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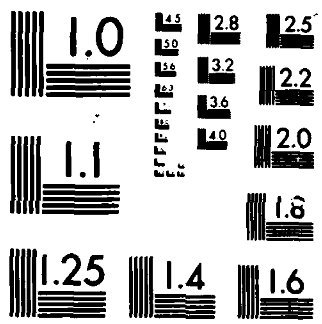

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RADIATION MEASUREMENTS FOR UCSB-FEL

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QIFEL021/83

RADIATION MEASUREMENTS FOR UCSB-FEL

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Abstract

A calibrated He-cooled Ge-bolometer will be used to measure 2 nW average spontaneous power at 380μm wavelength; the spectral analysis will use a Fabry-Perot. The more powerful laser output will be analyzed by a heterodyne spectrometer.

Introduction

The machine being constructed at the University of California at Santa Barbara will operate in two stages: in the first it will produce high power of infrared radiation and in the second this radiation will be efficiently up-converted (through the stimulated Compton scattering) into the optical region up to the UV region[1]. In this paper we are concerned with the measurement of the FIR radiation, that is, both the spontaneous and the laser radiation at 380 μm.

The very small power of spontaneous radiation ($<P_{spont}> 1$ nW) requires a *careful optics design*. In contrast, the high power of the stimulated emission ($P_{peak} \simeq 5 \div 15$ kW) and the long length of the pulse allow a relatively softer hardware.

For ease of reference the UCSB-FEL parameters are listed below.

Characteristics of the spontaneous power

The spontaneous power is given by[2]

$$P_{spont} = \frac{I}{e}\, \hbar\omega \cdot n$$
$$n = \pi\alpha\, N \left(\frac{\gamma\theta K}{1+K^2}\right)^2 \qquad (1)$$

where n is the number of photons diffused by one electron in the trip, α the fine structure constant and θ is the angle of scattering. Substituting in (1) the parameters of table 1, we get

$$P_{spont} = 0.6 \text{ mW} \qquad (2)$$

Since the response time of the power detectors is long, we have to measure the average power. This last, being the repetition rate 10 Hz, is

$$<P_{spont}> = 0.9\,\mu\text{W} \qquad (3)$$

The power will be emitted into the solid angle

$$\Delta\Omega = \frac{\pi}{\gamma^2} \qquad (4)$$

Table 1. UCSB-FEL parameters

Electron beam	Plane wiggler	Radiation and cavity
E = 3 Mev	L = 5.75 m	L_{cavity} = 7.1 m
γ = 6.88	λ_W = 3.6 cm	λ_{laser} = 380 μm
I = 2A	N = 160	P^{peak}_{spont} = 0.6 mW
r = 3 mm	B_o = 670 Gauss	$<P_{spont}>$ = 0.9 nW
T = 150 μsec	K = 0.16	P^{peak}_{st} = 5 ÷ 15 kW
f = 10 Hz		$\Delta\nu_{spont}$ = 3 GHz
$\frac{\Delta\gamma}{\gamma} \sim 10^{-5}$		$\Delta\omega$ = 2.10^{-2} stearad

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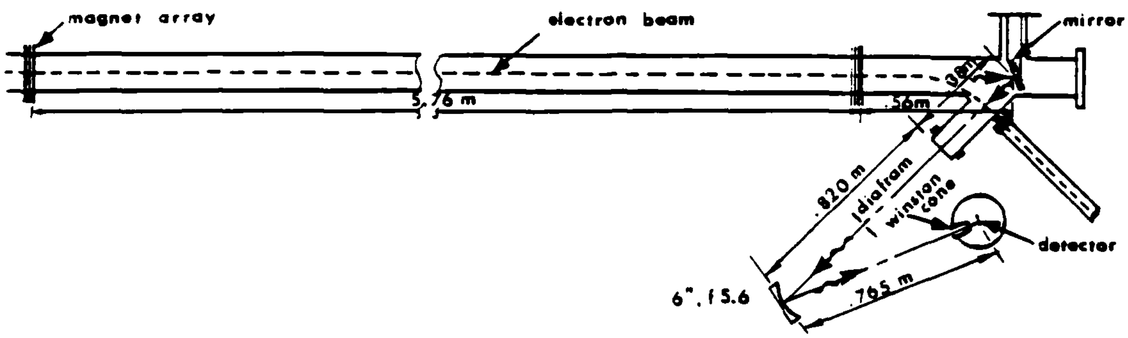
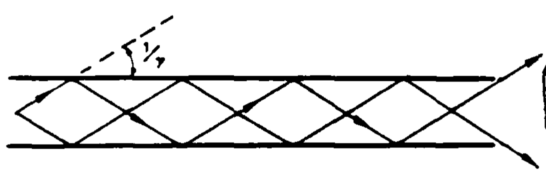


Figure 1. Scheme of the spontaneous radiation layout.

In our experimental design (fig. 1) the source has to be considered an extended source of length L since the detector is not far enough from it. Thus, owing to this, the power collected by the detector would result from the sum of all the elementary powers emitted by the charges $dq = I dx/c$ into the solid angle of the detector $\Delta\Omega^*(x) = A/x^2$. Here A is the area of the collecting lens and x is the distance from the emitting charge. However, since the long beam is emitting inside a cavity, the rays are reflected by its walls (fig. 2) and are guided to the output. Therefore, the far charges are, by this effect, brought nearer to the end of the cavity. In other words the cavity helps to reduce the long source to a point source at s distance $l = h\gamma$ from the output, where h is the dimension of the cavity (fig. 3).



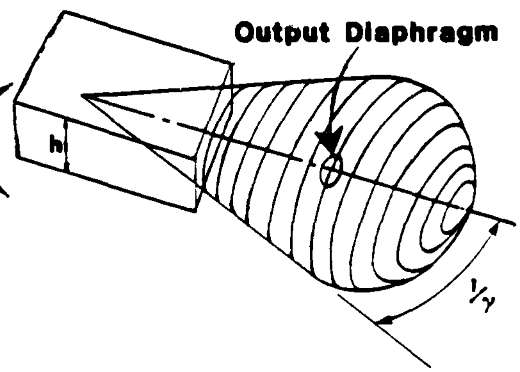


Figure 2. Sketch of two rays trajectories due to the reflections in the cavity.

Figure 3. The border profile of the cavity behaves as an emitting antenna: the angular distribution of the emission pattern is $1/\gamma$.

The area of the collecting lens is $A = 75\ cm^2$ and its distance to the "apparent" point source is 20 cm. The solid angle subtended at the point source is $\Delta\Omega^* = 6 \cdot 10^{-3}$; the total power going into the aperture is,

$$P_d = P_{spontaneous} \frac{\Delta\Omega^*}{\Delta\Omega} \simeq 40\ nW \qquad (5)$$

The absorption coefficient of quartz is less than 1% per cm and the refractive index m = 2.1076 at the wavelength λ = 380 μm[3]. The power P_d is further reduced by the reflectivity R of the 3mm thick crystal quartz window to the value,

$$P_d \simeq 30\ mW \qquad (6)$$

The radiation is focused on the detector by a concave mirror because any transmitting optics (quartz, silicon, polyethylene, TPX lenses) will have a higher absorption.[3] An iris will be used in order to measure a radiation whose bandwidth is determined only by the finite dimension of the wiggler. It will reduce the receiving solid angle to the value $\Delta\Omega = 10^{-4}$ and, in turn, the power P_d to the value

$$P_d \simeq 0.5 \text{ nW} \tag{6^1}$$

The linewidth of the radiation is $(\Delta\lambda/\lambda) = (1/2\ N) = 0.0031$ and therefore the spectral range is

$$\Delta\nu = 3 \text{ GHz} \tag{7}$$

Spontaneous power measurement

We shall be dealing with very low power so we have to measure it with a calibrated He-cooled Ge-bolometer. This will have a NEP of $1.3\ 10^{-13}$ W/Hz$^{1/2}$ with a receiving area of 2 mm^2.

We have to calculate the effect on the detector's NEP of the background radiation of our layout. It is given by the mean square fluctuation of the thermal source seen by the detector. In our simple case the detector views the radiation in a cone of a half angle α around its normal, the NEP of the detector is[4]

$$NEP_B = 2\sqrt{\pi}\ \sin\alpha\ \frac{(kT)^{5/2}}{c\,h^{3/2}}\ A^{1/2}\ B_o^{1/2}\ [J_4(x_1) - J_4(x_2)]^{1/2} \tag{8}$$

where the integrals

$$J_n(x) = \int_0^x \frac{x^n e^x}{(e^x-1)}\ dx$$

are tabulated by Rogers and Powell[5]. In (8) T is the temperature of the source, B_o the bandwidth in which the fluctuations are observed, A is the sensitive area of the detector and $x = h\nu/kT$. From (8) observing that: a) the bolometer will be equipped with a cut-on type filter (frequency range 50 μm-3mm), b) $\alpha = \sqrt{\Omega/\pi} = 10^{-1}$ rad and c) a lock-in amplifier will be used (because of the heterodyne receiving the bandwidth is 1 Hz) the NEP results in $NEP_B = 2\ 10^{-15}$ WHz$^{-1/2}$. This does not affect the measurement.

The accuracy of this power measurement can be estimated at about 20%.

Spectral analysis of the spontaneous-FIR radiation

Since the power is very weak, the spectrometer which exploits the heterodyne detection properties would be most suitable. In fact the voltage on the detector is proportional to the powers of the signal P_s and the local oscillator P_{LO}, as well as the cosine of the relative frequency difference, $V = C\sqrt{P_{LO}P_s}\cos[(\omega_s - \omega_{LO})]$[4]. C is a constant whose value depends on the convertion coefficiency. In the far infrared region the critical element of the system is the mixer. The schottky GaAs or InSb diode of the mixer (which combines non-lineary the two radiations) has the basic property of needing high power of radiation from the local oscillator (1-2 mW) in order to have acceptable losses[4,6]. Owing to this, the local oscillator has to be an optically pumped FIR laser[7] (see fig. 4).

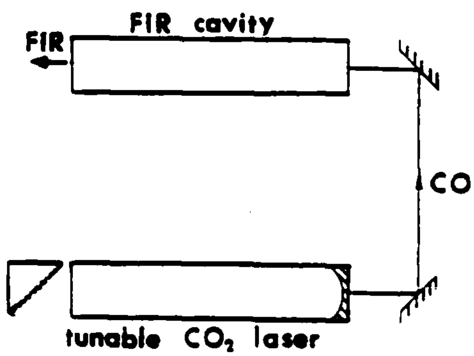


Figure 4. Optically pumped FIR laser system

Using the vapor substances mentioned below as active media and a spectrum analyzer with a frequency band of 200 GHz (Tectronix model 492 P) it is possible to cover the FIR spectrum almost entirely. The vapors with good emission lines are: HCOOH (wavelengths $\lambda_{1,2,3}$ = 393, 420, 433 μm), CH_3OH ($\lambda_{1,2,3,4}$ = 42, 70, 97, 119 μm), CH_2F_2 ($\lambda_{1,2}$ = 184, 214 μm), CH_3I (λ = 447 μm), D_2O (λ = 385 μm). The cw pump laser CO_2 has to be of a 20 W, single mode, single frequency laser. This sophisticated and expensive local oscillator suggests using a passive instrument as a grating or a Fabry-Perot.

Since it seems to be a good choice to divide the spectrum into 30 lines of width $\Delta\nu$ = 100 MHz, see fig. 5, the output power would be $P_{\Delta\nu}$ = 10^{-11} W), the Fabry-Perot only is viable. As a matter of fact the minimum dimension of the grating for the requested resolving power of 10^4 would be 2.5m. This size, furthermore, would bring about a high background radiation on the detector.

The Fabry-Perot, with the required resolution of 10^4, has instead the two surfaces 10 cm apart, as it results from the equation of the resolving power. We have hypothesized for the finesse the value 25-30 which is easily possible.

With the far infrared radiation, the metal meshes are used (fig. 6)[10]. The desired values for the reflectivity and losses, R=0.85 and A = 0.03 respectively, are obtained by choosing the appropriate period g and wire dimensions 2a and t of the meshes as shown by the following formulae[11]

$$R = 1\ \left(\frac{2\ w\ g}{\lambda}\right)\ ;\ A = \frac{2g}{u}\left(\frac{4\pi\ \epsilon_0 c}{\lambda_0 \sigma}\right)^{1/2} R \qquad (9)$$

where $w = -\ n\sin(\pi a/g)$, $u = 4a + 2t$ and σ is the conductivity of the wire. Usually the mesh material is Nichel, hence $\sigma = 0.14\ 10^6\ (cm)^{-1}$. The mesh, which meets the requirements has 400÷500 wires/inch and 2a=15.2÷11.2 μm.

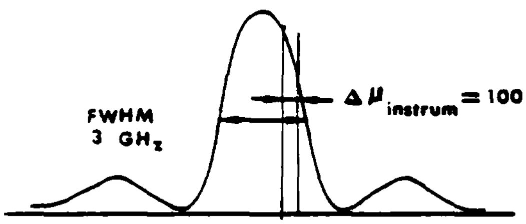


Figure 5. Expected spectrum of the spontaneous emission and bandwidth of the instrument.

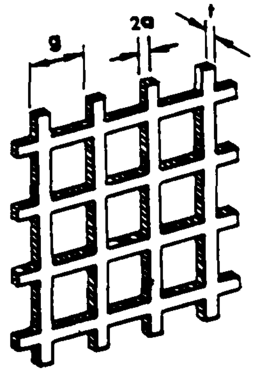


Figure 6. Meshes of the Fabry-Perot interferometer.

The transmitted power is about 65%, that is

$$P \sim 0.6\ 10^{-11}\ W \qquad (10)$$

In addition we note that the spectrum can be recorded by tuning either the Fabry-Perot spacing or the electron energy.

Pulse recording

The pulse can be recorded with a Putley detector. This typically has a spectral range of 200-3000 μm and a NEP of $10^{-11}\ WHz^{-1/2}$.

Notes on the laser radiation measurement

With the laser on, the signal is powerful. Consequently it can be recorded with a fast pyroelectric detector; the Molectron model P3-01 is good.

The power can be measured with a power meter, for instance with the Scientec Inc. power meter model 36-0801.

The spectral analysis has to be more accurate than in the case of spontaneous emission, since the spectrum bandwidth is not limited by the beam length (as in the Stanford experiment), then it can be very narrow.

In the Stanford experiment[12], the relative spectrum width of the stimulated radiation was $\Delta\nu_{st}$ = 0.008 μm unlike $\Delta\nu_{spont}$ = 0.031 μm of the spontaneous radiation, and the electron beam length was of some picoseconds. So, with a much longer pulse, the ratio between the two lines could be much less.

Therefore, the heterodyne system seems more useful. As a matter of fact, it may have a resolution of 10^6.

However, the high level of power in the signal channel allows us to use as a local oscillator a classical millimeter source like a Klystron or an Impatt Diode oscillator of 70 GHz (4 mm) or even better 140 GHz. These can be utilized for the generation of higher harmonics by means of a non-linear device, such as a Schottky barrier diode[13], since they yield enough power. For instance an Impatt Diode of the Hughes Company yields about 50 mW at λ = 2mm.

If 70 GHz is the bandwidth of the spectrum analyzer the order n of the needed harmonic is given by

$$\nu_{laser} - n\,\nu_{LO} \lesssim \frac{70}{2} \text{ GHz}$$

that is, if the frequency of the generator is 140 GHz, the requested harmonic is the sixth. With the conversion efficiency reported in the literature[14], more than 10 μW could be available. This amount of power is enough to cause the interference with the input signal.

Acknowledgements

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