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TOLERANCES FOR PLASMA WAKEFIELD ACCELERATION DRIVERS*

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Abstract

Transverse jitter tolerances are considered for beam-driven plasma accelerators. A simple model for jitter transfer from the drive to witness beam was developed and concrete examples were studied for: high-brightness witness bunch injectors; high-energy boosters for FELs; and future Linear Colliders. For the LC application, we consider a superconducting Linac designed to minimize the jitter conditions of the drive beam. We use a start-to-end tracking model to simulate expected jitter performance. The tolerances on each subsystem of the driver Linac are found to be very tight, especially for magnet vibration which must be controlled at the sub-nm level.

OVERVIEW

The electron beam-driven Plasma Wakefield Acceleration (PWFA) concept has been actively pursued in the past two decades with multi-GeV accelerating gradients demonstrated [1, 2]. Other test facilities are under construction and aim to demonstrate preservation of the accelerated beam quality [3, 4] and research practical applications such as FEL drivers. As the community moves towards progressing the PWFA concept into a viable engineering solution for a practical accelerator, it is timely to consider requirements for the required supporting infrastructure.

We consider here the jitter requirements on the main particle beams (henceforth referred to as "witness" beams) used in future accelerators powered by PWFA acceleration cells and the contribution from the jitter of the "drive" beams used to form the PWFA acceleration plasma bubble. The drive beam is usually mismatched to the accelerated bunch in terms of its geometric emittance, frequently having order-of-magnitude larger emittance; this is true for laser-driven as well as beam-driven plasmas. The stability requirements of the drive beam are dictated by the phase-space of the higher-quality witness beam.

We consider here the specific examples of high-brightness witness bunch injectors (HBI), a high-energy "doubler" application for FEL's (ED), and future Linear Colliders (LC). For each, we investigated the transverse tolerance requirements on the drive beam and the conventional accelerator component tolerances (RF, magnet, alignment etc.) necessary to meet these. The calculated tolerances were compared to an existing PWFA driver facility [2, 3] in a previous report [5] and were found to be 18 to 170 times tighter than achievable. This report summarizes work done to calculate the expected jitter performance of a purpose designed superconducting drive beam accelerator.

Typical requirements for a beam driven PWFA application are to drive the plasma cell with a multi-nC electron bunch which is highly compressed (>10 kA peak current) and tightly focused (<<100µm rms transverse size at plasma entrance). State-of-the-art high-brightness electron accelerators utilizing rf photo-injectors with conventional rf acceleration cavities and magnetic bunch compression systems can meet these requirements, but the achievable bunch emittances are necessarily in the multi µm-rad range. This should be compared with the nm-rad scale of required vertical emittance for the witness beam in a LC application. The acceleration channel seen by the witness bunch in the PWFA cells is formed by the drive beam and by design strongly focuses the witness beam within the plasma channel. It will therefore steer the witness beam according to any misalignment of the driver bunch. Given the large disparity between drive and witness bunch emittances, one would a-priori expect very tight fractional tolerances on the allowable drive beam jitter.

To investigate the magnitude of the driver jitter tolerance challenge, we put forward a simple analytic model of jitter transfer between the drive and witness beams in [5] which we also tested using a particle tracking model. Note that this jitter model does not include collective effects in the plasma which will further amplify any jitter. Using this jitter transfer model, we describe the jitter amplification of a physically realizable plasma cell and calculate the drive beam jitter tolerances implied by the witness bunch jitter requirements. We then compare these requirements to a simulated model of a real drive beam accelerator.

WITNESS BUNCH JITTER REQUIREMENTS

The allowable jitter of the witness bunch as it is delivered to either the undulators of an FEL or the collision point of a collider are shown in Table 1 below. The required jitter tolerances for an FEL application are dependent on the design of the undulators; typically the beam jitter must be a small fraction of the beam size in the undulators for useful lasing and a value of 0.1σ is used here for reference. The LC requirements are more complicated and are explained further below.

The combined effect of all jitter sources (i.e. multiple PWFA stages) must sum to beneath the requirements stated below.

Table 1: Required Delivered Witness Beam Jitter to FEL Undulator Section or Collision IP

Application	Horizontal Jitter Requirement / σ_x	Vertical Jitter Requirement / σ_y
PWFA LC	Insensitive	0.3
HBI	0.1	0.1
ED	0.1	0.1

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PWFA LC Application

The machine parameters for a PWFA-driven LC are taken from a design study considering multi-TeV collision parameters [6], here we consider the design for a 3 TeV (center of mass energy) collider for reference. Using the proposed design parameters, we calculate the collision tolerance. In the horizontal plane, the luminosity as a function of position offset for a Gaussian bunch is simply determined by the overlap integral for a given offset Δ:

$$L = L_0 exp\left(-\frac{\Delta_x^2}{4\sigma_x^2}\right).$$

Similarly, the luminosity as a function of horizontal angular offset θ_x can be written as:

$$L = L_0 \frac{1}{\sqrt{1+\left(\frac{\sigma_z}{\sigma_x}\tan\theta_x\right)^2}},$$

where, $\sigma_{x,z}$ are the design rms horizontal and longitudinal beam spot sizes at the interaction point. Given these, the maximum offsets in the horizontal plane required to ensure >99% of design luminosity are $0.3\sigma_x$ and due to the short bunch length, we are essentially insensitive to horizontal angular offsets.

In the vertical plane, the self-focusing of the colliding beams is much stronger (self-focusing length << bunch length) rendering the above formulae unusable. In this so-called high-disruption regime we must use a particle tracking code to calculate luminosity effects of vertical beam offsets. Here we use the beam-beam code GUINEA-PIG [7]. The luminosity as a function of vertical (position and angle) beam offset at the collision point is shown in Figure 1 below. The required relative beam offset to deliver >99% of design luminosity is $<0.1\sigma_y$ and the required angular offset $<0.3\sigma_{y'}$. These values were obtained by interpolation from the computed luminosity loss curves. Here and elsewhere, σ is the design rms size or angular divergence of the beam in question.

Note the relative insensitivity to angle vs. positional jitter. This can be taken advantage of by designing the PWFA acceleration cells such that jitter transfer from the drive beam only occurs in the IP angle phase. Hence, the angular jitter tolerances are used in the jitter requirement table above.

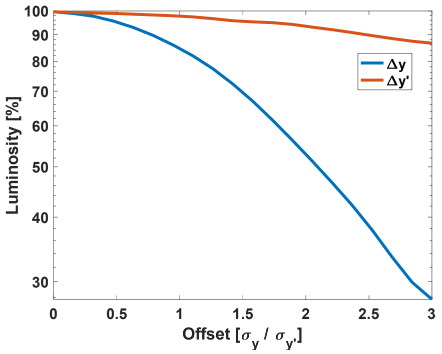

Figure 1: Percentage of nominal luminosity as a function of vertical position and angle offset relative to design rms vertical spot size and divergence. Results calculated using GUINEA-PIG for LWFA LC 3 TeV parameters.

PWFA CELL JITTER TRANSFER MODEL

An analytical model to describe the positional jitter of the witness bunch due to drive beam jitter was derived and tested with tracking simulations in [5]. With a total plasma length of L and an incoming drive beam jittering with a factor N with respect to its own beam size, the positional jitter of the witness bunch after the plasma (with respect to its own incoming beam size) is given by:

$$\left(\frac{\Delta_y^w}{\sigma_y^w}\right)^2 = \frac{L^2 N^2 \{\varepsilon_y^d/\beta_d M\}}{\varepsilon_y^w \beta_w M} \; and \; \left(\frac{\Delta_\theta^w}{\sigma_\theta^w}\right)^2 = 0\,.$$

where, M is a magnification factor inherent in the plasma accelerating device applied to the incoming/outgoing drive and witness beta functions $\beta_{d,w}$ and $\varepsilon_{d,w}$ corresponds to the geometric emittances of the drive and witness pulses. Note jitter transfer to the witness bunch only occurs in the positional phase, not in angle, and assumes a perfectly matched plasma device.

DRIVE BUNCH JITTER REQUIREMENTS

Corresponding requirements on the required jitter parameters (expressed in terms of the N factor described above), required to produce the desired witness bunch jitter properties shown in Table 1 are described more fully in [5], and reproduced below in Table 2.

Table 2: Drive Beam Jitter Tolerances

Application	Jitter tolerance (N)
HBI	6E-3
ED	4E-3
LC	1E-4

SUPERCONDUCTING RF PWFA DRIVER

The PWFA-LC application calls for 10 kHz beam repetition rate [6]. For this level of beam power requirement, a superconducting Linac is the most efficient choice for the driver beam. We consider here a 2-stage compression system using TESLA 1.3 GHz accelerating cavities similar to LCLS-II [8]. The injector is not modelled; we assume an initial 1mm rms bunch length with a longitudinal emittance matched to the required final compression requirements. The bunch is compressed to 300μm rms at the first bunch compressor (E=500MeV), with the final compression at 25 GeV down to 11 μm rms which gives the required ~30 kA peak current with a 3.2 nC bunch to drive the PWFA cell. Performing the final compression at the end of the Linac is convenient for a number of reasons: Reduction of HOM power loading in SC acceleration cavities by restricting intermediate bunch length; minimization of CSR effects in the compression chicanes; possibility to integrate final compression stage into final bunch delay system required to match multiple bunches in pulse to accelerated beam profile.

The extent of the final compression is limited by the level of energy spread which can be tolerated by the transverse focusing optics. This is optimized vs. the compression power of the final chicane which is limited in strength by the CSR emittance degradation effect.

The design beam parameters are listed in Table 3 below, with results from start-to-end particle tracking shown in Figure 2.

Table 3: Parameters for Superconducting PWFA Driver Accelerator

Parameter	Symbol	Value
Injector energy	E_i	135 MeV
RF Frequency	f_{rf}	1.3 GHz
Injector emittance	$\varepsilon^i_{x,y}$	5.0 µm-rad
Injector rms Bunch Length	$\sigma_{z,i}$	1.0 mm
Injector rms energy spread	δ_E/E	1.2 %
Bunch charge	Q_b	3.2 nC
Final Energy	E_f	25.0 GeV
Final rms Energy Spread	δ_E/E	1.5 %
Final rms Bunch Length	$\sigma_{z,f}$	11.3 µm
Final Transverse Size	$\sigma_{x,y}$	20 µm
Final Peak Current	I_{pk}	30 kA
Driver linac length	L	2.5 km
Average beta function	β	30 m

Table 4: Error parameters used in tracking simulations. "FACET" numbers reflect experience operating the 30kA peak current FACET accelerator [3], the "Upgraded" numbers reflect best performance possible with existing technology.

Property	Unit	FACET	Upgraded
Source Charge Fluctuation	%	1	0.1
Source Electron Position Fluctuation (laser spot jitter on cathode)	% $\sigma_{x,y}$	3	3
Initial Electron Laser Timing Error	fs	200	10
L1 Phase Jitter	degS	0.1	0.01
L2/L3 Phase Jitter	degS	0.25	0.01
L0P Phase Jitter	degS	0.1	0.01
L1 Amplitude Jitter	%	0.1	0.01
L2/L3/L0P Amplitude Jitter	%	0.25	0.01
BC0 & BC11 Magnet Strength Jitter	dB/B	1e-5	1e-6
BC14 & BC20 Magnet Strength Jitter	dB/B	1e-4	1e-6
L1/L2/L3/S20 Magnet Vibration (x/y), rms	µm	1.5/0.5	0.02/0.02
e- injector Magnet Vibration (x&y), rms	µm	0.1	0.02

The same Monte Carlo simulation was run as in [5] using the "Upgraded" error parameters from Table 4; note the simulation does not include plasma collective effects such as hosing which will further amplify any jitter. The relative rms jitter parameter, N, calculated for this machine design at the PWFA interaction point is shown in the left data point of Figure 2a: **N=1.5E-3 x 1.7E-3 (σ)** (horizontal x vertical). This jitter is supressed by an order of magnitude compared with the FACET-II case and would suffice for the FEL applications considered above. However, this is still an order of magnitude beyond the 1e-4 level required for a PWFA LC application. The other data points in Figure 2 show the rms jitter calculation with each error source removed from the calculation, one at a time. This shows the dominant contributor to the jitter parameter comes from the vibration of magnets. Figure 2b shows how the jitter parameter, N, varies with the magnet jitter by repeating the Monte Carlo analysis with different rms magnet jitter amplitudes (all other error sources included). It can be seen that to achieve the desired 1e-4 stability requirement, a rms magnet stabilization of <1nm is required. The ground exhibits natural vibration levels well above this amount at frequencies relevant for this accelerator. It should be noted, using a combination of beam-based feedback at lower frequencies and active magnet vibration isolation at higher frequencies, the CLIC collaboration have in the past demonstrated sub-nm vibration control is in principal possible [9]. Operating in the multi-kHz range, a SC accelerator, utilizing beam-based feedbacks, has lower residual ground motion to control, but cryo-magnets also have additional vibration sources not considered in the CLIC demonstration above. A strong R&D effort is needed to understand the practicalities of vibration control at the nm-level for a SC accelerator.

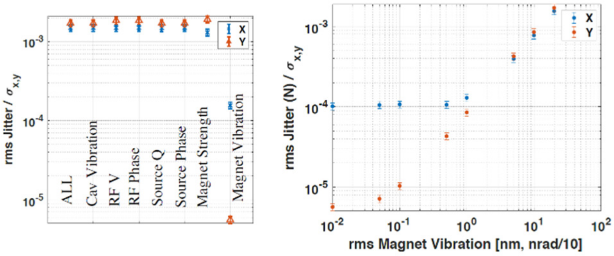

Figure 2a (left): Jitter parameter, N, using all error sources (left data point) and with individual error sources removed as labelled. 2b (right): Jitter parameter, N, with all error sources and varying levels of magnet vibration. Note angular vibration is 10X position vibration [i.e. x-axis value of 10nm is 10nm (horizontal or vertical) rms vibration and 100nrad in angle].

CONCLUSIONS

Using the jitter transfer model put forward in [5], we evaluated the jitter requirements for a PWFA Linear Collider application and two FEL driver applications. The required jitter tolerance on the drive beam were found to be in the range 1E-4 to 5E-3σ. Expected jitter values were studied for a warm (s-band) in [5] and superconducting (1.3 GHz) rf Linac source (here). The warm rf source was found to be too noisy by a factor of 150 to drive the LC PWFA application and by a factor of >3 times in the vertical and >80 times in the horizontal to drive an FEL application. A driver based on superconducting rf technology was found to meet the requirements for an FEL driver application but requires sub-nm magnet vibration suppression for a PWFA LC application. A next step would be to perform a more refined breakdown of the SC driver error sources and specify the largest tolerable error parameters in each case. Each considered error source as currently specified represents an R&D challenge to deliver a working system and warrants further careful analysis.

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