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X-RAY AND CHARGED PARTICLE DETECTION BY DETUNING OF A MICROWAVE RESONATOR*

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Abstract

Charged particle detection is important for beam alignment, beam loss, and background control. In case of halo detection, traditional wire scanner measurement utilizing carbon or tungsten wires is limited by the damage threshold of these materials. In this paper, we present an electrodeless method to measure halo with a diamond scraper. This measurement utilizes a microwave resonator placed around the diamond scraper, which is sensitive to charged particle-induced conductivity. Due to this transient induced conductivity in the dielectric, a microwave coupling to the resonator changes. Diamond in this case is chosen as a radiation hard material with excellent thermal properties. The absence of electrodes makes the device robust under the beam. The same measurement can be done for x-ray flux monitoring, which is important for measurement feedback and calibration at modern x-ray light sources. In this case, x-rays passing through the diamond sensing element enable a photo-induced conductivity and in turn detunes the cavity placed around the diamond. Diamond being a low-Z material allows for in-line x-ray flux measurements without significant beam attenuation.

INTRODUCTION

In 1944, The Soviet physicist Yevgeny Zavoisky discovered, that a single crystal CuCl2 placed in a 4 mT magnetic field absorbs a 133 MHz signal, resonantly. That was the first electron paramagnetic resonance measurement [1]. Since that time, the EPR measurement has been used to study metal complexes and organic radicals. The measurement is based on the change in microwave coupling to a high quality factor resonator due to miniscule changes in the microwave properties of sample inside.

While the EPR signal appears due to the change in the sample's magnetic permeability, we propose to measure the changes to resonator properties caused by variation of the electromagnetic properties of a thin diamond film that absorbs a small portion of the incoming x-ray radiation or high energy charged particles. In contrast to existing solid-state x-ray flux monitoring, the EPR-like measurement does not require electrodes and a high-voltage bias across the diamond. In such measurements, x-rays or charged particles will promote bounded electrons from valence zone to cross the band gap into the conduction band, changing the electromagnetic properties of the sensing element (diamond). This change will detune the resonator producing a signal correlated to the incoming radiation.

LASER PULSE ENERGY METER

We have a 515 nm laser (60 kHz rep-rate, 200 fs pulse length, 3W average power), which has high enough energy photons to excite electrons across the band gap of silicon. We used this laser beam to produce photoconductivity and measure signals from the resonator. We used a network analyzer to measure the reflection in a range of frequencies, producing standard reflection curves. The setup is shown in Fig. 1 and the measurement results are shown in Fig. 2. When the laser was off, we tuned the resonator coupling to achieve a tiny, -30 dB reflection. Once the laser was on, we increased the power and observed that the resonance became weaker (resonator decouples), until at 592 mW, it seemed that the resonance was gone. Note that the resonance was not really gone—what was gone was sufficient RF coupling to observe the resonance. We could keep the laser running at 592 mW and move the tuning pin until the critical coupling is restored.

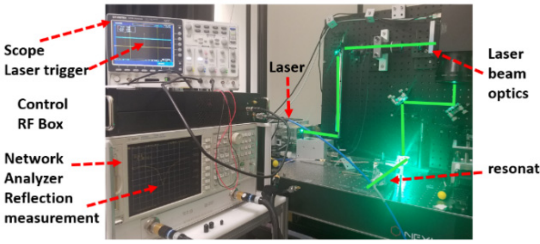

Figure 1: Laser flux monitoring experiment long relaxation time sample (high resistivity silicon) measurement with network analyzer.

We built a single frequency RF circuit to measure microwave detuning (proxy to laser flux) in the time domain. We set the oscillator at the resonant frequency, turned on the laser, and measured a time-domain signal at the laser repetition rate. The resulting signal had a large quasi-constant component proportional to the incoming laser flux, and then a ripple on top of it, with repetition rate of laser. In Fig. 3, we zoom in to obtain the time structure of the signal. This time structure includes the quality factor of the resonator effect paired with the relaxation times, that strongly depends on the sensing element composition. For practical applications, these effects can be calibrated. Sensitivity of the detector is determined by the quality factor of the resonator. There is a tradeoff between the time resolution of the measurement and the sensitivity, since both depend on the quality factor.

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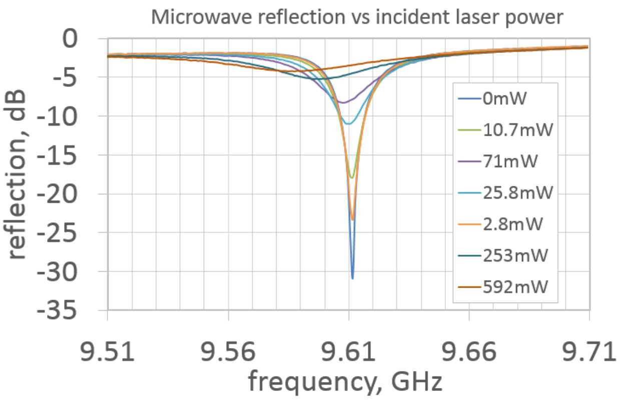

Figure 2: Laser power measurement with flux monitor.

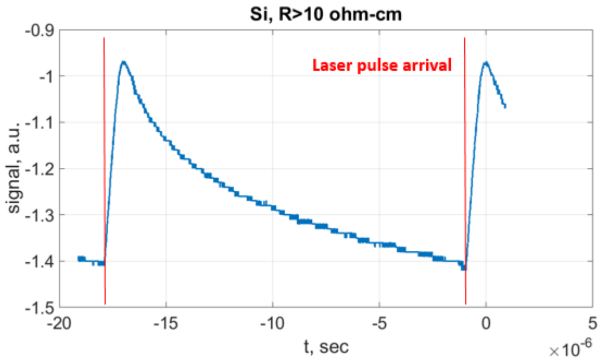

Figure 3: Time-resolved signal from the resonator, single laser pulse measurement.

X-RAY FLUX MEASUREMENT AT CHESS

Recently, we produced a device for x-ray flux monitoring working on this exact principle and utilizing diamond or silicon as the sensing material. The device was tested at the CHESS synchrotron at Cornell [2].

The measurements shown in Fig. 4 (red curves) are signals (voltage of microwave detector) of the reflection from the microwave resonator. The higher the x-ray flux – the higher this signal. This signal can be calibrated against an ion chamber (Fig. 4 blue curves) and used at the beamline. We relate these measurements to each other in a calibration curve: microwave detector – ion chamber (Fig. 5).

Figure 5 shows an important thing: microwave measurement is non-linear. Response needs to be fitted to a nonlinear curve based on calibration at various dosages using an ion chamber. This process however needs to be done only once and for a fixed energy.

Energies of few keV and higher x-rays, for which this device is designed, are three orders of magnitude higher than the diamond band gap and therefore flux measurement at different x-ray energies is identical.

At the same time, if we zoom in on the red curves (Fig. 4), we observe the time structure (Fig. 6) of the CHESS synchrotron beam! Indeed, the microwave measurement can be arranged to be prompt enough to measure certain time signal structures. The time response of the measurement has been designed, considering the quality factor of the resonator (trade off: sensitivity versus time resolution) and the time response of the semiconductor, which is adjustable by the level of doping and defects.

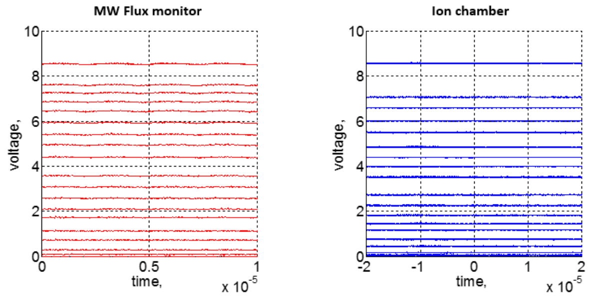

Figure 4: X-ray flux measurements with x-ray intensity swept in a wide range. Each curve – different x-ray flux from synchrotron. Left: microwave flux monitor measurement with silicon active element. Right: ion chamber measurement. Each red line corresponds to a blue line in terms of measurement conditions.

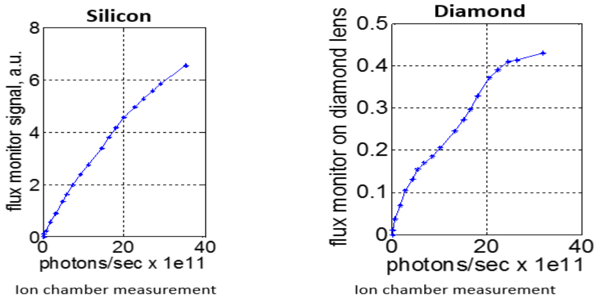

Figure 5: Experimental calibration of the x-ray flux measurement with silicon (left) or diamond (right) sensing plate.

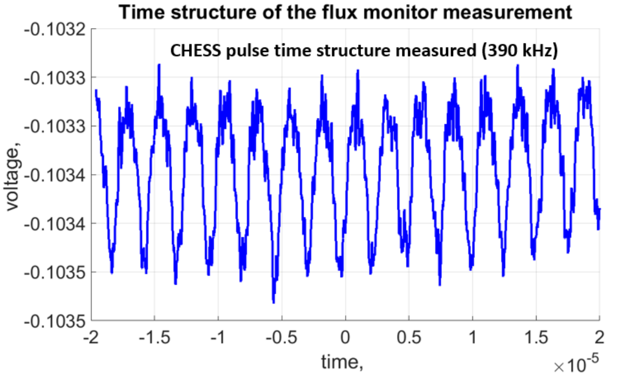

Figure 6: Raw data – reflection from a resonator with diamond inside and x-ray beam passing through the diamond at CHESS – the time structure (200 kHz) of an x-ray beam is measured.

10 KEV BEAM DETECTION

We built a similar detector to measure signal associated with the electron beam (Fig. 7). We are using a 10 keV DC gun to promote electrons across the band gap in the silicon plate inside of the aluminium resonator. Similar to experiments described above, we observe resonator detuning (Fig. 8) which is correlated to the charge of the electron beam. This measurement is more sensitive than the Faraday cup in our beamline.

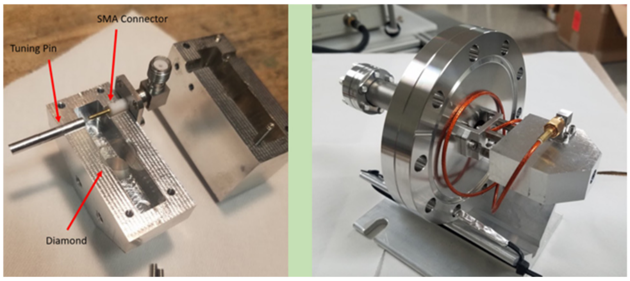

Figure 7: Resonator with a diamond inside mounted on conflat flange for electron beam charge measurement.

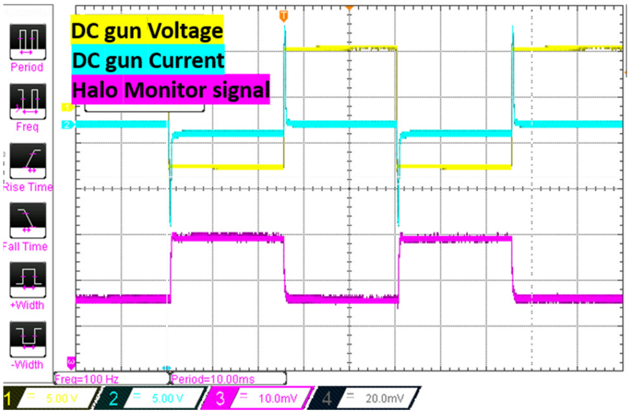

Figure 8: Signals from 10 keV DC electron gun testing including beam halo monitor.

CONCLUSION

We demonstrated that resonator detuning can be used to detect high energy particles and photons. In separate experiments, we detected green photons, few keV x-rays, and 10 keV electrons. While practical aspects of this measurement technique are being studied, the potential of this technique is obvious. We are designing the measurement approach and corresponding hardware on a case by case basis.

ACKNOWLEDGEMENTS

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