ELECTRON MULTIPACTING OBSERVATION AND SIMULATION IN THE APS PAR*

C.-Y. Yao, Y.-C. Chae
Advanced Photon Source, Argonne National Laboratory, Argonne, IL 60439, U.S.A.

Abstract

The Advanced Photon Source (APS) particle accumulator ring (PAR) has both fundamental and 12th harmonic rf systems. Gap voltage fluctuations occurred after vacuum work was performed on the PAR during a maintenance period. This has caused intermittent beam instability and prevented us from running the PAR fundamental rf system at normal power level. Our investigation concluded that the problem was caused by beam-induced electron multipacting in the center vacuum chamber of the cavity. We were able to suppress the multipacting by applying a solenoid field in the suspected region. Computer simulation is underway in order to find the location and the parameter range of the multipacting. In this paper we report the experimental observations and results of the simulation relevant to the phenomena.

INTRODUCTION

Gap voltage fluctuations appeared after vacuum work was performed on the APS PAR during a maintenance period. The gap voltage fluctuation has caused intermittent beam instability and prevented us from running the PAR fundamental rf system at normal power level. As a result of this problem, the injector beam stability and bunch purity were impacted. We investigated this problem and believe it was caused by beam-induced multipacting. We were able to suppress the multipacting by applying a small solenoid field in the suspected region. Computer simulation was performed but so far we have not been able to identify the location of multipacing and other parameters. This note describes the observation, the suppression method, and some analysis.

OBSERVATION AND CURE OF INSTABILITY

Figure 1 shows the geometry of the PAR fundamental cavity. It is a folded coax-type resonator. The outer cylinder and the inner cylinder with its inner conductor form a resonator. Only the inner conductor is in vacuum. A ceramic wall provided a vacuum seal between the inner conductor and other parts of the cavity.

The observed multipacting has the following characteristics:

1) It only appears when the fundamental gap voltage or power is above a certain value.
2) It happens only when beam is stored or injected into the PAR.
3) It is not affected by turning on or off the harmonic rf system.
4) The gap voltage fluctuation stops at beam charge of 6 nC or more.
5) The cavity was conditioned for extended periods of time. The conditioning improved beam stability initially, but the improvement has slowed or nearly stopped.

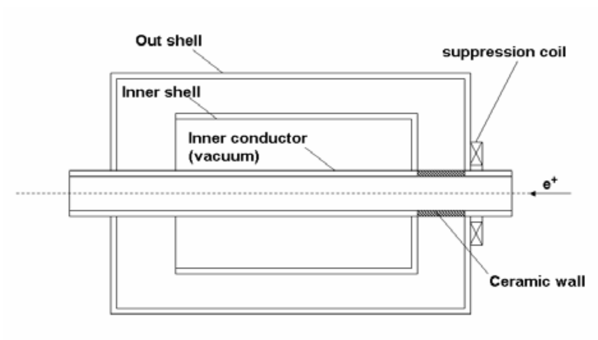

Figure 1: Schematic of the fundamental cavity.

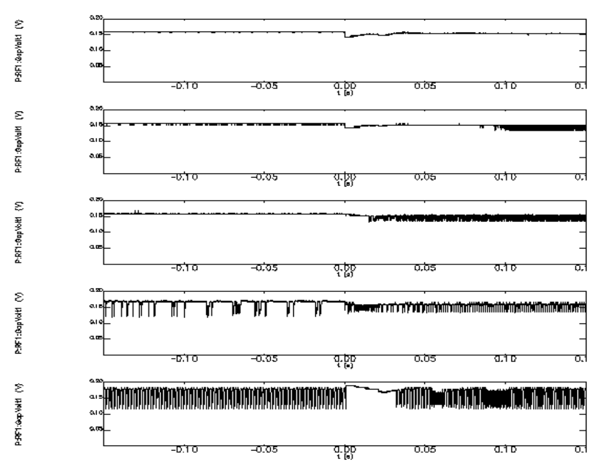

Figure 2: Scope traces of cavity field probe envelope signal of various gap voltage fluctuations during a PAR cycle. The top trace is when the cavity gap voltage behaves normally. For each subsequent trace the observed voltage fluctuation intensifies. The pattern changes in the middle part of the plot are due to beam loading change after beam extraction.

Figure 2 shows scope traces of the gap voltage envelope signal when the suspected multipacting is occurring. Figure 3 is an expanded view of the waveform showing more details of the waveform structure. An FFT analysis of the scope waveform indicated that the

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frequencies of the gap voltage fluctuation are from 700 to 1400 Hz.

During unstable conditions, the gap voltage of the fundamental cavity fluctuates significantly to as much as 30% of normal peak voltage. This must be compared with the nominal transient beam loading of 10%. Thus we exclude transient beam loading as a possible instability mechanism.

To investigate the possibility of cavity arcing, we also used an acoustic device and a scope to monitor the cavity noise while observing the gap voltage fluctuation. We did not find any evidence of internal arcing in the cavity.

Since we had experienced ion trapping during injection when certain conditions were met, we checked transverse beam motion with a spectrum analyzer and photon monitor images. We didn't observe any transverse beam centroid and shape oscillation during gap voltage fluctuations. We think that multipacting is the cause of the gap voltage fluctuations of the fundamental rf cavity.

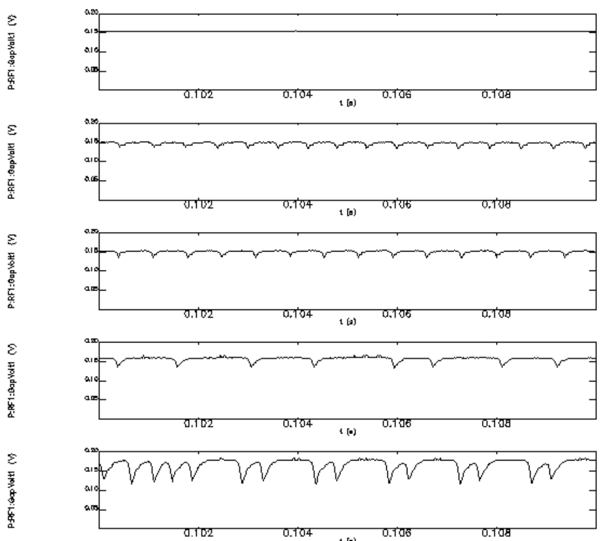

Figure 3: Expanded views of the scope traces. The falling edges are gap voltage drops at the start of a multipacting cycle and the trailing edges are at the recovery of gap voltage after a cycle.

Multipacting is well known in rf cavities and accelerators and there have been many publications [1] on this subject. Four conditions are necessary in order to sustain an electron multipacting process:

1) Any secondary electrons generated by the impact of electrons on a surface are accelerated in the rf field and gain sufficient energy to produce their own secondary electrons.
2) The combination of surface condition and the energy of the impacting electrons produces a yield coefficient of more than 1.
3) There is a resonance between the rf period and the time needed for secondary electron generation and acceleration.
4) The phenomenon repeats the process of secondary electron accumulation and discharge accompanied by gap voltage drop in the cavity.

Considering these characters of multipacting, especially 4) in the above list, which explains the repeated gap voltage drop, we think this is a multipacting phenomenon. We looked at various ways to suppress multipacting and concluded that the easiest way was to use a solenoid coil. Since we observed the instability after the inner cavity tube had been exposed to nitrogen or air during a maintenance, we assumed that the source of secondary electrons could be the ceramic wall in the cavity.

We installed a 200-turn solenoid field coil around the vacuum chamber near the ceramic wall of the cavity (shown in Figure 1) so that the magnetic field could penetrate the gap region. By applying a DC correction current of up to 10A we were able to totally suppress the multipacting and stabilize the rf gap voltage. Enhancement of multipacting was also observed at different correction currents.

THE SIMPLE MODEL OF MULTIPACTING

The successful suppression of the rf envelope instability by the correction coil convinced us that the instability was caused by multipacting. This led us to explain the phenomena by a simple model and detailed numerical simulations in order to have a consistent understanding of the observed phenomena. The following describes such efforts followed by some questions and conclusions.

Multipacting can only happen in a vacuum and requires a certain level of rf field. In the PAR fundamental cavity only the inner conductor area matches these conditions and therefore can develop multipacting. A ceramic surface without proper coating has a high secondary electron emission coefficient. An inquiry indicated that it was possible the ceramic chamber currently in the cavity does not have a coating. Here we provide an analysis based on a simple model described in [2].

The basic one-dimensional equation of motion of an electron under rf field can be written as

$$\ddot{x} = \frac{eE}{m_e}\sin(\omega t + \phi).$$

The solution to this equation can be written as

$$x = v_0 t + \frac{eEt}{m_e\omega}\cos\phi - \frac{eE}{m_e\omega^2}[\sin(\omega t + \phi) - \sin\phi]$$

and

$$v(t) = v_0 + \frac{eE}{m_e\omega}[\cos\phi - \cos(\omega t + \phi)].$$

A resonance condition occurs when an electron arrives at a point of second emission in at odd number of half rf cycles. Applying this to the single half-cycle case results in

$$v_f = \frac{k}{k-1}\frac{2eE}{m_e\omega}\cos\phi\,,$$

where φ is the rf phase at which secondary electrons are emitted, and k is the ratio of velocities at arrival and at emission. E is the peak rf field. The final or arrival energy of electrons can be expressed as the following, assuming the electrons are nonrelativistic:

$$W_f = \frac{2k^2}{(k-1)^2}\left(\frac{e^2E^2}{m_e\omega^2}\right)\cos^2\phi\,.$$

Here W_f is the kinetic energy. The displacement of an electron is expressed as

$$d = \frac{eE\lambda^2}{4\pi^2 m_e c^2}\left(\frac{k+1}{k-1}\pi\cos\phi + 2\sin\phi\right).$$

The beam longitudinal trajectory can be readily calculated for any given set of parameters. We found two initial phases and a set of parameters that satisfy the half-cycle multipacting condition. These are listed in Table 1.

Table 1: Parameters for Possible Multipacting

E	2.5 kV/m
k	2 to 4
φ	110, 290 degrees
W_f	121 eV
f	9.773 MHz
d	0.01 m

The electrical field in the main gap ceramic chamber area is near 100 kV/m, which is too high for multipacting according to the simple model estimate. We think that multipacting happens in the inner conductor area adjacent to the ceramic chamber where a lower field exists. This overly simplified model can only explain the phenomenon qualitatively. In a real cavity the magnetic field component modifies particle trajectory and affects the resonance condition. Nonuniform electrical field distribution in the main gap area also affects the resonance condition. These are not included in the simple model.

SIMULATION OF MULTIPACTING

Computer simulations were performed with the MULTIPAC2.1 [3] and SPIFFE [4] programs, but we could not produce multipacting in the chamber area. Figure 4 shows the simulation result with MULTIPAC2.1, which indicated the inner surface of the cavity outer shell as a possible spot for multipacting. But that area is not in vacuum. In these simulations we did not include circulating beam and in-cavity ceramic material in the calculation due to program limitations.

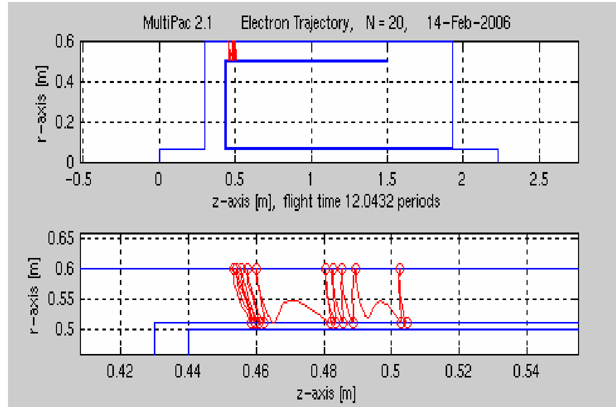

Figure 4: Simulation result with MULTIPAC. The top plot shows the location of a possible multipacting spot. The bottom trace is an expanded view of the spot area.

CONCLUSION

We investigated multipacting in the PAR fundamental cavity. A suppression coil was used to successfully remedy the problem. Our simulation has not found any multipacting site in the suspected area.

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