CONSTRUCTION STATUS OF A RF-INJECTOR WITH A CNT-TIP CATHODE FOR HIGH BRIGHTNESS FIELD-EMISSION TESTS

[1, 2]Young-Min Shin, [1]Greg Fagerberg, [1]Michael Figora, [1]Andrew Green
[1]Department of Physics, Northern Illinois University, Dekalb, IL, 60115, USA
[2]Fermi National Accelerator Laboratory (FNAL), Batavia, IL 60510, USA

Abstract

We have been constructing an S-band RF-injector system for field-emission tests of a CNT-tip cathode. A pulsed S-band klystron is installed and fully commissioned with 5.5 MW peak power in a 2.5 microsecond pulse length and 1 Hz repetition rate. A single-cell RF-gun is designed to produce 0.5 – 1 pC electron bunches in a photo-emission mode with duration 3 ps at 0.5 – 1 MeV. The measured RF system jitters are within 1% in magnitude and 0.2 degree in phase, which would induce 3.4 keV and 0.25 keV of energy jitters, corresponding to 80 fs and 5 fs of temporal jitters, respectively. Our PIC simulations indicate that the designed bunch compressor reduces the time-of-arrival (TOA) jitter by about an order of magnitude. Emission current and beam brightness of the field-emitted beam are improved by implanting CNT tips on the cathode surface, since they reduce the emission area, while providing high current emission. Once the system is commissioned in field-emission mode, the CNT-tip cathode will be tested in terms of klystron-power levels to map out its current-voltage (I-V) characteristics in pulse emission mode.

INTRODUCTION

Complex dynamics is concomitant with charged particles traveling through periodic lattice structures. When ions interact with scattering sites in a periodic structure, their interactive characteristics vastly change depending upon the condition of the interaction such as spatial distribution, composition, and energy-states of the scatterers, and energy-momentum distributions of the charged particles. If an interactive medium under the particle interaction is in a non-equilibrium state, for instance a lattice structure illuminated by a high power energy source, the dynamics would be even more complicated. Spatiotemporal variation of the interaction parameters would also have a strong dependence on the nature of the external driving source. A precise measurement technique with a sub-atomic scale spatial resolution is required to characterize this kind of charge-matter interaction occurring at the quantum mechanical level. Electron diffraction is a widely used technique for crystallography and combining it with an ultrafast pump laser provides temporal information of structural variations [1 – 3]. The electron pump-probe technique is typically capable of providing sub-angstrom spatial resolution and 100 fs of temporal resolution, which is sufficient for our experiments. We will investigate the interaction mechanism and particle dynamics in nanostructured crystals using this diagnostic method. The planned experiments need a bright, mono-energetic, non-divergent electron beam for precise electron radiation/scattering measurements with a low signal-to-noise ratio. It is crucial to push the beam emittance down to the channel acceptance of an interacting medium. An ultra-cold electron source with a high brightness, ideally up to the quantum limit, is a key element for the experiments because it supplies a sufficient number of coherent electrons to the phase space of the interaction-channel and eventually to a detector. One of our major plans is to develop a high brightness electron source with a CNT cold-cathode [4].

SIMULATION INVESTIGATION OF CNT-TIP COLD-CATHODE

We investigated field-emission characteristics of a nanotube array with finite-element-algorithm (FEA) simulations [5] combined with a modified Fowler-Nordheim (FN) model. A ratio of field distortion due to the presence of a charged object(s) in the space is parameterized by the electric field enhancement factor $\beta = E/E_0$, where E_0 (= U/L) is the electric field between the electrodes (U and L: the anode-cathode voltage and distance, respectively). For theoretical analysis, the local electric field, E, was approximated by various analytic forms (e.g. $\beta \approx \rho(1 + d/D)$, where D is the tip-to-tip distance) of the field enhancement factor, β. In principle, as the aspect ratio ($\rho = l/d$) of CNTs exceeds 1000, field emission from nanotubes would occur at a much lower applied voltage than typical field-emitters. Static field simulations can provide very accurate solutions of the local field distribution, E. The transverse emittances and intrinsic energy spread of the electron bunch emitted from a cathode are mostly determined by initial beam conditions, when electrons are created at a cathode surface.

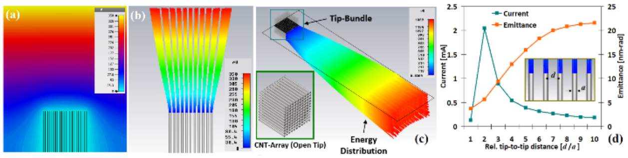

Figure 1: CNT-tip array cathode model (a) electrostatic field analysis with multiple tips (b)/(c) field-emission simulation with the static field (d) emission current and normalized emittance versus tip-to-tip distance (d/a).

Our field-emission simulation (Fig. 1) indicated that a 100 nm wide and 2 μm long CNT tip creates a beam with a high emission current density and small normalized emittance (a few tens of nanometers) due to the small space charge force [6]. As shown in Fig. 1 (c), although the phase-spaces of individual beams from the CNT tips are uncorrelated to each other at the initial emission time, the beam-to-beam correlation occurs as the beam evolves in time [7]. The simulation result verified that a CNT-tip array cathode could be designed for large emission current and small beam emittance by optimizing the field enhancement factor, in particular tip-to-tip distance (Fig. 1(d)). In addition, CNT tips have about two orders of magnitude lower field-threshold than other cold-cathode materials typically used [8].

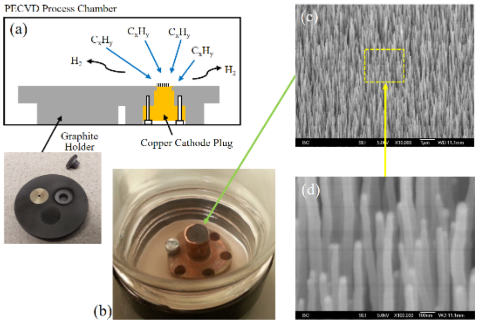

Figure 2: (a) PECVD process for CNT-tip growth on a copper cathode plug with a graphite holder (b) fabricated CNT-tip cathode (c)/(d) SEM images.

A cold-cathode with CNT tip arrays can be fabricated by plasma enhanced chemical vapor deposition processes (PECVD, Fig. 2). It is a precise nano-particle growing process to fabricate highly ordered vertically aligned CNT tip arrays [9,10]. The tips are free-standing multi-wall and single-wall nanotubes, ranging from 5 – 20 µm in length and 10 – 30 nm in diameter. IV-curves and beam profiles of cathodes will be measured to design their morphology for optimal field emission conditions.

INSTALLATION OF TEST SYSTEM

The lab was constructed with a RF-gun injector, a target chamber, and standard beam diagnostics. It has a mission of ultrashort electron beam R&D, including novel cathode development, high field RF studies, pump-probe electron diffraction experiments, coherent radiation source development, and accelerator science education. A major portion of the lab was already commissioned and will be fully available for the proposed experiments over the entire project period.

Figure 3 shows the commissioned lab at present: the pulsed S-band klystron is installed and fully commissioned with 5.5 MW peak power in a 2.5 µs pulse length and 1 Hz repetition rate. A single-cell RF photo-gun is designed to produce 0.5 – 1 pC electron bunches in a photo-emission mode with a duration of 50 fs – 3 ps and up to 20 pC in a field-emission mode at 0.5 – 1 MeV. The gun successfully passed a UHV test with 10^{-8} Torr level and its RF test result agreed well with the gun design. The gun was already assembled with the klystron system and vacuum beamline. The gun/HPRF (klystron) system and the laser system are cooled by the main chiller unit (OptiTemp OTC-10A), which is installed in FW-109. The chiller has a sufficient capacity to cool multiple devices simultaneously during operation. The femto-second laser system (Clark-MXR), including oscillator (ORC-1000, Nd:YAG), amplifier (TRA-1000, Ti:Sapp), pulse-compressor (PC-1000)/-stretcher (PS-1000), unit-controller, and built-in power supply/chiller are installed and tested on the optical table-I. All the system components are completely installed and already prepared for commissioning tests and beam-based experiments. The gun is commissioned with nominal operating conditions and it will be tested with a CNT-tip cathode.

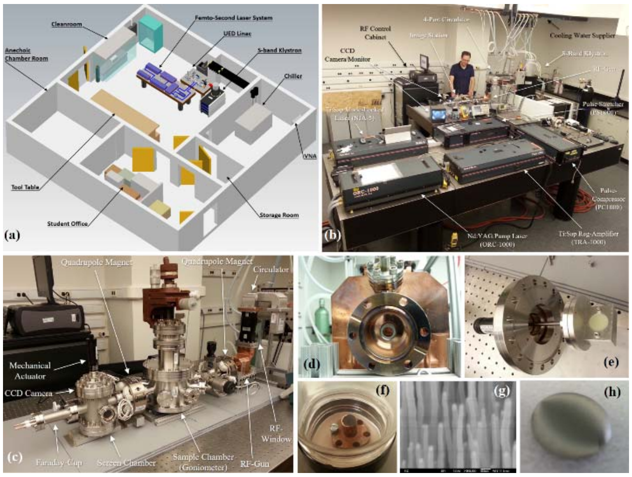

Figure 3: (a) 3D blue-print of NIU laser-accelerator lab (b) photo of the lab under construction/commissioning (c) field-emission electron beam source and femto-second laser system on two optical tables, including S-band klystron, RF-gun, beam diagnostic chamber, and laser components (d) front view of RF-gun (e) beam image station with a screen.

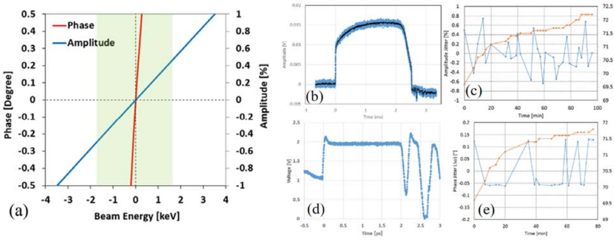

Figure 4: (a) RF phase/amplitude jitter versus corresponding beam energy jitter, obtained from simulations (b) RF-amplitude waveform and (c) its time-traced amplitude jitter, (d) RF-phase waveform and (e) its time-traced phase jitter.

In the RF photo-gun, the photo-electrons emitted by a femto-second laser are accelerated across a 6.75 mm gap in a single-cell RF cavity gun. With 100 MV/m peak acceleration field in a cavity with 6.75 mm gap and 1.6 pC beam charge, final kinetic energy = 0.675 MeV, and RMS bunch length before compression (σ_t) =~ 340 fs. The final normalized emittance (ε_n = 0.074 mm-mrad) mostly comes from thermal emittance at the photocathode and space charge repulsion force. The emittance is conserved while being transported through the gun. This implies that there is still room for reducing the beam size/emittance down to the minimum photocathode spot (a thermal emittance of 0.8 mm-mrad per 1 mm of RMS photocathode spot size was assumed in the simulation). During the proposed project, we will thus further decrease emittance to $\varepsilon_n < 0.050$ mm-mrad and also explore ways to lower thermal emittance further via extended R&D on cathode materials and field-emission and photo-emission processes. The beam brightness can be improved by replacing a conventional photo-cathode with a CNT-tip cathode as the brightness can be increased by the smaller emission area, while providing a high emission current density.

Ambient fluctuations of either RF-voltage (δV_g) or launching-phase ($\delta\phi_0$) or both can cause errors in beam timing, which will produce a jitter in the kinetic beam energy (δE_k) and in the corresponding exit time of the electron bunch (δt_e) from the gun relative to the designed trajectory. Our design analysis on the system indicates the permitted errors in RF-voltage and amplitude to stabilize the total time of flight (TOF) from the gun to an impact point in a sample chamber under the conditions of 100 MeV/m peak-field on a cathode and 70° RF launch angle: δV_g of ± 1 % and $\delta\varphi_g$ of ± 0.2° induce 3.4 keV and 0.25 keV of δE_g, corresponding to 80 fs and 5 fs of δt_e, respectively (Fig. 4(a)). The fluctuation in RF gap-voltage is thus a main source of the timing jitter. The measured data of output signals (Figs. 4(b – e)) indicate that the commissioned klystron system has RF-jitters in amplitude and phase smaller than predicted by the simulations. The system will thus operate with less than 80 fs jitter.

TIME-STABILIZATION

A main role of the bunch compressor (α-magnet) is to preserve the electron bunch length, and to act as an energy collimator that can be used to scrape away the unwanted dark current spectrum. The choice of a low-energy gun and transport beamline was made in an effort to decrease radiation shielding requirements. However, this limits the charge per bunch that can be delivered to the target chamber with ultra-short $\sigma_t < 100$ fs bunches. While other research groups use higher charge of 10 pC or more, the instrument is designed to operate with 10 fC to 10 pC. The reduced shielding requirements lower construction costs and enable wider usage due to reduced space requirements. The device is also designed to preserve TOF of the electron bunch from the photocathode to the interaction chamber. A system that is inherently time-stable can be more useful as an analytic tool in the laboratory. In a system with a great deal of time jitter, some outlier shots will end up outside the desired measurement window. A stabilized system can also be used to collect more data at some desired value of time delay, such as to better resolve a fast transition. Implementing a bunch compressor in the dispersive beamline is the key element to establish timing stabilization and sufficient bunch compression. The α-magnet works for a low energy beam control owing to its simplicity and relatively large negative dispersion [11]. Our simulations indicated that the compressor noticeably reduces the timing-jitter (Fig. 5(b)) [12]. As plotted in Figs. 5(c) and (d), with 1% RF-jitter the timing-jitter is decreased by about an order of magnitude: the RF time-jitter is reduced to ≤ 10 fs. In Fig. 5(a), the sign of correlation in the longitudinal phase space before and after the bunch compressor is flipped. As the beam is transported to the sample chamber, the longitudinal space charge force will act to decrease the beam energy spread (the beam tail is now more energetic than the head), while the bunch is also being compressed. Longitudinal emittance of 1×10^{-4} keV-mm in theory allows very small energy spread ($< 10^{-4}$). In the project, < 10 fs timing control will be pursued by developing the transport and focusing beam optics with a bunch compressor.

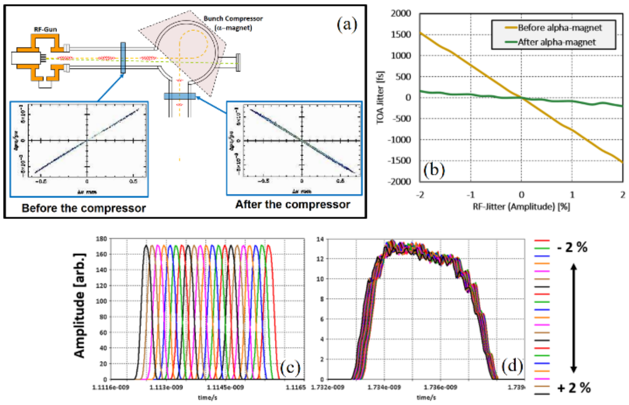

Figure 5: (a) Longitudinal phase space plots (inset) before and after the α–magnet (b) TOA-jitter vs RF-jitter (amplitude). Temporal profiles of electron bunch (c) before and (d) after the α-magnet with respect to RF-amplitude jitters (± 2 %).

CONCLUSION AND FUTURE PLAN

Our electron beam source operating with a $f_{RF} = 2.856$ GHz (klystron) is capable of producing 7140 bunches and 16 pC/bunch over $\tau_{RF} = 2.5$ μs nominal pulse length in a field-emission mode, corresponding to $I_{av}|_{RF} = 4.6$ mA average current over the full RF-cycle. The klystron is currently set up with pulse rep-rate = 1 Hz, and so an average beam current out of an electron bunch to be coupled with the 1 kHz rep-rate laser-pulses is 16 pA. However, the klystron PRR can be adjusted up to 300 Hz, so the maximum average beam current to contribute for the undulation can reach $I_{av}|_{laser} = 5$ nA. The electron gun simulation analysis modeled with a particle emission/tracking code showed that an electron beam of our RF-gun in the system would have $\varepsilon_N = 0.05 – 0.1$ mm-mrad emittance with the nominal bunch charge at 0.5 – 1 MeV beam energy. The emittance can be achieved by a cold-cathode (CNT-tip cathode).

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