ISBN: 978-3-95450-179-3 doi:10.18429/JACoW-FEL2017-WEA04

NOVEL CONCEPTS OF A HIGH-BRIGHTNESS PHOTOINJECTOR RF GUN

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Abstract

We propose here a program to design and manufacture a high performance, advanced source of electrons having high beam brightness (over 10^{16} A/m^2) and high bunch charge (~100 pC). Three innovations are being considered: (1) the use of a high peak cathode field, short-pulse RF gun; (2) the use of multi-layered diamond photocathode at low temperature; and (3) the utilization of THz ultrafast field emission gating. High peak cathode field is necessary to achieve a high brightness (low emittance) beam to be accelerated to relativistic energies before space-charge effects lengthen the bunch. The multilayered diamond photocathode is needed to obtain high QE with long wavelength laser in the first doped layer, beam cooling in the next layer, and negative electron affinity at the emission layer. High field single cycle THz pulses, produced by means of laser light rectification in a nonlinear crystal, allow to avoid a UV laser, provide high field emission charge (up to 1 nC) and ~1 GV/m pre-acceleration of sub picosecond bunches.

HIGH CATHODE-FIELD RESONATORS

A natural way to enhance brightness of beams emitted in a photoinjector gun is increasing of cathode fields in order to mitigate space charge effects [1,2]. The necessary high fields can be obtained avoiding a breakdown and a pulse heating by means of short high-power RF pulses. Because high brightness is extremely important parameter for XFEL applications, a possible solution could be to use an additional RF gun which emits short bunch train producing short high-power RF pulse. In recent experiments, it was shown that ~300 MW, 10 ns of RF power can be taken away from bunch train in ANL gun [3]. It is important that RF power in this case is phase locked with a laser of the first “driving” RF gun. The same laser can service the second high-brightness RF gun.

Note that high fields are necessary at near cathode area only because in the rest part of the resonator a flying beam is already relativistic one. That is why, we suggest a scheme of a gun consisted of two uncoupled cells powered independently (Figure 1). To obtain ~500 MV/m on the cathode surface in X-band, a large portion of RF power, about 70 MW, is directed into the half-cell section that has quality factor $Q \approx \pi \cdot f \cdot \tau$ of 370 (f=11.7 GHz, τ=10 ns). RF is coupled in using a coaxial coupler and a choke reflector. Approximately 20% of the power fed into the first section is required for the second 1-cell section to achieve an acceleration field of 150 MV/m. The power splitting between the two sections is done using a variable power attenuator and a variable phase shifter. The field structures in cells are shown in Figure 1.

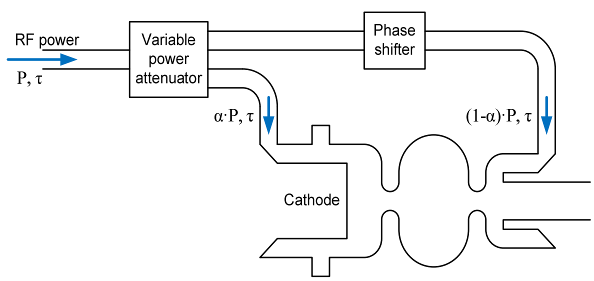

Figure 1: A schematic of the proposed two-cell photoinjector.

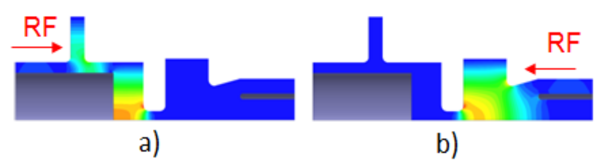

Figure 2: Field distribution in the first half-cell (a) and in the second cell (b).

ULTRAFAST FIELD EMISSION GATING

Another idea is to build a high brightness gun based on a gated picosecond flat field-emission cathode. Laser-based single-cycle THz pulse production by optical rectification and semiconductor switching yields high intensity, ~ 1 ps long THz pulses [4]. The 1 GV/m field strength of the THz pulse, combined with the RF gun accelerating field of ~100 MV/m, results in the emission of a short current pulse from the cathode. Compared to a standard photocathode, the beam brightness is increased due to the high additional accelerating field provided by the THz pulse. The proposed injection scheme does not require a UV laser, high emission charge (up to 1 nC) is emitted due to field emission at high THz fields for sub-picosecond bunch lengths.

In order to obtain the highest emission fields the THz pulse that is generated will be focused to the smallest possible size at the cathode by means of a parabolic mirror

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(Figure 3). Such scheme is well suitable to use the described THz emitter in a conventional RF gun. The mentioned parabolic mirror allows efficient focusing of the broadband THz pulse. In Figure 4 the incident pulse shown on the left, the field at the time correspondent to maximum of focusing is shown on the right. Field increasing near focal point is close to ~10 (Figure 5). Note that transverse magnetic field (Figure 6) in this time is close to zero so that the emitted electron bunch is not laterally deflected.

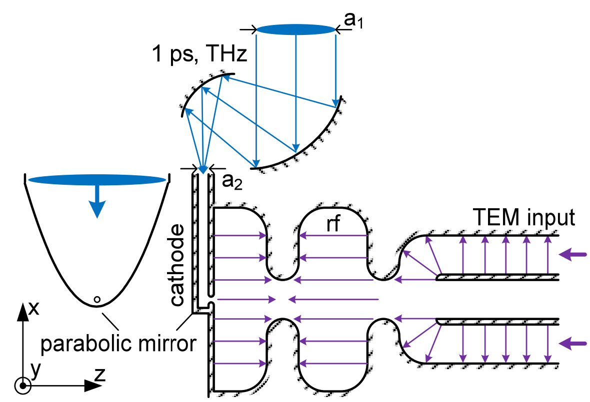

Figure 3: RF gun wherein electron emission is controlled by a picosecond THz pulse irradiating a metallic cathode.

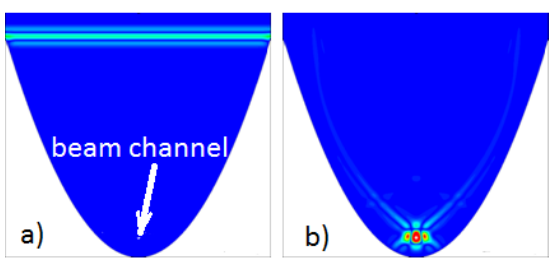

Figure 4: Field distributions at the parabolic mirror while focusing the short THz pulse, for the time correspondent to beginning of focusing at t=5 ps (a) and for time when focusing is close to maximum at t=33 ps (b).

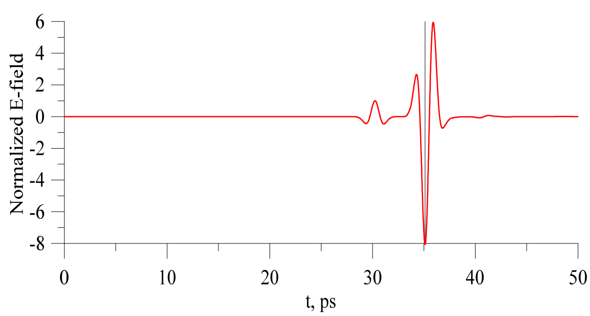

Figure 5: Electric field components at the focus of the parabolic mirror.

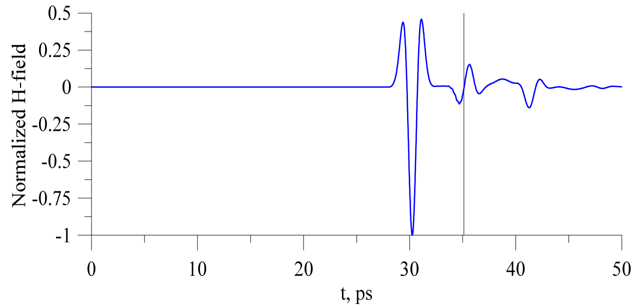

Figure 6: Magnetic field components at the focus of the parabolic mirror.

The anticipated parameters of the THz injector are summarized in the Table 1.

Because THz part of the gun has length ~100 µm electrons are able to increase energies up to energy of the rest level only. In a multi-cell structure consisted of sector waveguides with parabolic mirror at bottom (like in Figure 4) bunches can be accelerated to much higher energy due to Cherenkov synchronism with incoming portions of THz radiation. The incident pulse is shown in Figure 7a, fields and accelerated bunch are shown in Figure 7b.

Table 1: Anticipated Parameters of the THz-gated Injector

Parameters	Value
Cathode field, GV/m	8
Bunch length, ps	0.13
Cathode radius, mm	8×10^{-3}
Bunch charge, pC	25
ε_{th}, mm×mrad	9×10^{-4}
ε_{sc}, mm×mrad	0.13
ε_{RF}, mm×mrad	7×10^{-3}
Brightness, (A/m²×rad²)	2.2×10^{16}

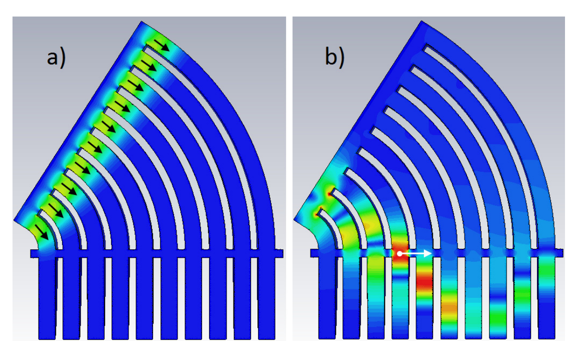

Figure 7: Concept for particle acceleration by a single picosecond THz pulse propagating in periodic accelerating gaps.

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DIAMOND PHOTOCATHODE

Diamond is considered as a prospective candidate for high-brightness photocathode. We propose an *n*-type conductivity, negative-electron-affinity diamond terminated on the surface with hydrogen (*n*-D:H) which is robust in air [5]. The photocathode is assumed to be cryogenically cooled to generate high charge bunches that have significantly reduced energy spreads and emittances. A key element of this injector will be a specialty 3-layer diamond photocathode cooled to 80 K (Figure 8) [6].

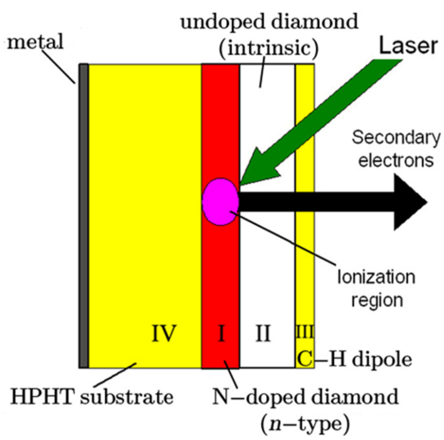

Figure 8: A basic sketch of diamond photocathode.

The layer I is a heavily *n*-doped diamond (i.e. it conducts electrons). *n*-doping can be obtained via introducing nitrogen or phosphorous impurities in the diamond lattice at concentrations of 10^{19}-10^{20} cm^{-3}. Most importantly, *n*-doping allows for the use of a longer wavelength laser (over 150–200 nm) due to the existence of impurity states in the bandgap of diamond that have electron activation energies (1.6 eV for *N* and 0.6 eV for *P*) much lower than the diamond bandgap of 5.5 eV. The layer II (undoped intrinsic diamond) will transmit electrons to the surface in an external RF field while removing excess electron energy to achieve the smallest energy spread and emittance. The layer III (C-H electric dipole formed after diamond surface hydrogenation) will enable high efficiency electron emission into vacuum.

Dynamics of free carriers in the described photocathode is shown in Figure 9. Three sequent snapshots are illustrated showing phenomena taken place in the layers.

Because the space charge induced emittance is inversely proportional to the cathode surface field, we assume to use feeding scheme based on short high-power RF pulses which was analyzed in the first paragraph.

The anticipated parameters of the diamond photocathode are shown in the Table 2 for two laser pulse lengths.

Note that diamond has indirect zone structure. Nevertheless, the cooled electrons in conducting band, being near minimum in the energy-momentum diagram (ε–p), move with close to zero velocity $v = d\varepsilon/dp$ [7]. So, these electrons at a low temperature T can be emitted with near to zero velocity ($v = (2kT/m)^{1/2}$) independently on particular orientation of a crystal with respect to emitting surface.

Cooling of electrons occurs mainly due to scattering by acoustic phonons. Several so-called optical phonons with typical energy ~0.17 eV in the diamond is negligibly small at the cryogenic temperatures.

In order to compensate possible positive charge arisen after emission, a so-called Schottky diode (metal n-doped diamond) is planned to be created at the backing removing accumulated charge between pulses. At emission side the trapped electrons can be removed using Boron-doped layer which does not contradict with the projected surface hydrogenation.

Table 2: Diamond Photocathode Performance and Anticipated Parameters of the 11.7 GHz Gun

Parameter	Version1	Version 2
Pulse duration, ps	0.1	0.5
Cathode radius, mm	3	3
Bunch charge, pC	100	100
Cathode field, MV/m	500	500
ε_{th}, mm×mrad (80 K)	0.17	0.17
ε_{sc}, mm×mrad	0.2	0.2
ε_{RF}, mm×mrad	1.4×10^{-2}	0.35
Brightness, (A/m^2×rad^2)	2.9×10^{16}	2.1×10^{15}

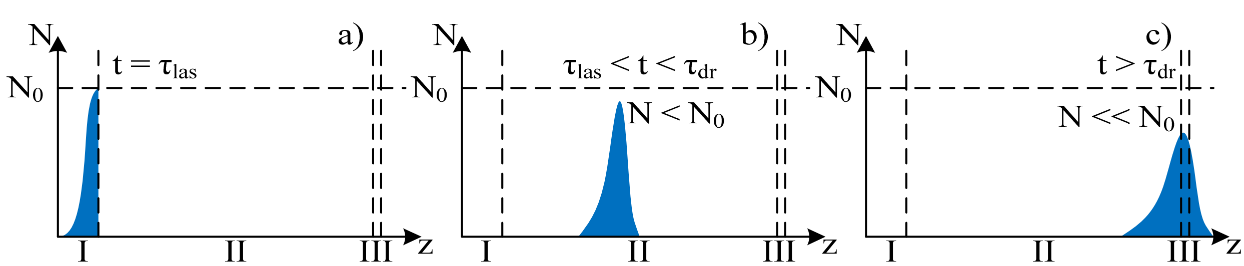

Figure 9: Free carrier packet dynamics in the layered diamond. Three snapshots are illustrated: (a) just-formed electron pulse upon the absorption of the laser pulse (b) electron pulse drift in the external electric field toward the NEA surface, and (c) onset of emission into vacuum.

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CONCLUSION

Three concepts were suggested: (1) to apply short-pulse, high-power RF sources maintaining high cathode fields; (2) to use ultrafast terahertz gating providing preliminary acceleration of bunches; (3) to apply cold diamond photocathode producing low-emittance bunches. These concepts are able to provide ~10^{16} A/m^2×rad^2 beam brightness.

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