ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-TUPOPT038

FAST-GREENS: A HIGH EFFICIENCY FREE ELECTRON LASER DRIVEN BY SUPERCONDUCTING RF ACCELERATOR

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Abstract

In this paper we'll describe the status of the FAST-GREENS experimental program where a 4 meter long strongly tapered helical undulator with a seeded prebuncher is used in the high gain TESSA regime to convert a significant fraction (up to 10%) of energy from the 220 MeV electron beam from the FAST linac to coherent 515 nm radiation. We'll also discuss the longer term plans for the setup where by embedding the undulator in an optical cavity matched with the high repetition rate from the superconducting accelerator (3 MHz or 9 MHz), a very high average power laser source can be obtained. Eventually, the laser pulses can be redirected onto the relativistic electrons to generate by inverse compton scattering a very high flux of circularly polarized gamma rays for polarized positron production.

INTRODUCTION

Improving the conversion efficiency of relativistic electron beam power into coherent short wavelength radiation is at the center of both scientific and industrial interests as it would enable light sources to reap the benefits of 100 years development in charged particle accelerator technology on how to be extremely efficient in terms of wall-plug energy usage. In the X-ray it would facilitate ultrahigh intensity X-ray laser pulses for single shot coherent imaging and Schwinger-field physics exploration, in the EUV it would meet the demands of fast throughput material processing (EUV-lithography) and at visible wavelengths it would enable high efficiency, high average and peak power lasers. It is helpful to note here how state-of-the-art X-ray sources based on the Free Electron Laser principle take advantage of only a minimal fraction ($< 0.1\%$) of the available power stored in the beam and most of it is is simply wasted on the beam dump.

The TESSA program aims at fundamentally addressing this current limitation in electron-based coherent radiation generation by exploiting a deeper understanding of the interaction of relativistic electrons with the electromagnetic field in tapered undulator systems, leveraging the progress in high brightness beam generation and control.

The physical concept behind our approach is the so-called Tapering-Enhanced-Stimulated-Spontaneous-Amplification regime of FELs where high intensity seed and pre-bunched electron beams are used in combination with strongly tapered undulators to sustain high gradient deceleration over extended distances and convert a large fraction of the beam energy into coherent radiation [1]. The main advantages of this coupling scheme are the absence of nearby boundary or media (i.e. this is a vacuum plane-wave interaction), so that there are basically no mechanisms for the energy to flow out of the particle-field system. In TESSA, the initial conditions for the system allow for particle deceleration at a very high average energy exchange rates (typically in excess of 10 MV/m) larger than in any known FEL, in order to beat the onset of sideband instabilities which have been known for decades to set the limit on tapered FEL energy exchange [2]. Previous experiments based on the TESSA concept [3] demonstrated efficiencies as high as 30% in the far-infrared. Nevertheless, they were carried out in a very low gain amplification regime resulting in a strong background signal from the seed laser which precluded obtaining direct measurements of the transverse and spectral profiles of the amplified radiation. A recent application of the TESSA concept in the THz regime demonstrated 10% conversion efficiency in 1 m long tapered helical undulator at 160 GHz [4].

Scientific and Technical Goals

The TESSA initiative at FAST is an FEL experiment aimed at demonstrating high extraction efficiency lasing (10% e-beam to light conversion) in a strongly tapered seeded regime in the visible range of the electromagnetic spectrum (initial tuning at 515 nm) with two stated scientific goals:

- The demonstration of single pass record high energy extraction efficiency from a relativistic electron beam in the visible region of the electromagnetic spectrum.
- The first experimental measurements of spectral and transverse profile characteristics of the radiation amplified in the TESSA regime of operation.

Both of these goals would represent significant breakthroughs for the development of future high efficiency light sources.

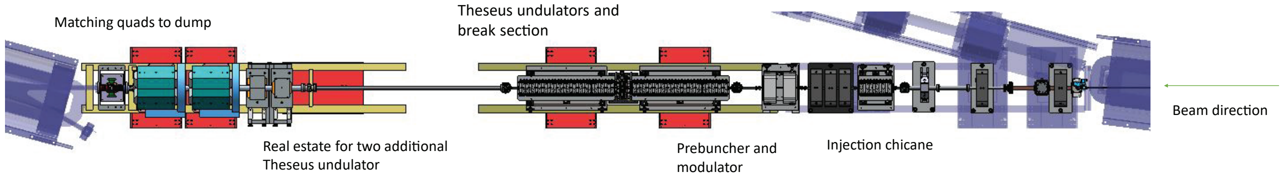

Figure 1: A schematic diagram of the proposed FAST-GREENS beamline. The beam moves from right to left. The injection chicane creates an offset in the electron beam trajectory to allow the injection of the input seed laser on axis. A modulator-chicane module is used to prebunch the beam at the seed wavelength. The energy is then extracted from the beam using four 1 m long undulator sections, separated by a quadrupole doublet to control the transverse beam size. Post-undulator diagnostics section includes matching quadrupoles, and a spectrometer dipole for beam energy measurements.

Upon successful demonstration of these goals, we would extend the FAST-GREENS research program to include other experiments which would take advantage of the unique high average power characteristics of the FAST linac.

In particular we would run the linac in pulse train mode and embed the TESSA beamline in an optical resonator in order to study the physics of the TESSA oscillator including the issues of the start-up and the establishment of longitudinal and transverse eigenmodes in the lasing [5]. Assuming an input beam power at the 10 kW level, even a 10% energy conversion efficiency would realize a 1 kW laser system. Note that given the pulse format and duty cycle (0.1%) of the FAST linac, the intrapulse peak power of the radiation approaches MW-levels.

This enormous level of visible laser power would enable gamma-ray production using inverse Compton scattering of the TESSO output with the relativistic electron beam. Preliminary estimates for the flux from such source yield 10^{11} ph/sec, higher than any other gamma-ray source available [6].

An interesting high energy physics application of the high-flux circularly polarized gamma-rays is to send the beam into a solid target for polarized positron generation. This is currently the main mechanism proposed to supply this particle species to the future linear colliders. In current design the source is based on gamma-ray generated by a 120 GeV passing through 100 m of undulator, but a compact, fully independent source based on ICS can significantly simplify the system and potentially allow for even higher polarization degree [7]. For all these reasons (and in recognition of the radiation wavelength), we have adopted the acronym FAST-GREENS: a Gamma-Ray high Efficiency ENhanced Source at the FAST Linac. While the long term goals of the program are well recognized and supported by the entire collaboration, this initial proposal will not address the experimental challenges in these long-term developments, and focus on the first proposed set of experiments.

A schematic of the FAST-GREENS beamline is shown in Fig. 1. The wavelength for the experiment is selected based on the availability of the strong seed signal. As the Yb-based laser previously purchased for the experiment provides pulses at 1030 nm, the choices are restricted to 515 nm or 257.5 nm. The THESEUS undulator has the flexibility to reach the UV region of the spectrum, but this would require increasing the beam energy to > 300 MeV and would also pose tighter requirements on beam emittance and unnecessarily complicated diagnostics. Henceforth, we then propose to tune the system at 515 nm where the linac can be conservatively operated at 220 MeV, the undulator tuned at the already demonstrated magnetic field amplitude of 0.75 T with a larger gap.

Table 1: Design Parameters for FAST-GREENS Experiment

Parameter	Unit	Value
Beam Energy	MeV	220
Bunch Charge	nC	1
Peak Current	A	600
Bunch Length, FWHM	ps	1.6
Normalized Emittance	mm-mrad	3
Uncorr. Energy Spread, FWHM	keV	220
Resonant Wavelenght	nm	515
Input Seed Power	GW	1
Laser Rayleigh Range	m	1.5
Undulator Period	mm	32
Undulator K		2.3-2

Nominal parameters for the FAST beam are reported in Table 1. The experiment is designed assuming an electron beam with 1000 pC charge, compressed to 0.6 kA by the magnetic chicane compressor with a normalized emittance of < 3 mm-mrad and a relative energy spread of 0.1%. The intense green seed pulse of nominal peak power 1 GW (2 mJ in 2 ps in order to homogeneously seed the entire bunch temporal current profile) is obtained from a recently purchased laser system from Amplitude that will be installed in a newly refurbished laser room located above the FAST linac. During the initial phase (Stage 0) of the experiment, the laser will not be needed and therefore the implementation plan for this component of the system is still subject of ongoing discussions within the collaboration.

Genesis simulations are performed to optimize the tapering of the undulator and indicate that up to 10% efficiency could be reached in the system. The results are shown in Fig. 2. Significant efforts are currently ongoing to explore different approaches to shape the temporal profile of the

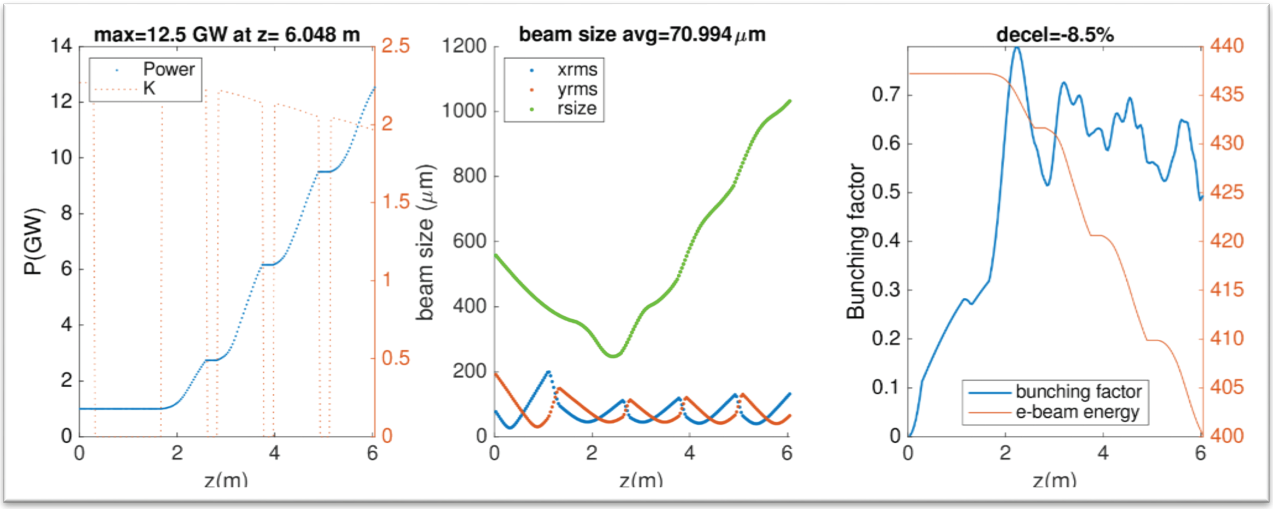

Figure 2: Results of Genesis simulation showing the design tapering and resonant energy along the undulator. The radiation and e-beam spot sizes and the bunching factor evolution are also shown.

electron beam from the FAST linac in order to match it to the TESSA application. Due to slippage effects it is of great importance to achieve the high peak current in a relatively long (1.5 ps or so) region of the electron beam while at the same time maintaining good emittance and low energy spread.

The experimental plan for FAST-GREENS has been divided in stages or phases where the various components can be added sequentially to the beamline. There are many advantages of a staged approach as it will allow to establish running conditions for the experiment in a time more compatible with the facility operation and the collaboration schedule, leaving ample time to implement improvements to the beamline. The initial phase of the experiment has been termed Stage 0 and will include propagation of the electron beam in the injection chicane, prebuncher, and first undulator section without any seed laser. The goals of this phase will be to establish alignment and transverse matching through the system, develop and commission the e-beam diagnostics, and demonstrate of undulator break-section components (quadrupole doublet and phase-shifter).

ACKNOWLEDGEMENTS

Work partially supported by DOE grant DE-SC0009914, DE-SC0018559 and DE-SC0017102

REFERENCES

[1] J. Duris, A. Murokh, and P. Musumeci, “Tapering enhanced stimulated superradiant amplification,” *New Journal of Physics*, vol. 17, no. 6, p. 063 036, 2015, `doi:10.1088/1367-2630/17/6/063036`

[2] A. Gover *et al.*, “Superradiant and stimulated-superradiant emission of bunched electron beams,” *Reviews of Modern Physics*, vol. 91, no. 3, p. 035 003, 2019, `doi:10.1103/RevModPhys.91.035003`

[3] N. Sudar *et al.*, “High efficiency energy extraction from a relativistic electron beam in a strongly tapered undulator,” *Phys. Rev. Lett.*, vol. 117, p. 174 801, 17 2016, `doi:10.1103/PhysRevLett.117.174801`

[4] A. Fisher *et al.*, “Single-pass high-efficiency terahertz free-electron laser,” *Nature Photonics*, vol. 16, no. 6, pp. 441–447, 2022, `doi:10.1038/s41566-022-00995-z`

[5] J. Duris, P. Musumeci, N. Sudar, A. Murokh, and A. Gover, “Tapering enhanced stimulated superradiant oscillator,” *Physical Review Accelerators and Beams*, vol. 21, no. 8, p. 080 705, 2018, `doi:10.1103/PhysRevAccelBeams.21.080705`

[6] Y. K. Wu *et al.*, “Performance and Capabilities of Upgraded High Intensity Gamma-Ray Source at Duke University,” in *Proc. PAC’09*, Vancouver, Canada, May 2009, pp. 3181–3183, `https://jacow.org/PAC2009/papers/TH4PBC06.pdf`

[7] I. Chaikovska *et al.*, “Positron sources: From conventional to advanced accelerator concepts-based colliders,” *Journal of Instrumentation*, vol. 17, no. 05, P05015, 2022, `doi:10.1088/1748-0221/17/05/P05015`