MAJOR TRENDS IN LINAC DESIGN FOR X-RAY FELS*

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Abstract

Major trends in the contemporary linac designs for x-ray free-electron lasers (XFELs) are outlined starting with identification of the key performance parameters, continuing with considerations of the design options for the electron gun and linac, and finishing with electron beam manipulation in the phase space.

KEY PERFORMANCE PARAMETERS

Pursuit of the XFEL demands improvements in accelerator technology for producing and accelerating high-brightness electron beams. The brightness of the electron beam $B_n = N_e (\lambda_c)^3/\varepsilon_x\varepsilon_y\varepsilon_z$, where N_e is the number of electrons in the electron bunch; $\varepsilon_x\varepsilon_y\varepsilon_z$ are the normalized horizontal, vertical, and longitudinal emittances; and $\lambda_c \approx 3.86\cdot10^{-11}$ cm is the Compton wavelength, plays the most important role in the FEL process. It was shown in [1, 2] that in the best possible scenario when electron beam and FEL parameters are optimized to yield the fastest growth rate of the microbunching, the inverse gain length in the FEL scales linearly with brightness and quadratically with the electron beam energy (a typo in [1] shows linear dependence), i.e.,

$$\frac{\lambda_u}{L_g} \propto \frac{K^2}{2+K^2}\left(\frac{E_b}{\hbar\omega_s}\right)^2 B_n, \tag{1}$$

where L_g is the gain length, $\hbar\omega_s$ is the x-ray photon energy, E_b is the electron beam energy, λ_u is the undulator period, and K is the undulator parameter.

The electron beam energy is the next most important parameter (after brightness) that strongly affects FEL performance. Besides Eq. (1), E_b appears in the optimization of FEL performance in a few other places. The first is a constraint on the geometrical emittance $\varepsilon_{x,y}/\gamma \le \lambda_s/4\pi$, providing that the electron beam size matches the light beam and electrons do not de-phase over the FEL gain length due to betatron oscillations. Here the relativistic factor γ was used instead of E_b. The second is a constraint on the relative energy spread σ_E/E_b, which is basically driven by the same de-phasing concern. The third is the FEL resonance condition $\lambda_s = \lambda_u/2\gamma^2 \times (1+K^2/2)$. Finally, the electron beam energy almost solely defines the cost of the electron beam delivery system. According to these listed constraints, the next-generation FELs should rely on the increased brightness of the electron beam and undulators with short periods in order to lower E_b and, thus, the cost of the FEL. Although, clearly, the undulator technology is extremely important, it is out of the scope of this review and, thus, we refer the reader to a recent publication [3].

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ELECTRON GUN

Production and acceleration of high-brightness electron beams are the two most challenging tasks for the electron gun and linac. The brightness is largely defined by the ability of the electron gun to produce a small emittance, and at present, the rf photocathode guns yield the brightest electron beams. Any advances in this area will allow for lowering the linac energy, thus saving on the construction cost of the facility, and also on the operation cost, as a smaller linac can be used. The ultimate brightness is defined by a so-called “intrinsic emittance” (IE), which is solely dependent on the cathode material work function φ_0 and an electron extraction mechanism. For example, measurements of the IE in the case of the photoemission from a Cu cathode shown in Figure 1 [4] demonstrate that it depends on the difference between photon energy $\hbar\omega$ and the effective work function $\varphi_{eff} = \varphi_0 - (e^3 E_c)^{1/2}$ (in CGS units), where e is the electron charge, and E_c is the applied electric field on the cathode

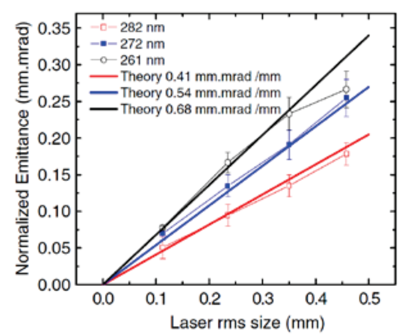

Figure 1: Normalized projected emittance versus laser spot size for three different laser wave lengths as shown in Ref [4]. Measurements were carried out for a copper cathode using a low charge less than 1 pC and E_c=25 MV/m. Theoretical fit assumes φ_0 = 4.3 eV. Thermal effects are not included.

surface responsible for reduction of the potential barrier due to the work function φ_0. Here one can see that the smaller the excess energy $\hbar\omega - \varphi_{eff}$, the smaller the IE [5]:

$$\varepsilon_{\text{intrinsic}} = \sigma_r \sqrt{\frac{\hbar\omega - \varphi_{eff}}{3mc^2}}, \tag{2}$$

where σ_r is the rms size of the laser beam on the cathode, and m is the electron mass. This trend was also observed with Mo, Nb, Al, and bronze cathodes [4] and is expected in semiconductor cathodes such as Cs_2Te and SbK_2Cs [6]. Thus, matching the work function of the cathode material to laser photon energy is expected to yield better IE. Some ideas aimed at production of the photocathode materials with desirable work function were proposed recently [6, 7]. For example, it was found that ternary alkali metal transition metal acetylides (Cs_2TeC_2) [8]

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exhibit substantial reduction of work function down to 1.7-2.4 eV from ~ 3 eV for a Cs_2Te photocathode.

In theory, the quantum efficiency (QE) of the cathode, i.e., the number of extracted electrons per incident photon, is directly connected to excess energy. A drop in QE is expected when one approaches the limit where the photon energy barely exceeds the effective work function. However, for small charge bunches, the drop in QE can be compensated with a more powerful laser, and for future x-ray FELs this could be a viable approach to an ultimately small emittance and, thus, ultimately bright beams.

Other effects such as surface roughness, electron-electron scattering near the cathode surface, and non-uniformity of electron emissivity over the cathode surface could also affect IE. Cathode contamination and lifetime are also important issues for a light source operating nonstop for long periods of time. Besides aiming for more robust cathodes, the current approach for overcoming adverse effects consists of improving the vacuum inside the rf gun. A promising concept has been proposed [9, 10], where a very-high-frequency (VHF) rf gun is projected to achieve low 10^{-11} Torr vacuum while holding a relatively high E_c = 20 MV/m in cw operation (see Figure 2). Assisting in achieving high vacuum are numerous high-conductance vacuum ports seen on the periphery of the central part of the cavity coupled to a pumping plenum containing non-evaporative getter (NEG) modules.

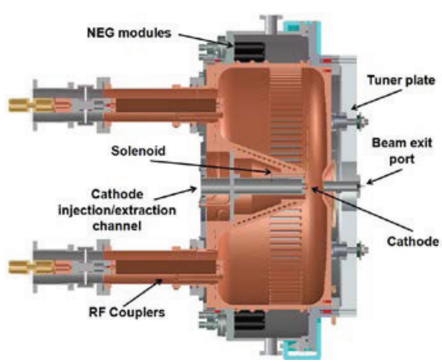

Figure 2: The VHF electron gun cavity showing main components and NEG pumping modules [10].

LINAC

According to Liouville's theorem, in an ideal case, the normalized brightness of an electron bunch is invariant along the electron beamline, but in reality, its conservation can only occur with carefully considered design of the electron beam delivery system. A good example of this practice is the LCLS linac equipped with a laser heater [11], two bunch compressors [12, 13], and a beam transport line where the normalized slice emittance remains practically unchanged over the entire process of the electron bunch acceleration and compression, resulting in an increase of the electron peak current from a few tens of amperes in the injector to up to a few kiloamperes at the end of the linac. Similar attention to all details of the beam delivery system, including field quality of magnetic elements, precision alignment of all magnetic elements and linac modules, transverse and longitudinal wakefields, coherent synchrotron radiation, intrabeam scattering, transverse and longitudinal space charge effects, microbunching instability, and diagnostics and feedback systems should be expected in the next generation of x-ray FELs. Obviously, the impact of all collective effects can be greatly reduced by using lower-charge bunches. Additionally, the uncorrelated energy spread that is artificially increased in the LCLS by the laser heater to suppress the microbunching instability in intense bunches can be reduced for low-charge bunches, resulting in brighter beams.

Evidently, a lower-charge bunch gives fewer photons. Increasing the bunch repetition rate will help to compensate this loss and boost the total number of photons integrated over the same period of time. However, normal-conducting linacs are quite limited in repetition rate under realistic operating conditions, and pragmatically, only superconducting rf (SRF) linacs can support high bunch repetition rate. Currently, an accelerating gradient over 20 MV/m can be reliably achieved in SRF in cw operation, but a lower gradient may be preferred when full construction and operating costs are considered. Aiming for future applications in the x-ray FELs, current R&D is focused on increasing the Q-factor of cavities at a 25 MV/m gradient. Promising results have been obtained using atomic layer deposition (ALD), where it seems possible to control the surface composition of niobium SRF cavities, control multipactoring, improve the Q-factor, and synthesize superconducting structures with a significantly improved critical field [14, 15]. It is then assumed that multiple FEL lines will be simultaneously supported by a single SRF linac [16-18], providing uniformly spaced electron bunches at a few-MHz repetition rate. The same high-repetition-rate performance is expected from the electron gun, and various scenarios are currently being considered including a DC gun [19], a superconducting gun [20], and a normal-conducting VHF gun, briefly described above.

The linear accelerator is usually the main cost driver for a FEL facility and substantial efforts are being devoted worldwide to the development of new acceleration technologies [21]. It is conceivable that future accelerators will be compact and inexpensive. One promising concept is to use hollow, cylindrical, dielectric tubes powered by a high-charge electron "drive" bunch whose main purpose is to produce Čerenkov radiation and excite strong electromagnetic waves in the structure. Trailing behind, a second low-charge "main" bunch navigates these waves and enjoys a speedy acceleration [22]. Preliminary studies [23] show that not only does a dielectric wakefield accelerator (DWFA) reduce the accelerator footprint afforded by speedy acceleration, but the DWFA is also capable of supporting high bunch repetition rates with uniform bunch spacing up to one million cycles per second.

PHASE SPACE BEAM MANIPULATION

Precise control over the electron partitioning in a 6D phase space and manipulation of the phase space occupancy offer enormous opportunities for optimization of XFEL performance. Currently, only manipulation in the 2D longitudinal phase space is widely used. It involves inducing the energy chirp with the RF system and compressing the electron bunch using one or more magnetic chicanes. Typically when the bunch leaves the last chicane it is not fully compressed and has some remaining chirp that is removed by off-crest acceleration in the downstream linac (which is an inefficient and costly option) or by using the wakefield created by the beam itself. However, often the wakefield produced in the linac is too weak and, thus, the task of removing the energy chirp can be better accomplished by a dedicated wakefield inducing element, like, for example, the dielectric channel tested in [24, 25] or corrugated pipe considered in [26].

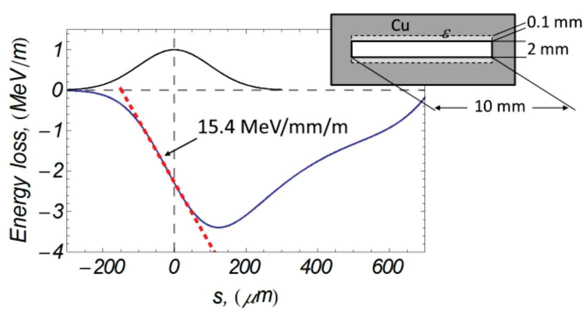

Figure 4: The energy loss distribution along the electron bunch (blue curve) in the 1-m long rectangular copper channel coated inside with 100 µm thick dielectric layer with the dielectric constant ε = 4.4 (insert). The bunch charge is 300 pC with density distribution shown by the black curve (courtesy of A. Kanareikin).

The emittance exchange technique proposed in [27] goes further and considers reduction of the transverse emittance at the expense of increasing the uncorrelated energy spread, thus, doing two useful things at the same time while preserving the 6D phase-space volume produced in the electron gun, i.e., obtaining small emittance and eradicating a need in the laser heater. This technique is particularly effective when it is combined with a round-to-flat emittance adapter [28]. Other approaches include non-symplectic applications for emittance partitioning [29]. Currently, all these techniques are undergoing intense theoretical and experimental studies [30-33]. Moreover, a double emittance exchange [34] was recently proposed as a convenient tool for beam manipulation in the longitudinal phase space including preparation of microbunching for seeded FELs.

Another direction of promising new research is centered on suppression of the shot noise of electrons and, thus, mitigation of the microbunching instability (i.e., see Ref. [35] and references therein).

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