DESIGN OF A COMPACT LINEAR ACCELERATOR FOR THE ULTRAFAST ELECTRON DIFFRACTION FACILITY

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Abstract

Ultrafast Electron Diffraction (UED) is a powerful tool to find 3-dimensional structures and dynamical transitions of chemical or biological samples with a femtosecond-range temporal resolution and an angstrom-range spatial resolution [1]. Due to the columbic field of electrons, UED can provide a higher cross section and a higher time resolution than those of the ultrafast photon diffraction with X-ray Free Electron Lasers (XFELs) [2]. In this paper, we describe the design concepts and ASTRA simulation results of a compact linac for an UED facility.

INTRODUCTION

Recently, both the ultrafast XFEL photon beam and the ultrafast electron beam have been used to get coherent diffraction images of chemical or biological samples [1–3]. With both methods, it is possible to get the animation movies of dynamical transition processes in chemical and biological samples. The ultrafast electron diffraction, however, has several advantages such as a larger cross section [1], a compact accelerator facility, and a lower radiation damage of the samples. As summarized in Table 1, the UED users' required beam energy is lower than 5 MeV, while their required rms bunch length is shorter than 80 fs, and the normalized transverse emittance is smaller than 0.06 μm. Therefore, it is challenging to generate such a high quality electron beam for an UED facility, and the performance and beam parameters of the UED facility strongly depends on the transverse and longitudinal space charge forces because its 3 dimensional beam densities are ultrahigh at a low beam energy. In this paper, we describe the layout, design concepts, and ASTRA simulation results of a 3 m long compact linac for an UED facility.

Table 1: Users' Required Beam Parameters and Budget

Parameters	Unit	Value
average kinetic energy	MeV	≤ 4.5
single bunch charge	pC	≥ 1
rms bunch length σ_z	fs	≤ 80
normalized transverse emittance ε_n	μm	≤ 0.06
rms beam size σ_x and σ_y	μm	≤ 200
rms divergence $\sigma_{x'}$ and $\sigma_{y'}$	μrad	≤ 25
total linac length	m	≤ 3
construction budget	M$	≤ 0.7

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CONSIDERATIONS FOR UED LINAC

Since it is experimentally demonstrated that RF photoinjectors can supply high quality electron beams, we optimized various linac layouts with an LCLS type 1.6 cell S-band RF gun [4], two solenoids, and two S-band standing wave RF cavities as shown in Fig. 1. If we use more RF cavities for the UED linac, we can get much better beam parameters. However, we limited the total number of the S-band RF cavities smaller than three to reduce the total construction budget. To obtain a high quality diffraction pattern, we need an ultrashort electron bunch with a low emittance and a sufficient charge. However, the transverse and longitudinal space charge forces are dominant in the UED linac because the final bunch length is ultrashort and the users' required beam energy is relatively low. The transverse and longitudinal space charge force are the main source of dilution in emittance, beam size, and bunch length. As shown in Fig. 1, however, the space charge forces and transverse beam emittance can be compensated by two solenoids, and the bunch length can be effectively compressed at a drift space between the second S-band RF cavity and the sample, where the velocity bunching is effectively done.

Impact of Space Charge Forces

Due to the Lorentz force from co-traveling electrons in a bunch, the transverse space charge force on an electron in the same bunch is given by

$$F_{\perp}(r) = \frac{Nq^2(1 - e^{-r^2/2\sigma_r^2})}{2\pi\varepsilon_0 l\gamma^2 r}, \quad (1)$$

where N is the number of electrons in the bunch, q is the charge of an electron, r is the radial coordinate, σ_r is the rms radial beam size, ε_0 is the permittivity of free space, l is the bunch length, and γ is the Lorentz factor, which is proportional to the total beam energy [5, 6]. As shown in Eq. (1), the transverse space charge force is proportional to the single bunch charge Nq, inversely proportional to square of beam energy and bunch length.

The longitudinal space charge force on the electron in the same bunch is given by

$$F_{\parallel}(dz) = \frac{3}{\pi} g \frac{Nq^2}{\epsilon_0 l^3 \gamma^2} dz, \quad g = 1 + \ln\frac{b}{a}, \quad (2)$$

where dz is the longitudinal coordinate within the bunch, a is the radius of a round beam inside a cylindrical vacuum chamber with a radius of b [5, 6]. As shown in Eq. (2), the

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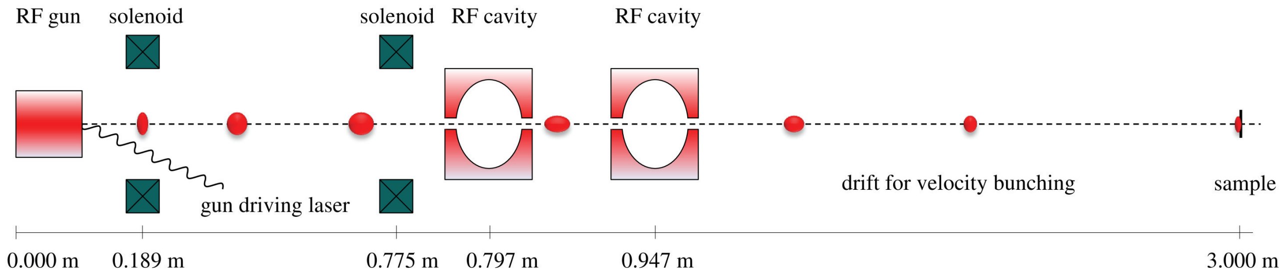

Figure 1: Layout of a 3 m long compact linac for an UED facility.

longitudinal space charge force is proportional to the single bunch charge, inversely proportional to cubic of bunch length and square of beam energy. Therefore, the space charge forces can be effectively reduced if we choose a lower single bunch charge as shown in Eqs. (1) and (2). However, there is a limitation to reduce the single bunch charge because users need at least 1 pC to produce the electron diffraction pattern with a high resolution. Since the single bunch charge is relatively high, the bunch length is ultrashort, and the beam energy is relatively low in the UED linac, the transverse and longitudinal space charge forces are not negligible. Therefore, we used ASTRA code [7] to optimize the compact UED linac properly.

Velocity Bunching

In general, a shorter electron bunch can be generated by shooting a shorter gun driving laser on a cathode of an RF photoinjector. However, as shown in Fig. 1, its bunch length can be increased again due to the strong longitudinal space charge force if the length of the gun driving laser pulse is too short. To minimize the debunching at the gun region, the gun gradient and the gun RF phase should be optimized to have a negative energy chirp as shown in the first figure of Fig. 2, where electron beam energies at the tail region are higher than those at the head region. If the electron beam energy is a few MeV, the speed of electron is lower than the speed of light. In this case, electrons at the tail region can travel faster than the electrons at the head region due to energy differences. After traveling a certain drift space, the electrons at the tail region can be closer to electrons at the head region, which means the bunch length compression. This is called as the velocity bunching [8, 9], and its reachable minimum bunch length is limited by the nonlinearity in the longitudinal phase space.

OPTIMIZATION OF UED LINAC

To compress the bunch length strongly with the velocity bunching at the exit of the RF gun, the slope of the energy chirp i.e., relative energy spread should be higher. However due to chromatic effects, RF focusing, and backward tracking, there are some beam losses in the gun and the solenoids if the energy spread is too high. To avoid the beam loss and to have a weak velocity bunching at the exit of gun, the beam energy spread should be small, and the energy chirp should be negative as shown in the first figure of Fig. 2 and the second figure of Fig. 3. To satisfy these conditions, the zero-crossing RF gun phase was carefully optimized, and a high gun gradient of 100 MV/m was selected to reduce the space charge forces in the gun region. Under the conditions, the electron beam can be accelerated quickly, and the beam dilution at the gun region due to space charge forces can be minimized. Then, as shown in the first figure of Fig. 3, a weak deceleration is applied by the second S-band RF cavity to keep the beam energy lower than 5 MeV. However, the velocity bunching at the exit of gun is limited due to the nonlinearity in the longitudinal phase space and a low energy spread as shown in the first figure of Fig. 2 and the second figure of Fig. 3. Therefore, as shown in Fig. 1 and the second figure of Fig. 2, the nonlinearity in the longitudinal phase space is compensated, and the energy spread is increased by adding two S-band standing wave RF cavities at the downstream of the RF gun for a much stronger velocity bunching.

After optimizing the gradients and phases of two RF cavities and the length of a drift space between the second RF cavity and the sample, the rms bunch length can be effectively compressed along the drift as shown in the third fig-

Table 2: Optimized Accelerator Parameters

Parameters	Unit	Value
RF frequency	MHz	2856
laser rms spot size	μm	58.2
laser pulse length	fs	20
laser rising/falling time	fs	7
laser longitudinal profile	·	flat-top
laser transverse profile	·	uniform
normalized thermal emittance	nm	52.8
maximum gradient of RF gun	MV/m	100
zero-crossing gun phase	deg	181.07
strength of 1st solenoid	T	0.137
strength of 2nd solenoid	T	0.05
maximum gradient of 1st cavity	MV/m	74
1st cavity phase from on-crest	deg	-84
maximum gradient of 2nd cavity	MV/m	66
2nd cavity phase from on-crest	deg	-100

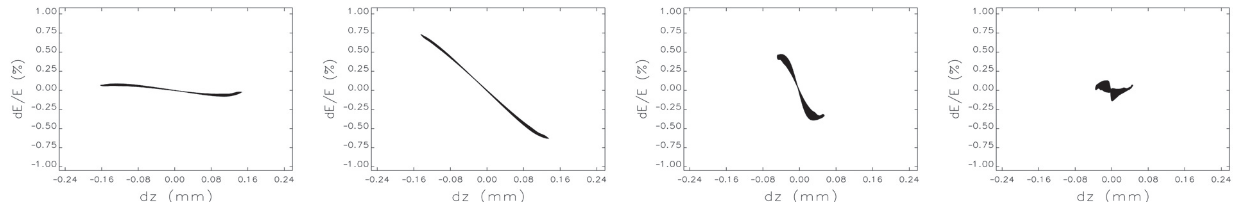

Figure 2: Longitudinal phase spaces (dz (mm), dE/E) along the beamline; at z = 0.70 m, 1.05 m, 2.50 m, and 3.00 m from left to right.

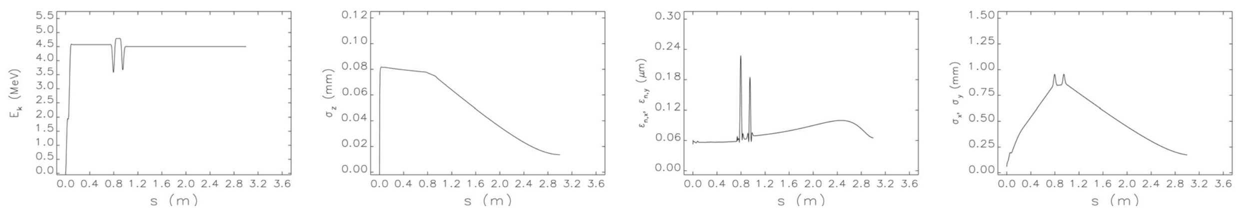

Figure 3: Optimized beam parameters along the beamline; kinetic energy, rms bunch length, normalized transverse emittance, and rms beam size from left to right.

ure of Fig. 2, and the final rms bunch length at the sample location is down to about 45 fs as shown in the fourth figure of Fig. 2 and the second figure of Fig. 3. However, due to space charge forces, the transverse beam emittance is gently increased after the second S-band RF cavity when the bunch length is compressed as shown in the third figure of Fig. 3. In that case, the beam size on the sample became larger than the users' required one. To compensate the emittance growth and to get a good focused beam on the sample, the strength of two solenoids were re-optimized [9]. As shown in the third and fourth figures of Fig. 3, the emittance is compensated properly, and the beam size is well focused at the sample location when the rms bunch length is about 45 fs. In addition, by choosing proper RF phases, RF gradients, and a drift length between the second RF cavity and the sample, the rms relative energy spread is also effectively reduced at the sample position as shown in the fourth figure of Fig. 2. The final optimized linac layout is shown in Fig. 1, and the final optimized accelerator parameters are summarized in Table 2. The kinetic energy, rms bunch length, normalized transverse beam emittance, and rms beam size along the optimized linac beamline are shown in Fig. 3, and the final beam parameters at the sample location are summarized in Table 3.

SUMMARY

For an UED facility, a 3 m long compact linac was designed with ASTRA code. By compensating nonlinearity in the longitudinal phase space with two RF cavities, its rms bunch length can be compressed down to 45 fs for 1 pC at 4.5 MeV. In addition, the emittance growth due to the space charge forces can also be compensated by optimizing two solenoids. Therefore, our optimized compact linac can supply sufficient beam parameters for an UED facility. We expect that the beam parameters can be improved further if we use more RF cavities for the UED linac.

Table 3: Optimized Beam Parameters at the Sample

Parameters	Unit	Value
average kinetic energy	MeV	4.5
single bunch charge	pC	1
rms bunch length σ_z	fs	45
normalized transverse emittance ε_n	μm	0.06
rms beam size σ_x and σ_y	μm	173
rms divergence $\sigma_{x'}$ and $\sigma_{y'}$	μrad	7.6
rms energy spread	keV	1.484

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