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A LASER PLASMA WAKEFIELD ELECTRON ACCELERATOR FOR THE ADVANCED PHOTON SOURCE AND LOW-ENERGY ACCELERATOR FACILITY*

K. P. Wootton†, W. J. Berg, J. Calvey, S. Chemerisov, J. Dooling, M. Edelen, V. Guarino,
C. Kozlowski, A. H. Lumpkin, V. Sajaev, F. Westferro
Argonne National Laboratory, Lemont, IL, USA
E. Aneke, Northwestern University, Evanston, IL, USA

Abstract

Recent developments in laser wakefield accelerators (LWFAs) lead us to consider employing this technology to accelerate electrons at the Advanced Photon Source (APS) facility. Previous experiments using LWFAs were performed at Argonne using the Terawatt Ultrafast High Field Facility. The injector complex serving the APS begins with an electron linac, producing beam energies on the order of 450 MeV. We consider that the infrastructure developed at the Linac Extension Area (LEA) could be usefully employed to develop a new LWFA injector for the APS linac. In the present work, we outline the proposed parameters of an LWFA using approximately a 100–TW–peak laser pulse focussed into a few-mm in extent pulsed gas jet. We are targeting electron beam energies in the range 300–500 MeV. Initially, we would use the LEA quads, diagnostics and electron spectrometer to demonstrate performance and characterize the LWFA beam, before moving the LWFA to inject into the Particle Accumulator Ring (PAR).

INTRODUCTION

The photon beams produced by the Advanced Photon Source Upgrade (APS-U) illuminate materials to solve the most pressing problems in science, engineering, and energy [1]. The high-power electron beams of the Low Energy Accelerator Facility (LEAF) at Argonne are used to create diagnostic radioisotopes for medicine [2]. As stewards of our facilities, we endeavour to most efficiently use electricity as we deliver needed beams.

Laser plasma wakefield accelerators (LWFAs) [3–6] are being developed to serve the needs of future electron accelerators, especially towards energy-frontier electron-positron colliders and free-electron lasers [7, 8]. We propose that an effort parallel to the high energy physics roadmap is needed to develop this technology as an injector to a storage ring lightsource [9–11], or for production of radioisotopes using electron beams. With an eye to material irradiation, previous work on LWFAs was performed at Argonne using the Terawatt Ultrafast High Field Facility (TUHFF) [12–14].

In the present work, we outline a a proposal to develop a LWFA linear accelerator as for electron beam irradiation or as an injector to the APS-U. We outline and motivate the proposal. Background and prior studies are outlined. Proposed experimental parameters are outlined using particle-in-cell simulations. To close, we discuss some of the potential opportunities enabled by such a research pursuit.

MOTIVATION

A distinguishing feature of the injector accelerator chain of the Advanced Photon Source (APS) is the Particle Accumulator Ring (PAR) [15]. Situated between the electron linac and the booster synchrotron, the PAR is used to accumulate electrons for APS electron beam operation. The large momentum aperture of the PAR ring (~0.1%) allows us to capture multiple injections from an LWFA before directing that beam on to the booster synchrotron. This approach is not unique: a number of studies have considered matching an LWFA to a ring [10, 11, 16–18].

Rather than attacking scientific problems associated with larger scale facilities (such as staging multiple accelerator segments together [19]), we propose to deploy a single acceleration stage. Specifically, we propose to develop a LWFA based on a supersonic transverse gas jet operated in the blowout regime, modelled along previous studies [20].

We envisage conducting this research in stages. Based on existing demonstrations of LWFAs at other laboratories, we propose to assembled and characterized a LWFA at the Linac Extension Area (LEA) [21–24] to demonstrate the feasibility of an LWFA for radioisotope production or as an injector to the APS. We would subsequently relocate the LWFA to inject into the Particle Accumulator Ring (PAR) [15], and demonstrate injection into the APS-U storage ring.

BACKGROUND

Presently at Argonne, the LEAF electron linac is used for the production of radioisotopes [2]. The linac can be configured to provide electron beams with energies up to 50 MeV and beam powers up to 25 kW.

The injector chain of accelerators at the APS begins with an S-band electron linac [15, 25]. The APS linac routinely provides electron beams of energies on the order of 450 MeV. The linac is typically operated to produce ~1 nC of beam charge at a linac repetition rate of up to 30 Hz (~13 W average beam power). The APS electron linac is illustrated in Fig. 1.

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† kwootton@anl.gov

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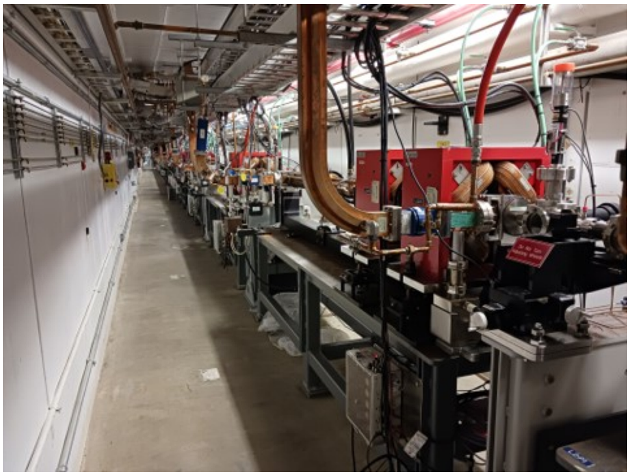

Figure 1: Photograph of the APS linac.

LPWA PARAMETERS

We use a plasma wavelength λ_p of [4]:

$$\lambda_p\,(\mu\text{m}) \approx \frac{3.3 \times 10^{10}}{\sqrt{n_0\,(\text{cm}^{-3})}}, \tag{1}$$

where n_0 is the electron plasma density in units of cm^{-3}. We use a peak laser intensity I_0 of [5]:

$$I_0 = \frac{2P}{\pi w_0^2}, \tag{2}$$

where P is the peak laser power and w_0 the radius of the laser pulse at $1/e^2$ of the peak intensity ($w_0 = 1.699$ FWHM). We use a laser strength parameter a_0 of [4]:

$$a_0 = \sqrt{\frac{2e^2\lambda^2 I_0}{\pi m_e^2 c^5}} \approx \sqrt{7.3 \times 10^{-19}\,[\lambda\,(\mu\text{m})]^2\, I_0(\text{W}\,\text{cm}^{-2})} \tag{3}$$

where λ is the laser wavelength, m_e the electron rest mass, and c the speed of light.

We chose parameters of the laser (wavelength, pulse energy, pulse duration) corresponding to commercially-available Titanium:Sapphire lasers. We chose a laser beam waist of $w_0 = 8.4\,\mu$m (FWHM 9.9 µm). In order to optimise electron acceleration, we chose to match the plasma wavelength to the laser pulse length using $c\tau_l = \lambda_p/2$ [20], where c is the speed of light in vacuum and τ_l is the laser pulse duration (FWHM intensity). For a fixed pulse duration of $\tau_l = 20$ fs, $\lambda_p = 12\,\mu$m. Using Eq. (1), this corresponds to an electron plasma density $n_0 = 7.5 \times 10^{18}$ cm. For this initial study, we use a uniform electron plasma density of length 1.2 mm. Parameters used in the present calculation are summarised in Table 1.

SIMULATIONS

We have performed particle-in-cell (PIC) simulations using Warp PBA (Plasma-Based Accelerators) in Sirepo [26, 27]. Snapshots of the plasma profile are illustrated in Fig. 2 and Fig. 3. The energy spectrum of the electron beam as it exits the plasma is illustrated in Fig. 4.

Table 1: Laser and Plasma Parameters

Parameter		Value
Laser wavelength	λ	0.8 µm
Laser pulse energy	E_l	1.1 J
Laser pulse duration	τ_l	20 fs
Peak laser power	P	55 TW
Laser beam waist	w_0	8.4 µm
Peak laser intensity	I_0	3.5×10^{19} W cm^{-2}
Laser strength parameter	a_0	4.8
Plasma wavelength	λ_p	12 µm
Electron plasma density	n_o	7.5×10^{18} cm^{-3}
Electron plasma length	L	1.2 mm

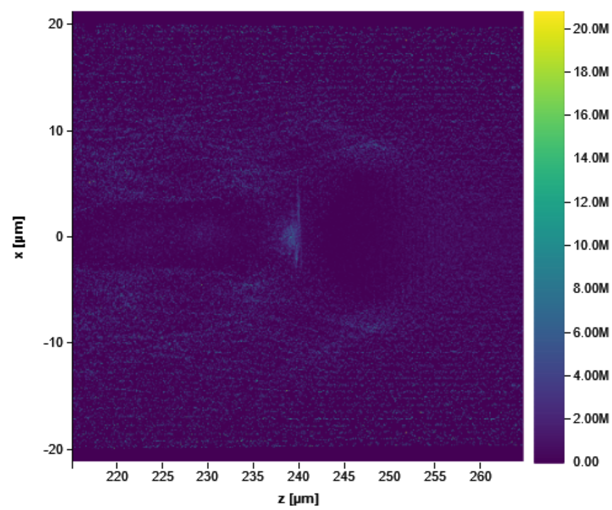

Figure 2: Snapshot of plasma simulation at position $z = 0.25$ mm (880 fs).

DISCUSSION

Many systems work together to support linear accelerator beam operations. At a facility-scale installation such as the APS linac, this requires significant wall-plug electrical power and dedicated personnel for all the related systems (e.g. radiofrequency cavities, magnets, utilities, beam operations). Shrinking the accelerator to a few millimetres length dramatically reduces the power demand and installed footprint.

We perceive that medium-term opportunities to develop and deploy LWFAs for accelerators such as synchrotron light source injectors [10] or for photonuclear transmutation. We need beams on target, but with perhaps less stringent goals for emittance and beam size than energy frontier colliders.

At present, LWFAs are not operational accelerators. Deploying such an accelerator for operations has the potential to shift the perception of these accelerators as ‘experiments’. We see such research to adopt advanced accelerator con-

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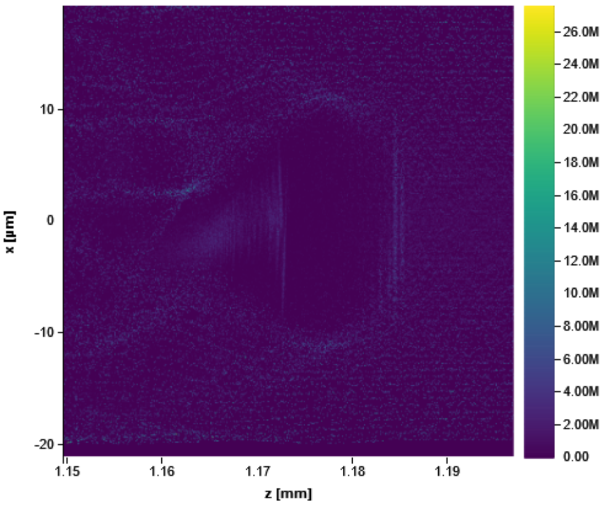

Figure 3: Snapshot of plasma simulation at position $z = 1.18$ mm (3990 fs).

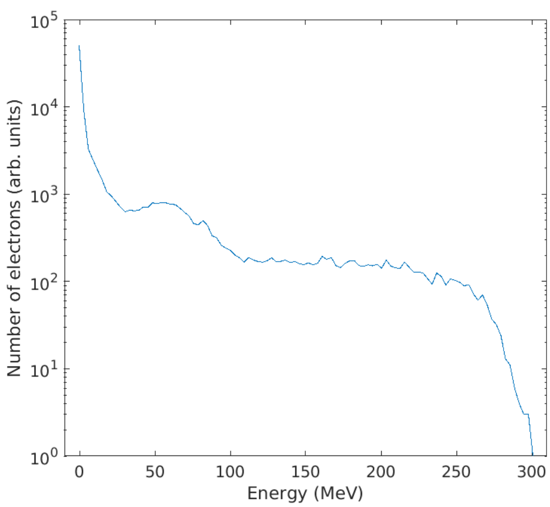

Figure 4: Simulated electron energy spectrum leaving the plasma (1.2 mm).

cepts to power accelerator facilities to further the field of accelerator science and engineering.

CONCLUSION

As a multi-program laboratory, Argonne operates major research facilities for both radioisotope production and synchrotron light. In the present work, we have used simulation to study the use of LWFAs as an injector for a synchrotron light source.

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