# A PERIODICALLY-SWITCHED ODE MODEL FOR N-BUNCH BEAMLOADING IN A STORAGE RING*



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*Abstract*

A new baseband formulation of the coupled cavity/longitudinal-bunch ODEs is derived. Assuming linearity, a model of the form $\dot{x}(t) = A(t)x(t) + B(t)u(t)$ arises, where $A(t)$ and $B(t)$ are piecewise constant, and periodic with the revolution period $T_o$. Such models, known in the control community as (periodic) switched systems, have known (in)stability criteria and control theoretic properties, which can be useful in the analysis and control of multiple bunch beamloading.

## 1 BASEBAND FORMULATION

The term beamloading is to imply here the dynamical interaction between a given cavity resonance and the $N$-bunches' longitudinal dynamics. Resonance implies bandlimitedness (BL), and a standard tool for the analysis of bandlimited signals and systems (ODEs) is the IQ formalism [1]. The formalism has been applied to beamloading, especially w.r.t. the cavity ODE in [2], [3].

In the way of review and to establish notation: The Fourier transform of the resonance $Z(j\omega)$, of order $M$ in $j\omega$, is assumed to be (effectively) zero for $\omega$ outside its band. Denote the positive part of the band by $\Omega$. Then using some carrier frequency $\omega_c \in \Omega$, the impulse response kernel of $Z(j\omega)$ is

$$z(t) = z_I(t)\cos\omega_c t - z_Q(t)\sin\omega_c t. \tag{1}$$

The utility of the IQ formalism lies in the fact that we need only consider the complex envelope, defined as $\tilde{z}(t) = z_I(t) + jz_Q(t)$, whose Fourier transform $\tilde{Z}(j\omega)$ is also of order $M$ in $j\omega$. In particular, the cavity output signal $v(t)$ to an (AM/PM) sinusoid $f(t)$ is obtained via $\tilde{v}(t) = \tilde{f}(t) * \tilde{z}(t)$.

### *1.1 Bunch Train Signal*

Use of the IQ formalism presupposes AM/PM signals of the form (1). It is now shown that the beam current, modeled here as an impulse train, *is seen by the resonance* approximately as an AM/PM signal about the carrier $\omega_c$.

The width of $\Omega$ determines the minimum number of bunches that need be considered in a time domain analysis; arbitrary gaps in the beam current may make this determination difficult. Here, the number of representative bunches $N$ is assumed known, chosen through modal analysis or made safely large.

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Define $N_o$ as the number of bunch current "segments": each $n$th beam current segment is of duration $T_b = T_o/N_o$ and has a charge $q_n, n = 1, \ldots, N_o$. $q_n$ may be identically zero if and only if the segment represents a gap; if there are no gaps $N = N_o$. Henceforth the word bunch shall mean bunch segment.

Let $\tau_{n,p}$ denote the $n$th bunch's deviation in arrival time at the cavity from the nominal, for the $p$th arrival. Of course if $q_n = 0$ then $\tau_{n,\cdot}$ is devoid of physical meaning; otherwise it is governed by the synchrotron ODE. However, the cavity sees the beam current as a signal, and that is the perpective of this section.

The time-infinite beam current is written, using Wilson's phasor convention [4], as

$$i(t) = -\sum_{n=1}^{N_o} q_n \sum_{p=-\infty}^{\infty} \delta\left(t - \left[p + \frac{n-1}{N_o}\right]T_o - \tau_{n,p}\right) \tag{2}$$

but, as proven in section 1.2, the following Proposition applies:

**Proposition** *The beam current (2) is seen by an $\Omega$-BL resonance approximately as*

$$i(t) \approx -q(t)\frac{2}{T_b}\left[\cos\omega_c t + \omega_c\tau(t)\sin\omega_c t\right]. \tag{3}$$

In (3), $q(t) = q(t + T_o)$ is a continous-time interpolation (CTI) of $q_n, n = 1, \ldots, N_o$, and $\tau(t)$ is a CTI of $\tau_{n,p}, \forall n, p$, as depicted in Figures 1-2 and defined in the next section. Note that $\tau(t)$ is of use only in discussing the beam current as a signal; when addressing the system aspect (section 1.3 and on), $\tau(t)$ will be abandoned.

### *1.2 Proof of the Proposition*

The Proposition is proved in three steps: interpolation, Taylor series approximation, and application of some Fourier properties.

**Interpolation** [1] The signals $q(t)$ and $\tau(t)$ are formally constructed via the interpolation kernel $S_{T_1}(t) = u(t + T_1/2) - u(t - T_1/2)$, where $T_1$ is some period, and $u(t) = 1$ for $t \geq 0$, and is zero otherwise. Define $\bar{q}_k = q_{-1+k \bmod N_o}$. Then formally,

$$q(t) = \sum_{k=-\infty}^{\infty} \bar{q}_k S_{T_b}(t - kT_b), \tag{4}$$

$$\tau(t) = \sum_{p=-\infty}^{\infty}\sum_{n=1}^{N_o} \tau_{n,p} S_{T_b}\left(t - \frac{n-1}{N_o} - pT_b\right). \tag{5}$$

## DISCLAIMER

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maximum rf output power of approximately 650 kW with 102 mA of stored beam. When driving the ring, the storage ring klystrons operate in class-A at a cathode voltage of 88 kV, with beam current ranging between 11 A to 15.5 A, depending on the amount of stored current. Unless equipment problems preclude, main/standby status between the four storage ring rf stations is typically switched on a weekly basis to equalize the operating time on the stations, resulting in a duty cycle of approximately 50%.

In both booster synchrotron and storage ring service, the APS klystrons are operating well below their design maximums, both in terms of rf output and collector dissipation. This has enhanced APS operational reliability, suggesting that loading power systems at approximately 70% of their design limits is a pragmatic approach to improving overall reliability.

## 2 COLLECTOR HEAT DAMAGE

On October 16, 1995, klystron #023 suffered a catastrophic failure during operation into the storage ring. At the time of the failure, the tube was operating at 80 kV/14 A, with approximately 250 kW rf output. The first and only sign of trouble was a HVPS trip on klystron ion-pump overcurrent, which fired the HVPS crowbar and shut down the klystron magnet and filament supplies. Subsequent investigation confirmed that both ion pump supplies indicated a current in excess of 10 mA. It was also determined that the filament was shorted. At this point, the decision was made to ship the klystron back to the Thomson factory for failure analysis and repair.

After further examination at the factory, it was discovered that cooling water had entered the evacuated region of the tube through a hole in the collector wall. Subsequent examination revealed several small areas on the interior surface of the collector where the spent electron beam had melted the copper, and one area where the local heating was sufficient to cause penetration of the collector wall, allowing water to enter the tube. Due to the extensive heat damage to the collector and contamination of the klystron rf structures caused by the water in the vacuum areas, the klystron was basically stripped down to its chassis and totally rebuilt. It was subsequently returned to service at APS.

After extensive investigation, the root cause of this failure was narrowed down to two possibilities: (1) A local obstruction to water flow on the exterior collector surface, which created a localized hot spot on the interior surface of the collector. This theory is reinforced by the fact that a small amount of stainless steel shavings, sufficient in size to possibly cause a small local disruption in water flow at the collector surface, were found inside the collector boiler when it was disassembled at the factory. It was assumed that the shavings were cuttings produced by pipe threading processes during facility construction that were in the cooling water flow and became trapped in the narrow water passages of the collector. (2) Collector outgassing caused spent beam to be ion-focused to a small area, locally exceeding the dissipation capability of the collector and creating an avalanche condition that rapidly increased temperatures high enough to melt copper. Such failure scenarios involving local heating seem plausible based on the fact that all klystron interlock systems were found to be functioning normally immediately after the tube failure, but such localized heating would not be detected by measuring return water temperature.

## 3 EXCESSIVE HARMONIC POWER PRODUCTION

Klystron #029 was removed from storage ring service on 12/8/96 at 4,949 hours due excessive harmonic output that was damaging the rf system harmonic damper loads. Coaxial cables connecting the harmonic damper loads to the waveguide damper probes became very hot during tube operation, indicating the presence of power at higher harmonics. Subsequent signal samples from the harmonic probes indicated higher harmonic levels relative to levels produced by other klystrons operating in the same socket. Changes were made in waveguide length between the klystron output and circulator input in an attempt to reduce the amount of harmonic power developed, but this had no effect. All other aspects of the tube operation were normal, with no sidebands or other instabilities noted. This tube is presently in spares storage, awaiting further testing.

## 4 SIDEBAND GENERATION

High-efficiency klystrons can become unstable and generate unwanted sideband energy under certain conditions. These sidebands can be at levels as high as –20 dBc and can also move about in frequency relative to the carrier. This allows them to pass through the storage ring cavity bandwidth and modulate the storage ring beam.

Klystron #030 is the only APS klystron that has been proven to generate sidebands (see Fig. 2), which began to

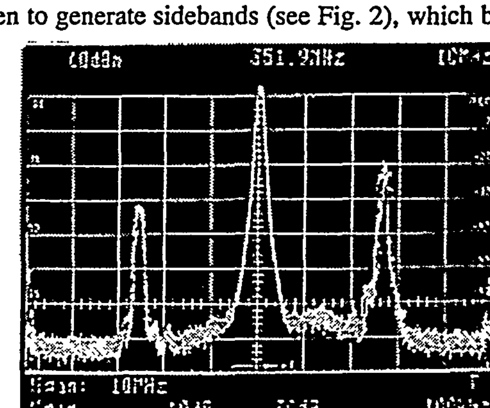

Figure 2: Klystron sidebands

appear at approximately 5,000 hours of operation. Two cavity tunings were performed to eliminate the problem, but ultimately it was determined that the klystron must operate at a minimum cathode voltage of 92 kV to be free of sidebands. This klystron had other operational problems (see the next section) that may be related to the tendency to produce sidebands.

## 5 GUN HIGH VOLTAGE LEAKAGE

At approximately 4500 hours of operation, klystron #030 developed a substantial DC leakage condition between the mod-anode and tube body. High reverse mod-anode currents (5 mA at Vmod-anode = 40kV, electron current flowing into klystron) were the first indication of the problem. The leakage path allowed klystron beam current to flow without any mod-anode bias applied to the tube (see Fig. 3). Subsequent gun leakage current tests indicate that this leakage condition has a very nonlinear voltage-current relationship, suggesting a field-emission discharge point somewhere in the gun. However, the klystron vacuum does not degrade when this leakage becomes measurable. This klystron is in storage until it can be HV-conditioned in an attempt to characterize and eliminate the leakage path.

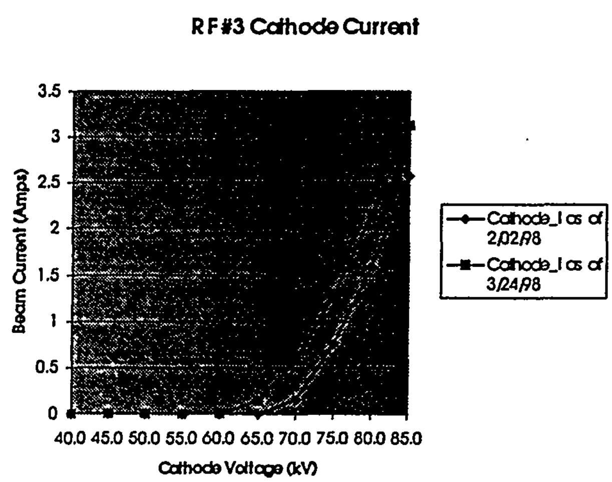


Figure 3: Effect of gun leakage

## 6 VACUUM PROBLEMS

Klystron #033 has exhibited symptoms of a slow vacuum leak. If left off without any ion pumping for longer than two hours, the tube vacuum will degrade, requiring ion pumping for approximately 30 minutes to recover sufficiently for HV operation. The tube also exhibits nonlinear rf gain characteristics between 38 and 40 watts of drive power, suggesting a possible multipactor condition at the input cavity. It is not clear if these two conditions are related. During normal operation, the tube vacuum always returns to normal, with ion pump readings in the area of 0.5 μA. This klystron also has had two instances of false poor vacuum caused by dirty insulators on the ion pump high-voltage connectors. The ceramic insulators in the ion pumps were cleaned, and the ion pump current returned to normal values.

## 7 BROKEN HIGH-VOLTAGE CONNECTORS

Several of the APS klystrons have experienced oil tank leaks due to cracked or broken high-voltage connectors. The damage to the connectors was caused by over-adjusting the bayonet clamp force of the connector when the mating plug was inserted. As a result, more attention is paid to connector insertion and use, which has reduced this type of failure to a minimum.

## 8 DIRTY RF WINDOWS

On June 14, 1998, klystron #033 suddenly began experiencing window arc detector trips while in storage ring service. Inspection of the output flange and window revealed evidence of arcing from center to outside conductor of the coaxial line between the output cavity window and the waveguide transition. The surface of the ceramic window was found to be very dirty. It was later determined that the arc detector trips began happening concurrent with the start of interior concrete block construction activity in the vicinity of this klystron. This work generated a very fine airborne dust that got past the klystron window air filtration system and resulted in a film of fine dirt particles on the klystron window.

The output waveguide of the klystron was removed, and the ceramic window was cleaned using a sandblast procedure with #60 grit at 6 psi. The tube was re-assembled and tested at full power with no further arc trips.

## 9 CONCLUSION

In general, the performance of the APS 352-MHz klystrons has been very good, with very few klystron-related problems interrupting accelerator beam time. Knowledge gained during the first four years of operation has improved our ability to identify potential problems and situations before they result in significant downtime. The long-term effects of low-power diode "standby" operation on the klystrons are still being studied to determine if this mode of operation is detrimental to the klystrons.

## 10 ACKNOWLEDGMENTS

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