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PICOSECOND PHASE SHIFT MEASUREMENTS AT 358 MHZ USING SYNCHROTRON RADIATION*

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For our purposes the most important property of synchrotron radiation is the time modulation of the emitted intensity, although it possesses many other qualities, such as broad spectral range, high brightness and 100% polarisation, which are being extensively utilised in many research fields [1,2]. The radiation from the S.R.* is modulated in exactly the same manner

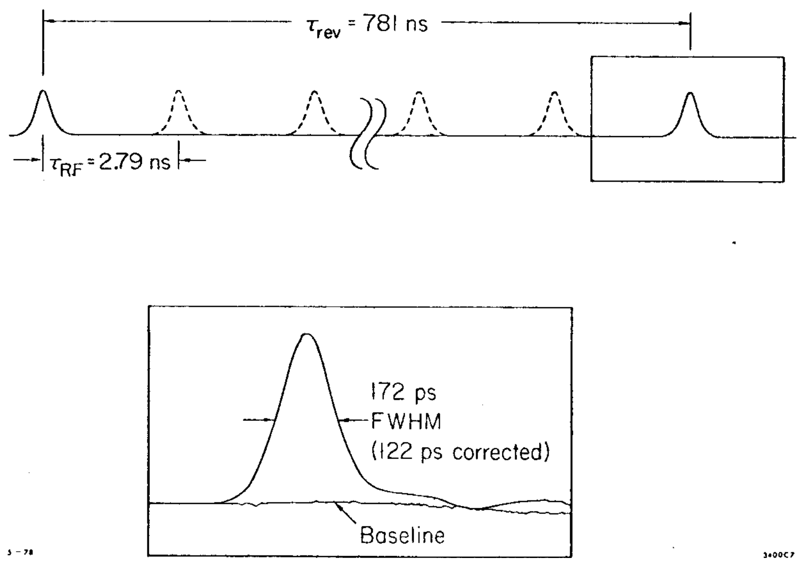

Fig. 1 Time structure of light pulses: T_{rev} is the going-around frequency for a single bunch, T_{RF} is the period of the S.R. radiofrequency. The lower bunch picture is experimental data taken for the paper of [4].

in which the electron beam is modulated. The electron pulse or bunch shape is nominally Gaussian [3] and is determined by S.R. parameters. The bunch length increases with stored current, this effect being different from one S.R. to another [4]. The S.R. radio frequency is an integer multiple of the revolution frequency, this being a constant since the electrons are highly relativistic ($v/c \simeq .9999998$). It is possible to have as many electron or positron bunches around the ring as the RF harmonic number, which is 280 in SPEAR. In our experiments SPEAR ran with only one circulating bunch, and we discuss this case.

For the case of a stable bunch and repetition period, the spectrum of the *modulation* of the radiation consists of a train of delta functions spaced at the revolution frequency, (1.28 MHz in SPEAR) their amplitude envelope

* Storage Ring

being the Fourier transform of the pulse shape. For SPEAR, a typical bunch length is about 200 ps FWHM (see Fig. 1). A Gaussian pulse with this width has Gaussian spectrum of 3.5 Ghz FWHM, i.e. amplitude down to half of the central peak value at 1.8 Ghz. It is possible to operate SPEAR with pulses as short as 100 ps [4]. Real S.R. pulses are generally not Gaussian or symmetric [5] thus the phases of the different components have no simple relationship with each other. Multiple-frequency phase-shift measurements must have the reference phase set up individually for each frequency.

The spectral purity of the revolution frequency harmonics is set by the stability of the S.R. RF system and the stability of the electron bunch. The bunches are prone to shape instabilities [6], their intensity varying with operating conditions and machine parameters. The instabilities appear as sidebands about the revolution-frequency harmonics. For sufficiently strong instabilities and high harmonics, the sidebands can be larger than the central line. Under most operating conditions, this is not a serious problem with SPEAR.

The spectral shape of the output from the detector phototube is, naturally, not identical with that of the source (see Fig. 2). A phototube is not a linear causal filter, since there is random time variation in electron transit times. In spite of this effect, the spectral purity of the harmonic lines is unaffected even at low intensities when the tube is in the single-photon counting mode. The combined effect of timing dispersion and tube noise is to degrade the signal-to-noise ratio of harmonic lines at the output of the detector.

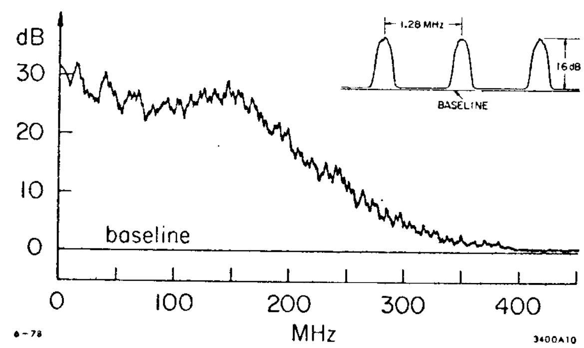

Fig. 2 The power spectrum of the modulation of synchrotron radiation from SPEAR measured using an RCA 8850 phototube. The amplitude profile represents primarily the frequency response of the phototube. Inset shows the response of the phototube in the vicinity of 358 MHz.

The power-frequency spectrum of the source and photomultiplier tube is measured with a spectrum analyzer (Tektronix 7L13). The spectrum has a S:N ratio at 358 MHz of 20dB and shows that it should be possible to make phase-shift measurements at frequencies up to about 400 MHz with the RCA 8850 tube. This power spectrum (Fig. 3) is in effect the product of the frequency spectrum of the source (which can be measured directly) and of the response of the phototube, although all relative phase information is lost. The frequency response of any phototube with resolution time > S.R. bunch length therefore can be simply and rapidly characterised and this has been done for several phototubes and contrasted with their "single electron" time response [7].

The decay time (τ) of a single fluorescent species can be deduced by measuring the phase delay (θ) between excitation and fluorescence radiation modulated at a single suitable frequency (ω). The relation between ω and τ is: $\tan\theta = \omega\tau$ [8]. The technique is restricted usually to measurement on samples having only a single exponential decay, and that within a range defined by the limited frequency range of conventional modulated sources.

However, it is possible to derive the impulse response of a causal filter from only the imaginary part of its Fourier transform [9] via the Hilbert transform. Thus it is possible to completely characterise the time (impulse) response or the complex frequency response of a linear system with only phase measurements.

Results

A number of test experiments were made using apparatus designed for time resolved fluorescence emission anisotropy studies of trytophan in proteins [11].

The operating conditions of the apparatus made direct observation of fluorescence emission difficult and all tests were made using a beam reflected directly onto the detecting photomultiplier tube. Phase shifts were produced by insertion of 1 cm water filled quartz cells into the beam and by the introduction of a thick glass slab. The total optical path length between the source and detector also could be altered by linear motion of the phototube along the axis of the beam. The aperture at the photocathode of the phototube was stopped down until rotation of the tube through 360° in its mount produced less than $\pm 0.5^{\circ}$ change in the phase of the direct beam in light of wavelength 320 nm. The photomultiplier was moved along the optical axis by a measured distance and the corresponding phase reading observed with respect to the RF reference. The results yielded $4.7 \pm .5$ degrees per cm of motion.

Signal-to-noise at the VVM (Vector Voltmeter H-P mod. 8405A) input limited the accuracy of the measurements we report. For conditions of poor S/N, the VVM would not yield a reading at all. Our reference signal comes directly from the S.R. master oscillator. It is possible to derive reference signals at any revolution frequency harmonic by filtering an electromagnetic pulse coupled from the beam by an antenna in the accelerator vacuum vessel. The spectral shape of this pulsed signal is very similar to that of the pulsed radiation, having the same combination of harmonics. The filter used for selecting a reference should be identical with the filter following the phototube (Fig.3) and the two should be simultaneously temperature stabilized to eliminate thermal drifts. Other techniques may be used to measure phase shifts, some of which are perhaps better able to deal with noise problems, i.e. lock-in techniques, heterodyning.

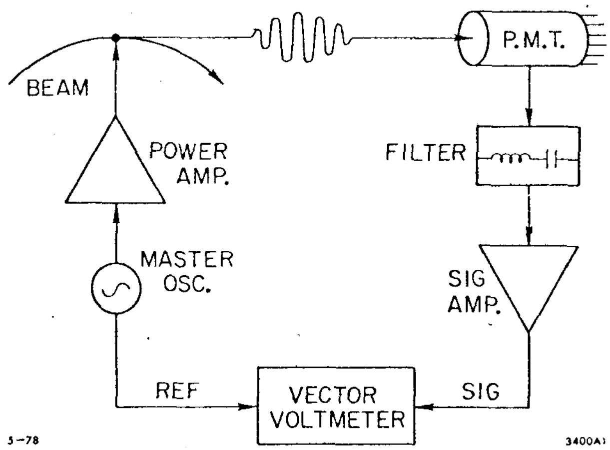

Fig. 3 Experimental apparatus: The filter attenuates harmonics 1.28 MHz away from 358 MHz by 16 dB. The signal amplifier has a gain of 36 dB.

Conclusions

Using synchrotron radiation from SPEAR and a simple arrangement of apparatus it has been shown possible to make phase shift measurements at 358 MHz. Synchrotron radiation source properties are such that it will be simple to apply this procedure to study short atomic and molecular fluorescence lifetimes using any optical system at any wavelength or to rapidly scan the excitation spectrum of a material in the time domain with sufficiently good time resolution to observe reaction kinetics in the picosecond range. Experiments could be carried out at any frequency in the range from 1.28 MHz to about 1 GHz limited only by the high frequency response of the detectors.

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