THE LHC RF: 2011 AND BEYOND

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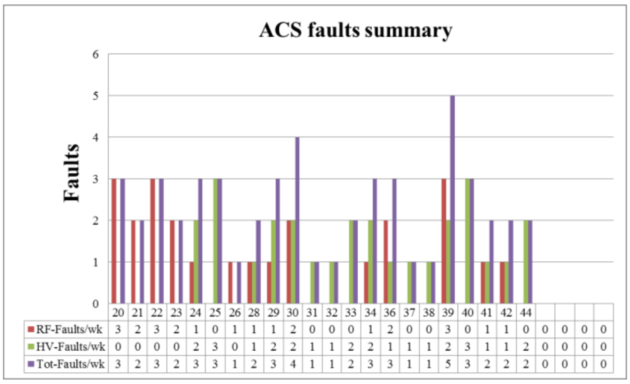
Abstract

The RF system performance in 2011 is presented, with statistics on the High Level faults. The few debunching events are explained. The changes to the RF parameters with respect to the previous run are reviewed. The survival of the RF to a klystron trip is studied: when half nominal current was reached in June 2011, a klystron trip was linked to the beam dump to prevent the beam circulating in the idling cavity from damaging the cavity and RF load. The action of the longitudinal blow-up on the beam current spectrum (or average longitudinal bunch profile) is shown for both protons and lead ions. The operation at 4 TeV and above is considered. Finally, a proposal for 25 ns operation and nominal beam current is presented.

RF RELIABILITY 2011

The RF High Level is reviewed first. Proton operation covered 25 weeks, from week 20 to 44. Figure 1 shows the distribution of the RF faults.



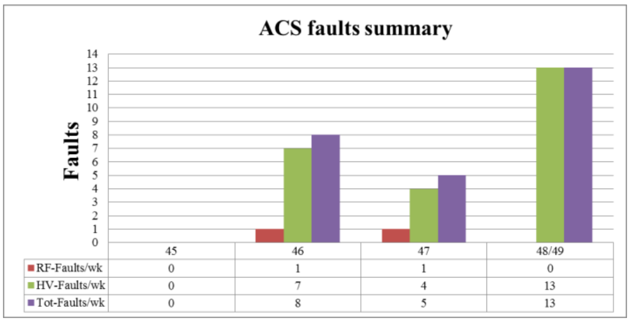
	20	21	22	23	24	25	26	28	29	30	31	32	33	34	36	37	38	39	40	41	42	44				
🟥 RF-Faults/wk	3	2	3	2	1	0	1	1	1	2	0	0	0	1	2	0	0	3	0	1	1	0	0	0	0	0
🟩 HV-Faults/wk	0	0	0	0	2	3	0	1	2	2	1	1	2	2	1	1	1	2	3	1	1	2	0	0	0	0
🟪 Tot-Faults/wk	3	2	3	2	3	3	1	2	3	4	1	1	2	3	3	1	1	5	3	2	2	2	0	0	0	0

Figure 1: RF High Level faults during the proton operation period (weeks 20 to 44).

We have recorded two faults per week on average, summing up to 52 faults total over the proton operation period, out of which:

- Nine faults were triggered by the arc detectors located in the cavity main coupler. These were false alarms and the problem was cured following a modification of the hardware (filters) on week 25.
- Twelve faults were triggered by the monitoring of the cavity Higher Order Mode (HOM) loops temperature. All occurred on Module 1 Beam 2 (M1B2) that is known to have a defective cavity (Cavity 3 Beam 2) that cannot be operated stably above 1.2 MV. It is intended to replace the module with a spare during long shutdown one (LS1).
- Seven faults came from the monitoring of the klystron heater. That aging equipment was recuperated from LEP and an upgrade is under study. In addition traces of oil were found on several High Voltage connectors (immerged in an oil bath). These are being modified during the shutdown.

Ions operation spanned four weeks and an half, from week 45 to 49. Figure 2 shows the distribution of the High Level RF faults during the period. The situation degraded much towards the end of the run, with a total of twenty-six faults (six and an half faults per week on average), and thirteen faults in the last ten days alone. The klystron heater monitoring triggered eleven faults. Four faults are due to the loss of communication between two PLCs.



	45	46	47	48/49
🟥 RF-Faults/wk	0	1	1	0
🟩 HV-Faults/wk	0	7	4	13
🟪 Tot-Faults/wk	0	8	5	13

Figure 2: RF High Level faults during the ion operation period (weeks 45 to 49).

Not all High Level faults resulted in a beam dump. Following the steady increase in beam current, the RF interlock chain was modified on July 14th. From then on a klystron trip would trigger a beam dump. The LHC had 142 physics fills from July 14th till the end of the run on Dec 7th, of which sixteen were dumped by the RF.

Violent debunching was observed on five occasions during physics. Figure 3 shows the phase noise Power Spectral density (PSD) of Cavity 1 Beam 1 on Aug 11th. The large spikes in the PSD can go unnoticed by the beam if they are far from a revolution frequency harmonic.

The signature of RF noise induced debunching is very characteristic: we observe a drop in the Fast Beam Current Transformer reading (FBCT) that records the bunched beam only, and an increase in the population of the abort gap, caused by the uncaptured particles (figure 4). It is interesting to note that, although the RF noise shakes one beam only, debunching is observed on both rings when it happens during physics (figure 4). The link is believed to come from the coupling at the Interaction Points. On Sept 20th, the abort gap population reached 1.2E11 protons before an intervention cured the problem. At 3.5 TeV, with the present position of the momentum collimators, the abort gap population is cleaned by the energy loss due to synchrotron radiation, in about fifteen minutes.

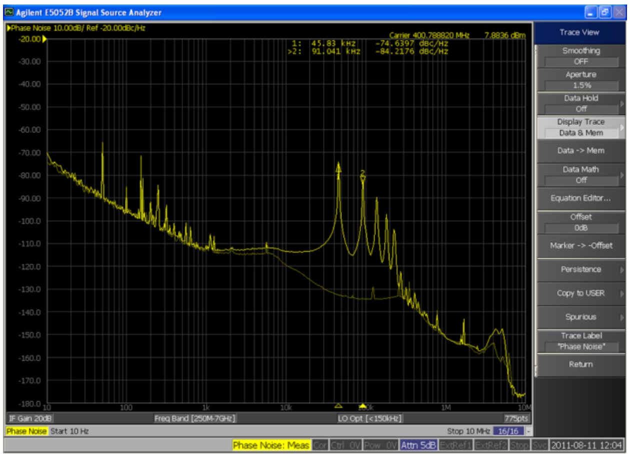


Figure 3: Aug 11th, Cav1B1 phase noise Power Spectral Density (PSD) on a logarithmic scale from 10 Hz to 10 MHz (offset from carrier). The background trace shows the normal PSD. The spikes at 45 kHz and harmonics were caused by an overflow in the klystron polar loop. No beam.

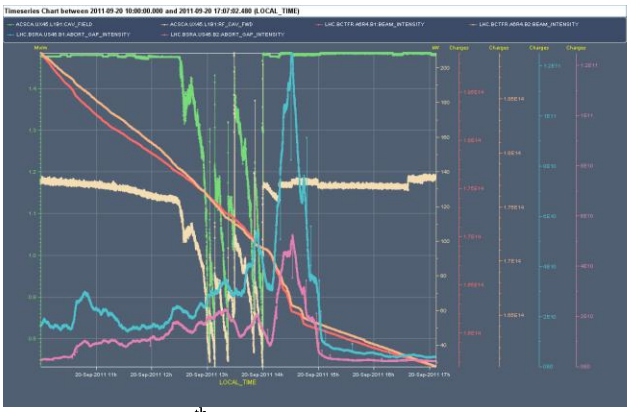


Figure 4: Sept 20th. Cavity1B1 field (green) and klystron output (beige) undergo large fluctuations (voltage varies between 1.5 MV and 1 MV), finally resulting in losses in both rings (FBCT in orange and red) and population of the abort gaps (violet and blue).

The debunching incidents have been understood

- Aug 11th. Cavity 4B1 and 4B2. Overflow in the phase loop of the klystron polar loop. The firmware was modified accordingly.
- Sept 20th. Large oscillations on Cav1B1 voltage, traced to a wrong phasing of the clocks of the modulator. The module had been replaced on Sept 19th and the clocks had not been re-calibrated.
- Oct 4th. Noise on Cav1B1 traced to a loose connector on the modulator card.
- Nov 20th. Ions physics. 5E9 charges in the abort gap of each ring, traced to a wrong phasing of the clocks to the Synchro module, whose firmware had been modified.
- Nov 26th. Ions physics. An overnight attempt to work with only six out of eight klystrons in beam 1 drove the remaining klystrons in saturation.

Besides these few incidents, the natural debunching is modest during the physics fill. Figure 5 displays the abort gap population for both rings, during physics and for all fills in a three weeks long period. At the end of the fills, the three microseconds long abort gap contains 9E9 p maximum (B1) and 5E9 maximum (B2), to be compared with the 2E14 p total beam intensity at the beginning of physics. As the power radiated in synchrotron light scales with γ^4, we expect an improvement with increased energy. The natural cleaning will be faster.

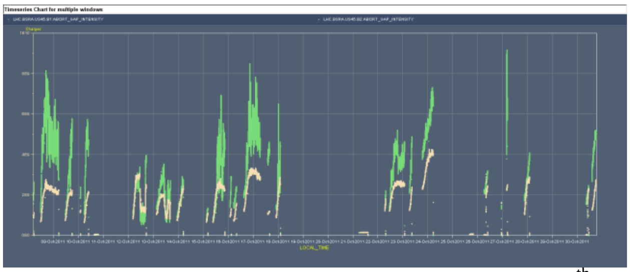


Figure 5: All physics fills (stable beams) from Oct 8th till Nov 1st. Observe the abort gap population, B1 in green and B2 in beige. Vertical scale 0 to 1E10 p.

NEW FEATURES 2011 VERSUS 2010

At injection, the SPS bunch has 1.5 ns length ($4\sigma_t$), and 4.5 10^{-4} energy spread $\Delta E/E$ ($2\ \sigma_E$), resulting in a $4\pi\sigma_t\sigma_E$ emittance of 0.5 eVs[*]. In 2011 the capture voltage was increased from 3.5 MV (2010) to 6 MV. The bucket area was increased from 0.9 eVs in 2010, to 1.2 eVs. Together with Injection Gap Cleaning, this reduced capture losses. In 2011 we have measured 0.5 % loss from injection to 3.5 TeV.

The voltage in physics was increased from 8 MV to 12 MV to provide a larger longitudinal emittance (at constant bunch length), thereby reducing the transverse emittance growth due to IBS. The longitudinal emittance blow-up was adjusted to keep the $4\sigma_t$ bunch length around 1.2 ns (later increased to 1.25 ns) during the 11-minute long ramp. At the beginning of the 3.5 TeV flat top we now have 2 eVs longitudinal emittance in a 4.7 eVs bucket (1.5 eVs in a 3.8 eVs bucket in 2010).

The One Turn Feedback was commissioned on all cavities. It reduces the transient beam loading to less than 0.5 degree pk-pk @ 400 MHz with 2100 bunches, 1E11 p/bunch [1].

SURVIVING A KLYSTRON TRIP

When a klystron trips, the beam induced voltage in the idling cavity may lead to a quench (if it exceeds the 2 MV

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[*] At CERN it is customary to quote the longitudinal emittance as $4\pi\sigma_t\sigma_E$. Note that, for a Gaussian distribution, and small filling factor, 95% of the particles are within a $6\pi\sigma_t\sigma_E$ area. The $4\pi\sigma_t\sigma_E$ area contains 86.5% of the particles.

conditioning level) and the reverse power extracted from the beam, and dissipated in the load may exceed the 300 kW maximum rating [2]. With nominal beam intensity (2808 bunches, 1.1E11 p/bunch, 1.2 ns long bunch) and cavity settings (1.5 MV/cavity, Q_L = 60000), a klystron trip results in 1.63 MV induced in the idling cavity and 500 kW dissipated in the corresponding load. The maximum load power sets the limit: when we exceeded 1100 bunches, mid-June 2011, we linked the klystron surveillance to the beam dump system. From then on, the trip of a single klystron would dump both beams in high intensity proton operation.

BEAM SPECTRUM AND LONGITUDINAL BUNCH PROFILE

Protons

In 2011 we have observed unexpected heating of some machine components (beam screen, kicker septa, collimator jaws), with a strong correlation with bunch length. These observations motivated detailed measurements of the average bunch profile and beam current spectrum. Figure 6 shows the beam spectrum at the end of the filling, for a proton beam. It is measured with a broadband Pick-Up (3 GHz bandwidth) and the displayed spectrum is corrected for the cable loss. The 20 MHz periodicity comes from the 50 ns bunch spacing.

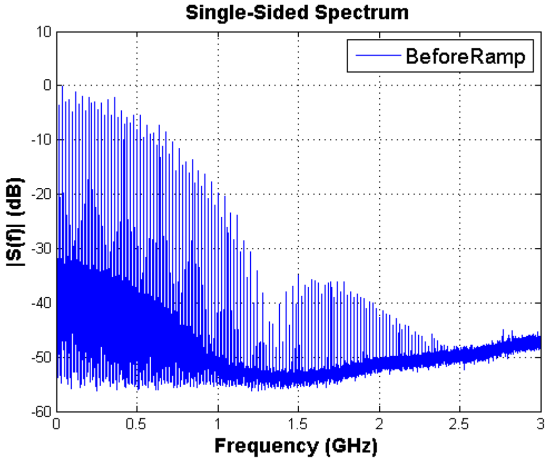

Figure 6: Beam spectrum at end filling. Protons, 50 ns spacing.

Figure 7 shows the average bunch profile obtained by inverse Fourier Transform[†], compared to a gaussian profile of same peak and area. The bunch profile is clearly not Gaussian: we observe a denser core and lower tails. This shape is produced by the longitudinal blow-up during the acceleration ramp in the SPS [3]. Compared to a Gaussian shape, it reduces capture losses in the LHC.

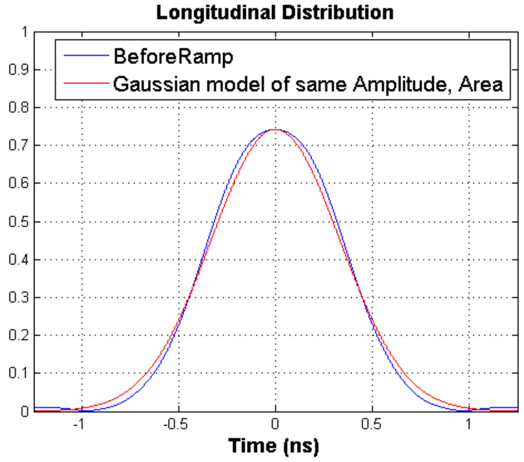

Figure 7: Bunch profile averaged over all bunches computed from the spectrum of figure 6 (blue), compared to a Gaussian of same amplitude and area (red). End of filling, protons, 50 ns spacing.

The high frequency components (lobe above 1.3 GHz in figure 6) get amplified during the longitudinal blow-up in the LHC ramp [4]. The spectrum does not change much during physics, while the bunch length increases slowly from 1.2 ns to 1.35 ns as a consequence of Intra Beam Scattering (figure 8).

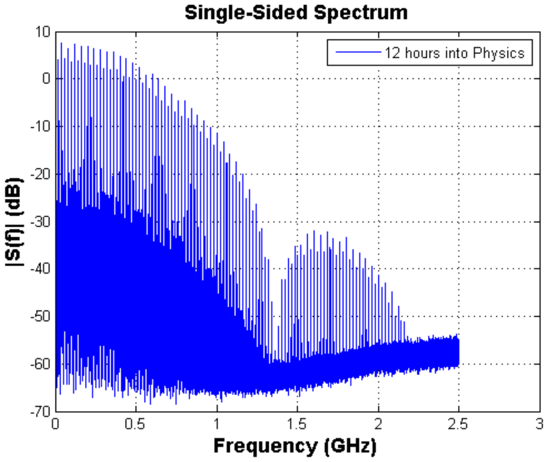

Figure 8: Beam spectrum after 12 hours in physics. Protons, 50 ns spacing.

Lead ions

The situation is much different with ions and provides for an interesting comparison: in November we collided Pb against Pb, with 352 bunches per beam at 200 ns bunch spacing. Figure 9 shows the beam spectrum during the filling. The spectrum (and therefore also the average bunch profile) is Gaussian, with no visible side lobe. The Gaussian shape is likely caused by the diffusion (RF noise and IBS), taking place in both SPS and LHC flat bottom, which is much stronger for Pb than protons.

[†] The measurement of figure 6 is done with a spectrum analyser and does not provide phase information. At injection and in collision, the stable phase is 180 degrees and the bucket is symmetric, resulting in a symmetric bunch profile. The phase of its Fourier Transform is therefore 0 or 180 degrees. To convert the spectrum shown on figure 6 to the time domain, we have assumed 180 degree phase shift for the first side lobe (above 1.3 GHz).

When longitudinal blow-up starts in the LHC ramp to maintain the desired 1.2 ns bunch length, the spectrum shows higher frequency components and the profile differs much from Gaussian (figures 10 and 11). The spectrum shows a side lobe extending from 1.3 GHz to 2.6 GHz.

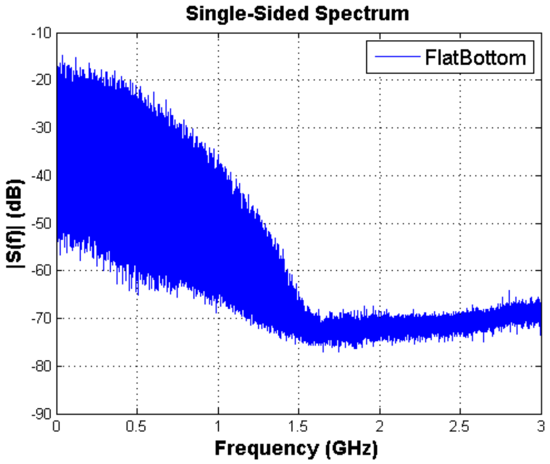

Figure 9: Beam spectrum at the end of filling, Pb.

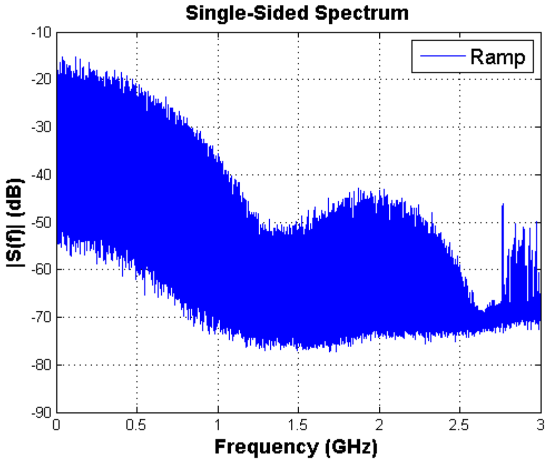

Figure 10: Beam spectrum during blow-up, Pb. (The lines above 2.8 GHz are caused by HOMs in the cable linking the Pick-up to the spectrum analyser).

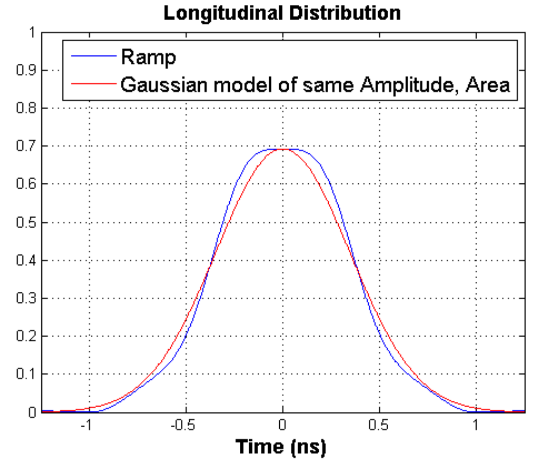

Figure 11: Average bunch profile during blow-up, Pb.

After a few hours into physics, the beam spectrum returns to a Gaussian shape, presumably as a consequence of IBS (figure 12).

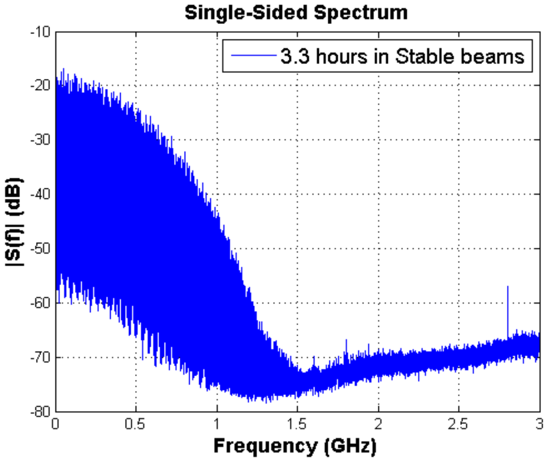

Figure 12: Beam spectrum after 3.3 hours in Physics, Pb.

The observations with Pb and the comparison with protons, suggest that the bunch profile is much affected by the longitudinal blow-up. Analysis is underway to understand the process and hopefully improve the method used. The results will be presented in an upcoming paper [5].

4 TEV AND BEYOND

At constant longitudinal emittance, the impedance threshold for both narrowband and broadband longitudinal impedances, decreases during the acceleration ramp, making the nominal intensity single bunch unstable [6]. Stability is restored by longitudinal blow-up: we keep the bunch length constant, thereby increasing the longitudinal emittance

$$\varepsilon \propto \sqrt{E}\sqrt{V} \qquad (1)$$

At constant bunch length and voltage the stability threshold is independent of energy [4][6][7]. As we increase the voltage during the ramp, the stability actually improves compared to the situation at injection.

25 NS SPACING AND NOMINAL INTENSITY

In 2011 we have circulated single bunches of intensity 2.85E11 p at 450 GeV [8]. As explained in the previous section, the stability margin actually improves in the ramp, thanks to the longitudinal emittance blow-up that keeps the bunch length constant. We therefore expect no problem related to the broadband longitudinal impedance.

We have circulated 2100 bunches at 25 ns spacing, 1E11 p/bunch, at injection energy [9]. The Low Level RF was designed to reduce the cavity impedance at the fundamental and our calculations indicate that the Landau damping provided by the 4 Hz synchrotron tune spread is sufficient to preserve stability at ultimate beam current (2808 bunches, 1.7E11 p/bunch) [10]. The damping of the cavity HOMs is also designed for above ultimate. These conclusions rest on calculations only and must be confirmed by measurements of the damping rate of coupled bunch modes during Machine Development sessions in 2012.

The transient beam loading caused by the gaps in beam current is compensated by the Low Level RF at the expense of klystron power. With future nominal beam intensity (2808 bunches, 1.1E11 p/bunch, 1.2 ns 4σ length), we need 200 kW in physics (1.5 MV/cavity, Q_L=60000) and 110 kW during filling (0.75 MV/cavity, Q_L=20000). With the present DC settings (50 kV, 8A), the klystrons saturate at 200 kW RF. For nominal beam operation we plan to change the DC settings, at the end of filling and before starting the ramp. With 57 kV and 8.7 A, the klystrons saturate at 270 kW RF, providing sufficient margin for regulation with respect to the 200 kW threshold. The change of klystron DC settings with beam circulating at injection energy, followed by the ramp, was tested successfully with 60 bunches per ring at 25 ns spacing [9]. It must be validated with longer batches in 2012.

CONCLUSIONS

Except for the last two weeks, the RF has performed very reliably in 2011

- We have a problem with Cav3B2. Field emission in this cavity is believed to cause the HOM temperature rise problems in the adjacent 2B2 and 4B2. Module 1B2 will be replaced during long shutdown one.
- We have no problem with the rest of the critical RF equipment (cavities, klystrons, main couplers, tuners, cryo-modules, etc…).
- We have an identified problem with the LEP recuperated klystron heaters. An upgrade is under study.

The debunching during physics is moderate. The abort gap population is equivalent to a fat pilot. It will be reduced with increased energy thanks to the natural cleaning from energy loss due to synchrotron radiation. The causes of the few debunching incidents during 2011 are understood.

With the increased capture voltage, the Injection Gap Cleaning, and the shielding, filling has been much easier in 2011. Injection losses will come back with 25 ns operation as the SPS parameters are less stable through the batch. Our strategy is to commission the longitudinal damper in 2012 in order to reduce future losses.

The longitudinal blow-up is an essential tool to the LHC operation. With it, stability actually improves during the acceleration ramp.

We are investigating more gentle technics of longitudinal blow-up, that would reduce the high frequency part of the beam spectrum and make the blow-up even more versatile, allowing its use at constant energy (batch per batch blow-up at injection for example to reduce IBS effects during filling).

For 25 ns operation, the present RF system can (likely) do with nominal intensity. Machine Development time is needed to prepare the road to 25 ns physics after long shutdown one.

ACKNOWLEDGEMENTS

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