# RECENT DEVELOPMENTS OF THE cSTART PROJECT

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*Abstract*

The combination of a compact storage ring and a laser-plasma accelerator (LPA) can serve as the basis for future compact light sources. One challenge is the large momentum spread (about 2 %) of the electron beams delivered by the LPA. To overcome this challenge, a very large acceptance compact storage ring (VLA-cSR) was designed as part of the compact STorage ring for Accelerator Research and Technology (cSTART) project. 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 the VLA-cSR to benchmark and emulate LPA-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 the Helmholtz Institute Jena (HIJ). The small facility footprint, the large-momentum spread bunches with charges from 1 pC to 1 nC and lengths from few fs to few ps pose challenges for the lattice design, RF system and beam diagnostics. This contribution summarizes the latest results on these challenges.

## INTRODUCTION

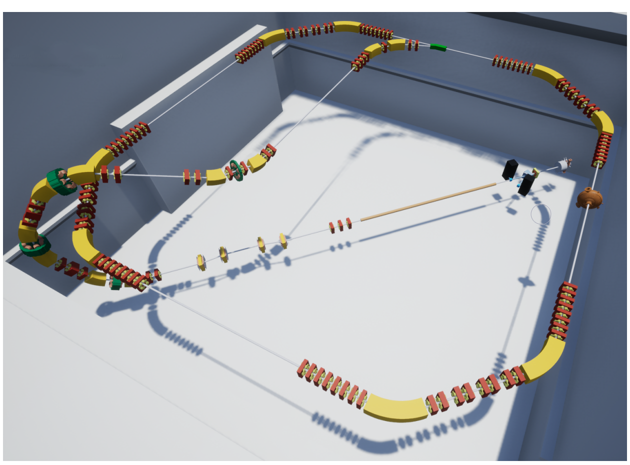

Figure 1: Artistic view of the cSTART project. The cSTART storage ring at a height of about 3.5 m is connected to the FLUTE injector by a complex 3D transfer line. The LPA (not shown) will be at the same height as the storage ring and uses the last part of the transfer line of FLUTE for injection.

Laser-based plasma acceleration 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 divergence and energy spread require dedicated beam transport systems and insertion devices [2]. Moreover, their repetition rate is limited to a few Hz compared to MHz at storage rings.

Table 1: Main Parameters of the cSTART Storage Ring

| Parameter | Value | Unit |
|---|---|---|
| Circumference | 43.2 | m |
| Energy range | 40 to 60 | MeV |
| Injection rate | 10 | Hz |
| Injection type | one-turn swap-out | – |
| Beam storage time | 100 | ms |
| Bunch charge | 1 to 1000 | pC |
| Revolution period | 144 | ns |
| Revolution frequency | 6.94 | MHz |
| Incoherent energy loss | 0.54 | eV |
| Damping time (h, v, l) | 29.5, 26.5, 12.6 | s |
| Coherent energy loss (1 pC, 20 fs) | 160 | keV |
| Critical frequency $f_{\mathrm{crit}}$ | 37.7 | THz |
| Tune (h, v, l) | 5.18, 1.66, 0.023 | 1 |
| Momentum compaction: | | |
| nominal | $14.8 \times 10^{-3}$ | 1 |
| reduced-$\alpha$ | $3.9 \times 10^{-3}$ | 1 |
| RF frequency | 500 | MHz |
| RF voltage | 500 | kV |
| Harmonic number | 72 | 1 |
| Vacuum pressure | $1 \times 10^{-8}$ | mbar |

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 also as injector to provide well-defined LPA-like bunches for benchmarking and to further explore injection of ultra-short, 10 fs-range electron bunches. An artistic view of the cSTART storage ring on top of FLUTE is shown in Fig. 1. 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.

With two different injectors, the beams at cSTART cover a large region in parameter space. In simulations, the LPA beam achieved a bunch charge of 20 pC with mean energy of

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50 MeV, energy spread of ~2 % and bunch length <20 fs [5]. Meanwhile, FLUTE can cover a bunch charge range from 1 pC to 1 nC with energies between 40 MeV to 60 MeV, energy spread ~0.1 % and bunch lengths from <1 ps down to a few fs. The relatively low electron energy of ~50 MeV means that energy losses due to incoherent synchrotron radiation are negligible and that damping times are in the order of tens of seconds [6]. As a consequence, the beam remains in non-equilibrium throughout the planned storage time of 100 ms. There will be a swap-out injection of a new bunch after 100 ms, i.e. extraction of the circulating bunch into a beam dump and on-axis injection of a new bunch. Only single bunch operation is currently foreseen.

These wide ranges of beam parameters provide challenges to the lattice design [6], the transfer line from the injectors [7–9], and the beam diagnostics [10], but will also provide a plethora of measurement data and opportunities for the analysis and control of non-equilibrium beam dynamics. This paper gives an overview of the recent developments to overcome these challenges.

## RING LAYOUT AND MAGNETIC LATTICE

The cSTART storage ring shall be very compact as a model for future compact light sources. This is naturally achieved by reusing the existing FLUTE hall, which leads to space constraints with a footprint of 15 m × 14.5 m. In addition, the ring will be mounted at a height of about 3.5 m. For the LPA-injector, the storage ring must have a sufficiently large momentum acceptance to accommodate its beam. The complex 3D shape of the transfer line from FLUTE (see Fig. 1) arises from a) spatial constraints and b) the need to compress the bunch, so that it is ultra-short at injection [7].

Several layouts of the storage ring have been studied, see Ref. [6] and references therein. The parameters of the final design are listed in Table 1. The ring has a circumference of 43.2 m and consists of four identical DBA arcs with a length of 6.95 m and four straight sections with a length of 3.85 m. One straight section is used as the injection section, while the other three sections are available for an RF cavity, advanced diagnostic systems, and accelerator physics experiments.

The magnet layout of one arc is shown in Fig. 2. Five families of quadrupoles (Q$n$) and two families of sextupoles (S$n$) for chromaticity correction are foreseen. Space is reserved for four additional sextupole families and one family of octupoles, e.g., in-between the quadrupoles of the straight sections. The beam position will be measured by button beam position monitors and corrected by dedicated horizontal and vertical corrector magnets. The lattice functions of one cell are shown in Fig. 3 for the operation mode with nominal momentum compaction. The magnetic layout is very flexible to support other operation modes, e.g., with reduced momentum compaction where the dispersion leaks into the straight sections.

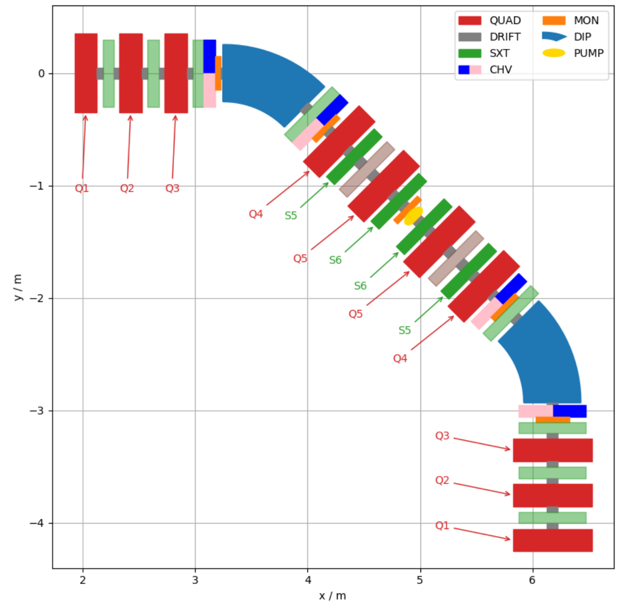


Figure 2: Magnet layout of the DBA lattice in one arc.

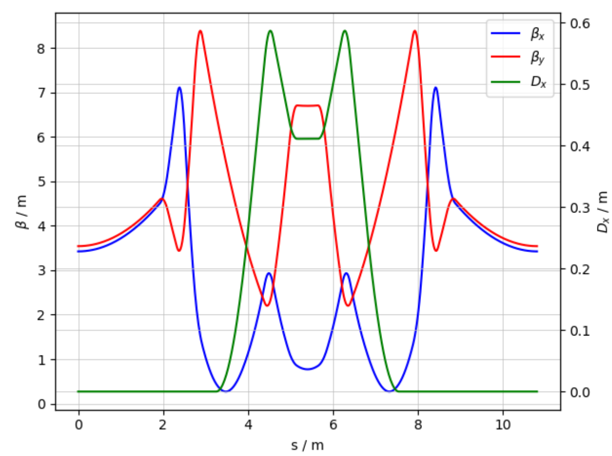


Figure 3: Lattice functions in one cell for an operation mode with nominal momentum compaction of $14.8 \times 10^{-3}$. The dispersion is located between the dipoles and does not exceed 0.6 m, while the momentum acceptance is about ±4 %.

## RF SYSTEM

An RF cavity will be placed in one of the straight sections. Several considerations affected the choice of the RF frequency: 1) A large RF acceptance requires a low RF frequency, which increases the length of the cavity; 2) A small equilibrium bunch length favors a high RF frequency; 3) The cavity must be able to provide a large accelerating voltage to increase the RF acceptance and to reduce non-linear effects. Finally, a cavity frequency of 500 MHz was chosen as a good compromise [11]. Available cavities at this frequency can provide an acceleration voltage of 500 kV for an input power of 50 kW [12, 13]. With a harmonic number of 72, this yields an RF energy acceptance of ~8 %.



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## BEAM DYNAMIC SIMULATION RESULTS

The Touschek lifetime of a bunch depends non-trivially on the bunch and machine parameters. Due to the large range in bunch charge and bunch lengths, the Touschek lifetime at cSTART varies by two orders of magnitude [6]. It is above 1 s for a bunch charge of 1.5 pC, but varies between 12 s to 1 s for a bunch with 150 pC and bunch length between 1 ps to 0.06 ps, respectively. Intrabeam scattering (IBS) is also non-negligible at the energy of 50 MeV. The IBS growth rates have been estimated [6] to be 0.12 $s^{-1}$ for a bunch of 1.5 pC and 12 $s^{-1}$ for 150 pC. The latter corresponds to a time scale of 83 ms and is, thus, shorter than the storage time of 100 ms and necessitate the on-axis swap-out injection. Keep in mind that these computations assume equilibrium conditions (especially for the bunch length).

While incoherent synchrotron radiation is negligible at energies of about 50 MeV, the ultra-short bunch lengths mean that the synchrotron radiation is emitted coherently. Since the intensity of coherent synchrotron radiation (CSR) scales quadratically with the number of electrons, it is not negligible. Especially after injection, when the bunch length is only a few femtoseconds, the energy loss per electron due to CSR can be as high as 160 keV [11]. The bunch starts to filament and, after a few ms, reaches a filamented RMS bunch length of about 15 ps [14]. However, about 40 % of the electrons are contained in sub-bunches with bunch lengths below 1 ps, see Fig. 4. These sub-bunches are surrounded by a halo of electrons, which increases the RMS bunch length. Note that these simulations only include the longitudinal dynamics.

These first results show the necessity to perform full 6D simulations that include not only the CSR but also Touschek and Intrabeam scattering.

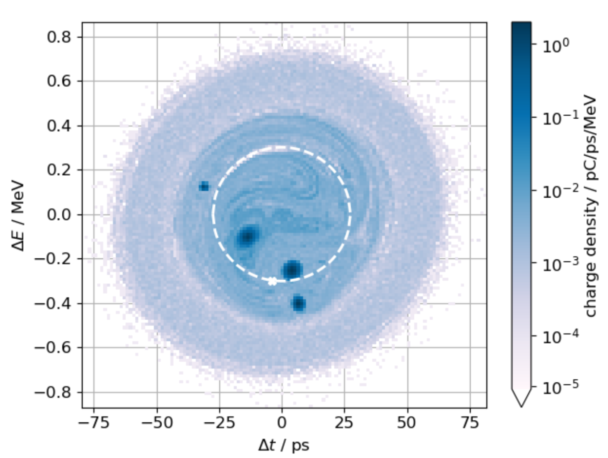


Figure 4: Simulated longitudinal phase space density after 100 ms for a 1 pC bunch. About 40 % of the particles are contained in four sub-bunches, each with $\sigma_{RMS} \leq 1$ ps [14].

## SUMMARY

The cSTART project develops the infrastructure and technology necessary for a compact LPA-based light source. A key part is the construction of a compact storage ring to capture and store sub-ps short bunches. The cSTART storage ring will have a circumference of 43.2 m, and a large momentum acceptance suitable for the injection of LPA-generated beams. Its two injectors will be the linac-based accelerator FLUTE and a laser-plasma accelerator. Three out of four straight sections are available to accommodate advanced diagnostic systems and accelerator physics experiments. The DBA lattice is flexible enough to provide operation modes with different momentum compaction factors. The RF system at 500 MHz will consist of a single cavity that provides an acceleration voltage of 500 kV at a power of 50 kW.

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. After filamentation, the bunch length can increase to several ps, while several sub-bunches, containing about 40 % of the particles, form with an RMS bunch length below 1 ps. Touschek scattering, intra-beam scattering, and coherent synchrotron radiation all play an important role in the beam dynamics. To study all these effects together requires the simulation in 6D phase space and may also require to define additional or new figures of merit for describing non-equilibrium beams in the future.

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