Machine Protection Issues for eRHIC

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Outline

• Overview of RHIC & eRHIC (3 slides)
  – RHIC Capabilities & Operation Experience
  – eRHIC Capabilities
• RHIC Machine Protection Systems (3 slides)
  – Permit systems and Beam Dump
• Energy in Beams for eRHIC (2 slides)
• Dependability Issues for eRHIC (2 slides)
  – Categories of beam loss
  – Types of failures
• Reliability Analysis & Design Preparation (2 slides)
• Dumping the eRHIC beams (2 slides)
• Summary
RHIC – a High Luminosity (Polarized) Hadron Collider

Operated modes (beam energies):
- Au – Au: 3.8/4.6/5.8/10/14/32/65/100 GeV/n
- U – U: 96.4 GeV/n
- Cu – Cu: 11/31/100 GeV/n
- p↑ – p↑: 11/31/100/205/250/255 GeV
- d – Au*: 100 GeV/n
- Cu – Au*: 100 GeV/n

Achieved peak luminosities:
- Au – Au (100 GeV/n): $195 \times 10^{30}$ cm$^{-2}$ s$^{-1}$
- p↑ – p↑ (255 GeV): $238 \times 10^{30}$ cm$^{-2}$ s$^{-1}$

Other large hadron colliders (scaled to 255 GeV):
- Tevatron (p – pbar): $110 \times 10^{30}$ cm$^{-2}$ s$^{-1}$
- LHC (p – p): $493 \times 10^{30}$ cm$^{-2}$ s$^{-1}$

Planned or possible future modes:
- Au – Au: 2.5 GeV/n
- p↑ – A*: 100 GeV/n (A = Au, Cu, Al)
- ³He – A*: 100 GeV/n (A = Au, Cu, Al)
- p↑ – ³He*: 166 GeV/n (asymmetric rigidity)
### eRHIC in RHIC tunnel

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>$10^{33} - 10^{34}$ cm$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>Electron energy</td>
<td>5 - 10 GeV</td>
</tr>
<tr>
<td>Electron current</td>
<td>50 mA</td>
</tr>
<tr>
<td>Electron polarization</td>
<td>80 %</td>
</tr>
<tr>
<td>Proton energy</td>
<td>50 - 250 GeV</td>
</tr>
<tr>
<td>Proton current</td>
<td>300 mA</td>
</tr>
<tr>
<td>Proton polarization</td>
<td>70 %</td>
</tr>
<tr>
<td>Center-of-mass energy</td>
<td>30 - 70 GeV</td>
</tr>
</tbody>
</table>

**Diagram:**
- Electron beam
- ePHENIX
- eSTAR
- Proton or HI beam
- Polarized e-gun
- SRF Linac 1.65 GeV
- 100 MeV dump
- Beam dump

**Text:**
- BROOKHAVEN NATIONAL LABORATORY
- Oct. 6 - 11, 2013
- ICALEPCS 2013
Each electron bunch sees an ion/proton collision once. Each bunch is accelerated up to full energy, is at 10 GeV for one turn, then is decelerated back through the Energy Recovery Linac and dumped.

Ions/proton magnet cycle
Each ion/proton bunch goes into collisions millions of times, during the many hours of “store” at full energy.
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Layers in Protection

ICALEPCS 2013

PS Interlock
Abort Kicker Systems
Post Mortem Data Dump & Analysis
ADO Controls
Notification Events

Abort Kicker Triggers
VME Processor ADO interface: read registers
Event Link

Quench Protection Assembly
Quench Link Interface
Permit Link Interface

Quench Detectors: Voltage Taps to A/D to DSP
Loss Monitors
Vacuum PLCs
PS Interrupts
Access Controls

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Brookhaven National Laboratory

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RHIC Beam Permit & Beam Dump

- 3 Permit Link systems
  - Beam Permit link
  - Blue ring Quench Permit Link
  - Yellow ring Quench Permit Link
  - 10 MHz carrier is monitored on each link

- Beam dump/abort kickers
  - One for each Ring (Blue/Yellow)
  - Redundant interface modules to permit links

- Two primary permit drops
  - Non-quench beam permit drop
    - Abort kickers fire, injection beam switch dropped
  - Quench permit drop
    - Additionally, magnet currents are dumped.
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## Energy in the Beams

<table>
<thead>
<tr>
<th></th>
<th>Electrons</th>
<th>Protons</th>
<th>$^2\text{He}^3$</th>
<th>$^{79}\text{Au}^{197}$</th>
<th>$^{92}\text{U}^{238}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>10</td>
<td>250</td>
<td>167</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>#bunches</td>
<td>180</td>
<td>111</td>
<td>111</td>
<td>111</td>
<td>111</td>
</tr>
<tr>
<td>Intensity/bunch*</td>
<td>3.6</td>
<td>10</td>
<td>6.0</td>
<td>6.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Energy Deposited</td>
<td>62**</td>
<td>89</td>
<td>178</td>
<td>107</td>
<td>107</td>
</tr>
</tbody>
</table>

* intensity/bunch is in units of # nucleons (e.g., 6e10 Au nucleons = 3.6e8 Au ions)
** assumes 6 turns of 180 bunches simultaneously stored in eRHIC ring

- At 10 GeV, the electron beam has 62 kJ of energy and will deposit ~810 MW of power into the dump.
Energy Loss in Normal Operation

- Cavity Losses
- Resistive Wall Losses
- Synchrotron Radiation Losses

Total power loss, MW

Top energy, GeV

5 10 15 20 25 30
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How to protect eRHIC?

eRHIC beam losses can be classified as

1. Ultra-fast: Losses that occur in less than 6 turns, or 77 microseconds.
   - Collimation
2. Fast: Losses that occur in more than 77 microseconds but less than 10 milliseconds.
   - Fast beam abort system
3. Intermediate: Losses that occur in less than 10 seconds.
   - Reduce beam current (automated), or
   - Fast beam abort system (if not fast enough)
4. Slow: Losses that occur in less than 100 seconds
   - Beam current can be dropped or turned off and problem corrected (or dumped if not fast enough)
5. Steady State: Anything longer than 100 seconds.
   - Beam current can be dropped and problem corrected

• All systems will be monitored and will alarm/notify.
Types of Failures?

• The MP prevents damage to equipment.
• What happens when it doesn’t do what it is “suppose” to do?
• Two categories of these types of failures
  – Logic errors in the design/implementation
  – Component failures
  – Since all the systems are automated, human error fits into the logic errors category
• Regardless of type of failure, two modes of concern
  – Failsafe modes: system aborts beam, etc.
  – Blind modes: system enters state that prevents abort = These are most dangerous!
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Overview

• Reliability analysis of RHIC MPS (as an integral part of eRHIC MPS) with decision support for additional system for electron ring
• Initial step: BPS – takes active decision
• Analyzing the probability of occurrence of crucial system failures: false beam abort, false quench, blind, dirty dump
• Identification of failure prone components
• Impact of design configuration of modules
Stages

1. To find system failures probabilities*
   – A modular, multistate, dynamic reliability model of BPS using competing risks theory
   – Implemented as a Monte Carlo Simulation

2. To find failure rates for failure modes**
   – Fault Tree Analysis of BPS modules
   – Determine vulnerable components
   – Module failure rates serve as an input to stage 1

Two of yesterday’s posters, for more details on Simulation and Fault Tree Analysis
*MOPPC075 : A Monte Carlo Simulation Approach to the Reliability Modeling . . .
**MOPPC076 : Quantitative Fault Tree Analysis . . .
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During beam abort, the number of accelerating bunches and decelerating bunches should be identical to avoid over-power/under-power SRF cavities.  
One beam dump at 10 GeV arc.  
One beam dump at one of the two 0.6GeV beam line.  
Additional beam dumps, if necessary, could be added to reduce response time.  
The relative timing of the abort kickers depends on their locations and is critical for keeping energy compensation in LINACs.
Fitting the high energy dump?

- Septum magnet: ±2 mrad
- 1 m magnet + 1 m Drift
- Separation @ dipole: 1.47 cm

- Separation @ exit of dipole: 3.2 cm
- Separation angle: 4.34 mrad
- To beam dump

- 4.4 cm between pipe
- 6 m long kicker
- 0.039 T dipole field
- 2.34 mrad kick angle
- 7 mm separation @ Septum
Summary

• eRHIC beams are powerful enough to damage equipment.

• eRHIC has new challenges both in response time and types and number of systems that get included in the machine protection systems.

• Dependability analysis is a critical part of the design process and helps identify blind failure modes in the MP systems.

• We are well on the way to identifying key design features that will be implemented to improve the RHIC and eRHIC MP systems.

Thank You!
RHIC Beam Permit & Beam Dump

• RHIC Magnet Systems
  – 1740 superconducting magnets over 2.5 miles
  – LHe Refrigerator operates at 4.5° K
  – Cold power interface quench protection
    • Bypass diodes during quench
    • Dump resistors switch in during quench
    • Quench detection primarily via voltage tap monitors on groups of magnets

• Other Systems
  – Vacuum interlocks
  – 382 beam loss monitor detectors
  – External radiation interlock systems
  – Access controls interlocks
Post Mortem Analysis

• Permit drops initiate high frequency data dumps of
  – Beam loss monitors
  – Magnet waveforms
  – Beam position monitors
  – Permit module data/timestamps
  – Quench detector data

• Automatic analysis is performed to help categorize the cause of the beam dump
  – Quench analysis
  – PS analysis