DESIGN OF A TIME-RESOLVED ELECTRON DIAGNOSTICS USING THz FIELDS EXCITED IN A SPLIT RING RESONATOR AT FLUTE

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Abstract

Time-resolved electron diagnostics with ultra-high temporal resolution is increasingly required by the state-of-the-art accelerators. Strong terahertz (THz) fields, excited in a split ring resonator (SRR), have been recently proposed to streak electron bunches for their temporal characterisation. Thanks to the high amplitude and frequency of the THz field, temporal resolution down to the sub-femtosecond range can be expected. We are planning a proof-of-principle experiment of the SRR time-resolved diagnostics at the accelerator test-facility FLUTE (Ferninfrarot Linac und Test Experiment) at the Karlsruhe Institute of Technology. The design of the experimental chamber has been finished and integrated into the design layout of the FLUTE accelerator. Beam dynamics simulations have been conducted to investigate and optimise the performance of the SRR diagnostics. In this paper, we present the design layout of the experimental setup and discuss the simulation results for the optimised parameters of the accelerator and the SRR structure.

INTRODUCTION

Temporal characterization of electron bunches is an important diagnostic tool for the control and optimisation of accelerators. The generation of ultra-short electron bunches in the femtosecond regime demands for time-resolved diagnostics with appropriate resolution. RF transverse deflecting structures have been demonstrated to be capable of providing few-femtosecond temporal resolution [1]. Recently, a new time-resolved diagnostics using THz fields excited in a split ring resonator (SRR) has been proposed [2, 3]. Thanks to the short pulse duration, high resonant frequency and high field enhancement of the THz pulses [4], such SRR diagnostics could allow for femtosecond resolution with single shot capability. Moreover, the small size of the SRR structures in the sub-millimeter range makes them more flexible in the integration into the accelerator, and combining several of them provides potentials for even better resolutions.

Analog to systems using RF deflecting structures, the SRR setup maps the temporal coordinate onto a transverse coordinate. As illustrated in Fig. 1, a driving laser system generates intense single cycle THz pulses though optical rectification. The THz pulses are absorbed in the split ring resonator structure and excite electric field enhancement for the resonant frequency inside the gap. The electron bunches,

which are generated by the same driving laser system through the photoelectric effects on a cathode, interact with the high amplitude THz field in the gap and are deflected in the transverse direction. The longitudinal density distribution of the electron bunch is translated into a transverse density distribution, which can be measured using a transverse beam imaging screen.
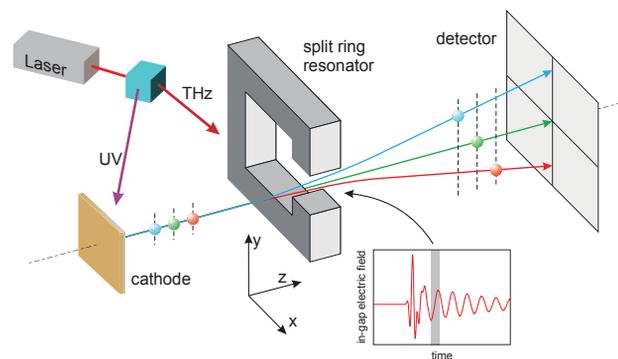

Figure 1: Principle of the SRR diagnostics [2].

In the following, the physical formulation of the streaking effect is shortly introduced for a SRR deflecting in the vertical direction. For an electron at a location z relative to the reference particle, the accumulated transverse momentum obtained from the THz field is

$$p_y = \frac{e}{c} \cdot V_0 \sin(kz + \Psi_0), \qquad (1)$$

where V_0 is the integrated deflecting field through the gap, k the wavenumber of the THz field, Ψ_0 the phase of the THz field. For operation around the zero-crossing phase with $\Psi_0 = 0$, the vertical momentum can be approximated by

$$p_y = \frac{e}{c} \cdot V_0 kz, \qquad (2)$$

which is in linear dependence on the longitudinal position z of the electrons inside the bunch. After a beam transport section to a downstream imaging screen, this vertical deflection is further translated into a vertical offset of

$$y = Sz, \quad S = \sqrt{\beta_{y,\text{SRR}}\beta_{y,\text{screen}}} \cdot \sin(\Delta\mu_y)\frac{eV_0 k}{\gamma E_0}, \qquad (3)$$

where the streak parameter S describes the strength of the streaking effect, $\beta_{y,\text{SRR}}$ and $\beta_{y,\text{screen}}$ are the beta-functions at the locations of the SRR and the screen, respectively, $\Delta\mu_y$
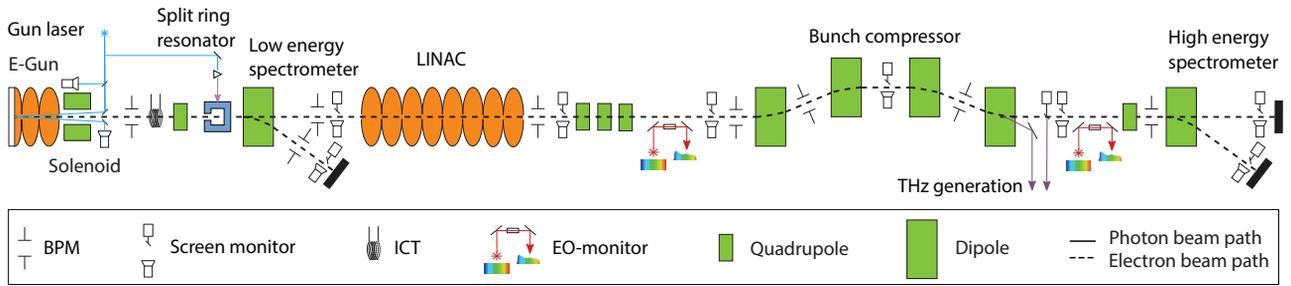
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Figure 2: Schematic layout of FLUTE including various diagnostics elements. The proof-of-principle experiment for the SRR diagnostics is located upstream of the low energy spectrometer. Not to scale.

the vertical phase advance from the SRR to the screen, γ the Lorentz-factor, E_0 the rest energy of electrons.

The achievable longitudinal resolution at the screen is given by the unstreaked beam size at the screen (assuming the unstreaked beam size can be resolved by the imaging system) divided by the streak parameter and reads as

$$R_z = \frac{\sqrt{\epsilon_N/\gamma} \cdot \gamma E_0}{\sqrt{\beta_{y,\text{SRR}}} \cdot \sin(\Delta\mu_y)eV_0 k}, \tag{4}$$

with ϵ_N being the normalized emittance of the electron bunch. Since the small gap size is the main limiting factor for the allowed transverse beam size $\sigma_{y,\text{SRR}}$ of the electron bunch, and thus the beta-function $\beta_{y,\text{SRR}}$, Eq. 4 can be formulated using the relation $\sigma_{y,\text{SRR}} = \sqrt{\beta_{y,\text{SRR}} \cdot \epsilon_N/\gamma}$ to

$$R_z = \frac{\epsilon_N E_0}{\sigma_{y,\text{SRR}} \cdot \sin(\Delta\mu_y)eV_0 k}. \tag{5}$$

It can be derived from this equation that a better resolution requires three aspects: smaller normalized emittance, which is a measure of the quality of the electron bunch to be measured; larger aperture at the SRR, stronger integrated deflecting field, and higher resonant frequency, all of which are defined by the design of the SRR structures; phase advance of 90 degrees from the SRR to the measurement location, which can be optimised in the accelerator optics designs.

In the following, the design of the proof-of-principle experiment for the SRR diagnostics, which is a collaboration among PSI (Villigen, Switzerland), KIT (Karlsruhe, Germany) and University of Bern (Bern, Switzerland), will be presented and the simulation results will be discussed.

EXPERIMENTAL SETUP

The accelerator test-facility FLUTE is currently under construction at KIT in collaboration with PSI and DESY. Its aims range from investigation of space charge and coherent radiation induced effects, bunch compression studies, systematic comparison of simulation code with measurement results, to studies with intense THz radiation [5]. Furthermore, it will serve as a test bench for advanced diagnostics and instrumentation.

The schematic layout of FLUTE is shown in Fig. 2. The total length of the accelerator is ~15 m. In the RF photocathode gun, electrons are generated and accelerated to an

energy of ~7 MeV. A solenoid focuses the electron bunch before it being accelerated by the main S-band linac accelerating structure to the energy of ~41 MeV. After a matching section with a quadrupole triplet, the electron bunch is longitudinally compressed in a magnetic bunch compressor.
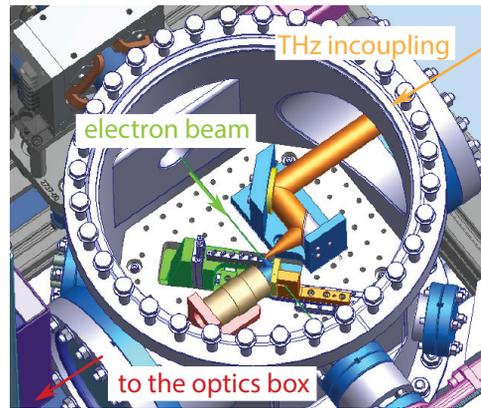

Figure 3: Technical drawing of the vacuum chamber.

The proof-of-principle experiment for the SRR diagnostics will be conducted at the low-energy section at FLUTE, as indicated in Fig. 2. The laser from the driving laser system with the fundamental wavelength of 800 nm and a pulse duration of 35 fs will be converted through third harmonic generation to a wavelength of 266 nm. The UV light will be further temporally stretched to a pulse duration of ~ps to reduce space charge effects in the generated electron bunch. The accelerated electron bunch will be deflected in the vertical direction by the SRR, and propagates towards a screen station in the straight section, where the vertically lengthened beam can be imaged. The vertically streaked electron bunch can be transported through a horizontal dipole onto the screen station in the dispersive section as well, where the energy distribution of the bunch can be measured in the horizontal plane in addition.

The intense THz radiation for exciting the SRR structures will be generated using the same driving laser system as used for the UV light required for the photo cathode. The short laser pulse of 35 fs with the fundamental wavelength of 800 nm will be directly propagated through a Lithium Niobate ($LiNbO_3$) inorganic crystal and produces THz pulses based on optical rectification techniques.

The THz pulses will be incoupled into a vacuum chamber housing the SRR structures. Figure 3 shows the technical drawing of the chamber interior. Two in-vacuum parabolic mirrors are available for focusing the THz radiation. An array of SRR structures with various geometries is mounted on a movable stage. A scintillator screen with the in-vacuum objective and the optics box will provide high-resolution transverse electron beam diagnostics [6].

SIMULATION RESULTS

Uncompressed electron bunches directly from the gun will be used for the proof-of-principle experiment. One of the main challenges is to transversely focus the electron bunch to propagate it through the small size of the SRR gap. Beam dynamics simulations using ASTRA [7] have been performed to optimise the gun and solenoid parameters with considerations of the space charge effect. The 3-dimensional electric and magnetic field distributions inside the gap, which have been simulated using the CST MWS program [8], have been integrated into the ASTRA simulation for a full characterization of the SRR streaking effect. The particle distributions are tracked to the locations of the two screens and pixelated into transverse images with a resolution of 10 μm/pixel.

The parameters of the SRR and the optimised accelerator settings are summarized in Table 1. The simulation is performed with 10^5 macro particles. Figure 4 shows the rms transverse beam sizes from the cathode to the entrance of the SRR. The vertical beam size has been chosen to be small to fit into the gap aperture, and at the same time as large as possible for a better longitudinal resolution (cf. Eq. 4).

Table 1: Simulation Parameters

Accelerator settings	
Laser rms pulse length	2 ps
Laser rms transverse size	5 μm
Bunch charge	50 fC
Gun gradient	120 MV/m
Gun phase	0 degree
Solenoid magnetic field	0.24 T
Bunch energy	7 MeV
Normalized rms transverse emittance	2.7 nm
SRR parameters	
Gap size in x	20 μm
Gap size in y	20 μm
Gap width in z	10 μm
Resonant frequency	300 GHz
Peak electric field	500 MV/m
Integrated field	10 kV

The simulated transverse particle distribution and the transverse electric field distribution at the entrance of the SRR is shown in Fig. 5, with indications of the SRR geometry in the gap region. The rms beam sizes are 4 μm in both the horizontal and vertical plane. The vertical deflecting
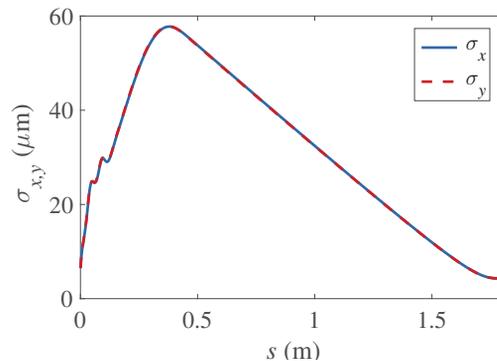

Figure 4: Transverse rms beam sizes from the cathode to the entrance of the SRR structure.

field is homogeneous in the gap region. With increasing distances from the gap centre, the horizontal field component increases, which puts constraints on the horizontal beam sizes to avoid beam shape distortion.
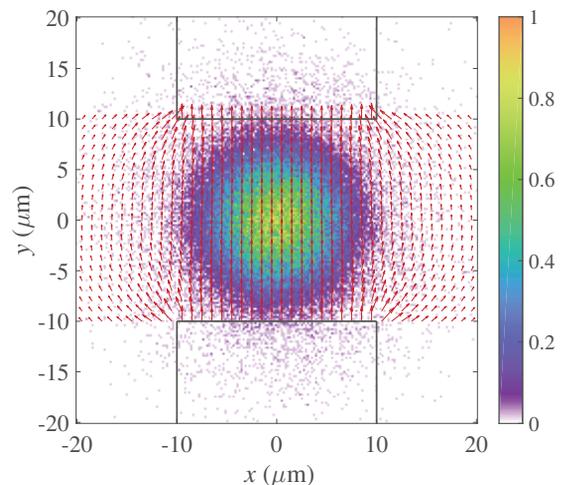

Figure 5: Transverse particle density distribution (color coded) from ASTRA simulation and transverse electric field distribution (red arrows) from CST simulation at the entrance of the SRR gap. The geometry of the gap is indicated by the black lines.

Figure 6 compares the simulated particle distribution at the exit of the SRR with the THz deflecting field switched on (left column) to that without the deflecting field (right column). Since the electron bunch with a rms bunch length of ~2 ps is comparable to the wavelength of ~3 ps of the resonant THz field, the deflecting field imposes several modulation periods on the vertical momentum (see Fig. 6 top left). It should be noted that those electrons located outside the gap region do not see the main deflecting field and therefore do not experience vertical momentum transfer. The bunch centre, which has the highest energy as a result of the on-crest operation of the gun, interacts at the zero-crossing phase with the deflecting field. The correlation between the vertical momentum and the energy is plotted in Fig. 6 bottom row.
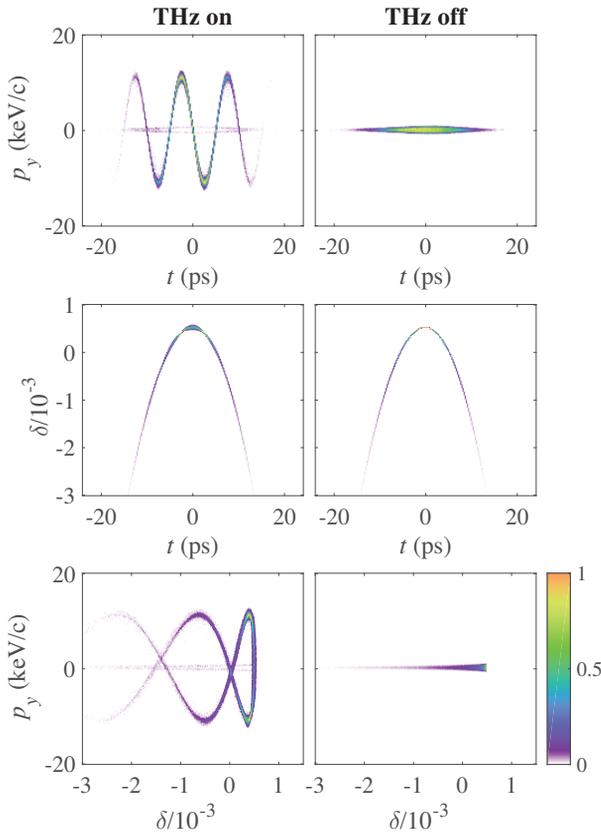
Figure 6: Particle distribution at the exit of the SRR structure at the exit of the SRR structure with the THz deflecting field switched on (left column) and off (right column). The color code corresponds to the particle density.
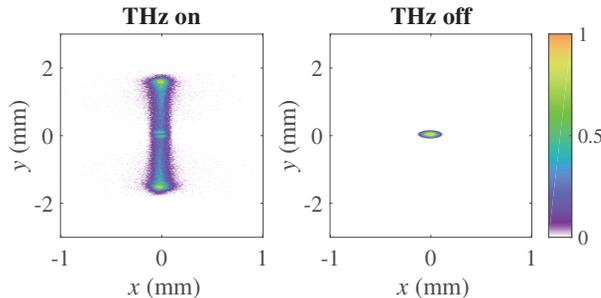

Figure 7: Simulated image of the electron bunch on the screen in the straight section. The color code corresponds to the image intensity.

In order to maximize the streaking effect (cf. Eq. 3), the accelerator optics has been designed to ensure a vertical phase advance of ~90 degrees from the location of the SRR to the location of the screens. The pixelated transverse image of the simulated distribution on the screen in the straight section is shown in Fig. 7. The increase of the vertical rms beam size from 0.05 mm to 1.11 mm, with the THz field switched off and on, respectively, is a clear indication for the streaking performance.
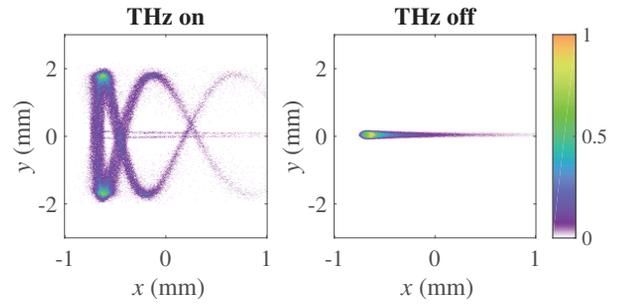
Figure 8: Simulated image of the electron bunch on the screen in the dispersive section. The color code corresponds to the image intensity.

More details can be seen in the simulated image on the screen in the dispersive section (see Fig. 8). While the horizontal axis scales linearly with the energy deviation δ, the vertical axis is a linear transformation from the vertical momentum p_y. The correlation between p_y and δ is very well represented in the transverse image on the dispersive screen, and is in good agreement with that expected from Fig. 6 bottom left. The broadening of the horizontal beam size in the energy slices is caused by the initial horizontal slice beam sizes that limit the energy resolution.

According to Eq. 5, the longitudinal resolution for this proof-of-principle setup at FLUTE is estimated to be $R_t = R_z/c = 18\,\text{fs}$ (using parameters from Table. 1). It should be noted that the assumed peak field gradient of 500 MV/m is based on a prudent estimate of the field enhancement in the gap. Peak gradient in excess of 1 GV/m for a resonant frequency of 1 THz could be expected, making temporal resolution in the few-femtosecond range possible.

SUMMARY AND OUTLOOK

A proof-of-principle experiment has been planned at the test facility FLUTE. The design of the experimental setup has been finished and the experimental chamber is now being built. Integration into the accelerator is expected in 2017. Beam dynamics simulations with considerations of the full THz field distribution have shown the feasibility of the SRR diagnostics. The streaking effect of the THz field should be easily detectable.

REFERENCES

[1] C. Behrens *et al.*, Nature Communications **84**, 3762 (2014).

[2] J. Fabianska *et al.*, Scientific Reports **4**, 5645 (2014).

[3] M. Dehler *et al.*, in *Proc. IBIC'15*, MOPB048 (2015).

[4] S. Bagiante *et al.*, Scientific Reports **5**, 8051 (2014).

[5] M. J. Nasse *et al.*, Rev. of Sci. Instrum. **84**, 022705 (2013).

[6] R. Ischebeck *et al.*, Phys. Rev. ST Accel. Beams **18**, 082802 (2015).

[7] K. Flöttmann, "ASTRA: A Space Charge Tracking Algorithm", http://www.desy.de/~mpyflo

[8] CST Microwave Studio, http://www.cst.de