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SPLIT-RING RESONATOR EXPERIMENTS AND DATA ANALYSIS AT FLUTE

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Abstract

FLUTE (Ferninfrarot Linac- Und Test-Experiment) is a compact linac-based test facility for accelerator and diagnostics R&D located at the Karlsruher Institute of Technology (KIT). A new accelerator diagnostics tool, called the Split-ring resonator (SRR), was tested at FLUTE, which aims at measuring the longitudinal bunch profile of fs-scale electron bunches. Laser-generated THz radiation is used to excite a high frequency oscillating electromagnetic field in the SRR. Electrons passing through the 20 µm × 20 µm SRR gap are time-dependently deflected in the vertical plane, leading to a vertical streaking of the electron bunch. During the commissioning of the SRR at FLUTE, large series of streaking attempts with varying machine parameters and set-ups were investigated in an automatized way. The recorded beam screen images during this experiment have been analyzed and evaluated. This contribution motivates and presents the automatized experiment and discusses the data analysis.

INTRODUCTION

The technically valuable THz light can be created by electron accelerators in an unmatched intensity by the Coherent Synchrotron Radiation (CSR) [1] effect. This effect requires a bunch length as short as the desired radiation wavelength. The development of techniques for creating and diagnosing such short bunches is of great interest. The SRR is designed for the measurement of the electron bunch length with a fs-resolution.

The SSR has been installed and evaluated at FLUTE [2] (KIT, Germany). In this experiment, the RF photo-injector created electron bunches of 10 pC with 5 MeV. A solenoid focuses the bunch onto the SRR gap, after which the bunches are drifting 1 m further downstream to a YAG screen. Simultaneously, a THz laser pulse excites an electric field that oscillates vertically with 240 GHz inside the 20 µm times 20 µm SRR gap. Consequently, while the bunch passes through the SRR gap a vertical kick is applied with the kick direction and strength changing within the passing time. This principle is sketched in Fig. 1. The bunch then produces a streaked image on the YAG screen, where the bunch length can be resolved from the vertical beam size.

EXPERIMENTAL CHALLENGES

To identify the streaking effect, ideally we would compare screen images of consecutive bunches with and without the influence of the streaking field. Blocking the incident THz laser pulse prevents the cause of streaking without affecting the rest of the experiment. However, the pointing stability before FLUTE's major upgrade [3] is insufficient for comparing individual images, see Fig. 2.

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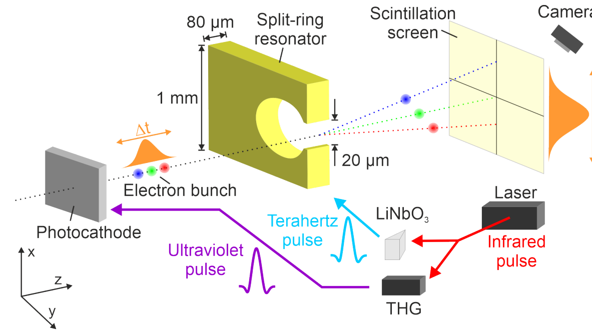

Figure 1: Working principle of the SRR experiment, in the middle the SRR with its gap of 20 µm × 20 µm × 80 µm.

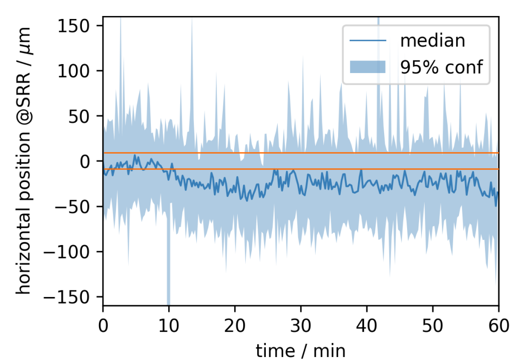

Figure 2: Bunch stability at SRR position, horizontal bunch position over 1h with 95% confidence level spans 100 µm. The orange lines refers to the 20 µm SRR gap size.

As a countermeasure, the bunch size was chosen larger than the SRR gap size. In addition, we did not only compared single screen images, but averaged over 50 shots, which provided much more stable images. The screen image in Fig. 3 shows the shadow of the SRR averaged over images generated by 50 electron bunches to ensure that the bunch indeed hits the SRR gap. With such a large beam size, only the bunch core travels through the SRR gap and is able to show streaking when unblocking the THz laser pulse. In theory this should be a sufficient change to be visible. However, manually observing averaged images, no streaking signal could be detected.

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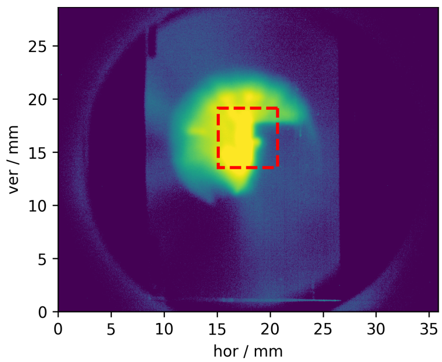

Figure 3: The YAG image shows the average of 50 frames of bunches, the c-shaped SRR blocking the beam.

2D SCAN EXPERIMENT

A detailed evaluation of the experimental setup has identified two mandatory conditions for successful streaking. First, the temporal synchronisation between the incident THz pulse and the electron bunch. And secondly, the spatial aiming of the THz pulse at the resonator, which influences the power coupling and finally the strength of the streaking field. Although both parameter were aligned carefully [4, 5], a systematic error cannot be excluded with certainty. A 2D scan was set up around the assumed correct alignment in both parameter axes, the scan progress is shown in Fig. 4.

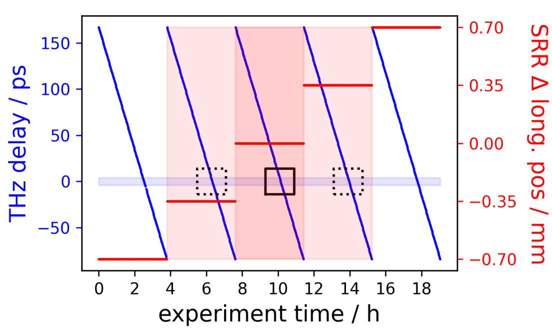

Figure 4: Parameters of the temporal-spatial 2D scan during a 20 h experiment. The light shades indicate a possible window for streaking per parameter. Their overlap is indicated by the black (dashed) boxes.

1st Axis: THz Delay

To manipulate the temporal synchronisation, the THz laser pulse was delayed by extending the path of the drive laser. After the THz laser pulse reaches the SRR, the streaking field builds up and then decays within only a few cycles. Therefore, a bunch is only affected by the THz pulse if the synchronisation is within a narrow window of 8 ps around an ideal synchronization.

The whole scan range considers 250 ps in 188 steps around the assumed ideal configuration of 0 ps. The 8 ps window spans 6 out of 188 scan steps, it is sketched in Fig. 4 by the horizontal light blue bar. Streaking is therefore only possible within 6 consecutive scan steps during each loop of the THz delay.

2nd Axis: Longitudinal SRR Position

A misplaced longitudinal (in electron flight direction) position of the SRR shifts the resonator perpendicular to the exciting THz laser pulse. A misalignment leads to a reduced intensity of the streaking field and eventually to a reduced vertical streaking in the beam screen image.

The THz pulse is focused to a waist diameter (FWHM) of $d \approx 1$ mm. During the scan, the SRR is moved by a motorized stage two steps around the pre-aligned position with 350 µm step width, see Fig. 4 in red.

The correct alignment is assumed to have an ideal coupling of the THz pulse and consequently to the full streaking amplitude on the beam screen. A misalignment of 350 µm already leads to a reduced THz intensity at the resonator and finally to a reduced streaking amplitude. The attenuation here is yet unknown. A misalignment of 700 µm or even more will most certainly prevent measurable streaking.

In the scan plot the light red box shows a window of a possible correct alignment. The adjacent two lighter red boxes show where streaking might be possible with an attenuated amplitude due to a 350 µm misalignment. The spacing between these clusters is roughly 4 h.

Combining the expectations for both axes leads to only one region in the scan that satisfies the criteria of both, temporal and spatial aiming. This forms the main cluster of six consecutive data points that show streaking with the full amplitude, shown by the solid black box in Fig. 4. Depending on the attenuation level of a 350 µm misalignment, streaking might also be detectable in the two adjacent, dashed clusters, again with 6 consecutive scan steps.

Finally, the position of the black (dashed) boxes indicate where streaking is expected, given that the pre-aligned timing and position are correct. Else this expectation pattern of main and secondary cluster shifts in time but will keep its shape.

NIPD ANALYSIS

The large data set acquired with this scan method requires an automated evaluation of the screen images that is sensitive to streaking. Because of the large bunch size w.r.t. the SRR gap size only the bunch core will be streaked. Depending on the streaking field strength it is possible, that the bunch core may not be streaked enough to tower over the entire bunch footprint. Then the bunch screen image will not increase in the vertical plane but the charge distribution within the bunch will become rearranged.

In each scan step two averaged images are recorded, with and without THz, each averaged over 50 single images. The quantity NIPD (normalized integrated absolute value of pixel count difference) was defined to give a measure of such charge rearrangement. NIPD is a scalar value that is zero if

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the two images are identical and monotonously increases by charge displacement.

The idea behind NIPD can be explained with Fig. 5: it shows a simulated data set of one scan step with the two averaged images, with THz off (left) and with THz on including successful streaking (center). The difference image (right) is calculated by subtracting their pixel count. The absolute value of all pixel in the difference image is then summed over a given region of interest (ROI) and normalized to the number of pixel ($I \cdot J$).

$$\mathrm{NIPD} = \sum_{i,j}^{I,J} \frac{\left| [\mathrm{diff.image}]_{i,j} \right|}{I \cdot J} \tag{1}$$

Where i, j are the column and row of the pixel in the difference image. Without the normalization, the sum equals the P1-matrix norm. To calculate NIPD from the simulation, the ROI of the experiment, a 5.6^2 mm^2 square was chosen, see also Fig. 3. Although for readability the simulated screen images are shown only within a 1.12^2 mm^2 square. The granularity of the difference image reflects the real resolution of the diagnostic camera that reads out the YAG screen. The simulated pixel count was upscaled to indicate not the number of simulated macro particles but the expected pixel count per unit charge. This makes the simulated beam screen image comparable to the real YAG screen. The simulated data

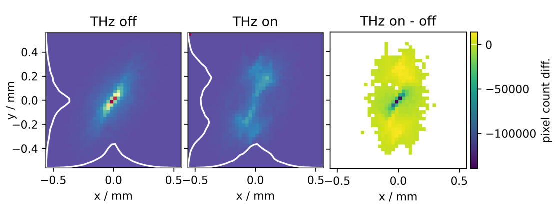

Figure 5: Simulated beam screen images without (l) and with (c) streaking. The right plot show the calculated difference image from which NIPD is calculated.

originates from a tracking simulation [6] with ASTRA [7] and yields a final result of NIPD = 57. Although the scenario does not accurately match the experiment beam parameter, the simulation clearly demonstrates the NIPD analysis and its sensitivity to charge displacement.

The NIPD value rises with charge rearrangement from streaking but also from any other source. Instabilities and general machine noise contribute to the difference image and therefore increases NIPD. A real data set therefore will always yield NIPD > 0. Slow drifts on the other hand do not further increase NIPD.

EVALUATION OF SCAN DATA

Evaluating every data set of the 20 h scan with the same NIPD analysis leads to Fig. 6. For the experiment settings of the scan recall Fig. 4. As discussed previously, streaking should appear in a clear pattern of a main cluster and one or two secondary clusters 4 h before and/or after the main cluster. The NIPD value should tower over the noise level by up to 57 for the main cluster and by an (unknown) attenuated increase for the secondary clusters. Inspecting the NIPD distribution in Fig. 6 indeed shows a suspicious pattern close to 0 h and 4 h. The NIPD value rises from 4 to 12 (0 h) in the seemingly main cluster (0 h) and from 4 to 8 in the seemingly secondary cluster (4 h). Also increased NIPD values can be found in three rich clusters (black boxes). Unfortunately all these irregularities could be traced back to acute instabilities in the RF power. Even including the irregular clusters, the data set sums up to a skew normal distribution as expected from a noise-dominated data set.

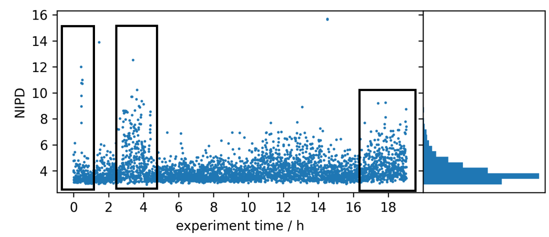

Figure 6: NIPD measured during a 20 h scan (l). The projected histogram (r) shows the expected skew normal distribution from noise. The boxed clusters of high NIPD value originate from acute RF instabilities.

CONCLUSION

The Split-ring resonator experiment has been set-up and run at FLUTE (KIT). The high experimental challenges required us to adapt our endeavours to scan two parameters: the temporal synchronisation and the longitudinal resonator position. A scan routine was developed and that led to an extensive amount of accruing data. For the scan data analysis NIPD was developed, a scalar measure that increases for charge rearrangement from streaking but also from noise. The expectation on a streaking signal position and amplitude within the scan was carefully discussed and the scan data evaluated. Unfortunately streaking could not be found that protrudes from the noise level.

At the moment FLUTE is undergoing major upgrades on multiple frontiers in parallel that promises a more stable operation in the near future. Also a new set of THz optics [8] will be installed that significantly reduce the losses of the streaking source. These measures will lead to a reduced noise and increased signal level that hopefully will enable us to separate the streaking signal from its background.

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