Microwave Measurement of the Mass of Frozen Hydrogen Pellets

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Abstract

A non-destructive method for measuring the mass of high speed, frozen hydrogen pellets is described. The measurement of pellet mass is based on the perturbation to a resonant cavity caused by a dielectric pellet passing through the cavity. An oscillator circuit is formed with a resonant cavity in the positive feedback loop of a microwave power amplifier. An injected pellet perturbs the resonance characteristics of the cavity causing a shift in the operating frequency of the oscillator proportional to the ratio of the pellet volume to the volume of the cavity. Through digital measurement of the frequency shift the size of the pellet is determined automatically.

Introduction

One of the currently researched methods of plasma fueling is the injection of frozen hydrogen pellets into the hot plasma[1]. Pellet fueling results in tokamak plasma discharges that have better particle and energy confinement than discharges fueled by gas puffing[2]. The pellets of cryogenic ($\sim 10K°$) hydrogen, weighing $\sim$ 100 μgms, are manufactured inside a pellet injector and then injected into the plasma with velocities between 800 and 1000 m/sec. An accurate knowledge of the pellet mass is essential for quantitative study of pellet fueling. Because the pellets manufactured within the injector are often non-uniform, it is necessary to develop an accurate and non-destructive method for determining the size of the pellets on shot-to-shot basis.

Two methods of measuring the pellet size have been previously investigated [2]. The mass of larger pellets was determined by shooting the pellets through a plate capacitor. Measuring the backscatter from a tuned microwave cavity perturbed by the pellet was investigated as a method for determining the mass of smaller pellets. In this article, the proposed scheme for determining the size of the pellets also involves measurement of the perturbation by the dielectric pellet to a resonant cavity. The pellet size is determined by measuring the shift in the resonant frequency caused by the dielectric perturbation.

The advantage of measuring the frequency shift as opposed to measuring the backscatter from a perturbed cavity is that the former method is more readily

automated. The frequency shift measurement, unlike the backscatter measurement, does not require frequent calibration and is not affected by the drift in the resonance characteristics of the cavity.

Experimental Procedure

Overview of the Experimental Set-Up

The instrument for measuring the mass of frozen hydrogen pellets consists of a resonant microwave cavity, a microwave amplifier, a directional coupler, a local oscillator, a mixer, an IF amplifier, a TTL driver, and a frequency counter (Fig. 1). The microwave amplifier, with a resonant cavity in its positive feedback loop, forms an oscillator. The operating frequency of the oscillator is determined by the dynamic range of the amplifier, the resonance characteristics of the cavity, and the phase shift introduced by the connecting cables.

$$2\pi\, f_0 = \frac{\omega_0}{\sqrt{1 + (\omega_0/Q)(l/c)}}, \tag{1}$$

where f_0 is the operating frequency of the oscillator, ω_0 is the resonant frequency of the cavity, Q is the quality factor of the cavity, l is the length of the connecting cables, and c is the speed of light.

A pellet gun is used to inject the hydrogen pellets into the cavity through the small apertures in the cavity's transverse walls. Introduction of a small dielectric (e.g. hydrogen pellet) causes perturbations to the cavity's resonant frequency and consequently, changes the frequency of the oscillations. The dielectric perturbation

3

is described by the equation

$$\frac{\omega' - \omega_0}{\omega'} = \frac{-\iiint_{\Delta V} dV (\epsilon - \epsilon_0) |\overline{E}_0|^2}{2 \iiint_V dV \epsilon_0 |\overline{E}_0|^2},$$ (2)

where ω' is the perturbed resonant frequency of the cavity, $\overline{E}_0$ is the unperturbed

electric field inside the cavity, ϵ is the permittivity of the perturbing dielectric, and

ΔV is the volume of the dielectric. It is evident from (1) that for $(\omega/Q)(l/c) \ll 1$

shift in the frequency of the oscillations is proportional to the ratio of the pellet

volume to the volume of the cavity.

$$\frac{\Delta f}{f} \propto \frac{\epsilon - \epsilon_0}{\epsilon_0} \frac{\Delta V}{V}.$$ (3)

The detection of a IF-range frequency shift resulting from the dielectric pertur-

bation is accomplished by heterodyning. Part of the signal power from the amplifier

is diverted to the input of a mixer via a directional coupler. The lowest frequency

component of the mixer output is a signal whose frequency is equal to the difference

between the operating frequencies of the local oscillator and that of the feedback

circuit. Clearly, the change in frequency of the IF output is equal to the change in

the resonant frequency of the cavity. A digital frequency counter triggered by the

pellet gun trigger is used to monitor the frequency of the mixer output.

"Proof-of-Principle" Experiment

In a "proof-of-principle" experiment, dielectric polyethylene pellets were used,

rather than pellets made out of frozen hydrogen, since the latter were more difficult

to work with. Pellets with the average volume of ~ 0.26 mm^3 were manufactured

4

inside a pellet injector. Pellet velocity was dependent on the pressure level of the driving gas. At 400 psi the velocities of several pellets were measured using a signal from two photodiodes, and the average velocity was determined to be $\sim$ 500 m/sec.

The polyethylene pellets were injected into a cylindrical copper cavity, inside which the TM_{010} mode of the EM fields was excited. The cavity dimensions were 26 mm diameter, and 15 mm length. Small non-radiating apertures in the centers of the transverse walls of the cavity allowed for the passing through of a pellet. The pellet moved along the central axis of the cavity with velocity such that the pellet's radial deflection as a result of gravitational acceleration was negligible. Therefore, during its presence in the cavity, a pellet caused a constant maximized shift in the frequency of the oscillator circuit.

Inductive loop coupling was used to couple the TM_{010} mode into the cavity. The noise produced by the Narda 60164 power amplifier initiated the oscillations. The frequency limitations of the amplifier and the directional coupler (Narda 3044-20) guaranteed that the higher frequency modes were not excited in the cavity. With the aid of the spectrum analyzer it was determined that the maximum energy of the oscillator circuit was located at a frequency $\sim$8.75 GHz. The output from the directional coupler was mixed with a signal from a local oscillator. T-junction for BNC cables was connected to the input of an HP 8473B detector in order to achieve a non-linear combination of the two signals. To select the frequency range of the shifted down signal, the output of the mixer was connected to a spectrum analyzer, and the frequency of the local oscillator was adjusted to yield the difference

5

frequency of 3 - 4 MHz.

The peak-to-peak value of the IF signal leaving the mixer was measured to be ~1 mV. The signal was amplified to the TTL level, rectified into a square wave, an additional transistor stage consisting of an emitter-follower was added to drive the 50 ohm input impedance of the frequency counter with the square wave signal. The operation of the frequency counter was based on counting the number of low-to-high transitions of the input signal during one cycle of a pre-set clock. Because this measurement scheme was an integer measurement, there was a ± 1 ambiguity in the number of cycles. A LeCroy 8590 scaler was used as the frequency counter, with its latch input connected to the output of the LeCroy 8501 programmable clock. The clock was triggered by the pellet injector trigger; and the LeCroy 8801 memory module was used to store the data.

Results

The expected frequency shift was calculated as

$$\Delta f = -f_0 \frac{(\epsilon - \epsilon_0) V_{pellet} E_0^2}{2 \int_0^R 2\pi d\rho \epsilon_0 |E_0 J_0(\frac{2.405\rho}{R})|^2} = -f_0 \frac{1}{J_1^2(2.405)} \frac{\epsilon - \epsilon_0}{\epsilon_0} \frac{V_{pellet}}{V}. \quad (4)$$

$$\Delta f = -8.75 \text{ GHz} \times \frac{1}{.25} \frac{1 \times .26}{8 \times 10^3} = -1.1 \text{ MHz}, \quad (5)$$

the dielectric constant of polyethylene [4] at 9 GHz is equal to 2. A typical shot, where a pellet can be observed is shown in Fig. 2. The frequency shift of 1 MHz lasted for ~ 30-50 μsec.

6 .

Extensions and Improvements

Higher operating frequencies may be necessary in order to accurately measure the size of smaller pellets or pellets travelling with greater velocities. In accordance with the "uncertainty principle" the frequency resolution is limited by the amount of time that the pellet spends in the cavity. For a fixed ratio of the pellet volume to the volume of the cavity, better resolution can be obtained at higher frequencies. Resolving power, in the case of the TM_{010} mode is proportional to the cubic power of the resonant frequency.

An alternative scheme for measuring the frequency shift may also be utilized. Reciprocal frequency counting involves counting the number of transitions of a fast clock during one cycle of the input signal, rather then the number of the input signal transitions during one cycle of an arbitrary clock. Reciprocal frequency counting provides higher contrast, and the perturbation due to the pellet can be calculated more easily.

Conclusion

An oscillator circuit consisting of a microwave cavity and a power amplifier was used to automatically measure the mass of fast-moving dielectric pellets. The dielectric perturbation caused by the pellet passing through the microwave cavity resulted in a shift in the operating frequency of the oscillator circuit; the frequency shift was proportional to the ratio of the pellet and the cavity volumes. In a "proof-of-principle experiment" it was shown that polyethylene pellets, with the average

volume of .26 mm^3 and velocity $\approx$500 m/sec, caused a a shift in the operating

frequency of the oscillator circuit that was within 10% of the predicted value.

References

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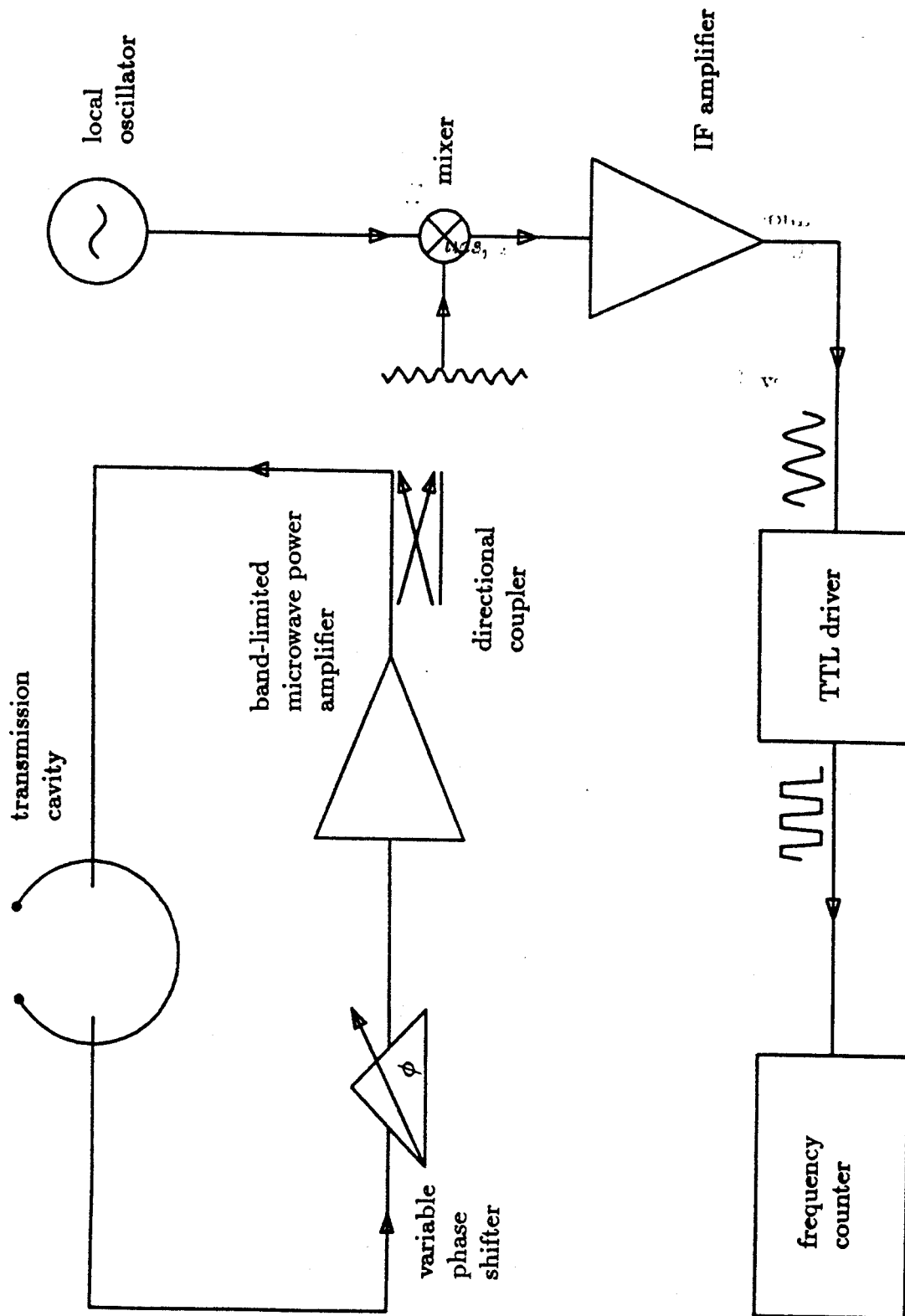[4] Purcell, E. M.,   Electricity and Magnetism. New York: McGraw-Hill Book Company, 1963.
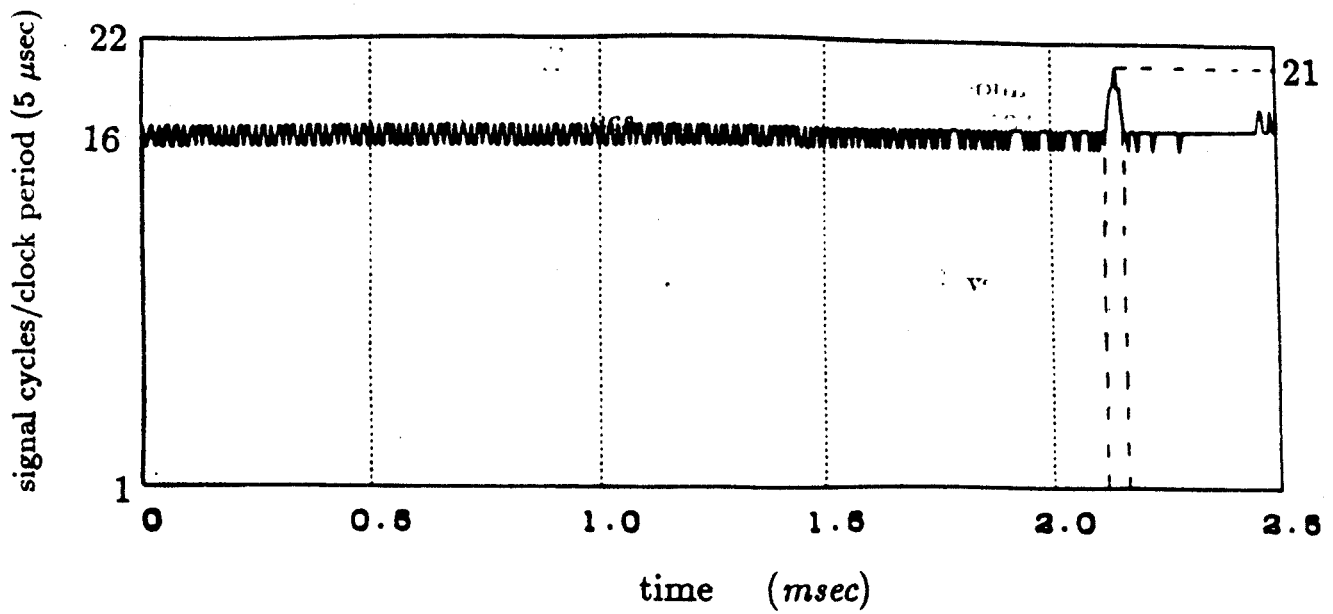
Figure 1. Block Diagram of the Experimental Set-Up.

Figure 2. Frequency Counter Data from a Pellet Shot.