High repetition-rate inverse Compton scattering x-ray source driven by a free-electron laser

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Abstract
We describe a hybrid free-electron laser (FEL)/inverse Compton scattering (ICS) system that can be operated at very high repetition rates and with higher average gamma-ray fluxes than possible from ICS systems driven by J/kHz laser systems. Also, since the FEL system can generate 100 mJ class photon pulses at UV wavelengths, the electron beam energy can be lower than for systems driven with ~micron wavelength lasers for attaining gamma rays of similar energy.

Keywords: inverse Compton scattering, free-electron laser, microtron

1. Introduction
Gamma rays from 1 to 20 MeV have been identified as probes for atomic structure, studying nucleosynthesis and the production of heavy elements beyond iron, and observing new fundamental processes in quantum electrodynamics. They can be used to study the giant dipole resonance, the Pigmy dipole resonance, other collective nuclear resonances, and their transition to chaotic resonances. Parity violations in weak–strong coupling mechanisms can also be studied. These considerations have led to interest in bright, tunable, and monoenergetic gamma ray sources, including using inverse Compton scattering (ICS) of micron-scale wavelength photon off highly relativistic electrons (>200 MeV) [1–3]. The PLEIADES ICS source [4] at the Lawrence Livermore National Laboratory was built as an alternative 4th generation light source to x-ray free-electron lasers (FELs), and was first operational in 2003 producing x-rays up to 120 keV. A new major ICS facility in Europe (the extreme light infrastructure —nuclear physics [5] in Romania) is currently in the preparatory stages for construction for studying fundamental nuclear physics as listed above.

Recently, interrogation with high-flux gamma rays have also been proposed as an approach for detecting special nuclear materials (SNM) and to address international nuclear proliferation concerns. Gamma rays with energies >6 MeV can be used for photofission and gamma rays with energies on the order of an MeV can be used for nuclear resonance fluorescence (NRF). NRF can be used both for non-destructive radionuclide assay (e.g., determining isotopic concentrations of SNM in stored waste containers) and for detection of contraband SNM at checkpoints. NRF-based detection schemes require high fluxes and narrow gamma-ray energy widths to be practical. Individual NRF resonances of SNM in the MeV range have widths of about an eV and NRF transitions from long-lived isotopes are separated by about a keV, thereby requiring a nearly monoenergetic source of gamma rays (with bandwidths approaching $10^{-3}$) for discrimination. High resolution transmission NRF was demonstrated in 2006 [6]. Subsequently, 1.7–2.2 MeV NRF has been used to detect $^{238}$U [7], 478 keV NRF has been used to detect $^7$Li [8], and 5.7 MeV NRF has been used to detect $^{208}$Pb [9]. Several novel ICS production schemes have been recently proposed [10–12], including two using superconducting energy-recovery linacs (ERLs) for high gamma-ray fluxes [13, 14]. All these systems depend on the
interaction between an external optical laser and a relativistic electron beam.

Here we alternatively describe a FEL/ICS hybrid where the photons for the ICS interaction do not come from an external laser. In this scheme, the photons are generated through an FEL interaction by the same electrons that are used for the ICS interaction. This scheme exploits the natural high repetition rate of RF accelerators, in many ways similar to the scheme used at the high-intensity gamma-ray source (HIGS) facility at Duke University [15] and also in some ways related to the microtron-driven Japanese Atomic Energy Agency (JAEA) compact x-ray source [16]. At only 0.3% duty factor, such a device would be capable of producing $10^{12}$, 1.3 MeV (peak) x-rays s$^{-1}$, based on a 6 MeV photo-injector followed by a 3-pass, 41 MeV microtron (total electron beam energy of 129 MeV). Using an FEL, the 129 MeV electron beam is used to generate 248 nm light which then generates the gamma rays by striking the electrons before they enter the FEL undulator. We propose a modest pulse format with 25 $\mu$s macropulses at 120 Hz, with 2700 electron bunches within each macropulse (micropulse repetition rate of 108 MHz), leading to $3.24 \times 10^5$ electron bunches (and gamma ray pulses) per second.

The HIGS facility uses a similar FEL/ICS hybrid approach, driven by the DUKE FEL storage ring. (The HIGS facility was used for the $^{238}$U NRF test reported in reference [7].) The three advantages of the proposed scheme are: (1) significantly high flux due to the higher duty factor capability of a linac-based system over a storage ring, (2) significantly larger bandwidth on axis due to the lower electron beam emittance and energy spread from a linac as compared to a storage ring, and (3) more compact size (the total accelerator can be 5 m long, or less). For comparison, the 1–2 MeV gamma-ray flux from the 54 m long HIGS source is about $4 \times 10^8$ x-rays s$^{-1}$; on the other hand, this length does provide the ability to generate gamma ray energies up to nearly 100 MeV. The JAEA system also uses a microtron (150 MeV total energy gain with 6 MeV gain per turn and 25 turns). However, the JAEA system uses a single 700 mJ Nd: YAG ICS collision laser, and is limited to 10 Hz (or about $10^4 \times 400$ keV x-rays s$^{-1}$). It is important to point out that both this proposed scheme and the HIGS scheme provide automatic synchronization between the electrons and the FEL photon pulses, eliminating any timing or synchronization issues. Finally, this flux can be increased by another two orders of magnitude by using CW superconducting instead of low-duty factor room temperature RF linac technology, similar to the proposed use of ERL technology in references [13, 14].

\section{System description}

It is well accepted that ICS can generate narrow-band, MeV-regime x-rays. Previous ICS sources tended to be low flux due to the small Thompson cross section ($\sigma_T \sim 0.655$ barn) combined with low laser repetition rates. The number $N_{\text{f, x-ray}}$ of x-rays generated per second by collisions between a laser pulse with $N_f$ photons and an electron bunch with $N_e$ electrons with $f$ collisions per second is

$$N_{\text{x-ray}} = f \frac{\sigma_T N_f N_e}{\pi (\sigma_t^2 + \sigma_e^2)},$$

where $\sigma_t$ is the transverse rms size of the laser pulse and $\sigma_e$ is the transverse rms size of the electron bunch. To quantify the magnitude of this expression, $N_{\text{x-ray}} \sim 10^6$ from a single interaction of a 250 pC bunch interacting with 0.1 J, 248 nm laser pulse, both with a radius of 35 $\mu$m. Some gains in flux can be made through reducing the transverse laser and/or electron beam dimensions, but to achieve a flux of $10^{12}$ x-rays s$^{-1}$ either the collision repetition rate frequency has to be $\sim 10^6$ or there needs to be a combination of increased repetition rate and an increased number of either photons or electrons. It is worth pointing out that increasing the average flux through frequency of collisions instead of laser field amplitude helps to suppress nonlinear ICS x-ray energy broadening.

\subsection{Basic system concept}

We increase the time averaged x-ray flux by using 324 000 electron pulses per second in the format described below, which is standard for room temperature linacs. This leads to an average current of only 81 $\mu$A (27 mA during each macropulse), which is well within conventional accelerator technology. We also consider the case where the electron bunches generate the laser pulses themselves through an FEL interaction. This scheme, very similar to how the HIGS x-ray facility operates, is robust and automatically provides timing synchronism between the electron bunch and laser pulse. Use of an FEL to generate a UV laser pulse also allows operation with a lower electron beam energy. Unlike the Duke configuration, in this proposed system the FEL is driven by a microtron and not a storage ring, removing limitations on FEL extraction efficiency (and optical power generated) and reducing ICS photon bandwidth growth, both imposed by storage-ring dynamics. We can generate 248 nm photon bunches using a near-concentric resonator in order to create a very small photon beam waist at the collision point at the center of the resonator. At the collision point, the electron beam will be at a small angle with respect to the optical resonator axis, and the x-rays are also emitted at that angle and will not interfere with the downstream optical mirror of the oscillator configuration. Specifically for the system we studied, a 129 MeV electron beam drives a 248 nm FEL, and the interaction between the 129 MeV electron beam and the 248 nm photons generates 1.3 MeV x-rays, with an average flux of $1.9 \times 10^{12}$ x-rays s$^{-1}$. The overall architecture is shown in figure 1. A 250 pC electron bunch is generated in the 1.3 GHz, 6 MeV photoinjector, operating with a micropulse repetition frequency of 108 MHz with a 25 $\mu$s macropulse as shown pictorially in figure 2.

There are 2700 electron bunches per macropulse, and about $3.24 \times 10^5$ electron bunches per second. The duty factor
is 0.3%. The average current from the photoinjector during the macropulse is 27 mA. The photoinjector will require about 16 MW of RF power during the macropulse and about 48 kW of average RF power. These repetition rates are easily achieved with L-band (1.3 GHz) photoinjectors [17] and represent no risk. Likewise, the RF power requirements can be met by conventional commercial klystron technology.

The electron bunches are injected into a three-pass, 41 MeV microtron linac, as shown in Figure 1. The linac, also operating at 1.3 GHz, has a gradient of 20 MV m⁻¹ and a total length of about 2.1 m. The linac RF fields will require about 16 MW of RF power and the electron beam 3 MW of additional RF power during the macropulse (19 MW total) from a second klystron, and about 57 kW of average RF power. The total amount of cooling at full repetition rate (≈200 kW including magnets and the klystron dumps) is challenging, but manageable.

The electron beam is bent in 180° dipoles on either side of the microtron, creating a return path through the linac twice. The beam from the photoinjector fills every 12th RF bucket (i.e., there are 12 RF periods between bunches). The beam paths through the dipoles are phased for maximum bunch separation such that every 47 MeV bunch is injected in the 4th RF bucket after a 6 MeV bunch and every 88 MeV bunch is injected in the 8th RF bucket after a 6 MeV bunch. The average current from all passes combined in the microtron linac is 81 mA during the macropulse, with a true average current of 243 μA.

The electron bunch length is 5 ps, leading to a current along the bunch of 50 A. The bunches pass through an FEL oscillator with 20 periods of 2.54 cm, and normalized undulator parameter of $K_{\text{rms}} = 0.5$ (with an undulator gap of 1.60 cm). The total undulator length is 13.84 m, with a total resonator loss of 1% (using low-loss KrF excimer laser optics). As a result of the gain and optical losses, each FEL optical pulse contains about 67 mJ of energy (extracting about 2% of the electron bunch energy in each pass), and as a result of the resonator length, there are about ten optical pulses within the resonator. The power density on the resonator mirrors is about 135 kW cm⁻² during the macropulse. This power density is challenging, but certainly achievable with modest development of ion-beam sputtered multilayer dielectric coatings [18].

Each of the ten optical pulses is coincident in the undulator with ten successive electron bunches, stimulating emission of about another mJ of 248 nm UV photons through the 0.508 m long undulator. Due to the tuning of the resonator (leading to additional slippage per pass), the optical pulse is longer than the electron bunch (which is 1.5 mm long), extending to about 2.5 mm (about 10⁴ wavelengths long). On the return path, the optical pulses travel in the opposite direction of the electrons, causing collisions. The undulator is not located in the middle of the resonator; rather, it is downstream of the center, allowing a primary ICS collision point in the center of the resonator and just before the undulator, as shown in Figure 3. Electron beam optics focus the electron bunch to a transverse rms size of 35 μm at the start of the undulator and UV optics with a resonator Rayleigh

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**Figure 1.** Hybrid FEL/ICS architecture driven by a 129 MeV microtron. For the nominal design parameters described in the text, the microtron accelerator including the two dipole magnets and return optics is about 4.5 m long by 1.5 m wide (assuming a conservative dipole field of 5 kG). The 6 MeV photoinjector with merge optics will require an additional 2 m of space. Only a 10 kW electron beam dump is needed, which is relatively small. The UV FEL resonator length is about 14 m long, based on a relatively conservative constraint of maximum power density on the UV optics (135 kW cm⁻²). In an actual design, we would physically place the accelerator below the optical cavity, leading to a total ICS source footprint of 14 m long by 1 m high by 1.5 m wide. The length can be reduced with improvements in UV optics. In addition to size shown, two klystrons and modulators are needed as well as a chiller or facility temperature-controlled water supply.

**Figure 2.** Electron injector micropulse and macropulse structure, with 324 000 electron bunches per second.

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1 See for example the 30 MW peak, 60 kW Thales TV-2022 klystron, www.thalesgroup.com/sites/default/files/asset/document/TV2022.pdf and the 10 MW, 250 kW Thales TH-2104 klystron, www.thalesgroup.com/sites/default/files/asset/document/TH2104.pdf.
length of 3.09 mm focus the UV pulse to about 16 μm. (The electron bunch transverse size is not decreased further to avoid additional x-ray energy broadening on axis due to beam divergence effects.) The undulator magnetic field strength leads to a maximum electron beam undulating angle of 1.97 mrad. Two-plane undulator focusing maintains a 35 μm beam size through the undulator. The first undulator magnet has a length three times the length of the normal undulator magnets (a length of 3.81 cm) to allow the electron beam to be injected into the undulator at an angle of 9.9 mrad. The ICS interaction point is right at the point before this first undulator magnet. The 9.9 mrad angle ensures the x-rays will pass to the side of the UV optics. (Alternatively, a ‘zig–zag’ bend [19] can be used to create the required ∼10 mrad angle between the electron beam at the collision point and the UV optical axis). There is a negligible reduction in x-ray photon energy due to the laser wavelength shift caused by this geometry (this energy shift is about 0.05% of the unshifted energy). With the parameters above, about 1.9 × 10¹² 1.3 MeV x-rays are generated per second, with a minimum relative bandwidth on axis of 0.08% making such a source suitable for NRF interrogation. A 1% bandwidth of the x-rays is achieved with a collimation angle of 0.4 mrad, collecting about 6 × 10¹⁰ photons per second.

A summary of the nominal operating parameters is provided in tables 1–4 for the electron beam, RF power, FEL and optical pulses, and ICS pulses.

### 2.2. X-ray bandwidth broadening

The minimum on-axis bandwidth broadening is given by

\[
\frac{\Delta E}{E} = \frac{1}{2(k_0 c \Delta t)^2} + \frac{1}{(k_0 \eta)^2} + 4 \left( \frac{\Delta \gamma}{\gamma} \right)^2 + \left( \frac{\varepsilon_P}{\varepsilon_0} \right)^2 + NL,
\]

where \(k_0 = 2\pi/\lambda\) is the laser light wavenumber, \(\Delta t\) is the laser pulse length, \(\eta\) is the laser focal spot size, \(\Delta \gamma/\gamma\) is the electron beam energy spread, \(\varepsilon_P\) is the electron beam’s normalized emittance, \(\varepsilon_0\) is the electron beam waist radius, and NL stands for nonlinear effects that arise with large normalized laser amplitudes (\(A \geq 1\) where \(A = \sqrt{8} e^2 P \left( \frac{m_e c^5}{\varepsilon_0 (k_0 \eta)^2} \right)^{3/2} \)).

### Table 1. Electron beam.

| Parameter            | Value |
|----------------------|-------|
| Electron bunch charge| 250 pC|
| Electron bunch energy| 129 MeV|
| Micropulse rep rate  | 108 MHz|
| Macropulse length    | 25 μs |
| Macropulse rep rate  | 120 Hz|
| Peak current         | 50 A  |
| Normalized emittance | 1 μm  |
| Energy spread        | 0.01% |
| Focused size         | 35 μm |

### Table 2. RF and accelerator system.

| Parameter            | Value          |
|----------------------|----------------|
| Number of klystrons  | 2              |
| Klystron power rating| 20 MW          |
| Total klystron power | 37 MW          |
| Average klystron power| 111 kW        |
| Number of linac sections| 2             |
| Length of each linac section| 1.03 m |
| Number of cells in each linac section| 9     |
| Total accelerator length| 6 m          |

### Table 3. FEL parameters.

| Parameter            | Value          |
|----------------------|----------------|
| Number of undulator periods| 20            |
| Undulator length     | 0.508 m        |
| Resonant wavelength  | 248 nm         |
| Undulator small-signal gain| 54%         |
| Intra-cavity pulse energy| 67.4 mJ     |
| Resonator length     | 13.84 m        |
| FEL mode radius at waist| 13 μm        |
| Average UV power density on the mirrors| 135 kW cm⁻² |

### Table 4. ICS parameters.

| Parameter                        | Value          |
|----------------------------------|----------------|
| X-ray energy                     | 1.3 MeV        |
| Electrons/bunch                  | 1.56 × 10⁹     |
| UV photons/pulse                 | 8.4 × 10¹⁶     |
| ICS x-rays/collision             | 5.8 × 10⁶      |
| ICS x-rays s⁻¹                   | 1.9 × 10¹⁵     |
| 1% collimation angle             | 0.395 mrad     |
| 1% flux                          | 5.7 × 10¹⁰ s⁻¹ |
| X-ray size at end of resonator   | 27.3 mm        |
| Minimum relative bandwidth       | 8.4 × 10⁻⁴     |

Figure 3. Notional schematic of interaction geometry. The undulator starts downstream of the center of the optical cavity. The undulator starts with an extra long magnet, requiring the electron beam (the solid black line) to be injected at a 9.90 mrad angle. The x-rays pass through the undulator gap and miss the mirrors.
UV optical pulse linewidth ($\sim 10^{-5}$) and the electron beam energy spread ($\sim 10^{-5}$) are negligible. The normalized UV laser amplitude is small ($A = 0.015$), leading to negligible nonlinear bandwidth broadening. If the microtron can conserve the nominal emittance from a modern high-brightness photocathode operating with 250 pC ($< 0.5 \mu m$ [20]), we can reduce the focused electron beam size to 20 $\mu m$, producing $3.3 \times 10^{12}$ 1.3 MeV x-rays s$^{-1}$ with a minimum relative bandwidth of $6.6 \times 10^{-4}$.

A linac-based hybrid FEL/ICS design is superior to a storage ring-based hybrid design because the ICS interaction can be made with electrons before their energy spread is spoiled by the FEL interaction. For our case, the induced energy spread from the FEL interaction is $\sim 4\%$, which would have lead to a minimum on-axis bandwidth of nearly 10% if the electrons lased before generating the ICS gamma rays.

2.3. Basic accelerator design

The overall accelerator design is conservative with the exception of regenerative beam breakup (due to the combination of multi-pass and relatively high linac current during the macropulse). We believe we can suppress regenerative beam-breakup by employing electron beam optics between the passes to provide negative gain for transverse offsets in the linac during successive passes, as has been studied before [21]. We can generate a 1 ps long, 250 pC bunch in the photocathode with a normalized transverse rms emittance of $0.5 \mu m$. A 25 A electron beam will have minimal space-charge induced emittance growth. We have performed preliminary accelerator modeling using the code PARMELA [22] to verify the basic concept and to show that a three-pass microtron will not appreciably increase the beam emittance. We used a simplistic microtron geometry, as shown in figure 1 with a 41 MeV accelerator between two half dipoles. After the beam is bent by the first 180° dipole, there is dispersion-based emittance growth, which is eliminated when the beam is bent back along the axis of the microtron. Although this model does not include some features of a full design (most importantly the merger section from the 6 MeV photoinjector), it does include electron bunch space charge effects, optics nonlinearities (including those from the dipoles), and realistic RF cavity field profiles for on-axis coupled RF structures. These preliminary results show it is relatively easy to maintain an emittance of $1 \mu m$, for the nominal bunch length and charges, as shown in figure 4 (the microtron was injected with a zero-emittance beam; the emittance growth shown should be added in quadrature to the beam emittance coming out of the photoinjector). These simulations also show that a solenoid at either end of the microtron linac (i.e. one before the linac and one after, for a total of two) will be enough for confining the beam, along with weak quadrupoles at the edges of the dipoles to correct for gap focusing. Because the 180° bends can be made iso-chronous or not, and because there is independent control of the phasing of the bunch through the microtron linac on each pass, there are several design approaches to take, such as keeping the bunch longer until the third pass in the microtron to eliminate effects from coherent synchrotron radiation (CSR) or keeping the bunch 5 ps long over its entire path in the accelerator. Note the simulations indicate <0.01% energy spread (the rms energy spread is 3.5 keV) for the electron bunch at 129 MeV.

2.4. Other accelerator considerations

An optimized design may include compressing the electron bunch to higher peak currents to allow a shorter undulator and increased extraction efficiency. The preliminary PARMELA calculations showed there are no show-stopper beam physics issues, but simulations did not include the effect from CSR. However, it is easy to show the induced energy spread (and resulting emittance growth) will be manageable using Schwinger’s expression for radiated power [23]:

$$P_{rad} = \frac{3^{2/3} \pi^2 e^2 c}{4 \pi^2 R^{2/3} \delta^{4/3}}$$

where $R$ is the bend radius and $\delta$ is the electron bunch length. A 129 MeV electron has energy of about 20 pJ. The maximum induced energy loss is about 1 fJ per 180° bend for a 250 pC, 5 ps bunch. Either keeping the bunch uncompressed until the last pass before the microtron linac or by allowing the dipoles to alternatively rotate the bunch head and tail will additionally help ensure the CSR effects are negligible. This CSR issue is minor compared to those managed for DOE x-ray FELs (XFELs), such as the Linac coherent light source (LCLS) [24]. CSR effects can be orders of magnitude larger for typical XFEL electron bunch parameters due to their high peak currents (e.g., 100 pC of charge with 25 fs length and with 0.3 $\mu m$ emittances for LCLS).

3. Discussion

Here we showed a simplistic design of a microtron-based electron acceleration with $\sim 1 \mu m$ emittances for 250 pC bunch charges, leveraging previous work on high-brightness mergers, which motivates the FEL/ICS hybrid concept. The FEL photons are by nature fully synchronized with the electron bunches and at the same repetition rate. Although the energy per photon bunch is lower than with high energy lasers (by one or more orders of magnitude), their repetition rate for this design is 324 kHz, far in excess of current high-energy-pulse laser technology. As a result, very high gamma-ray fluxes are possible, over $10^{12} \text{s}^{-1}$ in the example provided. Also, since the FEL laser pulse amplitude is lower, there is no nonlinear broadening of the scattered gamma rays. Finally, using a linac for driving the FEL and for the ICS (with each electron seeing an ICS interaction before the FEL interaction) provides a lower electron beam emittance and energy spread than for using a storage ring, resulting in better FEL interaction and a smaller intrinsic energy spread of the ICS-produced gamma rays.
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