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LONGITUDINAL BEAM DYNAMICS FOR DIFFERENT INITIAL DISTRIBUTIONS AT cSTART

M. Schwarz*, S. T. Braner, B. Härer, J. Schäfer, A.-S. Müller,
Karlsruhe Institute of Technology, Karlsruhe, Germany

Abstract

The compact STorage ring for Accelerator Research and Technology (cSTART) project aims to store electron bunches of LPA-like beams in a very large momentum acceptance storage ring. The project will be realized at the Karlsruhe Institute of Technology (KIT, Germany). Initially, the Fern-infrarot Linac- Und Test-Experiment (FLUTE), a source of ultra-short bunches, will serve as an injector for cSTART to benchmark and emulate laser-plasma accelerator-like beams. In a second stage, a laser-plasma accelerator will be used as an additional injector, which is being developed as part of the ATHENA project in collaboration with DESY and Helmholtz Institute Jena (HIJ). With an energy of 50 MeV and damping times of several seconds, the electron beam does not reach equilibrium emittance within the storage time of about 100 milliseconds. Therefore, the initial phase space distribution influences the later dynamics and beam properties. We perform longitudinal particle tracking simulations to investigate the evolution of the bunch lengths and phase space densities for different initial beam distributions.

INTRODUCTION

Laser-based Plasma Acceleration (LPA) can deliver electron bunches with high peak current and ultra-short bunch lengths on a compact facility footprint. This makes LPAs attractive candidates for light sources, since ultra-short bunches emit intense coherent radiation in the THz regime [1]. However, their large beam emittance requires dedicated beam transport systems and insertion devices [2]. Moreover, their repetition rate is limited to a few Hz compared to MHz at storage rings.

The cSTART project develops the infrastructure and technology necessary for a compact LPA-based light source. A key component is the construction of a very-large momentum acceptance compact storage ring to inject and store sub-ps short electron bunches. One injector is a LPA developed in cooperation with DESY and HIJ [3]. The linac-based accelerator FLUTE [4] will serve as an other injector to provide well-defined LPA-like bunches. In storing a sub-ps short bunch, the ring would act as a "multiplier" to push the few Hz injection rate to a MHz repetition rate. The required large momentum acceptance and limited construction space provide challenges to the lattice design [5], the transferline from the injectors [6, 7], and the beam diagnostics [8].

The main parameters of the cSTART storage ring are given in Table 1 and are based on the latest 45°-bending magnet design and an momentum acceptance of about 4 % [5]. The magnetic lattice supports different momentum compaction

Table 1: Main Parameters of the cSTART Storage Ring

Parameter	Value	Unit
Circumference	43.2	m
Injection rate	10	Hz
Beam energy E	50	MeV
Revolution period T_{rev}	144	ns
Revolution frequency f_{rev}	6.94	MHz
Dipole bending radius	1.019	m
Longitudinal damping time	13.1	s
Incoherent energy loss	0.54	eV
Coherent energy loss (1 pC, 20 fs)	160	keV
Critical frequency f_{crit}	37.7	THz
Cut-off frequency f_{cut}	25.4	GHz
Momentum compaction:		
nominal	14.8×10^{-3}	1
low-α	3.9×10^{-3}	1
RF frequency	500	MHz
RF voltage	500	kV
Harmonic number	72	1

factors and the simulations presented in this proceeding were performed with the low-α mode. The relatively low electron energy of 50 MeV leads to an almost negligible energy loss of only 0.54 eV per electron per turn. Correspondingly, the longitudinal damping time is 13.1 s and many orders longer than those at high-energy electron synchrotrons. The long damping time implies that the beam will not damp down to an equilibrium beam distribution by the time of the next swap-out injection. Hence, the initial distribution is critical for the development of the beam. For the simulations in this proceeding, we take as initial distribution a 1 pC bunch that was tracked through the transferline from FLUTE to the cSTART storage ring [9]. We also compare the results to a Gaussian bunch of the same bunch length and energy spread. Both bunches are simulated for 700.000 turns, corresponding to the 100 ms storage time.

SIMULATION CHALLENGES

We use the macro-particle tracking code BLonD [10] to simulate the longitudinal beam dynamics. BLonD computes the wake potential from a histogram of the macro-particles, with usually constant number of bins and binning range. Within the first thousand turns after injection, the bunch length periodically varies between a few fs to several ps [11]. Using constant bins requires a fs-scale binning over the range of 100 ps, which leads to numerical noise amplification and a spurious emittance growth. We, thus, use at each

* markus.schwarz@kit.edu

simulation step a binning range that is based on the minimum and maximum macro-particle position and keep the number of bins constant.

To benchmark the simulation parameters, such as the number of bins and macro-particles, we compute the average energy loss $\bar{U}$ of a Gaussian bunch under the influence of the free-space CSR impedance, because it can be calculated analytically for this case. The shielded CSR impedance [11] is used in the actual simulations. Using 1×10^6 macro-particles and 128 bins gives good agreement (<4 % difference) between the simulated energy loss and the analytical result. Notice that this number of macro-particles is close to the ~6.2×10^6 electrons of the 1 pC bunch.

INITIAL DISTRIBUTIONS

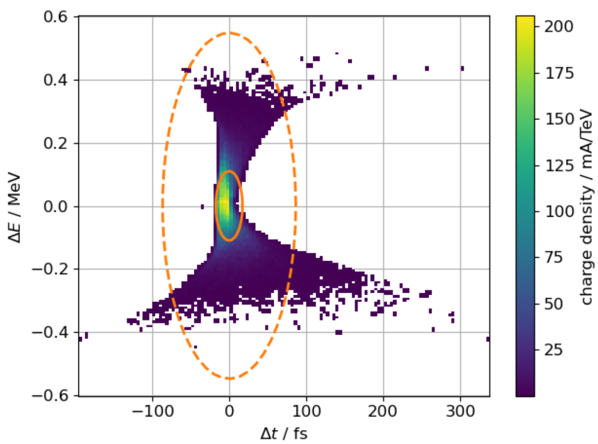

Figure 1: Initial phase space density with $\sigma_{t,\mathrm{STD}} = 17$ fs and $\delta_E = 2.64 \times 10^{-3}$. Ellipses show the 1σ (solid) and 5σ (dashed) contours of the Gaussian density with same σ_t and δ_E.

Figure 1 shows the initial charge phase space density obtained by tracking through the FLUTE transfer line [9]. Notice that the bunch energy of 41.5 MeV is smaller than the nominal energy of the cSTART storage ring. In the following discussions, we use the standard deviation STD of the longitudinal bunch profile as the measure of the bunch length σ_{STD}, unless noted otherwise. The bunch length and relative energy spread are $\sigma_{\mathrm{STD}} = 17.3$ fs and $\delta_E = 2.64 \times 10^{-3}$, respectively. However, the σ_{STD} is affected by the tails of the distribution. The Gaussian equivalent of the FWHM is only $\sigma_{\mathrm{FWHM}} = \mathrm{FWHM}/2.35 = 7.8$ fs and contains 50 % of the bunch charge. To compare the evolution of this initial bunch distribution to a different one, we also use a Gaussian distribution with the same σ_{STD} and δ_E (orange curves in Fig. 1).

AVERAGE BEAM PARAMETERS

Figure 2 shows the evolution of the bunch length σ_{STD} for the FLUTE (blue curve) and Gaussian-equivalent (orange curve) bunch. Within the first 1000 turns, the bunch length

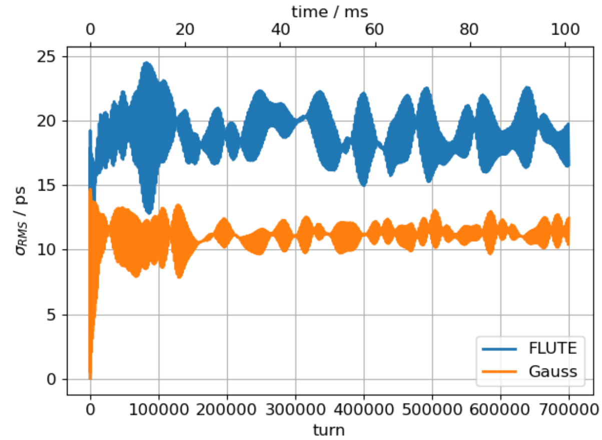

Figure 2: Bunch length σ_{STD}.

σ_{STD} oscillates between several ps and several fs [11]. After 10 000 turns, it increases to about 19 ps and 11 ps for the FLUTE and Gaussian-equivalent bunch, respectively. However, in both cases the bunch length σ_{STD} shows a beating-like oscillation, which indicates that the bunches have not reached an equilibrium.

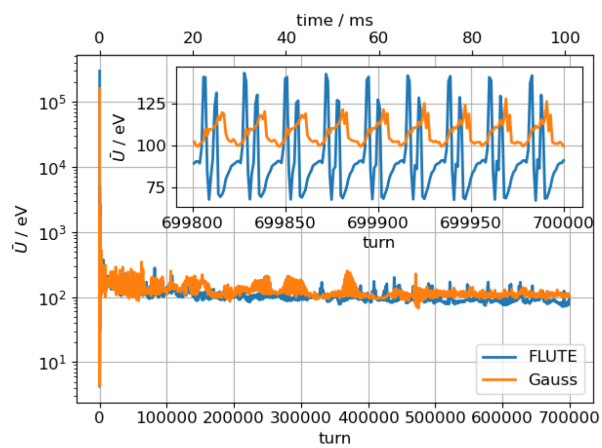

Figure 3: Average energy loss per turn per particle $\bar{U}$. The inset shows $\bar{U}$ over the last 200 turns.

Figure 3 shows the average energy loss per particle $\bar{U}$ for the two cases. The large initial values of 298 keV (FLUTE) and 161 keV (Gauss) are due to the ultra-short bunch length of $\sigma_{\mathrm{STD}} = 17.3$ fs. As discussed above, the FLUTE bunch is more compact than its σ_{STD} suggests, which leads to a higher average energy loss. Once the bunch length σ_{STD} increases to several ps, the average energy loss $\bar{U}$ rapidly decreases to about 92 eV (FLUTE) and 108 eV (Gauss). While these values are three orders of magnitude less than the initial loss, they are still at least one order of magnitude larger than what would be expected from the bunch length σ_{STD} alone: for Gaussian bunches of $\sigma_{\mathrm{STD}} = 19$ ps and $\sigma_{\mathrm{STD}} = 11$ ps, the expected average energy losses would only be $\bar{U} = 0.4$ eV and $\bar{U} = 8$ eV, respectively. The inset shows the last 200

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turns. Both cases show a non-trivial periodic pattern, in particular for the FLUTE bunch.

FINAL PHASE SPACE DENSITIES

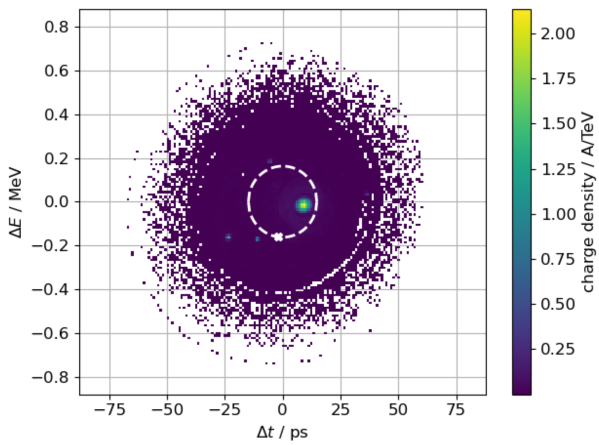

Figure 4: Gauss: Phase space density after 100 ms. For dashed white curve see text.

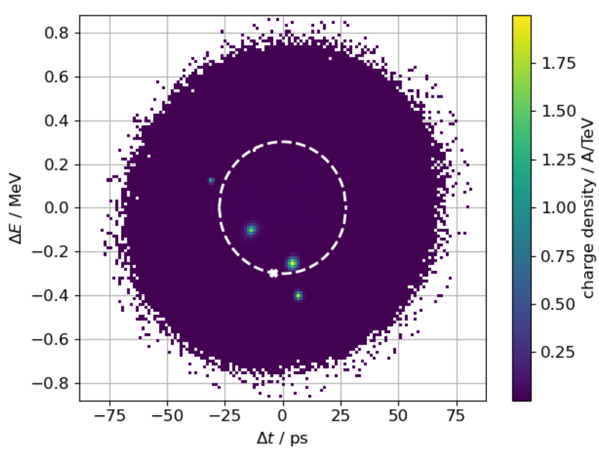

Figure 5: FLUTE: Phase space density after 100 ms. For dashed white curve see text.

These findings can be understood by investigating the phase space density. Figures 4 and 5 show the phase space density of the FLUTE and Gaussian bunch, respectively, after 100 ms (turn 700 000). Both densities display a large halo and one (or more) sub-bunches. In each case, the halo contains about 60 % of the electrons and extends to about 60 ps. For the Gaussian beam (Fig. 4), the single sub-bunch at the 3 o'clock position contains about 39 % of the total bunch charge. The FLUTE bunch (Fig. 5) has three sub-bunches, with the largest at the 5 o'clock position containing about 20 % of the electrons, and the other two containing about 10 % each. Therefore, about 40 % of the electrons are contained into sub-bunches much smaller than the halo. In fact, the RMS bunch length of all sub-bunches is ≤ 1 ps and one order of magnitude smaller than the STD bunch length.

The origin of the sub-bunches can be traced back to the first turn. After the first turn, the electrons have lost, on average, 298 keV (FLUTE) and 161 keV (Gauss), which corresponds to about 0.7 % and 0.4 % of the mean particle energy, respectively. The phase space position of the center of charge after the first turn is marked by a white cross in the figures. Since the bunch length is now several ps, the CSR decreases by several orders of magnitude after the first turn [11]. Without further collective effects due to CSR, the center of charge would perform dipole oscillations and trace out the dashed path in phase space. Filamentation due to the non-linear RF potential would still lead to a halo. Notice that the sub-bunches are located close to this path. Their exact formation depends on the complex interplay between filamentation and collective effects and is beyond the scope of this proceeding. Once formed, they perform dipole oscillations. Since the sub-bunches contain up to 40 % of the bunch charge, their alignment strongly determines the average energy loss. Whenever their "constellation" is such that two are "above" each other, their wake fields interfere constructively which leads to an increase in the average energy loss. With three major sub-bunches for the FLUTE bunch, this explains the complex periodic structure in the inset of Fig. 3.

CONCLUSION AND OUTLOOK

A key part of the cSTART project is the construction of a very-large momentum acceptance compact storage ring to capture and store sub-ps short bunches. The low beam energy of 50 MeV leads to long damping times and the bunch remains in non-equilibrium throughout the 100 ms of storage time. In this proceedings, we investigated the longitudinal dynamics of two 1 pC bunches with different initial distributions but same $\sigma_{\mathrm{STD}} = 17.3$ fs. While the standard deviation bunch length σ_{STD} reaches a large average bunch length in the order of 10 ps after about 10 000 turns, a beating-like oscillation remains. Similarly, the average energy loss $\bar{U}$ displays a complex periodic pattern. This is caused by sub-bunches which contain up to 40 % of the the total bunch charge. An important property of these sub-bunches is that their RMS bunch length is below 1 ps. Their formation is linked to the dynamics of the first turn, but their existence throughout the total storage time is a consequence of the bunch not reaching its equilibrium.

As next steps, we plan to investigate the effects on space-charge, since it is likely non-negligible at energies of only 50 MeV. Intra-bunch scattering is also a very important aspect of the beam dynamics which needs to be included. These effects require to go beyond the longitudinal plane and to consider the full 6D phase space dynamics.

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