INITIAL LATTICE STUDIES FOR THE BERKELEY FEMTOSECOND X-RAY LIGHT SOURCE

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Abstract

We present lattice studies for a proposed femtosecond synchrotron radiation X-ray source based on a recirculating accelerator. After a general description, we cover specific aspects of the lattice that are relevant to this type of machine and show preliminary results of particle tracking and briefly describe a new code developed for a comprehensive particle tracking in recirculating accelerators.

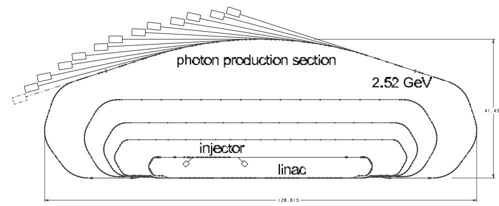

Figure 1: The layout, showing injector, linac, and four rings. The beam energies are 0.72, 1.32, 1.92 and 2.52 GeV

1 INTRODUCTION

The Berkeley Femtosecond X-ray Light Source [1] is a 2.5 GeV recirculating accelerator, where electrons reach their final energy in four passes through a 600 MeV superconducting linac based on TESLA cryomodules [2] after injection at 120 MeV. Figure 1 shows the layout of the main machine and its injector. Three magnetic arcs serve as a beam return to the linac for the next step of acceleration. The forth arc delivers the electron beam to an array of undulators and bend magnets in a photon production section. Although the baseline concept of this machine does not assume a deceleration and energy recovery and therefore does not have a return path in the forth arc, we include it in the lattice studies in order to accommodate energy recovery in future upgrades.

Based on site considerations shape and circumference of the machine's outer ring as well as the length of the photon production section and of the linac straight section were chosen. The circumferences of all three inner rings are less constrained but not totally arbitrary. Our base line design assumes 10 kHz bunch repetition rate from the electron gun. An electron bunch will finish a complete trip through the entire machine before the next bunch will come in. The average beam current through the linac is only 80 μA at a 1 nC bunch charge. If we will ever consider higher beam currents, we would prefer a uniform bunch spacing along the linac. The present choice of circumferences allows this for currents up to about 100 mA.

2 LATTICE DESCRIPTION

The lattice of all four rings has mirror symmetry relative to a central line dividing the machine into two halves. This seems to be the simplest solution for a lattice of a machine that works for simultaneous acceleration and deceleration of electrons. Besides a few specialized magnets in the "beam spreader" section, all magnets are of a conventional electromagnet design similar to those of existing synchrotron radiation sources.

2.1 Linac

The linac is the simplest part of the machine from a lattice point of view. Apart from a weak rf focusing that is only visible at electron beam energies below a few hundred MeV it has no other beam focusing elements. Like in a drift space, linac β-functions are freely expanded towards both ends of the linac.

2.2 Beam Spreader and Combiner

A beam spreader section (see Figure 2) directs the electron beams at various energies into their respective rings. The beam combiner reconciles different energy orbits into a single line in the linac. This is a rather sophisticated part of the lattice because of the inevitable proximity of beamlines of different energies. The magnet B0 begins the orbit separation. It bends the beam orbits between 22.276° and 6.218° depending on the energy. The downstream magnets B1 and B2 bend the orbits back. They complete the separation of different energy beams into rings 1, 2, and 3 and constrain dispersion which is otherwise too big to deal with in a region with small beta functions. The separation of ring 3 and ring 4 of 97 mm is sufficient to give room for a septum magnet B3 (see Figure 3a) that has the same polarity as B2. This magnet affects only the ring 4 beam and bends it away from the ring 3 beam. Then magnet B4 completes the separation of the ring 4 beam. Together all four magnets B0, B2, B3 and B4 act as a chicane with zero orbit displacement and zero dispersion at the exit. Quadrupoles are used for matching of the linac β-functions into the arcs.

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† This work was supported by the U.S.Department of Energy under Contract No. DE-AC03-76SF00098.

Their positions in the lattice are carefully chosen so that they do not stand side by side. Nevertheless a tight spacing requires a special design for the quadrupole shown in Figure 3b.

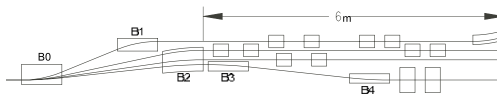

Figure 2: Beam spreader section.

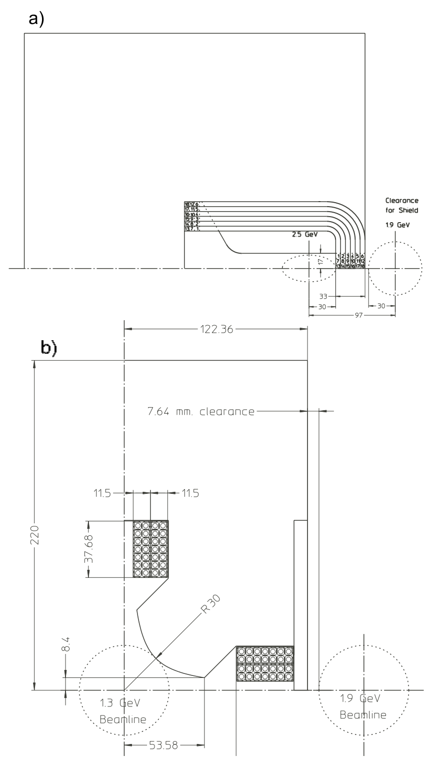

Figure 3: Crossections of a beam spreader septum bend magnet B3 (a) and a quadrupole (b). Dotted contours define vacuum chamber

2.3 Magnetic Arcs

Magnetic arcs transport the electron beams of different energies from the end of the linac to the back straight and from there to the beginning of the linac (or to the photon production section in case of arc 4). Ring 1 is shown as a typical example in Fig. 4. Lattice design of all arcs follows the same principle. All arcs are comprised of three 120° betatron phase advance cells each containing a string of bending magnets, three quadrupoles and three sextupoles. The third cell of each arc leading to the straight section is modified such as to simplify matching of the arc's optical functions to the optical functions in the straight section. This lattice approach allows us to maintain a zero dispersion function at the exit of the arc while tuning the R_{56} matrix coefficient. Present design assumes isochronous transport from the end of the linac to the end of the arc. However, it is easily adapted should electron bunch length adjustment be required at various stages of acceleration and deceleration. Sextupoles are used to compensate chromaticity and second order terms affecting isochronicity. Bending magnets, quadrupoles and sextupoles of different arcs are mechanically identical.

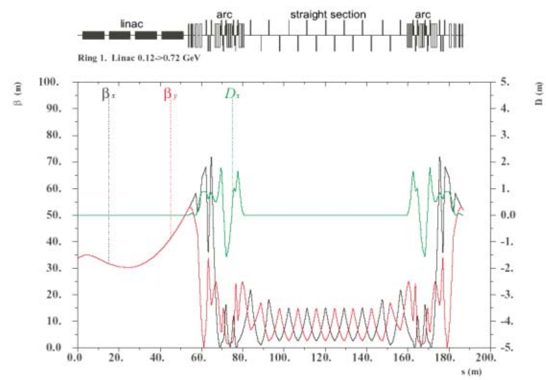

Figure 4: Lattice functions for ring 1. The effect of rf focusing is noticible in the linac.

2.4 Straight Sections

All straight sections have a simple FODO lattice containing two identical β-matching parts at both ends and a tune trombone in the middle. The tune trombones consist of four cells and allow tune adjustments in a range of approximately ± 0.5.

2.5 Photon Production Section

Figure 5 shows β- and dispersion functions of ring 4. The central part of this plot is the photon production section (PPS), which has six triple bend achromat cells with an arc angle of 6° per cell. The vertical and horizontal betatron phase advances per cell are π and 1.8π. All cells begin and end in the middle of a straight section, whose length is sufficient to host a 2 m long undulator. The magnetic field of the central bends of the cells is 2 T, so it can be used as a source of hard X-rays. An rf cavity operating in the first dipole mode is located between the arc and the PPS. The vertical β-function there is raised to 90 m. This is helpful for an efficient time-dependent rf orbit kick needed for X-ray bunch compression [3]. The transfer matrix between two rf structures across the PPS is the unit transfer matrix in both planes.

Due to the relatively low electron beam energy the effect of synchrotron radiation on the electron beam is practically negligible. Even at 2.5 GeV the average energy loss in the undulator farm is approximately 500 keV and the increase of the energy spread due to quantum fluctuations is approximately 50 keV, well below of the beam energy spread of ± 250 keV.

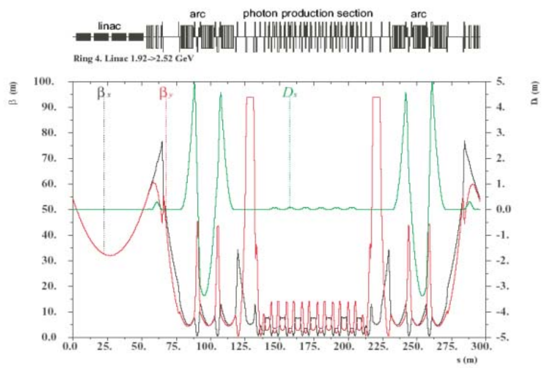

Figure 5: Lattice functions for ring 4 from the entrance of the main linac through the arc, the photon production section, another arc and back to the linac.

3 TRACKING STUDIES

The single particle dynamics of the arcs have been studied using the code COSY [4]. First, appropriate sextupole strengths were found to reduce second-order aberrations of the bunch length so that the longitudinal profile is more Gaussian. The sextupoles are weak enough (below 6 kG at 3 cm) that the change of transverse beam size is negligible for the ideal lattice. Then errors of various sorts were added. At the present stage, only random errors were considered and the the distribution is Gaussian with a cut off at 2.5σ. Specifically, the errors are the relative setting errors of dipoles, quadrupoles and sextupoles ($1 \cdot 10^{-3}$ rms), sextupole component in dipoles ($\sigma({}^{b_3}/_{b_1}) = 1 \cdot 10^{-4}$ at $r = 3$ cm) and quadrupoles ($\sigma({}^{b_3}/_{b_2}) = 5 \cdot 10^{-4}$ at $r = 5$ cm), transverse misalignment (150 μm rms), longitudinal misalignment (1 mm rms) and roll (0.2 mrad rms). The rms horizontal and vertical emittances are 20 mm mrad and 0.4 mm mrad, respectively. The rms momentum spread is 0.1 %. As shown in Fig. 6, the strongest effect of emittance increase is linear coupling introduced by the beam going through sextupoles with vertical offset (a few millimeters for certain cases). When orbit correction is applied, the coupling is greatly reduced.

A simulation tool was developed based on symplectic integration. The code allows one to switch at run time between real and Berz's Taylor series using a full polymorphic technique. This code is unlike most other tracking codes where the design orbit, included in the description of the element, literally traces the floor coordinates of the machine, violating both the physical and mathematical nature of the system. This ubiquitous defect requires the need for multiple elements to describe a single object if the beam recirculates through it or if the single object is shared by common lines (colliders).

Our new tools are designed using the concept of fiber bundles such that the fundamental component of a "beam line" is the discretized variable s on which physical data is attached as well as the geometrical transformations connecting the world of an individual magnet to the external

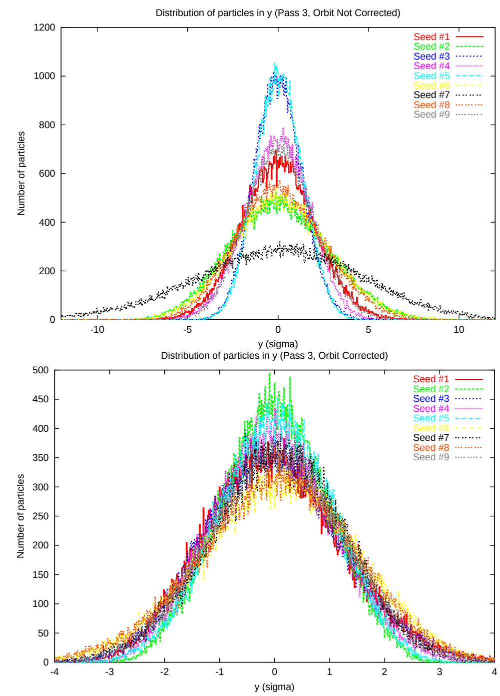

Figure 6: Vertical beam profile at the exit of ARC3 before (a) and after (b) orbit correction. Note the different scale!

world at that particular s. This allows us to handle recirculation through common elements having particles with different energies.

4 SUMMARY

A lattice for the recirculating accelerator has been designed that meets all requirements for the femtosecond X-ray source. The design permits a tunability of the time-of-flight parameters, betatron phase advances and chromaticity over the different components of the lattice. The photon production section has been designed with six identical cells with variable β-functions at the undulator and bend magnet X-ray source points. Tracking studies indicate that lattice design is insensitive to errors in magnetic field quality, but needs beam based alignment in case of alignment errors. Detailed studies and simulations of a beam-based lattice tuning technique for the machine commissioning are planed.

5 REFERENCES

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