CONSEQUENCES OF RF SYSTEM FAILURES DURING LHC BEAM COMMISSIONING

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Abstract

At nominal beam intensities, the loss of control of even a single RF cavity will require an immediate beam dump to avoid severe damage to RF equipment. During LHC beam commissioning, different beam structures and in particular lower intensities will be used. In this case it is possible that not all RF failures require a beam dump and that the beam may survive even if perturbed. Various RF failure situations and their consequences are analysed and possible strategies are suggested to ease operation during commissioning up to half the nominal beam intensity.

MAIN RF PARAMETERS FOR LHC

Each of the two proton beams is captured, accelerated and stored using eight super-conducting cavities housed in two cryogenic modules [1]. Each cavity, centre frequency $f_0 = 400$ MHz, and with a tuning range of ~100 kHz, is connected via a variable coupling loop, which allows the external quality factor Q_{ext} to be changed between ~15,000 and ~200,000, and a circulator to the klystron amplifier which can supply 300 kW. Each cavity has a low R/Q, 44 Ω, to give high stored energy and thus minimise transient beam-loading issues in coast, and can supply an accelerating voltage V_a up to 3 MV/ cavity, depending on the beam-loading.

POSSIBLE FAILURES

Possible failures can be looked at from the point of view of increasing seriousness:

- Loss of control of a single cavity; e.g a loop electronics problem, RF power system failure (but not HT)
- Loss of several cavities; e.g multiple failures of the above type, HT problem i.e. four cavities in one module lost
- Failures necessitating removal of one module; e.g a beam-vacuum leak, insulation vacuum leak, power or HOM coupler failure. These can be assimilated to a loss of four cavities as far as subsequent injection is concerned,
- Etc.

Note that a quench on a cavity implies an immediate beam dump and RF power stop to prevent a dangerous He pressure rise and damage to the cryostat.

In this paper we consider the problem of loss of control of up to four cavities, try to analyse the consequences and answer two questions for the commissioning period – can we continue with physics if there is a failure with beam present and can we inject a beam in the presence of this hardware problem? Each of these questions forces us to look at two issues: the first dealing with hardware protection to avoid aggravating the problem and the second looking at the effect on the beam - are we endangering the rest of the machine? An initial look at these problems has been presented in [2] and the particular problem of quenches will be studied in [3].

INITIAL CONDITIONS

This is a multi-variable problem. To ease the analysis we start from the nominal situation and then look at the effect of changes to these parameters.

RF system

The RF system parameters are adjusted at injection to fully compensate the phase modulation induced by the beam loading and hence help minimise capture losses and longitudinal emittance blow-up. In store the situation is different – here we to try to minimise both peak and mean power at high beam loading to maximise reliability and coast duration.

For the latter the cavity is tuned at the, so-called, ½ detuning value [4], $\Delta f_{det} = \frac{1}{4} f_0 R/Q \; I_{RF} / V_a$, where I_{RF} is the RF component of the beam current. The coupling is adjusted to give $Q_{ext} = 2 V_a / (I_{RF} R/Q)$.

At injection, where we require full control of the beam and where we need lower voltages for capture, stronger coupling, i.e significantly lower Q_{ext} than that given by the above formula is used.

The voltage at 7 TeV is 2 MV/cavity and at injection 450 GeV is 1 MV/cavity. (At both injection and top energy we can go to higher voltages if we have lower beam currents.)

Beams

The beams used for this analysis [5] are shown in Table 1 which also shows the values of Δf_{det} and $Q_{ext.}$ As commissioning progresses we move from bottom to top of the table. Single bunch and pilot beams are not considered as they are of very low intensity. M is the number of bunches and N_b the number of protons per bunch. $I_{rf} = 2I_{DC}F_b$, where I_{DC} is the DC beam current and F_b is the form factor for the bunch. At injection, $F_b = 0.75$ and $V_a = 1$MV, while at 7 TeV $F_b = 0.87$ and $V_a = 2$MV.

HARDWARE PROTECTION

Limitations

Two limitations are considered. Over-voltage in the cavity when control is lost can cause arcing and surface damage. The cavities are conditioned to 8 MV/m, i.e $V_a = 3$MV,

Table 1: Beams considered for this analysis and the corresponding values of Δf_{det} and Q_{ext}

Beam	M	N_b 10^{11}	I_{rf} A	Δf_{det} kHz	Q_{ext}	I_{rf} A	Δf_{det} kHz	Q_{ext}
			Injection			7 Tev		
25ns								
Nominal	2808	1.15	0.87	3.85	20,000	1.01	2.23	90,000
½ Nominal	2808	0.58	0.44	1.92	20,000	0.51	1.12	178,000
75 ns								
Nominal	936	1.15	0.29	1.28	20,000	0.34	0.74	267,000
½ Nominal	936	0.58	0.15	0.64	20,000	0.17	0.37	535,000
Initial Comm.								
156 bunches	156	1.15	0.05	0.21	20,000	0.06	0.12	1,515,000
43 bunches	43	1.15	0.01	0.06	20,000	0.02	0.34	4,545,000

and we take this as the limit. The beam induced power in the cavity goes via the circulator to a load. The latter is probably the weaker component and the power is limited nominally to 300 kW. This is conservative, but non-perfect matching in the waveguide elements can lead locally to high field values in the circulator which may cause arcing.

Transient effects.

When power to the cavity is lost the stored energy in the cavity decays at the resonant frequency while the beam-induced voltage builds up at $f_{rf} = hf_{rev}$, h being the harmonic number and f_{rev} the revolution frequency. An example of the transient is given in Fig. 1. The detailed shape depends strongly on the de-tuning etc. In general, the transient is fast, typical time scales are of the order of 100 μs, with a peak voltage decaying to a steady state-value. Both values decrease as Δf_{det} increases and Q_{ext} decreases. This is also true for the power in the load.

Cavity voltage / load power

Although commissioning beams are the subject here, it is instructive to look at how the de-tuning influences the powers and voltages induced by a nominal beam. From Table 2 we see that both can be very high. On-tune the power taken would be 2.7 MW and the voltage induced 5.3 MV. At the nominal de-tuning value of 2.23 kHz which we are obliged to use to keep the power requirements from the klystron within limits, the power is still above 1 MW and the voltage >3 MV. This will kill the load if nothing is done. In addition we have to ask where this power comes from. The loops will act to keep the beam at the correct energy and so this power must come finally from the other klystrons. This implies that the remaining seven klystrons will have to supply an extra 150 KW each and will trip off. There will be a cascade effect. There is serious danger with the nominal beam and the only choice is to dump the beam when losing control of a cavity.

For commissioning beams Table 3 shows the situation.

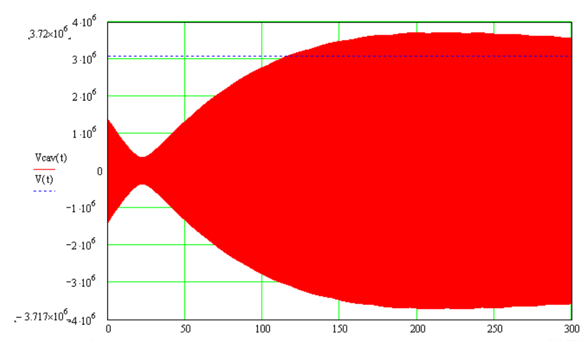

Figure 1: Envelope of cavity voltage after power trip. 25 ns nominal beam, $Q_{ext} = 120{,}000$, $\Delta f_{det} = 2$ kHz, $I_{rf} = 1.01$ A, $V_a = 2$ MV.

For 43 bunches there is no problem, for 75 ns nominal and 25 ns half nominal beam the limits are exceeded, particularly concerning the power. The figures in green show the result of a slight change in parameters, slightly more detuning and stronger coupling. These small changes bring the values within bounds and are permissible since the total power requirement at beam intensities lower than nominal allows some freedom.

Note that we assume here that we retain control at all times of the tuner and coupler. If not, we must rely on hardware protection interlocks. The measurement of cavity voltage and load power is used as part of the beam-dump interlock.

Table 2: Beam-induced power and voltage as a function of detuning. 25 ns nom. beam, Q_{ext} =120,000, $\Delta f_{det,opt}$ = 2.23 kHz, I_{rf} = 1.01 A, V_a = 2 MV, 7 TeV.

Δf_{det} kHz	P_{load} kW	V_a kV	Time to 90% µs	Peak V_a kV
0	2693	5333	210	5333
2	1106	3418	110	3755
4	400	2055	60	2800
6	193	1430	30	2400
8	112	1090		2300
10	73.1	878		2100
20	18.6	444		2100

Table 3: Beam-induced power and voltage as a function of detuning. 25 ns nom. beam, Q_{ext} = 120,000, $\Delta f_{det,opt}$ = 2.23 kHz, I_{rf} = 1.01 A, V_a = 2 MV, 7 TeV.

		I_{RF} A	ΔF_{det} kHz	Q_{ext} x 10^3	P_{load} kW	$V_{a\ ss}$ kV	$V_{a\ pk}$ kV
25ns ½ Nom.	450 GeV	0.44	1.92	20	80	376	
	7 TeV	0.51	1.12	178	512	2832	4200
			2.0	120	282	1726	1950
75ns Nom.	450 GeV	0.29	1.28	20	36.4	253	
	7 TeV	0.34	0.74	200	328	2402	3500
				120	255	1640	
43 bunch	450 GeV	0.013	0.06	20	0.08	11.8	
	7 TeV	0.016	0.03	200	1.1	136	

BEAM ISSUES

Transient effects

When a cavity trips, the voltage in that cavity changes from that imposed by the RF to that given by the beam-loading. There will be a transient on the total voltage. The main beam control phase loop will damp any induced phase oscillations but there will be quadrupolar oscillations leading to emittance blow-up. In this case a quadrupole/Hereward damping loop could be useful. However, as the phase loop keeps the beam and total voltage in phase, and, as the cavities are de-tuned, the resulting total voltage seen by the beam is a function of the beam-loading. At low beam currents the change will simply be as given by the loss of one cavity RF voltage but, as seen in Table 4, at half nominal current the voltage change for up to three cavities is small. It is only when four cavities are lost that the voltage becomes significantly lower. This "compensation" in voltage loss does not come for free. The power to produce it is coupled by the remaining active cavities via the beam into the tripped cavity. As a result a loss of two cavities is probably the maximum acceptable for half nominal beam.

Table 4: Total voltage seen by the beam in the event of a cavity trip and extra power required from other klystrons.

25 ns ½ nominal beam	Injection		Top	
	Vrf left	Extra power /cavity	Vrf left	Extra power /cavity
	MV	kW	MV	kW
Start	8	0	16	0
1 off	7.8	31	15.1	40.3
2 off	7.3	72	14.0	94
3 off	6.7	131	13.0	169
4 off	3.9	217	10.8	282

Instabilities

When the cavities are operational the impedance seen by the beam is significantly reduced by the RF feedback. This reduction is lost when the cavity trips. An instability can be driven by the difference in impedance between the $-nf_{rev}+mf_s$ and $nf_{rev}-mf_s$ (n = 0,1,2,3 etc.) sidebands on either side of the RF frequency. If the cavity is exactly on-tune it can be destroyed by beam-loading on the fundamental but in principle there is no instability. However, with de-tuning there is a difference in impedance. The lowest mode, n = 0, is damped by the main phase loop, but not the higher modes. Fig. 2 shows how the impedance on the sidebands, n = 1 to 5, can change with de-tuning. (The "negative" impedance on the left-hand side is stable for the modes cited above but not for the $-nf_{rev}-mf_s$ and $nf_{rev}+mf_s$ sidebands.)

To determine whether this impedance is dangerous the instability threshold impedance for different beams is required. This has been studied in detail in [6]. From this study, if we assume there is a programmed blow-up to 2.5 eVs from 1 eVs during acceleration (to reduce intra-beam scattering) and that the impedance frequency is ~ 400 MHz, then for a nominal beam the threshold impedance is ~ 0.8 MΩ for all energies.

The dependence of the threshold impedance R^{thr} on interesting parameters is given by,

$$R^{thr} \propto \varepsilon^{3/2} V^{1/4} h^{9/4} / (E^{3/4} I_0).$$

From this we see that if the emittance is kept at 1 eVs the threshold impedance at 7 TeV drops by a factor 4. Also, when the staged 200 MHz system is installed there will be a factor 6 reduction. These estimations assume that the there is negligible coherent frequency shift from the Im(Z/n), i.e. no loss of Landau damping.

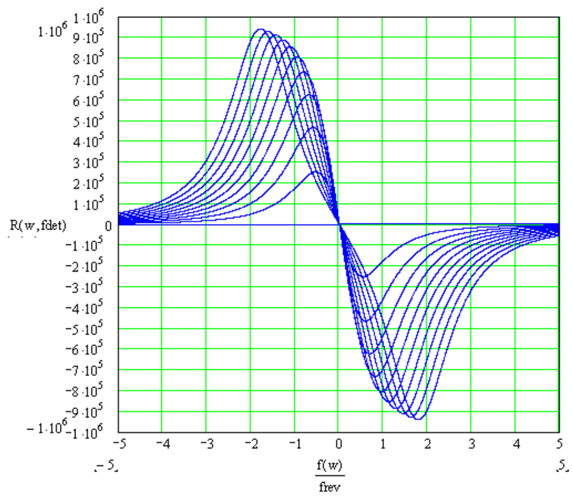

Figure 2. Difference impedance for one cavity with de-tuning. Q_{ext} = 20,000, Δf_{det} in steps of 2 kHz. Horizontal n = -5 to +5. Vertical -1 to 1 MΩ.

The calculated impedance for the first three modes for one cavity off is given in Table 5 for nominal and ½ nominal beam and the calculated de-tuning values. For nominal beam up to two cavities can be off before 0.8 MΩ is exceeded. For ½ nominal beam, even with eight cavities off the threshold impedance, now 1.6 MΩ, would not be passed. For 1 eVs at 7 TeV, one cavity off at nominal and four cavities at ½ nominal intensity would be acceptable.

As seen in Fig. 2 the impedance rises with increasing de-tuning. For injection into a passive cavity, Q_{ext} should be reduced to the minimum to give the lowest impedance. The de-tuning is also a free parameter. Table 6 gives the impedance as a function of de-tuning for Q_{ext} = 20,000. If the de-tuning is limited to <3 kHz then four cavities can be off for ½ nominal beam. However accurate tuning is necessary. The main source of error here comes from the He pressure, the variation of frequency with pressure being 150 Hz / mbar. This imposes a pressure variation in the cryostat below ± 5 mbar.

Acceleration and 7 TeV

As the available voltage decreases, the stable phase angle, φ_s, during acceleration rises, and the bucket size decreases. For 4 MV the φ_s peaks at a value of 8° at ~ 3.5 TeV. The bucket area is ~ 2.1 eVs at this energy. This imposes careful programming of any blow-up but nonetheless acceleration with 4 MV should be possible. At 7 TeV the lower bucket area due to a lower voltage will mean the bucket is fuller. This may have implications on beam lifetime in the presence of RF noise. In addition the bunch is longer and this leads to less luminosity. From Table 7 it is seen that the bunch length τ_b can be lowered and the ratio of bucket area A to bunch emittance ε_b can be increased by keeping ε_b at 1 eVs. This is an interesting option, even with full voltage available, if there are no instability or intra-beam scattering problems.

Table 5. Impedance seen by beam, one cavity tripped.

		Injection			7 TeV		
Beam	Mode n	Δf_{det} kHz	Q_{ext} 10^3	R kΩ	Δf_{det} kHz	Q_{ext} 10^3	R kΩ
25 ns nominal	1	3.85	20	300	2.23	120	100
	2	3.85	20	82	2.23	120	12
	3	3.85	20	30	2.23	120	4
25 ns ½ nominal	1	1.92	20	150	1.12	120	48
	2	1.92	20	41	1.12	120	6
	3	1.92	20	15	1.12	120	1.8

Table 6: Impedance seen by the beam as a function of de-tuning, Q_{ext} = 20,000.

	Impedance kΩ			
Δf_{det} kHz	1 cav off	2 off	3 off	4 off
20	840	1680	2520	3360
10	710	1420	2130	2840
5	480	960	1440	1920
3	320	640	960	1280
2	220	440	660	880

Table 7: Bunch and bucket parameters at 7 TeV

V_{total} MV	ε_b eVs	τ_b ns	A eVs
16	2.5	1.05	5.9
8	2.5	1.28	4.1
16	1	0.55	5.9
8	1	0.78	4.1

SUMMARY

The loss of power to up to two cavities can probably be accommodated when beam is present provided that the intensity/bunch is below ½ nominal for the 25 ns beam or below nominal for the 75 ns beam. This is true for all commissioning beams. To be able to accept this, the RF should work at or near to the half de-tuning criterion and with values of Q_{ext} below the optimum value given by minimum power consumption considerations. This is possible since not all klystron power capability is used at intensities below nominal. At higher intensities it is necessary to dump the beam to prevent serious damage to the RF hardware, the measured cavity field and circulator load power providing the trigger. When power to the cavity is lost both the tuner and the coupler should be blocked in position.

Beam intensities up to ½ nominal intensity can be injected into a machine with up to four cavities inactive, i.e. one module. The cavities should be set to their half de-tuning values and the coupler should be inserted as far as possible to lower the impedance. Acceleration and storage with reduced performance for lifetime and luminosity is possible for 4 MV. These two parameters can be improved if 1 eVs is kept throughout the cycle, though with this emittance the beam may be unstable or suffer from undue intra-beam scattering. At low intensities it is possible to push the voltage in the cavities beyond their nominal values towards the maximum of 3 MV. The frequency of the passive cavities must be maintained to within ± 0.75 kHz.

In the near future the working group involved in this study will attack the cases of cavity quenches, the response of a cavity to a beam dump in the presence of 1-turn feedback, and the detailed optimisation of the RF interlock system.

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