INVERSE FREE ELECTRON LASER ACCELERATORS FOR DRIVING COMPACT LIGHT SOURCES AND DETECTION APPLICATIONS*

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Abstract

Because of the broad application space for compact, 1-2 GeV accelerators, Inverse Free Electron Lasers (IFELs) are enjoying a rebirth of R&D funding. Efforts are under way in industry (RadiaBeam), academia (UCLA), and national laboratories (LLNL and BNL) to develop an ultra-compact IFEL energy booster for the photoinjector driven linear accelerating systems. The RUBICON collaboration integrates many of these institutions for proof-of-principle IFEL driven Inverse Compton Scattering (ICS) compact light source demonstrations. IFELs perform optimally in this mid-energy range, and given continual advances in laser technology, high average power IFELs with gradients well over 500 MeV/m are now feasible, leading to high quality, compact ICS and Free Electron Laser light sources. Importantly, IFEL operation can have excellent shot-to-shot energy stability, which is crucial when not only driving these light sources, but also for the downstream applications such as photofission, nuclear resonance fluorescence and stand-off detection.

INTRODUCTION

A recent resurgence of IFEL interest originated in a need for compact, high rep rate 1 GeV class accelerators to drive compact inverse Compton back scattered gamma ray sources (IGS) as well as emerging 4th generation X-ray light sources, such as FELs. For these systems to be deployable and of a practical footprint, a solution that goes well beyond the conventional S-band, Super Conducting (SC) and X-band radio frequency (RF) gradients is required. The IFEL is a natural driver for ICS as the same laser can be used for both the IFEL and ICS interaction, and laser recirculation offers a clear path to extremely high rep-rates/average power for the accelerator and ICS interaction. The ICS spectra generated from such devices (highly directional, quasi-monochromatic) can be utilized for photofission-based long distance stand-off interrogation of special nuclear materials (SNM) whose line width is relatively broad.

The US Department of Energy High Energy Physics program (DOE HEP) has historically supported IFEL for developing advanced acceleration techniques for the next linear collider R&D. A number of successful proof-of-principle IFEL experiments at BNL [1] and UCLA [2] independently demonstrated good electron beam capture (> 70%) and high gradient acceleration (> 70 MeV/m), respectively. However, since synchrotron radiation effects significantly degrade IFEL performance beyond 10 GeV, IFEL funding has been scarce since 2005.

*Work supported by DTRA Grant No. HDTRA-10P-0021
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IFEL DRIVEN ICS

Inverse Compton scattering (ICS), whereby a high power (TW class) laser beam collides with an electron beam, produces upshifted photons from that of the (near infrared) laser by γ^2 with a $1/\gamma$ emission angle, where γ is the energy of the electron beam [3] Stand-off detection of SNM, for example, requires 10-20 MeV directional gamma rays, which can be generated with an ICS system driven by up to a 1 GeV accelerator [4]. Here, photon induced fission produces signals of prompt neutrons and gammas (from initial fission), and delayed neutrons and gammas from daughter nuclei that are a signature of SNM. The accelerator size is the main driver for determining the footprint of these systems, giving advanced accelerators a strong advantage for deployable systems.

In an IFEL accelerator [5,6], electrons propagating through a magnetic undulator gain a sinusoidal transverse velocity vector and remain in phase with the transverse electric field of a co-propagating laser, see Fig. 1. Energy is transferred from the laser to the electron beam, thus giving the electrons a net acceleration throughout the undulator. This resonance condition in a helical undulator is governed, like that of an FEL, by,

$$\gamma^2 \approx \frac{\lambda_w}{2\lambda}(1+K^2), \quad (1)$$

where γ is the electron beam energy, λ_w is the undulator period; λ is the laser wavelength, and K the undulator parameter. In order for the electrons to both increase in energy and remain in phase with the accelerating field, the undulator is tapered (λ_w and K increase along the undulator).

Four key advantages of IFELs include (1) long interaction lengths compared to other advanced techniques (2) is a far field accelerator where the fields are in vacuum and not prone to field breakdown (3) energy efficient interaction especially important to laser

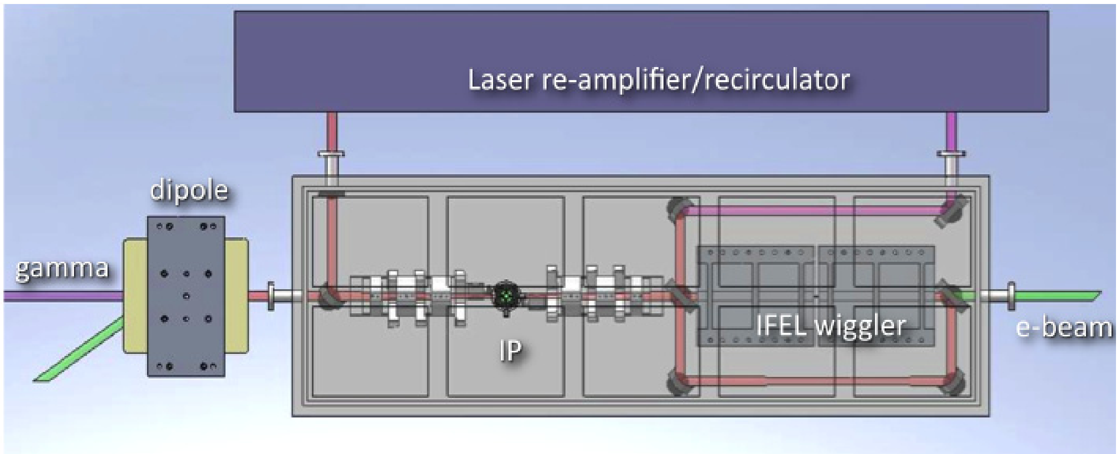

Figure 1: Interaction IFEL-ICS interaction Region with laser recirculation. Electron is injected from the right.

recirculation configurations (4) excellent output energy stability due to fixed configuration compared to nonlinear fluctuations.

When designing an IFEL, an optimized relationship between the IFEL drive laser Rayleigh range and total undulator length is L_u~$6z_r$, where a tight focus increases intensity, but a larger Rayleigh range maximizes gradient over the entire undulator [7]. The maximum accelerating gradient, assuming optimized single stage helical undulator, is defined by a maximum magnetic field, which can be achieved in the gap. Using formalism presented in Ref. [7], with about ~ 5 TW solid state laser (Ti:S), and using a state-of-the-art ambient temperature permanent magnet undulator, an accelerating gradient of about 500 MeV/m can be achieved. While such solid state laser driven system development is an ultimate goal of the IFEL program, 10 µm CO_2 lasers for the pilot IFEL have been traditionally used [1,2] due to practical aspects of satisfying resonant condition (Eq. 1) while operating at relatively low electrons energies.

Following this tradition, the **R**adiaBeam-**U**CLA-**B**NL-**I**FEL-**C**ollaborati**ON** (RUBICON) collaboration was formed to explore IFEL driven Compton light sources. The three primary objectives of the RUBICON proof of principle experiments include 1) demonstrate high IFEL acceleration gradient (~ 200 MeV/m) and good capture (> 50%) in a half-meter long accelerating structure at the Accelerator Test Facility at BNL 2) develop and experimentally demonstrate laser recirculation-reamplification to enable high average operation of IFEL in a pulse train mode and 3) demonstrate combined ICS/IFEL system in a pulse train mode.

For the integrated IFEL-ICS configuration, see Fig. 1, a single laser can drive both the IFEL and ICS interaction. If the laser is made to recirculate as shown in the figure, then the system's rep-rate can increase significantly, thus increasing the average power of the accelerator and ICS generated radiation. In Fig. 1, a photo-injector based low energy (~ 50 MeV) electron pulse train arrives from the right and passes first through the IFEL undulator, and then through the ICS interaction point (IP). For (recirculation) operation, after an electron pulse interacts with a laser pulse in the IP, the laser beam quality remains intact and it can be redirected into the IFEL undulator. The recirculated laser pulse accelerates the next electron bunch to the nominal energy (700-800 MeV), which in turn interacts at the IP with the next laser pulse to produce 12-15 MeV gammas. The IFEL process extracts not more than a few percent of the laser energy, hence, to achieve good system efficiency the laser pulse is re-amplified and re-circulated back towards IP. A gamma beam generated at the IP illuminates the stand-off target while the electron beam is disposed with the dipole magnet. The proposed system is very efficient, eliminating a 20+ meters long RF linear accelerator to drive ICS.

IFEL PARAMETERS

The future near infrared (NIR) IFEL laser will deliver near 5 TW peak power in relatively inexpensive configurations for achieving gradients well in excess of 500 MeV/m. To achieve this power, shorter pulse lengths, and thus less per shot energy is desired. Both Ti:S and glass laser technology can lead to the required high power, high repetition rate femtosecond performance. Ti:S systems presently exist on the market, ~ 10 mJ femtosecond pulses at the repetition rates of up to 1 kHz. Combined with the rapid development of high repetition rate photoinjector technology, development of such laser systems offer a sound path forward to high average power integrated IFEL-ICS systems.

Using 3-D IFEL simulations, the initial parameters for a high gradient IFEL to drive an ICS system for standoff detection were determined. The system was evaluated for the two cases: using a normal (room temperature) wiggler, and a cryogenically cooled wiggler for achieving higher peak field in the gap. The normal conducting schemes is shown in Table 1 and based on the up to date state-of-the-art technological capabilities. In the context of the stand off detection – due to a relatively broad photofission cross-section – ICS/IFEL system does not require large tunability to start with, as long as the target electron beam energy (700-800 MeV) is met.

Table 1: RUBICON Parameters in Comparison to a Future Deployable Application

Parameter	RUBICON	Final System
Input/final electron energy	50-150 MeV	75-700 MeV
Laser λ	10.6 μm	800 nm
Accelerating gradient	~200 MeV/m	>600 MeV/m
Laser power	.5 TW	5 TW
Rayleigh range	9 cm	15 cm
Wiggler length	60 cm	100 cm

RUBICON EXPERIMENT DESIGN

RUBICON efforts are to design and demonstrate a pilot experiment at the Accelerator Test Facility (ATF) at BNL to demonstrate high gradient (200 MeV/m), high average power recirculated IFEL. The RUBICON experiment will be undertaken at the ATF Beamline 2, which is already equipped with the CO_2 injection window. The 9-atm cavity located in the CO_2 room will generate the initial seed pulse, and pulse timing can be precisely adjusted with respect to the photo-injector drive laser, which defines timing of the electron beam. The ATF CO2 laser system, capable of TW pulses at 10.6 μm, which could be upgraded to 5 TW gives some head room for the initial experimental design calling for 0.5 TW. While the laser frequency is different from the intended end use system discussed above, it is ideal for the prototype experiment. Since the resonant condition in the wiggler scales like the square of the electron energy, RUBICON's goal of achieving acceleration from 50 MeV to 150 MeV in a 60 cm IFEL wiggler, using a 10 μm drive laser (see Table 1) is directly scalable to the end use acceleration from 75 MeV to 700 MeV in one meter, using 800 nm laser.

The undulator optimization was performed using a combination of codes RADIA, TREDI and 1D IFEL. A solution was chosen based on a permanent magnet Halbach configuration with 4 magnets per period. The helical undulator field, which is superior for IFEL applications, is obtained by superposition of two Halbach arrays rotated 90 degrees with respect to each other and shifted by a 1/4 of a period. The 3D field map generated with RADIA was input into the 3D particle tracking IFEL simulations, which confirmed good acceleration. The RUBICON IFEL optimization was performed initially in a 1D FEL code developed at UCLA, followed by more detailed optimization of the working point using the 3-D code GENESIS 1.3 [8], a powerful FEL simulation code custom modified to allow IFEL simulations. With the pre-buncher, Simulation confirmed an energy gain of about 200 MeV/m, and with a pre-buncher, beam capture exceeding 50%.

In order to increase average power operation, pulse train/recirculation operation of the IFEL-ICS shown in Fig. 1, will be demonstrated. The ICS interaction cross section is very small, and the overall photon loss is insignificant, so the laser after ICS IP can be immediately utilized for IFEL acceleration. The IFEL interaction consumes only 3-5% of the laser energy that can either be recuperated or otherwise compensated by an active laser cavity. In the same time, the photoinjectors offer the existing capability to produce bunch trains separated on the same time scale. As a consequence, one can recirculate the laser beam to run IFEL-ICS integrated systems shown in Fig. 1 in a pulse train mode, thus gaining signal enhancement to reach the target photon flux output.

The RUBICON IFEL recirculation design includes a train of 6 CO_2 pulses 12.5 ns apart, with up to 17 reamplification passes limited by the amplifier windows toleration of the average power. One fundamental aspect of the recirculated interaction will be to maintain a reasonable temporal mode structure in the laser beam despite the laser energy absorption by the electron beam. Simulations of the laser pulse evolution inside the active cavity include optical losses and laser energy consumption by the electron beam in the recirculated regime. These results indicate a relatively high tolerance by the CO_2 laser system in the presence of energy losses due to electrons acceleration at the core of the laser beam.

CONCLUSION

The RUBICON R&D program is presently underway at the Accelerator Test Facility at BNL, with the single pass experiment preparations ongoing, and the recirculation IFEL experiment at 10 μm planned for 2012-2013. The ultimate development goal is to enable a compact footprint, integrated, recirculated IFEL-ICS gamma-ray source [4]. In parallel, there is an ongoing synergetic IFEL R&D work at LLNL at optical wavelengths [9].

Besides the ICS, an important application of the high repetition rate IFEL technology is a driver for the next generation, room-size, GeV-class light sources, and FELs.

This work is supported by Defense Threat Reduction Agency (DTRA) SBIR Phase I Grant No. HDTRA-10P-0021.

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