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HOLLOW-CORE ANTI-RESONANT FIBER OPTICS AS A PATH TOWARDS PRACTICAL LASER-UNDULATOR BASED X-RAY SOURCES*

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Abstract

A new technique for laser-electron beam production of monochromatic x-ray sources using hollow-core, anti-resonant fiber optics is explored. This is predicted to produce vastly brighter, more monochromatic (<<1 % BW) x-ray sources than traditional inverse Compton sources and may provide a path towards a practical laser-undulator x-ray source.

INTRODUCTION

Tunable, monochromatic x-ray sources, in the form of x-ray free electron lasers (XFEL) have proven to be revolutionary radiation sources for materials science, biology, and even plasma physics [1]. The utility of such x-ray sources cannot be overstated and there is considerable interest in the construction of more XFELs to serve a broader suite of applications [2]. However, the large size, driven by the need for electrons in the ~10 GeV range, and thus, high cost, of such machines limits the number that can reasonably be built, even for national security applications such as were proposed for the MaRIE XFEL [3]. Significant effort has been focused on improving conventional XFEL technology so as to shrink the machines to a size conceivable for a top-tier research university to construct, although the costs and size would remain large and these techniques rely on nearly order of magnitude leaps in accelerator gradients [2]. Other projects seek to utilize laser-plasma accelerator technology to dramatically shrink the needed accelerator, although challenges remain with achieving the needed beam parameters and achieving the required repetition rate for typical XFEL applications [4].

In addition to the typical technical challenges, there are also materials science applications that require higher x-ray energies [3] than are typical for current XFELs, as well as significant interest in high-brightness pulses for the study of high-energy-density physics (HEDP) conditions [5]. These emerging requirements add further constraints to the challenge of lowering the size, and thus costs, for XFELs or XFEL-like x-ray sources. Typical HEDP applications require $>10^{10}$ monoenergetic photons on target in <100 ps flashes [5], while materials science with high-Z mate-rials demands photon energies approaching 100 keV [2, 3].

A promising solution has been seen in the development of bright inverse Compton Sources (ICS) which can instead utilize 10's of MeV electrons and thus accelerators that are orders of magnitude smaller and cheaper. ICS x-ray sources also have no challenge with 100 keV photon production [6], which is benefi-cial for high-Z material science and nuclear physics. The challenge lies in the typical low brightness of ICS x-ray sources, where photon production scales as Ne instead of Ne2 in XFELs [1, 5, 6]. Thus, large amounts of circulating beam current and scattering lower power are needed to generate useful ICS x-ray sources. Previous work has shown that modern accel-erators and lasers can create ICS x-ray sources that fit some of the needs of HEDP [5] and high-Z material science [6], but there remains many unmet x-ray source requirements for those applications. This paper outlines a proposal to massively enhance ICS x-ray production using Anti-Resonant Hollow-Core Fiber (HC-ARF) optics to increase the interaction length and thus increase the x-ray production efficiency as well as potentially create a true laser-undulator.

INVERSE COMPTON SCATTERING

Inverse Compton Scattering (ICS) can be thought of as the optical analog to a traditional magnetic wiggler and as such is an incoherent photon production pro-cess. The number of x-rays generated, and the central energy can be described by Eq. (1) and (2) [5]:

$$E_x \approx \frac{E_L}{4\gamma^2}\left[1 + a_0^2 + \gamma^2\theta^2 + {\phi^2}/{4}\right] \quad (1)$$

$$N_x = \sigma_T \frac{N_e N_L}{2\pi(\sigma_e^2 + \sigma_L^2)}. \quad (2)$$

In Eq. (1) E_x and E_L are the x-ray and laser photon energies respectively, γ is the Lorentzian gamma of the electron beam, a_0 is the normalized laser electric field, θ is the observation angle, and ϕ is the interaction angle (typically 0). For Eq. (2) N_x, N_e, and N_L are the number of x-rays, electrons, and laser photons respectively. The Thompson scatter cross section is σ_T, while the laser and electron beam sizes at interaction are σ_e and σ_L respectively. The inversely quadratic relationship with the beam sizes should be immediately noted and that N_L is very dependent on the interaction geometry. If the length of the scattering volume can be decoupled from the laser spot size via external laser confinement or advanced laser shaping techniques, then N_x scales linearly with interaction region length for a given laser intensity [5].

LASER UNDULATOR

The description of ICS as an optical analogue to magnetic wigglers then naturally lead to the concept of a laser undulator (LU) and true x-ray lasing using only 10's of

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MeV electrons [7]. Such a machine would be much brighter than an equivalent ICS x-ray source, as well as create much more monochromatic x-rays. The central x-ray energy follows the same equation as ICS, but now the number of photons is linearly dependent on the FEL Pierce parameter, ρ, which is dependent on peak current, a_0, spot size, and γ. Proper calculation of the x-ray yield must use well established FEL physics, adjusted for the use of a laser.

An LU also may allow for the creation of an entirely new class of "quantum" XFEL. This concept has been proposed several times but has remained practically out of reach due to the extreme electron beam and laser requirements. The requirement for relatively long (cm scale) and stable laser-electron interaction regions typically requires very large laser energies to generate a long enough Rayleigh length (Zr?)

$$Z_r = \frac{4E_L}{\tau_L \lambda_L I_L}. \quad (3)$$

There is an inverse relationship with laser intensity (I_L), wavelength (λ_L), and pulse length (τ_L). That makes it challenging to have a cm scale Rayleigh length while maintain high laser intensity. This practically translates into laser requirements in the 100-1000+ J range and thus are no longer able to operate at the high repetition-rate required for many XFEL applications.

HOLLOW-CORE CONFINEMENT

If instead of a free-space ICS or LU interaction, the laser is confined inside of a hollow-core fiber optic, then the challenge with Rayliegh length would be overcome and even an ICS source would become much brighter. This is like previous ideas to create optical undulators with carefully shaped optical waveguides [8] but instead seeks to use much simpler hollow-core fiber optics. The electron beam can also be confined with external magnetic fields, although relativistic electron beams have much longer effective Rayleigh lengths than an infrared laser beam. In either case, the resulting system will allow for much longer effective interaction lengths at the peak laser intensity, as shown in Fig. 1.

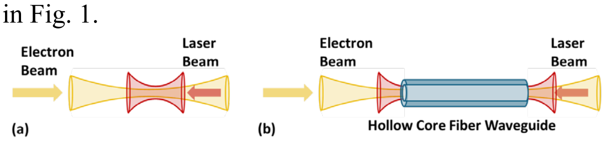

Figure 1: Cartoon of (a) a free space laser-electron beam interaction and (b) an hollow core fiber-optic confined laser-electron beam interaction showing the increased interaction distance enabled by the fiber optic.

Using typical hollow-core fiber-optics, the laser intensity that can be injected will be limited to ~10^{10} W/cm^2 due to damage limits of the fibers [8-10]. Although traditional hollow-core fibers can be quite large (1 mm inner diameters), their ~1 dB/m laser attenuation makes for firm damage lim-its as well as provides limits on how long the fiber can be in practice while maintaining a useful laser intensity undamaged. Traditional hollow-core fibers also support multiple optical modes, which makes their utility for generating an LU questionable.

If instead a AR-HCF technology is used, the laser intensity can be increased to >10^{12} W/cm^2 [9, 10]. The primary laser loss mechanism in AR-HCF is laser leakage and attempts to find the damage limits are typically limited by the break-down of air inside and around the fiber, which will not be a limit for this application due to the requirement of high-vacuum for the electron beam. The damage limits of these AR-HCF, especially with the joule-class lasers in vacuum, are not well known and under activation investigation by the authors. AR-HCF can also be used to send only a single optical mode, which makes the technology ideal for creation of a LU.

Increasing the laser intensity up to an a_0 of ~1 provides increasing advantage for x-ray generation, especially when attempting to make a LU. Not only is x-ray saturation, i.e. maximum x-ray generation, reached in a shorter length (using classic XFEL physics [1, 7]), but this shorter length in turn results in fewer wakefield losses from the electron beam while traveling through the fiber optic. The saturation length vs central x-ray energy for various laser intensities can be seen in Fig. 2.

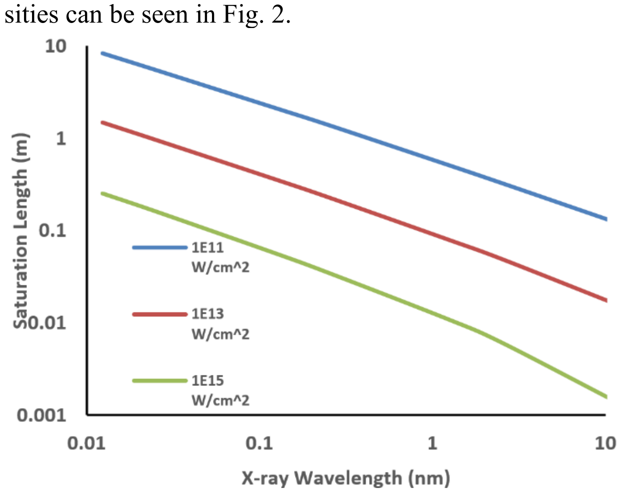

Figure 2: Saturation length for the LU vs central x-ray energy for various laser intensities for a beam designed to produce 10^{10} x-ray photons per pulse.

It is clear to see that the saturation length scales inversely with the provided laser intensity. If intensities on the order of ~10^{15} W/cm^2 can be sustained, then even 100 keV LU's seem theoretically possible.

The advantage of this AR-HCF technique is best illustrated by looking at the required minimum laser energy to create a LU vs x-ray central wavelength as seen in Fig. 3.

The AR-HCF system allows for a ~1000X reduction in laser energy and thus opens the possibility of using high repetition-rate industrial lasers to create an LU. One could also consider the creation of an optical cavity that reuses the laser energy. The optical cavity concept has been proposed for traditional ICS [6] and should work well for an AR-HCF confined ICS or LU based x-ray source.

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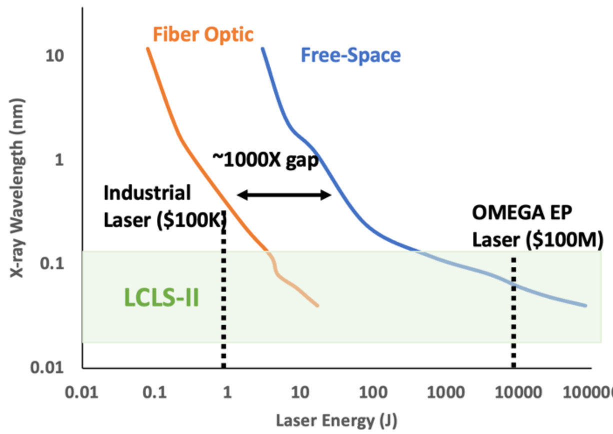

Figure 3: Minimum laser energy for a free-space and AR-HCF based LU vs x-ray central wavelength for a beam designed to produce 10^{10} x-ray photons per pulse. Standard XFEL analytic techniques and Ming Xie adjustments are used to generate these curves. Several laser costs of note are added.

PLANNED EXPERIMENTS

Experiments have been proposed to test the proposed AR-HCF x-ray production mechanism at the Brookhaven National Laboratory (BNL) Accelerator Test Facility (ATF). These experiments will determine the laser damage limits of current AR-HCF technology using the available 10 J CO_2 laser. Wakefield effects and difficulties in electron beam transport in the 100's of micron in diameter AR-HCF inner tube will be tested as well. Finally, full two beam interactions will be undertaken and x-ray yields measured. A high-resolution x-ray spectrometer will be used to determine if spectral sharpening occurs, which would be the first sign of x-ray gain and the beginning of the development of an LU. A cartoon of the experiment can be seen in Fig. 4.

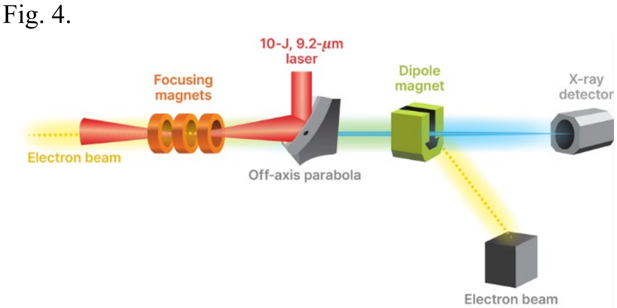

Figure 4: Cartoon diagram of AR-HCF experiment to test laser confinement for ICS and LU x-ray generation.

These experiments are supported by BeamNetUSA beam time and will occur in FY26.

CONCLUSION

A new concept for enhancing ICS x-ray generation and potentially opening the path to LU based x-ray generation using modern day AR-HCF technology is outlined. The initial modelling shows that external confinement of the laser provides a significant x-ray enhancement for the same laser energy and opens the possibility of creating a true LU with commercial laser technology. The initial experimental design is outlined to test this concept.

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