

# OBSERVATION AND EXPERIMENTATION OF STIMULATED TRANSITION RADIATION

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## Abstract

Stimulated transition radiation can be generated by recycling light pulses of coherent transition radiation in an optical cavity. At a specific cavity length, the light of a previous bunch coincides at the radiator with the arrival of a subsequent bunch. In this situation, the external electromagnetic field stimulates the emission of higher intensity coherent transition radiation. Observation and experimentation of stimulated transition radiation generated from short electron bunches at SUNSHINE will be presented.

## 1 INTRODUCTION

Stimulated Transition Radiation (STR) is emitted when electrons pass through the interface between two media of different dielectric constants with the presence of an external electromagnetic field with a proper phase. The following approaches, for example, can be used to provide the external field: repeatedly returning the radiation to the interface and establishing a system of interfaces [1]. At the SUNSHINE (Stanford UNiversity SHort INTense Electron source) facility [2], we generate coherent transition radiation (TR) in the far-infrared regime from a train of short electron bunches at a vacuum-metal interface (radiator). Therefore, the most appropriate external field for the STR study is the coherent TR emitted by previous electron bunches. This radiation is returned to the radiator by an optical cavity. The cavity length is adjusted such that the returned radiation arrives back at the radiator at the same time a subsequent electron bunch arrives there. The returned radiation pulse serves now as an external stimulating field. The diagram in Fig.1 illustrates the stimulation concept.

The principle of this stimulation process has been experimentally demonstrated by Lihn [3]. This paper reports further studies that had been conducted on the subject [4]. The studies investigate the generation of STR in more detail with a goal to maximize the stimulation enhancement leading to a high intensity coherent far-infrared radiation source.

## 2 STR CAVITY

Not only does the radiation in the cavity have to arrive at the radiator simultaneously with another in-coming electron bunch, but also its polarization must have proper direction to fulfil the stimulation conditions. The external radiation which can be used for stimulation should have the same polarization as that of the radiation emitted from the incoming electron bunch. While the timing condition

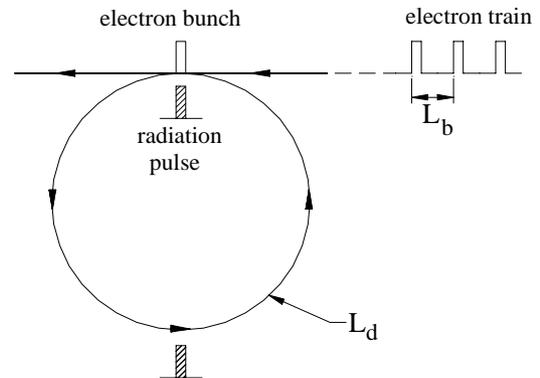


Figure 1: Stimulation by the radiation emitted from a previous electron bunch.

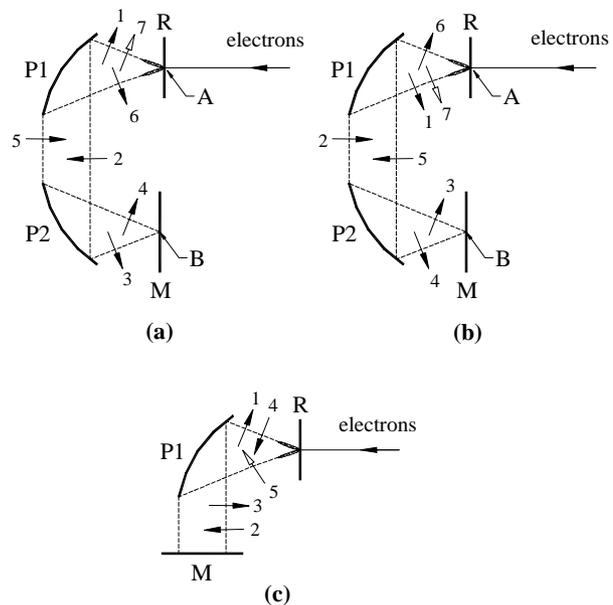


Figure 2: Schematic diagrams in (a) and (b) illustrate the optical cavity used for the STR study and the radiation polarization in the cavity. The diagram in (c) shows a simpler cavity setup but not suitable for the STR study.

can be accomplished by adjusting the cavity loop length, the polarization condition requires a specific arrangement of the cavity components.

A cavity as shown schematically in Fig. 2(a) and 2(b) can be used for the study of STR. It consists of a radiator (R), two off-axis parabolic reflectors (P1 and P2) and

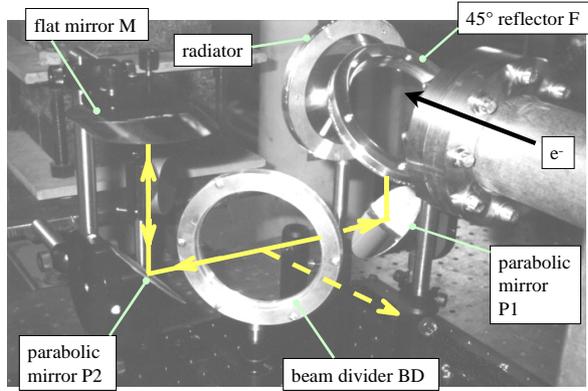


Figure 3: The STR cavity.

a plane reflector (M). The focal points of P1 and P2 are aligned on the radiator at point A and on the plane reflector at point B, respectively. P1 converts the divergent transition radiation emitted from point A to become parallel. P2 focuses the parallel light onto a point at B. The radiation is then reflected on M and transported back to P2, P1 and R at point A.

The polarization states of the radiation are traced through the cavity and are shown in Fig. 2. The polarization of the radiation in the upper half of the radiation cone is shown in Fig. 2(a) while that of the lower half is shown in Fig. 2(b). The numbers indicate chronological events. For example, the polarization state “1” is the polarization of the transition radiation just emitted from the electrons and the polarization state “7” is the radiation after passing through the cavity. The radiation polarization after one round trip travelling through the cavity has the same direction as that of the radiation emitted from an incoming electron bunch. That would not be the case if we would use a much simpler cavity with a flat reflector between P1 and P2 [Fig. 2(c)].

Figure 3 shows a picture of the actual experimental setup of the STR cavity at the end of the beam line. The whole cavity is placed at the end of the beam line after a 75- $\mu\text{m}$ -thick stainless steel window, which separates the evacuated beam line and the ambient air. Electrons pass through the stainless steel window and enter the cavity. At the radiator, the electrons generate transition radiation, which is then recycled in the cavity to start the stimulation. The foil reflector (F) tilted 45° about a horizontal axis is used to separate the transition radiation generated at R from the electron beam. The parabolic mirror P2 and the flat mirror F are mounted on a remote-controlled linear translation stage. This allows us to change the cavity path length without affecting the alignment of the cavity.

A beam divider (BD) is used to couple out some radiation energy from the cavity for monitoring, while the rest of the radiation is transmitted through the beam divider and remains in the cavity. The radiation extraction contributes to cavity losses, which must be chosen carefully to optimize the built-up of the energy in the cavity.

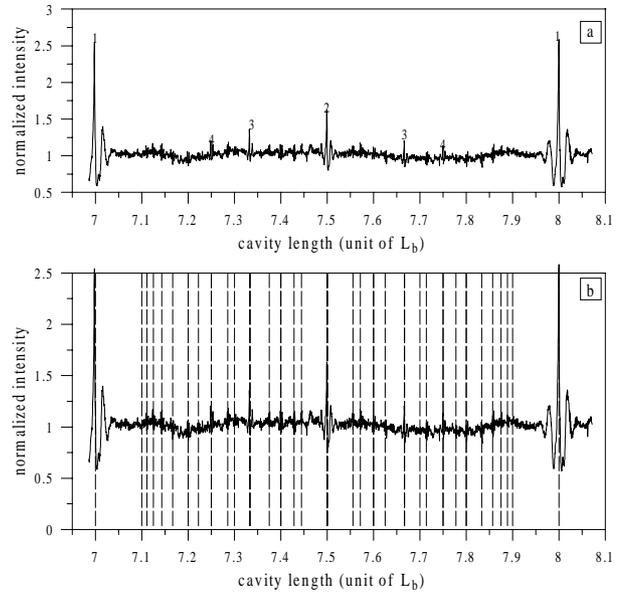


Figure 4: A typically STR cavity scan displaying many resonances. In (b), the scan is shown together with the locations (indicated by dashed-lines) where we expect stimulation up to the 10<sup>th</sup> order resonance to occur.

### 3 RESONANCE CONDITIONS

For a train of electron bunches with the interbunch distance  $L_b$ , stimulation will occur when the radiation generated from a previous electron bunch is in the cavity with a total path length  $L_d$  and coincides with an in-coming electron bunch. The resonance condition for this stimulation can be expressed as

$$nL_d = mL_b, \quad (1)$$

where  $m$  and  $n$  are integers. This condition states that when a radiation pulse has travelled  $n$  times through the cavity, it will coincide with the  $m^{\text{th}}$  incoming electron bunch.

Note that the frequency content of the STR will be the harmonics of the revolution frequency. In other words, the cavity length must be an integer multiple of the radiation wavelength. The resulting spectrum of STR therefore is a line spectrum with rather narrow spacing between lines.

### 4 CAVITY SCAN

The total cavity length is adjustable from  $7L_b$  to  $8L_b$ , where  $L_b$  is the interbunch distance ( $L_b = 10.5$  cm for our S-band linac). By varying the cavity length between  $7L_b$  and  $8L_b$ , stimulation at different resonances can be observed. A typical cavity scan is shown in Fig. 4(a). The numbers in the figure indicate the order ( $n$ ) of resonance; for example, the peak labelled “1” is the first order resonance (integer resonance or  $n = 1$ ) and the peak marked by “2” is the second order resonance (half integer resonance or  $n = 2$ ). In Fig. 4(b), we show the same scan together with the locations where we expect stimulation up to the 10<sup>th</sup> order

beam divider thickness ( $\mu\text{m}$ )	stimulation-enhancement $G_s$
127	$2.6 \pm 0.1$
76.2	$3.6 \pm 0.1$
50.8	$4.7 \pm 0.2$
25.4	$8.2 \pm 0.6$

Table 1: Stimulation enhancement with different beam divider thicknesses.

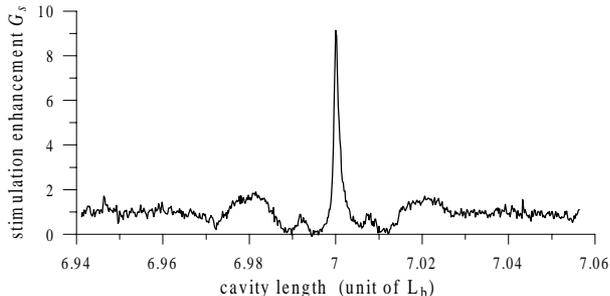


Figure 5: Maximum stimulation enhancement obtained from a cavity with a 25- $\mu\text{m}$ -thick Kapton beam divider.

resonance to occur. The scan confirms the occurrence of stimulated transition radiation. The stimulation enhancement  $G_s$  at an integer resonance for this setup is 2.5. This enhancement factor is directly related to how the energy builds up in the cavity and is limited by cavity losses [4].

## 5 STIMULATION ENHANCEMENT

To demonstrate the impact of losses in the cavity, the stimulation enhancement was measured for different thicknesses of Kapton beam dividers. The extracted energy depends on the reflection coefficient  $R$  or the reflectance  $|R|^2$  of the beam divider which varies with frequency due to thin film interference effects. Therefore, the thickness of the beam divider determines its reflectance and thus the extraction of energy in the stimulated transition radiation cavity. The coherent transition radiation spectrum at the STR experimental station is contained within  $20 \text{ cm}^{-1}$  because of the high frequency suppression from the transverse effect of a large beam size, after the beam scatters through the stainless steel window. In this frequency range, the average reflectance of a Kapton film beam divider decreases with the thickness. Therefore, decreasing the thickness of the beam divider results in a reduction of extracted energy thus reducing cavity losses. Table 1 shows the stimulation enhancement for a 127  $\mu\text{m}$ , 76.2  $\mu\text{m}$ , 50.8  $\mu\text{m}$ , and 25.4  $\mu\text{m}$  beam divider. As expected, when using thinner beam dividers to extract less radiation out of the cavity, the cavity losses are reduced, and thus the stimulation enhancement increases.

So far, the maximum stimulation enhancement at an integer resonance is achieved by using a 25  $\mu\text{m}$  Kapton beam divider. Figure 5 shows a cavity scan near an integer resonance from this setup demonstrating a stimulation enhance-

ment  $G_s = 9$ .

## 6 CONCLUSION

Stimulated coherent TR by the TR emitted by previous electron bunches is observed. The radiation pulse emitted from these previous bunches are recycled in an optical cavity. By adjusting the cavity length such that the radiation pulse coincides at the radiator with an incoming electron bunch, it can stimulate more radiation emission from the electrons. The optical cavity, consisting of metallic mirrors and reflectors, is arranged such that the circulated radiation pulses arrive with the proper polarization for the stimulation. Measuring the radiation intensity extracted from the cavity while adjusting the cavity length, we observed stimulation of transition radiation up to the  $10^{\text{th}}$  order resonance. With a 25- $\mu\text{m}$ -thick Kapton beam divider, we can obtain a factor of nine increase of the on-resonance radiation intensity over the off-resonance intensity. This implies that the STR can be developed to be a high intensity coherent far-infrared radiation source.

The cavity used in this experiment has high losses, including those from absorption in humid air, from non-perfect reflection, from mirror diffraction, and from radiation extraction. To improve the cavity performance for high radiation intensity, a better designed and engineered cavity must be considered. Such a design will have to include optical as well as microwave design features to properly treat electromagnetic radiation in this transition between both regimes. Suggestions of some cavity designs can be found in Refs [5] and [6]. Specifically, Ref [5] discusses an optical cavity with Q-switching and Ref [6] discusses a cavity suitable for diffraction radiation.

## 7 ACKNOWLEDGEMENT

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