Scenarios concerning the cryogenic system for the 400 MHz LHC sc. cavities

Basis for discussion

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Normal operation:
8 cavities per beam working up to nominal peak field of 5.5 MV/m. Expected *dynamic* load (no cavity degradation, i.e. $Q > 2\ 10^9$) about 4*25W=100 W *per module* or 16*25 W = 400 W *in total*.

During injection half of the field is foreseen, thus (less than) one-quarter dynamic load; while the LHC energy is ramped also the cavity fields will change. However, *at any stage* we need the freedom to change the cavity fields "as we like" to change e.g. the bunch length. In principal foreseen field changes are (even in the cryogenic time scale) slow, but for operational reasons an imposed 'speed limit' would be undesirable; to be discussed.

Low cost or emergency 'normal' operation:
Improbable but not *completely* to be excluded as *initial* 'low cost' or later as emergency scenario: Four cavities per beam at increased field level, i.e. one module (per beam) removed. One should always keep in mind that – due to the finite RF power capability[1],[2] – LHC can practically only be operated with significantly reduced beam current (luminosity) for cavity fields significantly above the nominal ones.
The most extreme option would be to try cavity operation with twice the nominal field[3], i.e. a single module per beam would deliver the full nominal voltage. Taking also the Q-slope ($\approx 1\ 10^9$ @11 MV/m) into account, the dynamic load increases to about 800 W per module.
Working with half the number of modules but field increases *below* a factor 2 will ask for correspondingly less dynamic load but also offer less than the nominal voltage to the beam. It remains to be demonstrated that we can reasonably operate LHC under such conditions (increased injection losses, shorter beam life time, beam stability).

Death of (at least) **one cavity** or its essential **ancillaries** [4]:
• Any coasting beam is lost immediately if no more controlled RF power is fed to any of the cavities.
• A new luminosity beam cannot be injected[5] before either the problem is solved or the corresponding module is exchanged (or removed); such an operation will take a few days minimum (warm up, slow vacuum breaking, exchange of modules under

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[1] with Q_{ext} increased to its maximum value to reach 8.25 MV/m (1.5 times nominal) transients of up to 300 kW appear already for only half nominal intensity LHC type beam (in *stable* coast).
[2] due to the probably missing 200 MHz system, injection damping has to be done with the sc. cavities (as far as this is possible), asking for *low* Q_{ext}. (speed). However, with half the number of cavities, already during injection the nominal peak field has to be reached, asking for increased Q_{ext}.
[3] provided that all cavities can stand this field without field emission (?)
[4] Power coupler, HOM couplers, tuner, controls, machine or insulation vacuum, RF supply system (klystron, circulator, wave guides, HV), … supposing that cryogenics is not the culprit.
[5] An uncontrolled cavity (even detuned and at lowest Q_{ext}) will excite coupled bunch mode instabilities

laminar air flow, slow vacuum pumping, cool down[6] and temperature stabilization). In theory one spare module is always ready, else an emergency solution with 4 overdriven cavities for lower current might be tried (see above).

Degraded cavity

Probable case in the life of LHC: If a cavity is *only field limited* but can still be driven at reduced field, the other 7 cavities in this beam should be able to take over the missing voltage (possibly only with reduced beam current). In the worst case the single degraded cavity allows only zero volts (enforced) and the 7 others run at 8/7 of the nominal voltage (about 6.3 MV/m). For constant Q-value, the dynamic losses in the 'good' module will increase by $(8/7)^2$, i.e. about 30% more, the 'bad' module changes by $(3/4)*(8/7)^2$, i.e. nearly no change. In reality the Q-slope on 8/7 field-increase corresponds to about 10% hence in total about 40% increase for the 'good' module and 10% for the 'bad' module (i.e. 25% increase for the *total* dynamic load of the two modules).

Processing:

Increased LHe consumption is probable during RF or He processing, but in case of cryogenic overload in parallel processing, cavities (of one module) can be processed partly in series. Thus processing presents no serious constraint (considering the actual budget situation) but it takes more time. A single cavity surpassing during processing the load foreseen for a whole module is certainly to be discarded, so this is no issue.

RF operation before official machine runs:

To have an operational RF system once the magnets are cold, it would be helpful if we could process cavities several days before the magnets are ready, i.e. we would need LHe supply while or even before magnet cool down. From the preliminary discussions this option seems not be possible for technical reasons (not only a budget problem), so that we have to allocate time for processing in the machine planning.

Future options:

• To run LHC with *ultimate beam current* does *not need more cavity field* (RF power is the limiting quantity), i.e. apart from possibly slightly increased losses from the power coupler and HOM system (synchrotron radiation ?), this should be nearly transparent for cryogenics.
• Higher cavity fields for better beam stability and life-time: These options are not seriously foreseen for the time being and – in view of the budget situation – are no serious arguments to increase today the size of the nominal cryogenics load

Cryogenics over-load:

Normally the superconducting RF system will always stay within the cryogenics load depicted above. However, in the improbable event of unforeseen problems, it would be good that some overload could be supplied to cope with it.

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[6] Warm up and cool down have to be possible without 'disturbing' the LHC magnets, else further delays and problems have to be envisaged.

<u>Conclusion:</u>

• For normal operation an absolute minimum is 100 W/module dynamic load without any reserve, corresponding to 400 W in total (normal case: 4 modules).
• To compensate for a single degraded cavity per beam (i.e. one cavity in two modules), about 40% increased load for the 'good' module (140 W), 10% for the 'bad' one (110 W). This corresponds to 25% increase in total load.
• Except the very improbable case of field doubling, all other envisaged operations should be possible within the range of the previous case. Field doubling would in fact ask for 800 W dynamic load per module

• On top of these loads come the static losses in cryostat (150 W per module) and LHe supply system
• These loads have to be guaranteed any time, i.e there should be enough available overpower for regulation swings – always consuming additional power,

• The <u>precise regulation</u> of pressure and level should always be guaranteed for the full range <u>between static load</u> (RF off, about 50 W per module) <u>and full load</u> as taken from the following tables.
• All dynamic losses are calculated under the assumption that the operating temperature is not higher than <u>4.5 K in the He tank</u>.

Load description	Nominal field	One degraded cavity per beam	Double field (all cav.)
Dynamic (peak field)	100 W	'good' mod.:140 W 'bad' mod.:110 W	800 W
Reserve	25+ W	25+ W	??
Static load	150 W	150 W	150 W
GHe (4.5 equiv.)			

Tab 1: Cryogenics loads <u>*per operated module*</u>

Load	Nominal	One degraded cavity per beam	Double field on one module, one module removed	Double field on two modules, two modules removed
dynamic	400 W	500 W	1000 W	1600 W
Reserve	100+ W	100+ W	? W	? W
Static	600 W	600 W	450 W	300 W
GHe				

Tab 2: <u>*Total*</u> cryogenics load (These loads do not include the transfer line losses and reserves for cryogenic regulation)