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**Citation:** Graves, W.S. et al. "MIT inverse Compton source concept." Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 608.1 (2009): S103-S105.

**As Published:** <http://dx.doi.org/10.1016/j.nima.2009.05.042>

**Publisher:** Elsevier

**Persistent URL:** <http://hdl.handle.net/1721.1/71616>

**Version:** Author's final manuscript: final author's manuscript post peer review, without publisher's formatting or copy editing

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# MIT Inverse Compton Source Concept

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## Abstract

A compact x-ray source based on inverse Compton scattering of a high-power laser on a high-brightness linac beam is described. The facility can operate in two modes: at high (MHz) repetition rate with flux and brilliance similar to that of a beamline at a large 2nd generation synchrotron, but with short  $\sim 1$ ps pulses, or as a 10 Hz high flux-per-pulse single-shot machine. It has a small footprint and low cost appropriate for university or industry laboratories. The key enabling technologies are a high average power laser and a superconducting accelerator. The cryo-cooled Yb:YAG laser amplifier generates  $\sim 1$  kW average power at 1  $\mu$ m wavelength that pumps a coherent cavity up to 1 MW stored power. The high-brightness electron beam is produced by a superconducting RF photoinjector and linac operating in CW mode with up to 1 mA current. The photocathode laser produces electron pulses at either 100 MHz with 10 pC per bunch, or at 10 Hz with 1 nC per bunch in the two operating modes. The design of the facility is presented, including optimization of the laser and electron beams, major technical choices, and the resulting x-ray performance with a focus on the 100 MHz mode.

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Inverse Compton; x-ray source; superconducting RF; linac; high-power laser; cryogenic; compact light source;

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## 1. Introduction

The pervasive demand for hard x-ray beams in modern medical, commercial, and academic research applications is in stark contrast to the quite limited availability of the benefits of the last forty years of synchrotron radiation source development. Only a small number of expensive, controlled-access, and often distant facilities are available worldwide, while small-scale metal anode sources, both fixed and

rotating, have improved little by comparison in this time period. The result is that across a wide array of possible applications, many cannot proceed, or proceed ineffectively, due to these restrictions. Enormous interest has therefore been generated by the possibility of using small-scale accelerators in combination with a high-power laser field to achieve brilliance currently available only at large facilities.

Many experiments, such as PLEIADES at LLNL [1], have demonstrated the physics of x-ray production via inverse Compton scattering, but the set-ups and resulting x-ray intensities were not optimal for x-ray users. With hopes of providing an

intense source for the “home lab,” Ruth et al. [2] are pursuing a small synchrotron as the electron source, where the electron current can be much higher than in the conventional linac demonstrations. In this paper we describe an alternate approach in which a short superconducting linac would be utilized. Although the time-average current is lower in the linac ( $\sim 1$  ma) than in the compact synchrotron (60 ma), the lower emittance in the linac case creates a much smaller and more effective electron-photon interaction volume for x-ray production, leading to brilliance levels over 1000 times greater. Quite remarkably, the emittance of the photon beam may approach that of third generation synchrotron sources, albeit at lower flux. Nevertheless this linac-based concept can outperform the best rotating-anode source by one to two orders of magnitude in flux, with full tunability and polarization control. The source size will be less than 10 microns, making it ideal for protein crystallography from small crystal samples, and for phase-contrast imaging.

Another important feature of the linac-based electron beam is short pulse lengths of 1 picosecond and below. In applications such as pump-probe spectroscopic measurements for determining chemical reaction pathways, the resulting short pulse x-ray source would be uniquely powerful.

## 2. X-ray Beam Optimization

The quality of the x-ray beam produced by inverse Compton scattering will depend heavily on the characteristics of the electron and laser beams involved in the interaction. In general, very low emittance electron beams are required to produce both large x-ray fluxes, due to the small interaction spot sizes required to produce a sufficient number of scattered photons, as well as high spectral brightness, due to the strong dependence of the x-ray beam spectral width on the electron beam divergence at the interaction point. Additionally, relatively short pulse lengths for both the electron and laser beams are desired to maximize the interaction within the Rayleigh diffraction length of the laser beam.

Assuming Gaussian laser and electron beam profiles, an analytic expression for the total x-ray dose produced by a head-on inverse Compton scattering interaction is given by [3]

$$N_x = \frac{N_e N_\gamma \sigma_T}{2\pi(x_L^2 + x_e^2)} FF \quad (1)$$

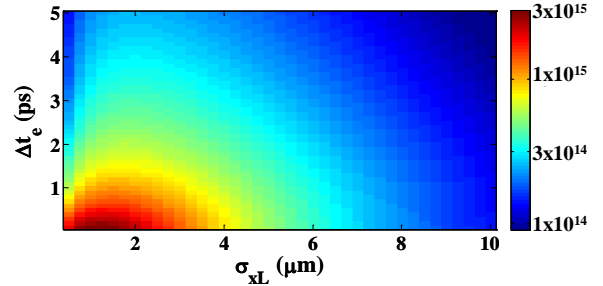


Figure 1: Numerically calculated brightness at 100 MHz repetition rate vs laser size and electron pulse length.

In equation (1)  $\sigma_T$  is the total Thomson cross section,  $N_e$  is the total number of electrons,  $N_\gamma$  the total number of photons in the laser beam. The term  $FF$  is a form factor less than unity that depends on rms pulse durations  $\Delta t_L$  and  $\Delta t_e$ , and beam spot sizes  $x_L$  and  $x_e$  at the interaction point for the laser and electron beams. It represents the degradation of the interaction efficiency for cases where the pulse durations exceed the interaction diffraction lengths of the laser and electron beams.

For most experimental parameters, the on-axis spectral width of the scattered x-ray beam will be dominated by the electron beam emittance. In this limit, the time averaged on-axis spectral brightness, in units of photons per second per unit area per unit solid angle per 0.1% bandwidth, can be approximated by the expression [3]

$$B_{avg} \approx 1.5 \times 10^{-3} \frac{N_e N_\gamma \sigma_T \gamma^2}{(2\pi)^3 \epsilon_{nx}^2 x_L^2} F_{rep} \quad (2)$$

where  $\epsilon_{nx}$  is the rms normalized electron beam emittance,  $\gamma$  is the electron beam Lorentz factor, and  $F_{rep}$  is the interaction repetition rate. Note that due to the trade off between the source spot size, x-ray divergence, and flux in this limit, the brightness is independent of the electron beam spot size.

In order for equation 2 to be valid, both the electron and laser pulse durations must be short compared to the laser Rayleigh length  $z_0$ . Additionally,  $x_L$  must not be so small that the nonlinear effects begin to degrade the scattered x-ray spectrum. For  $\lambda = 1 \mu\text{m}$ , and assuming  $a_{0max} \sim 0.1$ , pulse durations on the order of a pico-second and interaction spot sizes on the order of a few microns will be desired to achieve optimum x-ray beam brightness. Figure 1 shows numerical simulation results assuming parameters of  $E = 25 \text{ MeV}$ ,  $\epsilon_{nx} = 0.1$

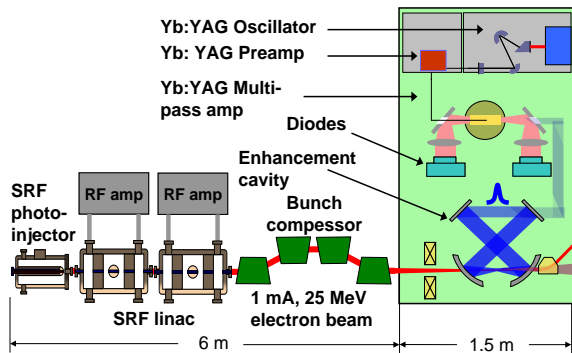


Figure 2: Major technical components including cryocooled high power laser and SRF linac.

$\mu\text{m}$ ,  $x_e = 2 \mu\text{m}$ ,  $\Delta t_L = 0.3 \text{ ps}$ ,  $\lambda = 1 \mu\text{m}$ ,  $Q_e = 10 \text{ pc}$ , and  $W_\gamma = 10 \text{ mJ}$ . Note that no nonlinear effects were included in this computation, which would likely impact the results for laser spot sizes less than  $2 \mu\text{m}$  for this example. It is seen that there is an optimum laser spot size of a few microns, with significant degradation in the x-ray beam brightness for electron beam pulse durations exceeding one picosecond. The optimization of high average flux, high spectral brightness inverse Compton scattering x-ray sources requires electron beams with low emittance ( $<1 \text{ mm-mrad}$ ) and short pulse duration ( $<1 \text{ ps}$ ), and tightly focused ( $<5 \mu\text{m}$ ), short pulse ( $<1 \text{ ps}$ ) lasers.

### 3. Accelerator Systems

The accelerator modules utilize superconducting RF (SRF) cavities that are optimized for low capital and operating cost, and efficient energy use. They are designed to produce an electron beam with very low emittance and energy spread in order to meet the goals of the x-ray source. The initial electron beam parameters include 40 MeV maximum energy, 100 MHz repetition rate to match the laser coherent cavity frequency, and a low charge of 10 pC/bunch to yield an average current of 1 mA. We choose to operate at low charge and high repetition rate to generate low emittance of 0.1 mm-mrad, low energy spread of 10 keV, and bunch lengths as short as 50 fs.

The novel SRF photoinjector [4] is configured as a quarter-wave cavity for compactness, using low RF frequency to enable operation at 4 Kelvin. The geometry is such that the ratio of peak surface magnetic field to peak cathode accelerating field is only 1.2 mT per MV/m, compared to ratios around 2 for a traditional elliptical cavity. This permits higher

accelerating fields at the cathode than any other CW photoinjector design. At a conservative maximum surface magnetic field of 100 mT this geometry can support CW cathode fields as high as 80 MV/m, although field emission is likely to limit the maximum gradient to a lower value near 40 MV/m. The high brightness electron pulses are generated by photoemission from a non-superconducting  $\text{Cs}_2\text{Te}$  cathode using self-expanding ellipsoidal bunches [5,6] produced by short ( $< 100 \text{ fs}$ ) laser pulses.

While SRF linacs are now operating throughout the world, these designs are biased toward large facilities. Technical choices such as pulsed operation at high gradient, operation at temperature of 2K, and the design of cryomodules and liquid helium refrigerators all aim for an economy of scale appropriate for large facilities, but these choices are less favorable when the goal is a compact, relatively low-cost source operating continuously. As an alternative approach we are designing TEM-mode low frequency SRF structures that operate at 4K, reducing the required wall-plug power by a factor of 4 due to improvements in thermal and mechanical efficiency. Raising the operating temperature requires reducing the gradient and operating RF frequency to maintain low heat loads. Therefore we will operate at a frequency of  $<500 \text{ MHz}$  (compared to 1-2 GHz for 2K cavities). The TEM-mode cavities are half the diameter of the commonly used elliptically-shaped TM-mode cavities.

### 4. Laser Systems

The cathode drive laser is required to have a FWHM pulse length of less than 100 fs and to have a parabolic radial intensity distribution [5] on the cathode in order to produce the desired self-shaping ellipsoidal electron bunches. The  $\text{Cs}_2\text{Te}$  cathode has a quantum efficiency exceeding 1% at 267 nm. Light at this wavelength will be produced by frequency quadrupling a 1  $\mu\text{m}$  drive laser. The most broadband 1  $\mu\text{m}$  laser materials are Yb:YLF and Yb:KYW with 50 and 40nm full-width-half-maximum bandwidth, enabling the direct generation of pulses as short as 30 fs when the full bandwidth is utilized.

The quadrupling efficiency is 10%, and 50% losses due to shaping and beam transport to the cathode are assumed. Accounting for these efficiencies and the cathode response, an average power of 10 W in the infrared is required to produce 1 mA of current.

Table 1: X-ray parameters

Parameter	Single shot	High flux
Tunable photon energy [keV]	3 – 30	
Pulse length [ps]	2	0.1
Flux per shot [photons]	$1 \times 10^{10}$	$3 \times 10^6$
Repetition rate [Hz]	10	$10^8$
Average flux [photons/sec]	$1 \times 10^{11}$	$3 \times 10^{14}$
On-axis bandwidth [%]	2	1
RMS divergence [mrad]	5	1
Source RMS size [mm]	0.006	0.002
Peak brilliance [photons/(sec mm <sup>2</sup> mrad <sup>2</sup> 0.1%bw)]	$6 \times 10^{22}$	$6 \times 10^{19}$
Average brilliance [photons/(sec mm <sup>2</sup> mrad <sup>2</sup> 0.1%bw)]	$6 \times 10^{11}$	$2 \times 10^{15}$

For the high power colliding laser, a diode-pumped, cryogenically-cooled Yb:YAG laser is used. Such a laser [7] delivering >250 W of average power in a diffraction-limited output has recently been demonstrated [8]. Due to the superior quantum efficiency (91%) of Yb:YAG, and the possibility of extracting the full stored energy of the crystal at liquid nitrogen temperature while maintaining the high beam quality, this source can develop 1 kW of average optical power using about 3 kW electrical wall-plug power. Due to the large beam cross section in the Yb:YAG crystal, a low average power (10 W) train of pulses generated from a mode-locked Yb:YAG oscillator can be directly amplified in the cryogenically-cooled Yb:YAG amplifier to the 1 kW average power level. The high power pulse stream is then coherently coupled into an enhancement cavity with a finesse of  $F=3000$ , i.e. a power or energy enhancement of 1000, such that a 10 mJ, 1ps pulse is continuously maintained in the cavity. The average power in the cavity will be 1 MW.

The coupling of the electron beam into the interaction region and of the x-rays out of the interaction region is currently planned via a 1 mm diameter hole in the cavity focusing mirrors. To reduce the loss of the TEM-00 Gaussian mode due to this hole the mode size of the beam on the mirrors must be larger than 1 cm, which also keeps the energy density on the mirrors significantly below the threshold of  $1 \text{ J/cm}^2$ .

## 5. X-ray Performance

Table 1 lists the expected x-ray properties based on numerical simulations using the laser and accelerator parameters described above. It also lists design performance for a single-shot mode that we do not discuss further due to space limitations. This source is ideal for phase contrast imaging because the source size is exceptionally small, and the beam has moderate divergence. As a result the coherence length of the photon beam is relatively large (>10 microns) at meter distances, while the beam can illuminate substantial area. Demagnifying optics could be used to further increase both coherence length and illuminated area while maintaining a compact geometry.

For protein crystallography, there is a strong premium on focal spot size to record diffraction patterns from crystals in the 10 micron size range. In this case uniform illumination of the sample crystal would argue for magnifying optics, which would expand the beam by roughly a factor of three, while decreasing beam divergence and thereby improving resolution. The compact source is also tunable, which is generally required for *ab initio* structure determination of complex proteins. The combination of all these attributes would support the most challenging structures determinations now possible only at large synchrotron facilities.

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