S07 - After LS1

Quenches: Will there be any?

or: how reliably can we operate 7000 SC magnets?

Arjan Verweij, TE-MPE

The plan is a crystal ball for understanding
what will happen over the next 5 years.

(Dan Wolfe)

A quench (irreversible transition from the SC to the normal state), is usually the result of a (local) temperature increase ΔT from T_{helium} to $T_C(B,I)$.

Quenches are part of normal operation of SC magnets. Magnets (incl. protection system) are designed to withstand quenches.

Of course, quenches should be reduced to a minimum, in order to:

- Optimize beam time.
- Reduce the risk of magnet failure (including quench heaters, by pass diodes, parallel resistances, extraction system, …). Quenches often cause high pressures, large internal voltages, and high temperature gradients. Each quench therefore always gives a small possibility ($\mathcal{O}(10^{-4})$) that the magnet will not work properly afterwards.

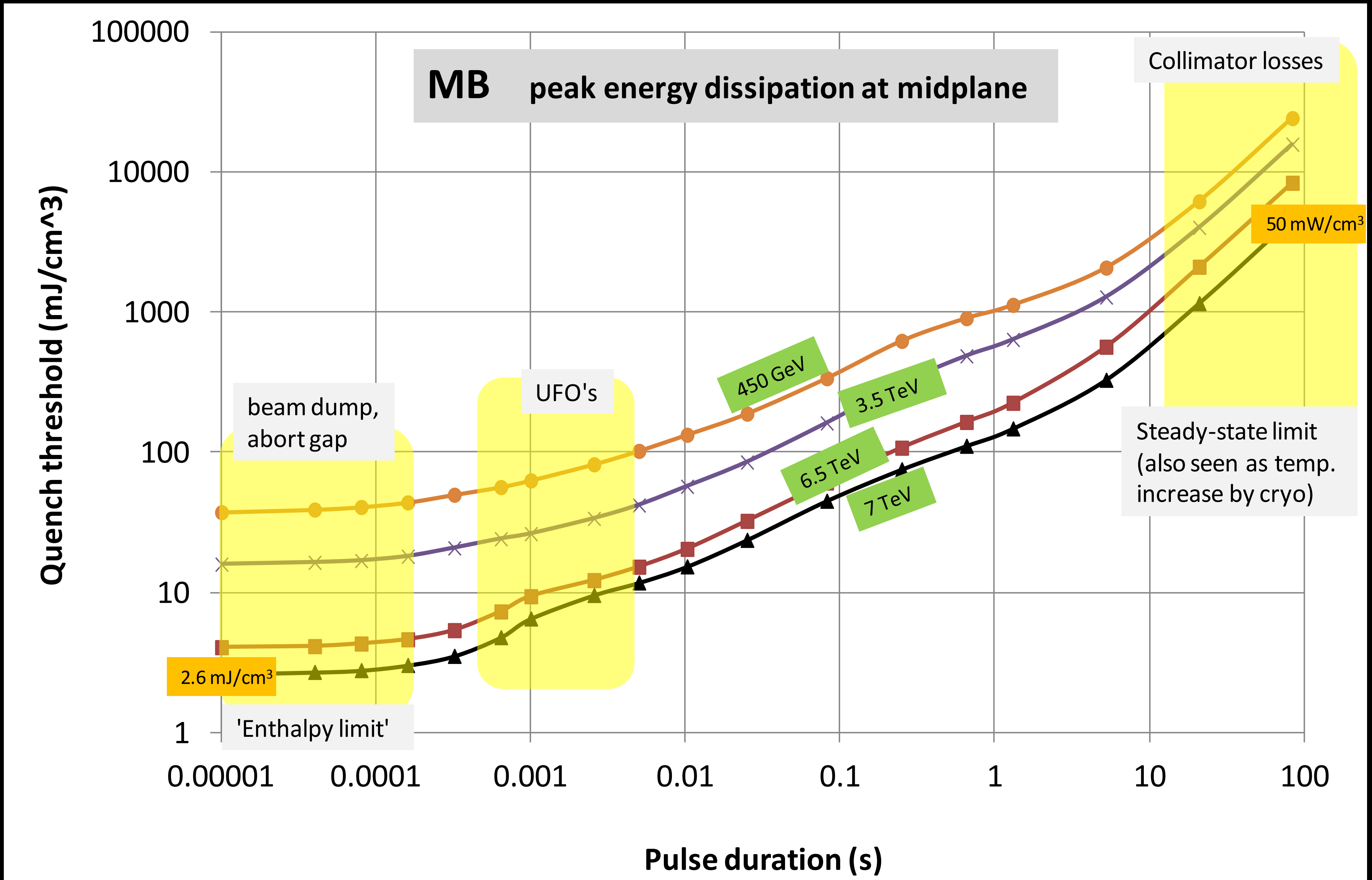
Difference 3.5 TeV ⇔ 6.5-7 TeV

At 6.5-7 TeV the SC magnets run much closer to the critical surface (J_C,B_C,T_C) while at the same time exposed to higher beam losses.

Example: main dipole	3.5 TeV	6.5 TeV	7 TeV
I	5900 A	11000 A	11850 A
I / I_C at B_{peak}	13%	44 %	55%
$B_{central}$	4.2 T	7.7	8.3
Stored energy	1.7 MJ	6 MJ	7 MJ
Splice heating for R=0.6 nΩ	20 mW	73 mW	85 mW
Joule heating at 10 K at B_{peak}	44 W/cm^3	230 W/cm^3	280 W/cm^3
dI/dt at FPA	-120 A/s (τ=50 s)	-110 A/s (τ=100 s)	-120 A/s (τ=100 s)
T_C	6.8 K	4.1 K	3.5 K
T_{margin}	4.9 K	2.2 K	1.6 K
Enthalpy (1.9 K to T_C) at B_{peak}	**16 mJ/cm^3**	**3.1 mJ/cm^3**	**1.9 mJ/cm^3**

<400 mW/cm^3 at 760 A

Quench threshold vs heat duration



1

Quench
⇓
FPA and dump

2

FPA
⇓
Quench

3

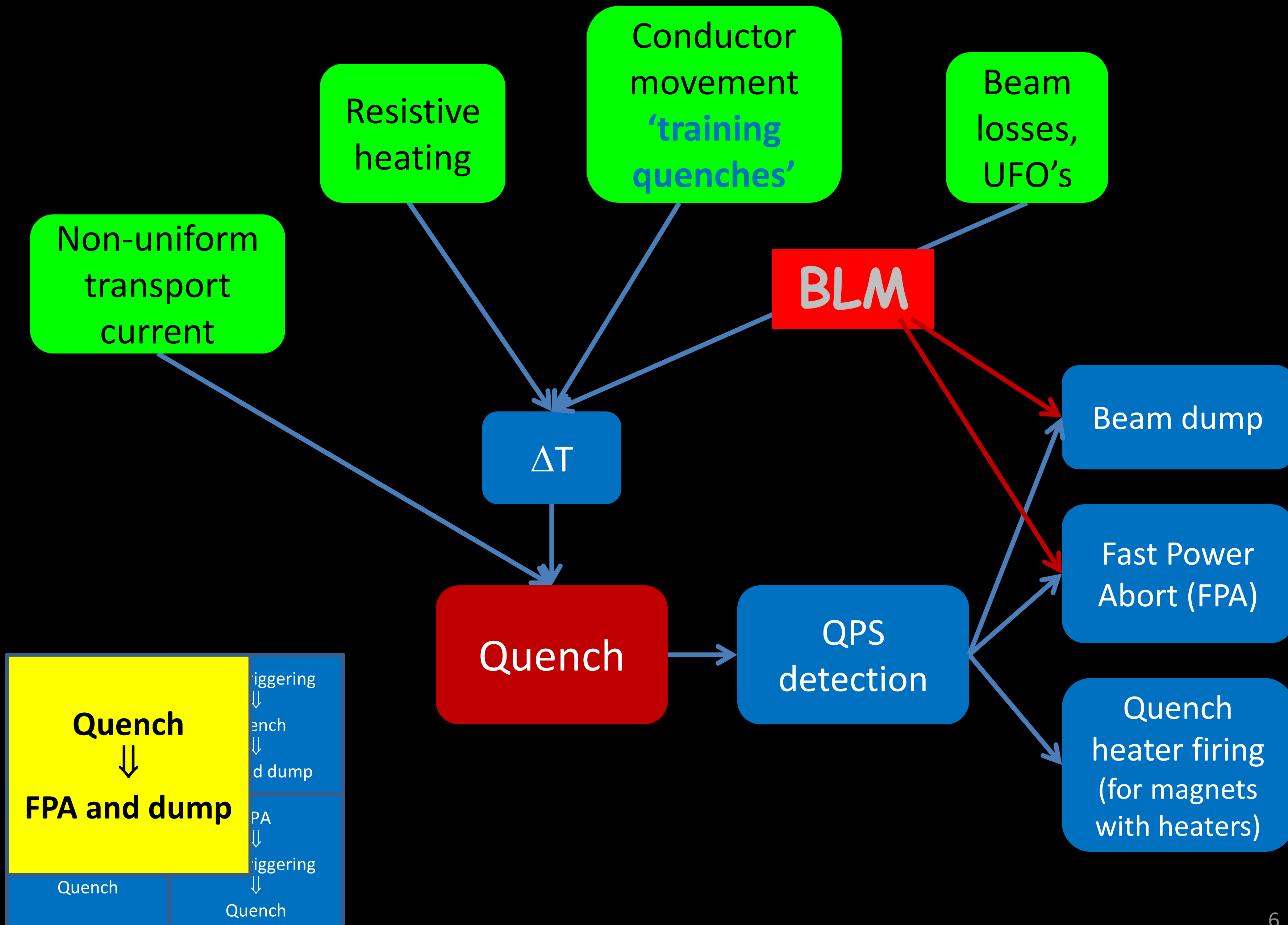
False triggering
⇓
Quench
⇓
FPA and dump

4

FPA
⇓
False triggering
⇓
Quench

Large impact on operation.
Ex.: it will take about 10 hrs to have again stable beams after a quench at 11 kA in a RB circuit.

Smaller impact on operation, but should be avoided as much as possible to reduce risk of magnet failure and reduce cryo recuperation time.



Conductor movement
'training quenches'
Resistive heating
Beam losses, UFO's
Non-uniform transport current
BLM
ΔT
Beam dump
Fast Power Abort (FPA)
Quench
QPS detection
Quench heater firing (for magnets with heaters)
Quench
⇓
FPA and dump
iggering
⇓
ench
⇓
d dump
PA
⇓
iggering
⇓
Quench
Quench

Quenches caused by resistive heating

- **Origin**: - Joule heating in a splice internal to the magnet coil,
  - local resistive heating in the SC if there are local defects.
- Very reproducible and, if it is a problem, are already observed during the magnet reception tests.
- Quenches of this type are **not** expected after LS1.
- However, tiny part of the coil will become more 'sensitive' to beam losses.

Quenches caused by non-uniform transport current (only in magnets wound from multi-strand cables, i.e. RB, RQ, IPQ, IPD, IT)

- **Origin:** Non-uniform joint resistance.
- The non-uniformity diffuses slowly through the cable ($\mathcal{O}$(10m/hr)), and are therefore not observed at magnet reception tests.
- Quenches are **not** expected at low dI/dt (1-10 A/s) or high neg. dI/dt.
- However, some strands will become more 'sensitive' to beam losses.

Training quenches (1/2)

RB

- Training will be dominated by the main dipoles.
- We have some (surprising) statistics from the HWC in May/June 2008 in S56 that can be used to estimate the number of training quenches after LS1.

  (see proceedings Chamonix 2009 and talk Ezio in S06)
- Training quenches can be done just after LS1 during a HWC campaign with 2-3 quenches per day and per sector, and several sectors in parallel.
- I would personally limit the number of RB quenches (just after LS1) to about 50-100. Note that after this, the gain in beam energy is only a few GeV per quench.

Other circuits

All other circuits will be trained to nominal before LS1 **(see also talk Mirko in S05)**. Training after LS1 (i.e. after a long thermal cycle) will probably be rather quick.

Training quenches (2/2)

It cannot be excluded that 4 years of additional powering, relaxation, and thermal cycling have another non-expected effect on the training.

A magnet that has been trained or has reached high current is **not** less sensitive to beam induced quenching.

Large de-training is not frequently observed, and training quenches during beam operation will therefore be rare (but requires that operating current is several % below training current).

Quenches due to beam loss (1/3)

In this business, every crystal ball
is very, very fuzzy (Seth Young)

Models:

- Energy deposition calculation along the magnet and over its cross-section
  (**Fluka, …**)
- Quench threshold calculation in the coil for a given energy deposition
  (**QP3, …**)

In a perfect world (without uncertainties in the models), we could set the BLM threshold slightly below the calculated quench threshold (of course after scaling and conversion from mJ/cm^3 to Gy/s)… **See talk Mariusz (S02)**

…and we would never have a beam induced quench, except for some losses with a duration less than about 300 μs (i.e. the time needed for detection+dump).

Quenches due to beam loss (2/3)

Unfortunately, even for a given loss type, occurring at a known position, the total inaccuracy in the quench threshold can be easily a factor 3.

Furthermore, there is an additional uncertainty of possibly a factor 5 since the type of loss and its location are unknown.

In order to be able to tune the BLM threshold, it was set equal to a master threshold times a monitor factor, where the monitor factor is <1, and can be set for each monitor independently.

Until LS1:

Knowing that we have defective 13 kA joints, a conservative BLM threshold is used (i.e. a small monitor factor) in order to minimize the probability of main dipole quenches, eventually propagating towards a defective joint.

Quenches due to beam loss (3/3)

After LS1: the BLM thresholds should be set so as to optimize the stable beams time, of course without putting in danger the safety of the magnets.

Proposal for the first year after LS1:

For each BLM family:

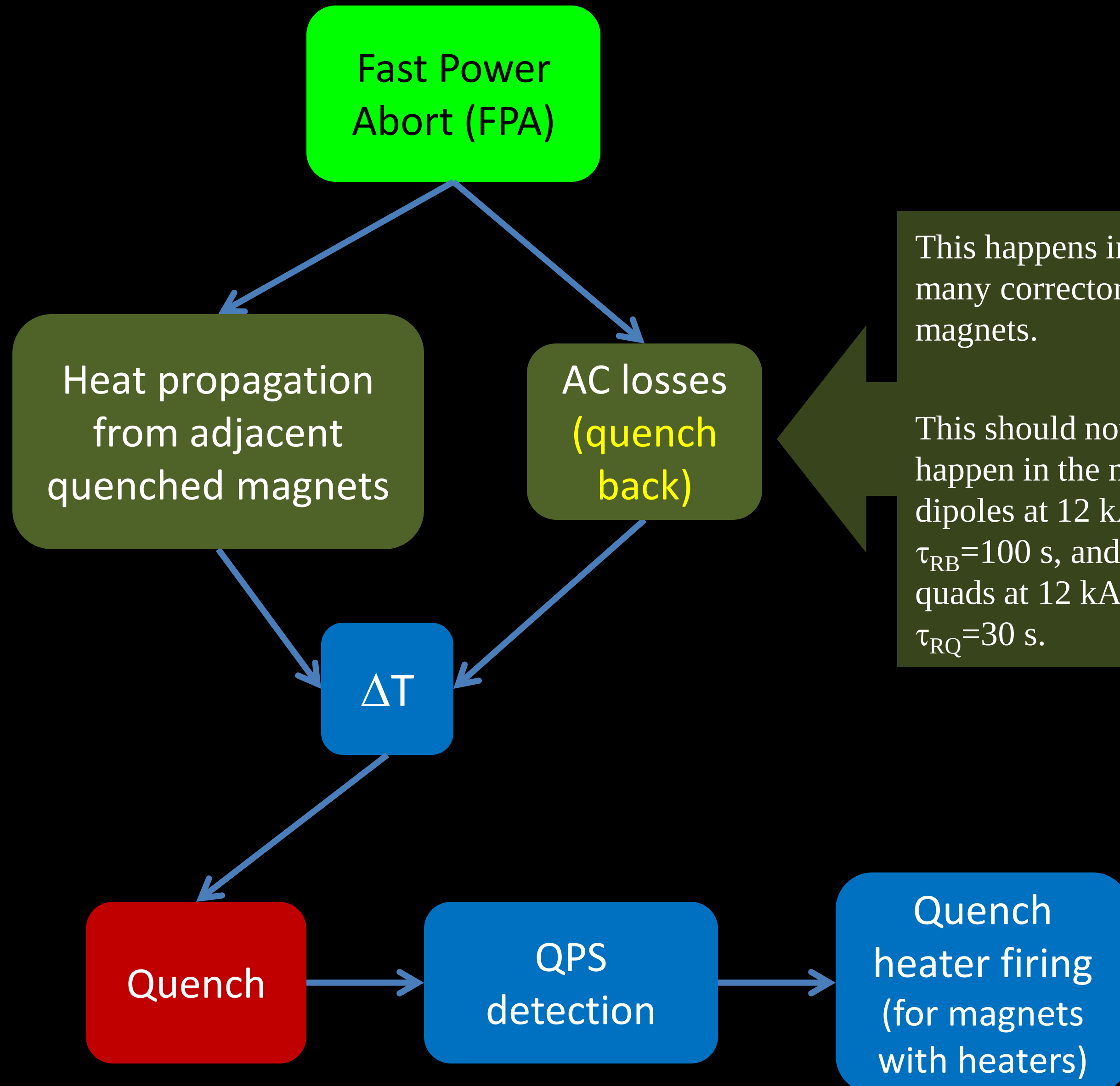
1. Set the initial BLM thresholds to the expected quench threshold. Best guess from models + experience from operation and MD's.
2. If a quench occurs **before (or without)** the BLM triggering a dump, then reduce the BLM threshold by 30%.
3. If the BLM triggers a dump **without** a quench then increase the BLM threshold by 30%.

- **There is no need to avoid all quenches.** Avoiding 80-90% seems a good target. Special care for magnets for which there are no spares.
- **The LHC machine is the in-situ test set-up.** More Lab measurements will help our understanding but will not affect the BLM setting in the machine.

Almost always from dipole to several other dipoles.

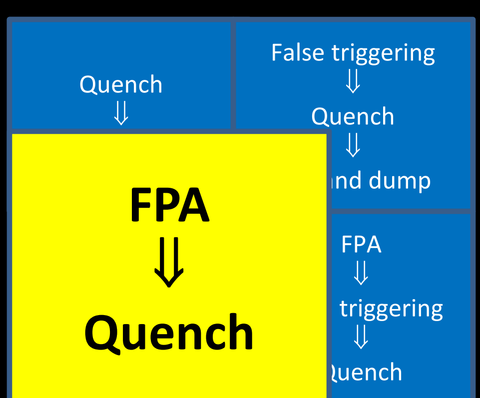
Very unlikely from dipole to quad or from quad to dipole.

Never for all other magnets.



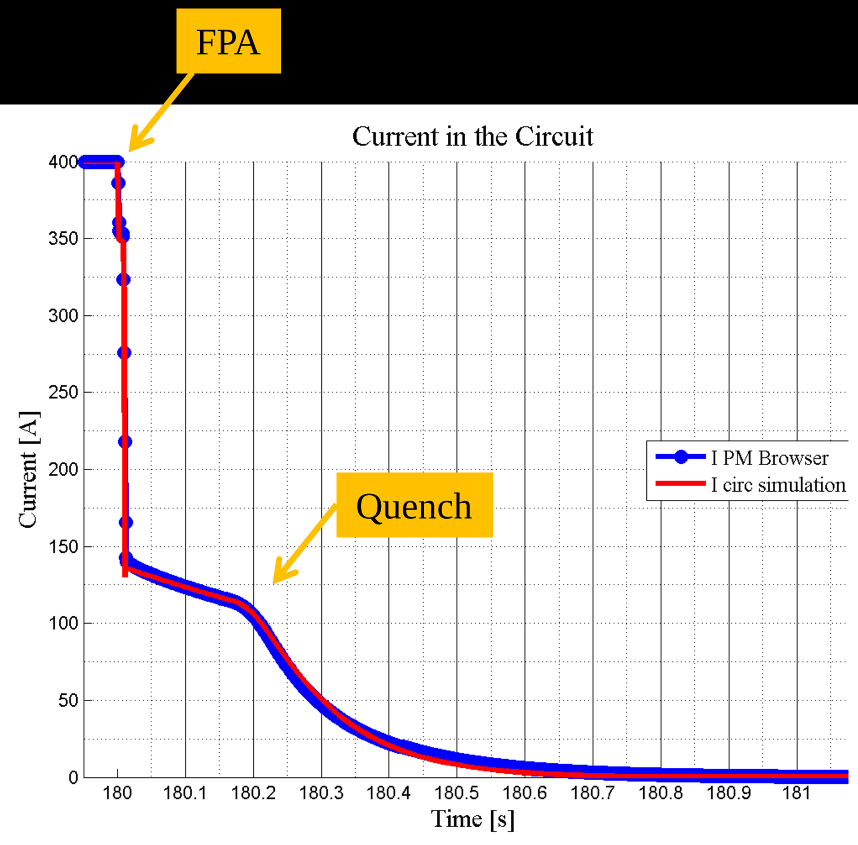
This happens in many corrector magnets.

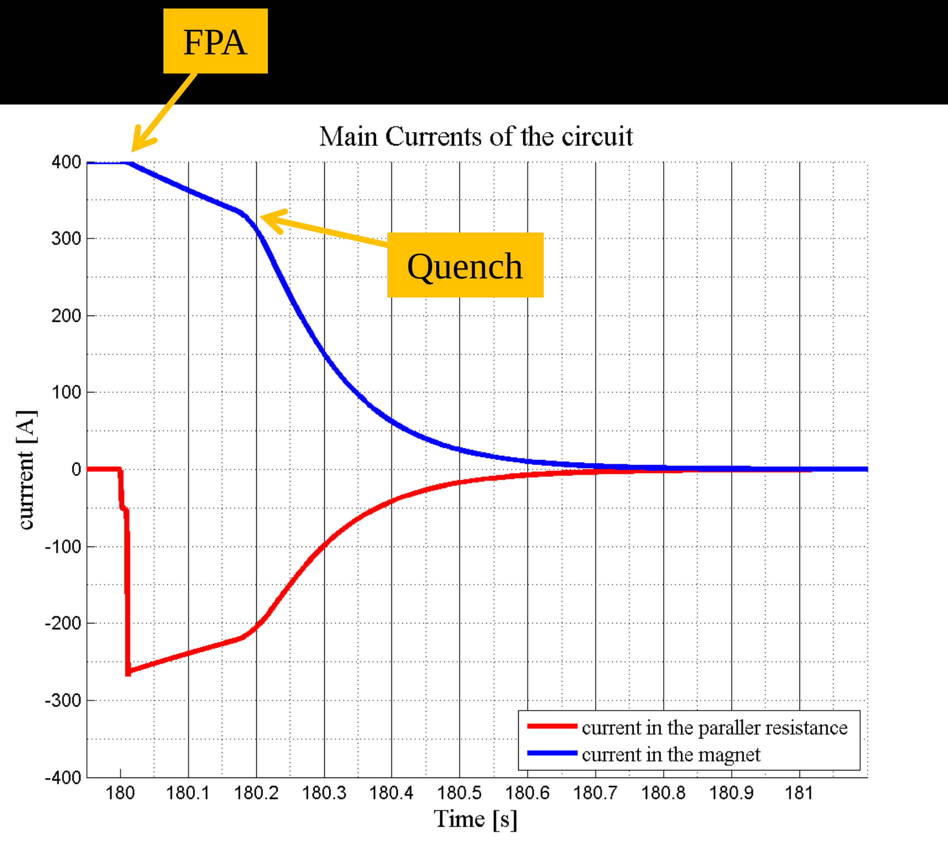
This should not happen in the main dipoles at 12 kA, τ_{RB}=100 s, and main quads at 12 kA, τ_{RQ}=30 s.

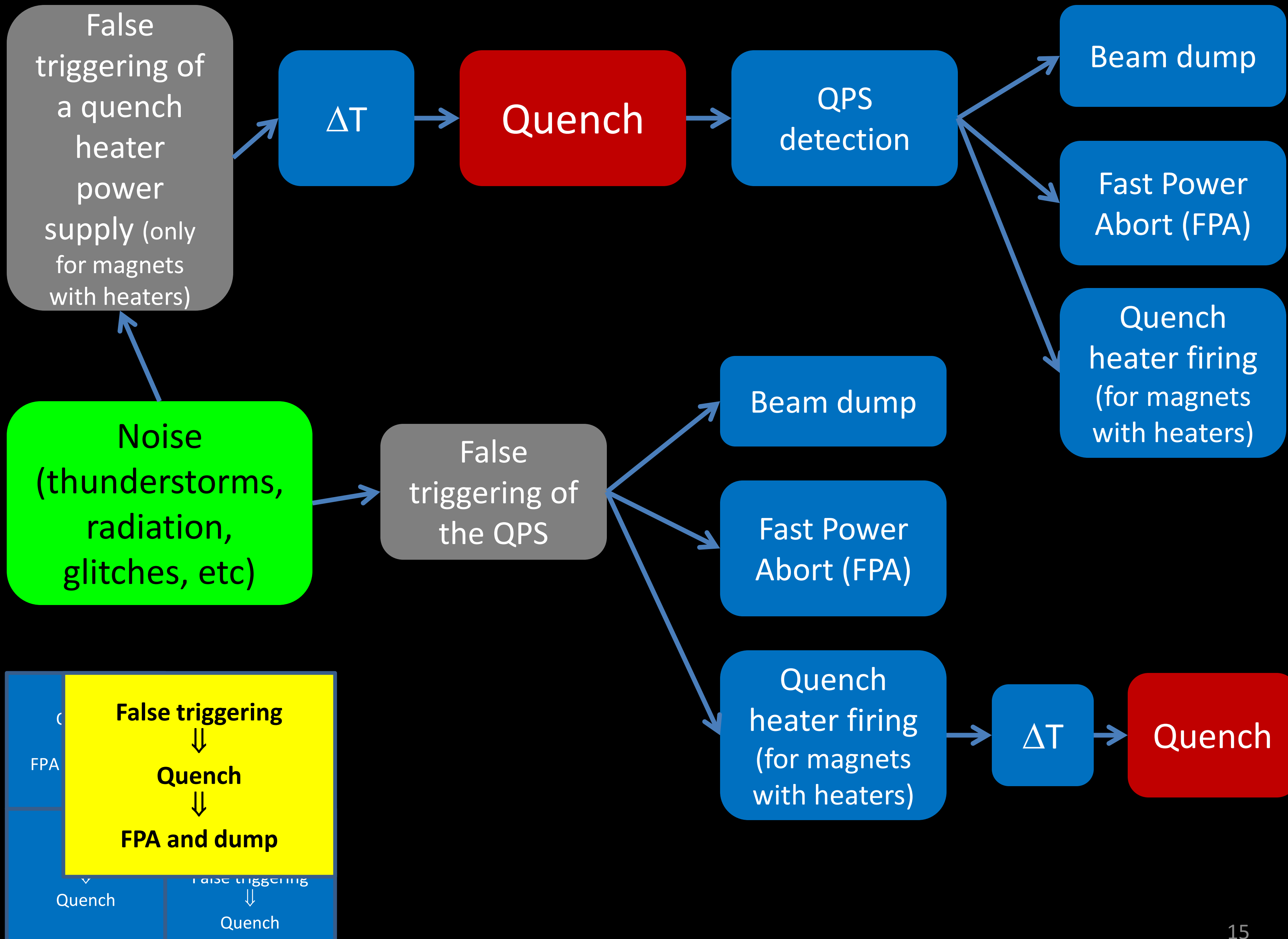


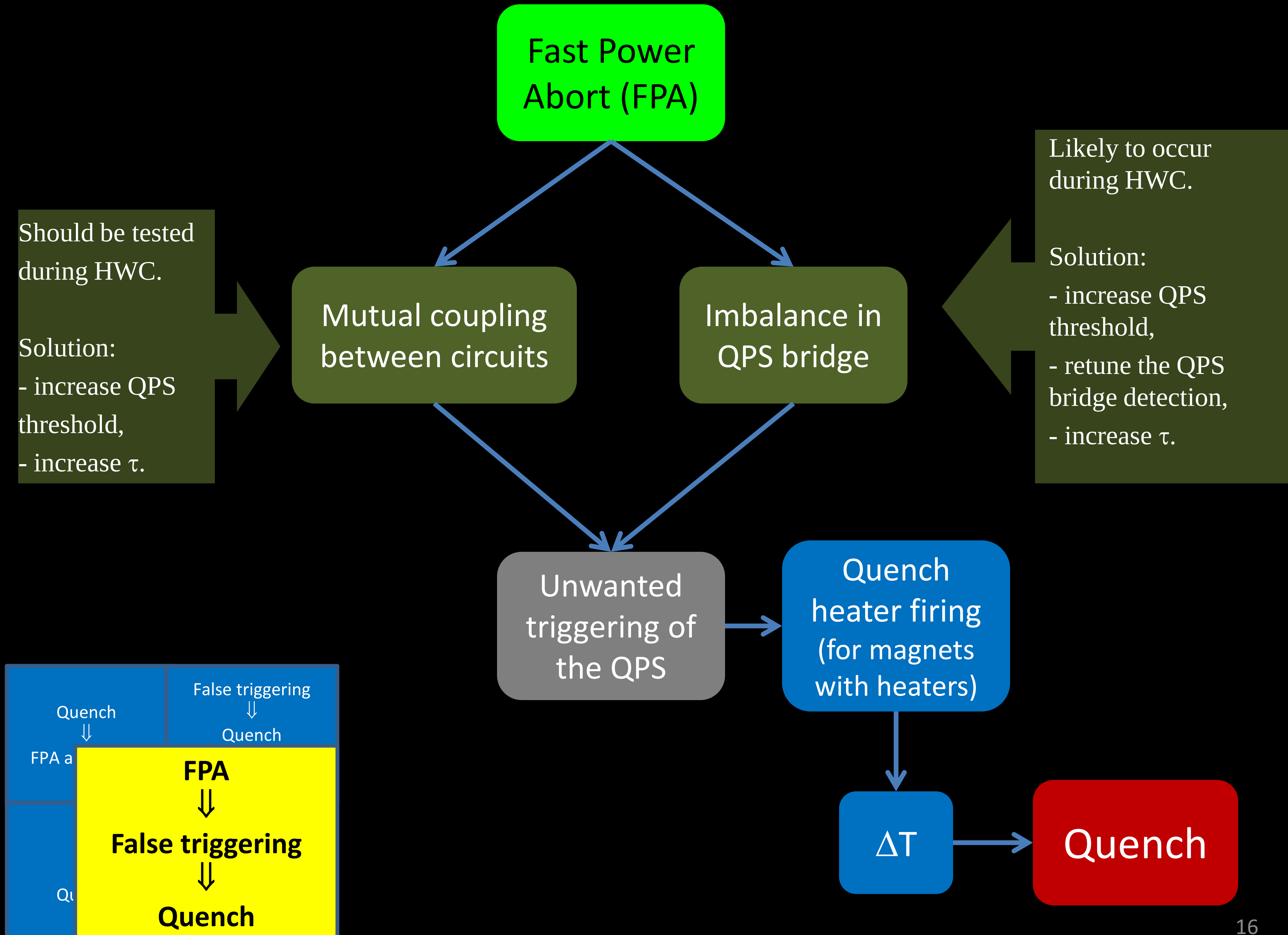
Example of quench back (RQTL9)

2xMQTL, R_{par}=0.2 Ω, EE=0.7 Ω, Uthr=0.1 V






False triggering of a quench heater power supply (only for magnets with heaters)
ΔT
Quench
QPS detection
Beam dump
Fast Power Abort (FPA)
Quench heater firing (for magnets with heaters)
Noise (thunderstorms, radiation, glitches, etc)
False triggering of the QPS
Beam dump
Fast Power Abort (FPA)
Quench heater firing (for magnets with heaters)
ΔT
Quench
False triggering
⇓
Quench
⇓
FPA and dump
FPA
Quench
⇓
Quench



Fast Power Abort (FPA)
Should be tested during HWC.
Solution:
- increase QPS threshold,
- increase τ.
Mutual coupling between circuits
Imbalance in QPS bridge
Likely to occur during HWC.
Solution:
- increase QPS threshold,
- retune the QPS bridge detection,
- increase τ.
Unwanted triggering of the QPS
Quench heater firing (for magnets with heaters)
ΔT
Quench
Quench
⇓
False triggering
⇓
Quench
FPA
⇓
False triggering
⇓
Quench

Quenches during HWC after LS1

Quench
⇓
FPA and dump

Yes, a certain number of training quenches depending on operating energy (<150).

False triggering
⇓
Quench
⇓
FPA and dump

None or very few.

FPA
⇓
Quench

Yes:
- when training the dipoles
- at the end of HWC during heat run (mainly in corrector circuits).

FPA
⇓
False triggering
⇓
Quench

Yes, but most problems will be solved during HWC by fine tuning the QPS.

Quenches after LS1

Quench ⇓ FPA and dump Yes, - possibly a few de-training quenches per year. - several beam-induced quenches.	False triggering ⇓ Quench ⇓ FPA and dump Yes, <10 per year, due to false triggering of the QPS. Probably none for the 13 kA circuits.
FPA ⇓ Quench Yes, - in case of a dipole quench, - always in certain types of corrector magnets.	FPA ⇓ False triggering ⇓ Quench To be seen…., but anyhow probably only in the corrector circuits.

Summary

Beam-induced quenches and false triggering of the QPS will be the main cause of those quenches that cause a beam dump. Possibly in total up to 10-20 per year.

Solutions to reduce false triggering are discussed by Reiner (S06).

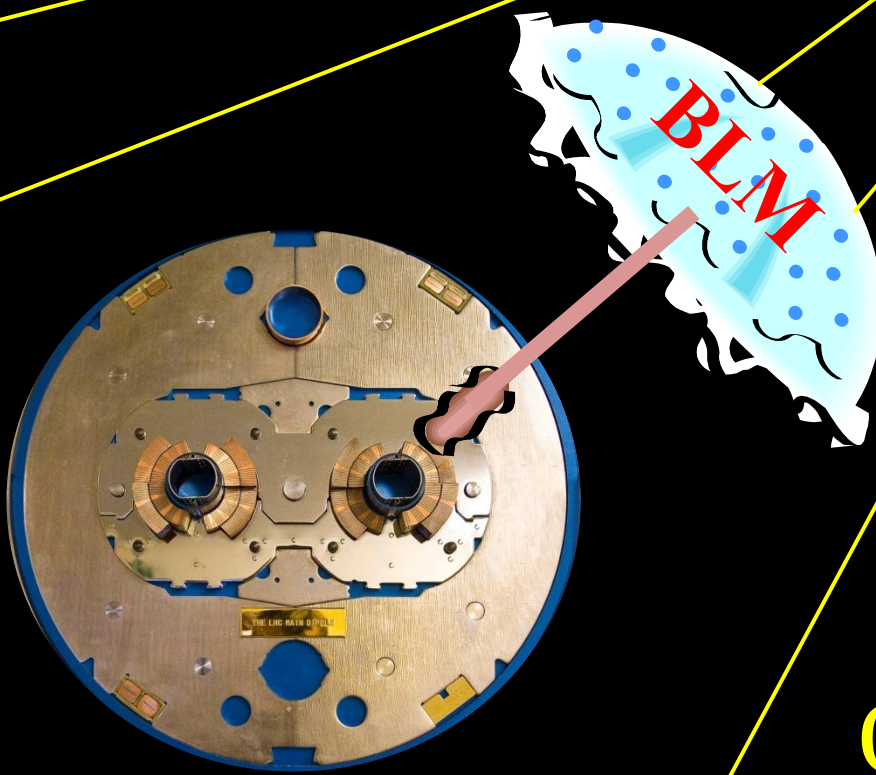
After consolidation of the 13 kA joints, the approach for the BLM settings can be less conservative than in 2010-2012 in order to maximize beam time. This will cause some quenches but, anyhow, a beam–induced quench is not more risky than a quench provoked by false triggering.

It is not easy to predict the number of BLM triggered beam dumps, needed to avoid magnet quenches (not sure how to scale beam losses and UFO's from 3.5 TeV to 6.5 TeV, and not sure if the thresholds at 3.5 TeV are correct).

See also talk Tobias (S07).

Quench events will be much more massive (ex: RB quench at 6 kA $\Rightarrow$2 MJ, RB quench at 11 kA $\Rightarrow$ 6-20 MJ), and as a result cryo recuperation much longer. We will also see more ramp induced quenches after the FPA in other circuits due to higher ramp rates and smaller temperature margins (mutual coupling).

The future looks bright



Questions?