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Smith-Purcell Radiation from a 50 MeV Beam

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A 50 MeV electron beam and a 1 mm period, 5° blaze, échelle grating have been used to produce radiation in the mid-infrared spectral region. The emission is highly collimated and forward-directed. The intensity level in the few ps pulse (2 nJ/sr) indicates a degree of coherent enhancement.

1. Introduction

The 50 MeV ATF accelerator at Brookhaven National Laboratory and a 1 mm period, 5° blaze, échelle grating were used to produce Smith-Purcell radiation. Forward-directed highly collimated emission in the mid-infrared region of the spectrum has been obtained. In the paper, a brief introduction to key aspects of the basic theory will be used to frame a discussion of the data. Conclusions and comments on the future directions will also be presented.

2. Theory

The relation between the wavelength of the emitted radiation (λ), the grating period (ℓ), the relative velocity of a beam electron (β), and the angle of emission (θ) (relative to the beam direction) is given by the well-known formula [1]:

$$\lambda = \ell\,(1/\beta - \cos\theta) \qquad (1)$$

In the parameter range which is of interest in the present work, θ will be small and $\beta \rightarrow 1$. The ratio of the wavelength and the grating period will fall in the range

$$\gamma^{-2} \leq \lambda/\ell \leq \gamma^{-1} \tag{2}$$

which corresponds to and angular spread which is forward-directed,

$$1/\gamma \leq \theta \leq \sqrt{2/\gamma}\ , \tag{3}$$

The energy emitted [2] by an electron at height b above a grating as it traverses a distance L is given by the expression:

$$\frac{dI}{d\Omega} = L\ \frac{2\pi e^2 g^2}{\ell^2}\ \frac{\beta^3 \sin^2\theta}{(1 - \beta\cos\theta)^3}\ \exp\left[-\frac{4\pi b/\gamma\ell}{1 - \beta\cos\theta}\right] \qquad \text{ergs/sr} \tag{4}$$

Examination of the first group of angular factors reveals that as $\beta \rightarrow 1$, the angular distribution is tipped into the forward direction and becomes highly peaked; features that are characteristic signatures of radiative processes in the high energy regime. In order to avoid cutting off this radiation with the exponential factor, the further constraint

$$\frac{4\pi b/\gamma\ell}{1 - \beta\cos\theta} \simeq 1 \tag{5}$$

must be observed. At $\theta \sim \sqrt{2/\gamma}$, $\ell \sim 2\pi b$ and as θ becomes still smaller ($\theta\gamma \rightarrow 1$), the period must increase in order to maintain coupling. Thus the optimum grating profile is an échelle.

In order to compare the predictions to an experiment, Eq. (4) must be multiplied by the number of electrons in the microbunch (N_e) and, if the pulse is short, by a factor which accounts for enhancement due to coherence. The remaining factor in Eq. (4) g^2, is simply π^{-2} in the strip grating limit [2] or a grating efficiency in a more detailed analysis [3].

3. Experiment

The ATF beam parameters are listed in Table 1 and the experimental layout is shown on Figure 1. A 50 MeV beam of 3 ps duration electron bunches is transported by dipole magnets a distance of 50 m into the experimental chamber. Quadrupole magnets just upstream from the 10 cm-long grating bring the electron bunch to an elliptical focus which is 260 microns in the direction normal to the grating surface and 590 microns in the parallel direction. The dimensions are monitored with a removable fluorescent flag.

The Smith-Purcell radiation was emitted in the horizontal plane by the vertically-oriented grating face and directed by three 2-inch diameter plano copper mirrors through a 1.375 inch clear aperture ZnSe window. This window limits the full acceptance angle of the collection system to 60 mrad. Light emitted through the window was focused by a 10 cm focal length, 3 inch diameter off-axis paraboloidal mirror onto a HgCdTe detector operating at 77 K. At 10 microns the detector responsivity and risetime were 100 V/W and 27 ns, respectively. Detector output was observed on a 100 MHz bandwidth oscilloscope. The detector housing was wrapped in lead sheet to reduce the detector response due to x-rays below the RF noise level.

In order to scan both the impact parameter and the emission angle, two remotely controlled stages were employed. The grating, flag and copper mirrors were all mounted on a breadboard. The breadboard was mounted on a linear stage so that it, and therefore the grating, moved horizontally, *i.e.*, normal to the thin dimension of the beam. By this motion, one could vary the impact parameter as well as bring the flag into the beam for beam alignment purposes. The first copper mirror was mounted on a rotating stage. By rotating this mirror, the emission angle collected could be varied. The scanning range of emission angle was limited to between 5° and 11 degrees, relative to the beam direction.

The variation in the radiation signal as the beam is moved toward the grating is shown on Figure 2. When the beam profile is folded into Eq. (4), the observed variation is in agreement with expectations based on the theory and the dimension of the beam. The angular distribution is shown on Figure 3. It is strongly collimated.

The peak signal contains between 1 and 2 nJ in a pulse that is a few ps long. The beam area is of the order of 2 cm^2. Taken together, these parameters indicate an intensity of the order of a kW/cm^2-sr. Theoretical analysis based on a detailed treatment of the effect of grating profile places this value between the limits predicted for rectangular and Gaussian pulse profiles. This is consistent with earlier predictions [4].

4. Conclusions

The spontaneous emission from the grating is remarkably bright and large enough to be used directly as a source in some types of spectroscopic investigation. It is also intriguing to consider the possibility of using gratings in place of undulators in a free-electron laser. Longer-wavelength coherent sources using beams of moderate energy to drive a grating have already been developed and there have been theoretical investigations of devices intended to operate in the IR-FIR [6]. The results to date are encouraging.

Acknowledgment

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References

[1] S. J. Smith and E. M. Purcell, Phys. Rev. 92 (1953) 1069.

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ATF Parameters:

$E = 50\ \mathrm{MeV}$

$dE/E = 0.3 - 0.5\ \%$

$\varepsilon_N = 1\pi$ mm-mrad

$Q_{\mu p} = 1$ n C (nominal)

$\tau_\mu = 10$ ps (uncompressed)

$(\mathrm{prf})^{-1} = 12.5$ or 25 ns (100 -pulses)

$I = 80 - 100$ mA

Table 1

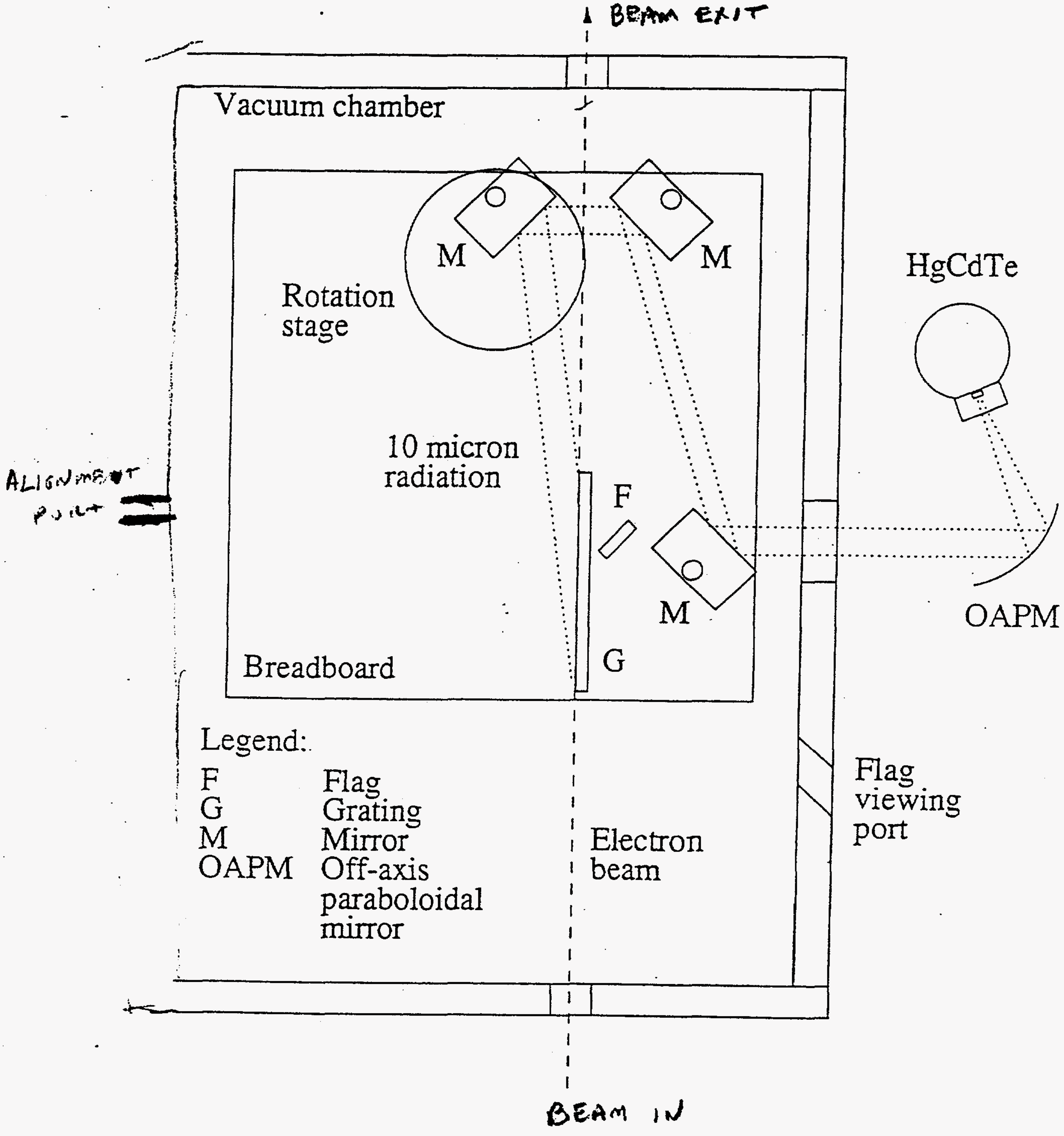
The beam parameters of the ATF accelerator

Figure Captions

Figure 1: The experimental layout of the 50 MeV diffraction radiation experiment.

Figure 2: The observed signal *vs.* grating position (closed circles). Response of signal channel with radiation beam blocked by IR absorber (open circles).

Figure 3: The angular distribution of the observed signal.


BEAM EXIT
Vacuum chamber
M
M
HgCdTe
Rotation stage
10 micron radiation
ALIGNMENT PORT
F
M
OAPM
Breadboard
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Legend:
F Flag
G Grating
M Mirror
OAPM Off-axis paraboloidal mirror
Electron beam
Flag viewing port
BEAM IN

Fig[illegible]

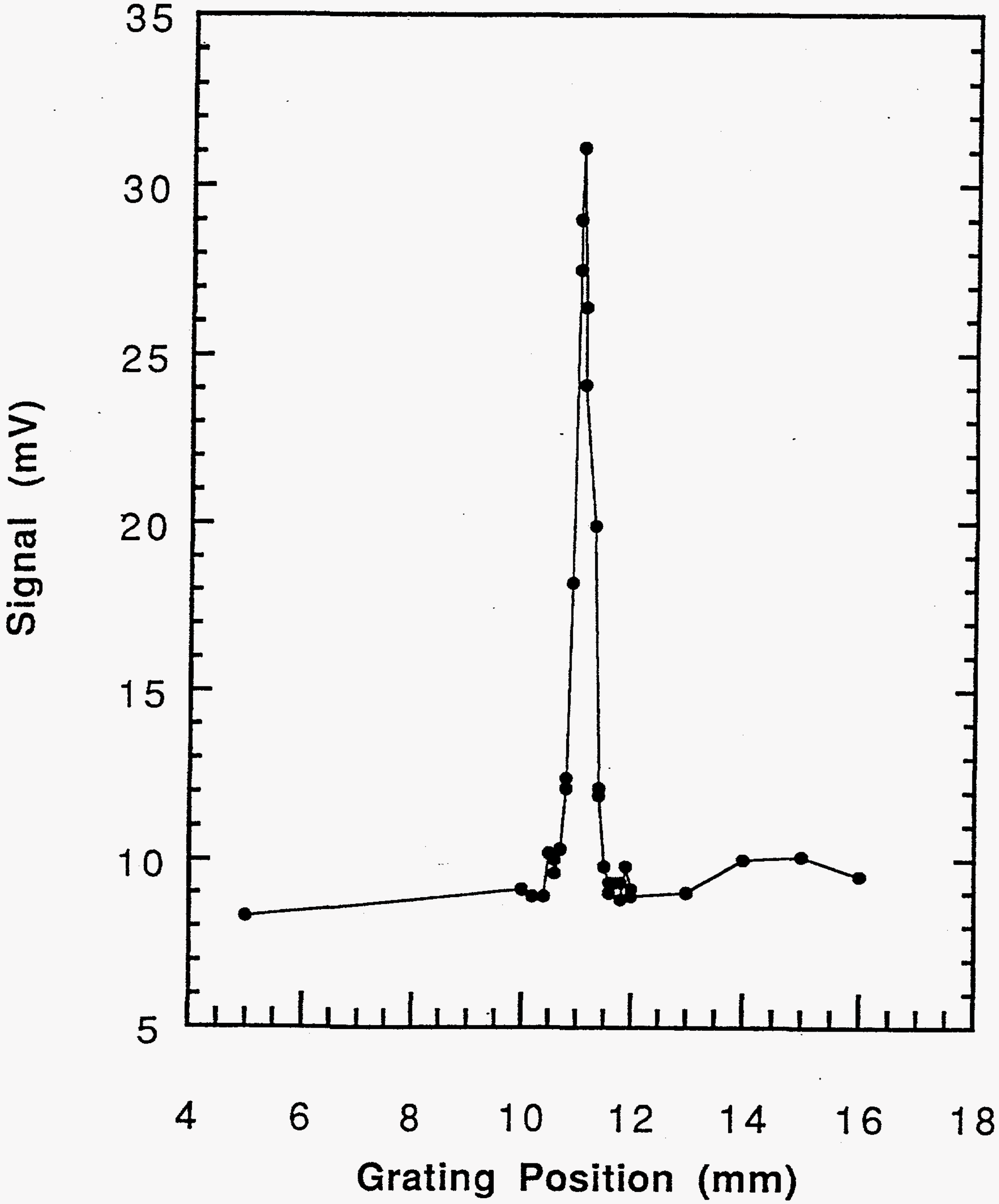
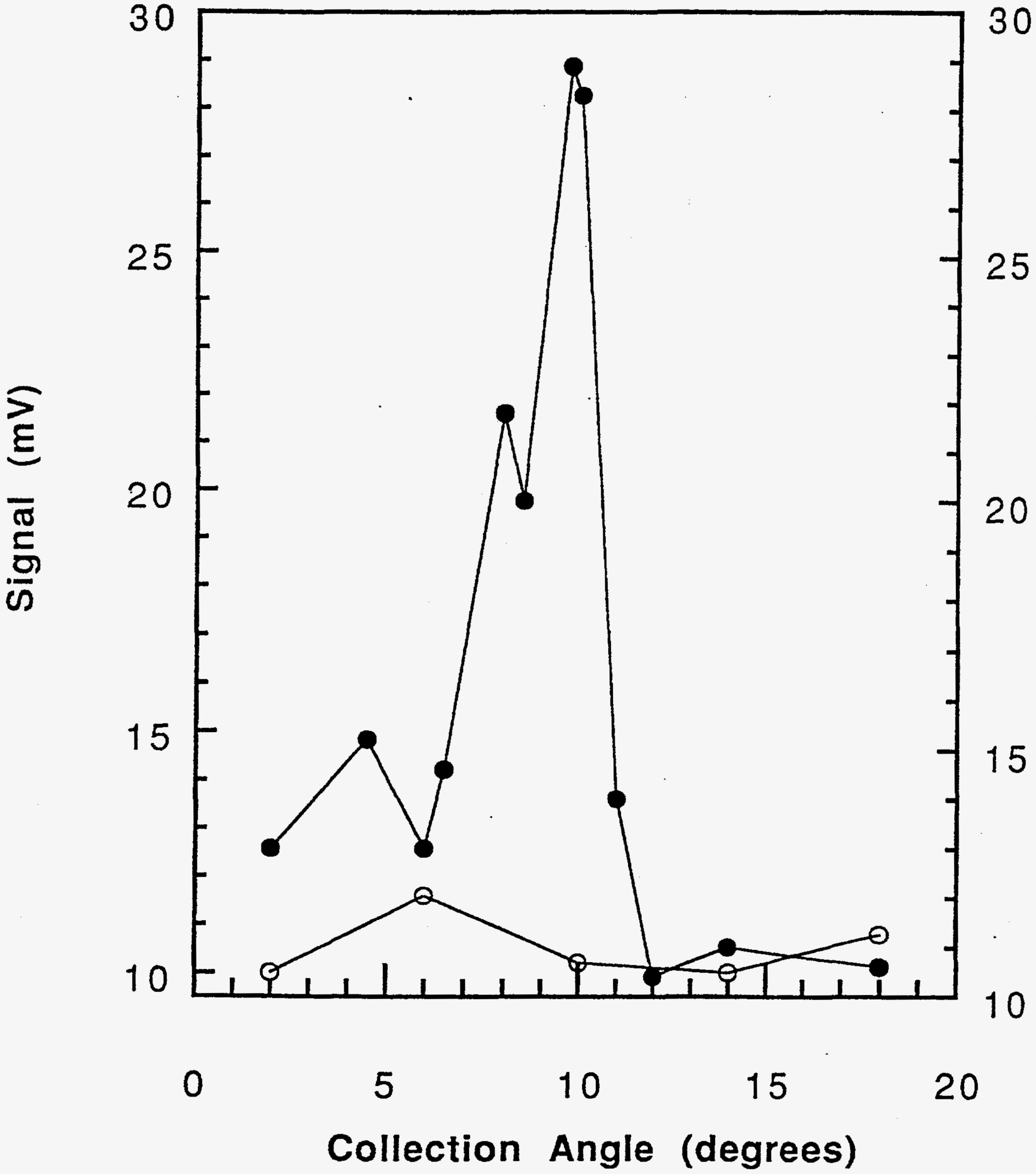

Signal (mV)
35
30
25
20
15
10
5
4
6
8
10
12
14
16
18
Grating Position (mm)

Figure 2


30
25
20
15
10
30
25
20
15
10
0
5
10
15
20
Signal (mV)
Collection Angle (degrees)

Figur