Title

A HIGH-FREQUENCY SCHOTTKY DETECTOR FOR USE IN THE TEVATRON

Author

Goldberg, D.A.

Publication Date

1987-03-01

LBL-22273 c.2

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

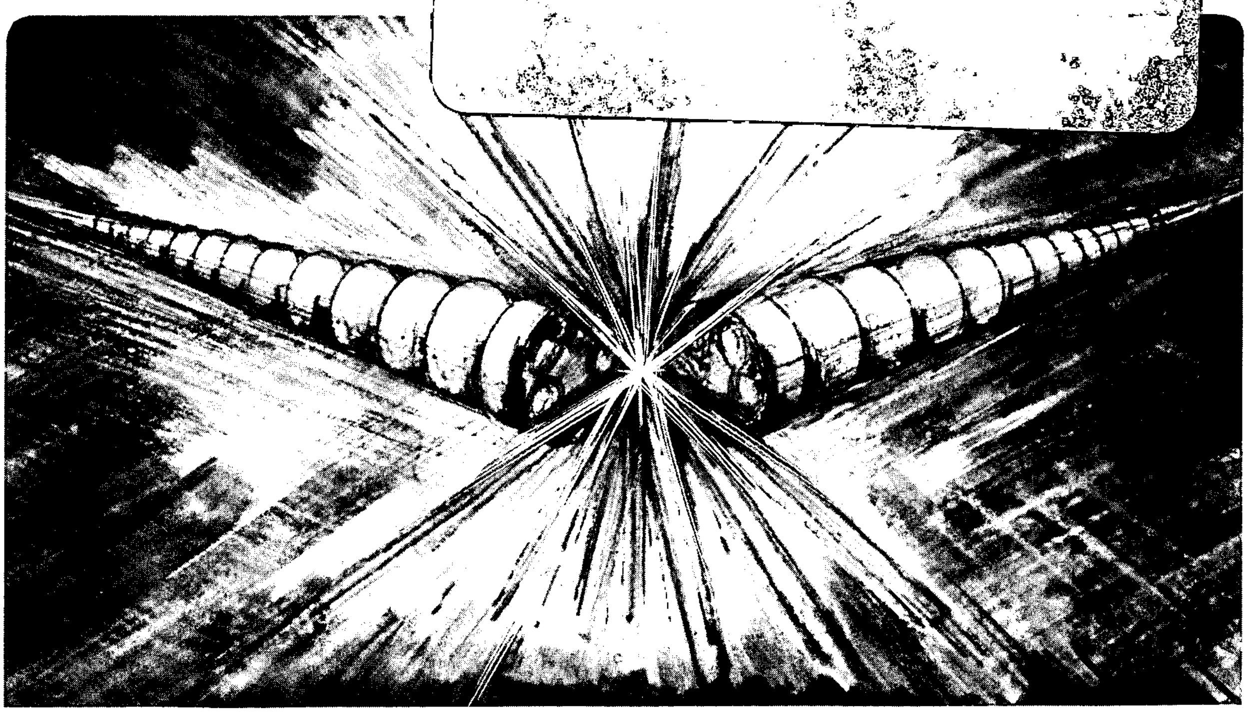
Accelerator & Fusion Research Division

Presented at the 1987 Particle Accelerator Conference, Washington, DC, March 16–19, 1987

A HIGH-FREQUENCY SCHOTTKY DETECTOR FOR USE IN THE TEVATRON

D.A. Goldberg, W. Barry, G.R. Lambertson, and F. Voelker

March 1987



Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

LBL-22273

A HIGH-FREQUENCY SCHOTTKY DETECTOR FOR USE IN THE TEVATRON*

D.A. Goldberg, W. Barry, G.R. Lambertson, and F. Voelker

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

March 1987

* This work was supported by the Office of Energy Research, U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

A HIGH-FREQUENCY SCHOTTKY DETECTOR FOR USE IN THE TEVATRON*

D. A. Goldberg, W. Barry, G. R. Lambertson, and F. Voelker
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

Abstract

A vexing problem associated with detection of Schottky signals from a bunched beam is the presence of the coherent signal, which can be 10 or more orders of magnitude greater than the Schottky signal. However, above the single-bunch cutoff frequency (SBCF), the coherent signal decays rapidly with frequency. To take advantage of this, we have constructed a Schottky detector for the Tevatron doubler to operate at roughly 2 GHz (the Tevatron SBCF is 200-300 MHz). To enhance signal power density, we have made the detector a high-Q (>9000) resonant rectangular cavity, which should provide a signal-to-noise-density ratio (S/N) of >10 dB for the Tevatron in the collider mode, and >20 dB in fixed target operation. The TM_{210} and TM_{120} modes, which are made to have slightly different frequencies, provide sensitivity to both vertical and horizontal particle motions. The 2 GHz Schottky signals are down-converted to frequencies below 100 kHz to permit analysis using a FFT spectrum anlayzer. The initial installation consists of a single cavity; a second detector will be built which employs a pair of phased cavities to permit discrimination between p's and $\bar{p}$'s. Details of the de-sign of both the cavity and the associated electronics are presented. The cavity is currently undergoing installation at the Tevatron.

Introduction

With the use of a suitable detector, one can sense fluctuations in the instantantaneous number and/or positions of particles in a cyclic accelerator. The nature of the signals from such detectors, the so-called Schottky signals, is described in detail in Ref. 1. Summarized briefly, the frequency spectrum of these signals consists of a set of bands occuring at integer multiples of the particle revolution frequency, and a second set which is displaced from the first due to the particles' betatron motion; if the beam is bunched, the synchrotron motion splits these bands into a set of possibly overlapping satellite lines. One can use Schottky signals to obtain a variety of diagnostic information on a particle beam without perturbing it.

Because of the relative weakness of Schottky signals, one important requirement for such a detector is very high sensitivity; other than using a large phased array of low impedance detectors, the only reasonable alternative is to employ some form of resonant detector. A second problem frequently encountered is the contamination of the Schottky signal by the much stronger coherent signal produced by the bunched beam; one way to overcome this problem is to make the detector resonant frequency well above the SBCF. An upper limit on the detector frequency is that it be below the cutoff frequency of the beam pipe; for the Tevatron collider this limit is about 2 GHz.

To make a Schottky detector satisfying both the above requirements we have chosen an rf cavity; to provide sensitivity to, and differentiability between, both vertical and horizontal motion, we have chosen a rectangular cavity. The lowest order modes of such a cavity which exhibit sensitivity to transverse beam position are the TM_{210} and TM_{120}, which respond to horizontal and vertical motions, respectively. By making the cavity slightly off square, we can use the resulting difference in resonant frequencies for the two modes to distinguish between the two motions.

To achieve the frequency resolution necessary for measuring the widths of the central synchrotron satellite lines (<3 Hz), and still provide reasonable data acquisition times, it is necessary to employ a FFT spectrum analyzer. This in turn necessitates down-converting the 2 GHz cavity signal to something below 100 kHz through the use of what amounts to a tuned radio receiver, described in more detail below. To minimize spectral smearing due to phase noise in the beam, the heterodyning signal is referenced to an rf signal from the Tevatron; because of the prohibitive cost of making a tunable receiver, it is necessary to tune the cavity to the (fixed) receiver frequency, rather than vice versa.

Detector Requirements

The principal requirements for the Schottky detector are summarized in Table 1. They arise largely from the above considerations in conjunction with the Tevatron parameters given in Table 2. It is planned to replace the present detector with a system comprising a phased pair of such detectors, to permit discrimination between p's and $\bar{p}$'s; in some cases this consideration also affected design choices.

Table 1. Design Goals

S/N	>10dB	(collider mode)
f_o	2044.5 MHz	
$\Delta f_{v,h}$	± 2 MHz	
Q_u	10,000	
tuning	±50 kHz	(single cavity)
	±15 kHz	(double cavity)
ΔT	±1.0 C°	(single cavity)
	±.25 C°	(double cavity)

Table 2. Tevatron Operating Parameters

f_{rev}	47.71 kHz	
η	.0028	
Δp/p	5×10^{-4}	(full width)
N	10^{12}	(fixed target mode)
	6×10^{10} per bunch	(collider mode)
$\sigma_{\perp}$	0.8 mm r.m.s.	

The above S/N is imposed on a machine operating to the specifications of Table 2; this makes it possible for the device to provide useful information for a machine operating at only 1/10 of the stated intensity. Several factors governing the choice of operating frequency have already been discussed. In addition, to minimize possible coherent signal contamination in multi-bunch operation, we chose the cavity frequency to be a half-integer multiple of the rf frequency; the multiple of 38.5 gives a fre-

*This work supported by the Office of Energy Research, U.S. Dept. of Energy, under Contract No. DE-AC03-76SF00098.

quency which is sufficiently below the beam tube cutoff frequency that the single-detector response is relatively unaffected by the beam tube ports, and that adequate isolation will be provided in the two-cavity system for cavity separation < 50 cm.

The actual TM_{120} and TM_{210} frequencies are displaced by ±2 MHz from the above f_o. This splitting should be low enough to permit reasonably narrow bandwidth in both the rf and 1st IF stages (see circuit discussion below), and yet high enough to avoid incidental coupling between the two modes; since the splitting frequency is also used as the frequency of the final IF stage, it should be high enough to permit signals from that stage to be transmitted over long distances without interference from the commercial AM band.

To translate the S/N requirement for the cavity into a Q-value we use the fact that the signal power developed by a pickup is given by

$$P = \langle (I_B x)^2 \rangle R_\perp T^2 / 4\lambda\!\!\!^-{}^2 \qquad (1)$$

where $\langle (I_B) \rangle$ is the rms of the product of beam current and beam displacement, and $\lambda\!\!\!^- = c/2\pi f$ and $R_\perp T^2$ is the product of shunt impedance and transit-time factor. For a circular accelerator with particle revolution frequency f_{rev} and a circulating beam of N particles, the "source term" for the Schottky signal is

$$\langle (I_B x)^2 \rangle = N(e f_{rev}^2)\, \sigma_\perp^2 \qquad (2)$$

Note that because Schottky signals result from fluctuations, this term is proportional to N (for many accelerators, N usually exceeds 10^{10}, rather than N^2 as would be the case for coherent signals; this accounts for the ability of signals due to coherent motion to completely overwhelm the Schottky signals.

When excited in the TM_{210} (or TM_{120}) mode, a closed rectangular cavity of length ℓ, an unloaded Q of Q_u and a matched output has a shunt impedance at resonance given by

$$R_\perp T^2 = \frac{64}{25\pi^2} Z_o Q_u T^2 \frac{\ell}{2\lambda\!\!\!^-} \qquad (3)$$

where Z_o is the impedance of free space, and T is the usual transit-time factor $\sin(\ell/2\lambda\!\!\!^-)/(\ell/2\lambda\!\!\!^-)$.

For the case of a cavity with beam ports at the end, Eq. 3 remains approximately correct as long as the port size remains small with respect to the wavelength. The product $T^2(\ell/2\lambda\!\!\!^-)$ has a broad maximum of ≃ .7 at $\ell/2\lambda\!\!\!^- \simeq 1.17$, giving $RT^2/Q_u \simeq$ 34 ohms. Using the Tevatron operating parameters given in Table 1, and assuming a 3 dB noise figure for the electronics (amplifier noise plus cable attenuation), we find that an unloaded Q of 10000 gives us a S/N of >13 dB in the collider mode, and >22 dB for the fixed target mode.

Note also that for an N-bunch machine with particle revolution frequency f_{rev}, if it is desired to process signals from individual bunches separately, the requirement that the cavity "ring down" to a voltage 1/e between bunches takes is

$$Q_L/f_o < \pi/N f_{rev} \qquad (4)$$

For the case of the Tevatron collider, where N = 3, a Q_L of 5000 would give a ring-down time of roughly 1/8 the bunch separation which would give nearly 70 dB pulse-to-pulse isolation. Finally, a loaded Q of 5000 gives a response which is >8 Schottky bands wide (FWHM) so that the detector response is essentially flat over the span of the central Schottky band.

The final requirements on tuning and temperature regulation are linked: The temperature stability is simply what is required to maintain the tuning tolerance. For the double cavity, the tolerance is based on the requirements that gains and phases be sufficiently matched to give 30 dB directional rejection; for the single cavity the tolerance is somewhat more arbitrary, and is based on keeping the response constant to 5%. In either case, the required temperature tolerances exceed those of the available water systems at Fermilab, and we decided that the entire assembly be installed in a thermostatically controlled box to be maintained at 110°F, roughly 10° higher than the warmest anticipated ambient temperature in the Tevatron tunnel.

Detector

The single cavity detector is shown in Fig. 1; the interior of the device consists of a rectangular cavity with rounded corners. Attached to either end of the cavity are beam tubes which also serve to support the structure when it is installed in the Tevatron. The requirements of high Q, good vacuum properties, mechanical stability, and reliability and ease of fabrication led to a choice of 6061 aluminum for the cavity itself. Vacuum joints involving aluminum surfaces are made using a radially expanding metal (REM) seal, somewhat similar to a Mott seal; the REM seal also serves as an rf joint.

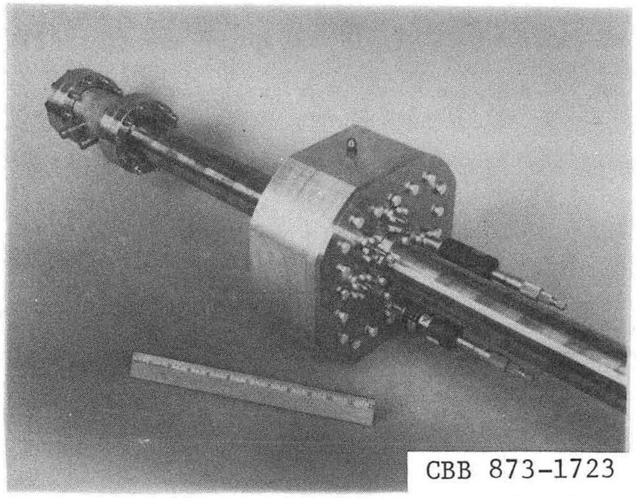


Fig. 1. Assembled Schottky Detector

The tuning requirements for the cavity cannot be achieved by machining tolerances alone (the sensitivity to transverse cavity dimension is approximately 330 kHz/mil), and so a pair of micrometer-controlled tuning plungers, shown in the figure, must be employed. Each of the coupling antennas consists of an axial rod mounted on an SMA fitting located roughly halfway between the cavity center line and its outer wall. Both the tuning plungers and the antennas, as well as a third antenna for injecting test signals, come mounted on conflat flanges. To minimize the number of REM seal adapters, the cover plate containing these feed-throughs was fabricated from a plate made of 1/2" aluminum bonded to 3/8" stainless steel. The former metal provided the required low resistivity interior surface; the latter permitted the use of con-flat seals for all feed-throughs.

To tune and test the cavity, we first modified the antenna lengths so that they provided matched coupling to the external 50 ohm loads. The tuning plungers were then adjusted to give the proper "ver-

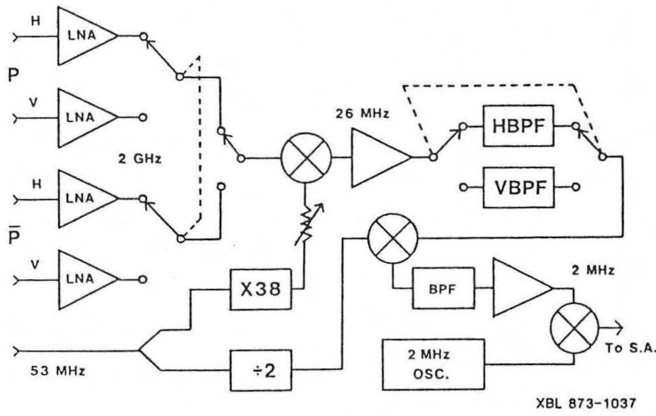


Fig. 2. Frequency Converter Block Diagram

tical" and "horizontal" frequencies (compensated for the system being at room temperature and not under vacuum). We then measured the unloaded Q-values and found them to be Q_v = 9500 and Q_h = 9200; the small difference is attributed to slight differences in the antennas and tuning plunger positions. We then measured the detector response using the bead measurement technique described in an accompanying paper [2], and obtained an RT^2/Q of (29±1) ohms. The reduction from the calculated value of 34 is due principally to the reduction of the fields near the cavity ends due to the beam apertures; together with the slightly low Q values, this results in a reduction of S/N of just over 1 dB to a still acceptable value of 12 dB.

As mentioned above, we chose a resonant frequency of >2 GHz in the hope that it would be far enough above the SBCF that we would not experience problems caused by coherent signals. In anticipation of the possibility that such signals would nonetheless be present (due either to insufficiently rapid frequency falloff, or coherent intra-bunch oscillations), we have constructed a broad-band (0.7-2 GHz) coherent-signal detector in the form of a 50 ohm stripline having a .04 ohm shunt impedance, to look at the frequency spectrum of such signals in the event they should be present. The auxiliary stripline detector is mounted in a short section of beam tube attached to the cavity beam tube, seen at the extreme left in Fig. 1. Coherent signals roughly 40 dB above the Schottky signals should be observable with such a detector.

Electronics

The circuit for converting the 2 GHz Schottky signal to a signal at <100 kHz is shown in Fig. 2. The input rf stage can switch-select either the vertical or horizontal signals from either p's or (after the double cavity is installed) $\bar{p}$'s. Separate narrow-band filters for the vertical and horizontal signals are used in the first IF stage to reduce noise power to the second mixer and thereby permit additional gain in this stage. As noted earlier, both the vertical and horizontal signals get down-converted to the same 2 MHz final IF. The final conversion stage is located on a separate chassis so that the 2 MHz signal can be used for transmitting signals from the detector location (station F0) to the main control room, roughly 1 km away. The variable frequency oscillator in the final conversion stage permits selecting different Schottky bands, and positioning of the desired band within the 100 kHz frequency window of the spectrum analyzer; it can also be used to compensate for small drifts in the cavity frequency.

To resolve the central synchrotron satellite lines, we need a frequency resolution small compared to the 28 Hz synchrotron frequency; to be able to measure the linewidths requires even better resolution. The principal limit to such resolution is phase noise introduced by either the beam or the measuring electronics. To minimize the effects of the former we have used a frequency conversion scheme referenced to the rf system (there are several sources for such a reference signal; we intend to experiment to see which most nearly duplicates the beam phase noise). Investigation of the latter indicates that the conversion circuit introduces no measurable phase noise relative to an instrument width of 3 Hz FWHM.

Temperature Control

To achieve the required temperature stability the detector assembly is enclosed in an insulated box having 2" styrofoam/plywood walls. The box temperature is maintained at 110° F by means of a thermostatically controlled heater (in the form of a long-life 150 W light bulb) and a muffin fan to ensure uniform air temperature. The control unit is an Omega Model CN-2002-P2 controller, which has the capability of a programmably variable output to the heater. The temperature sensing element is a platinum RTD mounted on the detector. Initial tests indicated that the system can maintain the cavity temperature to < ±0.2°C.

Acknowledgments

Design and construction of the cavity was done with the invaluable assistance of Tom Henderson and John Meneghetti. Similar assistance in the construction of the electronic circuits and the temperature control apparatus was provided by Jim Wise. Construction and testing of the auxiliary stripline detector was done by Jimmie Johnson. We are grateful for the encouragement and counsel of Fermilab personnel throughout this project, and most notably to Jim Crisp for his splendid cooperation in his role as our Fermilab liaison.

References

1. S. Chattopadhyay, "Some Fundamental Aspects of Fluctuations and Coherence in Charged-Particle Beams in Storage Rings," CERN Report 84-11 (unpublished).

2. W. Barry and G.R. Lambertson, "Perturbation Method for the Measurement of Longitudinal and Transverse Beam Impedance," these proceedings.

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720