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Electron Beam Conditioning by Thomson Scattering

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Abstract

A method is proposed for conditioning electron beams via Thomson scattering. The conditioning provides a quadratic correlation between the electron energy deviation and the betatron amplitude of the electrons, which results in enhanced gain in free-electron lasers. Quantum effects imply conditioning must occur at high laser fluence and moderate electron energy. Conditioning of x-ray free-electron lasers should be achievable with present laser technology, leading to significant size and cost reductions of these large-scale facilities.

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A single-pass, high-gain free-electron laser (FEL) operating in the self-amplified spontaneous emission mode has received much recent attention as a next generation light source producing intense, coherent x rays [1–4]. The performance of the FEL is limited by the electron beam quality, and typically the most demanding requirement is the transverse beam emittance. Beam conditioning [5–8] has been proposed as a method of mitigating this limitation by producing a correlation between the energy and betatron amplitude of the electrons. In this article we propose a new conditioning mechanism based on Thomson backscattering.

The FEL resonance condition is $(1 - v_z/c)\lambda_u = \lambda$, where λ is the radiation wavelength, λ_u is the undulator wavelength, and v_z is the electron axial velocity. The spread in axial velocity owing to a spread in beam energy and the betatron motion generates a deviation of the radiation frequency from the resonant frequency $\omega_r = 2\omega_u\gamma_r^2/(1 + a_u^2/2) = 2\pi c/\lambda_r$, where $\omega_u = 2\pi c/\lambda_u = ck_u$, γ_r is the Lorentz factor of the resonant electron beam energy, and a_u the normalized vector potential of the undulator magnetic field. Assuming an energy deviation $\delta\gamma = \gamma - \gamma_r$, and taking into consideration the transverse motion of the electrons in the focusing fields, characterized by the betatron wavenumber k_β, the relative frequency deviation is

$$\hat{\omega} = (\omega - \omega_r)/\omega_r = 2\delta\gamma/\gamma_r - (\lambda_u/\lambda_r)k_\beta^2 R^2/2 \ , \tag{1}$$

where R is the betatron amplitude (the maximum transverse excursion of the electron orbit from the axis) at the undulator.

The deviation from the resonant frequency Eq. (1) will reduce the gain of the FEL and degrade the performance. The exponential gain of the radiated power in a high-gain FEL [1–3] can be expressed as $P_{\rm FEL} \propto \exp(L_u/L_g)$, where L_u is the undulator length, and the power gain length is $L_g = (2\sqrt{3}\rho k_u)^{-1}[1 + (\hat{\omega}/2\rho)^2/9]$ assuming $(\hat{\omega}/2\rho)^2 < 1$, where ρ is the FEL parameter [1]. The gain length reduces to $L_g = (2\sqrt{3}\rho k_u)^{-1}$ for $(\hat{\omega}/2\rho)^2 \ll 1$, i.e., $\delta\gamma/\gamma_r \ll \rho$ and $(\lambda_u/\lambda_r)(k_\beta^2 R^2)/4 \ll \rho$. The later condition can be expressed in terms of the beam emittance $\epsilon = k_\beta R^2 \ll 4\rho\lambda_r/(k_\beta\lambda_u)$. This emittance constraint can be eliminated by *conditioning* the beam [5] such that the energy deviation from resonance of each electron is proportional to the square of its betatron amplitude, namely

$$\delta\gamma/\gamma_r = (\lambda_u/\lambda_r)k_\beta^2 R^2/4 \ . \tag{2}$$

A conditioned beam satisfying Eq. (2) has $\hat{\omega} = 0$ for each electron (provided the uncorrelated relative energy spread is much less than ρ), and the power gain length is minimized. For

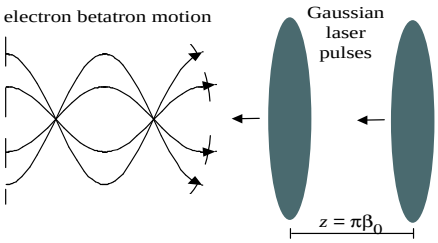

FIG. 1: Schematic of beam conditioning via Thomson backscattering. Two Gaussian laser pulses provide the nonlinear correlation between the energy deviation and the betatron amplitude.

example, consider parameters relevant to the proposed Linac Coherent Light Source (LCLS) [4] x-ray FEL: $\lambda_r = 1.5$ Å, $k_\beta^{-1} = 18$ m, $\lambda_u = 3$ cm, $\gamma_r\epsilon = 1.2$ mm mrad, and $\gamma_r = 2.8 \times 10^4$, then Eq. (2) implies a conditioned energy deviation of $\delta\gamma \propto R^2$ with $\delta\gamma(R = r_b) \simeq 3$, where r_b is the beam radius. This nonlinear energy deviation correlation should be achievable using Thomson scattering with present laser technology, as discussed in this Letter.

Several techniques for achieving the correlation Eq. (2) have been proposed using conventional (radio-frequency) accelerating and focusing structures [5, 6] or by vacuum acceleration [7]. Recently it was shown [8] that any beam conditioning using symplectic beam lines results in a strong beam head-tail focusing variation, which produces transverse emittance growth, severely limiting the benefits of conditioning with these conventional methods.

In this Letter, Thomson backscattering (TB) [9] of an intense laser pulse with the relativistic electron beam is proposed as a method of FEL conditioning. The number of TB photons (i.e., electron energy loss) is proportional to intensity of the laser pulse, which decreases off axis for a focused laser pulse. Therefore, TB of an intense focused laser pulse produces a correlation between the energy loss by an electron and its transverse location in the laser field, thus allowing beam conditioning (a schematic of the basic idea is shown in Fig. 1). Furthermore, the transverse force of the laser pulse on the beam is axially uniform, thus minimizing emittance growth. Limitations imposed by quantum fluctuations imply that conditioning must occur at high laser fluence and modest beam energy. For parameters of proposed x-ray FELs, TB conditioning requires $\sim 10^2$ J in ~ 10 ps, which is achievable with present laser technology, however, at low repetition rates ($\lesssim 1$ Hz).

TB was previously proposed as an incoherent x-ray source [9, 10] and as a cooling method

for relativistic beams [11–14]. The TB radiation frequency is [9]

$$\omega_T = N_h 4\gamma_0^2 \omega_L/(1 + a_0^2/2 + \gamma_0^2\theta^2) \; , \tag{3}$$

assuming $\gamma_0^2 \gg \gamma_\perp^2$ and small scattering angle $\theta^2 \ll 1$, where $\gamma_\perp^2 = (1 + a_0^2/2)$, $\omega_L = ck_L = 2\pi c/\lambda_L$ is the laser frequency, γ_0 is the Lorentz factor of the electron, a_0 is the normalized vector potential of the laser field, and N_h is the harmonic number. In the low-intensity limit $a_0^2 \ll 1$, radiation is scattered only at the fundamental $N_h = 1$. In the nonlinear limit $a_0^2 \gg 1$, many harmonics are produced, peaked near the critical harmonic number $N_h = 3a_0^3/\sqrt{8}$ for a circularly polarized laser.

For simplicity in the following analysis, a circularly polarized Gaussian laser field is considered with a normalized vector potential $\boldsymbol{a} = e\boldsymbol{A}/mc^2$, in the Coulomb gauge, given by $\boldsymbol{a} = (\hat{a}_0/\sqrt{2})[\cos(k_L\eta)\hat{x} + \sin(k_L\eta)\hat{y}]$, where $\hat{a}_0 = a_0 \exp(-r^2/r_L^2)$, r_L is the laser spot size ($k_L r_L \gg 1$ is assumed), and $\eta = z + ct$ (the laser pulse travels in the $-\hat{z}$ direction and the electron beam in the $+\hat{z}$ direction). Diffraction is neglected, which is valid provided that the laser pulse length $c\tau_L$ and electron beam length σ_z are less than the Rayleigh length $Z_\mathrm{R} = \pi r_L^2/\lambda_L$. The laser power and intensity are given by $P_L[\mathrm{GW}] \simeq 21.5(a_0 r_L/\lambda_L)^2$ and $I_L[\mathrm{W/cm^2}] \simeq 1.37 \times 10^{18} a_0^2/(\lambda_L[\mu\mathrm{m}])^2$, respectively.

The Lorentz equation, $d\boldsymbol{u}/dt = \partial\boldsymbol{a}/dt - (\boldsymbol{u}/\gamma) \times (c\nabla \times \boldsymbol{a})$, can be solved for the motion of the electrons in the laser field, where $\gamma = (1 + u^2)^{1/2}$ and $\boldsymbol{u}$ is the electron momentum normalized to mc. In the limit $k_L r_L \gg 1$ there exists two constants of motion: $d(\boldsymbol{u}_\perp - \boldsymbol{a}_\perp)/d\eta = 0$ and $d(\gamma + u_z)/d\eta = 0$ (i.e., transverse canonical momentum conservation and energy conservation in the wave frame). These equations can be integrated to yield the electron momenta $\boldsymbol{u}_\perp = \boldsymbol{a}_\perp$ and $u_z = (\gamma_0 + u_0)/2 - (1 + \hat{a}_0^2/2)/[2(\gamma_0 + u_0)]$, and, prior to the interaction with the laser, $\gamma = \gamma_0$ and $u_z = u_0$ are assumed.

The power radiated by a single electron can be calculated from the relativistic Larmor formula [15]

$$P = (2/3)e^2 c(\gamma + u_z)^2[(d\boldsymbol{u}/d\eta)^2 - (d\gamma/d\eta)^2] \; . \tag{4}$$

Using the electron orbits yields $P \simeq e^2 c(\gamma + u_z)^2 k_L^2 \hat{a}_0^2/3$. The electron energy loss is $mc^2 d\gamma/dt = -P$, or, assuming $\gamma \gg 1$,

$$d\gamma/dt = -(4/3)\gamma^2 r_e c k_L^2 \hat{a}_0^2 \; , \tag{5}$$

where $r_e = e^2/mc^2$. Equation (5) is valid provided the transverse canonical momentum is approximately conserved $\boldsymbol{u}_\perp \simeq \boldsymbol{a}_\perp$. By including the radiation reaction force, this holds

provided $4k_L r_e \gamma_\perp^2 \gamma/3 \ll 1$, which is typically well-satisfied. Equation (5) has the solution $\gamma \simeq \gamma_0(1+2t/\tau_R)^{-1}$, where t is the beam-laser interaction time (e.g., for a relativistic electron beam $t = \tau_L/2$) and $\tau_R = (2r_e c\gamma_0 k_L^2 \hat{a}_0^2/3)^{-1}$ is the radiation damping time. In practical units (assuming $r_b \ll r_L$), $\tau_R[\text{ns}] \simeq 45\lambda_L^2[\mu\text{m}]/(\gamma_0 a_0^2) \simeq 6.2\times 10^{19}/(E_b[\text{MeV}]I_L[\text{W/cm}^2])$, where E_b is the electron beam energy. For example, $\tau_R \simeq 6$ ns for $E_b = 100$ MeV and $I_L = 10^{17}$ W/cm^2.

Since higher energy electrons radiate more strongly than lower energy electrons, laser radiative cooling of electron beams can occur [11–14]. The normalized energy γ, root-mean-square energy spread σ_γ, and normalized transverse emittance $\epsilon_n = \gamma\epsilon = \epsilon_{n0}\gamma/\gamma_0$ of the beam decrease via

$$\gamma = \gamma_0 \left(1 + \tau_L/\tau_R\right)^{-1} \ , \tag{6}$$

$$\sigma_\gamma \simeq \sigma_{\gamma 0} \left(1 + \tau_L/\tau_R\right)^{-2} \ , \tag{7}$$

$$\epsilon_n \simeq \epsilon_{n0} \left(1 + \tau_L/\tau_R\right)^{-1} \ , \tag{8}$$

where $\sigma_{\gamma 0}$ and ϵ_{n0} are initial values. Laser cooling is limited by quantum excitation from discrete photon scattering [12–14].

For electrons within the spot size of the laser, $r^2 \ll r_L^2$, the normalized intensity of the laser has a quadratic dependence on radius, i.e., $\hat{a}_0^2 \simeq a_0^2(1 - 2r^2/r_L^2)$. For $r^2 \ll r_L^2$, the electron energy after TB, given by the solution to Eq. (5), is

$$\gamma \simeq \gamma_0 \left(1 + \gamma_0 \kappa_R c\tau_L\right)^{-1} + \left(\frac{2\gamma_0^2 \kappa_R c\tau_L}{1 + \gamma_0 \kappa_R c\tau_L}\right) \frac{r^2}{r_L^2} \ , \tag{9}$$

where $\kappa_R = 2r_e k_L^2 a_0^2/3$. In practical units, $\kappa_R c\tau_L \simeq 10^{-3} U_L[\text{J}]/r_L^2[\mu\text{m}]$, where U_L is the laser beam energy. As Eq. (9) indicates, TB produces the desired quadratic dependence of the energy on radius as required for beam conditioning.

For a beam undergoing betatron oscillations in a conventional beam lattice, with beta function β_0, before entering the FEL undulator, the simplest TB conditioner would require two laser pulses (with identical laser parameters). The first pulse would modify the energy of each electron such that $\gamma_1 \simeq \gamma_0 - \gamma_0^2 \kappa_R c\tau_L + (2\gamma_0^2 \kappa_R c\tau_L/r_L^2) r_1^2$, assuming $\gamma_0 \kappa_R c\tau_L \ll 1$. The transverse position of an electron in the lattice can be represented by $r_1^2 = [x_0 \cos\phi + \beta_0 (dx/dz)_0 \sin\phi]^2 + [y_0 \cos(\phi+\varphi) + \beta_0 (dy/dz)_0 \sin(\phi+\varphi)]^2$, where the subscript 0 denotes the initial value, $\phi \simeq z/\beta_0$, and φ is a constant. The electron beam would then be allowed to obtain a $\pi/2$ phase advance in the lattice, such that the transverse position becomes $r_2^2 = [x_0 \cos(\phi+\pi/2) + \beta_0 (dx/dz)_0 \sin(\phi+\pi/2)]^2 + [y_0 \cos(\phi+\varphi+\pi/2) + \beta_0 (dy/dz)_0 \sin(\phi+\varphi+\pi/2)]^2$.

At this point the beam would interact with the second laser pulse, modifying the electron energy such that $\gamma_2 \simeq \gamma_0 - 2\gamma_0^2\kappa_R c\tau_L + (2\gamma_0^2\kappa_R c\tau_L/r_L^2)R_0^2$, where $R_0 = (r_1^2 + r_2^2)^{1/2}$ is the betatron amplitude at the conditioner. If the electron beam is then accelerated to the resonant energy for the FEL interaction $\gamma_r = (1 + a_u^2/2)^{1/2}(\omega_r/2\omega_u)^{1/2}$, the resulting energy deviation $\delta\gamma = \gamma - \gamma_r$ is $\delta\gamma \simeq (2\gamma_0^2\kappa_R c\tau_L/r_L^2)R_0^2$. The betatron amplitude at the conditioner is related to the betatron amplitude at the undulator by the invariant $\gamma_0 R_0^2/\beta_0 = \gamma_r k_\beta R^2$. This TB method can satisfy the beam conditioning criterion Eq. (2) provided

$$2\gamma_0\beta_0\kappa_R c\tau_L/r_L^2 = (\lambda_u/\lambda_r)k_\beta/4 \; . \tag{10}$$

Multiple (M) applications of this TB method with $2M$ laser pulses could be considered to reduce the laser energy per pulse (U_L/M).

The laser pulse also provides a transverse ponderomotive force to the electrons $F_\perp = -mc^2\nabla_\perp\gamma = -(mc^2/\gamma_0\gamma_\perp)\nabla_\perp(\hat{a}_0^2/4)$, which will result in a transverse electron momentum kick $\delta p_\perp \sim F_\perp\tau_L \sim (mc^2/\gamma_0\gamma_\perp)a_0^2\tau_L r_b/r_L^2$. This can be neglected provided $\delta p_\perp \ll p_\perp = (\gamma_0 mc)r_b/\beta_0$. This condition implies $\beta_0 \ll \gamma_\perp\gamma_0^2 r_L^2/(a_0^2 c\tau_L)$, which can be easily satisfied by using strong external focusing during conditioning.

The above results are based on a classical analysis that neglects discrete photon scattering effects. This is valid if the number of photons scattered per electron N_γ is large, i.e., $N_\gamma \gg 1$, where $N_\gamma = -\Delta\gamma(mc^2/\hbar\omega_T)$ or

$$N_\gamma = (\pi\alpha/3)(c\tau_L/\lambda_L)(a_0^2/F_{cr}) \; , \tag{11}$$

where $\Delta\gamma \simeq -\gamma_0^2\kappa_R c\tau_L$ is the electron energy loss, $\omega_T = 4\gamma_0^2\omega_L F_{cr}$ is the on-axis ($\theta = 0$) TB photon frequency, and $\alpha = e^2/\hbar c \simeq 1/137$. Here, $F_{cr} = 1$ for $a_0^2 \ll 1$, and $F_{cr} \simeq 3a_0/\sqrt{8}$ for $a_0^2 \gg 1$ [9]. Note that N_γ is independent of the electron beam parameters, and the condition $N_\gamma > 1$ places a limit on the laser fluence since $N_\gamma \propto \lambda_L I_L\tau_L$ for $a_0^2 \ll 1$.

A limitation of TB as a method of beam conditioning arises from the quantum-statistical nature of scattering. The discrete scattering of a single photon generates an energy spread $\hbar\omega_T/mc^2$. After N_γ kicks, the total change in the beam energy spread σ_γ is given by $\Delta\sigma_\gamma^2 \simeq N_\gamma(\hbar\omega_T/mc^2)^2 \simeq -\Delta\gamma(4F_{cr}\lambda_C/\lambda_L)\gamma^2$, where $\lambda_C = h/mc$ is the Compton wavelength. Using Eqs. (6) and (7), the decrease in energy spread from radiative cooling is given by $\Delta\sigma_\gamma^2 \simeq 4(\Delta\gamma)\sigma_\gamma^2/\gamma$. Balancing this against the increase in energy spread due to quantum fluctuations

yields the rate equation $d\sigma_\gamma^2/d\gamma = 4\sigma_\gamma^2/\gamma - (4F_{cr}\lambda_{\rm C}/\lambda_L)\gamma^2$ with the solution

$$\sigma_\gamma^2 = \sigma_{\gamma 0}^2\,(\gamma/\gamma_0)^4 + (4F_{cr}\lambda_{\rm C}/\lambda_L)\,\gamma^3\,(1-\gamma/\gamma_0)\ . \tag{12}$$

The FEL interaction requires that the electron energy spread be within the FEL gain bandwidth, or $\sigma_\gamma/\gamma_r < \rho$. Using Eq. (12), this condition can be expressed as

$$4F_{cr}\kappa_R c\tau_L\gamma_0^4\lambda_{\rm C}/\lambda_L < \gamma_r^2\rho^2\ , \tag{13}$$

assuming $\sigma_{\gamma 0}/\gamma_0 < \rho$ and $\tau_L/\tau_R < 1$. In practical units Eq. (13) is $(U_L[{\rm J}]/\lambda_L[\mu{\rm m}])^{1/2}\gamma_0^2/r_L[\mu{\rm m}] < 10^4\gamma_r\rho$, assuming $a_0^2 \ll 1$. Because of the strong dependence of this inequality on γ_0, conditioning must be done at modest beam energy, i.e., typically $\gamma_0 \ll \gamma_r$ for an x-ray FEL. For example, if $\rho = 5\times10^{-4}$, $\gamma_r = 2.8\times10^4$, $\lambda_L = 1$ μm, $r_L = 50$ μm, and $U_L = 100$ J, the conditioning beam energy must satisfy $\gamma_0 < 840$.

Quantum fluctuations can also lead to normalized transverse beam emittance growth [12–14]. The electron receives a transverse recoil from the scattered photon. The change in the electron divergence $\delta\psi$ from a single scattering event is $\delta\psi \simeq \hbar\omega_T\theta/\gamma mc^2$. After N_γ collisions, the angular spread is $\Delta\langle\psi^2\rangle \simeq N_\gamma\langle(\delta\psi)^2\rangle \simeq (-\Delta\gamma/\gamma^2)(\hbar\omega_T/mc^2)\langle\theta^2\rangle$. The average Thomson scattering angle is $\langle\theta^2\rangle \simeq \gamma_\perp^2/2\gamma^2$. The change in normalized emittance from the transverse recoil is $\Delta\epsilon_n = \gamma\beta_0\Delta\langle\psi^2\rangle/2$. From Eq. (8), the normalized transverse emittance decrease from radiative cooling is $\Delta\epsilon_n = (\Delta\gamma)\epsilon_n/\gamma$. Balancing this against the increase due to the quantum fluctuations yields the rate equation $\gamma d\epsilon_n/d\gamma = \epsilon_n - (\beta_0 F_{cr}\gamma_\perp^2\lambda_{\rm C}/\lambda_L)$ with the solution

$$\epsilon_n = \epsilon_{n0}(\gamma/\gamma_0) + (\beta_0 F_{cr}\gamma_\perp^2\lambda_{\rm C}/\lambda_L)(1-\gamma/\gamma_0)\ . \tag{14}$$

To maintain good FEL performance, the emittance growth from quantum excitation should be much less than the initial emittance $\beta_0(\lambda_{\rm C}/\lambda_L)F_{cr}\gamma_\perp^2\gamma_0\kappa_R c\tau_L \ll \epsilon_{n0}$. In practical units, this requirement is $\epsilon_{n0}[{\rm mm\ mrad}] \gg 0.24\beta_0[{\rm cm}]\gamma_0 U_L[{\rm J}]/(\lambda_L[\mu{\rm m}]r_L^2[\mu{\rm m}])$, assuming $a_0^2 \ll 1$. For example, if $\beta_0 = 2$ cm, $\gamma_0 = 10^2$, $\lambda_L = 1$ μm, $r_L = 50$ μm, and $U_L = 100$ J, then $\epsilon_{n0} \gg 2\times10^{-4}$ mm mrad. For typical parameters, the growth in the beam energy spread from quantum excitation will be a more severe constraint than the transverse emittance growth.

The fluctuation effects described above [cf. Eq. (13)] imply conditioning must occur at moderate electron energy. For x-ray FELs, the low-energy electron bunch is typically compressed and accelerated before entering the undulator. Provided there is no particle mixing,

bunch compression does not change the energy correlation, but will amplify the relative energy variation [8]. The required energy variation for conditioning followed by bunch compression is $\delta\gamma = (\sigma_{zf}/\sigma_{zi})[\gamma_r(\lambda_u/\lambda_r)k_\beta^2 R^2/4]$, where σ_{zf} is the final and σ_{zi} is the initial bunch length. Bunch compression will also put a more stringent condition on the uncorrelated electron energy spread σ_γ, since compression amplifies σ_γ by σ_{zi}/σ_{zf}.

Table I lists two examples of TB conditioning for x-ray FELs. The first example considers a 1.06 μm glass laser system for conditioning a 1.5 Å FEL (near LCLS parameters [4]), and the second example considers a 0.8 μm Ti:Al_2O_3 laser system for conditioning a 0.4 Å FEL (near the parameters for the proposed "Greenfield" FEL [16]). Table I assumes a bunch compression factor of $\sigma_{zi}/\sigma_{zf} = 36$ [4]. The beam conditioning requirement is satisfied, as well as $N_\gamma \gtrsim 10$ and the energy spread condition $\sigma_\gamma/\gamma_r < \rho$ at the undulator. The laser parameters listed in Table I are achievable with present systems, albeit at low repetition-rate ($\lesssim 1$ Hz).

The above analysis and examples have assumed a Gaussian transverse laser profile with $r_L \gg r_b$, i.e., much of the laser energy (for $r > r_b$) is not used in the TB process. In principle, the transverse laser profile can be tailored such that the intensity satisfies the quadratic dependence $I_t \propto (1 - 2r^2/r_L^2)$ for $r \leq r_b$, and $I_t \simeq 0$ for $r > r_b$ [with laser power $P_t[\mathrm{GW}] \simeq 21.5(a_0 r_b/\lambda_L)^2(1 - r_b^2/r_L^2)$], thereby reducing the required laser power and energy for TB conditioning. The effective diffraction length for such a tailored pulse containing higher-order transverse modes will be shorter than for a Gaussian mode, and, therefore, some form of laser guiding might be required to extend the interaction length.

This Letter has proposed and analyzed FEL beam conditioning by TB using high-power lasers. TB can provide a quadratic correlation between the energy deviation and the betatron amplitude of the electrons, and an expression for perfect conditioning via TB was derived. The quantum nature of TB places limits on the applicability of this method. Requiring the number of photons scattered per electron be large implies large laser fluences. Requiring the energy spread induced by quantum fluctuations be small implies modest electron energies, i.e., typically TB conditioning must be done before accelerating the beam to the full FEL resonant energy for short-wavelength FELs. Examples relevant to proposed x-ray FELs indicate that TB conditioning is achievable with present-day technology. The repetition-rate of such laser systems is currently limited, but newly emerging diode-pumped, short-pulse laser technology is a promising path to higher average power. By using TB to condition

TABLE I: Parameters for TB conditioning of FELs at 1.5 Å and 0.4 Å. Electron beam parameters are at conditioner.

FEL parameters:		
Resonant FEL wavelength, λ_r[Å]	1.5	0.4
Normalized resonant energy, γ_r	2.8×10^4	5.4×10^4
FEL parameter, ρ	5.0×10^{-4}	2.6×10^{-4}
Undulator wavelength, λ_u[cm]	3	3
Betatron wavelength, k_β^{-1}[m]	18	18
Laser parameters:		
Laser wavelength, $\lambda_L[\mu\text{m}]$	1.06	0.8
Laser pulse duration, τ_L[ps]	18	14
Normalized intensity, a_0	0.5	0.5
Laser spot size, $r_L[\mu\text{m}]$	65	41
Laser power (Gaussian), P_L[TW]	20	14
Laser power (tailored), P_t[TW]	1.0	1.6
Laser energy (Gaussian), U_L[J]	371	198
Laser energy (tailored), U_t[J]	19	23
Rayleigh length, Z_R[cm]	1.2	0.66
Electron beam parameters:		
Normalized beam energy, γ_0	97	104
Normalized emittance, $\epsilon_n[\mu\text{m rad}]$	1.2	1.2
Beam radius, $r_b[\mu\text{m}]$	15	15
Beam length, σ_z[mm]	0.8	0.8
Beam charge, [nC]	1	1

beams in large-scale x-ray FELs, in which beam emittance is a limiting factor, the FEL gain can be enhanced thereby decreasing the overall length and cost of the FEL.

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