A Non-Conventional ERL Configuration for High-Power EUV FELs

M. Venturini and G. Penn

Lawrence Berkeley National Lab, University of California, Berkeley, CA 94709

Abstract

We show that a standard Linac configuration (consisting of accelerating sections, linearizing section, and magnetic chicane compressor) currently used in drivers for single-pass EUV/x-ray FELs is compatible with energy recovery, provided that certain timing constraints are met. By circulating the spent, rather than the fresh beam as in a conventional high-power ERL FEL design, the beam brightness can be more easily preserved thus facilitating lasing at short wavelength. As in a conventional ERL, the proposed design allows for energy-spread compression, enabling low-energy beam dumping and high energy-recovery efficiency. Results from numerical simulations presented in this paper show that this configuration could, in principle, support the generation of multi-kW average radiation power required for high-volume production EUV lithography.

Keywords: Free Electron Laser (FEL); Energy Recovery Linac (ERL);
EUV Lithography

1. Introduction

Interest in the industrial application of high-power Free Electron Lasers (FELs) to Extreme Ultra-Violet (EUV) lithography is mounting [1]. While the semiconductor industry plans to transition to EUV lithography are currently being supported by Laser Plasma Produced (LPP) radiation, it is generally expected that future high-volume production will require more powerful sources. The FEL potential for EUV lithography has long been recognized [2, 3, 4, 5]. Continuing progress in FEL physics, accelerator, and photo-gun technology is now bringing the realization of that potential within reach. However, there are still considerable challenges.

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18 To be attractive to the industry an FEL machine should be capable of
19 generating a few tens of kW average EUV radiation at the exit of the undu-
20 lator. Because demonstrated FEL efficiency $\eta = P_{\text{rad}}/P_{\text{b}}$, where P_{rad} and P_{b}
21 are the output radiation and electron beam average power, is typically only
22 a fraction of 1% the requirement is for several MWs electron beam power.

23 While there are few doubts that the driver-accelerator technology should
24 be based on Super Conducting (SC) linacs, views differ as to what machine
25 configuration would be best suited. Energy Recovery Linacs (ERL) represent
26 an obvious and appealing choice [3, 4]. ERL-based multi kW radiation FELs
27 in the IR have already been successfully demonstrated [6, 7] and a growing
28 body of research is supporting further technology development [8, 9, 10, 11,
29 12]. In the conventional ERL configuration the FEL is placed downstream of
30 the return arc past the linac, with transport through the arc providing the
31 necessary bunch manipulation (compression, correction of longitudinal phase-
32 space nonlinearities). Multi-turn acceleration is possible in principle, with
33 potential of further capital and operational cost reduction. However, in some
34 regards ERL is still an emergent technology and, more critically, delivery of
35 the high brightness needed for EUV lasing has yet to be demonstrated.

36 More recently, it was argued that Straight Topology (ST) FELs, where
37 the undulator is in line with the linac – the configuration of choice in all
38 existing EUV and x-ray FEL facilities – could be adopted for high-power
39 radiation production [5]. Lasing at the wavelength of interest has been
40 demonstrated. Moreover, without any further concerns, this configuration
41 can support tapered-undulator methods to enhance FEL efficiency beyond
42 SASE emission at saturation (pushing efficiency closer to 1%). The draw-
43 back, of course, is that MW electron beams would still be needed and the
44 absence of energy recovery adds to capital and operational costs and, perhaps
45 more importantly, makes the disposal of the spent beam quite challenging.
46 Unless progress is made on augmenting the FEL efficiency this configuration
47 is unlikely to be palatable to the industry.

48 It is not our goal here to make a detailed comparison of advantages and
49 limitations of the two machine solutions. Instead, we would like to point
50 out the merits of a hybrid configuration, Energy Recovery with Straight
51 Topology (ER-ST) FEL, that has the potential of reaping the benefits of
52 both while for the most part avoiding their main drawbacks. The idea is
53 to combine energy recovery with a ST FEL, *i.e.* to circulate the spent,
54 rather than the fresh, beam. All necessary beam manipulations needed for
55 lasing are done in the straight section of the machine upstream of the FEL

undulator as in conventional ST FELs, thus reducing the burden of preserving the brightness of the circulating beam. Energy-spread compression can be effectively performed on the spent beam after lasing, thus enabling low-energy beam dumping.

We should add that a similar configuration was tested at JLab [13, 14, 15] in the first incarnation of the ER-FEL program (IR-Demo), where a conventional bunch-compressor chicane was placed right ahead of the FEL undulator before recirculation, but in the absence of a harmonic-cavity linearizer. This configuration successfully demonstrated kW-level radiation power in the infrared but it would be ill-suited for efficient lasing in the EUV, where longitudinal phase-space linearization before compression cannot be dispensed with.

In the next section we discuss certain timing constraints peculiar to the hybrid configuration and lay out the basic operation mode. In Sec. 3 we illustrate the machine point design then used in Sec. 4 in a numerical model to estimate the FEL efficiency and beam energy spread at the dump. We conclude with a discussion of our results.

2. Timing constraints and basic operation mode

We adopt the basic layout shown in Fig. 1, with one-stage magnetic compression occurring in a conventional 4-bend chicane (BC). The beam is injected at energy E_i into the the linac section L1, followed by the harmonic cavity linearizer HL, with final acceleration imparted by the linac section L2. The beam energy at the bunch compressor (first passage, when the beam is accelerating) and FEL are E_{BC}^I and E_f respectively. After lasing the beam circulates along a return line, passes the BC for the second time at energy $E_{BC}^{II} = E_f - (E_{BC}^I - E_i)$ and is dumped at energy E_d .

Energy recovery is attained on the condition that the rf phase experienced by the accelerating beam ϕ^I and the returning (decelerating) beam ϕ^{II} through a linac section are such that

$$\cos \phi^{II} = -\cos \phi^I. \quad (1)$$

In a conventional ERL this condition is usually realized by setting $\phi^{II} = \phi^I \pm \pi$, upon carefully adjusting the pathlength of the returning beam.

A distinctive feature here is the presence of a magnetic chicane between sections of the linac. A magnetic chicane is not needed in a conventional

Figure 1: Schematic of the ER-ST FEL configuration (not to scale), in which the beam is circulated after lasing. Indicated are the main accelerator sections, a magnetic chicane compressor (BC), the FEL undulator, dump, and the beam energy at selected points. The second time it passes through BC the beam follows a shorter trajectory (dashed line) if $E_{BC}^{II} > E_{BC}^I$.

ERL FEL configuration where transport through the arc at the linac exit is exploited to impart the required compression; as a consequence all sections of the linac exhibit the same rf phase difference between first (accelerating) and second (decelerating) beam passage. The presence of the chicane modifies the timing constraints for energy recovery.

The simplest scenario is the one where the beam energy at first and second passage through the BC are equal, $E_{BC}^{II} = E_{BC}^I = (E_f + E_i)/2$, prompting the beam to follow the same trajectory through the chicane. As a result the same rf phase difference (e.g. π) between first and second passage through L1 and HL then applies to first and second passage through L2. Notice that the frequency of the HL cavities has to be an odd harmonic of the accelerating cavities in L1 and L2. The L1, HL, and L2 rf phases can be set independently. Any value of the L2 phase ϕ_{L2}^I is compatible with energy recovery, with a positive value providing some measure of control over the energy chirp and $\phi_{L2}^I \simeq 0$ maximizing acceleration and enabling more effective energy-spread compression, as we will see in the next sections. (In our conventions the rf waveform crest is at $\phi = 0$.) A disadvantage of this solution is that $E_{BC}^I = (E_f + E_i)/2$ will tend to be relatively high, forcing a larger requirement on the linearizer voltage, which roughly scales as E_{BC}^I .

Flexibility in the setting of E_{BC}^I comes at the cost of constraining the choice of the L2 phase. If $E_{BC}^I < (E_f + E_i)/2$, then $E_{BC}^{II} > E_{BC}^I$ and during the second passage through the chicane the beam will follow a shorter trajectory. In first approximation the pathlength difference is

$$\Delta z = (L_1 + 2L_B/3) (\theta_I^2 - \theta_{II}^2) > 0 \quad (2)$$

where θ_I and $\theta_{II} = \theta_I E_{BC}^I / E_{BC}^{II}$ are the bend angles in the magnetic chicane dipoles as experienced by the beam during its first and second passage respec-

Figure 2: Rf phases for first and second beam passage through the linac sections L1 (top) and L2 (bottom) as needed for energy recovery. Note that in L2 the separation in phase between first and second passage is $\pi - \Delta\psi$, where $\Delta\psi$ accounts for the difference in the pathlength between first and second passage through the BC magnetic chicane.

114 tively; L_B is the dipole length and L_1 the separation between first-to-second
 115 and third-to-fourth dipole.

116 Suppose the overall machine pathlength is adjusted so that $\phi_{L1}^{II} = \phi_{L1}^I + \pi$.
 117 The phase experienced by the beam during its second passage through L2
 118 will be shifted by $\Delta\psi = k_{\text{rf}}|\Delta z|$, i.e. $\phi_{L2}^{II} = \phi_{L2}^I + \pi - \Delta\psi$, where k_{rf} denotes
 119 the rf wavenumber, see bottom picture in Fig. 2. The condition for energy
 120 recovery, $\cos \phi_{L2}^{II} = -\cos \phi_{L2}^I$, then requires

$$\phi_{L2}^I = \frac{\Delta\psi}{2} > 0. \quad (3)$$

121 Notice the positive sign of the phase, countering the (positive) energy chirp
 122 on the beam emerging from the compressor (in our conventions, the bunch
 123 head is at $z < 0$ and positive energy chirp corresponds to the electrons in
 124 the bunch tail having larger energy). Here we have been assuming $\Delta\psi < \pi$.

125 For possible rf control issues when the the first- and second-pass beams
 126 are not exactly π apart in phase see Ref. [19].

Additional magnetic chicanes could be accommodated in principle but it is clear from the above observation that multi-stage magnetic compression becomes somewhat unnatural as the positive sign of ϕ_{L2}^I will tend to ‘de-chirp’ the beam while a positive chirp needs to be maintained for further compression. Multi-staged magnetic compression is not precluded but comes with additional constraints making it less desirable. Fortunately, a single-stage compression may be adequate – an important point made in the following sections – and even preferable (reduced sensitivity to the microbunching instability and smaller machine foot-print).

Although we specialized our discussion to the case $E_{BC}^I \leq (E_f + E_i)/2$, we should note that, in principle, E_{BC}^I can be higher, up to $E_{BC}^I = E_f$.

We propose to operate the machine with a positive setting of the momentum compaction through both arcs ($R_{56}^{\text{arcs}} > 0$) to stretch the bunches, reversing the bunch-length compression occurred in the BC ($R_{56}^I < 0$ for a standard 4-dipole chicane) and hence performing energy-spread compression. This is a critical feature to enable low-energy beam dumping thus easing beam disposal and maximizing energy recovery efficiency. Nonlinear lattice elements in the arcs can be employed to compensate distortions to the beam longitudinal phase-space caused by collective effects and the rf waveform and further reduce the energy spread.

We envision that the FEL will operate in SASE mode with tapered undulator to increase FEL efficiency. However, the proposed configuration is, in principle, compatible with a number of possible methods (e.g. self-seeding [16], RAFEL [17, 18]) aiming at improving the radiation longitudinal coherence and therefore further increasing the FEL efficiency.

3. Machine Design Considerations

The semiconductor industry has long adopted $\lambda = 13.5$ nm as the wavelength standard for transition to EUV lithography, for which high normal-reflectivity multilayer mirrors are available. With $\lambda_u = 18$ mm undulator period and $K = eB_0\lambda_u/2\pi mc \simeq 1$ undulator parameter, this wavelength as set by the (helical) undulator radiation resonance condition

$$\lambda = \frac{\lambda_u}{2\gamma^2} (1 + K^2) \quad (4)$$

can be obtained with $E_f = 600$ MeV energy electrons and Delta permanent-magnet undulator technology [20]. This somewhat aggressive choice is the

Figure 3: Longitudinal phase space (top) and current profile (bottom) at the exit of the APEX injector (left, $E = 95$ MeV) and exit of the last section of the linac L2 (right, $E = 600$ MeV). The beam head is to the left.

160 basis for the point-design machine considered in this paper but it is only
 161 meant to represent a reasonable starting point toward a more methodical
 162 parameters optimization, which will have to account for the trade-offs be-
 163 tween FEL efficiency, machine foot-print, beam clearance in the undulators,
 164 and cost.

165 An essential enabling technology for any high-power EUV FEL is a high-
 166 brightness, high rep-rate injector. Decisive progress has recently been made
 167 and more is expected shortly: X-ray FEL quality beams have been demon-
 168 strated at Cornell University [21] out of a DC gun injector and the normal-
 169 conducting rf gun APEX program at LBNL is on track to do the same by
 170 the end of this year [22]. Primarily because of our familiarity with its de-
 171 sign, here we adopt the APEX injector in taking a first stab at estimating
 172 the performance of our proposed machine configuration and tentatively se-
 173 lect $Q=300$ pC for the bunch charge, drawing on our experience from NGLS
 174 studies [23].

175 High rep-rate injectors are designed to perform considerable compression
 176 by velocity bunching, in order to compensate for the low beam peak current
 177 at the photo-cathode demanded by operation at relatively low accelerating
 178 gradient. In the APEX injector velocity bunching is essentially completed by
 179 the exit of the first 1.3 GHz TESLA-like SC accelerating cavity downstream
 180 of the gun, at about $E \simeq 15$ MeV, setting a lower bound to the energy of
 181 the beam injected into the linac.

Figure 4: Lasing through $L_u = 26$ m undulator length. Longitudinal phase space (top), current profile (center), and energy density (bottom) at the exit of the FEL (left) and exit of the last section L2 of the linac before the dump (right). Thanks to energy-spread compression, the relative energy spread at the dump is only about a factor 2 larger than that at the FEL in spite of the much lower beam energy (~ 15 vs. 600 MeV).

182 To maximize energy recovery one of the design goals is to set the beam
 183 energy at injection and dump to be as low as possible and about the same,
 184 $E_i \simeq E_d$: this causes energy constraints at either end of the machine to have
 185 a bearing on the other.

186 On the linac entrance side an important subsystem of any ER configura-
 187 tion is the low-energy merger line funneling the beam from the injector
 188 into the accelerator proper. Space charge effects in the merger can spoil the
 189 beam emittance and require careful investigation. We do not include the
 190 merger in the beam-dynamics model discussed here but we point to numeri-
 191 cal studies [24, 10] proposing designs that exhibit modest beam brightness
 192 loss at low energy. It is possible, however, that injection energy higher than
 193 15 MeV may be needed if one insists on using relatively high-charge and
 194 peak-current beams.

195 At the other end of the machine, the minimum E_d is set by the momentum
 196 acceptance of the transfer line into the dump. The linear and nonlinear con-

Figure 5: Evolution of the beam longitudinal phase space starting from the exit of a $L_u = 26$ m FEL undulator (green) illustrating energy-spread compression. The bunch is stretched by compression factor $C^{\text{arcs}} \gtrsim 1/C^I$ as it travels through the arcs to the entrance of L1 (black). By the time it enters the compressor chicane the second time (gray), the positive chirp is reduced by passage through L1. The bunch travels through the BC for the second time without much change (the residual chirp is too small to induce significant compression) and the residual chirp is eventually taken off by the 2nd passage through L2 (red). The net result is decompression of the bunch length and beneficial compression of the uncorrelated energy spread.

tributions to the correlated part of the energy spread can be largely corrected by appropriate choice of momentum compaction and placement of sextupoles in the arcs. The largest contribution to the energy spread is the uncorrelated component originating from the lasing process, which can amount to several MeV's, depending on lasing efficiency. Fortunately, energy-spread compression through the arcs will reduce the relative energy spread of the beam at the dump to a few %'s out of $E_d \simeq 15$ MeV. For comparison, the momentum acceptance specified in the Cornell ERL PDDR [10] is ± 2.5 MeV on a $E_d \simeq 10$ MeV average energy beam. The ambitious and attractive goal of keeping the electron energy of the dumped beam below the threshold for photon-neutron production in the dump material (about 12.5 MeV for Al [25]) may be feasible but the trade-off with beam quality would have to be carefully examined.

In contrast to FEL applications to science, which generally place a premium on a small radiation-pulse bandwidth, application to lithography poses a relatively lenient requirement set by the radiation bandwidth (about 2% FWHM) of normal-incidence reflectivity in available multilayer mirrors. We can, and should, take advantage of this relatively wide margin to allow for some correlated energy spread on the beam in the undulator. Broadening of

Table 1: Beam nominal energy at selected points.

energy	E_i	E_{BC}^I	E_f	E_{BC}^I	E_d
MeV	15	250	600	365	15

the radiation bandwidth will occur without significant penalty on FEL efficiency as long as the spread associated with the chirp over a few cooperation lengths remains somewhat smaller than the FEL Pierce parameter ρ_{3d} .

Tolerance for a relatively large correlated beam energy spread has several benefits: it relaxes the specs for the momentum compaction in the BC needed for compression (allowing for a reduced chicane foot-print and/or lessening the impact of Coherent Synchrotron Radiation (CSR) on the emittance) and it permits efficient use of the linac downstream of the BC (*i.e.* no need to operate the linac section L2 off-crest to compensate the energy chirp or employ unconventional means to control the energy chirp, [26]).

An important design parameter is the bunch-length compression factor. While higher peak currents increase FEL efficiency (everything else being equal) and thus favor higher compression, excessive compression degrades the beam by enhancing collective effects and may be counterproductive. Compression is also limited by the maximum tolerable energy chirp and acceptable linac rf phases and BC momentum compaction. We propose a working solution with 500 A peak current at the FEL, obtainable with about a factor 10 velocity bunching compression in the high repetition rate injector and a factor 10 magnetic compression. Setting $E_{BC}^I = 250$ MeV, the desired compression can be achieved in a single-stage magnetic compression with $R_{56}^I = -85$ mm and modest dephasing ($\phi_{L1}^I \sim -20^\circ$) in L1, while operating HL in rf trough ($\phi_{HL}^I = -180^\circ$) during the first beam passage.

For the rf structures we adopt TESLA-like 1.3 GHz accelerating and third-harmonic 3.9 GHz linearizing SC cavities. We should point out that while CW cryomodules accommodating these structures are presently under development for the LCLS-II project [29], higher-current operations would require further design work [10]. In contrast, JLab-style 1.5GHz SC structures have already been demonstrated in ERL FEL operations at high current but no associated harmonic cavities are presently available.

In our model machine we do not make provisions for a laser ‘heater’, the conventional method to control the microbunching instability in established EUV and x-ray FELs [27]. Thanks in part to use of single-stage magnetic compression [28] and a mode of lasing that does not involve seeding we expect

Table 2: Selected beam/machine parameters

Bunch charge	Q	300 pC
Inj. peak current	I_i	45 A
Inj. rms emittance	$\gamma\epsilon_\perp$	0.6 μm
BC dipole bend angle (1 st passage),	θ^I	95.5 mrad
BC max. dispersion (1 st passage),	η_x^I	0.45 m
BC mom. compaction (1 st passage),	R_{56}^I	-85 mm
BC compression (1 st passage),	C^I	11
BC dipole bend angle (2 nd passage),	θ^{II}	65.4 mrad
BC max. dispersion (2 nd passage),	η_x^{II}	0.31 m
BC mom. compaction (2 nd passage),	R_{56}^{II}	-40 mm
BC compression (2 st passage),	C^{II}	1.2
Arcs mom. compaction	R_{56}^{arcs}	112 mm
Arcs compression,	C^{arcs}	0.11

249 a small, if any, disruption (see our preliminary analysis in Appendix A). In
250 case it turned out to be a problem, there would be an incentive to explore
251 non-conventional ways to control the instability (e.g. [35]) and avoid the
252 complication and cost of the laser-heater system needed for a high rep-rate
253 beam.

254 Finally, we emphasize that all the parameters and design choices pre-
255 sented here should be revisited and undergo a methodical optimization before
256 a robust machine design can be established.

257 4. FEL efficiency and management of beam energy spread

258 4.1. Beam acceleration and lasing

259 We tested the machine point-design introduced in Sec. 3 with a numerical
260 model including *elegant* [30] macroparticle simulations for the beam accel-
261 eration and transport (see Tables 1-3) and Genesis [31] simulations for the

Table 3: Nominal linac parameters.

	L1	HL	L2
Voltage, V (MV)	273.3	20	368
1 st beam passage phase, ϕ^I (deg)	-21.7	-180	17.6
2 nd beam passage phase, ϕ^{II} (deg)	158.3	0	162.4

Figure 6: Beam images at the exit of the last section of linac L2 (before the dump) showing the benefit of larger energy-spread compression compared to Fig. 4. A larger energy-spread compression is accomplished by operating L2 closer to rf crest (and with higher E_{BC}^I in order to meet the ER condition, see Appendix B).

lasing process. We should point out at the outset that the numerical model we employ here is incomplete. We believe, however, that it is adequate for a first pass at estimating two critical performance metrics: achievable FEL efficiency and energy spread of the beam after deceleration.

For the beam injected into the linac we use results from ASTRA [32] simulations of the APEX injector for NGLS [33]. The longitudinal phase space of the beam at the exit of the APEX injector is shown in Fig 3, left; the beam energy is $E = 95$ MeV. In the *elegant* simulations we adjusted the nominal settings of L1 during first passage, Table 3, to accept the beam at this energy. As mentioned, we do not include the effect of the merger and make the assumption (which will have to be carefully verified) that a merger can be designed to induce a small effect on the beam emittance. The beam is tracked through the linac with inclusion of longitudinal rf wakes and CSR in the chicane. Upon a careful choice of the Twiss functions, the horizontal projected rms emittance (normalized) grows to an acceptable $\varepsilon_{nx} \simeq 1 \mu\text{m}$

Figure 7: Progression of the radiation pulse energy along the undulator (red); 1 mJ energy, corresponding to 0.5% FEL efficiency, is reached after about 26 m. In green is the bunching at the radiation wavelength.

277 through the compressor, with the vertical emittance remaining about un-
 278 changed $\varepsilon_{ny} \simeq 0.6 \mu\text{m}$.

279 At the exit of L2 (Fig. 4, left pictures) the macroparticle beam file is
 280 dumped and sampled by Genesis for the simulation in the FEL. The par-
 281 ticles are sampled into slices which are separated by 135 nm (10 radiation
 282 wavelengths). Propagation of the particles from L2 to the entrance of the
 283 undulator is done in linear approximation.

284 The FEL part of the beamline is taken to consist of up to 20 helical 2.16 m
 285 long undulator sections, each one with a period of 18 mm and consisting of
 286 120 periods. The largest value for the magnetic field on axis is 0.616 T. For
 287 a Delta design this should allow for a 7 mm magnetic gap.

288 The breaks between sections are 0.72 m long, corresponding to a 75%
 289 filling fraction. In the simulations the undulators are assumed to have equal
 290 focusing in both planes for a nearly uniform beta function of 5.3 m. In cases
 291 where the focusing would not be completely symmetric (for example simple
 292 planar undulators), a quadrupole with modest field strength could be added
 293 between each undulator section for comparable optics. Stronger quadrupoles
 294 could be used to produce smaller beta functions for improved performance.

295 Each undulator section has a uniform field strength, and the tapering oc-
 296 curs on a section-by-section basis. The undulator parameter starts at 1.034
 297 in the first five undulator sections and then decreases with a quadratic de-
 298 pendence to 0.9 in the last undulator section. For a fixed wavelength of 13.5
 299 nm, the tapering is designed to track an electron energy which evolves (for

Figure 8: The spectrum of the radiation pulse (green) as observed at the $L_u = 26$ m point along undulator fits comfortably within the width of the maximum normal-angle reflectivity of a multilayer Mo/Si mirror (red).

300 $s > s_0 = 14$ m) as

$$E_{\text{res}} = E_f - a_1(s - s_0) - a_2(s - s_0)^2 \quad (5)$$

301 with $a_1 = 0.6$ MeV/m and $a_2 = 0.008$ MeV/m².

302 The gain length in the core of the beam is roughly 0.5 m, and the bunching
 303 reaches its peak value after about 14 m. Because this is a SASE FEL, the
 304 bunching parameter steadily declines after 18 m, dropping by about a factor
 305 of 2 every 5 m. By 43 m the radiation barely interacts with the electron
 306 beam.

307 The evolution of the pulse energy and rms bunching parameter (weighted
 308 by the beam current) is shown in Fig. 7. The spectrum after 26 m, where the
 309 pulse energy is over 80% of the final value, is given in Fig. 8. The full width
 310 of the spectrum fits in the region of high reflectivity close to the maximum
 311 ($\sim 70\%$) of Mo/Si multilayer mirrors optimized for 13.5 nm [34].

312 4.2. Beam recirculation

313 We model recirculation of the beam from the exit of the FEL back to the
 314 entrance of L1 in a simplified way, by applying a transfer map consisting of a
 315 linear part and the single T_{566} nonlinear term. We adjusted R_{56} and T_{566}
 316 in the map empirically to optimize energy-spread compression and minimize the
 317 beam energy spread. Some of the energy spread is contributed by collective
 318 effects. We attempted to account for the effect from CSR in the arcs by

lumping together the contribution from each of the two arcs into discrete kicks (two per arc), using the steady-state model for CSR.

The smallest residual energy spread was found by setting $R_{56}^{\text{arcs}} \simeq 112$ mm, reasonably close to the value predicted by Eq. (B.10) in Appendix B for compensation of the linear chirp at the dump, with no need to introduce a significant nonlinear term T_{566} . In general, once the correlated part of the energy spread has been corrected we expect the slice relative energy spread at the FEL ($\sigma_{\delta,\text{f}}$) to evolve to

$$\sigma_{\delta,\text{d}} \simeq \sigma_{\delta,\text{f}} C^{\text{arcs}} C^{\text{II}} \frac{E_{\text{f}}}{E_{\text{d}}} \quad (6)$$

at the dump, where C^{arcs} and C^{II} are the bunch-length compression factors through the arcs and second passage through the BC chicane; $\sigma_{\delta,\text{d}}$ remains modest if C^{arcs} is sufficiently small (typically C^{II} will be close to unity).

The longitudinal phase space, current profile, and energy density at exit of the FEL and L2 (second beam passage, right before the dump) are shown in Fig. 4 (right pictures) for a $L_u = 26$ m long undulator. The energy spread observed on the beam at the dump is about 2% rms ($\sim 8\%$ full width). We can appreciate the effectiveness of energy-spread compression: in spite of the much lower beam energy (~ 15 vs. 600 MeV) the relative energy spread at the dump is only two times larger than that at the FEL. See Fig. 5 for an illustration of the energy-spread compression process.

It is possible in principle to augment the energy-spread compression and further reduce the beam energy spread by modifying the machine design and let the linac section L2 be operated closer to rf crest, Eq. (B.10). Because of the ER timing constraint, this requires setting a higher beam energy at the bunch compressor (first beam passage), Eq. (2) and (3). For an illustration of the effect, see Fig. 6, obtained with $\phi_{L2}^I \simeq 5^\circ$ (instead of $\phi_{L2}^I \simeq 17.6^\circ$) corresponding to $\phi_{L2}^{\text{II}} \simeq 175^\circ$ and $E_{BC}^I = 295$ MeV. Compensation of the linear chirp at the dump is achieved with almost a factor two larger energy-spread compression ($R_{56}^{\text{arcs}} = 172$ mm), thus reducing the rms energy spread to about 1%. However, to capture the full benefit of larger energy-spread compression some control of the nonlinear chirp becomes necessary ($T_{566} = -8$ m). We should note that, for simplicity, in generating the pictures of Fig. 6 we kept $E_{BC}^I = 250$ MeV while changing the rf phase during second passage through L2 – this is inconsistent with ER but adequate to model the intended effect on the beam.

Table 4: FEL parameters

u-period λ_u	18 mm
u-parameter K (max.)	1
u-length L_u	26 m
gain length L_g	~ 0.5 m
3D Pierce parameter $\rho_{3d} = \lambda_u / (4\pi\sqrt{3}L_g)$	1.6×10^{-3}
Avg. beta functions $\beta_x = \beta_y$	5.3 m
FEL efficiency η	0.5 %

353 5. Discussion

354 In summary, we have shown that a straight topology FEL in the EUV,
355 capable of lasing efficiency in the excess of 0.5% is compatible with energy
356 recovery. A key enabling feature is energy-spread compression, making low-
357 energy dumping of the spent beam possible. Our numerical results are based
358 on a 300 pC/bunch beam model, including the realistic dynamics through a
359 high rep-rate photo-cathode gun injector, as needed to support a high beam
360 average-power machine.

361 The model employed has some limitations: an important component (low-
362 energy merger) was not included and we have not worked out in detail the
363 lattice for beam transport of the recirculating beam from the FEL to the
364 dump in order to verify the attainment of the necessary momentum accep-
365 tance and dispersion control. However, we can invoke existing studies and
366 experience from operating machines to argue that these missing elements
367 should not pose insurmountable difficulties.

368 With a 0.5% efficiency, 30 kW radiation output in the desired bandwidth
369 is obtained with a 6 MW average beam power. For 600 MeV electron energy,
370 this translates into 10 mA average beam current, comparable to values al-
371 ready demonstrated at JLab [7], albeit at a smaller (~ 1 MW) beam power.
372 With 300 pC/bunch charge this current requires a 33 MHz repetition rate,
373 which can be supported by either a DC or the APEX VHF (186 MHz) gun.

374 Although a factor ten smaller than the target in the most advanced ERL
375 R&D programs (e.g. [10]), a 10 mA average beam current remains an ambi-
376 tious goal, particularly in an industrial setting (beam losses, machine protec-
377 tion, photo-cathode lifetime, machine reliability, etc.). In our study we have
378 found no fundamental beam-physics impediments to the goal of obtaining an
379 FEL efficiency suitable for a multi-kW power EUV source but other effects

not considered here (BBU instabilities, ion instabilities, scattering phenomena, beam halo, sensitivity to jitters and errors, etc.) should be looked at with care before reaching a definitive conclusion. In particular, the narrowing of the beamline aperture through the harmonic cavities is likely to pose a challenge to the management of the beam halo and containment of particle losses.

Our results assume a reasonable but likely not optimal choice of design parameters, which ultimately should seek to balance performance, risk, and cost. For example, a higher beam energy would allow for a larger undulator gap and ease concerns about beam control. The choice of beam energy at the bunch compressor chicane is also amenable to optimization: the desire to reduce the demand on the linearizer voltage (favoring lower energy) should be weighted against the advantages of a possible reduction of emittance growth from CSR and more aggressive energy-spread compression permitted by operation of the last linac section closer to rf crest. Similarly, the feasibility of dumping the electrons at energy below threshold for photo-neutron production should be closely investigated as well as the merit of operating with lower charge/bunch (including consideration of optics damage).

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Appendix A. Estimate of the microbunching instability

Microbunching is mostly driven by longitudinal space charge (LSC) in the accelerator section upstream of the BC and develops as the beam experiences dispersion in the BC magnetic chicane. It exhibits a spectrum peaked at wavelength $\lambda_{\text{main}} \simeq 2\pi|R_{56}|\sigma_{\delta,bc}$ where R_{56} is the BC chicane momentum compaction and $\sigma_{\delta,bc}$ the slice energy spread of the beam entering the chicane. LSC in the linac downstream of the compressor induces an energy modulation with dominant wavelength λ_{main} , which can be harmful to the lasing process.

We estimate the linear gain $g(k)$ of the instability through the BC chicane with a model that assumes gaussian slice energy spread distribution and an effective impedance to describe the impact of LSC on the beam

$$g(k) = \frac{4\pi I_i}{\gamma_{BC} I_A} k |R_{56}| e^{-k^2 R_{56}^2 \sigma_{\delta,bc}^2 / 2} \int_{s_i}^{s_{bc}} \frac{|Z(k)|}{Z_0} ds, \quad (\text{A.1})$$

where $R_{56} = R_{56}^I$, I_i is the injected beam peak current, $I_A = 17$ kA the Alfven current, and $Z_0 = 120\pi$ the vacuum impedance. For the LSC impedance we adopt the model [37], $Z(k) = i[Z_0/(\pi k r_b^2)][1 - 2I_1(\xi)K_1(\xi)]$ with $\xi = k r_b / \gamma$, where $r_b \simeq 1.7(\sigma_x + \sigma_y)/2$ is an effective transverse beam size. In the equation above k represents the wave number of density perturbations as seen in the beam *after* compression. We simplify the model further by assuming uniform acceleration between the injection point into the linac (s_i) and the bunch compressor (s_{bc}) and uniform beta-functions $\beta_x = \beta_y$. The gain is particular sensitive to the slice energy spread. In the absence of the laser heater we expect the slice energy spread to be dominated by intrabeam scattering.

Established IBS models [38] predict $\sigma_E \simeq 2$ keV by the time the beam reaches the BC. Using this value in our estimate we obtain a gain curve with $g \simeq 200$ peak at about $\lambda_{\text{main}} \simeq 50$ μm .

Assuming that the instability is primarily seeded by shot-noise, the resulting rms energy spread observed at the entrance of the FEL is

$$\sigma_\delta = \frac{4}{\gamma_f} \sqrt{\frac{\pi I r_c}{I_A}} \left[\int_0^\infty dk \left| g(k) \int_{s_{\text{bc}}}^{s_f} \frac{Z(k)}{Z_0} ds \right|^2 \right]^{1/2}, \quad (\text{A.2})$$

where now the integration extremes are the exit of the BC and entrance of the FEL, and r_c is the electron classical radius.

We find $\sigma_\delta \simeq 3 \times 10^{-4}$. If this were the width of a truly uncorrelated slice energy spread, the microbunching effect could be immediately dismissed as too small to matter ($\sigma_\delta \ll \rho_{3d} = 1.6 \times 10^{-3}$). However, because this spread is largely due to a relatively well defined modulation at λ_{main} , one may worry about the effect of micro E/z correlations. To model the latter, we repeated the *Genesis* simulations after applying a $\lambda = 50$ μm energy modulation with 150 keV amplitude to the beam. We found an FEL efficiency loss on the order of 10%, which is within the magnitude of run-to-run fluctuations.

The model used here is rough and tends to overestimate the effect of the microbunching instability. However, as a disclaimer we should add that we neglected the possible contribution from the injector, which may not be negligible when velocity bunching compression is large [36]. High-resolution numerical simulations [37] would be needed to confirm the validity of our conclusions.

Appendix B. Evolution of the linear energy chirp

The beam relative energy chirp h is defined as the correlation between the bunch particles relative energy δ and the longitudinal coordinate. Formally, $h = \langle z\delta \rangle / \sigma_z^2$, where $\langle \cdot \rangle$ is the average over the bunch population and σ_z is the rms bunch length. First, consider the case of negligible collective effects, FEL turned off (or very small FEL efficiency), and vanishing uncorrelated energy spread.

Assuming negligible correlations in the injected beam, the linear part of the relative energy chirp of the beam at the entrance of the bunch compressor (first beam passage) is

$$h_{\text{BC}}^I = -k_{\text{rf}} \frac{V_{L1}}{E_{\text{BC}}^I} \sin \phi_{L1}^I > 0. \quad (\text{B.1})$$

529 The sign follows from the choice $\phi_{L1}^I < 0$ so as to have a bunch-length
 530 compression factor $C^I = (1 + h_{BC}^I R_{56}^I)^{-1} > 1$. After compression the linear
 531 relative energy chirp becomes $C^I h_{BC}^I$ and observed at the entrance of the
 532 FEL

$$h_f = C^I h_{BC}^I \frac{E_{BC}^I}{E_f} - k_{rf} \frac{V_{L2}}{E_f} \sin \phi_{L2}^I. \quad (B.2)$$

533 In the situation of interest where the compression factor C^I is much larger
 534 than unity, the second term on the RHS of the above equation is generally
 535 small even for relatively large phase ϕ_{L2}^I and can be neglected.

536 The chirp seen at the exit of the return line right before the beam enters
 537 L1 again is

$$h_{arcs} = C^{arcs} h_f \quad (B.3)$$

538 and becomes

$$h_{BC}^{II} = C^{arcs} h_f \frac{E_f}{E_{BC}^{II}} - k_{rf} \frac{V_{L1}}{E_{BC}^{II}} \sin \phi_{L1}^{II}, \quad (B.4)$$

539 at the entrance of the BC (second passage), where $C^{arcs} = (1 + h_f R_{56}^{arcs})^{-1} < 1$
 540 is the compression through both recirculation arcs. This is less than unity
 541 as both the chirp at the FEL and momentum compaction through the arcs
 542 are positive, $h_f > 0$ and $R_{56}^{arcs} > 0$.

543 Using $\sin \phi_{L1}^{II} = -\sin \phi_{L1}^I$, Eq. (B.1), and the expression for the compres-
 544 sion factor through the BC, Eq. (B.4) becomes

$$h_{BC}^{II} = h_{BC}^I \frac{E_{BC}^I}{E_{BC}^{II}} (C^{arcs} C^I - 1). \quad (B.5)$$

545 As one may have expected, this equation indicates that we can remove the
 546 linear chirp by the exit of the chicane the second time around, $h_{BC}^{II} = 0$, if
 547 compression through the arcs is set to undo the compression from the chicane
 548 during first beam passage, $C^{arcs} = 1/C^I$. This condition is realized if

$$R_{56}^{arcs} = |R_{56}^I| \frac{E_f}{E_{BC}^I} \frac{C^I}{C^I - 1} \simeq |R_{56}^I| \frac{E_f}{E_{BC}^I}, \quad (B.6)$$

549 with the approximation in the RHS term valid for large C^I . Finally, the
 550 chirp at the exit of the linac into the dump reads

$$h_d = C^{II} h_{BC}^{II} \frac{E_{BC}^{II}}{E_d} - k_{rf} \frac{V_{L2}}{E_d} \sin \phi_{L2}^I, \quad (B.7)$$

551 where $C^{II} = (1 + h_{\text{BC}}^{II} R_{56}^{II})^{-1}$ is the compression factor for the beam second
 552 passage through the chicane and we used $\sin \phi_{L2}^{II} = \sin \phi_{L2}^I$, from the ER
 553 timing condition. Notice that the second term on the RHS in general cannot
 554 be neglected unless the phase ϕ_{L2}^I is very small. In order to compensate for
 555 this term and make the energy chirp h_d vanish, we need to allow for a small
 556 positive h_{BC}^{II} . From (B.5), this implies that C^{arcs} should be somewhat larger
 557 than $1/C^I$ and therefore R_{56}^{arcs} somewhat smaller than (B.6).

558 If lasing efficiency is large, the ensuing uncorrelated energy spread $\sigma_{\delta,f}$
 559 cannot be neglected and the linear energy at the exit of the return line is
 560 more accurately written as

$$h_{\text{arcs}} = \frac{h_f \sigma_{z,f}^2 (1 + h_f R_{56}^{\text{arcs}}) + \sigma_{\delta,f}^2 R_{56}^{\text{arcs}}}{\sigma_{z,f}^2 (1 + h_f R_{56}^{\text{arcs}})^2 + \sigma_{\delta,f}^2 (R_{56}^{\text{arcs}})^2}. \quad (\text{B.8})$$

561 In the limit $\sigma_{\delta,f} \rightarrow 0$ we recover (B.3). In the opposite limit, where $\sigma_{\delta,f}$ is
 562 large compared to the correlated part of the energy spread $\sigma_{\delta,f} \gg h_f \sigma_{z,f}$, we
 563 have

$$h_{\text{arcs}} \simeq \frac{\sigma_{\delta,f}^2 R_{56}^{\text{arcs}}}{\sigma_{\delta,f}^2 (R_{56}^{\text{arcs}})^2} = \frac{1}{R_{56}^{\text{arcs}}}. \quad (\text{B.9})$$

564 With this, we can write a compact expression for the momentum com-
 565 paction in the arcs required to cancel the linear chirp ($h_d = 0$):

$$R_{56}^{\text{arcs}} \simeq |R_{56}^I| \frac{E_f}{E_{BC}^I} \frac{1}{1 + k_{\text{rf}} |R_{56}^I| \frac{E_f - E_{BC}^I}{E_{BC}^I} \tan \phi_{L2}^I}. \quad (\text{B.10})$$

566 From Eq. (6) we observe that to reduce the slice energy spread of the
 567 dumped beam most effectively, the condition $h_d = 0$ should be realized with
 568 a C^{arcs} that is as small as possible. Because $C^{\text{arcs}} \sim \sigma_{z,f} / (R_{56}^{\text{arcs}} \sigma_{\delta,f})$ is inversely
 569 proportional to R_{56}^{arcs} , then R_{56}^{arcs} should be large (maximum stretching of the
 570 beam compatible with removal of the linear chirp). With the other relevant
 571 parameters kept fixed, Eq. (B.10) indicates that a smaller C^{arcs} results from
 572 operating L2 closer to crest, *i.e.* $\tan \phi_{L2}^I \rightarrow 0$. In the limit $\phi_{L2}^I \rightarrow 0$, we find
 573 $R_{56}^{\text{arcs}} \simeq |R_{56}^I| E_f / E_{BC}^I \simeq 2 R_{56}^I$, in agreement with (B.6). (Note that E_{BC}^I in
 574 (B.10) is a function of ϕ_{L2}^I through (2) and (3).)