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DEVELOPMENT OF A LINAC FOR INJECTION OF ULTRASHORT ELECTRON BUNCHES INTO LASER PLASMA ELECTRON ACCELERATORS

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Abstract

We are developing a C-band linac that produces ultrashort electron bunches as an injector for laser plasma accelerators to study their acceleration characteristics for realizing practical ultrasmall electron accelerators. We designed a linac to produce electron bunches with a longitudinal length of less than 10 fs and transverse dimensions less than 100 μm for injection into a proper phase of the laser plasma acceleration field. An RF gun and a buncher tube were precisely manufactured and they satisfied the designed performance producing the ultrashort electron bunches. Synchronizing electron bunch injection and plasma wave excitation requires a highly accurate timing control within 10 fs. An RF master oscillator with a single sideband phase noise of -150 dBc/Hz at 10 MHz has been developed for precise synchronization. A power supply for the klystron to generate a high power RF was also developed, which provides a 350 kV voltage pulse with a voltage jitter of 3.16 ppm. The power and phase stability performances achieved above the world's highest level.

INTRODUCTION

Particle accelerators are important tools for scientific discovery and medical treatment. However, their size and construction budget are large. Then, the accelerators cannot be widely used in small factories and hospitals in spite of their usefulness. It is strongly required to reduce the size and costs of the accelerators to fit into factory production lines or hospital operating rooms.

A high intense ultrashort laser pulse propagating in a plasma can excite a large amplitude traveling plasma wave with a phase velocity equivalent to a group velocity of the laser pulse at almost the speed of light in a vacuum. This plasma wave can trap and accelerate electrons. The laser plasma electron acceleration [1] has the potential to surpass the performance of the conventional RF accelerators because its acceleration gradient is of the order of 1000 times larger than that of the conventional one. So far, some laser plasma acceleration experiments with an acceleration length of less than a few 10 cm demonstrated the generation of electron beams with a peak energy of around 10 GeV and an energy spread of less than 10% [2]. However, stability of beam parameters, such as an energy spectrum, an emission direction, a beam divergence, a beam charge, and so on are still not sufficient as the practical accelerator. To solve this problem, it is essential to clarify the details of the phase space of the plasma wave acceleration field. However, it has not been sufficiently and experimentally investigated.

The Japan Science and Technology Agency (JST)'s Mirai Program [3] is conducting research aimed at demonstrating a small electron accelerator based on a laser plasma acceleration. Japan Synchrotron Radiation Research Institute (JASRI), which is one of the agencies for this project, is developing a linear accelerator based on the conventional radio frequency (RF) technology. This linac will be used as an ultrashort electron bunch injector into the laser plasma acceleration field. We aim to map the acceleration characteristics of the plasma wave by generating a highly stable electron beam and scanning the electron beam in the vertical, horizontal, and longitudinal positions with respect to the phase space of the plasma wave to reveal the above detail. Such an experiment has not been conducted so far. This paper reports the current status of the development of the ultrashort electron bunch linac.

DESIGN AND OUTLINE OF ULTRASHORT BUNCH ELECTRON LINAC

Because the plasma wave has a wavelength typically of the order of 10 to 100 fs, an injected electron bunch length must be less than 10 fs. In addition, the transverse dimensions of a planned plasma wave are typically the order of 10 to 100 μm because that is the same order of a transverse laser spot size. The transverse dimensions of the injected electron bunch also must be smaller than those of the plasma wave.

There are three possible methods to generate ultrashort electron bunches with a length of less than 10 fs. (1) The first method is using a photocathode RF gun driven by ultrashort laser pulses. However, there is no scientific evidence to generate a bunch of less than 10 fs directly from the cathode, and a long-term study should be needed to show the evidence. (2) The second is to use a magnetic chicane composed of dipole magnets to compress the energy chirped electron bunch [4]. This requires high costs and large components for the chicane. (3) The third we chose is to use an acceleration tube as a buncher to compress the electron bunch by using velocity bunching [5, 6]. Costs are lower than the second and components are not so large as the second.

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Since the linac generates a test bunch for diagnosing the acceleration characteristics of the plasma wave, it is preferable that a charge amount of the bunch is as small as possible to achieve the lowest emittance. However, the charge must be at least 100 fC that can be detected by the state-of-the-art current monitor technology. Table 1 shows the electron beam parameters of the linac.

Table 1: Specification of the Injector Linac for Laser Plasma Electron Acceleration (LPA). The Focal Point Means a Proper Position Inside the LPA Field

Item	Specification
Beam Energy	10 ~ 20 MeV
Beam Charge	10 ~ 1000 fC
Beam Pulse Width	< 10 fs
Beam Pulse Repetition	< 30 pps
RF Frequency	5712 MHz
RF Source Peak Power	< 50 MW
RF Pulse Width	1 ~ 4 μm
Beam Emittance	4 x 10^{-9} mrad
X & Y Focal Point Beam Size	~ 100 μm (rms)
Focal Point Bunch Length	< 10 fs (rms)

The main components along the electron beam transport of this linac are a C-band (5712 MHz) laser-driven photocathode RF electron gun [7], a solenoid coil for beam convergence, a C-band 2 π/3 mode traveling wave buncher tube, and a final Q triplet. Figure 1 shows the simulation results of the electron acceleration, the bunch compression, and transverse focusing [8]. Since the energy of the electron bunch is quite low near the cathode of the RF electron gun, the remnant magnetic fields and the space charge effects in the vicinity of the cathode greatly affect the beam characteristics. Hence, the vicinity region mainly determines the main beam features. Under these conditions, we optimized bunch transport, compression in the buncher, and focusing in the final Q triplet magnets to maintain the small emittance of the electron bunch. The simulations showed that the electron beam size is less than 10 fs longitudinally and several tens of μm transversely at the same time. As a result, it is shown that the electron bunch parameters well match the acceleration phase of the plasma wave field.

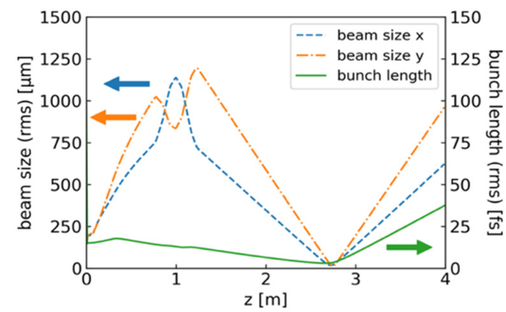

Figure 1: Transverse beam envelopes and a bunch length along the linac obtained by electron beam tracking simulations.

Because of the small phase space of the plasma acceleration fields, an outline of the linac with a timing system tightly synchronized between an RF system and a laser system, which we severely designed, is shown in Fig. 2. The major RF components are already developed, as which are described in the next section.

DEVELOPED MAJOR COMPONENTS OF ULTRASHORT BUNCH ELECTRON LINAC

The laser-driven photocathode electron RF gun and the traveling wave buncher tube were manufactured and tuned as shown in Fig 3. Low-power RF tests were conducted, and their results satisfied the designed performances.

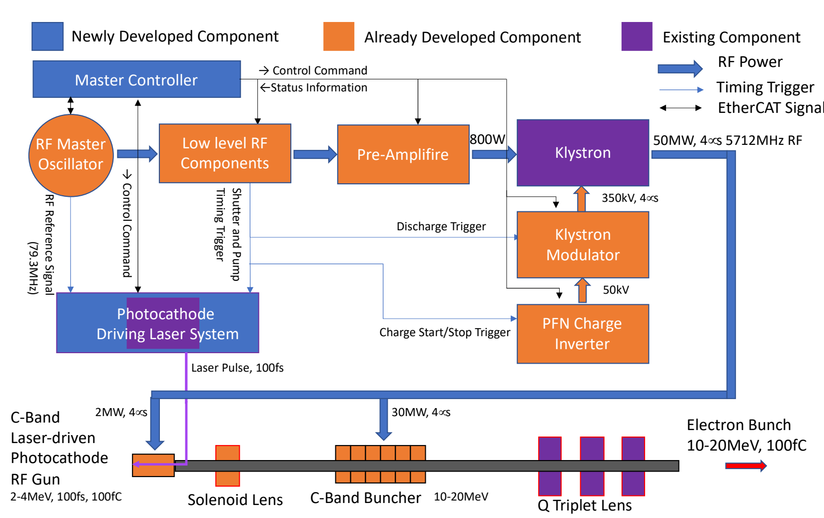

Figure 2: An outline of the linac with the precise synchronization between the RF and the laser pulses.

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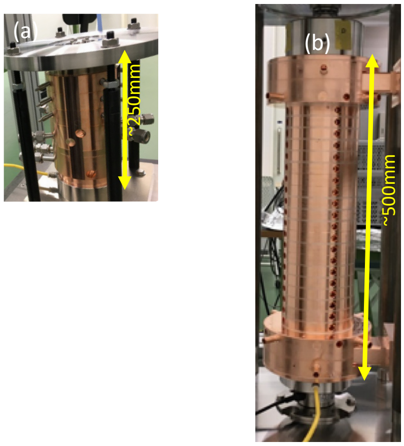

Figure 3: (a) laser-driven photocathode electron RF gun and (b) traveling wave buncher tube.

For the precise timing control between the RF reference signal and the laser pulse, a stable low phase noise RF master oscillator was developed. Figure 4 shows the RF master oscillator which generates a 11424 MHz signal for future use, a 5712 MHz signal for C-band RF, and a 79.3 MHz signal that is the synchronization reference for the laser system. We also developed a $TE_{0,1,15}$ mode cylindrical cavity filter with a high Q factor of larger than 10^5 for the RF master oscillator. Single sideband phase noises of the 5712 MHz output with the cavity filter were measured. Low phase noises of -80 dBc/Hz and -150 dBc/Hz at 10 Hz and 10 MHz, respectively, were obtained. The phase noise performance reaches the highest level in the world.

Figure 4: RF master oscillator.

A PFN charging inverter at 50 kV output and a 350 kV pulse klystron modulator were manufactured and their high-power tests were conducted as shown in Fig. 5. They can output a high voltage pulse of 350 kV and a pulse duration of 4 ms at a 30 pps repetition rate that drives the klystron. A voltage jitter for each pulse of 3.16 ppm (rms) also reaches the world's highest level by increasing a switching frequency of the inverter from 20 kHz to 40 kHz. This provides highly stable acceleration energy in the ultrashort electron bunch.

SUMMARRY

We develop the ultrashort electron bunch injector linac to study the acceleration characteristics of the laser plasma acceleration to check the practical feasibility of ultrasmall accelerators. We designed the linac to produce longitudinally ultrashort (<10 fs) and transversely small (<100 μm) electron bunches based on RF simulations and particle tracking simulations. Development of the components of the linac is in progress. We manufactured an electron RF gun and a buncher tube that satisfy the designed performance. Further, low level RF modules and high power modules were developed. The phase noise performance of an RF master oscillator (-150 dBc/Hz at 10 MHz) and the voltage stability of a klystron modulator (3.16 ppm) achieved the world's highest levels. The next issues of our study are developments of a trigger system, a control system, and a laser system that synchronizes with the RF master oscillator within a high precision of 10 fs.

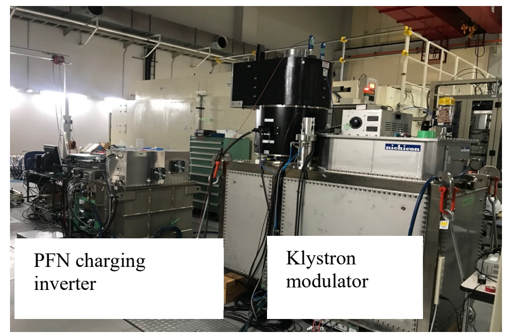

Figure 5: PFN charge inverter and klystron modulator during a high-power test.

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