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BUNCH LENGTH MEASUREMENT SYSTEM DOWNSTREAM THE INJECTOR OF THE S-DALINAC*

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Abstract

The S-DALINAC is a thrice recirculating electron accelerator with a continuous-wave beam at a frequency of 2.9972(1) GHz. Short bunches are crucial to enable tuning of the machine for operation as an energy-recovery linear accelerator. Currently, measurements of the bunch length are accomplished by using the radio-frequency zero-crossing method. Since this method is time consuming, a new setup for these measurements using a streak camera is developed. Optical transition radiation emitted from an aluminum-coated Kapton screen is used to map the bunch length information to a light pulse which enables an accurate measurement compared to a scintillating screen. The light pulse can then be evaluated with the streak camera. This contribution will present the current status of the measurement setup as well as its design and properties.

INTRODUCTION

The superconducting Darmstadt electron linear accelerator S-DALINAC was originally established as a twice-recirculating accelerator in 1991 operating at a radio frequency of 2.9972(1) GHz. An upgrade of the machine adding a third recirculation beamline in 2015/16 was performed. This beamline also features an adjustment system for the path length of the electrons in the second recirculation beamline with a range of 10 cm which is identical to the wavelength of the operation frequency (see Fig. 1). It is possible to recover the energy of this beam by passing the main accelerator a second time if this system is set to an 180° phase shift and the beam passing the main accelerator for the first time is led to the respective beamline. This operation mode called 1×ERL (1× Energy-Recovery Linear accelerator) was achieved in 2017 for the first time at the S-DALINAC [1]. Four years later a 2×ERL mode was demonstrated by accelerating and decelerating the beam twice [2]. More than 87 % of the beam energy were recovered in this mode. The efficiency was observed to decrease with the increase of the initial current at the electron gun. The effect is partly caused by the greater bunch length in high current operation. Therefore, the minimization of this parameter is important for reaching higher currents and efficiencies in ERL operation. This requires a setup for measuring the bunch length.

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BUNCH LENGTH MEASUREMENTS DOWNSTREAM THE INJECTOR

The current method for bunch length measurements is based on the radio-frequency zero-crossing method [3]. An RF (radio-frequency) cavity is used to impose a momentum chirp on a bunch.

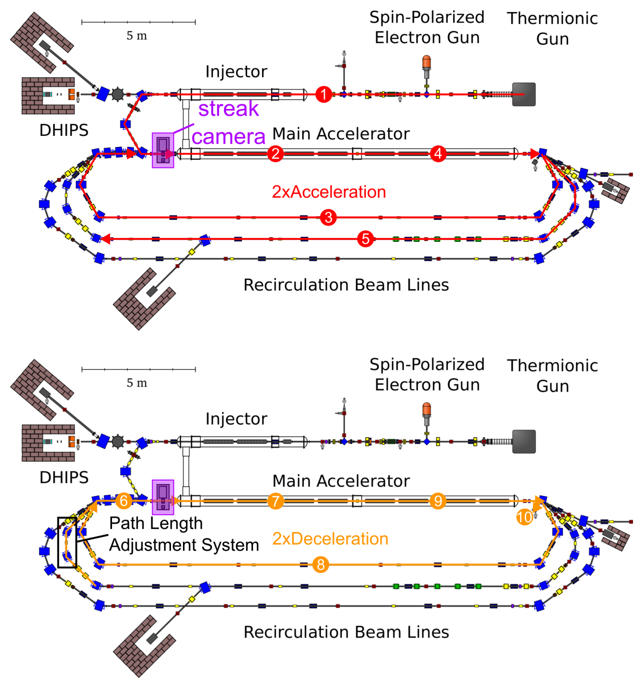

Figure 1: The layout of S-DALINAC including the beam path for operation in 2×ERL mode (following [2]). The top image shows the acceleration in this mode. After passing the injector in (1) the beam is led to its main acceleration in (2). Following the first recirculation beamline (3) the beam is accelerated a second time in the main accelerator (4). The beam then enters the second recirculation beamline (5). The bottom image shows the deceleration of the beam in 2×ERL mode. Because of the path length adjustment system the beam receives a phase shift of 180° in (6). The first deceleration takes place in (7) and the beam is again led through the first recirculation beamline in (8). The second deceleration stage (9) reduces the beam energy to the energy that was originally provided by the injector linac. At this energy, the beam is dumped (10). The intended bunch length measurement setup location for commissioning is also shown in purple.

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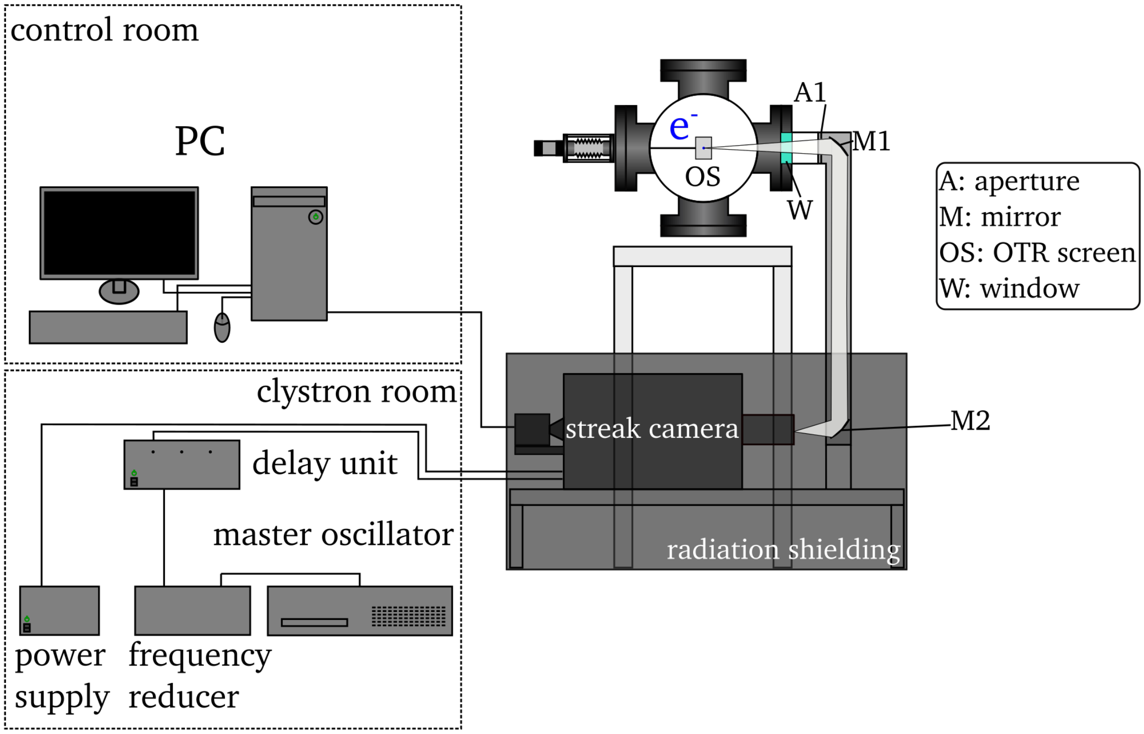

Figure 2: Current setup for measuring bunch lengths via OTR screens and a streak camera. The emitted light pulses from the screen are transported and focused via two off-axis parabolic mirrors on the entrance slit in front of the camera. All electrical devices for the streak camera will be stored in rooms that are protected from radiation.

After a dispersive section the transverse beam profile of this bunch is measured with a scintillating screen. Because of the dispersive section the size of the beam on the target is connected to the induced momentum chirp which again is dependent on the bunch length. Using this method to evaluate the bunch length has some significant drawbacks:

- The initial transverse beam size and the scintillating screen itself cause the measurement to be an upper estimate of the bunch length only.
- The measurement is only valid at the position of the used RF cavity and must be extrapolated otherwise.
- It is impossible to determine the bunch length value when all RF cavities are operated in intended operation, that is, when all RF cavities are operated at their design values.

These issues make it impossible to monitor the bunch length parameter in ERL operation properly. Therefore, a new setup for bunch length measurements downstream the injector has been developed. All components are currently in the procurement phase. Figure 2 shows a sketch of measuring bunch lengths with this new setup. An optical transition radiation (OTR) screen is used to create light pulses with the same length as the electron bunches. These pulses are transported via optical elements to a streak camera which then measures the length of these pulses. Next to the streak camera the setup requires an OTR screen, an electrical reference signal, a radiation shielding and optical elements. Details of the shielding will be determined from upcoming measurements. The electrical reference signal will be produced by the master oscillator.

The main goal with this setup is to provide an accurate and robust method for measuring the bunch length just before the main accelerator with a time resolution of better than 1 ps. This is required for specific machine settings and ERL operation. However, smaller values of the bunch length are favorable to further improve ERL operation [2]. In non-ERL operation the bunch length is 2 ps and will be monitored with this setup as well [4]. In the following section the contributions to the total time resolution of the setup will be discussed and estimates for the main contributions from the optical setup in front of the streak camera and the electrical reference signal will be investigated.

TIME RESOLUTION OF THE NEW BUNCH LENGTH MEASUREMENT SETUP

Several uncertainties contribute to the total time resolution R_t of the streak camera setup. Assuming no correlations between these contributions, the total resolution can be approximated by:

$$R_\mathrm{t} = \sqrt{R_\mathrm{ttd}^2 + R_\mathrm{slit}^2 + R_\mathrm{jitter}^2 + R_\mathrm{rest}^2}. \tag{1}$$

Here, R_ttd is the contribution from the transit time dispersion of the photoelectrons and the electrical deflector inside the streak camera. This is the lower limit to the resolution of streak cameras and can be estimated to be ≈ 100 fs for commercial devices [5]. This limit is assumed to be valid

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for the procured streak camera C10910 from Hamamatsu Photonics.

The beam profile of the light pulses reduces the resolution of the streak camera. It can be controlled with a slit in front of the device so that its contribution to the total resolution is R_{slit}. However, it is better to reduce the spatial intensity profile of the light pulse prior to entering the slit in the first place. This allows for more photons to be collected for the measurement and increases its accuracy. The optics in front of the streak camera and their impact on the resolution will be shown in the following section.

The electrical reference signal used to synchronize the streak camera with the S-DALINAC will be supplied by the master oscillator of the machine. Its phase noise creates a time jitter R_{jitter} that reduces the resolution of the setup. A measurement of this value at the location of the setup and its influence on the resolution is discussed below.

Finally, R_{rest} contains all contribution from minor sources to the total resolution. These are e.g. dispersion in the optics of the camera, misalignment of the orientation of the OTR screen and fluctuations of the beam. Although this value is assumed to be negligible, it can be estimated by measuring the total resolution and subtracting the other three contributions from it.

It follows that for achieving a total time resolution of at least 1 ps the condition below must be true:

$$\sqrt{R_{\text{slit}}^2 + R_{\text{jitter}}^2 + R_{\text{rest}}^2} < 995\,\text{fs}. \tag{2}$$

OPTICS OF THE NEW BUNCH LENGTH MEASUREMENT SETUP

A preliminary design assumed an optical system with a telescope and periscope in front of the streak camera [6]. The former reduced the beam profile of the light pulses and collimated them while the latter prevented a direct line of sight to the streak camera from the OTR screen. At the same time the streak camera could be located close to the floor of the accelerator hall which additionally protects the camera from radiation. Still, a radiation shielding around the streak camera was required to prevent gamma rays and neutrons from damaging the camera sensor at the end of the device.

After further simulations with the software OSLO (Optics Software for Layout and Optimization) [7] the optics were changed. Two main conditions must be met by the setup to be used in front of the streak camera:

- The light pulse created by the OTR screen has a large opening angle (14.6° in the lowest energy scenario). Collimating the light for transportation and focusing on the slit of the streak camera is required as soon as possible behind the screen window.
- The light pulse must be focused as small as possible through the input slit in front of the streak camera.

These conditions led to the current setup shown in Fig. 3. The refractive telescope was replaced by a mirror design because its focus on the streak camera slit was larger than with the purely reflective setup. At the same time the reflective setup can focus all wavelengths of the incident light and improve the accuracy of the bunch length measurement setup. The input optics of the streak camera include an achromatic relay lens which allows to make use of the independence from the wavelength. However, the input optics may be removed entirely. The alignment of the two off-axis parabolic mirrors in Fig. 3 was chosen so that aberrations caused by off-axis light beams could be counteracted [8]. At the focal point the spot size radius r of the on-axis light beams is 1.36 µm while the spot size radius of the off-axis light beams is 1.37 µm.

The contribution of the optical setup to the total resolution can be estimated with the acquired results. The screen at the end of the camera has a diameter d of 18 mm [9]. The slowest time the camera needs to streak over the screen in one cycle, T, is 100 ps. The contribution from the optical setup R_{slit} can be calculated following [10]

$$R_{\text{slit}} = \frac{T}{d} r, \tag{3}$$

resulting in a contribution to the time resolution of approx. 8 fs with the slowest streak speed. Further analysis of the setup in regards to tolerances in the components will be conducted before the necessary components are procured.

TIME JITTER FROM THE MASTER OSCILLATOR

The signal of an RF oscillator contains random fluctuations in phase. These are dependent on the offset frequency of the supplied carrier signal. An electrical device like the streak camera accepts a passband from the RF oscillator that contains these random fluctuations. This leads to a time jitter (or phase jitter) in the device which degrades the resolution of the measurement. A measurement of the time jitter from

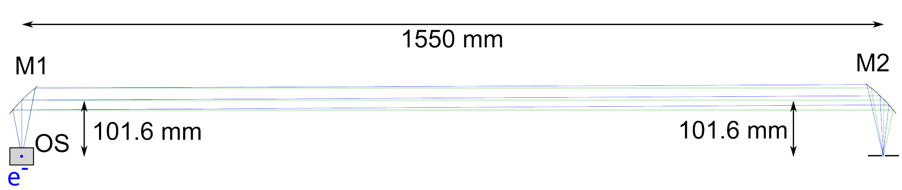

Figure 3: Sketch of the current optics setup in front of the streak camera. The rays shown are drawn by OSLO [7] and visualize the on-axis beams (green) and off-axis beams (blue). The latter are at a distance of 0.5 mm from the center of the electron spot on the target which is to be expected at the setup. Both mirrors are the same off-axis parabolic mirror with a focal length of 101.6 mm.

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the 2.9972(1) GHz master oscillator of the S-DALINAC at the commissioning location close to the main accelerator entrance was performed with a spectrum analyzer (Rohde & Schwarz FSV). A graph of the results from 120 min of measurements is shown in Fig. 4. The time jitter caused by the master oscillator is computed using the integration of the measured phase noise A following [11]

$$R_{\mathrm{jitter}} = \frac{10^{A/20}}{\sqrt{2}\pi f_0}. \tag{4}$$

Hereby, f_0 is the frequency of the master oscillator. Boundaries must be set for the integration. The upper integration limit is 200 kHz and is set by the passband of the streak camera. The lower limit is 100 Hz and was chosen because of anomalous behavior close to the carrier frequency. This is most likely caused by the phase noise of the reference oscillator inside the spectrum analyzer. A proper measurement method for phase noise close to the carrier frequency will be needed since this area has the most significant contribution to the time jitter. An average of 0.403(6) ps for R_{jitter} was calculated from the 120 min of measurements. While this value is still lower than the required total time resolution it is larger than the contribution from the optical setup. It is also a lower limit to the expected time jitter since the phase noise close to the carrier frequency could not be measured. This may increase the time jitter to a value over 1 ps. A new master oscillator with lower phase noise was procured. The time jitter of this device is yet to be measured and is expected to be smaller.

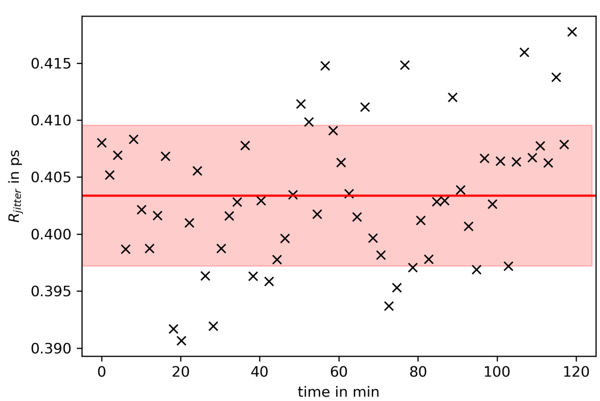

Figure 4: Measurements of R_{jitter} at 2.9972(1) GHz with a duration of 120 min. The phase noise for each measurement was integrated from 100 Hz to 200 kHz. The error band displays the standard deviation of the extracted average from all measurements.

CONCLUSION

A new setup for evaluating the bunch length behind the injector of the S-DALINAC is procured to improve 2×ERL operation by minimizing the bunch length. The optical setup in front of the streak camera and master oscillator of the S-DALINAC will have an impact on the total time resolution of the bunch length measurement. The optical setup was revised and will not significantly degrade the targeted resolution of 1 ps. Contributions from the master oscillator's time jitter have been estimated to amount to about 400 fs; however, future measurements close to the carrier frequency will need to demonstrate that the required resolution of better than 1 ps can be reached. A new master oscillator was procured and is expected to perform better than the current device [12].

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