COHERENT THZ RADIATION AT ELETTRA

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Abstract

Coherent synchrotron radiation (CSR) in the infrared has been observed at ELETTRA since the year 2005 [1] under several machine parameter settings in the SISSI beam line. Effort has been made to produce a "stable" THz signal for experimental use. The description of the machine settings to that end and the measurements performed are presented and discussed.

INTRODUCTION

A significant effort has been devoted in the last years to the production and detection of THz radiation. This range of the electromagnetic spectrum located in the spectral region 0.1-10 THz (3 – 0.03 mm, 3-300 cm^{-1}) between the microwave and the infrared region is indeed hardly accessible both to the optical and the electronic techniques commonly in use in the neighbouring ranges.

Usable synchrotron radiation is typically produced when electrons traverse the magnetic guide or insertion devices structures of a storage ring. The electrons normally travel in "bunches" with each bunch containing a large number of particles. The ratio of the radiated power P produced by multiple particles emitting synchrotron radiation over the radiated power of a single particle P_s can be written as:

$$P / P_s = N(1 - f) + N^2 f \qquad (1)$$

where N is the number of electrons and f is a longitudinal bunch density form factor [2]. For spectral ranges where f is not zero, P has a coherent term that scales as N^2 for large N. If N is very large as usually in synchrotron light sources (N ~ 10^{12} particles), the coherent part may easily dominate over the incoherent term. For N>>1 the ratio in eq. 1 becomes N(1+Nf) and the term Nf is called the coherence amplification factor. The power ratio in eq. 1 will increase and approach N with f→1 (long wavelength limit).

For a typical electron bunch with Gaussian longitudinal density function, the spectral range for coherent emission is also Gaussian with width $\omega_\sigma=1/\sigma_t$ where σ_t is the bunch length expressed in time and $f=1/\exp(2\pi\sigma/\lambda)^2$ with σ the bunch length and λ the cut off wave length. Thus a 100 ps electron bunch emits coherently for frequencies up to ~ 10 GHz. Such emission is normally not observed if the waveguide cut-off frequency of the metallic vacuum chamber is above 10 GHz (for Elettra the cut-off is at 30GHz). If however the electron bunch is short enough (i.e., 10 ps duration i.e. 0.1 THz), or a short period modulation of the bunch density can be imposed, a coherent emission at observable frequencies can occur.

Recently, it has been demonstrated that synchrotron radiation storage rings can provide a huge amount of brilliant and broadband radiation in the THz region [3]. At present, bursts of CSR have been detected at several storage rings [3-8] (MAX-I, NSLS VUV ring, ALS, MIT South Hall Ring, ANKA), while steady state CSR has been obtained only at BESSY (and very recently also at ANKA), when the optics is tuned to obtained the so-called "low-alpha" mode [9, 10] with however very low charge/bunch intensities.

Since the summer of 2005 the Accelerator group at Elettra has started a rigorous program to establish operation conditions providing stable and controllable THz radiation. The properties of the coherent THz emission were characterized at the large acceptance angle IRSM beam line, SISSI, at the bending magnet section B 9.1 [11]. In fact the IR beamline has two branches equipped with appropriate instrumentation and detection systems for future expansion into rapidly evolving research fields enabled by the high power THz radiation.

THZ PRODUCTION

In general strong CSR signal produced in a dipole magnet is observed when the electron bunch length σ (or a density modulation inside it) is comparable or shorter than the CSR critical length $\sigma_c = \lambda_c/2\pi$ where λ_c is the cut-off wavelength [2,12]:

$$\lambda_c = \sqrt{\frac{4h^3}{\rho}} \qquad (2.a) \qquad\qquad \lambda_c = \sqrt{\frac{6h^3}{\pi\rho}} \qquad (2.b)$$

h is the full vertical aperture of the vacuum chamber at the radiation extraction port and ρ the bending radius. The equation 2.a considers also the bending magnet vacuum chamber curvature whereas 2.b is for vanishing curvature. The above relations comprise the two necessary conditions for a strong CSR production namely the cut-off condition and the maximum interference effect coming from the density form factor of equation 1 (i.e. when 2πσ/λ→1) while in general $\sigma \ll \sigma_s = \sigma_c(\ln N)^{1/2}$ where σ_s defines the upper limit for a detectable coherent signal (weak coherence).

For Elettra σ_c = 0.88 mm (0.61 mm for vanishing curvature) and σ_s ~ 3 mm, whereas the natural bunch length at 2 GeV is 5.6 mm. Thus, in order to have coherent emission the electron bunch length should

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therefore be less than 3 mm and for strong emission even shorter, namely 0.88 mm or less. Moreover, the machine having neither the flexibility to easily change the momentum compaction α nor performing full energy injection (for the lack until 2007 of a full energy injector, restricting the maximum injection energy to 1 GeV) obliged us to experiment at lower energies using the strong energy dependence ($\sigma \approx E^{2/3}$) on the natural bunch length. Indeed for Elettra we have:

Table 1: Natural bunch length vs. Energy at Elettra

Energy (GeV)	**Bunch length**
2	5.6 mm
1	1.9 mm
0.75	1.3 mm
0.6	0.9 mm

It is clearly evident from Table 1 that energies at or below 1 GeV fulfil the weak coherence condition. Therefore, Elettra was set at 700 GeV and some weak coherence signal was already observed in 2005. However it was soon evident that much shorter electron bunch lengths were required for a strong signal. Fixing the machine working point energy at 900 MeV we tried to perturbate the bunches creating thus micro bunching structures with longitudinal scales of the order of 0.9 mm. Immediately huge coherent signal bursts were observed as shown in Figure 1 with a beam filling of about 13%. Here by increasing the ring current above 30 mA, a broad feature grows fast at wavelengths < 20 cm^{-1}(ω=0.6 THz or λ=0.5 mm).

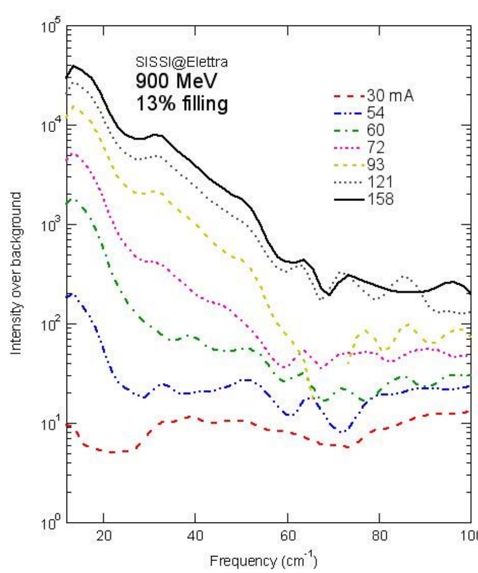

Figure 1: CSR emission spectra in the THz range at different multi bunch currents (2006)

The increase in intensity of this spectral feature with the ring current is accompanied by a continuous broadening until current of 158 mA where the cut-off frequency reaches the values 50 cm^{-1}. The intensity gain with respect to the global conventional source was by more than two orders of magnitude, compared to a factor of 10 for the incoherent regime, which provides unambiguous evidence for coherent emission in the THz range. The spectral emission at several bunch fillings (95% and 13% of the total 432 available buckets) and in the 4-bunch operational mode was further characterized in order to get better understanding of the mechanism creating the observed coherent emission. Figure 2 shows the dependence of integrated intensity between 5 and 25 cm^{-1} on the single bunch current. In all cases a strong non-linear enhancement of the THz spectral weight is observed above a certain current threshold value. Both at 13% filling and in the 4-bunch mode the current threshold (see arrows in Fig. 2) is found around 1 mA/bunch which corresponds to the microwave threshold current per bunch for longitudinal ring impedance of 0.15 Ohm. The fact that the THz signals were observed around 1 mA/bunch at 0.9 GeV is a clear evidence of the role of the instability in the generation of the CSR in this case.

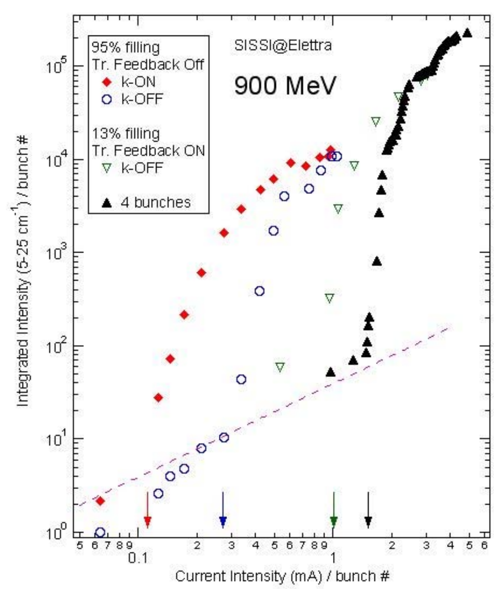

Figure 2: Integrated spectral intensity of the THz emission for different filling conditions.

At 95% filling (i.e. < 1 mA/bunch) in order to obtain CSR it was necessary to excite the electron beam either by switching off the transverse feedback, thus rendering the beam unstable, or by activating the injection kickers creating both deformations and density modulations of the bunch.

In the 4-bunch mode, huge coherent signals were again measured for currents >1 mA/bunch. Attempts to combine this with the normal Elettra SR-FEL operations have shown that, as expected, the lasing suppresses the CSR signal due to FEL induced Landau damping. On the other hand, since the laser is pulsed, CSR bursts seem to occur at complimentary time intervals i.e. when the laser is in relaxation. Further experiments are scheduled and many interesting measurements are planned, provided the proposed femto-slicing FEL experiments get funded.

Next step was to investigate the steady state CSR. The machine was set to energies where the corresponding bunch lengths (~1mm) are much less to the necessary for weak CSR emission. However, in both 700 and 750 MeV no steady state was observed but instead very strong signals of pulsed CSR were measured for currents < 0.3 mA/bunch (the microwave limit there is 0.36 mA/bunch) when rendering the beam unstable. It is interesting to note that stabilizing the beam resulted in strong reduction of the CSR signal (see Figure 3).

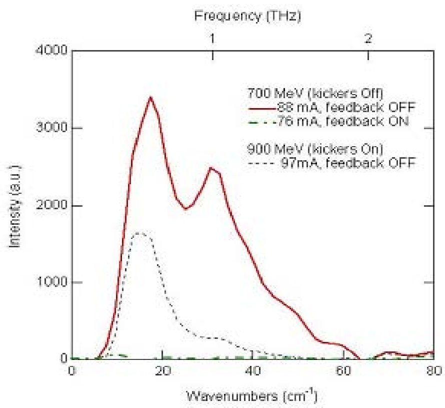

Figure 3: Coherent bursts at 700 MeV

The coherence intensity dependence on energy is shown in Figure 4. It becomes clear that above 1.2 GeV the coherent signal is strongly reduced even if externally excited by the kickers.

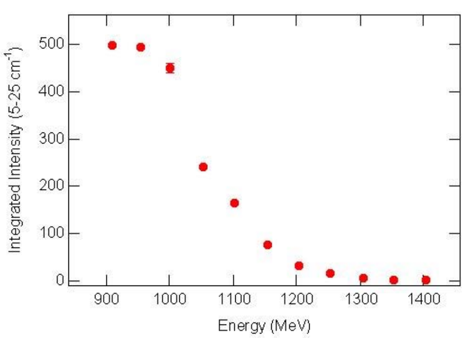

Figure 4: Energy dependence of the coherent signal

A quasi periodic bursting at about 100Hz was observed (see Figure 5) for a high single bunch current of about 9.5mA when operating in single bunch at 1.1 GeV, clearly created by the low frequency instability oscillation mechanism.

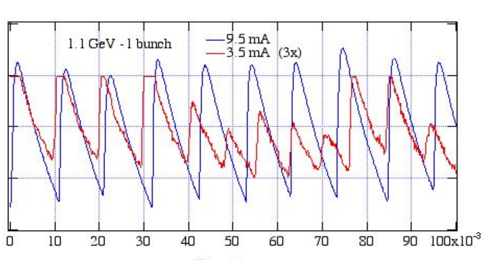

Figure 5: Quasi periodic bursts are observed for a 9.5mA single bunch at 1.1 GeV.

Streak camera acquisition, (see Figure 6) reveals the presence of a 5-ps micro structure (1.5 mm) which can be the main responsible for the observed CSR.

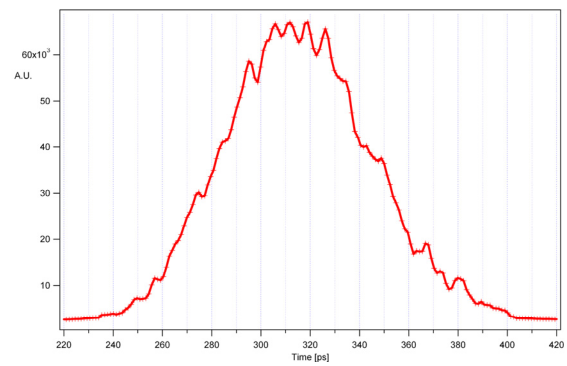

Figure 6: Single bunch longitudinal profile with 9.5mA acquired by the streak camera.

DISCUSSION

Strong pulses of THz radiation can be produced at Elettra by reducing the machine energy and introducing strong charge density modulation inside the bunches. As expected CSR is observed even if the nominal bunch length is longer than the one defined by the critical length.

Another option to induce CSR emission could be to add to the low-energy operational mode a “low-alpha” optic, although the latter requires significant modifications of the present machine lattice.

Finally a detailed characterization of the radiation so far obtained is needed in order to understand its utility for experiments. For example, for eventual applications requiring pulsed CRS, one can investigate CSR at higher energies by modulating the bunch density. This can be well suited to a wide variety of pump-probe experiments.

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