Proposal for research in high-brightness electron guns using high-field cathodes

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1. BACKGROUND

This proposal describes four closely related research tasks based on electron emission from metallic surfaces illuminated by a high-intensity, pulsed laser in the presence of a very high electric field. This emission can be used to develop electron guns of unprecedented brightness, but under certain circumstances it can be detrimental to the operation of conventional RF photoelectric sources.

Recent work by Hernandez and Brau at Vanderbilt University has shown that laser-induced electron emission from metallic surfaces is strongly enhanced in very high electric fields by a variety of effects that are only partially understood. These effects include photoelectric field emission and laser-plasma formation. At laser intensities above about 10^{11} W/m^2 runaway emission is observed at all wavelengths. The threshold nature of this effect, together with the observation of damage to the surface of the tip, indicate that the runaway emission is due to laser-plasma formation, despite the fact that the laser intensity is an order of magnitude below the nominal plasma-formation threshold observed at low electric fields. In the linear regime, below the plasma threshold, the quantum efficiency for photoemission from tungsten in very high fields is observed to be strongly wavelength dependent, even above the photoelectric threshold. However, at 266 nm the quantum efficiency approaches unity, an improvement of four orders of magnitude above the value observed at lower fields. The current density is observed to be as high as 10^{11} A/m^2, which exceeds that of conventional RF-photoelectric guns by about four orders of magnitude.

This enhanced emission at high fields can be a blessing or a curse. On the one hand, unit quantum efficiency for photoelectric field emission at a current density $>10^{11}$ A/m^2 represents a breakthrough that could be of enormous benefit for the development of high-brightness electron guns. On the other hand, spurious emission due to laser-plasma formation will hinder the development of high-brightness electron injectors and laser-synchrotron sources. This is particularly true since the effect occurs at infrared wavelengths below the photoelectric threshold.

At the present time, the development of high-brightness electron guns is being pursued at laboratories around the world for a variety of purposes. Several applications of high-brightness electron injectors come immediately to mind:

(1) *High-energy physics*: As colliding-beam experiments in high-energy physics push to higher and higher energy, the cross sections for electron-electron or electron-positron interactions diminish, making it necessary to increase the luminosity of the colliding beams. The luminosity depends on a number of factors, including the normalized brightness of the electron beam. In recent experiments at Vanderbilt, electron beams formed by photoelectric field emission have demonstrated extraordinary current density in nanosecond pulses, with a normalized brightness as much as six orders of magnitude higher than that obtained in conventional RF photoelectric electron injectors. This could have enormous impact on future experiments in high-energy physics since the electron-beam brightness would be higher than that achievable with damping rings.

(2) *Incoherent radiation sources*: In laser-synchrotron X-ray sources, such as the Vanderbilt University MXI device, the X-ray spectral brilliance increases in direct proportion to the electron-beam brightness. The same is true of conventional undulator radiation. The normalized brightness of storage rings decreases with increasing energy as ′ with fixed magnetic field and peak current, whereas the normalized brightness of RF linacs is more-or-less independent of γ, so the brightness of linacs using RF-photoelectric injectors exceeds that of storage rings above about 1 GeV. For this reason it has been proposed that energy-recovery linacs be used in place of storage rings in fourth-generation synchrotron-radiation sources. A high-brightness electron gun using photoelectric field emission might improve the spectral brilliance of these devices by several orders of magnitude. The application of high-brightness guns to laser-synchrotron X-ray sources is of particular interest at Vanderbilt. The MXI X-ray source has successfully demonstrated its ability to produce images, and increased brightness would enhance its capabilities. In addition, the improved quantum efficiency observed in high electric fields would relax the requirements on the cathode drive laser system, reducing the complexity and cost of the MXI X-ray source.

In addition, there is another very important reason for our interest in photoelectric field emission for laser-synchrotron sources at Vanderbilt. During the commissioning of the MXI device we observed spurious emission in the gun cavity associated with the high-power infrared laser used to create Thomson backscatter. The infrared laser, which is directed down the accelerator toward the electron source, illuminates the cathode and the surrounding cavity walls with an intensity of about 500 MW/cm^2. This is well below the nominal threshold for laser plasma formation, but it causes electron emission in spite of the fact that the photon energy (about 1 eV) is below the work function of copper. The charge in the emitted pulse is of the order of 1 μC, which is large compared to the 1 nC emitted from the cathode irradiated by the picosecond uv cathode-drive laser. This spurious current may represent an emission process similar to the subthreshold laser-plasma emission observed by Hernandez and Brau in very high DC fields. The problem is now avoided in the MXI machine by including a chicane in the electron beamline and blocking the laser light, but this increases the cost and complexity of the device and affects the beam quality. With better understanding of the spurious current it should be possible to reduce the complexity and improve the reliability and performance of the MXI device.

(3) *Free-electron lasers*: As free-electron lasers are extended to shorter wavelengths, the electron-beam emittance and brightness must be improved to match the smaller wavelength. The brightness required for the TESLA test facility, for example, is at the upper limit of conventional RF-photoelectric injector technology. In addition, superconducting RF linacs with energy recovery have recently demonstrated enormous increases in average FEL power, with more gains expected in the near future, and there are plans to extend this technology to ultraviolet and X-ray wavelengths. However, the injector has been identified as the critical technology requiring development to achieve militarily useful average power levels. Conventional RF-photoelectric injectors are difficult to use in SRF cavities due to the heat load of the laser on the cathode, so DC guns must be used. However, the limitations of DC injectors make it difficult or impossible to extrapolate this technology to the MW range or to shorter wavelengths. If

the quantum efficiency can be increased by several orders of magnitude by using the high-field effects observed in recent experiments at Vanderbilt, then the average heat load even in a 1-MW device might be as little as 1 W. This is comparable to the dynamic heat load in a single SRF cavity, and would be substantially less in a low-power source used to drive an X-ray free-electron laser. The development of high-field cathodes could provide a credible path to extremely high average power in SRF free-electron lasers for military and civilian applications.

Vanderbilt also has a specific interest in the application of high-brightness electron guns to free-electron lasers. A photocathode-driven electron source for the Mark-III FEL would make it possible to control the electron and infrared micropulse repetition frequencies. If the gun were driven at the 60^{th} subharmonic of the ~3 GHz RF frequency, the FEL laser cavity would contain only one infrared pulse. The pulse train outside the laser cavity would have a 21-ns spacing, so an individual micropulse could easily be selected by the Pockels-cell pulse slicers now in use at the FEL Center. Single-pulse effects could be studied without the effect of leakage through the Pockels cell, which is especially important for MALDI experiments. Control of the pulse repetition frequency would also make it possible to investigate the effect of pulse spacing on ablation, and answer questions such as how close do the infrared micropulses have to be spaced to yield efficient surgical ablation at 6.45 μm? In addition, improved brightness obtained by means of a high-field cathode would make it possible to extend FEL operation to shorter wavelengths, especially if the photocathode is placed in a 1.6-cell photocathode gun similar to that used in the MXI experiments, since the reduced beam loading would make it possible to accelerate the beam to higher energy. The new gun could be mounted on the straight-through port of the Vanderbilt FEL, injecting directly into the linac and avoiding the alpha-magnet pulse compressor. This arrangement would not interfere with ordinary operation of the thermionic gun. On other hand, if the photoelectric injector is used in connection with the alpha-magnet phase compressor, the photocurrent from the cathode could be phase-compressed to a much higher value. Either way, the gun would enable control of the micropulse length and chirp, which would make it possible, in turn, to further compress the electron and optical pulses, perhaps to as little as 100 fs.

A further reason for interest in high-brightness electron guns for FEL applications is the possibility of constructing a tabletop UV/X-ray FEL using Thomson backscatter. In such a device the electron beam is counter propagated against a high-power infrared laser, which acts as the undulator. Even at relatively modest electron-beam energy the backscattered coherent radiation is in the UV or X-ray region. Computations show that it is possible to achieve saturated lasing with an electron beam having a peak current on the order of milliamperes if the brightness is as high as expected from photoelectric field-emission sources. This experiment can be conducted at relatively modest cost by using a needle cathode electron gun like the one now operating at Vanderbilt together with the 10-J, terawatt laser installed for the MXI X-ray source. The development of a tabletop UV or X-ray FEL would be immediately useful for experiments in materials science and nonotechnology, but would also shed light on the physics of ultrashort-wavelength free-electron lasers that is needed in the development of major facilities such as the LCLS at SLAC.

This proposal comprises four closely related tasks, together with theoretical backup support. The first two tasks explore the nature of laser-induced emission from metallic surfaces in very high fields using experimental facilities already available at Vanderbilt. Specifically, we propose to investigate the quantum efficiency and brightness of photoelectric field emission from needles at various wavelengths and the conditions for subthreshold laser-plasma formation in high fields using the DC gun operating in the Physics Department, and to explore the spurious emission observed in the ATF/MXI RF gun in the FEL Center. These tasks can be carried out relatively quickly at a modest cost. The results from these two experiments will be compared and used to develop high-brightness DC and RF guns for application to incoherent and coherent light sources. It is expected that the results will be immediately useful for improving the brightness and reliability of the ATF/MXI injector while reducing its complexity and cost.

The second two tasks are more adventurous and more costly, but have high payoff. In the first of these tasks an RF injector and test stand will be constructed using a photoelectric field-emission cathode in an RF cavity similar to the ATF/MXI design. When it is completed and operational and the tests are completed, the designs that are developed will be carried over to the MXI machine, and the injector itself will be installed in the main IR FEL system. This will make it possible to achieve shorter wavelengths and single laser micropulses in that device for applications in materials science, biology, and surgery. In the last task the DC gun will be cloned and installed in the MXI laboratory. There it will be used to explore the emission from high-field cathodes using picosecond laser illumination in both the photoelectric and laser/plasma regimes. When these tests are completed the gun will be used in conjunction with the 10-J terawatt laser to make the first Thomson-backscatter tabletop FEL. Since the high-power IR laser is available at no cost to this program, the cost of these pioneering experiments is quite modest.

2. PROPOSED WORK

The objective of the proposed work is to investigate both the physics and the application of high-field laser-induced emission in high-brightness electron guns. The proposed work consists of four distinct but closely related tasks. These include: DC experiments using needles to provide a controlled investigation of the physics of electron photoemission in high fields; RF experiments using the ATF/MXI 1.6-cell gun to understand the spurious emission encountered there; applications of high-field photoemission to the Vanderbilt FEL; and numerical simulations. The simulations will be used both to understand the results from the DC and RF experiments and to apply the results to the development of new, high-brightness injectors.

(1) **DC experiments:** Recent experiments at Vanderbilt using 1-μ tungsten needles at surface electric fields as high as 10^{10} V/m have demonstrated intense electron emission from nanosecond laser pulses at wavelengths of 532, 355, and 266 nm. For irradiation at 266 nm, where the photon energy exceeds the photoelectric threshold, photoelectric field emission is observed to occur with unit quantum efficiency at the highest high electric fields. When the laser intensity exceeds about 10^{11} W/m^2, which is below the nominal threshold for laser-plasma formation by nanosecond pulses, large current excursions are observed at all wavelengths. Experiments are proposed to explore both these effects, and to characterize in time and space the electron beam that is emitted.
(a) Using the existing apparatus with nanosecond laser pulses from existing lasers at uv wavelengths, the brightness of the electron emission will be measured. The quantum efficiency at lower electric fields and at wavelengths longer than 266 nm will be measured, and the peak and average current increased by using larger needles, up to 10 μm tip radius, for the purpose of developing new DC and RF guns. Using infrared laser wavelengths from available lasers, the effect on electron emission of laser damage, surface roughness, and contamination of the surface of the tip will be quantified, and the relation of this emission to the spurious emission observed in the ATF/MXI electron gun established.
(b) The existing DC gun will be cloned and installed in the FEL Center. There it will be used to examine the emission of electrons using picosecond UV laser pulses from the MXI cathode-drive laser to investigate further the possibilities of developing new, high-brightness RF guns using this technology.
(c) The cloned DC electron gun will be used with the high-power (TW) picosecond IR laser to examine ultrahigh-brightness Thomson backscatter from the high-brightness, pulsed DC electron beam. Calculations indicate that it is possible to use this combination to construct a tabletop Thomson FEL operating in the near ultraviolet. This would represent a dramatic extension of FEL technology.

(2) **RF gun tests:** The purpose of these experiments is to investigate the spurious current observed from infrared irradiation of the ATF/MXI RF injector. The experiments would be carried out in two stages, as follows:
(a) The first level of experiment we propose is to characterize the emission that has been observed using the current ATF/MXI machine, and to attempt to determine its source. To do this, we need only personnel time to run the machine, and a small amount of money

for electron-beam diagnostic tools. This will permit us to evaluate the dependence of emission on the infrared laser power and the electric field in the gun. The results will be compared with the DC experiments by means of the simulations discussed below.

(b) The next level of experiment involves building a free-standing injector test stand, with which we could perform much more detailed measurements on a system that is both easily accessible and available without interfering with operations of the main MXI machine. The main MXI machine is likely to be heavily committed to imaging work beginning this summer. Using the test stand we will prepare various cathode materials and geometries. Preliminary calculations indicate that photoelectric field emission can be used with cathodes larger than the needle geometries investigated by Hernandez and Brau. This would open up a wider field of applicability of this work to systems in which needle cathodes may not be appropriate. For example, if the nominal electric field in the cavity is 50 MV/m, and the cathode is 1-cm long with a tip radius of 1 mm, the electric field at the tip is 300 MV/m. The quantum efficiency of tungsten at 266 nm observed at this electric field is 20%, which is several orders of magnitude larger than the low-field value. The space-charge-limited current density in this electric field is on the order of 10^9 A/m^2, so the peak current from an emitting area of 10^{-8} m^2 (about 1% of the tip area) is about 10 A. This could be increased by using more of the tip area or by longitudinal phase compression before or after the linac. Although the staff at Vanderbilt do not have extensive experience in gun development, we will have the assistance of AES, as we did in the development of the laser-synchrotron X-ray source, as well as the collaboration of the staff at ANL, who are interested in developing a similar gun. The laser driver is likely to be the most problematic component, though the ATF has a laser that was used to drive their FEL oscillator experiment. A vendor, like Positive Light, should be able to update the design for greater reliability and ease of tuning. The laser should be capable of achieving 100-200 μJ/micropulse, with micropulses spaced 21 ns apart, in macropulse bursts lasting up to 8 microseconds. The laser and the main RF would have to be synchronized to sub-picosecond timing. Staff at the FEL Center have extensive laser experience in-house from maintaining a 20-J, 8-ps laser from Positive Light for the MXI project, and from maintaining a pair of optical parametric generator lasers.

(3) **FEL experiments:** Based on the results from the RF test stand, the photocathode gun will be moved from the test stand and installed on the straight-through port of the Vanderbilt FEL. The laser driver for the cathode will be installed in the diagnostics room, near the control room, where it can be adjusted and tuned while the FEL is running. The pulse compressor will be installed in the klystron room, near the accelerator, since it does not require very much adjustment and is not so sensitive to environmental conditions. Once it is operational, the photocathode gun can be used without interfering with operation of the thermionic RF gun used now. After the initial installation and experimentation, this second gun will have little impact on the FEL user schedule, and it should be possible in a single day for one shift to use the thermionic source and the next to use the photocathode source.

(4) **Simulations:** We propose to do simulations of two types, these being simulations of the electric fields using Poisson/Superfish type codes, and simulations of the electron trajectories using PARMELA type codes, all of which are currently in use at

Vanderbilt. In this effort we will be helped by collaboration with ANL, who have already started doing such simulations. Besides being a prerequisite to trajectory calculations, field simulations will be used to analyze the electric-field effects on spurious electron emission in the ATF/MXI machine. Simulations of the electron trajectories in the test stand and FEL guns will be used to design and use the new RF guns. In addition, electron trajectories may be important for secondary emission and residual gas ionization in the ATF/MXI injector. The scope of the simulation work may be divided up in the following way:

needle cathodes: Electron trajectories and the area of the emitting cathode need to be studied to yield high peak currents while maintaining a small phase space area (optimize the electron beam brightness). Experience with the current FEL thermionic gun suggests that properly shaping the entrance and exit nose cones enhances the brightness and current. There is also the possibility of using a DC "grid" close to the needle to control emission. The desirability of further pulse compression in an alpha magnet or other magnetic compression scheme will be studied.

infrared (spurious) electron emission: The emission processes responsible for the spurious current observed in the ATF/MXI 1.6-cell gun are not understood, and may be a combination of subthreshold laser-plasma formation, ionization of the residual gas, and secondary emission. The high surface electric fields in the gun, of the order of 40 MV/m field, presumably contribute to the emission. To relate the results from needle experiments and to study the possible role of various processes, simulations will be used to follow the trajectories of primary and secondary electrons emitted at various places in the gun. We already have a working Superfish model of the ATF/MXI gun, and these field solutions can be used in further calculations for ruling out some of these mechanisms.

FEL experiments: Currently it is envisioned that the new photocathode gun will go on the straight-through port of the Vanderbilt FEL. This will make it possible to use both the present thermionic gun and the new photoelectric injector without interference. However, it may be better to send the photocathode beam through the alpha-magnet phase compressor. Simulations with PARMELA will help to answer this question. Errors in the laser timing, and hence the electron emission, will be studied to better understand the requirements on the laser. Vanderbilt is currently developing new diagnostics that will make it possible to compare the predictions with the simulations.