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Protection of Hardware: Powering Systems (PC, NC and SC Magnets)

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US Particle Accelerator School

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Protection of:

- **People**
- **Powering Equipment** – Power Converters
- **Loads** (protected from powering equipment)

  Normal conducting magnet loads

  Super conducting magnet loads

General Protection techniques

- **Redundancy** – Two independent paths leading to protective action
- **Fail-safe design** – Anticipated problems turn system off safely
- **Response to power outages** – Line power and internal control power
- **Testing of protection circuits** – Initially and periodically
- **Trouble-shooting aids** – latched status bits and transient recordings
- **Self-contained protection** – Block unsafe external influences.

People (not specific subject of talk, but…)

- **Tunnel Interlocks**
  – redundant and fail-safe

- **Door Interlocks** - fail-safe

  Turns off power source and discharges stored energy in capacitance

- **Captured Key Systems** –

  "Kirk" keys for high-power systems

- **LOTO Procedures**
  – Locking off sources of power (with verification)
  – Discharging and grounding sources of stored energy

People Protection

13.8 kV Disconnect Using Kirk Key Interlock

Door Requiring 2 Kirk Keys to open

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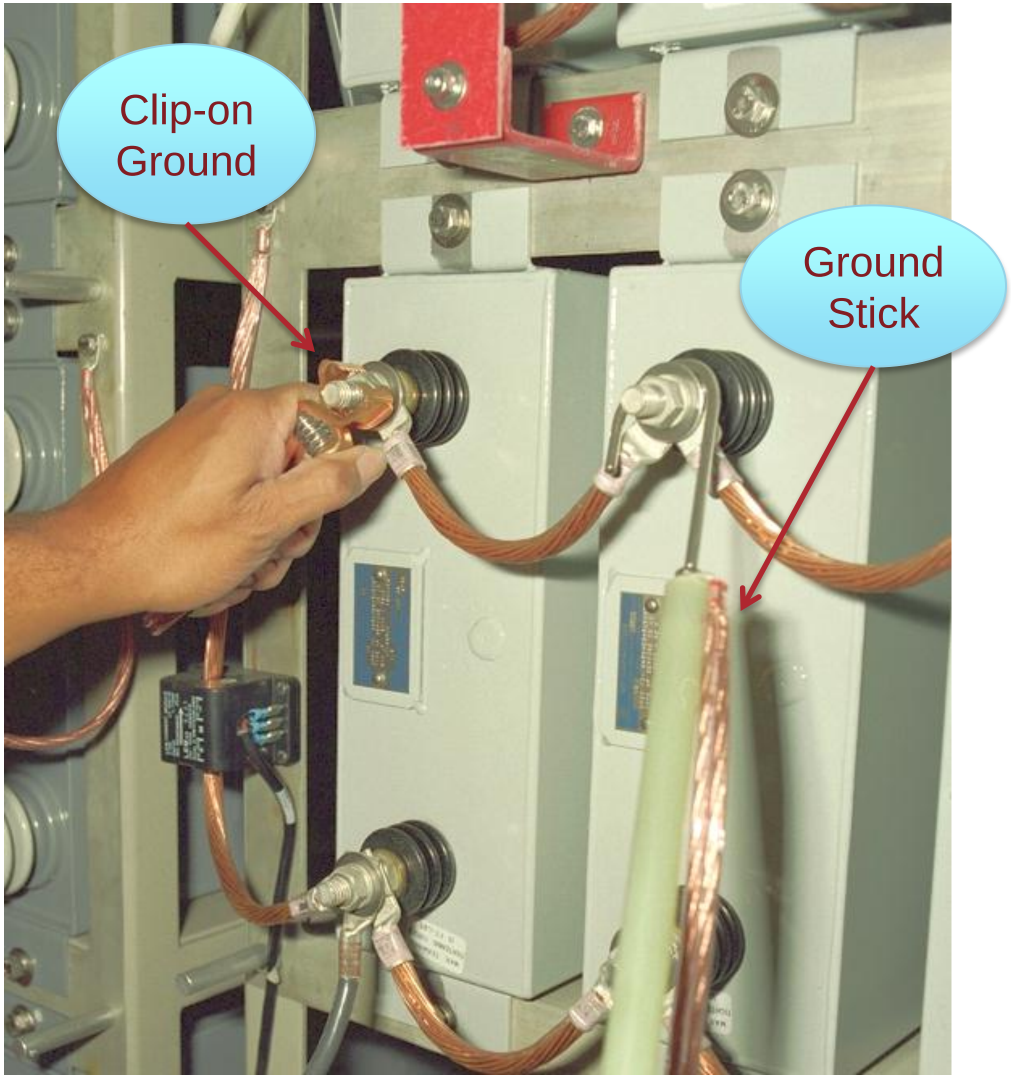
People Protection

People Protection



Power Converter Protection

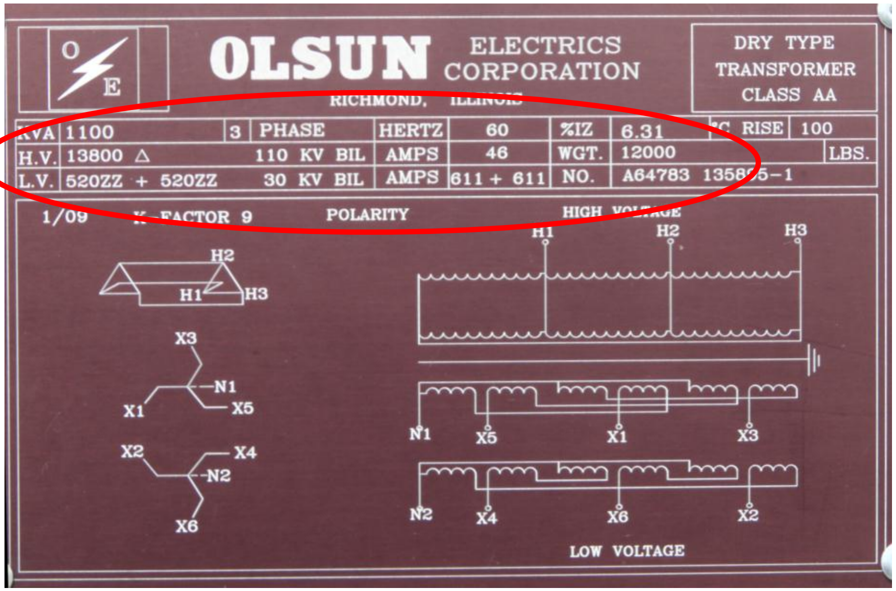
Power Converter Protection

- **A/C overcurrent protection** – breakers, fuses, c.t current monitors, transformer impedance calculation.
- Knowledge of the available short circuit current of the system allows the proper coordination of fuses, breakers, bracing of cables/bus-work and surge current ratings of the solid-state switching devices.

- **Neglecting cable resistance and stray inductance, the available short circuit current in a power system is ultimately limited by the leakage impedance of the AC power transformer upstream of the location of interest.**

Power Converter Protection

POWER SUPPLY SHORT CIRCUIT CURRENT



Nominal Secondary Current

$$Inom = \frac{VA}{2 * 3 * \frac{LV}{\sqrt{3}}}$$

- Transformer Rating
- 2 secondaries
- 3 coils (3-phase)
- Line-Neutral secondary voltage

$$Inom = \frac{1100e3}{2*3*\frac{520}{\sqrt{3}}} = 611 \text{ amps}$$

$$Isc = \frac{Inom}{\%Z} \qquad Isc = \frac{611}{0.0631} = \textbf{9700 amps}$$

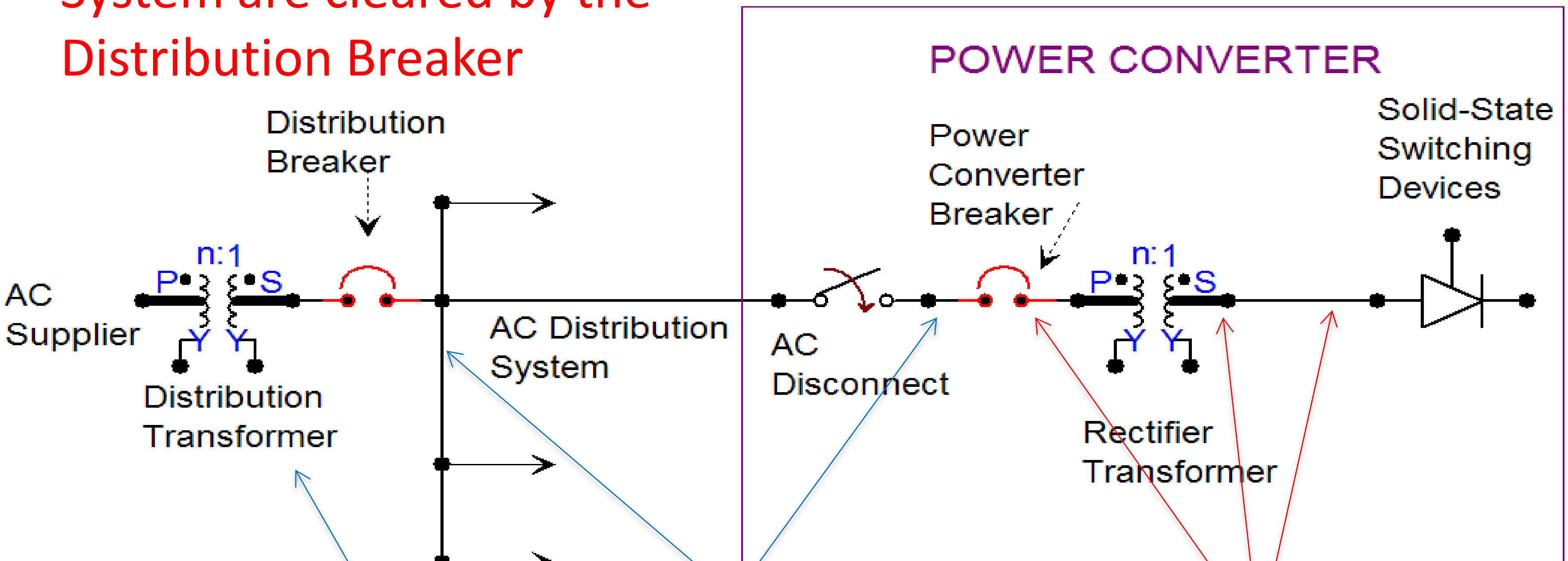
Transformer Leakage Impedance

IMPORTANT: The Power Converter protection design (breakers, SCR ratings, bracing, etc.) should take into account the available short circuit current.

Power Converter Protection

Faults on the AC Distribution System are cleared by the Distribution Breaker

BREAKER COORDINATION



For faults here, The current is limited by the %Z of The Distribution transformer

Faults here, should be cleared by the PC breaker

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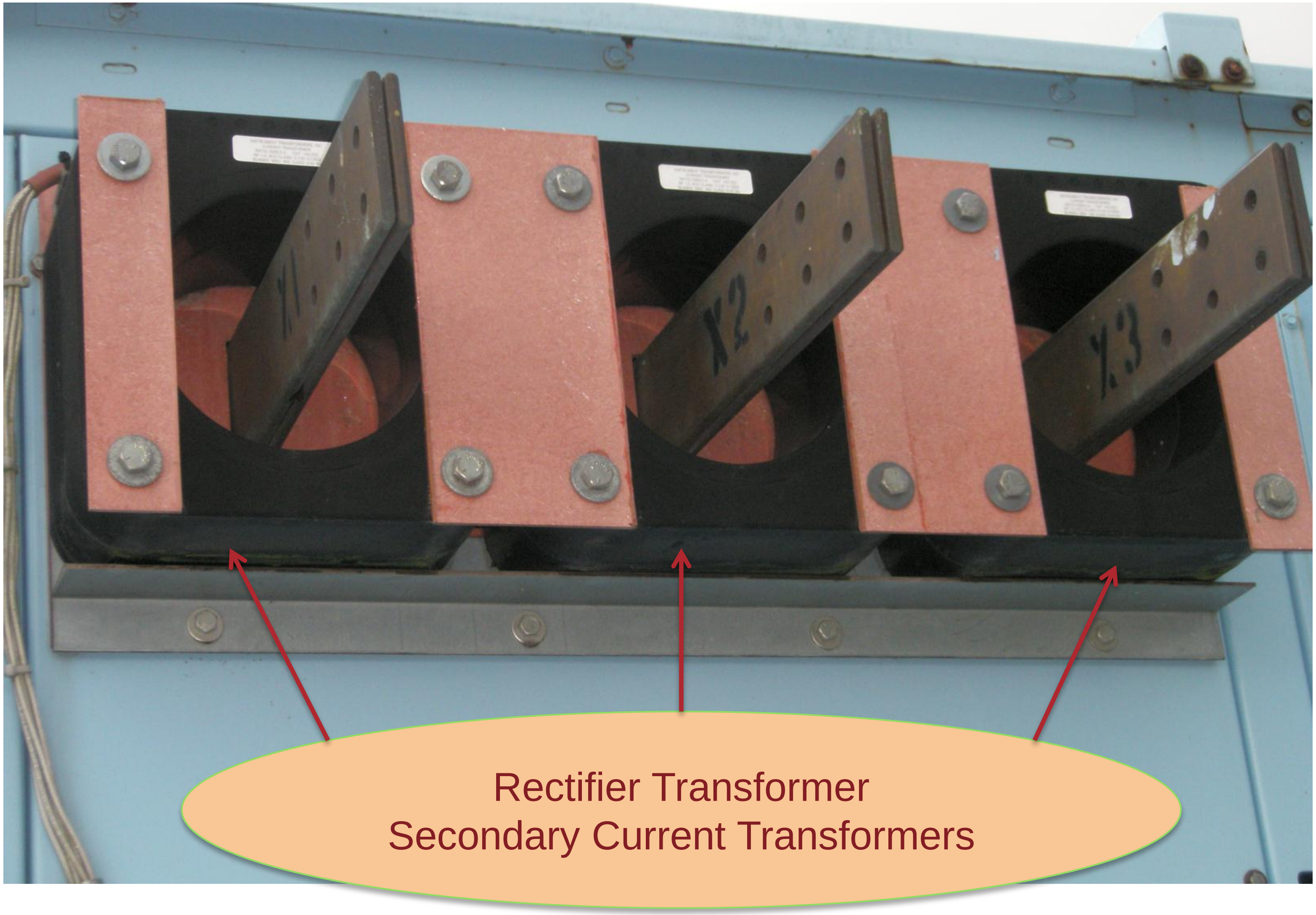
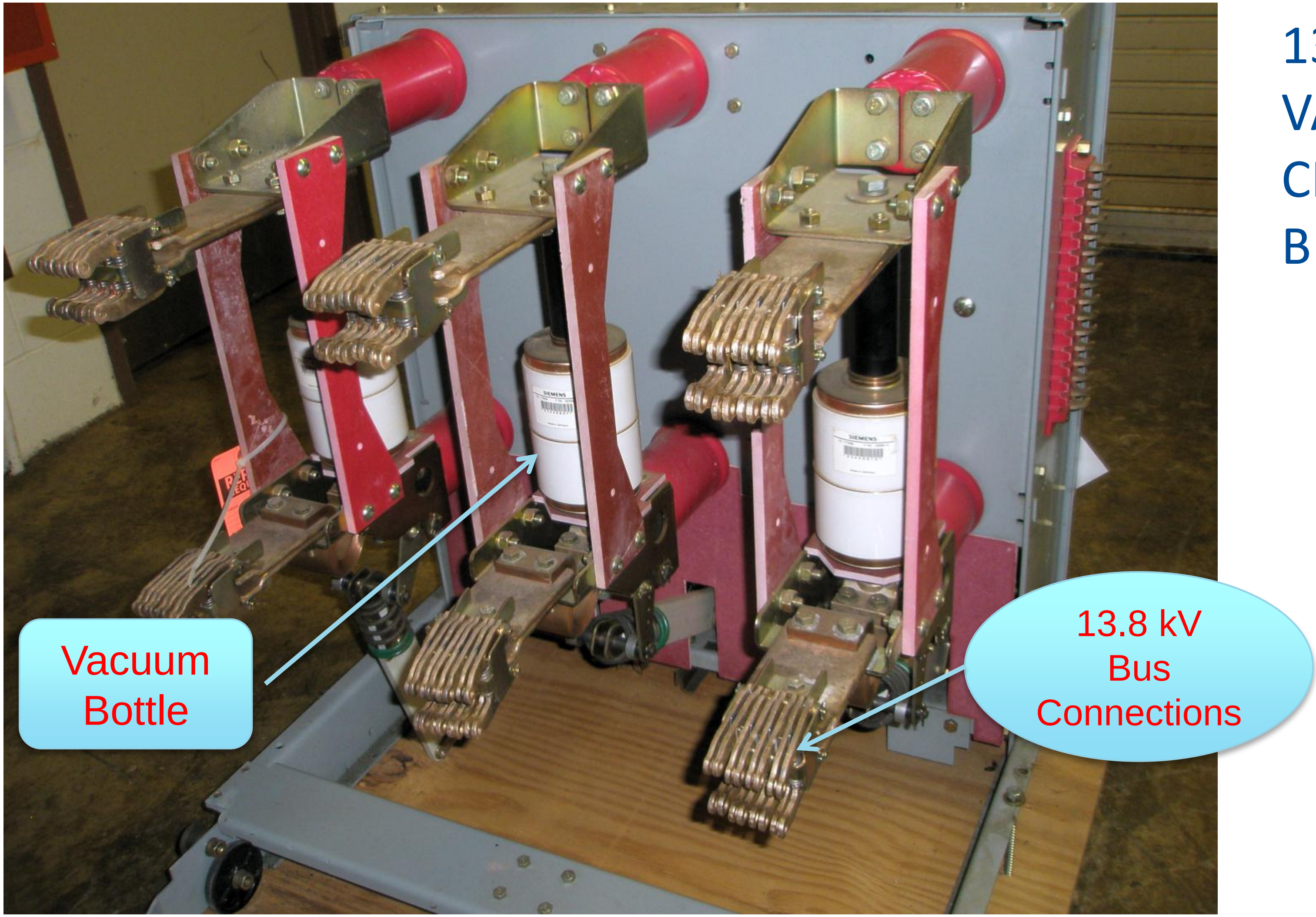
Power Converter Protection



Power Converter Protection



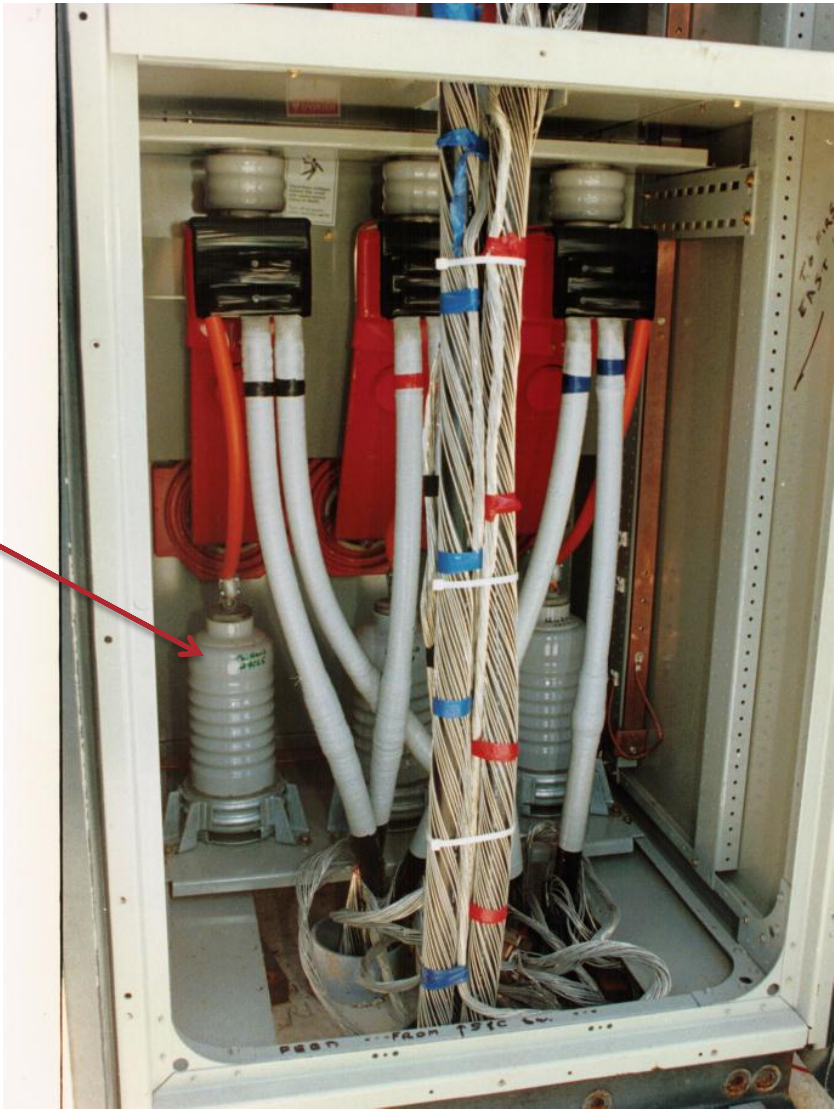
13.8 KV
VACUUM
CIRCUIT
BREAKER

Power Converter Protection

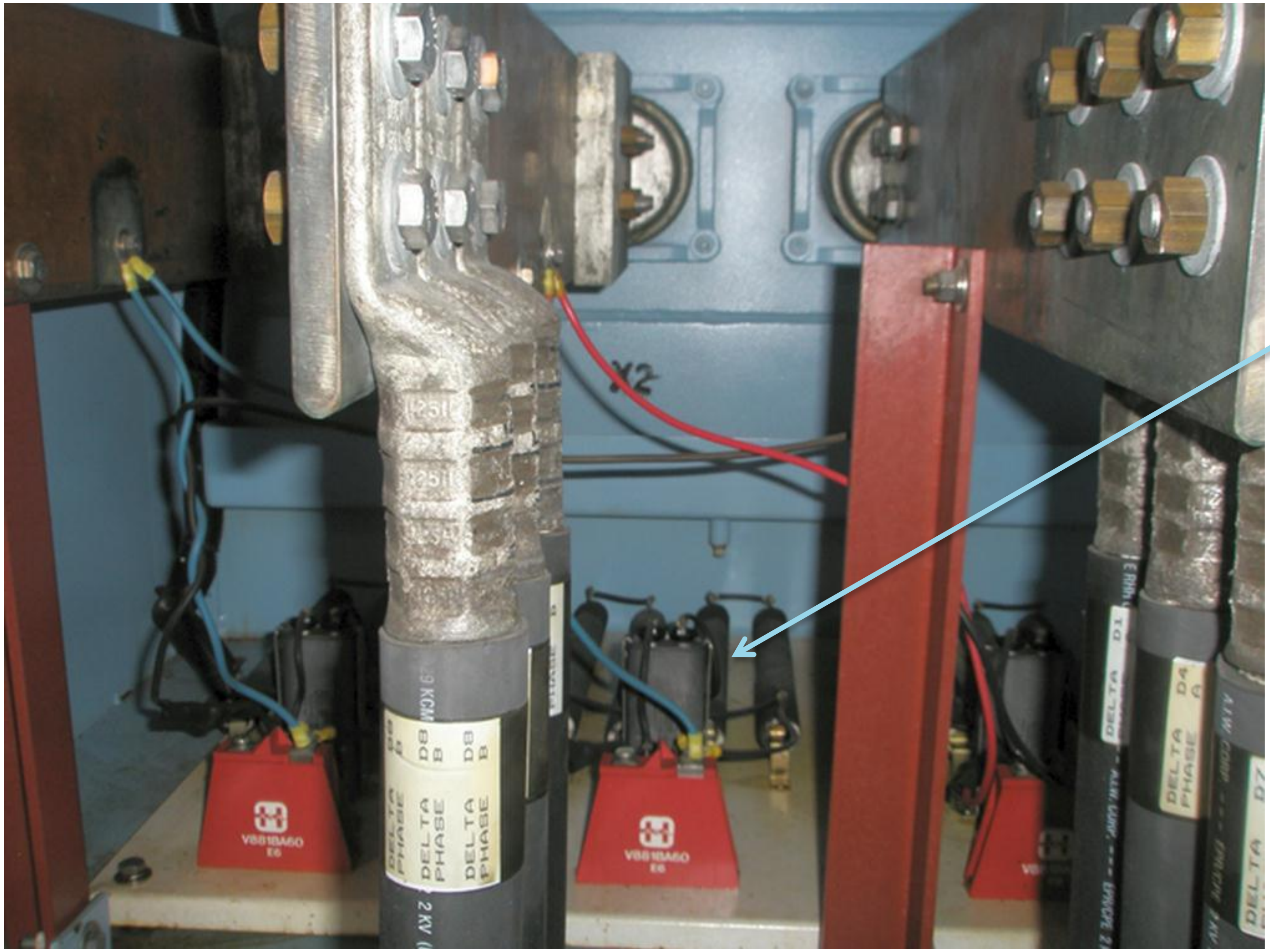
- A/C **voltage** protection
  - MOV's or lightning arrestors on PC transformer primary
  - RC snubbers on PC transformer secondary
  - Transformer and switch gear testing according industry standards (e.g., 110 kV impulse testing on 15 kV rated equipment)

Power Converter Protection

Lightning Arrestors



Power Converter Protection



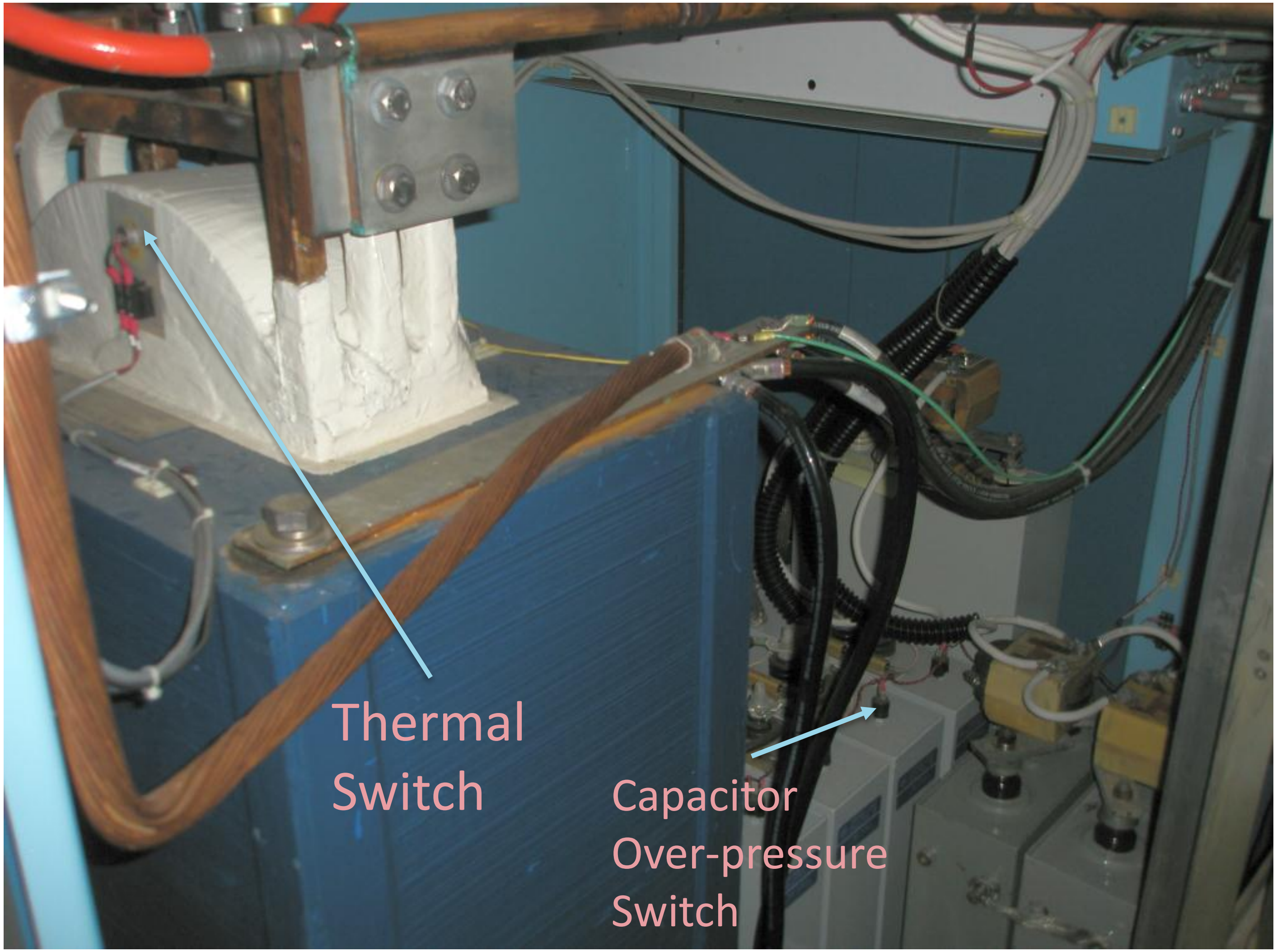
Snubber Circuits

Power Converter Protection

DC side protection

- Passive filter protection
  - Choke temperature
  - Capacitor monitoring (over-pressure)
- SCR ratings
  - Voltage (rated 2.5 x operating)
  - Current – really temperature
  - Temperature including thermal cycling
  - Thermal switch protection
- Overcurrent protection,
- Water flow/differential pressure.

Power Converter Protection



Passive Filter Components

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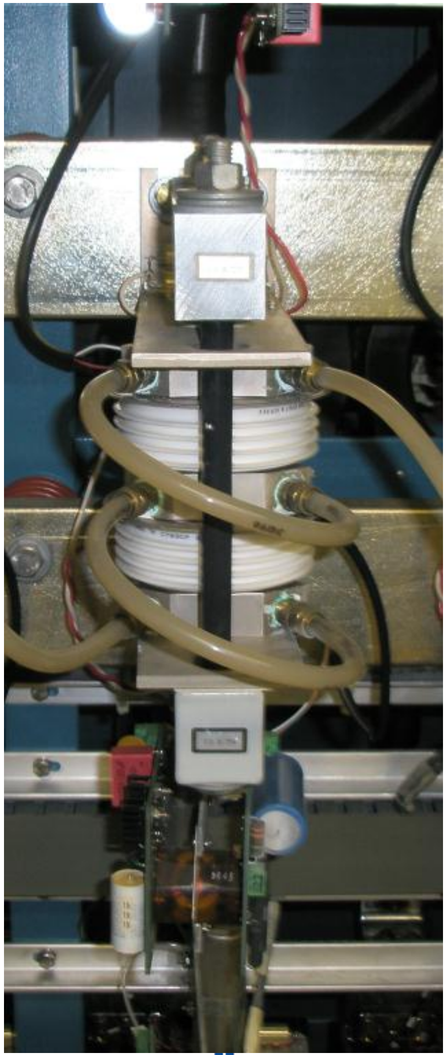
Power Converter Protection

Main Injector Dipole Power Supply SCR Bridge (1000 volts, 7.5 kamp)



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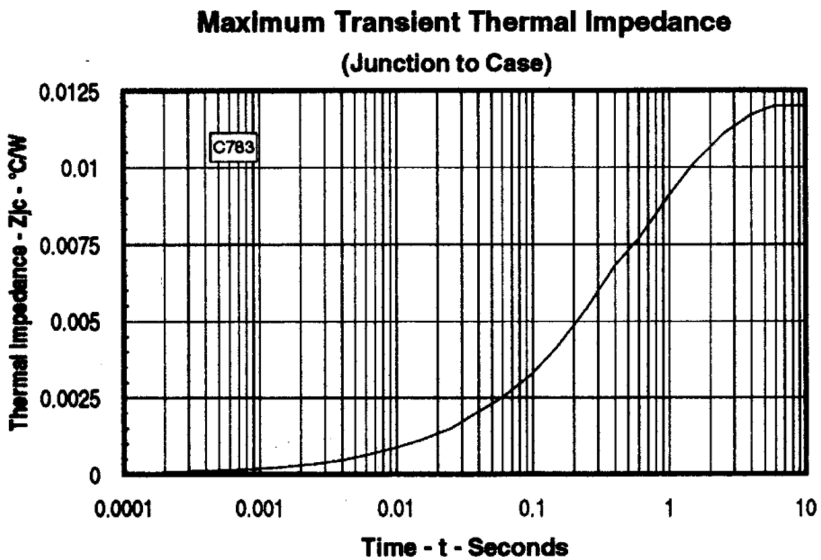
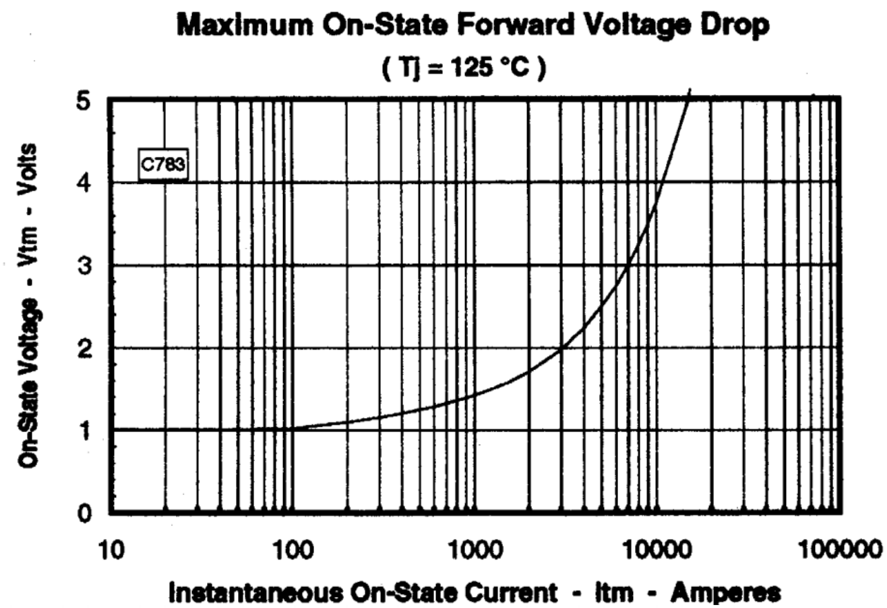
SCR Junction Temperature – DC case, single device





Thermal Characteristics

Maximum Thermal Resistance, Double Sided Cooling			
Junction-to-Case	$R_{\theta(j-c)}$	0.012	°C/W
Case-to-Sink	$R_{\theta(c-s)}$	0.002	°C/W

Assuming

1000 amps DC

From Curve Vd=1.4 volts

Tamb = 35 C

T_j= Idc * Vd * (Rj-c + Rc-s) Tamb

1000 * 1.4 * (0.012 + 0.002) + 35

= 54.6 C

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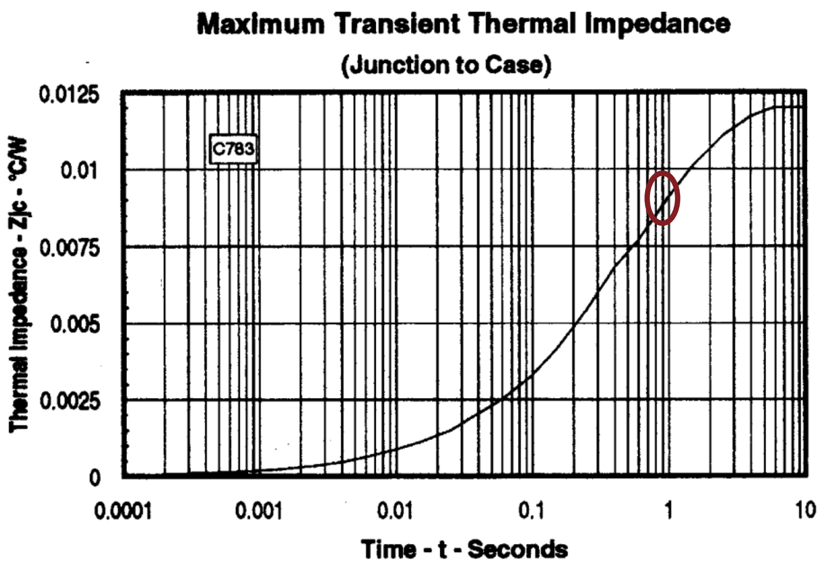
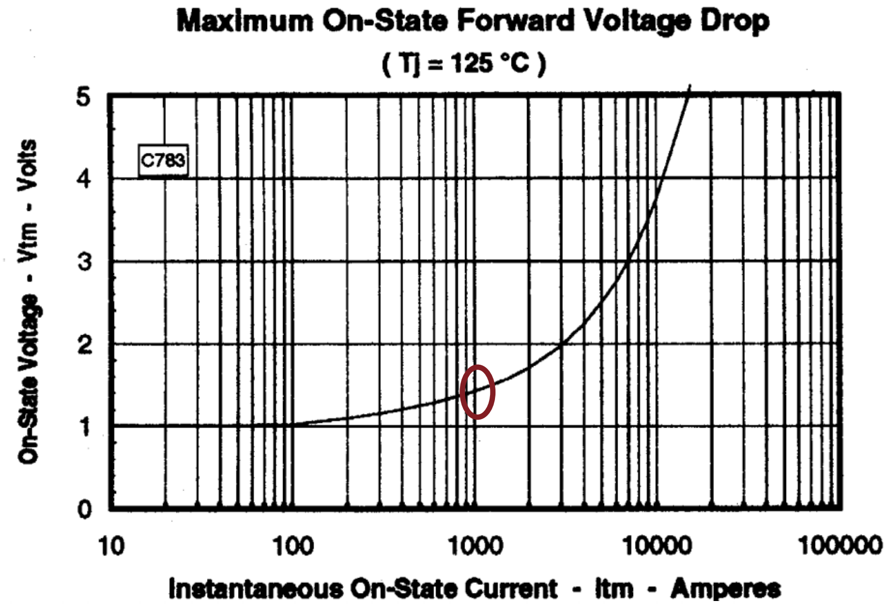
SCR Junction Temperature – Impulse case, MI PC Bridge





Thermal Characteristics

Maximum Thermal Resistance, Double Sided Cooling			
Junction-to-Case	$R_{\theta(j\text{-}c)}$	0.012	°C/W
Case-to-Sink	$R_{\theta(c\text{-}s)}$	0.002	°C/W

Assuming:

6000 amps for 1 second, 6 devices in parallel,
Current = 6000/6 =1000 Amps
From Curve, Vd=1.4 Volts.
Pwr = 1.4 * 1000 = 1.4 kW
1/3 duty factor (3-phase bridge) – 467 watts

ΔT_j= Pwr * (Rj-c(@1sec))

467 * (0.009)

= 4.2 C

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Power Converter Protection

- **Response to power loss**
  - Maintain control voltages
  - Bypass bridge
  - Open breaker

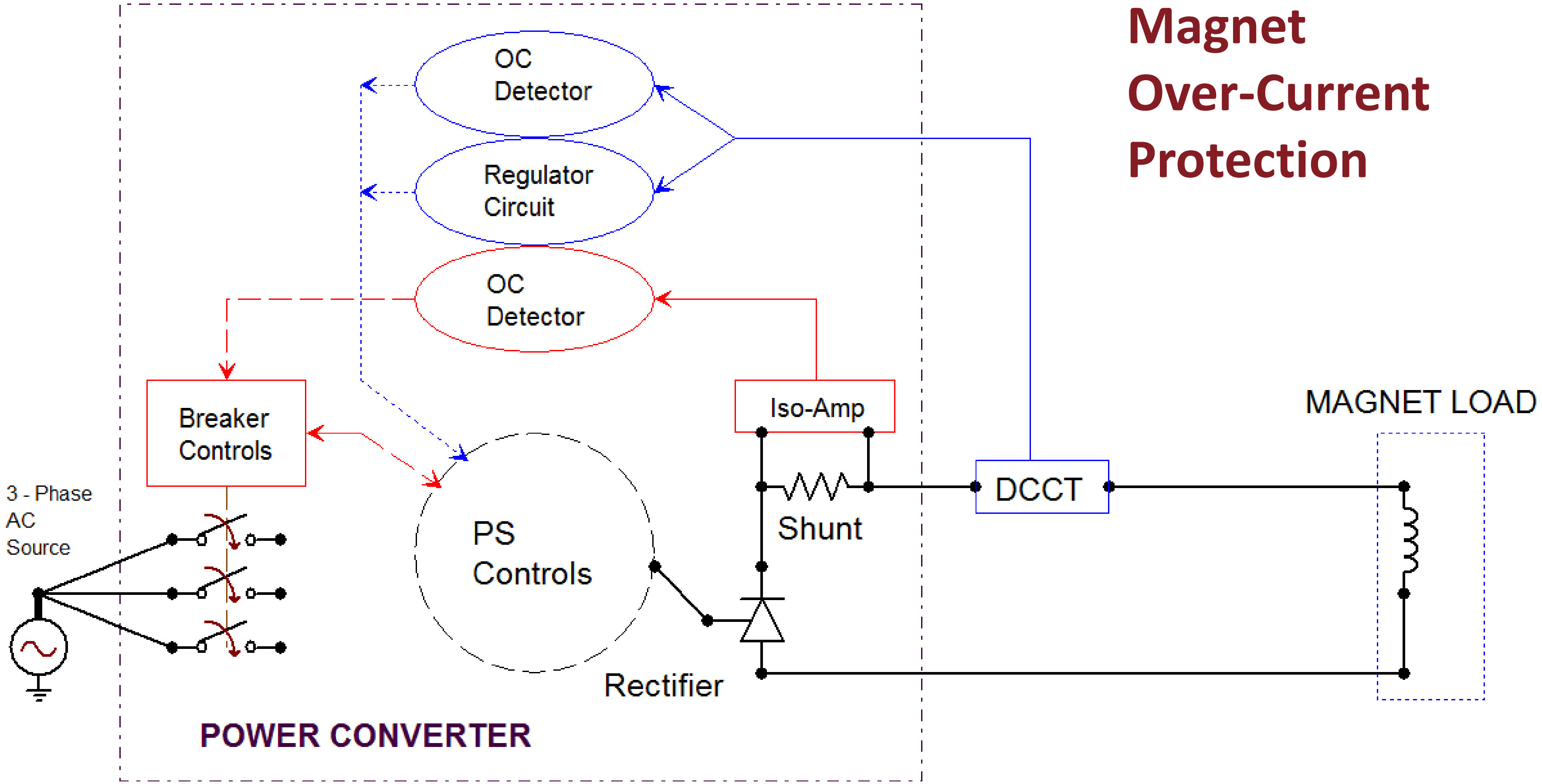
Protection of Conventional Magnets

Magnet Overcurrent Protection

- Peak current trips
  - Compare regulation DCCT to trip threshold (set in hardware)
  - Sense disconnected DCCT cable and trip
  - Use shunt measurement as backup to failed DCCT (which could cause OC)
  - Operate on shunt with electronic circuit rather than panel meter *(unreliable in our experience)*

Protection of Conventional Magnets

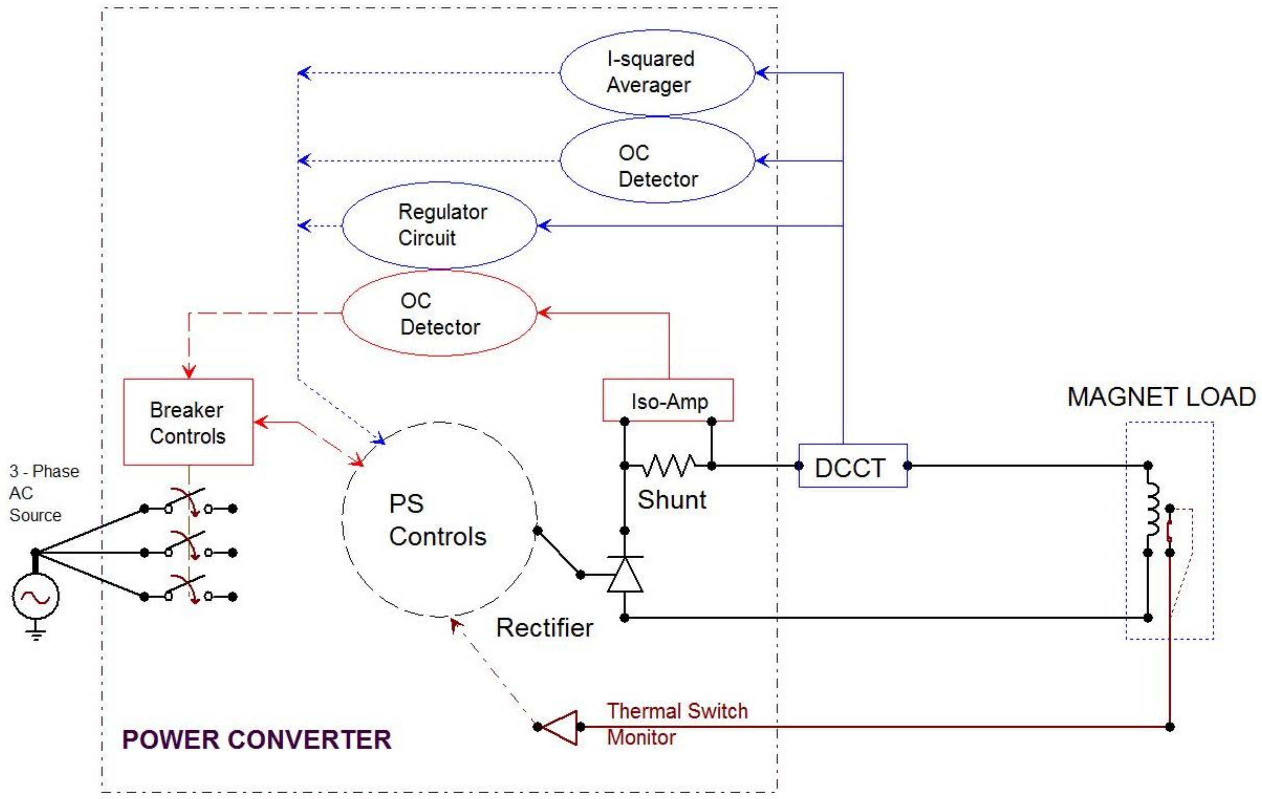
Magnet Over-Current Protection



Magnet Overcurrent Protection (cont.)

- RMS current trips (ramped loads)

- Put transducor signal into squaring circuit and average over a defined time.
- Compare to trip threshold
- Thermal Switch mounted on magnet coil



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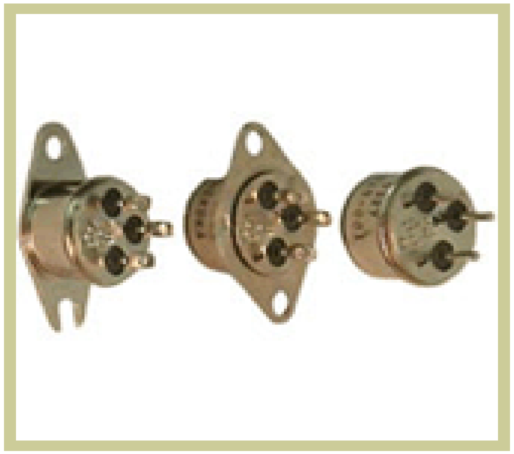
Protection of Conventional Magnets

Thermal Protection of Magnets

- <u>Thermal Switches </u>– usual protection for magnets



Use NC contacts!

Make sure the switch is electrically insulated from magnet!

<u>Experience:</u> very reliable if thermal switch is connected to the correct power supply – carefully test that the sensor is connected correctly. We usually use a heat-gun.

If load has multiple, independent water paths, use multiple thermal switches!

Magnet Voltage-to-Ground Protection

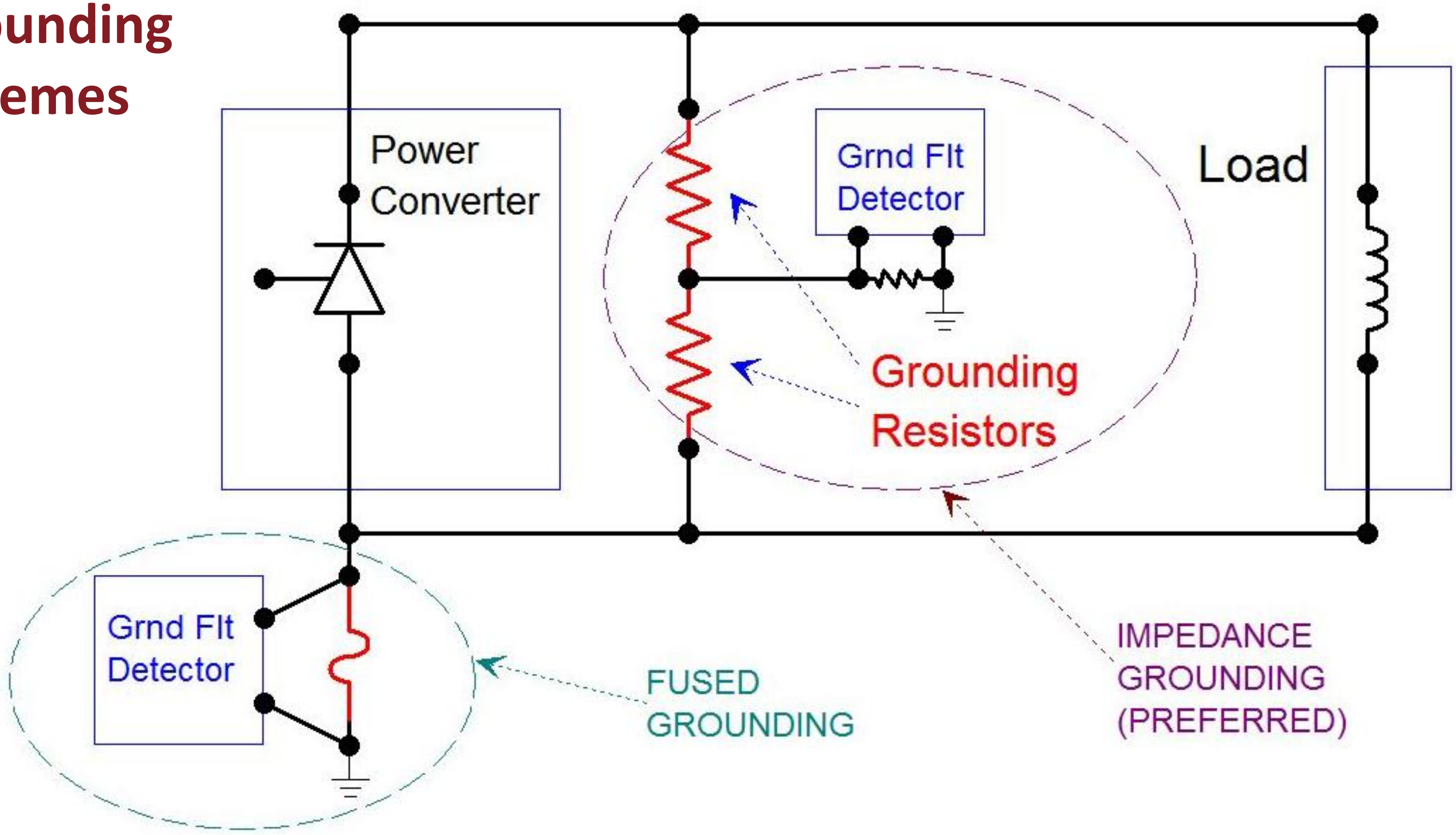
- Design and testing of magnet insulation system **must** be coordinated with worst-case voltages magnets will experience while operating in their circuit.

Magnet Voltage-to-Ground Protection

- Simple case: one power converter
- Grounding schemes – fuse at terminal vs. distributed, high impedance ground. We prefer the latter because,
  - Minimal ground fault current
  - Maximum operating voltage-to-ground = ½ PC output voltage
  - Avoids fuse rating issues (DC fuse interruption).
  - Minimize average V-to-G in single loop, multiple power supply systems.

Protection of Conventional Magnets

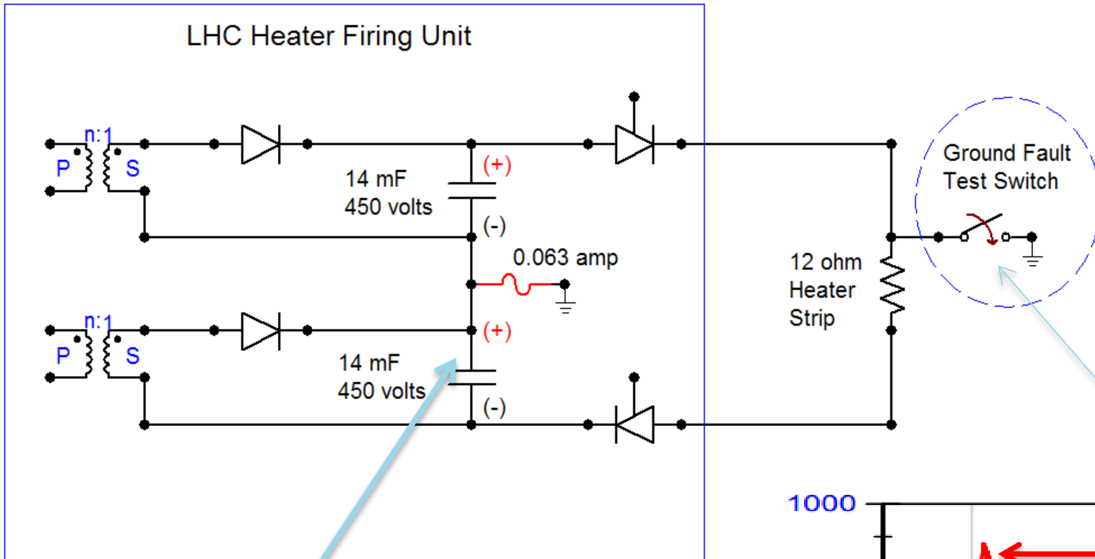
Grounding Schemes



Protection of Conventional Magnets

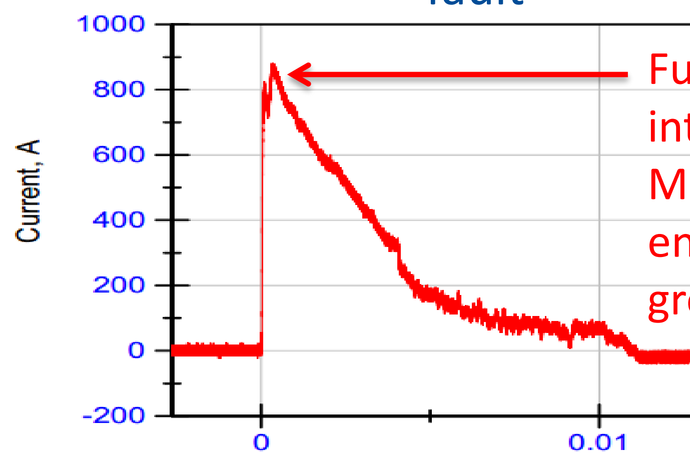
Ground Schemes and Fuses

Does the fuse have the interrupting capacity
to handle a ground fault on the load?



Test fuse by intentionally generating a ground fault

Center-point grounding keeps voltage balanced on load



Fuse fails to interrupt
Most of capacitor energy goes into ground fault,

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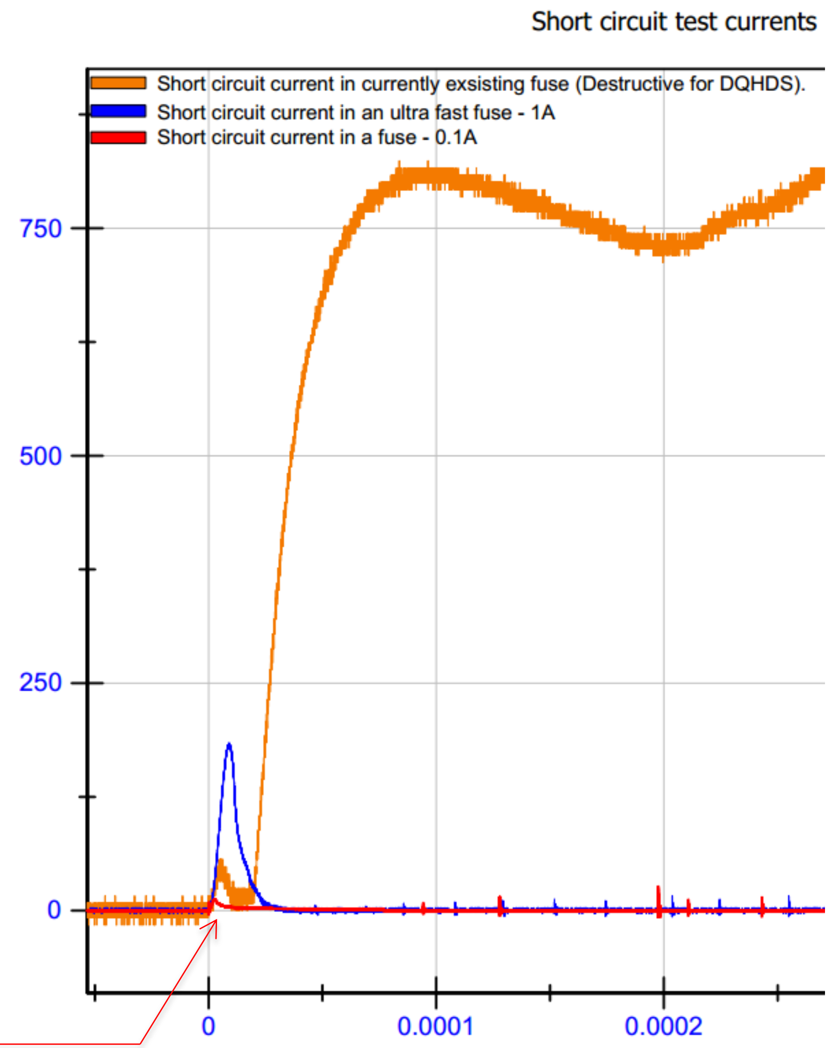
Protection of Conventional Magnets

Ground Schemes and Fuses

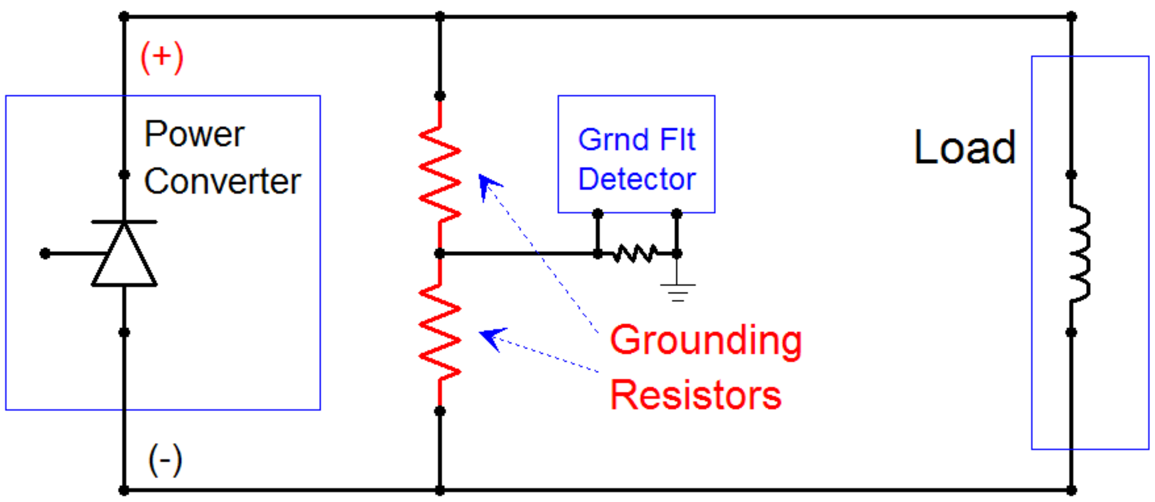
Tests showing the effect of 3 different fuses



Original fuse replaced by 0.1 amp ultra-fast fuse rated to interrupt 450 volt DC circuit

Magnet Voltage-to-Ground Protection

- Impedance of grounding resistors in kohm range - must dominate leakage currents of system.
- Max operating V = ½ power converter V.
- If ground fault near (–) terminal, magnet near (+) terminal goes to +V to gnd.



Magnet Voltage-to-Ground Protection

- Insulation needs to be strong enough to avoid second ground fault at +V, which would result in high current path. If no second fault, ground current very limited.
- Power Converter/Magnet system should be hipotted beyond +V level.
- Hipotting generally should be performed after prolonged tunnel accesses or after any work on the load or power converter.

Protection of Conventional Magnets

Other Conventional Magnet Protection Issues

- Avoid External Moisture (can cause insulation failure).
  - Old MR magnets
- *Corona* destroys insulation

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Protection of Superconducting Magnets

Protection of Superconducting Magnets

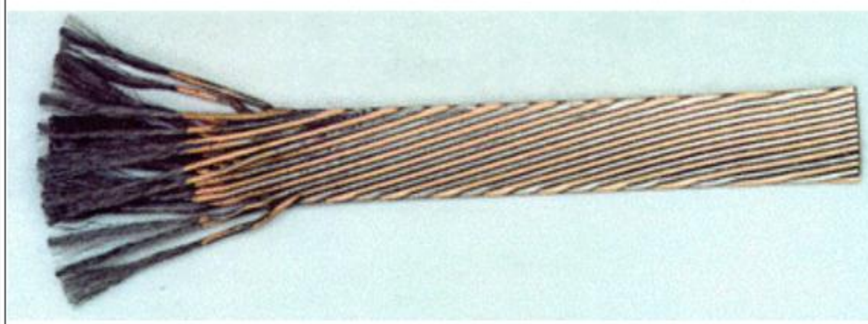
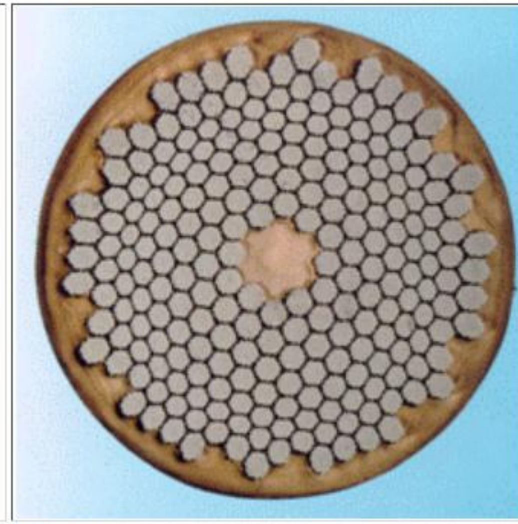
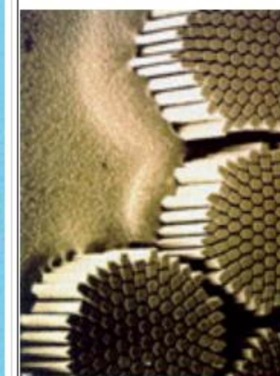
Superconducting Cable and Magnets

- Magnets are wound with Superconducting cable (Nb/Ti) most commonly
- Wire becomes superconducting (R=0) below a critical temperature (usually <10K). Low temperatures are established and maintained in a bath of liquid helium that is cooled in a cryogenic refrigeration system.
- Superconducting cable is made of several wire strands, each made of many superconducting filaments within a copper matrix.
- Copper stabilizes the cable and provides alternate current path for a short time when superconductor “quenches” or leaves its superconducting state.

Protection of Superconducting Magnets

LHC Magnet Wire

The cables house 36 strands of superconducting wire, each strand being exactly 0.825 mm in diameter. Each strand houses 6300 superconducting filaments of Niobium-titanium (NbTi). Each filament is about 0.006 mm thick, i.e. 10 times thinner than a normal human hair.

		
Cable	Strand	Filaments

Protection of Superconducting Magnets

Superconducting Cable and Magnets (cont.)

- The cable has a “short sample” maximum current. The maximum current increases with decreasing helium temperature.
- A magnet wound with the wire has lower maximum current because magnetic fields within the magnet decrease the cable’s maximum conduction.
- A magnets maximum current can be increased by lowering its temperature. (Example: TEV went from 4000 amps to 4400 amps when helium temp was reduced ¾ degree at a cost of $6M).

Protection of Superconducting Magnets

Magnet	Short Sample Limit	Maximum Operating Current	Operating Temperature	MIITs Limit	Cable Cross Section
Units	Amps	Amps	°K	A^2S	mm^2
LHC: Main Bend	13 k	11.5 K	1.85	32 M	22
LHC: Main Quad	13 k	12.1 K	1.85	32 M	22
LHC: 600A	600	550	1.85	50 K	1
TEV: Dipoles		4.4 K	4.5	7 M	10*

$$* \; A_{Tev} \approx A_{LHC}\sqrt{\frac{7\,MIITs}{32\,MIITs}}$$

$$A_{Tev} \approx 22mm^2 \times .47$$

$$A_{Tev} \approx 10mm^2$$

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Protection of Superconducting Magnets

QUENCHING

- A magnet conducting current in superconducting mode at cryogenic temperature can suddenly lose its superconductive state, usually beginning at a particular spot in the magnet cable, when something causes the temperature at that spot to rise above the critical temperature.
- Once the initiating spot quenches, the heat generated from the resistance typically keeps it in the quenched state and the quenched area spreads to nearby areas with a speed known as the “quench velocity”.

Causes of Quenching

- Training - motion
- Excess dI/dt – eddy currents
- Particle beam heating
- Cooling system problems
- Exceeding the short sample limit
- Spontaneous quenches – unknown origins

Heating of the Initiating Spot

- The initiating spot starts to heat first, and keeping its ultimate temperature below a damaging level (450K) is critical to protecting the quenched magnet.

Adiabatic Approximation of Temperature rise

- A simplified way of thinking about the temperature rise at the initiating spot is to imagine it as a length of copper wire (M grams), constant resistance (R ohms) and constant heat specific heat (C joules/gram degree C).
- *Then the adiabatic temperature rise of the spot will be:*

$$\Delta T = R * \frac{\int I^2 \, \mathrm{dt}}{\mathrm{M} * \mathrm{C}} = \frac{R}{M * C} * \int I^2 \, \mathrm{dt}$$

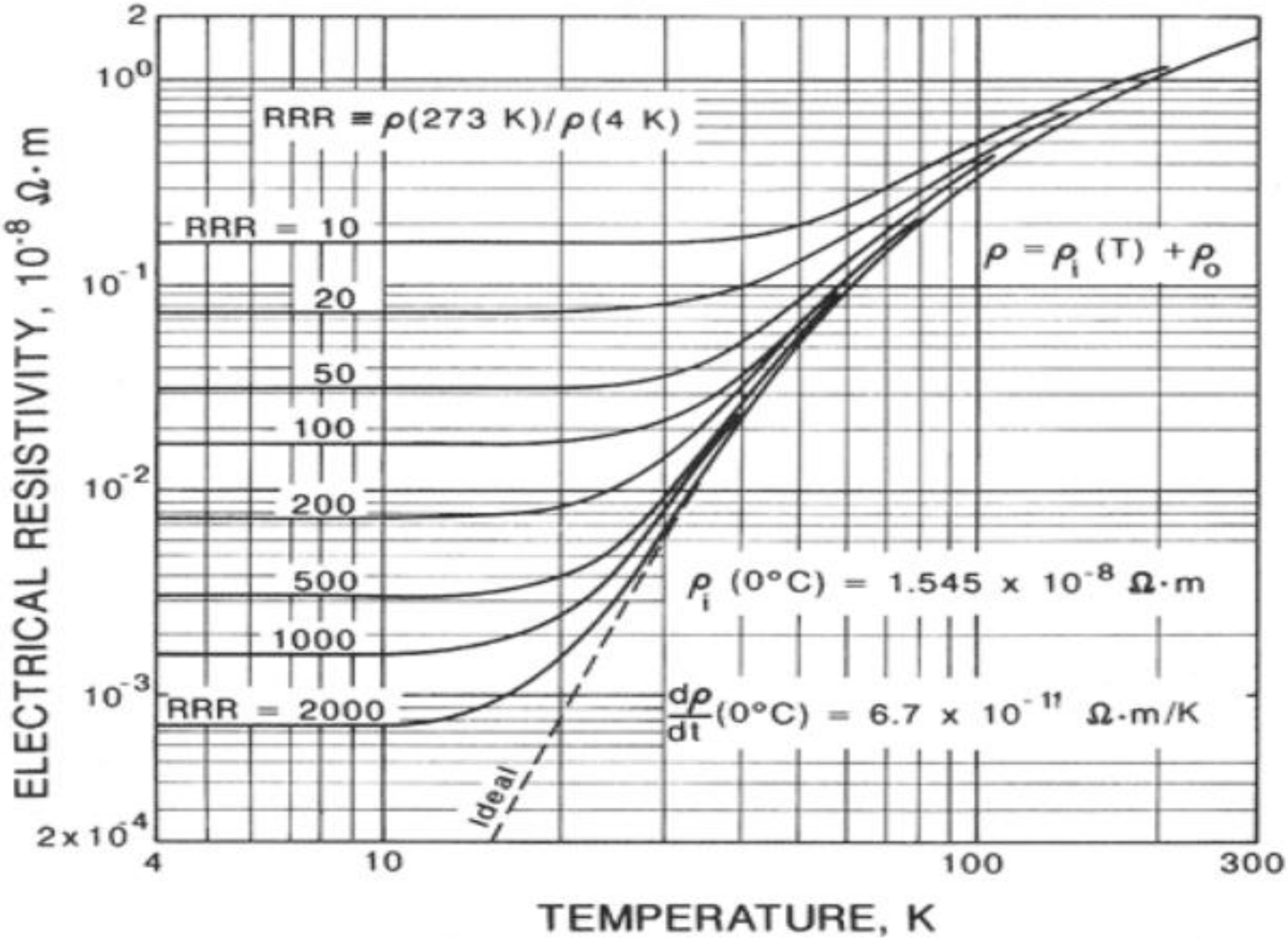
Note: the temperature rise Is independent of wire length (R/M)

You can calculate an integral of I squared that will raise the temperature of the initiating spot from 10K to 450K . This is called the "MIIT" limit of cable or magnet. Usually this number is in "Million of Amp-Squared-Seconds" hence the term "MIIT".

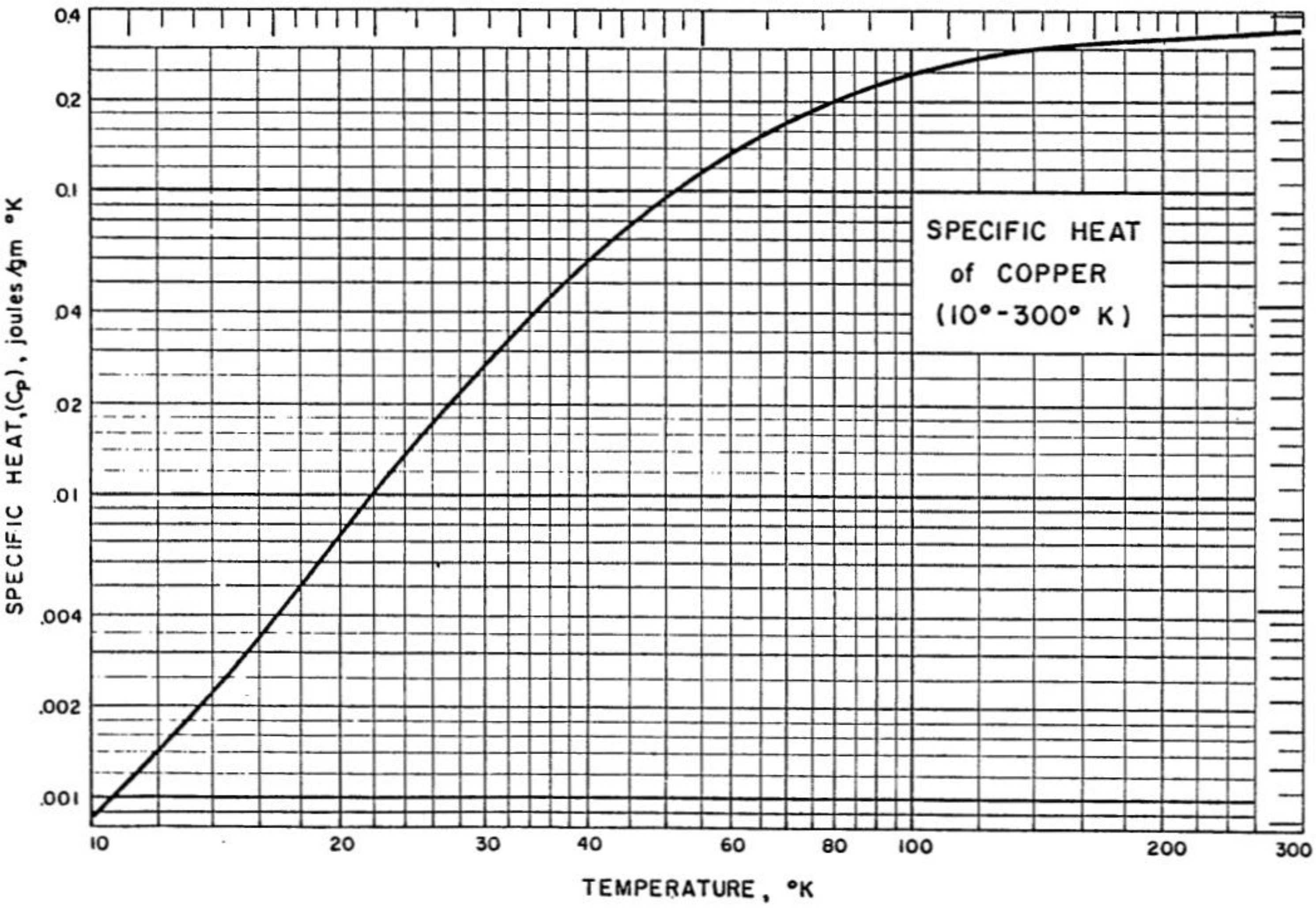
Protection of Superconducting Magnets

- In real life, the resistance varies by about 100 between cryogenic and room temperatures and the specific heat varies by about 300.
- The calculation of MIITs is more straightforward because both R and C increase with increasing temperature, and thus tend to compensate each other.
- For each superconducting wire the maximum MIITS can be calculated that will limit the temperature rise to a safe level.

Protection of Superconducting Magnets

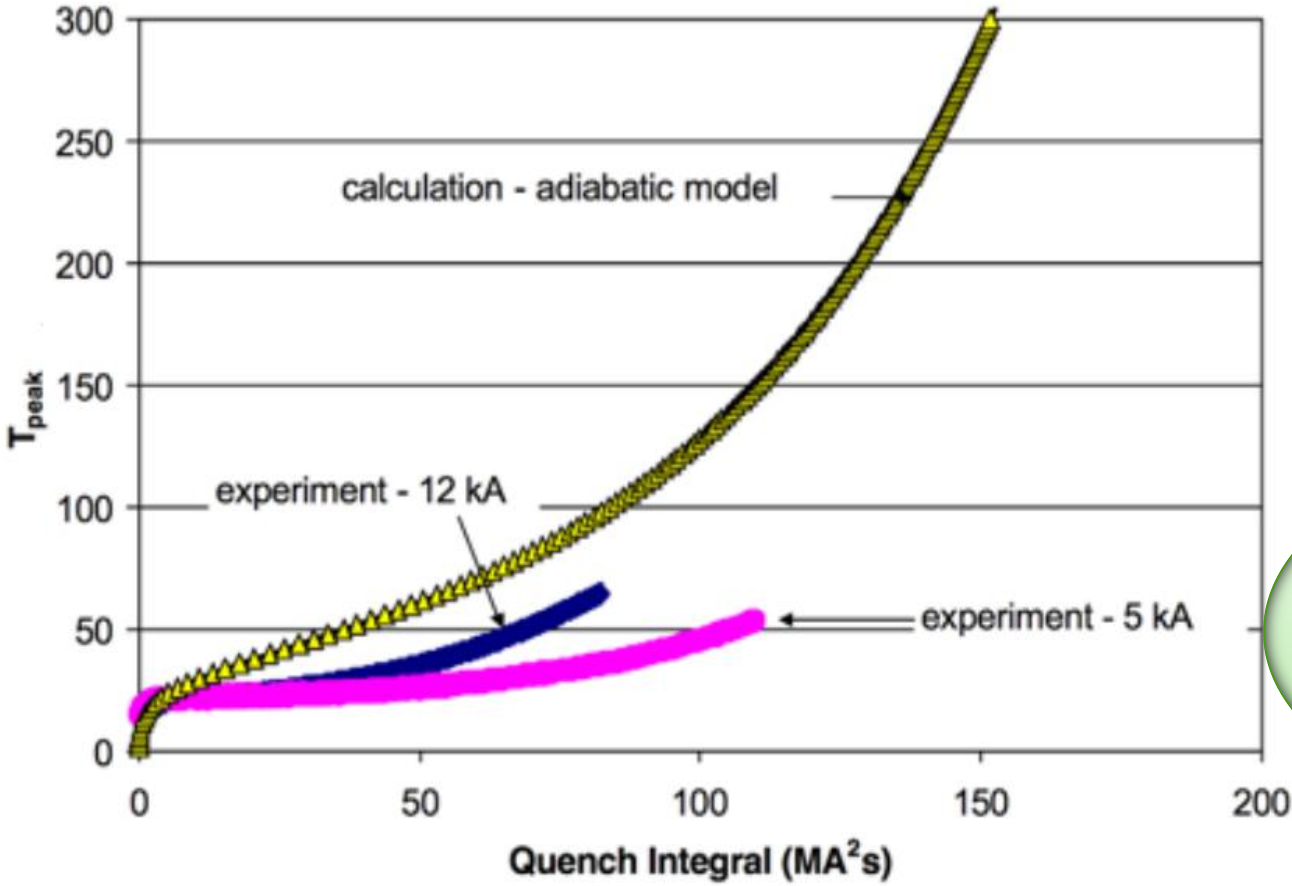


Protection of Superconducting Magnets



Protection of Superconducting Magnets

Actual Temperature vs Calculation
SC Bus in LHC Triplet Magnet



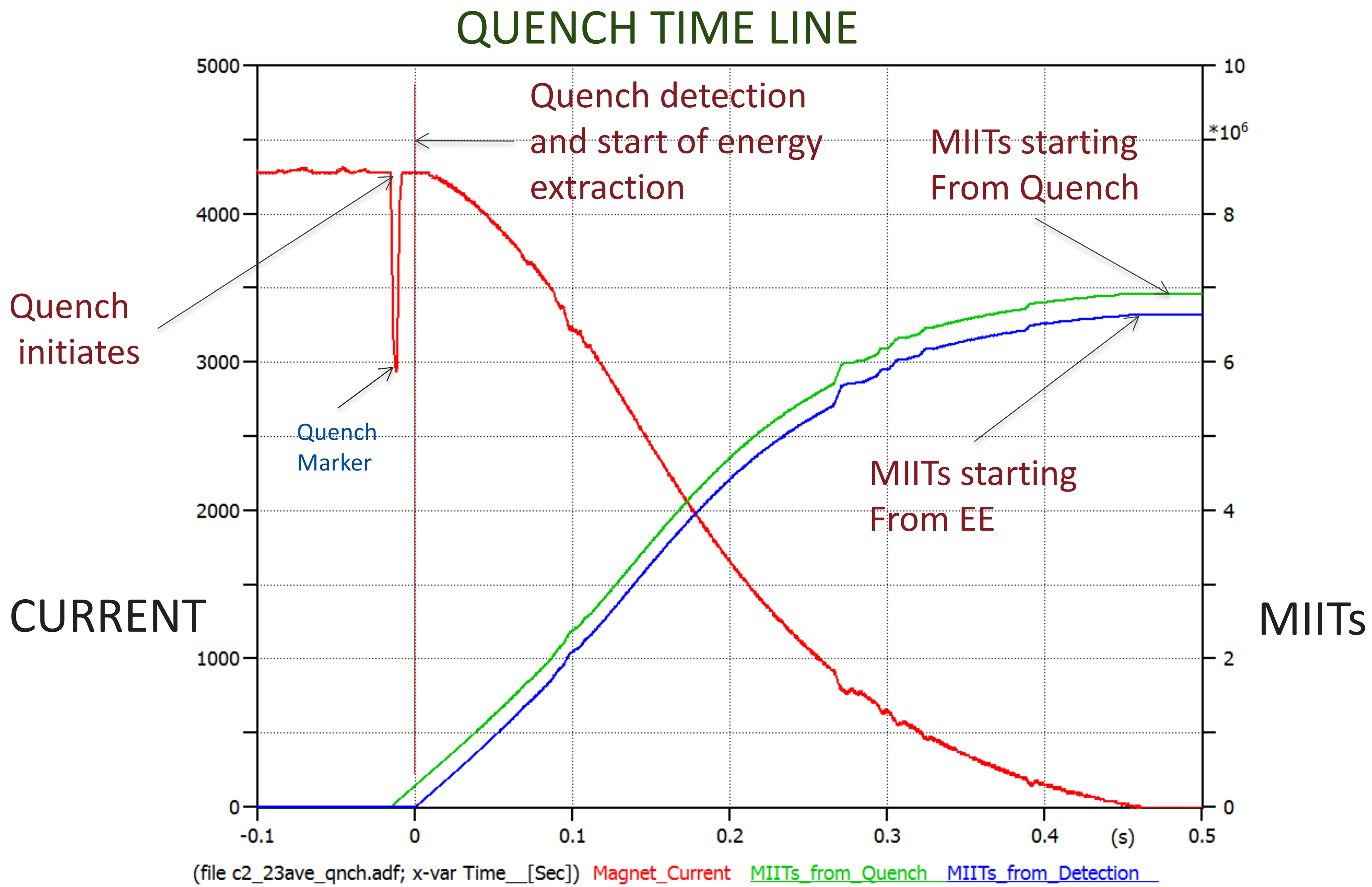
Important:
Always verify the calculations with testing

Adiabatic Model is Conservative

MIIT's

- Examples of maximum allowable MIITs:
  - Tev Dipole: 7 MIIT's;
  - LHC Dipole: 32 MIIT's;
  - Tev correction coil: 3.2 KIITs (Thousand amp squared seconds).
- **Time Scales Involved for limiting MIITs;**
  - For a TEV dipole running at 4 kAmps (16 MIITs/sec), the current in the quenching magnet must be **substantially reduced** within 7/16 seconds.
  - For an LHC dipole running at 10 kA (100 MIITs/sec), the current in the quenching magnet must be **substantially reduced** within 0.3 seconds.
  - For a TEV correction element running at 50 Amps (2.5 KIITs/sec), the current in the quenching magnet must be **substantially reduced** within 1.5 seconds.

Protection of Superconducting Magnets



Protection of Superconducting Magnets

Methods for Limiting MIIT's After Detection of Quench

1. Reduce PC voltage to zero if cable resistance is enough to limit the MIIT's (e.g. TEV Extraction Quadrupole loops).

2. Reduce voltage and use dump circuit (insert a resistance, as in the TEV Main Quadrupole Correction Coil Loop).

3. Reduce voltage and fire Heaters* (e.g. TEV Low Beta).

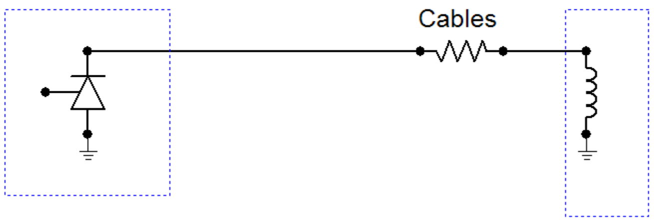
** Heaters are steel strips that are pressed against the outer windings of a magnet. They are designed to have reasonably low thermal insulation but enough electrical insulation to avoid arcing to the magnet winding.*

When a quench is detected, the Heater Firing Circuit (HFU) is triggered and discharges the energy in a capacitor bank into the resistive strip. This energy is sufficient to initiate a quench in a large fraction of the magnet cabling. The growth in resistance of this large volume of quenching cabling is sufficient to reduce the magnet current before it reaches its MIIT limit.

Protection of Superconducting Magnets

Methods for Limiting MIIT's After Detection of Quench (1)

Reduce PC voltage to zero if cable resistance is enough to limit the MIIT's (e.g. TEV Extraction Quadrupole loops).



System Data:
4 magnets, 0.46 H each
Cable R=2.45
L/R = 0.75 sec (τ)
Imax = 50 amps
KIITS max = 3.2

$$IIT = I^2 * \frac{\tau}{2}$$

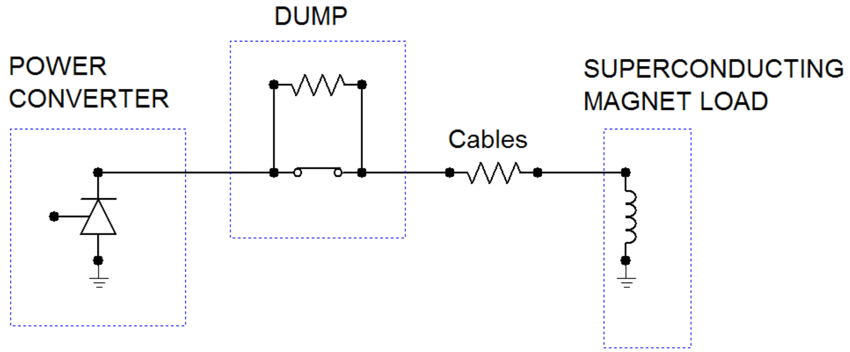
$$IIT = 50^2 * \frac{0.75}{2}$$

= 0.94 KIITs

Protection of Superconducting Magnets

Methods for Limiting MIIT's After Detection of Quench (2)

Reduce voltage and use dump circuit (insert a resistance, as in the TEV Main Quadrupole Correction Coil Loop).



$$IIT = I^2 * \frac{\tau}{2}$$

System Data:
90 magnets, 0.46 H each
Cable 5.8 ohms
Dump R = 20 ohms
L/R = 1.6 sec. (τ)
50 amps
Maximum KIITS: 3.2

Without Dump

$$IIT = 50^2 * \frac{7.14}{2}$$

= 8.9 KIITs

With Dump

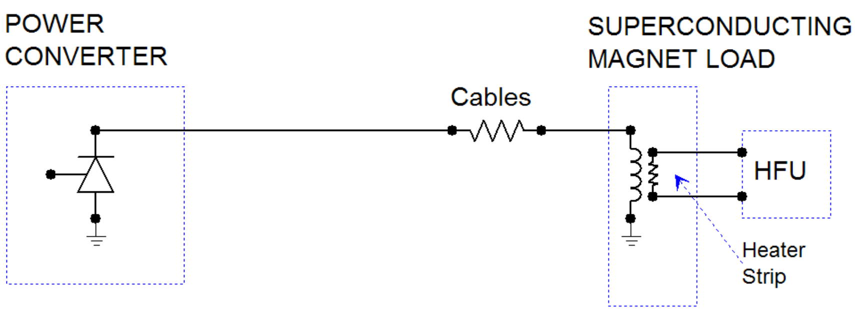
$$IIT = 50^2 * \frac{1.6}{2}$$

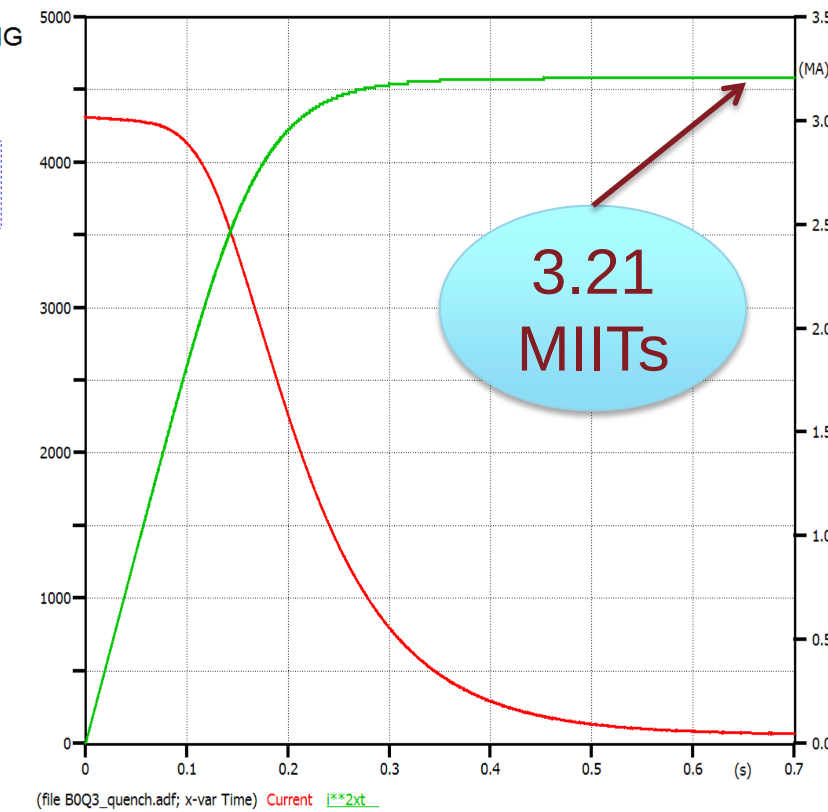
= 2.0 KIITs

Protection of Superconducting Magnets

Methods for Limiting MIIT's After Detection of Quench (3)

Reduce voltage and fire Heaters (e.g. TEV Low Beta).





System Data:

2 magnets, 0.046 H each

5000 amps

5.18 MIITs

Bus Resistance, 0.003 ohms

Effective Resistance estimated from current decay = 0.375 ohms

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Heaters

Two examples of heater circuits are:

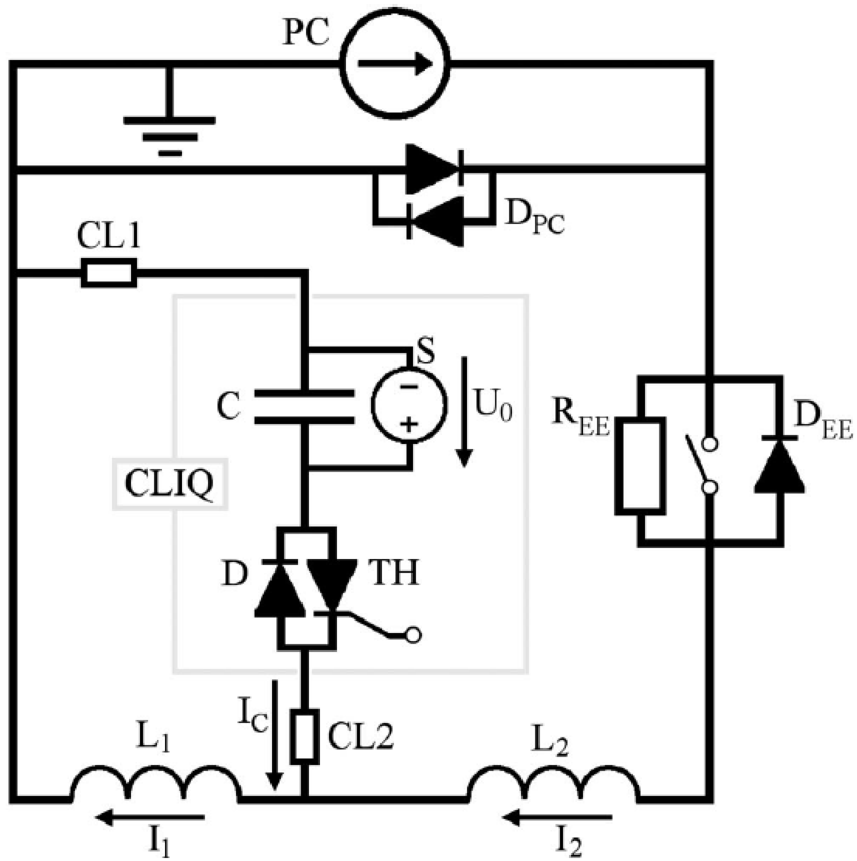
Circuit	Capacitance	Voltage	Energy	Strip Resistance	Discharge Time
TEV dipole	6.6 mF	450 V	0.67 kJ	20 ohms	18 ms
LHC dipole	7 mF	900 V	2.8 kJ	12 ohms	84 ms

Protection of Superconducting Magnets

New type of induced quenching – a substitute for heaters

Coupling Loss-Induced Quench (**CLIQ**) – E. Ravaioli, CERN

Discharge capacitor bank into magnet coil, inducing high-frequency ringing and a di/dt quench.



Series Magnet Strings with Large Stored Energy

- *The accelerator world often contains extended systems with many magnets and large stored energy.*

Two examples:

Accelerator	Number of Magnets	Maximum Current	Total Inductance	Energy
TEV Ring	776	4.4 kA	30 H	290 MJ
LHC Dipole Sector	154	11.5 kA	15.4 H	1,018 MJ

Protection of Superconducting Magnets

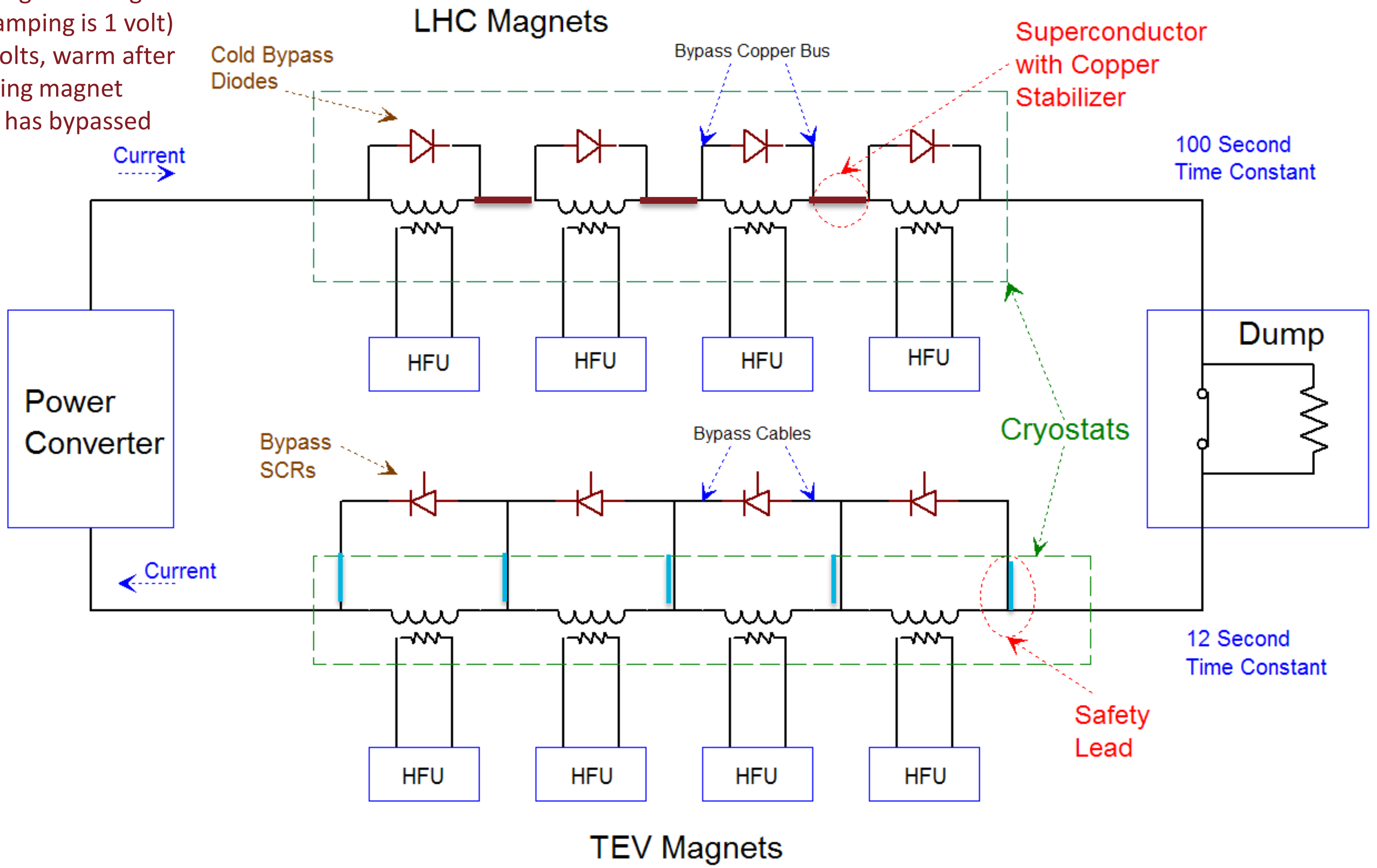
Series Magnet Strings with Large Stored Energy

- It is impractical to remove this much energy from the magnet systems in a fraction of a second, so an approach using Heater Firing, “Bypassing” and “Energy Extraction” has been used. When a quench is detected in one of the magnets, the quench protection system takes three actions:
  - Fire the HFU on the quenching magnet
  - Establish a bypass path for the main circuit current to go around the quenching magnet while its own current decays within a fraction of a second.
  - Open Switches to insert Dump (Energy Extraction) Resistors so that the magnet circuit current will decay on a multi-second time scale.

- The time constant of the dump is coordinated with the number of MIIT’s that the **Bypass Path** can absorb without overheating.
  - TEV = 12 sec time constant
  - LHC dipole sector = 100 sec time constant

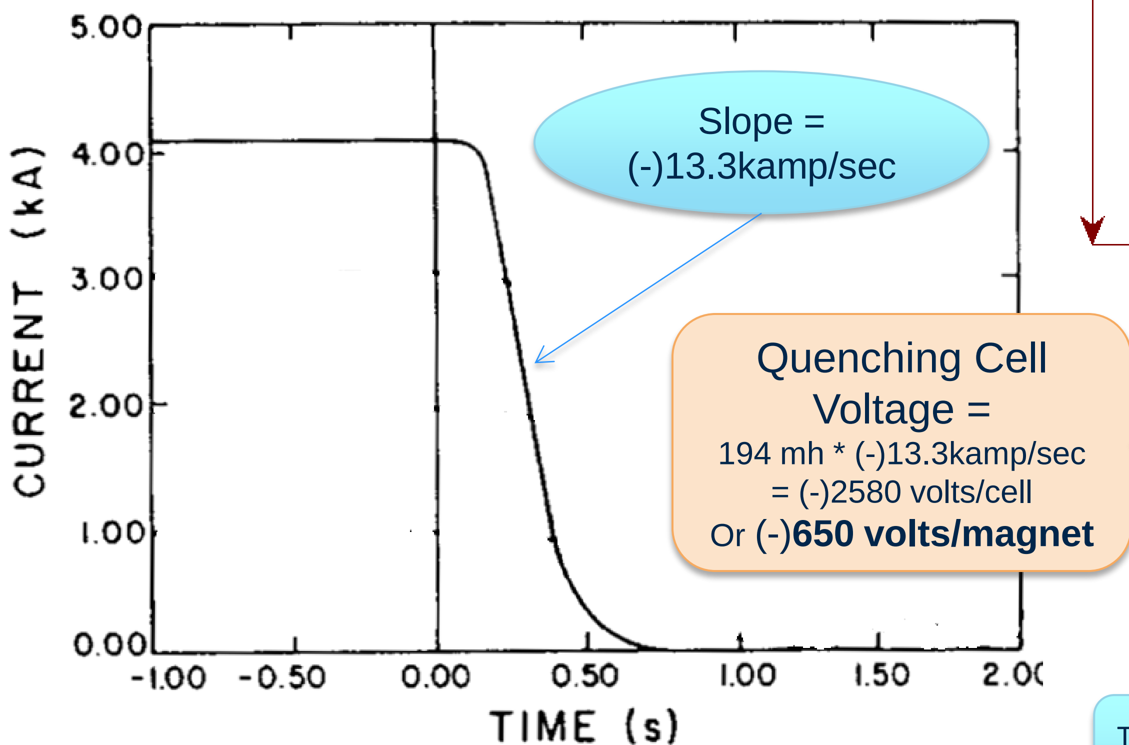
Protection of Superconducting Magnets

LHC diode Vf = 6 volts cold (magnet voltage while ramping is 1 volt) Vf = 1 volts, warm after quenching magnet current has bypassed into it.

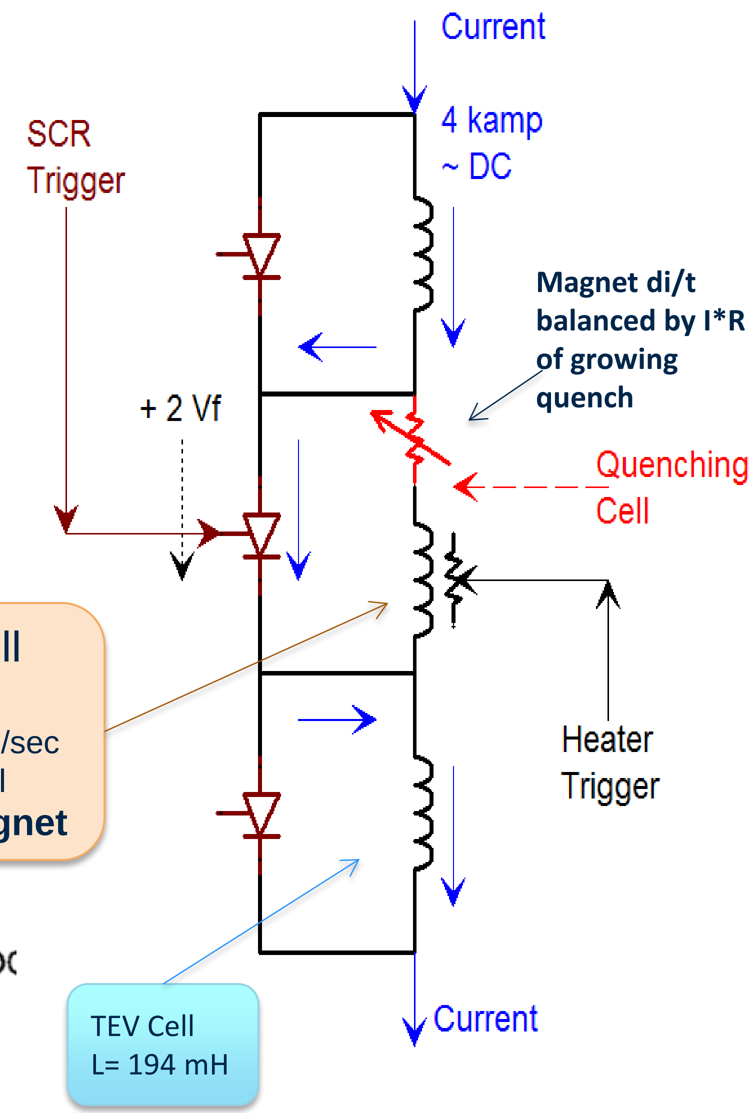


Protection of Superconducting Magnets

What Happens to a magnet when the heaters are fired and the current is "Bypassed"?



Magnet current



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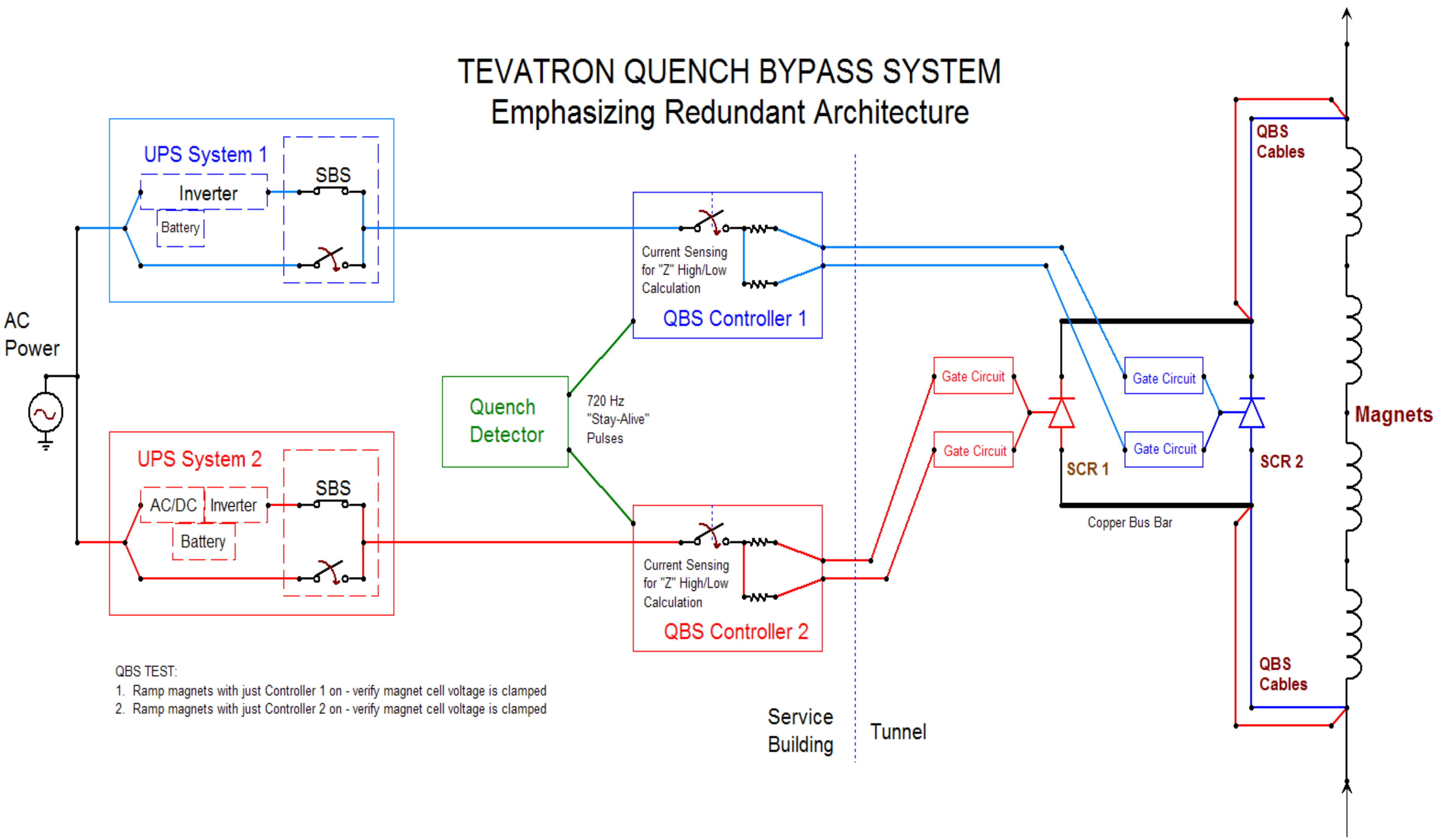
Protection of Superconducting Magnets



Protection of Superconducting Magnets

Review of four different cases for Post Energy Extraction MIITs

	Post Energy Extraction	Maximum Rating
• TEV Extraction Quad:	0.9 KIITs	3.2 KIITs
• TEV Main Quad Correction Loop:	2.0 KIITs	3.2 KIITs
• TEV Low-beta:	3.2 MIITs	5.2 MIITs
• TEV Dipoles:	5.0 MIITs	7.0 MIITs

QUENCH DETECTION

- **What are we detecting?** Basically, the extra I * R "resistive" voltage that should not be there in a superconducting load. (R= resistance of quenching cable as quench propagates)
- **How much Time do we have?** ΔT = time between the initiation and detection of a quench.
  - Remember, MIITs start accruing from moment that initiating spot quenches.
  - Once quench is detected and protection system responds, a certain number of (post dump) MIITs will be deposited.
  - So maximum ΔT = (Max MIITs – post dump MIITs) divided by the current squared

Protection of Superconducting Magnets

QUENCH DETECTION – how much time do we have?

- Example A: Quadrupole correction loop (slide 51).
- Max = 3.2 KIITs; post Energy Extraction (EE) = 2.0 KIITs.

$$\Delta T = \frac{IITs(rating) - IITs(post\ EE)}{I(pre\ Quench)^2}$$

$$\Delta T = \frac{3.2\ KIITs - 2.0\ KITTs}{50^2} = 0.48\ \text{seconds}$$

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Protection of Superconducting Magnets

QUENCH DETECTION - how fast does Resistive Voltage grow?

- Example A (from previous slide)

> " Experiments were done on **dipole correction elements** during which a heater was fired to cause a quench condition while 50 Amps was being conducted through the element. The coil voltage reached 10 volt level within approximately 0.25s." - compared to 0.48 seconds from previous slide

So a 10 volt detection threshold would be sufficient. We were able to operate without nuisance trips with a threshold of 4 volts.

Protection of Superconducting Magnets

QUENCH DETECTION – how much time do we have?

- Example B: The Main Tevatron Loop
- Post EE MIITs = 5 MIITs @ 4 kA. See plot.

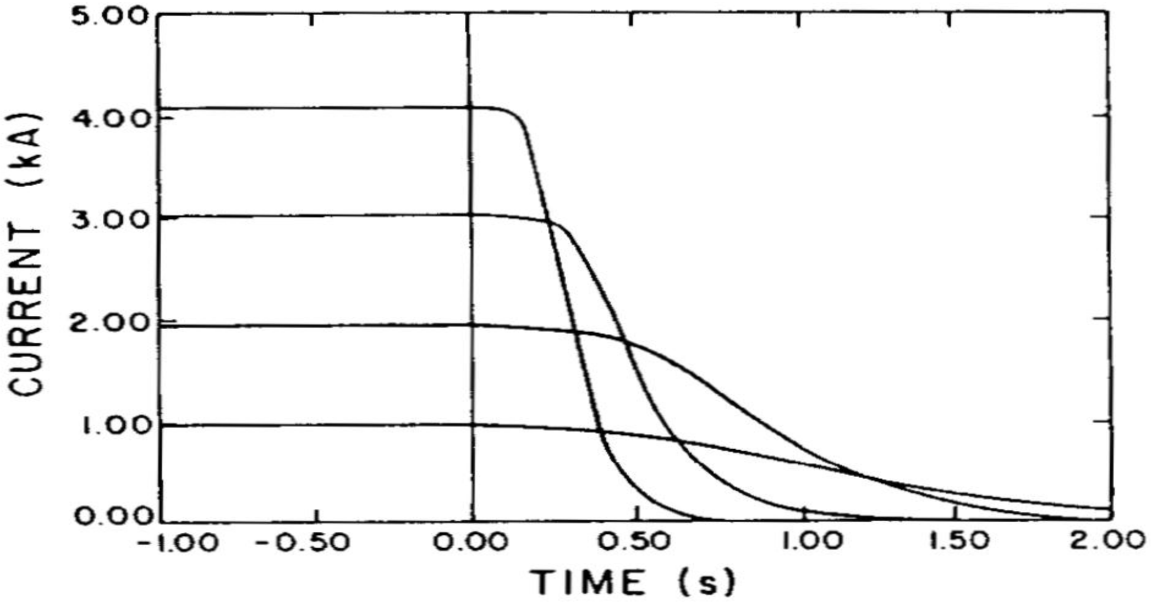


Figure 10. Magnet current for quenches at different currents.

QUENCH DETECTION – how much time do we have?

- Example B: The Main Tevatron Loop (cont.)
- Detection time allowed:

$$\Delta T = \frac{7MIITs - 5MITTs}{4kamps^2} = 0.125 \text{ seconds}$$

Protection of Superconducting Magnets

QUENCH DETECTION –

how fast does Resistive Voltage grow?

Example B: The Main Tevatron Loop

Hairpin plot shows growth to .1 volt in 100 ms. @ 4 kA.

The hairpin data for voltage vs. time can be extrapolated to longer pieces of cable by a summation procedure, giving the voltage as a function of time for an arbitrarily long piece. The combination of that calculation with the MIITs allowable specifies that the quench must be detected at a level of 0.5 V at 4 kA. This detection level is required in order to protect against quenches which start in the single conductor in low field regions outside the coil.

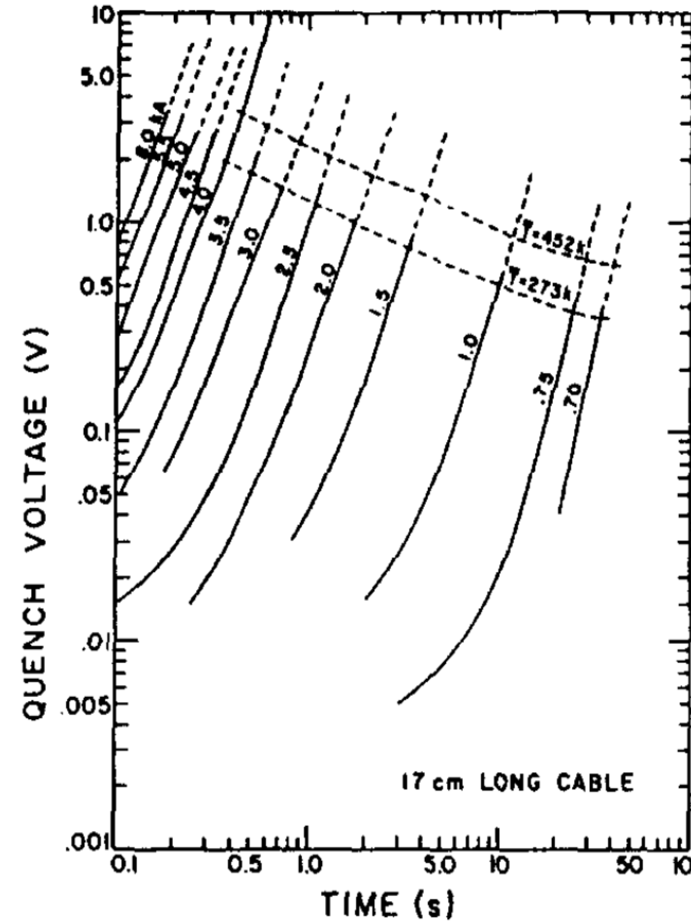


Figure 5. Voltage vs. time from hairpin measurements at different currents.

Protection of Superconducting Magnets

Quench Detection Sensitivities

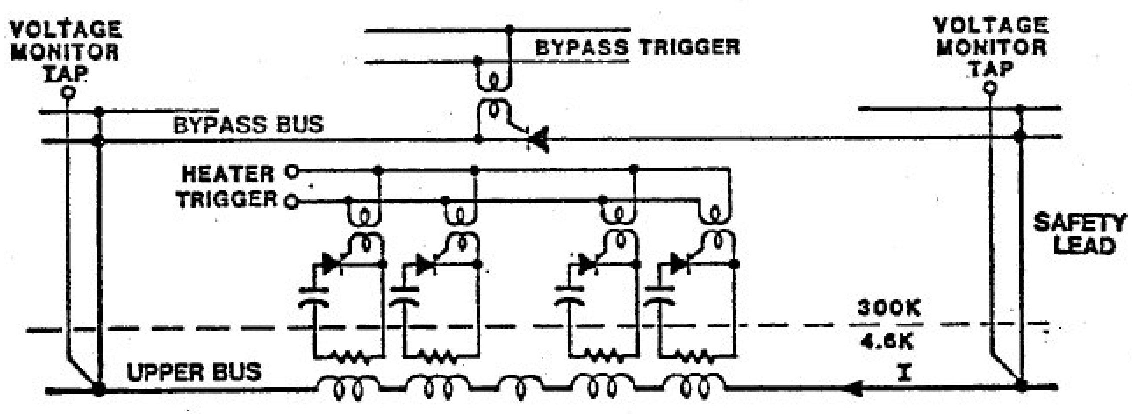
System	Trip Threshold	Averaging Time
Tevatron Quad Correctors	4.0 volts	10 ms
Tevatron Main Dipoles	0.5 volts	50 ms
LHC Main Dipoles	0.1 volts	10 ms
LHC 600 amp Circuits	0.4 volts	200 ms

Protection of Superconducting Magnets

How do you detect Resistive Voltage?

- **Example A**, Correction Quad loop: Compare voltage across 45 magnets with that across the other 45 magnets (carefully, using center tap). Look for 4 volt difference.

- **Example B**, TEV Main Loop:

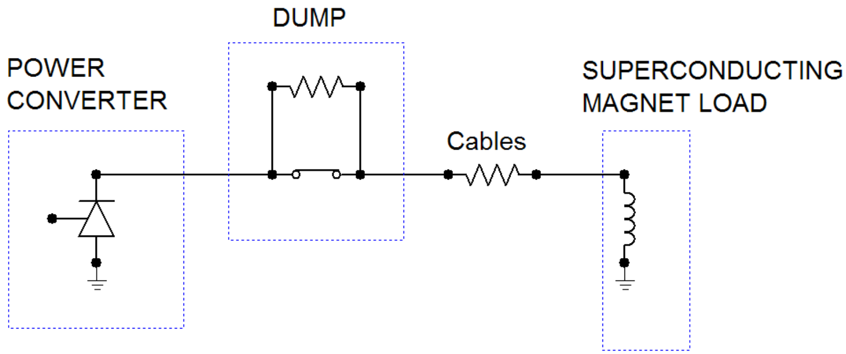


Compare voltage across 4 Cells (5 magnets each). Simply stated, look for a 0.5 volt difference

Protection of Superconducting Magnets

How do you detect Resistive Voltage?

- **Example C**, LHC 600 amp Corrector Circuits



Quench Voltage, Vq :

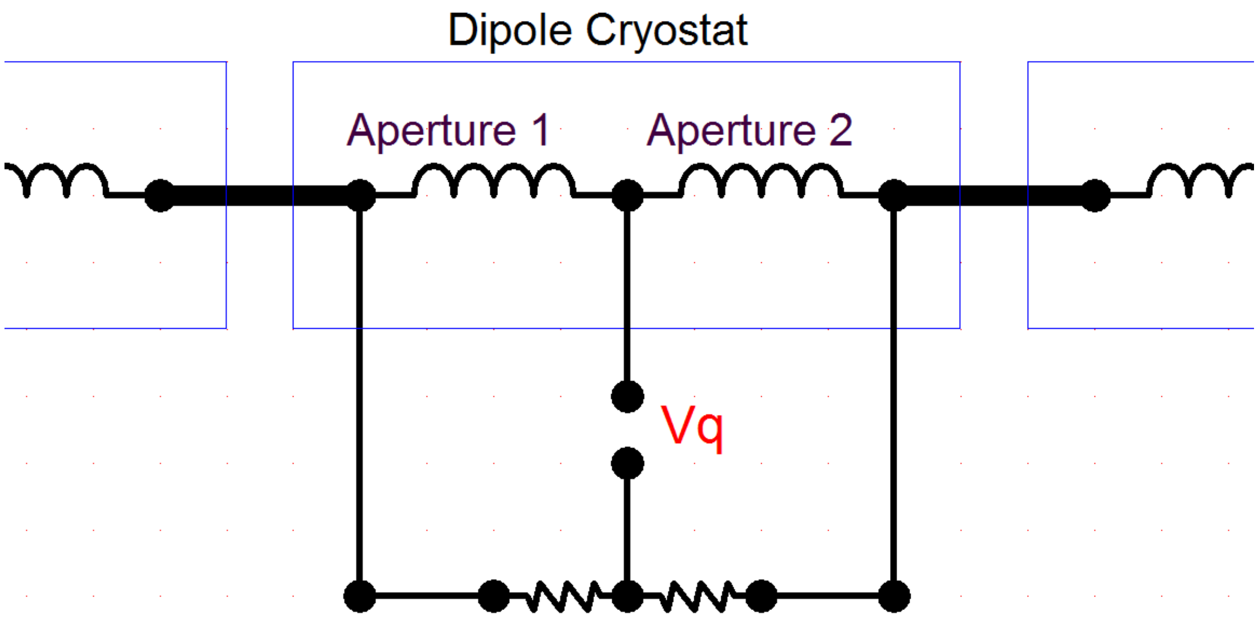
$$Vq = Vmag - Lm * \frac{di}{dt}$$

Derive di/dt from measured current, compare it (properly scaled with L) with the measured magnet voltage. Look for a 0.4 volt difference

This method is sensitive to noise on the measured current signal and to the complex impedance of the magnet. (The LHC is still making upgrades to these quench detection systems)

How do you detect Resistive Voltage?

Example D, LHC 13kamp Dipole Circuits



Look for a 0.1 volt difference

Protection of Superconducting Magnets

Comparing Quench Detection Approaches

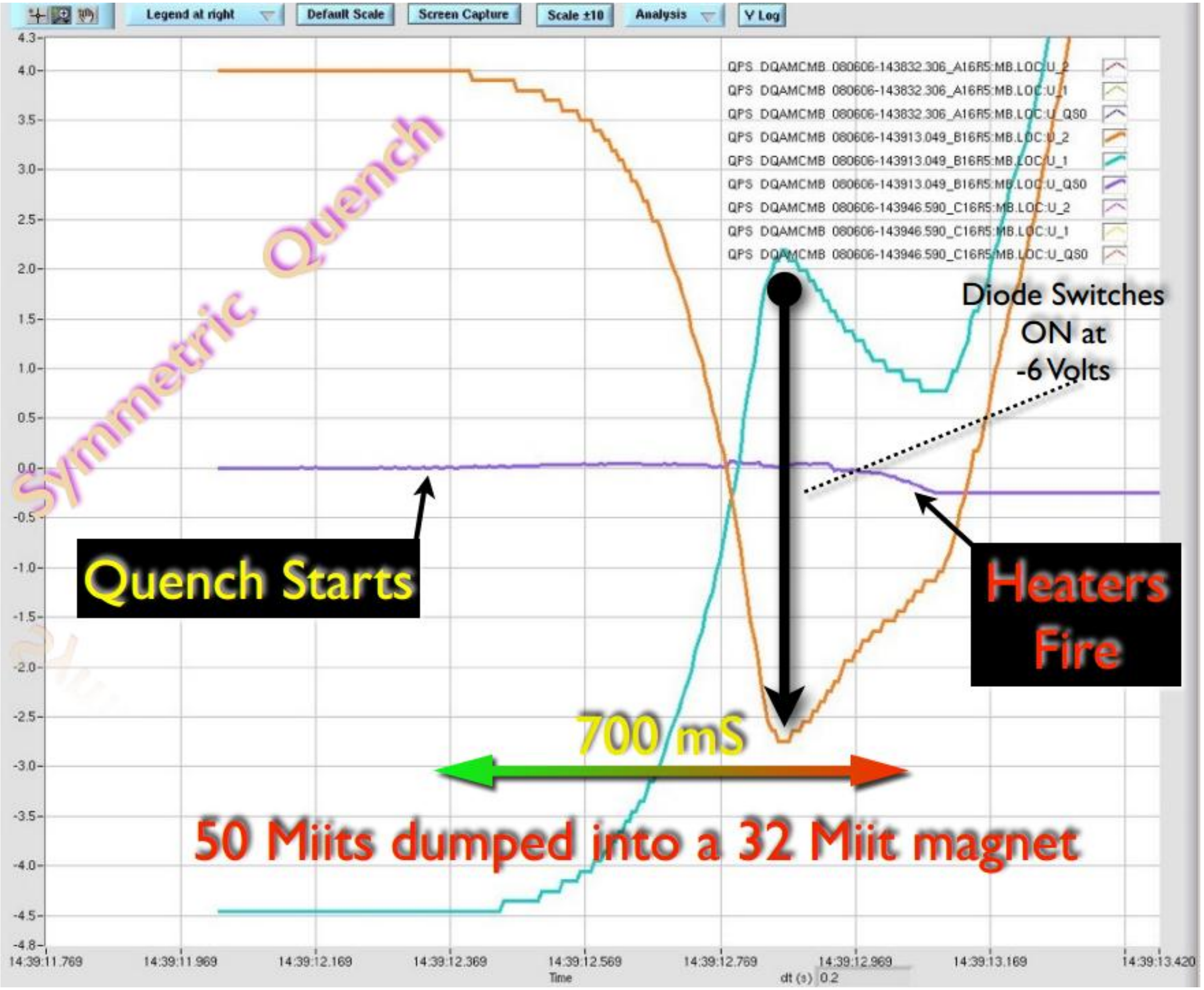
- The approach comparing similar magnet voltages to each other typically allows lower quench detection thresholds.
  - No di/dt noise issues
  - No complex magnet impedance issues

- Comparing **<u>just</u>** two magnet voltages to each other introduces a vulnerability to symmetric quench growth in both magnets. The LHC encountered this in the main dipole bus and mitigated the possibility with an additional system comparing 4 magnets to each other.

Protection of Superconducting Magnets

Late detection because of a symmetric quench

Note: System survived this 50 MIIT dump.



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Protection of Superconducting Magnets

- After all the proper designs and protections implemented, in large systems you often run into the UNEXPECTED.

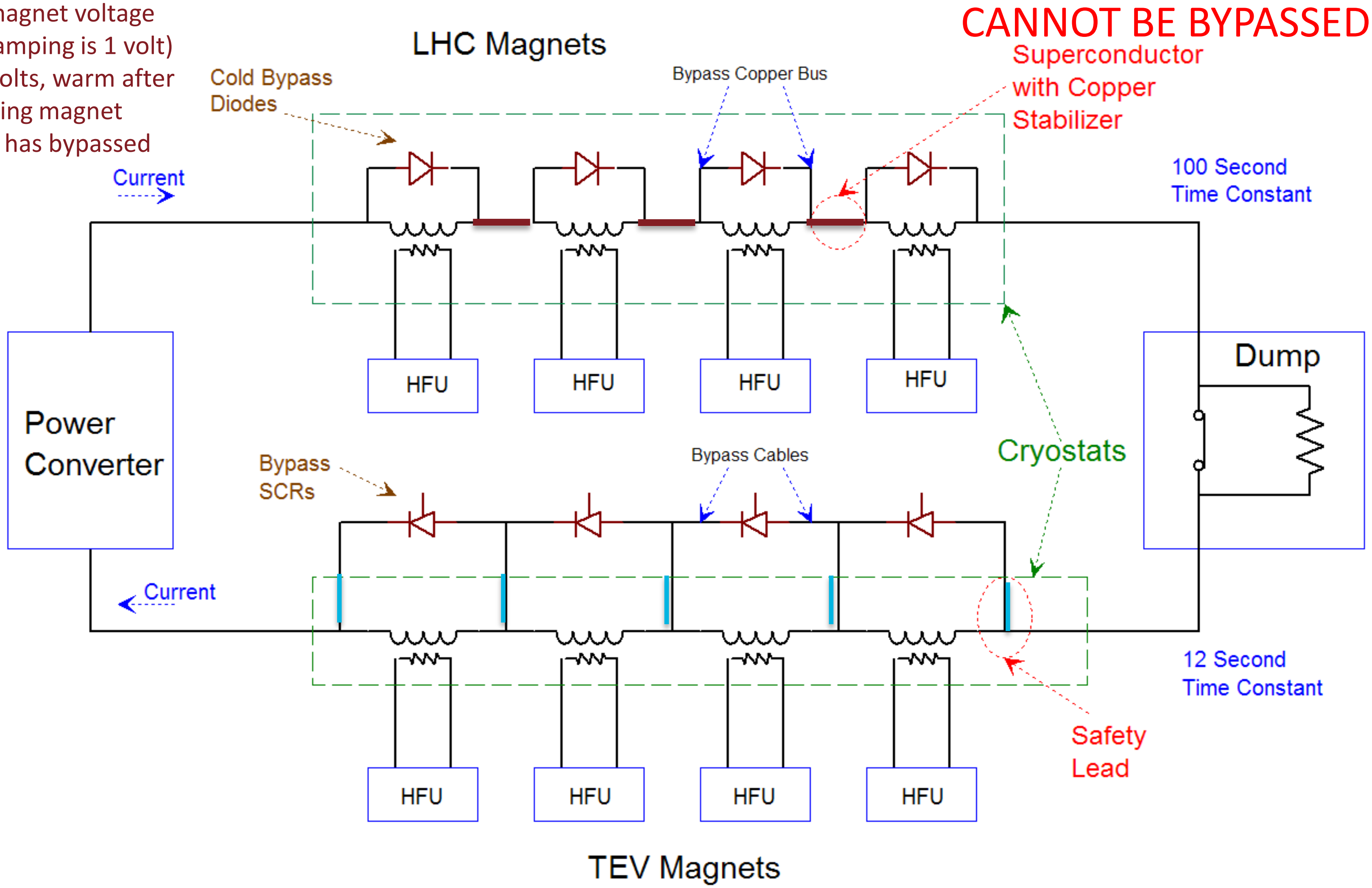
TEVATRON

CABLE PROBLEM

The 800 GeV fixed target run began ominously; it began with a magnet failure. Four similar failures followed during the next four months. The Tevatron dipoles come in two types, known as TB and TC. They are four pole devices, with an upper and lower bus which may be far apart electrically. One bus runs straight through the dipole, from one end to the other--one half turn. The other bus forms the remainder of the 110 turns of the dipole. The TB and TC magnets differ in that the TB (TC) magnet has the inductance on the lower (upper) bus. There are also slight mechanical differences in their construction. The TC magnets have about 30 cm of superconducting cable from the magnet to magnet splice to the point at which the conductor leaves the collared coil assembly. The Lorentz force from the fringe field at the end of the magnet produced flexing of the cable as the current was ramped up and down. Individual strands began breaking, and the ends of the broken strands were likely to produce ground faults or bus-to-bus shorts. The last four failures occurred in the span of about six weeks. At that point, the machine was shut down and all the TC magnets were repaired by opening the cryostats and securing the leads together with Kevlar string to prevent motion. This shutdown

Protection of Superconducting Magnets

LHC diode Vf = 6 volts cold (magnet voltage while ramping is 1 volt) Vf = 1 volts, warm after quenching magnet current has bypassed into it.



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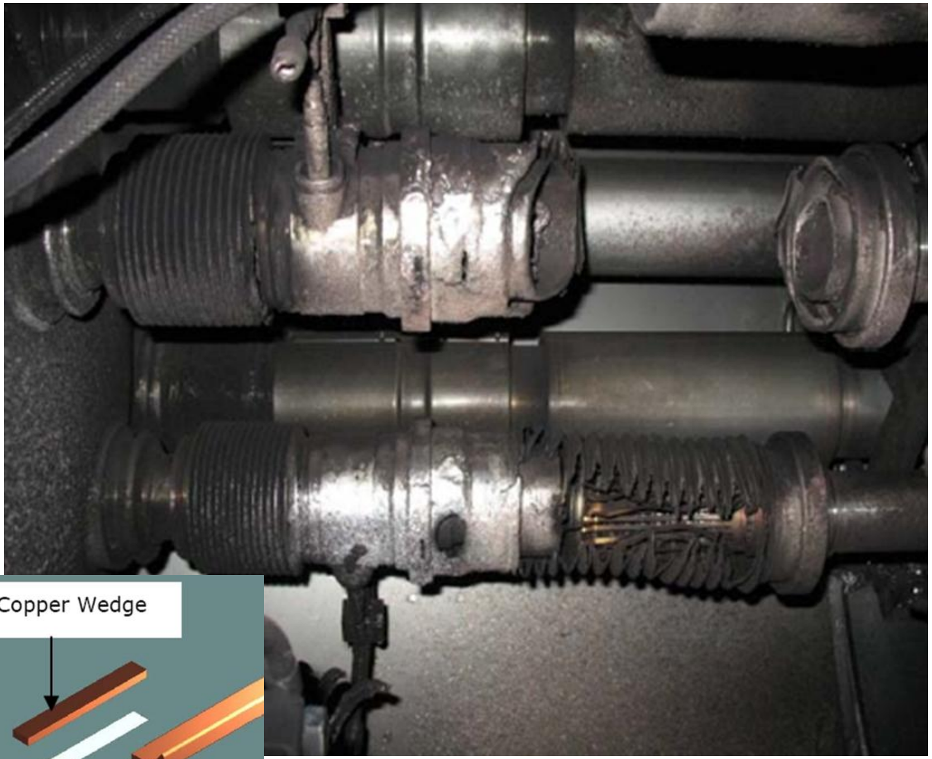
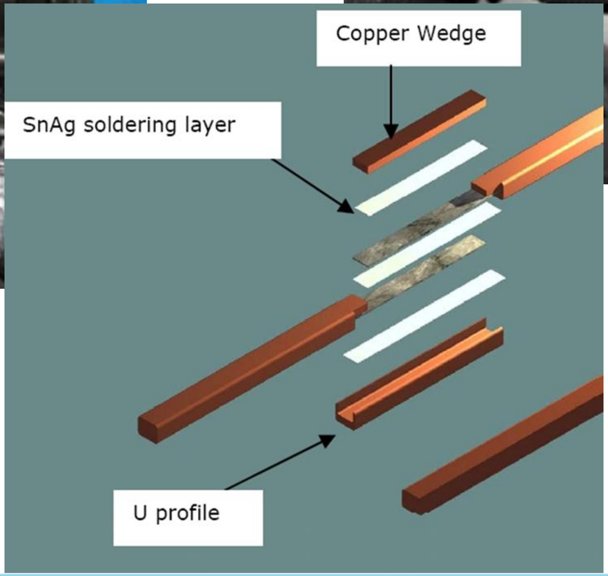
Mistakes





ADDITIONAL SLIDES

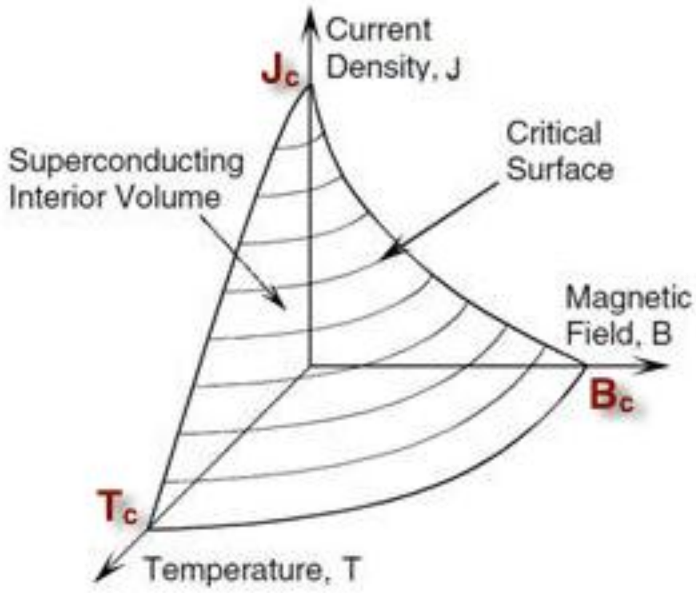
Definitions

- **Power Converter** – Any device that converts one form of voltage/current to another form. In this context, usually refers to a power supply that converts the incoming AC line to DC.
- **MOV** - Metal Oxide Varistor, non-linear device for controlling over-voltages
- **SCR** - Silicon Controlled Rectifier, a solid state switch were applying a voltage to the "gate" will switch the device from an open circuit to a diode.
- **DCCT** - Direct Current , Current Transformer
- **CORONA** -
- **HFU** - Heater Firing Unit
- **Quench** - This is the sudden runaway loss of superconductivity driven by the heat of normal conduction, driven by the loss of superconductivity, driven by………
- **QBS** - Quench Bypass Switch
- **DUMP** – process of inserting resistors into a circuit consisting of superconducting elements to remove stored energy
- **Superconductivity** -is a phenomenon of exactly zero electrical resistance and expulsion of magnetic fields occurring in certain materials when cooled below a characteristic critical temperature.
- **Type 1** category of superconductors is mainly comprised of metals and metalloids that show *some* conductivity at room temperature. They require incredible cold to slow down molecular vibrations sufficiently to facilitate unimpeded electron flow in accordance with what is known as BCS theory
- **Type 2** superconductors: Except for the elements vanadium, technetium and niobium, the Type 2 category of superconductors is comprised of metallic compounds and alloys. They achieve higher Tc's than Type 1 superconductors by a mechanism that is still not completely understood. Conventional wisdom holds that it relates to the planar layering within the crystalline structure (see above graphic).
- **Upper critical field** (UCF) is the magnetic field (usually expressed in teslas (T)) which completely suppresses superconductivity in a *Type II* superconductor at 0K (absolute zero).
- **Lower critical field** is the magnetic field at which the magnetic flux starts to penetrate a type-2 superconductor.

Definitions

"Critical SURFACE" "CABLE Short Sample CURVE" "MAGNET Short Sample LIMIT"

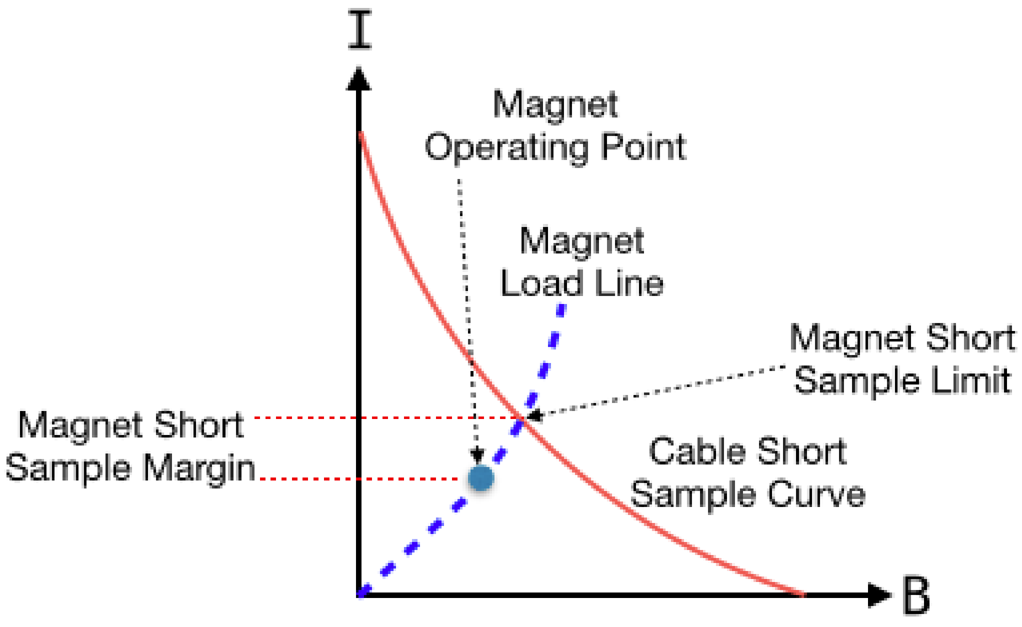
- These three terms, which are directly related but distinctly different, are often referred to using slightly different or abbreviated names. Starting with the most general term, "Critical Surface", each of the three terms is increasingly more specific and less general.
- **Critical SURFACE:** This is the 3 dimensional surface in Temperature, Magnetic Field, and Current Density space under which a specific conductor remains superconducting.



The points where this surface intersects the three axes are called the critical points; T_c, B_c, and J_c respectively.

Definitions

CABLE Short Sample CURVE: This is the 2 dimensional curve in Magnetic Field and Current space formed by the intersection of the critical surface and a plane of constant operating temperature, where the current density is integrated over the cross section of a specific cable. This curve is measured with a "short sample" of the cable placed in different magnetic fields while the current is increased slowly until a quench occurs.



Definitions

- **MAGNET Short Sample LIMIT:** This is the current where the magnet (peak field) load line intersects the cable short sample curve.
-
- **MAGNET Short Sample MARGIN:** This is just the difference between the operating current and the magnet short sample limit.
-
- **MAGNET Temperature MARGIN:** This is just the temperature elevation necessary to diminish the magnet short sample margin to zero.

- **Quench:** This is the sudden runaway loss of superconductivity driven by the heat of normal conduction, driven by the loss of superconductivity, driven by………

Protection of Superconducting Magnets

- The exact (adiabatic) relationship between MIITs and temperature depends on only two things, the intrinsic conductor material properties and the cross sectional area squared:

$$A^2 D \int_{T_0}^{T} \frac{C(T)}{\rho(T)} dT = \int_0^{\infty} I(t)^2 dt = MIITs$$

Protection of Superconducting Magnets

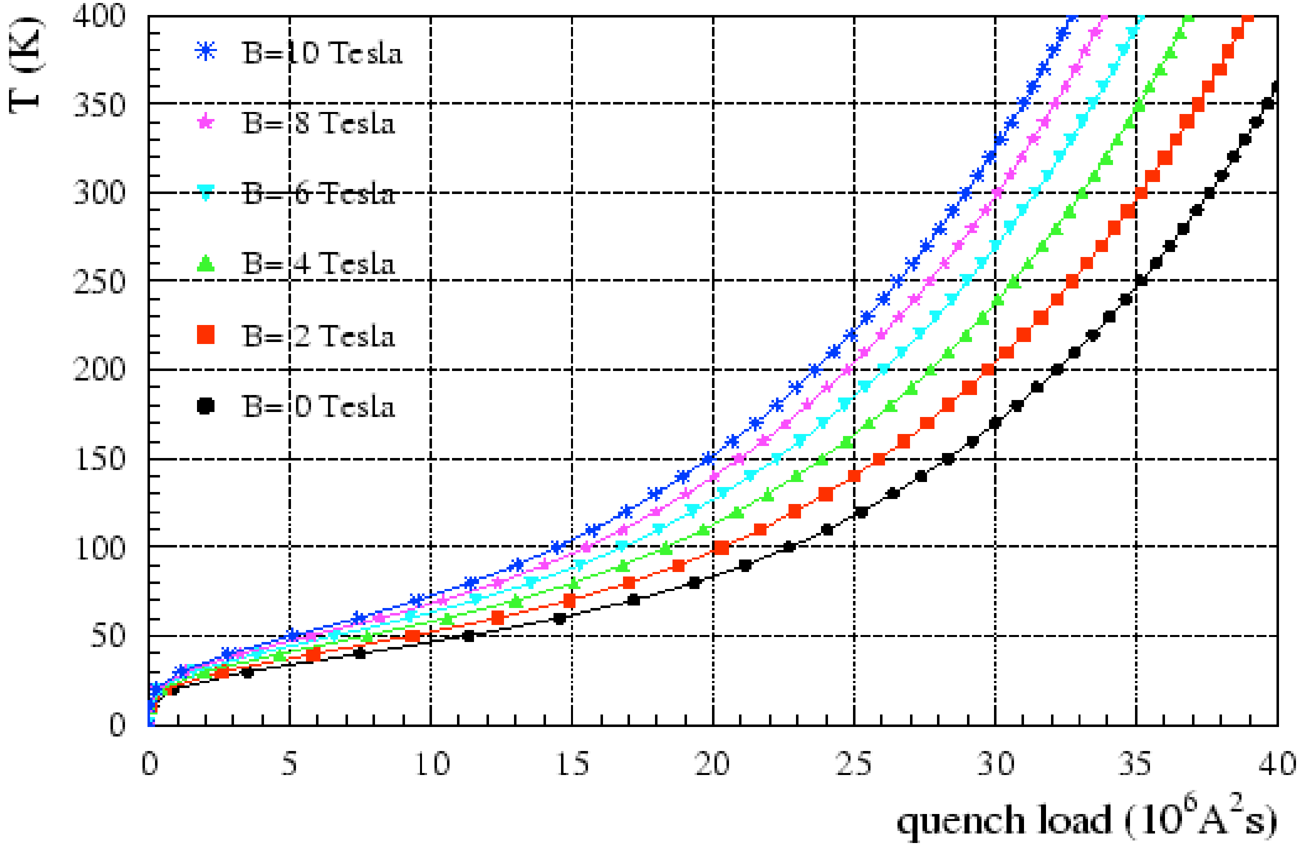
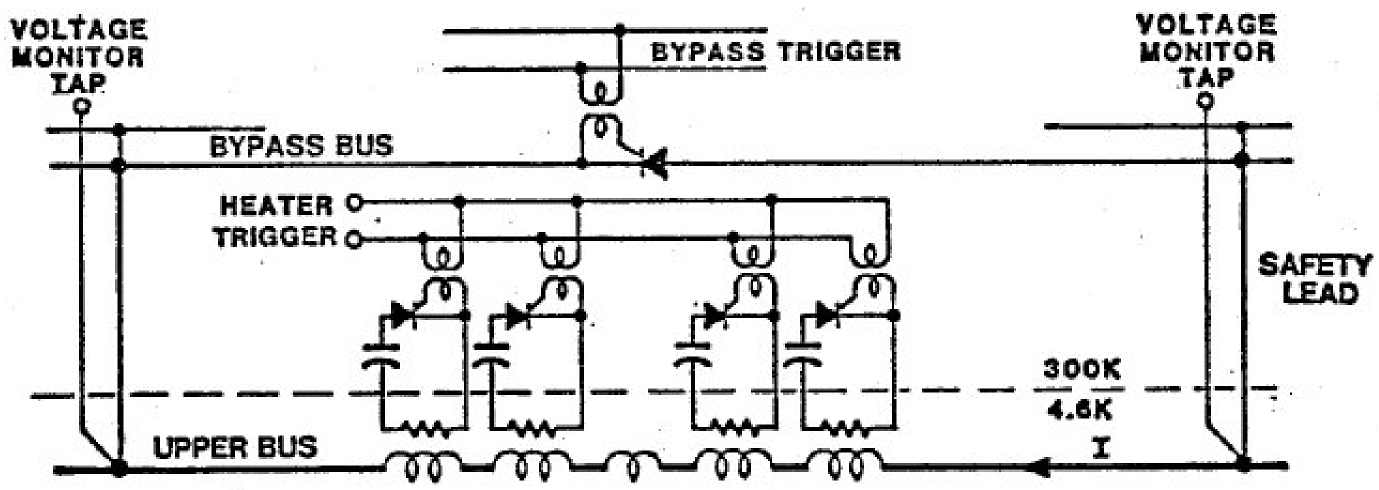


Figure 3.1: Calculated hot spot temperature as a function of the quench load for the outer cable of the LHC dipole magnet ($RRR = 100$, $r_{cu/sc} = 1.9$, $A_{tot} = 19.2442 mm^2$).

Limiting MIIT's After Detection of Quench

- **Series magnet strings:** fire heaters, bypass quenching magnet (SCR's or Diodes) and dump circuit to protect bypass elements.



Tevatron Quench Protection Cell