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DEMONSTRATION OF A TUNABLE ELECTRON BEAM CHOPPER FOR APPLICATION IN 200 kV STROBOSCOPIC TEM

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Abstract

For the last several decades, time-resolved transmission electron microscopes (TEM) exploring the sub-microsecond timescale have relied on the photoemission technology to generate the single or train of electron bunches. However, the complexity of additional laser system and the availability of high repitition rate laser limit applications of the laser-driven approach. Lately we have made substantial progress towards pioneering a new kind of time-resolved TEM, complementary to the existing laser-based techniques. Using a tunable RF beam-chopper, we are able to retrofit an exsiting TEM providing a pulsed electron beam at a continuously tunable reptition rate up to 12GHz and a tunable bunch length. In the article we will briefly discuss the working principle and experimental progress to date.

INTRODUCTION

During the last decade, new concepts of time-resolved TEM machines have been introduced: dynamic or single-shot TEM (DTEM) [1], and ultrafast or stroboscopic TEM (UTEM) [2]. Both DTEM and UTEM are based on the laser-photocathode concept to generate probing electron bunches. In the modern technological era, many breakthroughs rely on understanding how advanced nanoscopic materials or devices operate at rates approaching or exceeding 1 GHz. For example, spintronics exploits ferromagnetic resonances in magnetic materials that occur in the GHz regime. In UTEM, data are repeatedly collected over extended periods of time, and the thermal load from the pump laser must be managed so that the process under study stays reversible. Therefore, even though lasers with higher repetition rates are available, UTEM systems typically operate at much less than 0.1 GHz, and sometimes even at ~0.1 MHz, depending on the experiment. We proposed a GHz RF technology fills an important gap in this landscape that is inaccessible to the laser-based UTEM. In contrast to most laser-driven processes, many processes driven electrically or magnetically can be cycled indefinitely at GHz frequencies, thus enabling truly in operando microscopy, with the most notable example being switching in a semiconductor device. This class of problems, characterized by electrical stimulus and lack of an extended cool-down time, is largely distinct from the class of problems typically studied in laser-based UTEM systems. Thus, a purely electrical approach to pump/probe electron microscopy complements existing laser-based approaches by reaching much higher repetition rates in the study of driven processes.

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THE TECHNICAL APPROACH

The basic principle of GHz stroboscopic TEM [3, 4] is presented in Fig. 1. A small part of the RF signal to the DC beam-bunching device will be diverted to the sample through a phase-locked delay line. Similar to UTEM, issues such as heating can be anticipated; however, the essential difference here is that the near- *in operando* examination of devices or device structures is feasible, since their realistic operation is electromagnetically driven and long thermal cool-downs are typically not a problem. More specifically, our high-rate stroboscopic microscope can reveal the inner workings of advanced devices in unprecedented ways by concurrently enabling high-resolution imaging, as well as analytical, diffraction, and other capabilities.

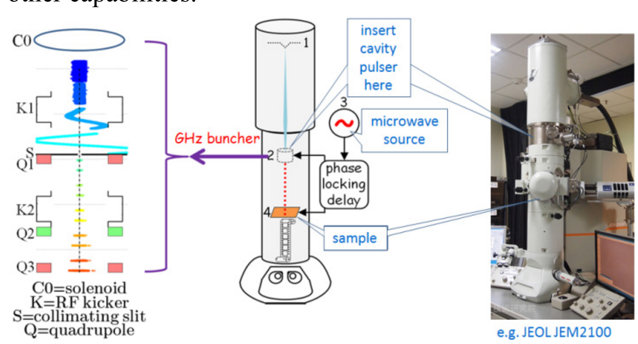

Figure 1: Basic principle of the stroboscopic laser-free high-duty cycle TEM: 1) DC electron source; 2) DC beam bunching device; 3) RF source; 4) the sample.

The whole concept of GHz TEM relies on the development and commissioning of a special highly tunable (both high repetition rate and single electron bunch length) GHz buncher. The basic principle of the GHz Electron Buncher (EB) is shown in Fig. 1 (far left). It consists of three major functional components: electron beam modulator (a.k.a. kicker), beam chopping aperture (slit), and quadrupole magnet. The incoming longitudinal DC electron beam traverses the optical z-axis. The first

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dark blue straight segment in Fig. 1 represents a segment of the DC beam originating before z=0 cm. We track this segment of the beam, and take snapshots along the downstream components shown by different beam colors in Fig. 1. The incoming beam is softly focused by a custom condenser lens (C0), thus allowing a large fraction of the current emitted from the gun to be collected, collimated, and aligned into the EB with a small convergence angle. At the entrance of the EB, the DC beam picks up a transverse sinusoidal momentum from the electromagnetic (EM) field in a beam kicker. Since the EM field oscillates with the radial frequency f0, the modulation force on the incoming electron depends on the time at which it arrives in the kicker (K1 in Fig. 1). The amplitude of the sinusoidal motion grows in the perpendicular direction as the modulated beam propagates in the z-direction. A beam slit, working as a collimating aperture, is placed on the optical axis downstream of K1. The slit chops the beam and converts it into a pulsed sequence. However, after drifting a certain distance, the beam will expand, and both the beam size and divergence will increase. As shown in Fig. 1, the addition of quadrupole magnets and a second beam kicker can demodulate the beam and reduce the emittance growth and energy spread (i.e. improve the spatial and temporal coherence of the beam).

The resulting electron pulse length is controlled by both the modulation strength and the slit radius. In order to achieve a short pulse, either a large kick or a small aperture is required. Thus, to reduce the energy spread for a given pulse length, the slit radius should remain as small as reasonably possible, thus reducing the required kick strength. At the same time, if the beam transverse size is larger than the slit aperture, the EB will not be able deliver effective chopping. Using C0 to create a soft crossover at the slit/aperture plane allows optimal modulation and chopping, upon turning the EB on. Normal TEM operation with a low-emittance DC beam is restored by turning off both C0 and the EB components.

The beamlet repetition rate out of the EB (i.e. the strobe frequency) can be continuously tuned over an ultrawide range by changing the beam modulation frequency applied by the beam kicker. The hardware implementation of the kicker is a customized dielectric-lined traveling-wave transmission stripline (DTWTS) that is driven by an external RF signal. The RF drive frequency, equivalent to the beam modulation frequency, is adjustable through the EB control system. The specially designed kicker is able to synchronize the time-dependent kick force with the incoming beam velocity at virtually any frequency within the tunable range of the kicker.

IMPLEMENTATION

We have finished all buncher/C0 components: the C0 unit, DTWTS, magnetic quadrupole, and the vacuum/radiation shielded housing with a connector plate, hosting the buncher, which is compatible with C0 mating interfaces and with standard JEOL mating interfaces. All components have been finalized in terms of full mechanical design and drawings, and have been ordered from various vendors and shops. Figure 2 contains the full descriptive information, for the ease of understanding. The final fabricated assembly is shown in Fig. 3.

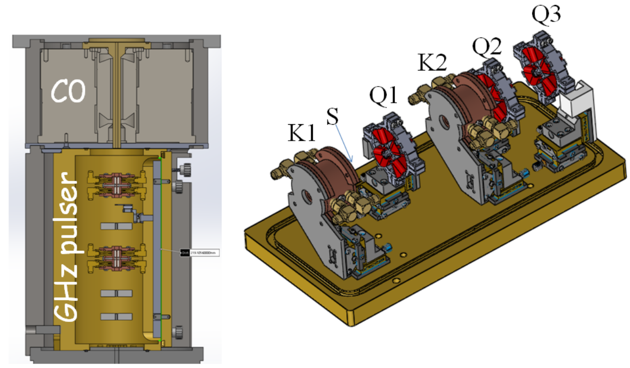

Figure 2: Engineering design of the entire unit, consisting of focusing C0 element and GHz buncher. All components are mounted on the vacuum compatible 3-axis translation stage.

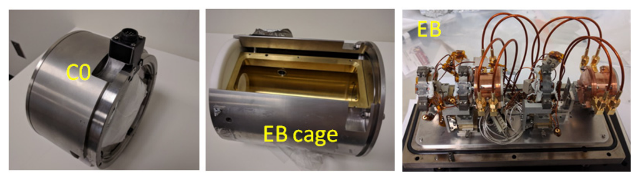

Figure 3: The finished C0/EB assembly.

THE PRELIMIARY TEST

The prelimnary test was conducted at Euclid using a top gun part of a decommissioned 200 keV TEM. The gun was installed horizontally, in order to accommodate a downstream beamline that will be used to test the GHz buncher module and to characterize and quantify the time structure of the resulting bunch trains. We rebuilt the Labview-based control system to control and interlock the HT unit, vacuum, SF6, etc., and commissioned the 200 keV beam. Figure 4 shows the entire Gun system and C0/EB integration at Euclid.

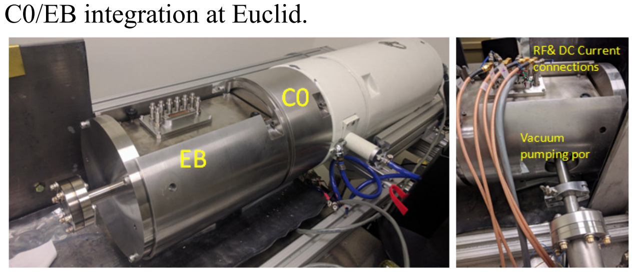

Figure 4: Integration of C0 and EB.

The first benchmarking experiment was to demonstrate the chopped beam. In order to do this, limited by other diagnostics, we reconfigured the EB, as shown in Fig. 5. Instead of demodulation, we change the phase of K2 to use it as a deflector, so that the chopped beamlets alternately deflect in the opposite direction. After a certain drifting distance, they can land at different position on the downstream YAG screen, i.e., the time separation between beamlets is measured by the transverse spatial separation.

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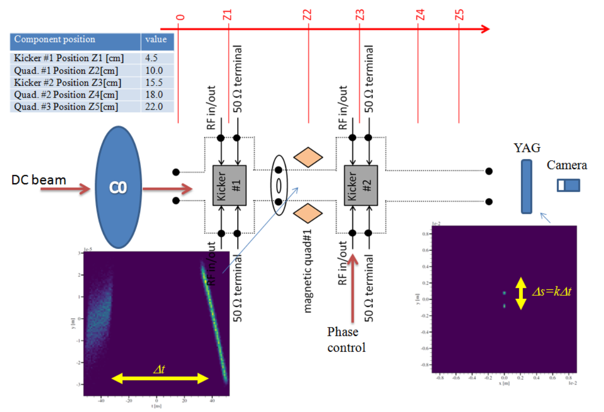

Figure 5: Benchmarking experimental configuration.

The EB characterization experiments are still ongoing. Data are being processed. Here, we only list a few preliminary results. Figure 6 demonstrates the beam modulation by Kicker1. While increasing RF power to drive the kicker, the beam becomes wider (in response to the kicker orientation). Figure 7 shows the chopped beam in the configuration shown in Fig. 5. A 30-μm slit (aperture) was used in the experiment. The beamlets didn't show a clear separation (see Fig. 7). After an intense investigation, poor beam quality due to a worn-out tungsten cathode was identified to be the main cause. We just replaced the cathode, and the experiment is expected to resume soon.

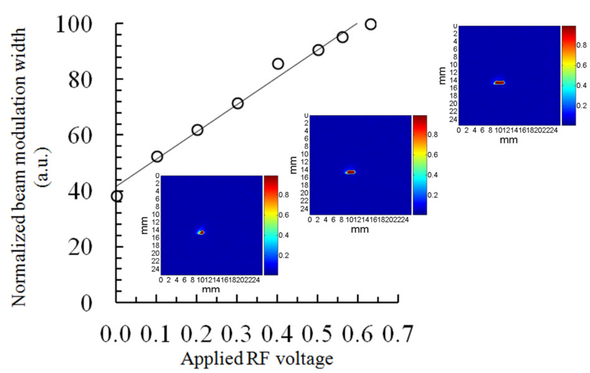

Figure 6: The measured 150 keV beam modulation by the 1st Kicker.

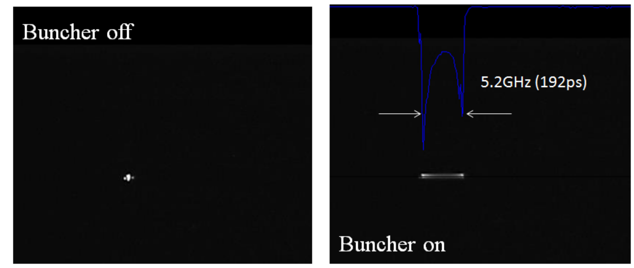

Figure 7: The 150 keV beam was chopped. Due to the worn-out cathode, the poor beam quality leads to an unclear separation between the chopped beamlets.

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