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LHC MD 3165: RF power limitations at flat bottom

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Summary

This note describes the power measurements at flat bottom with the half-detuning beam-loading scheme in the LHC performed with the aim to provide the basis for the extrapolation of the present RF power margins for Run 3 and the High-Luminosity LHC (HL-LHC). Due to the unavailability of HL-LHC beam currents for testing in the present LHC, as well as to the large error bars on power measurements, the maximum RF power available is estimated by determining the maximum RF voltage that can be maintained under several scenarios.
MD 3165 took place on 15th September 2018 between 11:00 and 16:00 and between 28th October 2018 21:00 and 29th October 2018 04:00

Contents

1 Introduction

During the MD, RF parameters were adjusted aiming at operating the machine at flat bottom with the half-detuning beam-loading compensation scheme (optimum detuning and loaded quality factor), and measurements of the power limits were conducted. In the half-detuning beam-loading compensation scheme [1], the minimum steady-sate RF power consumption in the presence of gaps in the beam is

$$P = \frac{V I_{\mathrm{RF,pk}}}{8}\,, \tag{1}$$

with V the RF voltage in the cavity and $I_{\mathrm{RF,pk}}$ the peak RF beam current. This minimum power consumption is achieved with optimum detuning given by

$$\Delta f = -\frac{1}{4}\left(\frac{R}{Q}\right) f_{\mathrm{RF}}\,\frac{\mathrm{Im}(I_{\mathrm{RF,pk}})}{V}\,, \tag{2}$$

where (R/Q) is the ratio of the shunt impedance to the quality factor of the cavity fundamental mode (equal to $45\,\Omega$ in the LHC), and f_{RF} the RF frequency; and with the optimum loaded quality factor

$$Q_{\mathrm{L}} = \left|\frac{1}{2}\,\frac{f_{\mathrm{RF}}}{\Delta f}\right|\,, \tag{3}$$

assuming that the RF voltage without beam loading and beam current are perpendicular.

Thus, with an injection voltage of 6 MV (0.75 MV per cavity) and a DC beam current of $I_{\mathrm{DC}} = 0.55\,\mathrm{A}$ ($I_{\mathrm{RF,pk}} \approx 2I_{\mathrm{DC}}$), the steady-state power consumption in the LHC is around 100 kW at $\Delta f = -6.6\,\mathrm{kHz}$ and $Q_{\mathrm{L}} = 30k$. However, transients of up to 150 kW are observed at the extremities of the batches. Doubling the beam current for the HL-LHC will therefore require working close, or perhaps beyond, the available (theoretical) klystron power of about 300 kW, depending on the adopted injection voltage. While the injection voltage has been lowered in operation for better stability (with nominal beam, to help with injection oscillations) and to gain some experience for the future, an increased extraction voltage in the SPS is expected, potentially with the Q22 optics, calling for an increased injection voltage in the LHC in order to capture large-emittance bunches.

Beam dumps with 50 kV high voltage (HV) (with an RF power of 230 kW) and reduced saturation power made evident that the power transients play an important role to determine the sufficiency of the RF system for injection in the HL-LHC. In the first part of this MD, conducted in the MD3 block (2018), power transients were studied with nominal beam intensity and reduced available power from the klystrons, to create similar conditions to those expected in the future. Motivated by the beam dumps at the reduced klystron HV, operation was moved to 58 kV (for an RF power of 300 kW) at injection with the nominal beam and a capture voltage of 6 MV; the second part of MD 3165, conducted in MD4, aimed at verifying the voltage limits at this klystron HV.

During the MDs, all cavities were optimised in terms of Q_{L} and tuner phase in order to maintain the maximum possible voltage with beam. The detuning angle is given by

$$\tan\phi = -2Q_{\mathrm{L}}\,\frac{\Delta f}{f_{\mathrm{RF}}}\,, \tag{4}$$

Line	Unit	1B1	2B1	3B1	4B1	5B1	6B1	7B1	8B1
Phase	°	-146	75	101	108	124	-68	-65	-115
Steps	1	10070	10250	9660	10340	9660	9860	8410	8450

Line	Unit	1B2	2B2	3B2	4B2	5B2	6B2	7B2	8B2
Phase	°	33	2	-16	-167	40	-161	-128/-130	73.7
Steps	1	9920	9190	8380	8400	12775	11840	10320	10970

Table 1: Optimum tuner phase (optimized in 2018 for full-detuning) and tuner absolute steps at 400.789 MHz.

where ϕ is the difference with respect to the initial tuner phase for the central frequency of 400.789 MHz (Table 1); e.g. for $\phi = 10°$ and $Q_{\mathrm{L}} = 40\mathrm{k}$, the corresponding detuning is around 880 Hz. Table 1 also lists the absolute tuner steps for 400.789 MHz, optimised in 2018 for full-detuning first without beam, and then finely-adjustment with beam. Results however show that the detuning for half-detuning operation was not optimum for some lines.

In the following, the process to convert the raw signals collected during the data acquisitions into power measurements is presented. A detailed description of the MD settings and procedure is given in Sections 2 and 3 for the first and second parts of MD 3165, respectively. Lastly, in Section 4, the analysis of the corresponding power measurements is discussed.

1.1 Power measurements

The voltage raw in-phase (I) and quadrature (Q) signals acquired by the Tuner and Set Point (SP) modules from directional couplers (in the range $[-\frac{FS}{2}, +\frac{FS}{2} - 1]$ with full-scale $FS = 2^{16}$), can be converted into power (amplitude and phase) as follow

$$|P| = \frac{I^2 + Q^2}{FS^2} \times 1200\,\mathrm{kW} \qquad \text{and} \qquad \phi = \tan^{-1}\left(\frac{Q^2}{I^2}\right) . \tag{5}$$

Buffer acquisitions (measurements) from the SP module, conducted during this MD, were acquired with the `raw = False` option, which converts the raw data to a full scale of 1:

$$\left\{ \begin{array}{c} I \\ Q \end{array} \right\} \rightarrow \frac{1}{FS} \left\{ \begin{array}{c} I \\ Q \end{array} \right\} . \tag{6}$$

In the Tuner module containing forward (FWD) and reflected (RFL) signals, this option re-scales the buffer according to

$$\left\{ \begin{array}{c} I \\ Q \end{array} \right\} \rightarrow \frac{1}{FS} \left\{ \begin{array}{c} I \\ Q \end{array} \right\} \times 1200\,\sqrt{\mathrm{kW}} . \tag{7}$$

The input and output power measurements form the Switch-and-Protect (SWAP) module are in units of dBm.

2 MD 3165 on 15.09.2018

Bunch injections at 450 GeV conducted in this MD corresponded to the 25ns_2556b_2544_2215_2332_144bpi_20injV3 scheme (BCMS) and the RAMP_PELP-SQUEEZE-6.5TeV-ATS-1m-2018_V3_V1_MD3@0_[START] beam process. Nominal transverse emittance and bunch length (at injection) are used. No changes were done to optics, orbit, collimation settings and the feedback system.

2.1 Fill 1 (#7175)

For the first fill of the MD, the klystron HV was 50 kV (allowing for a peak power of 230 kW, assuming a 60 % efficiency), and the injection voltage was set to 6 MV (0.75 MV per cavity). A batch of 12b was injected in both beams of the LHC, and bucket-by-bucket measurements of the power consumption with circulating beam were conducted. After injection of the first 144b batch in B2, 3B2 was the only cavity to reach saturation, contrasting with observations in May in which saturation was observed in all lines. The RF klystron forward power was observed to reach 180 kW in the transients for some lines. Five consecutive 144b batches were injected afterwards on B1 and B2, and corresponding power measurements for all lines were taken. With circulating beams, measurements were performed for all lines with the 1-turn feedback both open and closed.

2.2 Fill 2 (#7176)

For the second fill, the total cavity voltage was increased to 8.0 MV (1.0 MV per cavity). The loaded quality factor of cavity 5B1 was changed to $Q_\mathrm{L} = 25$k (from the operational 20k in all other cavities) in order to provide the same RF forward power than the other cavities, namely, 150 kW. After injection of 12b and two batches of 144b (and taking the corresponding power measurements), the tuner phase was optimized to reduce power consumption in the half-detuning scheme for 2B1, 4B1, 8B1, and 3B2; these cavities showed saturation as well as problems in the preceding operational period. With transients, the RF klystron power was observed to reach 220 kW for some lines. For the 3B2, Q_L was changed from 25k for 160 kW to 40k for 125 kW by the end of the fill. A programmed dump was performed due to the large population in the abort gap.

2.3 Fill 3 (#7177)

A batch of 12b and five batches of 144b were injected for both beams; power measurements were conducted after the injection of the second 144b batch.

With a voltage of 1 MV per cavity and nominal batched beam, the theoretical optimal Q_L is 38k, requiring 145 kW (calculated), see Table 2. A scan of Q_L from an initial value of 20k to 50k, in steps of 5k, was performed for all cavities, except 5B1 and 3B2 for which Q_L was 5k and 10k higher at all steps. Measurements show a spread of about 5k among the lines in the optimum value. Power measurements were conducted at the start of the scan and, as expected, the operational 20k was found not to be optimal from the power consumption point-of-view. At around 25k, saturation was not observed in most lines anymore, and the

1.1×10^{11} ppb (15.09.2018)

Voltage [MV]	Peak current [A]	Detuning [kHz]	Q_{L} [10^3]	Power [kW]
1.0	1.16	-5.2	38	145
1.125	1.16	-4.7	43	163

1.3×10^{11} ppb (28.10.2018)

Voltage [MV]	Peak current [A]	Detuning [kHz]	Q_{L} [10^3]	Power [kW]
1.0	1.37	-6.2	32	171
1.5	1.42	-4.3	47	266

Table 2: Optimum detuning and loaded cavity factor, and the corresponding expected (minimum) klystron power, at the first and second MD (bunch populations of 1.1×10^{11} ppb and 1.3×10^{11} ppb) for different cavity voltages.

optimal Q_{L} was found around the theoretical value (40k). Slightly reduced transient powers were observed with respect to those in the previous fills. For 3B2, Q_{L} was reduced from the final 60k to 55k at the end of the fill.

The voltage was then raised to 9 MV total (1.125 MV per cavity); in this case, the theoretical optimal Q_{L} is 43k requiring 163 kW. Following the power measurements with circulating beam, Q_{L} was then reduced from the initial Q_{L} of 50k for all lines (except 5B1 and 3B1) to 20k in steps of 5k (for 5B1, Q_{L} was 5k higher at each step). For 3B2, the initial Q_{L} was first lowered until the voltage was stable (at around 45k – above it, the tuner was moving); then, similarly to the other lines, Q_{L} was reduced in steps until reaching 20k. At $Q_{\mathrm{L}} = 25$k, some lines were saturating and, at 20k, most lines showed saturation (25k for 5B1). Cavity 3B2 could not maintain voltage for a Q_{L} below 25k. This fact suggests that operation is currently at the limit. Later, all lines were set to $Q_{\mathrm{L}} = 30$k, except for 5B1 ($Q_{\mathrm{L}} = 35$k); this line was eventually not able to keep the requested voltage, dropping to below 0.7 MV. The maximum power transients during this period were observed to reach 220 kW again. The beams were dumped following observation of significant losses, and the tune of cavity 5B1 was optimized at the beginning of the following fill.

2.4 Fills 4 (#7178) to 6 (#7180)

For the fourth fill, all cavities were set to 40k and the total voltage was kept at 9 MV. Following the injection of the first 144b batch (after the first 12b batch) most lines in both beams showed saturation. Cavities 3B1, 4B1, 5B1, 1B2, and 3B2 reached the largest RF klystron forward power (around 180 kW). Moreover, the latter cavity was not able to maintain voltage, dropping to 1.05 MV. After injection of a second batch of 144b, cavities 6B1, 8B1, 2B2, and 3B2 reached saturation. Finally, the beams were dumped due to the large population in the abort gap.

Similar measurements were repeated at 9 MV but for a Q_L of 35k (corresponding to a theoretical 166 kW forward power). Following the injection of the first 144b batch, cavities 3B2 and 7B2 showed saturation and 6B1 did not maintain the voltage, dropping below 0.7 MV. Losses were observed for both beams, becoming very large for B1, increasing the abort gap population significantly and leading to the beams being dumped.

For the sixth (last) fill of the first MD 3165, power measurements at a Q_L of 45k (for a theoretical forward power of 163 kW) were performed with 12b+144b beams, and saturation was observed in all lines. The problem of the cavity 6B1 voltage persisted and beams were dumped due to significant beam losses in B1. For the recovery stage, the tuner phase of cavity 5B1 was set from 126° to 133° and its Q_L from 25k to 20k.

3 MD 3165 on 28.10.2018

Bunch injections during the MD made use of the `RAMP_PELP-SQUEEZE-6.5TeV-ATS-1m-2018_V3_V1_M4@0_[START]` beam process and the `25ns_2556b_2544_2215_2332_144bpi_20injV3` scheme (BCMS). Nominal transverse emittance and bunch length (at injection) are used. No changes were done to optics, orbit, collimation settings and the feedback system. In addition to the adjustment of the cavity Q_L and tuner phase, voltage partitioning and pre-detuning were tested.

3.1 Fill 1 (#7378)

Prior to the injection of the beams, the tuners of the 1B1, 3B1, 5B1 and 7B1 cavities were calibrated. At the start of the MD, the klystron HV was 58 kV allowing for a peak 300 kW, assuming a 60 % efficiency), and the total injection voltage 6 MV (0.75 MV per cavity), with a loaded quality factor of 40k. The injection voltage was later changed to 8 MV and a 12b batch (bunch intensity of 1.3×10^{11} ppb) was injected for each beam. Saturation was observed in 1B2 and 3B2 at around 250 kW RF klystron forward power following the injection of the first 144b, but the beams were dumped due to intense beam losses.

Two sets of 12b batches were then injected in B1 and B2 for the adjustment of the transfer lines. A first batch of 144b was injected in both beams and saturation was observed in several B1 RF lines and in most B2 RF lines, reaching maximum klystron forward powers of around 280 kW. After the injection of the second 144b batch, high losses were observed; saturation, however, was not observed neither in B1 nor in B2. With a third 144b batch circulating, the tuner phase of each line was manually adjusted, looking at the cavity forward amplitude in the beam segment for operation with half-detuning.

Once all cavities were adjusted, the total RF voltage was increased –first for B1– from the initial 8 MV to a maximum of 12 MV (1.5 MV per cavity) in steps of 0.5 MV. At each step, power measurements were conducted, and saturation was first observed in the line 6B1 at 11 MV. At this point, by adjusting the main coupler motor position, the loaded quality factor is first set to 45k and then 50k, where saturation of the 6B1 was found to cease. Line 6B1 was observed to saturate once again (in some cases) when the total voltage was increased to 11.5 MV, and to remain saturated at the maximum tested voltage of 12 MV, a point at which 4B1 also showed saturation.

A similar step-wise increase of the RF voltage was later conducted for B2. At 9.5 MV, saturation was found in 3B2. Increasing Q_L from 40k to 45k (for a theoretical 170 kW forward power instead of 177 kW) for 3B2, brought this line below saturation. The total voltage of 9.5 MV was then partitioned in such a way that the cavity 3B2 provided half of the voltage of each of the other cavities. Once the total voltage for B2 reached 11 MV (after three more steps), Q_L was adjusted to 45k for all lines (except 3B2 which already was at this value), and saturation was observed at 1B2 (sometimes). The loaded quality factor of all lines was then increased to 50k and 1.53 MV per cavity (except 3B2 for which Q_L remained uncharged, with a voltage of 0.77 MV). Finally, once the total voltage for B2 was set to 11.5 MV, saturation in 1B2 and 2B2 was observed. At this point, beams were dumped due to a significant intensity loss (around 20 %–30 %). With the optimized lines, the RF klystron power remained on average around 125 kW–200 kW, with transients surpassing 250 kW.

3.2 Fills 2 (#7379) to 4 (#7381)

For the second fill of this MD, 12b and 144b batches were injected for both beams with the present 12 MV total voltage. Following the injection of the 144b batch, all lines were observed to saturate (some reaching 280 kW in the beam segment) but they eventually recovered, except for 5B1 and 6B1 which drop to around 1.2 MV and 0.6 MV, respectively. During this period, significant losses were observed for B1 (intensity decay from the initial 1.3×10^{11} ppb to almost 0.9×10^{11} ppb), and the beams were dumped.

At the start of the third fill, the voltage of all other lines for B1 was increased to 1.6 MV per cavity in order to compensate for the reduced voltage from cavities 5B1 and 6B1 (which would be set at a reduced 1.2 MV per cavity for a total of 12 MV). The voltage of these cavities, however, further decayed to 0.75 MV although it partially recovered. Voltage partitioning was then set for a total of 11.5 MV (1.15 MV for 5B1 and 6B1, and 1.53 MV for all the rest), and saturation was observed in all lines, except for 8B2 and 3B2, after injection of 12b+144b for both beams. Cavities 6B1 and 2B2 were not able to maintain voltage and debunching was observed in both B1 (much more severe) and B2, leading to their dump.

A further drop of the RF voltage was observed in line 6B1 during the fourth fill of this MD. Consequently, Q_L was reduced to 40k for 5B1 and 6B1, with an RF voltage of 1.15 MV. Similarly, Q_L was reduced from its latest setting of 45k to 35k for 3B2, but the RF voltage remained at 0.77 MV. With this configuration (total voltage of 11.5 MV for both beams with voltage partitioning), the corresponding batches of 12b and 144b were injected for each beam. As in previous fills, cavity 6B1 saturated and failed to keep the voltage (dropping to around 0.75 MV and leading to significant losses), all lines for B2 were observed to saturate (except for 3B2 and 8B2), and the voltage of line 2B2 decayed (but remained around 1.45 MV). The klystron RF power reached 280 kW (and slightly above) for some lines during transients. Beams were dumped due to significant intensity losses in B1.

3.3 Fills 5 (#7382) and 6 (#7383)

Fill 5 started with a total RF voltage of 11.125 MV with voltage partitioning (1.15 MV for 5B1, 0.79 MV for 6B1, and 1.53 MV for the rest of the lines of B1) and 11.5 MV for the lines of B2. At the injection of the 144b batch for each beam, saturation was observed in lines 1B1, 2B1, 3B1, 4B1, 7B1, and 8B1, as well as all lines of B2 except 3B2 and 8B2. Optimization of the forward power via the adjustment of the cavity tune with circulating beam was performed during this fill. All cavities were manually tuned, but beams had to be dumped after cavities 3B1, 8B1, and to a lesser extent 2B1 and 2B2 failed to maintain the requested constant voltage. The average klystron power for the no beam segment was around 125 kW for most lines, with transients seen to reach the klystron limit.

With the cavities pre-detuned, saturation was reached by the 2B1, 3B1, 4B1, 2B2 and 4B2 lines following the injection of the 12b batches for each beam during the sixth fill. After injecting the 144b batch in B1, cavity 7B1 started to saturate as well and, simultaneously, problems to keep the requested constant voltage were observed in 2B1, 3B1, and 8B1. In the case of B2, lines 5B2, 6B2, and 7B2 also started to saturate following the injection of the 144b batch, and 2B2 showed problems to maintain its constant voltage. The tuners were then set to automatic mode for all lines of B2: this left the cavity tuning motor steps unchanged for half of the lines, and moved them by up to 20 steps for the rest (except 1B2 with 30 steps). The coupling motor position for 1B2 was then adjusted to increase Q_{L} from the initial 50k, the same as the other cavities, to 55k and 60k, but losses in voltage were observed. Lastly, Q_{L} was reduced to the initial 50k, and then to 45k. An average klystron power of almost 250 kW (no beam segment) was observed in most lines. All tuners were set back to automatic mode at the end of the fill.

3.4 Fill 7 (#7384)

Prior the injection of 12b + 96b for B1 and B2, Q_{L} was set to 40k for all cavities and the total RF was reduced to 8 MV. Saturation of the 3B2 line, as well as significant beam losses for both beams, were observed as power measurements were taken with beam. With a total of 1308 bunches per beam, the tuner phase of some of the cavities that showed problems to keep the voltage in the previous fills was adjusted while the corresponding limit for saturation was scanned. For cavity 3B2, saturation was found below $-22°$ and above $-12°$, with an optimum of $-16°$; for 2B2, below $-340°$ and above $20°$, setting it to $0°$; for 6B1, the tuner phase was set to $-72°$, with saturation found below $-92°$ and above $-52°$; for 2B1, below $42°$ and above $97°$ phase tune show saturation, and thus it was set to $65°$; and finally, 7B2 was set to $-133°$ due to saturation being observed below $-153°$ and above $-103°$. With this configuration, power transients were observed to reach around 250 kW, with the average klystron power around 100 kW–200 kW.

Following the voltage drop of 3B2 to around 0.53 MV, the total RF voltage was increased initially to 9 MV for both beams, and then to 9.5 MV for B1. After setting $Q_{\mathrm{L}} = 45\mathrm{k}$ for all lines (except 3B2, at 35k), the total voltage was further increased to 10.5 MV for B1, and 10 MV for B2, at which point lines 8B1, 1B2, and 2B2, were observed to saturate. These cavities remained saturated after increasing Q_{L} to 50k (3B2 was kept unchanged), so their tuner phases were adjusted. For cavity 1B2, saturation was found above $41°$ and the tuner phase was set to $31°$; for 2B2 saturation took place below $0°$ and above $10°$; and for 8B1, the tuner phase was set to $-115°$, where the line did not saturate anymore. Further increasing the total cavity voltage of B1 to 11 MV, saturation was observed again (in 7B1) when it reached 11.5 MV. For B2, lines 1B2, 2B2, 5B2, 6B2, 7B2, and 8B2 saturated at 11 MV. The tuner phase of cavity 2B2 was scanned afterwards to find the limits of saturation, however, saturation was found at all phases. At the end of the fill, Q_L was pushed to 55k for all lines, resulting in a small reduction of the forward power. A final inspection showed that lines 6B1 and 7B1, as well as 1B2, 2B2, 3B2 (at 35k), 5B2, 6B2, 7B2, and 8B2 were all at saturation.

4 Analysis

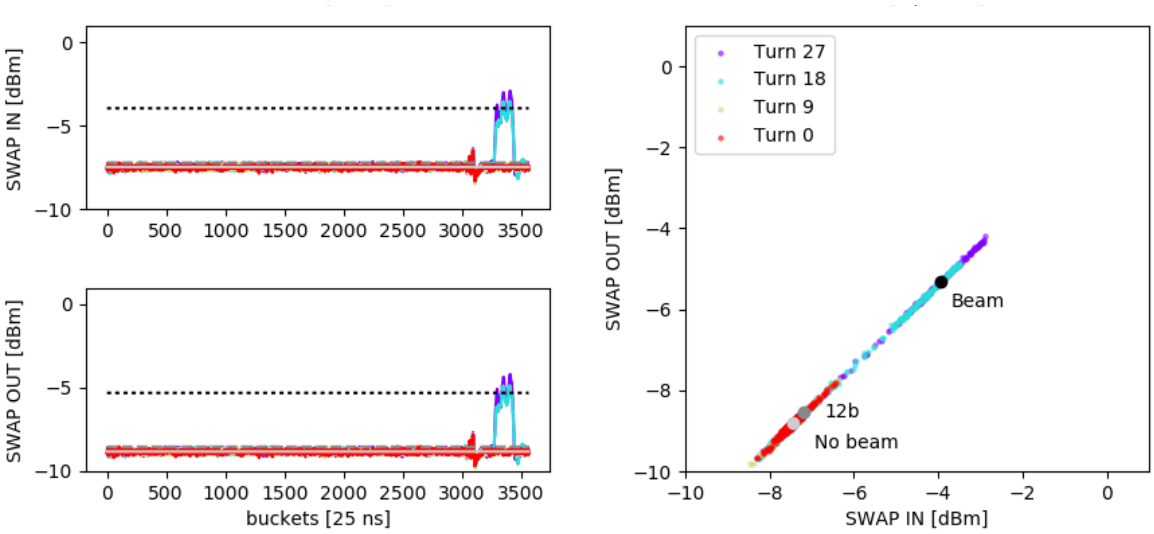
Measurements of the klystron forward power from the Set Point (SP) module, the forward and reflected cavity power from the Tuner module, and the input and output power of the Switch-and-Protect (SWAP) for each line were triggered a few turns before the injection of each 144b batch. Each measurement typically consisted of $i_\mathrm{tot} = 36$ turns, acquired every 25 ns buckets.

For each SP phase signal, the level of the beam and no-beam segments was first found. This allowed to identify the 12b and beam segments in the SP amplitude signal, as well as in the Tuner phase and amplitude signals. Measurements were then split turn by turn, discarding those with wrong synchronization (that is, acquisition where the data of one turn overwrote the data of a previous turn). Then, the average, minimum, and maximum magnitude of the phase and amplitude of the klystron forward power, cavity forward and reflected power over the 12b, beam, and no-beam segments were found over the turns before and after the injection of the first 144b batch (typically at turn $i_\mathrm{144b} = 14$–15). Due to delay in the response of the system to regulate the voltage, a transient is seen over the first turns after the injection of the 144b batch, after which it reaches a steady maximum; for this reason the averages corresponding after the beam injection are computed only a few turns after the injection of the 144b batch (that is, for turns in the range $[i_\mathrm{144b} + 3, i_\mathrm{tot}]$).

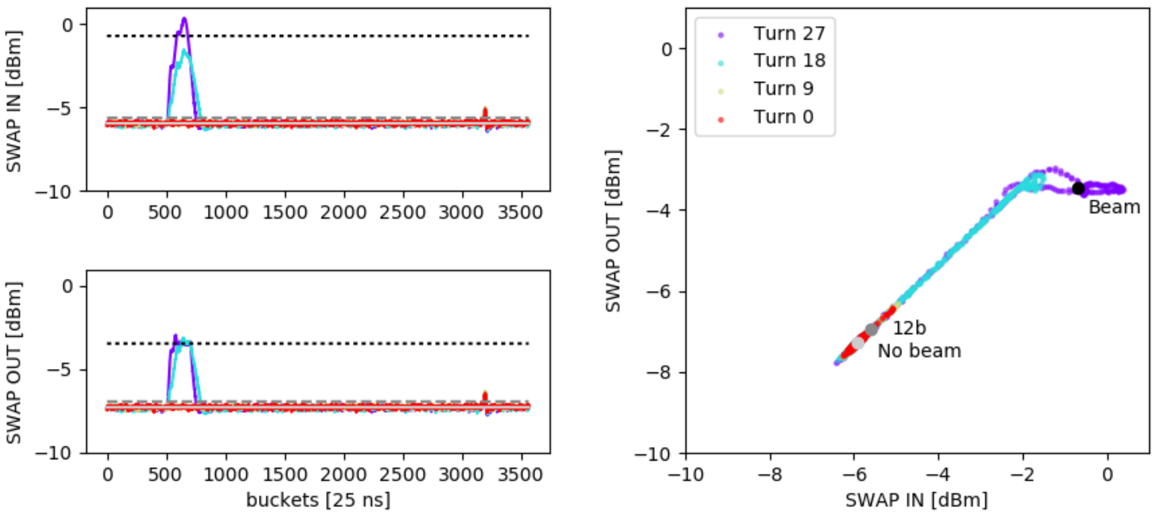
4.1 Saturation detected by the SWAP module

The output power of the SWAP module is adjusted during the yearly commissioning to have an input power level of 0 dBm when the klystron reaches saturation (both for 50 kV and 58 kV klystron HV), and to clamp at this level. Figure 1a shows the typical behaviour of the SWAP measurements, illustrated for the 8B2 line during the second MD. Before the injection of the a 144b batch, the input power remains, on average, constant (solid gray line), as seen in the top-left plot. Similarly, the output power remains constant, as seen in the corresponding bottom-left plot. The circulating batch of 12b generates a power transient in both the input and output power signals, with an average slightly higher than the power for the no beam segment (dashed gray line). The steady-state beam loading, however, is typically obtained for batches with more than 40 bunches (spaced by 25 ns). The power transient significantly increases thus for the injected 144b batch, with its amplitude increasing turn-by-turn during the first turns, but reaching a steady maximum a few turns after the injection of the 144b (dotted black line). Below saturation, the input/output response of the SWAP module is linear, as seen in the corresponding right plot. When the input power reaches the clamping threshold (typically occurring at the beam segment where more power is required), the output power saturates at the corresponding level; the characteristic response is seen in the right plot of Fig. 1b.

In this preliminary analysis, to determine the saturation status for a given measurement,



(a) Line 8B2: no saturated (28.10.2018 22:06:35)



(b) Line 8B2: saturated (28.10.2018 01:11:28)

Figure 1: SWAP measurement of the input and output power for line 8B2 showing no saturation (*top*) and saturation (*bottom*). The average of the input/output power over each segment are indicated by lines: for the no beam and 12b segments (solid light gray and dashed dark gray, respectively), the average is taken over all turns before the injection of the 144b (typically at turn $i_{144\mathrm{b}} = 14$–15); for the beam segment (dotted black), the average was performed for all turns after $i_{144\mathrm{b}} + 3$.

a linear fit of the distribution of points corresponding the no beam (and 12b) segment (before and after injection of the 144b) was performed. Then, the resulting linear function was evaluated at the average input power of the beam segment (after injection of the 144b): the measurement was considered saturated if the average output power of the beam segment was 1σ (of the same distribution of output power points) below the expected output power computed from the linear fit.

Parameter		Unit	4B1	6B1	7B1	2B2	4B2	8B2
Bunch population		10^{11} ppb	1.13	1.03	1.13	1.25	1.07	1.25
Voltage (maintained)		MV	1.50	0.77	1.51	1.50	1.10	1.48
Cavity tuner motor steps		1	7026	9874	8130	5791	6752	6970
Main coupler motor position		mm	19	24	18	23	23	23
Loaded quality factor		1	49801	40933	55105	48607	40487	47276
Power (amplitude)								
SWAP input	no beam ave.	dBm	-5.4	-6.2	-6.1	-4.6	-6.0	-5.9
	beam ave.	dBm	-0.3	-0.4	0.0	0.6	-1.0	-0.7
	beam max	dBm	0.8	0.0	0.4	1.2	0.2	0.7
SWAP output	no beam ave.	dBm	-6.7	-7.3	-7.4	-5.8	-8.7	-7.3
	beam ave.	dBm	-3.6	-3.5	-3.6	-3.3	-5.8	-3.5
SP klystron FWD	no beam ave.	kW	137	94	93	150	96	145
	beam ave.	kW	281	272	260	242	189	271
Tuner cavity FWD	no beam ave.	kW	137	92	103	133	79	121
	beam ave.	kW	312	162	189	236	198	257
Tuner cavity RFL	no beam ave.	kW	165	95	108	148	89	127
	beam ave.	kW	405	163	136	226	207	308

Table 3: Saturated lines reaching 0 dBm (based on SWAP behaviour).

Despite the clamping threshold of the SWAP power being set in steady-stated measurements without beam at 0 dBm, measurements showed that saturation starts at around the −2 dBm level, and this has to be further investigated. Table 3 lists measurements of selected lines that reached saturation and a SWAP input power of 0 dBm. A given measurement was considered to reach 0 dBm –in this preliminary analysis– if the average input power of the beam (saturated) segment plus 2σ (of the same distribution of points) reached 0 dBm. For each line in Table 3, the bunch intensity at the time (from BCTFR) and cavity voltage were retrieved from Timber, and the cavity Q_{L} was estimated from the coupler motor steps via calibration data. For the input power at beam level, the maximum excursion of the saturation region is included.

4.2 Power transients in the klystron and cavity power

The behaviour of transients in the klystron forward power is illustrated in Fig. 2 for the same power measurement with circulating beam of line 8B2 in Fig. 1b. With the optimum half-detuning scheme, the power amplitude in both the beam and no beam segments is, in theory, equal; moreover, in the I-Q plane, the amplitudes, on average, of these segments, are equal, although they can exhibit different phases (not necessarily a 90°-angle, as it depends on the beam current). Despite the conducted tuner phase adjustments, this is not observed for most of the lines. A possible partial explanation for this is the batches being short (3×48b) and with gaps with respect to the filling time of the cavity, and thus, the measurements might reflect only the transients, but not the steady-state in the beam segment.

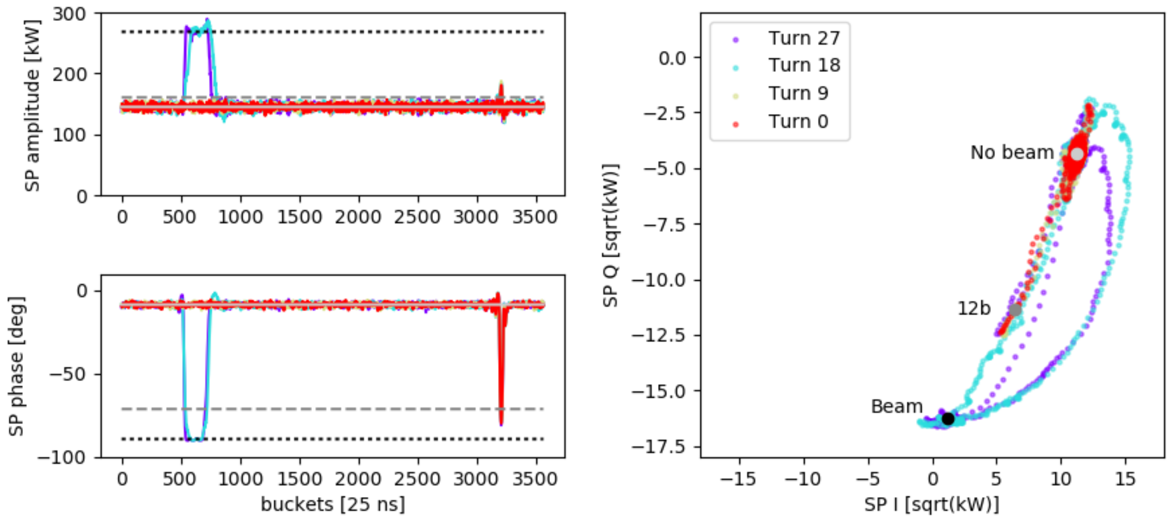


Figure 2: SP measurement of the klystron forward power for line 8B2 at saturation (28.10.2018 01:11:28).

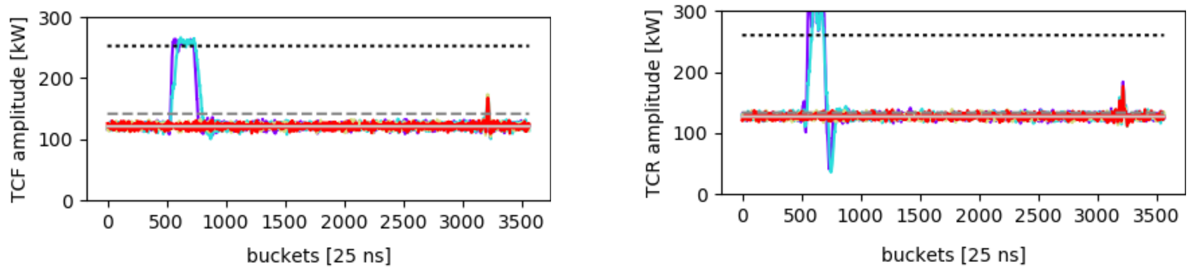


Figure 3: Tuner measurement of the cavity forward and reflected power for line 8B2 at saturation (28.10.2018 01:11:28).

The transients in the cavity forward and reflected power, as acquired by the Tuner module for the corresponding measurements of Fig. 2, are shown in Fig. 3.

Figure 4 summarize the SP klystron forward power measurements for both MDs. In this preliminary analysis, some lines are missing since their corresponding data was discarded due to the wrong synchronization of the acquisitions; a more detailed analysis with more relaxed thresholds might prove other acquisitions to contain useful data. For each line, a pair of points represent the average klystron power in the no beam (light) and beam (dark) segments for both B1 (blue) and B2 (red). The dotted lines represent the maximum available klystron power for the corresponding high voltage during the MD. The lines that exhibit saturation (based on the SWAP response) in the beam segment (filled markers) took place close to the maximum available klystron power (slightly above the corresponding limit); measurements of lines not at saturation are shown with empty markers. For 50 kV, the maximum klystron power was around 175 kW–220 kW for all lines, while at 58 kV, this range increases to 240 kW–280 kW. These limits are also obtained during the commissioning without beam, by slowly ramping the klystron power until saturation is reached.

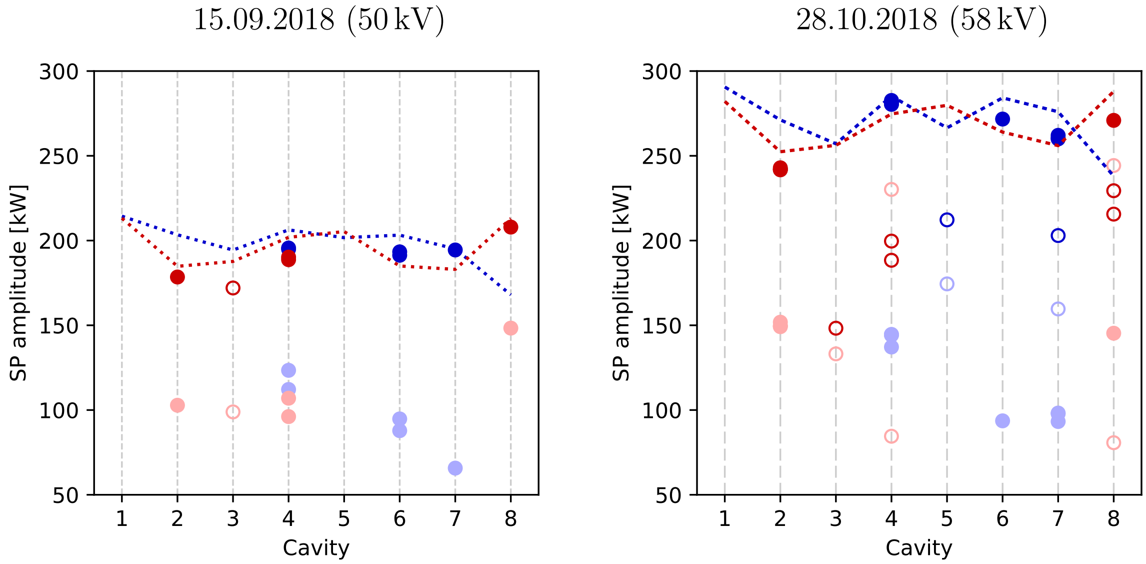


Figure 4: SP klystron forward power measurements for all lines (B1 in blue, B2 in red) during the first (*left*) and second (*right*) MD 3165. Light (dark) markers represent the no-beam (beam) segments and the dashed line shows the maximum available klystron power. The empty markers show measurements with no saturation.

5 Summary

With circulating beam and optimum loaded quality factor, the maximum voltage that each line can maintain has been studied. With 50 kV HV, no pre-detuning, and the present average bunch intensity (nominal beams), the first MD showed that a total RF voltage of 9 MV (1.125 MV per cavity) is at the limit of the klystron operation at injection; and that the theoretical required power of 175 kW per line seems to be the maximum beam-compatible klystron power with 230 kW saturation point. This suggests that capturing the beams of HL-LHC intensity might be difficult, depending on the capture voltage required. From the second MD, it was found that 1.53 MV was the maximum possible cavity voltage on 13 out of 16 cavities, with 1.15 MV on one and 0.75 MV on the remaining two lines (as they were not able to maintain more). Several cavities were not able to maintain the total full RF voltage of 11.125 MV–11.5 MV with both neither manual nor automatic detuning. While an RF voltage of 1.3 MV per cavity is stably maintained in all lines except 3B2 with circulating beam, operation with 1.46 MV per cavity leaves little margin in detuning and Q_{L}.

Measurements from the SWAP input and output power at saturation showed that clamping took place at around −2 dB, despite it being set to 0 dB, and has to be investigated in more detail. However, as the klystron response is flat close to the saturation levels, the output power is not expected to differ significantly to the results discussed above. The measurements of the power transients at beam injections with all the different tested conditions have to be further analyzed to better understand the saturation of each line and its corresponding margins. The turn-by-turn data of power transients will be compared with BLonD simulations to better understand their levels, and benchmark the simulation tools.

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