ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-MOPOMS052

6 MeV NOVEL HYBRID (STANDING WAVE - TRAVELING WAVE) PHOTO-CATHODE ELECTRON GUN FOR A THz SUPERRADIANT FEL

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Abstract

A novel 6 MeV hybrid photo injector was designed and commissioned at the Schlesinger center in Ariel University in Israel as an on-going collaboration with UCLA. 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 less than 3μm, and a 150 fs pulse duration at up to 1 nC per pulse. The Hybrid gun is driven by a SLAC XK5 Klystron as the high-power RF source, and third harmonic of a fs level IR Laser amplifier (266 nm) to extract electrons from the Cathode. The unique e-gun will produce a bunched electron pulse to drive a THz FEL, which will operate at the super-radiance regime, and therefore requires extraordinary beam properties. It will also be used for MeV UED experiments in a separate line using a dogleg section. Here we describe the gun and presents experimental results from the gun and its sub-systems, including energy and charge measurements, compared with the design simulations.

HYBRID PHOTO-CATHODE GUN

A Hybrid S-band (2856 MHz) photo injector is in operation in Ariel University [1, 2], also seen in Fig. 1. It was designed by the PBPL (Particle Beam Physics Laboratory) group at UCLA [3], based on a lower-energy prototype [7]. Main purpose on the gun is to drive a 150 kW, ultra-fast THz-FEL, using a 90 cm Undulator, emitting super-radiantly at 1-3 THz [6]. In order for the electrons to emit coherently, the emitting electron bunch must be shorter than the wavelength of the emitted radiation (Fig. 2).

Figure 1: FEL beam line at the Schlesinger center in Ariel University

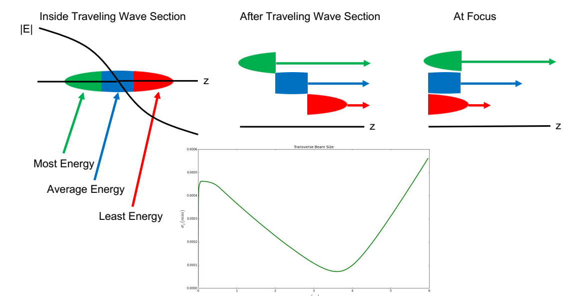

Figure 2: Conversion of applied velocity bunching by the traveling wave section of the gun, to a density bunching after a drift. Green line shows longitudinal compression of the e-bunch.

RF Cavity Design

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 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 Fig. 3 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 on the beam that reverse the usual bunch lengthening induced after the gun exit in standard 1.6 cell 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 [8]. 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 Fig. 3.

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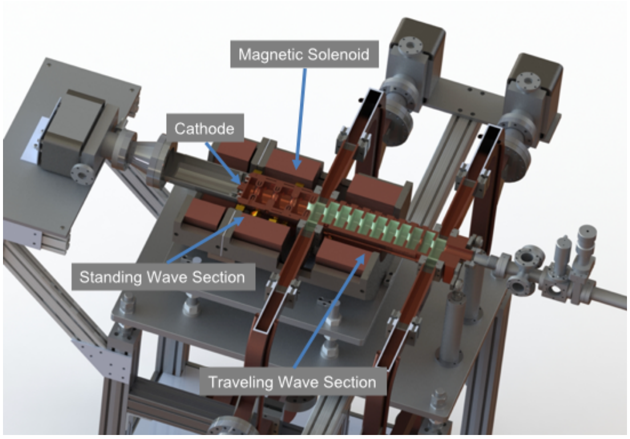

Figure 3: Hybrid gun layout, horizontal cut.

RF System

The RF power for the gun is supplied by a 25 MW Klystron which has been manufactured by SLAC (XK-25) [9]. 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 [4], which determines the requirements for the driving Modulator. The modulator 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, although it typically works at 1 Hz. A low-level RF master oscillator at 2856 MHz is locked to the photo-cathode laser, while the oscillator's signal is being amplified to app 500 W using a kW-level pulsed amplifier. The amplified signal is seeding the Klystron. This method allows phase synchronisation between the laser and RF system with a jitter of ~100fs. 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. Figure 4 plots simulation results of the emitted power from the Klystron as a function of the field amplitude in the standing wave section of the gun (accelerating section). This data will be used as a reference for the kinetic energy measurements of the electron beam.

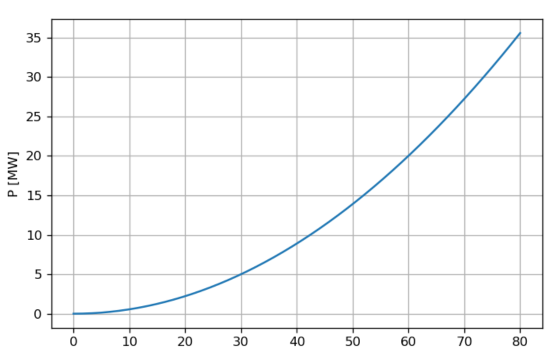

Figure 4: Klystron power vs electric field amplitude in the standing wave section of the gun.

Photo-Cathode Laser System

As a photo-electrons source, we use an "Astrella" laser amplifier by Coherent. The amplified signal has a 35 fs pulse duration [5] and 6 mJ per pulse at a repetition rate of 500 Hz. An analog locking system, based on mixing of the master oscillator signal with the 40th harmonic of a 71.4MHz signal from a diode installed inside the seed oscillator, was designed and built in-house, in order to lock the laser to an external oscillator source. A third-harmonic dual BBOs system provides a UV pulse to extract electrons off the Copper cathode, with a conversion efficiency of 9%. Before hitting the cathode, the fs UV pulse is stretched by a fused silica crystal rod to a duration of 1 ps.

DIAGNOSTICS

Beam diagnostics include Yitrium Aluminum Garnet (YAG) screens for beam size and position monitoring. A multi-slit single-axis emittance measurement system, and a dipole spectrometer to measure energy and spread.

The screen assembly is based on a 10 mm diameter, 10μm thick YAG crystal, placed perpendicularly to the beam propagation direction, and viewed using a back mirror positioned at 45 deg to the beam propagation direction. We use 1μm Aluminum coated silicon mirrors fabricated by CNR-IFN. The cameras are scA Basler monochromatic cameras, equipped with a 100 mm Nikkor Macro lens attached via a manual iris shutter. The whole screen assembly is placed within a 10 cm vacuum cube on a compressed-air operated actuator. Pulse energy and energy spread measurements are based on beam deflection using a dipole spectrometer and a YAG screen to analyze the obtained profile.

Pulse Measurements and Characterization

Electrons kinetic energy was measured using a Dipole spectrometer and a YAG screen downstream. We measured beam deflection and translated it to energy while varying the RF phase and the temperature of the cavity. Figure 5 shows the measured energy results compared to the results of GPT simulations performed in the design stage. These results give a clear indication that the electric field amplitude within the standing wave section of the hybrid gun is app 50 MV/m (or 15 MW from the Klystron according to Fig. 4).

Charge measurements required a faraday cup (made by RadiaBeam), with 50 Ohm impedance. A YAG screen was installed just before the cup in order to verify we measure all the electrons by properly focusing them into the cup. We then varied the RF phase and measured peak charge at each step. Figure 6 shows the results of the charge measurements as a function of the RF phase. Maximal charge extracted from the Cathode was 30 pC, mainly due to a poor quality UV stretcher rod which reduced UV power to 50%, resulting in quantum efficiency of app 10^{-6}. Using a different type of cathode, for example a Magnesium cathode, one can expect a much larger pulse charge.

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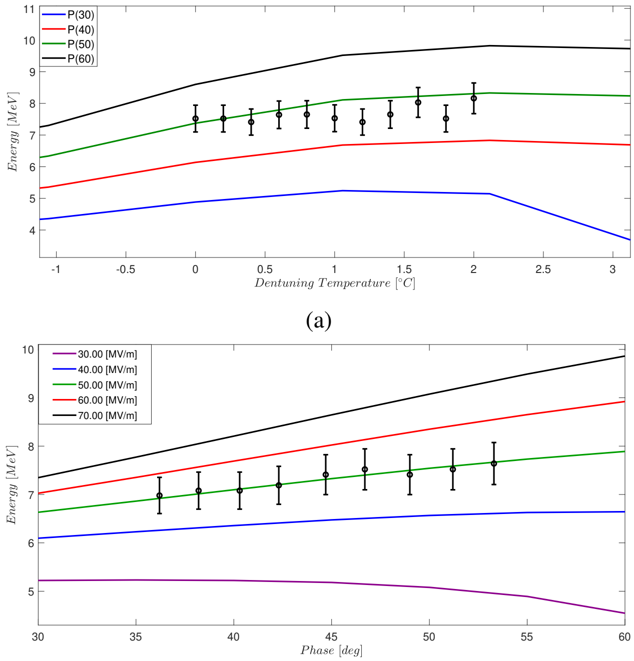

(a)

(b)

Figure 5: Kinetic energy measurements vs RF phase (a) and cavity temperature (b). Lines present GPT simulation results, Black crosses mark the experimental measurements.

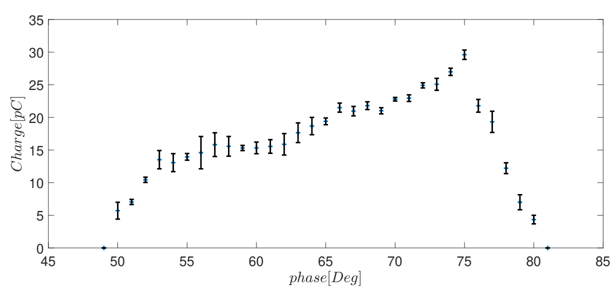

Figure 6: Pulse Charge measurements vs RF phase.

SUPER-RADIANT THZ UNDULATOR

The main goal of the Hybrid beam line is to drive a super-radiant THz FEL. The Super-radiance term [6] indicates a coherent emission from all the electrons within a single pulse, which in practice dictates a pulse that is shorter than the wavelength of the emitted radiation. When this condition is satisfied, the output energy of the radiation is proportional to N^2 where N is the number of the emitting electrons in a single pulse. The THz Undulator was designed and fabricated in-house, and is unique since his gap can vary, and his orientation is horizontal (horizontal motion of the Undulator's jaws) as can be seen in figure 7. A rectangular waveguide is responsible for modes selection. Expected emission is in the order of tens of kilo-watts, in a frequency range of 1-3 THz. A proper detection system for the THz emission is being built these days, and THz measurements are expected in the coming year.

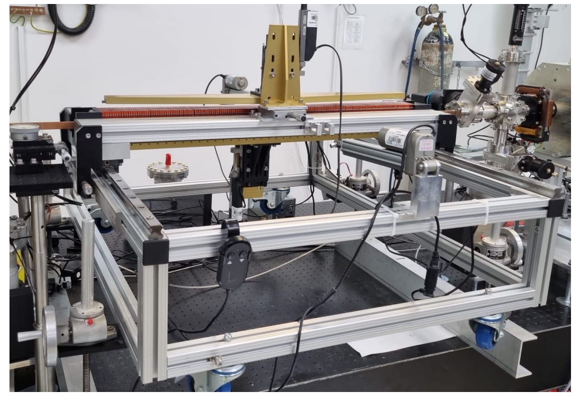

Figure 7: Variable gap Super Radiant THz Undulator.

PARALLEL BEAM LINE VIA A DOGLEG SECTION

The ability to perform several experiments using a single electron gun is very beneficial for small scale facilities such as a university. The lack of space and operational budgets usually limit the number of experiments conducted in such facility. We intend to use a dogleg section (half chicane) in order to create a parallel beam line, enabling execution of several experiments. This beam line will include an experimental chamber in which UED or pump-probe experiments will be feasible. The problem is mainly the inferior beam quality after passing such dogleg. A theoretical model based on transfer matrices was developed in our group, and simulations based optimization demonstrated the ability to reconstruct beam parameters such as emittance and pulse duration after such a section, using first and second order electron-optics. The beam line schematics and optimization results can be seen in [10, 11].

CONCLUTIONS

The Hybrid photo-cathode RF gun at the Schlesinger center in Ariel university is fully operational, and meets the electron beam design parameters. Pulse duration measurements and transverse emittance measurements confirmed the design parameters. Charge was measured to be on the low side currently, mainly due to laser problems. Experimental results are in full agreement with simulations, and a very stable beam operation was achieved. Undulator for super-radiant THz emission was installed and measuring and characterization of THz radiation is in process.

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