# COMPARISON OF DIFFERENT APPROACHES TO DETERMINE THE BURSTING THRESHOLD AT ANKA

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## *Abstract*

The synchrotron light source ANKA at the Karlsruhe Institute of Technology provides a dedicated low-$\alpha_c$-optics. In this mode bursting of Coherent Synchrotron Radiation (CSR) is observed for bunch charges above a threshold current that depends on beam parameters. This threshold can be determined by several approaches, e.g. bunch lengthening or changes in the THz radiation spectra. This paper compares different methods and their implementation at the ANKA storage ring outlining their advantages, disadvantages and limitations, including reliability and possibility of real time analysis.

## INTRODUCTION

Besides regular CSR emission, one can observe outbursts of radiation for certain beam parameters. Although it is often seen as an instability limiting beam parameters, it could also play a role in improving storage rings as THz sources. To do so, understanding the process is a key requirement. One important step towards this goal is the clear determination of bursting thresholds.

Bursting can be explained by the wake-field acting back on the bunch itself: In the bending magnet emitted waves from the tailing electrons can catch up with the leading electrons and interact with them. Besides the defining synchrotron radiation bursts this may lead to bunch lengthening [1] and to fluctuations in the bunch length [2].

Table 1: ANKA machine settings

| | |
|---|---|
| Circumference | 110.4 m |
| $f_{rev}$ | 2.715 MHz |
| $f_s$ | 13 kHz |
| $V_{RF}$ | $4 \times 450$ kV |
| Energy | 1.3 GeV |
| Filling pattern | single bunch |
| Current range | $0.15\,\mathrm{mA} < I < 2.0\,\mathrm{mA}$ |

Since all measurements mentioned in this paper were carried out with one single bunch inside the ANKA storage ring, interaction between different bunches does not have to be taken into account. The most important parameters used are shown in Table 1.

## BURSTING MEASUREMENTS

### *Experimental Setup*

One method to determine the bursting threshold is to measure the emitted CSR power. We use two ultra-fast detectors for THz radiation that also allow to resolve the bursts' time structure. The first is a Hot Electron Bolometer [3] (HEB, FWHM pulse width $< 165$ ps), the second a Schottky diode [4] (FWHM pulse width $\approx 130$ ps). For this paper, the peak signal of both detectors is logged for 500 000 consecutive turns for every current step .

To investigate the bunch length and longitudinal profile we mainly use a streak camera (see Table 2). Recently, electro optical spectral decoding methods to measure the bunch length in a single shot have become available [5]. For this paper, all bunch lengths were obtained from streak camera data.

Table 2: Streak Camera

| | |
|---|---|
| Manufacturer | Hamamatsu |
| Model | C5680 |
| Plugins | synchroscan, dual sweep |
| Time Resolution | 0.37 ps |
| Point spread (RMS) | 1.40 ps |

The images taken by the streak camera are evaluated by SCIRAS, a custom made software, that distinguishes different bunches, discriminates noise and is able to detect synchrotron oscillations. Using parallelization (OpenCL) it can automatically track information on length and longitudinal position of the electron bunch and also display these information in real time. We determined the point spread function by measuring the signal of a 50 fs-laser pulse (instead of synchrotron radiation). The resulting value of $l_{PSF} = 1.40$ ps is treated as a constant error on the bunch length measured by the streak camera $l_{SC}$, thus:

$$l_i = \sqrt{(l_{SC,i})^2 - (l_{PSF})^2} \qquad (1)$$

Where $l_i$ is the bunch length resulting from the $i$-th image. The final values are obtained by taking $N = 100$ consecutive streak camera images, each with a slow sweep duration of 500 $\mu$s. The resulting bunch length $\bar{l}$ is the average of those measurements. Since the bunch length is not constant, the standard deviation $\mathrm{SD}(l) = \frac{1}{N-1}\Sigma_i^N \left(\bar{l} - l_i\right)^2$ is considered as the bunch length fluctuation.

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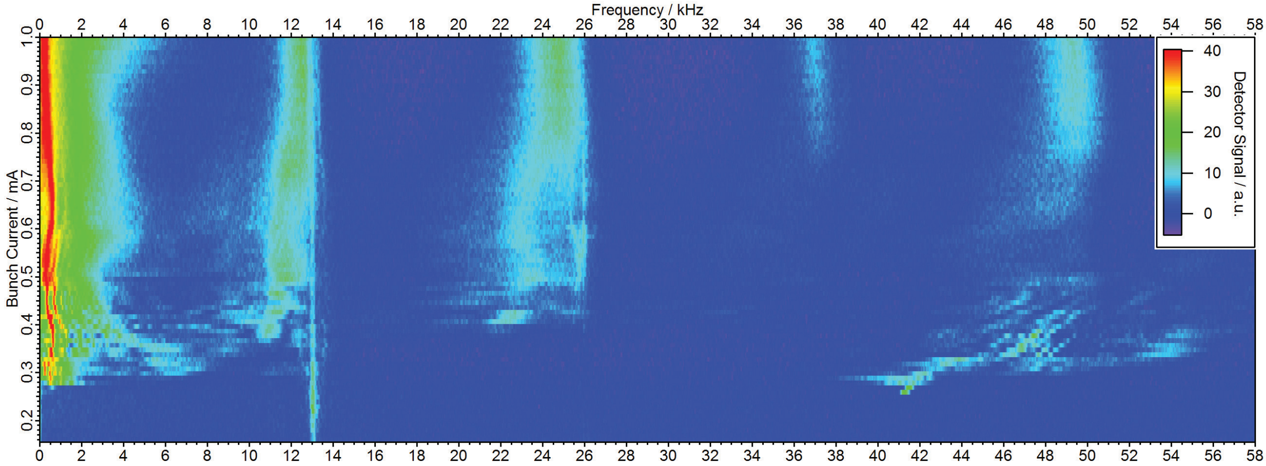

Figure 1: Spectrum resulting from FFT of time domain data. Rainbow colorcode stands for intensity of frequencies in arbitrary units (red: maximum, blue: minimum). Higher currents are not shown, since no change is observed. The line at 13 kHz can be identified with the synchrotron frequency $f_s$.

### *Measurement Results*

As a first approach, we take the FFT of the HEB time domain data. Figure 1 shows the resulting spectogram. Using this method we observe different bursting regimes. For currents below $0.23\,\mathrm{mA}$ there is *steady state emission*. In this region, $f_s$ is the only frequency appearing in the spectogram. *Regular bursting* starts at $0.23\,\mathrm{mA}$ and exists up to $0.27\,\mathrm{mA}$. For currents above this value the relatively sharp line at about $41.5\,\mathrm{kHz}$ that defines this bursting regime starts to spread out. So we refer to the the next mode as *spread bursting*. It exists up to about $0.52\,\mathrm{mA}$. The next regime (starting at $0.34\,\mathrm{mA}$) is marked by the appearance of modulation bands of $f_{burst} \approx 12\,\mathrm{kHz}$. This *resonant bursting* persists up to the highest measured current of $2\,\mathrm{mA}$. A possible explanation for these regimes can be found in [6].

Indirectly looking at the beam using incoherent radiation and a streak camera, one result is that the bunch length grows with current (Fig. 2). Furthermore, the fluctuation of the bunch length, defined by the standard deviation, has a peak at about $0.5\,\mathrm{mA}$ and a local minimum at about $0.52\,\mathrm{mA}$. For higher currents the fluctuations grow stronger. The low statistics resulting from a few data points taken for currents higher than $1.5\,\mathrm{mA}$ suggests that the fluctuations drop again. The rise for very low currents can be explained by a bad signal to noise ratio.

The bunch lengthening seen in Fig. 2 can be used to determine the bursting threshold: Regular bursting starts when the current satisfies [7]

$$k \times I^{3/7} > \sigma_{z,0} \tag{2}$$

with the optics-dependent constant $k$, the bunch current $I$ and the natural bunch length $\sigma_{z,0}$. For currents considerable above the bursting threshold the left hand side of (2) gives the bunch length. On the other hand $\sigma_{z,0}$ is reached at very low currents. Therefore, $k$ and $\sigma_{z,0}$ can usually be obtained with the streak camera. One way to do so is to fit the (empirical) function

$$\sigma_z(I) = \sqrt[4]{\left(k \times I^{3/7}\right)^4 + \left(\sigma_{z,0}\right)^4} \tag{3}$$

to the measured bunch lengths. This function is constructed in a way that at it converges to the left/right hand side of (2) for high/low currents. We obtain: $k = (7.82 \pm 0.01_{stat} \pm 0.14_{syst})\,(\mathrm{ps} \times \mathrm{mA}^{-3/7})$ and $\sigma_{z,0} = (3.82 \pm 0.02_{stat} \pm 0.29_{syst})\,\mathrm{ps}$ with $\mathrm{cov}(\sigma_{z,0}, k)_{stat} = -0.56$ and thus:

$$I_{th} = (0.19 \pm 0.06_{stat} \pm 0.03_{syst})\,\mathrm{mA}$$

This result is compatible with the threshold obtained by the spectogram in Fig. 1. The accuracy of this method to determine the onset of regular bursting is usually limited by extrapolation which manifests in the covariance of the fit parameters. But even if there are measurements carried out for very low currents, this method has two disadvantages: It does not allow to detect bursting on-line, and it is insensitive to other thresholds.

In [2], it has been shown that oscillations of the bunch length show the same periodicity as the measured bursts. This suggests that the amplitude of bunch length fluctuations $\mathrm{SD}(l)$ might be connected to the intensity of bursts. To quantify this we look at the standard deviation of data aquired by the THz radiation detectors; this is displayed in Fig. 2. The values show a step at about the onset of spread bursting at $0.27\,\mathrm{mA}$. The HEB curve then rises slightly with the current until it drops for higher currents. Since this detector is optimized for very low signal, this drop can be explained by saturation. In general the data aquired by the Schottky diode shows a similar behavior but reaches a plateau wich lasts from $0.45\,\mathrm{mA}$ to $0.6\,\mathrm{mA}$ before it slowly drops.

Comparing the bunch length fluctuations $\mathrm{SD}(l)$ to the intensity of bursts $\mathrm{SD}(HEB)$ and $\mathrm{SD}(Schottky)$, there are

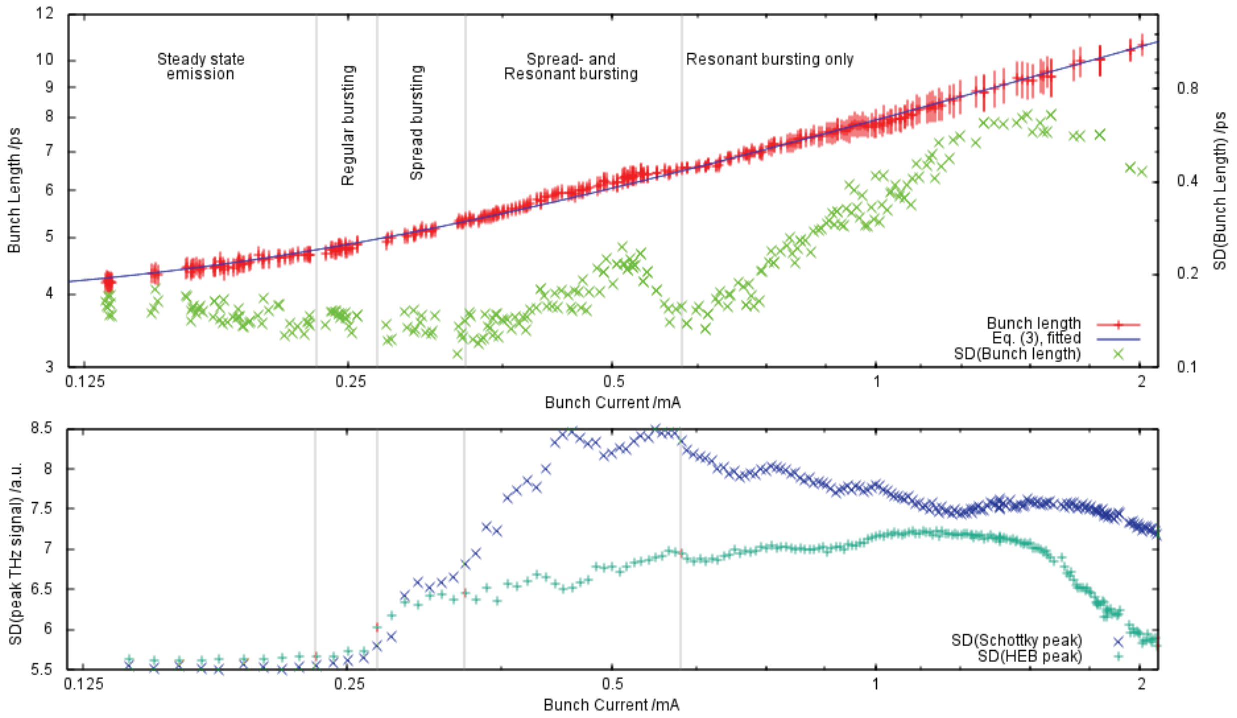

Figure 2: The upper plot shows the bunch length measured with the streak camera over current and a fit of Eq. 3 to this data (blue, continuous line). To give a better impression for the development of bunch length fluctuations, the standard deviation of the measurements is not only shown in the error bars but also shown as individual points. Systematic error due to binning is $0.1\,\mathrm{ps}$ on both axis. The lower plot shows the standard deviation of the peak THz signal over the same horizontal axis as the upper plot. Thresholds obtained from Fig. 1 are included as reference.

some features they have in common: Coming from low currents there is a baseline before the first rise. This rise is at the start of spread bursting for fluctuations of THz radiation and at the start of resonance bursting for bunch length fluctuations. Furthermore, there is a maximum at about $0.5\,\mathrm{mA}$ and a drop for the highest currents measured. Both SD($l$) and SD($Schottky$) show a change in behavior at about the end of spread bursting. Nevertheless, the three curves are far from parallel and so it is not clear whether bunch length measurements can be a tool to determine any of the other thresholds besides the onset of regular bursting.

## CONCLUSION

Bolometric methods and methods using bunch length information obtained by a streak camera have been used to qualitatively describe bursting behavior. It has been shown that spectrograms obtained by the HEB or the Schottky diode indicate multiple thresholds between different bursting regimes. The bunch length itself can only be used to determine the onset of the regular bursting regime; however there might be a possibility to link changes in bunch length fluctuations to transitions between the different regimes.

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## REFERENCES

[1] M. Klein et al. “Studies of Bunch Distortion and Bursting Threshold in the Generation of Coherent THz-Radiation at the ANKA Storage Ring”, PAC 2009, FR5RFP095

[2] Y.-R. E. Tan et al. “Low Alpha Configuration For Generating Short Bunches”, PAC 2009, TH6PFP009

[3] A. D. Semenov et al. “Monitoring Coherent THz-Synchrotron Radiation with Superconducting NbN Hot-Electron Detector”, Proceedings of IRMMW-THz 2009

[4] Advanced Compound Semiconductor Technologies GmbH, Merckstr. 25, D-64283 Darmstadt, Germany; www.acst.de

[5] N. Hiller et al. “Electro-Optical Bunch Length Measurements at the ANKA Storage Ring”, IPAC 2013, MOPME014

[6] V. Judin et al. “Bursting Patterns of Coherent Synchrotron Radiation in the ANKA Storage Ring”, IPAC 2013, WEPEA011

[7] N. Hiller et al. “Status of Bunch Deformation and Lengthening Studies at the ANKA Storage Ring”, IPAC2011, THP021