# STUDIES FOR A WAKEFIELD-OPTIMIZED NEAR-FIELD EO SETUP AT THE ANKA STORAGE RING

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*Abstract*

ANKA, the synchrotron light source of the Karlsruhe Institute of Technology (KIT), is the first storage ring with a near-field single-shot electro-optical (EO) bunch profile monitor inside its vacuum chamber. Using the method of electro-optical spectral decoding, the current setup made it possible to study longitudinal beam dynamics (e.g. microbunching) occurring during ANKA's low-alpha-operation with sub-ps resolution (granularity). However, the setup induces strong wake-fields spanning the distance between consecutive bunches which cause heat load to the in-vacuum setup for high beam currents. This heat load in turn leads to a laser misalignment thus preventing measurements during multi-bunch operation. Fortunately, the EO setup also allows us to directly study these wake-fields so simulation results can be compared to measurement data. This paper reviews a possible redesign of the setup, aiming to reduce the effects of the wakefield.

## INTRODUCTION

An in-vacuum setup for for electro-optical bunch profile measurements is in regular operation at the ANKA storage ring since its installation in 2013 [1]. The measurement is based on the Pockels effect – a crystal becomes birefringent when it is exposed to an electric field. When a laser pulse is sent through the crystal, this birefringence then turns the linear polarization of a laser pulse into an elliptical one. At ANKA, a 5 mm thick Gallium Phosphide (GaP) crystal and a near-infrared laser (central wavelength 1030 nm) are used.

There are two possible measurement options: Electro optical sampling can be used to span time ranges of multiple nanoseconds. Here a short laser pulse is delayed with respect to the bunch arrival time and samples the electric field inside the electro optical crystal over many revolutions. Electro optical spectral decoding on the other hand allows to measure the bunch profile in a single shot. Here a long, chirped laser pulse is used. Afterwards one can reconstruct the time information by using a single shot spectrometer [2]. Using this mode it is possible to resolve substructures on the electron bunch, that only persist for a small number of revolutions [3].

Until now, the usage is limited to single-bunch operation. During the first measurements that were performed during multi-bunch operation, a decrease of the signal intensity was observed. The reason is that the laser has to be coupled into an optical fiber after passing the free space part inside the vacuum chamber. This step is very sensitive already to small misalignments, but the setup itself generates long ranging wakefields which cause the setup to heat up and makes misalignments unavoidable [4]. To overcome this limitation, a wakefield-optimized near-field EO setup is designed from scratch. A second design goal is a fast decrease of the wakefields' amplitude, to minimize biases when measuring electron bunches with a spacing of 2 ns.

For simulation and design, *CST Particle Studio* [5] is used. Its wakefield solver assumes a gaussian bunch shape (RMS bunch length $\sigma_z$) and can derive time dependent electromagnetic fields at defined points in space. Furthermore it computes the impedance and the integral over the longitudinal wake potential [6]

$$k_l = \frac{1}{\sqrt{2\pi}\sigma_z} \int_{-\infty}^{\infty} W_\parallel \exp\left(-\frac{s^2}{2\sigma_z^2}\right) \mathrm{d}s, \qquad (1)$$

which is called the wake loss factor. To calculate the power an electron bunch looses by traveling through the structure, the correlation $P = k_l \times Q_b^2 \times f$ can be used, where $Q_b$ is the bunch charge, and $f$ the frequency bunches are passing by.

## THE INSTALLED SETUP

The setup currently in operation has been designed by PSI and DESY for electro-optical bunch length measurements at SwissFEL and the European X-FEL [2]. The in vacuum part consists of a holder for the electro optical GaP crystal and a prism with a silver coated surface, which serves as a mirror.

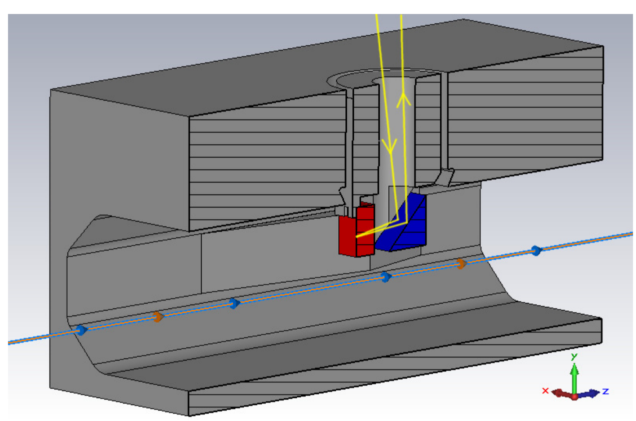

Figure 1: Cut through the beam pipe and the installed EO setup. The electron beam travels from the left to the right, the laser (yellow) enters from the top, is reflected at the mirror (blue), transverses the GaP crystal (red), is reflected at its back side and then travels back the same way.

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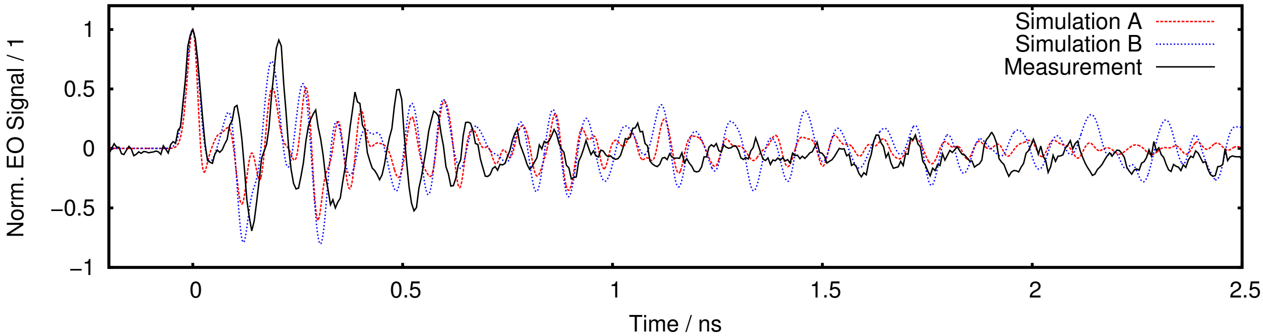


Figure 2: Signal of the installed EO setup, normalized to the first peak (Coulomb-peak at $t = 0$). For *Simulation A* and *B* the bunch length is set to 3.4 mm respectively 4.5 mm, which are both possible values for the (non-constant) bunch length. Furthermore the position of the line where the laser passes the crystal differs by about 2 mm. Note that *Simulation B* matches the measured curve better for small times but has the tendency to overestimate the amplitude of the wake fields at later times, while it is the other way around for *Simulation A*.

A CAD drawing is shown in Fig. 1. For ANKA an impedance protection has been added, that allows to protect the setup and makes sure that it does not influence the beam when it is not in use.

The wake loss factors of this setup for different bunch lengths are shown in Fig. 5, where they are compared to the ones of the optimized setup. For the measurements presented in this paper, a heat load of $P = 2.15$ W per bunch is calculated ($\sigma_z \approx 3.5$ mm, $Q_b \approx 860$ pC).

To simulate the EO signal in *CST Particle Studio* a line of field probes recording $E_y$ is placed along the line where the laser passes the crystal. To have a realistic model of the modulation, one has to take into account the speed of the laser light while integrating over the laser path. Defining the point in time when the laser hits the reflecting surface of the crystal as $t = 0$ one yields an EO signal $M$ with

$$M \propto \int_{-T}^{T} E_y\left(z(t), t\right) dt = \int_{-T}^{T} E_y\left(\frac{c_0}{n} \times |t|, t\right) dt, \quad (2)$$

where $T$ is the time, the laser needs to pass through the crystal in one direction, and $n$ is the refractive index of GaP. The result of this method can be seen in Fig. 2. The first peak corresponds to the Coulomb field of the electron bunch, the ringing is due to wakefields.

The differences between simulation and measurements might be explained in several ways. First of all, there are and always will be differences between the CAD model and the real setup. For example the (small) angle between incoming and outgoing direction of the laser has been neglected. Also the absolute position where the laser passes the crystal is not known very precisely. As the effects of those differences accumulate, they play a bigger role for later times. Secondly, the bunch is constant in the simulation, in the measurement however, as a sampling method is used to span the wide range, bunch charge is decreasing with every sampling point. And while the decreasing signal strength has been corrected in the measurement data, this cannot be done for the decreasing bunch length.

## THE OPTIMIZED SETUP

As the currently used arm mount is part of the beam pipe, it should not be altered. Especially the impedance protection has to be kept. Besides this constraint the optimized EO arm is designed from scratch, iteratively searching the optimal values for a limited number of components. The components were added step by step, being optimized on the basis of the previous optimum.

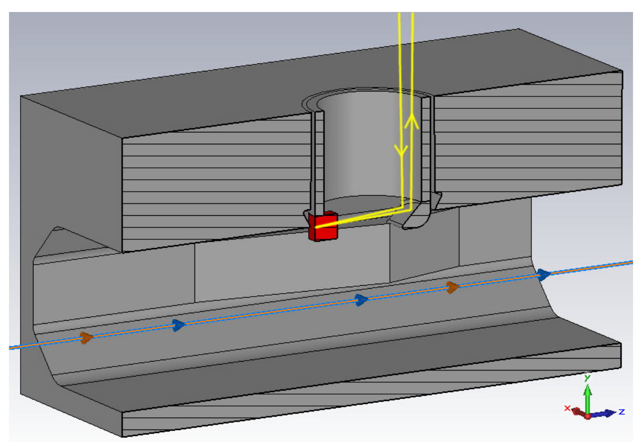

Figure 3: Cut through the beam pipe and the optimized EO setup. The electron beam and the laser travel similar to the one in Fig. 1. The mirror is now integrated into the arm, while the opening has been enlarged to allow the wake energy to leave the measurement area.

The final optimized setup is shown in Fig. 3. The mirror has been integrated into the arm, and there is a direct line of sight from large areas of the crystal to the exit of the setup at the top side. Furthermore the diameter of the hole has been increased from 10 mm to 24 mm. All these measures are taken so that the wakefield can propagate out of the measurement region as fast as possible.

Furthermore the crystal width, height and thickness are changed from $\Delta x \times \Delta y \times \Delta z = 10 \times 10 \times 5\,\mathrm{mm}^3$ to $\Delta x \times$

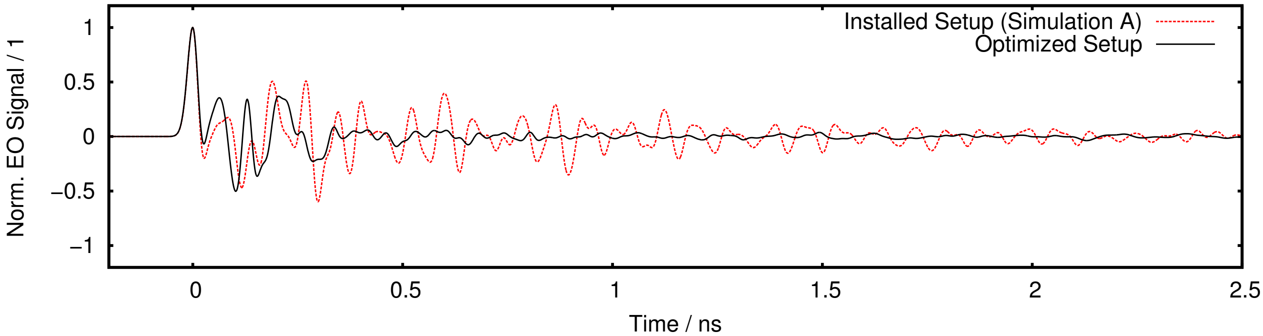


Figure 4: Simulated signal of the optimized and the currently installed EO setup (*Simulation A* from Fig. 2). Especially note the decrease of the remaining wakefield at $t \approx 2$ ns, where a trailing bunch would be located.

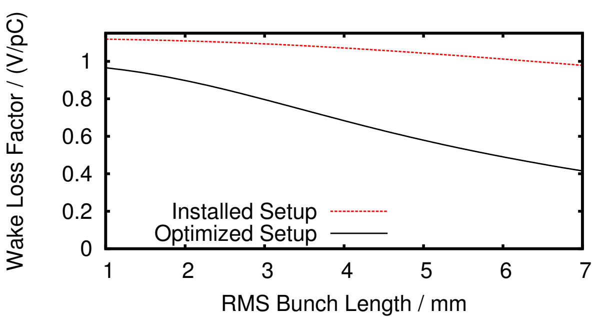


Figure 5: Wake loss factor of the installed and of the optimized setup. As in short bunch operation long bunches usually correspond to most bunch charge, a low wake factor is most important for longer bunches.

$\Delta y \times \Delta z = 5 \times 5 \times 5\,\text{mm}^3$. As the field is damped inside the crystal, this increases the expected signal. Additionally the decreased volume stores less energy.

While offering the same signal strength, the new geometry has a significantly lower wake loss factor (see Fig. 5) than the currently installed one. For the measurements presented in this paper the expected heat load would be reduced from 2.15 W to 1.48 W per bunch. Also note that the wake loss factor for long bunches improves more than for short bunches. This is a very useful feature, because the bunch lengths scales less than proportional with the bunch charge ($\sigma_z \propto Q^{3/7}$ in microbunching regime), but power loss for a given bunch lengths scales quadratically with bunch charge (see Eq. ). So when the bunch lengthening is taken into account, one will expect $P \propto \sigma_z^{14/3}$.

The temporal development of the wakefield of a single bunch can be seen in Fig. 4. For the optimized setup the amplitude decreases much faster, dropping below 30 % of the amplitude of the Coulomb peak already after 0.23 ns (installed setup: 0.90 ns), and below 10 % after 0.32 ns (installed setup: 1.77 ns).

## CONCLUSION AND OUTLOOK

The suggested, optimized setup fulfills both design goals: It reduces the wake loss and features a fast decreasing wakefield inside the EO crystal. This combination will allow to reliably carry out near field EO bunch profile measurements in multi bunch operation, leading to deeper insight into possible bunch-bunch interaction during microbunching. There are still some minor adjustments planned, e.g. to simplify manufacturing the setup. Also an off-line characterization is planned, before finally installing the new EO arm into the ANKA beam pipe.

## ACKNOWLEDGMENTS

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