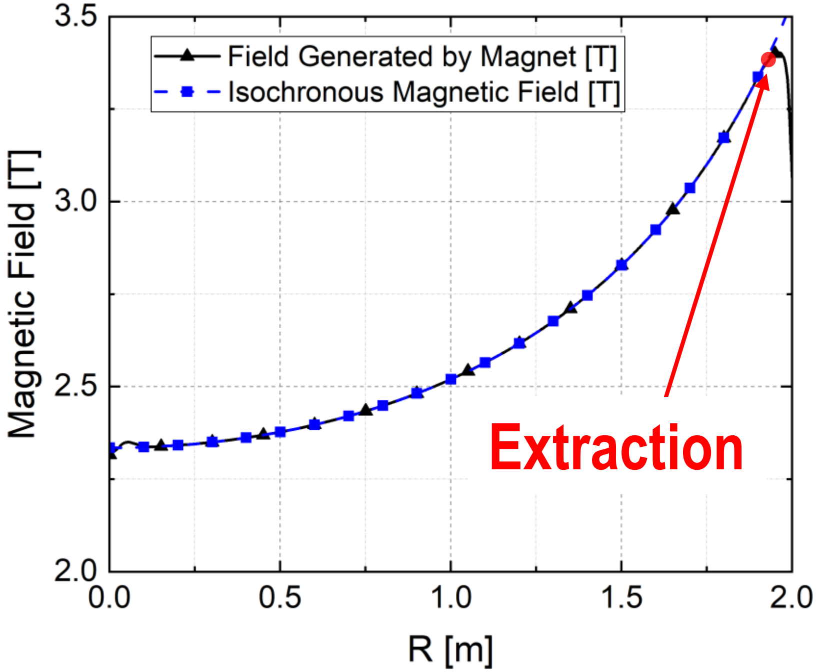
□ Mapping Points on xy Plane



□ Field Distribution

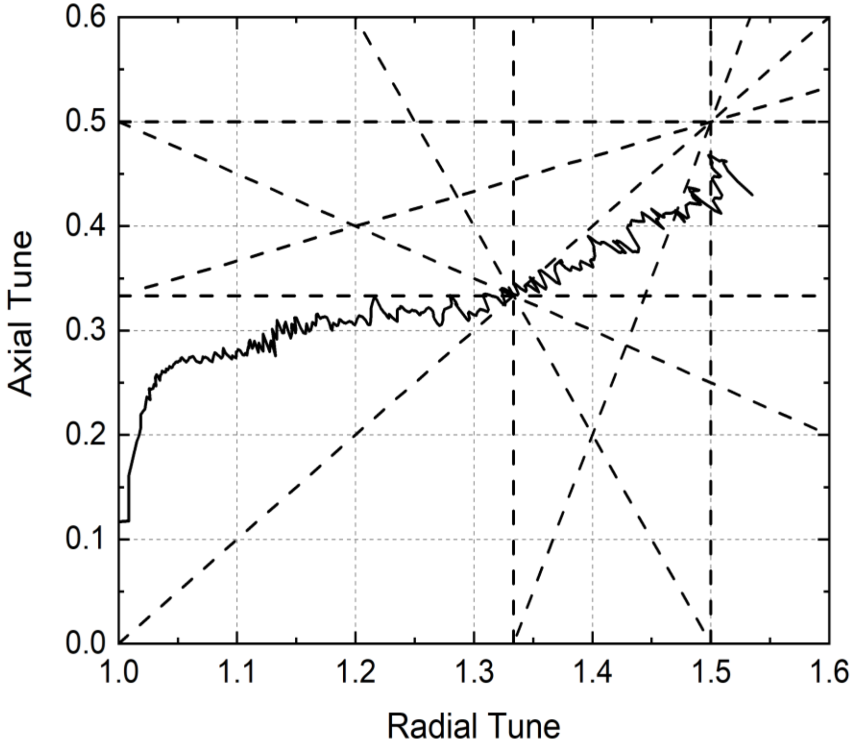
Automatic iteration process

Δ(Angle width ratio)
$= (B_{iso} - B_{cal})/(B_{hill} - B_{valley})$



□ Tune Diagram: using "Cyclone" code

10 MeV to 4620 MeV with 10 MeV interval



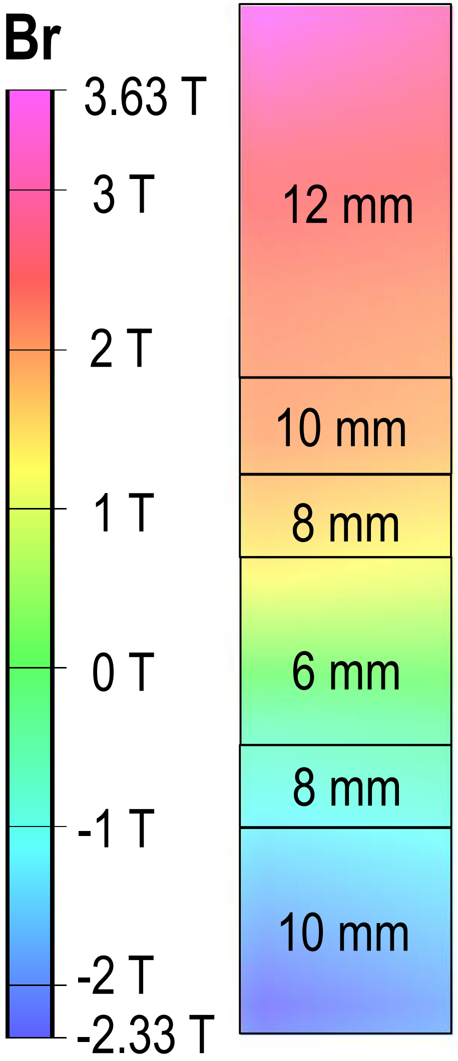
Missing Parameters in This Draft Design
- RF field simulation
- Reference field shaping
- Injection / Extraction

Park, Jeong Hwan
<hwan1022@snu.ac.kr>

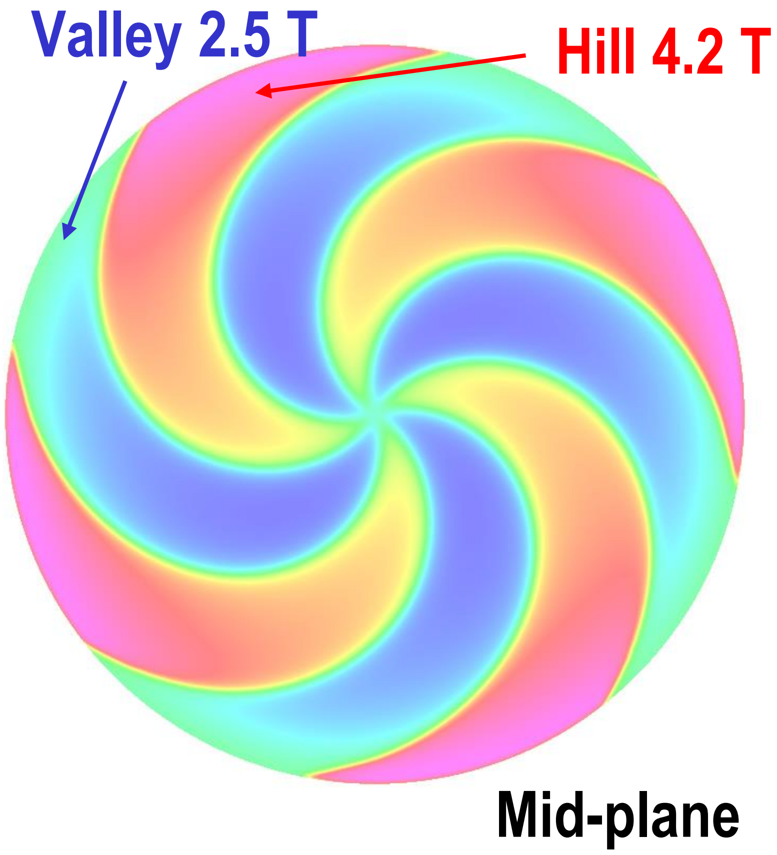
3.1.3 Electromagnetic Design: Coil Configuration with 20 % I_c Margin

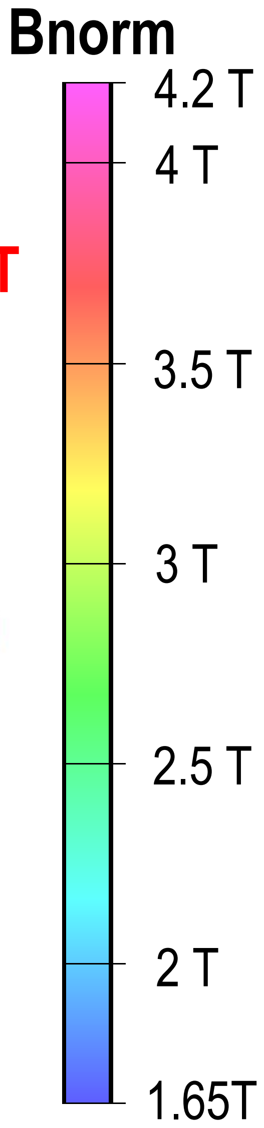
■ Finalized Magnet Configuration: Corresponding Parameters & Field Distribution

□ **Asymmetric** Multi-Width Configuration



□ Magnetic Field Distribution





□ Key Parameters

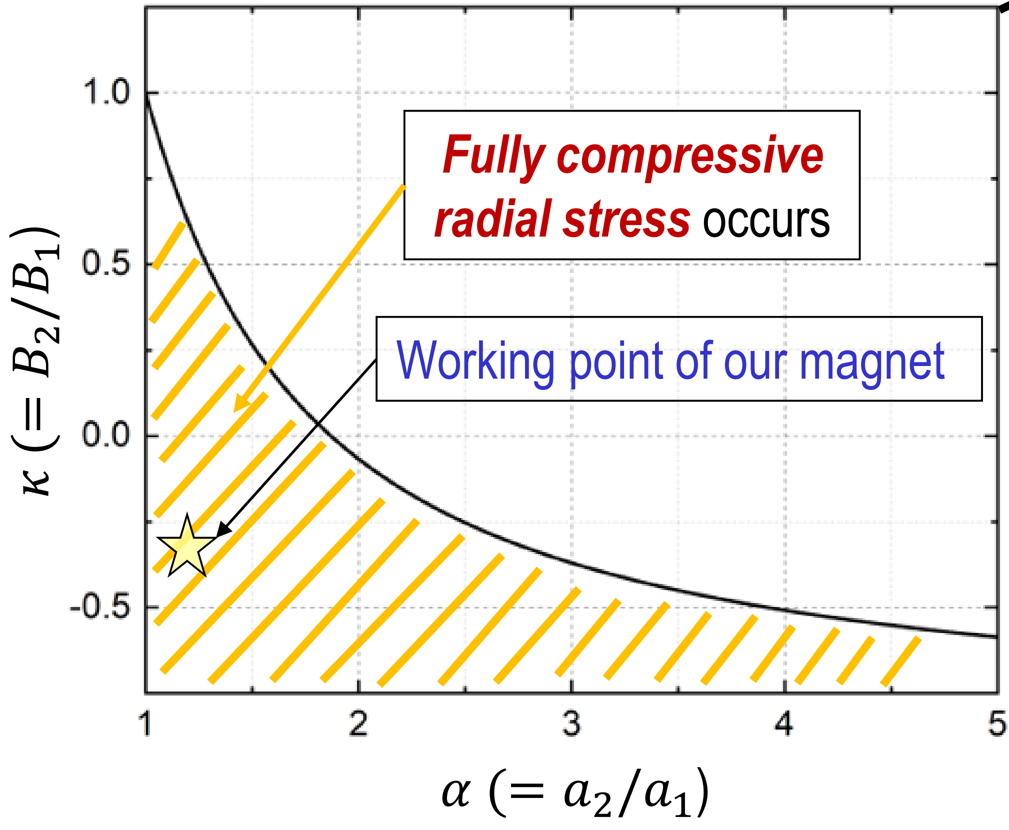
Parameters	Value
Bending Limit, *K* [MeV]	1540
Magnet Dimension [m]	6.2 (D) 3 (H)
Weight [ton]	540
Conductor Usage [km]	112

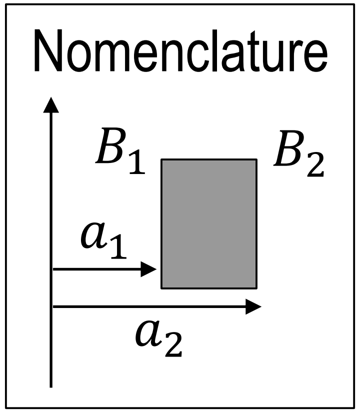
Contents

3.2 Mech. Analysis with Force Balance Equation: Peak Strain < 0.33 %

- Governing Equation (Force Balance Equation) : $\sigma_r - \sigma_h + BJr + r\frac{\partial \sigma_r}{\partial r} = 0$

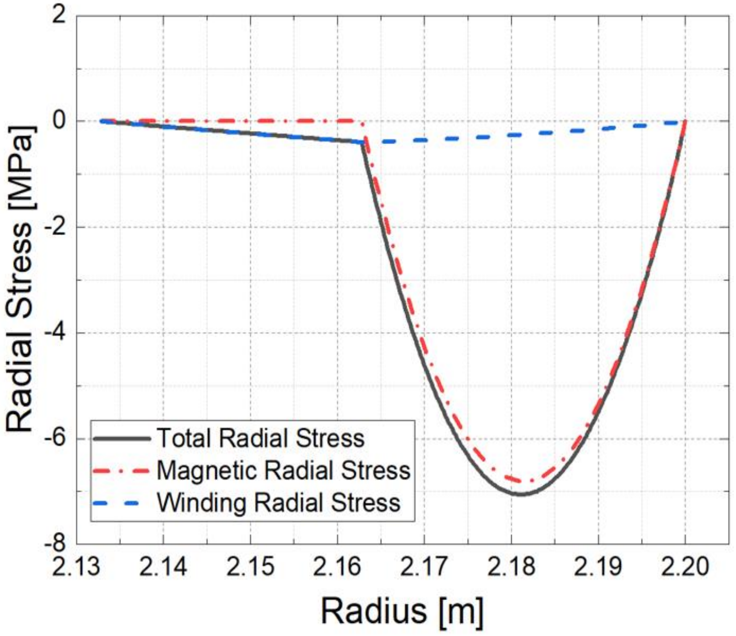
□ "Analytic Condition" for Fully Compressive Radial Stress

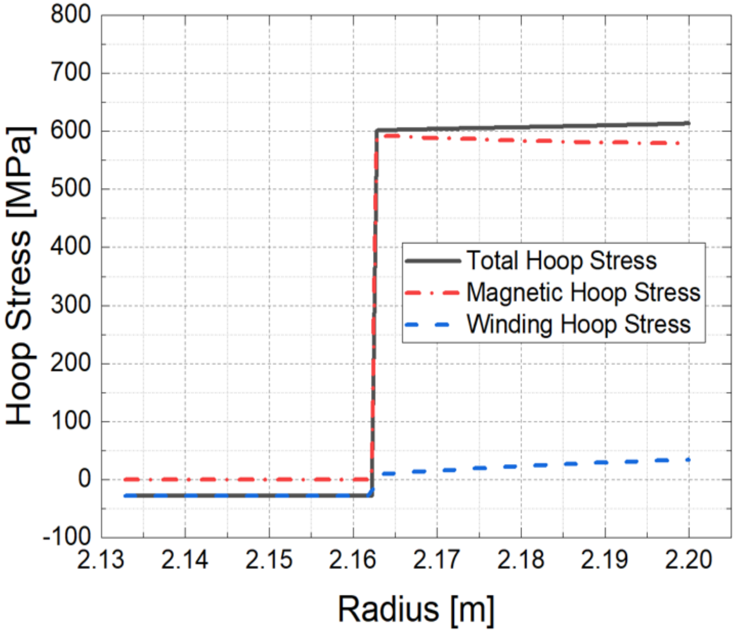




□ Peak Hoop Stress in "6-mm" Coils

- 3-kg winding tension
- Bending and thermal stress neglected
- Maximum hoop stress: 612 MPa
- Maximum hoop strain: **0.33 %**





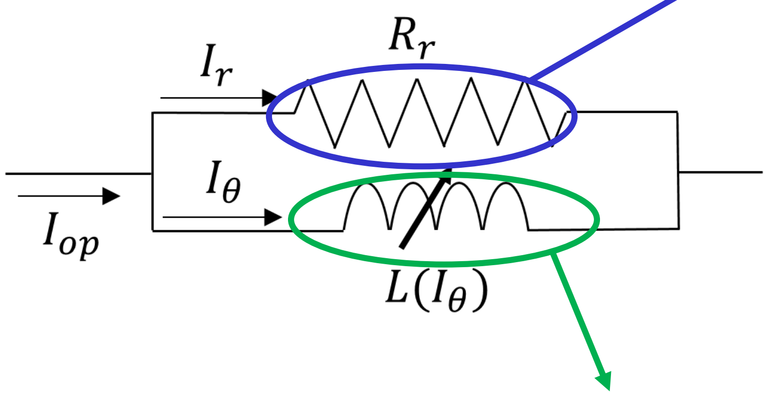
presented by Jeonghwan Park at "Tue-Mo-Po2.05-04 [27]"

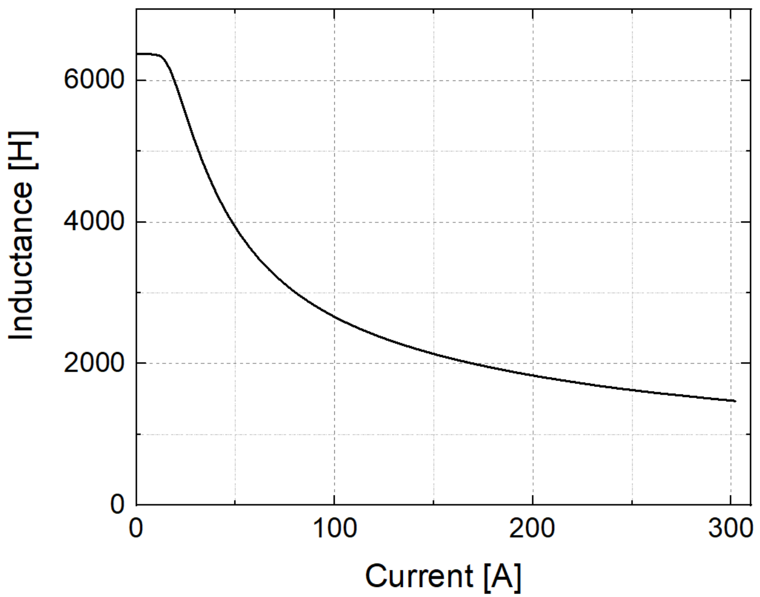
Park, Jeong Hwan
<hwan1022@snu.ac.kr>

3.3 Operation Analysis: NI Characteristcs Considered Charging Analysis

■ Charging Scenario with “Active Control System” + “Overshoot Technique”

□ Analysis Circuit Model





□ Contact Resistance

10 T metal insulation HTS insert in Grenoble 32T

Ref) Xavier CHAUD *et al.*, “A 10 T HTS insert made of MI Pancakes Tested in a Magnetic Field up to 20 T,” presented at EUCAS 2019, Glassgow, UK, 2019.

R_{ct} > 1,000 $\mu\Omega \cdot \mathrm{cm}^2$ in previous studies

Ref) T. Lecrevisse *et al.*, “A (RE)BCO Pancake Winding With Metal-as-Insulation,”.*IEEE. Trans. Appl. Supercond.*, vol.26, no. 3, 2016

□ Strategy for Reducing Charging Delay

(1) Use of bundle tape

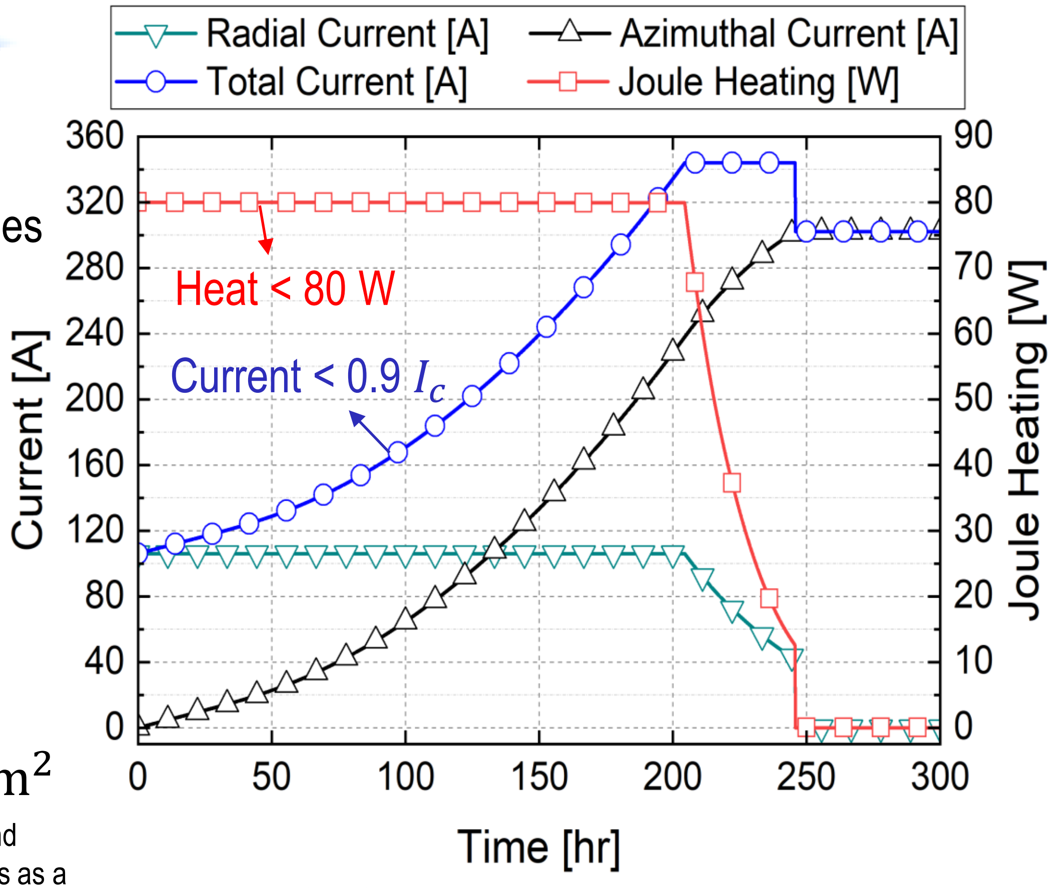
Ref) T. Watanabe *et al.*, “HTS Coils Wound by Bundle Conductor Composed of No-insulated REBCO Tapes,” presented at EUCAS 2019, Glassgow, UK, 2019.

(2) Increase R_{ct} > 20,000 $\mu\Omega \cdot \mathrm{cm}^2$

Ref) WD Markiewicz *et al.*, “Quench transient current and quench propagation limit in pancake wound REBCO coils as a function of contact resistance, critical current, and coil size,” Supercond. Sci. Technol, 32, 2019, 105010

□ Charging Analysis Results

Total Radial Resistance: **7.1 mΩ**



It takes 250 hrs to charge the magnet

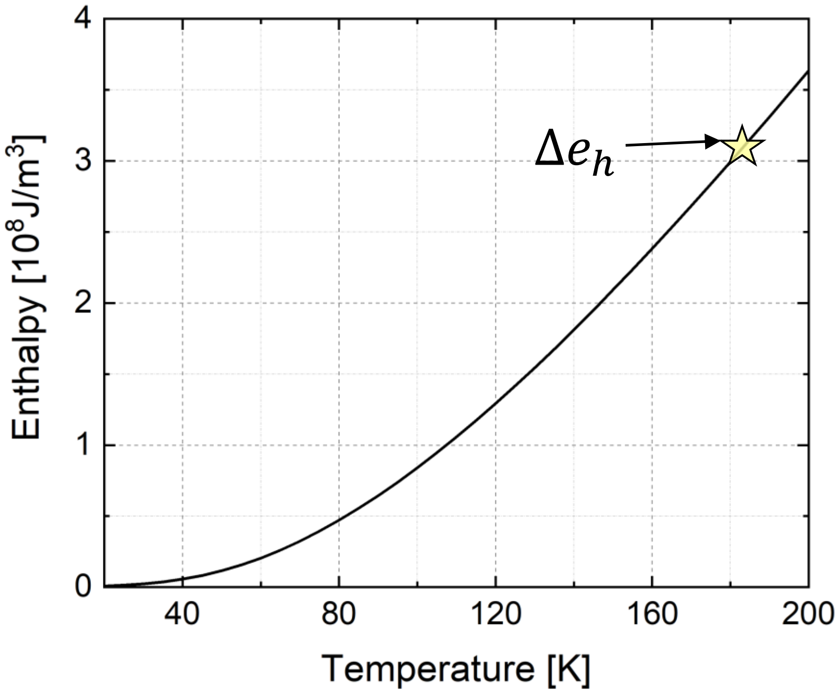
Park, Jeong Hwan
<hwan1022@snu.ac.kr>

3.4 Preliminary Quench Analysis: 168 K Rise, 4.3 MN Unbalanced Force

- Temperature Rise
  - Enthalpy Analaysis: **~170 K** rise.

Total energy: 67 MJ
Winding volume: 0.21 m^3

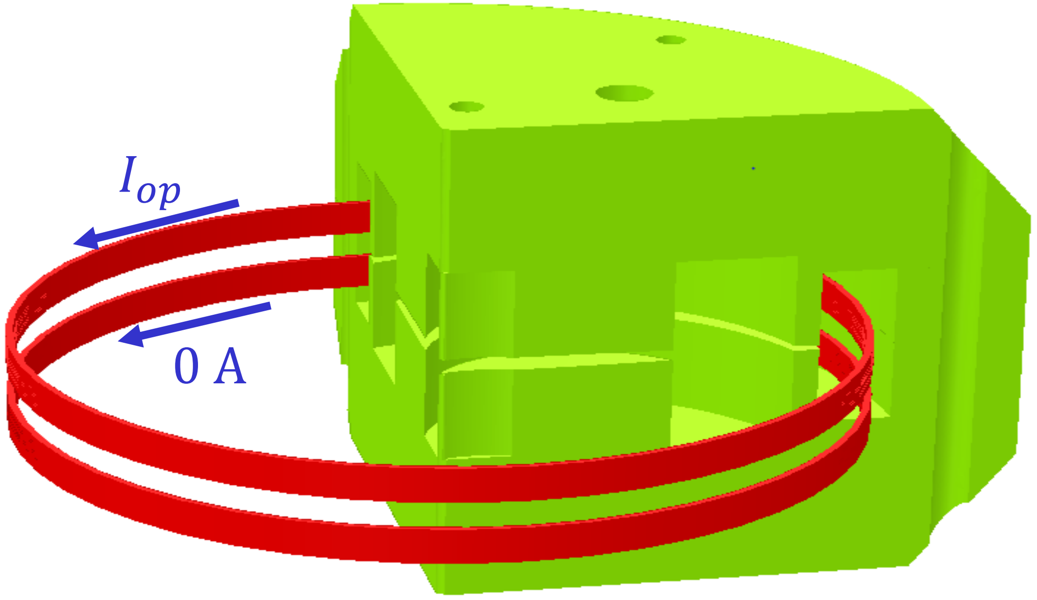
$\Delta e_h = 3.2 \times 10^8$ J/m^3



- Unbalanced Force (Worst Scenario)
  - Total Axial Lorentz Force: 4.4 MN

A situation that one split coil is fully discharged

Fig. Quarter model for magnetic simulation



Other issues (maybe critical) on quench scenario
(1) Overstress in NI magnet;
(2) Screening-current induced stress

Contents

4. Summary: 385 MeV/u NI-HTS Magnet (6.2 m OD; 540 tons; 20 K)

- Carbon Ion Accelerator
  - Injection
  - Acceleration
    - Cyclotron
      - Magnet
        - Electomagnetic
          - Field Strength
            - Coil ← Multi-width technique
            - Yoke ← Parameter sweep
          - Homogeneity
            - Configuration
            - Screening current
            - Construction error
            - Shimming
        - Mechanical
          - Winding
          - Thermal
          - Bending
          - Magnetic
            - Transporting current
            - Screening current
        - Operation
          - Charging analysis
          - Cryogenic system
          - Fatigue
        - Quench
          - Overstress in quench
          - Unbalanced force
          - Tempature rise upon quench
      - RF dee
    - Synchrotron
  - Extraction

Use of Defect-irrelevant-winding? (Coil)
Presented by Uijong Bong et al.
Wed-Af-Po3.24-10 [104]

Thermal eraser (Screening current)
Presented by Jeseok Bang et al.
Thu-Af-Or24-04

Future Works

- Beam Stability
  - Equilibrium orbit analysis
    - Tune diagram
    - Isochronous condition
  - Beam Tracking
    - Single particle tracking
      - RF phase
      - resonance
    - Multi particle tracking

Thanks for your attention

Acknowledgement: This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2018R1A2B3009249).