12th Int. Particle Acc. Conf. IPAC2021, Campinas, SP, Brazil JACoW Publishing
ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB255

LONGITUDINAL BEAM DYNAMICS AND COHERENT SYNCHROTRON RADIATION AT cSTART

M. Schwarz*, E. Bründermann, B. Härer, D. El Khechen, A. Malygin, A.-S. Müller, M. J. Nasse, A. I. Papash, R. Ruprecht, J. Schäfer, M. Schuh, P. Wesolowski
Karlsruhe Institute of Technology, Karlsruhe, Germany

Abstract

The compact STorage ring for Accelerator Research and Technology (cSTART) project aims to store electron bunches of laser-wakefield accelerator-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 Ferninfrarot Linac- Und Test-Experiment (FLUTE), a source of ultra-short bunches, will serve as an injector for cSTART to benchmark and emulate laser-wakefield accelerator-like beams. In a second stage a laser-plasma accelerator will be used as an 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. Furthermore, the critical frequency of synchrotron radiation is 53 THz and in the same order as the bunch spectrum, which implies that the entire bunch radiates coherently. We perform longitudinal particle tracking simulations to investigate the evolution of the bunch length and spectrum as well as the emitted coherent synchrotron radiation. Finally, different options for the RF system are discussed.

INTRODUCTION

Laser WakeField Acceleration (LFWA) can deliver electron bunches with high peak current and ultra-short bunch lengths on a compact facility footprint. This makes LWFAs 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 LWFA-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 an LWFA developed in cooperation with DESY and HIJ [3]. The linac-based accelerator FLUTE [4] will serve as a second injector to provide well-defined LWFA-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 lattice design [5, 6], the transferline from the injectors [7], and beam diagnostics [8].

* Markus.Schwarz@kit.edu

The main parameters of the cSTART storage ring are given in Table 1 and are based on the latest 45°-bending magnet design [9]. It is very flexible and allows for a large-acceptance optics, to store large-momentum spread beams, or a low-α optics for short-bunch operation. The relatively low electron energy of 50 MeV leads to an almost negligible energy loss of only 0.4 eV per electron per turn. Correspondingly, the longitudinal damping time is 16.7 s and many orders longer than those of high-energy electron synchrotrons. The long damping time implies that the beam will not damp down to an equilibrium Gaussian beam distribution by the time of the next injection. In this sense, the dynamics of the low-energy electron beam at cSTART is similar to that of a proton beam.

Table 1: Main Parameters of the cSTART Storage Ring

Parameter	Value	Unit
Circumference	44.4	m
Injection rate	10	Hz
Beam energy E	50	MeV
Revolution period T_{rev}	148	ns
Dipole bending radius	1.273	m
Longitudinal damping time	16.7	s
Incoherent energy loss	0.4	eV
Coherent energy loss (1 pC, 20 fs)	160	keV
Critical frequency f_{crit}	53	THz
Cut-off frequency f_{cut}	43	GHz
Momentum compaction:		
large-acceptance	1.8×10^{-2}	1
low-α	8×10^{-3}	1
isochronous	1.08×10^{-4}	1

RADIATION PROPERTIES

Another consequence of the low energy is that the critical frequency of the synchrotron radiation is $f_{\mathrm{crit}} = 53$ THz, which is many orders below the X-ray regime common for high-energy electron synchrotrons. The spectrum of the emitted synchrotron radiation is proportional to the real part of the parallel-plates impedance Z [10], shown in Fig. 1 (blue curve). The plate separation of 32 mm leads to a cut-off for frequencies below $f_{\mathrm{cut}} = 43$ GHz. For low frequencies, i.e. $f_{\mathrm{cut}} < f \ll f_{\mathrm{crit}}$, the impedance follows the $f^{1/3}$ power law. The impedance is exponentially suppressed above the maximum frequency at $0.29 f_{\mathrm{crit}} \sim 15.3$ THz.

Radiation is emitted coherently at a given frequency if the emitter is shorter than the corresponding wavelength. In this case, the intensity scales with the number of electrons

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB255

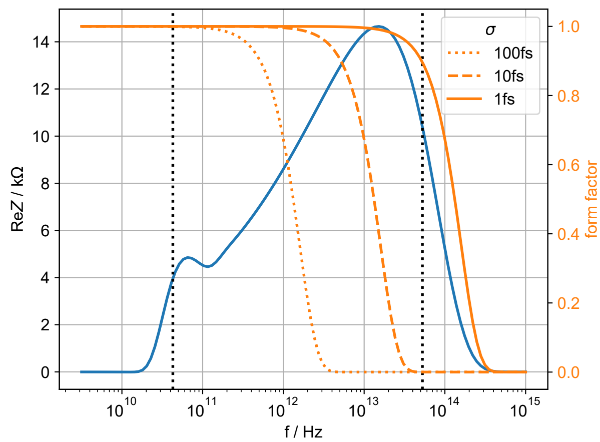

Figure 1: Real part of the parallel-plates impedance [10] (blue) and form factor of a Gaussian bunch for different bunch lengths σ (orange). Vertical lines indicate the cut-off and critical frequencies at 43 GHz and 53 THz, respectively.

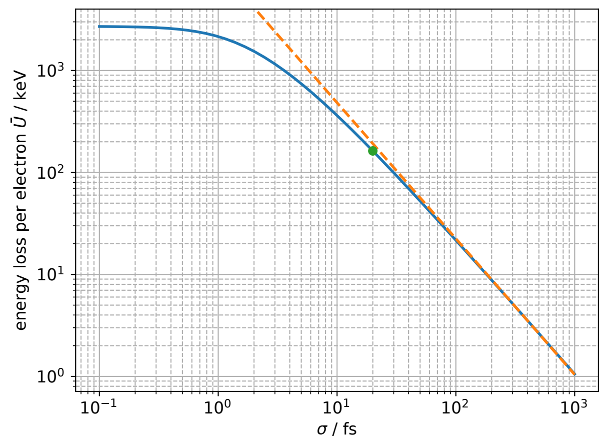

Figure 2: Energy loss for different bunch lengths of a 1 pC Gaussian bunch (blue) and the analytical estimate (dashed).

squared N_e^2 compared to the linear dependence for incoherent radiation. The degree of coherence is given by the form factor of the bunch $|\Lambda(f)|^2$, which is the modulus squared of the Fourier transform $\Lambda(f)$ of the bunch profile $\lambda(t)$. It is 1 at completely coherent frequencies and 0 for incoherent radiation. The form factors for beams with a Gaussian bunch profile and different bunch lengths σ are shown in Fig. 1 (orange curves). An extremely short bunch with $\sigma = 1$ fs radiates coherently up to about $f = 1/(2\pi\sigma) \simeq 160$ THz, which is three times larger than f_{crit}. Thus, a 1 fs short bunch radiates almost entirely coherent.

The emitted coherent synchrotron radiation (CSR) leads to an energy loss U for the bunch given by [11]

$$U = 2\, e^2 N_e^2 \int_0^\infty \Re Z(f)\, |\Lambda(f)|^2 \mathrm{d}f. \qquad (1)$$

The average energy lost to the bunch is $\bar{U} = U/N_e$, while the energy loss (or gain) of each particle depends on the wake potential. Notice that $\bar{U}$ strongly depends on the overlap of the impedance and the form factor, which leads to a strong dependence on the bunch shape. This dependence is plotted in Fig. 2 for a 1 pC Gaussian bunch. The dashed line shows the analytical estimate based on long bunches whose spectrum only overlaps with the low-frequency part of the impedance. The dot marks a bunch length that can be expected to be delivered from FLUTE [7]. The energy loss increases with decreasing bunch length, as the overlap between the impedance and form factor increases. However, bunches shorter than about 1 fs radiate almost entirely coherent and decreasing the bunch length does no longer increase the energy loss significantly. Even though the energy loss of 0.4 eV due to incoherent synchrotron radiation is negligible, the average energy loss caused by CSR for a 1 pC bunch of 20 fs reaches 163 keV and drops to 22 keV for 100 fs. On one hand, this makes the ultra-short bunches a source of very intense coherent THz radiation. On the other hand, the CSR wake potential leads to non-linear beam dynamics.

LONGITUDINAL DYNAMICS

The longitudinal phase space densities of the bunches delivered by the injectors (either FLUTE or the LWFA) are highly irregular [7], and the presence of e.g. tails implies that quantities like FWHM or RMS can only give a rough description for the distribution. Nonetheless, we assume simplified Gaussian bunches in the following discussion, with detailed studies foreseen in the future. All beam dynamics simulations have been performed with the longitudinal tracking code BLonD [12].

Isochronous Lattice

The RMS energy spread of the bunches delivered by FLUTE can be adjusted in the range of 1 per mill to 1 percent. The latter is in the order of magnitude for the bunches injected from the LWFA. Assuming no energy loss and no RF system, the RMS bunch length after one revolution period T_{rev} is given by $\sigma_{\mathrm{RMS}}^{(1)} \simeq \alpha\, \delta_{\mathrm{STD}}\, T_{\mathrm{rev}} + \sigma_{\mathrm{RMS}}^{(0)}$. For an energy spread of $\delta_{\mathrm{STD}} = \Delta E_{\mathrm{STD}}/E = 0.1$ %, this implies an "elongation rate" of 1.2 ps/turn in the low-α optics and the sub-ps bunch length is lost after one turn. The ring lattice is flexible enough to allow for a nearly isochronous operation mode [9] that reduces the phase slip factor, and hence the bunch elongation, by three orders of magnitude. Figure 3 shows a practically constant RMS bunch length (blue) when collective effects due to CSR are neglected. However, higher-orders of the momentum compaction can no-longer be neglected and lead to large tails. As a result, the RMS bunch length increases significantly (orange), but the Gaussian equivalent FWHM bunch length stays nearly constant (dashed). When CSR collective effects are included as well, the bunch elongates quickly (green) and the emitted CSR intensity drops rapidly. In this case the "elongation rate" of 60 fs/turn is still significantly lower than in the low-α optics.

RF System

The RF system needs to provide sufficient power to compensate for the CSR-induced energy losses and have a high

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB255

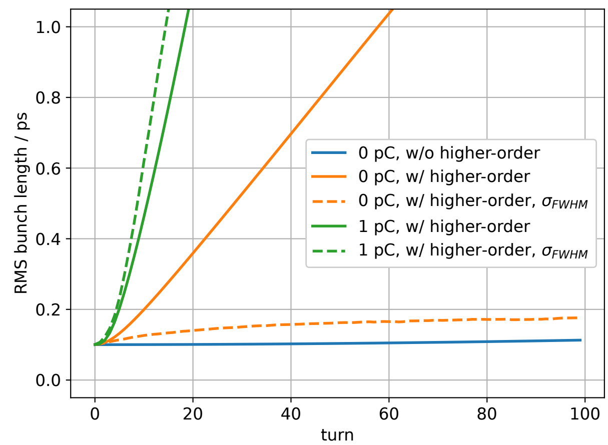

Figure 3: RMS bunch length for 1 pC Gaussian bunch and $\delta = 1 \times 10^{-3}$ for the isochronous lattice; collective effects have been ignored for 0 pC.

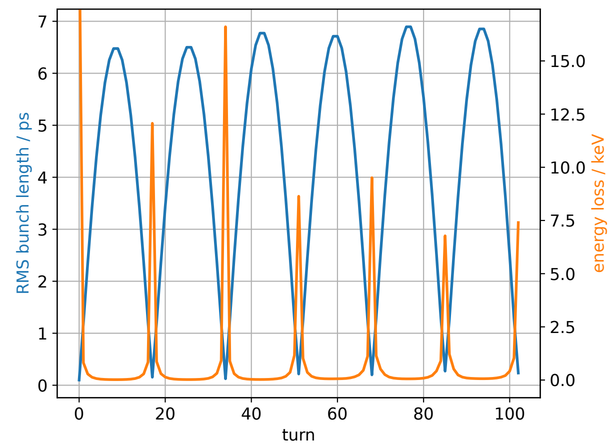

Figure 4: RMS bunch length (blue) and energy loss (orange).

energy acceptance to capture the large energy spread beam from the LWFA. Since the former can peak at up to 200 keV, the RF voltage V must provide several hundreds of kV. Moreover, the RF energy acceptance is given by

$$\delta_{\max} = \frac{\Delta E_{\max}}{E} = \sqrt{\frac{-2\beta^2 q}{\pi E \eta} \frac{V}{h}}, \tag{2}$$

where h denotes the harmonic number. Hence, a large $\delta_{\max}$ requires a large voltage and small harmonic number. In the following, we chose $h = 74$, corresponding to an RF frequency of 499.6 MHz. ELETTRA-type cavities, also used at KARA [13], operate at this frequency and can provide up to 630 kV [14]. A 3 GHz system would require a six times higher voltage to have the same $\delta_{\max}$ but could be more compact.

Figure 4 shows the bunch length (blue) for a 1 pC bunch with initial RMS bunch length of 100 fs and an energy spread of $\delta_{\mathrm{STD}} = 0.1\,\%$. The RF voltage of 465.085 kV was chosen such that one synchrotron period equals exactly 34 turns and gives an energy acceptance of $\delta_{\max} = 10\,\%$. As the bunch length begins to increase due to the energy spread, the CSR energy loss (orange) quickly decreases from its initial value of 22 keV. Consequently, the bunch rotates almost rigidly in phase space under the influence of the RF only and the bunch length displays quadrupole osciliations. A sharp increase in the CSR energy loss occurs when the RMS bunch length returns to (close) its initial value every half synchrotron period (17 turns). The ultra-short bunch length is recovered, in spite of some degradation of the phase space density. The top of Fig. 5 shows the phase space density after three synchrotron periods together with the 5-σ contour of the inital Gaussian distribution. A degradation of the initial Gaussian distribution is visible, and caused by the non-linear CSR wake potential as well as filamentation due to the RF potential. The former becomes dominant for shorter initial bunch lengths, while the latter becomes more important for larger energy spreads.

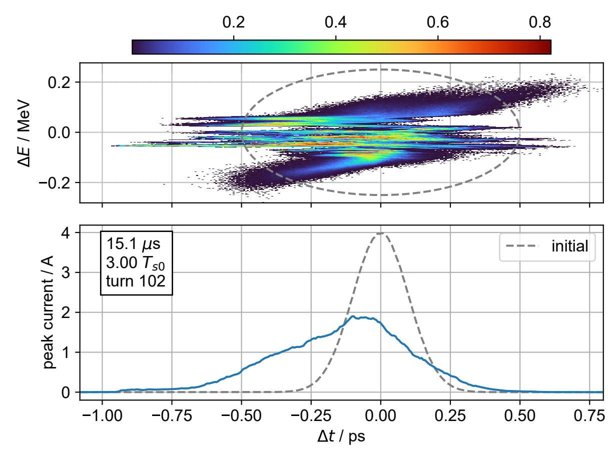

Figure 5: Longitudinal phase space density (top) and peak current (bottom) after 3 synchrotron periods and the 5-σ contour and peak current of the initial Gaussian beam (dashed).

SUMMARY

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 leads long damping times and synchrotron radiation with a critical frequency of 53 THz. The bunch spectrum of ultra-short bunches can reach up to this frequency and results in strong CSR and the corresponding energy loss is non-negligible. Using the isochronous optics, the continuous bunch "elongation rate" is 60 fs per turn. By using an RF system in the low-α optics, the inital sub-ps bunch length, and corresponding intense emission of CSR, can be recovered periodically for several synchrotron periods. It is planned to use bunch distributions obtained from detailed simulations of FLUTE and the LWFA as simulation input.

REFERENCES

[1] S. Hillenbrand, R. Assmann, A.-S. Müller, O. Jansen, V. Judin, and A. Pukhov, "Study of laser wakefield accelerators as injectors for synchrotron light sources", *Nucl. Instrum.*

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB255

Methods Phys. Res. Sect. A, vol. 740, pp. 153–157, 2014. doi:10.1016/j.nima.2013.10.081

[2] A. Bernhard *et al.*, "Progress on experiments towards LWFA-driven transverse gradient undulator-based FELs", *Nucl. Instrum. Methods Phys. Res. Sect. A*, vol. 909, pp. 391–397, 2018. doi:10.1016/j.nima.2017.12.052

[3] E. Panofski *et al.*, "Developing a 50 MeV LPA-based injector at ATHENA for a compact storage ring", presented at the IPAC'21, Campinas, Brazil, May 2021, paper TUPAB163, this conference.

[4] M. J. Nasse *et al.*, "FLUTE: A versatile linac-based THz source", *Review of Scientific Instruments*, vol. 84, p. 022705, 2013. doi:10.1063/1.4790431

[5] A. I. Papash, E. Bründermann, and A.-S. Müller, "An optimized lattice for a very large acceptance compact storage ring", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 1402–1405. doi:10.18429/jacow-ipac2017-tupab037

[6] A. I. Papash, E. Bründermann, A.-S. Müller, R. Ruprecht, and M. Schuh, "Design of a very large acceptance compact storage ring", in *Proc. IPAC'18*, Vancouver, BC, Canada, Apr.-May 2018, pp. 4239–4241. doi:10.18429/jacowipac2018-thpmf071

[7] B. Härer *et al.*, "Non-linear features of the cSTART project", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 1437–1440. doi:10.18429/jacow-ipac2019-tupgw020

[8] D. El Khechen *et al.*, "Discussion of suitable diagnostic components for the cSTART project", presented at the MT ARD ST-3 Meeting, Karlsruhe, Germany, Sep. 2020, unpublished.

[9] A. I. Papash *et al.*, "Modified lattice of the compact storage ring in the cSTART project at Karlsruhe Institute of Technology", presented at the IPAC'21, Campinas, Brazil, May 2021, paper MOPAB035, this conference.

[10] J. Murphy, S. Krinsky, and R. Gluckstern, "Longitudinal wake field for an electron moving on a circular orbit", *Particle Accelerators*, vol. 57, pp. 9–64, 1997.

[11] B. W. Zotter and S. Kheifets, *Impedances and Wakes in High Energy Particle Accelerators*, Singapore: World Scientific, 1998.

[12] CERN Beam Longitudinal Dynamics code BLonD, https://blond.web.cern.ch/.

[13] D. Einfeld, A. Fabris, F. Perez, M. Svandrlik, and S. Voigt, "Layout of the ANKA RF system", in *Proc. EPAC'98*, Stockholm, Sweden, Jun. 1998, paper TUP47G, pp. 1820-1822.

[14] M. Bocciai, A. Fabris, D. Lachi, C. Pasotti, M. Rinaldi, and M. Svandrlik, "Operational experience with the ELETTRA RF system", in *Proc. EPAC'98*, Stockholm, Sweden, Jun. 1998, paper TUP12C, pp. 1758–1760.