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DETECTION OF X-RAYS AND CHARGED PARTICLES VIA DETUNING OF THE MICROWAVE RESONATOR

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Abstract

Critically coupled microwave resonator is a finely balanced system, reflection at the resonance is virtually zero. Small changes in dielectric properties of resonator parts destroy this balance, small reflection can be detected from the resonator. This measurement is used in electron paramagnetic resonance studies. In this paper we discuss two accelerator - related applications of this technology. First is related to beam halo measurement taking advantage of high sensitivity of the microwave measurement. High energy particles crossing the diamond inside of a tuned resonator induce a weak conductivity in the sensing material. This small change results in resonator decoupling providing a signal proportional to a number of particles crossing the diamond plate. Second application considered is the x-ray flux monitoring. In this case it is x-ray induced photoconductivity which alters resonator coupling and produces a signal. Interestingly, sensing dielectric material embedded in a resonator can be a diamond or kapton window, refractive lens or part of a silicon monochromator. Thus an inevitable x-ray absorption on optical elements of the beamline is used to monitor x-ray flux online.

INTRODUCTION

Flux monitoring is a must at modern x-ray light sources for alignment, measurement feedback and calibration. Dedicated x-ray flux monitors occupy space, absorb part of the beam and cannot be easily relocated. At the same time numerous x-ray beamline elements (vacuum windows, monochromators, refractive lenses, zone plates to name a few) inevitably absorb portion of the x-ray beam which is proportional to incoming flux. At present there are no devices which can measure flux non-invasively based on this parasitic absorption. In this paper we report on the first measurement of the x-ray flux based on parasitic absorption in silicon and diamond samples. This measurement utilizes a microwave resonator placed around the beamline element which is sensitive to photoinduced conductivity due to x-ray absorption. Microwave spectroscopy measurement [1], having an incredible dynamic range of six orders of magnitude is expected to be very sensitive. In this paper we will describe the measurement method and report on experimental progress to date.

When microwaves are fed into a resonator there is an interaction between the resonator and external microwave network which affects how microwaves are absorbed inside the resonator. There is a dimensionless parameter, the microwave *coupling* β, that characterizes the interaction of the resonator with the external network: β = *(power loss in external circuitry)/(power loss in the resonator)*. It turns out that critical coupling, i.e. when the microwaves fed into the resonator at resonance frequency do not reflect back from it, is achieved when $\beta = 1$. The reflection coefficient at resonance is $R = (1-\beta)/(1+\beta)$. For low power measurements like the ones described here, it is always possible to integrate a tuning screw in the external circuitry (see Figure 1), in order to tune the coupling to critical. Modern network analyzers are sensitive down to -80 dB = 0.000001% power reflection! If there is even a very small change in the electromagnetic properties of the resonator and its contents, the change will reduce the coupling to the resonator – and the minimum reflection will change. This is the main idea behind our proposed measurement approach.

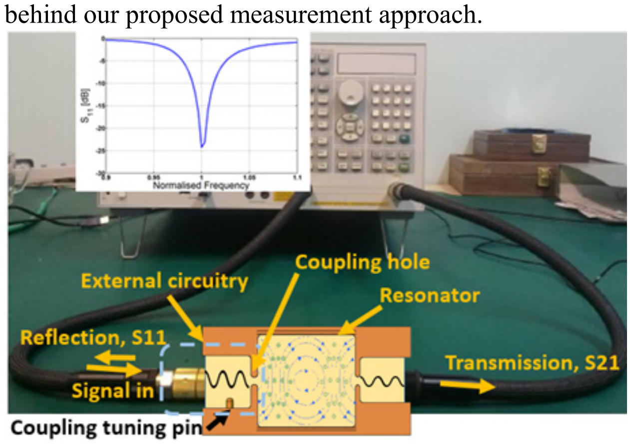

Figure 1: Network analyzer measurement. Measurement setup and a typical reflection (S11) curve as a function of frequency.

FLUX MONITORING RESONATOR

The x-ray flux monitor (XFM) was designed to be a microwave resonator, where sensing media (diamond or silicon plate) was positioned in the middle of the electric energy density (Figure 2). In such configuration cavity detuning due to x-ray-induced photoconductivity in the sensing media is significant.

The resonator of the XFM was designed to have a high quality factor (measured Q=5000, close to design value). A standard rectangular waveguide connector (WR112) bolts onto the launcher, which produces the TE11 mode in a cylindrical waveguide. The RF launcher is connected to the resonator. The TE11 mode excites a TE111 mode in the resonator volume. There is a coupling pin at the entrance to the resonator that can go in and out to adjust coupling to the resonator. It was possible to disassemble the resonator to replace the sample from diamond to

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silicon, etc. After reassembly the coupling had to be adjusted to critical with a tuning pin. X-rays are passing through the RF launcher and the resonator, with a sensing plate in the middle.

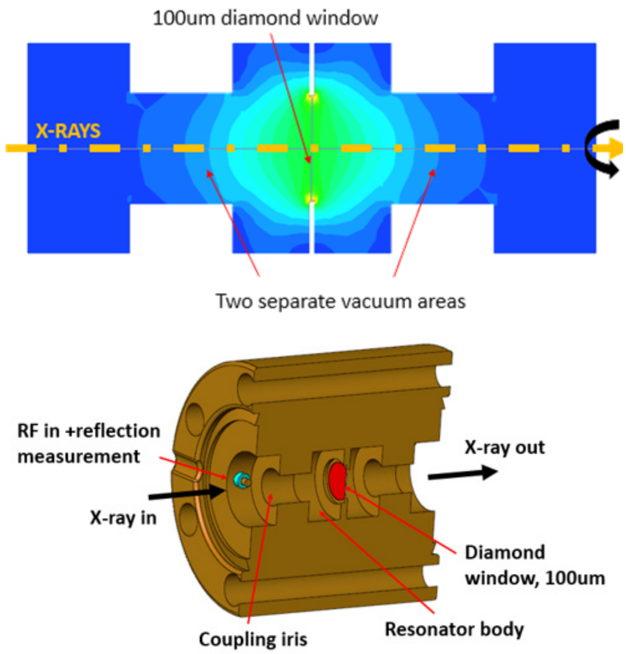

Figure 2: Top: electric energy density in a resonator. Bottom: engineering design of the diamond window with flux monitoring.

The resonator was fabricated from aluminum (Figure 3) and cold tested. Even without a tuning pin, it showed close to critical coupling, very close to the RF design.

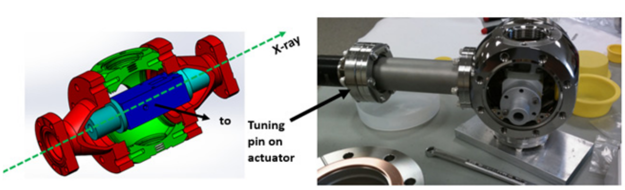

Figure 3: Left: Design of a resonator embedded into the vacuum cavity. Right: vacuum assembly in process.

EXPERIMENT AT CORNELL

We secured beam time at the Cornell High Energy Synchrotron Source (CHESS). All of the components, including the resonator, vacuum chamber and components, RF signal generator, and microwave circuit were shipped to Cornell. During assembly, a silicon sensing sample (300-µm thick) had been installed into the cavity, and after assembly, the resonance coupling was tuned. Then, the RF measurement circuit was connected to the assembly, and the output signal was measured with an oscilloscope. It was observed that when the incoming x-ray flux changed, so did the XFM output signal (see Figure 4). These measurements correlated with ion chamber measurements.

Comparing XFM measurements to ion chamber measurements allowed the XFM to be calibrated. We did this for both the silicon and diamond sensing plates (see Figure 5).

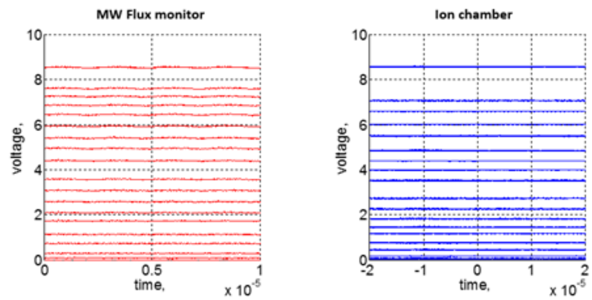

Figure 4: X-ray flux sweep measurement. Left: microwave flux monitor measurement with silicon active element. Right: ion chamber measurement.

Note that the XFM reading in Figure 4 shows a faint ripple. If we zoom in on it, the CHESS x-ray pulse structure of 390 kHz repetition rate can be observed (Figure 6). A resonator with an eigenfrequency of 10 GHz and a quality factor of 5000 has a characteristic time response of Q/f = 500ns. Therefore, such measurements have ~ 2 MHz time resolution, if the time response of the sensing element is prompt.

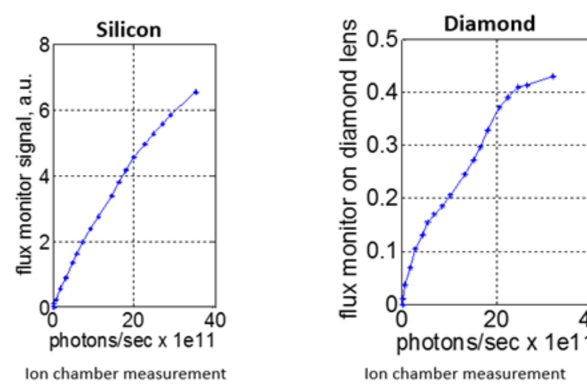

Figure 5: Experimental calibration of XFM with silicon (left) or diamond (right) sensing plate.

If needed, the time resolution can be improved by decreasing the quality factor of the resonator. This will result in a reduction of the sensitivity. Note that when x-rays promote bound electrons across the band gap to the conduction band, they tend to go back to the valence band in a certain characteristic time that depends on material, doping, concentration of dopants, and existence and distribution of defects. These parameters can be optimized for specific time response of a semiconductor.

For proof-of-principle measurements at CHESS, we built the RF circuit. It was driven by a RF signal generator. A network analyzer was used to tune the coupling and identify the resonance frequency after each sensing sample replacement. All these devices are extremely expensive and bulky; they cannot be used in a commercial device. For that reason, we rebuilt the RF circuit and included an inexpensive narrowband X-band oscillator to replace the RF generator. The entire microwave circuit and a power supply were packaged into

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the electronics box (Figure 7), which serves as a controller for the XFM. An RF cable runs from the controller to the resonator, and a BNC cable runs to the oscilloscope to display the resulting signal.

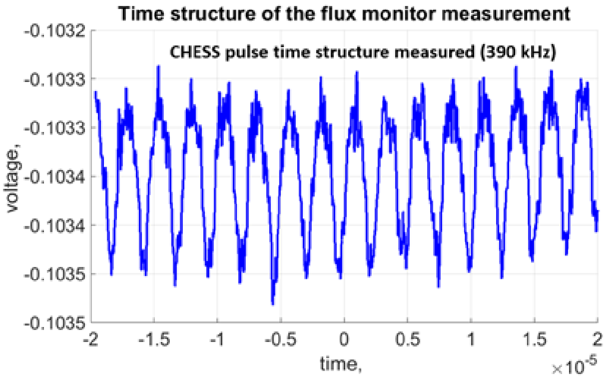

Figure 6: Time structure of the flux monitor signal, - CHESS pulse time structure.

Compared to diamond xBMPs, this flux monitor does not require electronic grade diamond, which also allows one to use fluorescence for beam position monitoring on the same beamline element. Figure 8 shows fluorescence images from a joint Euclid – 1BM experiment studying the use of diamond as a monochromator [2]. Different diamond grades under x-ray radiation at the 1BM beamline of APS exibit different color of fluorescence.

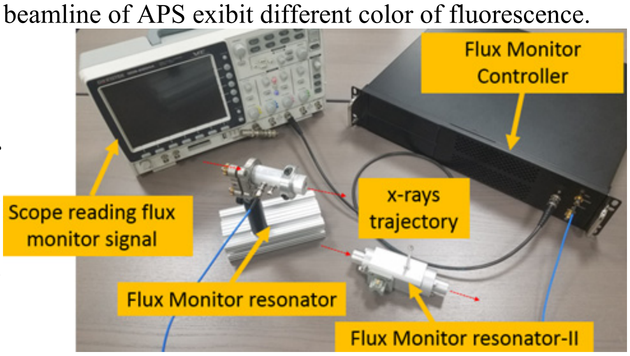

Figure 7: Time structure of the flux monitor signal, - CHESS pulse time structure.

Figure 8: X-ray fluorescence on diamonds of different grades.

X-ray fluorescence can be used for transverse profile measurement of the x-ray beam. In the end the diamond window furnished with the resonator around it can serve also as a transverse profile and position x-ray beam monitor with integrated flux and timing monitor.

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