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

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09/26/2019
1. Introduction
   1.1 Former Studies on Heavy Ion Accelerator for Cancer Treatment
   1.2 Key Concepts: Multi-width & No-Insulation Technique & 20 K Cryocooling

2. Design Overview
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   2.2 Design Process: Design Flowchart
   2.3 Design Target: Extraction Energy of 385 MeV/u

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   3.4 Quench Analysis: Temperature Rise & Unbalanced Force

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

- **Synchrotron**
  - Several systems are available (HIMAC, HIT…)
  - (1) Large space
  - (2) AC operation: complex control
  - (3) Discontinuous beam

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

- **Multi-Width (MW)**
  Minimization of conductor usage

- **Cryocooling**: 20 K operation
  1. Helium free cryogenic system
  2. >100 stability margin than LTS

NI: “Quench Current Bypass”

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2.1 Overview Table: Requirements & Physical Constants & Dimension

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

<table>
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<th>Design Process</th>
<th>Requirements</th>
<th>Physical constants</th>
<th>Dimension</th>
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<tr>
<td><strong>A. Cost</strong></td>
<td>Compactness</td>
<td>Iron Weight</td>
<td>Main Yoke Configuration</td>
</tr>
<tr>
<td>1. EM Design</td>
<td>Field Strength</td>
<td>Conductor Length</td>
<td>$h_1, h_2, t_1, t_2$</td>
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<td><strong>B. Performance</strong></td>
<td>Field Distribution</td>
<td>Magnetic Rigidity</td>
<td>Coil Configuration</td>
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<td>2. Beam Stability Design</td>
<td>Isochronous Field</td>
<td>AVF</td>
<td></td>
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<tr>
<td><strong>C. Reliability</strong></td>
<td>Mechanical Integrity</td>
<td>Mechanical Strain</td>
<td>Hill Yoke Configuration</td>
</tr>
<tr>
<td>3. Mechanical Analysis</td>
<td>Operating Scenario</td>
<td>Charging Time</td>
<td>$\ell_0$, Coil size</td>
</tr>
<tr>
<td>4. Operation Analysis</td>
<td>Quench Scenario</td>
<td>Overstress</td>
<td># of dps</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unbalanced Force</td>
<td>Cowinding</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Temperature Rise</td>
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</table>

Analysis from field distribution & coil parameters

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2.2 Design Process: Design Flowchart

- 7 Steps for Specified Design Process

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<td>3. Mechanical Analysis</td>
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<tr>
<td></td>
<td></td>
<td>4. Operation Analysis</td>
</tr>
</tbody>
</table>

1. Main yoke configuration
2. Multi-width coil configuration
3. Hill yoke design
4. Estimate Ic
5. Mechanical analysis
6. Beam stability analysis
7. 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: Ic(\(|B, \theta, 20 \text{ K}\))
5: Strain
6: Tune diagram
7: Charging delay & quench analysis

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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

GEANT4 Simulation Results


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3.1.1 Electromagnetic Design: Parameter Sweep for Main Yoke

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

□ Simplified 2D Axisymmetric Model

\[ B_{app}^{3D}(r) = \alpha(r)B_h(r) + (1 - \alpha(r))B_v(r) \]

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

□ Gauss-Newton Method

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

where \( B_{iso} \):

<table>
<thead>
<tr>
<th>h, w</th>
</tr>
</thead>
<tbody>
<tr>
<td>m_0c</td>
</tr>
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</table>

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

- \( h, w \)

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3.1.2 Electromagnetic Design: Hill Yoke Design toward Isochronous Field

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

- Mapping Points on xy Plane
- Field Distribution
- Tune Diagram: using “Cyclone” code

Automatic iteration process

\[ \Delta \text{(Angle width ratio)} = \frac{(B_{iso} - B_{cal})}{(B_{hill} - B_{valley})} \]

\( \Delta \) (Angle width ratio) = \( B_{iso} - B_{cal} \) / \( B_{hill} - B_{valley} \)

- RF field simulation
- Reference field shaping

Missing Parameters in This Draft Design

Injection / Extraction

10 MeV to 4620 MeV with 10 MeV interval

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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**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending Limit, $K$ [MeV]</td>
<td>1540</td>
</tr>
<tr>
<td>Magnet Dimension [m]</td>
<td>6.2 (D) 3 (H)</td>
</tr>
<tr>
<td>Weight [ton]</td>
<td>540</td>
</tr>
<tr>
<td>Conductor Usage [km]</td>
<td>112</td>
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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 %

Nomenclature:

- \( B_1 \)
- \( B_2 \)
- \( a_1 \)
- \( a_2 \)
- \( \alpha = \frac{a_2}{a_1} \)
- \( \kappa = \frac{B_2}{B_1} \)

Presented by Jeonghwan Park at “Tue-Mo-Po2.05-04 [27]”
### 3.3 Operation Analysis: NI Characteristics Considered Charging Analysis

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

- **Analysis Circuit Model**
- **Contact Resistance**

![Diagram of Analysis Circuit Model](image)

- **Charging Analysis Results**
  - **Total Radial Resistance:** 7.1 mΩ

### Strategy for Reducing Charging Delay

1. **Use of bundle tape**

2. **Increase $R_{ct} > 20,000 \, \mu\Omega \cdot \text{cm}^2$**

**It takes 250 hrs to charge the magnet**

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

- Temperature Rise
  - Enthalpy Analysis: ~170 K rise.

<table>
<thead>
<tr>
<th>Total energy: 67 MJ</th>
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<td>Winding volume: 0.21 m^3</td>
</tr>
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</table>

\[ \Delta e_h = 3.2 \times 10^8 \text{J/m}^3 \]

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

A situation that one split coil is fully discharged

Other issues (maybe critical) on quench scenario

\[ \{ \begin{align*} & (1) \text{ Overstress in NI magnet;} \\
& (2) \text{ Screening-current induced stress} \end{align*} \]

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- Carbon Ion Accelerator
  - Injection
  - Acceleration
  - Extraction
  - Cyclotron
  - Synchrotron

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

- Magnet
  - Electromagnetic
    - Field Strength
      - Homogeneity
        - Winding
        - Thermal
        - Bending
        - Magnetic
      - Configuration
        - Screening current
        - Construction error
        - Shimming
    - Transporting current
      - Screening current

- Mechanical
  - Winding
  - Thermal
  - Bending
  - Magnetic

- Operation
  - Charging analysis
  - Cryogenic system
  - Fatigue

- Quench
  - Overstress in quench
  - Unbalanced force
    - Tempature rise upon quench

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

Thermal eraser
*Presented by Jeseok Bang et al.*
*Thu-Af-Or24-04*
Thanks for your attention

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