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Coherent Transition Radiation Produced by a 1.2 MeV Electron Beam

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Abstract. We describe a method of generating very high-frequency coherent radiation using an electron beam source with a maximum beam energy of 1.2 MeV. We show that, though the high frequency cutoff for the radiation generated when the beam impacts a target at normal incidence is reduced by transverse beam size effects, it is nevertheless possible to generate much higher frequencies by a judicious choice of the angles of incidence and observation.

INTRODUCTION

Electron beam devices such as klystrons function by bunching an electron beam and extracting energy using a cavity resonant at the bunching frequency or at some harmonic of the bunching frequency. For a beam bunched to a sub-picosecond length, it might be possible to extract radiation at a very high harmonic if a suitable resonant cavity could be fabricated. This becomes very difficult as frequencies approach a teraHertz. Alternatively, a broadband radiation mechanism can be used to simultaneously generate radiation at all the harmonics of the bunching frequency. Since the radiation mechanism is broadband, the electrons emit radiation at frequencies as high as the Fourier content of the bunched electron beam allows. One extremely broadband radiation mechanism is transition radiation (1).

We have used a microwave gun (2) and a bunching magnet to produce electron bunches with picosecond pulse lengths at a repetition rate of 2.853 GHz. Using transition radiation, we produced radiation from these bunches at all the harmonics of the bunching frequency out past the 400th harmonic. This mm-wave and far-infrared radiation can be filtered and used for spectroscopic studies in materials science, biophysics, or condensed matter research. The radiation from this device has an interesting time structure. It contains picosecond pulses but each of the constituent harmonics in the pulse spectrum has quite a narrow linewidth. The peak power of the picosecond pulses is roughly a kilowatt.

This capability is delivered from a compact source whose complexity, size, and cost are more comparable to a mode-locked laser system than to an accelerator. The footprint for the entire device, including control racks, is only about five square meters.

EXPERIMENTAL DESCRIPTION

The electron gun used in these experiments is based on a design developed for use as the injector for the Mark III free-electron laser at Duke University (3). It is a stand-alone electron beam source generating a high brightness beam with energies between 0.8 and 1.2 MeV. The gun fills every RF bucket, so the time structure of the electron beam consists of picosecond bunches at the repetition rate of the RF source. In figure 1 we show a schematic of the transition radiation source. A CO_2 laser heats a 3-mm diameter LaB_6 cathode to approximately 1800 °K. Electrons boiled off from the cathode are accelerated by the microwave cavity fields up to an energy ranging from 0.8 to 1.2 MeV. A compact air-cooled klystron producing 1 MW at 2.853 GHz during a 5-μs pulse provides the microwaves necessary to drive the cavity. The electrons which exit the cavity are sent into an alpha magnet(4). This magnetic achromat has a positive chronicity, i.e., electrons with higher energies take longer to pass through the magnet than low energy electrons. This effect cancels the debunching produced as the electrons drift from the cavity to the alpha magnet (free space has a negative chronicity) and, in addition, produces a net bunching of the electron bunches. The energy spread of the electrons is quite large at the output of the electron gun. A filter in the alpha magnet reduces the energy spread of the electron beam and allows a linear part of the electron distribution in longitudinal phase space to pass. This distribution, when allowed to converge to a longitudinal focus, can result in an extremely short bunch length. After the electron bunches leave the alpha magnet, they are steered and focused onto a metal target. Due to the high brightness of the electron beam, it is possible to focus the beam to submillimeter size even at low energies. The parameters of the electron beam used in the experiments reported here are listed in Table 1.

TABLE I. Electron beam parameters.

Beam energy	0.95–1.2 MeV
Micropulse repetition rate	2.853 GHz
Macropulse average current	62 mA
Macropulse duration	2 μs
Micropulse duration	1 ps. [a]
Peak current	20 A [a]
Normalized *rms* transverse emittance	3.5π mm-mrad

[a] The peak current and micropulse duration are inferred from the transition radiation measurements.

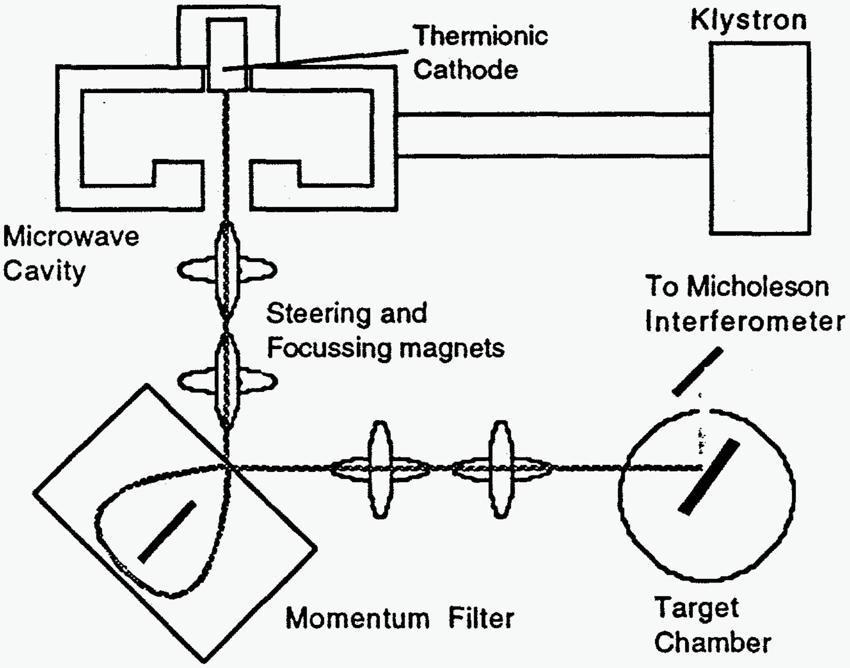

FIGURE 1. Experimental layout of the transition radiation source.

Measurement system

Radiation emitted from the metal target was directed out of the vacuum chamber through a fused silica window. The radiation was then collimated by a TPX lens and analyzed by a computer-controlled scanning Michelson interferometer with a 25-μm Mylar beamsplitter. A Golay cell sensed the power output of the interferometer as a function of the moving mirror's position. The resulting interferograms were Fourier transformed and corrected for the wavelength dependence of the beamsplitter and detector.

Effects of the angle of incidence

One problem with coherent transition radiation at very low electron beam momenta is the presence of a form factor due to transverse coherence. As noted by Shibata et al. (5), a transverse distribution of transition radiators introduces a form factor described, for a uniform transverse distribution, by the equation:

$$f(\lambda)=\left\{\frac{J_1[2\pi(\rho/\lambda)\sin\theta]}{\pi(\rho/\lambda)\sin\theta}\right\}^2 \qquad (1)$$

where θ is the angle of observation and ρ is the radius of the transverse distribution. This is obviously just the two-dimensional Fourier transform of a normalized uniform transverse distribution. Since the angle of observation is normally equal to $1/(\beta\gamma)$ this equation implies that we want the quantity $\pi\rho/(\lambda\beta\gamma)$ to be much smaller than unity so that the form factor is approximately one. This then leads to the conclusion that one must focus the beam to a very small spot size for a low energy beam. Although submillimeter dimensions can be achieved with a high brightness electron beam, such dimensions still limit the production of high-frequency radiation for very low momenta electron beams.

The derivation of equation (1) assumes that the electrons travel at the speed of light. For the work in that reference this was a good assumption but it is a poor assumption for the momenta used in this experiment. When an electron beam with velocity significantly less than the speed of light strikes a target at an angle of incidence θ the radiation produced will have a phase difference that varies linearly across the transverse dimensions of the beam. If one calculates the phase difference for the radiation produced by two electrons separated by a transverse distance x, and traveling at a speed βc when observed at an angle α, as shown in figure 2, the phase difference $\Delta\phi$ is:

$$\Delta\phi=\frac{2\pi x}{\lambda}\left[\frac{\tan(\theta)}{\beta}-\frac{\sin(\theta+\alpha)}{\cos\theta}\right] \qquad (2)$$

If the observation angle is equal to $1/(\beta\gamma)$ the phase difference is zero for an angle of incidence very close to $\theta=\tan^{-1}(\beta\gamma)$. Adding this angle to the observation angle one finds that the angle of observation is along the metal surface. If the angle of observation is slightly smaller than $1/(\beta\gamma)$ it is still possible to find an angle (slightly smaller than $\theta=\tan^{-1}(\beta\gamma)$) at which the phase difference is zero. As an example of this, let $\gamma=2$. Then the angle of incidence should be 60° and the angle of observation should be 33°. If the angle of observation is chosen to be 25°, the phase difference is zero for an angle of incidence of 59.55°. Thus there is a choice of angles that will eliminate the transverse phase variation and the resulting high frequency cutoff. For our case, $\gamma = 3$ so the angle of incidence should be 70° and the angle of observation should be 20°. We chose to operate near this with an angle of incidence of 68° and an angle of observation of 18°.

MEASUREMENTS

In figure 3a we show an interferogram of the radiation emitted for an angle of incidence of 35°. The spectrum of this scan is shown in figure 3b. Though the spectrum shows content at high frequency, it is quite sensitive to the electron beam size and does not extend to frequencies as high as simulations of the system would indicate possible.

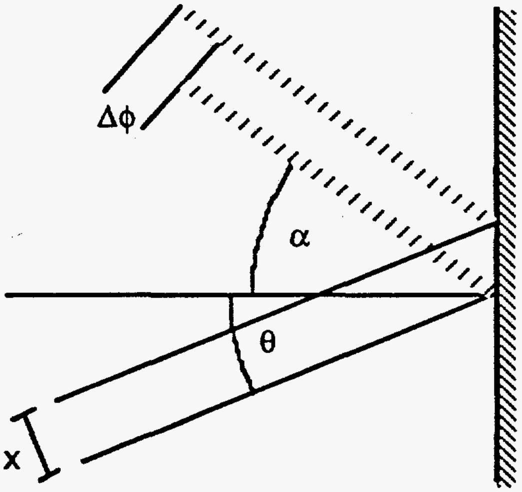

FIGURE 2. Two electrons separated by a distance x strike a target at an angle of incidence θ and produce two transition radiation waves at an angle α with a phase differing by $\Delta\phi$.

In figure 4a and 4b we show the interferogram and spectrum from radiation produced at an angle of incidence of 68°. The spectrum now extends well past 1 THz. out to harmonics as high as the 400th.

CONCLUSIONS

RF electron guns are compact devices which can be designed to produce very short, i.e. sub-picosecond, pulses. The beam current produced by such guns contains frequency components extending to several teraHertz. The mechanism of transition radiation is inherently broadband and can produce radiation whose spectrum replicates that of the beam current. However, for low momenta beams, interference effect across the transverse dimension of the beam tend to cancel the higher frequency components. We have shown here that one may choose the angles of incidence and observation in a manner which will eliminate the cancellation and extend the high frequency components of the radiation.

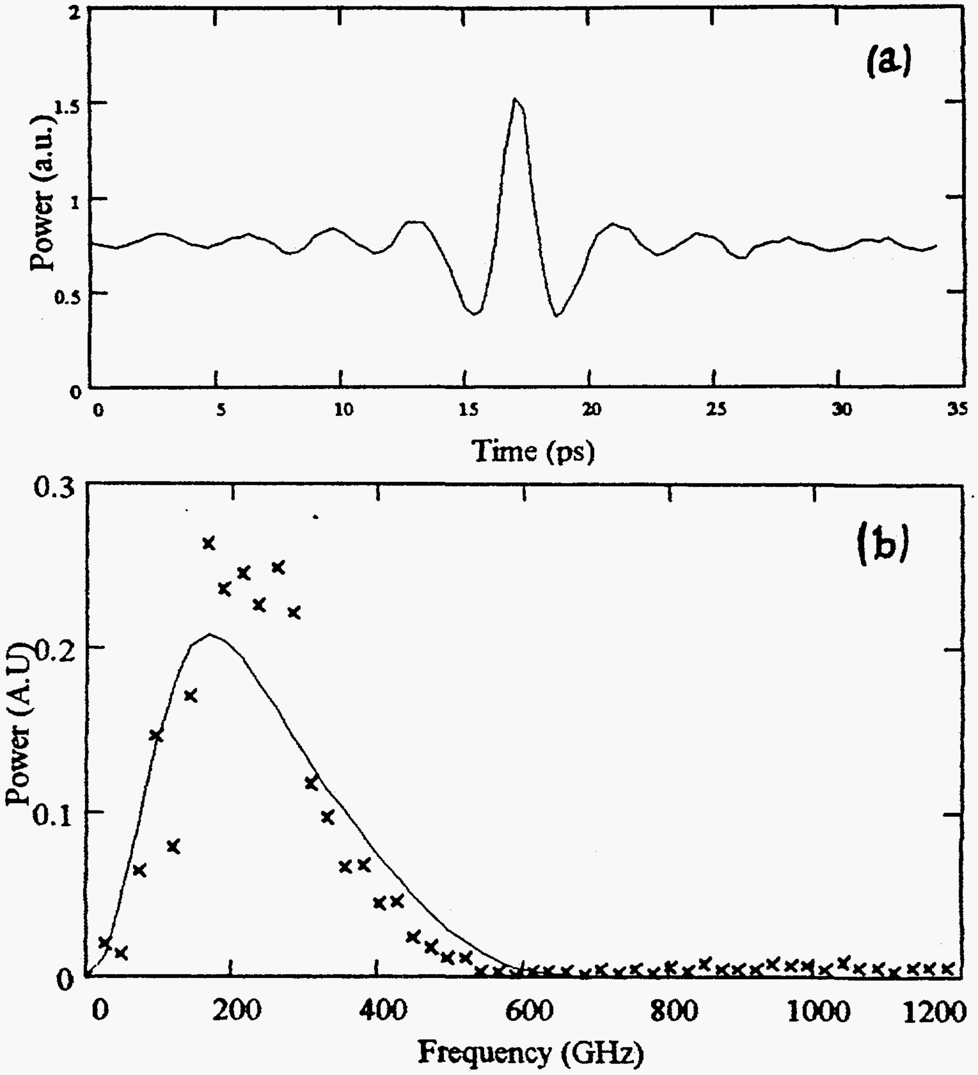

Figure 3. The interferogram for a 35% angle of incidence is shown in (a). In (b) we show the calculated spectrum from (a).

One might reasonably conclude that only the beam size in the tangential plane is important and that one could therefore use quite a large size beam in the sagittal plane. Experimentally, we found that this was not the case. The spot size had to be small in both dimensions to produce high frequencies. We do not understand this behavior at this time. We will try to understand this phenomenon better in future work.

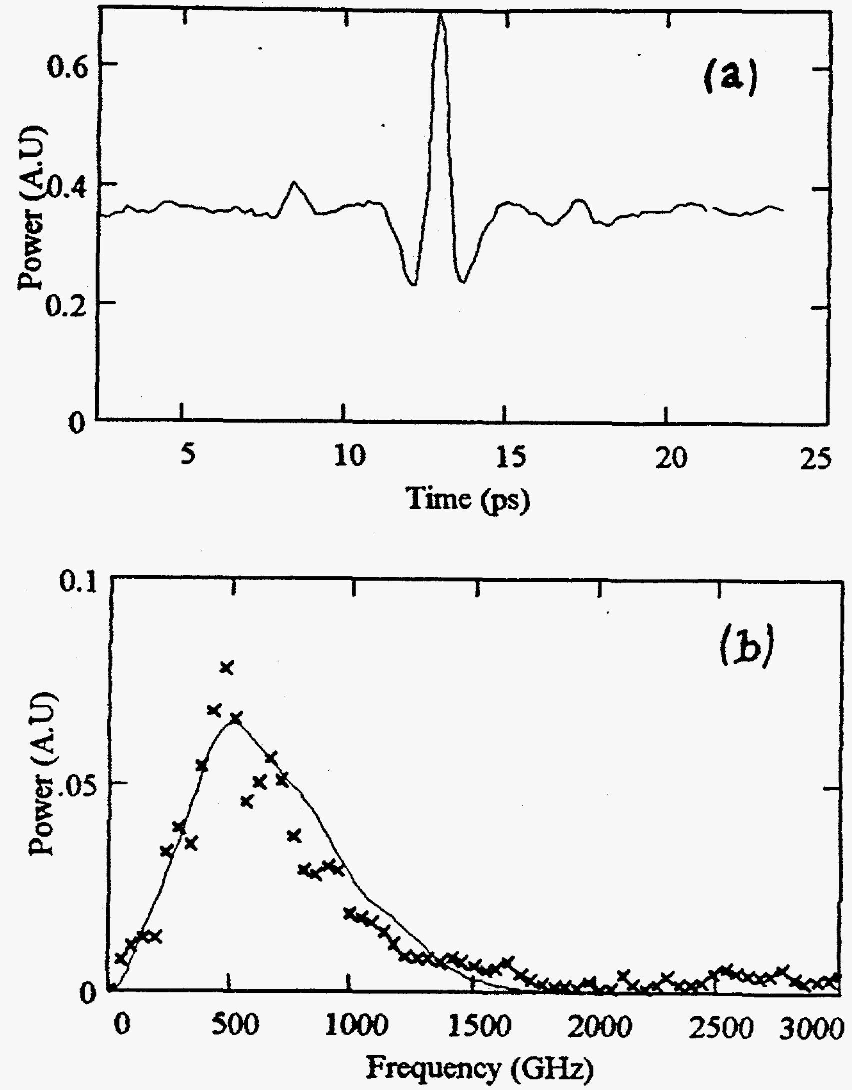

Figure 4. The interferogram (a) and the spectrum (b) for a 65° angle of incidence. Note the change of frequency scale from figure 3.

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