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FLEXIBLE FEATURES OF THE COMPACT STORAGE RING IN THE cSTART PROJECT AT KARLSRUHE INSTITUTE OF TECHNOLOGY

A. I. Papash†, A. Bernhard, E. Bründermann, D. El Khechen, B. Härer, A.-S. Müller, R. Ruprecht, M. Schwarz, J. Schäfer, Karlsruhe Institute of Technology, Karlsruhe, Germany

Abstract

Within the cSTART project (compact storage ring for accelerator research and technology), a Very Large Acceptance compact Storage Ring (VLA-cSR) is realized at the Institute for Beam Physics and Technology (IBPT) of the Karlsruhe Institute of Technology (KIT). A modified geometry of a compact storage ring operating at 50 MeV energy range has been studied and the main features of the new model are described here. The new design, based on 45° bending magnets, is suitable to store a wide momentum spread beam as well as ultra-short electron bunches in the sub-ps range injected from a laser plasma accelerator as well as from the Ferninfrarot Linac- Und Test Experiment (FLUTE).

The DBA lattice of the VLA-cSR with different settings and relaxed parameters, split elements and higher-order optics of tolerable strength allows to improve dynamic aperture and momentum acceptance to an acceptable level. This contribution discusses the lattice features in detail, expected lifetime, injection, tolerances and different possible operation schemes of the ring.

INTRODUCTION

R&D on laser plasma acceleration is pursued with the aim to clear up key issues on the feasibility of a new generation of very compact sources of synchrotron radiation for future users [1]. Laser Plasma Accelerators (LPA) feature short bunch lengths and high peak currents combined with a small facility footprint. For wavelengths longer than the length of the emitting electron bunch, the photon emission becomes coherent [2]. Thus, the radiation intensity from the terahertz (THz) to the infrared range increases dramatically. The combination of a storage ring and a laser plasma accelerator might be a basis for a new generation of compact light sources and advancing user facilities to different commercial applications. [3].

Meanwhile, the post-LPA beam is not directly suitable for storage and accumulation in conventional light source facilities. The energy spread of post-LPA beams well exceed the values at existing light sources [4]. The initially ultra-short electron bunches will quickly be elongated in existing storage rings. Due to the expansion of electrons in the plasma “bubble” with large divergence and momentum spread the effective normalized beam emittance will grow significantly leading to an increase of bunch length due to synchro-betatron coupling in the dispersive sections of the storage ring [5].

A dedicated storage ring with adapted features is realized at KIT with the purpose to provide the experimental "proof of principle" of injection and storage of ultra-short electron bunches (sub-ps to tens of fs) as well as beam with large momentum spread of about 1% (rms) after laser plasma cell [6]. To test the ring’s performance the compact linear accelerator FLUTE will serve as an injector of 50 MeV bunches [7].

†alexander.papash@kit.edu

FLEXIBLE LATTICE

Different geometries, lattices and operation modes of a compact storage ring have been extensively studies and the results have been reported at [2-4, 8-11]. The parameters of the facility and the electron beam are presented in Table 1. The ring footprint fits to the FLUTE experimental hall [7]. The highly non-linear lattice with flexible features and relaxed parameters is composed of four equal double bend achromat (DBA) sections (see Fig. 1).

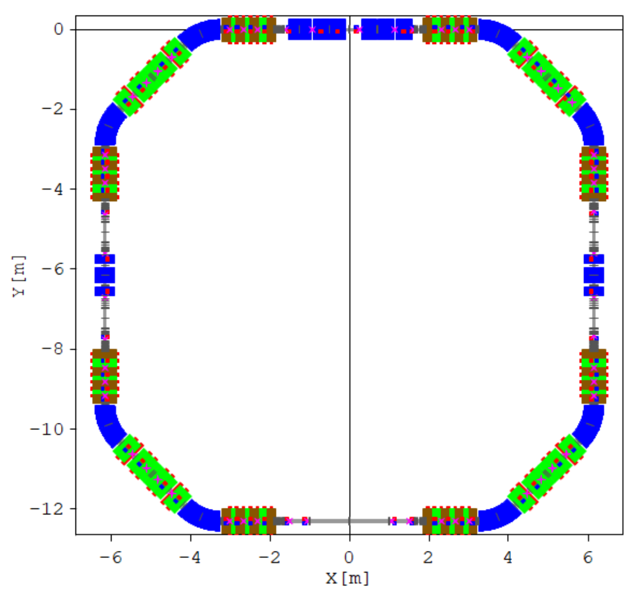

Figure 1: Layout of the cSTART ring.

Different operation modes to pursue accelerator R&D activities were described earlier [11]. The lattice of the cSTART storage ring satisfies contradictory features:

- The energy acceptance is increased to >5% to accommodate particles with large momentum deviation.
- The amplitude of the dispersion function is limited to keep a compact beam size in the bending sections.
- The dynamic aperture is large enough for stable storage of wide momentum spread beam.
- Additional sections for dedicated Accelerator Research and Development (ARD) experiments are included into the ring lattice.

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Table 1: Parameters of Ring and Beam

Parameter	Values
Energy range	40 to 100 MeV
Magnetic rigidity, $B{\cdot}R$	0.133 to 0.334 T·m
Circumference (footprint)	43.2 m (12.5×12.5 m)
Ring periodicity	four
Lattice	90° (2×45°) DBA cell
Operation modes	DBA FDDF/DFFD
	Reduced–α FDDF/DFFD
Quadrupole magnets	Double split
Arc sections $N \times L_{ARC}$	4×6.95 m
Straight sections $N \times L_{STR}$	4×3.85 m
Mom. Comp. factor – variable	$+2{\cdot}10^{-2}$ to $-1{\cdot}10^{-2}$
SR losses at 50 MeV	≤ 0.4 eV per turn
Natural Chromaticity DBA (α)	$\xi_{h,v}= -8/-8$ (–12/–14)
SR damping time $\tau_h/\tau_v/\tau_s$	36/33/15 s (50 MeV)
Energy spread – variable	$\sigma_E = 10^{-4}$ to 10^{-2}
Momentum acceptance lattice	± 5.5% (DBA FDDF)
Dispersion max – DBA, m	0.57/1.4 (FDDF/DFFD)
Dispersion max – reduced-α, m	0.3/0.7 (FDDF/DFFD)
Rotation period/frequency	144 ns / 6.944 MHz
RF frequency /RF harmonic	500 MHz / h_{RF}=72(4×18)
Betatron tunes (DBA FDDF)	$Q_{h,v}$= 5.575/1.239
Betatron tunes (DBA DFFD)	$Q_{h,v}$= 5.157/2.543
Vacuum chamber (full size)	70 × 40 mm
Dynamic Acceptance (h/v)	168/27 mm·mr
Emittance of injected beam (rms)	10 nm /1 mm·mr (norm)
Dynamic Aperture (horizontal)	±15 mm (±125σ_x)
Dynamic aperture (vertical)	±10 mm (±50σ_y)
Injection type	On-axes single bunches
Lifetime – 1 ps bunch (50 MeV)	10 to 0.2min (2÷200 pC)
Lifetime – 10 fs bunch (50 MeV)	10 s to 0.1 s (2÷200 pC)
Emittance IBS growth rate	0.12 s^{-1} (10^7 part/bunch)
Emittance IBS growth rate	12 s^{-1} (10^9 part/bunch)
Vacuum	Better than 10^{-10} mbar
Bunch length (rms)	~10 fs to 1 ps
Bunch charge	1 pC to 1 nC
Bunch intensity	$6{\cdot}10^6$ to $6{\cdot}10^9$ particles

The compact ring fits into the existing FLUTE experimental hall while short distances between elements lead to high strengths of quadrupole and sextupole magnets. Nine families of sextupoles are incorporated into the compact ring lattice to suppress linear and higher-order resonance driving terms and to open dynamic aperture.

Second-order terms of chromaticity are minimized by dedicated sextupole magnets rather than by octupoles. Three families of relatively weak octupole magnets suppress the Amplitude Dependent Tune Shifts (ADTS) while dynamic aperture is preserved.

To limit magnetic field strength all quadrupole magnets are split in halves and sextupole magnets are flanked in-between. Ring lattice was adjusted for mirror symmetry of inter-leaved sextupoles. To limit the strength of sextupole fields the correction of naturally negative chromaticity is realized in both planes by multiple sets of sextupole magnets rather than by single elements. The strength of chromatic sextupole families is limited by the distribution of sextupole field between nine families. The side effect of increased amplitude of the dispersion function is a slight reduction of geometric momentum acceptance of the ring.

The phase advance between two chromatic sextupoles is close to π and symmetry conditions are applied for Twiss parameters. The betafunctions are split at the sextupole locations so that lenses acting in vertical and horizontal planes have little mutual influence. The resonance driving terms are reduced due to lattice periodicity and mirror symmetry.

Because of the cancellation of ADTS, the betatron tune footprint remains confined in a very limited area. The relatively large distance to potentially harmful lower-order resonances and the small tune footprint justifies the choice of this working point for the cSTART storage ring. The optics is flexible and the working points can easily be adjusted and varied in a large range.

Solid block magnet technology based on MAX-IV 3 GeV ring experience [12] will be employed to guarantee lowest possible tolerances of random magnet errors at level of 30 µm in the blocks and 50 µm between girders. Roll errors are limited to 50/100 µrad (rms) while the beam orbit will be centered better than 0.5 mm.

Fluctuations of beam energy are reduced to 10^{-4} by stabilization of dipole magnets field at a level of $2{\cdot}10^{-5}$. Tune jitter will be suppressed to 10^{-3} by stabilization of quadrupole gradients at 10^{-4} level. Spurious fluctuations of chromaticity will be less than $5{\cdot}10^{-3}$ due to the stabilization of sextupole fields at a level of $5{\cdot}10^{-4}$. Tolerances on spurious fluctuations of ADTS set at 10^{-2} level will be satisfied by stabilization of octupole gradients better than 10^{-3}. Spurious sextupole components must not exceed 0.2 m^{-3} for dipoles and 0.6 m^{-3} for quadrupoles. Residual octupole components of dipoles, quadrupoles and sextupoles must be less than 15 m^{-4}.

EVOLUTION OF BEAM PARAMETERS

Beam losses at high energy electron storage rings are originated by different single but large angle scattering

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processes like elastic and inelastic scattering of circulating electrons at nuclei and electron shells of residual gas atoms and molecules [13], large angle single scattering of electrons on each other inside the bunch – the Touschek effect [14]. The lifetime of electrons in storage rings depends on many factors like beam energy, residual gas pressure, current density, rate of synchrotron radiation damping, dynamic aperture and momentum acceptance of the ring, amplitude of RF voltage and momentum compaction factor.

The lifetime of electrons in the cSTART storage ring has been studied at different beam energies (see Fig. 2). A single bunch has been tracked through the lattice with DBA optics [11] using the optics code OPA [15]. The RF harmonic number h_{rf}=72 corresponds to a 500 MHz RF system. Simulations have been performed at a vacuum level of 10^{-10} tor. The average charge of residual gas nuclei is Z=7 and residual gas molecules are composed of two atoms n=2. The coupling ratio between horizontal and vertical planes was artificially set to 100% to improve lifetime.

The upper limit of particle lifetime for very low intensity beam in absence of Touschek scattering is shown by curve 1 (black dashed line) of Fig. 2. Curve 2 (red) represents the lifetime of a low charge beam with 10^7 electrons/bunch (charge 1.5 pC/b), curve 3 (green) – the lifetime of moderate intensity beam with 10^8 electrons/bunch (15 pC/b) and curve 4 (blue) – the lifetime of high intensity beam with 10^9 electrons/bunch (150 pC/b). The expected lifetime of 50 MeV electrons circulating in a bunch with $\sigma_\tau = 1\, ps\, (rms)$ pulse length is about 17 min at low charge and it is reduced to ~12 s at high charge. Touschek scattering dominates at low energy range.

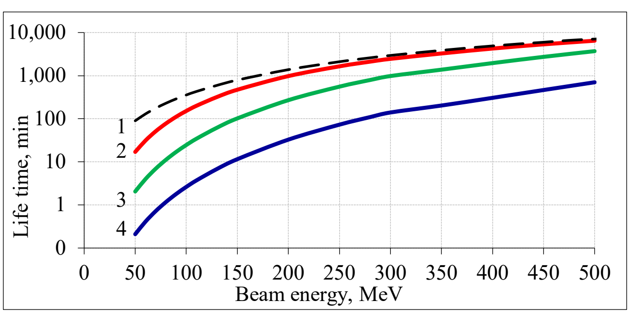

Figure 2: Computer simulations of the expected lifetime of electrons in the cSTART storage ring at different energies: 1 – vacuum losses (Touschek is off); 2 – low charge 1.5 pC/bunch, 3 – moderate intensity 15 pC/b; 4 – high charge 150 pC/b.

The expected lifetime of 50 MeV electrons at short bunch lengths (reduced–α operation mode) is shown in Fig. 3. Curve 1 (red) represents the lifetime of low charge beam with 10^7 electrons per bunch (charge 1.5 pC/b), curve 2 (green) – the lifetime of moderate intensity beam with 10^8 electrons per bunch (15 pC/b) and curve 3 (blue) – the lifetime of high intensity beam with 10^9 electrons per bunch (150 pC/b). The expected lifetime of 50 MeV electrons circulating in a bunch with $\sigma_\tau = 60\ fs\ (rms)$ pulse length is about 100 s for low charge and lifetime is reduced to ~1 s at high charge. The lifetime of ultra-short bunches (≤10 fs) drops below 100 ms at high beam intensity.

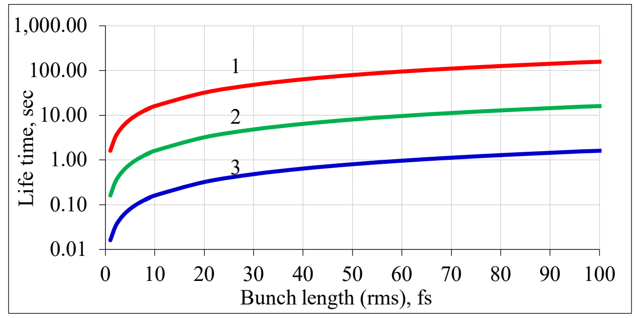

Figure 3: Computer simulations of expected lifetime of 50 MeV electrons at different pulse lengths: 1 – low charge 1.5 pC/bunch, 2 – moderate intensity 15 pC/b; 3 – high charge 150 pC/b.

At small energies the total rms energy spread of electrons in the storage ring is the result of a combination of average growth rate opposed by radiation damping [13]. At 50 MeV energy range the SR damping is extremely slow – in a range of 20 to 30 seconds. The expected lifetime of these low-energy electrons is less than the damping time and the particles circulate at non-equilibrium conditions. Multiple small angle intra-beam Coulomb scattering (IBS) of the particles on each other causes a growth of the beam momentum spread, induces synchrotron oscillations around the nominal energy orbit and leads to the growth of beam emittance [16].

For the cSTART storage ring and 50 MeV beam energy one can roughly estimate the IBS growth rates of beam energy spread and beam emittance as $(\tau_{IBS})^{-1}$~0.12 s^{-1} for 10^7 particles/bunch and up to ~12 s^{-1} for 10^9 particles/bunch. The growth rate due to IBS scattering is about 100 times more than the Touschek loss rate of the particles in a bunch of 1 ps pulse length (rms). To mitigate the degradation of beam quality one can apply swap-out injection at high repetition rate of up to 100 Hz as it was proposed for a 25 MeV electron storage ring designed for the Compton backscattering studies [16].

CONCLUSION

The detailed design of a very large acceptance compact storage ring has been done so far. Studies of CSR effects, beam lifetime and evolution of beam parameters, beam injection and extraction, beam diagnostics and orbit correction have been performed.

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