THE LHC RF SYSTEM - EXPERIENCE WITH BEAM OPERATION

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Abstract

The LHC RF system commissioning with beam and physics operation for 2010 and 2011 are presented. It became clear in early 2010 that RF noise was not a lifetime limiting factor: the crossing of the much feared 50 Hz line for the synchrotron frequency did not affect the beam. The broadband LHC RF noise is reduced to a level that makes its contribution to beam diffusion in physics well below that of Intra Beam Scattering. Capture losses are also under control, at well below 0.5%. Longitudinal emittance blow-up, needed for ramping of the nominal intensity single bunch, was rapidly commissioned. In 2011, 3.5 TeV/beam physics has been conducted with 1380 bunches at 50 ns spacing, corresponding to 55% of the nominal current. The intensity per bunch (1.3×10^{11} p) is significantly above the nominal 1.15×10^{11}. By August 2011 the LHC has accumulated more than 2 fb^{-1} integrated luminosity, well in excess of the 1 fb^{-1} target for 2011.

PROTON RF OPERATION 2010

With single bunch pilot (5×10^9 p), there were no observable issues when the synchrotron frequency crossed the much feared 50 Hz line during the ramp. The lifetime was very good: the bunch lengthening (4 σ length) was around 30 ps/hour at the 450 GeV injection energy and 6 ps/hour at 3.5 TeV. The single bunch intensity was then increased up to the nominal 1.15×10^{11} p with no issue at 450 GeV but, at that intensity, the bunch was initially unstable during the ramp, due to the significant adiabatic bunch length reduction (resulting in less than 600 ps, from a measured 1.2 ns at injection) and consequent loss of Landau damping. The bunches were blown up longitudinally in the SPS to achieve stability. This temporary solution increased capture losses though. It was used until the deployment of the LHC longitudinal emittance blow-up [1]. The LHC blow-up is active through the ramp and adjusted to keep the bunch length at 1.2 ns, thus achieving longitudinal stability as predicted [2]. We injected 0.5 eVs emittance bunches from the SPS (1.5 ns long), captured with 3.5 MV and increased the voltage linearly though the ramp to 8 MV, kept in physics. The proton run came to an end in October with 368 nominal bunches (12% of the nominal ring intensity) and 150 ns bunch spacing. More details on the LHC RF operation 2010 can be found in [3].

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RF NOISE AND BEAM DIFFUSION

At 3.5 TeV the synchrotron radiation damping time is about two hundred hours. The target for longitudinal emittance growth time caused by RF noise was 13 hours minimum at 7 TeV (equal to the synchrotron radiation damping time at that energy). RF noise was a major concern during LHC design: klystrons convert HV ripples to phase modulation whose frequencies are harmonics of 50 Hz, extending to 600 Hz in the LHC. During acceleration the synchrotron frequency crosses the 50 Hz line and problems were expected. The RF was therefore designed to reduce noise sources and minimize their impact on the beam. The LHC RF profited from the experience of SPS p-pbar RF operation. The RF Beam Control system was designed with a strong Beam Phase Loop (BPL) that compares the beam phase (averaged over all bunches of a given ring) with the cavity field vector sum and minimizes the error by acting on the RF. The BPL reduces the noise on the dipole mode 0 synchrotron sidebands ($f_s \sim 28$ Hz in physics). Without it the phase noise at f_s leads to 300-400 ps/hour bunch lengthening at 3.5 TeV/c. By changing the BPL gain, we can increase the level of the phase noise Power Spectral Density $S_{\phi\phi}(f)$ (PSD) at the synchrotron frequency until its effect is significantly above the one of Intra Beam Scattering (IBS). As RF-caused bunch lengthening is proportional to the PSD sampled by the beam at the synchrotron frequency,

$$\frac{d\sigma_\phi^2}{dt} = \frac{\Omega_s^2}{2\pi} S_{\phi\phi}\left(\frac{\Omega_s}{2\pi}\right) \qquad (1)$$

we can then scale down the noise power by the BPL gain to estimate the RF contribution. This exercise gives 2.5 ps/h in physics [3,4]. In 2011, with 1380 bunches per ring and 1.3×10^{11} p/bunch, the observed bunch lengthening is around 15 ps/hour in physics, dominated by IBS effects.

CAPTURE REVISITED IN 2011

With the RF parameters of 2010, the SPS bucket at extraction was much larger than the LHC bucket (twice as long, 70% taller and three times the area), resulting in uncaptured beam at injection into the LHC. The uncaptured beam drifted gently in the machine and would occasionally be deflected by the kicker at a later injection, leading to a dump of the whole circulating beam by the machine protection. Reduction of the SPS bunch length would not be a lasting solution due to longitudinal instability in the SPS, for bunch lengths below 1.5 ns, with the future 25 ns spacing. Instead, the LHC RF voltage was increased to 6 MV at injection to capture more off-momentum particles. As a result, the capture losses were substantially reduced. In addition transverse injection gap cleaning was commissioned: to remove the uncaptured beam, the transverse kicker excites the small population in the next injection segment during filling, at frequencies that span the betatron band so that the particles are driven to the betatron collimators before the next injection. The RF voltage during physics was increased from 8 MV in 2010 to 12 MV in 2011 (linear variation through the ramp from 6 MV at injection to 12 MV at flat top), to accommodate for increased longitudinal emittance and thereby reduce transverse blow-up caused by IBS. The ramp duration was reduced from 15 to 11 minutes, during which the longitudinal blow-up keeps the bunch length around 1.2 ns, resulting in 1.9 eVs emittance in a 4.7 eVs bucket at 3.5 TeV.

SCRUBBING WEEK APRIL 2011

The 2010 configuration was initially re-established, with a bunch spacing reduced to 75 ns. A week of scrubbing with high bunch intensity (1.5×10^{11} p/bunch) and 50 ns spacing followed. We reached 900 bunches (40 % of nominal current), but only at 450 GeV. The RF used the occasion to monitor the heating of the cavities HOM dampers and the power extracted, and found no problem. Following the success of the scrubbing week, it was decided to operate with 50 ns bunch spacing in 2011.

SURVIVING A KLYSTRON TRIP

As the beam intensity was increased in spring 2011, the vacuum degraded in the warm section closest to the outer two cavities and arc detectors in the waveguide close to the main coupler would trigger. These were false alarms caused by radiation and the problem was solved by upgrading the detectors electronics and by ANDing the detector signals by pairs.

The effects of an RF trip were periodically re-evaluated:

1. Particle loss (de-bunching) following the non-adiabatic reduction of the bucket and subsequent population of the abort gap,
2. Multi-bunch instability caused by the impedance of the idling cavity at the fundamental mode,
3. Voltage induced by the beam in the idling cavity,
4. Reverse power crossing the circulator (potential for arcing) and dissipated in the load.

The de-bunching was regularly monitored by intentionally switching a klystron off with beam. For example, with 1102 bunches (1.21×10^{14} p total) a klystron trip resulted in only 5×10^{9} p populating the 3 μs long abort gap. These particles would then loose energy through synchrotron radiation, move to the momentum collimator and be scraped out of the machine after ~ 15 min at 3.5 TeV. The 5×10^{9} p were well below the safe level estimated at 5×10^{10} p maximum in the abort gap. With nominal parameters in physics the synchrotron tune spread provides enough Landau damping to stabilize the beam with one klystron tripped, at the nominal beam current 0.58 A DC [3]. The critical limitation comes from the beam-induced voltage (that should not exceed 2 MV) and the load power (rated 300 kW CW maximum). These are reached with a klystron trip at around half nominal beam current [5]. Therefore, when we exceeded 1100 bunches mid-June, we linked the klystron surveillance to the beam dump system: from then on, the trip of a single klystron would dump both beams. From July 14th till August 18th, 5 out of 43 physics fills were terminated by an RF fault.

LONGITUDINAL STABILITY

Small-amplitude but long-lasting dipole oscillations are observed at injection. Neither the number of bunches per batch nor the distance between batches has a significant influence. The effect does not appear to be a multi-bunch instability. A similar behaviour is observed with single-bunch injections at high bunch intensity. Figure 1 shows the successive injections of two batches, with 12 bunches and 36 bunches respectively. The amplitude of dipole oscillation (1-2 degrees average) initially grows for 5 to 10 minutes after injection, resulting in fast bunch lengthening (not shown). Then very slow damping takes place (~30 minutes time constant) with a slower lengthening. The phenomenon disappears during the ramp and has had no effect on machine operation so far.

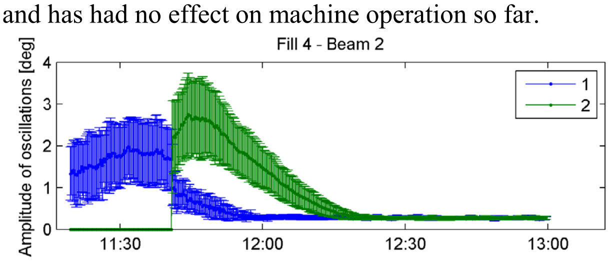

Figure 1: Amplitude of the dipole oscillation following injection. Mean, min, max over all bunches of a batch.

HEATING AND BUNCH PROFILE

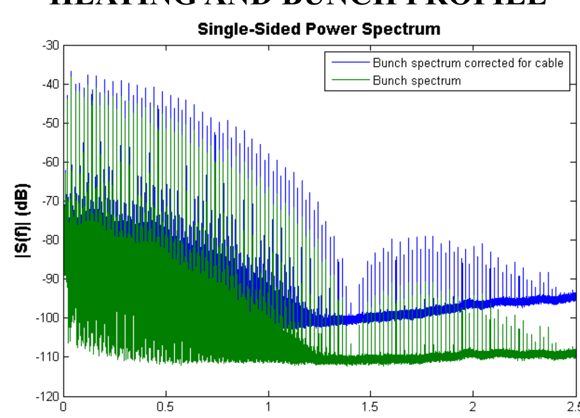

Figure 2: Beam current spectrum with 1380 bunches, without and with compensation for cable response.

When the number of bunches reached 1200 we observed unexpected heating of a collimator jaw and the kicker tanks. There was a strong dependence on bunch length. We are studying the possibility of physics with longer bunches as a mitigation for this heating problem. At present the average 4 σ length is 1.2 ns at the beginning of physics and grows to 1.35 ns after ten hours. Figure 2 shows the power spectrum of the beam current after six hours of physics. The 20 MHz spaced line pattern is created by the 50 ns bunch spacing. After compensation for cable attenuation and dispersion, an inverse FFT gives an estimate of the average bunch shape: there is a good fit with the parabolic amplitude density model. The bunch tails are much lower than in the Gaussian model, consistent with the excellent observed lifetime.

LATEST PERFORMANCES

With the injection gap cleaning active, capture losses are slowly cleaned out of the machine during the injection plateau resulting in virtually no loss at the beginning of the ramp. The efficiency of the RF capture can be estimated by comparing the intensity injected into the machine to the one arriving at 3.5 TeV. The figure is around 0.5% loss with 55% nominal intensity.

Figure 3 shows the evolution of bunch length and the deduced growth rate, starting at the beginning of the flat top. There is a transient (whose origin is not fully understood) lasting for 30 minutes after the beams are put in collision. Thereafter the rate decreases gently from 30 ps/h down to 8 ps/h towards the end of the nine hours long fill.

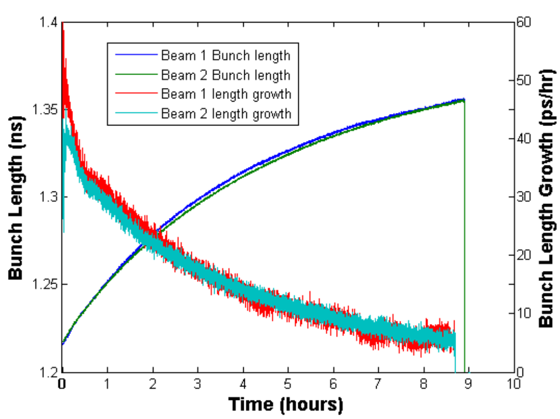

Figure 3: Evolution of bunch length mean and growth rate during physics. 1380 b/beam, 1.3×10^{11} p/bunch.

The LHC RF is designed to minimize transient beam loading: we keep the voltage constant during beam and no-beam segments. If the cavities are detuned for half beam current, perfect compensation of periodic beam loading is possible, in theory, with a constant klystron power, by modulating its phase only [6]. Figure 4 shows the performances achieved with 1380 bunches per beam. The effect of the gaps is clearly visible: the voltage amplitude varies by ± 0.3% and the phase by ± 0.5° only. The klystron phase changes by 60° in the no-beam gaps while its power is modulated at the transitions only.

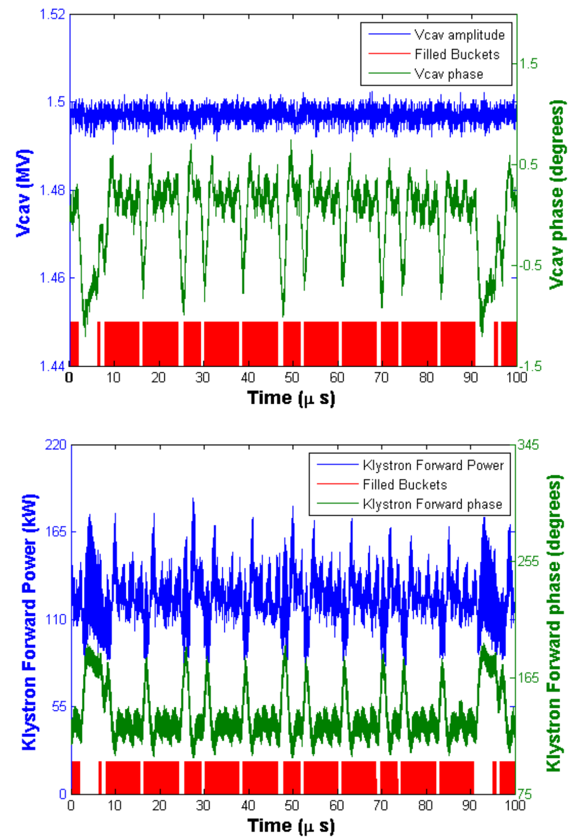

Figure 4: Cavity field (top) and klystron drive (bottom) in physics conditions. Beam current in red. The revolution period is 88.9 μs.

CONCLUSIONS

In August 2011, 3.5 TeV/beam physics is being done with 1380 bunches at 50 ns spacing, corresponding to 55% of the nominal current. The LHC has so far accumulated more than 2 fb^{-1} integrated luminosity well in excess of the 1 fb^{-1} target for 2011. The RF system has lived up to expectations. We are eager to move to 25 ns spacing and higher beam current.

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