IMPEDANCE CONSIDERATIONS FOR THE DESIGN OF THE VACUUM SYSTEM OF THE CERN PS2 PROTON SYNCHROTRON *

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ABSTRACT

In order for the LHC to reach an ultimate luminosity goal of 10^{35}/cm^2/s, CERN is considering upgrade options for the LHC injector chain, including a new 50 GeV synchrotron of about 1.3 km length for protons and heavy ions, to be called the PS2 [1]. The proton energy will be ramped from 4 GeV to 50 GeV in 1.2 s, and the design proton current for LHC operation is 2.7 A. In the LARP framework, we are studying the instability thresholds and the impedance requirements of the vacuum system for the PS2. Goal of this study is to develop an impedance budget for the machine.

INTRODUCTION

We consider the standard single and multi-bunch collective effects that may be an issue in the PS2. For single bunch, we study the microwave instability and the transverse mode coupling instability (TMCI); for multi-bunch, the transverse coupled bunch instability. While the impedance budget will include many components in the machine, at present, we only have sufficient information to include the resistance of the beam pipe, the vacuum flanges that connect the various pieces of the vacuum chamber, and space charge impedance in our estimate. Note that earlier estimates of the impedance and its effects in the PS2 can be found in Ref. [2].

Table 1 presents selected PS2 parameters that will be used in the calculations. The equations used, unless indicated otherwise, can be found in Ref. [3].

BROAD-BAND IMPEDANCE

Estimating the single bunch instabilities requires knowledge of the broad-band impedance or short-range wake of the important ring components such as RF cavities, beam position monitors (BPMs), bellows, collimators, transitions, kickers, pumping slots. At present, the details for these contributions are being gathered up, however, we have sufficient information of the basic vacuum chamber and the flanges to begin adding up the contributions and get a first overview of the potential instability issues in PS2. We remind here that the beam parameters in PS2 will require its impedance to be roughly half of that of the extant PS.[2].

Table 1: Selected PS2 parameters. Subscripts 0 and f indicate parameters at, respectively, injection and extraction.

Parameters	Value	Units
Circumference, C	1346.4	m
Chamber half apertures, $b_x \times b_y$	63×32.5	mm
Initial, final energies, E_0, E_f	4, 50	GeV
Bunch population, LHC beam N_b	4.2	10^{11}
Average current, I	2.7	A
Long. emittance ($4\pi\sigma_t\sigma_\delta$), ϵ_l	0.4	eV-s
Norm. emittances, (LHC) $\gamma\epsilon_x = \gamma\epsilon_y$	3	π μm
Rms bunch length, σ_{t0}, σ_{tf}	3.8, 1	ns
Rms rel. energy spread, $\sigma_{\delta 0}$, $\sigma_{\delta f}$	3.2, 1	10^{-3}
Transition gamma, γ_t	26i	
Slippage factor, η_0, η_f	-0.037, -0.0012	
Synchrotron tune, ν_{s0}, ν_{sf}	18, 0.8	10^{-3}
Vertical tune, ν_y	6.71	
Average beta function, $\bar{\beta}_y$	32	m

Resistive Wall Impedance

The longitudinal resistive wall (RW) impedance is given, in the case of a round pipe with thick walls, by

$$Z = (1-i)\frac{\ell}{2\pi b}\frac{1}{\delta_s\sigma_c} \; . \qquad (1)$$

with ℓ the pipe length, b the pipe radius, and σ_c the metal conductivity. The skin depth $\delta_s = \sqrt{2c/Z_0\sigma_c\omega}$, with c the speed of light, $Z_0 = 377\,\Omega$, and ω the frequency. However, it is Z/n, with $n = \omega/\omega_0$ (ω_0 is revolution frequency) that is the important quantity for longitudinal stability. Taking ℓ to be the ring circumference, $b = 32.5$ mm, $\sigma_c = 1.35 \times 10^6\ \Omega^{-1}\mathrm{m}^{-1}$ (SS), and evaluating at the typical frequency of the bunch, $\omega = c/\sigma_z$, we find that the RW component of the PS2 impedance is $|Z/n| = 0.55$ (0.28) Ω at injection (extraction). Transversely, we can characterize the strength of interaction by the kick factor k_y, defined as the average of the bunch wake W_y; in the resistive wall case

$$k_y = \langle W_y \rangle = \frac{\Gamma(1/4)}{2^{3/2}\pi^2}\frac{c\,\ell}{b^3\sigma_z^{1/2}}\sqrt{\frac{Z_0}{\sigma_c}} \; , \qquad (2)$$

with $\Gamma(1/4) = 3.63$. For the PS2, $k_y = 24$ (47) V/pC/m at injection (extraction).

Vacuum Connections

There will be a significant number of vacuum connections; we assume here that the number is 1500, though this

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is likely an overestimate. Each connection is made with a ConFlat flange pair and has a narrow gap that—if not bridged with suitable rf shields—present a tiny cavity to the beam with additional impedance. For our estimates we consider a generic geometry shown in Fig. 1; we consider the model to be a cylindrically symmetric, small rectangular cavity with depth $h = 10$ mm and gap $g = 1.5$ mm, connected to a beam pipe of radius $b = 30$ mm. A small cavity is inductive to a long bunch, *i.e.* the longitudinal bunch wake is given by $W_z \approx -c^2 L\lambda'$, with λ the longitudinal bunch distribution and prime indicates taking the derivative of a function. For our small cavity the inductance L can be approximated by

$$L = \frac{Z_0}{2\pi cb}\left[gh - \frac{g^2}{2\pi}\right] . \qquad (3)$$

The vertical wake is given by $W_y = 2c^2 L\lambda/b^2$.

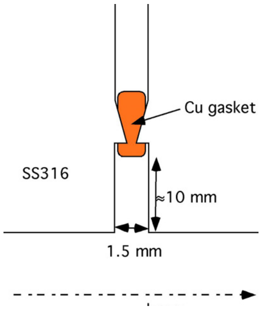

Figure 1: Geometry of a vacuum flange.

To verify these equations we have performed numerical calculations using I. Zagorodnov's 2D, finite difference, time-domain wakefield program, ECHO2D [4]. The longitudinal example is given in Fig. 2, where we show the wake of a $\sigma_z = 40$ mm bunch due to one flange. (Note that a bunch much shorter than the PS2 bunch length was used, to make the calculations easier; but since the cavity is still inductive to a 40 mm bunch, the form of the wake and the inductance L remain unchanged.) We find good agreement between the numerical and analytical results, and the same is true in the transverse case. A fit to the numerical results gives $L = 80$ pH (the analytical result is 71 pH); for 1500 flanges $L_{tot} = 120$ nH, or $|Z/n| = 0.17\,\Omega$ at both injection and extraction; and $k_y = 5$ (19) V/pC/m at injection (extraction). Finally note that the flange is a $\lambda/4$ short, which means that it will ring at 7.5 GHz; for the bunch lengths of consideration for the PS2 the heating and HOM losses will be infinitesimally small.

Space Charge Impedance

In a proton machine space charge can be important, and the effect can be approximated by the space charge (SC) impedance, given by

$$\frac{Z}{n} \approx i\frac{Z_0}{2\gamma^2}\left(1 + 2\ln\frac{b_y}{\sigma_y}\right) . \qquad (4)$$

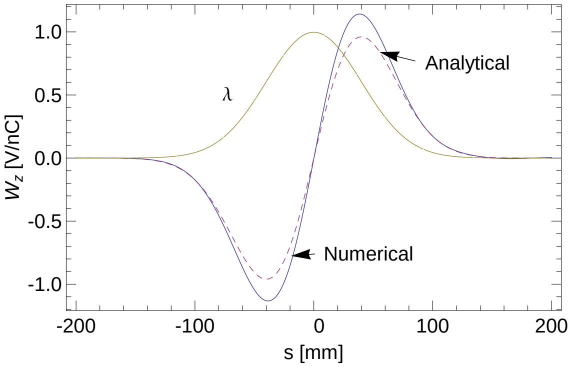

Figure 2: Longitudinal wake of a flange, assuming a Gaussian bunch with $\sigma_z = 40$ mm (blue), and the analytical approximation (dashes). The bunch shape λ is also shown.

Here γ is the Lorentz energy factor, b_y the typical vertical beam chamber half-height, and σ_y the typical vertical beam size in the ring. Because of the γ^{-2} dependence this effect is important primarily at lower energies. For PS2 parameters $|Z/n| = 50$ (0.5) Ω at injection (extraction).

We summarize the PS2 impedance budget we have accumulated so far in Table 2.

Table 2: Impedance budget for the PS2, including objects considered so far, assuming no Cu plating of the beam pipe.

Item	Z/n [Ω] **Inj.**	 **Extr.**	k_y [V/pC/m] **Inj.**	 **Extr.**
RW	$0.39(1-i)$	$0.20(1-i)$	24	47
Flanges	$-0.17i$	$-0.17i$	5	19
SC	50i	0.5i		
Total	0.39+49i	0.20+0.13i	29	66

Cu Coating of the Chamber

It is under consideration to provide the chamber with a highly conductive layer of copper, 10–20μm thick. Following the method of Burov and Lebedev [5], we have obtained the impedance of a round 2-mm thick, SS beam pipe that has been coated on the inside with 20 μm of Cu (See Fig. 3). The effect of the coating is strongly frequency dependent with the most benefit at the higher frequencies (1 MHz and above), and a moderate reduction (by about a factor 2–4) at frequencies that drive multi-bunch instabilities. A similar estimate for a 2μm coating showed no significant benefit (except at single bunch frequencies); therefore, we conclude that any coating would need to be above 10 μm thick to significantly affect the multi-bunch instabilities. Note that a low-SEY coating of amorphous carbon will go on top of the Cu but will not contribute significantly to the impedance.

There is an upper limit for the coating thickness besides technological considerations: A highly conductive layer

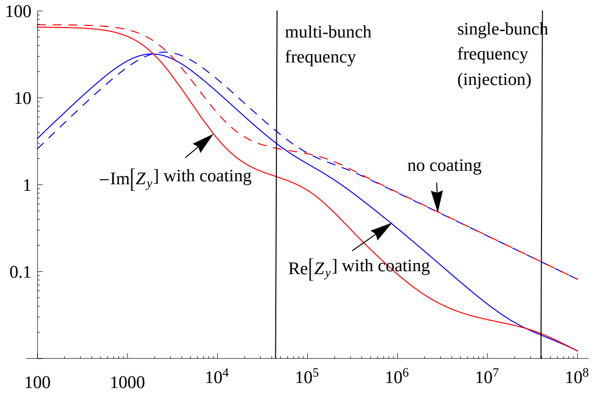

Figure 3: Vertical impedance Z_y in [MΩ/m] *vs.* frequency f in [Hz], for the PS2 beam pipe, assuming 2 mm thick SS, when it is (solid)/ is not (dashed) coated with 20 μm of Cu.

will increase the amount of eddy currents induced by the ring magnets. The eddy currents retard and also distort the field. The currents are proportional to $\dot{B}t\sigma_c$ (t is the thickness of the material). The field retardation due to the chamber is [6]

$$\tau = \frac{\mu_0 b t \sigma_c}{2} \tag{5}$$

where b is the average half height. This is about 80 μs for the 2-mm stainless wall. For a $\dot{B}$ of 1.5 T/s this corresponds to a field error of about 0.07% near injection which would be acceptable. Adding 20 μm of Cu would raise this to 0.1%. The eddy currents do give rise to a sextupolar field, however, which can affect the beam dynamics and change the chromaticity of the machine. Preliminary investigation indicates that this effect may not be completely negligible.

INSTABILITIES

Single Bunch Instabilities

The microwave instability is often characterized by the Boussard criterion

$$\frac{N_{th}}{N_b} \lesssim (2\pi)^{3/2}\frac{|\eta|\sigma_z E\sigma_\delta^2}{e^2 c N_b |Z/n|} \ , \tag{6}$$

with N_{th} the number of bunch particles at threshold (and other parameters as defined in Table 1). It is known to be a very rough estimate of the threshold. Taking the total $|Z/n|$ for the three impedance components, we obtain $N_{th}/N_b = 27$ (59) at injection (extraction). The threshold is very comfortably above the nominal current even before taking credit for any Cu coating.

The TMCI threshold can be approximated by [7]

$$\frac{N_{th}}{N_b} \sim (0.7)\frac{4\pi E\nu_s}{e^2 N_b \bar{\beta}_y k_y} \ . \tag{7}$$

Combining the contribution from the resistive wall and 1500 flanges we find that $N_{th}/N_b = 10$ (2.5) at injection (extraction). We see that at extraction the margin is not so large, and is likely to shrink as the impedance budget becomes more complete. Cu coating may become an important element in reducing the overall impedance and maintaining a comfortably high threshold against TMCI.

Transverse Coupled Bunch Instability

The RW impedance is often the dominant contributor to the transverse coupled bunch instability in storage rings. Assuming only this source of impedance, the growth rate can be estimated as [8]

$$\Gamma = \frac{c}{4\gamma}\frac{m_e I}{m_p I_A}\sqrt{\frac{\ell}{1-[\nu_y]}}\langle\bar{\beta}_y A_y\rangle \tag{8}$$

where

$$A_y = \frac{4}{\pi^{1/2} b^3}\sqrt{\frac{1}{Z_0 \sigma_c}} \ , \tag{9}$$

with m_e, m_p, the mass of the electron, proton, $I_A = 17$ kA, and $[\nu_y]$ the fractional part of the vertical tune. For the stainless-steel chamber we estimate $\Gamma = 7800$ s^{-1} at injection and 760 s^{-1} at extraction, corresponding to 30 and 294 turns, respectively. The injection growth rate will be challenging to control with feedback. Note that in this case the Cu coating is of relatively little benefit because of the low frequencies involved, but we may expect a factor of 1.5–2 decrease in growth rate for a Cu-coated chamber, everything else being equal.

CONCLUSIONS / DISCUSSION

The present baseline of the vacuum system considers elliptical stainless steel chambers. We find that for a bare stainless steel chamber, the resistive wall wake alone will lead to multi-bunch instability that will need to be damped, whereas for the single bunch, transverse mode coupling instability (TMCI), the threshold is above the design beam current, though this instability may become an issue once other impedance contributions are taken into account. The benefit of coating the chamber with copper of varying thickness has also been studied and is shown to raise the TMCI threshold but unlikely to prevent the need for a transverse damping system.

REFERENCES

[1] M. Benedikt et al., Proc. Conf. on Part. Accel. Vancouver, BC, Canada, 2009 (in press).

[2] V.A. Lebedev, Proc. Beam '07 CARE workshop, CERN, p.167 (2007).

[3] Chao and Tigner, eds, Handbook of Acc. Physics and Engineering, 3rd Printing (World Scientific, 2006), pp. 230–237.

[4] I. Zagorodnov and T. Weiland, Phys. Rev. ST Accel. Beams, **8**, 042001 (2005).

[5] A. Burov and V. Lebedev, Proc. of EPAC02, p. 1452.

[6] R.E. Shafer, FNAL Report TM-991 (1980).

[7] S. Krinsky, BNL-75019-2005-IR, 2005.

[8] A. Wolski et al, LBNL-59449, Feb. 2006.