COHERENT SYCHROTRON RADIATION DETECTOR FOR A NON-INVASIVE SUBPICOSECOND BUNCH LENGTH MONITOR*

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A Coherent Synchrotron Radiation (CSR) detector has been developed in a collaboration involving CEBAF and the University of Virginia (UVA) to monitor non-destructively the length of a sub-picosecond bunch with high sensitivity. The monitor employs a state of the art GaAs Schottky whisker diode developed at UVA, which is operated at room temperature at a wavelength of a few hundred microns. The detector is capable of detecting radiation power as low as ten nanowatts, depending on the operating wavelength. In this paper we will describe the details of design specifications, parameter ranges, and features of the monitor and will also report its performance and comparison between the measurement results and calculation. The measurement results will be cross-compared with an independent bunch length measurement using a phase modulation and detection technique.

Following a brief discussion of the need for such a monitor, the following topics will be discussed: brief discussion on the theory of the device and the experimental arrangement, the properties of the Schottky diode detectors which are particularly convenient for our application, a summary of the measurement results, a summary of future plans and improvements to the monitor, and finally, a set of conclusions.

I. Introduction

In order to achieve the smallest energy spread in the extracted CEBAF beam, one would like to set and maintain the bunch length of the beam microbunches as short as possible [1]. The CEBAF injector specification requires the 4σ bunch length to be under 1.2° at 1497 MHz. Routinely, CEBAF achieves 4σ bunch lengths of under 0.6° as measured by an invasive bunch length monitor based on phase transfer function measurements [1,2]. Because the measurement is invasive, it is done only sporadically during beam operations, and does not provide a continuous picture of the beam state. Therefore, CEBAF initiated studies to develop a non-invasive monitor.

In storage rings it is possible to infer the bunch length by using RF “cavities” tuned to harmonics of the fundamental frequency, at high enough frequency that the bunch spectrum is changing as a function of frequency. By observing the power that is radiated into the cavity and by independently measuring the average current, one infers the bunch length from the power and an estimate of the longitudinal form factor [3], assuming the bunch is Gaussian. Longer bunch lengths produce a decrease in the RF current driving the cavity, and less power coupled out to the RF detector. Typically, the cavity dimensions are of the same order as the bunch length.

In order to apply this idea to a linac beam as at CEBAF, two difficulties must be overcome. First, because the full width bunch length is of order 500 μm, RF detection type monitors must be replaced by something that detects radiation of wavelength of order 500 μm. Assuming that a non-invasive and non-destructive monitor is desired, one is led to explore using the Coherent Synchrotron Radiation emitted from the beam in bends, in the regime of several hundred microns radiation wavelength. The problem of detecting such radiation with low noise has been solved using Schottky barrier diodes developed at the University of Virginia.

Second, the beam distribution is not expected, *a priori*, to be Gaussian in a non-storage ring application. Therefore, a separate calibration measurement must be done in order to obtain the relation between output CSR power and bunch length, which is intimately related to the details of the longitudinal bunch distribution. This can be done at CEBAF because there is an independent method to determine the bunch length.

It should be noted that because the power usually goes down with increasing bunch length, such a monitor provides an operationally useful means of triggering processes that can be used to optimize the bunch length. Once the CSR power falls below a predetermined trip level, the invasive method of bunch length optimization can be invoked to correct the setup.

II. Theory

The CEBAF injector provides beam at 45 MeV. Before being injected into the first linac, the beam is bent horizontally in an injection chicane, which allows the relatively low energy injector beam to be merged with the higher energy recirculated beam. The injection chicane has four dipoles of bend radius 2.6 m, the first of which has a synchrotron radiation port of 1 cm^2 area. The port has a single crystal quartz window; the radiation is collected with reflecting optics and focussed onto the Schottky detector about 10 cm off axis from the port centerline. Fig. 1 gives a theoretical plot of the power through the port for four different values of the bunch length (4σ = 0.4°, 0.5°, 0.6°, and 0.7°) assuming a Gaussian distribution. It is assumed that the detector bandwidth is 20%, the average current is 100 μA, and the acceptance angle is about 15 mrad. The transition from coherent to incoherent emission occurs at a radiation wavelength of order the bunch length, and gives a power increase of 5×10^5 at long wavelengths.

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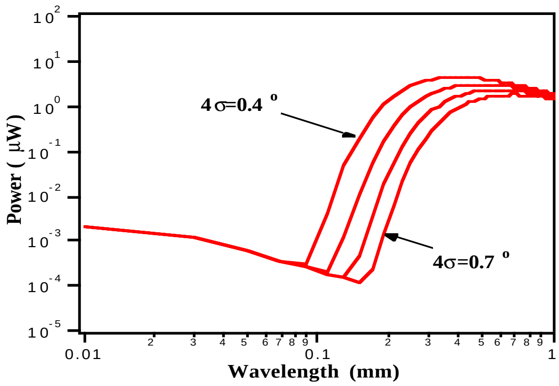

Fig. 1 Plot of Power vs. Wavelength for Injector CSR Port

For a given bunch length, the power peaks at higher levels and shorter wavelengths as the bunch length is made shorter, the total power rising because the emission is rising at shorter wavelengths. If the operating wavelength of the detector is fixed, the power depends very sensitively on the bunch length, more sensitively for larger numbers of electrons per bunch. Therefore, monitoring the CSR power at a fixed wavelength is equivalent to monitoring the bunch length. The optimal wavelength for the detector depends, of course, on the desired bunch length. Finally, it should be noted that the CSR power goes as the current squared, all else remaining constant.

The calculations above were made assuming a Gaussian form factor. Using the data acquired with the invasive bunch length device, one may estimate the longitudinal distribution more precisely and compute the coherent enhancement factor more exactly. Qualitatively, the picture presented above does not change.

III. Schottky Diode Detectors

The Schottky diodes used for these measurements were developed and fabricated by the Semiconductor Device Laboratory of the University of Virginia. They are designed for mixing applications and video detection in the far infrared (about 500 GHz to 3 THz). The diode chip contains several thousand individual circular anode wells in a layer of insulating $Si0_2$. The anode wells are plated with platinum followed by a top layer of gold. The platinum, in contact with the GaAs epitaxial layer below the $Si0_2$, form the Schottky diode. Below the epitaxial layer is an n++ GaAs substrate which is soldered to a metal post to form an ohmic contact. This “honey-comb” diode structure was first developed by Young and Irvin [4]. The fabrication and design of these diodes is described in the literature [5,6].

The radiation is coupled to the diode by a four wavelength long wire travelling wave antenna formed from the 1 mil whisker wire that contacts the anode. The antenna length is defined by the distance from the diode to a 90 degree bend which inductively cuts off the remaining length of wire to the induced current. The travelling wave antenna in free space has a symmetric pattern about the axis of the wire. Introducing a 90 degree corner reflector 1.2 wavelengths behind the antenna results in a sharper radiation beam. The corner cube used for these experiments was designed at the Max Planck Institute for Radio Astronomy in Bonn [7]. The radiation is focussed onto the corner cube using an off-axis parabolic mirror (60 mm focal length, Melles Griot 02 POA 019). The performance of whisker contacted diodes as mixers and video detectors versus frequency was investigated by Wood [8]. The video responsivity (V/W) of a diode is inversely proportional to junction capacitance and to frequency. Therefore, the best video detector will have a low junction capacitance, which implies a small anode diameter. The corner cube mounted diode exhibits a wide bandwidth. An external mesh filter was used to achieve a known bandwidth (about 15% to 18% with a very high transmission of 0.93 to 1.00. The mesh filters were a freestanding copper film with cross shaped apertures. A complete description of modelling, fabrication and test results for the mesh filters is discussed by Porterfield, *et al* [9].

A picture of the corner cube and diode assembly is given in Fig. 2, where the scale of the device is seen from the SMA connector on the right side of the cube.

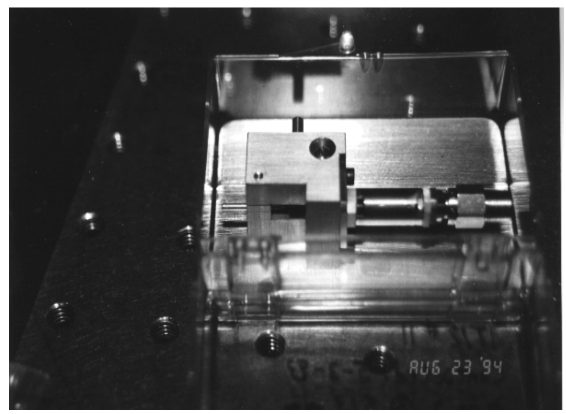

Fig. 2 Corner Cube and Schottky Diode Assembly

IV. Results

Several tests of the CSR diodes have been done. During our first set of tests in February, the CSR signal was observed at the end of a run. After improving the signal amplification and isolating the diodes from damage by ground loops, the coherent emission from the CEBAF bunches was again measured with a new biasing and amplification circuit, and found to be in agreement with expectations given the large radiation spot that was measured.

Fig. 3 gives a plot of CSR power vs. the beam current, along with a fit to the current squared dependence expected for coherent emission.

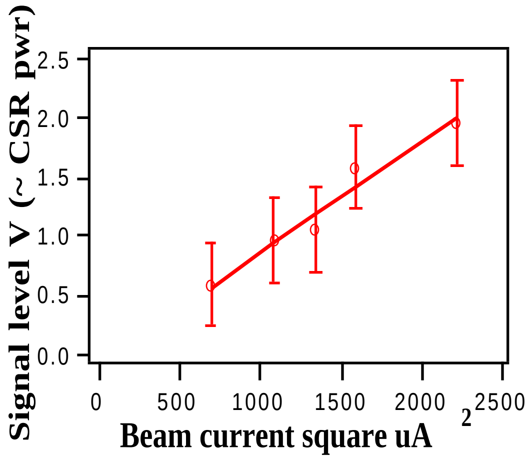

Fig. 3 CSR Power vs. the Square of the Beam Current

In Fig. 4, the fact that the CSR power depends on bunch length is shown. In Fig. 4 the measured CSR power (Schottky diode output voltage) is plotted as a function of the chopper phase of the CEBAF injector. The two curves are for two different diodes operating at wavelengths of 331µm and 216 µm. Zero degrees on the chopper gang phase corresponds to the nominal optimized setting yielding minimum bunch length (4σ=0.6°) as measured by the invasive monitor. If the chopper phase is varied in either direction away from this optimal setting, the invasive monitor shows that the bunch length is increased. As is evident, the CSR power falls on either side of the minimum bunch length configuration, as it should. Given that a 4° change in the chopper phase produces a change of the bunch length from 4σ = 0.5° to 4σ = 1.65° as measured by the invasive monitor, a change in the bunch length of 0.1° (200 fsec) is detectable with the 216µm diode and a change in bunch length of 0.25° is detectable with the 331µm diode. That the 216µm diode should be more sensitive for short bunch lengths may be seen from Fig. 1.

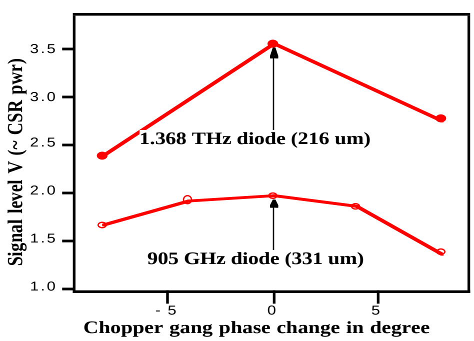

Fig. 4 CSR Power vs. Chopper Phase

V. Future Plans

There are several enhancements that will be pursued in the near term. They are related to computer control and analysis of measurements, coupled with automatic update of the bunching parameters of the injector. An externally triggered A/D card is being purchased to digitize the CSR output signal. In addition, a computer controlled biasing supply is being acquired so that diode validation can be done from the control room. These two additions will produce an operational final monitor. We have run diodes for several hours with no degradation in performance. After a reasonable CSR power trip level is determined, the invasive bunch length monitor will be invoked whenever the power falls too low to correct any bunch length problems that arise. There are well defined correction procedures based on the invasive monitor [10] that can be automated with good results.

Normalization of the measurement is done using standard current monitor cavities [11]. As these are accurate to better than one percent, the normalization should be good to two percent, much smaller than the power changes to be detected. Calibration of the measurement will proceed in the same way as that it occurred for the invasive bunch length measuring system. By systematically changing the bunching parameters it is possible to completely characterize the CSR output as a function of bunch length.

VI. Conclusions

A coherent synchrotron radiation bunch length monitor has been installed in the CEBAF injector. This room temperature device has detected coherent synchrotron radiation at roughly the expected level. We have verified experimentally that the output power varies with the bunch length and that detectors at shorter wavelengths are preferred. We have also verified the high bandwidth of the Schottky detector and used it to study the stringent case of pulsed CEBAF beam, which has very low average power.

VII. References

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