STUDY OF THE COLD CATHODE RF ELECTRON GUN BASED ON DOPED DIAMOND FILMS AT CAEP

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Abstract

Diamond films, especially nitrogen doped ultra-nanocrystaline diamond (UNCD) films are considered as promising field emission cathodes because of their low threshold field as well as high thermal conductivity, high breakdown field and chemical inertness. At the present a half cell S-band RF gun which is expected to provide high current electron bunches for a compact THz-FEL facility has been constructed to study the field emission properties of diamond films at the Institute of Applied Electronics in CAEP. The films are deposited on a metallic base of molybdenum by microwave plasma chemical vapour deposition (MPCVD) methods. After installed in the RF gun, an electric field of nearly 90 MV/m can be achieved on the surface of the films so as to obtain high current electron bunches. Here the basic concepts, the experimental setup and results are presented.

BACKGROUND

A compact THz-FEL facility is currently under development at the Institute of Applied Electronics in China Academy of Engineering Physics (IAE/CAEP)[1]. As the electron sources, an RF gun is utilized to provide more than 100 pC of charge during one RF circle. After further acceleration and compression, a peak current of 10 A (corresponding to a pulse length of 10 ps in FWHM) is injected into the undulator and generates coherent terahertz radiations with a peak power of 1 kW. The RF gun originally employed a thermionic cathode of LaB_6 the performance of which is greatly restricted by the back-bombardment of reversing electrons during the macro pulse of several microseconds[2]. Therefore, an alternative new RF gun based on cold cathodes was developed. The back-bombardment would be completely suppressed in the new gun so as to obtain high quality beams.

The cold cathodes may be diamond films which have low threshold field, high thermal conductivity, high breakdown field and chemical inertness. To date nitrogen doped ultrananocrystaline diamond (UNCD) films are thought one of the most promising field emission cathodes due to the good electrical conductivity and high density of emission sites[3]. However studies of UNCD films are mostly focused to lower the threshold field while we demands high current at much higher fields. To fulfill these needs a test stand has been constructed which consists of an S-band half cell RF gun and a Farady cup, as shown in Fig.1. The diamond film is deposited on a metallic base of molybdenum and then put into a small hole at the end of the gun. An electrical field of nearly 90 MV/m can be applied on the surface of the film.

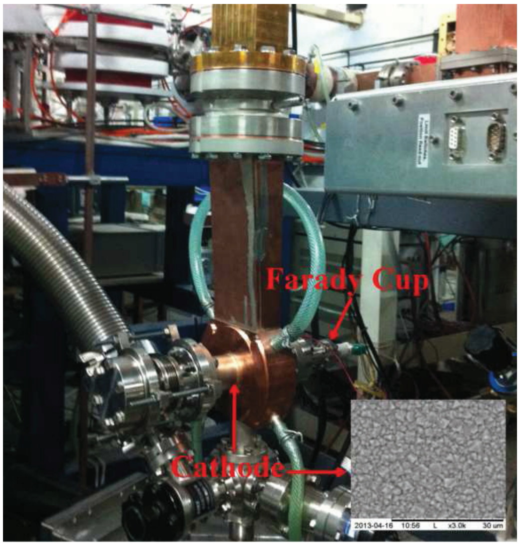

Figure 1: A view of the test stand.

FIELD EMISSION IN RF FIELD

Field emission can be described by the so-called Flower-Nordin equation[5]

$$J(E) = a\frac{E^2}{\phi}\exp\big(\frac{b}{\sqrt{\phi}}\big)\exp\big(-c\frac{\phi^{\frac{3}{2}}}{E}\big) \qquad (1)$$

where a, b, c are constants, ϕ the work function and E the applied electric field. In an RF field, E follows a cosine shape as $E_0\cos(\omega t)$ where ω is the angular frequency of the field. Insertion of $E_0\cos(\omega t)$ into Eq.1 and a few algebraic operations will give

$$J \sim a'\exp\left(-c\frac{\phi^{\frac{3}{2}}}{E_0}\frac{(\omega t)^2}{2}\right) \qquad (2)$$

Compared with gaussian distribution, we find

$$\frac{1}{2\sigma^2} = \frac{c}{2}\frac{\phi^{\frac{3}{2}}}{E_0} \qquad (3)$$

which means the longitudinal distribution of electrons is gaussian[4]. Take copper (ϕ=4.65 eV) as an example, the

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emission current density with respect to the RF phase determined by Eq.1 is compared with that by Eq.3 (see Fig.2). The emission is apparantly concentrated around the peak field and the rms temporal length is roughly 12 degrees. Note that the emission in a thermionic RF gun lasts for half of the RF circle so that the annoyed back-bombardment is inborn. The narrowed emission in the context of a cold cathode RF gun shows the potential of completely suppressing it.

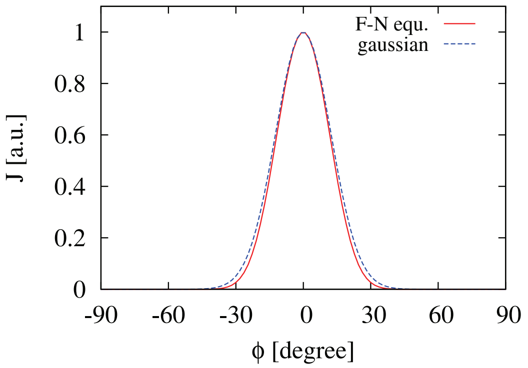

Figure 2: Field emission w.r.t. the RF phase from copper surface.

Field emission is strongly dependent on the field applied and little emission can be observed below the threshold field. In an RF gun operating in macro pulse mode, the electric field builds up gradually. Without considering beam loading in the gun, the stored energy is given by[6]

$$U(t) = \frac{Q_0}{\omega}\frac{4\beta}{(1+\beta)^2}(1-e^{-t/\tau})^2 P_+ = U_f(1-e^{-t/\tau})^2 \tag{4}$$

where Q_0 is the unloaded quality factor, β is the waveguide-to-cavity coupling strength, $\tau = 2Q_0/\omega(1+\beta)$ is the time constant, P_+ is the forward power and U_s is the stored energy at steady state.

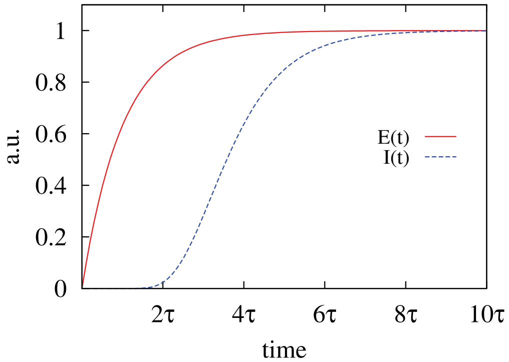

Figure 3: Peak field and average current during a macro pulse. Here $Q_0 = 8500$, $\beta = 1.85$ and so $\tau = 0.33\mu$s.

The transient peak electric field on the surface of the cathode is related to the stored energy by $U = \alpha E^2$ and at steady state we have $U_s = \alpha E_s^2$. Replacing U and U_s in Eq.4 by E and E_s respectively gives

$$E(t) = E_s(1-e^{-t/\tau}) \tag{5}$$

By integrating and averaging Eq.2 within one RF circle we can obtain the average current of that circle at a given transient peak electric field of E which evolves as Eq.5. Figure 3 shows the peak field and average current with respect to time during a macro pulse. The emission falls behind the RF field by roughly 2τ and it takes another 3τ to approach the maximum. The macro pulse should last more than 5τ to obtain stable current.

SIMULATIONS

The performance of the cold cathode RF gun was investigated by simulations. Remember that the emission current is gaussian with respect to RF phase or time. Here we suppose an rms width of 15 degrees. Other parameters involved with particle tracking are listed in Table 1. The tracking was finished by Astra[7].

Table 1: Simulating parameters

half cell length	2 cm
resonant frequency	2856 MHz
peak electric field	60 MV/m
cathode size	ϕ6 mm
bunch charge	70 pC
rms bunch length	15 degree 2σ cutoff

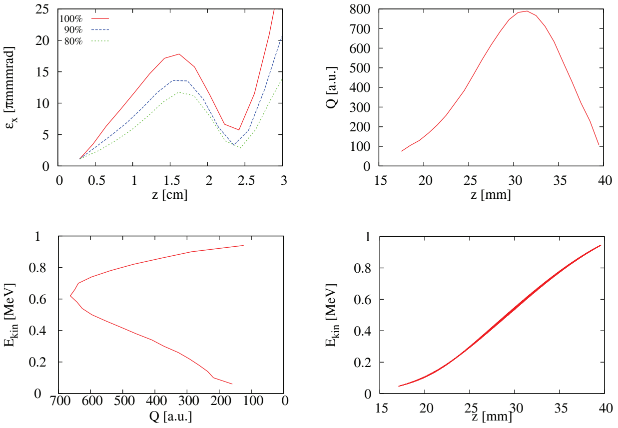

Figure 4: Transverse emittance evolvement (upper left) and longitudinal and kinetic distribution at the gun exit.

The most concerning result is the longitudinal distribution of the bunch. From Fig. 4 we can tell that almost all electrons can escape the gun and the back-bombardment is gone. Another common problem in thermionic RF guns, the energy spread is still large and takes an rms value of

40%. The normalized transverse emittance in the case of a cathode size of 6 mm in diameter at the gun exit is ∼5 π mmmrad, depending on the particles taken into account, which also prevails over thermionic guns.

EXPERIMENTS AND DISCUSSIONS

As mentioned before, it takes about 2τ to build strong enough field for field emission. This was verified by our experiments, as shown in Fig. 5. The time constant is as same as that in Fig. 3. In the measurement, the emitting current became observable after 0.6 μs, roughly 2τ, agreeing well with theoretic model.

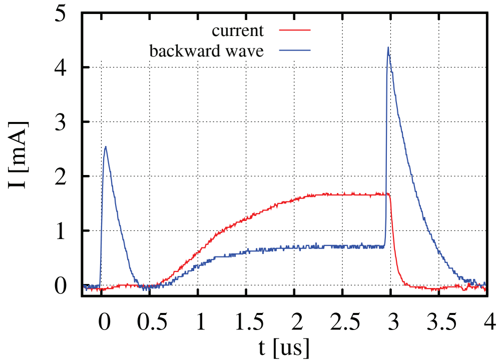

Figure 5: Measurement of emitting current and backward wave.

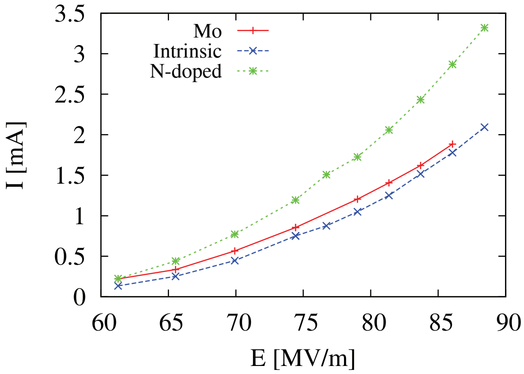

Figure 6: Emitting current (corresponding to the maximum current in Fig. 5) with different kinds of cathodes.

Since the electric field is very high, there is concern on proving the current is emitted by the cold cathode other than by the cavity wall. To do that a naked molybdenum base was inserted into the cathode hole and its emission was measured. Figure 6 shows the currents emitted by the base and different diamond films. The differences showed the contribution of the cathode to the emission. Although the currents from diamond films are not so much larger than that from the naked base, it showed the trend of obtaining much stronger emission by improving the deposition conditions. And this will be our future work.

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