INVERSE FREE ELECTRON LASERS FOR ADVANCED LIGHT SOURCES

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Abstract

Laser accelerators hold the promise for high gradient acceleration and production of ultra short electron bunches. Among these, the inverse free-electron laser has recently demonstrated to be a mature and reliable scheme ready to step up from successful proof-of-principle experiments to cutting-edge applications. The very high gradient and the multi kAmp peak current of the output beam make it an attractive option in the hundreds of MeV to few GeV energy region. We examine the feasibility of using an IFEL driven by an high power Ti:Sa laser source to generate soft x-rays by FEL interaction in an undulator. A control of the slippage of the radiation over the ultrashort spikes of the IFEL-microbunched beam current is implemented to increase the gain and maintain the 200 as-long pulse structure in the radiation profile.

INTRODUCTION

While the wall plug efficiency of laser based accelerators still falls short of the requirements needed to cost-effectively build a high energy physics linear collider, high-gradient, short-wavelength advanced accelerator schemes are an attractive option to produce electron beams suitable to drive 4th generation x-ray lasers where one can choose peak brightness over average brightness. The small transverse emittances and high peak currents of current conventional radiofrequency based designs [1, 2] are within the reach of advanced state-of-the-art laser based accelerators. The requirements on the beam relative energy spread (less than few thousandths) could be tougher to satisfy but the progress in the experimental results in these last few years [3] brings closer to reality an advanced accelerator driven x-ray laser with an attractive reduction of the footprint and henceforth of the costs of such machines.

Among the various advanced accelerator schemes, the inverse free-electron laser (IFEL) is one of the most promising and well understood in terms of control of longitudinal phase space, trapping efficiency and final energy spread [4]. Using a high power laser and a properly designed undulator the IFEL has recently demonstrated accelerating gradients superior to conventional rf accelerators and very high energy gains [5]. Moreover, the IFEL is a far-field vacuum acceleration scheme which preserves the beam emittance through acceleration and it is in principle free of optics damage threshold limitations. Finally, the energy transfer mechanism, just the inverse of the well known FEL principle at the basis of the last generation light source facilities, is very efficient and one can design undulators able to transfer more than 75 % of optical power to beam power [6]. The final efficiency is in fact only limited by the wall-plug to optical conversion efficiency which for common high power laser systems is still quite low (below 1 %).

Even though many limitations arise when one considers the IFEL for multi-GeV energies mostly due to the synchrotron radiation losses from the wiggling electron trajectories, the tremendous progress and commercial availability of ultrahigh power laser sources makes the IFEL scheme a very feasible and convenient choice in the hundreds of MeV to few GeV energy, which is just the energy region for x-ray FEL drivers.

The detailed control over the electron beam longitudinal phase space obtainable with the interaction of a powerful laser and relativistic electrons passing through an undulator has already captured the interest of FEL physicists. In fact the IFEL mechanism in its not-accelerating prebunching version has been already proposed to be used at LCLS to enhance the SASE characteristics (ESASE). The short high current spikes obtained converting the IFEL-induced energy modulation into density modulation at the scale of the optical wavelength are foreseen to shorten the undulator distance needed to reach saturation and to produce sub femtosecond X-ray pulses [7].

In this paper we conjugate the advantages of using an IFEL as a prebuncher with its high gradient capabilities to design a soft X-ray source based on an IFEL accelerator. The design aims at producing coherent radiation in the so called water window region of the electromagnetic spectrum (λ = 3-4 nm) and it is tailored on the SPARC linac which is a state-of-the-art injector delivering a high brightness electron beam at 200 MeV energy in its final stage of construction at Frascati [8].

IFEL DESIGN

In Table 1 we report the input parameters considered for the IFEL design.

The electron beam input parameters like energy, energy spread and peak current are the nominal values of the SPARC linac [9]. In this design exercise we have considered to use a portion (20 TW out of 100 TW) of the high power laser foreseen to be installed in the same experimental area of the high brightness injector [10]. The ratio between the laser rayleigh range and the undulator length has been set to maximize the integrated gradient and so the final energy gain [11]. The choice for the IFEL coupling is

Table 1: IFEL input parameters

parameter	fixed value
Energy	210 MeV
Energy spread	0.5 %
Current	1 kA
Wavelength	800 nm
Peak Power	20 TW
Wiggler length	2 m
wiggler gap	7 mm
Rayleigh range	0.2 m
Waist position	1 m

a permanent magnet helical undulator. The particle transverse velocity is always different than zero and parallel to the electric field of a circularly polarized laser (easily obtainable from a linearly polarized pulse, using a high power quarterwave plate) so that the energy transfer mechanism between photons and electrons is always turned on. The undulator gap is set to 7 mm in order to be able to propagate without clipping along the undulator length both the laser and the electron beam. To ensure feasibility of the undulator construction, the Halbach relation

$$B_{max} = 1.79 e^{-\lambda_w/g} [Tesla] \tag{1}$$

which yields the maximum attainable magnetic field amplitude for a given gap g and period λ_w has been used as an upper bound for the magnetic field. [12]. The optimized variations for period and field amplitude are reported in Fig. 1a. The resulting resonant energy

$$\gamma_r = \sqrt{\frac{\lambda_w(1+K^2)}{2\lambda}} \tag{2}$$

along the helical undulator is also shown (Fig. 1b). In (2) K is the normalized peak magnetic field amplitude and λ is the driving laser wavelength.

In order to guarantee an high quality final longitudinal phase space for the accelerated beam the ponderomotive resonant phase is varied along the undulator. In Fig. 2 we show the longitudinal phase space and its projection on the energy and time axis obtained tracking particles through the undulator and laser electromagnetic fields with the 3D IFEL code `TREDI`[13]. At the beginning the resonant phase is close to zero to improve capture efficiency while later in the undulator after the particles have been already captured and bunched its value grows to $\pi/3$ to maximize the accelerating gradient and reduce the final energy spread. The latter in particular is one of the most sensitive parameters for a 4th generation light source driver. The stable accelerating region of phasespace formed by the ponderomotive IFEL potential ensures that small variations in driving laser power and time/spatial jitter only affect the capture efficiency reducing slightly the final peak current and not the other parameters of the accelerator like final energy and

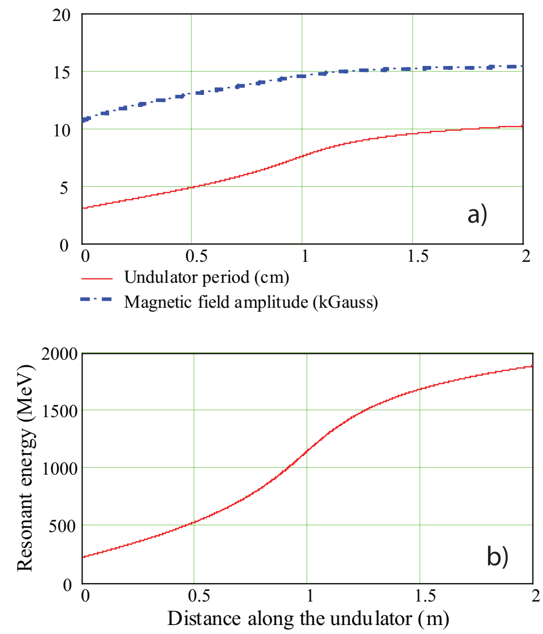

Figure 1: Variation of period and magnetic field amplitude along the undulator (a). The resonant energy is also shown (b).

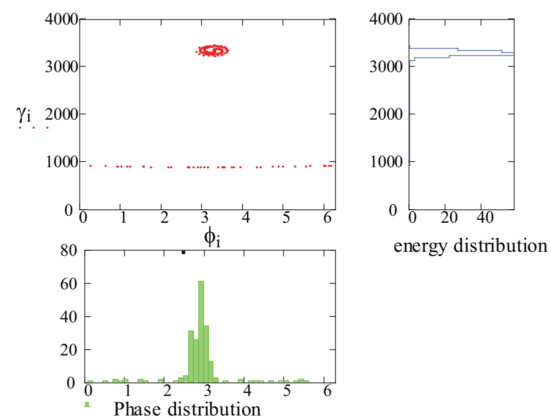

Figure 2: Simulated longitudinal phase space of the electron beam at the exit of the IFEL accelerator.

energy spread [13]. The output accelerator parameters are summarized in Table 2.

The average gradient obtained in this design is quite large, more than one order of magnitude larger than conventional rf-based designs. A length of just 2 m of undulator is sufficient to reach an energy of 1.5 GeV suitable to drive a x-ray laser at the water window wavelength (3 nm) which is the goal of our design exercise. The high peak current results from the bunching at the optical wavelength that takes place in the IFEL (see Fig. 3).

SLIPPAGE DOMINATED FEL

The undulator magnet envisioned to be used to generate the soft x-ray radiation is the same of the one being built

Table 2: IFEL output parameters

Energy	1.7 GeV
Energy spread	< 0.5 %
microbunch length	250 as
Peak current	6 kAmp
Avg. gradient	750 MeV/m

and installed for the SPARC project. The FEL parameters are reported in Table 3.

Start-to-end simulations of the entire system are performed using the output phase space from TREDI as the starting distribution in Genesis 1.3 [14]. Even though the physical mechanism of the interaction is the same along the system, it is required to use a different code to model the IFEL interaction since due to the strong tapering the period-averaged classical FEL approximation is not valid anymore, and the explicit 3d Lorentz-force equation solver is used for the particle dynamics in the simulation of the IFEL with TREDI. At the same time for the light generation section of the system, TREDI does not take into account the evolution of the electromagnetic field which has to be calculated using Genesis. The longitudinal phase space is periodic with period equal to the driving laser wavelength. The FEL simulation is performed over a window including a portion of the accelerated beam of a length such to include 6 to 8 periods of 800 nm. In Fig. 3 we show the beam parameters along the electron bunch coordinate inside the simulation window. The energy spread at the peak of the current is almost as large as the FEL ρ parameter and this degrades the interaction. Further work is needed in the optimization of the last section of the IFEL accelerator in order to minimize this effect.

The Genesis simulation result is shown in Fig. 4. The final peak power is limited to only few MW and in the longitudinal profile of the newborn radiation there is no trace of the attractive sub-fs structure of the incoming electron beam.

To explain these results, we must keep in mind that the the duration of the current spikes is only 1/10th of the optical wavelength, that is 250 attoseconds or $\sim$ 90 nm. Considering the fact that in the undulator the radiation slips one radiation wavelength each undulator period, after only 30 periods of undulator the radiation has slipped over the peak

Table 3: FEL parameters

Radiation wavelength	3 nm
Undulator period	2.8 cm
Undulator K	1.65
Periods per section	77
Number of sections	6
ρ parameter	$4.5 \cdot 10^{-3}$

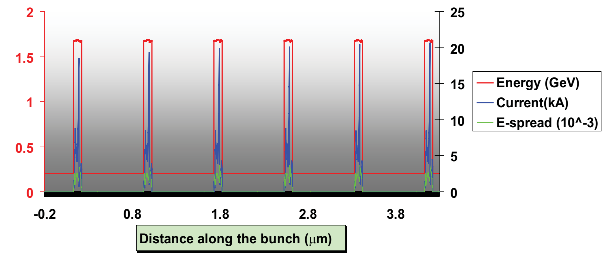

Figure 3: Electron beam current along the bunch. The current spikes are very short (250 as) and distant an optical period 2 fs between eachother.

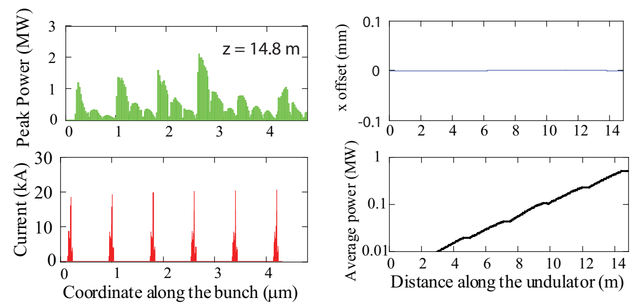

Figure 4: Output of the SASE simulation.

of its gain medium. An FEL driven by such beam would operate in a strongly slippage dominated regime. Clearly the problem is reduced if the IFEL accelerates the electron beam to higher energies enabling the production of shorter wavelength radiation. In this case in fact the length of each current spike would be the same, being fixed by the IFEL driver wavelength) and the shorter wavelength FEL radiation would experience a high gain for a larger number of undulator periods before slipping away of the high peak current region. Unfortunately the IFEL accelerator design gets more complicate for higher final energies since it requires a larger laser power and it also involves staging of two different IFEL modules. Moreover the planned extension of the SPARC photoinjector, SPARX [15], is foreseen to deliver coherent soft X-rays and user and diagnostics availability make attractive the few nm region of the electromagnetic spectrum.

One possible solution to the slippage problem is to take advantage of the microbunch train structure of the electron beam. In principle one could retard the charged particles inserting a magnetic path length between different undulator sections so that the radiation would slip faster over the electrons and take over the next high current spike at the beginning of the next undulator section. A cartoon illustration of this scheme is shown in Fig. 5. The advantage in this configuration is twofold: i) the FEL radiation only experience high gain and is amplified over the entire undulator length and ii) the magnetic chicane inserted to delay the electrons between undulator sections is a positive R_{56} element which helps the conversion of energy modulation into

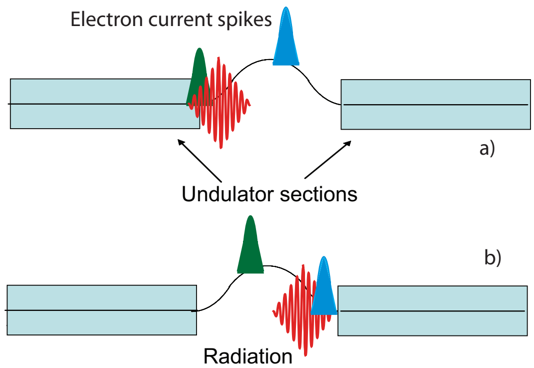

Figure 5: Schematics of chicane to compensate slippage inserted between undulator sections.

density modulation and so accelerates the microbunching process enhancing the FEL instability in a optical-klystron like configuration [16].

Without a coherent seed over all the electron bunch, on the other hand, the enhancement of the FEL interaction will not take place since the phase of the electromagnetic field and of the induced bunching starting in the different high gain high current regions is completely random being determined by the shot-noise in the electron beam. Suitable seeds at these short wavelengths are of course lacking at this time, but the strong progress in high harmonic generation in gas [17] could help in this regard. In Fig. 6 we show the results of the GENESIS simulation obtained introducing a coherent seed over the entire macrobunch length so that there is a definite phase relationship between the radiation and the bunching in the different current spikes and the FEL interaction can start constructively at the beginning of each undulator section. In the upper right corner the x-trajectory of the electron beam is represented. The bumps represent the magnetic chicanes located in between different undulator sections. The final peak power is > 1 GW and the radiation is composed by a train of sub-fs spikes locked with the 800 nm IFEL drive laser phase.

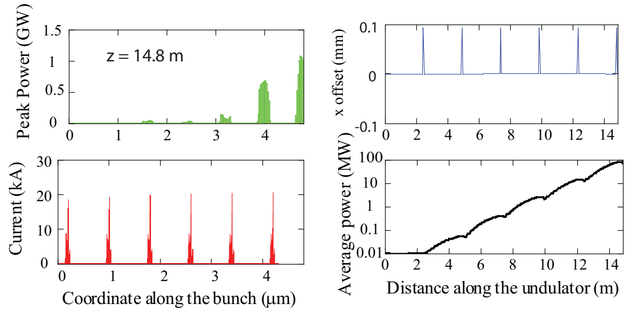

Figure 6: Output of the GENESIS1.3 simulation with a seed and with the magnetic chicanes between the undulator sections.

CONCLUSIONS

We propose the use of an inverse free electron laser to drive a 4th generation light source in the soft X-ray region of the electromagnetic spectrum. Taking advantage of the high gradient and of the precise control over the longitudinal electron beam phase space, the inverse free electron laser accelerator delivers a high current, high energy electron beam. The sub-fs structure on the current induces strong limitations due to the slippage on the FEL dynamics. If one wants to preserve the structure and increase the final power, some special precautions have to be taken. It is worthwhile to note that even if in this paper we considered the inverse free-electron laser as the advanced accelerator scheme to generate the electron beam, a similar output beam structure is likely to be found using other laser and/or plasma based accelerators. The considerations and the solutions discussed here are applicable to those cases also. Another benefit of the proposed laser driven source is the synchronization and phase-locking of the x-ray pulse with an external high power laser for pump-probe experiments.

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