Radiation Effects in Superconducting Quadrupoles for BigRIPS In-flight Separator at RIKEN


Contents

- Introduction (Facility, Magnet)
- Beam(Radiation) Heat load
- Dose Estimate ~1MGy in 9 years
- Impurities in He gas (T, CH₄)
- Excitation voltage & coil movement

“Any indication of degradation of superconducting coil?”
RIBF project at RIKEN
(Radioactive Isotope Beam Factory)

- 442 RI beams produced
- 157 New Isotopes

Since 2007

Aimed at making significant progress in the studies of exotic nuclei far from stability
RIBF Accelerator Complex

- Deuteron ~ U ions
  \[ E = 345 \text{ MeV/nucleon} \]

- Max beam power ~ **13kW** for Kr & Ca in 2016
1\textsuperscript{st} STQ (Superconducting Triplet Quadrupoles)

- Air-Core type superconducting triplet Quads
  - Triplet in Single Cryostat
  - LHe Bath Cooling
- In the close proximity of the production target
- Exposed to very high radiation

Dose accumulated $\sim 890$ kGy

In 9-years operation

Operational experiences related to radiation effects

Operation data
STQ1 Superconducting Triplet Quadrupoles

- NbTi superconducting Coils with Cu stabilizer
  PEI Insulated conductor 1.46 x 2.36 mm
  54 filaments with φ175 μm
  Cu/super ratio 1.33  Ic [A] 2100A @ 7T

- Flat Racetrack Coil
  - Wet winding
  - “layer by layer”
  - Epoxy Resin with Fillers
  - Supported in Coil case

<table>
<thead>
<tr>
<th></th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective length [m]</td>
<td>~ 0.5</td>
<td>~0.8</td>
<td>~0.5</td>
</tr>
<tr>
<td>Field Gradient [T/m]</td>
<td>24</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Number of turns</td>
<td>745</td>
<td>1315</td>
<td>1315</td>
</tr>
<tr>
<td>Ampere turn [kA]</td>
<td>552</td>
<td>825</td>
<td>825</td>
</tr>
<tr>
<td>Nominal current [A]</td>
<td>740</td>
<td>628</td>
<td>628</td>
</tr>
<tr>
<td>density [A/mm²]</td>
<td>188</td>
<td>159</td>
<td>159</td>
</tr>
<tr>
<td>Max field at coil [T]</td>
<td>6.0</td>
<td>6.9</td>
<td>7.0</td>
</tr>
<tr>
<td>Tc [K]</td>
<td>6.7</td>
<td>6.3</td>
<td>6.3</td>
</tr>
<tr>
<td>Ic/I0p</td>
<td>3.7</td>
<td>3.5</td>
<td>3.4</td>
</tr>
<tr>
<td>Stored energy [MJ]</td>
<td>0.34</td>
<td>1.21</td>
<td>0.81</td>
</tr>
</tbody>
</table>

4K total cold mass ~ 3.5 tons in LHe bath (1000L)
Observed Beam Heat load

- Heat load to STQ1 cryostat caused by radiation

- 1st Observation
  Dec. 2008  $^{48}\text{Ca}^{20+}$ 345MeV/u + Be 15, 20 mm
  10~40 W  for 0.5~2.3 μA

- 2010 - 2014
  $^{18}\text{O}^{8+}$ 345MeV/u + Be 60 mm
  $^{48}\text{Ca}^{20+}$ 345MeV/u + Be 10, 15 mm
  $^{70}\text{Zn}^{30+}$ 345MeV/u + Be 10 mm
  $^{124}\text{Xe}^{52+}$ 345MeV/u + Be 4 mm
  $^{238}\text{U}^{86+}$ 345MeV/u + Be 3 mm

- Typical Beam Current  ~ 0.5 ~ 4 μA
- Beam Power ~ 7 kW
- Observed Heat load 4 ~ 40 W

- Comparison with radiation transport calc. by PHITS simulation code

Simulation results agree within factor of ~2 In a wide range of mass $A = 18 \sim 238$
Cryogenic Control

- Cryo-control system before 2015
  
  LHe level is kept constant (~87%) by varying heater power

<table>
<thead>
<tr>
<th>Power</th>
<th>LHe level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased &gt; 87.1%</td>
<td></td>
</tr>
<tr>
<td>Decreased &lt; 87.0%</td>
<td></td>
</tr>
</tbody>
</table>

  Heater Control

  Beam Heat load (fluctuation)

  Level Sensor

  Liq. He

  Heater

  Worked well with fluctuation of < 50W

  10% of cooling capacity

  Heat load is evaluated by comparing ave. heater powers

  Intense $^{48}$Ca Beam (~8 μA, 6.6 kW) + Thick Target (~20mm)  
  Dec. 2014  
  Large Beam Heat load ~80W  
  > 15% of Cooling Capacity

  Too large heat load fluctuation

  Rapid increase of cold return gas makes Cryogenic system unstable

- Introduce “beam load heater”

  Beam Load Heater Output

  100W

  0

  10μA

  Beam Current

  Slope depends on Target thickness

  Compensate beam heat load fluctuation
Observed max beam heat load of **170 W** (\(^{48}\)Ca with 20 \(\mu\)A + 20 mm Be target) in 2016

1/3 of cooling capacity
Dose Estimate

PHITS simulation
Local Heat Deposit

Max density @ P1 coil

Operation Record

<table>
<thead>
<tr>
<th>Season</th>
<th>Beam</th>
<th>Target Thickness (mm)</th>
<th>Integrated Current (p μA day)</th>
<th>Dose (kGy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014</td>
<td>2Q</td>
<td>1, 3, 4, 7</td>
<td>0.3</td>
<td>43</td>
</tr>
<tr>
<td>2014</td>
<td>4Q</td>
<td>4, 5, 6, 7</td>
<td>0.1</td>
<td>30</td>
</tr>
<tr>
<td>2015</td>
<td>2Q</td>
<td>1, 3, 4, 5</td>
<td>0.3</td>
<td>44</td>
</tr>
<tr>
<td>2015</td>
<td>4Q</td>
<td>12, 15, 20, 30</td>
<td>3.8</td>
<td>85</td>
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<tr>
<td>2015</td>
<td>2Q</td>
<td>1, 3, 4, 5</td>
<td>0.3</td>
<td>44</td>
</tr>
<tr>
<td>2016</td>
<td>2Q</td>
<td>2, 5, 7</td>
<td>0.2</td>
<td>60</td>
</tr>
<tr>
<td>2016</td>
<td>4Q</td>
<td>15, 20</td>
<td>2.9</td>
<td>62</td>
</tr>
<tr>
<td>2016</td>
<td>2Q</td>
<td>2, 4, 5, 7</td>
<td>0.4</td>
<td>77</td>
</tr>
<tr>
<td>2016</td>
<td>4Q</td>
<td>15, 20</td>
<td>3.9</td>
<td>15</td>
</tr>
<tr>
<td>2016</td>
<td>4Q</td>
<td>4, 7, 10</td>
<td>0.2</td>
<td>49</td>
</tr>
<tr>
<td>2014</td>
<td>4Q</td>
<td>15, 20</td>
<td>6.8</td>
<td>172</td>
</tr>
</tbody>
</table>

Operation Record

<table>
<thead>
<tr>
<th>Beam</th>
<th>Target Thickness (mm)</th>
<th>Heat deposit density (mW/cc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18O8+</td>
<td>20</td>
<td>0.45</td>
</tr>
<tr>
<td>48Ca20+</td>
<td>30</td>
<td>3.5</td>
</tr>
<tr>
<td>70Zn30+</td>
<td>12</td>
<td>3.5</td>
</tr>
<tr>
<td>78Kr36+</td>
<td>7</td>
<td>2.0</td>
</tr>
<tr>
<td>238U86+</td>
<td>4</td>
<td>20</td>
</tr>
</tbody>
</table>

per 1 p μ A

890 kGy
Observed Impurities in He gas form STQ1 cryostat

- Tritium (T)
  - $^4\text{He}(n,d)T \ (E_{th}=22\text{MeV})$ reaction in LHe bath
  - Radioactivity in vent gas from STQ1 cryostat at warm-up monitored by Gas-monitor ALOKA MGR-133

- Hydrocarbon (CH$_4$
  - Dissociation of epoxy?
  - CH$_4$ concentration in He gas at discharge line of compressor by Gas Chromatograph
  - Observed when start circulating He gas in STQ1 cryostat at pre-cooling or purification
Quench Records & Accumulated Dose

5 quenches: P2, SX, P3 coils
P1 coil never quenched

2008 P2 @ 616, 625A (training quench)

2010-2017 Accumulated Dose (kGy)

- SX@10A w P3@500A (beam induced)
- SX@-31.6A w P3@628A(max) (training quench with different polarity)
- P3@628A(max) w SX@-32.5A(max) (training quench with different polarity)

P2@624A

All of them are due to thermal cycle
Excitation voltage of P2 quench ramp

Oct. 15 2014 (~200kGy)  First ramp after pre-cooling
Stepwise ramp-up with ramp rate 0.4A/s
  100A step (<600A), 10A step (>600A)

Operation log data
Analog monitor output of PS
Sampling speed of 125msec

Quench @ 624A
(max 628A)
Spikes in excitation voltage

Spikes in excitation voltage @ 90A
Spikes in excitation voltage

Spikes disappeared in 2nd ramp-up
Coil movement due to thermal cycle

Can we see difference between ramps in different accumulated dose periods?
Comparison of different ramps

V vs I plot of 1st P2 ramp-up after pre-cooling

Slope: Voltage drop due to DC cables
Intercept: inductance of P2 coil (ramp speed 0.4 A/s)

No distinct difference between different ramps (different dose)
Smaller disturbance may be detected with faster logging system

No signal of degradation
Summary

- Beam Heat load to Cryostat
  Evaluated by heater power analysis of operation data of BigRIPS cryogenic system
  PHITS simulation results agree within a factor of 2
- Dose Estimate
  Operation records (beam current) & Local heat deposit estimated by PHITS simulation
  Accumulated dose of STQ1 coil : order of 1 MGy (890kGy)
- Excitation voltage as coil motion
  No distinct difference between different ramps (different dose)
  No signal of degradation
- Impurities in He gas from cryostat
  Tritium and CH$_4$ in STQ1 cryostat increase, as the dose increases