ISBN: 978-3-95450-241-7 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2022-MOP26

# BUNCH LENGTH MEASUREMENT SYSTEMS AT S-DALINAC*

A. Brauch†, M. Arnold, J. Enders, L. E. Jürgensen, N. Pietralla, S. Weih
Technische Universität Darmstadt, Institute for Nuclear Physics, Darmstadt, Germany

*Abstract*

A high-quality beam is necessary for electron scattering experiments at the superconducting Darmstadt electron linear accelerator S-DALINAC. An optimisation of the bunch length to typical values of < 2 ps is performed to reach a high energy resolution of $10^{-4}$. Currently, this is accomplished by inducing a linear momentum spread on the bunch in one of the accelerating cavities. The bunch length can then be measured with a target downstream. This method is time consuming and provides only an upper limit of the bunch length. Two new setups for bunch length measurements will improve the optimisation process significantly. On the one hand, a new diagnostic beam line is set up in the low energy beam area. It includes a deflecting copper cavity used for measuring the bunch length by shearing the bunch and projecting its length on a target. On the other hand, a streak camera placed at different positions downstream the injector and the main linac will be used to measure the bunch length. Optical transition radiation from an aluminium coated kapton target is used to perform this measurement. The present layout of both systems and their current status will be presented in this contribution.

## INTRODUCTION

Since 1991 the institute operates the S-DALINAC for high-resolution electron scattering experiments [1]. It is a thrice-recirculating linear electron accelerator that produces a continuous-wave electron beam at a frequency of 2.997 GHz. The accelerator is designed to reach its maximum energy resolution of $10^{-4}$ with bunch lengths < 2 ps [2]. Currently, this property of the electron bunches is checked with a method involving the last cavities of injector and linac as well as a dispersion calibrated target. By operating these cavities 90° off-crest the length of the passing bunches is changed and made visible on the beam target. As a result, an estimate for the bunch length can be extracted. Although the method works and provides a useful result for accelerator diagnostics, it causes some difficulties:

- Because of the intrinsic transversal beam size of the bunch and broadening caused by the used targets, the bunch length measured is only an upper estimate.
- The bunch length is only determined at the position of the last cavities of injector and linac and must be extrapolated for other locations.
- The method does not allow for an evaluation of the bunch length when all cavities are operated as intended.

* Work supported by DFG (GRK 2128) and the State of Hesse within the Research Cluster ELEMENTS (Project ID 500/10.006).
† abrauch@ikp.tu-darmstadt.de

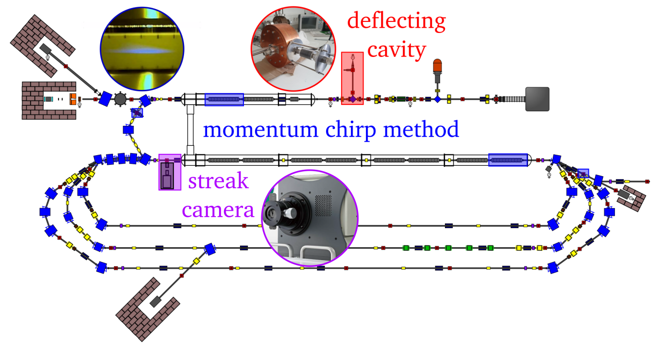


Figure 1: Floorplan of the S-DALINAC. The positions for the current method for bunch length measurements (picture from [3]) are highlighted in blue. The new methods using a deflecting cavity and a streak camera (picture from [4]) are planned to be used at the locations in red and purple.

To tackle these issues, two new devices for bunch length measurements are planned to be used at the S-DALINAC. One of these is a deflecting copper RF cavity that is placed in an upward diagnostic beam line (see Fig. 1). It will enable a bunch length measurement in the normal-conducting beam line area in front of the injector. While it is possible to do a bunch length measurement with the prebuncher this method also only provides an upper estimate of the bunch length [3]. Instead, the deflecting cavity will allow for a direct measurement of the bunch length. The width broadening caused by the target is planned to be eliminated by replacing the target with a wire scanner. The simulated properties of the diagnostic beam line and its current status will be presented in the following section. The other device is a streak camera used for the high energy areas of the accelerator. Therefore, the planned setup and its parameters will be presented here.

## SETUP FOR BUNCH LENGTH MEASUREMENTS IN FRONT OF THE INJECTOR

A sketch of the setup for bunch length measurements with the deflecting cavity is shown in Fig. 2. A dipole magnet, which can be used to lead the beam into the upward diagnostic section, is situated downstream a chopper prebuncher system. The magnet is broadening the beam in one transversal dimension. The energy resolution of the bunch can be estimated by measuring the width on the target. A deflecting copper cavity with its $TM_{110}$ mode imposes a shear on the bunch for the bunch length measurement.

ISBN: 978-3-95450-241-7 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2022-MOP26

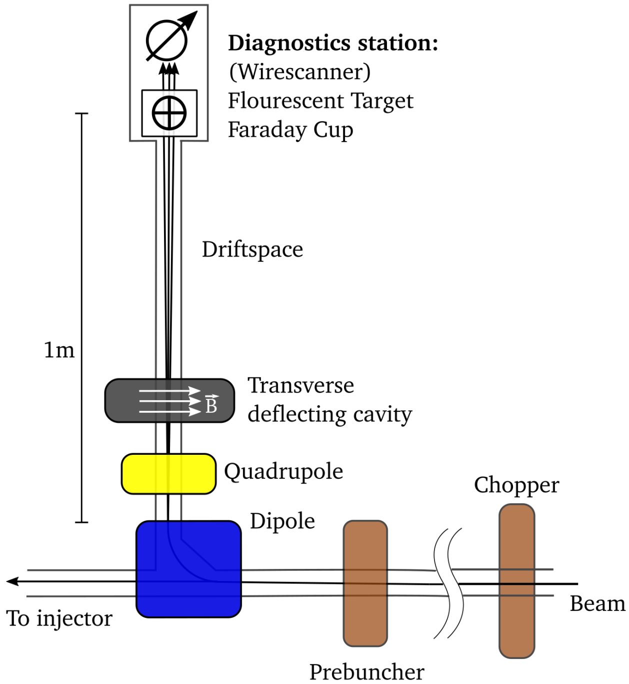


Figure 2: Sketch of the planned setup for bunch length measurements in front of the injector of the S-DALINAC (following [3]).

Likewise, the increased width in the other transversal dimension caused by the cavity is related to the bunch length. A quadrupole magnet is placed between the dipole magnet and deflecting cavity to improve the accuracy of the bunch length measurement (for details see below).

### *Simulation of Diagnostic Setup*

Using the particle tracking code ASTRA [5] (and elegant [6] for the dipole) the setup was simulated with various bunch configurations. The width and length of normal distributed electrons in a bunch can be given in terms of standard deviations. Here the bunch length is defined as $\sigma_{z_0}$ and the bunch width in one transversal dimension is given as $\sigma_x$ (here assumed as the x-dimension, for simplicity). The total width on the target at the end of the diagnostic setup is given by:

$$\sigma_x = \sqrt{\sigma_{x,0}^2 + \sigma_{x,TDC}^2} = \sqrt{\sigma_{x,0}^2 + \left(\frac{2\pi}{\beta\lambda}\frac{d\langle x\rangle}{d\varphi}\sigma_{z_0}\right)^2}. \quad (1)$$

$\sigma_{x,0}$ is the width of the bunch without the influence of the deflecting cavity. $\sigma_{x,TDC}$ is the width increase by shearing the bunch when it passes the deflecting cavity. Rearranging Eq. (1) for the bunch length yields:

$$\sigma_{z_0} = \frac{\beta\lambda}{2\pi}\frac{\sqrt{\sigma_x^2 - \sigma_{x,0}^2}}{\frac{d\langle x\rangle}{d\varphi}}. \quad (2)$$

This formula requires two measured values before the bunch length can be extracted. One of these is a derivative of the mean beam position as a function of the phase of the cavity that obeys the following relation:

$$\frac{d\langle x\rangle}{d\varphi} = l\frac{p_{x,0}}{p_z}. \quad (3)$$

$p_{x,0}$ is the deflecting momentum caused by the cavity. It depends on the phase $\varphi$ at which the deflecting cavity is operated. $p_z$ is the longitudinal momentum of the bunch in beam direction and $l$ is the length of the path between the target and the centre of the cavity. Instead of measuring the values on the right hand side of Eq. (3), the mean value in the deflected dimension of the projected bunch distribution $\langle x\rangle$ is measured. This is done for various values of $\varphi$ around the set point for the bunch length measurement. A linear fit is applied to the measured values and the slope of this fit is equal to the right hand side of Eq. (3). The derivative is determined easily during operation in this manner and this has to be done only once (unless the momenta are changed). The other value to be measured for using Eq. (2) is the intrinsic width of the bunch in the deflecting dimension $\sigma_{x,0}$. By switching off the deflecting cavity this value is evaluated on the target screen.

The simulations had the goal to check whether the proposed measurement setup can be realised under the conditions of the beam in this location. This was achieved by multiple simulations with increasingly complex bunch distributions with a particle size of 5000. The first tests used a Gaussian bunch with a point like transversal beam size (essentially the electrons are aligned like pearls on a necklace). For the final runs the whole area from thermionic gun to the target of the diagnostic section was simulated using a realistic bunch. Space charge effects were not considered due to the small charge of the S-DALINACs bunches (33 aC – 6.7 fC).

The simulations were performed with bunch lengths of 3.57 ps, 9.94 ps and 16.54 ps that cover the range of the expected bunch lengths at this setup. It was found that the intrinsic width of the bunches $\sigma_{x,0}$ is too large for an accurate measurement (at least a relative uncertainty of 10%). A good accuracy can only be obtained when $\sigma_{x,TDC} \gg \sigma_{x,0}$ according to other works [7]. As a result, a quadrupole magnet was added to the setup. Also the chopper in front of the diagnostic section is causing a initial shear on the bunches. This shear can either increase $\sigma_x$ or reduce it depending on the direction the deflecting cavity is shearing the bunch. The shear direction of the deflecting cavity is fixed by one of two possible set points of $\varphi$. The increased $\sigma_x$ will be called $\sigma_{x,+}$ and the reduced $\sigma_x$ will be called $\sigma_{x,-}$ from now on. The initial shear of the chopper is compensated by measuring $\sigma_{x,+}$ as well as $\sigma_{x,-}$ and use their mean value to calculate the bunch length [8]. Finally, the simulated beam images have a size that is barely fitting into the installed beam pipe in the diagnostic section. Since the radiation caused by the electrons hitting the beam pipe with an energy of 250 keV is not inhibiting the measurement, the beam pipe diameter will not be increased. The low currents in the µA-range used for the measurement will also lead to only minor amounts of radiation.

11th Int. Beam Instrum. Conf. IBIC2022, Kraków, Poland JACoW Publishing
ISBN: 978-3-95450-241-7 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2022-MOP26



The extracted bunch length measurements from the images are summarised in Table 1. The simulated bunch distributions on the target screen are given in Fig. 3.

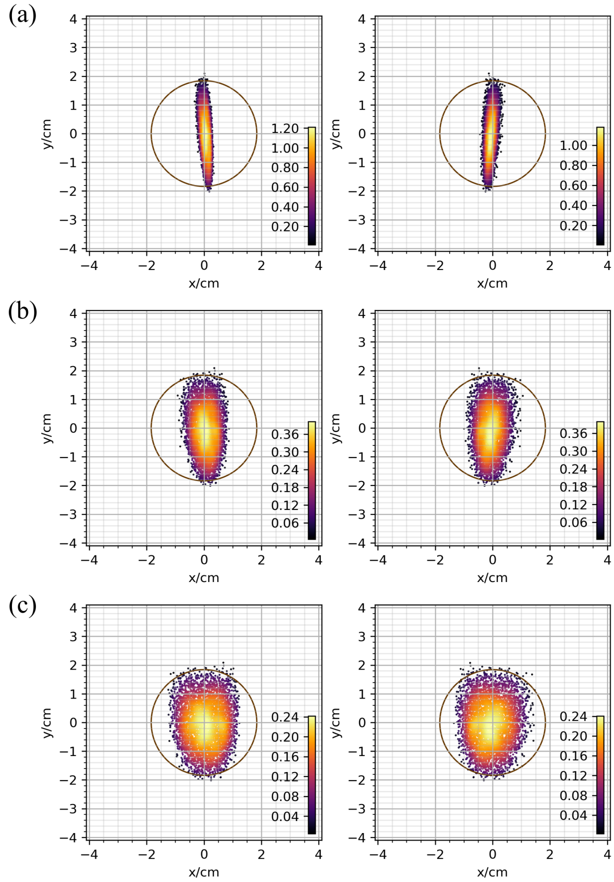


Figure 3: Distribution of the electrons hitting the target at the end of the diagnostic section. Cases (a)-(c) are identical to the cases shown in Table 1. The left side shows the set point of $\varphi$ leading to the larger width $\sigma_{x,+}$ on the screen. The right side shows the set point of $\varphi$ leading to the smaller width $\sigma_{x,-}$ on the screen. The brown circle shows the beam pipe currently installed in the diagnostic section. The normalised relative density is shown in the colours of the dots and has arbitrary units. The simulation results for these figures can be found in Table 1.

Table 1: Simulation results from the images in Fig. 3. The tested bunch lengths $\sigma_{z_0,\mathrm{code}}$ do not deviate more than 2% from the measured bunch lengths extracted from the images $\sigma_{z_0,\mathrm{screen}}$. $\sigma_{x,+}$ and $\sigma_{x,-}$ are the image widths on the beam target for each set point of $\varphi$ that are used to calculate $\sigma_{z_0,\mathrm{screen}}$.

| cases | (a) | (b) | (c) |
|---|---|---|---|
| $\sigma_{z_0,\mathrm{code}}$ | 3.57 ps | 9.94 ps | 16.54 ps |
| $\sigma_{z_0,\mathrm{screen}}$ | 3.57 ps | 10.01 ps | 16.88 ps |
| $\sigma_{x,+}$ | 4.50 ps | 11.84 ps | 18.71 ps |
| $\sigma_{x,-}$ | 4.07 ps | 11.34 ps | 18.11 ps |

# SETUP FOR BUNCH LENGTH MEASUREMENTS BEHIND THE INJECTOR UP TO 10 MeV

Because of the high energies behind the injector a different setup at this position is planned to be used for bunch length diagnostics. This setup involves the use of a streak camera that transforms light pulses with a photocathode into low energy electron bunches. These bunches are deflected with a pair of electrodes and hit a phosphor screen where the bunch length can be read out. Figure 4 shows a sketch of the streak camera.

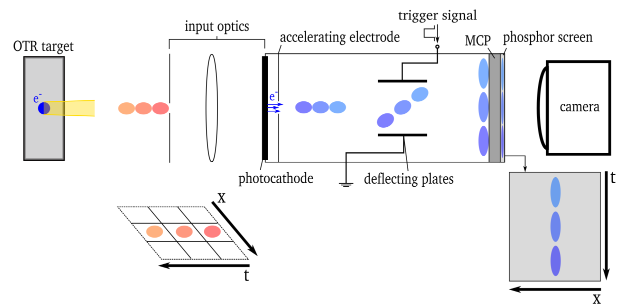


Figure 4: Sketch of a streak camera and its internal setup. Photoelectrons are created and deflected with a pair of electrodes to enable the measurement of the bunch length on a phosphor screen (following [4]).

Because of the camera being only receptive to visible light the electron bunches behind the injector must be transformed to light pulses. This will be achieved by using optical transition radiation (OTR) targets. They conserve the temporal structure of the bunch and are implemented in S-DALINAC already for emittance measurements. This light must be transported to the slit in front of the streak camera via a telescope and periscope. The former reduces the transversal size of the light pulse and improves the accuracy of the measurement just like the quadrupole magnet does for the deflecting cavity. The latter is used to prevent a direct line of sight between camera and target. This prevents radiation from the direction of the target from causing damage to the device. Covering the camera beneath a massive lead shielding prevents radiation from any other direction from entering the camera. The last mirror of the periscope will be an off axis parabolic mirror focusing the light pulse directly on the slit of the camera.

To be able to measure the typical bunch lengths of the accelerator, a resolution of $\leq 1$ ps is required. Multiple factors contribute to the resolution of a streak camera, but the most important factor is the slit size in front of the camera. This resolution factor $R_{\mathrm{slit}}$ can be estimated by multiplying the whole slit width $b_{\mathrm{slit}}$ with the velocity $v_{\mathrm{streak}}$ the camera deflects the bunches over its screen at the end of the device.

$$R_{\mathrm{slit}} = b_{\mathrm{slit}} v_{\mathrm{streak}} \tag{4}$$

ISBN: 978-3-95450-241-7 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2022-MOP26

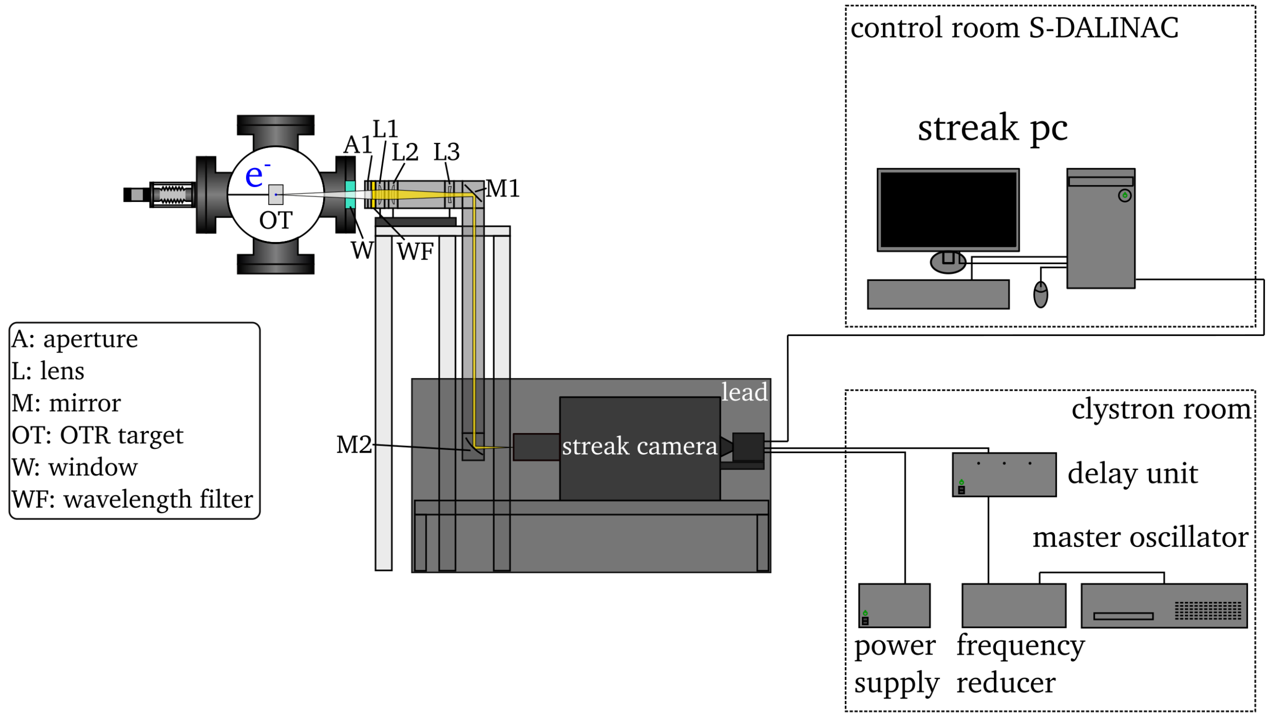


Figure 5: Proposed setup for a streak setup to measure bunch lengths via OTR targets. The created light pulses enter a telescope followed by a periscope leading the light to the streak camera close to the floor. The last mirror in the periscope is concave so that the light is focused on the small entrance slit of the camera.

Using $v_{\text{streak}}$ of the proposed device (C10910 by Hamamatsu) and a resolution value of 1 ps one would require a slit width of 94.4 µm. This highlights the necessity of the optics setup in front of the camera. Figure 5 shows the proposed setup for the streak camera.

## CONCLUSION

For a high-quality beam at the experimental sites of the S-DALINAC the bunch length must be optimised to a value of < 2 ps. In front of the injector a diagnostic section with a deflecting cavity will enable measurements of the bunch length. Simulations of this section revealed the necessity of a quadrupole magnet because of the large beam width decreasing the accuracy of the measured bunch lengths. For the superconducting areas of the accelerator a setup involving a streak camera is planned to be used. Because of the required resolution and the vulnerability of the camera a telescope-periscope setup is intended for the device.

## REFERENCES

[1] N. Pietralla, "The Institute of Nuclear Physics at the TU Darmstadt", *Nucl. Phys. News*, vol. 28, no. 2, pp. 4–11, 2018. doi:10.1080/10619127.2018.1463013

[2] F. Hug, "Erhöhung der Energieschärfe des Elektronenstrahls am S-DALINAC durch nicht-isochrones Rezirkulieren", Ph.D. thesis, Technische Universität Darmstadt D17, Darmstadt, Germany, 2013.

[3] S. Weih, "Injector Optimization at the Superconducting Darmstadt Linear Electron Accelerator S-DALINAC", Ph.D. thesis, Technische Universität Darmstadt D17, Darmstadt, Germany, 2022.

[4] Hamamatsu Photonics K.K., Universal streak camera C10910 series, https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/sys/SHSS0016E_C10910s.pdf

[5] S. M. Lidia, K. Floettmann, and P. Piot, "Recent Improvements to the ASTRA Particle Tracking Code", in *Proc. PAC'03*, Portland, OR, USA, May 2003, paper FPAG015, pp. 3500–3502.

[6] M. Borland, "ELEGANT: A flexible SDDS-compliant code for accelerator simulation", Argonne National Lab., IL, USA, LS-287, 2000. doi:10.2172/761286

[7] D. Marx *et al.*, "Lattice considerations for the use of an x-band transverse deflecting structure (TDS) at SINBAD, DESY", *J. Phys.: Conf. Ser.*, vol. 874, p. 012078, 2017. doi:10.1088/1742-6596/874/1/012078

[8] D. X. Wang *et al.*, "Measurement of femtosecond electron bunches using a rf zero-phasing method", *Phys. Rev. E*, vol. 57, pp. 2283–2286, 1998. doi:10.1103/PhysRevE.57.2283