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SPLIT RING RESONATOR EXPERIMENT - SIMULATION RESULTS

J. Schaefer*, B. Haerer, A. Malygin, A.-S. Müller, M. Nabinger, M. J. Nasse, T. Schmelzer, M. Schuh, T. Windbichler, Karlsruhe Institute of Technology, Karlsruhe, Germany

Abstract

FLUTE (Ferninfrarot Linac- Und Test-Experiment) is a compact linac-based test facility for accelerator and diagnostics R&D. An example for a new accelerator diagnostics tool currently studied at FLUTE is the split-ring resonator (SRR) experiment, which aims to measure 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. Particles passing through the SRR gap are time-dependently deflected in the vertical plane, which allows a vertical streaking of an electron bunch. This principle allows a diagnosis of the longitudinal bunch profile in the femtosecond time domain and will be tested at FLUTE. This contribution presents an overview of the SRR experiment and the results of various tracking simulations for different scenarios as a function of laser pulse length and bunch charge. Based on these results possible working points for the experiments at FLUTE will be proposed.

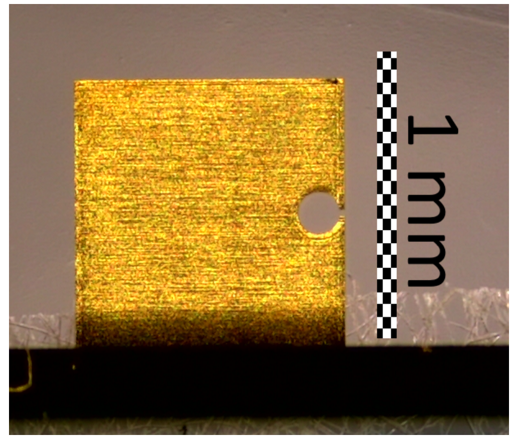

Figure 1: Image of the split-ring resonator device. The streaking EM field is located in the split of the ring with a size of 20 µm by 20 µm.

INTRODUCTION

The Ferninfrarot Linac- Und Test-Experiment FLUTE [1] is a test facility at KIT. The low-energy section of FLUTE is already in operation and starts with the RF photoinjector directly followed by a solenoid. After the solenoid the beam either follows a straight line or is deflected by a spectrometer dipole. Both beam paths end in a YAG screen in the same distance. Between the solenoid and the spectrometer dipole the SRR is installed at 1.7 m behind the cathode. A picture of the device is shown in Fig. 1. The machine parameters of FLUTE like e.g. RF parameters, pulse shaping etc. can be controlled freely, this makes FLUTE a versatile test bench for new devices. At the moment the new diagnostic system of a split-ring resonator (SRR) is investigated (in a collaboration with PSI and University of Berne). The aim of the SRR is to provide a fast diagnostic device capable of measuring the bunch length and the longitudinal bunch profile with a femto-seconds resolution.

While the SRR experiment is being set up, suitable machine parameters for a proof of concept experiment are investigated in simulations. The main challenge in the experiment is to thread the electron bunch through the tiny SRR aperture of 20 µm by 20 µm which currently still leads to heavy beam losses. The following chapters give an overview of the experimental environment, the relevant degrees of freedom and the simulations setup in order to reduce beam losses.

SRR CONCEPT

Effectively, the SRR setup works like an ultra-fast streaking camera and can be used to diagnose the longitudinal phase space of a bunch with a resolution of down to 18 fs [2]. In order to excite the streaking field in the SRR gap, the pulse of the FLUTE drive laser is split up and one part is converted into a pulse of intense THz radiation [3]. This THz pulse is focused on the 20 µm by 20 µm resonator gap of the split-ring where it stimulates a standing electromagnetic wave oscillating with 300 GHz. The field amplitude of the wave front is enhanced by a factor of 100 by the resonator structure, reaching accelerating gradients of up to 500 MV/m [2]. The strong EM field applies vertical kicks to the electrons in the bunch while they pass through. This leads to a vertical streaking which can be seen on the forward YAG screen in the straight section as illustrated in Fig. 2, part a). The shown energy spread is distributed symmetrically around the beam center. Like a streak camera, this principle allows diagnosing the bunch length from the size of the streaked bunch image on the screen and the EM field amplitude. However, if a bunch is longer than half a period length of the streaking EM field

$$z_{\text{rms}} = 0.5\, c/f = 0.5\,\text{mm} = 1.6\,\text{ps}, \qquad (1)$$

the bunch overlaps its projection on the screen image and the bunch length cannot be resolved anymore. In some simulated scenarios the bunch length exceeds this limitation several times. These long bunches can be analysed using the YAG screen on the dispersive spectrometer beam path of FLUTE. The path differences in the dipole effectively sorts the bunch by its energy in the horizontal plane. Combined with the vertical streaking results in a looped screen image as sketched in Fig. 2, part b). This unfolds the overlap on the screen image and effectively eliminates the bunch length limitation described in Eq. (2). In addition, the knowledge of the streaking EM field amplitude is no longer required for

* jens.schaefer2@kit.edu

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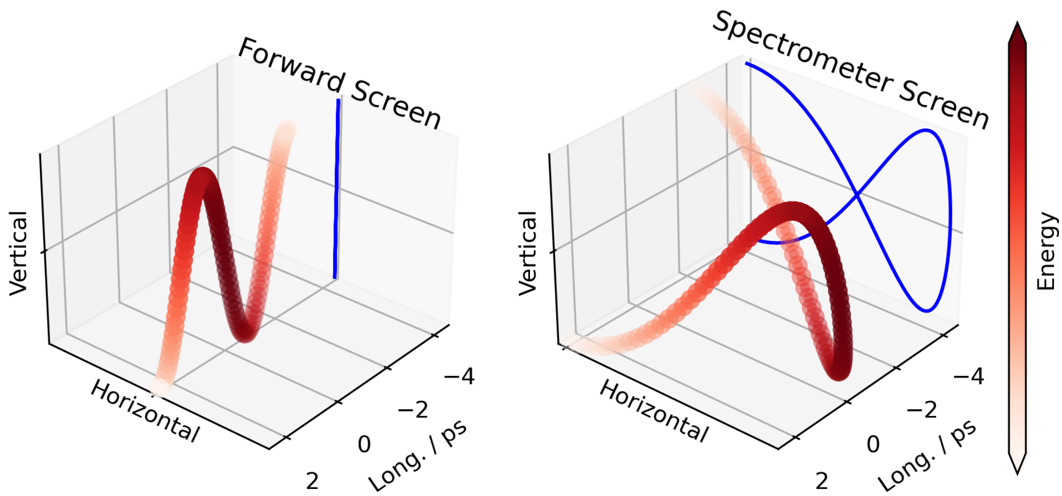

Figure 2: Sketched screen image. Electron bunch with symmetric energy distribution. Projection visible on beam screen in blue. a) Forward screen without dispersion, overlapping screen image prevents diagnosis of the full bunch length. b) Dispersive screen after spectrometer shows bunch vertical sorting by energy resulting in loop shaped image and unravels the whole bunch length on the screen.

the calculation of the bunch length. Instead, the frequency of the streaking field is sufficient. The screen image reveals the phases of the streaking sine-like field between head and tail of the bunch. The bunch length is then calculated by

$$z = 1/f \times (\phi_{\mathrm{Head}} - \phi_{\mathrm{Tail}})\,/360°. \tag{2}$$

Figure 2, part b) illustrates a streaking of 540° with a streaking frequency of 300 GHz results in a bunch length of 5 ps.

The screen image in the dispersive section reveals the energy of each particle by its horizontal position. Also, the charge distribution in the screen image can be calculated from the distribution of the pixel brightness and the total bunch charge. Thus, this looped screen image reveals the charge and energy profile along the longitudinal axis of the bunch. The combination of spectrometer and split-ring resonator allows diagnosing the complete longitudinal phase space of an electron bunch rendering it to a very powerful and versatile diagnostic device.

CONTROLLED BUNCH GENERATION

As the electrons are extracted from the cathode by the drive laser pulse via photoelectric effect [4], the electron bunch inherits its spacial dimensions of the laser pulse. The intensity of the laser pulse together with the quantum efficiency of the copper cathode and the currently present RF voltage in the gun define the amount of released electrons. Sophisticated treatment of the drive laser makes laser pulse length, diameter and intensity adjustable. This allows control over the initial electron bunch length, diameter and charge. For controlling the bunch charge, the laser intensity can be used to compensate other dependencies like from the RF settings.

The repelling space charge forces create divergence, which increases with higher charge and smaller bunch volume. A change in the divergence of the bunch and also in the bunch length changes the resulting energy and energy spread. Usually, such influences are negligible, but for focusing on the tiny SRR gap such details have significant impact on the size of the beam waist.

For reducing the electron losses at the SRR aperture, a given bunch should be accelerated such, that the overall energy spread is minimized. A minimum energy spread is desired as this reduces the chromatic effects of the solenoid and thus decreases the beam waist in its focal point. This helps to reduce the beam waist in the focal point due to lower chromatic effects from the solenoid. A change in the parameters of the laser pulse affects the strength of the space charge forces and therefore requires a different RF phase for minimum energy spread.

SIMULATION OPTIMIZATION

The streaking EM field in the SRR gap decays outside of the gap volume. Particles outside of the SRR gap may get scattered or blocked by the device but do not experience the EM field in a relevant strength [2]. This would lead to misleading measurements, therefore it is desired to maximize the spacial overlap between the beam spot and the SRR gap. Different scenarios have been simulated using the simulation tool ASTRA [5] in order to optimize parameters for this goal. The tracking tool ASTRA has been chosen as it allows a precise control of the calculation of space charge forces. In the following the different scenarios are discussed.

With the always present dark current of FLUTE the bunch should have at least a charge of 1 pC for a useful signal-to-noise ratio. In this campaign Gaussian laser pulses with a spot size 50, 250 and 500 µm (RMS) have been studied, each with intensities resulting in 1, 20 and 50 pC charge. The laser pulse length can be set to six values in the range from 0.7 and

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4 ps (FWHM) by exchanging dispersive quartz rods of different lengths in the laser path. The laser pulse length of 4 ns (FWHM) as well as the peak RF field gradient of 70 MV/m are kept constant for now, but will be varied in future studies. For every individual version of these nine bunches a set of two consecutive optimizations was performed as follows.

At first, a bunch is created at several different phases of the accelerating field and tracked for half a meter. The tracking results are evaluated for their energy spread. To reduce the required simulation steps, the data points are extrapolated with a fourth degree polynomial fit, which allows to retrieve the RF phase to obtain minimum energy spread. An example plot of a phase scan for a 20 pC bunch with 4 ps length and 500 μm laser pulse radius is shown in Fig. 3.

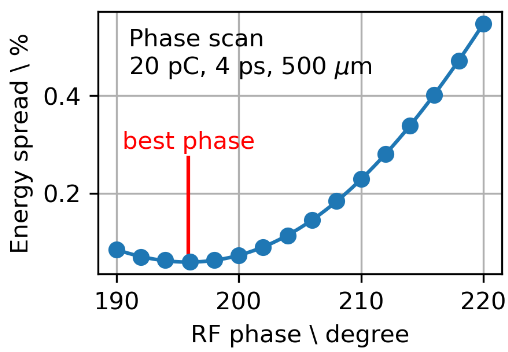

Figure 3: Automated phase scan for an example bunch. After tracking from the cathode half a metre, the particle distributions are evaluated for their absolute energy spread. The plot shows the data results, a fit with a fourth polynomial and the result of the best phase for a minimum in energy spread.

Afterwards, with the ideal phase applied, a scan of the solenoid magnetic field is performed. The bunches are tracked up to the SRR position at 1.731 m and the particle distributions are evaluated on their vertical bunch size. Again, all tracking results are evaluated, fitted and the solenoid strength for minimum bunch size can be calculated. After this optimization procedure, each bunch is tracked past the SRR position with ideal machine parameter and the losses at the SRR aperture are counted. This allows to compare the different bunches by their expected losses at the SRR aperture which should be as small as possible. So far, the losses are so high for every considered case, that one cannot expect to resolve the surviving electrons on a screen image from the background. In order to find suitable machine parameters, additional simulations with different laser parameters are foreseen. In addition, the adjustment of the simulation precision is a serious technical challenge, that will be addressed in the next chapter and has to be tackled as the very next topic.

SIMULATION CHALLENGES

ASTRA allows control of the lower and upper bound of the step size of the tracking computations, called Runge-Kutta step size. This allows to simulate the streaking in the SRR which happens on a μm scale. ASTRA even offers a built-in scan routine but this performs the single steps in serial computations. For parallel computing a python based framework was developed in-house which executes all steps of a parameter scan in independent threads. The framework takes charge of adjusting the input files, starting all files in parallel and post-processes the tracking results. After scanning the RF phase and evaluating the tracking results for their energy spread, the phase for minimum energy spread can be extrapolated to a realistic precision of a tenth of a degree. The optimum phase is then used for the next scan of the solenoid strength. In order to reduce the required amount of macro particles for a stable simulation result, the scan of the solenoid strength is not evaluated directly for particle losses at the aperture but for a minimum in beam size at the position of the aperture. After the second optimization a third tracking run using the optimized machine parameters is performed with high precision and evaluated for its particle loss at the SRR aperture.

At the moment, the challenge is to find a Runge-Kutta step size and a suitable amount of simulated macro particles such, that the simulation results converge to a stable end result while keeping the computing time on a minimum. An increase in precision directly couples with a steep increase of required computation time which makes it very time-consuming to find converging results. The splitting of a simulation into steps with adapted precision is a promising strategy which will be the next step to achieve fast and stable results.

SUMMARY AND OUTLOOK

A SRR is currently being tested as longitudinal diagnostic device at the FLUTE test facility. A tracking based optimization routine was created which finds machine parameters to minimize the bunch losses on the SRR aperture. A set of nine bunches with three different diameters and charges was studied to minimize the bunch losses on the SRR aperture. While testing this small parameter volume, the simulation results did not seem to converge to stable results. The Runge-Kutta step size used by the simulation code has been identified as as critical parameter that needs to be adapted towards precise but fast simulations. Careful investigation of the simulation precision and a wider parameter range are the next steps in order to find machine parameters for the experimental validation of the SRR setup.

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