Beamdump Experiments Driven by a Plasma Wakefield Accelerator

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I. INTRODUCTION

Plasma wakefield accelerators promise to deliver high-energy electron and positron beams from compact accelerators. Current research on plasma wakefield acceleration (PWFA) is focused on producing high-quality beams in experiments operating at 10 Hz or less, but typical applications require beam rates in the 100 Hz - 100 MHz range. "Dark Sector" beamdump-based searches require high-intensity, medium-energy beam drivers [1]. Plasma wakefield acceleration has the potential to extend the energy reach of these experiments.

In this Letter of Interest, we examine beamdump experiments as an application of a plasma wakefield accelerator based on beam parameters that the field aims to demonstrate in the next decade, namely: energies in the range of 10-100 GeV, bunch intensities in the range of 1×10^8 - 1×10^{10}, beam emittances in the range of 1 μm - 100 μm, and repetition rates up to 1 MHz.

II. BEAM PARAMETERS FROM PLASMA WAKEFIELD ACCELERATORS

To date, the highest energy gain observed in a PWFA experiment was the "energy doubling" result from the E167 experiment at SLAC. This experiment produced 84 GeV electrons starting from a 42 GeV beam in less than one meter of plasma [2]. The energy spectrum of the beam was continuous and only a small fraction of the beam electrons achieved 84 GeV. The E200 experiment accelerated a beam of electrons from 20 GeV to 29 GeV with a spectrally distinct peak [3]. The amount of charge in the accelerated bunch was 28 pC. The E200 experiment also demonstrated positron acceleration in a plasma wakefield with 5 GeV energy gain and 126 pC in the accelerated bunch [4]. The beam emittance was greater than 100 μm in the E200 experiments. The AWAKE experiment at CERN used a 400 GeV proton beam to accelerate a bunch of electrons from 20 MeV to 2 GeV [5]. The amount of accelerated charge in the bunch was roughly 1 pC, but subsequent experiments demonstrated the acceleration of 100 pC of charge at sub-GeV energies.

There are a number of planned and on-going beam-driven plasma wakefield experiments that will improve upon the results listed above. We summarize them in Table I. For beamdump experiments, the critical parameters are the beam energy and beam intensity. The E300 experiment at FACET-II plans to demonstrate 10 GeV acceleration of a witness beam while preserving beam emittance [6]. The final beam energy will be 20 GeV. High-transformer ratio experiments may be able to extend the energy reach of the plasma wakefield accelerator at the expense of witness bunch charge. If FACET-II can reproduce high-transformer ratio experiments recently demonstrated at ANL [7], this would increase the energy gain in the plasma to 20-80 GeV using a 10 GeV drive beam. High-transformer ratio experiments are planned for both FACET-II and FlashForward. AWAKE plans to extend its plasma source to achieve energies above 50 GeV, without relying on high-transformer ratio acceleration [8].

While non-trivial, PWFA experiments have already demonstrated the capability of producing high energy electron beams at low charge and low repetition rate. Producing high-intensity beams may be more challenging. At FACET, the witness bunches were accelerated by an average of 5.3 GeV energy with an average bunch charge of 115 pC ($N_w \approx 7 \times 10^8$) [3]. The experiment was carried out at 1 Hz, which gives an average current of 0.115 nA. Based on our current understanding of PWFA, it should be possible to increase the repetition rate to 100 Hz without significant modifications of the plasma source. In addition, it should be possible to increase the amount of accelerated charge by a factor of 5. Combining these improvements would increase the average current to 57.5 nA. The X3 experiment at FlashForward plans to investigate PWFA at rates up to 1 MHz [9]. The results of this experiment will provide critical insight into how to push beam rates above 1 kHz.

Experiment	Lab	Driver	Witness	N_w	Eng. Gain [GeV]	δE [%]	ε [μm]	Rate
FlashForward X2 [10]	DESY	e^-	e^-	3×10^9	1	< 1	< 10	10 Hz
FlashForward X3 [9]	DESY	e^-	e^-	3×10^9	1			< 1 MHz
FACET E300 [6]	SLAC	e^-	e^-	8×10^9	> 10	< 1	3	1-30 Hz
FACET E300 e^+	SLAC	e^-	e^+	5×10^9	> 5		< 10	5 Hz
FACET E300 H.T.R.	SLAC	e^-	e^-	2×10^9	40	< 1	< 10	1-30 Hz
AWAKE++ [8]	CERN	p^+	e^-	5×10^9	50	< 1	< 20	< 1 Hz

TABLE I. Planned capabilities from on-going and upcoming PWFA experiments. Driver refers to the particle type of the beam driver, witness refers to the particle type of the witness beam. N_w is the number of particles in the witness beam.

III. THE EXPERIMENTAL LANDSCAPE

There are a number of searches that can be conducted in beamdump-type experiments. These include searches for axions [11], millicharged particles [12], and general forms of light dark matter [13–17]. Parameters for these experiments are shown in Table II.

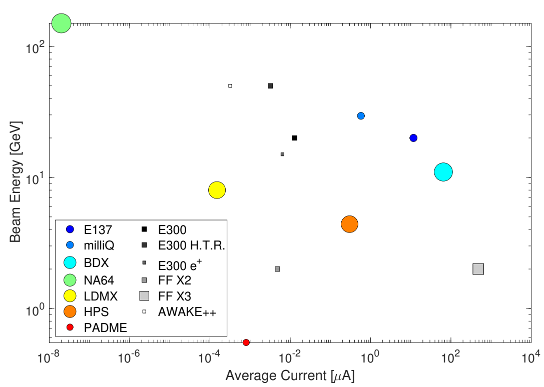

FIG. 1. Colored circles: Beam energy and average current for past and planned beamdump experiments. The size of the circle is proportional to the log of the beam rate. Gray squares: Beam energy and average current of planned plasma acceleration experiments. The size of the square is proportional to the log of the beam rate.

Beamdump experiments employ a variety of techniques to detect rare interactions. For the purposes of this LoI, the most significant difference between the experiments is whether or not the search relies on kinematic measurements of beam particles. For kinematic searches, the detector attempts to reconstruct individual particle trajectories and is therefore limited to low average currents on target, but at very high repetition rate [14, 15, 17]. Other experiments look directly for particles that are generated in and pass through the beam dump before reaching the detector [11–13]. These experiments expect high average current and are compatible with high-charge bunched beams. Some detector types work best with bunched beams because this is useful for rejecting out-of-time backgrounds [18]. Finally, positron beams may be used to enhance production rates of dark matter particles and are compatible with a bunched-beam format [19].

Figure 1 plots the beam energy and average current of the experiments listed in Table II on a log-log scale. The log of the repetition rate of the experiments is represented by the size of the marker. Parameters of planned plasma wakefield acceleration experiments are shown on the same plot. Results are expected from the E300 experiment at FACET-II and the X2 experiment at Flash-Forward within the next two years. Results from the E300 high-transformer ratio experiment, E300 positron experiment, and X3 experiment are expected within five years. The AWAKE++ experiment will follow the currently planned AWAKE Run-II experiment which aims to demonstrate 10 GeV acceleration in the next 5 years.

IV. PATHS TO HIGHER LUMINOSITY

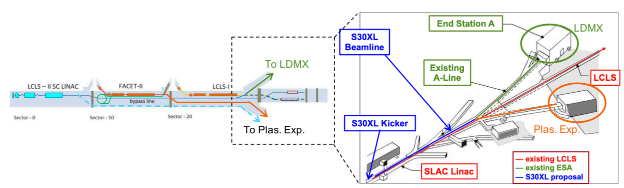

FIG. 2. Possible configuration of the SLAC accelerator complex that could provide beam to fixed-target experiments in End Station B at 120 Hz in the case of the normal-conducting FACET-II linac, or up to 62.5 KHz from the superconducting LCLS-II linac.

The main limitation on future plasma-driven fixed-target experiments is the beam repetition rate. The planned operation for FACET-II is 10-30 Hz, but the normal-conducting linac is capable of accelerating electron beams at a rate of 120 Hz. Although untested, it is likely that existing plasma source technology will work at 120 Hz. Going beyond 120 Hz requires a superconducting linac, such as the one used at DESY Flash-Forward [9], or the use of bunch trains as planned for AWAKE++ [20]. At SLAC, the LCLS-II superconducting linac could potentially provide high-repetition rate beams to a plasma-driven accelerator in End Station B because most LCLS-II pulses are sent to the dump in the Beam Switch Yard [21]. Figure 2 shows an example layout of the SLAC accelerator complex that could provide beams from FACET-II or LCLS-II HE to experiments

Experiment	Beam	E [GeV]	N_b	Rate	I_{avg}	Run Time [days]	EOT
E137 SLAC [11]	e^-	20	4×10^{11}	180 Hz	11.6 μA	30	1.8×10^{20}
milliQ SLAC [12]	e^-	29.5	3×10^{10}	120 Hz	0.576 μA	98	8.4×10^{18}
BDX JLAB [13]	e^-	11	1.6×10^{6}	250 MHz	65 μA	285	1×10^{22}
NA64 CERN [14]	e^-	50-150	5×10^{6}	Spill	20 fA	90	1×10^{12}
LDMX SLAC [15]	e^-	4-8	20	46.5 MHz	150 pA	120	1×10^{16}
HPS JLAB [16]	e^-	4.4	5×10^{4}	40 MHz	300 nA	28	4.5×10^{18}
PADME LNF [17]	e^+	0.55	1×10^{5}	50 Hz	800 fA	250	1×10^{14}

TABLE II. Previous and on-going beamdump-based searches. EOT refers to the total number of electrons (or positrons) on target.

Accelerator	Linac Energy	After Plasma	Bunch Charge	Rate	Current	EOT/year
NC to ESB	10 GeV	20-50 GeV	0.2-2.0$\times10^{10}$	120 Hz	19-190 nA	0.4-4$\times10^{19}$
SC to ESB	8 GeV	16-40 GeV	0.3-3.0$\times10^{9}$	1-62.5 kHz	0.5-30 μA	0.1-6.0$\times10^{21}$

TABLE III. Potential beam parameters for experimental delivery in SLAC's End Station Beam. "NC to ESB" refers to the normal-conducting FACET-II linac. "SC to ESB" refers to the superconducting LCLS-II HE linac. The LCLS-II HE linac can provide higher repetition rate but is limited to 30 μA total beam current.

in End Station B. The maximum allowable current from the SC linac is 30 μA, which would imply a 62.5 kHz rep rate for 0.5 nC bunches and result in 6×10^{21} electrons-on-target/year, which would be competitive with other advanced beam dump experiments. Possible running scenarios are listed in Table III. We note that while the drive linac is an important aspect of achieving higher luminosity, there are fundamental plasma physics issues that must be addressed before claiming that we can achieve high-luminosity plasma acceleration.

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