

A Long Term Reliability Challenge at the RHIC

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70 YEARS OF
DISCOVERY

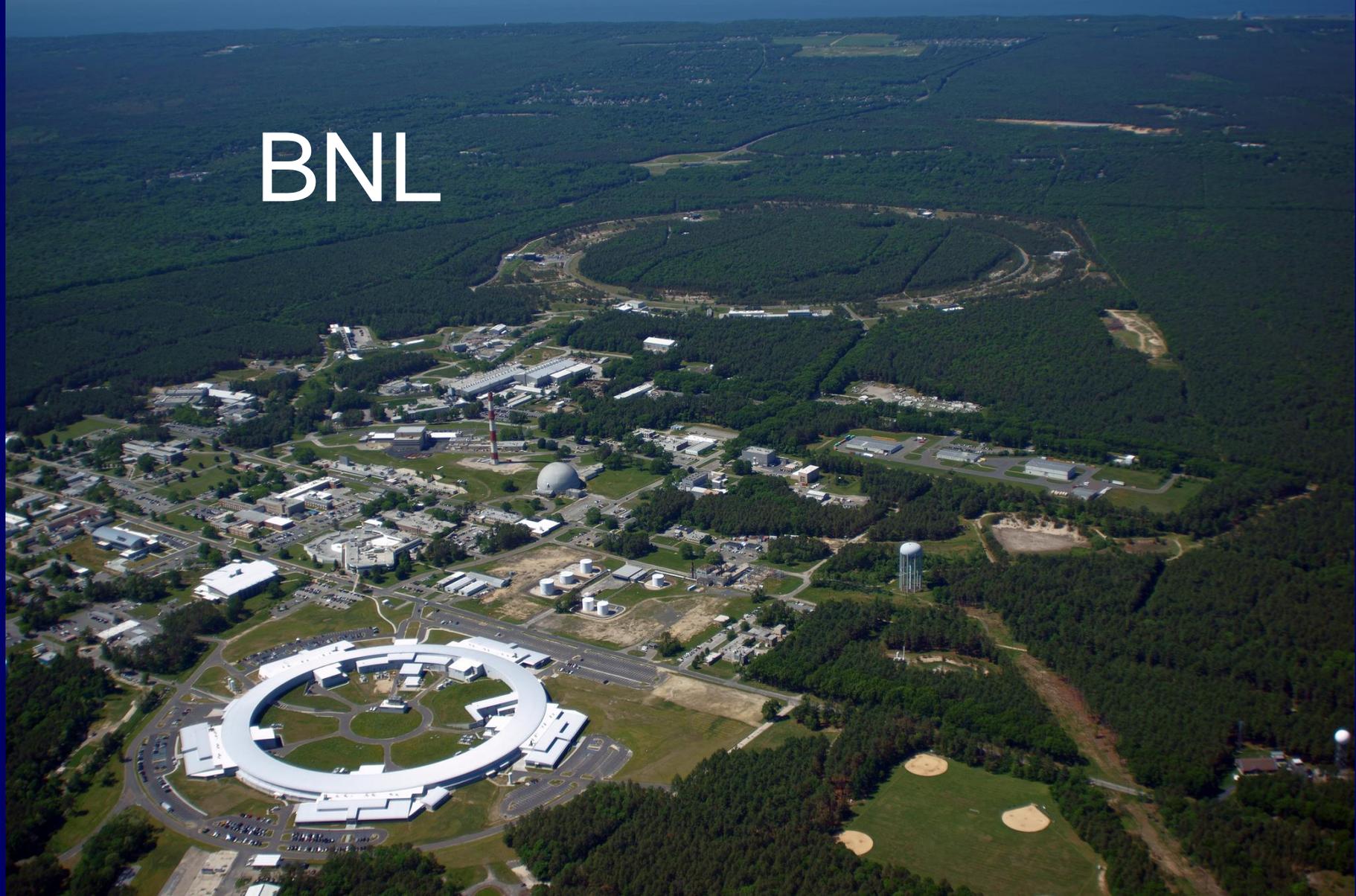
A CENTURY OF SERVICE

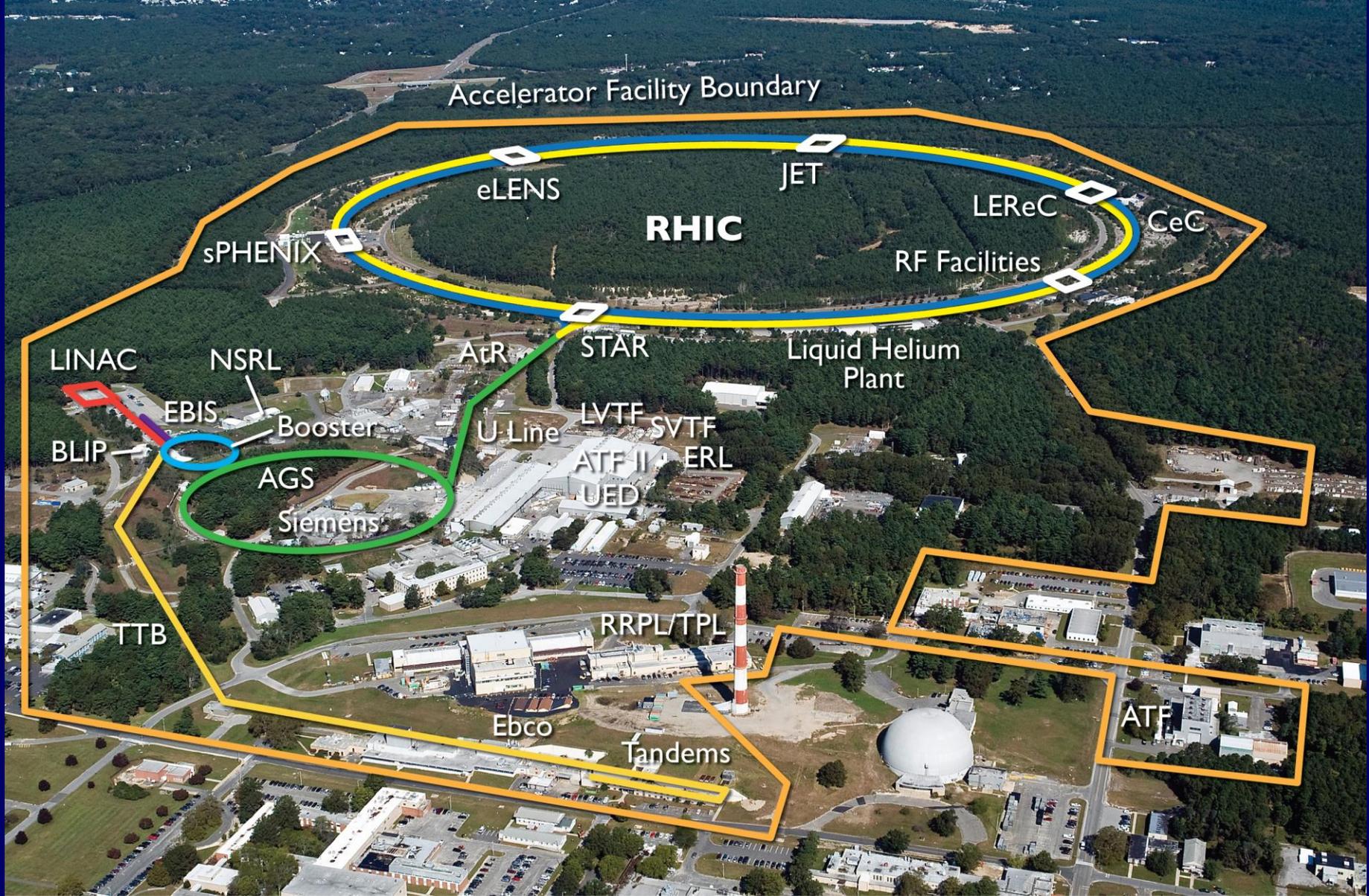


Abstract

Long term reliability is critical for any successful particle accelerator operation. The Relativistic Heavy Ion Collider (RHIC) is now faced with a reliability challenge owing to age, continual performance improvements, and even best practice design considerations. This presentation will focus on our experience with the RHIC quench protection diodes; a passive part of the machine protection system. The history and the effect that failed diodes have had on RHIC operations during the recently completed Runs 16 and 17 will be reviewed.

BNL





Accelerator Facility Boundary

RHIC

eLENS

JET

LEReC

CeC

RF Facilities

sPHENIX

LINAC

NSRL

AtR

STAR

Liquid Helium Plant

EBIS

Booster

U-Line

LVTF

SVTF

ERL

BLIP

AGS

Siemens

ATF II

UED

TTB

RRPL/TPL

EbcO

Tandems

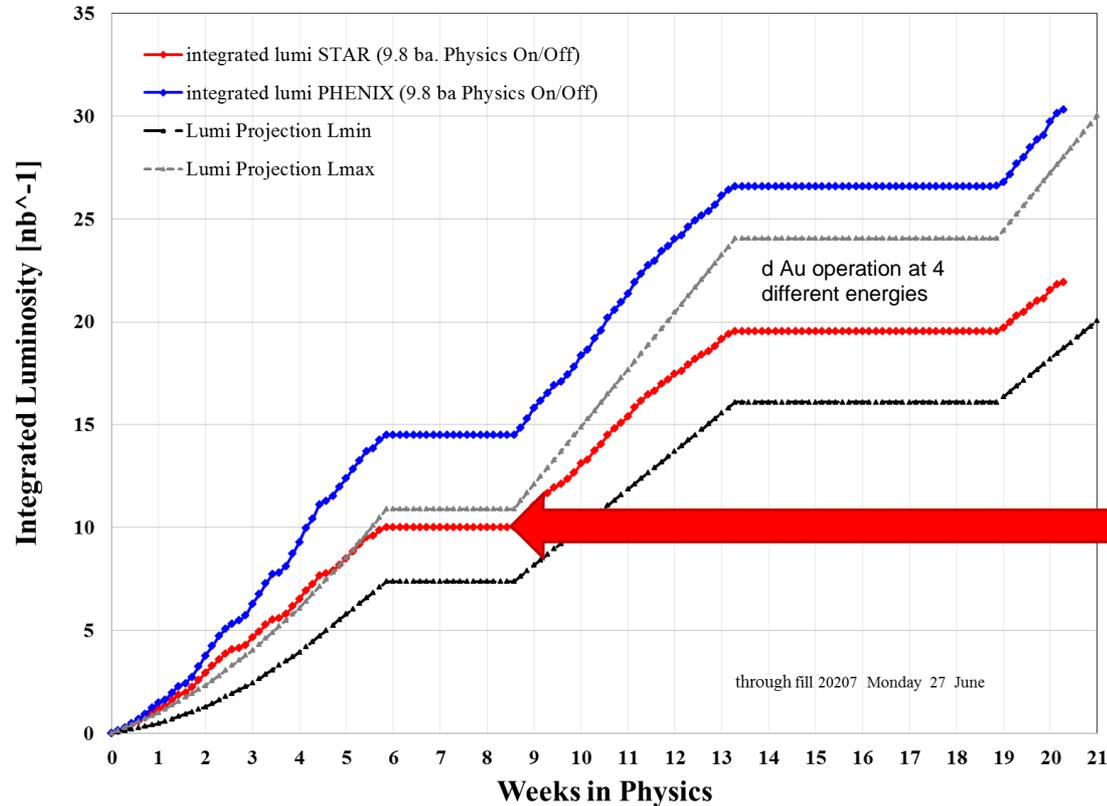
ATF

This Presentation

- The Reliability Concern
- Machine Protection Systems
- The Abort Kicker System
 - Best design practice
- The Quench protection diodes
- Diode Failure History
 - AGE
 - Radiation
- Operations with a compromised diode
- Prognosis

Run16 Delivered Luminosity

Au x Au $\sqrt{s} = 200$ GeV



Bottom Line
Run16

19 day interruption to
the physics program
during 2016 to replace
a quench protection
diode

The Reliability Concern

- Abort Kicker Pre-fires that may damage Quench Protection Diodes
 - A pre-fire is defined as a Thyatron spontaneously discharging a PFN through an abort kicker magnet unintentionally.
 - **Given the right conditions even one pre-fire has the potential to cripple an experiment detector or a quench protection diode.**
 - The abort kicker system is part of the RHIC MPS.
 - Kickers remove circulating beam from the ring(s) when:
 - an operator wants to terminate circulating beam
 - the MPS senses an anomalous condition.
 - one discharges unintentionally severely distorting the orbit

Pre-fires caused PHENIX RUN15 MPC Damage aggravated by “the right” conditions

Store# 19050

May 11

Damaged South
Impacted North

19116/18

May 28

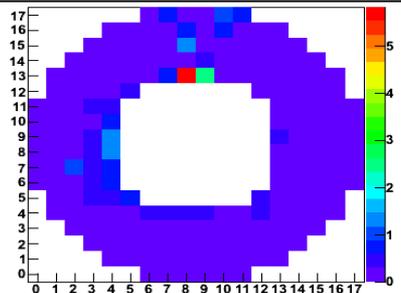
We got lucky
No add'l damage

19134

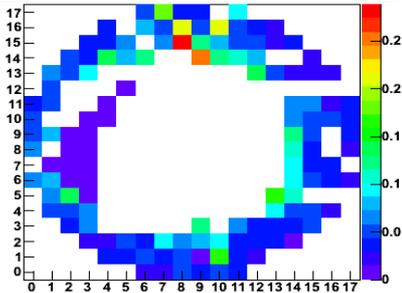
June 1

The end of the
MPC in Run 15

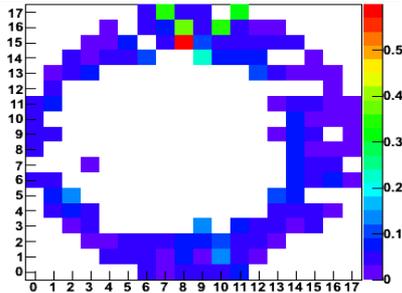
Energy Per Crystal, SMPC Trigger 0



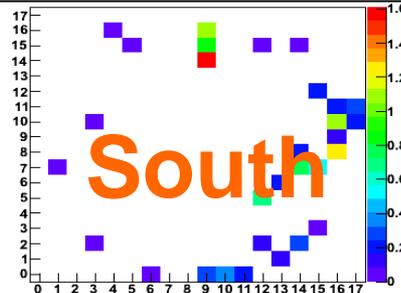
Energy Per Crystal, SMPC Trigger 0



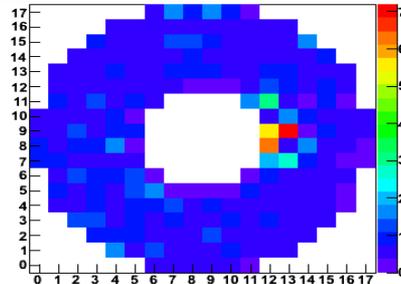
Energy Per Crystal, SMPC Trigger 0



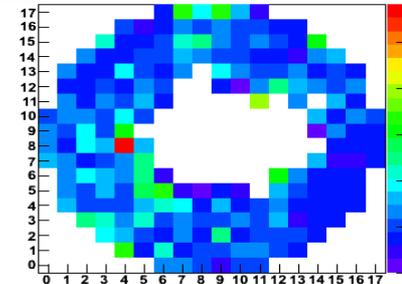
Energy Per Crystal, SMPC Trigger 0



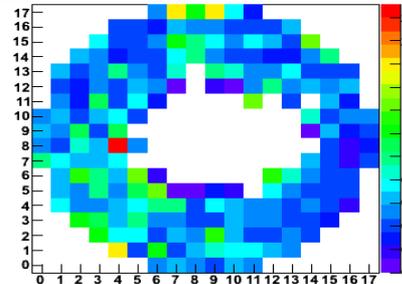
Energy Per Crystal, NMPC Trigger 0



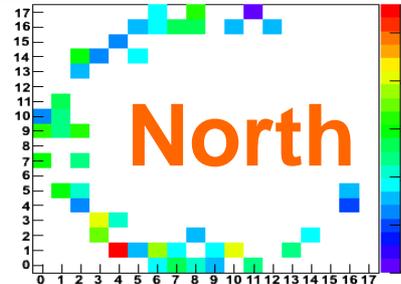
Energy Per Crystal, NMPC Trigger 0



Energy Per Crystal, NMPC Trigger 0



Energy Per Crystal, NMPC Trigger 0



RHIC Machine Protection Systems

Active

- Permit Link
 - Aborts circulating beam via abort kickers given inputs from systems like:
 - Vacuum
 - Loss monitors
 - Power Supplies
 - Personnel Protection System
 - Rf
 - Beam Position & Coherence Monitors
 - Cryogenic “lead flow”
 - Abort Kicker voltages
 - Experiment MPS

Passive

- Quench Protection Diodes
 - Diodes bypass the current from the other superconducting magnets in a string around a quenching (resistive) magnet

The Abort kicker System

The source of the problem

The Abort Kicker System (best design practice)

Original Kicker Requirements

5 Kickers per Ring

- Beam Should be aborted if one kicker fails to fire.
- If one kicker pre-fires then the other four are triggered to fire
- **Typical Voltage** **~27 kV**
- **Typical Current peak** **21 kA**
- **Current Rise Time to minimum Kick** **900 ns**
- Bunch Revolution Time **12.86 μ s**
- Abort Pulse Length min **~13 μ s**
- Abort Gap **1 μ s**
- Beam must be aborted within **4 turns, 52 μ s**
- Maximum delay for redundant trigger **0.7 μ s**
- Minimum Jitter **10 ns**

These Parameters dictated the use of a Thyatron!

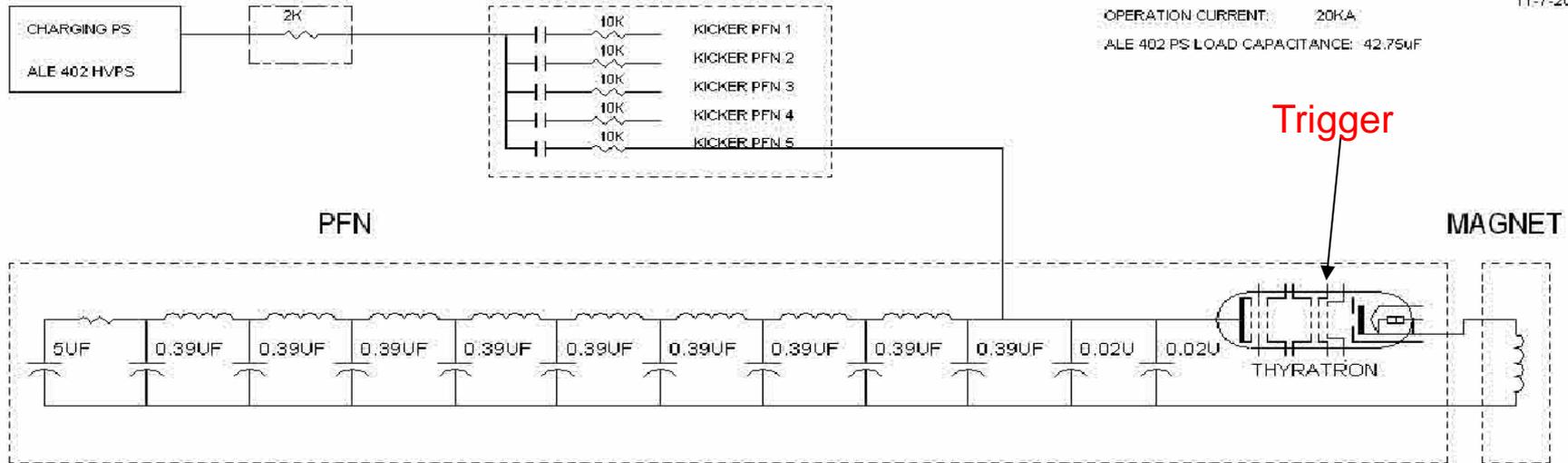
Abort Kicker System Circuit Diagram

RHIC ABORT KICKER SYSTEM DIAGRAM



JIANLIN MI
diagram1.skcd
11-7-2007

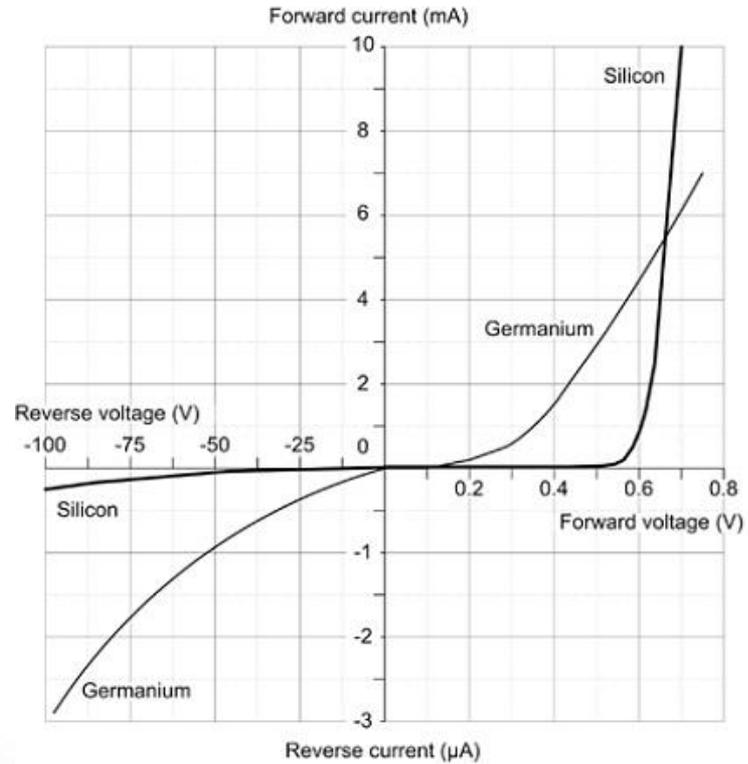
TEST VOLTAGE: 30 KV
 OPERATION VOLTAGE: 27KV
 OPERATION CURRENT: 20KA
 ALE 402 PS LOAD CAPACITANCE: 42.75uF



Abort Kicker System

- **The culprit: pre-fire is defined as a Thyatron spontaneously discharging a PFN through an abort kicker magnet unintentionally.**
- **The voltage on the abort kickers' PFNs is ramped up to match the energy of the RHIC beam and is maintained at high voltage (27 kV) during each RHIC store**
- **There are 5 kicker modules in each ring. Over a ten year period there have been an average of 8 pre-fires per ring per year**
- **Even after a great deal of effort there were 7 yellow pre-fires and 6 blue pre-fires (+ 4 caused by a bad trigger card) in 2017.**
- **Radiation is thought to be one contributing cause that triggers a thyatron to fire. The Pulse Forming Networks (PFN) are in the beam enclosure**

Quench Protection Diodes



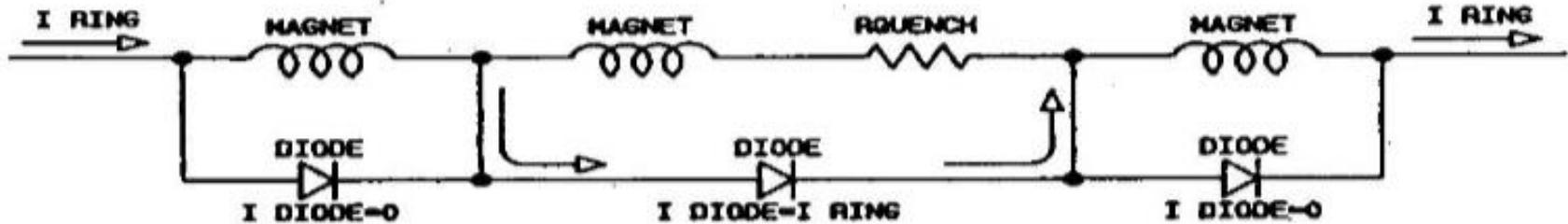
Basic Diode Operation

Blocks current flow in the reverse (voltage) direction

Quench Protection Diodes

- Each magnet (except the DX dipole) is capable of dissipating its own stored energy without being damaged
- The purpose of the diodes is to bypass the current from the other superconductive magnets in a string around a quenching (resistive) magnet
- When cold the diodes have a high forward break over voltage, in RHIC, **3 to 10 volts**.
- During normal ramping operation ($di/dt = 25.8$ amps/sec) the forward voltage across an arc dipole never exceeds **0.625 volts**
- If a magnet becomes resistive this voltage quickly rises and the diode conducts
- Once the diode conducts it heats up in milliseconds and its forward voltage drop decreases

Superconducting Protection Diodes



Diodes in Service

Diodes in Arc Dipoles	264
Diodes in Arc Quads	274
Insertion Components	362

Total= 900

Spare Diode Assemblies

Type 01	26
Type 02	2

What Happens if a Diode Fails?

- Diode Opens
 - The field is unaffected and machine runs normally. If other magnets Quench things behave normally but if the magnet with the open diode Quenches its coils can be severally damaged. In all the testing done for RHIC a diode has never opened.
- Diodes Forward Voltage Increases
 - This is the known effect of radiation damage to such diodes. As the forward drop increases the power dissipated in the diode increases, this may cause the diode to short. If the effect is not uniform across the diode small sections of the diode might turn on first and over current. This is one explanation for what may have happened to the diode which failed in 2016

What Happens if a Diode Fails?

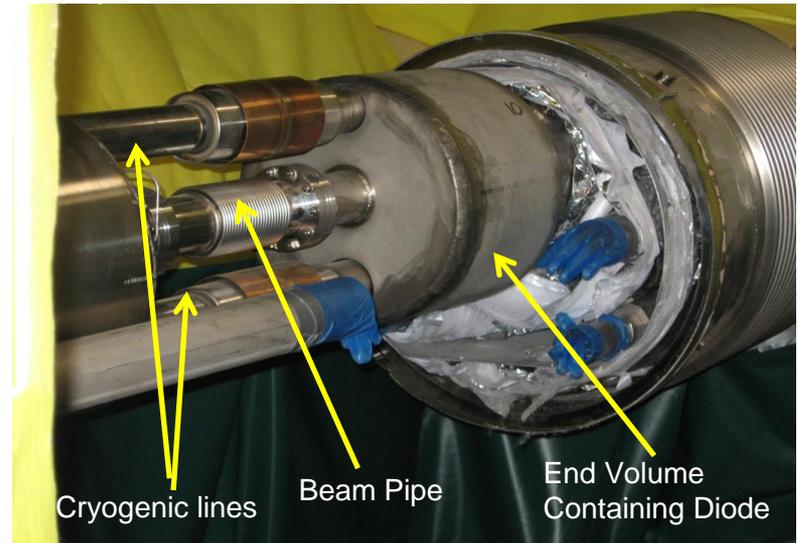
- Diode Shorts (2016)
 - Because of the inductive voltage drop across the magnet current is shared between the diode and the magnet coil when ramping. This will dramatically reduce the rate at which the magnet can be ramped. As a test in 2016 (B10D19) the ramp rate was reduced by a factor of 6 and the magnet could still not be ramped!
- Diodes Forward Voltage Decreases (2017)
 - During normal ramping the voltage across a dipole magnet is less than a volt. As long as the forward voltage drop of the diode remains above this value, Ramping will remain unaffected. It is not understood why the forward voltage drop of a diode should be reduced. The present case with Y07D06.

Replacing a Quench Protection Diode (2016)

Cryostat - encloses SC magnets



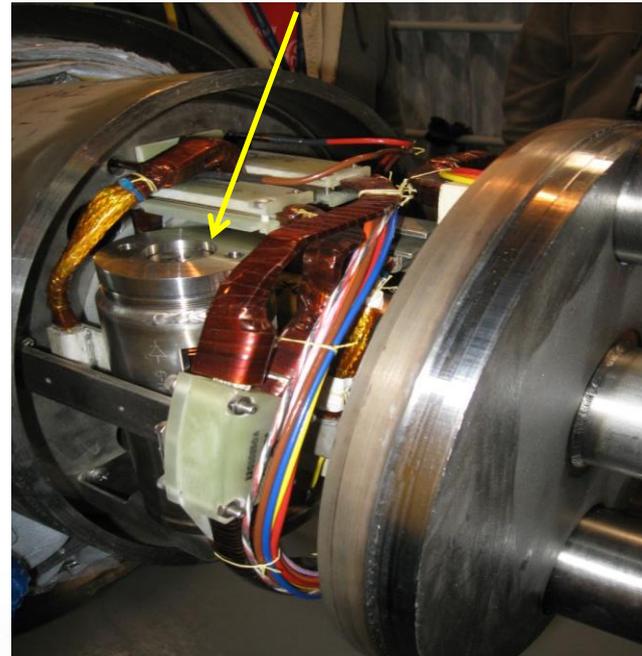
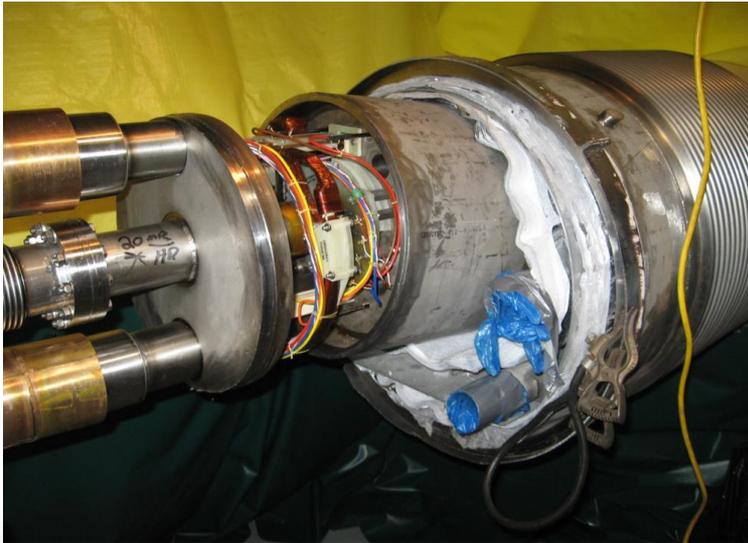
Cryostat Cut Open



Replacing a Quench Protection Diode (2016)

The Diode

End Volume Cut Open



Want More Information?

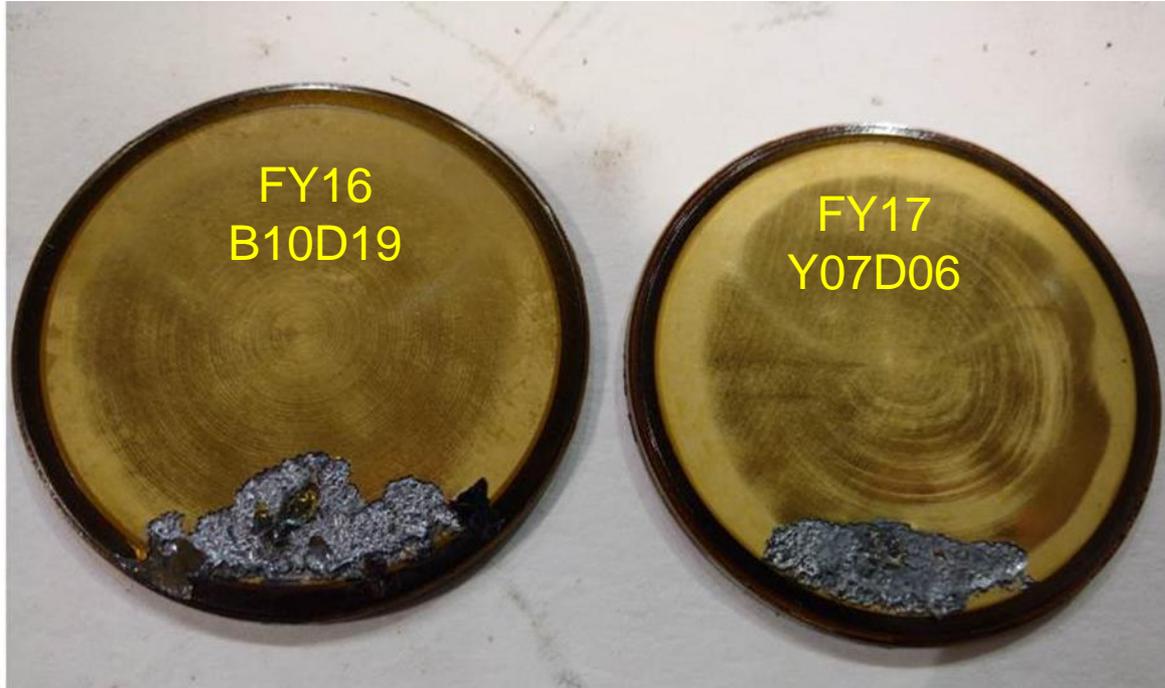
See Paul Sampson, WAO 2016, Shanghai China,
Tuesday 20 September talk titled:

“UNSCHEDULED SHUTDOWN – Management
and Damage Control”

Diode Failure History

- There have been two known diode failures in RHIC and one diode discovered with a reduced forward voltage drop. (1 out of 168 tested)
 - In 2016, B10D19 failed partially shorted. This failure occurred after a massive quench in which this magnet **probably** quenched while being sprayed with beam. The magnet was able to be ramped after this event one time but failed shorted afterwards during another “Quench Link Interlock”. (Type 2 Diode)
 - In 2017, Y07D06 failed partially shorted. This occurred after a massive QLI in which the magnet **probably** quenched while being sprayed with beam. This was caused by the failure of the delayed abort system. We were able to run with the diode in this condition from March 11, 2017 to the end of the run in early July. (Type 1 Diode)

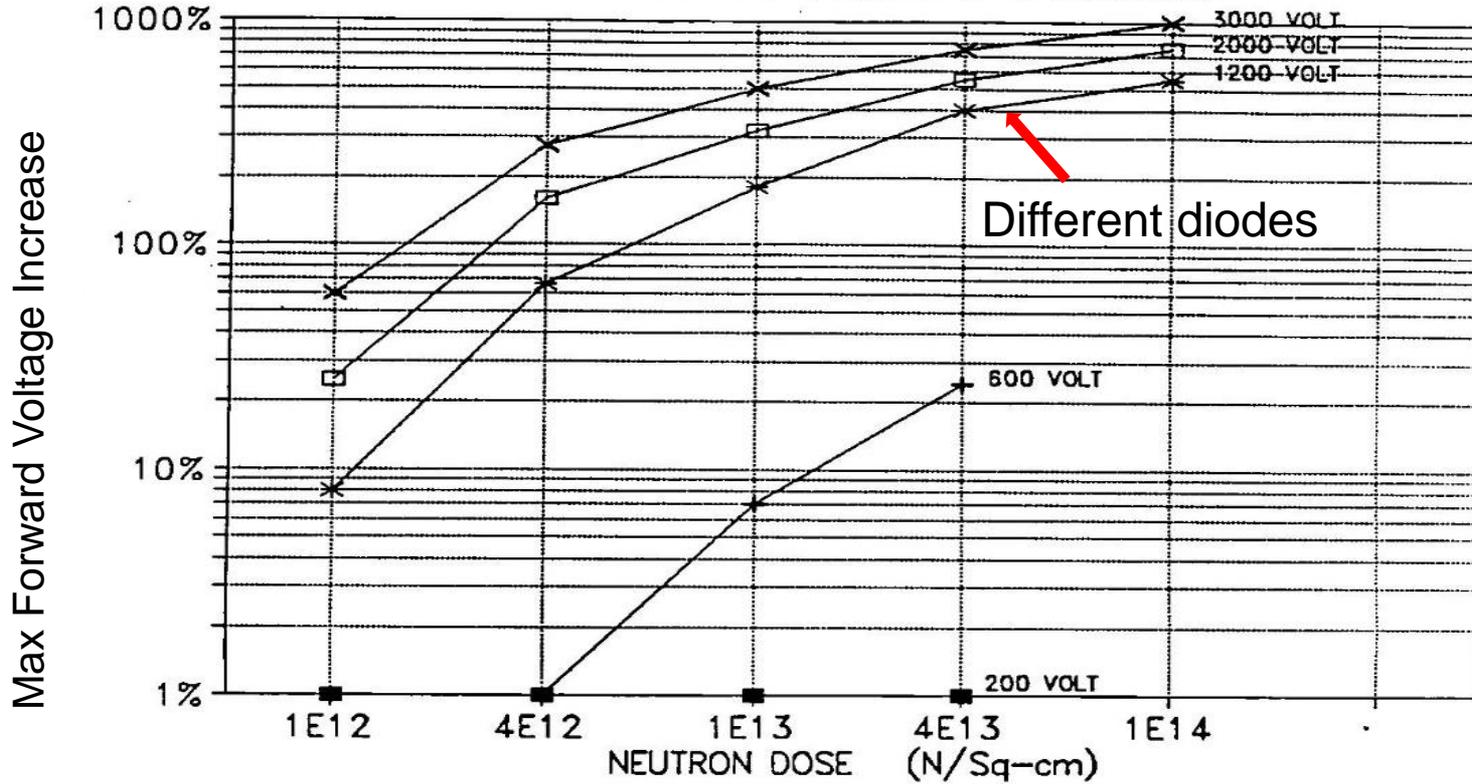
Damaged Diodes



Radiation Effects on Cold Diodes

- **Radiation effects may not be uniform across the diode -
- “Gradient Effect”**
- **A gradient of different Forward Voltage Drop (FVD) may cause current crowding across the diode worsening the effect**
- **There is an annealing process whereby warming the diode up reverses some of the radiation damage. Maybe as much as 80%**
- **One of the only ways to determine the health of a diode is to study its FVD at high current when cold**

VFM DEGRADATION vs NEUTRON DOSE DATA FROM VARIOUS SOURCES



Powerex Proposal for RHIC Diodes

Diode Radiation Exposure Estimates

- The estimated integrated lifetime exposure of RHIC diodes from the specification to procure the diodes was:
 2×10^{12} neutrons/cm²
- Pre-RHIC BNL Testing showed problems with similar diodes at:
 5×10^{12} neutrons/cm²
- Integrated exposure at ionization chamber closest to diode this run:
0.1 kGy
- Estimated integrated diode exposure extrapolating from ionization chamber for this run:
11 kGy (difficult to relate dose to neutron flux)

What Can be Done

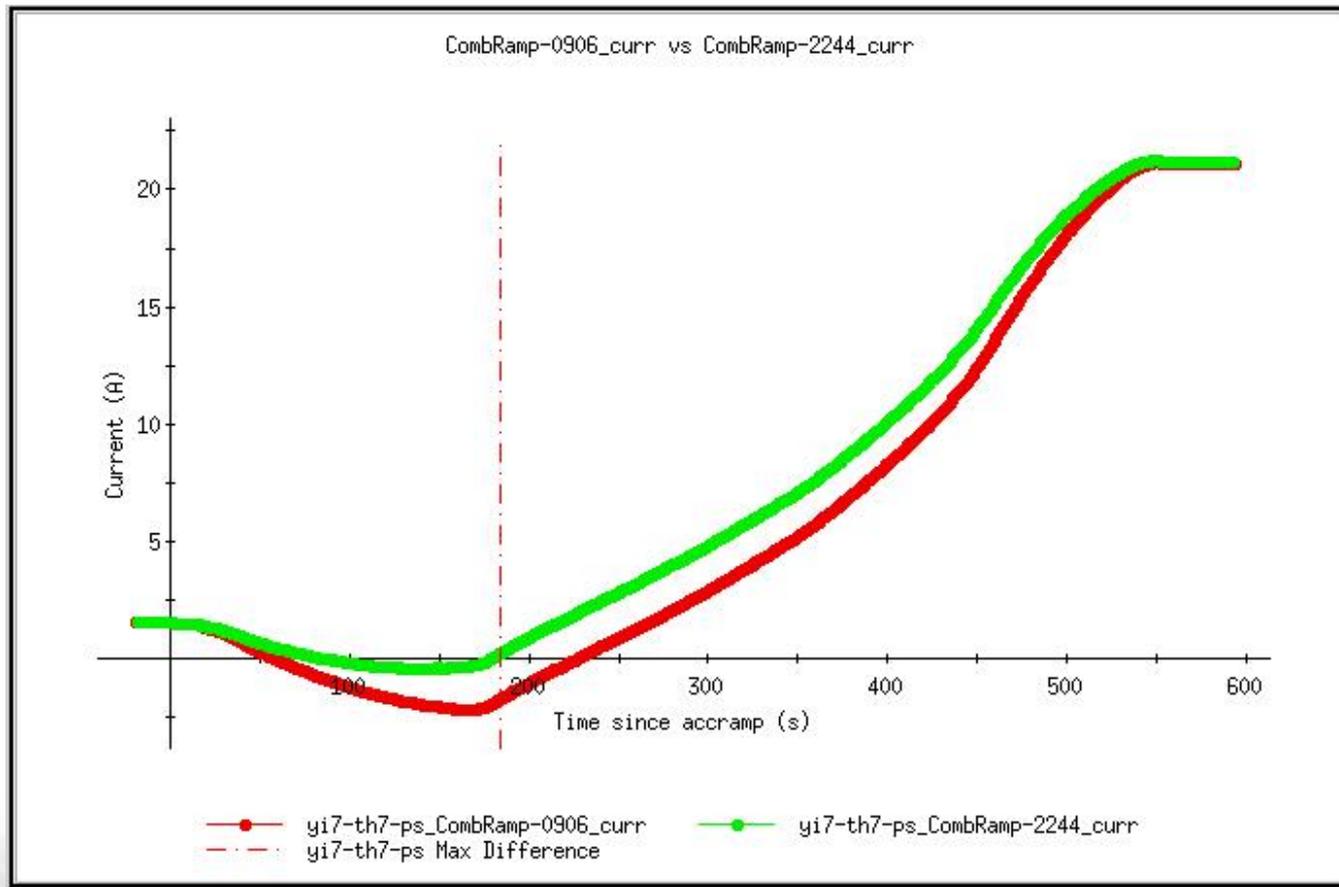
- **Compare present data to original diode data**
 - **So far a dead end but still looking**
- **Develop a diagnostic to Identify Unusual Wave shapes during turn offs**
 - **In Progress**
- **Reassemble original test facility and retest some diodes**
 - **Do we want to open more magnets in the ring?**
 - **What will tests tell us?**
- **Run Tests on the Diode that failed**
 - **How severe is the gradient FVD**
- **Run Low Current Tests on the Cold system and measure FVD.**
 - **Develop a history on our diodes**
- **Try to determine actual Diode exposure**

Operations with a partially shorted Diode (FY2017)

Testing Whether a Diode is Partially Shorted

- We can tell by changes in the voltage tap read backs across a string of magnets during a Quench or normal shutdown. If a diode is conducting current the voltage drop across the magnets will change. Associated changes in voltage can be seen by analyzing dv/dt plots.
- If a diode is partially conducting less current will be flowing through the magnet and so its field will be reduced. This can be detected by changes in the correction magnet currents around the effected magnet. This has proven to be a very sensitive indication of the current diverted by the Y07D06 diode. [next slide]
- A diode conducting current produces additional heat loads on the cryogenic system. These changes were observed on each QLI near Y07D06 after the events of 3/11/17.
- We can make measurement in the ring at local voltage taps

Changes in yi7-th7 corrector power supply (2017)



Difference in current (before {red} and after {green} diode damage) flowing through the corrector magnet indicates corrector is compensating for reduced field in the dipole. The corrector is part of the orbit control system.

Observations of yi7-th7 power supply (2017)

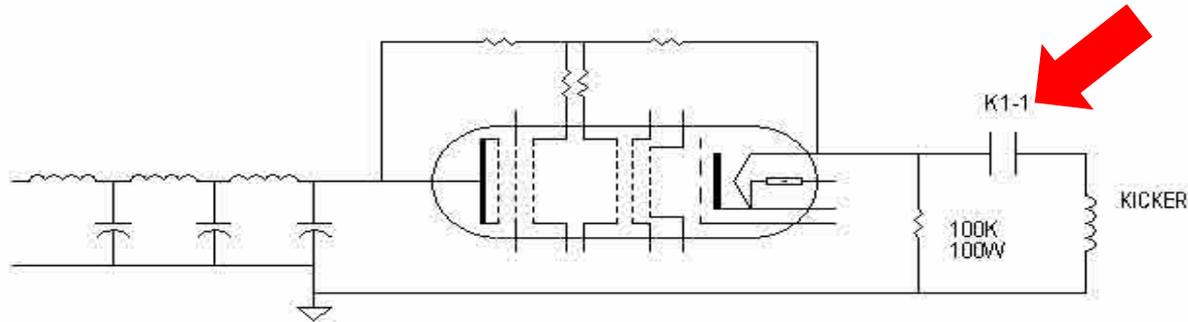
- **The correction strength of yi7-th7 was monitored after every QLI after 3/11/17. The current through the diode was estimated based on this correction**
 - **After the event 54 amperes out of approximately 1000 amperes was going through the diode at Slow Factor 1 (25.8 A/sec ramp rate)**
 - **At Slow Factor 2 (12.9 A/sec ramp rate), 9 amperes went through the diode**
 - **It was observed that after clean quenches the current through the diode decreased and after dirty quenches it increased ?**
- **Concerns were either we would run out of correction or the correction would go to zero possibly indicating an open diode.**
- **The magnet will be opened and the Diode in Y07D06 will be replaced in the September 2017**

The Prognosis

Thyratron Prefires

A solution to this problem would be to put another switch in series with the Thyratron whose pre-firing characteristics is decoupled from that of the Thyratron

ABORT KICKER MAGNET SWITCH TEST CIRCUIT



The Prognosis

- Much work has gone into investigating the inclusion of a switch (mechanical or solid state) in series with the thyatron
- The use of a mechanical switch was tested during Run17. The first attempt failed.
- The major issue is to determine the amount of beam lost (due to the orbit change) from the time the “Quench Link” triggers the shunting of the current in the magnets and the firing of the abort kickers that is delayed due to the introduction of the switch in series with the thyatron.

Conclusions

- We are unable to make measurements that will predict when a diode will fail.
- Magnet quenches can, at best be localized to a string of 5 magnets making it difficult to determine which diode might experience the most heating.
- Machine Protection Systems that can cause damage can and do exist. Be aware.
- The spontaneous thyratron trigger problem has gotten a lot of attention at CERN, BNL, and elsewhere. It is not an easy one to solve – hence the series switch solution being developed at RHIC.
- Further per bunch intensity increases are planned to meet the demands of the sPhenix experiment (>2023) increasing the risks for diode damage.

Additional Slides

Failed Diode at Sector 10

Edge closest to beam 230 $\mu\text{R}/\text{Hr}$ In April

67 mm



2.88 mm thick

After 3 months
cool down
65 $\mu\text{R}/\text{Hr}$ &
39 $\mu\text{R}/\text{Hr}$

Edge furthest from beam

100 $\mu\text{R}/\text{Hr}$ in April

Abort Kicker Pre-fire Protection Bump

- Bump generated in 11 o'clock arc pushes orbit to -21mm. In a pre-fire condition bunches kicked by the pre-firing module will crash into the cryostat at that location, preventing damage to the experiments. In 1 o'clock arc is a compensation bump to adjust for off-center orbit in quads and sextupoles in the pre-fire bump.
- Chronic losses in the arc are due to Au^{+78} beam created during collisions and off-momentum particles at the protection bump peak. The peak loss is located at g10-lm20 loss monitor, located just downstream of dipole 19 where the failure occurred

