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DEMONSTRATION OF A NOVEL LONGITUDINAL PHASE SPACE LINEARIZATION METHOD WITHOUT HIGHER HARMONICS

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Abstract

Nonlinear correlations in the longitudinal phase space of electron bunches can be a decisive limitation to the achievable bunch length compression and attainability of small energy spreads. To overcome the restrictions imposed by nonlinear distortions, the longitudinal phase space distribution must be linearized. Previously, a novel linearization procedure based on the controlled expansion of the bunch between two radio frequency cavities operated at the same fundamental frequency has been presented in [1]. A demonstration of this linearization method is presented in this work.

INTRODUCTION

Many modern particle accelerator applications, such as high voltage transmission electron microscopy, require electron bunches with minimal energy spread [2]. Here, beam energies in the range of a few MeV are of particular interest in terms of time-resolved microscopy applications. The resolution of the microscope can be limited by chromatic aberrations of the beam optics. Nonlinear correlations in the longitudinal phase space distribution of an electron bunch can limit the minimum attainable energy spread. These not only result from the field curvature in the gun cavity, but also build up in a free drift section due to the nonlinear relation $\gamma = 1/\sqrt{1-\beta^2}$ between particle velocity and energy.

A common approach dedicated to removing these nonlinearities is based on the use of a higher harmonic structure [3]. Such a cavity is operated at a higher harmonic frequency and thus requires a separate rf system. An alternative linearization concept without the use of higher harmonic cavities has previously been proposed [1]. The method is based on the controlled expansion of the bunch between two cavities operated at the same fundamental rf frequency and is thus denoted as *stretcher mode*.

THE REGAE BEAMLINE

The measurement data presented in this work were recorded at the Relativistic Electron Gun for Atomic Exploration (REGAE) located at DESY [4]. REGAE is a conventional linear accelerator containing two accelerating rf structures operated at 2.998 GHz and was designed to produce high quality ultrashort electron bunches on the order of 10 fs with ultralow charge of around 80 fC. The photocathode inside the gun cavity is irradiated by an ultraviolet laser beam, thus producing an electron bunch which mimics the shape of the laser pulse. The electrons are accelerated to a kinetic energy E of currently around 3 MeV. The buncher cavity is located about 1.3 m further downstream. A schematic overview of the main elements in the REGAE beamline is given in Fig. 1.

The beamline features an S-band transverse deflecting structure (TDS) with minimized level of aberrations in the field distribution and optimized rf efficiency [5]. Generally speaking, a TDS induces a correlation between the longitudinal position of a particle and its transverse momentum, and thus the longitudinal particle distribution can be imaged.

The dipole energy spectrometer is equipped with a fiber optics scintillator screen and a subsequent EMCCD camera. The dispersion of the spectrometer was measured to be $D_x = (247 \pm 1)$ mm. Plugging in a typical horizontal beam size of $x_{\mathrm{RMS}} = 40$ m on the spectrometer detector screen yields an estimated resolution of around $x_{\mathrm{RMS}}/D_x = 1.6 \times 10^{-4}$ for the relative energy spread. Due to the fact that the deflection takes places in the horizontal direction, while the TDS shears the bunch in the vertical direction, the combination of both diagnostics can be employed to image the longitudinal phase space.

STRETCHER MODE

The stretcher mode linearization formalism is based on an analytical description of the evolution of the longitudinal coordinates along the beamline. The phase space is constructed from the longitudinal position ζ of the particle in the co-moving frame and the Lorentz factor γ, which indicates the energy of the particle. Only cavities and free drift segments are incorporated in the formalism. Considering two particles propagating in a free drift from z_0 to z, the relative shift $\Delta\zeta(z)$ develops as

$$\begin{aligned}\Delta\zeta(z) &= \frac{1}{\beta_{\mathrm{r}}}\left[\sum_{k=1}^{\infty}\frac{1}{k!}\frac{\mathrm{d}^k\beta}{\mathrm{d}\gamma^k}\bigg|_{\gamma_{\mathrm{r}}}(\delta\gamma)^k\right]_{z_0}(z-z_0)\\ &\approx \left[\frac{1}{\gamma_{\mathrm{r}}^3\beta_{\mathrm{r}}^2}\delta\gamma + \frac{2-3\gamma_{\mathrm{r}}^2}{2\gamma_{\mathrm{r}}^6\beta_{\mathrm{r}}^4}(\delta\gamma)^2\right.\\ &\quad\left.+\frac{2-5\gamma_{\mathrm{r}}^2+4\gamma_{\mathrm{r}}^4}{2\gamma_{\mathrm{r}}^9\beta_{\mathrm{r}}^6}(\delta\gamma)^3\right]_{z_0}(z-z_0), \quad (1)\end{aligned}$$

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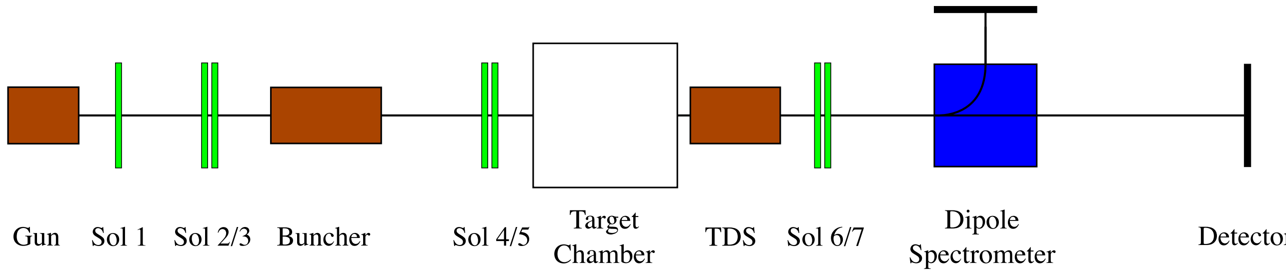

Figure 1: Schematic overview of the REGAE beamline featuring the rf cavities (brown), magnetic solenoids (green), dipole spectrometer (blue) and detector screens (black). The position of the target chamber is also indicated.

where $\delta\gamma$ is the energy deviation from γ_r, β_r denotes the normalized velocity of the reference particle and $[\cdot]_{z_0}$ indicates that the expression must be evaluated at the position $z = z_0$ [1, 3]. From the relation obtained in Eq. (1) it can be seen that while the higher order terms vanish rapidly for large values of γ, distortions will arise for low energies on the order of a few MeV, which corresponds to the typical mean beam energy obtained at most rf photoinjectors. The impact of a cavity on the longitudinal phase space can be described in a similar manner. By means of an iterative application, the evolution of the longitudinal phase space along a given beamline can thus be described. The full formalism has been presented in [1, 6].

According to the stretcher mode concept, a configuration of cavity gradients and phases $\{E_{g,b}, \phi_{g,b}\}$ for gun and buncher exists which produces a linearized phase space distribution in either ζ or γ [1]. Thus, the longitudinal extent or the energy spread of the electron bunch can be minimized. The crucial point in both cases is that the gun cavity is operated at an off-crest phase, and the electron bunch expands in the drift between gun and buncher cavity. Consequently, the bunch occupies a larger phase interval in the buncher cavity. Therefore, the field curvature of the buncher is greater than the phase space distribution of the evolved electron bunch. This principle is similar to a higher harmonic system. In stretcher mode, however, the same fundamental rf frequency can be used for both cavities.

RESULTS

By operating the gun cavity at a debunching phase, the accumulated energy spread, which is even larger in comparison to on-crest operation mode, can be compensated by the buncher cavity. This application of the stretcher mode will be referred to as Energy Spread Compensation (ESC). An exemplary cavity configuration which eliminates first and second order phase space correlations at REGAE is given by $E_g = 80.0\,\mathrm{MV/m}$, $\phi_g = 45.0\,\mathrm{deg}$, $E_b = 9.24\,\mathrm{MV/m}$ and $\phi_b = -72.80\,\mathrm{deg}$, where $\phi = 0$ is defined as the maximum energy gain phase.

The evolution of the longitudinal phase space in a parameter region around the linearization settings specified above was studied with Astra simulations [7], in which the longitudinal phase space distribution behind the buncher cavity was analyzed for a variety of buncher phase values around the

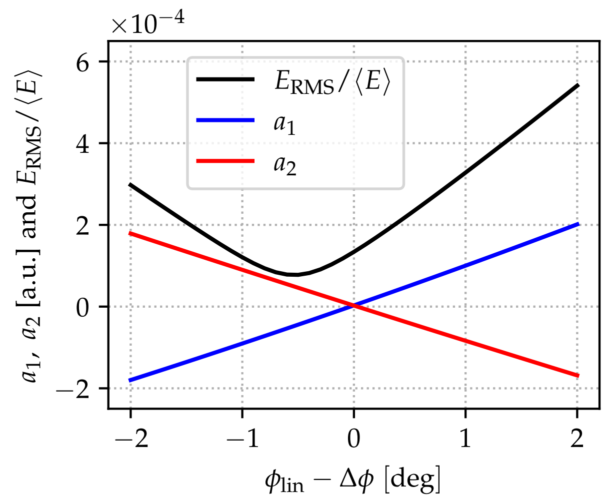

Figure 2: Astra simulation of the ESC scheme; adapted from [8].

linearization phase $\phi_{\mathrm{lin}} = -72.80\,\mathrm{deg}$. A cubic fit was applied to each respective phase space distribution. Scanning the buncher phase directly impacts the longitudinal phase space distribution, and these changes manifest themselves in the coefficients derived from the applied fit. The electron emission time was set to 2.1 ps and space charge effects were not included in these simulations.

Figure 2 shows Astra simulations of the first and second order fit coefficients a_1 and a_2 along with the relative energy spread $E_{\mathrm{RMS}}/\langle E\rangle$ as a function of ϕ_b indicated with respect to ϕ_{lin}. The zero-crossing of first and second order occur at the same cavity parameter configuration, which indicates that linearization in the sense of second order correction has been achieved. Here, the relative energy spread reads $E_{\mathrm{RMS}}/\langle E\rangle = 1.3 \times 10^{-4}$ at a mean beam energy of $\langle E\rangle = 3.082\,\mathrm{MeV}$. The local minimum of $E_{\mathrm{RMS}}/\langle E\rangle$ occurs at a slightly different phase value due to the fact that a nonzero slope $a_1 \neq 0$ partially compensates third order contributions.

As can be deduced from Fig. 2, two aspects are required for the demonstration of stretcher mode: the zero-crossings of first and second order coefficients of the longitudinal phase space distribution must occur at the same cavity settings and a local minimum of the relative energy spread must be observed in the vicinity of the aforementioned zero-crossing.

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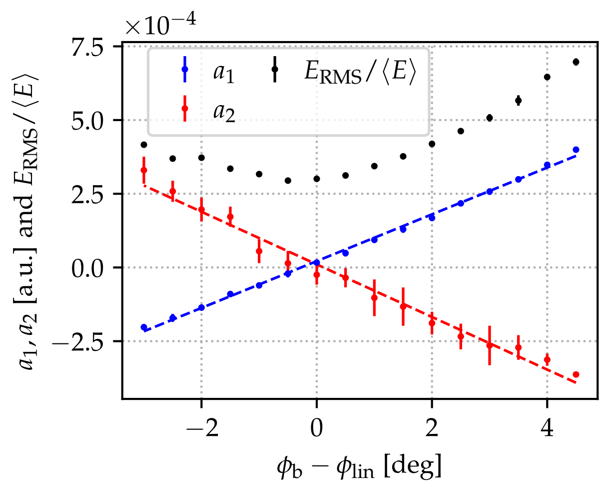

Figure 3: Measurement data of the ESC scheme; adapted from [8].

Measurements of the longitudinal phase space evolution were recorded using the dipole spectrometer in combination with the TDS at the REGAE beamline. The photocathode laser was adjusted to produce a bunch charge of 30 fC. A low bunch charge was deliberately chosen in order to reduce space charge effects, and a scan of the buncher phase was performed. At each distinct phase setting, a total of ten beam and background images were recorded. After subtraction of the averaged background from the beam images, a seeded region growing algorithm was applied to isolate the beam signal from the remaining image noise.

A cubic fit was applied to each processed detector image, which represents the longitudinal phase space distribution for the respective cavity parameter configuration. The first and second order fit coefficients a_1 and a_2 are shown in Fig. 3, together with the relative energy spread spread $E_{\mathrm{RMS}}/\langle E \rangle$. It can clearly be seen that the zero-crossings of a_1 and a_2 occur at nearly the same phase value; ϕ_{lin} was defined here as the buncher phase setting where first and second order are both closest to zero. In addition to this, a local minimum of the relative energy spread can clearly be observed. Thus, the ESC scheme of the stretcher mode has been successfully demonstrated.

The fact that the zero-crossings do not occur at the identical phase settings implies that the buncher gradient was not set to the optimal value. This would require a higher precision than that which is currently achievable with the REGAE rf system. In addition the energy spread measurements are resolution limited, i. e., the beam size on the spectrometer detector is increased by the contribution of the horizontal emittance and beta function. Thus, the energy spread is overestimated, which explains the slightly larger minimum energy spread of the measurements in comparison to the simulations. An overview of the main beam parameters recorded in the course of the measurements is given in Table 1.

Last but not least, an exemplary depiction of the linearized longitudinal phase space using the ESC scheme

Table 1: Overview of Beam Parameters Measured in ESC Stretcher Mode

Beam property	**Measured value**
$\langle E \rangle$ [MeV]	3.077 ± 0.001
Q [fC]	28.2 ± 0.9
$\epsilon_{\mathrm{n},x}$ [nm]	86 ± 2
$\epsilon_{\mathrm{y},x}$ [nm]	113 ± 4

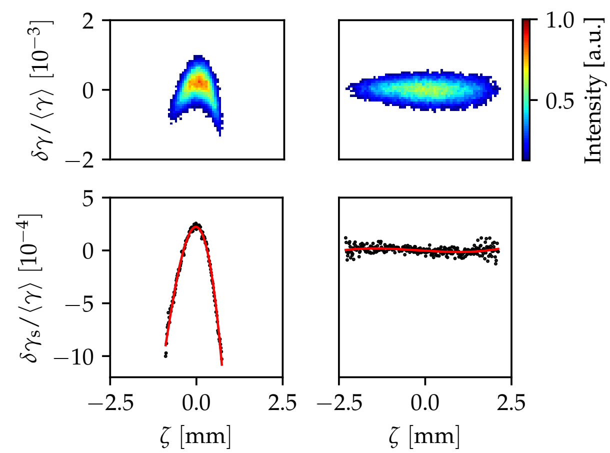

Figure 4: Comparison between on-crest (left) and ESC (right) operation mode; adapted from [8].

of the stretcher mode is given on the right side of Fig. 4. For comparison, the longitudinal phase space distribution recorded using only the gun cavity operated at the on-crest phase is shown on the left. The effect of the linearization can clearly be identified.

CONCLUSION

The applicability of the novel longitudinal phase space linearization method presented in [1] has been demonstrated with measurement data recorded at the REGAE beamline in Hamburg. First and second order contributions in the longitudinal phase space distribution have been successfully eliminated without the use of a higher harmonic cavity.

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