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Generation of sub-fs electron beams at few-MeV energies

K. Floettmann

DESY, Notkestr. 85, 22603 Hamburg, Germany

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ABSTRACT

Time resolved electron diffraction is an alternative approach to FEL based X-ray experiments for the study of structural dynamics of matter on the relevant timescales. The required electron beam parameters are demanding in terms of emittance and bunch length and require the operation at charges typically well below 1 pC. Moreover the energy is low – a few MeV only. The longitudinal compression of the bunches can be realized with a simple longitudinal focusing scheme in a drift. In this paper the question of what limits the bunch length in this parameter regime is addressed by means of numerical simulations. Beside emittance increasing space charge effects also rf-curvature and nonlinear compression are identified as limiting factors.

1. Introduction

Electron bunches with a temporal duration in the fs range gain increasing interest as probes e.g. for investigations of the structural dynamics of matter. The focus of interest is on FEL applications which require GeV electron beams with typical bunch charges larger than 100 pC. A complementary approach is time resolved electron diffraction where low electron beams of hundreds of keV up to a few MeV are utilized and the bunch charge can be below 100 fC. In the first case the bunch compression is performed by means of velocity bunching in a string of cavities [1] or by magnetic bunch compressors at higher energies [2] while in the first case bunches have to be either produced directly with the required length [3] or a simple longitudinal focusing scheme (also called ballistic bunching) can be applied [4].

This contribution concentrates on the last case and the question what ultimately limits the achievable bunch length. For the study – primarily based on tracking simulations – the Relativistic Electron Gun for Atomic Exploration REGAE [5] serves as baseline setup.

REGAE is a $\sim$5 MeV electron linac build at DESY in a cooperation of the Max-Planck Society, the University of Hamburg and DESY. The primary goals of REGAE are time resolved electron diffraction experiments for studies of structural dynamics of matter. Besides it serves as test bed for accelerator developments e.g. in the field of beam dynamics, diagnostics, synchronization, and photo cathodes. Furthermore a plasma experiment is in preparation for which the REGAE bunches will be injected into a laser driven plasma to probe the fields inside the plasma [6]. Shortest electron bunches are mandatory both for time resolved electron diffraction as well as for the external injection experiment at REGAE. It should be noted however that from an experimental point of view limitations arise due to diagnostics problems and due to synchronization limits which restrict the usability of bunches below 10 fs. The focus of this study is hence on the general beam dynamics rather than on fully worked-out accelerator design.

2. REGAE

Fig. 1 presents a schematic overview of the first section of REGAE. The electron bunches are photo emitted inside the 1.6 cell rf gun operated at 3 GHz. The beam reaches the final energy of $\sim$5 MeV already at the exit of the gun, so that the downstream buncher cavity is operated off-crest to introduce the required energy spread for the bunching in the following drift. For the electron diffraction experiments extremely small emittances are required which can only be reached at bunch charges well below 1 pC.

Fig. 2 presents simulation results for input parameters as compiled in Table 1. All simulations are performed with the tracking programm ASTRA [11]. The parameters of the bunch at the cathode are not readily achieved but are chosen to explore the limits of the setup. Challenging is not only the assumed perfect cylindrical shape but already the small transverse size of the beam is difficult to be realized due to the unavoidable distance of the last focusing lens to the cathode. It is assumed that for the generation of the low charge a photo cathode with low quantum efficiency and corresponding low kinetic energy of the electrons is employed.

While the transverse beam size increases strongly right after emission from the cathode before being focused to a constant size

E-mail address: Klaus.Floettmann@DESY.De

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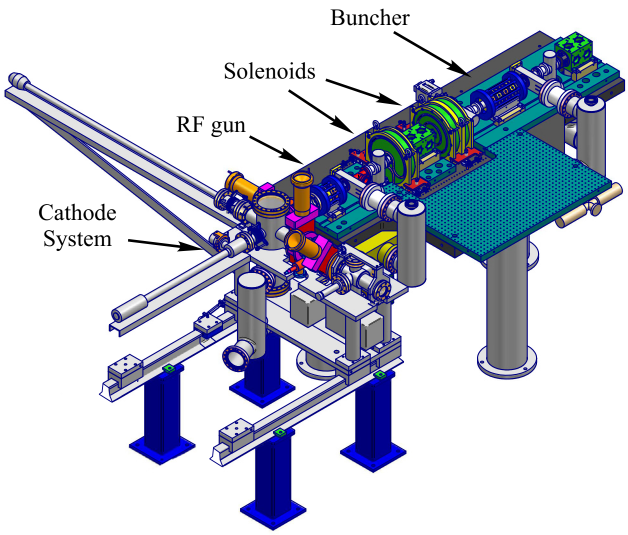

Fig. 1. The first section of the REGAE facility.

the emittance increases due to space charge nonlinearities slowly from the initial 3 nm up to about 10 nm along the beam line. When the bunch passes the buncher cavity at $z \approx 1.5$ m, a correlated energy spread is introduced, such that particles in the tail of the bunch gain a higher energy and hence travel at higher velocity than particles in the head of the bunch. In the following drift the bunch length decreases by a factor 63 from the initial 132 μm (440 fs) to a minimum of 2 μm (7 fs) at a longitudinal position of ~ 5.5 m – the position of the target chamber – before it increases again.

3. Longitudinal focus and space charge

Space charge forces counteract any desired focusing of a beam both in the transverse and in the longitudinal direction. Since in the longitudinal focus the bunch is however compressed only in one dimension as compared to the two dimensions in a round transverse focus the effect of the space charge force is vastly different.

In a transverse focus the radial space charge field scales as $E_r \propto r/R^2$ where r is a radial position inside the bunch while R denotes the radius of the charge distribution and a bunch with aspect ratio $A = R/L < 1$ (L bunch length in the average rest system of the bunch) is assumed. An electron at a constant position r/R experiences hence a divergent force as the radius of the distribution decreases towards zero. As a result even a bunch with zero emittance could not be focused down to a point like spot size. Instead the inward traveling particles transfer kinetic energy into potential energy in the space charge field until they stop (in the average rest system) and gain the energy back while traveling outward. This so-called laminar focus (Fig. 3) in which the trajectories of individual particles do not cross each other is an ideal case which is reached in the longitudinal center part of realistic distributions. Toward the head and the tail of a distribution the lower space charge field allows particles however to cross over as in a linear focus. This mixed focus leads to a strong emittance growth, which can be avoided only by focusing just modestly to shallow round foci in the transverse direction.

In the longitudinal focus, however, the space charge field scales as $E_z \propto \varsigma/L$ where ζ is a longitudinal position inside the bunch and an aspect ratio $A > 1$ is assumed. The defocussing field is hence constant which allows to reach point like foci if a zero emittance beam would be available. In general all particle trajectories run

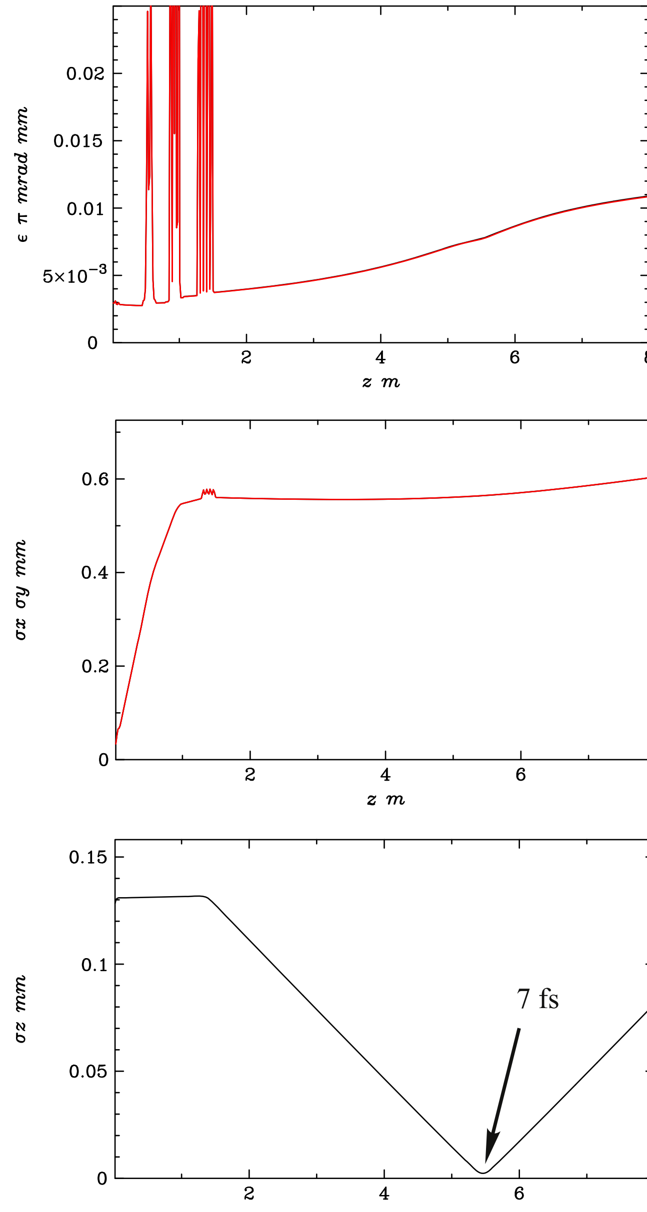

Fig. 2. Emittance (top), beam size (middle) and bunch length (bottom) versus longitudinal position along the REGAE beam line for parameters as compiled in Table 1.

through a linear focus, i.e. head and tail particles exchange their positions (cf. Fig. 3), without excessive emittance growth so that strong foci can be realized.

4. Bunch compression limitations

In the REGAE setup the bunch length at the longitudinal focus cannot be reduced below 7 fs rms just by increasing the focusing strength, i.e. the buncher voltage. The longitudinal phase space at the position of the longitudinal focus displayed in Fig. 4 shows structures related to rf-curvature, nonlinearities in the compression process and to longitudinal nonlinearities of the space charge field.

While the current – the projection of the phase space onto the longitudinal axis – in this example is rather uniform over the bunch length with a small spike only in the front, a setup with