SYSTEM OF THE SPS

I.R. Collins, O. Gröbner, N. Hilleret, J.M. Jimenez and M. Pivi, CERN, Geneva, Switzerland

Abstract

The SPS has recently exhibited strong pressure rises, up to 10^{-7} Torr with $6\cdot10^{12}$ circulating protons, caused by intense electron bombardment as a result of electron multipacting, in the presence of LHC type beams. A number of potential remedies to combat the build-up of an electron cloud have been discussed in the context of the LHC. These proposals have ranged from using well–defined surfaces, provided by special coatings, preparations or treatments and/or in-situ cleaning, such as bake-out or beam scrubbing, to the integration of longitudinal clearing electrodes or solenoid fields. For completeness, machine parameters, such as the bunch separation, have also been reconsidered.

These potential cures to limit the pressure rises in the SPS in the presence of LHC type beams are addressed in this paper.

1 INTRODUCTION

Beam–induced electron multipacting was first observed in the ISR over two decades ago [1]. There electrons, generated by beam ionisation of the residual gas, were accelerated by the electric field of successive bunches towards the vacuum chamber wall. In a specific location of the machine, where a test aluminium vacuum chamber had been installed, a very fast increase in pressure due to intense electron stimulated desorption impeded normal operation of the machine. The fact that the pressure in only this test chamber exhibited such dramatic increases and not the rest of the machine could be explained by beam–induced electron multipacting since aluminium exhibits a larger secondary electron yield than stainless steel used elsewhere.

In the LHC the main source of electrons will be from photoelectrons generated from the walls of the vacuum chamber when irradiated with synchrotron radiation. In the SPS, as in the ISR, synchrotron radiation will be absent and therefore photoelectrons will not be generated. Rather mechanisms such as beam ionisation or particle loss will be present to trigger any potential beam–induced multipacting.

An important issue concerning the vacuum system of the SPS is to ensure that the vertical emittance in the SPS is not affected by the residual gas density since this emittance will be preserved in the LHC and ultimately will lead to a degradation in LHC luminosity. The emittance growth, integrated over the SPS acceleration cycle from 26 GeV to 450 GeV, due to the residual pressure (N_2 equivalent) can be estimated from [2]:

$$\frac{d\varepsilon}{dt} = 0.16\left\langle\beta\right\rangle\frac{P(Torr)}{\gamma}$$

where γ is the relativistic factor. For a β of 40 m the emittance growth due to beam–gas interaction is estimated to be insignificant for pressures less than 10^{-7} Torr. Electron cloud simulations indicate that improving the gas density by two orders of magnitude does not inhibit its creation, rather simply delays its onset [3].

Before embarking on intensive programs to improve the vacuum in the SPS it should be investigated whether such actions will be beneficial. Measures, such as activation of the titanium sublimation pumps, so far seldom used, will provide significant additional pumping speed, especially at the low pressures. However, for reasons of minimising the longitudinal impedance of the SPS for LHC beams, a RF screen to provide a smooth vacuum chamber transition will shield the vacuum ports between the main dipoles. Since such a screen may limit the installed pumping speeds, possible revision of these components is not excluded.

In addition, *ex–situ* vacuum firing or Ar ion glow discharge cleaning of vacuum chambers, where possible, followed by *in–situ* bake–out are beneficial to reduce the static and dynamic outgassing.

The following section is divided into two, representing two approaches to combat any potential multipacting in the SPS vacuum chambers; namely, measures to limit the electron cloud density and measures to reduce the multipacting.

2 POTENTIAL REMEDIES

2.1 Limit electron cloud density

One approach to minimise the detrimental effects of an electron cloud in the SPS is to limit the electron cloud density. Surface treatments and/or surface coatings to reduce the secondary electron emission of the vacuum chamber surface will limit the electron cloud density or alternatively clearing electrodes and/or external solenoid fields may be introduced that limits the growth of an electron cloud.

2.1.1 Surface Treatments

In general, removal of water from a surface *via* an *in–situ* bake–out reduces the secondary electron emission of most materials. Air baking followed by an *in–situ* bake–out, resulting in a roughened surface, can reduce satisfactorily the secondary electron yield of Cu [4]. It is yet to be shown that such a treatment is applicable to stainless steel. In practice only the straight sections of the SPS can be baked since many of the vacuum chambers were not designed for bake–out, being welded *in–situ* or sandwiched between the poles of the magnet.

Laboratory experiments, based on a coaxial multiwire structure, to simulate beam–induced multipacting have been made to both benchmark simulations and to identify candidate surface treatments to combat electron multipacting [5]. Figure 1 shows the minimum pulse amplitude from the pulse amplifier to trigger multipacting as a function of electron dose during multipacting as determined by the integrated current measured on a collector. The higher the minimum pulse amplitude the lower the secondary electron yield. There it can be seen that copper and stainless steel exhibit similar multipacting thresholds at comparable electron doses. Significant improvement was found after a bake–out to 300˚C of the stainless steel consistent with the notion that bake–out reduces the secondary electron yield. Both stainless steel and copper chambers were conditioned with a freon–11 plasma discharge, a known procedure for reducing secondary electron yields [6]. The chamber was conditioned by back–filling with freon–11 to a pressure between $5\cdot10^{-4}$ Torr and 10^{-2} Torr whilst multipacting occurred. After a few minutes discharge multipacting could no longer be triggered with the existing pulse generator, limited to ~220V. The chamber was then vented to atmospheric pressure for one week with air, representing exposure during installation of a vacuum chamber in a machine. The chamber was then re–pumped and multipacting re-triggered. A rapid re–conditioning of the vacuum chamber is observed indicating that the chambers retained a memory of the plasma conditioning. Plasma conditionings with gases such as ArO and N_2 produce similar memory effects. Further studies are underway to better understand this phenomenon and to refine the choice of gas discharges.

Surface conditioning can be achieved by photon and/or electron bombardment. In the SPS there will be no synchrotron radiation and therefore photon scrubbing will not be an available remedy to condition the vacuum chambers. However, during the remaining lepton fills for LEP, photon scrubbing scenarios for the LHC may be studied in the SPS. The photon flux on the dipole chambers is at present reduced due to the tungsten synchrotron radiation masks located at the extremities of the dipole chambers. A rough estimate of the accumulated photon dose during a year of LEP filling of 10^{21} photons/m may, in part, explain the lack of adequate pre–conditioning with synchrotron radiation. In order to observe photon scrubbing some of these synchrotron radiation masks should be removed and lepton beams with a high duty cycle should be used.

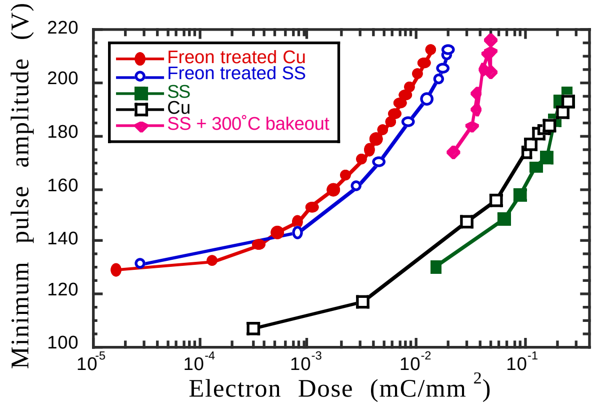

Figure 1: Minimum pulse amplitude required to trigger multipacting in the laboratory system as a function of the integrated electron dose: Stainless steel (SS) and copper (Cu) before bake–out (lower curves) or after bake-out at 300˚C (SS). Conditioning SS or Cu with Freon–11 plasma and after venting to air for one week (upper curves).

During electron multipacting in the SPS, with LHC–like proton beams, the vacuum chambers are subject to electron bombardment. If one assumes that the dynamic pressure rise (hydrogen [7]) is only due to electron bombardment then a crude estimate of the electron dose per injected beam can be made from the installed pumping speed and laboratory data for the electron stimulated desorption yield.

$$\frac{Electron\ flux}{Injected\ beam} = \frac{G\cdot e\cdot \Delta P\cdot S}{A\cdot \eta}\left(C/s\cdot mm^2\right)$$

where

ΔP is the observed initial dynamic pressure rise in the SPS arc (10^{-7} Torr [8]).

S is the installed hydrogen pumping speed (64 l/s).

e is the electron charge.

G is a factor to convert Torr l to molecules (1 Torr $= 3.22\cdot10^{19}$ molecules at 300K).

A is the surface area bombarded (assumed here to be 4 strips 5 mm wide and 6.7 m long, the length of the vacuum chamber between pumps).

η is the electron stimulated desorption yield from unbaked stainless steel (~0.1 [9]).

The estimated electron scrubbing rate in the arc per injected beam is of the order of $3\cdot10^{-8\partial}$C/(s·mm^2). With the present duty cycle of 5% conditioning is expected to be marginally observable over a 12 hour period, consistent with the observed 17% reduction in the pressure under these conditions [8]. It is estimated that with a duty cycle of 30% an observable cleaning after running period of greater than 2 hours would be observable (estimated dose of $5\ 10^{-5}$ C/mm^2) [10]. Unfortunately, electron scrubbing in the SPS will only reduce the SEY of the vacuum chamber surfaces to the critical yield. Once below the critical yield multipacting will stop and no further conditioning can occur. Any recontamination, such as re–adsorption of residual gases on the surfaces, will increase the SEY and multipacting will be re–triggered. In the LHC the situation is different in that photoelectrons will be created continually and will be accelerated by the beam potential and bombard the walls of the vacuum chamber/beam screen thereby providing a continuous conditioning mechanism.

2.1.2 Surface Coatings

Tried and tested coatings to reduce electron multipacting in RF windows, such as Ti, TiO, TiN, Cr_2O_3, Gold black, micro–grooving [11]. Alternative coatings, such as the non–evaporable getter coatings (TiZrV) are presently being developed at CERN [12]. All such coatings unfortunately require an *in–situ* bake–out to reduce their secondary electron yields to acceptable levels. Since *in-situ* bake–out is regarded as a complex procedure in the arcs of the SPS, an *ex–situ* coating is therefore not an attractive solution. An alternative option would be to perform the coating *in–situ*, with a metal such as titanium, providing both a low secondary electron yield and additional distributed pumping. However, such a remedy would require major modifications to the SPS vacuum chambers and therefore this option is not retained as a potential solution.

2.1.3 Clearing Electrodes

The effectiveness of localised clearing electrodes, *i.e.* at the extremities of the main dipoles, should be evaluated. If the electrons are predicted to obtain significant longitudinal velocities then localised clearing electrons can be tested. UHV compatible strip electrodes, 'glued' onto the vacuum chamber, might be a plausible alternative.

2.1.4 External Solenoid Fields

The effect of an external solenoid field on the electron cloud during multipacting has been studied by passing a current through a wire coiled around the vacuum chamber of the coaxial multi–wire structure. Multipacting, triggered by pulse amplitudes of 210 V and 195 V, can be completely suppressed with a solenoid field of 4.7 Gauss and 3.5 Gauss, respectively as shown in Figure 2. Experiments on SPS vacuum chambers, wound with an external coil, can be performed to determine the required field strength to suppress electron multipacting in the otherwise field free regions.

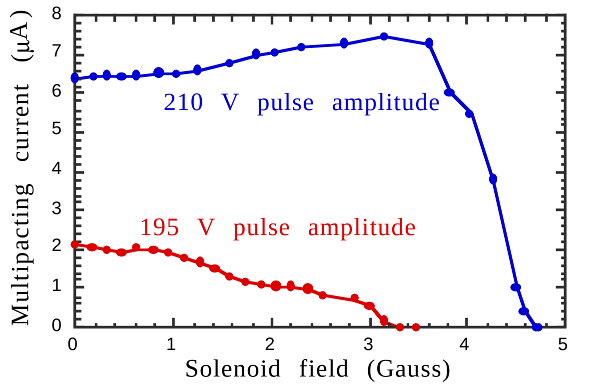

Figure 2. Multipacting intensity as a function of solenoid field for pulse amplitudes of 210 V and 195 V.

Table 1 summarises the potential remedies for the SPS, classified into three categories: 1) simple, 2) possible and 3) complex. These are defined as: remedies that does not require that the vacuum system be opened, remedies that does not require *in–situ* bake–out and remedies that require a treatment/conditioning followed by an *in–situ* bake–out, respectively.

Table 1: A summary of the potential remedies for the SPS vacuum system (arc and straight sections) indicating the degree of complexity.

	Degree of Complexibility	
Potential Remedy	Arc (Dipole)	Straight sections
In–situ electron scrubbing	1	1
Clearing electrodes	2	2
Plasma conditioning with memory effect (*i.e.* Freon11, N_2, ArO) + electron scrubbing)	2	2
Ex–situ coating (*i.e.* TiN, TiZrV, Cr_2O_3) + *in–situ* bake–out	3	1
Air baking + *In-situ* bake–out	3 (?)	1
External solenoid field	In–effective	1

2.2 Avoid multipacting conditions

The second approach to minimise the detrimental effects of an electron cloud in the SPS is to avoid multipacting conditions. This may be achieved by selecting more favourable vacuum chamber dimensions and/or beam parameters, such as bunch spacing, bunch train filling *etc.*

2.2.1 Optimising the vacuum chamber dimension.

It has been shown theoretically using both an analytical model and numerical simulations for the electron cloud in the LHC that the critical secondary electron yield depends on the dimensions of the vacuum chamber [13]. Similar calculations should be performed for the LHC beams in the SPS and where possible the chamber dimensions may be optimised to provide more favourable conditions to avoid electron multipacting. However, the vacuum chamber dimensions in the SPS, in general, cannot be changed.

2.2.2 Beam Parameters

For the LHC the effect of increasing the bunch spacing at the cost of machine performance was studied [14]. By doubling the 25 ns bunch spacing the critical secondary electron yield for nominal bunch intensity is predicted to increase by more than a factor of two, from 1.35 to 2.8. This effect is basically due to the fact that the generated secondary electrons will have more time to travel across the vacuum chamber and be lost when interacting with the wall. However, if the electron reflectivity at these low energies turns out to large, doubling the bunch spacing may not be such an attractive remedy. In addition, doubling the bunch spacing will result in a reduction in luminosity by a factor of 2 for ATLAS, CMS and ALICE but would not provide colliding beams for LHCb! Increasing the bunch intensity by a factor of $\sqrt{2}$ to maintain the nominal luminosity would double the number of events per crossing in the experiments and would have implications on the vacuum stability of the LHC vacuum system due to ion induced desorption. Alternative schemes of satellite bunches or missing bunches in the bunch train have also been considered for the LHC. Such measures for the SPS are covered in a separate paper [15].

3 RECOMMENDATIONS

Before embarking on modifications of the SPS vacuum system it is strongly recommended that the requirements of the vacuum system be identified. Tests should be performed in the forthcoming SPS machine developments to:

• Study the emittance growth versus degraded vacuum. If necessary, regions of the machine that can be baked should be baked out, in combination with a coating or treatment to reduce the secondary electron yield.

• Investigate electron scrubbing by monitoring the pressure and measuring *in–situ* the secondary electron yield during long coasts (12h) with a high duty cycle (30%).

• Test memory coatings (Freon11, ArO, N_2 discharges) with electron conditioning.

• Test clearing electrodes, localised and distributed, that are perhaps applicable also to the long straight sections of the LHC.

• Test effectiveness of external solenoid fields.

• Test photon scrubbing for the LHC by removing some of the synchrotron radiation masks and using lepton beams with a high duty cycle.

If it is mandatory to have lower gas densities and/or vacuum chambers with a low secondary electron yield then venting, even with clean gas, must be minimised, in which case re–conditioning will be required.

4 REFERENCES

[1] "Beam induced multipacting."
O. Gröbner.
10th International conference on high energy accelerators, Protvino, July 1977.

[2] N.V. Mokhov and V.I. Balbekov, in Handbook of accelerator physics and engineering, edited by A.W. Chao and M. Tigner, World Scientific, p216 (1999).

[3] F. Zimmermann, these proceedings

[4] "Lowering the secondary electron yield of technical copper surfaces by strong oxidation".
I. Bojko, J.–L. Dorier, N. Hilleret and Ch. Scheuerlein
CERN Vacuum Technical Note 97–19 (1997)

[5] M. Pivi, Ph.D thesis, University of Torino, December (1999).

[6] "Freon plasma surface treatment for multipactoring".
J.W. Noé
Nuclear Instruments and Methods in Physics Research A328, 291 (1993)

[7] Residual gas analysis at BA5 of the SPS indicates that the gas density is dominated by hydrogen. G. Moulard, private communication.

[8] M. Jimenez *et al.*, these proceedings.

[9] K. Kennedy, unpublished engineering note 2/7/1986

[10] N. Hilleret *et al.*, these proceedings.

[11] "Recipes for coating RF windows".
R.M. Sundelin and H.L. Phillips, in Handbook of accelerator physics and engineering, edited by A.W. Chao and M. Tigner, World Scientific, p396 (1999).

[12] "Non–evaporable getter films for ultrahigh vacuum applications".
C. Benvenuti, P. Chiggiato, F. Cicoira and Y.L'Aminot
J. Vac. Sci. Technol., **A16(1)**, 148 (1998)

[13] "Electron cloud simulations for the LHC straight sections".
F. Zimmermann
CERN LHC Project Note 201 (1999)

[14] "Beam–induced electron cloud in the LHC and possible remedies".
V. Baglin, O. Brüning, R. Calder, F. Caspers, I.R. Collins, O. Gröbner N. Hilleret, J–M. Laurent, M. Morvillo, M. Pivi and F. Ruggiero.
CERN LHC Project Report 188 (1998)

[15] R.Cappi *et al.*, these proceedings.