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MODIFIED LATTICE OF THE COMPACT STORAGE RING IN THE cSTART PROJECT AT KARLSRUHE INSTITUTE OF TECHNOLOGY

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Abstract

The compact storage ring project for accelerator research and technology (cSTART) is realized at the Institute for Beam Physics and Technology (IBPT) of the Karlsruhe Institute of Technology (KIT). Combination of a storage ring and a laser wake-field accelerator (LWFA) might be the basis for future compact light sources and advancing user facilities. Meanwhile the post-LWFA beam should be adapted for storage and accumulation in a dedicated circular accelerator. Modified geometry of compact ring operating at 50 MeV energy range has been studied and main features of a 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 fs range from the Plasma cell as well as from the ferninfrarot linac- und test- experiment (FLUTE). The DBA lattice with different settings and relaxed parameters, split elements and higher order optics of tolerable strength allows improving the dynamic aperture and momentum acceptance to acceptable level. This contribution discusses the lattice features in details and different possible operation schemes of a ring.

INTRODUCTION

A dedicated storage ring with adapted features should be built and tested in order to provide experimental "proof of principles" on possible operation with beams after a laser wake-field accelerator [1]. Stable rotation of ultra-short (~fs) bunches, storage of a wide-momentum spread beam in a circular ring would be a solid ground for further R&D on LWFA facilities.

Meanwhile the post-LWFA beam is not directly suitable for storage and accumulation in conventional storage rings. New generation rings with adapted features are required. One important goal of the project is to demonstrate injection and storage of a post-LWFA beam in a storage ring. As a first stage the compact linear accelerator FLUTE will serve as an injector of 50 MeV bunches to test the ring's performance [2].

The cSTART ring will be used also for accelerator R&D studies. Different geometries, lattices and operation modes of a ring to store electron beam at 50 MeV energy range have been extensively investigated and results of preliminary studies were reported at [3-5].

Ring dimensions are strongly limited by the compact size of the FLUTE Bunker [2] while maximum value of dispersion function should be limited in order to accommodate wide momentum spread beam. A highly non-linear DBA lattice with 22.5° gradient dipoles, split quadrupoles and two-meter-long straight sections has been chosen as a best candidate for further detailed studies [4, 5]. Later it was realized that short straight sections cannot accommodate all necessary equipment and proposed set up is not flexible to manage different operation modes. Also bending magnets with high gradient can't guarantee the required parameters in specific case of a wide momentum spread beam.

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STORAGE RING

Final setup of the cSTART ring includes flat (no gradient) 45°sector bends, split quadrupoles with relaxed parameters, sextupole and octupoles lenses, diagnostic equipment. Four-meter-long straight sections accommodate elements of injection, equipment for dedicated diagnostics and physical experiments. An OPA code and new ring geometry were used for computer simulations [6]. The ring layout is shown in Fig. 1.

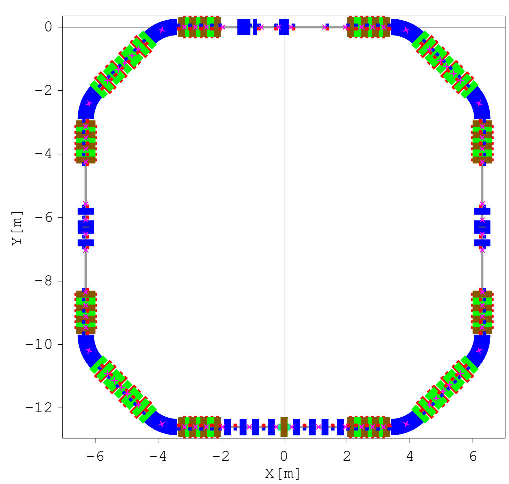

Figure 1: Layout of the cSTART ring.

A special transfer line delivers short bunches from the FLUTE linac to the ring and includes focusing elements, energy analyzer and bunch compressor that provides phase space "gymnastics" of the ultra-short bunches [7].

The ring should accommodate large momentum spread beam and allow circulation of ultra-short bunches at non-equilibrium conditions:

- Momentum acceptance is increased to about ±6%.
- Dynamic aperture (DA) is opened to ±20 mm at position of maximum value of horizontal betatron function β_x.
- Strength of sextupoles is limited to open the DA.

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Straight sections are designed as modular units for:

- injection elements are shown at top straight of ring layout, RF system, diagnostics.
- dedicated wigglers (set of dipoles) for a variable momentum compaction factor experiment (blue blocks at left and right straights of a ring).
- phase compressors of chicane type, undulator and laser stochastic unit (bottom straight in Fig. 1).
- ring should be fitted into existing FLUTE bunker.

Parameters of a ring are listed in the Table 1. Ring lattice incorporates four equal achromatic sections. Double bend achromat composed of two 45° dipoles and 12 quadrupoles forms one cell with total bending angle of 90° (Fig. 2). Quadrupoles are split in halves and sextupoles are flanked in-between. Bending radius of 45° sector magnets with flat poles is 1,273 m, effective length is 1 m. One cell of cSTART lattice is composed of two sections with mirror symmetry, see dashed line in Fig. 2.

Table 1: Parameters of the cSTART Ring

Parameter	Split Q Lattice
Energy range	50 MeV
Magnetic rigidity, $B{\cdot}R$	0.167–1.67 T·m
Circumference (footprint)	44,4 m (13×13 m)
Periodicity / cell	4 / DBA 2×45° bends
Straight sections $N \times L$, m	4 × 4 m
Mom. Comp. factor variable	$+2\cdot10^{-2}\ldots-1\cdot10^{-2}$
SR losses/turn (50 MeV)	< 1 eV
Natural Chromaticity	$\xi_{x,y} = -24$ / -20
Damping time $\tau_x/\tau_y/\tau_s$	h/v/l = 37/34/16 s
Energy spread variable	$\sigma_E = 10^{-4}$ to 10^{-2}
Momentum acceptance	± 5.5%
RF frequency / F_{ROT} / h_{RF}	500 / 6.8 MHz / 73
Betatron tunes Q_x/Q_y	5.652 / 1,265 (DBA)
Vacuum chamber (full size)	60 × 40 mm
Dynamic Aperture (h/v)	20 / 14 mm
Dynamic Acceptance (h/v)	100 / 20 mm·mr
Unnorm/norm emittance (h)	10nm / 1mm·mr
Betatron tunes Q_X/Q_Y	5,844 / 8,461 (DBA)
Bunch length (rms)	~2 fs to 1 ps
Bunch charge	1.6 to 160 pQ
Bunch intensity	10^7 to 10^9 particles 20 ms
Lifetime at 50 MeV	to 20 minutes

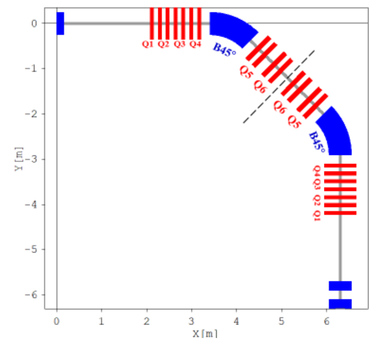
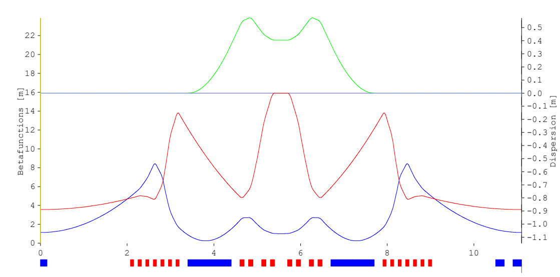


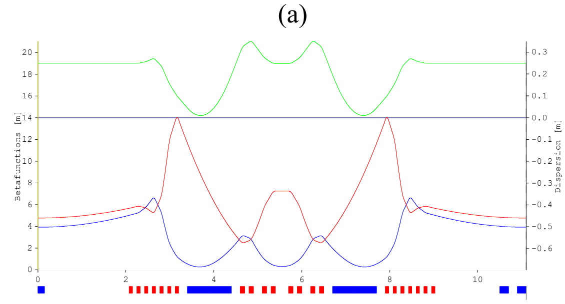
Figure 2: One cell of cSTART ring. 45° flat bends are marked as blue sectors, quadrupoles (in red) are splitted in halves and sextupoles are flanked in-between (not shown).

At 50 MeV energy range the SR damping is extremely slow (~20 s) and ring will operate at non-equilibrium conditions. Different operation modes are required to pursue accelerator R&D activities [8, 9]. Ring lattice with flexible optics was adopted for a cSTART (Fig. 3). The DBA mode with achromatic straight sections and FDDF quadrupoles will be suitable for regular operation as well as for commissioning and tuning (Fig. 3a). Presence of dispersion at position of a variable field dipoles is necessary for a tunable compaction factor experiment. Ring optics with reduced momentum compaction factor ($\alpha=8\cdot10^{-3}$), FDDF quads and dispersion function leaking to all straight sections (Fig. 3b) should satisfy abovementioned requirements. Similar operation modes but with DFFD quadrupoles as well as ultra-low–α optics also available.

The lattice compromises contradictory conditions.



(a)



(b)

Figure 3: 90° cell of ring lattice with FDDF quads. Horizontal betatron function is marked by blue, vertical β–function – by red, dispersion function – by green. 45° bends shown as blue strips, double split quads – as red blocks: (a) DBA optics with achromatic straights and momentum compaction factor $\alpha=1.8\cdot10^{-2}$; (b) reduced–α optics ($\alpha=8\cdot10^{-3}$) with distributed dispersion.

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A small circumference of the ring leads to strong focusing quadrupoles. The acceptance of cSTART ring is limited by strong sextupoles required to compensate high negative chromaticity. At the same, the beam of large momentum spread (σ_p~1%) should be accommodated for stable rotation. By proper choice of ring set up, in particular, by splitting of strong quads in dispersion sections of a ring the strength of the quadrupoles was essentially reduced. Nine families of chromatic and harmonic sextupoles help to open the dynamic aperture and restore momentum acceptance. Location of horizontal chromatic sextupoles at mirror symmetry position with local maxima of horizontal beta-function and dispersion helps to reduce integrated strength of sextupoles. The phase advance per cell was adjusted to minimize leading resonance-driving terms.

NONLINEAR OPTICS

Sextupole and octupole magnets of early versions of a ring were integrated into the quadrupole magnets as combined function elements. A thorough investigation revealed however that the long magnets with multipole components will be the source of strong nonlinearities and limited dynamic aperture. Another concern was that the focusing strength and sextupole/octupoles setting were tied to each. It was feared that the lack of tuning options could become a problem and long quadrupole magnets were split up into two halves of equal strength and flank sextupoles in-between. Zoomed view of focusing and diagnostic elements is presented in Fig. 4. Solid magnet block in front of first bend (and mirror reflection behind the second bend) is shown in Fig. 4a; magnet block at dispersive part of the DBA cell between two 45° sector magnets – in Fig. 4b.

Family of combined function magnets Q1 includes skew quadrupoles and octupoles to control coupling as well as change the sign of curvature of momentum compaction factor. Nine families of sextupoles suppress Resonance Driving Terms (RDT) as well as linear $\xi^{(1)}_{x,y}$ and quadratic $\xi^{(2)}_{x,y}$ chromaticities. Originally a strategy was pursued where high order RDT, in particular, three terms for amplitude-dependent tune shifts α_{ij} and second order chromaticity $\xi^{(2)}_{x,y}$ were cancelled by the octupoles. However, it became clear that due to high octupoles strength the dynamic aperture has been shrinking.

Based on experience of MAX-IV 3 GeV ring [10] a new approach was taken in which chromatic octupoles have been removed and three families of harmonic octupoles cancel only ADTS terms while octupoles strength is limited. The octupoles have been placed where they are most efficient for each driving term α_{xx}, α_{xy} or α_{yy}. It was also noticed that an overall optimization does not call for complete cancellation of the first-order driving terms.

Because of the cancellation of ADTS the tune footprint remains confined in a very limited area. The relatively large distance to potentially harmful lower-order resonances and the small tune footprint justify the choice of working point for the cSTART ring from a nonlinear optics point of view. The cSTART optics is flexible and working point can be easily adjusted.

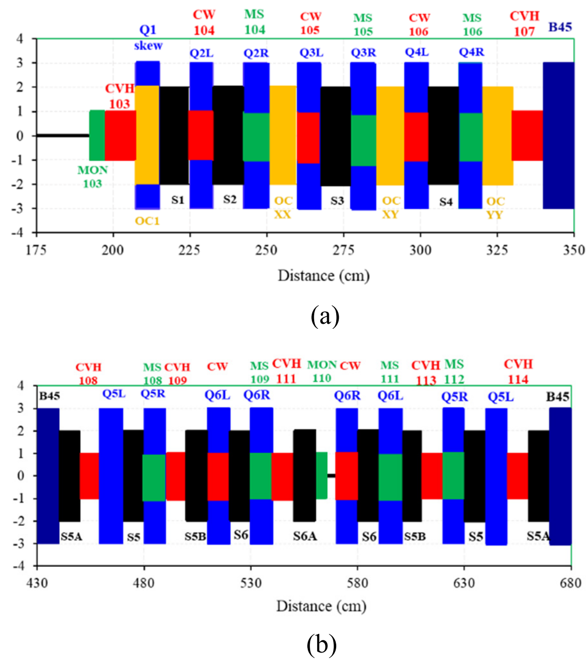

Figure 4: Zoomed view of focusing and diagnostic elements: a) magnet block in front of first 45° bending magnet (B45); (b) blocks between two 45° sector magnets. Dedicated correctors (CHV) as well as additional wiring correctors (CW) inside quadrupole magnets are marked by red; Monitors (MON) and strip-line BPM (MS) – by green; Quads – by blue color, sextupoles – by black, octupoles – by brown.

Ring components will be manufactured as solid block magnets machined as one piece [10]. It allows to limit misalignment errors to 30 µm and roll errors to 100 µrad (rms) as well as center beam orbit with accuracy better than 0.5 mm. Fluctuations of beam energy is reduced to 10^{-4} by stabilization of dipole magnets field at level of $2{\cdot}10^{-5}$. Tune jitter will be suppressed to 10^{-3} by stabilization of quadrupole gradient at 10^{-4} level. Spurious fluctuations of chromaticity will be less than $5{\cdot}10^{-3}$ by stabilization of sextupoles at level of $5{\cdot}10^{-4}$. Tolerances on spurious fluctuations of ADTS set at 10^{-2} level will be satisfied by stabilization of octupole gradient better than 10^{-3}. Spurious sextupole components must be limited to 0.2 m^{-3} for dipoles and to 0.6 m^{-3} for quads. Residual octupole components of dipoles, quadrupoles and sextupoles must be limited to 15 m^{-4}.

CONCLUSION

Detailed design of a very large acceptance compact storage ring has been done so far. Studies of the CSR effects, lifetime, beam injection and diagnostics, orbit correction were performed and reported at IPAC-21 conference.

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