A CHIRPED-PULSE REGENERATIVE-AMPLIFIER FEL FOR THE GAMMA-GAMMA COLLIDER*

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During a Workshop on Gamma-Gamma Colliders in Lawrence Berkeley Laboratory, it was pointed out that an 1-μm laser that can produce 1-J, 1-ps pulses at a few hundred hertz is required. With high-power scalability and ease of formatting, an FEL can be a promising candidate for such a laser. We propose an FEL scheme based on chirped-pulsed regenerative amplification to achieve this high peak-power laser. The 1-ps pulse of a solid-state laser will be stretched, amplified, and recompressed to achieve the high peak power. The system is relatively simple and consists of mostly components that have already been demonstrated. This paper will describe the proposal and the important issues of such a scheme.

I. INTRODUCTION

For high-rate gamma production in a gamma-gamma collider, a laser that can produce 1-J, 1-ps pulses with wavelength longer than 1 μm is needed. This laser, when Compton-backscattered by a high-energy electron beam, can produce a high-intensity beam of high-energy gamma rays [1].

To achieve the 1-Joule laser pulses, we propose to use chirped-pulsed amplification (CPA) in a free-electron laser (FEL). CPA using solid-state-laser gain media has produced peak powers as high as a few terawatts [2]. In solid-state media, this technique appears to have a maximum average power of 1 watt [3], possibly limited by the thermal characteristics of the gain media. CPA in a FEL has been proposed as a mean to generate femtosecond vacuum-ultraviolet pulses [4] but, thus far, no experimental results on CPA with an FEL have been reported. An FEL is the ideal amplifier medium for CPA because the high-quality electron beams forms a low-distortion, high-gain medium whose gain curve can be tuned to match the input wavelength. Unlike solid-state media, FEL amplifiers are scalable to high repetition rates. Thus, a CPA FEL potentially can be developed into a high-average-power terawatt laser.

Beside tunability and high-average-power capability, an FEL amplifier can be quite efficient, especially if the wiggler is tapered. Efficiencies as high as 4.5% have been demonstrated with tapered wigglers in the infrared [5]. However, a tapered-wiggler FEL amplifier usually has a low single-pass gain. This problem can be circumvented by operating the FEL as a regenerative amplifier. In a regenerative amplifier, an input laser pulse is amplified repetitively by electron pulses in a synchronous cavity. The intracavity power builds up to reach saturation and to efficiently extract energy from electron pulses.

II. PROPOSED SCHEME

The proposed CPA regenerative-amplifier FEL system is shown in Fig. 1. It has the following subsystems: a solid-state laser, a pulse stretcher, an FEL regenerative amplifier, and a pulse compressor. The output of the solid-state laser is a 1-ps, 1-mJ pulse at 1.05 μm. It will be pulse stretched from 1 ps to 50 ps at the pulse stretcher. It is injected into the regenerative-amplifier FEL to be amplified to the 1-J energy level. It is pulse-compressed in the pulsed compressor to the 1-ps pulse length.

The solid-state laser has a Nd:YLF oscillator and a large bandwidth regenerative amplifier. The system is commercially available.

The pulse stretcher and pulse compressor consist of linear dispersive elements that convert between frequency chirp and pulse length. Each of them consists of a pair of gratings [6]. They are different by the stretcher having an extra lens. The grating pair introduces a frequency-dependent temporal delay as given by:

$$\begin{aligned}\tau(\omega) = \tau_0 - \mu^{-1}(\omega-\omega_0) \\ +\vartheta(\omega-\omega_0)^2\end{aligned} \qquad (1)$$

where τ_0 is the fixed delay at $\omega = \omega_0$, ω_0 is the central frequency of the laser, μ, is the linear dispersion of the grating pair, and ϑ is the higher-order term that is usually negligible. The linear dispersion, μ, is a function of the grating separation b, the groove spacing d, and the angle γ which is the angle between the incident and diffracted beams for a grating

$$\mu = \frac{\omega_0^3 d^2\left(1-\left(\frac{\lambda}{d}-\sin\gamma\right)\right)}{4\pi^2 c\, b} \qquad (2)$$

Neglecting the higher-order terms, the length of the stretched pulse can be estimated by

$$\tau_{stretch} = \frac{4bm^2\lambda\Delta\lambda}{d^2 c\cos^3\theta} \qquad (3)$$

where m is the grating order, λ is the central wavelength, Δλ is the bandwidth and θ is the diffracted angle. Estimates using equation (3) show that an 1-ps pulse can easily be stretched to 50 ps.

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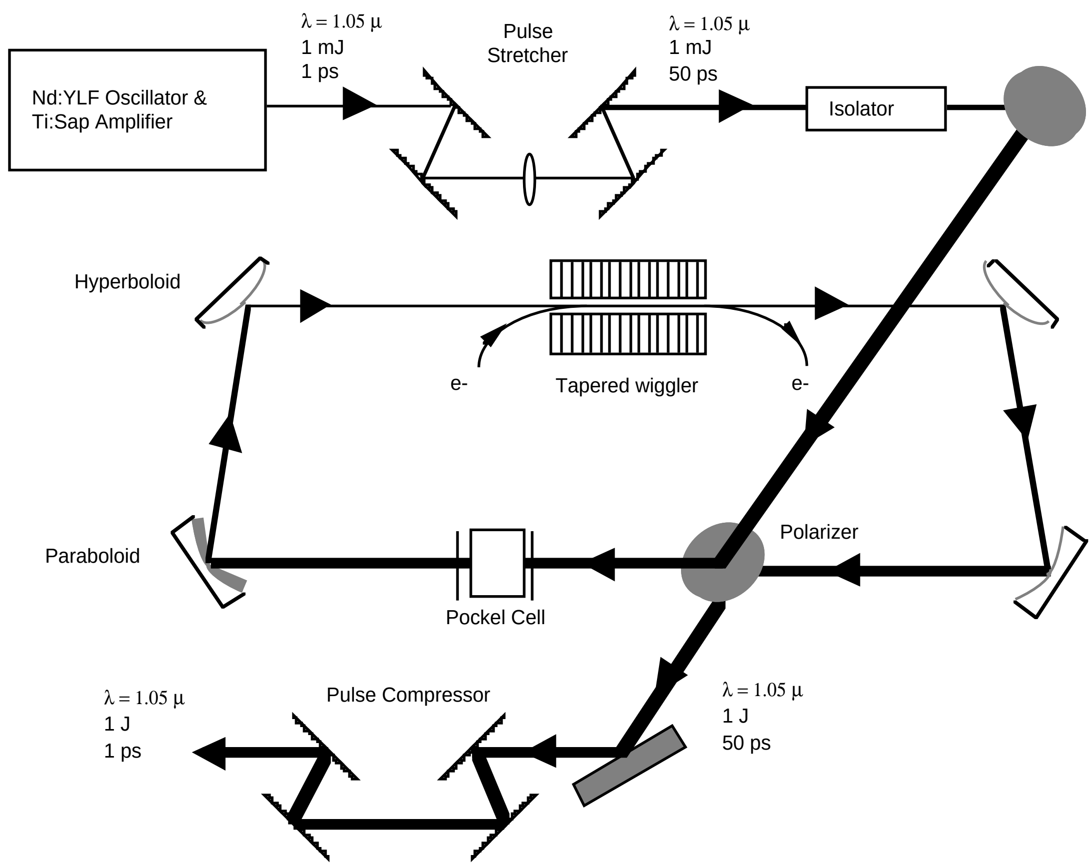

Figure 1: Schematic of a chirped-pulse regenerative-amplifier free-electron laser.

The regenerative amplifier FEL consists of a high-brightness electron beam, a tapered wiggler and a ring resonator. Its parameters are summarized in Table 1. The parameters of the high-brightness electron beam were chosen similar to those of the Los Alamos Advanced Free Electron Laser (AFEL). At a bunch charge of 3 nC, the AFEL electron beam has an rms normalized emittance of 2.5 π mm mrad, an energy spread of 0.5%, and a pulse length of 10 ps [7]. This high-quality electron beam can be obtained at higher bunch charge by lengthening the pulse length. The wiggler is tapered to achieve higher extraction efficiency. The parameters are being chosen similar to a high-efficiency wiggler that was designed for the recent AFEL High-Average-Power-Upgrade Project [8]. The AFEL wiggler will have a length of 36 cm and an extraction efficiency of 7%. The ring resonator consists of 2 hyperboloids and 2 paraboloids with a total cavity loss of 2%. The peak power densities on these optical elements, probably made of dielectric, are kept below 2 GW/cm^2 to avoid damages of the optics. At an optical power of 20 GW, the optical spot on the mirrors needs to have a radius larger than 25 mm. A grazing-incidence ring resonator based on hyperboloids and paraboloids has been designed, constructed, and operated in a high-power FEL [9]. The laser pulse will be switched in and out of the resonator by changing its polarization using an electro-optical switch like the Pockel cell. The Pockel cell has a switch time of nanoseconds that is small compared to the round trip time of the resonator.

III. NUMERICAL SIMULATIONS

To assure the feasibility, we have performed preliminary numerical simulations of the regenerative amplifier FEL performance using a one-dimensional FEL code called FELP [10] using parameters shown in Table I. The input optical pulse is assumed to be a parabolic pulse with 50 ps pulse length and 1 mJ pulse energy, yielding a peak power of 20 MW. The input beam is focused in the center of the 10% tapered wiggler to a waist of 144 μm in radius. If we assume the Rayleigh range to be 50 cm (half the wiggler length), the optical beam waist at the ends of the wiggler is 631 μm.

Over 95 passes, the intracavity power saturates at 20 GW. The high intracavity power allows the optical field to extract energy efficiently from the electron beam. For the 10% quadratically tapered wiggler, the highest extraction efficiency is about 4.5%. In each pass, the extracted energy is a few percentages of the energy of the electron pulses (600 mJ). Over approximately 95 passes, the accumulated optical pulse energy reaches 1 J.

IV. DISCUSSION

The approach described here depends on chirped-pulse amplification (CPA). The frequency chirp has to be preserved in the regenerative FEL amplifier. A compressed pulse of

FWHM of 1 ps has a transform-limited bandwidth of 440 GHz. At 1 µm, this bandwidth corresponds to a relative spectral bandwidth of 0.15%. In an FEL amplifier, the gain bandwidth is determined by the number of wiggler periods N_W. For N_W =100, the FEL gain bandwidth is around 0.5% for a uniform wiggler and will be larger for a tapered wiggler. This bandwidth is considerably larger than the chirp of the 1-ps pulse. Therefore we expect the bandwidth of the laser pulse can be preserved in an FEL amplifier even with an unchirped electron pulse.

Table I: Parameters of Regenerative FEL Amplifier

Electron Beam

Pulse charge	q	15 nC
Pulse width	τ	50 ps nominally
Peak current	I	300 A
Pulse frequency	f	54.167 MHz
Beam energy	E	38.5 MeV (γ = 76.3)
Normalized emittance (rms)	ε_n	2.5 π·mm·mrad
Energy spread	$\Delta\gamma/\gamma$	0.5% (FWHM)

Tapered Wiggler

Taper in k_W		10%
Period	λ_W	1.023 cm
Length	L_W	1 m (N_W = 100)
Full gap	2H	3 mm
Peak magnetic field	B_W	0.585 T
Wiggler parameter (rms)	a_W	0.5586

Ring Resonator

Type		Ring, stable
Cavity length	L_c	5.534 m
Mirror radius of curvature	R_c	70 cm
Rayleigh range	z_R	50 cm (~ L_W/2)
Beam radius at waist	w_o	.378 mm
Beam radius at wiggler end	w	.753 mm
Wiggler clear aperture	2a	2.8 mm
Round-trip loss	α	2%

Table 2: Simulation Results

Wavelength	λ	1.053 µm
Small-signal gain	g_{ss}	100%
Saturated gain	G	2.1%
Intracavity power	P_{cavity}	20 GW
Extraction efficiency	η	$\leq$ 4.5%
Pulse energy	E_p	1 J
Pulse width	τ	15 ps

Special attention is required to insure that the mirrors in the resonator will retain the reflectivity and not be damaged in the high intracavity power. In this design, the peak laser intensity on the hyperboloid mirrors located 1.5 m from the waist is less than 2 GW/cm^2, below the damage threshold of dielectric mirrors.

The design described here is a point design derived from our experience with AFEL showing the feasibility of this approach. Optimized parameters can be derived with respect to specific Gamma-Gamma Collider and further simulations.

V. SUMMARY

We described a point design of a chirped-pulse regenerative-amplifier FEL system that can achieve the 1-J, 1-ps pulse needed for a Gamma-Gamma Collider. This design uses subsystems that are readily achievable with existing technology.

VI. REFERENCES

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