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EUV FEL LIGHT SOURCE BASED ON ENERGY RECOVERY LINAC WITH ON-ORBIT LASER PLASMA INJECTION *

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Abstract

We report on a week-long study of a conceptual design of EUV FEL light source based on an energy recovery linac (ERL) with on-orbit laser plasma accelerator injection scheme. We carried out this study during USPAS Summer 2023 session of Unifying Physics of Accelerators, Lasers and Plasma applying the art of inventiveness TRIZ [1]. An ultrashort Ti-sapphire laser accelerates electron beams from a gas target with mean energy of 20 MeV, which are then ramped up to 1 GeV in a four-turn scheme with a series of fixed field alternating gradient magnets and two superconducting cryomodules. The electron beam is then bypassed to an undulator line optimized to generate extreme ultraviolet (EUV) light of 13.5 nm with peak power at kW level in a single pass.

INTRODUCTION

The development of RF photo-cathode guns in 80s provide the high-brightness electron beams needed to realize FEL ushering a new era for light sources in UV and X-ray region. Meanwhile the conventional accelerator stages/technologies required to bring the electron beams to relativistic GeV scale for light generation would measure upto hundred of meters. The spatial extent of this kind of light source can be made compact in two ways by minimizing the space occupied by the accelerating structures. The first approach is to accelerate the electrons in a recirculation mode with energy recovery for increased efficiency and the second is laser-plasma accelerators. Since the fidelity of low energy (MeV scale) laser-plasma accelerator (LPA) are improving, we consider a case of combining a LPA in an energy recovery linac (ERL) to drive a single pass SASE FEL in the EUV region as shown in Fig. 1. We introduce an on-orbit laser plasma accelerator for electron beams with mean energies of 20 MeV. The electron beams gain energy of 245 MeV per turn in synchronized cryomodule while being circulated in fixed field alternating gradient (FFA) arcs. The electron beams achieve 1 GeV energy after four turns and are bypassed to a undulator line for generating radiation at 13.5 nm. After that, the timing correction chicane is activated, changing the path length and thus shifting the bunches to decelerating phase of SRF cavities, for energy recovery.

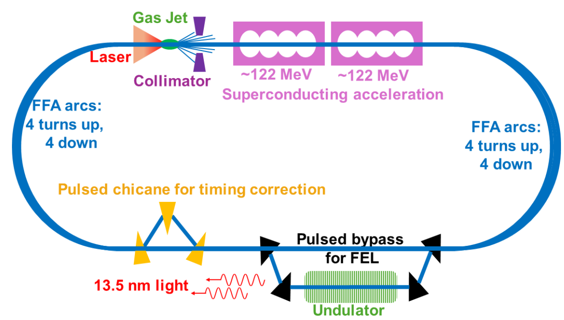

Figure 1: Schematic diagram of ERL based EUV FEL source with on-orbit laser plasma injector. Figure is not drawn to scale..

In this report, we specify associated parameters for an ERL driving a EUV FEL with on-orbit laser plasma injector of Fig. 1. First we identify the necessary laser specification and gas target to enable laser wakefield acceleration of electron bunches with mean energy of 20 MeV, tens of pico-Coulomb charge and geometric emittance of less than 50 nm. Then we consider a scaling FFA lattice to accomodate electron beams from (20−)265 − 510 − 755−1000 MeV with mean energy gain of 122.5 MeV from each superconducting cryomodule per pass. After that we consider Halbach type undulator made from permanent magnets to determine the undulator gap, period and length necessary to achieve radiation power approaching 1 kW output at 13.5 nm. Finally, we close with discussions on issues and options of re-circulation and recovery for laser, electron beams in ERL before and after FEL.

LASER-PLASMA ACCELERATOR

Recent demonstrations of ∼1 μC electron acceleration from kilo-joule laser OMEGA EP [2] and stable generation of ∼2.2 pC electron acceleration at 2.5 Hz with 170 mJ Ti-Sapphire laser [3] in the MeV range indicate promise of MeV range laser wakefield accelerators for application in various fields. We consider employing the supersonic gas jet

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target [4] used in both experiments [2, 3] along with ARCO Hybrid Ti-Saphh laser from Amplitude [5] or Quark 30/45 from THALES [6] to drive a laser plasma accelerator with mean electron energy of 20 MeV, total charge of 12-22 pC and geometric emittance < 33 µm mrad and beam divergence of less than 5°. Following similar approach to Ref. [7], we estimate the desired laser and gas-target parameters for laser wakefield acceleration [8] and the corresponding anticipated plasma and electron beam parameters in Table 1. We note that ≤ 1% of the electron beam charge with energy spread ≤ 10^{-3} transmits through the collimator (Fig. 1) to be accelerated in the cryomodules.

Table 1: Parameters For Laser-plasma Accelerator

Parameter	Symbol (Unit)	Value
Laser		
Energy	$\mathscr{E}_l$ (mJ)	50
Wavelength	λ_l (nm)	800
FWHM pulse width	τ_l (fs)	25
Rayleigh range	z_R (µm)	50
Waist size	w_0 (µm)	3.57
Peak Intensity	I_0 (W/cm^2)	1×10^{19}
Normalized amplitude	a_0	2.2
Gas target/Plasma		
Electron density	n_e(cm^{-3})	5×10^{18}
Plasma wavelength	λ_p (µm)	14.96
Maximum field gradient	E_{max} (GV/m)	2.24
Dephasing length	L_{dph} (mm)	5.18
Depletion length	L_{dpl} (mm)	5.23
Electron beam		
Mean energy	$\gamma_0 mc^2$ (MeV)	20
Total charge	Q (pC)	12 − 22
RMS divergence	$\sigma_{x'}$ (mrad)	< 85
Geometric emittance	ϵ (µm mrad)	< 33

ENERGY RECOVERY LINAC BASED ON FFA APPROACH

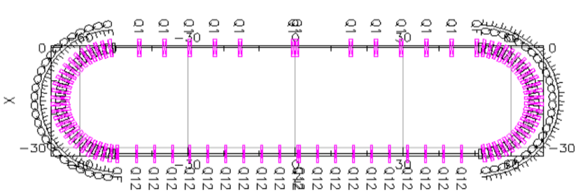

Figure 2: Preliminary lattice design of energy recovery linac.

We borrow a multipass approach with energy recovery using FFA from the success of CBETA [9, 10]. The collimated 20 MeV electron beams pass through two cryomodule gaining mean energy of 122.5 MeV per cavity. For convenience, the accelerating voltage of rf cavities is kept fixed to maintain constant gain per turn until the electrons reach 1 GeV in four turns. This sets the required momentum acceptance factor of 3.77 for the FFA arcs. For this project, we selected the non-scaling FFA approach that require easier magnets than for scaling FFA. Fig. 2 shows the skeletal layout of chosen FFA simulated using BMAD [11]. This layout is 140 m long and 30 m wide covering an area of 4200 m^2.

Fig. 3 shows beta function (β), dispersion (η), and orbit along path lengths in FFA arcs for (a) 300 MeV and (b) 1 GeV electron beams. The maximum horizontal beta function (β_A) for 300 MeV is almost 8 times as that of 1 GeV beam whereas it differs by less than factor of 2 for vertical beta function (β_B). For 300 MeV beam , the dispersion function in horizontal plane remains within 15 cm while it increases almost by a factor of 2 to an average of 30 cm for 1 GeV beam. Likewise, the orbit shifts by almost 30 cm between 300 MeV and 1 GeV. The lattice design needs further tuning to minimize dispersion functions and orbit differences to meet the condition for acceleration over multiple recirculations; this requires setting differences in orbit length from one energy to next to be smaller than the RF wavelength or adopting the vertical FFA approach [12]. Vertical FFAs [12] along with delay chicanes may come handy for resolving path length and timing issues.

FEL

1 GeV electron beams are transported to an undulator line using kicker magnets where they pass through an Halbach type permanent magnet undulator to generate EUV light centered at fundamental wavelength of 13.5 nm. We consider Samarium-Cobalt (SmCo) based permanent undulator with a fixed period of 3 cm, peak magnetic field 0.8 Tesla and gap of 8.6 mm to achieve a net deflection parameter of $K = 2.21$ [13]. We alter electron beam current and rms size slightly to obtain variation in FEL Pierce parameter from ~ 10^{-4} to ~ 10^{-3} which affects gain length, saturated power as well coherence length and RMS bandwidth significantly. For our calculations, we apply 1D cold beam limit approximation [13] and summarize our results in Table 2. Our results indicate that saturated radiation power could be doubled to ~0.75 kW with a short undulator length of 32 m by compromising coherence and bandwidth by almost a factor of 2 using a tighter electron beam with rms beam size of 5 µm instead of 15 µm while keeping the same beam current as shown in Table 2. This indicates the feasibility of generating peak power in the kW range at 13.5 nm from a FEL light source by a slight increase in the beam current while keeping other parameters constant since radiation power is directly proportional to the beam current. We can increase peak beam current by improving injection efficiency from LPA and use higher repetition rate lasers to increase average power. An alternative approach with charge accumulation of LPA electrons in an accumulator ring and timed injection would also provide higher current beams. Last but not least, seeded or electron beam manipulated FELs could also considered for delivering higher peak power [13].

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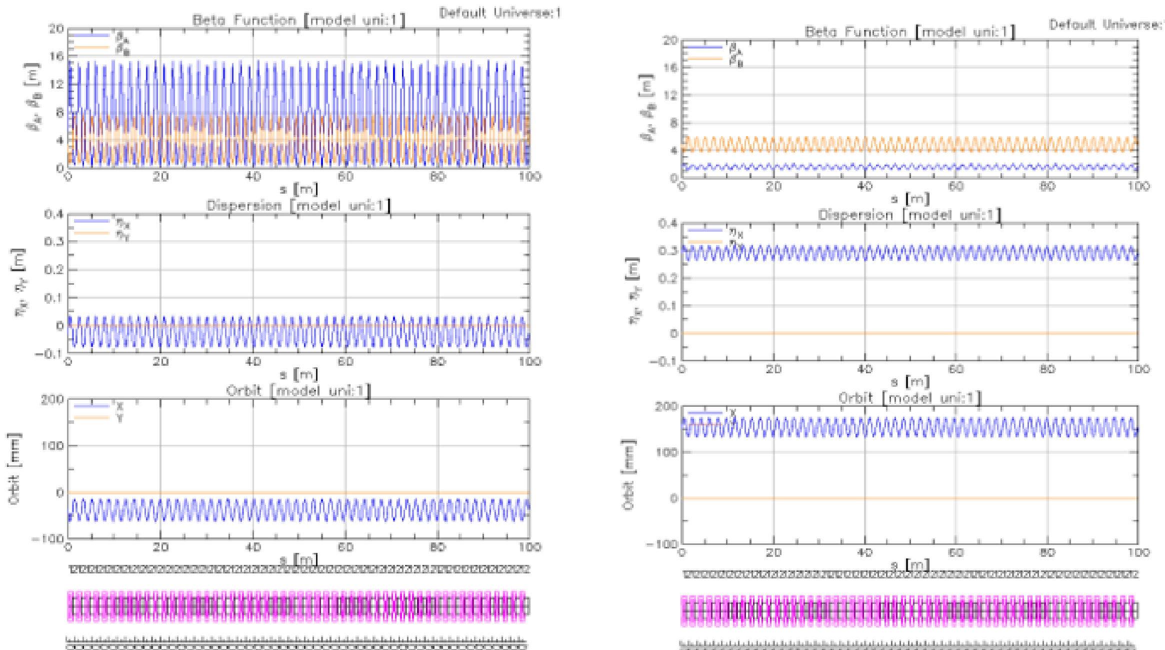

(a) (b)

Figure 3: Betafunctions, dispersions, and orbit plotted versus longitudinal path for (a) 300 MeV and (b) 1 GeV electron beams in the arc section.

Table 2: Parameters for FEL Light Source at 13.5 nm

Parameter	Symbol (Unit)	Value	Value	Value
Electron beam				
Mean energy	$\gamma_0 mc^2$ (GeV)	1	1	1
Peak current	I (Amp)	0.5	0.5	0.1
RMS bunch length	σ_τ (fs)	25 – 200	25 – 200	25 – 200
RMS beam size	σ_x (μm)	15.0	5.0	15.0
Undulator / FEL				
Undulator period	λ_u (cm)	3.0	3.0	3.0
Undulator length	L_u (m)	66.0	33.0	42.0
Peak magnetic field	B_0 (T)	0.8	0.8	0.8
Gap for SmCo	g (mm)	8.64	8.64	8.64
Deflection parameter	K	2.21	2.21	2.21
Pierce parameter	ρ	4.51×10^{-4}	9.37×10^{-4}	2.64×10^{-4}
Spontaneous radiation power	P_s (kW)	12.95	6.65	1.69
Radiation at 13.5 nm				
Gain length	L_g (m)	3.06	1.47	5.22
Saturation length	L_{sat} (m)	66.52	32.02	113.6
Saturated power	P_{sat} (W)	360.8	749.6	42.24
Coherence length	σ_l (fm)	8.69	4.26	9.1
RMS bandwidth	σ_ν	4.12×10^{-4}	8.4×10^{-4}	3.94×10^{-4}

DISCUSSION

This preliminary study explored the possibility of using a laser wakefield accelerator as an injector to a multipass energy recovery linac based on scalable FFA magnets to use as a EUV FEL light source in the kW range. While feasible, several open technical questions remain to be answered to realize such a device. The details of superconducting rf cavities, phase and timing issues, practical FFA lattice, collimation of laser accelerated electrons, recirculating used electron beams for continuous radiation generation, 3D FEL calculations and simulations as well as effects of incoherent and coherent synchrotron radiation and collective beam effects are missing. The rigorous analysis required for tackling these queries and issues are left for the readers to dwell on.

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REFERENCES

[1] A. Seryi and E. I. Seraia, *Unifying Physics of Accelerators, Lasers and Plasmas*, CRC Press, Boca Raton, Florida (2023). https://library.oapen.org/handle/20.500.12657/50889

[2] J. L. Shaw *et al.*, "Microcoulomb ($0.7 \pm^{0.4}_{0.2}$ μC) laser plasma accelerator on OMEGA EP", *J. Manage. Sci. Rep.*, vol. 11, no. 1, Apr. 2021. doi:10.1038/s41598-021-86523-5

[3] S. Bohlen *et al.*, "Stability of ionization-injection-based laser-plasma accelerators", *Phys. Rev. Accel. Beams*, vol. 25, no. 3, p. 031301, Mar. 2022. doi:10.1103/physrevaccelbeams.25.031301

[4] A. M. Hansen *et al.*, "Supersonic gas-jet characterization with interferometry and Thomson scattering on the OMEGA Laser System", *Rev. Sci. Instrum.*, vol. 89, no. 10, 10C103, Jul. 2018. doi:10.1063/1.5036645

[5] Arco - Amplitude, https://amplitude-laser.com/products/femtosecond-lasers/lasers-for-science/arco/

[6] Laser datasheets | Thales Group, https://www.thalesgroup.com/en/markets/specific-solutions/lasers/laser-datasheets

[7] M. Turner *et al.*, "Compact Ring-Based X-Ray Source With on-Orbit and on-Energy Laser-Plasma Injection", in *Proc. NAPAC'16*, Chicago, IL, USA, Oct. 2016, pp. 435–438. doi:10.18429/JACoW-NAPAC2016-TUA3CO03

[8] E. Esarey *et al.*, "Physics of laser-driven plasma-based electron accelerators", *Rev. Mod. Phys.*, vol. 81, no. 3, pp. 1229–1285, Aug. 2009. doi:10.1103/revmodphys.81.1229

[9] G. H. Hoffstaetter *et al.*, "CBETA Design Report, Cornell-BNL ERL Test Accelerator ", arXiv:1706.04245 [physics.acc-ph], 2017. doi:10.48550/arXiv.1706.04245

[10] A. Bartnik *et al.*, "CBETA: First Multipass Superconducting Linear Accelerator with Energy Recovery", *Phys. Rev. Lett.*, vol. 125, no. 4, p. 044803, Jul. 2020. doi:10.1103/physrevlett.125.044803

[11] Bmad Overview, https://www.classe.cornell.edu/bmad/overview.html.

[12] S. Brooks, "Vertical orbit excursion fixed field alternating gradient accelerators", *Phys. Rev. Spec. Top. Accel Beams*, vol. 16, no. 8, p. 084001, Aug. 2013. doi:10.1103/physrevstab.16.084001

[13] K.-J. Kim, Z. Huang, and R. Lindberg, Synchrotron Radiation and Free-Electron Lasers: Principles of Coherent X-Ray Generation. Cambridge University Press, 2017. doi:10.1017/9781316677377.

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