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Design Considerations for a High-Efficiency High-Gain Free-Electron Laser for Power Beaming

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Abstract

Power beaming from ground-based systems to space-based platforms has been proposed by a number of researchers as a means of delivering energy to orbiting satellites and stations. This paper considers the use of a seeded high-gain high-efficiency Free-Electron Laser (FEL) amplifier based on a conventional linac as the source for power beaming. While the wall-plug efficiency of a single pass FEL is likely to be considerably lower than a recirculating system, electrical efficiency is unlikely to be a serious consideration for first-generation power-beaming systems. Moreover, the simplicity of the proposed scheme scales well from existing and completed experiments.

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1. Introduction

High average-power, high-brightness electron-beams allow for new applications especially in beam-radiation interaction and production. One such application is power beaming from ground-based sources to space-based platforms The concept of power beaming has been around since the 1960's but technical and economic hurdles prevented implementation [1]. The Free Electron Laser has been examined as a possible source for ground-based beaming already [2, 3]. Here we examine a high efficiency, high-gain FEL that can take advantage of recent progress in photoinjectors and high average-power lasers. We consider a system capable of delivering 1 KW of electrical power to a platform in geo-stationary orbit.

2. Assumptions & Efficiencies

An FEL-based system for beaming power from ground to space can be idealized as composed of the following: an accelerator, the radiator (FEL), ground optics, the atmosphere, and the receiving station. An estimate of the energy efficiency (optical or electric) guides the design of the FEL. Simplistic arguments were used; the breakdown of the efficiencies assumed is given in Table 1, and yields an overall optical efficiency of about 0.076% from "wall-plug" to satellite electrical power (at 840 nm).

Table 1: Power beaming assumed efficiencies. The assumptions are based on simplistic arguments, and are meant only to provide an order-of-magnitude estimate of the energy requirements.

Parameter	Efficiency
Geometric (Diffraction)	<64%
Solar Panel Conversion	~50%
Atmospheric Transmission	~80%
Ground Optics Transmission	>50%
Beam to FEL Conversion	≡10%
Wall to Beam Conversion (60% to RF, 10% to Beam)	6%
FEL output to Space Power	*12.7%*
Wall Plug to Space Power	*0.076%*

A more relevant figure of merit is the electron-beam power needed as earth-based electricity is

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abundant and inexpensive compared to space-based electrical production. The desired figure of merit depends on the FEL efficiency, η_{FEL} (in converting e-beam power to optical power): this study began with η_{FEL} = 10%, thus, one might expect an overall electron beam power of about 78 KW. As is discussed in the next section, the FEL efficiency — for the parameters chosen here — is difficult to raise above about 6%. Thus, a 100 KW class accelerator is needed. While the efficiencies listed are reasonable estimates, the strong effect of atmospheric turbulence has not been taken into account [4]. Here we assume that techniques such as adaptive optics can be used to limit the effect of the atmosphere.

The central wavelength of the FEL is chosen to simultaneously maximize the transmission efficiency through the atmosphere and the energy conversion-efficiency of solar panels — 840 nm satisfies these constraints while still being at a wavelength where conventional seed-lasers exist. Setting the electron-beam energy as high as possible maximizes the beam power while lowering the average beam current requirements. However, FEL efficiencies drop and undulator designs become awkward (long periods) with higher beam-energies. On the other hand, peak current is critical to FEL performance as well as to mitigating the effects of diffraction after saturation. Guided by semi-analytic codes, past design and constraining the undulator period to a maximum of about 6 cm and an undulator parameter of no more than 3, a beam energy of 200 MeV was selected initially, and then optimized to 226 MeV.

3. Prototype Design

Unlike conventional FEL sources in which various optical parameters need to be optimized, the primary consideration here is efficiency: the high average-power requirements demand efficient extractions of energy from the electron beam. The initial FEL parameters used for the optimization are listed in Table 2.

A seed laser of 1 KW was used for all simulations — an ambitious but achievable number. The pulse format of the seed laser was assumed to match that of the accelerator. A system scaled from typical UCLA designs was used: an RF system of 4 μs in duration and an uncompressed bunch-length of 5 ps. Here we assume a bunch train of 1000 microbunches, each with 3.5 nC of charge, and operating at 100 Hz — a selection well-suited to an L-band system. Various other bunch and RF formats have been considered.

Table 2: Initial FEL parameters used in the simulation studies

Parameter	Value
Central wavelength	840 nm
Beam Energy	226 MeV
Beam Current	500 A
Beam Emittance (norm. rms)	5 μm
Beam Energy Spread	0.15%
Undulator Period	6 cm
Undulator Parameter	3.0
Focusing (β-function)	87 cm

3.1 Simulations & Optimization

The parameters that remain to be determined by simulation include the undulator focusing, length, tapering gradient and taper start-point. A series of simulation were performed using the 3D FEL-simulation Genesis 1.3 [5]; keeping the parameters of Table 2 fixed, while varying the remaining parameters. The best efficiencies found for 20 m and 40 m undulators were 2.6% and 6.7%, respectively. These efficiencies were optimized (primarily) by changing the tapering gradient and starting point position. The overall taper for the optimized undulators were 5% and 15% starting at 12.5 m for the 20 m, and 40 m long undulators, respectively. Efficiencies as high as 13% were achieved, but with an unrealistically long (150 m) undulator.

4. Conclusions

Optimization of a high-gain FEL yielded a system capable of producing 1 KW of electric power in space using a 40 m undulator and a ≈100 KW electron beam. This design relies on improvements to photoinjectors and lasers that may allow for high repetition-rate, high-brightness beam production and for high-power seeding of the FEL.

5. References

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