DESIGN OF A SCHOTTKY SIGNAL DETECTOR FOR USE AT THE RELATIVISTIC HEAVY ION COLLIDER (RHIC)*

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Abstract

We report on the design for a Schottky detector for RHIC in the form of a resonant cavity. The cavity is similar to the one previously constructed for the Fermilab Tevatron [1] which was used in the successful detection of Schottky signals [2], but differs slightly in its design, and more significantly in its implementation. In particular, the cavity will be used to detect both longitudinal and transverse signals (the latter via the TM_{111} mode), and, through the use of improved signal- analyzer capabilities, we will be able to look directly at the 2 MHz second IF, rather than having to convert the signal to baseband, a feature which will give greater flexibility, relax the absolute temperature-regulation of the cavity, and is indeed almost a necessity given the 79 kHz width and frequency-variability of the Schottky bands. In addition to the design, we present results of measurements of the cavity properties.

1 INTRODUCTION

The incoherent, or Schottky, signals from the beam can provide useful information on beam characteristics [3]. These include momentum spread (from the frequency spread of longitudinal signals), synchrotron tune, transverse emittance (from the amplitude of transverse signals), and the fractional incoherent betatron tune.

Detection of the incoherent signal of a bunched beam is complicated by the presence of the much stronger coherent signal. The latter is (usually) expected to appear most strongly at the RF frequency and its harmonics, but produces strong signals at all multiples of the revolution frequency, as well as at their betatron sidebands; its power scales with the number of particles per bunch N as N^2, whereas that of the incoherent signal scales as N. Since N typically is 10^9 or greater, the incoherent signal is many orders of magnitude weaker than the coherent signal. For a Gaussian bunch, in the absence of intra-bunch oscillations the coherent signal spectrum is limited in extent to maximum frequencies of the order of

$$f_{roll\text{-}off} \approx \frac{1}{2\pi\sigma} \tag{1}$$

where σ is the bunch length. The rate of fall-off of the coherent signal with frequency depends on the details of the bunch shape, but for most shapes it is usually tens of dB per octave for at least several octaves beyond $f_{roll\text{-}off}$. If the coherent signal can be reduced to within even 20 or so dB above the Schottky signal, the latter can usually be distinguished from the former on the basis of its greater frequency spread (see Ref. 2). For a typical bunch length of approximately 1 ns in RHIC, the roll-off frequency is about 160 MHz.

To maximize the signal-to noise ratio of the extremely weak Schottky signals, one wants a high-shunt-impedance detector such an a resonant cavity; to maximize the signal-to-coherent-background-signal ratio, one chooses a cavity resonant frequency as far above $f_{roll\text{-}off}$ as possible, consistent with it not exceeding the cutoff frequency of the attached beam pipe. (The RHIC beampipe cut-off frequencies are 3.3 GHz for TM modes, and 2.5 GHz for TE modes.) A further refinement is to operate the cavity at a frequency which is approximately a half-integer multiple of the RF frequency, in order to minimize the contamination from any residual coherent signals. The RHIC RF frequency of 197 MHz results in a multiple of 10.5 to arrive at an operating frequency of 2.07 GHz. A similar device has been built and operated at FNAL for several years [1,2].

2 CAVITY DESIGN

The cavity design uses TM_{120} and TM_{210} modes in a rectangular cavity to independently sense both vertical and horizontal beam signals. In addition, the cavity is designed to use the TM_{111} mode to detect longitudinal beam signals.

The practical upper limit of transverse modes is given by the beampipe TE mode cut-off, and this sets the transverse dimensions of the cavity to be approximately 154mm in width. To differentiate the frequencies of the horizontal and vertical modes, we introduce a small difference of 0.5 mm in the two transverse dimensions, which results in a frequency difference of 4 MHz between the two dipole mode polarizations. (The reasons for this choice will be discussed in Section 4).

The dipole modes are relatively insensitive to the longitudinal dimension of the cavity (the dependence being a second-order effect of the beampipe apertures), and we are free to choose this dimension to select a suitable monopole-mode frequency for longitudinal signal detection. A length of 64.7 mm was chosen to give a TM_{111} mode frequency of 2.74 GHz without

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degrading the shunt impedance of the transverse modes by more than a few percent.

The Schottky signal power (per betatron band) is given by

$$P = \left\langle I_{beam}^2 \, x^2 \right\rangle \left(\frac{\omega}{c}\right) \frac{R_\perp T^2}{4} \qquad (2)$$

(the transverse-impedance convention employed here is that the $R_\perp T^2/Q$ in eq. 2 is k times the $R_\perp T^2/Q$ as defined in refs. 1 and 2), where for Schottky signals

$$\left\langle I_{beam}^2 \, x^2 \right\rangle = N \left(e \, f_{revolution}\right)^2 \sigma_\perp^2 \qquad (3)$$

and for the RHIC Schottky cavities

$$R_\perp T^2 = 9 \ \mathrm{M\Omega m^{-1}} \qquad (4)$$

From Eqs. 2 and 3 we see that $\langle x^2 \rangle$ can be obtained from the Schottky spectrum if one knows cavity characteristics and the beam properties. In turn, knowing the β-function at the cavity allows one to calculate the beam emittance.

Because of the success of the FNAL detector [2] and the similarity of the operating parameters, the mechanical design of the present cavity differs very little from the previous one. The principal changes are that because of the more stringent vacuum requirements at RHIC, we replaced the aluminum cavity body with one of copper-plated stainless steel, which also enabled us to replace the aluminum-clad stainless steel cover with a copper-plated stainless steel one. This in turn permitted the soft aluminum vacuum seal to be replaced with a Helicoflex® one.

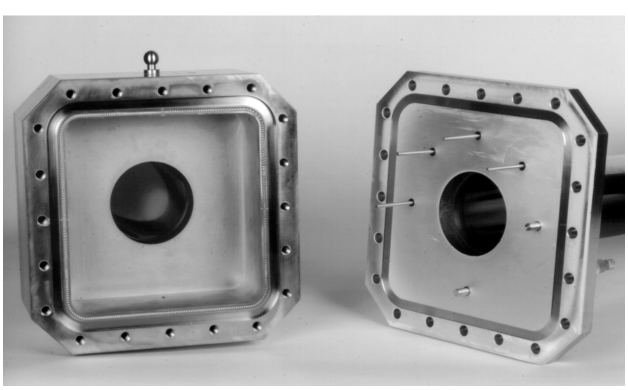

Figure 1: Cavity with cover plate removed to show rectangular cavity with (oversized) coupling probes, and tuners.

The detector, with the cover plate removed, is shown in fig. 1. The horizontal and vertical E-field signals are detected using E-field coupling probes mounted on the cover plate and located on the *x*-and *y*-axes, respectively. Another two couplers are located at 45° from the horizontal and vertical, to be used for detection of longitudinal signals, and for the injection of test signals. Two tuning plungers, similarly oriented, are positioned on the horizontal and vertical axes; these are necessary to compensate for frequency errors arising from machining tolerances and the shifts due to the coupling probes. The symmetry of the arrangement of probes and tuners effectively suppresses any imperfection-induced coupling of the two dipole modes.

3 CAVITY MEASUREMENTS

To provide critical coupling of the horizontal and vertical probes to the respective dipole modes, S_{11} measurements of the cavity were made. Several iterations were necessary due to the influence of the probes on all cavity modes, and their length was gradually but significantly reduced from that shown in figure 1. Figure 2 shows the S_{21} response of the cavity measured using the vertical probe and one of the 45° probes.

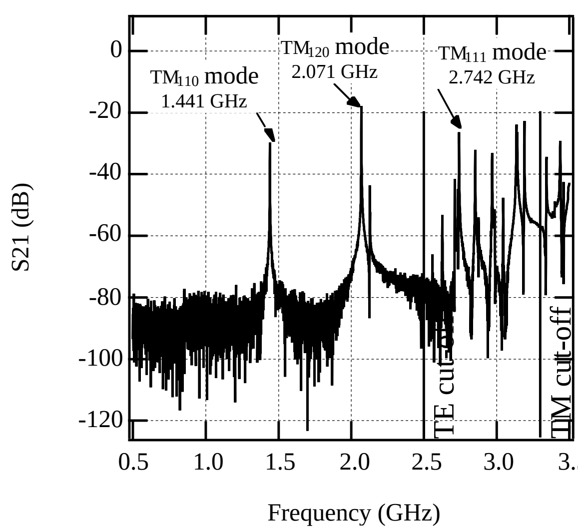

Figure 2: S21 spectrum measured from the vertical coupling probe to a 45° probe.

A perturbation technique was used to measure the R/Q of each mode [4]. A cylindrical “bead” (needle) oriented along the beam axis was used for all measurements. Because the relevant form factor (see ref. 4) cannot be calculated for a needle, it had to be obtained experimentally by comparing the needle’s response to that of a spherical bead using the on-axis field of the longitudinal TM_{111} and TM_{110} modes. Figure 3 shows the phase shift produced in TM_{120} mode by the needle as a function of longitudinal needle position, for various transverse offsets. Integrating the square root of

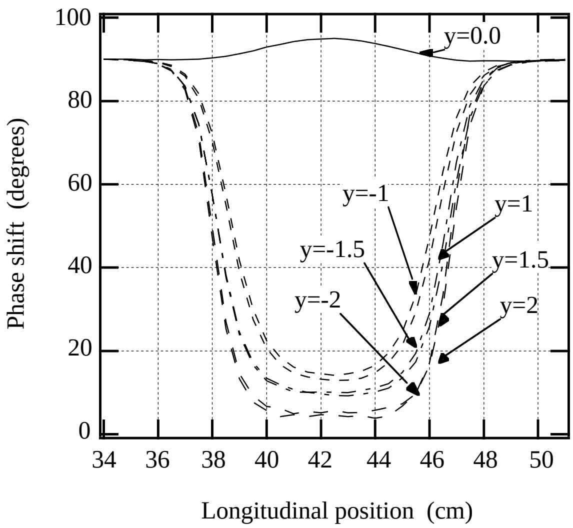

Figure 3: Phase shift due to perturbation of the TM_{120} mode by a needle at various y (vertical) offsets.

the associated perturbation in mode frequency allows the calculation of the $R_{\|}T^2/Q$ of the mode. $R_{\perp}T^2/Q$ is obtained from quadratic fit to $R_{\|}T^2/Q$ as a function of radial offset, from the relation

$$\frac{R_{\perp} T^2}{Q} = \frac{1}{kr^2} \frac{R_{\|} T^2}{Q} \tag{5}$$

which can be seen in figure 4. No transit time correction has been applied in this figure, and the transit time factor for relativistic ß=1 for this mode is T = 0.52. Table 1 lists the mode characteristics.

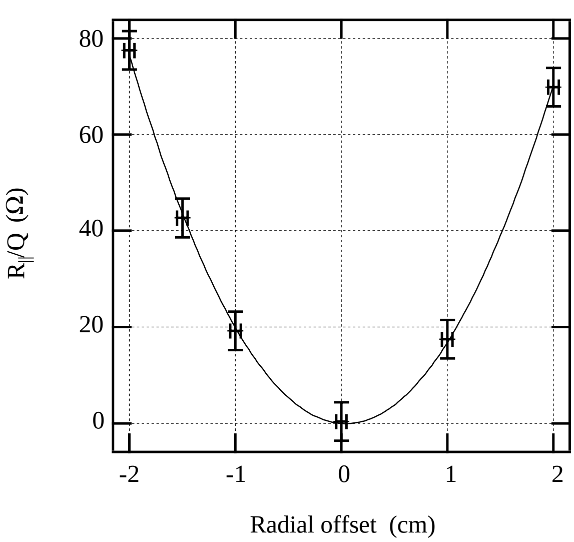

Figure 4: Measured ($R_{\|}/Q$) as a function of horizontal offset of the perturbing needle, with quadratic fit. No transit time correction has been applied.

Table 1: Cavity parameters.

Mode	Parameter	Value
TM_{120}	Frequency	2.071 GHz
	$Q_{unloaded}$	10,000
	$R_{\perp}T^2/Q$	900 Ω
	$R_{\perp}T^2$	9 MΩ/m
TM_{210}	Frequency	2.067 GHz
	$Q_{unloaded}$	10,000
	$R_{\perp}T^2/Q$	900
	$R_{\perp}T^2$	9 MΩ/m

4 ELECTRONICS

As described in ref. 2, rapid data acquisition requires converting the detector signals to frequencies low enough that one can employ an FFT signal analyzer; using a conversion scheme referenced to the RF signal will minimize the phase noise in such a signal. The relatively small vertical-horizontal frequency difference permits a relatively simple half-integer-multiple demodulation scheme for converting the signals to a frequency which is easily transmitted over long distances (so that the receiver can be located in the vicinity of the detector) and can, without further demodulation, be displayed on a wide-band signal analyzer. On the other hand, to minimize extraneous noise, we wanted this signal to be at a high enough frequency that it would be above that of the commercial AM band. We (somewhat arbitrarily) chose ±2 MHz as a frequency difference which would permit both these requirements to be satisfied. Because of the ≈80 kHz revolution frequency, use of a wide-band signal analyzer eliminates a number of difficulties associated with the frequency shift that accompanies change of particle type; it also avoids the need for retuning the cavity to compensate for small temperature drifts.

REFERENCES

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