A PHOTOELECTRON SOURCE FOR THE STUDY OF SMITH-PURCELL RADIATION

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Abstract

The interaction of an electron beam with a metallic grating surface produces an electromagnetic wave known as Smith-Purcell radiation. This phenomenon could lead to more compact FEL's, provided that strong coupling between beam and surface can be achieved. A crucial factor in this respect is the emittance of the beam. We present the initial measurements of the emittance of the beam produced by a rather simple and robust photoelectron source, which is being installed in the terminal of a 3MV Van de Graaff for a detailed investigation of the Smith-Purcell radiation in the relativistic regime.

1 GENERAL

One possible approach to the development of compact and relatively inexpensive FEL's would be the use of the radiation produced when an electron beam passes very close over the surface of a metallic grating. This phenomenon was first observed in the mid-50's by Smith and Purcell[1] and has recently been studied again with relativistic electron beams[2]. The relationship between the wavelength λ of the emitted radiation, the angle θ of observation relative to the direction of the electron beam and the period λ_0 of the grating is given by:

$$\lambda = \lambda_0(1/\beta - cos\theta)$$

where β is the ratio of the electron beam velocity to that of light. This expression has now been verified over a wide range of angles and wavelengths[2, 3] and offers the most obvious method of selecting the desired wavelength, namely the variation of the angle of observation. The question of the angular distribution of the spontaneously emitted power is still under investigation but there have been suggestions recently[3] that the power may have a sharp peak in the very forward direction, as indicated by the expression:

$$\begin{aligned}\frac{dP}{d\Omega} &= \frac{1}{2\varepsilon_0} eI \frac{L}{\lambda_0^2} \frac{\beta^3 \sin^2\theta}{(1-\beta\cos\theta)^3} \\ &\quad \exp[-\frac{4\pi b}{\gamma\lambda_0(1-\beta\cos\theta)}] |R(\theta,\phi)|^2\end{aligned}$$

where I is the beam current passing over a grating of length L, and at a nominal distance b over it. The quantity $|R(\theta,\phi)|^2$ is a measure of the grating efficiency and can be estimated numerically. For high values of β and small emission angles θ, the parenthesis $(1-\beta\cos\theta)$ is very small and dominates the pre-exponential term. It is also worth noting the strong influence of the quantity b in the exponential part of the above expression. It is assumed that all of the beam is at a height b; for a more realistic beam with a Gaussian profile of σ=1.0, a relativistic factor γ=8.0 and a nominal position of 0.5mm above a grating of period 1.0mm., the expected angular distribution of the emitted power would be as shown in figure 1.

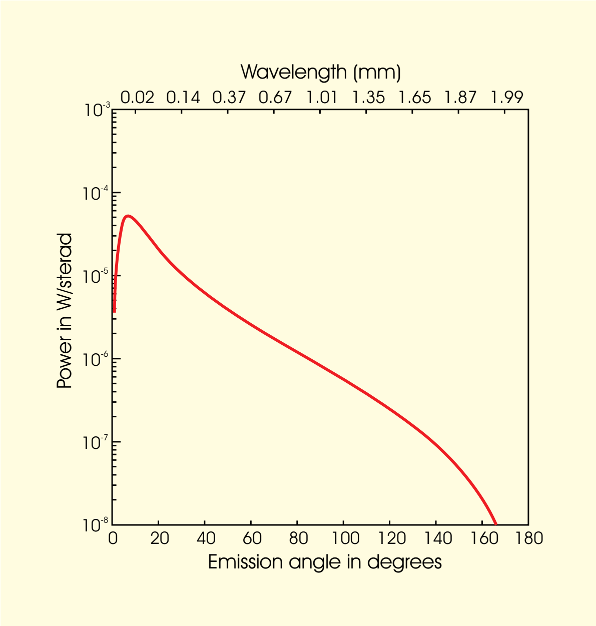

Figure 1: Predicted angular distribution of Smith-Purcell radiation. See text for details.

Thus, for efficient coupling between the beam and the grating, it is desirable to have a high brightness beam placed close to the grating surface and an optical system that allows collection of light at shallow angles relative to the beam direction.

2 THE EXPERIMENTAL ARRANGEMENT

Our experiment is based on a 3MV Van de Graaff accelerator in the Physics Department of the Technical University, Munich, and is intended to address some of the issues raised by previous work at Oxford. The use of Van de Graaff accelerators imposes fairly severe reliability requirements on the electron gun which is situated in the high voltage terminal of the accelerator and is, consequently, accessible with difficulty. With this in mind, we opted for a photoelectron source. The general schematic of the experiment is shown in figure 2.

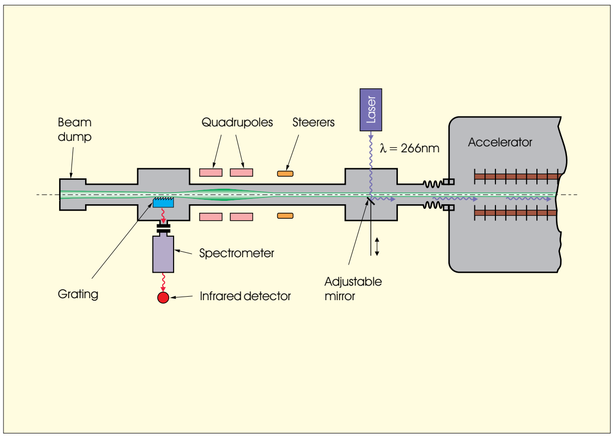

Figure 2: Schematic of the experimental arrangement.

A frequency-quadrupled laser beam of 266nm. wavelength will be injected into the terminal of the accelerator by means of an adjustable mirror that allows accurate positioning of the laser light onto the target. The latter consists of a small tantalum disc, 4mm in diameter, with the possibility of axial adjustment of its location in order to achieve Langmuir flow in the acceleration gap of the gun. The extraction potential for the photoelectrons, which is also the electron beam injection voltage into the accelerating tube, is set by tapping into the acceleration column of the Van de Graaff (See figure 3).

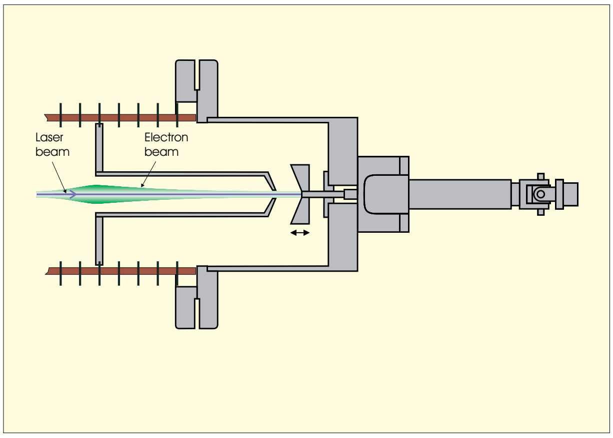

Figure 3: Schematic of the photoelectron source.

The terminal is thus entirely ‘passive’ in the sense that there are no power supplies inside it. Since the ratio of injection voltage to total accelerating tube voltage is fixed, the focusing effect of the tube entrance is constant over the operating range of the machine.

The accelerated electron beam will be focused, by means of a quadrupole doublet lens, over the grating surface and then dumped onto a beam dump. Since the collection of light in the very forward direction and the verification of the theoretical prediction mentioned earlier is of primary concern, we have designed a rotating, 3-mirror assembly that will allow us to reach emission angles of approximately 10^0 relative to the beam direction. The light, which will have a wavelength of approximately 100μm, will then pass through a Czerny-Turner spectrometer and will be detected by means of a Ga-doped Ge photoconductive detector with a response time of 20-30 ns.

3 PHOTOELECTRON SOURCE TESTS

We have recently carried out measurements of the intensity and angular spread of the photoelectrons emitted from a tantalum target bombarded with a laser beam of 266nm. Although the measurements were not intended to be a full investigation of the phase-space occupied by the electrons, nevertheless they provided a reasonable estimate of the beam emittance. This is adequate for the preparation of the experiment and the calculation of the electron beam optics.

The experimental arrangement consisted of a cathode in the form of a tantalum disc, placed 9mm behind a flat anode. The anode, which was held at ground potential, had a central aperture of 10mm diameter through which the laser beam could illuminate the cathode. A negative potential of 15kV was applied to the cathode. The extracted electrons were detected by means of a movable Faraday cup which had a diameter of 13mm and which could be positioned at various points along the optical axis of the system (See figure 4).

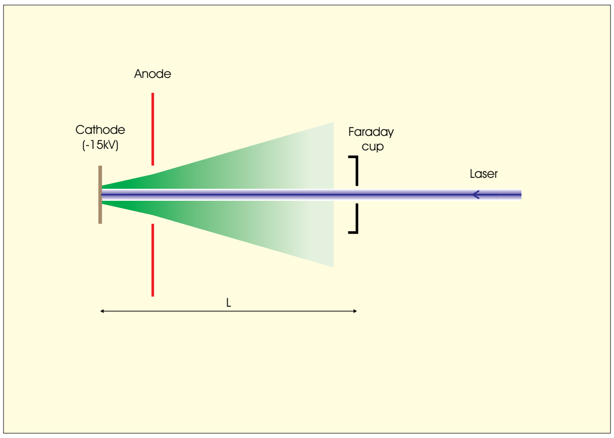

Figure 4: Schematic of the emittance measuring system.

The position of the cup relative to the anode and the amount of current intercepted by it were then recorded. The size of the laser spot on target was found to be approximately elliptical in shape, with major and minor semi-axes of 2 and 1mm, respectively. The full beam intensity was 500mA and the pulse width 15-20ns, fwhm.

Table I
Predicted beam emittances

Beam	Assumed, at origin			Predicted, after acceleration			
fraction	x_0	x'_0	ϵ_n	z_0	r_0	r'_0	ϵ_n
(%)	(mm)	(mrad)		(mm)	(mm)	(mrad)	
100	2.1	1200	1.6	-18	0.64	356	56
95	2.1	700	0.9	-20	0.4	330	32
91	1.9	500	0.6	-21	0.28	311	21
90	1.65	500	0.5	-22	0.25	299	18
84	1.4	400	0.4	-23	0.18	288	13
81	1.0	200	0.1	-23	0.07	283	5

Field index $n = 0.925$ (see text for details)
Emittances (ϵ_n) in $\pi mm.mrad$

The analysis is based on the comparison of the measurements of beam size at various locations with the predictions of our beam transport code. The shape of the electric field in the cathode-anode space, where acceleration takes place, has a strong influence on the size and divergence of the beam as it emerges from the anode aperture. For a flat anode and cathode one might consider a uniform field. However, in view of the large size of the anode aperture relative to the anode-cathode seperation, this assumption may not be valid. Our code allows for investigation of the effects of this field, provided that it can be represented by a function of the form $E \sim z^{\eta-1}$, where z is the distance along the axis and η is a parameter specified by the user. For uniform fields, η=1, while for a Pierce geometry η=4/3. Apart from calculating the beam size at the Faraday cup position, the code also works 'backwards' and estimates the beam radius (r_0) and divergence (r'_0) of the apparent waist at a distance z_0 from the cup. These numbers, therefore, determine a new emittance for the beam. This emittance is going to be greater than the original one at the point of origin of the electrons, due to the non-linear effects of the space charge forces in the cathode-anode gap.

These numbers are listed in Table I, together with the values of beam diameter and divergence at the photocathode and the value of the field index η that gave the best fit to the measured beam sizes; all emittances in Table I have been normalized by multiplication with the factor $\beta\gamma$. If we assume that the electrons are emitted with a Maxwellian distribution in their divergence x', then the normalized rms emittance $\bar{\epsilon_n}$ would be given by the expression[4]:

$$\bar{\epsilon_n} = 2r_c(\frac{kT}{m_0c^2})^{1/2}$$

where r_c is the radius of the emitting spot (2mm in our case) and the other symbols have their usual meaning. Using a kT value of 0.1eV, which is not an unreasonable assumption, we obtain an rms value of the original emittance of about 1.8πmm.mrad. This is consistent with the first entry in Table I. We conclude, therefore, that the beam emerging from the extraction aperture is likely to have a normalized emittance, for the full beam, of about 60πmm.mrad. Smaller fractions of the beam will have smaller emittances. The emittance values for beam fractions less than 100% were estimated by progressively reducing the initial beam size x_0 and/or divergence x'_0 until the predicted beam size at the Faraday cup was 13mm. The results of these calculations are tabulated in Table I. Note that under these assumptions, 80% of the beam would have a normalized emittance that is almost a factor of 10 down on that of the full beam.

4 SUMMARY

We have produced photoelectron pulses of up to 1A amplitude and 15-20ns duration, from a tantalum cathode bombarded with, typically, 5.5 mJ of laser light at 266nm. The normalized emittance ϵ_n of a 500mA beam is, approximately, 60πmm.mrad, while the emittance of 80% of the beam is 5πmm.mrad. The optical system for the injection of the laser light into the terminal of the Van de Graaff is currently being installed and we expect the first results of the experiment in the autumn of 1996.

5 REFERENCES

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