FREE-ELECTRON LASER DRIVEN BY A 500 MeV LASER PLASMA ACCELERATOR BEAM

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Abstract

A laser plasma accelerator is under construction at Peking University and several hundred MeV electron beams are expected. In this paper we discuss applying a 500 MeV beam with 1% relative energy spread to FEL. Bunch decompression method is considered to deal with the large energy spread of the beam. Emittance growth induced by large divergence and energy spread during beam transport has been treated with the chromatic matching manipulation. Simulation shows that 100 MW level, 6.3 fs , 0.008 bandwidth output can be obtained for 30 nm FEL. TGU method with assumed matched beam is also discussed as a comparison.

INTRODUCTION

Laser Plasma Accelerator (LPA) is considered as a promising candidate to drive compact short-wavelength Free-Electron Laser (FEL) owing to its capability to generate high energy electron beams in centimeter scale, which is of great interest for university scale labs. Undulator radiation utilizing laser plasma accelerated beam has been reached in the VUV and soft-X region [1, 2]. However, the percent level relative energy spread and chromatic induced emittance degradation during beam transport hinder the application of LPA beam to short-wavelength FEL. Controlled injection to improve beam quality and stability is being pursued by the LPA community. Even though, with presently demonstrated LPA beam, FEL may be realized when undulator adjustment and beam manipulation are performed to meet the requirement of high-gain FEL. To overcome the energy spread issue, two methods have been proposed, i.e., a proper dispersed beam coupled to a Transverse Gradient Undulator (TGU) [3] and a decompressed beam coupled to a longitudinally tapered undulator [4, 5]. However, chromatic effect induced emittance growth during beam transport can seriously affect either of the two energy spread compensation scheme. Recently, a so-called chromatic matching manipulation which synchronizes the energy slice waist slippage and the FEL slippage is proposed to address the chromatic effect for the decompression scheme [6]. For the TGU scheme, a matching beamline with sextupoles to correct the chromaticity is necessary [7].

In this paper, we discuss the application of an expected 500 MeV LPA beam at Peking University to a 30 nm FEL. Bunch decompression method with chromatic matching manipulation is considered, while TGU scheme with the LPA beam assumed to be matched at the undulator entrance is also discussed as a comparison.

LASER PLASMA ACCELERATOR AT PKU

Peking University is developing a multi-functional laser plasma acceleration experimental platform (see Fig.1) utilizing a high contrast 5 Hz, 200 TW, 800 nm laser system. After two stage CPA compression, the laser pulse with 5J energy is compressed to 25 fs. For laser proton acceleration, the laser is transported to the plasma mirror chamber to further increase its contrast ratio, then interact with a solid target to produce 15 MeV proton beam. For laser electron acceleration, the laser pulse is directly delivered to the gas target chamber to interact with a supersonic gas jet. The 200 TW laser system is ready to deliver the pulse, while the first experiment is still under preparation. A gas jet of adjustable length and several diagnostic devices including a 2 GeV electron spectrometer are also ready. Expected electron beam parameters for the first experiment are several hundred MeV energy with several MeV energy spread, tens of pC bunch charge, 0.1 mm·mrad normalized emittance.

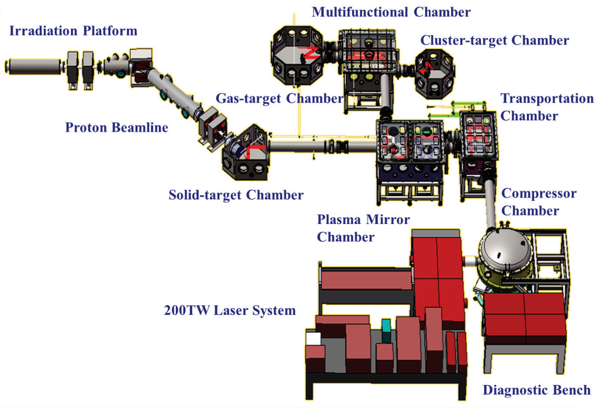

Figure 1: Laser plasma accelerator at Peking University.

BEAM MANIPULATION

Based on the capability of laser plasma accelerator at PKU, we discuss using a 500 MeV, 10 fs (FWHM), 40 pC LPA beam with 1% rms relative energy spread and 0.1 mm·mrad rms normalized emittance to drive 30 nm FEL. The parameters are summarized in Table 1. The beam is assumed to be 6D Gaussian in phase space and no correlation in both transverse and longitudinal phase space. Due to the μm scale beta function in plasma accelerator, the initial rms beam divergence is at mrad level, which is orders larger than that of electron beam from conventional accelerator. Large beam divergence leads to fast beam expansion at the very beginning of the transport beamline. Along with large energy spread, beam divergence drastically increase the chromatic emittance. With second order optics notation, geometric emittance after a transport beamline is given by [6]

$$\varepsilon_{total} \approx \sqrt{\varepsilon_0^2 + \left(\frac{t_{126}}{r_{11}}\sigma_\delta \sigma_{x_0'}^2\right)^2}, \tag{1}$$

where ε_0 is the initial geometric emittance, σ_δ is the relative energy spread and $\sigma_{x_0'}$ is the initial beam divergence. For the LPA case, chromatic term dominates over the initial emittance, resulting several mm·mrad emittance growth after the transport beamline. Noting that the chromatic effect increase the beam emittance by rotating different energy slice to different phase space orientation, thus introducing an energy related slice waist slippage along the undulator, it is possible to sort these energy slices and synchronize them with the FEL pulse. As a result, the FEL pulse can always 'see' a low emittance slice focused at its waist.

Table 1: LPA and FEL Parameters

LPA parameters	**Symbol**	**Value**	**Unit**
pulse energy	E_l	5	J
pulse duration	τ_l	25	fs
laser wavelength	λ_l	800	nm
rep. rate	f_l	5	Hz
Beam parameters			
beam energy	E_b	500	MeV
bunch charge	Q	40	pC
rms norm. emittance	$\gamma\varepsilon_{x,y}$	0.1	mm·mrad
rms beam divergence	$\sigma_{x',y'}$	1	mrad
bunch duration(FWHM)	τ_b	10	fs
rms energy spread	σ_γ/γ	1%	
FEL parameters			
radiation wavelength	λ_r	30	nm
undulator period	λ_u	15	mm
undulator length	L_u	6	m
undulator strength	K	2.38	

A schematic of the chromatic matching beamline coupling the LPA beam to a 6 m long 15 mm period undulator is shown in Fig.2. It is composed of a triplet to refocus the beam, a chicane to introduce the energy sorting and another four quadrupoles to tune the synchronization. The chicane also reduces the beam slice energy spread since it decompresses the bunch, which is of benefit. The quadrupole strength for the refocusing triplet is up to 200 T/m, while for the tune quadrupoles is below 80 T/m.

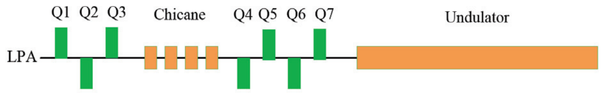

Figure 2: schematic of the chromatic matching beamline.

Figure 3 shows the ELEGANT [8] tracked transverse beam phase space at the undulator entrance (a,d), center (b,e) and exit (c,f), up to second order. Here transport matrix element $r_{12} = r_{34} = 0$, $r_{11} = r_{33} = 30$, $t_{226} = t_{446} = 0$, $t_{126} = t_{346}$. Chicane strength is scanned from 100 µm to 1 mm to obtain maxmium FEL power. Slice to slice focusing along the undulator can be seen clearly in the x plane while is distorted by the undulator natural focusing in the y plane. Only part of all energy slices are successively focused to waist, corresponding to high current region of the decompressed beam (see Fig. 4). The beam is decompressed by a factor 6 through the chicane and an energy chirp of 0.01/7.19 µm is introduced, with peak current decreased from 3.5 kA to 650 kA. It should be noted that the total normalized beam emittance is increased from 0.1 mm·mrad to 5.7 mm·mrad due to the chromatic effect, mainly in the first triplet.

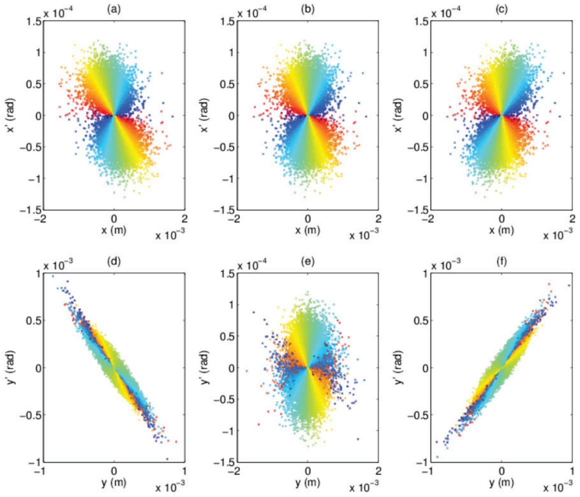

Figure 3: Transverse phase space at undulator entrance (a,d), center (b,e) and exit (c,f) for x (up) and y (down) plane.

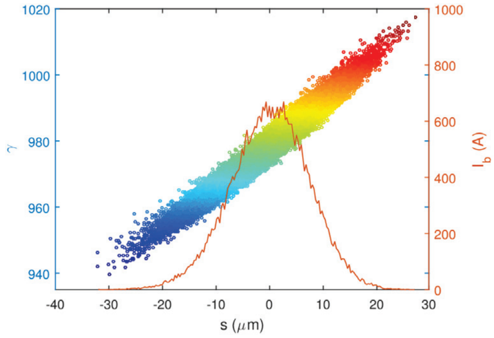

Figure 4: Longitudinal phase space and beam current distribution at undulator center.

FEL SIMULATION

FEL simulation is conducted with GENESIS [9] using ELEGANT tracked beam distribution. To compensate the energy chirp created by the decompression, a linear undulator taper is applied according to

$$\frac{\Delta a_w/a_{w0}}{\Delta z} = -\frac{\lambda_r}{\lambda_u}\left(\frac{1+a_w^2}{a_w^2}\right)\frac{\Delta\gamma/\gamma_0}{\Delta s}, \qquad (2)$$

where a_{w0} is undulator strength at center, γ_0 is beam central energy. To apply the taper to the whole 6 m undulator, the relative taper strength $\Delta a_w/a_{w0}$ is about -2.2% for the chirp.

As is shown in Fig.5, significant FEL power gain is obtained with chromatic matching manipulation. Without the manipulation, there would be no amplification since the emittance is increased to about 6 mm·mrad due to the chromatic effect. Without undulator taper, FEL tends to saturate at 5 m with 10 MW power. With undulator taper, the amplification lasts longer and FEL power reaches 100 MW level.

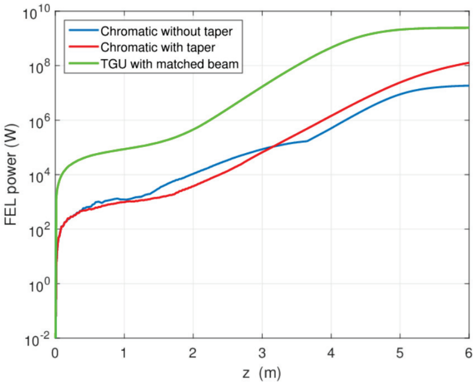

Figure 5: FEL power for untapered chromatic matching (blue), tapered chromatic matching (red) and TGU with assumed matched beam (green).

As a comparison, we simulated a TGU case with transverse gradient parameter $\alpha = 54\mathrm{m}^{-1}$ and beam dispersion $\eta = 2.5\,\mathrm{cm}$ for the same LPA beam, assuming it is matched to the undulator entrance, i.e., $\sigma_x = \sqrt{\beta_x\varepsilon_x} \approx \sqrt{L_u\gamma\varepsilon_x/2\gamma} \approx \sqrt{3m \times 0.1\,\mu\mathrm{m}/978.5} = 17.5\,\mu\mathrm{m}$. TGU case is able to reach higher FEL power up to GW level owing to its much higher peak current than the decompressed beam. All electrons matched to its resonant condition contribute to the FEL power for the TGU case, while only those slices focused to wasit contribute to the FEL gain for the chromatic matching case, which further increases the power difference for the two cases.

Fig.6 shows the time profile for untapered chromatic matching (blue) and tapered chromatic matching (red) and TGU (green) simulation. A 6.3 fs (FWHM) single spike FEL pulse is obtained, owing to lasing of only the part of slices which are focused to waist along the undulator. This is even shorter than the initial bunch length before decompression. The TGU case can also obtain single spike FEL pulse with 13.3 fs (FWHM) duration since the slippage length is comparable to the bunch length when no decompression is applied. The corresponding sprectrum is shown in Fig.7, where single spike spectrum is also obtained. Undulator taper can narrow the bandwidth to 0.008(FWHM) since it compensates the energy chirp, which is comparable to the TGU method.

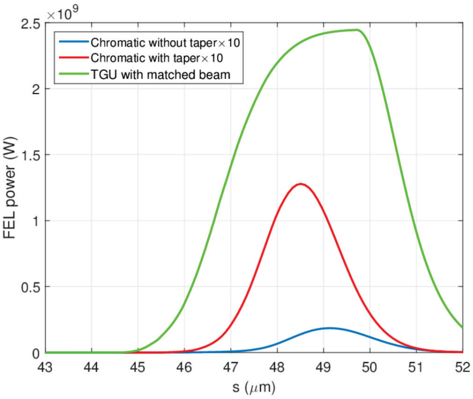

Figure 6: Time profile for untapered chromatic matching (blue) and tapered chromatic matching (red) and TGU case (green).

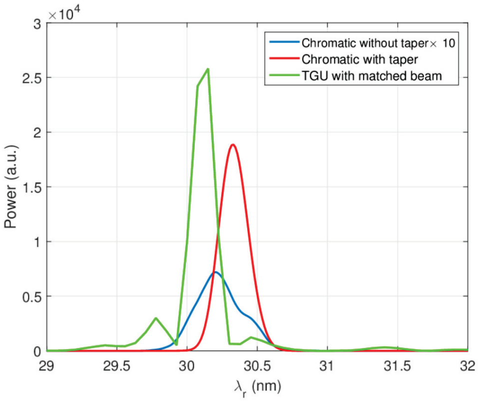

Figure 7: Spectrum for untapered chromatic matching (blue) and tapered chromatic matching (red) and TGU case (green).

It is worth noting that matching the 0.1 mm·mrad LPA beam to TGU entrance requires complicated beamline to correct the chromatic effect. Since initial beam size before dispersion acts as an equivalent energy spread and reduces the FEL performance, the TGU case requires to minimize the beamsize before dispersion, making it quite sensitive to initial emittance, while chromatic matching case is insensitive because the chromatic emittance is the dominant term.

CONCLUSION

We present here a preliminary study of applying an expected 500 MeV LPA beam at Peking University to FEL. It is shown that with chromatic matching manipulation, the 30 nm FEL can reach 100 MW power at 6 m undulator exit, with single spike FEL pulse of 6.3 fs and 0.008 bandwidth. The TGU method may reach higher FEL power but requires more complicated transport beamline to correct the chromatic effect and the FEL pulse length is longer than the chromatic matching method.

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