THE OPTICAL SYSTEM FOR A SMITH-PURCELL EXPERIMENT AT 45MeV

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Abstract

Smith-Purcell (SP) radiation has been used to investigate the longitudinal profile of a 45MeV, picosecond long bunched beam at the FELIX facility, FOM Institute. The three important optical elements that made this experiment possible were (*i*) high quality optical filters, (*ii*) non-imaging light concentrators, (*iii*) and a system to rapidly change between gratings.

INTRODUCTION

Smith-Purcell radiation is produced when a bunch passes close to the surface of a metallic grating, causing it to radiate a small portion of its energy [1] [2]. The wavelength of this radiation is distributed according to the Smith-Purcell formula:

$$\lambda = \frac{l}{n}\left(\frac{1}{\beta} - \cos\theta\right) \qquad (1)$$

where λ is the radiated wavelength, l is the period of the grating, n is the order of Smith-Purcell radiation, θ is the angle of the emitted radiation relative to the beam direction, $\beta = \frac{v}{c}$, and v is the velocity of the particle. Thus, the choice of grating affects the range of wavelengths produced. For most practical purposes, the emitted wavelengths are in the far infrared.

The assembled equipment can be seen in figure 1, which shows the vacuum chamber, with a graphical representation of the beam direction. This contains the grating assembly, which causes the emitted SP radiation to be emitted out through a crystalline quartz window. This maintains the integrity of the beamline vacuum, whilst being transparent to far-infrared radiation. The radiation is then collected by the optical system, where it is detected by an array of 11 pyroelectric detectors.

PYROELECTRIC DETECTORS

Typically, the detection of far-infrared radiation is achieved by using cryogenic detectors. Pyroelectric detectors, however, although of lower responsivity, work at room temperature and are a useful inexpensive alternative to costly cryogenic detectors.

The detector's sensing element is made from *lithium tantalate*. Compounds such as this exhibit an electrical polarisation that varies in response to changes in temperature. A change in flux of incident radiation results in a temperature change, and therefore produces a measurable difference in potential across the element.

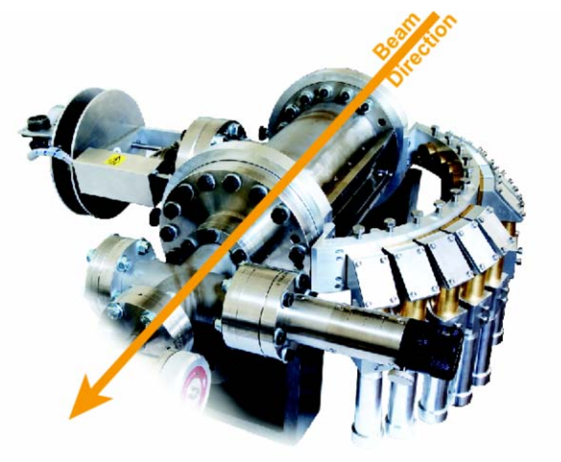

Figure 1: The assembled equipment used to investigate the longitudinal profile.

THE GRATING ASSEMBLY

The range of SP wavelengths observed depends upon the periodicity of the grating. It is, therefore, useful to use multiple gratings during the experiment to expand the recorded wavelength range as far as possible.

Methods were also needed to efficiently separate Smith-Purcell and 'background' radiation (i.e. all radiation that does not come from the periodic structure). To this end, a 'blank' of the same dimensions as the gratings was included. This enables some of the 'background' radiation to be identified as such and removed from the analysis.

The gratings and blank were machined from aluminium, and mounted on a 'carousel' structure (see figure 2). The carousel is situated inside the vacuum chamber, opposite the crystalline quartz window, and can be moved back and forth within the chamber. The carousel can be rotated by $90°$ to allow different period gratings to be presented towards the beam. Emitted radiation is directed out through the crystalline quartz window.

THE LIGHT COLLECTION SYSTEM

The light collection system consists of several parts:

- a non-imaging light concentrator,
- the Waveguide Array Plate (WAP) filter, and its holder,
- a $45°$ plane mirror,
- the optical housing itself.

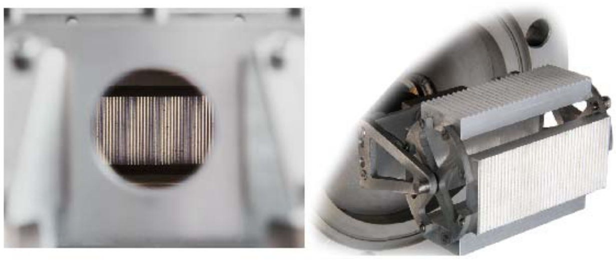

Figure 2: The ‘carousel’ containing 3 aluminium gratings with different periodicity, and one blank piece with the same dimensions. The carousel can be rotated by $90°$ during the experiment, and enables a quick turn-around of results.

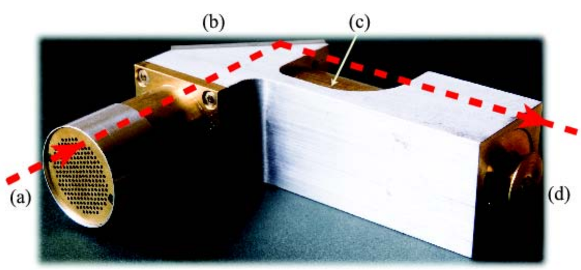

Figure 3: The assembled optical system, and the path of radiation passing through it. Shown are (a) the WAP filter and its holder, (b) a $45°$ plane mirror, (c) a non-imaging light concentrator, and (d) the position of the detector, when attached to the optical system.

The optical housing, in combination with the $45°$ plane mirror, holds the optical equipment in a $90°$ ‘elbow-bend’ arrangement. This places the detectors at $90°$ relative to the infrared (Smith-Purcell) beam. With this set up, it is possible to insert lead shielding between the beamline and the detectors/electronics, providing essential protection from X-rays. The assembled optical system, and the path taken by radiation passing through it, can be seen in figure 3.

Non-Imaging Light Concentrators — Winston Cones

Non-imaging light concentrators, or in their most common form, Winston cones [5], have many applications in situations where a high light collection efficiency is desired. In this experiment, their use was threefold:

- to improve the amount of collected radiation,
- to provide a more monochromatic source of radiation,
- to discriminate against very long wavelength background radiation.

The essential principle of the light concentrator is that any light incident within a finite range of incidence angles will emerge through the exit aperture. This incident

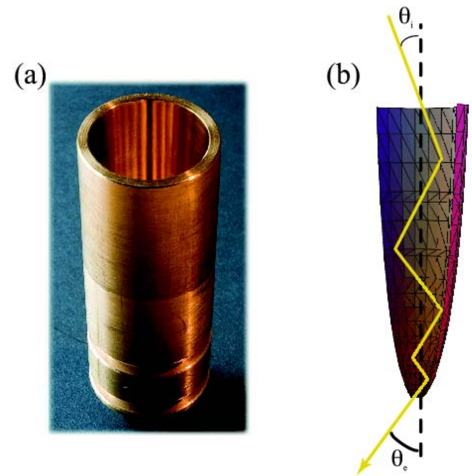

Figure 4: (a) A brass non-imaging light concentrator as used in this experiment, (b) light reflecting through the concentrator.

light undergoes multiple internal reflections (see figure 4) from the interior parabolic surface of the light concentrator, emerging from the exit aperture within a finite range of exit angles. The entry and exit angles are related through Liouville’s theorem:

$$A \sin^2\theta_i = A \sin^2\theta_e \tag{2}$$

The ‘concentration factor’ of a light concentrator is defined as the ratio of entrance aperture to exit aperture area. However, since the exit aperture is much smaller than the entrance, the range of exit angles is much larger. Therefore, in order to take full advantage of its concentrating properties, the exit aperture of the cone must be as close to the detector as possible.

The light concentrators used in this experiment were primarily defined by several experimental constraints, such as the entrance aperture being constrained to 21mm diameter, and the exit aperture not exceeding 3mm diameter. Further upper limits were placed on the length of the cone, and the maximum angle at which radiation could exit the cone, and still be detected (the pyroelectric detector has a maximum detectable incident angle of $60°$). The final dimensions of the cone are:

- $\theta_i = 6.3°$,
- $\theta_e = 60°$,
- Entrance aperture diameter $= 21$mm,
- Exit aperture diameter $= 2.8$mm,
- Overall length $= 71.5$mm,
- Concentration factor $= 23$ — i.e. 23 times more light is collected with a concentrator, than without one.

As noted earlier, the Smith-Purcell effect results in an angular distribution of wavelengths. The equation governing this distribution, however, is for an observer at infinity, which is not the case in this setup. In this case, a finite range of Smith-Purcell wavelengths could be accepted

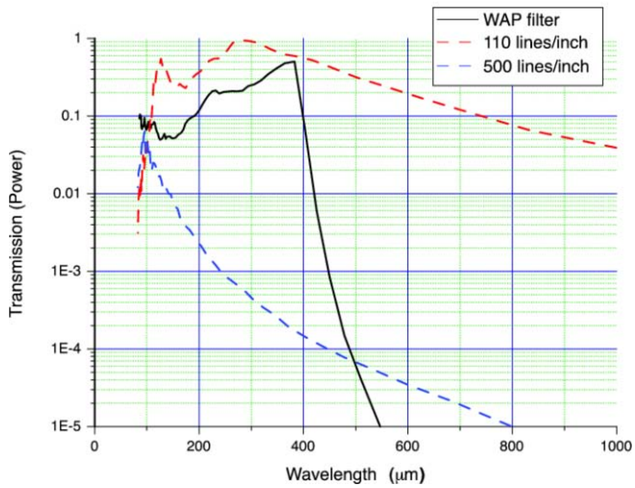

Figure 5: A comparison of power transmission characteristics of a WAP filter (solid line) and two wire mesh filters (dashed lines). Note the steep cut-off of wavelengths by the WAP filter after its designed wavelength, compared to the gentle slopes of the wire mesh filters.

by each detector. Light concentrators, however, only accept a small range of incident angles. This limits the range of angles accepted by the optical system, essentially moving the detectors further from the grating towards infinity. The result of this is to make the collected radiation more monochromatic.

Furthermore, as an additional aside, the small exit aperture diameter of 2.8mm ensures that wavelengths longer than this are diffracted back out of the concentrator. This gives the concentrator the additional benefit of providing useful long wavelength background discrimination.

Waveguide Array Plate (WAP) Filters

Waveguide Array Plate (WAP) filters are a type of dichroic filter, and are described extensively in [3] and [4]. In this case they were made from 21mm brass discs, drilled with a hexagonal close packed arrangement of holes. The size, separation, and the depth of these holes determines the peak transmitted wavelength of the filter. Each filter is designed to pass only a specific range of wavelengths and reject all others. Thus, they give a very efficient rejection of unwanted wavelengths. WAP filters can be designed to allow a very high transmission of a particular wavelength (ideally, the desired Smith-Purcell wavelength), with a steep cut-off beyond that. This becomes especially apparent when comparisons are made with other filtering methods, such as wire mesh filters, which have a much gentler suppression of longer wavelengths (see figure 5).

SUMMARY

Three important pieces of equipment were brought together successfully during a recent Smith-Purcell experiment at the FELIX facility, FOM Institute. These were,

1. an improved method of filtering background radiation (WAP filters),
2. a 'carousel' holding three gratings and a blank, which proved essential in both extending the observed wavelength range and discriminating against background radiation.
3. non-imaging light concentrators, which significantly improved the amount of collected radiation, as well as providing a more monochromatic source of radiation and discriminating against very long wavelength background.

The combination of these three elements allowed the use of an array of pyroelectric detectors for the measurement of SP radiation. This robust and inexpensive system was used for the study of the longitudinal profile of the FELIX electron bunches.

REFERENCES

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

[2] G. Doucas, M. F. Kimmitt et. al. "Electron Bunch Shape Determination by Coherent Smith-Purcell Radiation", Proceedings of EPAC 2002, p1870—1872

[3] C. Winnewisser, F. Lewen, H. Helm, "Transmission Characteristics of Dichroic Filters Measured by THz Time-domain Spectroscopy", Apply. Phys. A 66, p593—598 (1998).

[4] M. Bozzi, L. Perregrini, J. Weinzierl, C. Winnewisser, "Design, Fabrication and Measurement of Frequency Selective Surfaces", Optical Engineering (2000).

[5] A. Rabi, R. Winston, "Ideal Concentrators for Finite Sources and Restricted Exit Angles", Applied Optics Vol. 15, No. 11, November 1976.