
CERN

Protection and Interlocks

CERN Accelerator School – May 2014

benjamin.todd@cern.ch

To Take Away Today

* the protection context is vital
  – need to consider system, machine and organisational level impact

* risk analysis is a core part of every engineer's toolbox
  – zero risk does not exist

* specification of protection and interlocks is a compromise
  – they don't add to the function, but are an insurance for when things go wrong.
  – they do add to complexity, so will make the system less reliable.

Contents

1. The Context - Accelerator Challenges

    Stored Beam Energy
    Stored Magnetic Energy

2. Risk Analysis

    Safety – Protection – Plant
    Powering Protection
    Interlock Implementation

3. An Example Realisation

    Beam Interlock System
    Failure Modes Effects and Criticality Analysis

4. Murphy's Law – Lessons Learned **** if I have time left ****

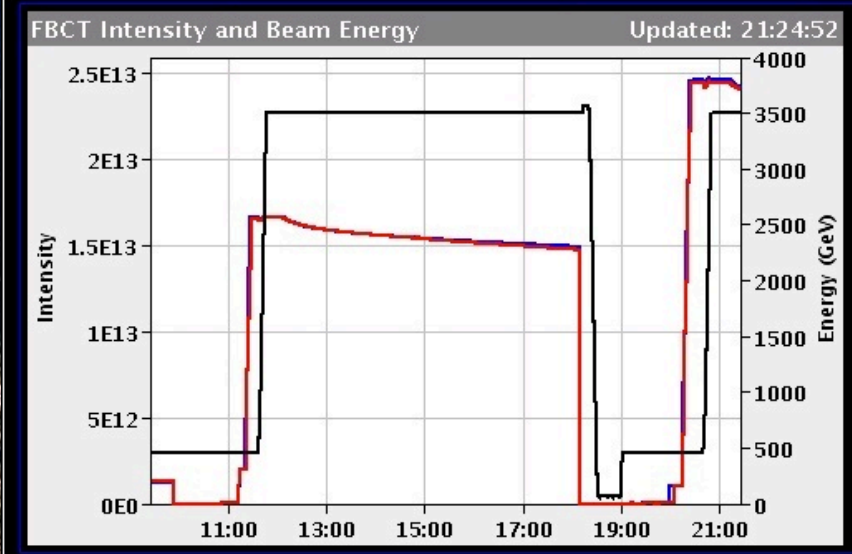
    September 2008
    January 2013

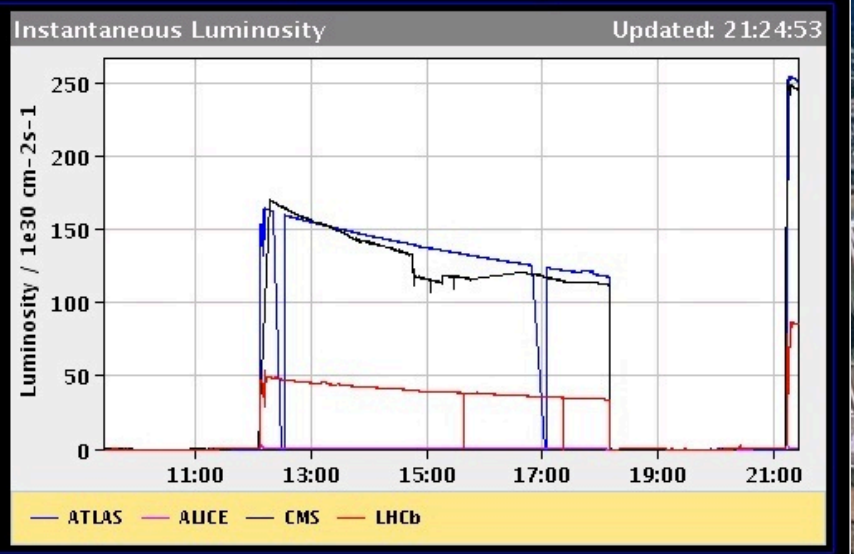
CERN Accelerator Complex

LHC Page1 | Fill: 1645 | E: 3500 GeV | 22-03-2011 21:24:54

PROTON PHYSICS: STABLE BEAMS

Energy:	3500 GeV	I(B1):	2.43e+13	I(B2):	2.41e+13





Comments 22-03-2011 21:21:07 :

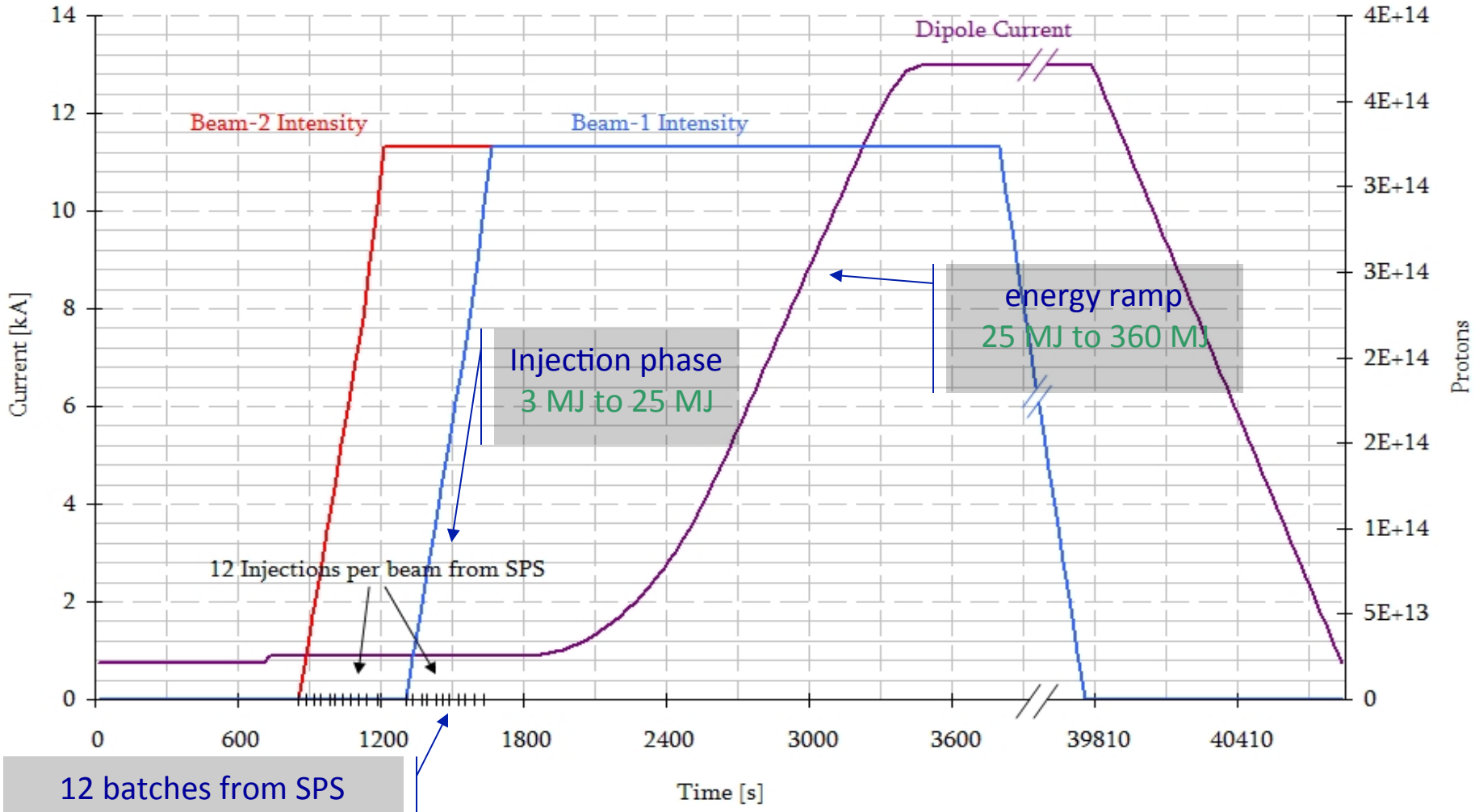
STABLE BEAMS

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	true	true
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

AFS: 75ns_200b_194_178_188_24bpi9inj

PM Status B1: ENABLED | PM Status B2: ENABLED

LHC Magnetic Cycle



12 batches from SPS
(each 218 or 288 bunches)
≈3 MJ per batch

Technological Challenges

…To see the rarest events…
LHC needs high luminosity of 10^{34} [$cm^{-2}s^{-1}$]
→ 3 x 10^{14} p per beam

particle fluence near machine
= radiation-tolerant electronics

… to get 7 TeV operation…
LHC needs 8.3 Tesla dipole fields with circumference of 27 kms (16.5 miles)

… to get 8.3 Tesla …
LHC needs super-conducting magnets <2°K (-271°C)
with an operational current of ≈13kA
cooled in super fluid helium
maintained in a vacuum

1 ppm

Stored energy per beam is 360 MJ

Stored energy in the magnet circuits is 9 GJ

two orders of magnitude
higher than others

A magnet will QUENCH
with milliJoule
deposited energy

Technological Challenges

Kinetic Energy of 200m Train at 155 km/h ≈ 360 MJ

Stored energy per beam is 360 MJ

Stored energy in the magnet circuits is 9 GJ

[2]

Technological Challenges

Kinetic Energy of 200m Train at 155 km/h ≈ 360 MJ

Stored energy per beam is 360 MJ

Stored energy in the magnet circuits is 9 GJ

Kinetic Energy of Aircraft Carrier at 50 km/h ≈ 9 GJ

[3]

Protection Functions

Beam Protection:	Beam Energy	→	Beam Dump

100x energy of TEVATRON

0.000005% of beam lost into a magnet = quench
0.005% beam lost into magnet = damage

Failure in protection – complete loss of LHC is possible

Powering Protection:	Magnet Energy	→	Emergency Discharge

10-20x energy per magnet of TEVATRON

magnet quenched = hours downtime
many magnets quenched = days downtime

magnet damaged = $1 million, months downtime
many magnets damaged = many millions, many months downtime

Protection Functions

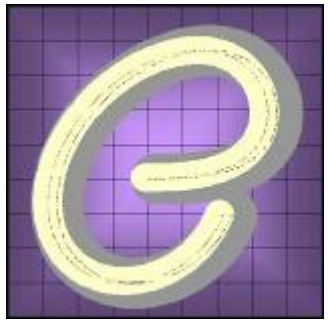
Beam Protection:	Beam Energy →	Beam Dump

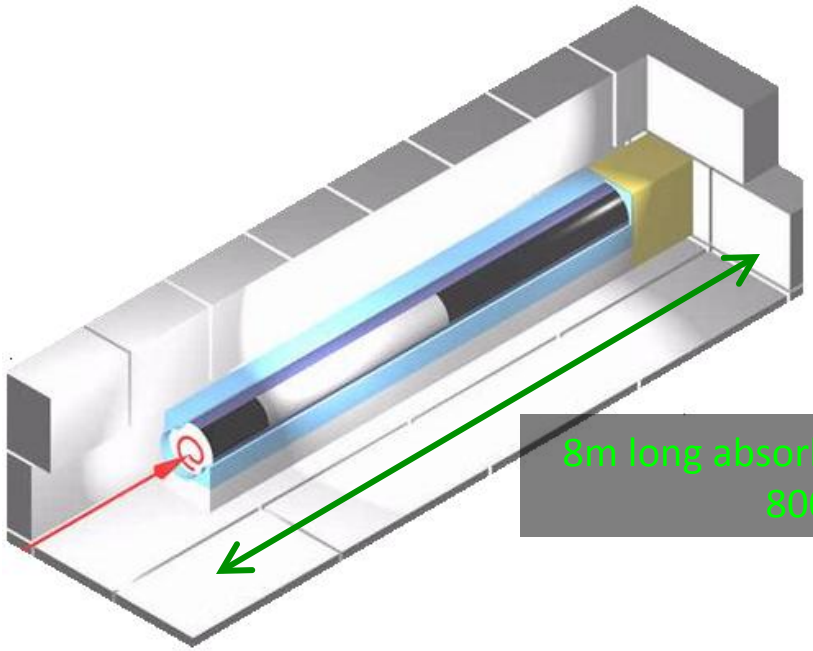
100x energy of TEVATRON

0.000005% of beam lost into a magnet = quench
0.005% beam lost into magnet = damage

Failure in protection – complete loss of LHC is possible

Beam is 'painted' diameter 35cm





Concrete Shielding

8m long absorber Graphite = 800°C

[4]

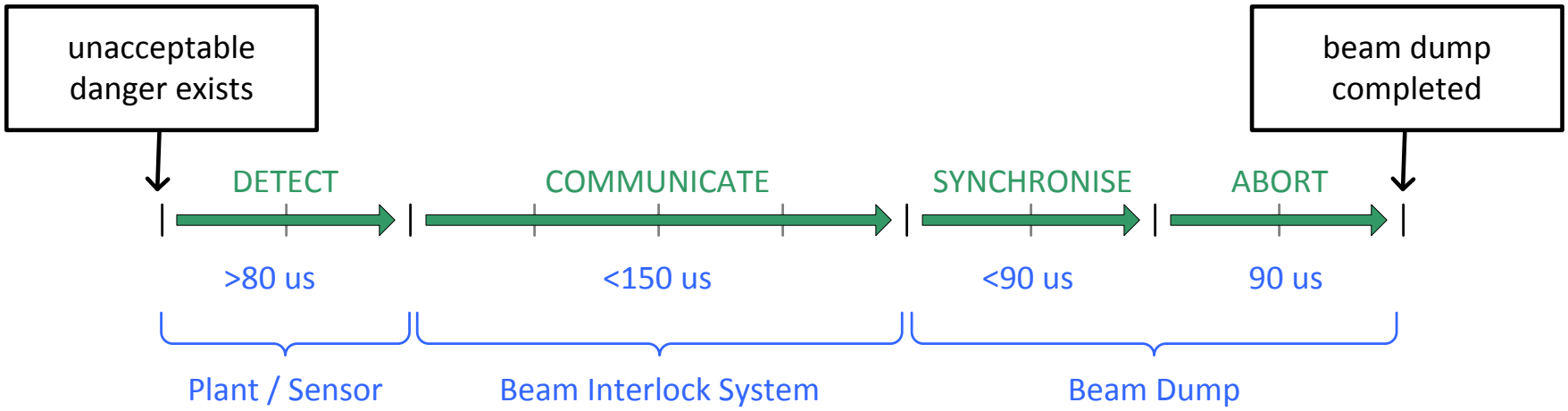
Protection Functions

Beam Protection: Beam Energy → Beam Dump

100x energy of TEVATRON

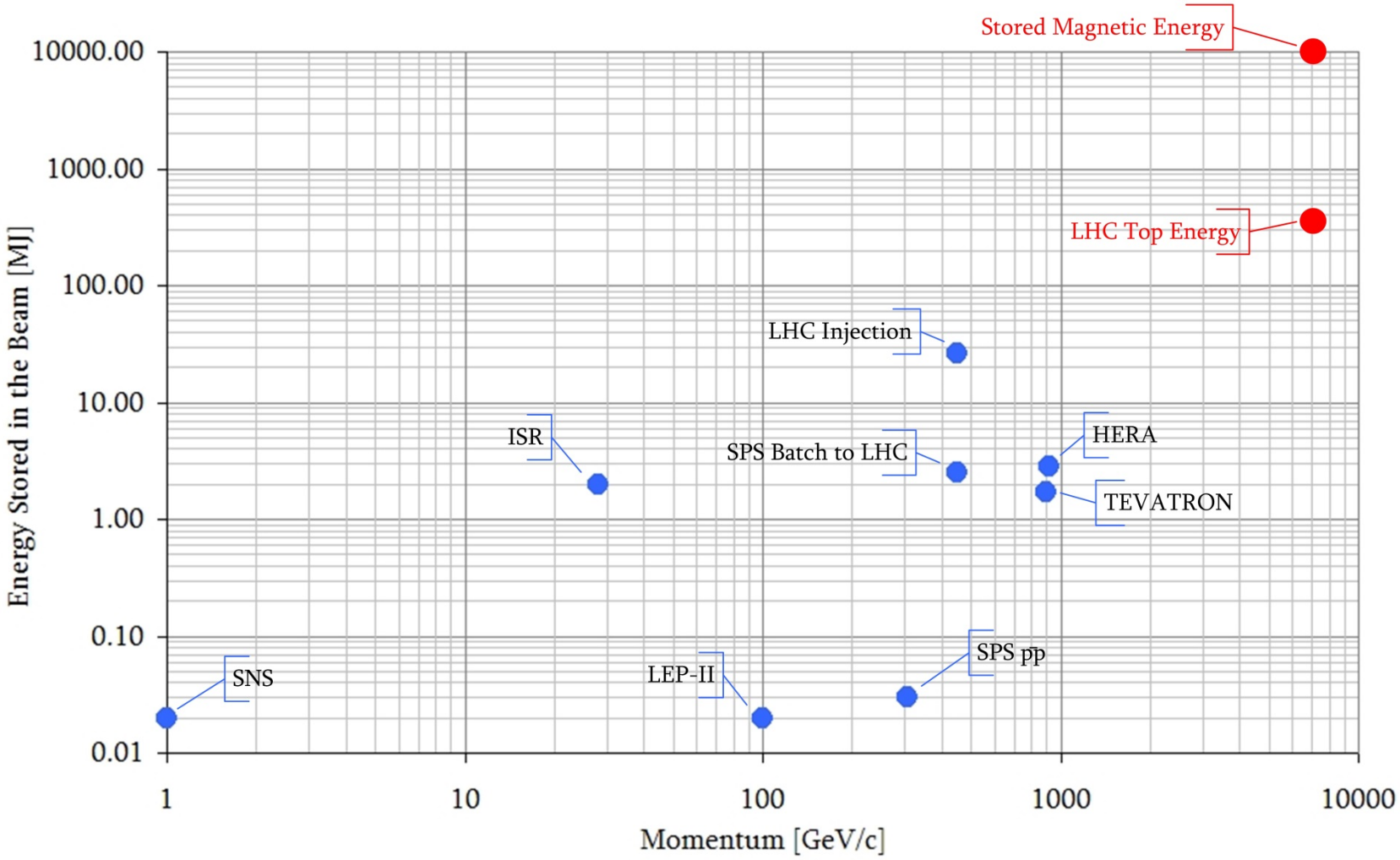
0.000005% of beam lost into a magnet = quench
0.005% beam lost into magnet = damage

Failure in protection – complete loss of LHC is possible



To protect against fastest failure modes ≈ 400 µs over 27km

Comparison of LHC with others

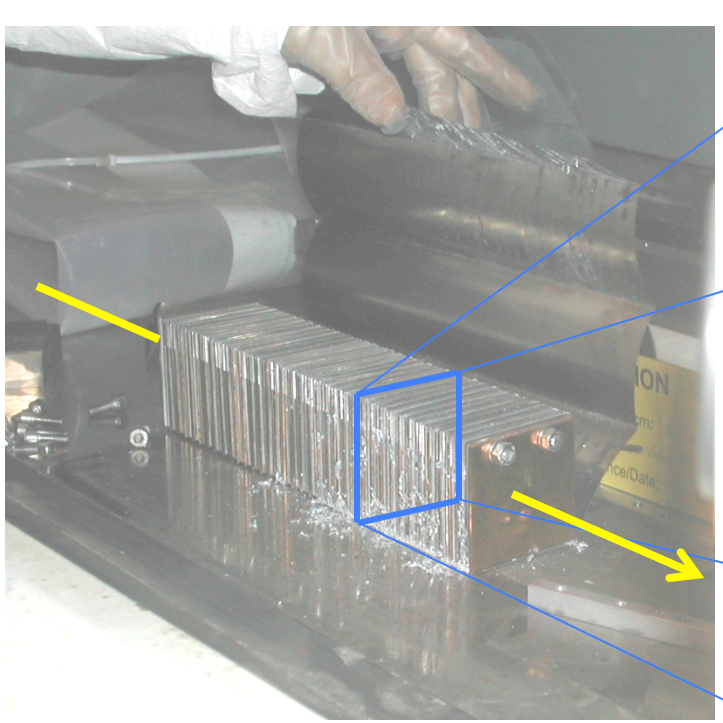


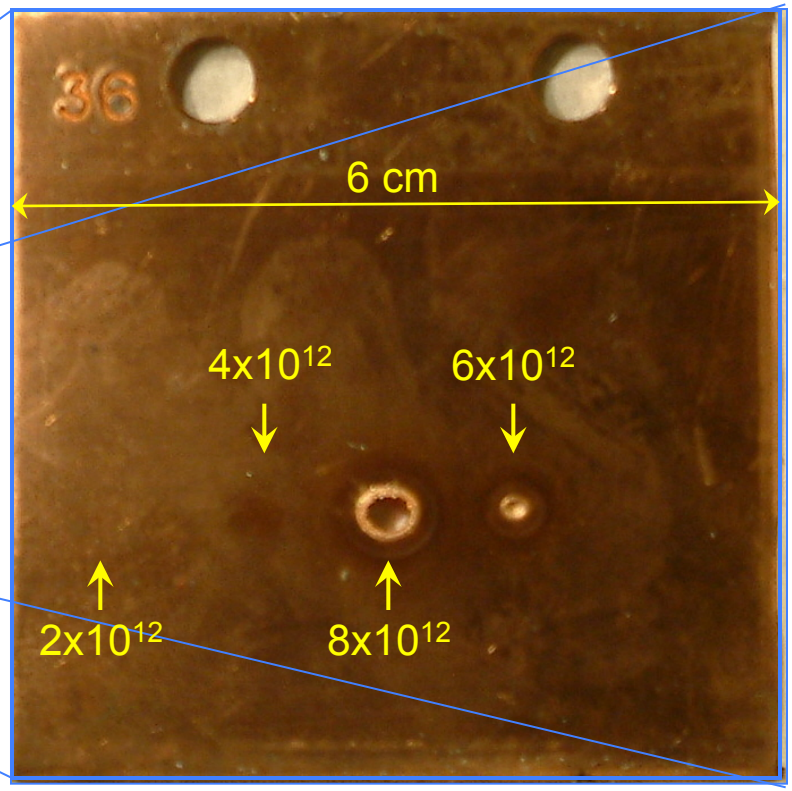
powering is split into sub-sectors:
energy in each circuit manageable, allows for a staged commissioning

[5]

SPS Experiment at 450 GeV

Controlled SPS experiment to qualify simulations
At 450GeV … $8x10^{12}$ protons causes damage





beam size $\sigma_{x/y}$ = 1.1mm/0.6mm
Plate 2mm thick

0.1% LHC Full Beam Energy! Beam in LHC is 10x smaller!!

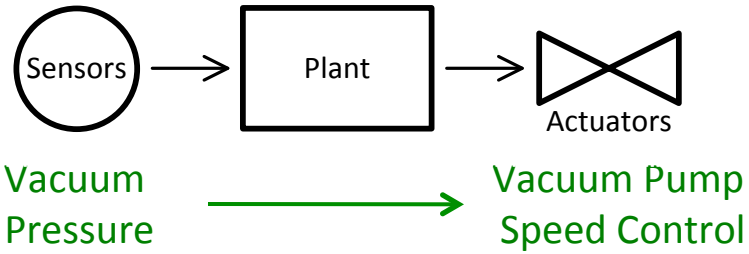
[6]

Plants, Protection and Safety

Safety – Protection – Plant

Vacuum Example:
- maintain correct pressure

Plant Systems:
Fulfill operational requirements



Safety – Protection – Plant

Plant Protection:

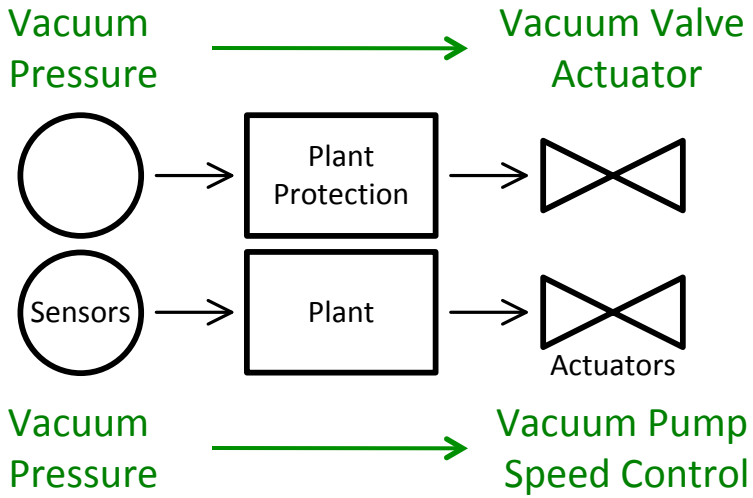
Ensure plant stays within limits

Plant Systems:

Fulfill operational requirements

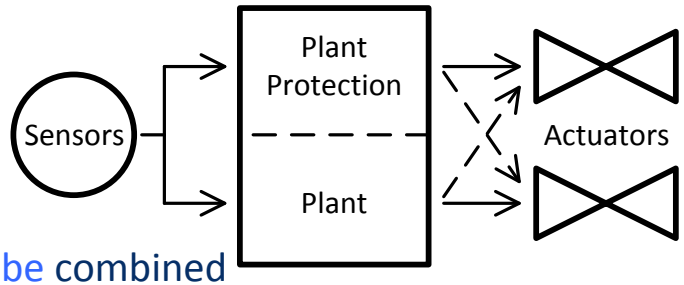
Vacuum Example:

- maintain correct pressure
- bad pressure = close valves



Safety – Protection – Plant

Vacuum Pressure → Vacuum Valve Actuator



Plant Systems:

Ensure plant stays within limits

Fulfill operational requirements

- Sensors, Actuators and Process may be combined
- No rules regarding combination
- Must meet functional requirement

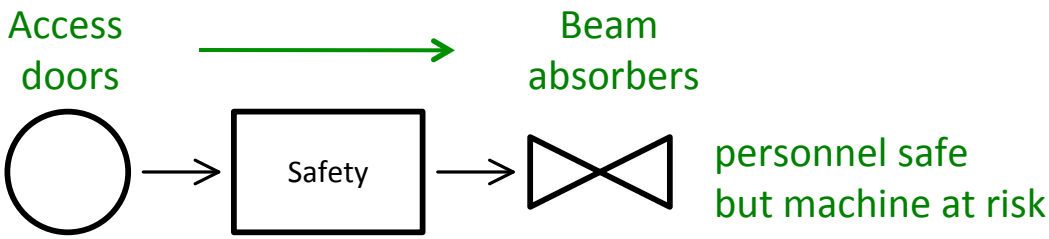
Vacuum Pump Speed Control

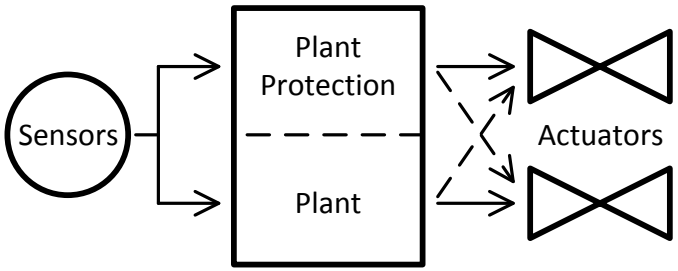
Safety – Protection – Plant

Personnel Safety System:

People in perimeter – stop machine

- cannot be merged with plants
- Must meet legal requirement





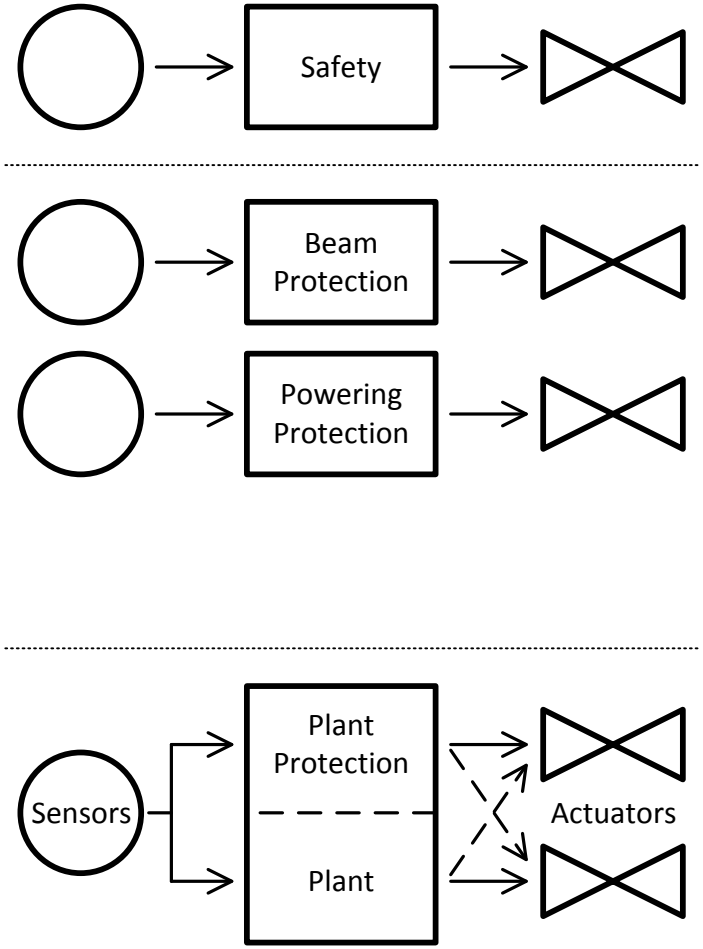
Safety – Protection – Plant

Machine Protection System:

Prevent damage to machine

Prevent undue stress to components

- No rules regarding implementation
- Must meet functional requirement



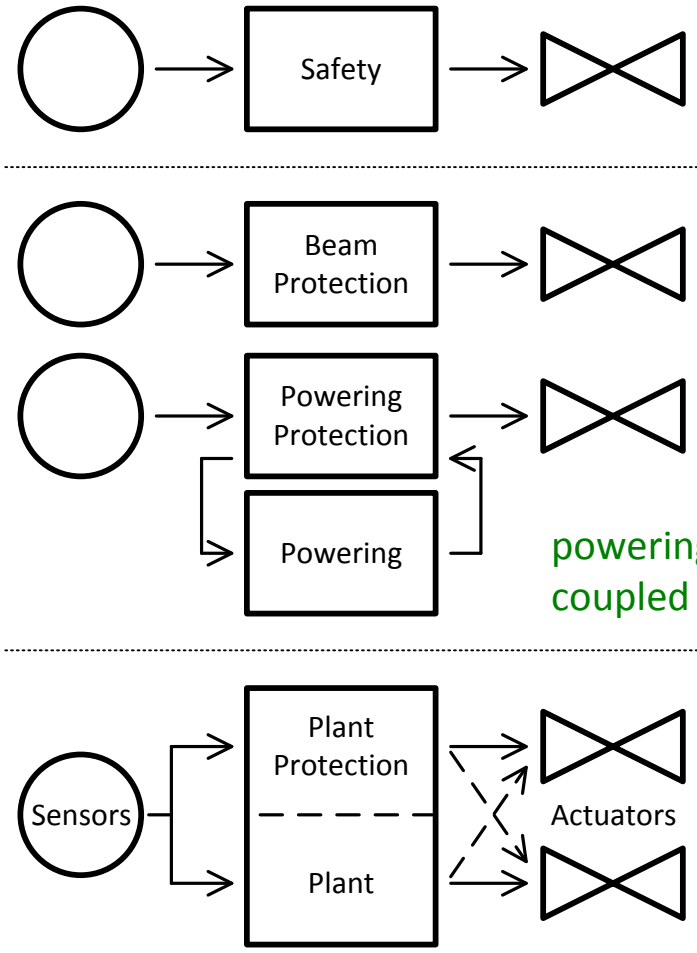
Safety – Protection – Plant

Machine Protection System:

Prevent damage to machine

Prevent undue stress to components

- No rules regarding implementation
- Must meet functional requirement

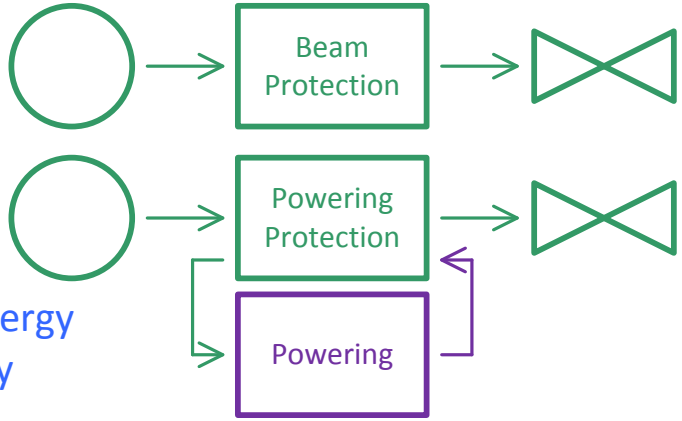


powering protection closely coupled to powering plant

Safety – Protection – Plant

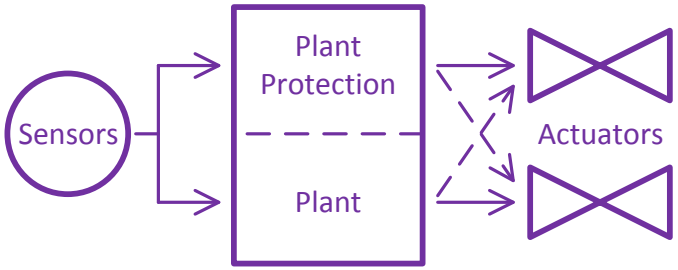
Personnel Safety System:

Machine Protection System:



danger will exist – prevent – extract energy
danger exists – protect – extract energy

Plant Systems:



So…

Each of these systems has a job to do…

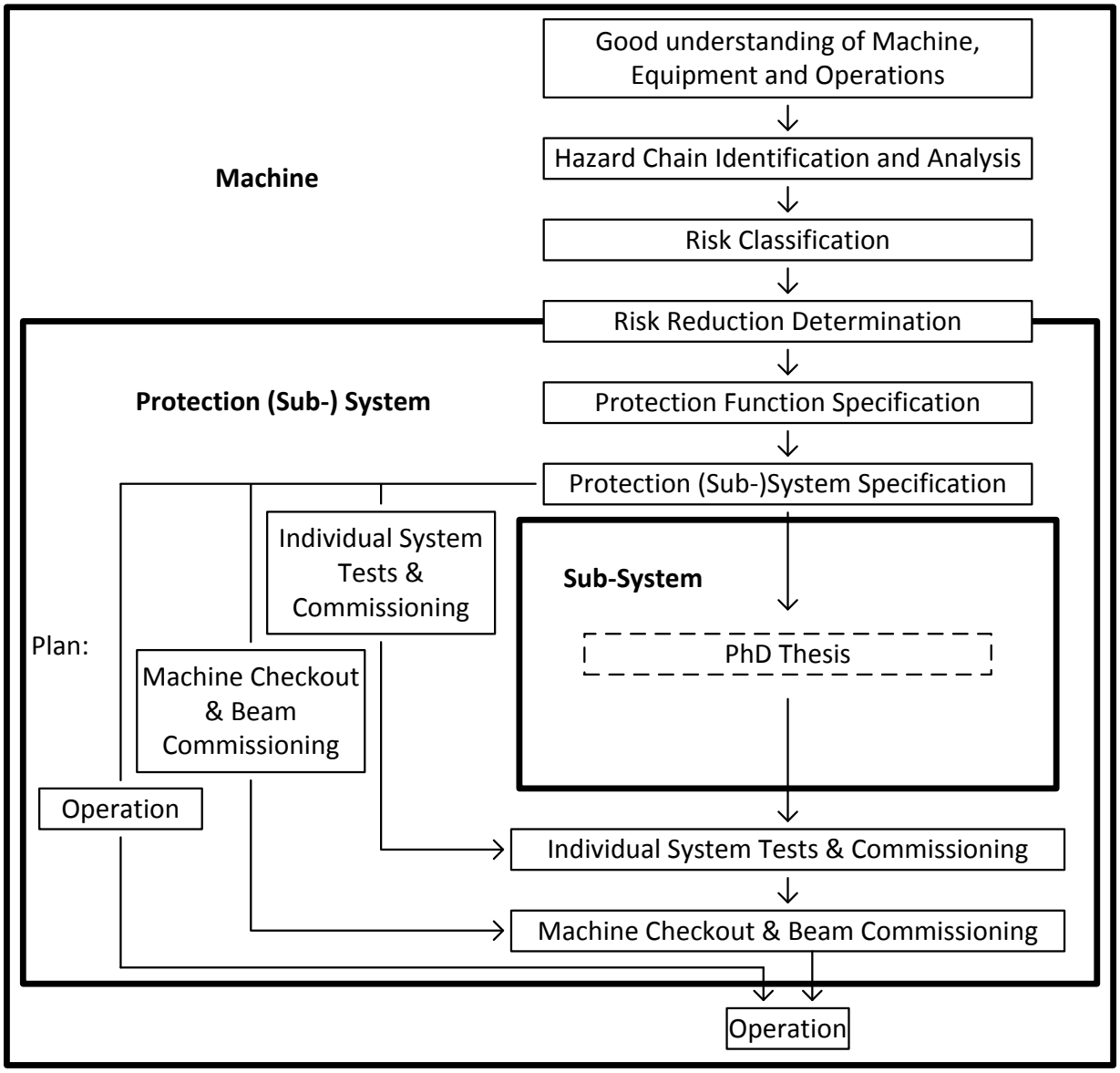
If they malfunction, we are in a tough situation

Everything that can malfunction, will eventually malfunction…
Prepare for and accept malfunction as “normal”.

Build the systems using a risk-based approach

e.g. Safety Systems – IEC 61508 inspired

Protection System Lifecycle

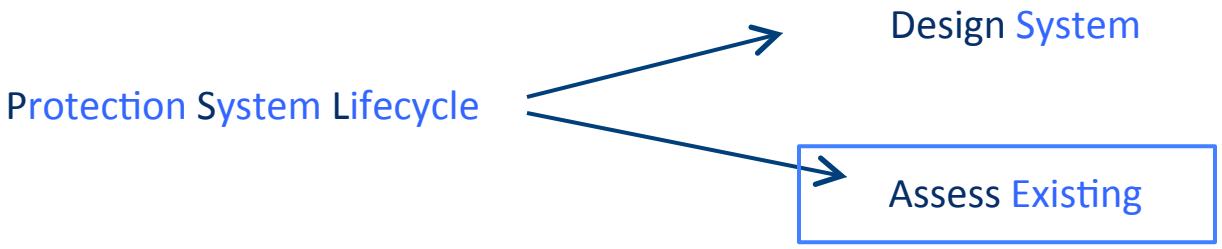


[7]

Protection System Lifecycle

systems involved in protection are unique
certain technologies used have never been tried on this scale before
high cost of failure

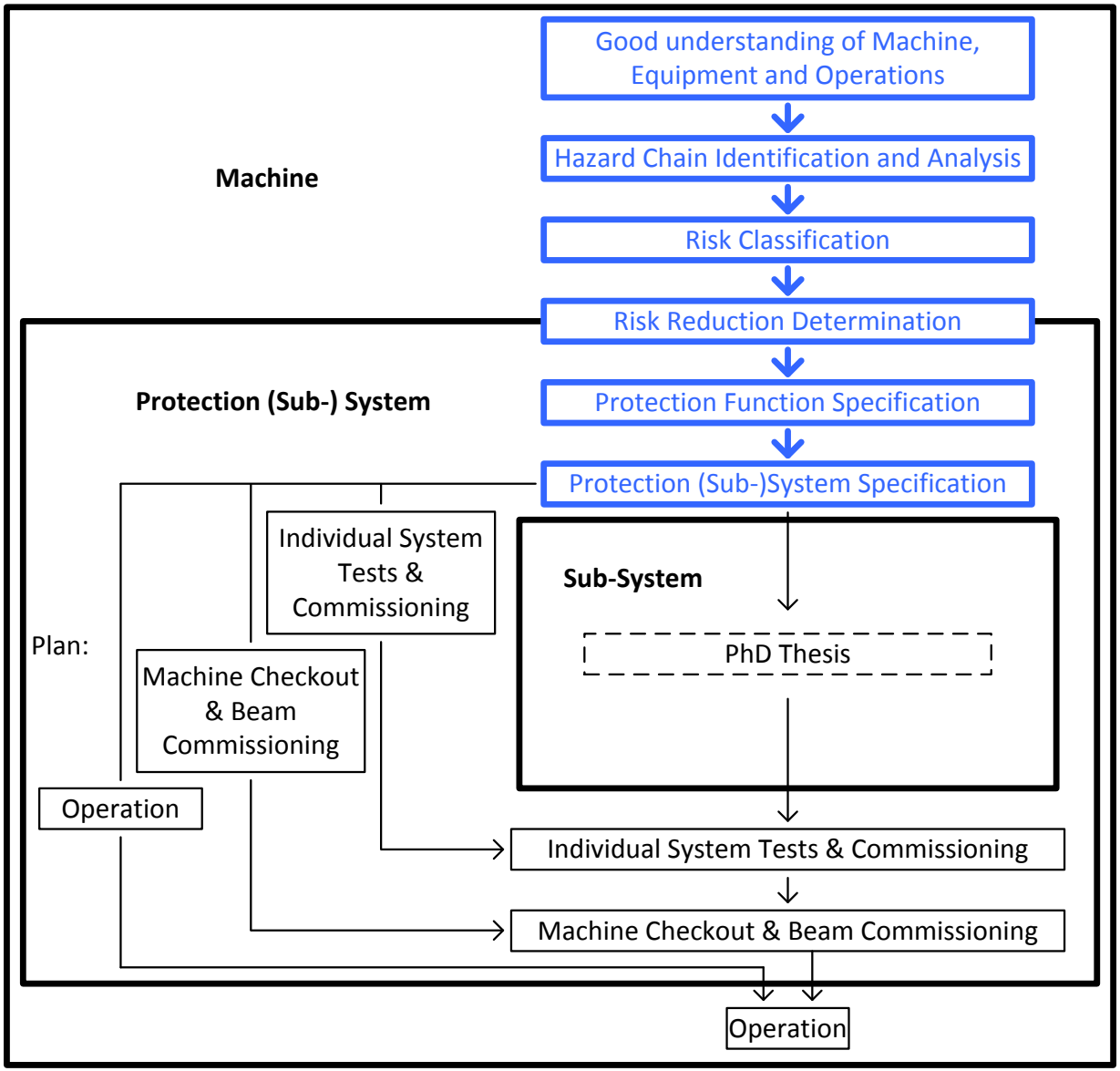
development and analysis of machine protection as if it were a safety system



worked example
Dipole Magnet Protection – **9GJ**

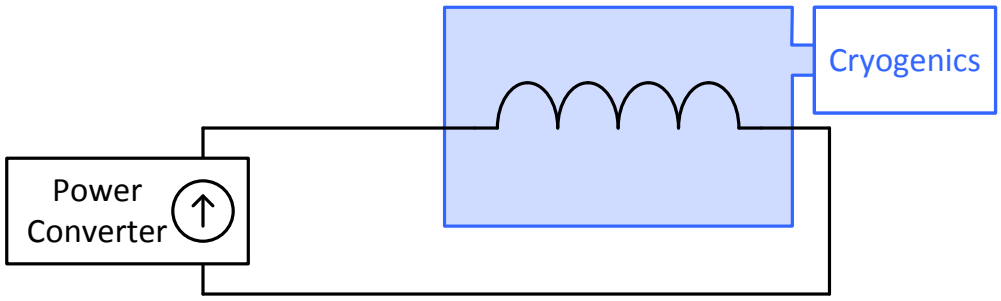
[7]

Protection System Lifecycle



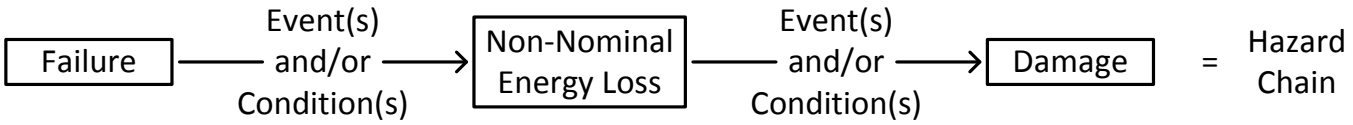
[7]

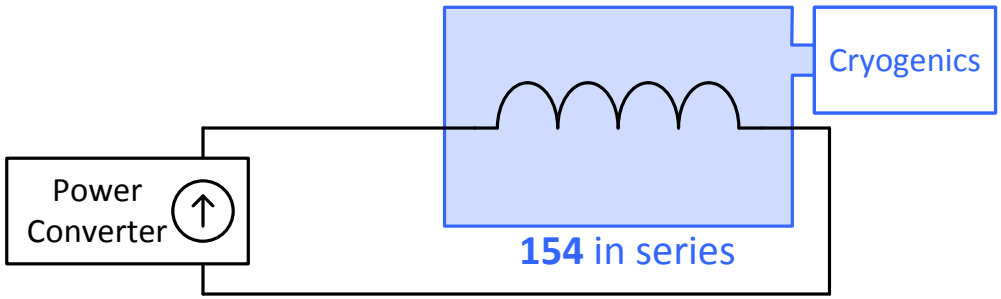
Protection System Lifecycle



Equipment Under Control → Magnet
Cryogenics
Power Converter

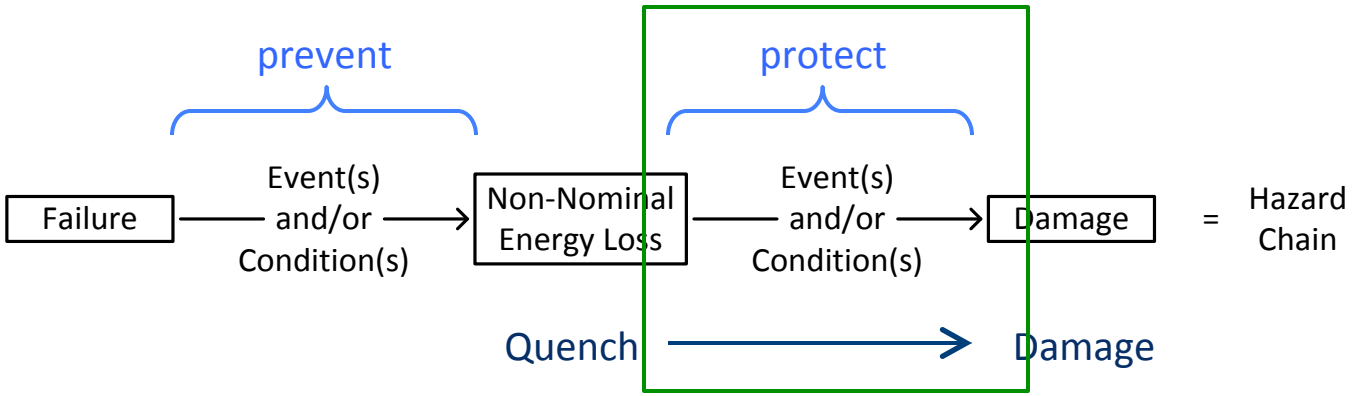
[9]

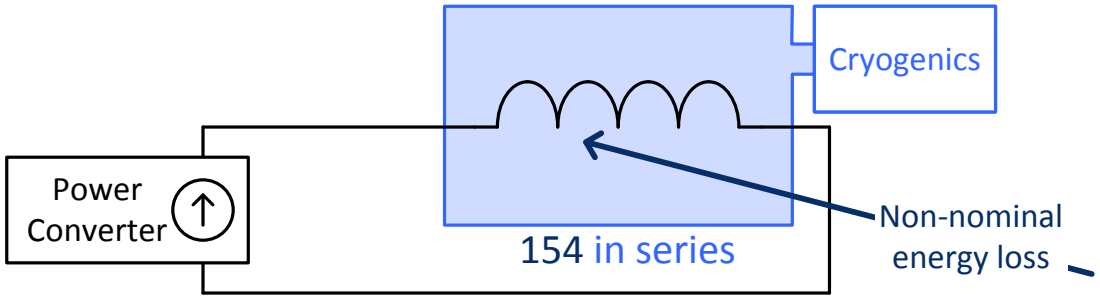




Equipment Under Control → Magnet
Cryogenics
Power Converter

[9]





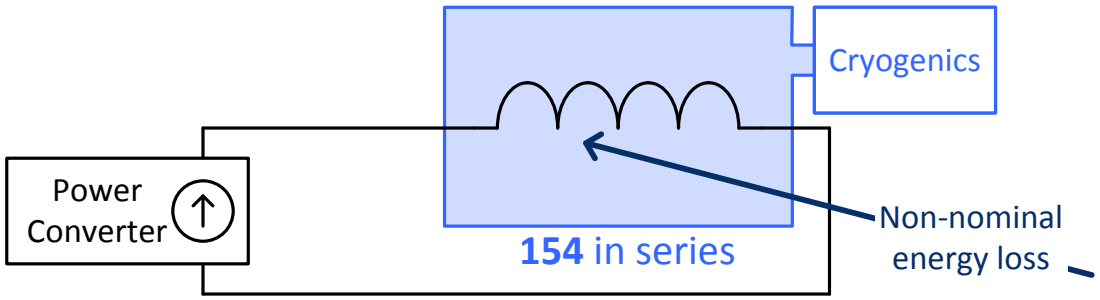
Equipment Under Control → Magnet
Cryogenics
Power Converter

Hazard Chain: from Quench to Damage…

- Resistive zone appears in a magnet
- I^2R losses begin
- Zone heats up

(heat propagates to neighbouring magnets)

- Damage to magnets

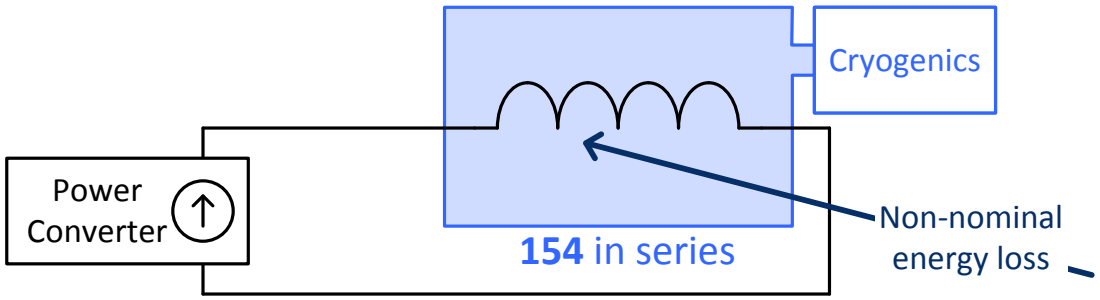


Hazard Chain: from Quench to Damage…

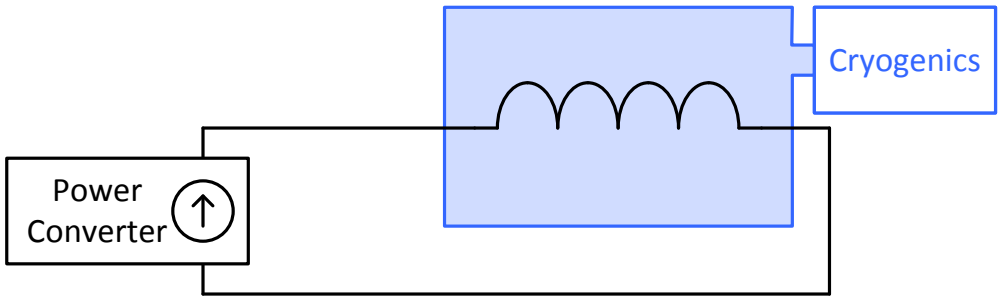
- Resistive zone appears in a magnet
- I^2R losses begin
- Zone heats up

(heat propagates to neighbouring magnets)

- Damage to magnets

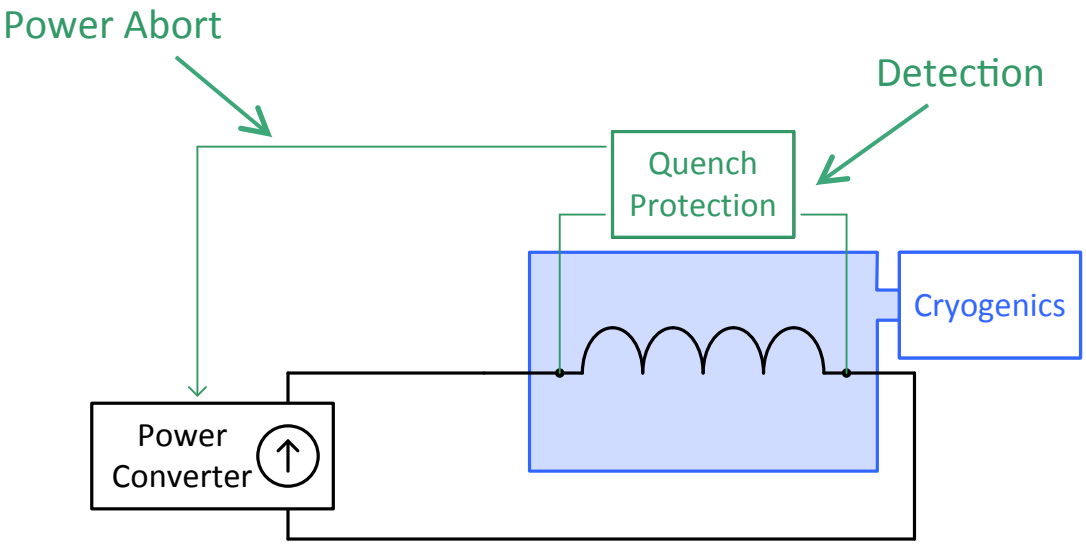


What Protection Functions and Protection Systems are in place?



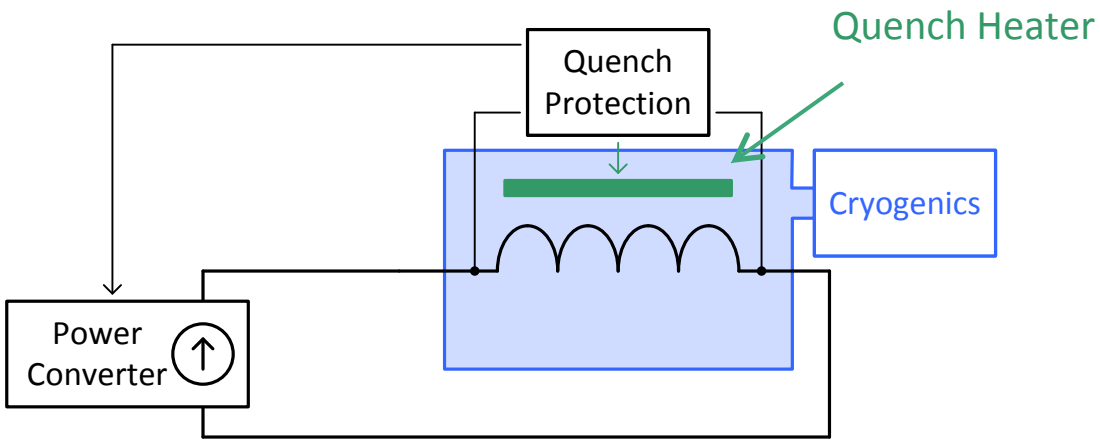
when quench occurs…

- Turn off Power Converter



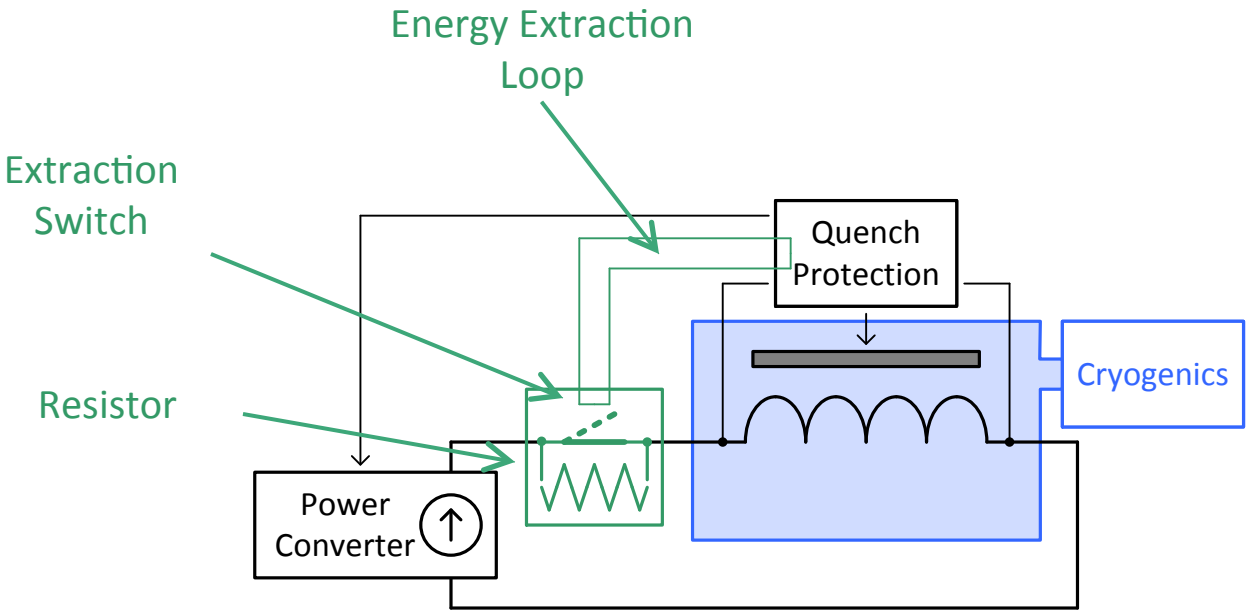
when quench occurs…

- Turn off Power Converter



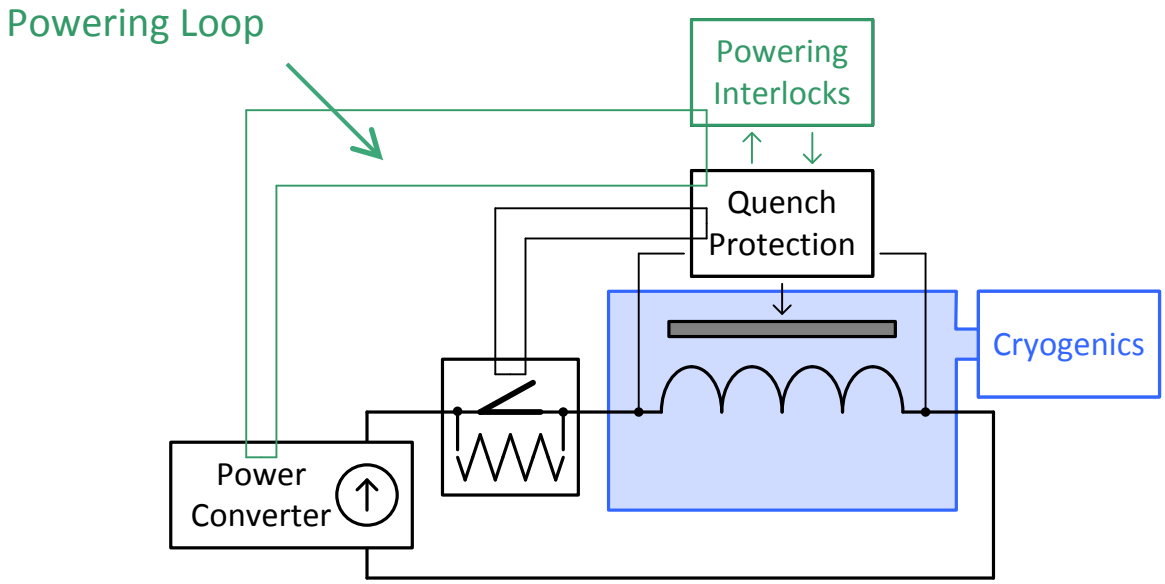
when quench occurs…

- Turn off Power Converter
- Propagate Quench



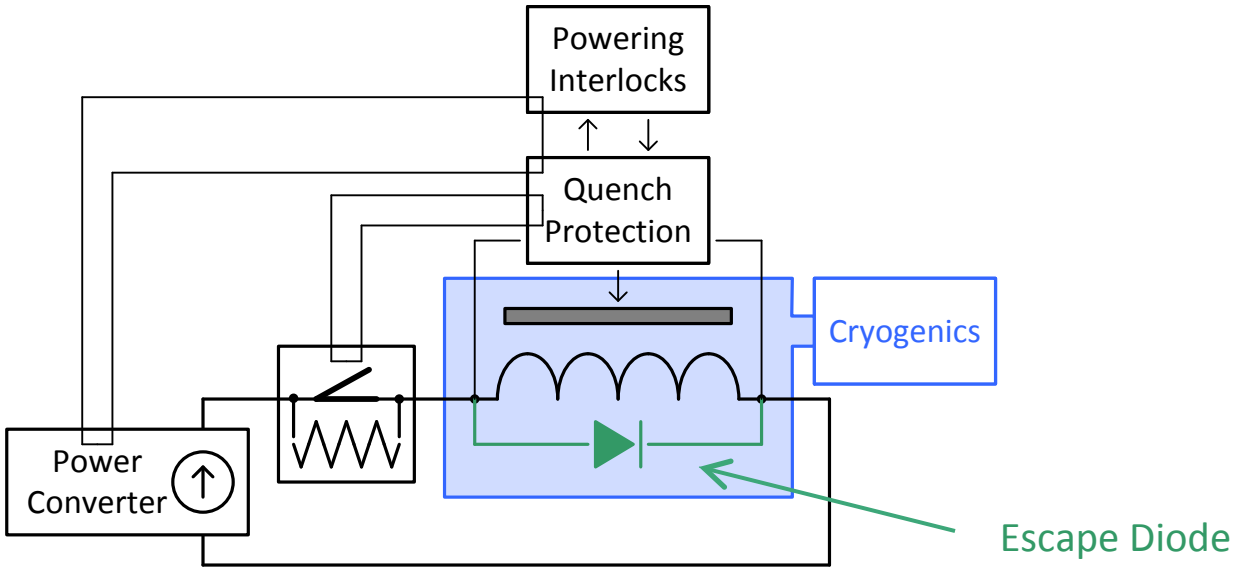
when quench occurs…

- Turn off Power Converter
  - Propagate Quench
    - Extract Energy



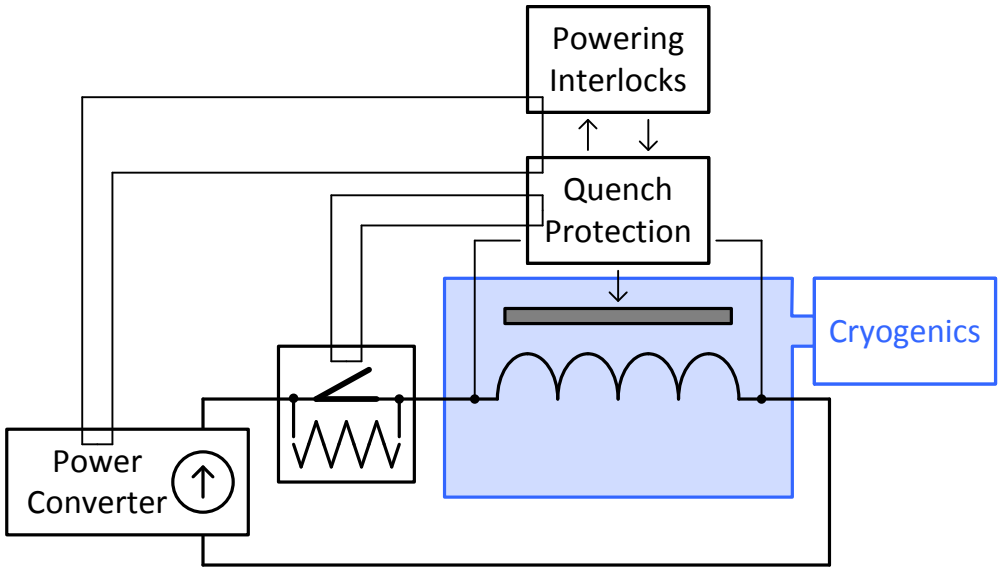
when quench occurs…

- Turn off Power Converter
  - Propagate Quench
    - Extract Energy
  - Link Related Circuits



when quench occurs…

- Turn off Power Converter
  - Propagate Quench
    - Extract Energy
  - Link Related Circuits

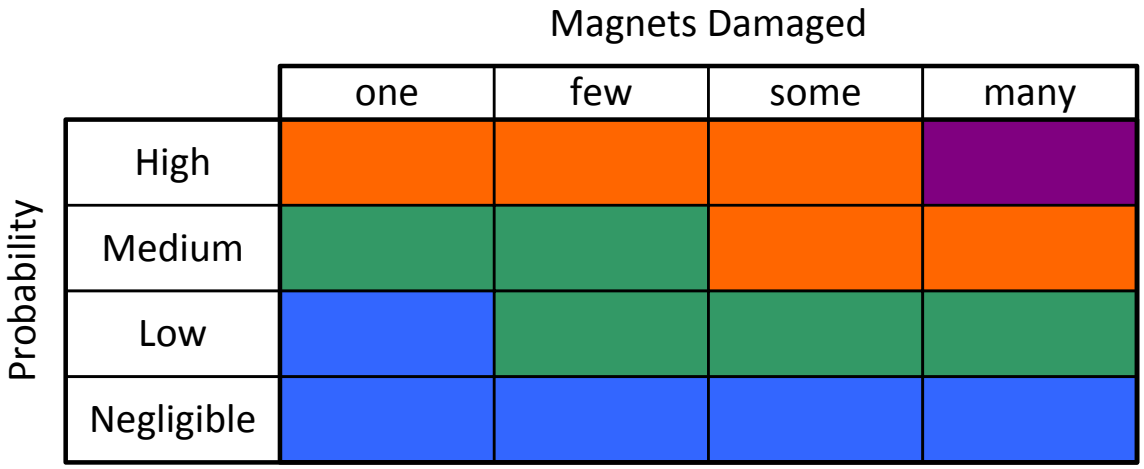


when quench occurs…

- Turn off Power Converter
  - Propagate Quench
    - Extract Energy
  - Link Related Circuits

classify probability and consequence using risk matrix

Colour boundaries, probabilities, consequences intentionally vague = talking points

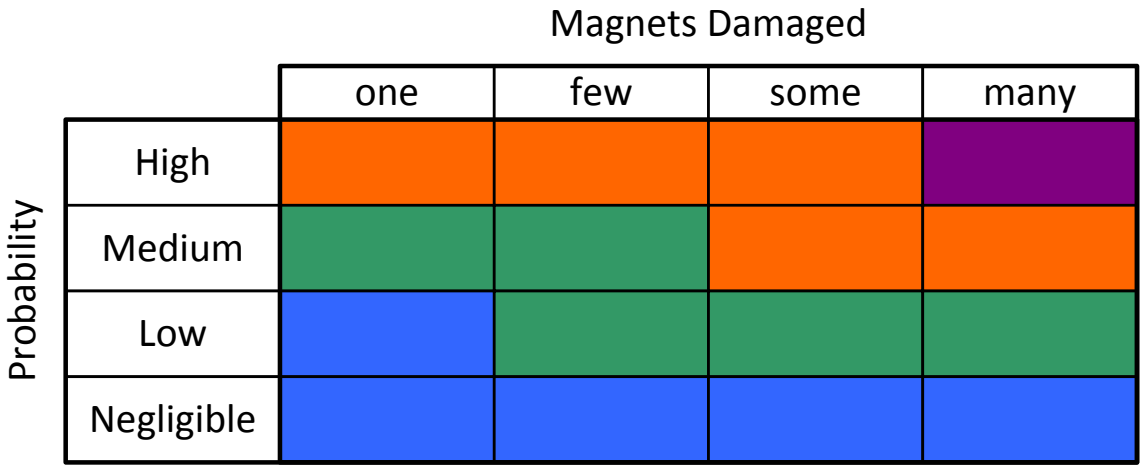


risk, if function didn't exist, according to system experts…

- Turn off Power Converter
  - Propagate Quench
    - Extract Energy
  - Link Related Circuits

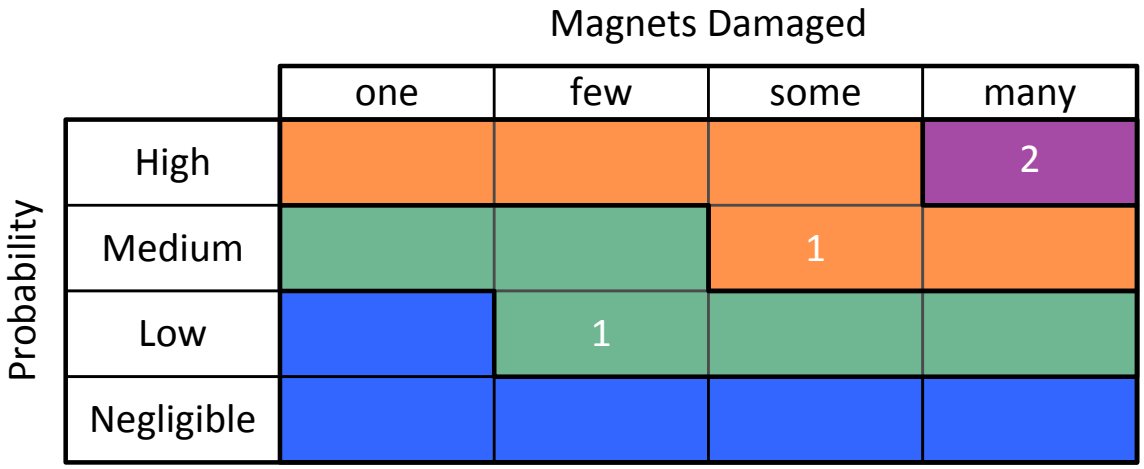
classify probability and consequence using risk matrix

Colour boundaries, probabilities, consequences intentionally vague = talking points



risk, if function didn't exist, according to system experts…

- Turn off Power Converter = **purple**
  - Propagate Quench = **orange**
    - Extract Energy = **purple**
  - Link Related Circuits = **green**



- Turn off Power Converter = **purple**
  - Propagate Quench = **orange**
    - Extract Energy = **purple**
  - Link Related Circuits = **green**

[9]

determine risk reduction level using matrix

original	desired	reduction
		3
		2
		1

- Turn off Power Converter = **purple**
  - Propagate Quench = **orange**
    - Extract Energy = **purple**
  - Link Related Circuits = **green**

determine risk reduction level using matrix

original	desired	reduction
		3
		2
		1

= dependability requirements

- Turn off Power Converter = **purple**
  - Propagate Quench = **orange**
    - Extract Energy = **purple**
  - Link Related Circuits = **green**

[9]

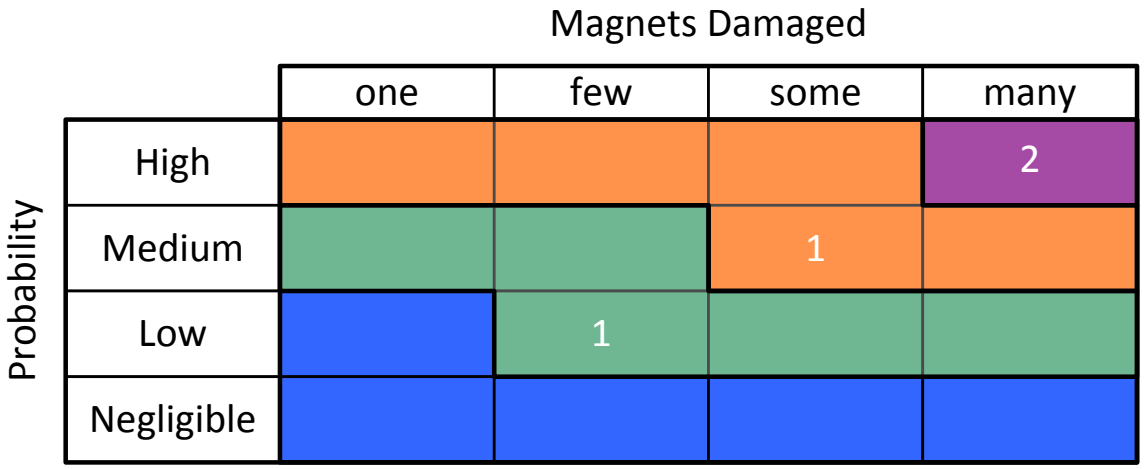
determine risk reduction level using matrix

original	desired	reduction
		3
		2
		1

= dependability requirements

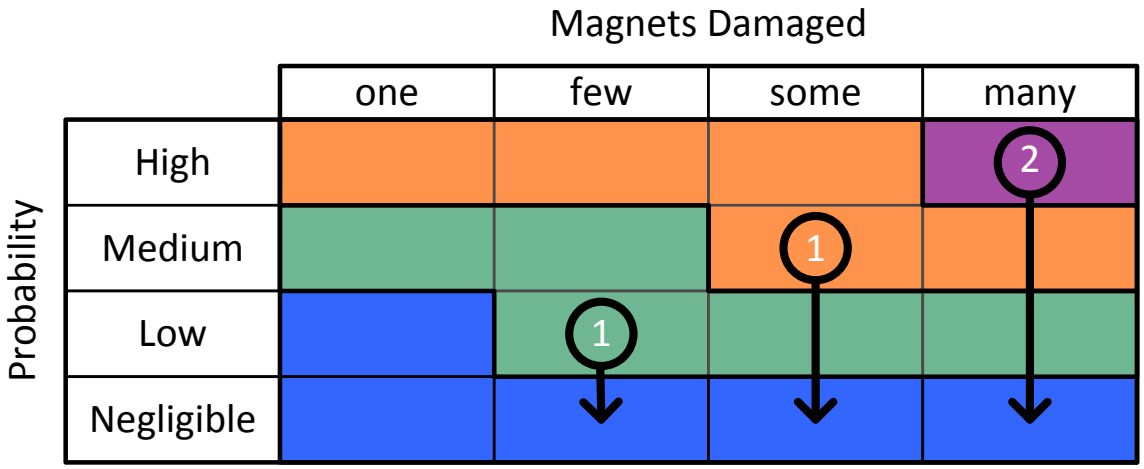
- Turn off Power Converter = **purple** = **3**
  - Propagate Quench = **orange** = **2**
    - Extract Energy = **purple** = **3**
  - Link Related Circuits = **green** = **1**

[9]



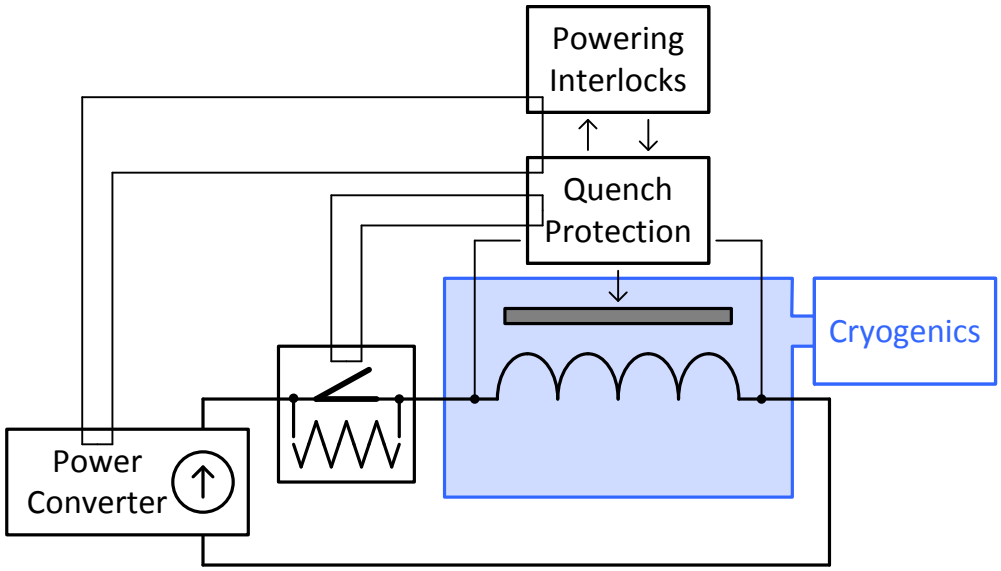
- Turn off Power Converter = **purple** = **3**
  - Propagate Quench = **orange** = **2**
    - Extract Energy = **purple** = **3**
  - Link Related Circuits = **green** = **1**

[9]



- Turn off Power Converter = **purple** = **3**
  - Propagate Quench = **orange** = **2**
    - Extract Energy = **purple** = **3**
  - Link Related Circuits = **green** = **1**

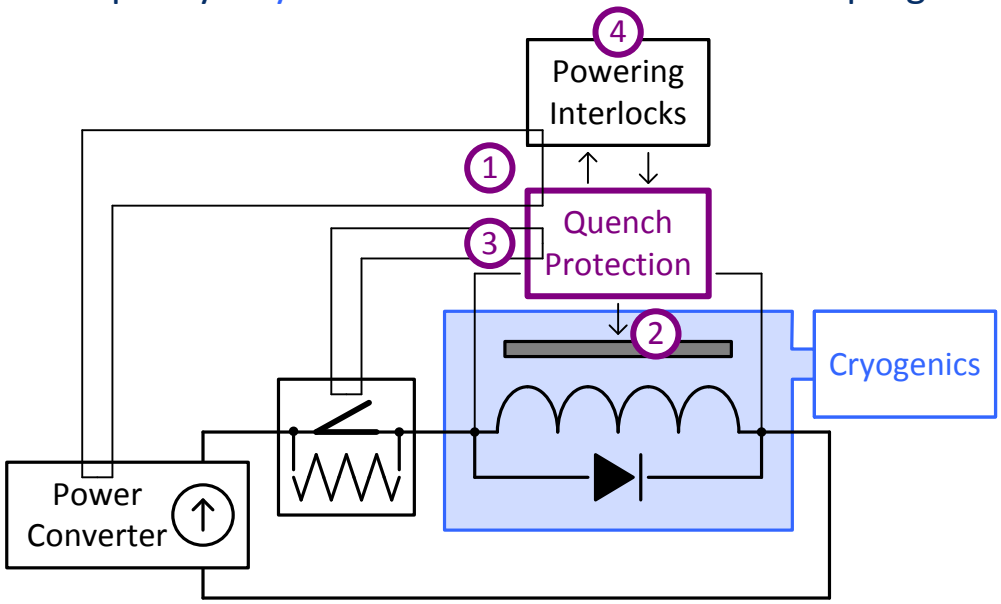
[9]



- Turn off Power Converter = **purple** = **3**
  - Propagate Quench = **orange** = **2**
    - Extract Energy = **purple** = **3**
  - Link Related Circuits = **green** = **1**

[9]

How do we qualify a system meets a level? How about programmable logic?



- Turn off Power Converter = **purple** = **3**
  - Propagate Quench = **orange** = **2**
    - Extract Energy = **purple** = **3**
  - Link Related Circuits = **green** = **1**

[1]

So…

Each of these systems has a job to do…

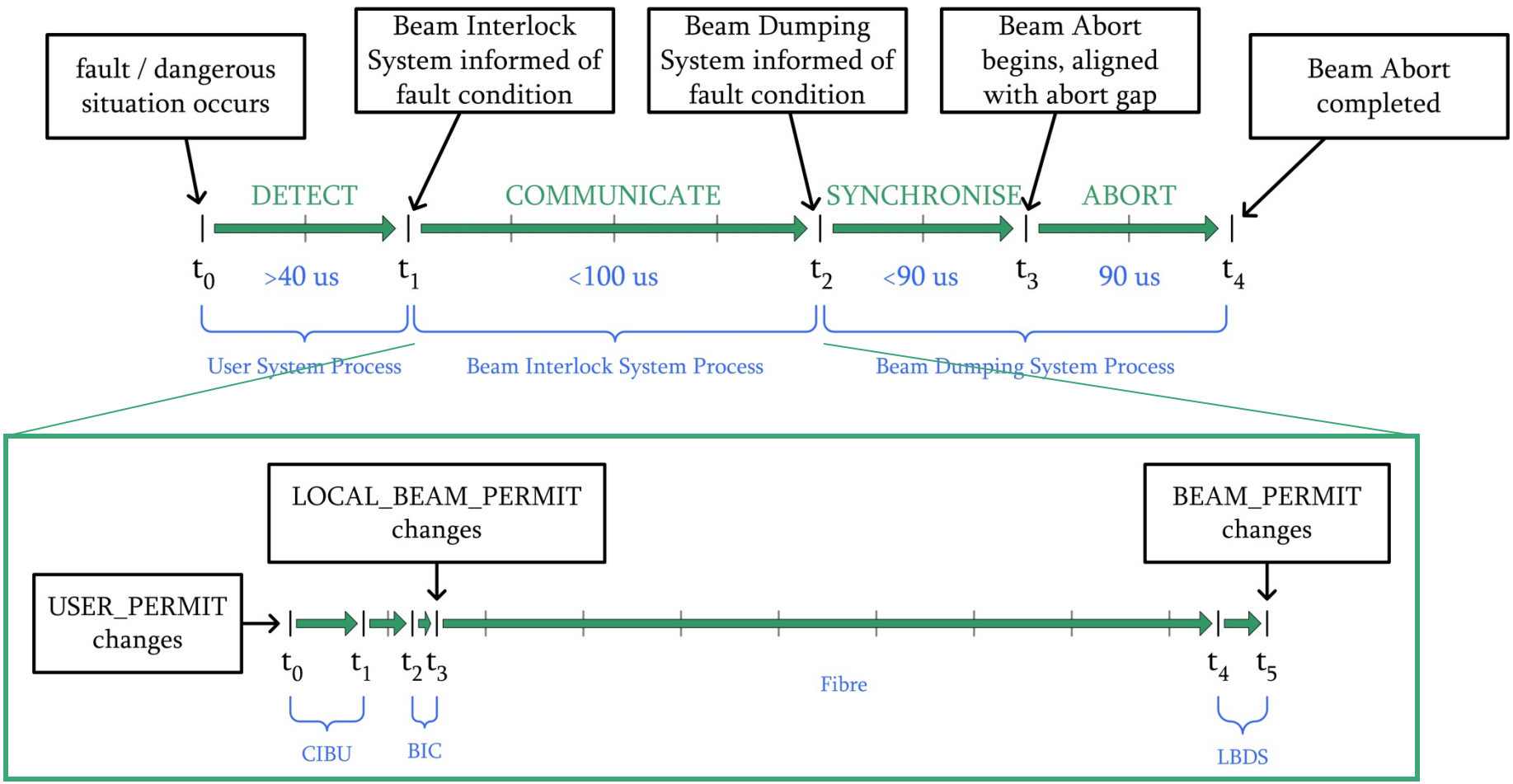
If they malfunction, we are in a tough situation = “risky”?

Everything that can malfunction, will eventually malfunction…
Prepare for and accept malfunction as “normal”.

Realise functions using a high-reliability approach, determine failure rates and modes

An Example System, Risk Reduction Level 3

The LHC Beam Interlock System



[8]

The LHC Beam Interlock System

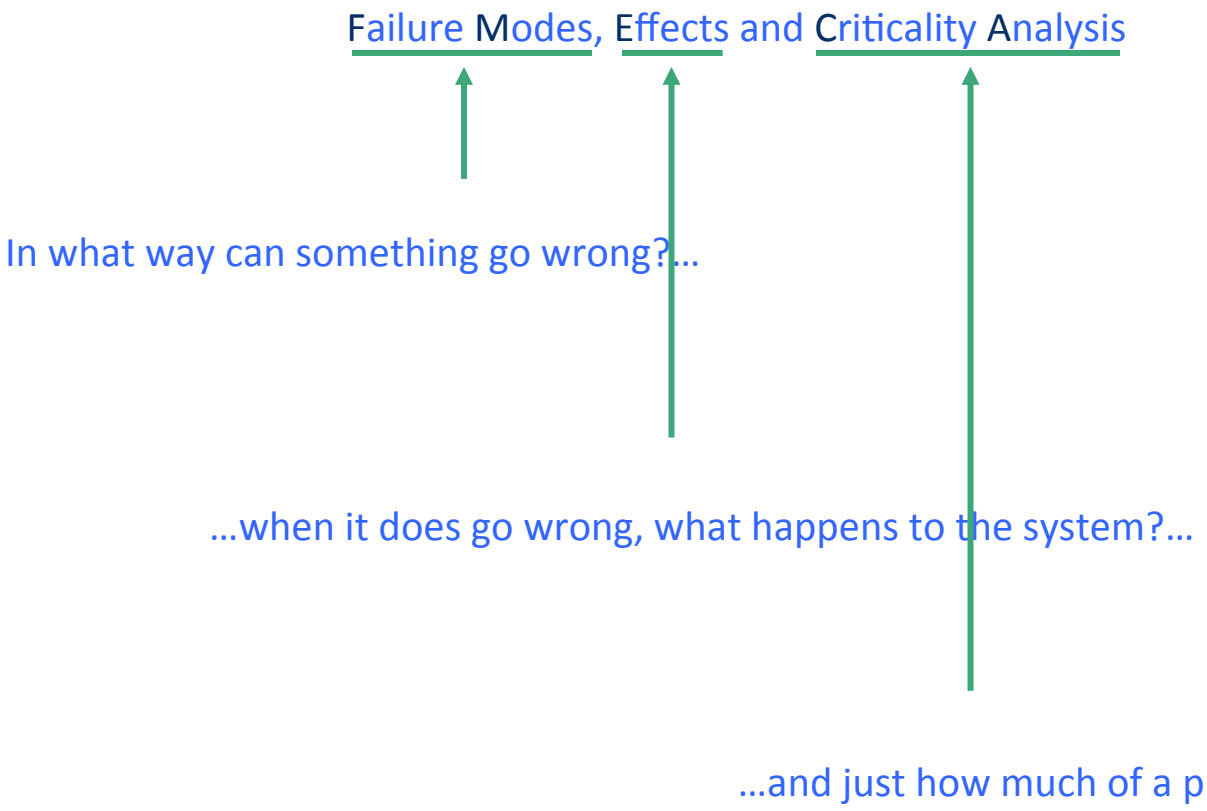
BIS has a dependability specification

"…[BIS] must react to a single change in USER PERMIT by correctly actioning the relevant BEAM PERMIT with a safety better than or equal to Risk Reduction Level 3. Less than 1% of missions must be aborted due to failures in the Beam Interlock System..."

High Dependability → High Safety
High Reliability
High Availability
Maintainable

[8]

RRL3 or better?? = FMECA



[8]

FMECA

MIL-STD-1629

FMECA starts at the Component Level of a system

Break a large system into blocks, defining smaller, manageable sub-systems

get subsystem schematics, component list, and understand what it does

MIL-HDBK-338  MIL-HDBK-217

get MTBF of each component on the list, derive P_{FAIL}(mission)

MIL-HDBK-338  FMD-97

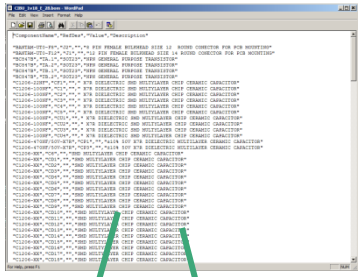
derive failure modes and failure mode ratios for each component

explain the effect of each failure mode on both the subsystem and system

determine the probability of each failure mode happening. Draw conclusions!

[8]

FMECA



Bill of Materials

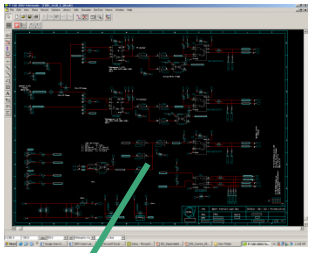
	A	B	C	D	E	F	G
1	**Failure Mode Effect and Criticality Analysis**						
2							
3	**CERN: European Organisation for Nuclear Research**						
4							
5	CRITICALITY WORK SHEET		**System:**	BEAM INTERLOCK SYSTEM			**SubSystem:**
6							
7	**Part ID**	**Part Description**	**Base**	**Reference**	**Failure Mode**	**Failure Mode**	**Reference**
8			**Failure Rate**	**BFR**		**Frequency Ratio**	**FMFR**
9	*(schematic RefDes)*		*(/10^9h)*		*(FMD-97)*	*(FMD-97)*	
10							
11	J1	*Burndy F12*	3.9	MIL-HBDK-271F-15-(1-2-3)	*Open BF*	0.000	FMD-97-2-47/NE12 Cable FM
12			*3.9*		*Open BD*	0.060	
13			*3.9*		*Open M*	0.090	
14			*3.9*		*Open NE*	0.241	
15			*3.9*		*Intermittant Operation*	0.552	
16			*3.9*		*Shorted BF*	0.000	
17			*3.9*		*Shorted BD*	0.006	
18			*3.9*		*Shorted M*	0.008	
19			*3.9*		*Shorted NE*	0.043	

MIL-HDBK-217F
or manufacturer

FMD-97

MIL-HDBK-338

[8]



Schematic

H	I	J	K	L	M	N	O
			Criticality of system for: Blind Failures, Beam Dumps, Maintenance and No Effect				
					AB/CO/IN	**Benjamin TODD**	
CIBU			**Version:**	1v0		**Date:**	28.1.05
Failure Mode Effect Analysis *(BF, BD, M, NE)*	**Failure Mode Effect Description**	**Detection Method (BD automatic)**	**P(Fail) During Mission** *(CIBU)*	**P(Blind Fail) Permit A** *(Permit Loop A)*	**P(Blind Fail) Permit B** *(Permit Loop B)*	**P(Fail) Beam Dump** *(CIBU)*	**P(Fail) Maintenance** *(CIBU)*
BF	Permit A/B Fail Blind	Monitoring/Test	0.00E+00	0	0	0	0
BD	Permit A/B break	Monitoring/Test	2.35E-09	0	0	2.346E-09	0
M	Command/Response Fail	Monitoring/Test	3.52E-09	0	0	0	3.519E-09
NE	No Effect	None	9.38E-09	0	0	0	0
BD	Permit A/B break	Monitoring/Test	2.15E-08	0	0	2.1528E-08	0
BF	Permit A/B Fail Blind	Monitoring/Test	0.00E+00	0	0	0	0
BD	Permit A/B break	Monitoring/Test	2.28E-10	0	0	2.28E-10	0
M	Command/Response Fail	Monitoring/Test	3.14E-10	0	0	0	3.135E-10
NE	No Effect	None	1.68E-09	0	0	0	0

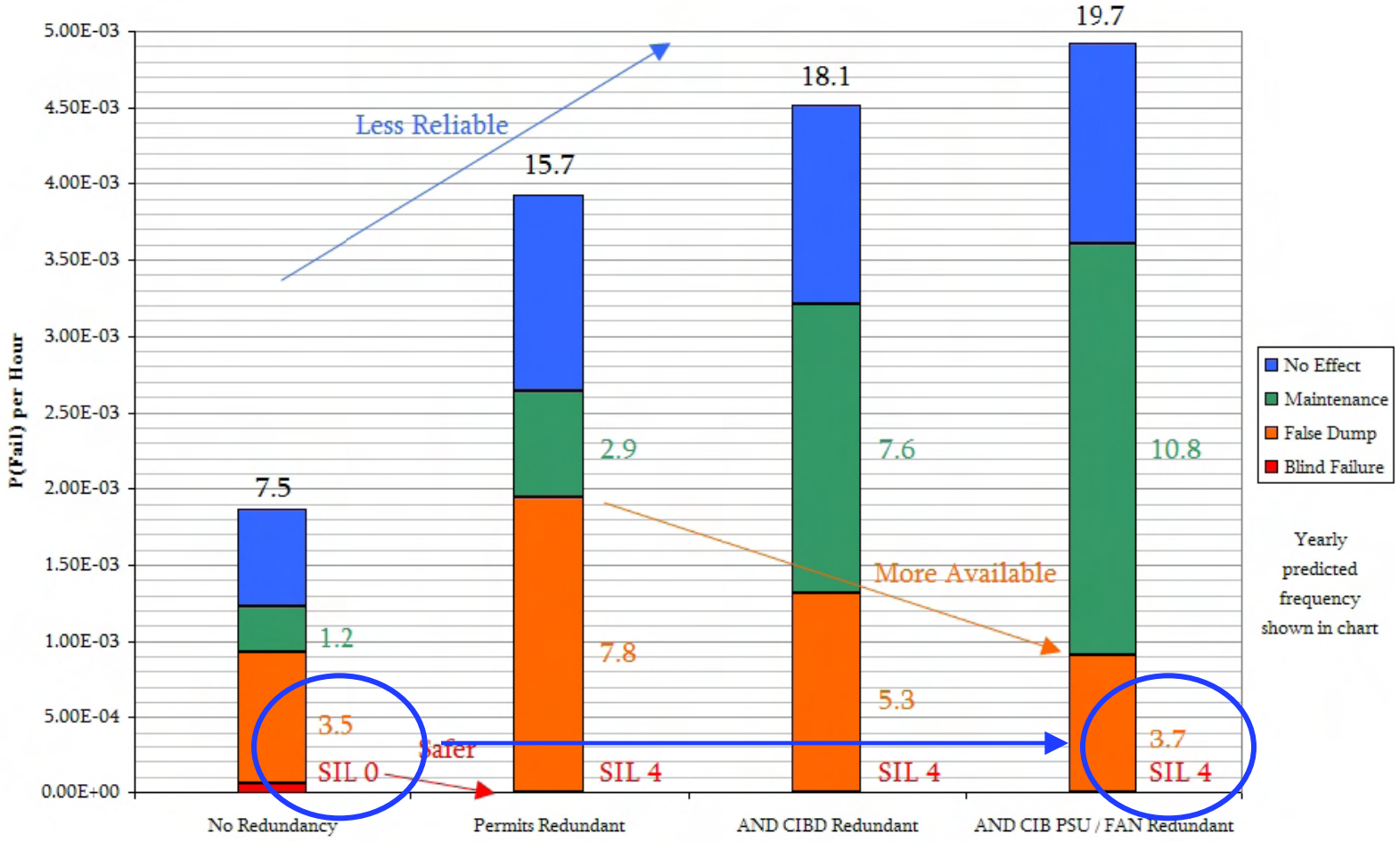
multiply through

Designer Knowledge

MIL-HDBK-338

[8]

Dependability vs. Configuration



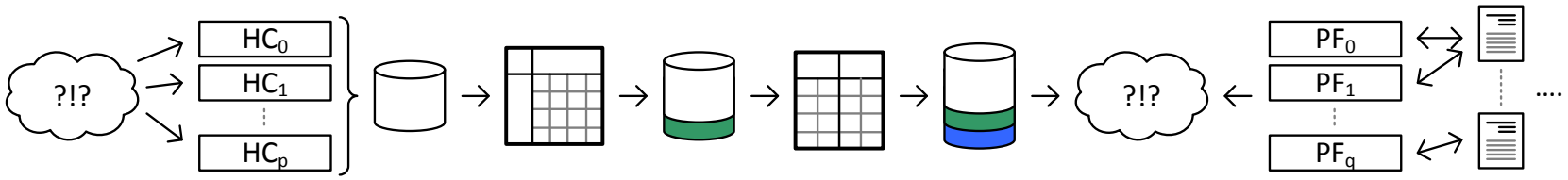
[8]

So…

It's clear that this is a huge amount of work

- Miminise the number of systems which need the highest levels
- Minimise the parts of the systems which need any level at all
- Separate critical function from non-critical function

Murphy's Law – Practical Example
September 2008



not all circuits had been commissioned to 5 TeV - Final Main Dipole Circuit Commissioning

- Electrical Fault at 5.2 TeV in dipole bus bar, between quadrupole and dipole

Post-Analysis: R = 220 nΩ, nominal = 0.35nΩ

- Electrical Arc developed and punctured helium enclosure

Post-Analysis: 400 MJ dissipated in cold-mass and arcing

- Helium Release into the insulating vacuum

Post-Analysis: Pressure wave caused most damage

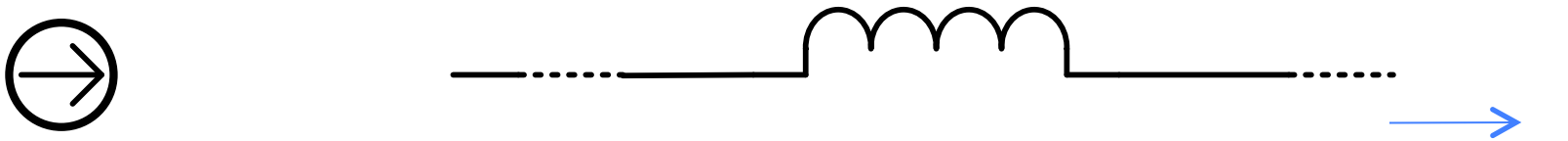
Hazard Chain had been identified in initial stages…

Probability classified as negligible
Risk Reduction Level was therefore minimum

Installation did not conform to simulations…

Case 1: September 2008

Dipole circuit = main bending magnets



Power Converter

13kA (3ppm)
±190V

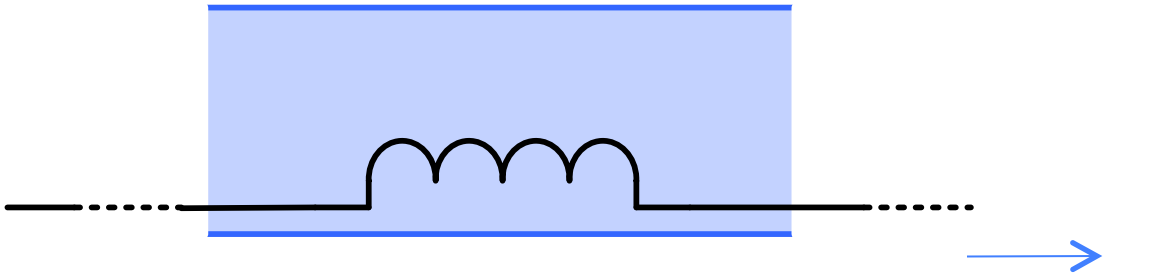
Dipole Magnet

+ 153 in series

Case 1: September 2008

Dipole circuit = main bending magnets

Helium Bath
1.9K = -273°C = -456°F



Power Converter

13kA (3ppm)
±190V

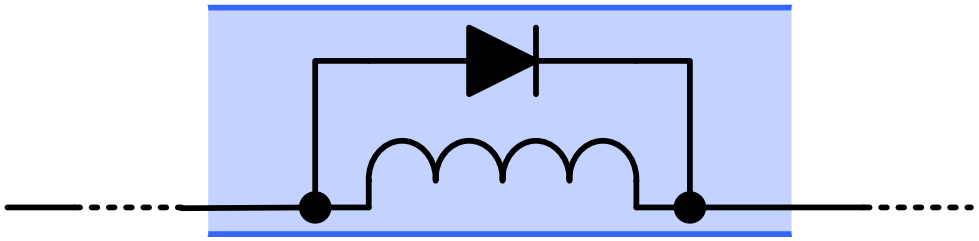
Dipole Magnet

+ 153 in series

Case 1: September 2008

Magnet Protection Function

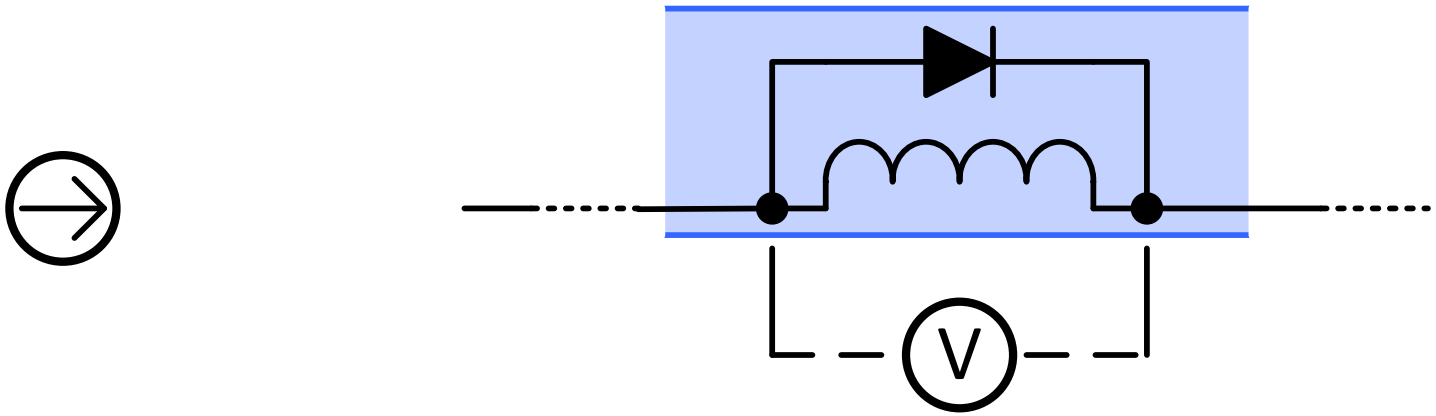
Escape Diode
If magnet quenches = path for current



Case 1: September 2008

Magnet Protection Function

Escape Diode
If magnet quenches = path for current

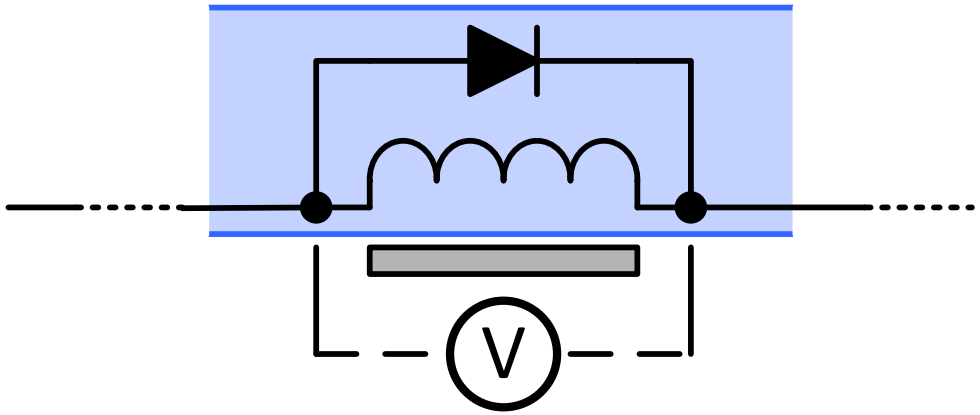


Quench Detector
detects magnet quench

Case 1: September 2008

Magnet Protection Function

Escape Diode
If magnet quenches = path for current



Quench Detector
detects magnet quench

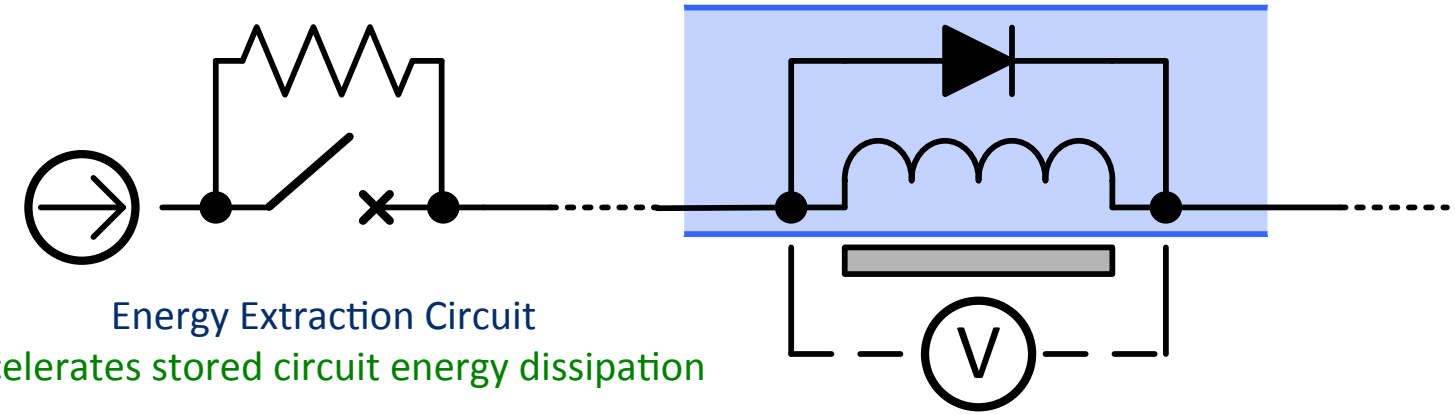
triggers

Quench Heater
spreads energy along magnet

Case 1: September 2008

Magnet Protection Function

Escape Diode
If magnet quenches = path for current



Energy Extraction Circuit
Accelerates stored circuit energy dissipation

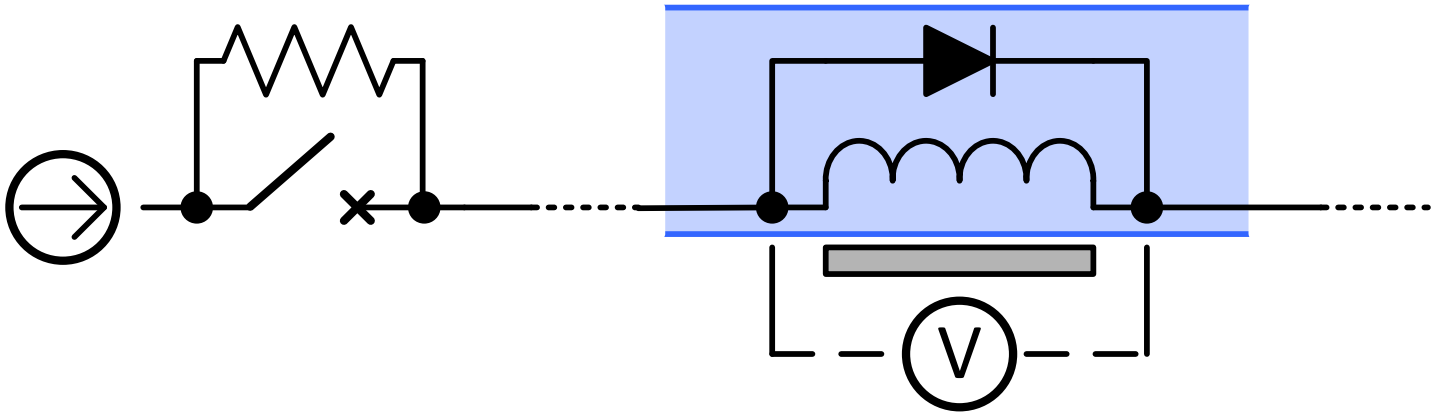
Quench Detector
detects magnet quench

triggers

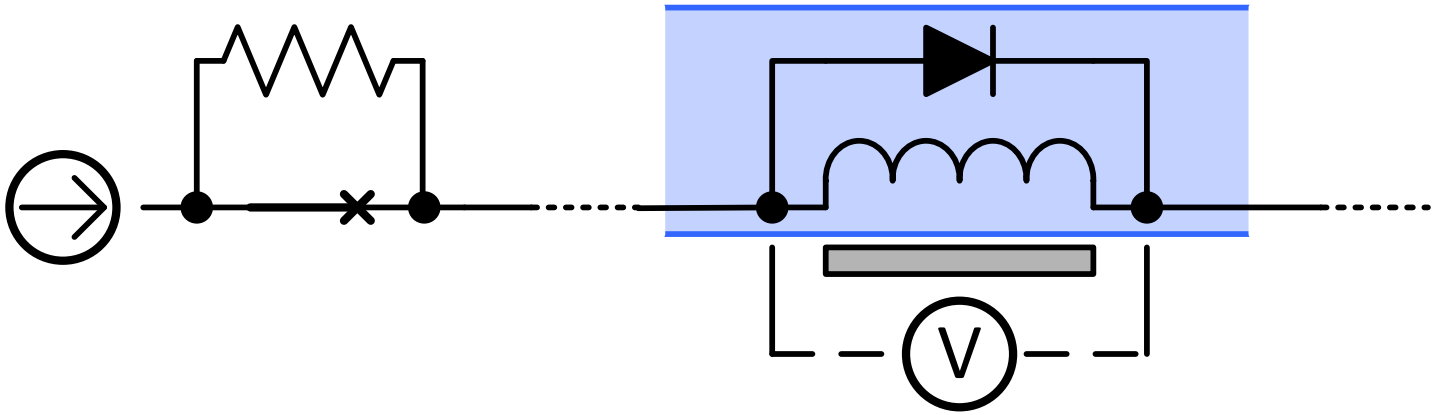
Quench Heater
spreads energy along magnet

Case 1: September 2008

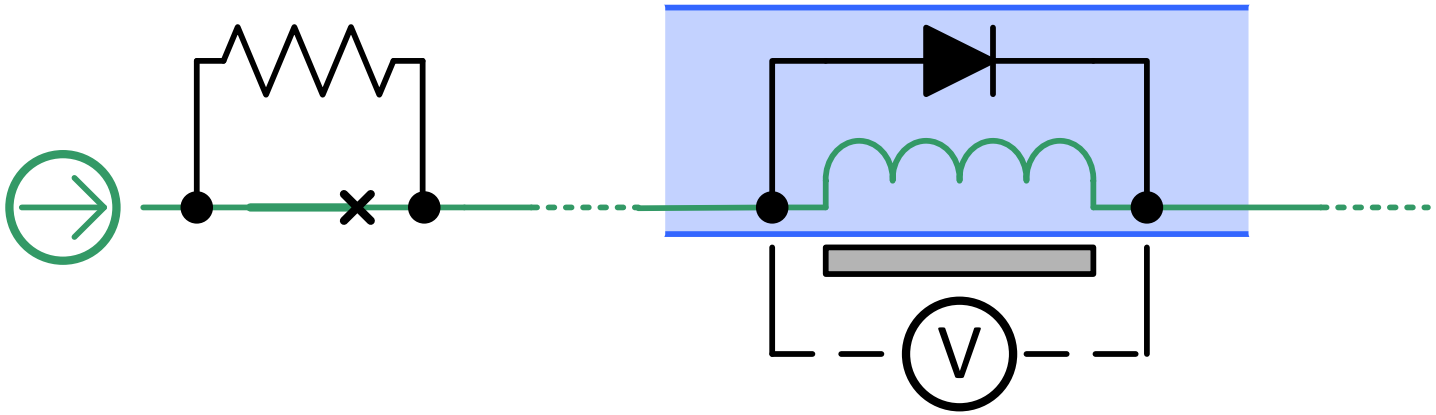
normal sequence….



Case 1: September 2008



Case 1: September 2008



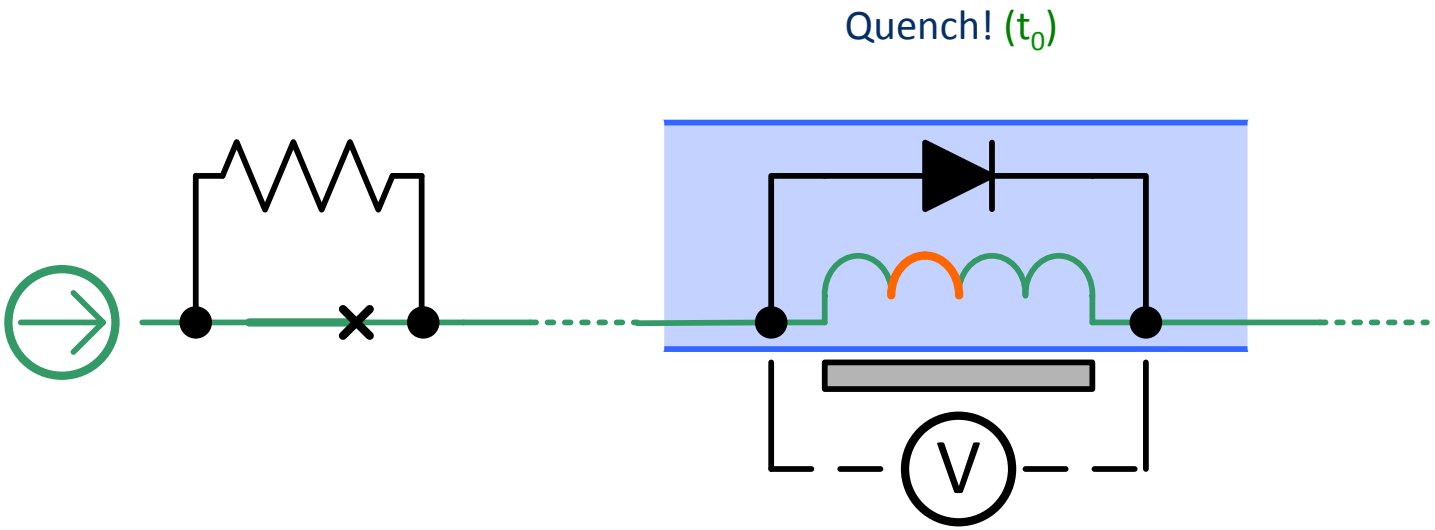
7 TeV operation:

13 kA forward current
100mH dipole inductance

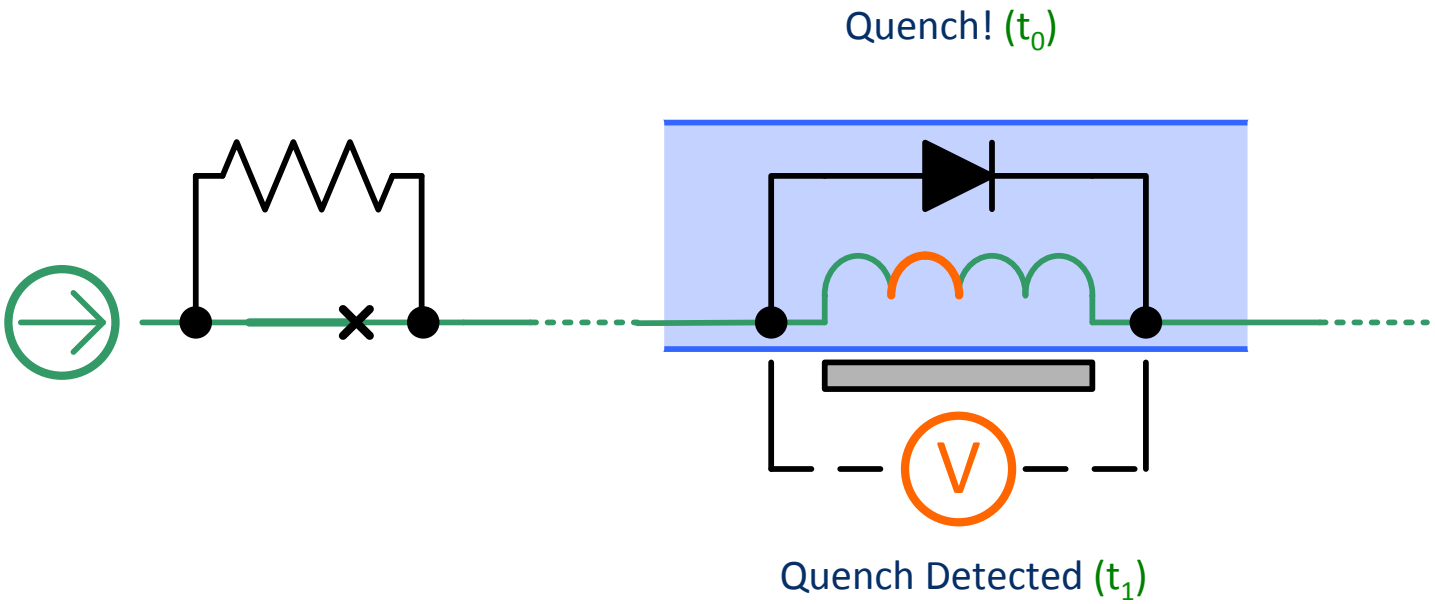
Single magnet energy = 8.5 MegaJoules
Circuit magnet energy = 1.3 GigaJoules

milliJoules = Quench

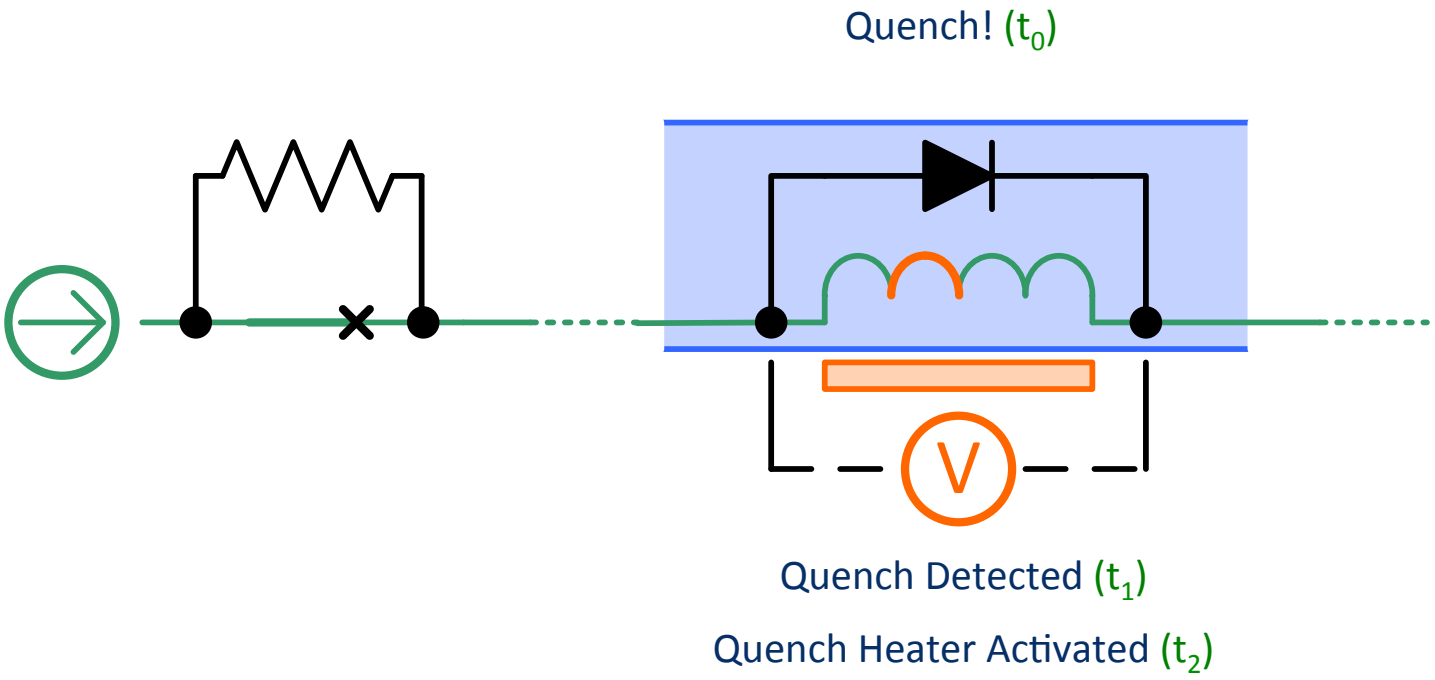
Case 1: September 2008



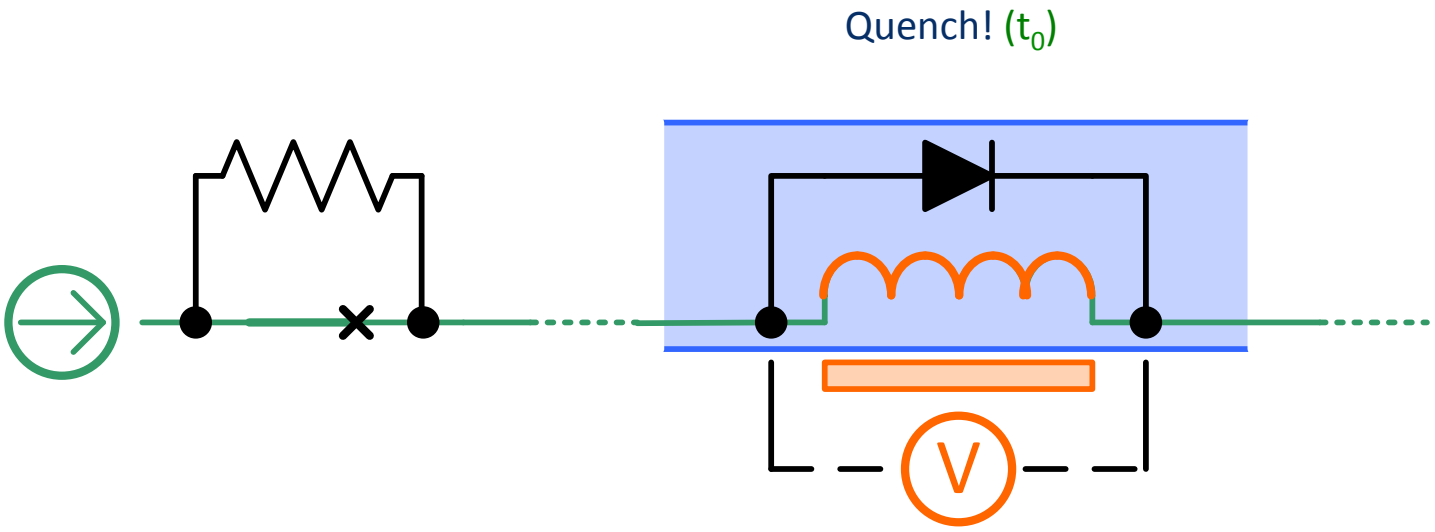
Case 1: September 2008



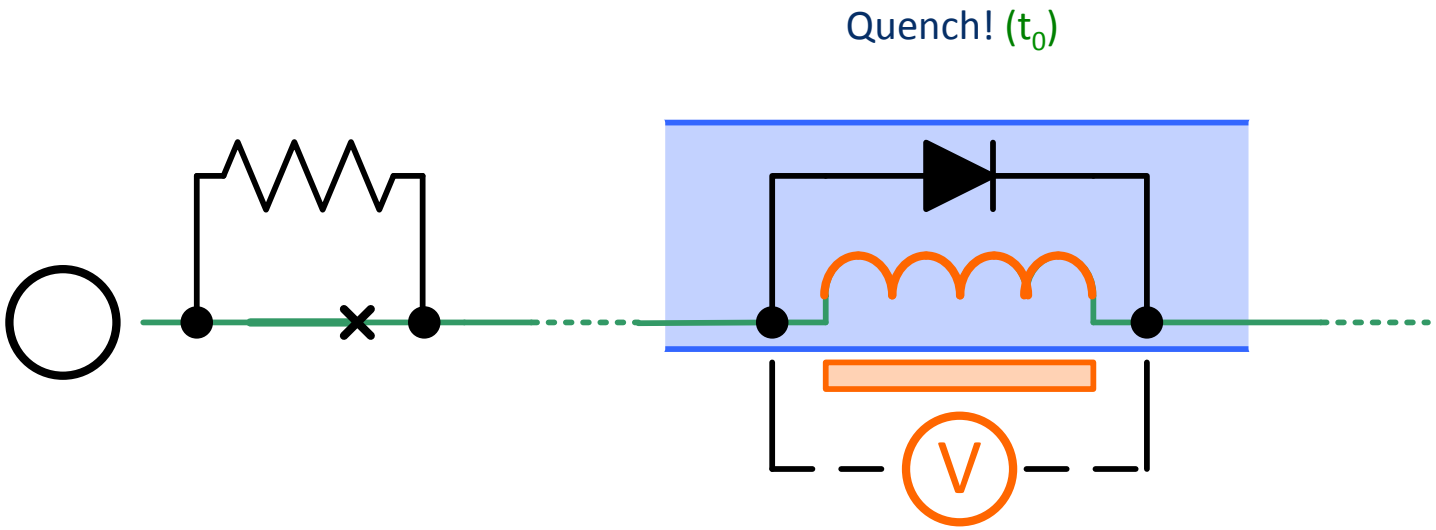
Case 1: September 2008



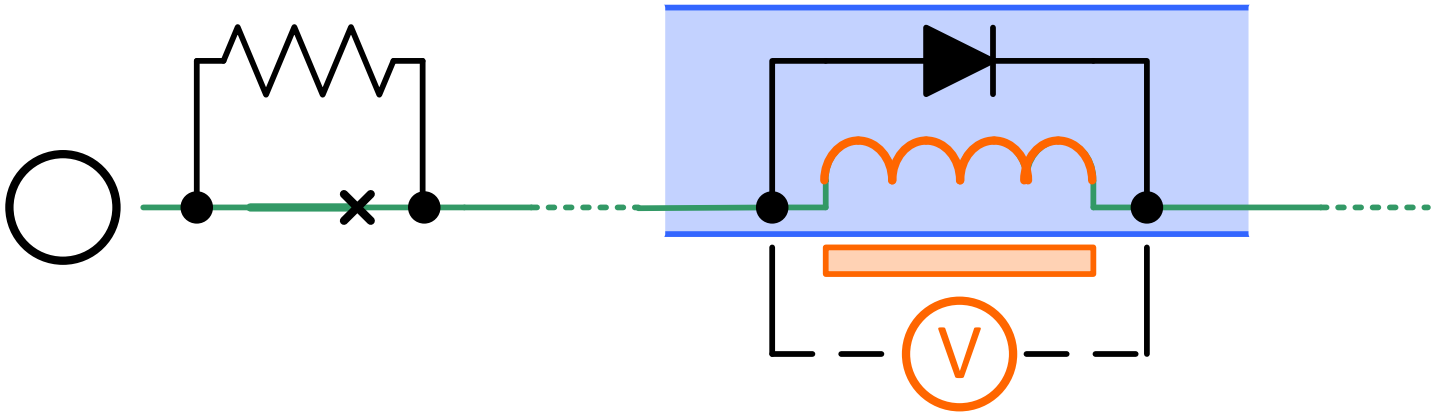
Case 1: September 2008



Case 1: September 2008



Case 1: September 2008



Quench! (t_0)

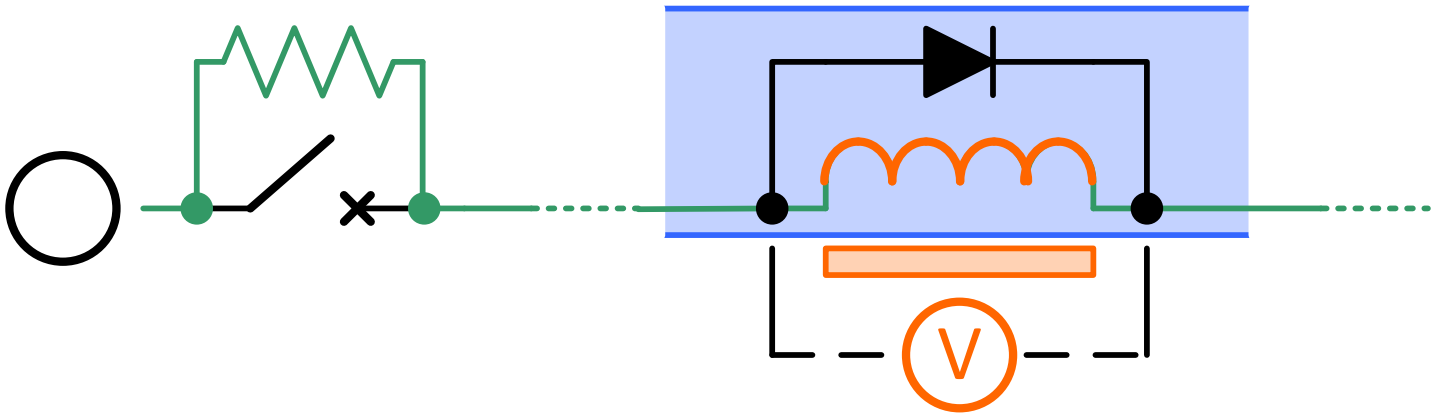
Quench Detected (t_1)

Quench Heater Activated (t_2)

Power Converter Switched Off (t_3)

Beam abort (t_3)

Case 1: September 2008



Quench! (t_0)

Quench Detected (t_1)

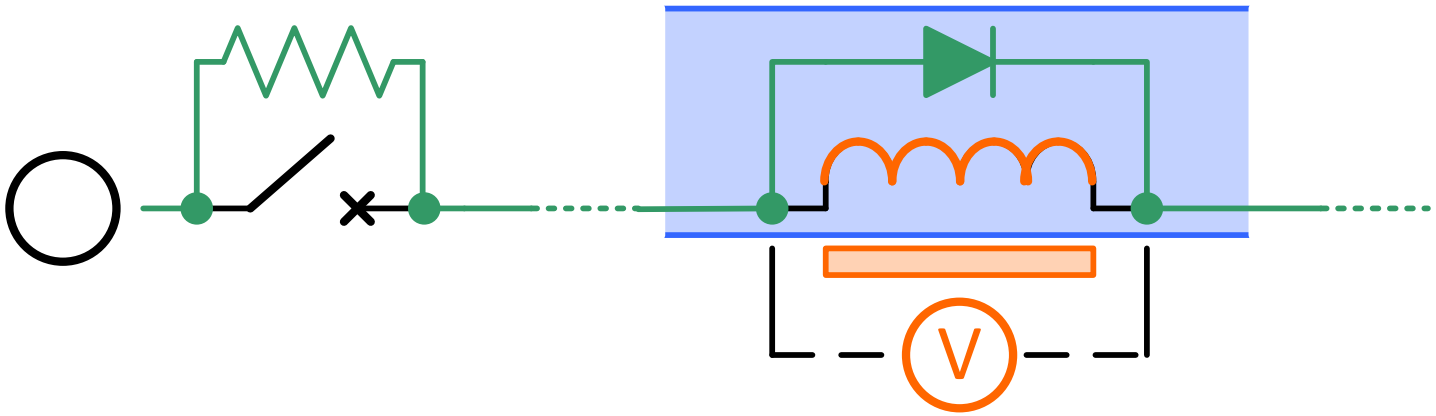
Quench Heater Activated (t_2)

Energy Extraction Switches Opened (t_3)

Power Converter Switched Off (t_3)

Beam abort (t_3)

Case 1: September 2008



Quench! (t_0)

Quench Detected (t_1)

Quench Heater Activated (t_2)

Energy Extraction Switches Opened (t_3)

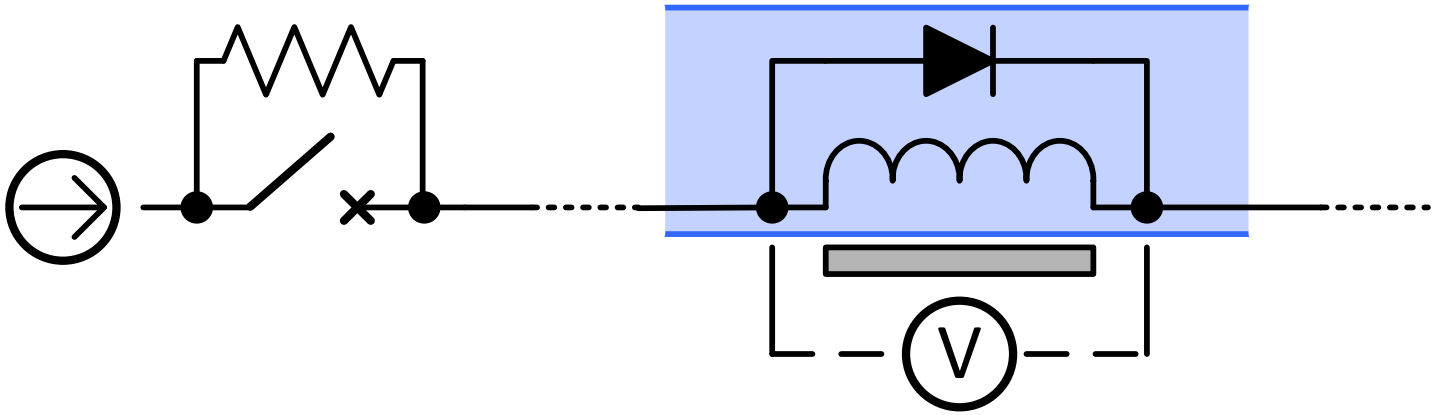
Power Converter Switched Off (t_3)

Beam abort (t_3)

Diode Starts to Conduct (t_4)

Case 1: September 2008

Quench! (t_0)



Quench Detected (t_1)

Quench Heater Activated (t_2)

Energy Extraction Switches Opened (t_3)

Power Converter Switched Off (t_3)

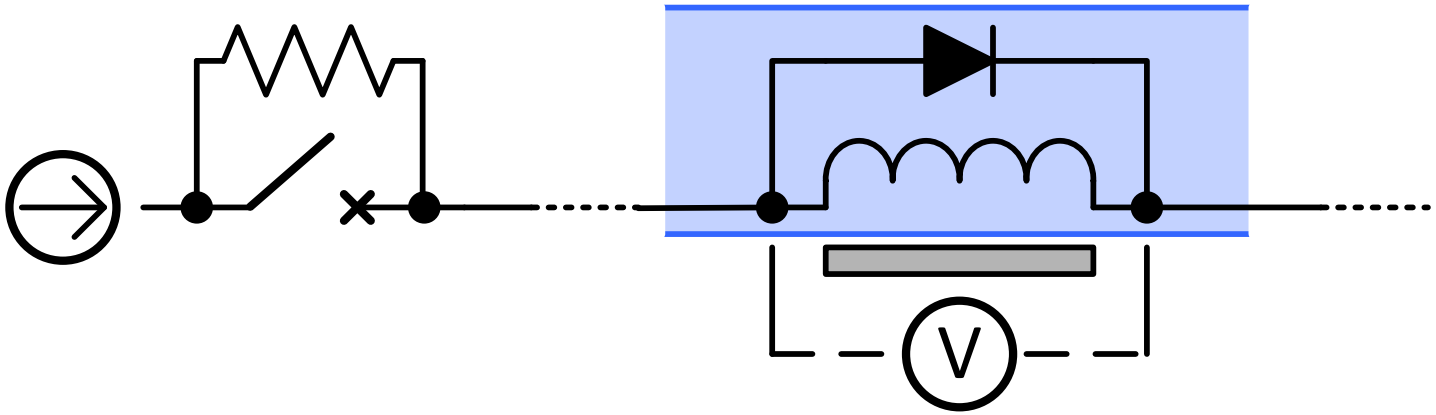
Beam abort (t_3)

Diode Starts to Conduct (t_4)

Circuit Energy is Dissipated (t_5)

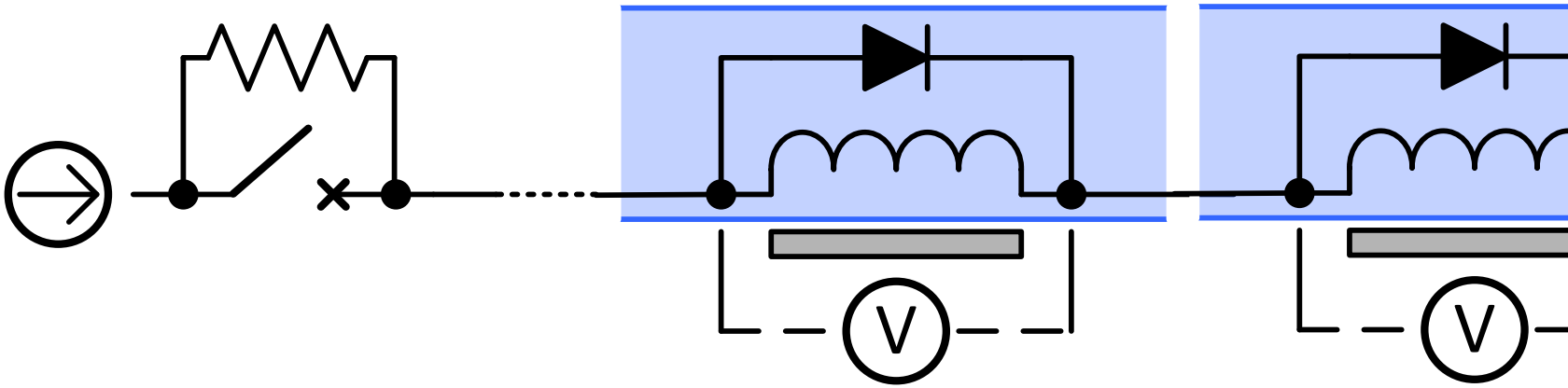
Case 1: September 2008

19th September – commissioning last circuit to 5 TeV = 9kA forward current



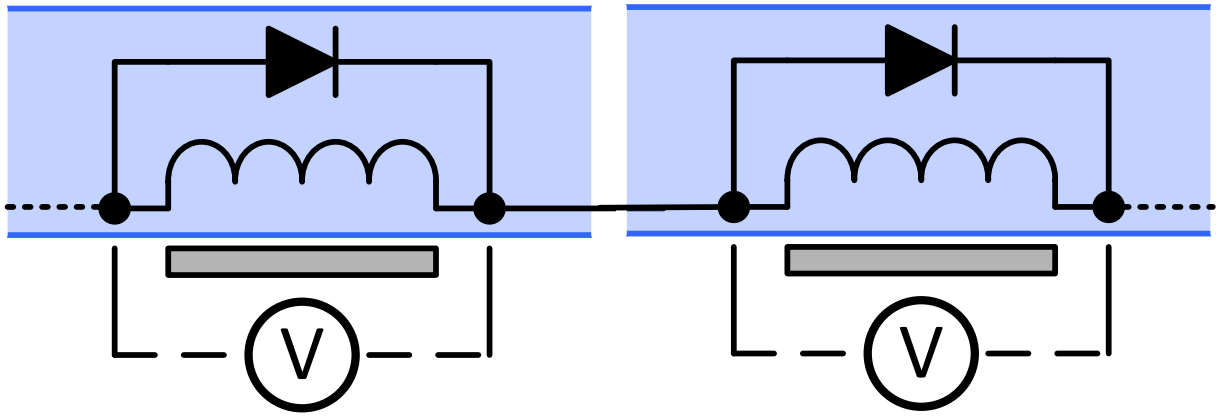
Case 1: September 2008

19th September – commissioning last circuit to 5 TeV = 9kA forward current



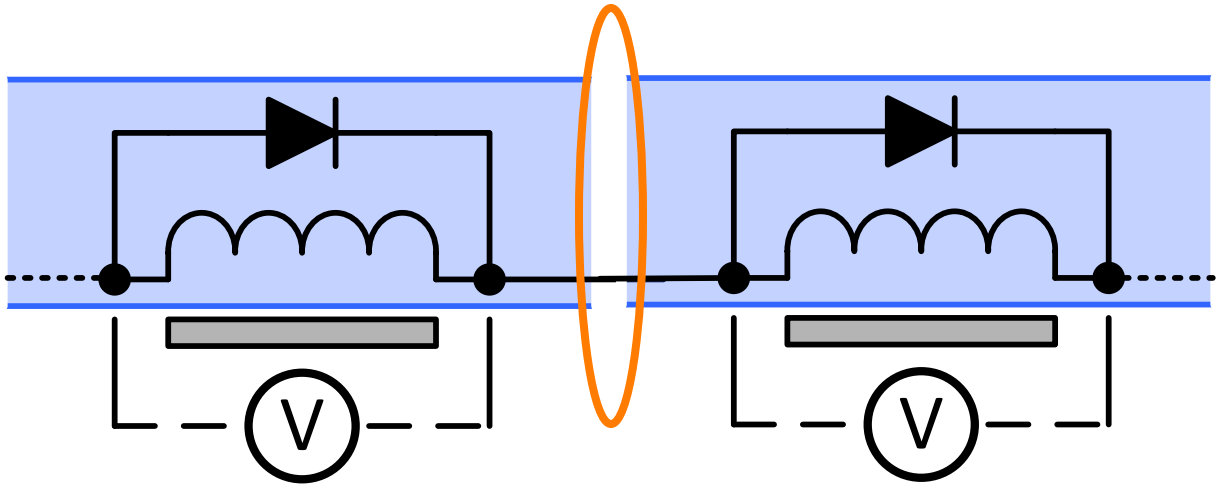
Case 1: September 2008

19th September – commissioning last circuit to 5 TeV = 9kA forward current

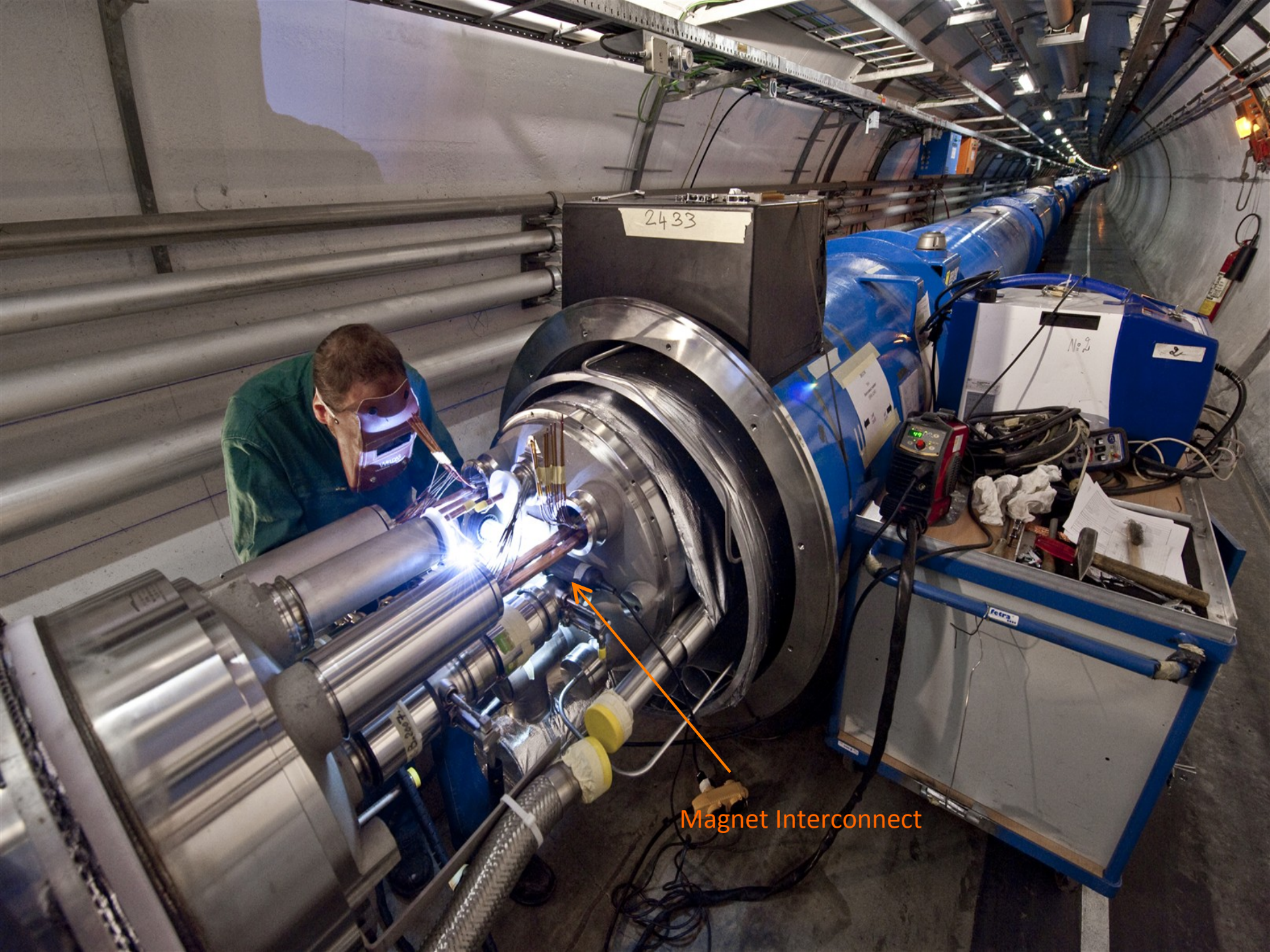


Case 1: September 2008

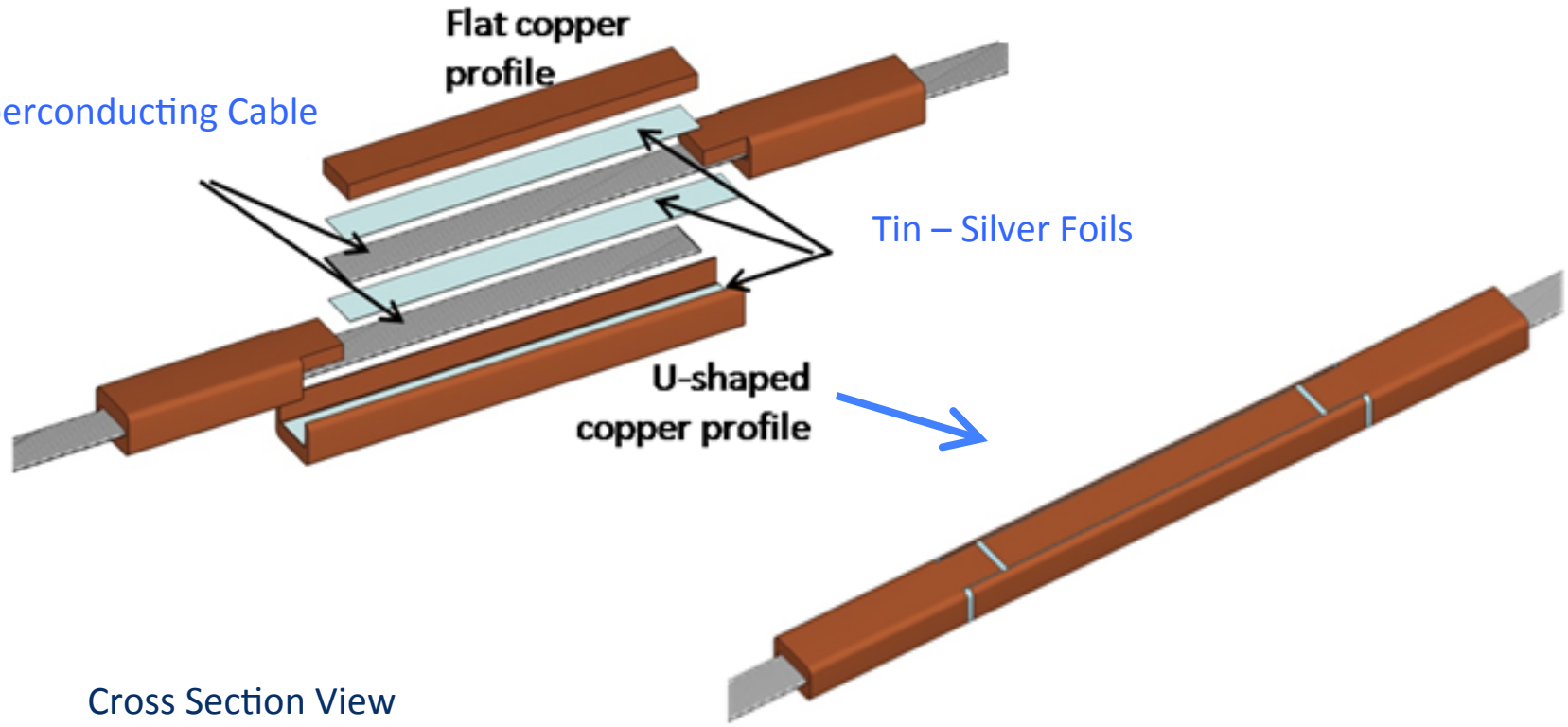
19th September – commissioning last circuit to 5 TeV = 9kA forward current



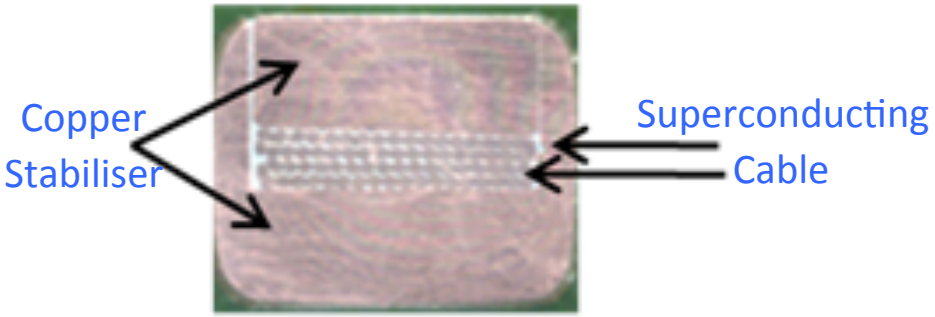
Magnet Interconnect


2433
Magnet Interconnect

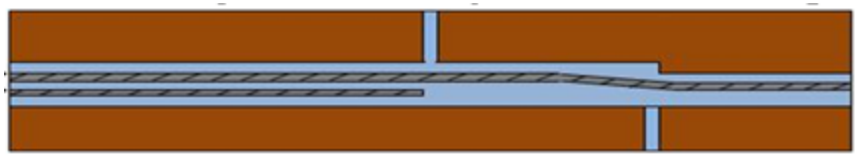
Ideal 13 kA Connection Scheme



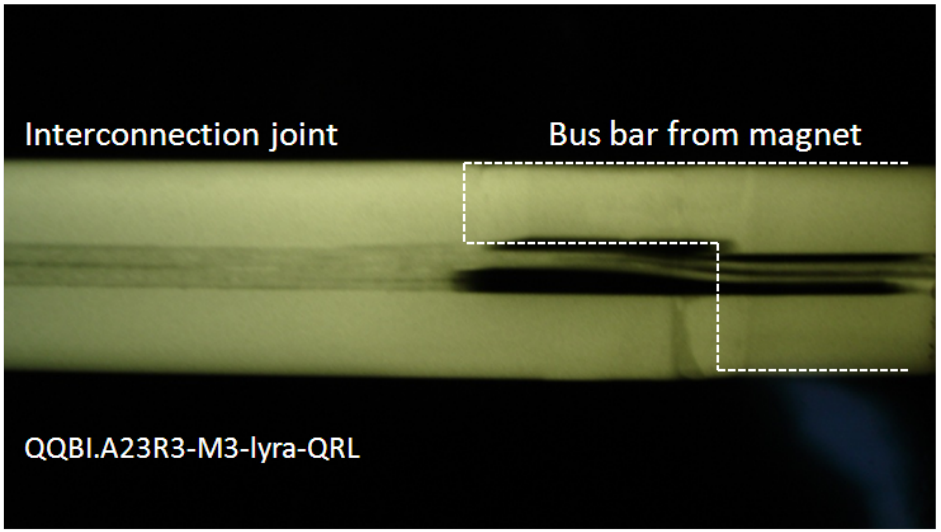
Cross Section View



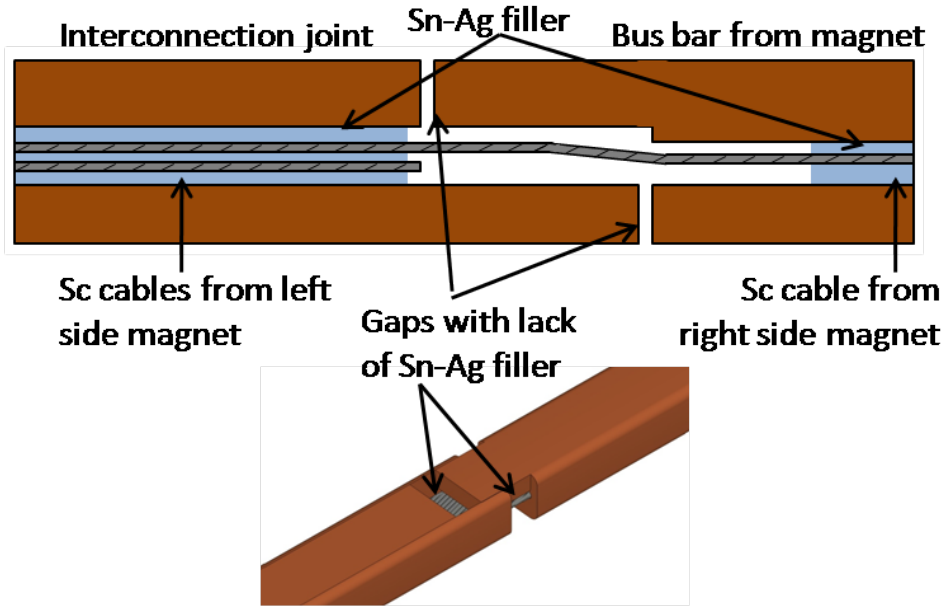
Longditudinal View – filled with Solder

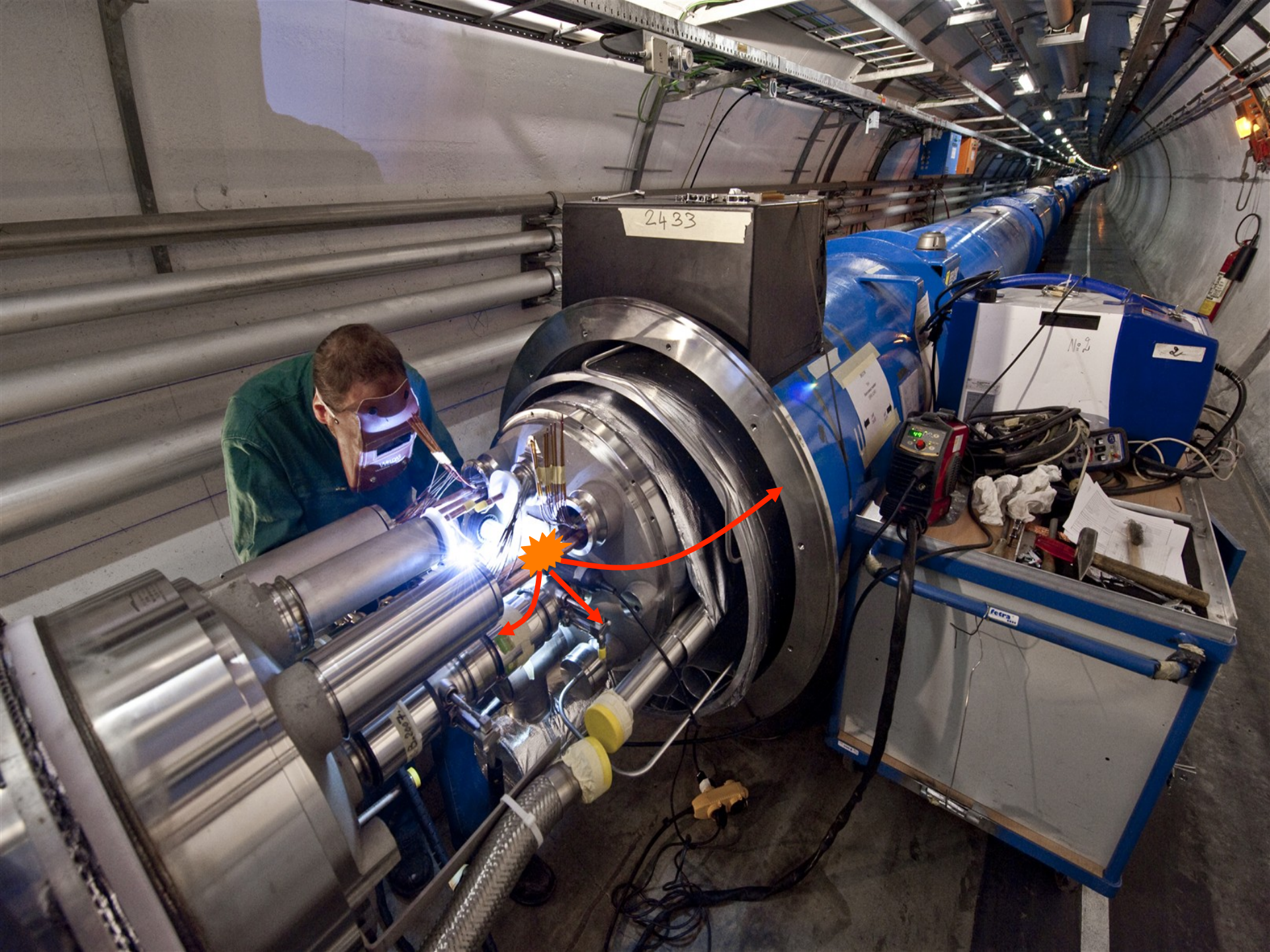


Observed Interconnections

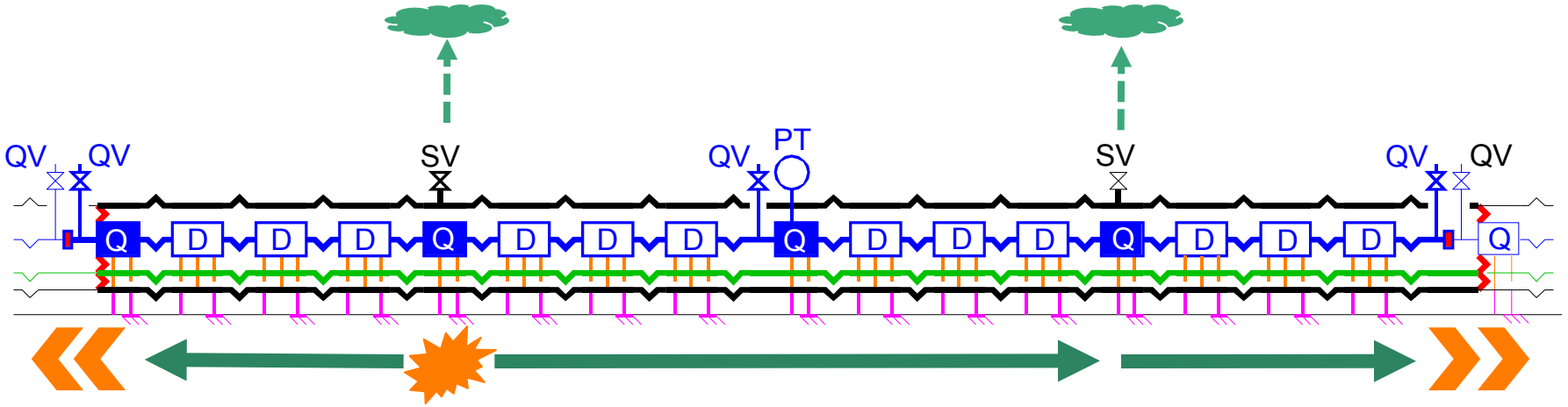


Defective interconnetion-bus bar transition
γ-ray picture (left) and scheme (right)




2433

Incident and Pressure Wave



- Cold-mass
- Vacuum vessel
- Line E
- Cold support post
- Warm Jack
- Compensator/Bellows
- Vacuum barrier

1. Pressure Wave propagates inside insulation Vacuum enclosure

2. Rapid Pressure Rise

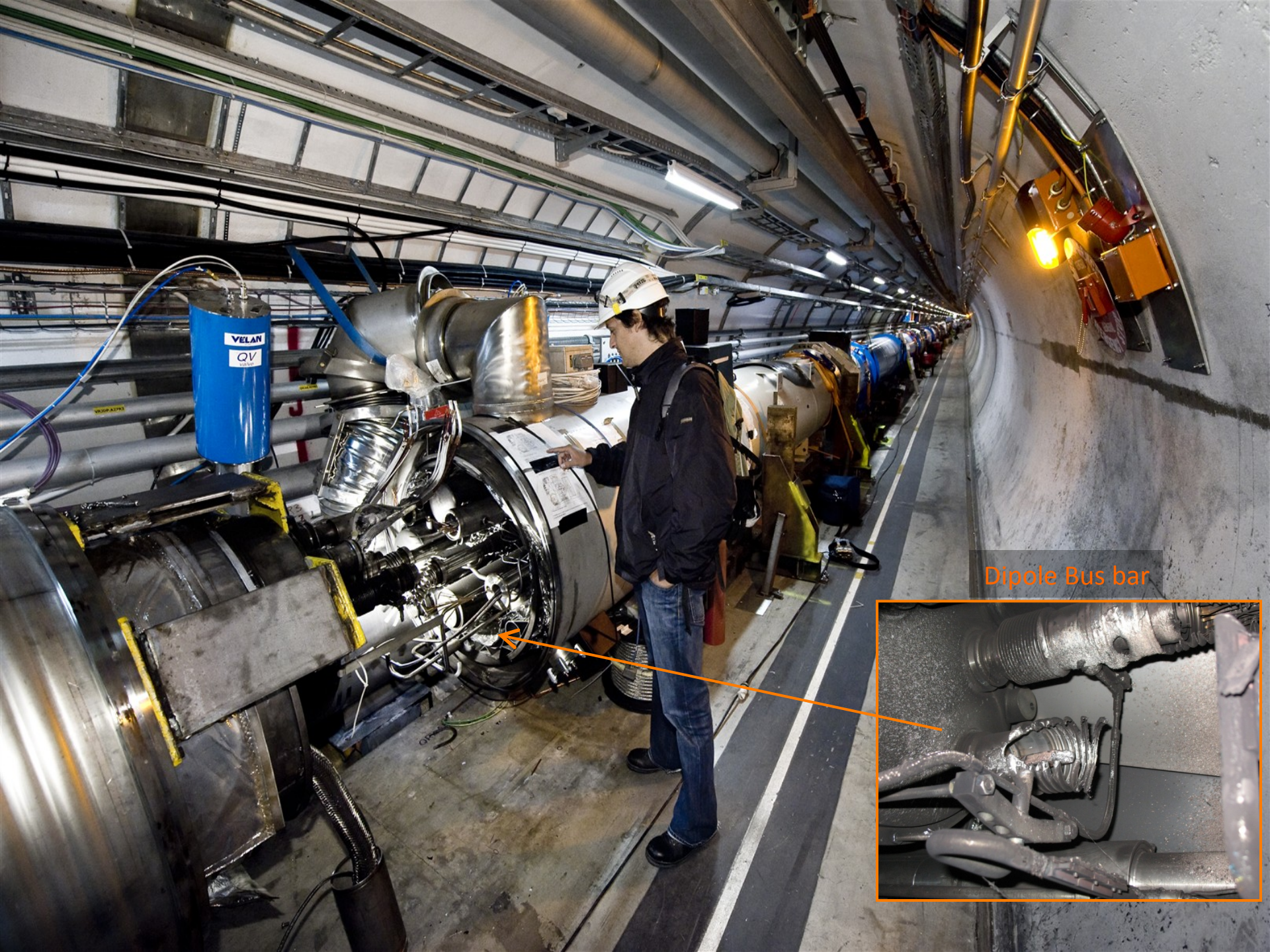
Self actuating relief valves could not handle pressure

Design: 2Kg He/s Incident: ~20 kg He/s

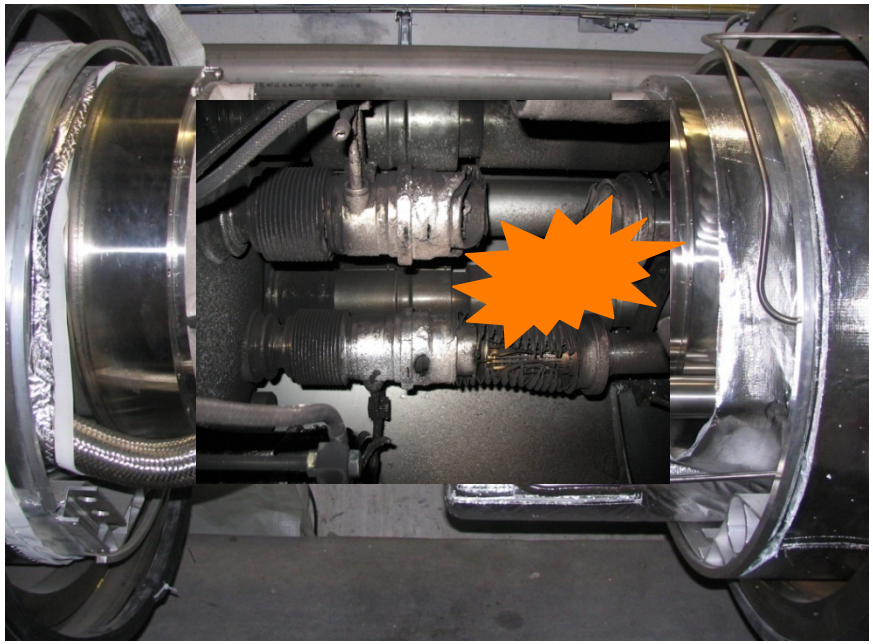
3. Forces on the vacuum barriers (every second cell)

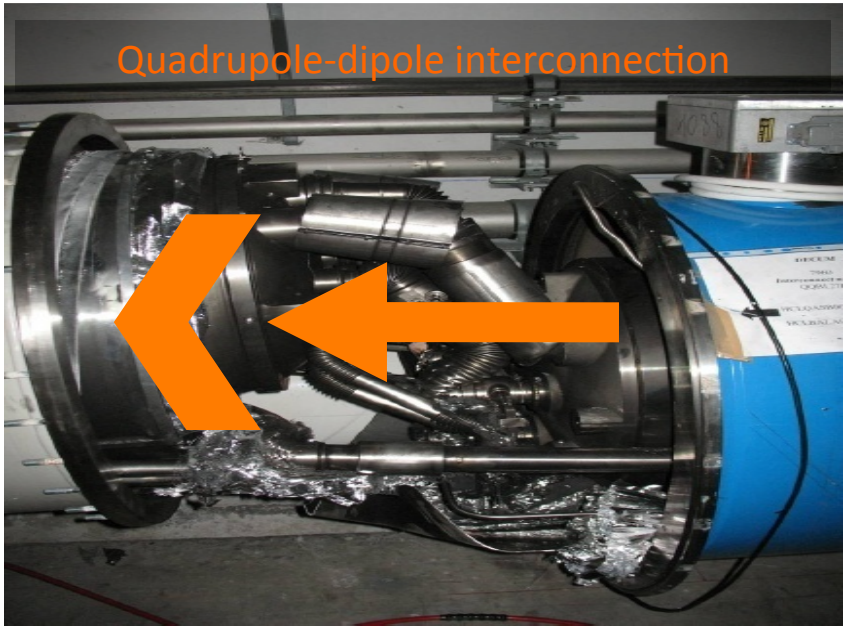
Design: 1.5 bar Incident: ~8 bar

- Several Quadrupoles Displaced by ~50 cm
- Cryogenic line connections damaged
- Vacuum to atmospheric pressure


VELAN
QV
Dipole Bus bar

Collateral Damage

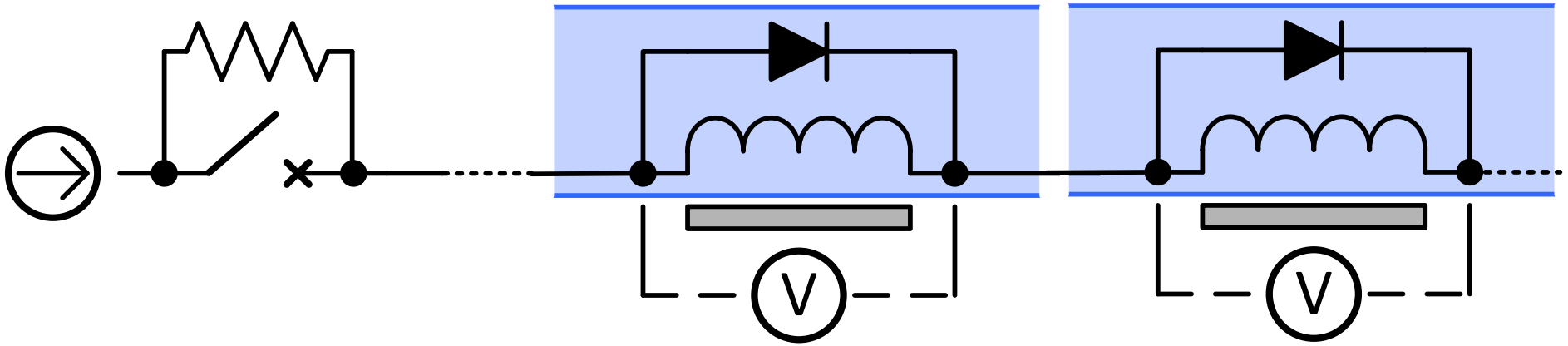




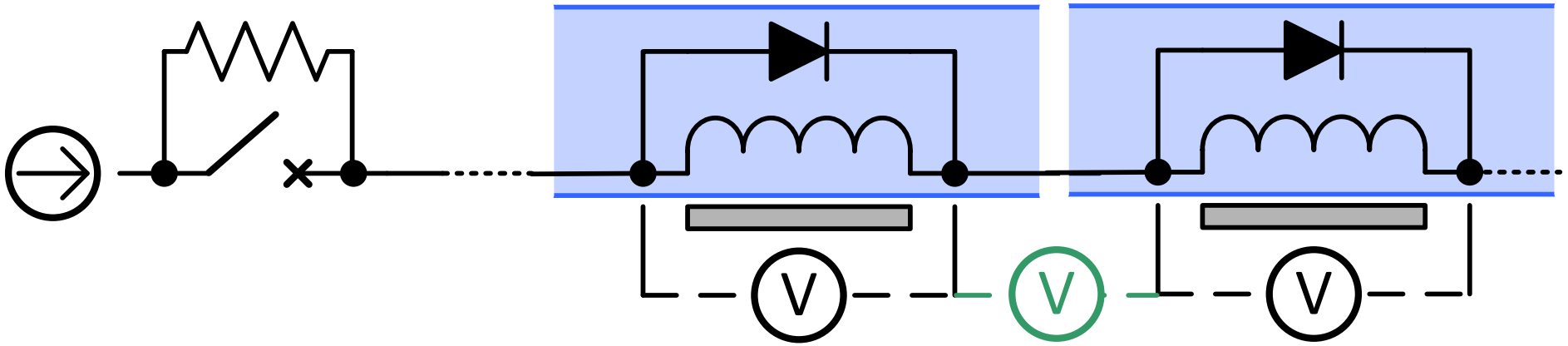
Main Damage Area: 700m

- 39 dipoles and 14 quadrupoles effected
  - moved to surface:
- 37 replaced and 16 repaired

Magnet Protection



Magnet Protection



Interconnect impedance is measured
Energy Extracted if impedance unacceptable

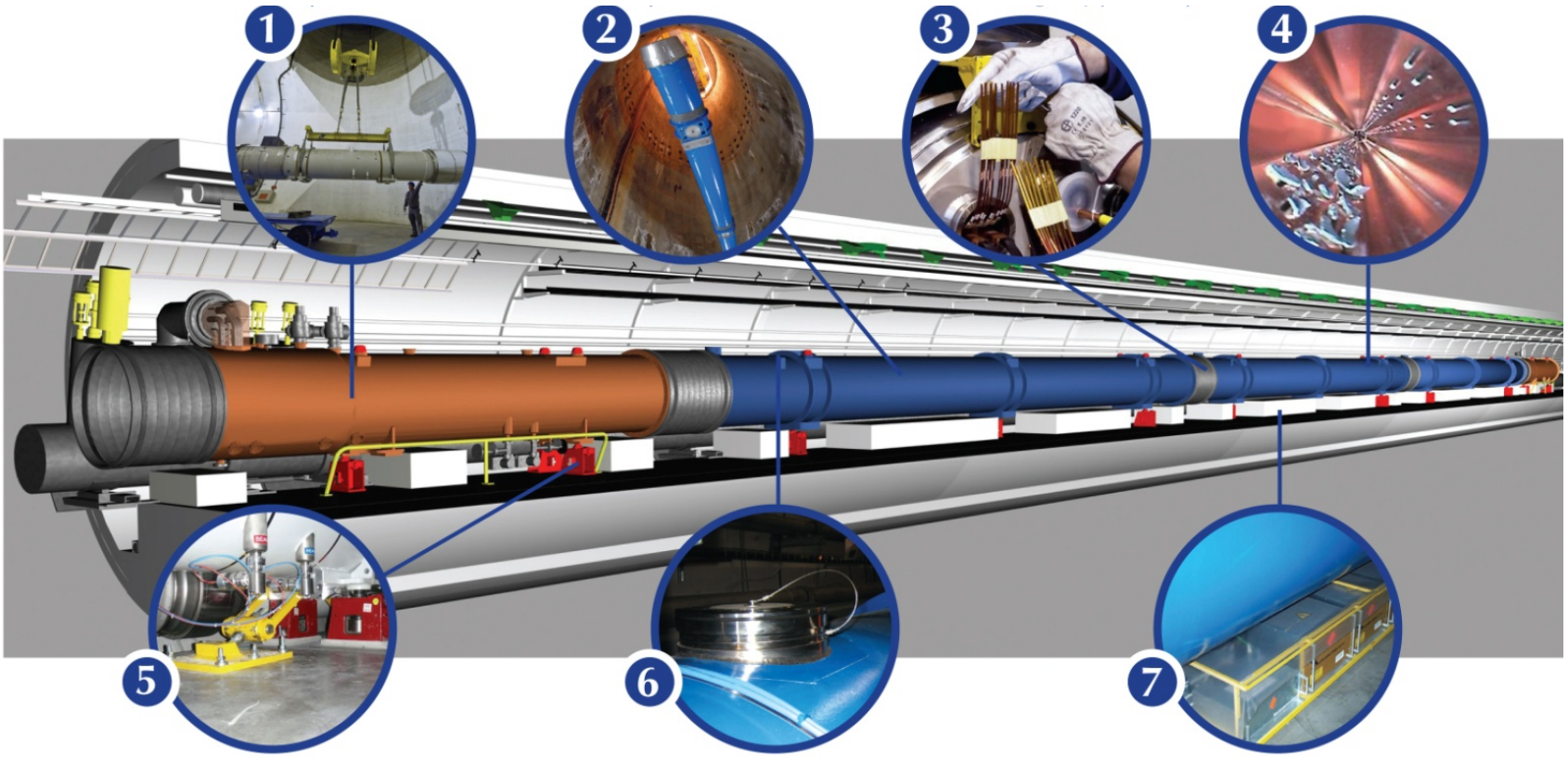
2009: LHC repair and consolidation

14 quadrupole magnets replaced

39 dipole magnets replaced

204 interconnections repaired

4km beam-tube cleaned



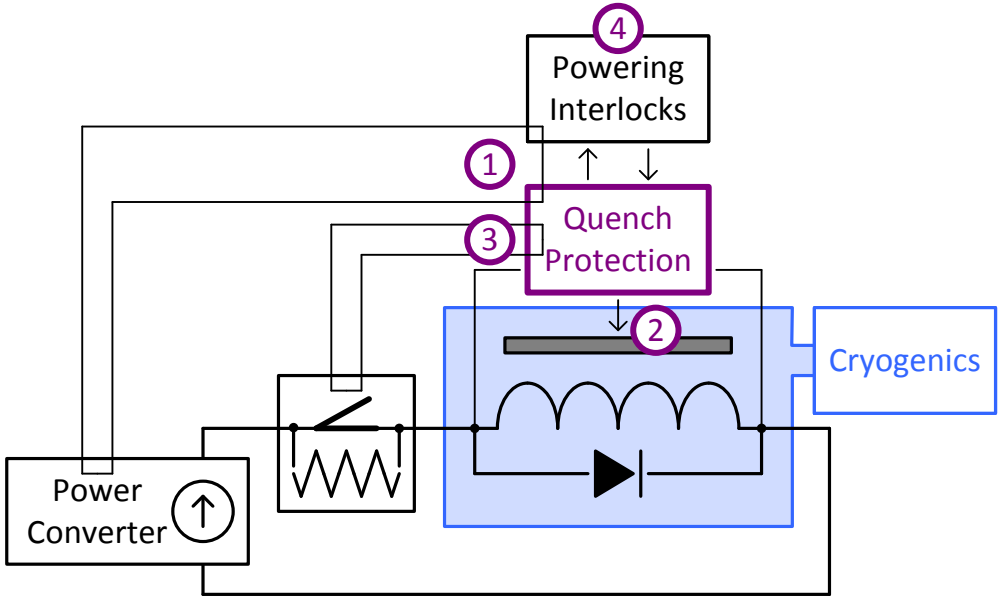
longitudinal restraining system quadrupoles

900 ports for helium pressure release

6500 new detectors and 250km cables for new Interconnect Protection System

Collateral damage mitigation

Almost Another Murphy's Law in Practice January 2013



quench tests forced a quadrupole magnet quench, all four protection functions failed to activate

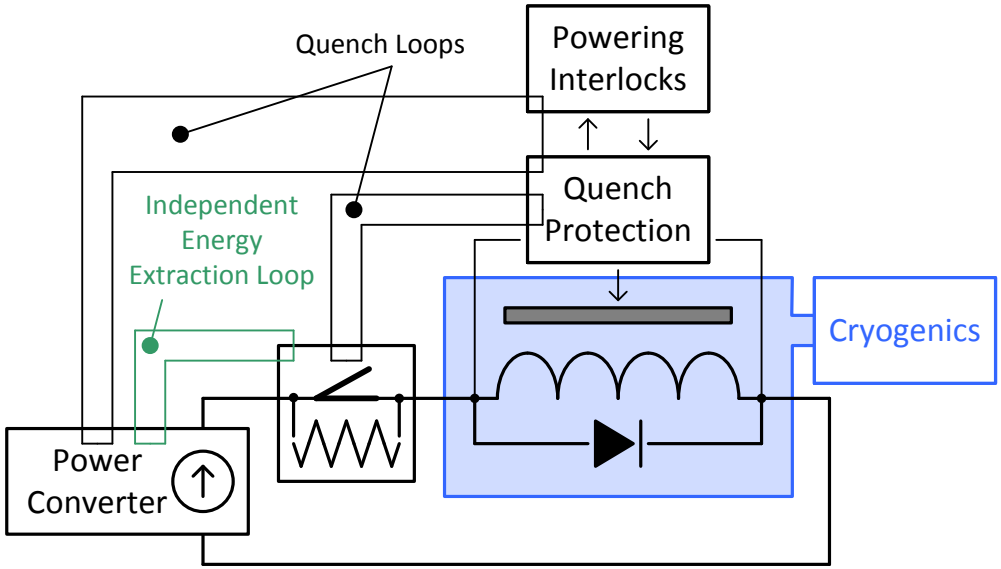
- Six months earlier a thunderstorm tripped several QPS detectors
- Piquet team needed to manually intervene to rearm

Post-Analysis: mitigation of this need by new firmware, piquet did not intervene

- Firmware update was not applied to this particular circuit

Post-Analysis: time and revalidation pressure

- Missing rearm does not prevent the circuit from being powered
- Circuit powered and unprotected for six months
- Event was repeated as failure of protection functions was not identified immediately
- Failure of this nature on dipole circuit represents most critical risk level for CERN.



QPS protection functions have too high a Risk Reduction Level

1. Qualification of QPS Functions

2. Addition of Independent Energy Extraction Loop Study

In Conclusion…

Coming Soon…

Year	Peak Energy [TeV]	Peak Intensity [p]	Peak Luminosity [cm^{-2} s^{-1}]
2010	3.5	4×10^{13}	2.0×10^{32}
2011	3.5	2.0×10^{14}	3.6×10^{33}
2012	4	2.2×10^{14}	7.7×10^{33}
$LS_{1\text{-}2}$	≈6.5	≈3×10^{14}	≈1×10^{34}

To Take Away Today

* the protection context is vital
  – need to consider system, machine and organisational level impact

As engineers building power systems, you need to understand how they will be used

* risk analysis is a core part of every engineer's toolbox
  – zero risk does not exist

Qualitatively and quantitatively determine how and how likely things are to go wrong

* specification of protection and interlocks is a compromise
  – they don't add to the function, but are an insurance for when things go wrong.
  – they do add to complexity, so will make the system less reliable.

In the academic – industrial world of HEP, you cannot trust only "it worked in the past"

Specifically If you ask "how reliable is this" and the reply is "great, it never broke down yet".

Take a closer look.

Fin!
Thank You!

References and Further Reading

[1] Concept developed in collaboration with by M. Zerlauth et al. (CERN)

[2] Picture source: http://en.wikipedia.org/wiki/File:Alstom_AGV_Cerhenice_img_0365.jpg
Shared as: http://creativecommons.org/licenses/by-sa/3.0/deed.en

[3] Picture source: http://militarytimes.com/blogs/scoopdeck/2010/07/07/the-airstrike-that-never-happened/
Shared as: public domain

[4] Diagram courtesy B. Goddard, J. Uyhoven et al. (CERN)

[5] Livingston plot - courtesy R. Assmann (ex CERN), adapted from:
http://indico.cern.ch/event/115634/session/7/contribution/7/material/slides/1.pdf

[6] Based on work from V. Kain et al
http://cds.cern.ch/record/858162/files/lhc-project-report-822.pdf

[7] Ph. D thesis – M. Kwiatkowski CERN
http://cds.cern.ch/record/1632194/files/CERN-THESIS-2013-216.pdf

[8] Ph. D thesis – B. Todd CERN
http://cds.cern.ch/record/1019495?

[9] Machine Protection of The Large Hadron Collider at CERN
https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6136929