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A non-conventional ERL configuration for high-power EUV FELs

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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.

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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 [2–5]. 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.

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

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

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

It is not our goal here to make a detailed comparison of advantages and limitations of the two machine solutions. Instead, we would like to point out the merits of a hybrid configuration, Energy Recovery with Straight Topology (ER-ST) FEL, that has the potential of reaping the benefits of both while for the most part avoiding their main drawbacks. The idea is to combine energy recovery with a ST FEL, i.e. to circulate the spent, rather than the fresh, beam. All necessary beam manipulations needed for 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 [13–15] in the first incarnation of the ER-FEL program (IR-Demo),

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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 Section 3 we illustrate the machine point design then used in Section 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 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^I_{BC} and E_f respectively. After lasing the beam circulates along a return line, passes the BC for the second time at energy $E^{II}_{BC}=E_f-(E^I_{BC}-E_i)$ 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

$$\cos\phi^{II} = -\cos\phi^I. \tag{1}$$

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 ERL FEL configuration where transport though 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, $E^{II}_{BC}=E^I_{BC}=(E_f+E_i)/2$, 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^I_{L2} is compatible with energy recovery, with a positive value providing some measure of control over the energy chirp and $\phi^I_{L2}\simeq 0$ 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 $E^I_{BC}=(E_f+E_i)/2$ will tend to be relatively high, forcing a larger requirement on the linearizer voltage, which roughly scales as E^I_{BC}.

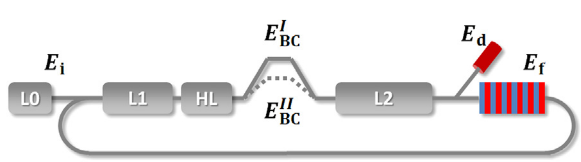

Fig. 1. Schematic of the ER-ST FEL configuration (not to scale), in which the beam is circulated after lasing. Indicated are the main accelerator sections, a magnetic chicane compressor (BC), the FEL undulator, dump, and the beam energy at selected points. The second time it passes through BC the beam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

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

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

where θ_I and $\theta_{II}=\theta_I E^I_{BC}/E^{II}_{BC}$ are the bend angles in the magnetic chicane dipoles as experienced by the beam during its first and second passage respectively, L_B is the dipole length and L_1 the separation between first-to-second and third-to-fourth dipole.

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

$$\phi^I_{L2}=\frac{\Delta\psi}{2}>0. \tag{3}$$

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

For possible rf control issues when the first- and second-pass beams 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^I_{L2} 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

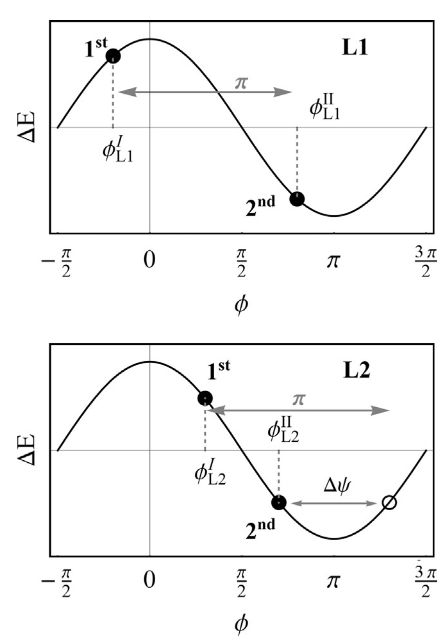

Fig. 2. Rf phases for first and second beam passage through the linac sections L1 (top) and L2 (bottom) as needed for energy recovery. Note that in L2 the separation in phase between first and second passage is $\pi-\Delta\psi$, where $\Delta\psi$ accounts for the difference in the pathlength between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