Failure Scenarios and Mitigation (?)

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• The Problem

- When a crab cavity gets out of control and changes its voltage/phase, the beam may also get out of control: bunch is ‘banged’ by a single CC passage(*): $eV_{\perp} \approx c \cdot p_{\perp}$
- If the speed of change is so fast that the beam dump system – requiring 3 turns (≈ 300 μs) in the worst case – cannot react in time, severe machine damage is possible.
- Here we consider

  only the possible voltage/phase change scenarios

  the possible aftermath for the beam is not analyzed. –> T.B.

(*) The main RF can change rapidly causing much less problems: the cavity voltage is very small compared to the large bucket height: $eV_{\parallel} \lll c \cdot \sqrt{\Delta p_{\parallel}^2}$

– Time scales of ‘incidents’

3 groups of incidents

1) Intrinsically safe events (if interlock works !)

+ Mains power cut (anywhere EDF ….. local small trafo):

RF power supply has enough stored energy to survive many ms (mains 50 … 300 Hz -> 20 … 7 ms) : no problem

+ Thermal problems … in low power electronics, controllers:

Develops >> 1 ms : no problem

2) Unsafe events outside cavity, Q_{ext} important

– RF arcing in high power part (waveguide, coupler):

Full arc develops within about 1 μs: rely on 'cavity speed'

– Operator or control-logics error:

'instant' RF power change: rely on 'cavity speed'

3) Unsafe events inside cavity, Q_{ext} (nearly) unrelated

– Cavity quench: fast, Q_{ext} not directly involved

– Strong multipacting (MP): fast, …. as above ..

– Time scales of equipment changes

Any tuner of a (high-powered sc.) cavity is mechanical:
too slow to change significantly within 300μs

Q_{ext} is changed[(#)] by mechanical means
(stepper motor, ….) generally even slower than tuner:
too slow to change significantly within 300μs

During the total 'fast' incident (300 μs):
$\Delta\omega$ and Q_{ext} are what they were at onset

No hope for 'fast detunig' or 'fast ramp-up of Q_{ext}'

(#) if foreseen at all

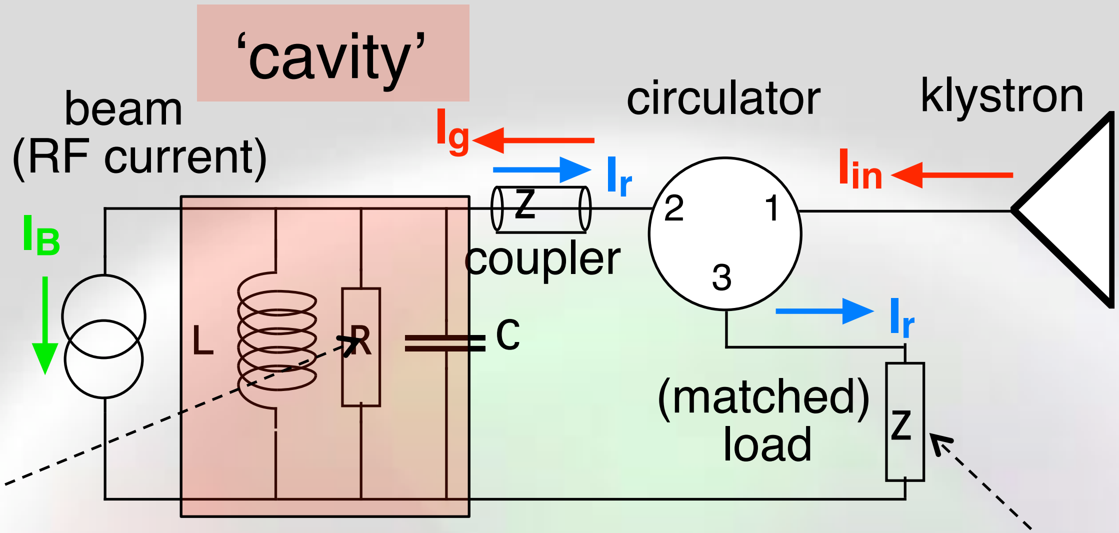
- **Elementary Cavity-Beam-RF relations**

"Common Knowledge":

SuperConducting cavities are slow

.. but only <u>on the test-stand</u> : 'weak' input antenna

not in a machine !!



Large R
= high Q_0

– Beam current 'directly coupled': Fast changes possible

– Compete with beam: strong RF coupling to cavity: Z << R ➔
Q_{ext} (= the coupler's apparent Q) << Q_0
Natural field decay time $\tau_F = 2\, Q_{ext}/\omega$ **fixed** by Q_{ext}: "fast"

– RF power 'strongly coupled': Fast changes possible by RF

Q_{ext} is not a 'free parameter':
determines also many other system properties !!!!!!

To get a small decay – say to 75% – within 300 μs

$$\exp(-300\mu s/\tau_F) \geq 0.75$$

$$\rightarrow \tau_F \geq 1000\mu s = 1 ms$$

@ 400 MHz: $Q_{ext} = \tau_F\, \omega/2 = 1'250'000$

– If cavity detunes by 100 Hz: ΔP_{RF}=2 kW OK

1 kHz: ΔP_{RF}=200 kW not OK

– BW = f/Q = 320 Hz

If cavity body shakes by ± 4 Hz ($\Delta f / f = 10^{-7}$)

±1° phase stroke

– **Z_T = 1300 MΩ/m**

(without RF feedback; RF planned 'off' at injection:

even cavity detuned, Z_T is present !! (f drifts)

(@ 800 MHz $Q_{ext}=\tau_F\, \omega/2$ = 2'500'000)

Intermezzo: transverse Beam-Cavity Interactions

Generalized Panofsky-Wenzel theorem

$$\Delta p_x = -\frac{i \cdot e}{\omega} \cdot \frac{dV_z}{dx} \rightarrow -\frac{i \cdot e}{\omega} \cdot \frac{V_z}{x} \quad (dipole \ \text{mode})$$

A beam not on axis ($x \neq 0$) sees a longitudinal voltage proportional to displacement parameter x:

Longitudinal Beam-Cavity interaction

Δp_x, V_z 90° out of phase

For crabbing operation

Δp_x, Bunch centre 90° out of phase

(set like this since we want only tilt, no kick for bunch center !!)

→ Bunch Center ($==I_b$), V_z in phase !!!

Good news (for machine protection):

the beam drives a transverse voltage with phase for

crabbing the bunch,

NOT kicking the whole bunch !

Bad news (for RF installation):

worst phase angle for parasitic longitudinal interaction

(for $x \neq 0$)

Beam passing at offset x sees $$V_{||} = x \cdot V_{\perp} \omega / c$$

(only magnitudes, forget 90° phase factor 'i' here)

Beam takes/gives **power,** induces **voltage** for x≠0: **Q_{ext}**

Assume **ultimate beam current** (1.7 10^{11} p/bunch, 25ns)

With Q_{ext}=1'250'00, if beam travels off axis at

x=±1 mm takes/gives 21 kW RF power

$Z_{||}$ = 12 kΩ (without RF feedback: injection ?)

A Q_{ext} of 1'250'000 => field decay to 75% in 300μs

seems feasible

(but lower Q_{ext} preferable for phase-noise (=microphonics) even when 'wasting' some RF power)

Till now only ‘break-**down**’ of field considered

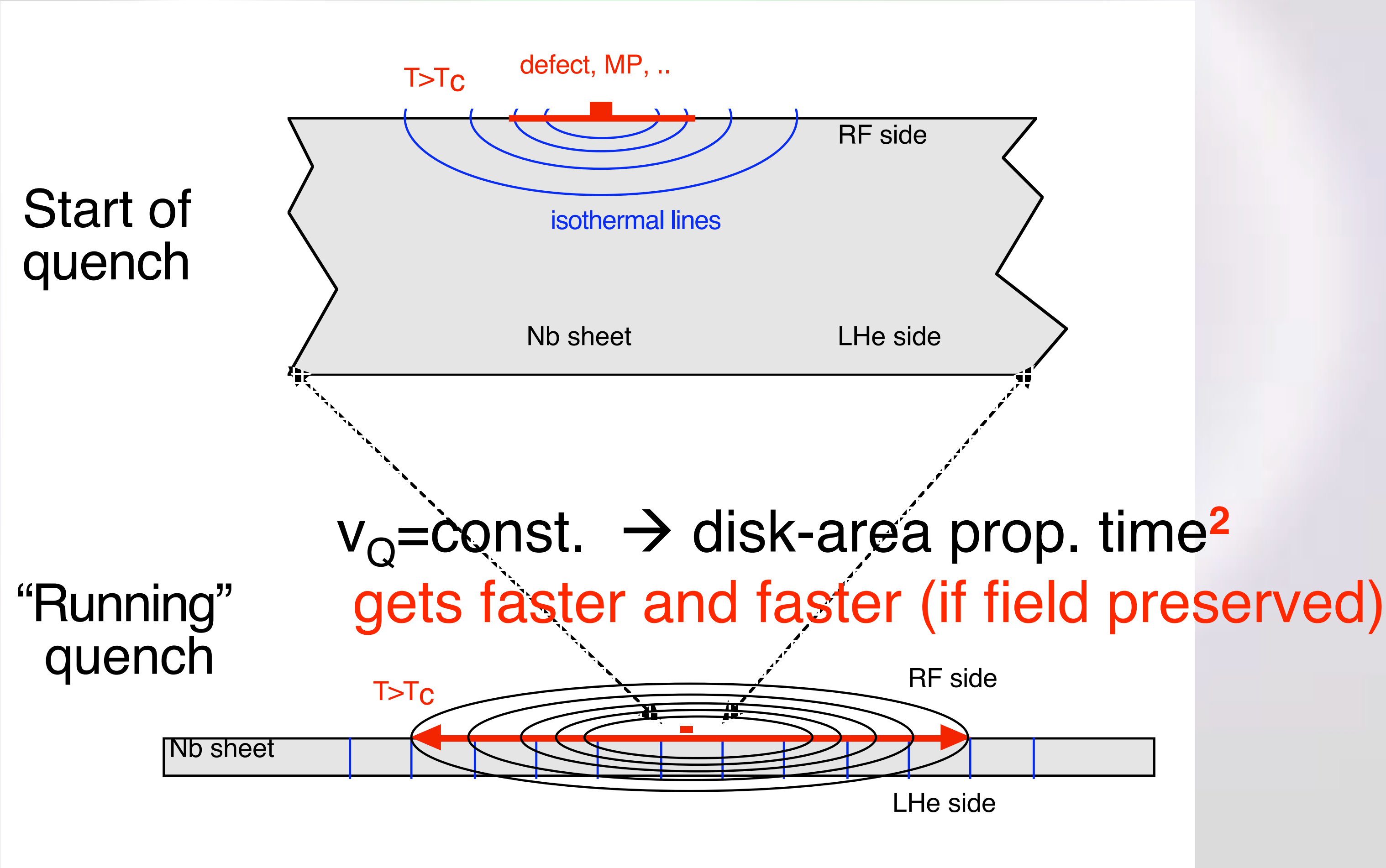
If the operator / control logics orders: rise field or shift phase (while else the RF power chain is still working)

Need a ‘perfect’ interlock (spikes = false alarms!):
Pull dump instantly and cut RF power: let fields decay by Q_{ext}
(best ‘in parallel’ for ‘local’ option)

Footnote:
For all aspects considered till now it reveals that
800 MHz cavity is worse by factor 2, 4 and 8
according to quantity examined (for same τ_F and x)

Cavity Quench Rule: "Thermal processes are slow" .. but:

- Specific heat of metals (as Nb) gets very low at low T
- RF power …MW/m² (T>T_c): quench development can be fast
  [Stored energy only some J: no damage (if RF power is cut by I/L)]



From lab tests with adapted antenna (Q_{ext} = some 10^9):

Typical break-down time scale: milli-second(s)

(Quench essentially lives from cavity stored energy)

With strong coupling + RF power as necessary with beam:

RF feedback fights to keep voltage up as long as possible:

Total breakdown duration is even longer !

Seems good ….

but:

“300 μs timer” starts ticking when the beam dump is triggered

at quench **recognition**

The start of the quench is not ‘announced’!
It can only be ‘guessed’ from field (and power ?) behavior within the ‘clutter’ (spikes,…) of other feedback actions
(false alarms –> beam-dump = low integrated lumi !!!).

In lab-test field drops ‘immediately’ ….: There is a quench!

With strong RF power quench initialization is ‘hidden’:
First, RF power demand increases while field ‘stays up’
… and quenched area > T_c increases as time^2
When quench is recognized, already large Nb area above T_c
→ poss. rapid breakdown when RF runs out of power

For a CC in the beam the field decay within 300 μs
after quench recognition can become sizable !

(RF) Multipacting (or multipactor)

- Exists ‘closed’ track (at … field level, … field band)

- Surface has secondary emission yield $Y(E) > 1$
  (‘dirt effect’: changes e.g. by cryo-pumping gas, ….)

- Electron impact energy is where $Y(E) > 1$

1 electron, Y electrons, Y^2 electrons, …. , Y^n electrons

Within e.g. T=1 μs @ 400 MHz = 400 oscillations:

$N=Y^{400}$ electrons:

assume very modest Y=1.1 →

$N=3 \cdot 10^{16}$; $I=e\,N\,f_{RF} = 2 \cdot 10^{6}$ A;

$P=I \cdot E_{imp}$= many MW $U_{loss} = P\,T$ =many J

(in reality space charge blows it apart before!)

Multipacting can eat energy very rapidly <u>if sustained</u>

<u>'Erratic' fast field changes possible</u>

In the lab the field drops rapidly:

low input power, only stored energy sustains MP

MP stops when (falling) field leaves the level/band

(Field may rise again if no quench as in Nb/Cu cavities)

With high power, field may be kept up longer:

recognition of incident to pull beam dump (see quench) …

MP may trigger quench, having already a large area > T_c when it is recognized (pull dump): **can be very fast**

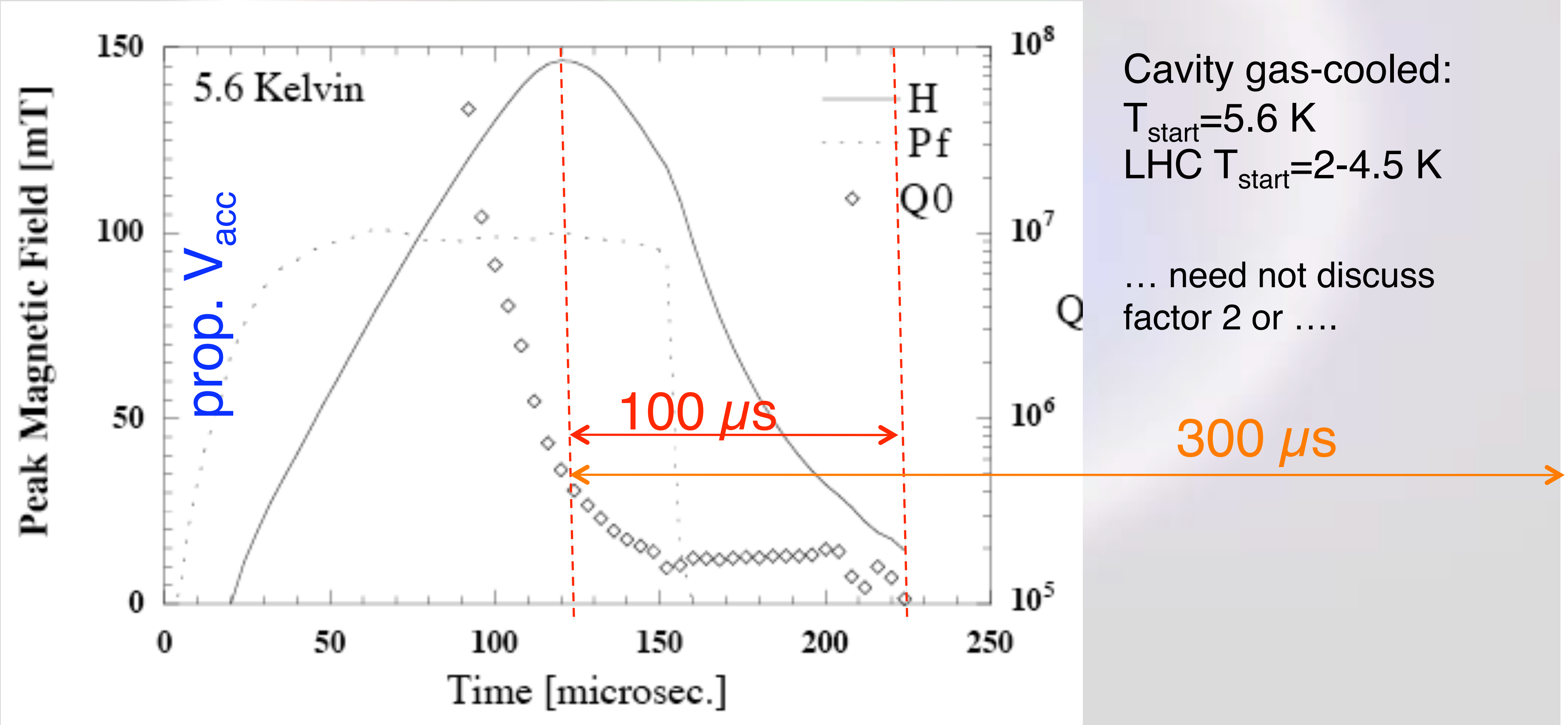
For those who do not believe in theory: Experimental Test

Response of Superconducting Cavities

to High Peak Power

T. Hayes, H. Padamsee, Cornell University / TPP02 PAC95

(Process cavities with high power pulses to (briefly) reach maximum field,
Q_{ext} as the usual one in high current accelerators as LHC)



Cavity gas-cooled:
T_{start}=5.6 K
LHC T_{start}=2-4.5 K

… need not discuss factor 2 or ….

Mitigation (to be valid for ALL incidents)

Attractive proposal: **Use many lower-V cavities, if one of them has an incident only small 'relative' effect**

– **All cavities have common points (RF drive, logics,..) such an incident affects ALL cavities**

– **LHC has to remain a low impedance machine:**
Significant struggle for corresponding HOM damping with a single cavity per station (4(#) if 'local' 2 detectors)
'Unnecessary' multiplication –> "design impossible"

(#) per beam

– **Space**: length in ring, underground RF / cryo galleries

– **$$$$** ('a detail' relative to other costs in LHC ?!?)

Conclusions

To make a long story short, consider:
"A Chain is as Strong as its Weakest Link!"

The fastest V change is caused by Quench or MP:
Not worthwhile considering details of other incidents(&).

One can NOT guarantee that the voltage stays at its nominal value(#) for
300 *μ*s after *recognition* of an incident (= pull dump)

Need orbit, collimator setting, robustness ..?.., ..?.. to survive a sizable V-change

(#) within a "small" margin

(&) extensively done by the author !

If we really need a stable voltage: Ask outside consultant
(someone having promising references)

Restoring the dead Lazarus to life again

Transforming water into wine

Thank you for listening