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FIRST OPERATION OF A HYBRID E-GUN AT THE SCHLESINGER CENTER FOR COMPACT ACCELERATORS IN ARIEL UNIVERSITY

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Abstract

A novel hybrid photo injector was designed and partially tested at the UCLA Particle Beam Physics Laboratory. It was later commissioned at Ariel University in Israel as an on-going collaboration between the two universities. This unique, new generation design provides a radically simpler approach to RF feeding of a gun/buncher system, leading to a much shorter beam via velocity bunching owed to an attached traveling wave section of the photo-injector. This design results in better performance in beam parameters, providing a high quality electron beam, with energy of 6 MeV, emittance of app 3 μm, and a 150 fs pulse duration at up to 1 nC per pulse. The unique e-gun will produce an electron pulse for a THz FEL, which will operate at the super-radiance regime, and therefore requires extraordinary beam properties. This paper briefly describes the gun and presents initial operational results from the gun and its sub-systems.

INTRODUCTION

A Hybrid S-band (2856 MHz) photo injector was commissioned at Ariel University [1] (Figure 1). The injector is the heart of the Schlesinger Compact Accelerators Center, it was designed by the PBPL group at UCLA, which previously designed and tested a smaller (lower energy) type of such Hybrid structure [2]. This photo-injector beam will be used to drive a 150 kW, ultra-fast THz-FEL, using a 90cm Undulator, emitting radiation coherently from all the electrons within the pulse. This results with enhanced emission (therefore termed super-radiance) [3]. In order for the electrons to emit coherently, the emitting electron bunch should be shorter than the wavelength of the emitted radiation.

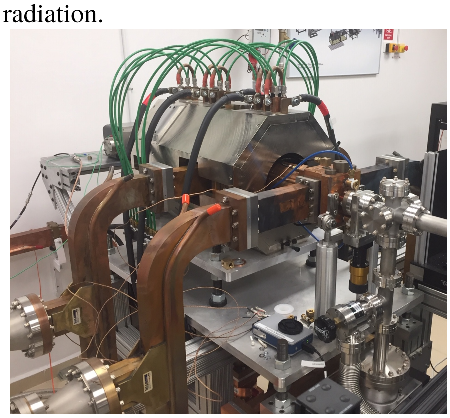

Figure 1: Comissioned Hybrid system at the Schlesinger center in Ariel University

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RF CAVITY DESIGN

As shown schematically in Figure 2, The Hybrid cavity is an integrated structure consisting of a relatively low gradient initial standing wave (SW) gun cells (3.5) connected at the input coupler to even lower field, long traveling wave (TW) section (9 cells) with most of the RF power passing through the device and being directed to a load (another acceleration section can be added later). This new and novel design strongly mitigates RF reflections, as the SW section represents a small fraction (~10%) of the power usage, and the TW section is approximately impedance matched to the input waveguide. Thus there is no need for an RF circulator or coupler system to protect the klystron. The RF coupling shown in Figure 2 is accomplished in the fifth cell encountered by the beam, with the SW section electrically coupled to it on-axis. This mode of coupling is particularly fortuitous, as it is accompanied by a 90 deg phase shift in the accelerating field, resulting in strong velocity bunching effects (Figure 3) on the beam that reverse the usual bunch lengthening induced after the gun exit in standard 1.6 cell photo-injectors.

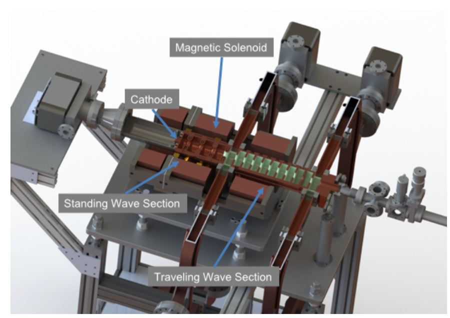

Figure 2: Hybrid gun layout, horizontal cut, marked are the standing wave and traveling wave sections, as well as the cathode location and the magnetic solenoid

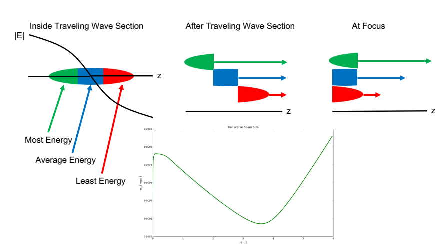

Figure 3: Conversion of applied velocity bunching by the traveling wave section of the gun, to a density bunching after a drift. Green line shows longitudinal compression of the e-bunch.

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The structure is cooled with a single water circuit to operate at a tightly controlled temperature (0.1 deg C). The water channels are cut in a novel V-shape for ease of fabrication. The TW section is a short broadband waveguide, and has essentially no sensitivity in operation over a wide range of temperatures (±10 deg C). On the other hand, the SW portion is resonant, with a Q-width of ~300 kHz, or approximately 7 deg C. Within this temperature range, the phase of the SW section response is highly sensitive. Thus one may tune the relative phase of the SW section (which is temperature sensitive) to the TW phase (which follows the RF input phase). This sensitive tuning also induces relatively small variations in the amplitude response of the TW section, thus permitting a range (at least 10 degrees) of phase tuning between the SW and TW sections. During the high power testing of the gun, we determined the proper working temperature using a VNA. We launched a signal via the input coupler, and measure response using a built-in antenna in the first cell. We varied the temperature while measuring S21 signal in order to determine the nominal working temperature, and found it to be 25.6 deg C as can be seen in Figure 4.

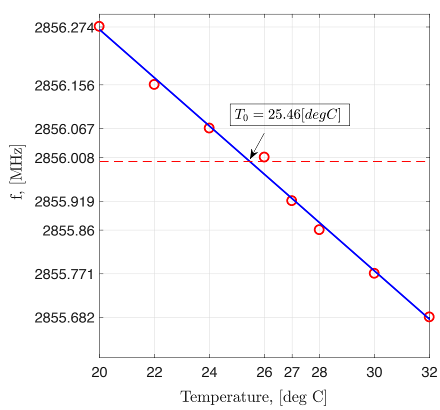

Figure 4: Gun mode frequency (S21) vs temperature of RF structure. Dashed red line marks the required operational frequency (2856 MHz)

GUN SOLENOID

As is common in low gradient, integrated photo-injectors, focusing solenoids are placed over the initial cells to control the beam, as transverse space-charge effects are more pronounced with low α_{RF} (the normalised vector potential of the accelerating field) designs [4]. Despite the need for focusing close to the cathode, the required solenoid fields are not high, peaking at 1.5 kG, thus making the solenoid implementation practical. This large Solenoid, with three separate sections (each with a different static magnetic field profile) is covering most of the gun cells as can be seen in Figure 1. Solenoid is water-cooled using 16 inlets, at a rate of app 90 L/min, keeping it at a stable temperature of 25 deg C. Scanning the inner section of the Solenoid using a Hall Probe both axially and transversely showed similarity of the magnetic profile to simulations, as well as a flat magnetic profile within 20mm radius around the Solenoid axis. The support design allows moving the Solenoid in all directions independently from the RF structure, in order to center it properly.

RF SYSTEM

The RF power for the gun is supplied by a 25 MW Klystron which has been manufactured by SLAC (XK-25) [5]. The Klystron requires an electrical pulse of 250 kV @250 A. A pulse transformer with a ratio of 1:12 is located in the bottom of the Klystron, which determines the requirements for the driving Modulator: 25 kV at 3 kA. The modulator was built in UCLA, and is based on charging and discharging of oil capacitors via a Pulse Forming Network (PFN — a lumped-element circuit that behaves like a transmission line and delivers a rectangular pulse), and is limited to 5 Hz operation, and will typically work at 1 Hz. A low-level RF master oscillator at 2856 MHz is the heart of the RF system. The photo-cathode laser is locked (PLL) with the oscillator, while the oscillator's signal is being amplified to app 500 W using a kW pulsed amplifier. The amplified signal is used as a seed for the Klystron. This method allows phase synchronisation between the laser and RF system to ~100 fs. S band SF6 filled Copper waveguides carry the RF signal to the gun, and a circulator is protecting the Klystron from high-power damaging reflections from the gun. The triggering method is presented in the synchronization diagram (Figure 5.

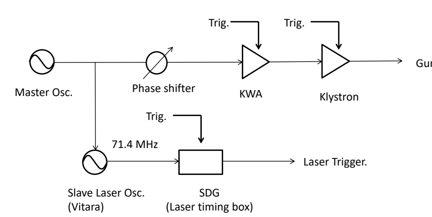

Figure 5: Synchronization diagram of RF and fs Laser system.

PHOTO-CATHODE LASER SYSTEM

In order to liberate a single beam of reasonably high charge from the metal photocathode, having a quantum efficiency of ~1E-4, one should start with a laser system that produces at a minimum 2 mJ of pulse energy in the IR (800 nm). We use an "Astrella" laser amplifier by Coherent, with 35 fs pulse and 3 mJ per pulse @500 Hz. An analog locking system, based on mixing of the master oscillator signal with the 40th harmonic of a 71.4 MHz signal from a diode installed inside the seed oscillator, was built in-house, in order to lock the laser to an external clock. A third-harmonic system provides the needed UV pulse to extract electrons off the Copper cathode, with conversion efficiency of 9%. Before hitting the cathode, the fs UV pulse is stretched by a fused silica crystal to 1 ps. The laser pulse is inserted into the gun through a UV transparent window and deflected towards the Cathode by a slightly-off-axis mirror downstream the

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Cathode at an angle of close to 90 deg. A 4f optical setup, allows control over the laser spot diameter on the Cathode.

HIGH POWER TESTING

Operation of the gun requires launching RF signal of more than 20 MW into the gun structure. High power RF field entering a cavity can cause effects such as field emission of electrons from protrusions on the surface. These effects can cause multipacting or sparks which can destroy the RF gun or the RF window. For this reason, a careful and rigorous conditioning process was necessary, to prevent such possible damage. The conditioning process was performed very carefully and gradually. We started with a short RF pulse (500 ns) and a low pulse peak power (~500 kW–2 MW). The solenoids were switched on with full range current 120–170 A in the coils, and were water-cooled to room temperature. The resonance frequency of the cavity was re-tuned using the cooling/heating water system as was discussed above, in order to wake the right mode in the gun. For a set (short) pulse duration, the voltage output from the high-voltage modulator was swept gradually and was extended at 0.1 kV steps. Only when at least 5 un-eventful minutes have past, we ramped the voltage another step, up to the full range (36 kV max), providing roughly 22 MW of RF output. At each significant breakdown, the RF output power is stopped and the dedicated control software waited until vacuum recovery level was reached once again. It took roughly two weeks to get to the full range of the average power (~22 MW), with yet a very short pulse duration. Next, the RF pulse duration was increased by 0.5 µs and the above process was repeated. The conditioning work was very challenging and events like arcing and sparks occurred much more often as the pulse duration increased. Figure 6 shows typical data collected during four un-eventful pulses. RF power was measured both in the forward and backward directions and inside the gun. High voltage from the modulator was monitored constantly, in case a significant drop or a spike occurs, and the Klystron output power needs to be stopped. Power forward is orders of magnitude higher than reflected power due to the use of a circulator in the RF line to prevent Klystron damage from reflections. A month took for the process to be completed, and 22 MW can now be sent into the cavity without any breakdowns or arcing.

PRELIMINARY OPERATION AND BEAM CAPTURING

Full operation of the electron gun was performed for the first time on March 2019. In the first stage, synchronization between RF and diagnostics was tested, and Dark current was observed, with no laser running yet. We replaced the YAG screens with larger size scintillators in order to improve the brightness and see the electrons better and on a larger surface. This made it easier to find the beam before the setup was fine-tuned. One of the first images is presented in Figure 7. We were able to focus the beam using the external solenoid, and verify it was indeed an electron beam. Ring and center dot in the image are an algorithm designed to find in real-time the beam center and spot dimensions.Unfortunately, before we could properly characterize the electron beam and take more and better images, we suffered from a series fault in our Laser system, which is not yet solved. We are working to bring the laser system back to specs and continue to find the right operational parameters for the gun, and measure beam parameters such as energy, emittance and charge.

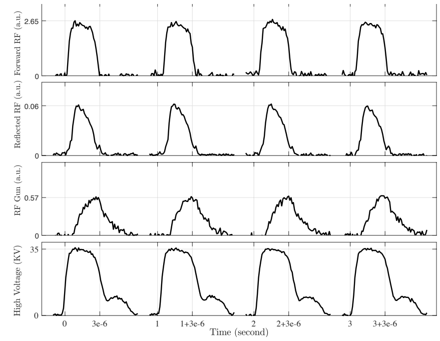

Figure 6: Typical data collected during four RF pulses. RF power is measured both in the forward and backward directions and inside the first cell of the SW section of the gun. High voltage output from the modulator is monitored as well. Power forward is orders of magnitude higher than reflected power.

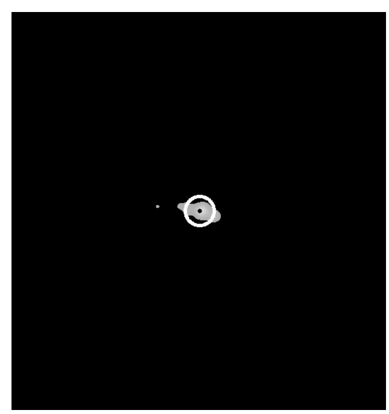

Figure 7: Beam capturing using a scintillator screen. This is a temporary screen, tilted at 45 deg (this is the reason for the elongated shape of the image). Ring and center dot in the image are an algorithm designed to find beam center and spot dimensions.

CONCLUSION

The Hybrid gun at Ariel university is ready for operation. All of its systems are currently running well except for a fault in its laser system. Once this problem is solved, beam characterization can proceed and comparison to design parameters can be made.

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