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A RECTANGULAR WAVEGUIDE WITH DIELECTRIC COATINGS AS A DEDICATED WAKEFIELD DECHIRPER AT ELBE*

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Abstract

Based on the Rayleigh-Ritz method and an eigenmode expansion of the wake function, we devised a semi-analytical description of the wakefield inside a dielectrically lined rectangular waveguide. We implemented this method and employed it to determine the geometrical parameters of a dedicated dechirper for the use at the light source ELBE in Dresden-Rossendorf. In 2016, a construction team at ELBE built a dielectrically lined rectangular waveguide with the given geometry. Subsequently, we carried out experiments with this prototype at ELBE. In this contribution, we present the model structure and compare the results obtained semi-analytically with experimental data.

INTRODUCTION

At ELBE, the linear accelerator facility of the Helmholtz-Zentrum Dresden-Rossendorf (HZDR), in particular, planned laser-plasma experiments and combined ELBE-laser experiments (e.g. on Thomson scattering) make an optimal compression of both the beam's length and energy width necessary. Relating to the typical bunch compression procedure using magnetic chicanes a general conflict exists, as this scheme basically sacrifices a narrow energy spread for small bunch lengths. The energy width is even significantly increased as the induced chirp 'survives' the chicane.

Previous to considering dechirpers for the task of reducing the final energy spread of the particle bunch, the above-mentioned issue was often solved by running the electron beam off-crest in an additional radio-frequency module driven at a higher harmonic of the accelerating mode. Yet, this method is inefficient concerning the ratio between its cost and the improvements to the beam quality as it is expensive both financially and spatially, and requires additional maintenance efforts.

A different concept that fulfils the purpose of reducing the energy spread of a particle beam is the so-called 'dechirper'. In this comparatively simple waveguide structure a wakefield is generated through either dielectric coatings or periodic corrugations in its walls.

Figure 1 serves to illustrate the general principle of the dechirper: before entering the dechirper, the head of the bunch has a lower energy than the tail, which constitutes the initial chirp. This bunch now passes through a dechirper structure and generates a wake potential, c.f. [1]. Along the uniform bunch profile the wake potential is nearly linear and corresponds to an energy loss. Depending on the position of

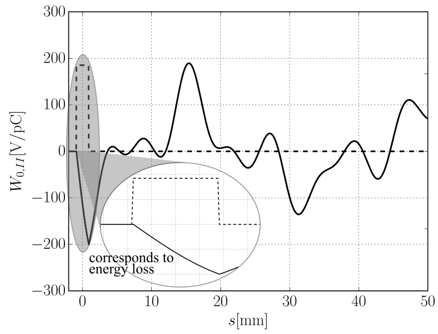

Figure 1: The longitudinal wake potential $W_{0,||}$ of an arbitrary uniform bunch generated in a rectangular dechirper. The zoomed-in part of the wake potential along the bunch shape (dashed line) corresponds to an energy loss.

the particle in the bunch, this energy loss differs. Particles in the tail of the bunch generally experience a larger energy loss. Overall, this energy modulation counteracts the original chirp of the bunch and reduces the energy spread.

The corrugated form of a cylindrical dechirper was proposed by Bane et al. as a dechirper for the NGLS at SLAC in [2]. In 2014, a scientific cooperation with a second group from Berkeley and the PAL in Korea, was able to implement a rectangular waveguide with corrugated walls as a dechirper at the PAL-FEL, [3].

Also in the year 2012, Antipov et al. suggested the use of a dielectrically coated rectangular waveguide as a silencer for the FACET (c.f. [4]) and reported on first successes of a cylindrical, dielectrically lined dechirper structure at the ATF at BNL, [5]. In [7] and [8], the same authors report on tests with an alumina-coated rectangular waveguide at ATF and show first experimental results for the tuning of the gap width of the dechirper and the resulting adjustment of the final wakefields determining the dechirp.

Despite these first experiments mentioned above, wakefield dechirping still remains a new field of study.

In cooperation with the HZDR, we started studies on both, the analytic properties of the dielectrically lined rectangular dechirper and its applicability for the specific situation at the ELBE accelerator facility, in 2013 (c.f. [9] and [10]). Subject of the research presented in this work is the dechirper prototype that the ELBE team constructed in 2016 which has subsequently been used in measurement experiments.

THE DECHIRPER PROTOTYPE USED AT ELBE

The general geometry of a rectangular waveguide with dielectric coatings can be seen in Fig. 2. The outer waveguide

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is made of a highly conductive metal, in case of the ELBE dechirper aluminium. The dielectric plates are mounted to the top and bottom of the waveguide. Mechanical drives allow for a manipulation of the gap width between these two dielectrics.

The dechirper, which has a length of $L = 80$ cm, is inserted into the beam line within a cylindrical vacuum chamber. This chamber has a diameter of 10 cm, which limits the width of the dechirper and the maximum achievable gap width. A width of $a = 5$ cm has been chosen. The vacuum chamber also holds mechanical drives that allow for a tuning of the distance between the two dielectric plates even after the dechirper has been taken into operation. These drives also make it possible to close the dechirper entirely and bring the closed dechirper towards one side of the vacuum chamber. This removes it from the beam path far enough for it to have a negligible effect on the dechirper, and thus makes it possible for the dechirper to remain inside the beam line of ELBE even if no experiments with it are being performed. To simplify the geometry and the construction process, the terminating walls in x-direction have been left out in the prototype. The necessary electric termination in this transversal direction is instead provided by the walls of the vacuum chamber. Parameter studies have been performed to ensure that this deviation from the used model has no significant influence on the experimental results. These showed that the wakefield is not influenced by the width of the dechirper once a certain threshold is passed.

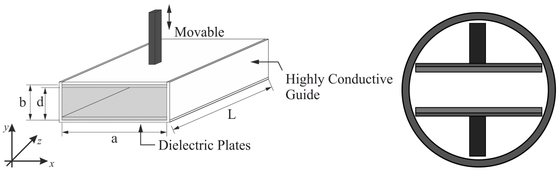

Figure 2: Left: Schematic depiction of the general model of a rectangular dechirper (with a length L, a width a and a total height of b) with dielectric coating (thickness $b - d$). Right: Schematic profile of the dechirper prototype inside the vacuum chamber.

Under these conditions and taking the mechanical drives into consideration, the maximum achievable gap width at ELBE was limited to 35 mm.

The coating material needs to be suited for the use in ultra-high vacuum. Especially glass-ceramics were considered in the design process due to their low propensity to outgas. In the end, MACOR was chosen for the dielectric coating. Its dielectric constant is $\varepsilon_r = 6$ for the used sample, which is comparable to the permittivity of diamond, which has previously been proposed in [4].

The samples of MACOR used for the dechirper prototype at ELBE have a thickness of $b - d = 3$ mm (where b denotes the total height of the dechirper and d the position of the upper dielectric). The choice of this parameter has been subjected to manufacturing limitations. Parameter studies have been performed that indicate that thicker layers, as used in this particular dechirper, are more favourable for the chosen dielectric.

The expected short-range wake potentials in this dechirper (gap width 12 mm) for different shapes of the electron pulse can be seen in Fig. 3. These theoretical benchmarks have been computed with our code *WIzaRD*, which calculates the wake function inside the dielectrically lined rectangular dechirper semi-analytically. *WIzaRD* is based on the fact that the eigenmodes of the here observed dechirper type can be analytically described, and computed semi-analytically. The wake function is then expanded into a series of these eigenmodes, which has the advantage that it delivers an analytical expression for the wake function. A detailed description of the algorithm behind *WIzaRD* can be found in [6].

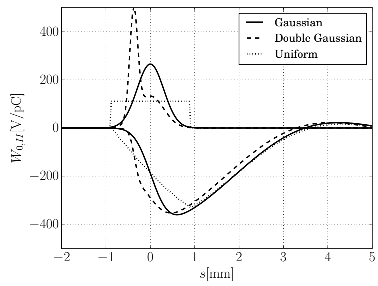

Figure 3: Wake potentials of different bunch shapes (solid line: Gaussian, dashed line: double Gaussian, dotted: uniform) of the same length derived from a convolution with the wake function of the model structure. The maximum amplitudes of the wake potentials over the length of the bunches are very similar for the different distributions, since these are dependent on the overlap of the wake function and the shape functions of the bunches, which have to be normed to the same area. The slopes of the wake potentials radically differ since they depend on the shape of the pulse.

Another aspect that should be mentioned is that at the maximum achievable gap width of 35 mm there will still be a wakefield generated inside the dechirper. Yet, its effect may be assumed to be very small and will thus be neglected. The state of the maximally opened dechirper will be regarded as the state of a 'turned off' dechirper, as a complete removal of the dechirper from the beamline as described above would require additional adjustments of the beam.

EXEMPLARY PHASE SPACE COMPUTATIONS

In this section, we present exemplary phase space computations that illustrate the dechirper effect on different bunch shapes. For this, the programme *WIzaRD* has been utilised to calculate the wake function of an exemplary dechirper for different gap widths.

The energy shift introduced by the dechirper is proportional to the wake potential and the proportionality factor is the total charge of the pulse. This means that the form of the energy shift results directly from the particle distribution (c.f. Fig. 3) and, by implication, has nothing to do with the initial energy distribution of the particle bunch, and neither with the total energy of the pulse. This means for the following phase space studies, the energy distribution of the particle beam can be chosen arbitrarily.

For the phase space of the test bunch in our studies, 1000 particles were created and randomly assigned a position according to the particle distributions introduced in the previous sections, and an energy according to a fixed energy distribution. This distribution has been chosen such that the effect of the dechirper is most easily visible for a total charge of

$$q_p = 100\,\text{pC},$$

which is the maximum achievable bunch charge of the ELBE thermionic gun that has been available for the experiments. More specifically, a Gaussian with a standard deviation of

$$\sigma_E = 1.6\bar{6}\,\text{keV},$$

and a mean of

$$\mu_E = 5\,\text{keV},$$

has been chosen. This Gaussian was then imprinted with an energy chirp. This chirp has been introduced as a uniform increase in energy starting from $E_{low} = 100\,\text{keV}$, at the head of the bunch and ending at $E_{high} = 220\,\text{keV}$, at the tail of the bunch. The total energy width of the beam is thus 120 keV. The resulting position-dependent energy variation was then added to the original energy distribution and stored for all particles of the beam.

The initial phase space created in this way is then modulated using the wake potentials of different bunch shapes. Here, a single Gaussian profile (referred to as bunch 1 from now on), a double Gaussian (bunch 2) and a uniform particle distribution (bunch 3) of the same total lengths were used. The discretely computed wake potentials are interpolated using a one-dimensional, linear interpolation. This energy change is then added to the initial energy of the particle. This procedure is additionally performed for several gap widths to show the different behaviours of the dechirper in these cases. The gap widths 6 mm, 12 mm and 35 mm have been chosen as examples. The resulting phase spaces for the initial particle distribution and the dechirped beam are shown in the following figures.

Figure 4 shows the dechirping effect of the structure on the model Gaussian with the given energy distribution. The energy modulation is stronger with increasing gap width. The non-linear behaviour of this effect with respect to the gap width is also clearly visible. For a gap width of 35 mm, the effect of the dechirper on the phase space of the particle bunch is nearly negligible; just a slight modulation of the energy in the range of a few keV can be seen. This modulation is, as could be expected from Fig. 3, stronger at the tail than at the head of the bunch. A reduction of the gap width to 12 mm increases the effect of the dechirper. The curvature of the wake potential, also depicted in Fig. 3, is clearly imprinted on the formerly linear energy chirp. In the central region of the bunch between −0.5 mm and 0.5 mm, the

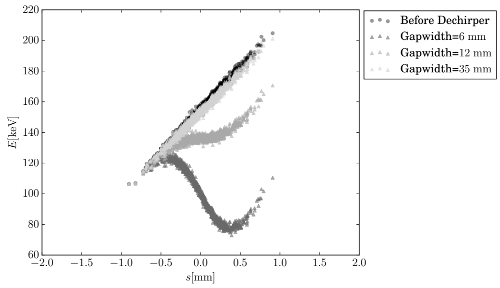

Figure 4: Phase space of bunch 1 before and after the model dechirper with varying gap widths. The overall energy reduction caused by the dechirper is, as intended, stronger on the tail of the bunch than on its head. The curvature of the wake potential shown in Fig. 3 is clearly visible in the curved, wave-like behaviour of the phase space after dechirping. Increasing the gap width from 6 mm to 12 mm significantly reduces the effect of the dechirper, increasing it further to 35 mm nearly completely negates it.

nearly uniform slope of the wake potential of the Gaussian pulse nearly compensates for the initial chirp, leading to a minimal energy width of ≈ 20 keV in this region. This does not, however, include the head and tail of the bunch, which due to the curvature of the Gaussian pulse, increase the total energy width to ≈ 80 keV for the total pulse. Decreasing the gap width even further to 6 mm again significantly increases the effect of the dechirper, so much in fact that it overcompensates the initial chirp and leads to a new chirp in the opposite direction, where the tail of the bunch has a lower energy than the head. This new phase space has now an energy width of ≈ −60 keV. This shows again the significant influence of the gap widths on the overall effect of the dechirper and the power of the tuning: within a range of just 3 cm of gap width, the initial energy chirp of the bunch can be either nearly left uninfluenced up to already significantly overcompensated by the dechirper.

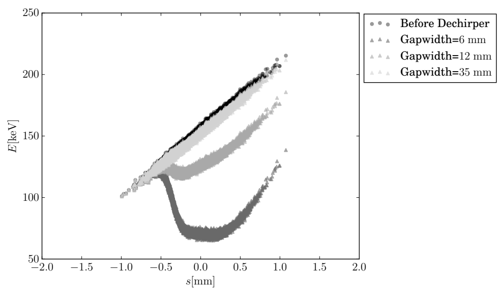

Figure 5: Phase space of bunch 2 before and after the model dechirper with varying gap widths. The curvature of the wake potential is visible in the behaviour of the phase space after dechirping, leading to a valley-like region in the centre of the dechirped phase space. An increase in the gap width again significantly reduces the effect of the dechirper.

Figure 5 shows a similar study conducted for the double Gaussian particle distribution. The effect of the dechirper with varying gap widths is again clearly visible, from a nearly negligible effect at 35 mm to a very strong overcompensation of the initial chirp at 6 mm gap width. The behaviour of the wake potentials is again imprinted on the phase space after the dechirper. In the case of the 6 mm gap width it leads to a valley of nearly constant energy after the dechirper in the region between about −0.3 mm to 0.3 mm, which coincides with the second of the two Gaussians and subsequently the flatter part of the slope of the wake potential. Like for the single Gaussian, though, at the head and tail of the bunch, the energy width of the dechirped phase space increases to ≈ −50 keV. And even if the mentioned valley does have a very low local energy width, the global mean energy width was nevertheless reduced to just ≈ 60 keV.

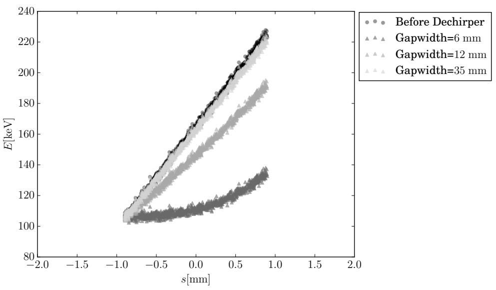

Figure 6: Phase space of bunch 3 before and after the model dechirper with different gap widths. Despite the uniform particle bunch, the dechirped phase space for the lowest gap width clearly shows a curvature.

Figure 6 shows the effect of the dechirper with varying gap widths on a uniform particle bunch. Again, the influence of the gap is easily visible. Due to the uniform pulse and its wake potential displayed in Fig. 3, the dechirped pulses show the least curvature compared to the other pulse forms. For the two larger gap widths, nearly no curvature is discernible, though for a gap of 6 mm width, it is clearly visible. This curvature results from the non-linearity of the wake function and has nothing to do with the shape of the pulse itself. What does influence this curvature, and thus the wake potential, is the length of the pulse compared to the length of the first flank of the wake function. For this pulse, the length of the pulse coincides with nearly the total length of the first flank of the wake function, and thus, all non-linearities in that region will influence the wake potential.

EXPERIMENTAL SET-UP

The measured quantity in the experiments conducted at ELBE was the particle energy spectrum of the beam. The dechirper effect, as shown in the previous sections, basically amounts to an overall energy loss and a narrowing of the energy width of the beam. In the energy spectrum, this would correspond to

1. a decrease of the average energy, and

2. a decrease of the standard deviation of the beam energy.

Depending on the gap width of the dechirper and the bunch charge of the particle beam, these changes will be more or less pronounced.

In the experiments, the studied bunches were generated by a thermionic particle gun. The maximum achievable pulse charge was limited to ≈ 100 pC. With previous parameter studies in mind, this corresponds to an energy loss of ≈ −40 keV that the particles of the bunch can maximally experience for an average gap width. This is very small compared to the usual chirp of the ELBE beam during normal operation, which is in the range of several MeV.

The small effect of the prototype compared to the usual chirp at ELBE poses an experimental challenge: the variations in the dechirp created by adjusting the gap width are insignificant compared to the initial chirp. To compensate for this, both the chicane and the second module were deactivated, so that a particle bunch without an initial chirp was used during the experiments. This has the advantage that the effect of the dechirper could be measured directly, and not in correlation with the initial chirp of the beam.

On the other hand, this also changes the objective of the experiments. The action of the dechirper on the particle beam can generally be understood as a summation of the phase space profile and the dechirp. This means that while the energy width of the initially chirped beam is compensated by the dechirp, the initially unchirped beam is imprinted with the profile of the dechirp. The general energy loss of the particles is not affected by whether or not the beam is initially chirped, so that a general decrease in the average energy of the spectrum of the particle bunch can still be expected. However, instead of narrowing the energy width of the spectrum, the dechirper will imprint the beam with its own phase space profile, and thus *widen* the spectrum. Therefore, the *standard deviation of the beam will* ***increase***. This is technically the inverse effect of what the dechirper ideally should accomplish, but it can serve as a proof of principle.

Another limitation resulting from the circumstances at ELBE is that next to the energy spectrum, neither the longitudinal phase space, nor the particle distribution of the bunch, nor the bunch length could be measured directly. Both, the bunch length and also an approximated particle distribution, are reconstructed from measured data using phase-space tomography methods.

EXPERIMENTAL RESULTS

The energy spectra of the used particle bunch have been measured for different gap widths using an energy spectrometer behind the dechirper. From the spectra, the average energy and the standard deviation were calculated. The results for the maximum gap width of 35 mm were taken as a reference. The total bunch charge amounted to 60 pC for this particular bunch.

For the reconstruction of the phase space of the bunch used in the semi-analytical predictions of the results, a double Gaussian bunch profile was employed as it fits the reconstructed phase spaces best and can be described analytically. The length of the particle bunch has been extracted from phase space tomography, and is assumed to be 3.6 mm throughout this section.

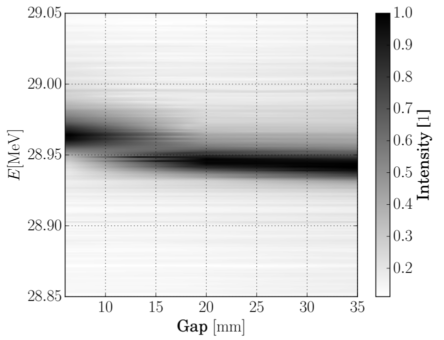

Figure 7: Normed total intensities of the energy spectra recorded for the measured bunch plotted over the gap width of the dechirper. The gap width has been increased in increments of 1 mm between 6 mm and 25 mm, and in increments of 5 mm until the dechirper's maximum gap width of 35 mm was reached. The data has been interpolated for the gap widths that have not been measured. The white gap occurring between 10 and 15 mm gap width is due to there being two energy peaks.

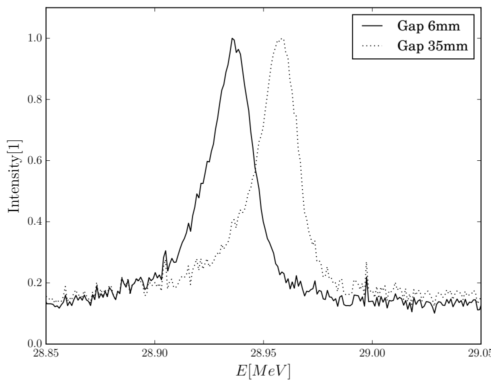

Figure 8: Normed intensities of the energy spectra, shown for the lowest and largest measured gap width from Fig. 7.

The shift of the high intensity peak at $\approx$ 28.95 keV towards lower energies in Fig. 7 and Fig. 8 clearly shows the energy reduction induced by the dechirper if the gap width is decreased. An increase in the width of the spectrum is not easily visible. In Fig. 9, the progression of the average energies and the standard deviations of the energy spectra of the chosen bunch are shown, measured for different gap widths and compared to data computed with *WIzaRD*. Both quantities are referenced against the open dechirper, i.e. the dechirper with a gap widths of 35 mm in the figure. The semi-analytically predicted shift in the average energies for lower gap width is in the same order of magnitude, but lower than the experimentally observed shift. The

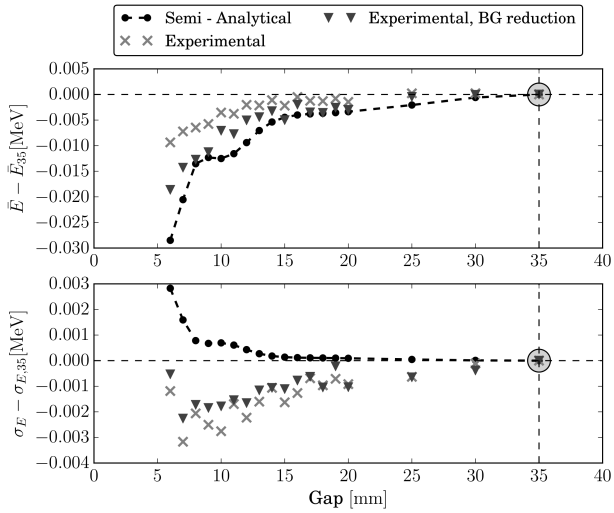

Figure 9: Progression of the average energies and the standard deviations of the energy spectra of the measured bunch for different gap widths of the dechirper. Both quantities are given in comparison to the case of the dechirper at 35 mm (marked in the figure). The figure shows the raw experimental data, the experimental data after a reduction of the background by a quadratic polynomial and the semi-analytical predictions carried out for the extracted bunch length assuming a double Gaussian bunch shape (dashed line).

discrepancy between both curves is highest for gap widths lower than 10 mm. When the background of the spectra is fitted with a quadratic polynomial (using an in-built Python function based on the non-linear least squares fitting technique) and subtracted, the accordance of the experimental and semi-analytical results can be increased. As an example, the discrepancy between the semi-analytical prediction and the experimental values is $\approx$ 20 keV for a gap width of 6 mm. Introducing the background reduction decreases this discrepancy to $\approx$ 10 keV.

For the standard deviations, the experimental results do not match the semi-analytical predictions. Both the raw data and the data after the background reduction suggest a minimal decrease of the standard deviation of the spectrum when decreasing the gap width. The semi-analytically calculated results, however, suggest an increase of the width of the spectrum for decreasing gap widths, which would be in better accordance with the generally expected (inverse) effect of the dechirper. However, both shifts are only in the range of a few keV and thus, as expected, very minimal.

SUMMARY

In this contribution, we have introduced the dechirper structure designed for ELBE. We have shown the energy modulating effect of the dechirper by using the semi-analytical programme code *WIzaRD* to simulate the interaction between the employed particle beam and the generated wake potential for different pulse shapes. To complement these simulations, experiments with the prototype have been performed at ELBE. These have shown the inverse dechirper effect on a beam without an initial energy spread in form of a decrease in the average energy of the bunch, which matches the semi-analytical predictions well. The predicted increase in the standard deviation of the energy spectrum of the particle beam could not be observed in the experimental series presented here and needs to be investigated further. This serves as a proof of principle of the dechirper's capability to influence the longitudinal phase space of the beam. In the future, we plan to expand on these studies and compare the prototype to other types of dechirpers in further experiments.

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