Optical Energy Recovery for a High Duty Cycle Gamma Ray Source

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Abstract

Energy efficiency is a critical aspect of every high energy physics accelerator due to the very large demands in terms of luminosity due to the vanishing cross-sections. Laser-based accelerators have to confront this issue, especially given that high peak power solid-state laser systems with efficiency above single digit percent levels have yet to be demonstrated. To draw a comparison with conventional accelerator techniques, klystron power amplifiers have efficiency approaching 80 % nowadays. This sets a fundamental limit on the applicability of laser-based accelerators for HEP or any other flux-hungry application. This letter describes a possible solution to this problem based on the concept of optical energy recirculation enabled by strong energy exchange between relativistic electrons and laser beams in tapered undulators.

Concept

To understand the concept we review first the Inverse Free Electron Laser (IFEL) acceleration scheme. In an IFEL, the energy exchange between the laser and electron beams takes place in vacuum, mediated by the oscillatory motion induced by the periodic field of a wiggler magnet. In order to keep resonant condition in the undulator with an increasing energy electron beam, the undulator period and amplitude are tapered, (i.e. varied) along the interaction[1-3]. A unique advantage of IFEL is its quasi-plane wave, nearly one-dimensional nature, which allows for large transverse acceptance acceleration of relatively large beam charges, without the need to worry about beam wakefield effects. Even more importantly, the interaction does not involve near field boundaries or media (dielectric or plasma) for coupling the EM waves to the electrons. This is important for two reasons. First, the laser only propagates in vacuum enabling the preservation of a high quality optical mode, a critical advantage for recirculation. Second, in this system there is by definition no 'heat' dissipation and no media boundaries exposed to breakdowns. Energy can only be exchanged between the laser and electron beams. Importantly, these characteristics allow the IFEL to be used effectively in reverse as a decelerator in the so called Tapering Enhanced Stimulated Superradiant Amplification (TESSA) scheme [4-5], as we already showed experimentally [6], to recover the laser power downstream after the high energy beam has been used.

The novel idea at the core of the proposal is to take advantage of the unique features of this interaction to implement an optical energy recirculation scheme where a high power laser pulse is used to accelerate electrons at high energy in an IFEL undulator to an interaction point and then a second undulator operating in the TESSA regime is used to recover the optical energy by quickly decelerating the electron beam. The energy-recovered laser pulse would then be stored in an optical cavity and fully available for re-use for subsequent pulse interaction, thereby enabling to increase the rep-rate of the accelerator/interaction only limited by power management considerations on the cavity mirrors.

We study the application of the concept in conjunction with an Inverse Compton Scattering interaction [7] as a high flux polarized 15 MeV gamma ray source for polarized positron production[8,9] where the beam energy is 600 MeV, but there might be other uses for this scheme, either to replenish laser pulses in other laser advanced accelerator schemes or in gamma-gamma colliders. By using a MHz rep-rate electron bunch train from an SRF linac injector and embedding the IFEL accelerator and decelerator sections in a low loss optical cavity, a very high number of laser-electron collisions can be achieved per second, with a great advantage in terms of wall-plug efficiency and system cost. According to initial studies, this idea provides the foundation of the first energy-recovered laser-driven ICS gamma ray source uniquely capable of operating at extremely high duty cycle generating more than 10^{13} – 10^{14} polarized gamma-ray photons/s as required by the demands of a polarized positron source.

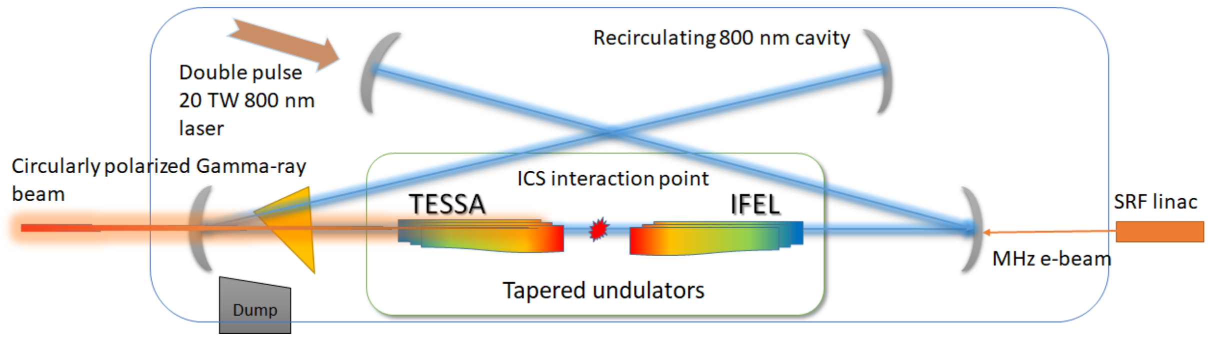

Figure 1. Cartoon schematics of the concept. A CW photoinjector and SRF linac generate a MHz-train of 100 MeV electron pulses. A compact 1 m long strongly tapered IFEL undulator driven by a circularly polarized Joule-class 5-10 TW laser pulse accelerates the electrons up to 0.6 GeV energy. The accelerated electrons collide with a counter-propagating laser pulse at the exit of the IFEL undulator and produce polarized gamma-ray photons. Downstream of the interaction, the laser beam energy is fully recovered by a TESSA decelerator section. The replenished laser pulse is then reflected back to be used to interact with the rest of the electron beam pulse train.

Our approach is fundamentally based on the fact that high energy electrons are only needed in the system to scatter off the laser photons at the ICS point and this process occurs with minimal energy loss. On average, less than 1/100 electrons participate to the interaction and with a max loss of 15 MeV (out of >500 MeV) to the gamma ray energy in the process. Therefore, the largest portion of the e-beam energy is available to be restituted to the optical pulse. In the proposed system, the main losses per cavity roundtrip result from the absorption on the cavity mirrors --below 1 % per pass-- and from the gamma-ray generation (these are minimal for the laser as less than 1 part in 1E5 of the main optical pulse is scattered in each collision). In order to re-gain the small amount of lost energy per pass, the TESSA section is tuned to decelerate the electron beam to a lower final energy than what injected by the linac.

Important issues for this concept are related to the injection in the cavity of the initial high power laser pulse, managing the average power on the cavity mirrors, and in general a lack of a suitable test-bed for these studies as there are no accessible facilities in the mid-high energy range that would allow even a few-passes demonstration experiment.

References

[1] Kroll, N., P. Morton, and M. W. Rosenbluth. "Free-electron lasers with variable parameter wigglers." *IEEE Journal of Quantum Electronics* 17.8 (1981): 1436-1468.

[2] J. Duris, et al. High gradient inverse free electron laser acceleration in helical geometry, Nature Communications, 5, 4928 (2014).

[3] J. T. Moody, S. G. Anderson, G. Anderson, S. Betts, S. Fisher, A. Tremaine, and P. Musumeci. Ultrashort laser pulse driven inverse free electron laser accelerator experiment. Phys. Rev. Accel. Beams 19, 021305 (2016)

[4] J. Duris, P. Musumeci and A. Murokh. Tapering Enhanced Superradiant stimulated amplifier. *New J. Phys.* 17 063036 (2015).

[5] A. Gover, R. Ianconescu, A. Friedman, C. Emma, N. Sudar, P. Musumeci, and C. Pellegrini. "Superradiant and stimulated-superradiant emission of bunched electron beams". Rev. Mod. Phys. 91, 035003 (2019)

[6] N Sudar, P Musumeci, J Duris, I Gadjev, M Polyaniy, I Pogorelsky, M. Fedurin, C. Swinson, K. Kusche, M. Babzien, A. Gover. High efficiency energy extraction from a relativistic electron beam in a strongly tapered undulator. Physical review letters, 117, 174801 (2016).

[7] I. Gadjev et al. An inverse free electron laser acceleration-driven Compton scattering X-ray source. Scientific Reports. Volume 9, Article number: 532 (2019).

[8] T. Omori, et al. "Design of a polarized positron source for linear colliders." Nucl. Instr. and Meth. A: 500.1-3 (2003): 232-252.

[9] V. Yakimenko, and I. V. Pogorelsky. "Polarized γ source based on Compton backscattering in a laser cavity." Phys. Rev. Accel. Beams 9.9 (2006): 091001.