Feasibility study for the hard x-ray free electron laser based on synergistic use of conventional and plasma accelerator technologies

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We access the possibility of using a conventional RF accelerator as an injector for the plasma driven wakefield accelerator. Conventional accelerators deliver high quality beams with low emittance and low energy spread. Once injected into the plasma wake, the emittance may be preserved upon proper beam matching while the energy spread may not due to long beam duration delivered by the conventional accelerator. Parameters of the overall accelerator system and the free electron laser which uses such a beam are estimated.

I. INTRODUCTION

Hard x-ray free electron lasers (XFELs) are great diagnostic tools in modern science. A number of XFELs have been constructed worldwide in the past decade [1–5]. In the past, Los Alamos National Laboratory has expressed interest in hosting a similar facility to support ongoing Programs [6]. The facility has been envisioned based on a conventional radio frequency (RF) accelerator technology. As a result, the estimated size and cost of the anticipated facility turned out to be large, which significantly decreased attractiveness of this project.

The cost and size of an XFEL are driven mostly by the cost and size of the electron linear accelerator (linac). The electron beam in an XFEL must reach the energy above 10 GeV in order to generate radiation with wavelength below 1 Å with conventional undulators. The required beam energy translates into about 1 km-long accelerator built with conventional RF technology. Advanced accelerator concepts are currently under development and may provide solution for increasing accelerating gradients by several orders of magnitude [7–10]. So far, the most mature concept is acceleration of particles in a plasma wave [7, 8].

Programs for developing FELs using the laser wakefield accelerator (LWFA) technology exist all over the world [11–17]. So far, there has been a single experimental demonstration of this concept at soft x-ray wavelengths [17]. The main challenge in adopting the LWFA technology for XFELs is yet insufficient quality of the accelerated beams [18, 19]. The accelerated electrons in LWFAs typically originate from the background plasma [20–25]. That naturally does not allow for much control over injection. As a result, injection typically happens over an extended distance rather than instantaneously and the resulting electron bunch has large energy spread.

Alternatively, plasma accelerators can accelerate electron beams produced and pre-accelerated by conventional RF accelerators [26]. The use of the RF accelerator as an injector to an LWFA is motivated by the high quality of the injected beam compared to beams produced inside plasma during self-injection. Such a scheme would take advantage of high quality beams produced in RF accelerators and fast acceleration to full energy in a strong field provided by plasma. In principle, this combination may produce high quality electron beams at high energy required for XFELs. The purpose of this paper is to explore possibility of utilizing plasma accelerator technology for XFELs. We review the current state of the art and explain challenges in achieving high enough maturation of the technology.

II. PRE-CONCEPTUAL DESIGN OF AN FEL BASED ON LASER ACCELERATOR TECHNOLOGY

In this section we put together a sample pre-conceptual design of the LWFA based on an RF injector, which is suitable for the XFELs. We focus on designing a system, which closely matches the XFEL designed for MaRIE [27, 28].

The goal is to achieve FEL lasing at photon energy of 42 keV. We assume the use of the undulator, which has already been designed for MaRIE [28]. That requires the electron beam to reach the energy of 12 GeV and peak current of 3 kA at the undulator entrance. Most of the acceleration is envisioned to happen in plasma. The uncertainty in the beam’s quality and its high energy after the LWFA stage does not allow for temporal compression of the beam prior to undulator. That implies that the electron beam needs to be fully compressed prior to injection into the LWFA. This setup allows to keep the induced energy spread at the minimum level since the bunch inside the plasma wake is short. Reaching beam current of 3 kA is a challenging task for high brightness accelerators. The MaRIE linac design was able to reach high current at energies as low as 1 GeV [27]. It is extremely difficult
to design an accelerator reaching full compression at significantly lower energy. As a result, the RF accelerator must provide acceleration for high brightness beams to the energy of ∼1 GeV with the peak current of ∼3 kA. The conventional approach to designing such systems is to implement 2-3 compressors at intermediate energies [1–5, 27]. In this paper we assume that a low energy linac section designed for MaRIE can be used to deliver the beam with required parameters.

![Diagram of the free electron laser based on the plasma accelerator technology and RF linac as injector](image)

FIG. 1. Schematics of the free electron laser based on the plasma accelerator technology and RF linac as injector

The schematics of an XFEL based on the LWFA technology and an RF injector is shown in Fig. 1. The energy of the electron beam being injected into the LWFA is high. To large degree, this concept is similar to the successive acceleration in a multi-stage LWFA. There is a strong belief in the filed that efficient injection can be implemented in a quasi-linear regime of the plasma wave [16, 29, 30]. This regime is characterized by a weakly nonlinear excited plasma wave, in contrast to the highly nonlinear regime (e.g. bubble regime) [31]. Weekly nonlinear regime provides high efficiency of charge coupling, it is less sensitive to distortions of the laser pulse and plasma-driven beam instabilities, and does not result in self-injection of plasma electrons exhibiting a dark current. On the other hand, the quasi-linear regime of acceleration does not provide sufficient self-focusing, so it needs to be complimented by an external laser guidance, e.g. capillary [32] or plasma channel [33] to overcome laser diffraction and extend interaction region for enhanced efficiency.

A large number of relevant parameters for such a system can be estimated using scaling laws of LWFA [34] and FELs [35]. These parameters are listed in Table I. The parameters are estimated self-consistently balancing multiple constraints at different stages of the machine. Order-of-magnitude estimates based on parameters summarized in Table I show that it is possible to design an FEL at hard x-ray wavelengths, which is based on the laser accelerator technology. External injection of electrons into the plasma accelerator results in a beam of a high enough quality to achieve lasing.

### III. KEY TECHNOLOGICAL GAPS

Possibility of injecting external beams into a plasma wakefield has been demonstrated experimentally [36–38]. However, presently these experiments are at the proof-of-principle stage rather than being a well established technique. Injecting an electron beam into a plasma wake is a complicated problem, which requires advancements in several areas before the technology reaches maturity. Some of these challenges such as suppression of instabilities, increasing captured bunch charge, increasing wall plug efficiency, reduction in degradation of the beam’s quality during acceleration, increasing accelerated beam’s energy, etc. are general problems for the plasma-based accelerators [39] and a plan for retiring those risks has been outlined [40]. Combining RF and plasma accelerator technologies imposes additional complications.

#### A. An injector for ultra-short bunches

Electron bunches which are suitable for plasma-based accelerators must have low bunch charge on the order of few picocoulombs. Such a bunch charge is an order of magnitude smaller than conventionally produced in RF photoinjectors developed for modern light sources [41]. These photoinjectors can operate at such small bunch charges [42, 43] but they are not optimized for this regime. As such, a dedicated research in designing guns operating at small charges [44, 45] as well as development of the beam manipulation schemes capable of producing short bunches [28] must be conducted.

At the same time, the use of a RF accelerator as an injector is not necessarily a superior option compared to self-injection of electrons from plasma. The quality of accelerated beam in the considered pre-conceptual design is comparable to the quality of beams achieved in self-injection experiments [46–51]. The main reason for the RF accelerators failing to outperform plasma-based self-injectors is due to already mentioned difficulty to generate ultra-high peak current electron bunches, which are routinely generated from plasmas. The RF injectors have to generate longer bunches in order to produce the same overall bunch charge. That translates into the increased rms energy spread acquired by the bunch during successive acceleration in a highly nonuniform plasma wakefield.
TABLE I. Key design parameters for XFEL based on a LWFA

| Laser parameters |  |  |  |
|------------------|--------------------|-----------------|------------------|
| Laser wavelength | 1 µm | Laser duration | 97 fs |
| Laser radius     | 50 µm | Laser intensity | 5.36 \cdot 10^{18} \text{ W/cm}^2 |
| Relativistic amplitude | 1.4 | Laser pulse energy | 41 J |

| Plasma parameters |  |  |  |
|-------------------|--------------------|-----------------|------------------|
| Plasma density    | 1.33 \cdot 10^{17} \text{ cm}^{-3} | Plasma wavelength | 100 µm |
| Plasma length     | 54 cm | Injected beam parameters |  |
| Bunch energy      | 1 GeV | Bunch current | 3000 A |
| Bunch length      | 1 µm | Bunch radius | 0.31 µm |
| Bunch charge      | 10 pC | Normalized emittance | 0.2 µm |
| Beta function     | 0.91 mm | Slice energy spread | 3.3 MeV |
| Rms energy spread | 1.8 MeV | Extracted beam parameters |  |
| Bunch energy      | 12 GeV | Bunch current | 3000 A |
| Bunch length      | 1 µm | Bunch radius | 0.16 µm |
| Bunch charge      | 10 pC | Normalized emittance | 0.2 µm |
| Beta function     | 3.38 mm | Slice energy spread | 3.3 MeV |
| Rms energy spread | 835 MeV | FEL parameters |  |
| Undulator wavelength | 1.86 cm | Undulator strength | 1.22 |
| Undulator length  | 87 m | Photon energy | 42 keV |
| Radiation wavelength | 0.3 Å | 3D gain length | 4.33 m |
| Radiation radius  | 11.6 µm | Radiation bandwidth | 14 % |
| Radiation power   | 56 GW | Number of photons | 2.76 \cdot 10^9 |

B. An interface between conventional and plasma accelerator

Matching an electron beam from a conventional RF accelerator into a plasma accelerator is a complicated task, which has only been accomplished at the proof-of-principle level [38]. First of all, there are tight requirements on the positioning (few µm) and time jitter (\sim 1 fs) of the beam [26]. In addition, the electron beam must be tightly focused into plasma in order to avoid transverse overfocusing leading to the degradation in the beam quality [52]. The estimated beta function for the beam (similar to Rayleigh length in optics) is at the sub-mm level as indicated in Table I. Such tight focusing cannot be achieved with conventional accelerator elements used to control the beam since they are physically large objects. The use of a tapered plasma density profile as a way to overcome this issue has been actively studied [53–55] but has not been demonstrated yet.

Extraction of the plasma accelerated beam and matching it to the following conventional accelerator beamline is a challenging task as well [56]. Large energy spread in accelerated beams makes it difficult to steer them with conventional beamline elements based on magnets since their tuning depends on the beam energy. Alternative methods for controlling the beam using plasma lenses have been proposed but this technology are still at the R&D stage [57], although rapidly reaching maturation [58, 59].

C. Preservation of beam quality in a LWFA

Electron beams in LWFAs are accelerated with electromagnetic fields which have large gradients and in the environment, which is specifically chosen to produce large collective response to external forces. Lack of high quality beams accelerated in plasma has been a long standing problem in the field [39, 40]. Degradation of beams coming from an RF injector is likely to be a larger problem compared to self-injection. The quality of externally injected beams is expected to be better by design. That requires tighter beam focusing to provide proper matching inside the wake and larger local electron density inside the beam, which in turn triggers larger response from the background plasma. At the same time, it is harder to preserve high quality of bright beams compared to their less bright plasma generated counterparts.

Diagnostics of beams in LWFAs is significantly underdeveloped [60] compared to the conventional RF accelerators. Ultra-short duration of the accelerated bunches and poor stability of plasma accelerators make many conventional techniques unsuitable. Time resolved diagnostics of the bunches is almost nonexistent with rare exceptions [61]. At the same time, lasing inside the undulator is sensitive to the slice properties of the beam rather than the rms beam quality. Development of appropriate beam diagnostics is a critical element for building, commissioning, optimizing, and operating an XFEL based on the plasma accelerator technology.

High quality of the beams needs to be preserved inside a meter-long plasma as indicated in Table I. Creating a uniform focusing channel of such a long length and preserving laser beam quality is a challenge. Dielectric capillaries [62] and plasma channels [63] are actively used for the LWFA but the technology is not yet mature enough to meet the requirements for the XFEL.
D. Lasing with electron bunches produced in LWFA

An XFEL based on a plasma accelerated electron accelerator is expected to lase and reach saturation within 100 meters as indicated in Table I. The rms energy spread of the beam is expected to be much larger compared to the energy spread of bunches delivered by conventional RF linacs. However, this energy spread is in fact an energy chirp (energy of particles linearly changes along the bunch) rather than uncorrelated energy spread (similar to temperature in the co-moving frame). In that respect, the LWFA-driven electron bunches have unique properties, and a lot of studies can be done toward optimizing performance of an XFEL driven by a chirped beam. These studies may include the use of transverse gradient undulators (TGUs) to reduce the bandwidth of the light and beam manipulation schemes to either produce ultra-short (well below femtosecond) or two-color light pulses.

E. Designing experiments for FELs with unique light properties

The light generated in XFELs driven by the plasma-based accelerators will have unique properties very different from those of XFELs driven by conventional RF linacs. In the baseline scenario, the light pulse will have a small number of photons and a large chirp. This kind of light is not suitable for imaging and coherent spectroscopy experiments, which require monochromatic light pulses. At the same time, unique properties of the light may be utilized for designing different class of experiments. The light pulse with a strong chirp opens possibility for its further compression below the attosecond duration similar to the chirped pulse amplification (CPA) technique for visible light. Strong chirp also allows for time resolved measurements with subfemtosecond resolution since wavelength sensitive streaking is equivalent to time streaking.

IV. CONCLUSIONS

At this point, the use of an RF linear accelerator as an injector for the plasma wakefield accelerator seems possible for driving x-ray free electron lasers at sub-angstrom wavelengths. Pre-conceptual design parameters of such system are listed in Table I. These parameters are derived self-consistently using scaling laws for LWFA and FELs. There is a lot of room for improvements there and it is likely that an XFEL with better characteristics can be constructed after detailed studies are performed. At this time, plasma accelerator technology is not mature enough to be immediately implemented. A number of key components still need to be developed and demonstrated for a functional XFEL.

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