BUNCH INDUCED MULTIPACTORING

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Introduction

A circular vacuum chamber section, 160 mm inner diameter, made of aluminium alloy (Antico 100) has recently been installed in the ISR to measure the ion desorption coefficient and to test the stability against ion induced pressure bumps in the presence of a high intensity beam. In this 7 m long section sudden pressure increases to more than 10^{-8} torr were observed coinciding with the displacement of a bunched beam from the inner injection orbit to the centre of the vacuum chamber, see Fig. 1. In spite of the pressure rise triggered by a low intensity bunched beam, the vacuum remained stable with coasting beams of more than 25 ampères, suggesting that, contrary to the intensity dependent ion induced pressure bump, it is the bunched structure of the beam which causes the pressure

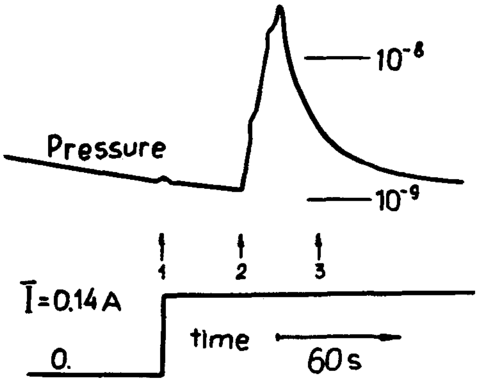

Fig. 1. Pressure spike observed during slow displacement of a bunched beam across the aperture :

1 injection - 40 mm, 2 - 10 mm and 3 + 10 mm radial position from centre of the vacuum chamber

increase. Indeed, by changing the RF-parameters and varying the bunch length or the number of bunches, the effect could be reduced or completely suppressed. With 20 bunches a threshold current of about 120 mA was found. The proposed explanation for the pressure rise is gas desorption due to electrons bouncing between the walls of the vacuum chamber under the influence of the radial electric field of the proton bunches - a phenomenon known as multipactoring in RF-accelerating cavities. The presence of an excessive number of electrons could indeed be observed via large current spikes on the adjacent clearing electrodes.

Threshold condition

The lowest beam current at which electron multipactoring can occur follows from the condition that electrons at the wall must gain sufficient energy in the electric field of the protons to cross the vacuum chamber between successive bunches. If the secondary electron yield of the surface is above unity, a rapidly increasing number of electrons will bounce in synchronism with the bunch frequency back and forth across the beam pipe.

This threshold can be obtained with good approximation by assuming a constant electric field E produced by short rectangular bunches of uniform density. During the passage of a bunch, τ, an electron with charge e and mass m acquires the momentum

$$\Delta p = e\,E\,\tau\,.$$

Its velocity is

$$v = (e/m)\,E\tau\,. \tag{1}$$

In a machine of radius R, the time between n equidistant bunches is

$$T = 2\pi R/nc$$

where c is the velocity of light. To cross the vacuum chamber of radius r_p between bunches requires

$$v > ncr_p/(\pi R)\,. \tag{2}$$

For circular geometry the electric field at the chamber wall can be expressed by the peak current $\hat{I}$ of the bunch

$$E = 60\cdot\hat{I}/r_p \tag{3}$$

where $\hat{I}$ is related to the average circulating beam current $\bar{I}$ through

$$\hat{I} = 2\pi R\bar{I}/(n\tau c). \tag{4}$$

Combining equations (1) to (4) the threshold for multipactoring

$$I_{th} = \frac{c^2 m}{120\pi^2 e}\left(\frac{n\,r_p}{R}\right)^2. \tag{5}$$

A more refined calculation which takes into account the movement of the electrons in the radially varying field during the passage of the bunch leads to a threshold which differs from this result by less than 10%.

In the ISR where only 20 out of 30 buckets are filled, $\hat{I}$ has to be multiplied by a factor of 1.5 and the threshold current is lowered by the corresponding amount. For ISABELLE this factor is 4[1].

Table

Multipactoring threshold corrected for the ratio of empty to full buckets

	R(m)	r_p(m)	n	$\bar{I}_{th}$ (mA)
ISR	150	0.08	30	74
ISABELLE	471	0.04	44	1.5

The average bunched beam current in both machines is well above the multipactoring threshold. Nevertheless, in the ISR the effect has so far only been observed on the aluminium test chamber and not on the standard stainless steel pipes - this, in spite of bunched currents exceeding the threshold by about a factor of 4. The difference in behaviour can be attributed to the lower secondary electron yield of stainless steel with respect to aluminium.

Average secondary electron yield

The threshold has been derived without considering the secondary electron yield which depends intimately on the material and its surface condition and must exceed unity before multipactoring can occur. Fig. 2 shows the secondary electron yield as function of the primary energy for samples of stainless steel (316 LN) and aluminium alloy (5086) after a bakeout at 300°C for 24 hours[2]. For both materials the yield increases strongly with electron energy and exceeds unity at energies of 30 to 40 eV already.

During the passage of a proton bunch the electrons are accelerated in an electric field - not constant as assumed above - but increasing towards the beam.

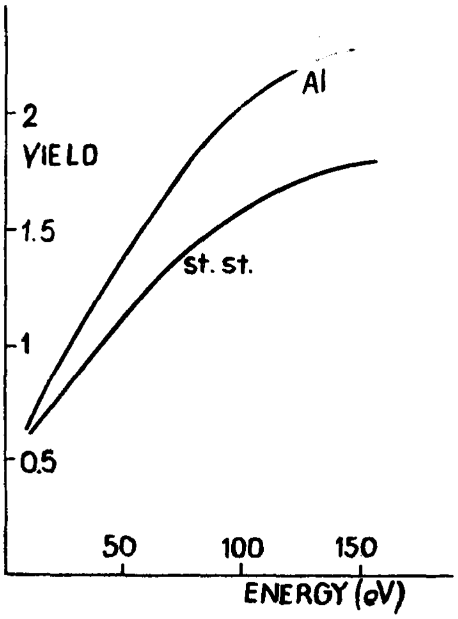

Fig. 2. Secondary electron yield-defined as the ratio of the number of secondary electrons and the number of incident primary electrons - as function of the primary electron energy measured on samples of aluminium (5086) and stainless steel (316 LN) after a 24 h bake-out at 300° C. Private communication from N.Hilleret.

Therefore, depending on their initial radial position, electrons gain more or less energy, hence produce a different number of secondary electrons. The equation of motion of the electrons outside the beam in a circular geometry is

$$m \frac{d^2 r}{dt^2} = e\, E_o\, r^{-1} \tag{6}$$

with $E_o = 120\, \bar{I} \pi R/(n\tau c)$. A first integration gives the energy for an electron initially at rest at the radius a

$$m \left(\frac{dr}{dt}\right)^2 = 2e\, E_o\, \ln(a/r). \tag{7}$$

A second integration yields

$$t(r) = \frac{2a}{\sqrt{2(e/m)E_o}}\, G(a/r)\,. \tag{8}$$

The function

$$G(a/r) = \ln(a/r)/(a/r) \sum_{\nu=0}^{\infty} \frac{(2 \ln a/r)^{\nu}}{(1;2;\ \nu+1)}$$

with $(1;2;\ \nu+1) = 1(1+2\cdot 1)(1+2\cdot 2)\ \dots\ (1+2\cdot\nu)$ is evaluated numerically. Using ISR parameters, Fig. 3 shows for a bunch length $\tau = 20$ ns and circulating currents of 75, 140 and 250 mA the electron energies as function of their radial position. The curves a and b are obtained for $\bar{I} = 140$ mA using a bunch length of 10 and 30 ns respectively, and demonstrate the strong dependence of the electron energy on τ.

Using the energy dependence of the yield and the energy gain as function of the initial radial position an average secondary electron yield is calculated. For this purpose the electrons are assumed to be uniformly distributed over the aperture when a bunch arrives. This assumption may be justified for beam currents exceeding the threshold because then electrons arrive early on the opposite wall and the secondaries have time to redistribute themselves. The presence of a weak coasting beam which influences the distribution of the secondary electrons and provides them with an initial velocity has also been found to enhance multipactoring.

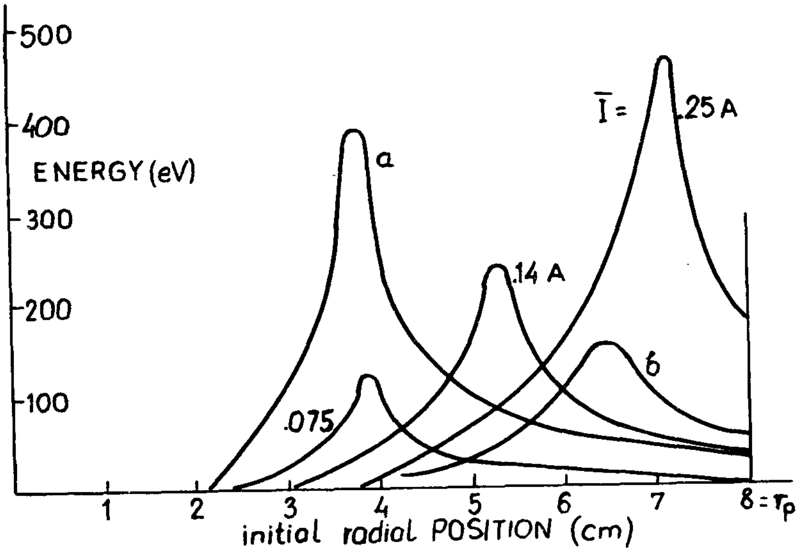

Fig. 3. Electron energy in eV as function of radial position in the ISR vacuum chamber for an average current of 0.075 A, 0.14 A and 0.25 A calculated for a rectangular bunch of 20 ns. Curves a and b are obtained for I = .14 A and with τ = 10 ns and 30 ns respectively.

The average secondary electron yield for aluminium and stainless steel vacuum chambers as function of the beam current is shown in Fig. 4. From the threshold of 120 mA observed for the Al-chamber in the ISR, one concludes that the yield has been overestimated by about 30%. Correcting for this difference, the average yield for baked stainless steel remains less than 1 for beam currents above 250 mA - consistent with the absence of multipactoring in normal ISR vacuum chambers.

Laboratory results

The multipactoring effect observed in the ISR has been reproduced in the laboratory simulating the bunched beam by a pulse train applied to a wire electrode

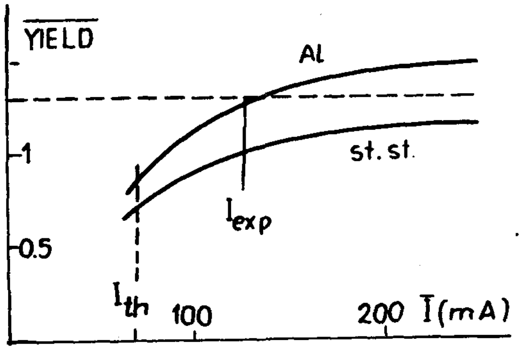

Fig. 4. Average secondary electron yield for aluminium and stainless steel obtained from figs. 2 and 3 and assuming uniformly distributed electrons. As seen from the observed threshold, I_{exp}, the calculation overestimates the yield by about 30%. With this correction, stainless steel should not multipactor in the ISR.

positioned along the centre of a vacuum tube. Comparative tests on unbaked chambers of aluminium and stainless steel have both shown strong multipactoring. However, while the effect remained practically unchanged in the Al-chamber, the stainless steel pipe had a distinct improvement with time and after several hours multipactoring could no longer be triggered even by increasing the amplitude of the applied pulses. Since only the pressure response could be monitored and not the electron bombardment of the wall, it is not clear as to whether the secondary electron yield or the electron desorption coefficient had decreased due to a cleaning action. The usefulness of multipactoring as an alternative surface cleaning method to the currently used glow discharge is being investigated.

Inverting the polarity of the applied pulses negatively charged bunches can be simulated. Preliminary results suggest that multipactoring could equally well occur in electron-positron machines. Methods of suppressing multipactoring by coating the aluminium with a layer with low secondary electron yield (e.g. titanium nitride/3/) are being studied.

Acknowledgement

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