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A Brighter Future: Next-gen Electron & Photon Probes for Quantum Science Frontiers

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Abstract: Our project explores the emerging theories in quantum electrodynamics combined with nonlinear optical techniques (e.g., four-wave mixing) to enhance the quality of electron beams in XFEL technology.

INTRODUCTION

In the 1900s, photographer Eadweard Muybridge rigged 12 consecutive cameras with a tripwire to produce sequential pictures depicting a horse's motion. These images were monumental in proving that horses amid their gallop are momentarily airborne, but more importantly, they developed the concept known as time-resolved imaging [1]. Today's frontier in sequential motion photography resides on fundamental questions about quantum dynamics utilizing X-ray free electron lasers (XFELs) to understand interactions between light and matter on the femtosecond scale–a quadrillionth of a second. [1][2] This is game-changing for our fundamental understanding of nature's smallest, fastest, and most elusive constituents that play an essential role in chemistry, biology, and quantum physics. [2] High-quality electron beams are at the heart of these unique sources, which currently rely on decades-old laser upconversion and shaping approaches [3], thus hampering their advancement.

Through vigorous calculations and computer simulations, we first prove physical theories and follow by building instrumentation informed by this theory. This sparked the design of our hollow-core fiber (HCF) system, where high-energy light can be tailored temporally with a wider range of parameters while maintaining its quality and efficiency [4][5]**.** By completely redesigning the mechanisms of our electron source, we reach the potential for higher peak energies in our beamlines than ever before, creating a generation of unprecedented XFEL technology.

METHODS

Our first objective is to create a high-quality temporally-tailored photoinjector laser beam to produce high brightness and current electron beams [6], and then extend infrared laser shaping capabilities to reduce microbunching instabilities as demonstrated in Ref. [7]. However, by increasing the brightness of the beamline, we need to consider a way to minimize optical damage since previous spatio-temporal and programmable laser pulse synthesis may not be feasible [8] which is now being investigated through start-to-end photoinjector laser models [9].

The proposed HCF-based solution enables high-energy photons to propagate through a controlled vacuum, differing from traditional optical approaches. Additional benefits of the HCF include light guidance over an *unmatched spectral band over a wide range of frequencies and dynamic control of optical properties inside the HCF.*

First, we ran Python simulations to create an accurate mathematical model for four-wave mixing (FWM) conversion inside the HCF. Then we applied the information provided by these models to design and create an accurate schematic of the system.

RESULTS AND INTERPRETATION

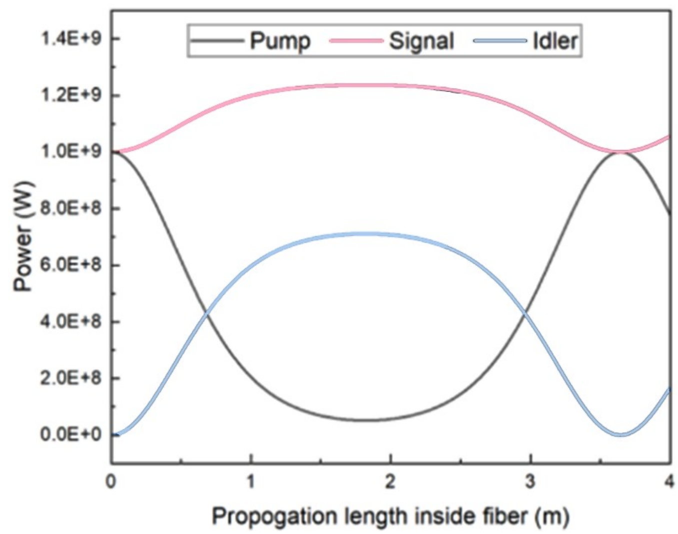

Figure 1: Simulated energy transfer between 3 waves (*input* pump and signal with *output* idler) propagating through HCF.

The code simulation shows that given the specific parameters like gas type, pressure, and inner-core radius, the optimal length of the fiber is approx. 1.75 meters, where the idler is at its max. At the start of the fiber, the idler wave does not exist when energy is at 0, shown by the blue line, but through four-wave mixing (FWM), the idler gains energy as the pump and signal propagate through the optical fiber. The simulation also shows efficient energy transfer since nearly all of the pump's energy is transferred to the signal and idler.

CONCLUSIONS

Our results indicate the **optimal fiber length**, **gas type, fiber radius**, and **total energy** in our Hollow Core Fiber system. These measurements are critical to the experimental setup for our lab. Furthermore, we have shown that the HCF exhibits unique qualities that support the use of **brighter electron beams** while **minimizing material damage from** *high peak power*, thus making it <u>an asset for improving XFEL technology</u>.

In the future, we plan to:

1) **Further validate FWM technology** by running more simulations to discover and refine more parameters for the optical fiber

2) **Examine dynamic electron beam control** by determining more effective ways to shape the beams spatiotemporally.
3) **Transfer designs to facilities** such as Stanford SLAC and make them accessible to the public.

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