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DESIGN OF A VERY LARGE ACCEPTANCE COMPACT STORAGE RING

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Abstract
Design of a very large acceptance compact storage ring is underway at the Institute for Beam Physics and Technology of the Karlsruhe Institute of Technology (Germany). Combination of a compact storage ring and a laser wakefield accelerator (LWFA) might be the basis for future compact light sources and advancing user facilities. Meanwhile the post-LWFA beam is not fitted for storage and accumulation in conventional storage rings. New generation rings with adapted features are required. Different geometries and lattices of a ring operating between 50 to 500 MeV energy range were investigated. The model suitable to store the post-LWFA beam with a wide momentum spread (1% to 2%) and ultra-short electron bunches of fs range was chosen as basis for further detailed studies. The DBA-FDF lattice with relaxed settings, split elements and high order optics of tolerable strength allows improving the dynamic aperture up to 20 mm. The momentum acceptance of the compact lattice exceeds 8% while dispersion is limited. The physical program includes turn-by-turn phase compression of a beam, crab cavities, dedicated alpha optics mode of operation, nonlinear insertion devices etc.

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, cost-effective accelerators and sources of synchrotron radiation for present and future users [1]. Laser Wakefield Accelerators (LWFA) feature short bunch lengths and high peak currents, combined with a small facility footprint. This makes them attractive as injectors for synchrotron light sources, as the length of the emitted photon pulse is directly proportional to the length of the emitting electron bunch. LWFA with their intrinsically short bunches would, therefore, allow to study processes on a much faster time scale than currently possible with the bunch lengths customary for synchrotron radiation source storage rings.

Furthermore, for wavelengths longer than the length of the emitting electron bunch, the photon emission becomes coherent [1]. Thus, the intensity of terahertz (THz) to infrared radiation increases dramatically. LWFA bunches would therefore allow to extend the spectrum of coherent synchrotron radiation in the THz to mid-infrared range, a region currently difficult to access with high intensity and high repetition rates. The combination of a circular storage ring and a laser wake-field accelerator might be a basis for a new generation of compact light sources and advancing user facilities to different commercial applications including multi-user medical applications etc.

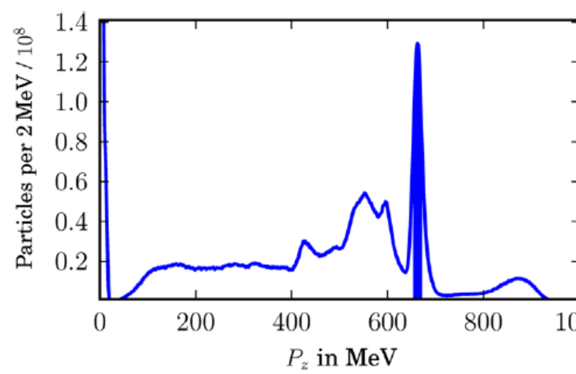

Figure 1: Longitudinal momentum distribution of electron beam generated by Laser Wake Field Accelerator, taken from [2]. Central peak energy is 662 MeV. Assuming Gaussian distribution of main spike (solid line) the energy spread of post-LWFA e-beam corresponds to FWHM=2–3% (σ_p=1.3 %).

Meanwhile the post-LWFA beam is not directly suitable for storage and accumulation in conventional light source Facilities [2]. Despite the small initial beam size at laser spot the beam is spread out quickly because of the large angular divergence and high energy spread (Table 1)[1].

The wide energy distribution of electron beam generated by Laser Wake Field Accelerator (Fig.1) is not of Gaussian shape [2]. Nevertheless, assuming the Gaussian distribution of main spike shown in Fig.1, the energy spread of post-LWFA electron beam might be estimated as 15-20MeV at the central peak energy 662 MeV, which well exceeds momentum spread of e-beam (10^{-3}) at existing light sources. The full width at half maximum of the main peak approximated by a Gaussian shape is FWHM=2–3% (σ_p=1.3%). As a consequence, 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 [3].

Table 1: Parameters of post-LWFA Beam after Plasma [1]

Energy of central peak	662 MeV
RMS momentum spread	1.2 %
Number of particles	~$10^7 \div 10^9$
Normalized emittance	25 mm·mr
RMS bunch length σ_l	2.4 μm
RMS pulse width τ_{rms}	8 fs
RMS divergence $\sigma_{X'}$	10 mr

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Growth of normalized emittance leads to an increase of bunch length due to synchro-betatron coupling in dispersive sections of a ring [4].

STORAGE RING

One should provide "proof–of-principles" on possible operation with beams after a laser wake-field accelerator. Experimental evidence of stable rotation of ultra-short (fs) bunches, storage of a wide-momentum spread beam in circular rings would be a solid ground for further R&D on LWFA facilities.

Extensive studies of possible configurations of very large acceptance compact storage ring have been done at KIT [5] and the results are presented here.

cSTART storage ring will operate in an energy range of 50 to 500 MeV. The main tasks are following:

--study stable rotation of 10 to 100 fs ultra-short bunches

--store single spikes of e-beam of 20–200 pC charge and possibly, up to 1 nC

--store beam of wide momentum spread (σ_p=1–2%)

--operate with beam of emittance $\varepsilon \leq$30 nm·rad (rms)

In order to fit the abovementioned requirements the ring should satisfy the following features:

--momentum acceptance of the ring should be more than ±6% to accommodate wide beams

--ring dispersion must be small (D<25 cm) to fit large energy spread beam in bending sections of a ring

--the dynamic aperture should be large >±15mm to allow the stable rotation of a wide momentum spread beam

--option for phase compressors of chicane type and laser stochastic units installed in straight sections of a ring

--the compact ring should be fitted in existing FLUTE bunker [6]

Parameters of ring are listed in Table 2. The 50 MeV test bench facility FLUTE [6] will serve as ring injector.

Table 2: Parameters of the VLA-cSR Ring (relaxed settings)

Parameter	3Q-split lattice
Energy range, MeV	50 – 500
Magnetic rigidity, T·m	$B{\cdot}R$ = 0.167–1.67
Circumference, m	44,112
Ring periodicity	4 (two 45° FDF-DBA)
Split DBA super-cell (cell/–cell)	2×22,5° / –(2×22,5°)
Straight sections	4 × 2 m
Momentum compaction	6,03 × 10^{-3}
SR losses/turn (50/500 MeV)	<1 eV / 4,3 keV
Horizontal damping partition Jx	1,397
Damping time τ_X / τ_Y / τ_l, seconds	24 / 34 / 21 (50 MeV)
RF frequency / F_{ROT} / h_{RF} (MHz)	3000 / 6.8 / 440
Injection energy/ inj.energy spread	50 MeV / σ_p=2·10^{-2}
Inj.beam emittance(norm/unnorm)	<10 mm·mr/<100 nm·r
Natural emitt/nat.en.spr. (no IBS)	0,18 nm·r / σ_p = 4·10^{-5}
Betatron tunes Q_X / Q_Y	5,844 / 8,461
Phase advance (supercell) hor/vert	μ_X= 2.92π / μ_Y= 4.23π
Natural Chromaticity (per cell)	$\xi_{X/Y}$ = –16/–21 (–4/–5)
Dynamic Accept X/Y(incl. errors)	120/20 (70/10) mm·mr
Beta-functions–middle straight, m	$\beta_{X/Y}$ = 1.8 / 1.2
DBA Dispersion max (distr), m	0.25 (±0.15)
Dynamic Aperture hor / vert, mm	(–14…+18) / (± 6)
Momentum acceptance (bare lat.)	±6÷8 %

Beam parameters after FLUTE can be smoothly adjusted to be similar to those after the LWFA while bunches after FLUTE linac more stable and reproducible than e-spikes after laser wake field. The synchrotron radiation damping time exceeds 20 s at beam energy of 50 MeV and it is considered as slow adiabatic process.

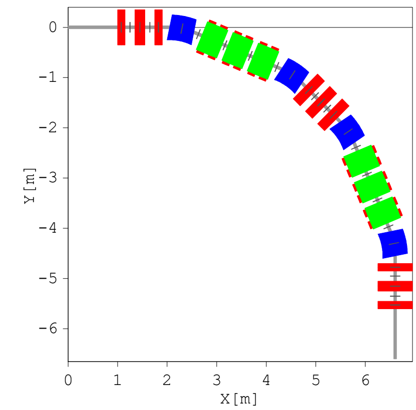

Figure 2: cSTART lattice (one cell is shown). Gradient bends (blue) add to vertical focusing, quadrupoles (red) in dispersive sections are splitted in doublets, families of main chromatic sextupoles (green) are splitted in triplets. Central sextupole of each triplet is flanked between quads.

Modified version of the ring lattice with relaxed parameters is composed of four equal achromatic sections. Two double bend achromats form one cell with total bending angle of 90° (Fig.2). Split triplets are located in the dispersive parts of DBA. Bending radius of 22.5° high gradient magnets is 1,273 m, effective length is 0.5 m. One cell of cSTART lattice is composed of two sections with mirror symmetry (Fig.3). The lattice compromises contradictory conditions. A small circumference of the ring leads to strong focusing quadrupoles while the dispersion must be kept small. The acceptance of cSTART ring is limited by strong sextupoles required to compensate high negative chromaticity while dispersion is small. At the same time, the beam of large momentum spread (σ_p=1÷2%) should be accommodated for stable rotation. By proper choice of ring lattice, in particular, splitting of strong quads in

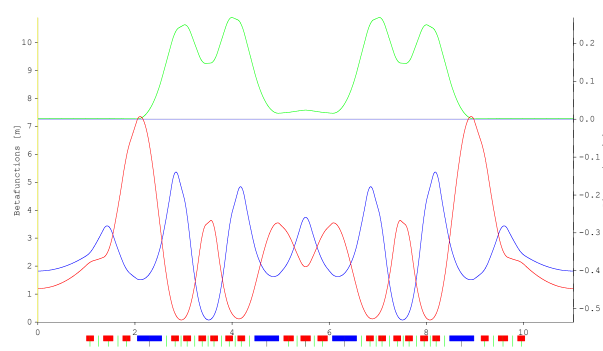

Figure 3: Ring lattice. One cell is composed of two halves with mirror reflection. Horizontal beta-function in blue, vertical – in red, dispersion - in green. Bends shown as blue strips, quads - red. High order elements treated as thin lenses (green strips).

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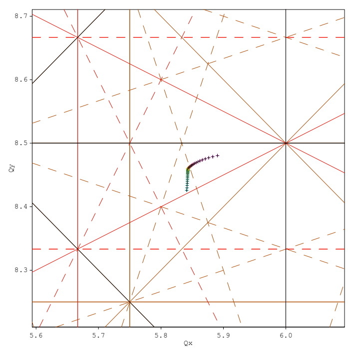

Figure 4: Tune diagram of cSTART ring. Combination of sextupoles and chromatic octupoles helps to localize and wrap up foot-print of chromatic tune deviation for particles with momentum offset of up to δp/p≤ ±10%.

dispersion sections of a ring we reduce strength of the quadrupoles from 40 down to <16m^{-2}. The *"–I"* condition was realized and chromaticity per unit cell was reduced. 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 from 35m^{-2} to <12m^{-2}. The phase advance per cell was adjusted to minimize leading resonance-driving terms.

The dynamic aperture of the optimized lattice with split quadrupoles and relaxed parameters was opened to ±20 mm in order to fit the wide momentum-spread beam. Harmonic sextupoles expand momentum acceptance of the ring to ±6% in the horizontal plane and ±8% in the vertical plane.

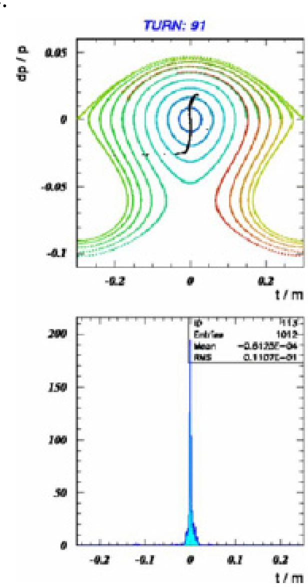

Figure 5. Simulations of 10 fs pulse in an cSTART lattice [8]: top figure – up-right position of ultra-short pulse after 90 turns of rotation in longitudinal phase space (vertical axis is momentum spread). Bottom figure – bunch intensity. Horizontal axis in bunch width in length units, vertical axis - relative units of beam intensitsity.

Harmonic sextupole and chromatic octupoles will be used for non-linear studies, in particular, to minimize ADTS, to operate the ring at a negative momentum compaction factor, to manipulate the bunch width and shape.

Combination of sextupoles and chromatic octupoles helps to localize and wrap up the foot-print of chromatic tune deviation for particles with momentum offset (Fig.4). Chromatic octupoles reduce tune deviation to $\delta Q_{X,Y} \leq 0.03$ for off-momentum particles even at ±10% momentum offset. Strength of octupoles should be limited to preserve ring acceptance. Tight tolerances on misalignments, roll-offs, field errors etc. lead to a design of solid magnetic blocks similar to MAX-IV 3 GeV ring magnets [7].

Rotation of 10 fs pulses in cSTART lattice has been simulated and results are presented in Fig. 5. After hundreds of turns one could observe peaks of ultra-short bunches. Different experiments with ultra-short bunches and turn-by-turn phase compression of a beam, coherent synchrotron radiation, optical stochastic cooling, crab cavities, dedicated alpha optics modes including operation at negative compaction factor, non-linear insertion devices etc. will be provided in available straight sections of a ring.

SUMMARY

Preliminary studies on optimized lattice for a very large acceptance compact storage ring have been done so far. The realization of such a ring would provide a "proof of principles" and solid ground to build next generation synchrotron light sources based on laser wake-field accelerator injectors.

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