Study of thermal detectors for longitudinal beam diagnostic

Lara Hijazi and Pierre Favier

Supervisor: Nicolas Delerue, LAL, Orsay

Abstract

We detail the whole detection chain of a given experiment. We take the example of Smith-Purcell radiation [1] detection since it is an active area of research as beam diagnostic in particle accelerators. Investigations on the different detectors available are performed, in addition to an overview of the amplification and conversion system. A background analysis is also presented and several ways to suppress it are mentionned.

1 Introduction

In particle accelerators, diagnostics are necessary to control beam's quality. There are several relevant beam parameters such as the emittance, the energy spread, the charge distribution... But among all these parameters, we will discuss only longitudinal size σ_z - or beam length - since this is of great importance for accelerator tuning.

For this purpose, there exists several diagnostics. One constists in applying a high voltage on the head of the beam and the same but opposite voltage on the tail in order to rotate the beam such as the longitudinal direction becomes the vertical one. Then a simple screen allows a direct visualisation of the beam size. However this method is destructive and can lead to severe space charge effects during the rotation which truncate the measure. Moreover the distance between the vertical push and the screen needs to be known with high accuracy to avoid over rotation.
Transition radiation can be used as a second method [2]. This radiation is emitted when a beam of charged particles cross two media with different dielectric constants. The radiation wavelength is of course directly related to the beam characteristic and a spectrometer allows the determination of the size. However this process can affect the beam length when crossing the media, in addition to redirect the eventual background with the transition radiation. This leads to a superposition of signal and background wavelengths on the final spectrum.
The third method is the one we mainly discussed during our four ministage sessions, it is based on Smith-Purcell radiation [1].

2 Smith-Purcell radiation

As shown on Fig. 1, when a beam of charged particles passes upon a grating, the beam-associated electromagnetic waves are reflected on the gratings and interfere coherently. This lead to a characteristic radiation in the mm-range (far-infrared), known as Smith-Purcell radiation (SPR).

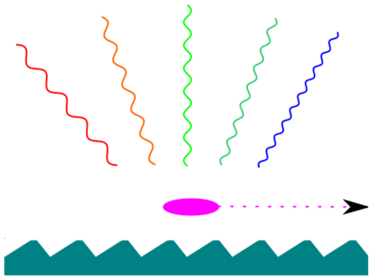

Figure 1: *Smith-Purcell radiation occurs when an electron beam passes across a grating*

This radiation is recorded by the detection chain shown on Fig 2. The beam profil can then be reconstructed by taking the inverse Fourier transform of the frequency spectrum. However we need to increase signal over noise ratio (S/N) by reducing the background impact.

3 Signal filtering and focalisation

Coupling between the beam and the accelerator acts as a background producer. Indeed the beam loses energy through synchrotron radiation in magnets, transition radiation or diffraction radiation, and all these photons can reach the detector.

We can suppress most background with several levels of filters.

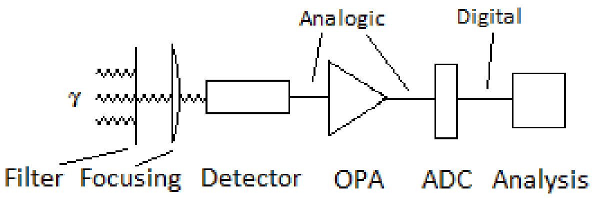

Figure 2: *The detection chain. The focused and filtered radiation is directed towards a detector, whose signal is amplified by Operational Amplifier (OPA) and converted by Analogic-to-Digital Converter (ADC) to be read on a computer.*

The first level is to maximize S/N ratio using geometrical considerations. Indeed we can focalise signal from our grating into a small area with tubes and mirrors as shown on Fig. 3. The mirror is an off axis parabolic mirror (OAP), it allows efficient focalisation of the incoming radiation. Note that instead of OAPs, we could have used Winston cones. They are pipes with parabolic shapes and inner reflective surfaces that collect the radiation towards the detector and provide additional filtering. However OAPs are cheaper and preserve the spatial distribution.

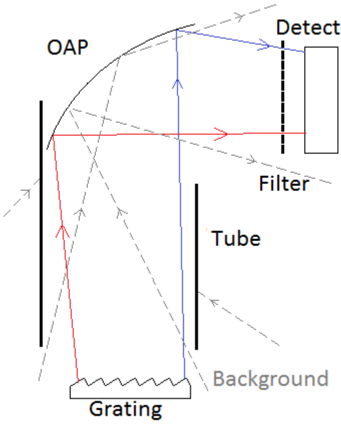

Figure 3: *Several levels of background suppression and focalisation. The non vertical background radiation(dash line) is absorbed by the tube while most of the remaining is rejected by the filter. The off axis parabolic mirror (OAP) is primarily here to focalise the signal.*

In addition to these geometrical filters, we need to place frequency filters before the detector to suppress final background radiations. Indeed we can determine the background frequency range by putting a ”blank” grating, meaning a smooth surface. When a beam passes across this surface, it emits no SPR and the background properties can be evaluated. The interesting point is, in this case, the accelerator is in the same condition as during the experiment, thereby we know excatly how the background behaves. Hence we can place filters above the grating to reject background radiation.
The best filters in our case are waveguide area plates (WAP). They are based on arrays of metallic waveguides whose dimensions favor low wavelengths to propagate and attenuate longer ones. Like a high pass filter in electronics.

It should be noted that if the background is too high, meaning peaks comparable to that of the signal, it cannot be suppressed by these methods. In this case, further investigations need to be performed and detector's properties have to be carefully considered.

Now that we know how to minimize background radiation and in which frequency range the radiation is emitted, we can think of which detector is the most efficient.

4 Detector choice

Since SPR occurs in the mm-range (far infrared), we have essentially four choices for our detector.

4.1 Bolometers

Bolometers are made of an thin absorber and a thermistor, both connected to a thermal reservoir. Incoming infrared radiation warms up the absorber, resulting in a change of the resistance of the thermistor. The resistance variation is then measured and one can deduce the power of the incoming radiation.

Note that best sensitivity is achieved after cooling bolometer to a few K.

4.2 Thermopiles

Thermocouples use the fact that two conductors submitted to a temperature gradient lead to a voltage, known as the Seebeck effect.
Incoming radiation warms up one side of the detector, while a voltmeter measures the induced voltage. Knowing the conversion factor - or Seebeck coefficient - we can deduce the wavelength of the radiation.

Usually thermocouples are coupled in series to increase signal, and form a thermopile.

4.3 Golay cells

They are small metal cylinders, closed by blackened metal plate at one end and by a flexible metalized membrane (mirror) on the other end. A scheme is shown on Fig. 4. The pneumatic chamber is filled with gas, and the light from a LED is reflected on the mirror and goes inside a photocell. When the infrared radiation falls on the blackened metal, it heats the gas and causes its expansion. The increasing pressure deforms the mirror and the light from the LED is deviated. The resulting angle is then determined and related to the input radiation power. Golay Cells have a wide usable frequency range, between 0.02 THz (15 mm) and 20 THz (0.15 μm).

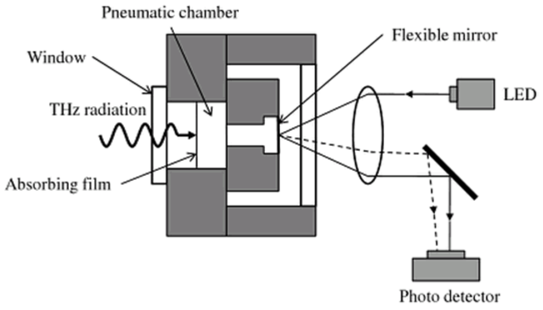

Figure 4: *Scheme of a Golay cell. The incoming radiation heats the gas, which expand and deform the mirror. The light emitted from the LED is thus deviated proportionally to the deposited energy.*

4.4 Pyroelectrics

They are made of pyroelectric crystals, meaning a spontaneous electric polarization occurs when they are heated or cooled. Temperature variations slightly move the atoms of the crystal, resulting in a change in polarization and consequently in a voltage. Note that the output voltage depends on the temperature variation and not on the actual value.

4.5 The pros and the cons

The following table summarizes the different properties of each detector. We use two parameters to evaluate them: their sensitivity and their noise-equivalent-power (NEP).

The sensitivity (S) is defined as the output voltage over the input power and is measured in V/W or A/W. The higher the sensitivity is, the higher output voltage the detector provides for a given input power.

The NEP corresponds to the input signal that gives a S/N ratio of 1. It is measured in $W/\sqrt{Hz}$. The lower the NEP is, the weaker radiation the detector can measured before being saturated by the noise.

Detector	**S** (V/W)	**NEP** ($W/\sqrt{Hz}$)	**Advantages**	**Disadvantages**
Bolometer	10^5	10^{-13}	Very sensitive, ultra low NEP	Expensive, cooling system
Thermopiles	246	$1,3.10^{-9}$	Large temperature range	Corrosion, complexity
Golay cells	3.10^4	$1,2.10^{-10}$	Sensitive	Fragile, slow response
Pyroelectrics	10^5	10^{-10}	Sensitive, fast response time	High HEP (compared to bolometers)

Values for bolometers, thermopiles, Golay cell and pyroelectric detector can be found respectively in Ref. [3, 4] [5], [6] and [7].

One can see on the above table that bolometers have the lowest NEP and among the highest sensitivity, they are thus the most sensitive detectors in the THz range. However they are really expensive and large. On the contrary pyroelectric detector are cheaper and show good enough properties to be used for this experiment. Golay cells are too fragile, and thermopiles are not sensitive enough compared to the others detectors.

Pyroelectric detectors were thus chosen for this experiment.

5 Amplification

Any detector gives a small output voltage, usually around a few mV. We thus need to amplify this signal to allow its detection in the acquisition system.

This amplification is usually done by operational amplifiers (OPA), which essentially consists in a high number of coupled transistors.

The important parameter in OPA is their gain, define as the ratio between the output voltage over the input voltage. OPA allow a gain between $10^6 - 10^8$, but of course the output voltage cannot exceed the alimentation voltage of the OPA. In this case there is a saturation, which is noxious for the device.

The gain is of great importance for us since the output voltage is related to the frequency of the bunch.

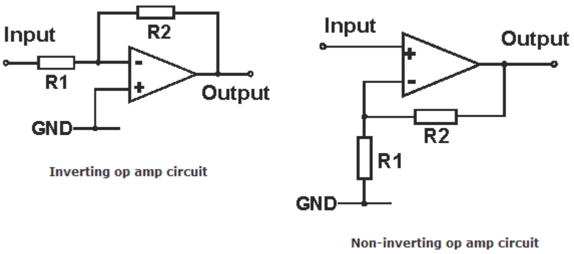

Figure 5: *On the left, an inverting OPA with a gain* $G = -R2/R1$. *On the right, a non-invariant OPA with a gain* $G = 1 + R2/R1$.

Hence we need a gain which remains constant in the frequency range we are interested in. This ability is characterized by the bandwidth of the OPA. An OPA with a bandwidth between 10 MHz and 10 GHz, even with a high gain, will not be suitable for our experiment. We need a gain from 20 GHz to 400 GHz approximately. Not too short because we need a large frequency spectrum to reconstruct the bunch profil. But not too large to reduce acquisition time and useless data analysis.
Note that OPA can be either non-inverting or inverting, meaning the output signal can be either of the same sign of the input voltage, or of the opposite sign. These two configurations can be seen on Fig. 5. This is important to know because the gain is not the same for both cases. Indeed for an inverting OPA, $G_i = -R2/R1$, while for a non-inverting OPA $G_{n-i} = 1 + R2/R1$. The absolute gain is thus slightly better with a non-inverting OPA. However this difference is often negligible regarding the difference of the resistances value.

The amplified signal needs then to be converted into a lisible format for the computer. Note that the sign of the output signal is not relevant for the converting system.

6 Analog-to-digital converter

Analog-to-digital converters (ADC) are used to convert a continuous quantity (a voltage in our case) into a number of bits.
Since the number of bits is discrete, there is precision of conversion below which two voltages are expressed as the same bit.
Indeed the precision is $p = \frac{V_{max}}{2^N}$, with V_{max} the maximum input voltage and N the total number of bits available.
For $V_{max} = 10V$ and N = 8, we have p = 20 mV, meaning we are not able to identify two signals separated by V < 20mV.

As OPA, ADC are characterized by their bandwidths, and of course both bandwidth need to match to be fully efficient.

Finally, the digital signal can be recorded on a computer and analysed.

7 Conclusion

We presented different types of thermal detectors. Each one has its own specificities and we showed that pyroelectric detectors are the most suitable for this experiment.
We explained how to measure the longitudinal profile of a beam of charged particles and gave an example of a detection chain, from the emission of the radiation to the software treatment. This requires more than just a detector, it needs an analysis of the environnement of the source, in addition to amplification and conversion elements.

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