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MANIPULATIONS OF DOUBLE ELECTRON BEAMS WITHIN ONE RF-PERIOD FOR SEEDED SM-LWFA EXPERIMENT*

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Abstract

Schemes of double electron beams (e-beams) have wide applications in laser wakefield and plasma accelerations. At the ATF the seeded self-modulated laser wakefield acceleration (seeded SM-LWFA) is being conducted, which requires the first e-beam to initiate small plasma wakefield, whose amplitude is significantly amplified by the CO_2 laser, and a second e-beam traveling after the first one to probe the accelerated electrons. To create and preserve the significant amount of wakefield in the seeded SM-LWFA experiment, the first e-beam must be ultra-small in spot size and ultra-short in bunch length within the interaction region. To probe the wakefield the separation between both e-beams is required ~10-ps and the second beam must have a smaller intrinsic energy spread and ultra-small beam spot size. Design of the double beams within one RF-period (2856 MHz) to meet these strict requirements at the ATF is presented. Generation and delivery of the double beams through the ATF transport including a bunch compressor are experimentally investigated.

INTRODUCTION

To date the BNL-ATF can provide ~15-ps 5-J CO_2 laser, which allows to perform the self-modulated laser wakefield acceleration (SM-LWFA) experiment using the CO_2 laser. Preliminary modeling of the SM-LWFA process using 15-ps, 0.5-TW CO_2 laser at plasma density of 8.9×10^{16} cm^{-3} shows the density is too low to permit relativistic self-focusing for the conditions of the ATF experiments. But it shows using a seeded electron beam (e-beam) or call it as the first bunch to generate small plasma wakefield, whose amplitude is amplified by the CO_2 laser can help to build up the SM-LWFA wakefield. A seeded e-beam propagates at the head of the laser pulse and generates a rather weak wakefield amplitude, and then the small amplitude of seed-wakefield can be successfully enhanced by factor of $\sim10^3$ by the following strong CO_2 laser beam. Simulations present that the seeded e-beam must be shorter than 165 fs rms and tiny in spot size [1]; otherwise, the small wakefield can neither be excited nor match to the tiny plasma and laser beam. At the ATF the e-beam is generated by a photo-cathode-based s-band RF-gun (2856 MHz). The minimum bunch length in order of ps rms can be obtained taking advantage of the micro-bunching in the RF-gun and ballistic compression in the s-band linacs [2]. Thus, a bunch compressed must be employed to compress the seeded bunch down to sub-ps rms. To achieve a tiny e-beam in the interaction region (IR), an in-vacuum permanent mini-quadruple is installed near IR. Since the generated wakefield radius is small, 10's μm, the witness e-beam or call it as the second bunch must be tiny, smaller than the wakefield radius. Simulations suggest that the intrinsic energy spread of the witness be narrow, which requests the witness beam run at linac-RF on-crest. The wakefield is damped quickly, and thus the separation of the seeded and witness e-beams is ~10-ps, which indicated both seeded and witness e-beams need to sit on the same RF wave within one RF period.

GENERATION OF DOUBLE ELECTRON BEAMS WITHIN ONE RF-PERIOD

Generation of Double Beams within One RF-Period

With applying the proper laser beam splitter and optical transport double drive-laser beams with adjustable separation within one RF-period can be generated to illuminate the photo-cathode to produce double e-beams at the ATF. For this specific experiment, the separation of double drive-laser beams is adjustable varied from 5-ps to 35-ps. The intensity of both laser beams is also adjustable. Totally two schemes of double laser beams are tested. Figure 1 shows the electron bunch charge vs RF-gun's phase for the two schemes of double drive laser beams. The separation of double laser beams is ~30-ps in scheme A while it is ~20-ps in scheme B. Note that the first beam's bunch charge is lower than the second one at the same amount of distributed laser energy for both beams. This is attributed to the fact that the first bunch arrives earlier than the second one relative to the RF-wave on the cathode. The bunch charge is measured at a Faraday cup located at the RF gun exit.

In principle, the position of e-beam on the RF-wave can be moved due to the strong bunching in the RF-gun and ballistic compression in the entrance of linac. The separation of double e-beams is expected to be shorter than the double lasers' separation on the cathode, which is generally confirmed by PARMELA simulations. In the beam studies, stronger double e-beams-separation compression is observed: ~30-deg of double drive lasers separation results in only 15-ps e-beam separation while 20-deg laser separation results in ~10-ps e-beam separation. But such strong compression is not observed in the PARMELA simulations. The mechanics of beam

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dynamics to cause the interesting phenomena is being investigated.

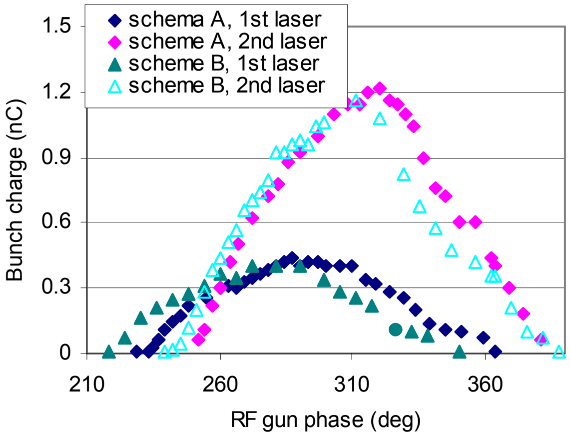

Figure 1: Electron bunch charge profile vs RF-gun phase for different schemes of double drive-laser beams.

Measurements of Double E-beams Separation

Basically there are several solutions to measure the separation of double e-beams. The first one is to determine the optimum linac-RF phase of individual e-beam through tuning the beam at a certain-energy; the difference of the optimum linac-RF phase for individual e-beams is equivalent to the separation of double e-beams. The second solution is to transport the combined two beams to an energy spectrometer and measure the energy difference, from which the separation of double e-beams can be derived. Figure 2 shows the double e-beams taken at an energy spectrometer with compressor off. It shows the energy difference is ~0.7-MeV corresponding to 10-ps separation. Both solutions are used to roughly estimate the separation and the conclusion is self-consistent. We conclude that 30-deg laser separation results in 10-ps e-beam separation. But these above two solutions can't be applied to the case when the bunch is fully compressed resulting in significant energy-spectrum distortion [3-5]. We may measure double e-beams separation for the particular case using the last solution, which is to mix the signal from strip-line monitor with 2856-MHz RF wave and then measure the mixed signal on the oscilloscope. The procedure to measure it is described as below. Firstly, the first laser beam is blocked but the second laser beam is transported; and then the mixed signal is recorded as A and the phase shift at this point is called as ϕ_1. Secondly, the second laser beam is blocked but the first laser beam is transported; and the phase shifters are adjusted until the signal on the scope is same as A and then the phase shift is recorded as ϕ_2. The separation of the double e-beams is ϕ_2-ϕ_1. It can be used to measure double e-beams separation particularly when the energy spectrum is severely distorted after employing a bunch compressor.

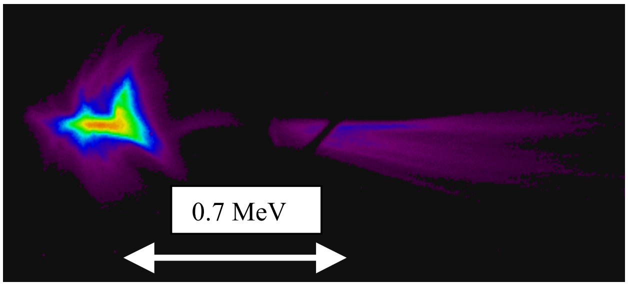

Figure 2: Double beam images at energy spectrometer (note the bunch compressor is off); dispersion is in horizontal direction; right image is the first e-beam; and the left image is the second e-beam.

Transport of Double Beams to the IR without Employing the Bunch Compressor

At the ATF schemes of double beams have many applications for other experiments besides the seeded SM-LWFA experiment. Some require sub-ps bunch length while some only need ps-level bunch length. Without the compressor the ATF has capability to provide ps-level bunch length. Delivery of double beams without the bunch compressor to the IR is tested. Figure 3 shows the beam images taken at interaction point (IP): single first e-beam (left), second beam (middle) and the combination of both beams with 10-ps of separation (right). It shows the spot sizes for these beams are very close, ~80-µm rms.

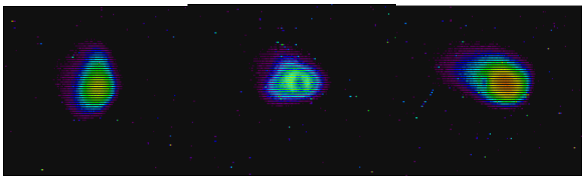

Figure 3: Beam images at IP without employing the bunch compressor: the left one is single first beam; the middle one is single second beam; the right one is the combinations of double beams with 10-ps of separation.

TRANSPORT OF DOUBLE BEAMS WITH BUNCH COMPRESSOR

The seeded SM-LWFA experiment needs double beams with strict requirements: the first e-beam must be short in sub-ps and tiny in beam spot size; the second beam must be in ps-level, narrower energy spread, and tiny in beam spot size. To achieve the sub-ps bunch length the bunch compressor must be employed at the ATF. Our basic idea is to arrange the first e-beam on the full compression and the second e-beam at linac-RF on-crest. With this arrangement, the bunch length of the first beam can be compressed down to sub-ps while the energy spread of the second beam is still narrow due to its sitting at linac-RF on-crest.

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Bunch Compression through Chicane

We need to determine how many degrees of RF-phase off-crest from two linac sections to induce suitable correlated energy spread required for full bunch compression. Elegant code suggests that the initial 1.7-ps rms bunch length can be compressed down to 110-fs rms by employing ~0.3% rms of correlated energy spread in the compressor, ~11-deg RF off-crest from two s-band linac sections theoretically. Although to date there is no reliable diagnostic at the ATF to directly judge whether the bunch is in full compression, there are some evidences. The coherent synchrotron radiation effects created in a bunch compressor can significantly distort the longitudinal energy spectrum and increase the transverse emittance when the bunch is fully compressed. We may make use of observations of energy spectrum and emittance growth to measure the degree of RF off-crest for full compression. The energy spectrum vs RF off-crest is measured at an energy spectrometer at the end of ATF H-line. We observed the energy spectrum is severely bifurcated at ~11-deg off-crest [5]. The transverse emittance is measured through monitoring the beam images at the four beam profile monitors (BPM) in the downstream of the compressor. Emittance as function of RF-phase off-crest is obtained, which indicates the emittance is increased significantly at ~11-deg off-crest [5]. Thus, results from measurements on energy spectrum and emittance are consistent. In addition, coherent edge radiation (CER) at the 3rd bend is measured later by another group [6] and the measurements agree with our observations.

Preliminary Beam Optics Development

Preparation of a good beam tune for double e-beams with the energy difference of ~1-MeV is non-trivial, which basically consists of three tasks: task 1 - tune single beam at a certain energy (e.g., 60-MeV) and RF on-crest; task 2 - prepare a tune for simulated double e-beams using the single beam; and task 3 - switch to real double e-beams scheme and deliver them using the tune developed in task 2. The separation of double e-beams is chosen to be 11-deg by adjusting the laser transport delay so that the first beam is at 11-deg off crest for full compression and the second beam is at RF on-crest to have minimum energy spread. Firstly, the single beam tune is optimized at 60-MeV with chicane-on and setting RF-phase at on-crest (beam image at IP is shown Fig. 5). A MathCAD program is developed to measure the beam spot sizes at BPMs to obtain the twiss parameters at the beam line to compare with predictions. It is useful for the tune optimizations particularly for double e-beams. Figure 4 shows the typical results β_x and β_y in beam line, which show the measurement data β_x (red square) and β_y (blue diamond) roughly agree well with the theoretical prediction β_x (red line) and β_y (blue dash-line). Secondly, single e-beam is used to simulate double e-beams to further optimize the tune: the first step is to shift the e-beam energy to ~61-MeV at RF on-crest as a "second beam" and deliver it through the beam line using the optimized tune based on task 1; the beam size at IP is ~110-µm rms shown in Figure 5. The second step is to shift 11-deg off crest as a "first beam" based on the first step and then measure the beam size at the IP. The beam spot size is ~140-µm rms. Some itineration is required for obtaining a tune to have reasonable good simulated-double beams. Lastly, we need to deliver real double e-beams using the tune, which will be tested shortly.

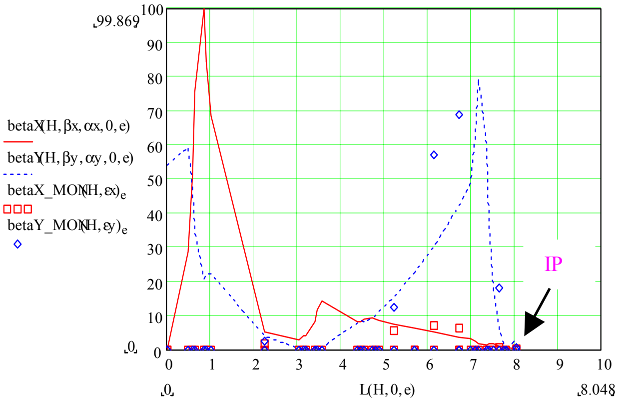

Figure 4: β_x and β_y (m): measurements and predictions

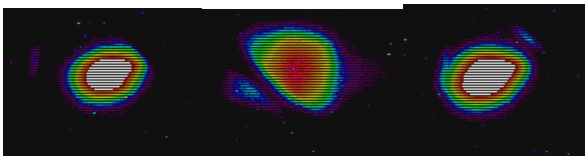

Figure 5: Beam spot size at IP: on-crest and central energy (left); on-crest and energy shift (right); 11-deg off-crest (middle)

SUMMARY

Schemes of double e-beams have wide applications in laser wakefield and plasma accelerations. On-going SM-LWFA experiment at the ATF requires double beams with 10-ps of separation to have high-qualities (sub-ps bunch length, tiny beam spot size, etc). Double e-beams are generated and transported through beam line including the bunch compressor and get reasonable-good beams: seeded beam in sub-ps and 140-µm; and witness beam in ps in bunch length, 110-µm beam spot size and narrow energy spread.

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