COHERENT THz MEASUREMENTS AT THE METROLOGY LIGHT SOURCE

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Abstract

The Metrology Light Source (MLS) [1] is the first storage ring optimized for THz generation [2]. It applies a bunch shortening mode, based on a flexible momentum compaction factor 'α' optics. The short bunches emit coherent THz radiation. We report on measured THz signals as a function of different machine parameters. Two type of measurements are presented in this paper. The first part presents THz bursting thresholds for a variety of ring parameters compared with theoretical predictions and similar results achieved at BESSY II. The second part discusses an example of a special machine tuning, where the coherent THz signal suddenly and unexpectedly vanishes. Some measurements are shown to demonstrate this effect, a physical explanation is missing.

INTRODUCTION

Electron bunches can emit coherent THz radiation, if they are sufficiently short compared with the wavelength of the emitted radiation and if this wavelength is shorter than the cut off wavelength of the vacuum chamber. THz signals at the MLS are detected in the range from 2 cm^{-1} to more than 33 cm^{-1} (= 1THz). These signals are very sensitive to the machine tuning, their power could vary by some orders of magnitude. Depending on several parameters, the emitted radiation could be of cw character below a current threshold, modulated only with the bunch repetition rate. This is called a stable emission process. At higher currents, above the current threshold, THz signals are stochastically emitted in bursts. At the transition from stable to unstable emission the temporal appearance of the THz radiation is of periodic character, with repetition rates in the order of the synchrotron oscillation frequency f_s [3].

As a result of the interaction of the bunch with its own synchrotron radiation field, the bunch becomes unstable by a loss of Landau damping, [4] and [5, 6]. An example of this stability transition at 629 MeV and 0.5 mA single bunch current is shown in Fig. 1, where the frequency of the temporal THz emission pattern as a function of the applied rf-voltage is shown. The intensity of the signal is indicated by a colour code. Below 300 kV no signal is detected, above 300 kV a clear periodical signal arises at 15 kHz and shifting with the voltage.

At the instability threshold bunch length and bunch current are related by

$$(\sigma_0 c)^{7/3} = \frac{c^2 Z_0}{2\pi F 3^{1/3}} I\rho^{1/3}/(V f_{rf} f_{rev}), \qquad (1)$$

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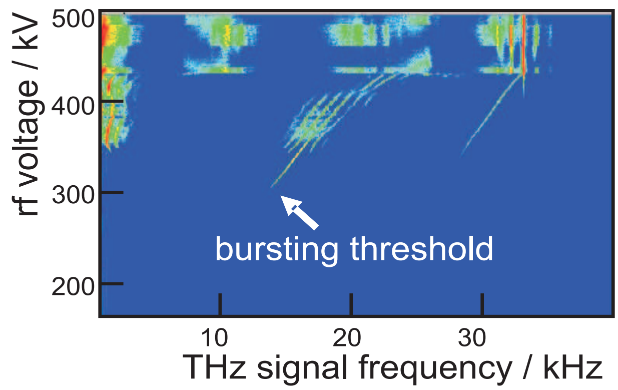

Figure 1: MLS THz signals at the bursting threshold. Vertical axis: applied rf-voltage amplitude, horizontal axis: frequency of the detected THz signals. The colour indicates the THz signal intensity.

where σ_0 is the bunch length, I the single bunch current, c the speed of light, Z_0= 377 Ω the free space impedance, F= 7.456 a form factor, ρ the dipole bending radius, V the cavity voltage, f_{rf} the rf-frequency and f_{rev} the revolution frequency. For BESSY II, a consistent set of calculated values satisfying this equation are $\rho_B = 4.25m$, f_{rfB}= 500 MHz, f_{revB}= 1.25 MHz, V_B= 1.4 MV, I_B= 1 mA and σ_{0B}= 8.7 ps. The bunch length σ_0 is here defined as the calculated, rms, zero current bunch length without any coupling effects into the transverse planes. To compare thresholds at different machine parameters, a scaled current $\tilde{I}$ can be introduced

$$\tilde{I} = (I\rho^{1/3}/(V f_{rf} f_{rev}))/(I_B \rho_B^{1/3}/(V_B f_{rfB} f_{revB})) \quad (2)$$

As shown in Fig. 1, the increasing voltage does destabilize and not stabilize the bunch at a fixed bunch current. By applying the formulas for the threshold, this can be confirmed. With increasing voltage also f_s increases, stabilizing the bunch. But more dominating is the resulting bunch shortening, which increases the effective peak current and finally the bunch become unstable.

Short electron bunches can be easily produced in the MLS by the low α optics tuning, expected values of σ_0 can be <1 ps. These short bunches emit coherent THz radiation, which can be observed at an IR and a THz beam line of 43 x 65 mrad^2 acceptance [7]. Fast and slow detectors are available to detect the radiation.

THz BURSTING THRESHOLDS IN THE MLS

The machine parameters of BESSY II and MLS are quite different, which makes a comparison between the data more interesting. Some of the machine data are listed in Tab. 1. A plot of the theoretical bursting threshold calculation is shown in Fig. 2 with the calculated bunch length σ_0 indicated on the vertical axis and the scaled single bunch current $\tilde{I}$ on the horizontal axis. Theoretical results are plotted as a blue line, BESSY II results are shown as triangles [8]. Only 3 out of 5 points are shown, the two missing points are out of the figure but all follow the blue line in good agreement. There is a difference in the σ_0 values and the measured bunch lengths. From streak camera measurements [9] it is found, that at the bursting threshold the bunches are 1.5 times longer than the σ_0 value, following the black dotted line. This additional lengthening is probably caused by a potential well effect. The theory [4] does not include a bunch lengthening. For a variety of machine parameters bursting current thresholds are measured at the MLS. Streak camera data from the MLS are not yet available, therefore the calculated σ_0 is applied. In the example of Fig. 1 the threshold is well detected, but it is not always clearly detectable. The parameter variation includes a single bunch current from 0.35 mA to 1.7 mA, a cavity voltage from 40 kV to 550 kV, and beam energies of 450 MeV (full circles) and 629 MeV (open circles). These machine settings were scaled as discussed above and plotted in Fig. 2. Differently coloured circles indicate different machine shifts. The data follow fairly well the red, dotted line.

Table 1: Main MLS and BESSY II User Optics Parameters

parameter	MLS	BESSY II
beam energy / MeV	105 to 629	1700
circumference / m	48	240
rf-frequency f_{rf} / MHz	500	500
harmonic number	80	400
rf-voltage V / kV	320	1500
dipole bend. radius / m	1.53	4.23
dipole vacuum chamber full height / mm	50	50

There is a systematic difference in the data with respect to the theoretical line. For a given bunch current, the σ_0 values have to be reduced by a factor 1.4 to match the measured data and to get agreement, indicating the effect of a bunch shortening (inductive) impedance. Several points are deviating from the linear plot, we expect that these are results from not sufficiently accurate measurements. From the general trend we expect deviations for longer bunches, when the vacuum chamber impedance becomes more involved. Even ion trapping might be involved, it was shown in [2] that trapped ions could strongly change the emitted THz power and might influence the bursting threshold.

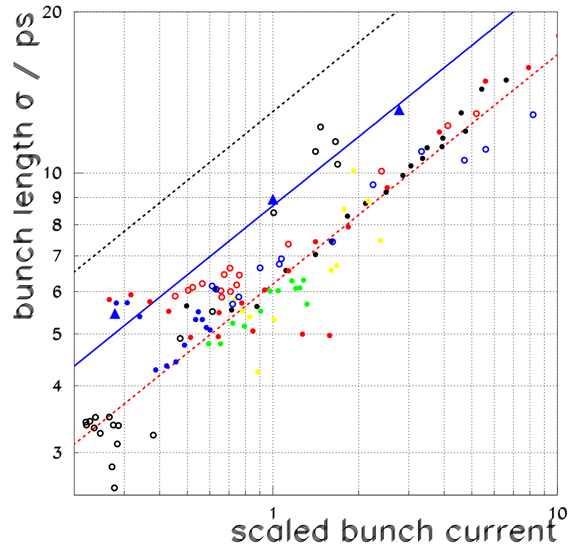

Figure 2: Scaled bursting threshold current $\tilde{I}$ and bunch length σ_0. Blue line: theory; blue triangles: BESSY II data; circles: MLS data. All data are measured with a liquid He cooled InSb detector of one MHz frequency response.

THz SIGNALS AS A FUNCTION OF RF VOLTAGE

In the second set of experiments THz radiation is generated in a low alpha optics at 250 MeV. The machine was tuned to f_s=10 kHz at 250 kV and α = 0.0002, corresponding to σ_0 = 0.5 ps. The THz signal at the exit of the THz beam line was detected with a room temperature DTGS detector of few 10 Hz frequency response (Fig. 3) or alternatively with a liquid He cooled Ge detector of few kHz response (Fig. 4). From the general scaling conditions of the bursting threshold, it can be shown, that an increase in rf-voltage shortens the bunch and drives the bunch into a more unstable situation, see also Fig. 1. In any case, more THz power is expected. This is in general true and was verified in many measurements.

However, with the machine settings discussed here, there is a situation when the THz signal instantly falls back to the level of the incoherent intensity above a threshold voltage amplitude. This is shown in Fig. 3, where as a function of time the rf-voltage is scanned between 100 kV and 430 kV, per cycle it takes about 45 minutes. Several beam parameters are recorded during these scans. Fig. 3 (left) shows for example the rf-voltage (blue line), the multi bunch current (green) decaying from 3.8 mA to 0.5 mA and the THz signal intensity (red). Depending on the bunch current the THz signal power vanishes above a threshold voltage, typically about 300 kV. This becomes visible in the last two rf voltage scans in the time range from 155 minutes to 169 minutes and 200 minutes to 220 minutes. First indications of this effect are already visible at the peak voltage values in the first 3 voltage scans, where the THz drops down for some few points. Some of the signals within the small black box are shown enlarged in Fig. 3 (right), the horizontal beam position and the THz signal. These data are taken close to the voltage, where the THz signal becomes suppressed, at 168.7 minutes. Both signals show an oscillation of about 20 s per cycle. The change in horizontal beam position ranges from -20 μm to 30 μm. The reason of this oscillation is not clear. During the rf voltage scan the orbit deviations are of dispersive character and the orbit is controlled by an automatic feed back of the rf frequency on a one second time scale. In this limited voltage range where these oscillations appear, it seems to be difficult to stabilize the orbit. Also the THz signals become extremely sensitive to the orbit. Orbit position and beam size are recorded with the beam size monitor discussed in [10].

In a different measurement, recorded about half a year earlier, THz signals where taken with a Ge detector. These results are shown in Fig. 4. Some more beam parameters are shown, like beam position (horizontal pos-x and vertical pos-y), beam cross section (FWHM-x, FWHM-y) in both planes. The THz signal modulation goes together with modulation in beam position and cross section. The change in position is about 50 μm, the change in cross section is about 5 %, and a 50 % gain in life time during the suppression of THz radiation. This life time gain indicates a bunch lengthening. A similar, but less pronounced behaviour is observed at 350 MeV.

The optics in these measurements is tuned to small chromaticities in all three planes. This experiment was repeated with a single bunch of about 6 μA and a Ge detector to record the THz radiation. The results show the same appearance (data not shown). Ion trapping in a single bunch is very unlikely, which excludes a trapped ion induced effect. From the theoretical estimate the bursting threshold should be at 10 times larger currents. The increased voltage required to provoke this effect indicates, that the bunch current is driven in an instability which blows up the bunch length and coherent THz radiation becomes suppressed. This is supported by the fact, that the life time improves when the THz signals become suppressed. An explanation of this effect is missing.

FUTURE PLANS

A streak camera is installed and will be used for bunch length measurements. These results should complete some of the missing information on beam properties in the MLS.

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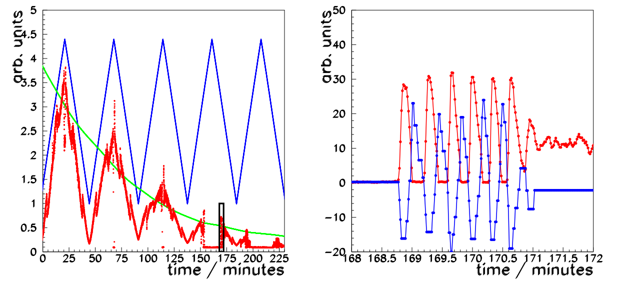

Figure 3: Rf-voltage scans and THz signals as a function of time (horizontal axis). Left: THz signals (red), rf-voltage (blue) and beam current (green). The data inside the small black box are shown in the right part of the figure: horizontal orbit position (blue) and THz signal intensity (red) are oscillating during the voltage scan.

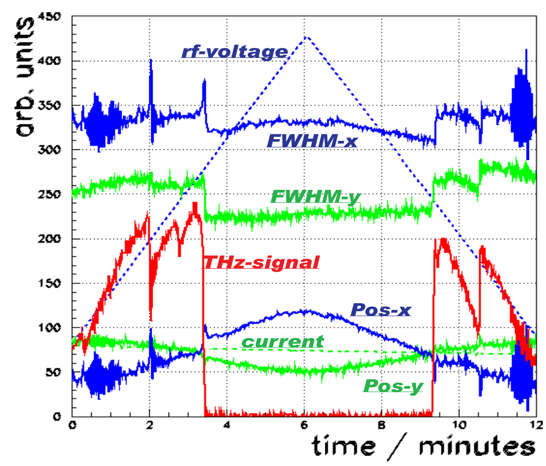

Figure 4: Rf-voltage (amplitude on vertical axis), THz signals, orbit position and beam size are indicated in the figure as a function of time (horizontal axis). The THz signal is suppressed between 3.5 minutes and 9 minutes.

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