IDENTIFICATION OF THE SPS IMPEDANCE AT 1.4 GHz

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Abstract

In the SPS spectrum measurements of very long single bunches were used in the past to identify sources of longitudinal microwave instability. Shielding of the identified objects significantly improved the beam stability. However, longitudinal instabilities are still one of the limitations for high intensity LHC beams in the SPS. Recently the same measurement technique was used again, revealing a strong high frequency resonance. During the slow de-bunching with the RF switched off, the presence of different resonant impedances leads to a line density modulation at the resonant frequencies. Longitudinal profiles of bunches of various intensities were acquired. For sufficiently high intensities their spectra show a fast growing and strong modulation at 1.4 GHz. Measurements using two transverse optics with different transition energy are compared. Reproducing the measurements with numerical simulations, including the known SPS longitudinal impedances, allowed the parameter range of this unknown source to be determined. Possible candidates as impedance sources in the SPS ring are investigated.

INTRODUCTION

Beam measurements done at the SPS in the past allowed to identify the dominant impedances responsible for longitudinal microwave instability [1]. During these measurements, a new technique was used, based on the spectrum of the unstable bunch modes. Single high intensity proton bunches were injected into the machine with RF off and their spectrum was observed during slow de-bunching. The interaction of these intense bunches with different resonant impedances leads to line density modulations at the resonant frequencies and thus can help to identify the sources of the instability. As a result the sources found so far were either shielded or removed, allowing the injection of much higher intensities into the SPS.

Today, as the LHC injector, the SPS operates at intensities of $\sim 1.6 \times 10^{11}$ p/b, and more than 3×10^{11} p/b will be requested for the high-luminosity LHC [2]; then longitudinal instabilities could become one of the main limitations again. Indeed, the 50 ns spaced LHC beam in the SPS is already unstable at very low intensities. The instability is suppressed up to the present intensities by the additional $4^{\rm th}$ harmonic RF system and the controlled longitudinal emittance blow-up [3].

To investigate the current SPS impedance and prepare for higher intensity operation, similar measurements with RF off were performed last year. This paper presents the results obtained during two machine study (MD) sessions where different SPS optics were used. Both of them revealed a strong resonance peak at 1.4 GHz. Simulations using the present SPS impedance model were then carried out to identify the parameter space of this resonance; possible impedance sources are under investigation.

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MEASUREMENTS

Single proton bunches of various intensities were injected into the SPS with RF off at 26 GeV/c (above transition). The bunch lengths at injection were $\tau \sim$ (25-30) ns with longitudinal emittances of $\varepsilon_l \sim$ (0.23-0.26) eVs. Bunches were much longer than those used in operation ($\tau \approx 4$ ns), providing a better resolution of the mode spectrum. At the same time, the momentum spread was small enough to ensure that the bunches became unstable with a slow de-bunching time t_d [1].

Bunch profiles were acquired in two optics for a time $t_{\rm acq}$, comparable to their respective de-bunching time t_d. In the first case with transition energy $\gamma_t = 22.8$ (Q26) and $t_d \approx 85$ ms, we used $t_{\rm acq} = 92$ ms, while in the second one with $\gamma_t = 18$ (Q20) and $t_d \approx 30$ ms, we had $t_{\rm acq} = 40$ ms. Each profile was Fourier analyzed to obtain the mode spectrum.

For the measurements in the Q26 optics, a scan of the bunch intensity was performed in the range $(0.4 - 2.0) \times 10^{11}$ p. An example with an average intensity of $N_p = 1 \times 10^{11}$ is presented in Fig. 1, where one can see a rich mode structure. The peaks at 200 MHz and 800 MHz are from the fundamental mode of the two traveling wave RF structures which have high $R_{\rm sh}/Q$ and low Q (see Table 1), where $R_{\rm sh}$ is the shunt impedance and Q the quality factor. Small peaks between 400 MHz and 1 GHz probably correspond to the higher-order modes of the main 200 MHz RF system. However, the source of the large peak at 1.4 GHz is not obvious. The high amplitude and the fast growth rate of the mode (Fig. 1, bottom) cannot be attributed to a high harmonic of the mode excited by the 200 MHz RF system. Instead, it points to a broad-band resonant impedance at 1.4 GHz with high $R_{\rm sh}/Q$ and low Q, which, modulated by the 200 MHz structure, shows smaller peaks around 1.2 GHz and 1.6 GHz.

Measurements were repeated in the Q20 optics, which has a different dispersion along the ring. Figure 2 shows an example of the mode amplitude projection at $N_p = 1.9 \times 10^{11}$; again, the peak at 1.4 GHz is very strong. As expected, much better bunch stability was observed

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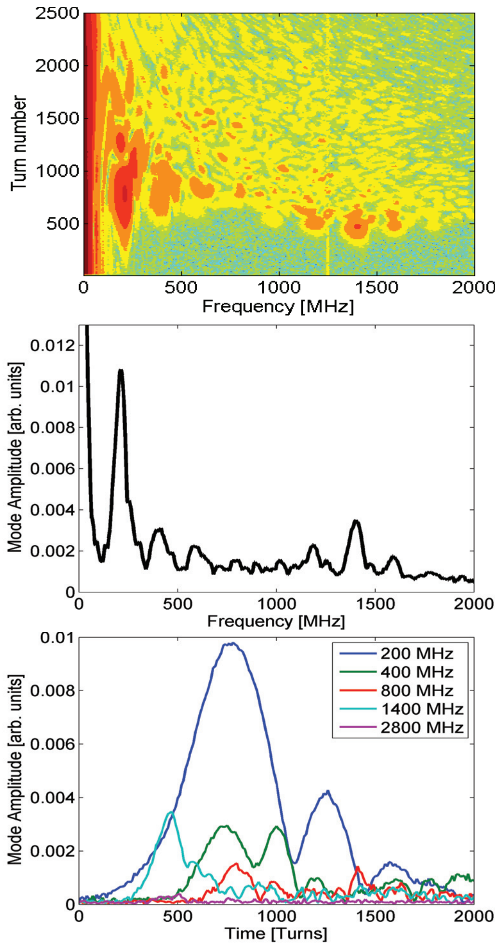

Figure 1: Fourier analysis of longitudinal bunch profiles measured in the Q26 optics. Top: contour plot in frequency domain. Middle: projection of the Fourier spectra of all the bunch profiles acquired. Bottom: mode amplitude at different frequencies (20 MHz bandwidth each). $N_p = 1 \times 10^{11}$.

in Q20, due to the about 2.8 times higher slippage factor $\eta = 1/\gamma_t^2 - 1/\gamma^2$ compared to Q26. To determine the threshold of stability, the maximum amplitude at 1.4 GHz, A_{1400}, relative to the maximum amplitude at 200 MHz, A_{200}, is plotted in Fig. 3 as a function of intensity for both optics. The approximate thresholds are indicated by the vertical lines (0.8×10^{11} in Q26, 1.9×10^{11} in Q20) and their scaling with $|\eta|$ is close to the expected. However, for a more accurate scaling, one should take into account the difference in the initial conditions of the injected bunches (e.g. bunch length, particle distribution) and in the de-bunching time.

SIMULATIONS

To identify the parameter space of the impedance seen at 1.4 GHz, macro-particle simulations were done using the present impedance model of the SPS and the Q26 optics. The simulation data were analyzed with the same methods as the experimental data.

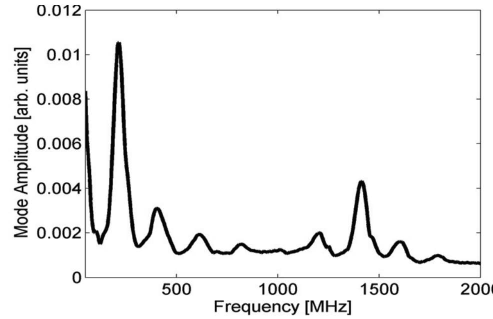

Figure 2: Projection of the Fourier spectra of all the bunch profiles acquired for measurements around $N_p \sim 1.9 \times 10^{11}$ in the Q20 optics.

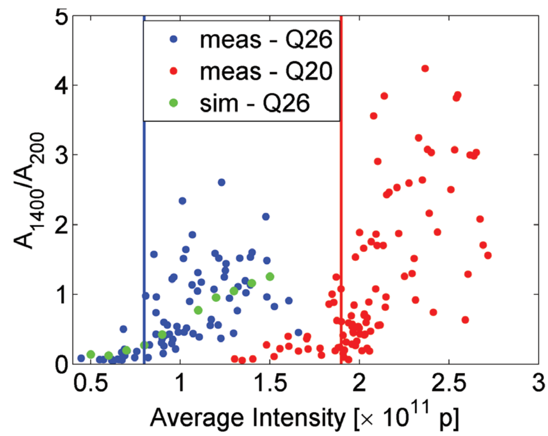

Figure 3: Relative mode amplitude A_{1400}/A_{200} versus bunch intensity for all the measurements. The vertical lines indicate the instability thresholds. Simulation results for the Q26 optics are shown as well, which used the SPS impedance model including a resonant impedance at 1.4 GHz with $f_r = 1.4$ GHz, $R_{sh} = 400$ kΩ and $Q = 10$.

The main contributors to the longitudinal impedance are the in total six traveling wave RF cavities (200 MHz and 800 MHz). Their parameters (including the strongest HOM), assuming resonant impedances, are shown in Table 1 [4].

Table 1: Impedance of the RF cavities

	f_r [MHz]	R_{sh} [MΩ]	Q
TWC200-F (long)	200.2	2.86	150
TWC200-F (short)	200.2	1.84	120
TWC200-H	629.0	0.388	500
TWC800-F	800.8	1.94	300

Different kickers contribute significantly to the present SPS impedance budget. The kicker impedance included in our model was obtained from electromagnetic simulations [5].

In addition to the known contributions from RF cavities and kickers, a resonance at 1.4 GHz was introduced into the impedance model. Simulations were then performed to identify the parameters of this impedance by comparing the growth rates and the relative maximum amplitudes A_{1400}/A_{200} above the instability threshold (at 1×10^{11} p) with the measurements. All three parameters ($f_{\rm r}$, $R_{\rm sh}$, Q) were scanned. However, the dependance on $R_{\rm sh}$ was the most critical as it should be for a broad-band impedance [6]. An example with $f_{\rm r} = 1.42$ GHz, $R_{\rm sh} = 400$ kΩ and $Q = 10$ in the Q26 optics is presented in Fig. 4, where a good agreement with the experimental data in Fig. 1 can be seen. Furthermore, the behavior of the

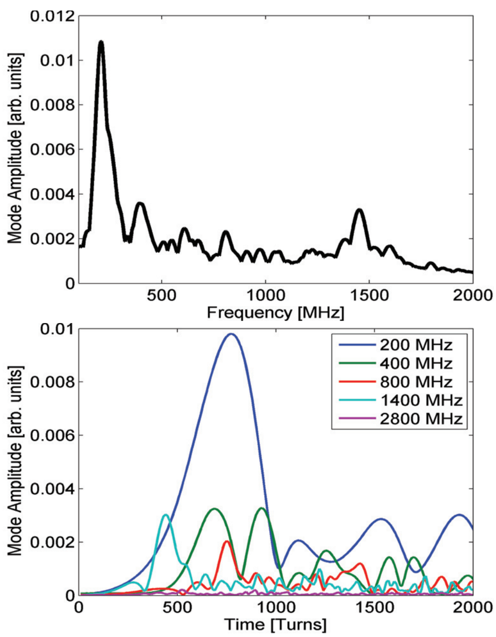

Figure 4: Fourier analysis of longitudinal bunch profiles obtained from simulation in the Q26 optics. Top: projection of the Fourier spectra of all the bunch profiles acquired. Bottom: mode amplitude at different frequencies (20 MHz bandwidth each). $N_p = 1 \times 10^{11}$.

ratio A_{1400}/A_{200} as a function of intensity, found in simulations for the same parameters, is in very good agreement with the measurements as well (Fig. 3). Based on these scans, the range of parameters of the 1.4 GHz resonance that are compatible with observations were obtained and are shown in Table 2. Knowing this narrow region eases the identification of responsible impedance sources in the machine.

Table 2: Parameter space of the 1.4 GHz resonance

f_r [GHz]	$R_{\rm sh}$ [kΩ]	Q
1.35 - 1.45	250 - 400	5 - 10

IMPEDANCE SOURCES

Comparison of simulations with beam observations indicate that the impedance responsible for the 1.4 GHz peak in the unstable bunch spectrum should be broad-band, $2\pi f_r/(2Q) \gg 1/\tau$, with a high value of $R_{\rm sh}$ and a very low quality factor Q, see Table 2. At the moment the most possible candidate is a resonant peak in the impedance of the SPS vacuum flanges. Several types of these flanges are used for the connection of all the machine elements in the ring. For example, the isolating flanges with dielectric inserts are installed at each side of the beam position monitors (BPMs) in the SPS to minimise the effect of eddy currents on the beam measurements and there are in total about 220 BMPs in the machine. For each flange of this type the $R_{\rm sh}$ of the resonant impedance at 1.4 GHz is around 100 Ω [7] giving $\sim$50 kΩ total, which is too low to explain the high impedance deduced from this study. Careful analysis is still necessary to estimate their contribution to the SPS impedance budget. In addition to a high frequency component, the isolating flanges have a large impedance at low frequencies. By-passes were already installed in similar devices in other (low energy) CERN machines [8] but not in the SPS. Other possible impedance sources are under investigation (HOMs in one of the two SPS RF systems).

CONCLUSIONS

Beam measurements with about 25 ns long single proton bunches injected into the SPS with RF off were conducted, in order to identify the impedances responsible for the present longitudinal instabilities. Measurements performed in both the Q20 and Q26 optics revealed a strong resonance peak at 1.4 GHz, which had already been observed in 2001. They indicate that the corresponding impedance source should have a high $R_{\rm sh}/Q$ value with relatively low Q. Using the present SPS impedance model, we performed simulations that were able to determine the parameter space of this impedance. The identification of possible devices in the machine is on-going with many vacuum flanges spread around the ring being the most likely candidate.

REFERENCES

[1] T. Bohl, T. Linnecar, E. Shaposhnikova, Phys. Rev. Lett., v. 78, 1997, 3109

[2] O.S. Bruning, F. Zimmermann, Proc. IPAC12, New Orleans, LA, USA, 2012.

[3] E. Shaposhnikova, T. Bohl, T. Linnecar, Proc. PAC'05, Knoxville, TN, USA, 2005.

[4] T. Linnecar, E. Shaposhnikova, SL-Note 96-49 RF, 1996.

[5] C. Zannini, talk at LIU-SPS BD WG, March 2013 http://paf-spsu.web.cern.ch/paf-spsu/meetings/2008.htm

[6] E. Shaposhnikova, Proc. PAC'01, Chicago, IL, USA, 2001.

[7] B. Salvant, talk at LIU-SPS BD WG, May 2011. http://paf-spsu.web.cern.ch/paf-spsu/meetings/2008.htm

[8] R. Cappi, Proc. PAC'89, Chicago, IL, USA, 1989.

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