PROPOSAL FOR AN RF ROADMAP TOWARDS ULTIMATE INTENSITY IN THE LHC

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Abstract

The LHC currently operates with 1380 bunches at 50 ns spacing and 1.4 10^{11} p per bunch (0.35A DC). In this paper the RF operation with ultimate bunch intensity (1.7 10^{11} p per bunch) and 25 ns spacing (2808 bunches per beam) summing up to 0.86A DC is presented. With the higher beam current, the demanded klystron power will be increased and the longitudinal stability margin reduced. One must also consider the impact of a klystron trip (voltage and power transients in the three turns latency before the beam is actually dumped). In this work a scheme is proposed that can deal with ultimate bunch intensity. Only a minor upgrade of the Low Level RF is necessary: the field set point will be modulated according to the phase shift produced by the transient beam loading, thus minimizing the RF power while keeping the strong feedback for stability and reduction of the RF noise.

INTRODUCTION

The LHC has operated so far with a cavity voltage (amplitude and phase) constant over one turn. Given the strong modulation of the beam current at the revolution frequency (twelve successive injections during filling, presence of a 3.2 µs long abort gap in physics, and a series of smaller gaps required by the SPS and LHC injection kicker risetime, Figure 1), the requirement that the voltage phase be constant over one turn leads to a large required klystron power to compensate the transient beam loading.

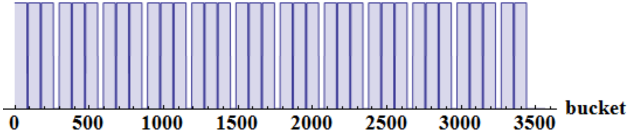

Figure 1: Filling pattern [1]. 25 ns spacing. 2835 bunches. The 3564 available buckets are shown in the x-axis.

The classic optimal detuning (klystron current aligned with the cavity voltage) does not minimize the requested peak power during the turn in the presence of gaps. In the LHC we use an "half detuning" algorithm, that minimizes and keeps constant the klystron power over the whole turn [2][3]

$$\left[\frac{\Delta f}{f}\right]_{half} = -\frac{1}{4} R\!\!\diagup\!\!Q \, \frac{I_{rf,pk}}{V} \tag{1}$$

where V is the cavity voltage, R/Q = 45 ohms, and $I_{rf,pk}$ is the peak RF component of the beam current

$$I_{rf,pk} = 2 f_b n_b q \frac{1}{T_b} \tag{2}$$

with n_b the number of protons per bunch, q the charge of a proton, T_b the bunch spacing, and f_b the bunch form factor (between 0 and 1).

If we keep the voltage constant over one turn, and with beam current orthogonal to the cavity voltage (180 degrees stable phase), the required klystron power during the beam and no-beam segments are [3]

$$P_{beam} = \frac{1}{8}\frac{V^2}{Q_L R/Q} + \frac{1}{2} Q_L R/Q \left[\frac{V}{R/Q}\frac{\Delta f}{f} + \frac{I_{rf,pk}}{2}\right]^2 \tag{3}$$

$$P_{no-beam} = \frac{1}{8}\frac{V^2}{Q_L R/Q} + \frac{1}{2} Q_L R/Q \left[\frac{V}{R/Q}\frac{\Delta f}{f}\right]^2 \tag{4}$$

With the "half detuning", the klystron power remains constant over one-turn while the phase of its drive is switched between beam and no-beam segments. The loaded Q_L can then be optimized to minimize the power. Figure 2 (dotted blue trace) shows the klystron power vs. Q_L for nominal beam current (2808 bunches, 1.1 10^{11} p/bunch, 0.56 A DC), 25 ns bunch spacing, 300 ps rms bunch length (f_b =0.75 for a Gaussian distribution), and 1.5 MV per cavity (present situation in physics). In this case, the RF would be operated with Q_L at 60k, requiring 200 kW while the LHC klystrons saturate at 300 kW RF.

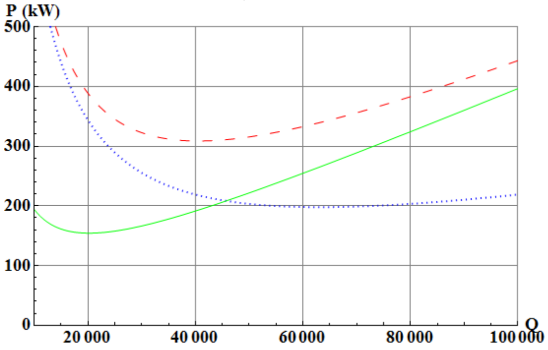

Figure 2: Klystron power vs. Q_L with half detuning. Dotted blue trace: physics conditions, nominal beam current (0.56 A DC), -3.2 kHz detuning. Dashed red trace: physics conditions, ultimate beam current (0.86 A DC), -4.9 kHz detuning. Solid green trace: injection conditions, ultimate beam current, -9.8 kHz detuning.

The dashed red trace corresponds to ultimate intensity (1.7 10^{11} p/bunch). The optimal Q_L is now 40k, and the requested klystron power exceeds the available 300 kW. **The present scheme cannot be extended beyond nominal.**

The situation is different with injection conditions as the cavity voltage is lower (0.75 MV/cavity). The solid green trace (ultimate beam current) indicates an optimal Q_L= 20k, requesting only 155 kW per klystron. Therefore, it is possible to enforce a strictly constant RF voltage over one turn ("half detuning") during filling at ultimate intensity. But it will be necessary to deviate from this scheme in physics.

PHASE MODULATED RF VOLTAGE

The idea is to accept the modulation of the cavity phase by the beam current (transient beam loading) and adapt the voltage set point for each bunch accordingly. This method was proposed by Boussard for the LHC [2] and was also implemented in PEP II [4].

Using the results and notations of [4], with much simplification for the 180 degree stable phase, the transfer functions from beam amplitude a_B to cavity amplitude a_V and phase p_V are

$$\frac{a_V}{a_B} = -\frac{2\pi\,\Delta f_0\left(2\pi\,\Delta f_0 - 2\pi\,\Delta f\right)}{\left(s+\sigma\right)^2 - 2\pi\,\Delta f\left(2\pi\,\Delta f_0 - 2\pi\,\Delta f\right)} \qquad (5)$$

$$\frac{p_V}{a_B} = -\frac{2\pi\,\Delta f_0\left(s+\sigma\right)}{\left(s+\sigma\right)^2 - 2\pi\,\Delta f\left(2\pi\,\Delta f_0 - 2\pi\,\Delta f\right)} \qquad (6)$$

where Δf is the actual detuning and Δf_0 the optimal detuning to the beam current, i.e. the detuning that makes the klystron current aligned with the cavity voltage. We will refer to this as full detuning

$$\left[\frac{\Delta f_0}{f}\right] = -\frac{1}{2}\,{}^{R}\!/_{Q}\,\frac{I_{rf,avg}}{V} = -{}^{R}\!/_{Q}\,\frac{f_b\,I_{DC}}{V} \qquad (7)$$

Note that the full detuning is a function of the average RF component of beam current while the half detuning depends on the peak RF component. The ratio between the two is not two to one in the presence of beam gaps. The damping rate σ is related to the loaded Q_L and RF frequency f

$$\sigma = \frac{\pi\, f}{Q_L} \qquad (8)$$

The solution proposed for the LHC [2] (not operational yet) and used at PEP II [4] is to operate at full detuning (equation 7), and let the beam gaps modulate the cavity phase, while keeping the klystron current amplitude and phase unchanged over the turn. When operating at full detuning, the amplitude of the cavity voltage is not affected by the beam gaps (equation 5), but the phase of the cavity field varies as a first order low-pass filtering of the beam current modulation (equation 6)

$$\frac{p_V}{a_B} = -\frac{2\pi\,\Delta f_0}{s+\sigma} \qquad (9)$$

Figure 3 shows the modulation of the cavity phase in physics, with ultimate intensity per bunch and the filling pattern shown on Figure 1: clearly visible are the effects of the various gaps. The modulation of the cavity phase changes the bunch spacing and therefore the collision point. As the filling pattern of the two rings is very similar, and as the abort gaps "collide" at the symmetric IP1 and IP5, the phase modulations will cancel out for ATLAS and CMS, and the resulting displacement of the collision vertex will be much smaller than the above 65 ps (that is already acceptable compared to the 1.2 ns 4σ bunch length). For ultimate beam current, with 1.5 MV/cavity, the full detuning would be -7.8 kHz. The klystron power becomes independent of the beam current and decreases monotonically with Q_L. For 60k, we would only need 105 kW. So there is enough margin to increase the cavity voltage to 16 MV/beam if needed, corresponding to an acceptable 185 kW with the proposed scheme.

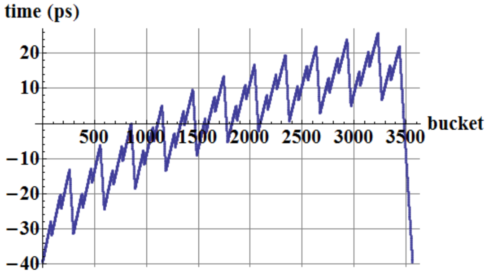

Figure 3: Modulation of the cavity phase by the transient beam loading in physics. 2835 bunches, 1.7 10^{11} p/bunch, 1.5 MV/cavity, Q_L=60k, full detuning (-7.8 kHz).

The behaviour during filling is investigated, with 0.75 MV/cavity, Q_L=20k, 25 ns spacing, and ultimate bunch intensity. The klystron current is kept constant, and the beam induced phase modulation is observed halfway through filling, when its effect is maximum (Figure 4).

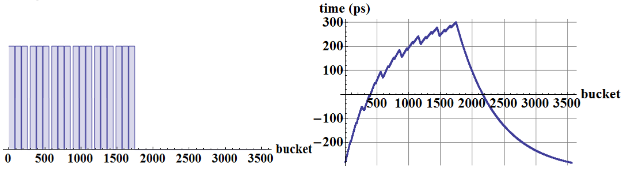

Figure 4: Filling pattern (halfway through filling) and beam induced phase modulation. 0.75 MV/cavity, Q_L=20k, full detuning (-8 kHz), ultimate current.

The cavity phase modulation is much larger than in physics because the voltage is reduced and the gap now spans half a turn. We observe 600 ps pk-pk. During the ~8 μs length of the next injected SPS batch the phase slips by 200 ps, that would result in unacceptable capture losses. **While filling it is preferable to keep the present scheme: constant cavity voltage and half detuning**. At ultimate current, that calls for an acceptable 155 kW.

Once filling is completed, and before starting the ramp we would move from "constant cavity voltage" (half detuning) to "phase modulated voltage" (full detuning), while adjusting the voltage set-point. To achieve this, a modification to the tuner algorithm and the implementation of an algorithm to compute the voltage set-point are necessary. At start ramp, the full detuning corresponds to -16 kHz. We need 78 kW for 0.75 MV/cavity at Q_L=20k. At that moment in the cycle, the modulation of the cavity phase would be twice that shown on Figure 3 because the voltage is halved. The full detuning would be kept through the ramp and in physics, with continuous adaptation of the voltage set point bunch by bunch to minimize transient klystron power. An algorithm was proposed at EPAC 2006 [5]. We will also look at the method used at PEP II [6]. The main coupler and voltage functions will remain unchanged.

STABILITY

In this paper the global issue of longitudinal stability of the ultimate intensity beam in the LHC is not addressed but only the effect of the cavity impedance at the fundamental. The growth rate and tune shift of coupled-bunch mode *l* (dipole) can be computed from the cavity impedance (assuming $\Delta\omega_l << \Omega_s$)

$$\sigma_l + j\Delta\omega_l = -\frac{\eta\, q\, I_{DC}\, f_b}{2\beta^2\, \Omega_s\, E\, T_{rev}} \sum_{p=-\infty}^{\infty} \omega\, Z(\omega) \qquad (10)$$

with

$$\omega = (p.h + l)\omega_{rev} + \Omega_s \qquad (11)$$

For a cavity at the fundamental, only two terms in the above infinite sum are not negligible: $p = 1$ and $p = -1$. The impedance $Z(\omega)$ is much modified by the strong RF feedback that transforms the cavity impedance to a flat response with 700 kHz two-sided bandwidth, independent of the cavity Q_L [8]. Stability is preserved if the growth rate is significantly smaller than the tune spread $\Delta\Omega_s$ [9]

$$\sigma_l < \frac{\Delta\Omega_s}{4} \qquad (12)$$

Table 1 summarizes the results with ultimate beam current (0.86A DC), using a simple linear model for the RF feedback loop and a conservative bunch form factor equal to one.

Table 1: Growth rate of the least stable mode caused by the impedance of the eight cavities at the fundamental

Energy (GeV)	Q_L	Detuning (kHz)	Total RF voltage (MV)	σ max (s^{-1})	Synchrotron frequency (Hz)	$\Delta\Omega_s/4$ (s^{-1})
450	20000	-9.8	6	1.8	56.6	12.4
450	20000	-16	6	**3**	56.6	**12.4**
7000	60000	-7.8	12	0.3	20.4	4.5

The first row corresponds to filling, with constant voltage set-point and half detuning. When filling is finished, we start voltage phase modulation and move to full detuning (second row). The last row gives the situation during physics. Listed growth rates and tune shift are maximum over all modes. The bunch length is kept at a constant 1.2 ns, with the classic LHC longitudinal blow-up [10]. The least stable situation is encountered with full detuning at injection (second row). Still, the maximum growth rate (3 s^{-1}) is significantly lower than $\Delta\Omega_s/4$ (12.4 s^{-1}). So stability is guaranteed. In addition, a longitudinal damper acting via the main accelerating cavities will be commissioned in 2012. Modes with significant growth rates extend to $l \sim 30$, which are well within the bandwidth of this system.

The first revolution sideband (f_{rev} =11 kHz) would be crossed twice. Preliminary analysis of the consequence of imperfect alignment of the One-Turn Feedback [11] (not included in the above analysis) suggests no problem.

SURVIVING A KLYSTRON TRIP

When a klystron trips, the circulating beam induces full beam loading voltage in the cavity and the RF power then flows through waveguide and circulator into the load [7]. Operation at full detuning, with an accepted phase modulation is very beneficial to the situation following a klystron trip as the cavity is further detuned with the new scheme. With ultimate current (0.86A DC), Q_L=60k, and full detuning, a klystron trip leads to an acceptable 1.4 MV beam induced voltage and 350 kW beam induced power that can be taken by the load during the 270 µs latency until the beam is dumped.

CONCLUSIONS

The present scheme (constant cavity voltage – amplitude and phase – and half detuning) cannot be used for physics, above nominal intensity, as it requires excessive RF power. To reach ultimate intensity we propose to ramp and collide with a scheme that allows phase modulation of the cavity field by the beam gaps while adjusting the voltage phase set point accordingly, bunch per bunch. With the tuner at "full detuning" that scheme allows for operation at ultimate intensity with only 185 kW RF for 2 MV/cavity. The beam induced voltage and RF power following a klystron trip are acceptable. During filling, the present scheme should (and can) be kept up to ultimate.

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