Towards high brightness electron beams from multifilamentary Nb₃Sn wire photocathode

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In order to find electron sources of low emittance and high quantum efficiency, single tip cathodes with a microstructured surface are investigated. Emission currents up to 310 A were obtained, by combining a 2 ns, 50 kV accelerating voltage pulse with a 266 nm wavelength, picosecond ($\sigma_t = 6.2$ ps) laser delivering a few μ J pulse energy. The multifilamentary cylindric Nb₃Sn tip with a typical diameter of 0.8 mm provides quantum efficiencies up to 0.5%. The microstructured needle has also been tested in a combined diode-rf electron gun with 500 kV, 250 ns pulsed bias voltage as a first step towards reducing emittance-spoiling space-charge forces.

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I. INTRODUCTION

In order to find better metallic cathode materials, capable of producing high-charge beams with low emittance, we have recently investigated [1] metallic composite multifilamentary wires of the type used in the superconducting magnet technology (LHC, ITER) and known in the literature as low-temperature, technological superconductors. Initially, the main idea behind this particular choice was to take advantage of the micrometric array structure of these wires and use the field-enhancement effect in a way similar to the field emitter arrays (FEA) technology [2]. The surprise was the discovery of two charge-emission regimes depending on the laser intensity (or equivalently laser fluence), one of them, at intensities between 5 and 10 GW/cm² (fluences around 100 mJ/cm²), with a very large charge-emission capacity. At this level of laser intensity we could extract charges in the nC range without destroying the cathode, which corresponds to quantum efficiency of 0.5%. This was unexpected for metal cathodes.

The most established electron emission processes used in modern electron guns for accelerators are based on thermionic emission and laser-induced photoemission from semiconductors and metals. These technologies offer electron beams bright enough to drive some of the most demanding linear accelerator facilities, the coherent x-ray free electron lasers (XFELs) like the linear coherent light source (LCLS), Spring-8 Angstrom compact free electron laser (SACLA), the Free Electron Laser in Hamburg (FLASH), and Fermi at Elettra. The related electron guns are operated by means of a laser-illuminated copper cathode, by heating a cerium hexaboride (CeB₆) single crystal,

and by a laser-irradiated semiconductor Cs₂Te cathode, respectively. A transversal emittance (beam size $\times$ divergence) on the order of π mm mrad could be demonstrated. In today's linear accelerators the emittance of the electron beam is limited by the thermal emittance, $\varepsilon_{\text{thermal}}$, which is the intrinsic emittance of the electron source. This can be expressed as [3]

$$\varepsilon_{\text{thermal}} = \frac{R}{2} \sqrt{\frac{2E_{\text{kin}}}{3m_0c^2}} \quad (1)$$

with R the beam radius, in the case of a uniform radial distribution, E_{kin} the maximum kinetic energy of the emitted electrons, and m_0c^2 the mass energy of an electron. The production of short electron bunches with lower emittance and higher brightness would be the most direct way to reduce the cost and size of XFELs [4]. According to Eq. (1), the emittance at the source can be reduced by reducing the kinetic energy of the electrons and by decreasing the size of the electron emitting spot size [5]. For a minimal emittance, the ideal electron gun should also emit from the smallest possible surface. Practical limits are however imposed by the optical damage threshold of the cathode material. This limits the laser spot size and the generated current density. Furthermore, after electron emission, space-charge forces lead to Coulomb expansion of the electron beam. This spoils the emittance if the electron bunch is not accelerated fast enough to relativistic speed.

In principle, field emission (FE) is an excellent choice for achieving a bright electron source. The maximum extractable FE current density was reported to be above thermionic and photoemission [1]. FE potentially yields lowest emittance at the source compared to all other electron emission schemes, thanks to the small area of emission [6]. Among FE-based electron sources, different technological approaches have been explored in view of compact FELs, e.g., SwissFEL[7]. The single tip emitter with an apex radius of a few tens of nanometers is reported to deliver

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high charges at moderate emittance [8]. Deformation of the nanoscale tip by heating (Joule effect) is reported to affect stability and long-term performance. Gated FEAs could in principle deliver the required low emittance but the technology suffers from very low charge extraction, cumbersome preparation, and inhomogeneous electron beam profiles. This makes them still inappropriate as reliable electron sources for large scale facilities [2,6,9–13].

Here we illustrate that the investigated microstructured needle sample introduced for the first time in our previous work [1] combines high quantum efficiencies, typically associated with semiconductor cathodes, with prompt electron emission at moderate vacuum conditions, usually a characteristic of metal cathodes. The electron emission process is associated to field-assisted photoemission, by use of a UV laser pulse, combined with a pulsed 50 kV bias voltage. Similar to FE-based cathodes the current density is high, paired with a longer lifetime and nC charge extraction. The multifilamentary Nb₃Sn wire is therefore an excellent candidate for a high brightness electron source. For these metal wires we have estimated a low emittance in spite of the large beam charge. High quantum efficiency, comparable to semiconductor cathodes, has been achieved, without the cumbersome preparation and vacuum conditions.

In this extended paper, we present a detailed description and production process of our samples. We will discuss the results of charge and emittance measurements obtained for different cathode configurations and electron guns (50 and 500 kV acceleration). The laser intensity is varied in two ways: by doubling the laser pulse energy and by varying the laser spot size. The additional measurements presented in this paper confirm the earlier result and are analyzed in the context of the three-step model for photoemission [14] and geometrical field enhancement.

The paper is organized as follows: Section II describes the experimental setup and the preparation procedure of the multifilamentary needle cathode. Section III presents the experimental results from a tabletop 50 kV diode-based accelerator, followed by Sec. IV where the results of the multifilamentary-wire cathode in a 500 kV combined diode-rf electron gun [15] are discussed.

II. EXPERIMENTAL SETUP AND CATHODE PREPARATION

A. Experimental setup

The laser system and the fast high-voltage pulser of our tabletop, compact electron-gun test facility have been described in [8]. We synchronize a Nd:vanadate (Nd:VAN) mode-locked picosecond laser system (longitudinal Gaussian distribution with $\sigma_t = 6.2$ ps and $\lambda = 266$ nm) with a fast high-voltage pulser to extract the charge from the cathode. The high-voltage pulses have a 2 ns FWHM, an amplitude V_{tip} up to 50 kV with a rise/fall time of 1 ns. The time jitter is in the order of 200 ps from pulse to pulse. The electrical field at the cathode tip can be varied by changing the distance between the cathode and anode. Electric fields on the order of 15 MV/m can be stably achieved.

The laser pulse energy, measured outside the high-vacuum chamber (HV) can reach a maximum of 12 μJ and is reduced to 2–5 μJ at the cathode position in order to avoid damage (Fig. 1). The laser energy stability is 4%. The transverse laser intensity profile at the position of the cathode $I_{\text{laser}}(r)$ is Gaussian with an FWHM which can be varied between 40 and 200 μm . The laser spot size on the cathode can be changed using a movable lens (telescope).

As shown in Fig. 1, the HV chamber comprises a phosphor screen SCR2 located at the end of the chamber

FIG. 1. The experimental setup of the 50 kV electron gun, used to measure the beam charge and the emittance. PPT is the pepperpot for measuring the beam emittance, SCR1 is a Ce:YAG screen, FC is the Faraday cup for measuring the beam charge, and SCR2 is a phosphor screen at the end of the vacuum chamber. The inset shows the cathode with the aluminum support and wire cathode.

($z = 610$ mm). A ladder possessing an insertable tungsten pinhole array (pepperpot, PPT) and a Ce:YAG (yttrium aluminum garnet) screen SCR1 is placed at $z = 310$ mm. A Faraday cup (FC) can also be inserted at $z = 480$ mm to measure the charge emitted by the cathode. The FC cannot be biased and there is no magnet to filter out positive charges. The efficiency of the cup is not measured, e.g., by considering and correcting for the secondary electron emission. The charge is measured directly as the integrated signal of the recorded current through a shunt resistor. Located near the cathode ($z = 70$ mm) a movable (XYZ) solenoid can produce a magnetic field of up to 110 mT. The vacuum chamber is pumped by a 50 l/s turbo pump and the pressure in the system was in the 10^{-5} mbar range. The system allows fast exchange of the cathode and is usually not baked. The cathodes are wires with size of 0.8 mm in diameter and are mounted on an aluminum support of 5 mm diameter as shown in the inset of Fig. 1. The height of the wire cathode above the support is adjustable and is used to change (optimize) the field enhancement at the wire tip.

B. Cathode composition and preparation

Each cathode is a piece of wire (strand), 0.8 mm in diameter and several millimeters long. It is cut out from a spool of either a nonreacted, precursor wire, containing

FIG. 2. The multifilamentary-wire technology. Many filaments are compacted together to form a multifilamentary composite wire. After a heat treatment the filaments transform partially in the superconducting compound Nb_3Sn . In a real strand the number of filaments is much larger (10^4 – 40^4) than showed in the sketch.

Nb in a copper-tin bronze matrix or from a reacted one containing Nb_3Sn . Within a strand the Nb or Nb_3Sn is arranged in the form of very fine filaments (2 – 5 μm diameter) which are collected into groups, twisted together, and embedded in the bronze matrix. Because of its brittleness, Nb_3Sn cannot be extruded and drawn. The solution is to proceed by assembling a billet including Nb and bronze, and then processing the billet until the desired wire size is achieved as illustrated in Fig. 2. In more detail, for the multifilamentary cathodes manufactured by the so-called bronze route, first, a pure Nb rod is inserted in the hole of a drilled bronze billet which is drawn to a small hexagonal bar. Many such hexagonal bars are then packed together in a copper billet with a tantalum (Ta) inner jacket. This package is then consecutively drawn to smaller and smaller diameters until the desired filament diameter is reached. The bronze route process results in a wire with a large number of Nb filaments which are almost uniformly distributed in a bronze matrix surrounded by a Ta barrier and a Cu jacket, as shown in Fig. 3 (left panel) and Fig. 4. This is the so-called nonreacted wire. It contains several thousands of Nb filaments surrounded by a bronze matrix. Finally, the nonreacted wire is heat treated to form the Nb_3Sn intermetallic compound, by diffusion of Sn from bronze into the Nb filaments. The standard heat treatment procedure “temperature/time” is described by the sequence: $210/50 + 340/25 + 450/25 + 575/100 + 650/200$ [in $^\circ\text{C}/\text{hr}$]. The result is the so-called reacted Nb_3Sn wire which is superconducting below 18.3 K. To avoid bronze formation in the copper jacket of the final cathode, the Ta jacket acts as a diffusion barrier against outward Sn diffusion, Fig. 4. Typical for the bronze route technology is the presence of a small nonreacted Nb core in the center of the Nb_3Sn filaments [16]. This fact makes the reacted wires interesting not only because they are superconducting but also because they offer an additional structure of pure Nb with a diameter smaller than the nominal filament diameter.

The superconducting property of the reacted wire is noteworthy in view of the large currents which could in principle be extracted from such a cathode and transported

FIG. 3. (a) Scanning electron micrograph pictures of an etched cathode with Nb_3Sn columns. The typical length of the freestanding columns is several tenths of μm . Some of the columns are broken to visualize the column length (several 10 's of μm). (b) Nonetched, polished cathode.

FIG. 4. A close-up view to a typical bronze route strand used in our measurements. The wire has 14326 filaments grouped in 754 bunches of 19 filaments each, $6.6 \mu\text{m}$ in diameter surrounded by a Ta barrier and a Cu stabilizer sheath. A SEM picture of the structure is shown on the bottom left. The full diameter of the multifilamentary cathode is 0.8 mm .

thus without thermal losses. A reacted Nb_3Sn cathode could be a good candidate for a superconducting rf gun operating at 4.2 K . Unfortunately, our electron-gun test facility does not permit testing at low temperatures. At this time the cathodes, either the reacted or the nonreacted ones, were studied only at room temperature.

In order to enhance the electrical field at the filament tips, some of the cathodes tested were etched using HNO_3 acid to remove the bronze core and the Cu jacket over a length of several tens of μm . This leaves the filaments of Nb (nonreacted wires) or Nb_3Sn (reacted wires) exposed. The difference between an etched and a nonetched wire cathode is shown in Fig. 3.

Finally, we have compared the results from our multifilamentary Nb_3Sn cathodes with the one obtained from a Cu cathode wire of the same dimension (0.8 mm) under identical measurement conditions.

III. BEAM CHARACTERIZATION

A. Charge emission and quantum efficiency

Our standard experimental procedure was to monitor the charge emission as a function of the laser intensity (power/area) and accelerating voltage for different samples. The charge values reported here are as measured by the Faraday cup without any corrections for cup efficiency. The quantum efficiency (QE) defined as the number of emitted electrons per incident photon was calculated using the following formula:

$$QE = \frac{N_e}{N_{\text{ph}}} = \frac{Q}{W} \left(\frac{\hbar\omega}{e} \right), \quad (2)$$

where N_e is the number of emitted electrons and N_{ph} the number of incident photons. Q is the total charge, W the laser energy, and $\hbar\omega$ the photon energy.

The laser intensity I_{ph} is calculated with the relation

$$I_{\text{ph}} = \frac{W}{\sqrt{2\pi}\sigma_r S_{\text{spot}}} \quad (3)$$

and is varied by changing the laser spot area on the cathode, S_{spot} . With this definition it is clear that the QE is defined relative to the laser spot on the cathode and not relative to the whole cathode surface. Illuminating the entire wire surface (diameter 0.8 mm) is possible but it would be counterproductive from the point of view of emittance decrease. The minimal spot radius ($40 \mu\text{m}$) is large enough to cover at least three bunches of filaments (~ 60 filaments).

The typical result for charge emission and QE for an etched, nonreacted Nb_3Sn cathode is shown in Figs. 5 and 6 as a function of laser intensity for two laser energies, 2.3 and $4.6 \mu\text{J}$. For each energy, the laser intensity was modified by changing the laser spot size on the cathode but keeping the laser energy and pulse duration constant. Two different regimes characterized by low-charge and high-charge emission have been observed for all Nb_3Sn wires tested.

As Fig. 5 illustrates, in the first regime for laser intensities up to 2 GW/cm^2 , the maximum charge extracted is around 30 pC . As expected the charge emitted is higher at higher laser energy; the number of emitted electrons is proportional to the number of photons indicating single-photon emission. Typical for this low-charge regime is the round, symmetric transversal beam shape as shown in Fig. 7(b).

The QE, shown in Fig. 6, is on the order of 10^{-5} . These are typical results for metallic photocathodes [17–19].

FIG. 5. Charge versus laser intensity for an etched, nonreacted wire at two different laser energies. For each energy, the laser intensity is modified by changing the laser spot size and keeping the laser power constant. The blue region marks an unstable operation of the gun between the low and the high charge regime as shown by the much larger error bars. The lines are a guide to the eye.

FIG. 6. Quantum efficiency versus laser intensity for an etched, nonreacted wire at two different laser energies. For each energy, the laser intensity is modified by changing the laser spot size and keeping the laser power constant. The QE is calculated using Eq. (2). The blue region marks an unstable operation of the gun between the low and the high charge regime as shown by the much larger error bars. The lines are a guide to the eye.

Assuming that the charge emission is in concert with the laser pulse width, the duration of the charge emission at the cathode is $\tau_b = 2\sqrt{2\ln 2}\sigma_t = 14.57$ ps (FWHM). The beam is emittance dominated, because the laminarity parameter $\rho < 1$, where

$$\rho = \frac{Q\sigma_{xy}^2}{2I_0\gamma\tau_b\epsilon^2}, \quad (4)$$

σ_{xy} is the electron beam radius, $I_0 = 17$ kA is the Alfvén current, γ is the relativistic factor, τ_b is the time width of the electron beam and ϵ is the measured emittance (0.4 mm mrad for a charge of 30 pC).

The room temperature QEs for the multifilamentary cathodes with different preparation properties (reacted, nonreacted, etched, nonetched) are very similar as it is

shown in Fig. 7(a). A possible difference between the reacted (superconducting) and nonreacted (normal conducting) wires, if any, can be revealed only at low temperature (4.5 K), when the reacted wire becomes superconducting. We observe a clear difference between the QE of the Nb₃Sn cathodes and the reference Cu cathode (a polished Cu wire of the same diameter as the multifilamentary-wire sample). The copper wire has a systematically lower QE, which is more than an order of magnitude smaller for accelerating fields ≥ 40 kV.

We observe a small difference in the QE for the two laser energies used. The explanation is based on the known fact that the field-enhancement factor for a cylindrical wire increases with the radius reaching a maximum at the wire edge. At higher laser energy, in order to have the same intensity the spot radius must be increased. This results in a larger average enhancement factor. At the lower energy, the spot size is smaller and the enhancement factor is reduced. Therefore we get a larger QE at the higher laser energy.

At intensities larger than 2 GW/cm², the operation of the gun is unstable. This is characterized by large differences in charge emission from pulse to pulse. The standard deviation is typically 50% but can increase up to 100% and more. At laser intensities higher than ~ 3 GW/cm², the instability disappears and the stable operation is recovered. In this second regime, the extracted charge is in the nC range, a factor of 100 increase over that in the first regime. Also the beam transverse profile is no more round as shown in Fig. 8(b). The laminarity parameter ρ is ~ 10 and is calculated using a measured emittance of 0.6 mm mrad at a charge of 2.5 nC. Accordingly, the beam in the second regime is space-charge dominated. In this high-charge regime the charge emission of the multifilamentary cathode is close to what is usually reached with semiconductor cathodes [19] providing QEs in the order of 0.5%.

In principle, the high-charge regime could be attributed to the explosive electron emission (EEE) [20]. With the

FIG. 7. Experimental results and numerical fit for the low-charge regime. (a) QE versus applied voltage for different cathodes. The numerical calculations for Cu and Nb according to the three-step model are represented by the dashed lines. Fit parameters for Nb are $\phi = 4.73$ eV, $\beta = 2000$ m⁻¹, $T = 1200$ K and for Cu $\phi = 4.68$ eV; $\beta = 1800$ m⁻¹, $T = 2000$ K. (b) Electron beam profile recorded at SCR2.

FIG. 8. Experimental results and numerical fit for high charge regime. (a) Quantum efficiency as a function of the applied voltage for nonreacted/nonetched and nonreacted/etched samples. The lines represent the numerical results for Nb using the three-step model. Fit parameters for reacted (I) $\phi = 4.73$ eV, $\beta = 150'000 \text{ m}^{-1}$, $T = 3000$ K and for nonreacted (II) $\phi = 4.73$ eV, $\beta = 120'000 \text{ m}^{-1}$, $T = 3000$ K. (b) Electron beam profile at SCR2, affected by space-charge forces.

same experimental setup, using a sharp ZrC tip (apex of a few tens of nm) [8], the EEE regime starts for power densities above 1 GW/cm^2 . A strong erosion of the ZrC tip was observed after a few hours of operation [21]. On the contrary, our Nb₃Sn multifilamentary wires did not show any sign of damage even after a hundred hours of operation and for laser intensities up to 10 GW/cm^2 . This indicates that, for the multifilamentary-wire cathodes, the driving mechanism responsible for the high-charge regime is not connected to EEE.

In order to interpret our experimental results, we used the three-step model of photoemission from metallic cathodes. It was first proposed by Krolikowski and Spicer [14] and was recently revisited by Dowell [22]. This modern formulation includes the calculation of QE and emittance on the same footing. The three-step model is based on the following three steps.

(1) *Photon absorption*.—The incoming photons of frequency ω and energy $E_{\text{phot}} = \hbar\omega$ are absorbed by electrons with energy E located in an energy band $[E_F - \hbar\omega, E_F]$. After the photon absorption, the electrons are promoted to a band with energy $E + \hbar\omega$. From the total number of incident photons N_{ph} only a fraction $N_{\text{ph}}^{\text{abs}} = [1 - R(\omega)]N_{\text{ph}}$, where $R(\omega)$ is the reflectivity of the cathode material, are absorbed. Assuming that the photon energy is higher than the height of the potential barrier, $\hbar\omega > \phi$, each absorbed photon excites exactly one electron and then by consequence the total number of absorbed photons $N_{\text{ph}}^{\text{abs}}$ is equal to the total number of excited electrons N_e^{exc} . From Eq. (2) the QE can be expressed as

$$QE = \frac{N_e}{N_{\text{ph}}} = [1 - R(\omega)] \frac{N_e}{N_{\text{ph}}^{\text{abs}}} = [1 - R(\omega)] \frac{N_e}{N_e^{\text{exc}}}. \quad (5)$$

The probability that an electron of energy E absorbs a photon is proportional to the number of occupied states with energy E and the number of available states with energy $E + \hbar\omega$ which is

$$dN_{e,1} = P_1(E, \omega) dE = F(E)N(E)[1 - F(E + \hbar\omega)]N(E + \hbar\omega) dE, \quad (6)$$

where $N(E)$ is the electron density of states, $F(E)$ is the Fermi-Dirac distribution function at energy E , and ϕ_{eff} is the effective work function including the Schottky effect [see Eq. (14)].

(2) *Travel to the surface*.—Incoming photons penetrate few nanometers in the material so that the excited electrons have to travel a certain length from the absorption points to the surface. The probability that an electron of energy E reaches the surface is [22]

$$dN_{e,2} = P_2(E, \omega) dE = \frac{1}{1 + \frac{\lambda_{\text{opt}}(\omega)}{\lambda_{e-e}(E)}} dE, \quad (7)$$

where $\lambda_{\text{opt}}(\omega) = \lambda/4\pi k$ is the laser penetration length, a function of the laser wavelength λ and imaginary part of the complex index of refraction $\eta = n + ik$ which can be obtained from [23]. $\lambda_{e-e}(E)$ is the energy dependent electron-electron scattering mean-free path. Following a suggestion of Dowell [22] and using the known energy dependence of the scattering length $\lambda_{e-e}(E') \sim 1/E'^{3/2}$ [14] with energy E' measured relative to the Fermi level E_F , the value of the scattering mean-free path is obtained by scaling from a known energy value, e.g., $E_m = 8.6$ eV and the mean-free path $\lambda_m(8.6 \text{ eV}) = 22 \text{ \AA}$ at this energy, i.e. $\lambda_{e-e}(E') = \lambda_m(E_m/E')^{3/2}$. Taking the average of this relation over the energy range of excited electrons $E' \in [\phi_{\text{eff}}, \hbar\omega]$ gives

$$\tilde{\lambda}_{e-e}(\omega) = \frac{\int_{\phi_{\text{eff}}}^{\hbar\omega} \lambda_{e-e}(E') dE'}{\int_{\phi_{\text{eff}}}^{\hbar\omega} dE'} = \frac{2\lambda_m E_m^{3/2}}{\hbar\omega \phi_{\text{eff}}^{1/2}} \left(\frac{1}{1 + \sqrt{\frac{\phi_{\text{eff}}}{\hbar\omega}}} \right), \quad (8)$$

a value independent of energy but strongly dependent on all other cathode parameters.

(3) *Emission from the surface*.—Electrons that arrive at the surface need to have enough momentum in the normal

direction to the surface to overcome the barrier. Analyzing the kinematic conditions at the interface between cathode and vacuum and requiring the conservation of parallel momentum, one obtains that only electrons that arrive at the surface within a cone of angle $\theta_m(E)$ can escape. The maximum escape angle is given by

$$\cos\theta_m(E) = \sqrt{\frac{E_F + \phi_{\text{eff}}}{E + \hbar\omega}} \quad (9)$$

and the number of electrons with initial energy E which can escape to vacuum is given by

$$dN_{e,3} = P_3(E, \omega)dE = d(\cos\theta)dE \quad (10)$$

with $\cos\theta_m < \cos\theta < 1$.

Combining these three steps, the total number of escaped electrons is

$$N_e = \int_0^\infty P_1(E, \omega)P_2(E, \omega)P_3(E, \omega)dE = \int_0^\infty dE \rho(E)F(E)\rho(E + \hbar\omega)[1 - F(E + \hbar\omega)] \int_{\cos\theta_m(E)}^1 d(\cos\theta)P_2(E, \omega). \quad (11)$$

Similarly, the total number of photoexcited electrons is

$$N_e^{\text{exc}} = \int_0^\infty P_1(E, \omega)P_3(E, \omega)dE = \int_0^\infty dE \rho(E)F(E)\rho(E + \hbar\omega)[1 - F(E + \hbar\omega)] \int_{-1}^1 d(\cos\theta), \quad (12)$$

where in this case the lower limit in the $\cos\theta$ integral has been replaced by -1 and the probability P_2 (travel to surface) is removed as being irrelevant. Finally, using Eq. (5) and modifying the integral lower limits based on the fact that only electrons with energy higher than $E_F + \phi_{\text{eff}} - \hbar\omega$ can escape and that the excited electrons have energy higher than $E_F - \hbar\omega$, the QE is given by

$$QE = [1 - R(\omega)] \frac{\int_{E_F + \phi_{\text{eff}} - \hbar\omega}^\infty dE \rho(E)F(E)\rho(E + \hbar\omega)[1 - F(E + \hbar\omega)] \int_{\cos\theta_m(E)}^1 d(\cos\theta)P_2(E, \omega)}{\int_{E_F - \hbar\omega}^\infty dE \rho(E)F(E)\rho(E + \hbar\omega)[1 - F(E + \hbar\omega)] \int_{-1}^1 d(\cos\theta)}. \quad (13)$$

The parameters for this model are: the reflectivity $R(\omega)$, the photon penetration depth $\lambda_{\text{opt}}(\omega)$, the work function of the photocathode material ϕ , the electron-electron scattering length λ_{e-e} [22,23], the field-enhancement factor β , and finally, the photon energy $\hbar\omega$. The QE depends functionally also on the energy dependence of the density of states and on temperature through the Fermi distribution function $F(E)$.

The experimental results were fitted with the above formula using a calculated density of states for Nb and Cu from FLEUR [24], a freely available full potential linearized augmented plane wave code, based on density-functional theory. The integrals were calculated numerically.

The external voltage applied to the cathode results in a reduced work function by an amount proportional to the square root of the applied voltage an effect known as Schottky effect. The Schottky effect together with the field-enhancement factor caused by the geometrical shape of the needle is considered in the three-step model through the effective work function ϕ_{eff} . The work-function reduction as a function of the applied voltage and field enhancement is given by

$$\phi_{\text{eff}} = \phi - \Delta\phi, \quad \Delta\phi = \sqrt{\frac{e^3 \beta V_0}{4\pi\epsilon_0}}, \quad (14)$$

where $\beta[m^{-1}]$ is the geometrical field-enhancement factor defined as $\mathcal{F} = \alpha\mathcal{F}_0 = \beta V_0$, with V_0 the nominal applied voltage and $\mathcal{F}$ the electric field at the tip.

A work-function reduction allows more electrons to escape and as a result the QE increases.

To estimate the field-enhancement factor for our cylindric wire cathode, we performed an electrostatic simulation for the flat wire tip using a finite element solver. The cylindric wire has a diameter of 0.8 mm with rounded edges (radius 200 nm). In the experimental configuration (tip height of $d = 3.5$ mm), the calculated field-enhancement factor is $\alpha \approx 7.5$ (Fig. 9), corresponding to $\beta = \alpha/d = 2000 \text{ m}^{-1}$.

FIG. 9. Simulated macroscopic field-enhancement factor at the center of the Nb₃Sn (location of laser spot) as a function of tip height above the support. The inset shows the field-enhancement map mimicking a real needle geometry with radius 0.4 mm (only half of the needle cylinder shown), at a tip height of 3 mm. Curvature radius at the edge is 100 μm .

FIG. 10. Pepperpot profiles from an electron beam in the low-charge regime (a) with $\epsilon_n = 0.4$ mm mrad and the high-charge regime, and (b) with $\epsilon_n = 0.6$ mm mrad.

Additionally, we take into account the loss of electrons during propagation from the cathode to the detector, due to the space-charge forces, applying a correction proportional to the applied accelerating voltage, i.e. $QE_{\text{fit}} = QE_{\text{calc}} \cdot V_0/V_{\text{max}}$, where $V_{\text{max}} = 50$ kV is the maximum voltage of our pulser.

The three-step model is well suited in describing our experimental results for the low-charge regime as presented in Fig. 7 for different cathode materials (solid lines). The experimental data were fitted using the work function, $\phi = 4.73$ eV, and a field-enhancement factor $\beta = 2000$ m $^{-1}$, similar to previously reported values [5]. On the contrary, in the high-charge regime [Fig. 8], we had to assume a significantly larger field-enhancement factor in order to fit the experimental data with the three-step model. We need a $\beta = 1.2 \times 10^5$ m $^{-1}$ and $\beta = 1.5 \times 10^5$ m $^{-1}$, for the non-etched and etched sample, respectively. This is more than a factor of 60 higher than that in the low-charge regime.

The apparently very large increase of the field-enhancement factor for the high-charge regime, which is not sustained by the sample geometry and is clearly not physical, suggests that a plasmonic effect could be at play at the wire surface. The surface roughness with a moderate geometrical field enhancement of the same order as that observed in the low-charge regime ($\beta \sim 2000$ m $^{-1}$), together with a surface plasmon effect, can enhance the charge emission at the filament level or even at a smaller length scale, resulting in the large fictitious values of the field-enhancement factor from the three-step fit with the Schottky effect included. The fact that plasmonic effect can lead to an enhanced photoelectric effect was predicted and observed in [25].

B. Emittance measurement

The emittance was measured with a pepperpot (PPT) made of a stainless-steel foil, 10 mm $\times$ 10 mm with a 20×20 hole array of 50 μ m diameter. The pepperpot is introduced in the HV chamber by a ladder at a distance 316 mm away from the cathode, as shown in Fig. 1. The

beam image on the phosphor screen placed at the end of the HV chamber at 610 mm, using a 35 keV beam, is shown in Fig. 10(a) for the low-charge regime and 10(b) for the high-charge regime. In (b) the beam transversal dimensions are larger than the pepperpot. This is a result of the high charge in the beam resulting in a large space-charge repulsion and by consequence a large transversal expansion of the electron beam.

In Fig. 10(b) we observe a central spot which is very bright. This is in good agreement with our particle in cell (PIC) simulations (Fig. 11) that show a high charge density, central bullet with a large halo. The PIC simulation mimics

FIG. 11. Particle in cell simulation for electron beam propagation across the beam line shown in Fig. 1. Because of space-charge forces the 4 nC electron beam splits into several sub-bunches of different energies towards the end of the beam line. The drift region is 610 mm long.

the experimental setup with the 35 kV acceleration voltage of a 4 nC charge emitted from a flat Nb wire cathode.

From our measurements, the normalized emittance of the part of the beam intercepting the pepperpot was calculated, using XANAROOT [26]. We get a value around 0.6 mm mrad for a beam of 2500 pC, i.e., in the high-charge regime. However, we are aware of the fact, supported also by the PIC simulations, that the pepperpot intercepts only a part, i.e., the bullet and not the halo, of the emitted electron beam.

In the low-charge regime, for a charge of 30 pC, we measured an emittance of $\epsilon_n = 0.4$ mm mrad. The emittance in this case is surely overestimated due to the blur produced by the long integration time needed to obtain a good signal/noise ratio.

Emittance conservation for a subrelativistic electron beam over the long distance from the cathode to the pepperpot is challenging. The ejected electron bunch at the cathode is short due to the picosecond ($\sigma_t = 6.2$ ps) laser pulse used for electron emission. Because of the space-charge forces, the electron beam expands longitudinally and transversely during the beam propagation to the PPT screen and spoils the electron beam emittance, especially in the high-charge regime. The longitudinal expansion of the beam, due to the longitudinal space-charge forces, could be suppressed by using a higher acceleration gradient, like the typical accelerating gradient encountered in an rf gun (~ 100 MV/m). In Fig. 11 the particle in cell (PIC) simulation shows the beam expansion due to the space-charge forces acting on a 4 nC electron bunch. Soon after ejection at the source, the electron bunch breaks apart into several parts. The simulation indicates the formation of a central bullet with a high charge density and kinetic energy followed by two heavily space-charge dominated sub-bunches at lower energy.

The beam optics in our experiment has been set to transport the high-energy part of the beam towards the PPT for emittance characterization. The emittance measurement presented in Fig. 10(b) is attributed to the on-axis bullet observed in the simulation. Clearly observable is also the background caused by the trailing electrons (green, yellow color code) which suffer from emittance blowup.

From the presented measurements of charge and emittance, one can estimate the transversal brightness, B_n , as

$$B_n = \frac{I_p}{4\pi^2 \epsilon_n^2} = 10^{13} \text{ A}/(\text{rad}^2 \text{ m}^2), \quad (15)$$

where $I_p = Q/\sqrt{2\pi}\sigma_t$ is the peak current, ϵ_n is the normalized emittance and under assumption of the electron bunch length being equal to the laser pulse duration. This assumption is valid only in the vicinity of the cathode, since space-charge forces expand the electron bunch significantly upon propagation (Fig. 11).

IV. WIRE TEST IN A COMBINED DIODE-RF ELECTRON GUN

A. Experimental system

In the hope to fight against the destructive effect of the large space-charge, we have installed a multifilamentary-wire cathode (not reacted, polished, etched) in a 500 kV diode-rf electron gun. The accelerator beam line, operating at 10 Hz repetition rate, is shown in Fig. 12. The 500 kV pulser with its elliptical diode electrodes and the diagnostic beam line have been described in detail in [15,17]. Recently, low emittance electron beams at low charge ($\sim$ pC) have been demonstrated in this combined diode-rf electron gun using a flat metal cathode [5]. Here we wanted to explore the potential of the multifilament wire cathode to produce a high charge, low emittance electron beam by taking advantage of the high-gradient diode configuration and the subsequent acceleration to 5 MV in an S-band rf accelerating cavity.

The 500 kV pulser driven by a pulse forming network uses a Tesla coil to generate a damped oscillating waveform with a dominant negative peak voltage lasting around 250 ns FWHM (Fig. 15). The peak voltage is adjustable in the range 0–500 kV [27,28]. The gap between the diode electrodes is variable between 0 and 30 mm. For mechanical constraints, the anode is separated from the rf cavity entrance plane by a drift distance of 166 mm. To prevent an expansion of the beam during this drift and to match the beam size to the rf accelerating cavity, a pulsed solenoid is installed 51 mm after the anode iris [Fig. 13(d)]. The two-cell rf cavity,

FIG. 12. Accelerator beam line with the 500 kV pulser and the two-cell 1.5 GHz rf structure. The UV laser is steered onto the cathode via an in-vacuum mirror located downstream the rf cavity. WCM: wall current monitors; ICT: integration current transformer [5].

FIG. 13. Close-up view of the electron source with (a) insert for holding the Nb_3Sn wire, (b) hollow cathode, (c) anode, (d) pulsed solenoid with drift distance, and (e) rf cavity.

Figs. 12 and 13(e), has a frequency of 1.5 GHz and is fed with an rf forward power of 4 to 5 MW with 5 μs pulses, corresponding to an accelerating gradient between 40 and 45 MV/m [29].

The Nb_3Sn wire is centered in the hollow cathode (316L stainless steel) through a polished, plane Cu insert [label (a) in Fig. 13] which is 1.7 mm recessed from the cathode surface. The wire has been mounted in two different configurations with an extension of 0 and 6 mm with respect to the Cu insert surface [Figs. 14(a) and 14(b), respectively].

B. Electron beam characterization

In order to explore the optimum conditions for beam extraction out of the diode, the experiment was performed first with the 2 mm hole diameter stainless steel (316L) anode and later without the anode in order to benefit from the larger aperture of the 16 mm diameter hole of the anode-mounting fixture (M20 thread) (Fig. 14). Surprisingly, in both configurations the extracted charge was only several pC.

With the retracted wire [Fig. 14(a)], we could detect a maximum charge of 6 pC by means of the Faraday cup at the end of the beam line. The pulser was operated at 220 kV, with a diode gap of 20 mm, corresponding to a gradient of 11 MV/m. Operation at higher gradients

FIG. 15. Pulse voltage waveform (yellow) and x-ray scintillator signal (blue). The laser pulse (green) is synchronized to the pulsed high-voltage source and illuminates the cathode when the negative bias voltage is the largest.

resulted in systematic breakdown between the anode and the cathode. After the drift line the electron bunch was accelerated in the accelerating structure to 3.8 MeV. The normalized emittance measured with a pepperpot was 0.6 to 0.7 mm mrad.

With the wire extending out of the cathode surface [Fig. 14(b)] less charge (2 pC) was extracted. This time, the optimum pulser voltage was 87 kV with a diode gap of 14 mm. The lower gradient (6.2 MV/m) at lower voltage resulted in a reduced final beam energy of 1.6 MeV and a larger measured emittance of 1.4 mm mrad. Breakdown appeared on the thread of the M20 screw at the positive swing prior to the negative swing shown in Fig. 15 and sparks were observed at the end of the wire.

Moving the laser spot on the wire surface in order to increase the charge emission resulted in systematic breakdown at each laser shot.

In conclusion, with the wire cathode installed, the combined diode-rf gun could be operated only at significantly lower gradients and well below the nominal performance of a flat Cu cathode. The long field cycle of the pulser (250 ns FWHM) provoked breakdown already at relatively low gradients (12 MV/m) and hindered stable operation of

FIG. 14. Nb_3Sn wire installation inside the 500 kV pulsed gun. Wire flushed with the cathode surface (a) and 6 mm above the cathode surface (b). In this configuration the anode has not been mounted to facilitate charge transport towards the rf cavity. Only its M20 thread is visible.

the wire cathode in this configuration. This gradient was significantly lower compared to the tabletop 50 kV gun operated at 20 MV/m presented in Sec. II. We believe that breakdown in the tabletop 50 kV gun is prevented by the considerably shorter rf field cycle (2 ns FWHM vs 250 ns FWHM).

Operating the wire cathode in a conventional S-band rf cavity-based electron gun with gradients up to 100 MV/m could help to circumvent breakdown issues due to the short time length of an rf oscillation (180 ps) and to operate the wire cathode with gradients similar or larger as in the tabletop scheme. Such an experiment is in preparation at the SwissFEL injector test facility at the Paul Scherrer Institute and will be performed in near future.

V. CONCLUSIONS AND OUTLOOK

A new kind of metallic multifilamentary needle photocathode with a microstructured surface has been investigated. This cathode combines the fast response of metallic cathodes with a QE comparable with that of some semiconductor photocathodes. Two emission regimes have been observed. The first one is at low laser intensities of up to 2 GW/cm² and is characterized by values of QE typical for metallic photocathodes. It is well explained by the three-step model including Schottky effect and a moderate ($\beta = 2000 \text{ m}^{-1}$) field enhancement at the tip. The second regime with a QE 2 orders of magnitude higher (up to 0.5%) appears at laser intensities on the order of 3 GW/cm². In spite of the large extracted charge (up to 4.8 nC), high current density, and large laser intensity, no laser ablation was observed after a hundred hours of continuous operation at 10 Hz. In this regime the three-step model could be fitted to the experimental results only by using a very large field-enhancement factor, $\beta \sim 10^5$, pointing towards possible plasmonic effects.

Stable operation of the multifilamentary-wire cathode in the high voltage combined diode-rf electron gun at high charge failed. We could extract not more than 6 pC of charge with an emittance of 0.6 mm mrad, close to the one expected for metallic cathodes. In the presence of laser illumination the high charge emitted came from the systematic breakdown observed at every laser pulse. We believe that the difference in behavior between the low voltage (50 kV) and high voltage (500 kV) operation originates from the pulse length of the bias voltage being 2 ns (low voltage) and 250 ns (high voltage). Longer pulses provoke breakdown at lower gradients.

Operation of the multifilamentary-wire cathode in a 3 GHz (100 MV/m) rf photogun is the next step towards a full characterization of this new type of cathode [7]. At 3 GHz the equivalent pulse time for the high gradient would be below the ns range, although the rf pulse length can be up to one microsecond long. We believe that stable operation in such an environment is possible given the

short time in which the high field is present on the surface of the cathode.

Applications like free electron lasers, ultrafast electron diffraction, as well as linear colliders can benefit from this new electron source with high brightness. In a free electron laser, the gain length ($L_g \propto B^{-1/3}$) could be reduced using this kind of source with increased brightness B , as compared to the typical value for a rf photogun.

Up to now, we have investigated only one technological superconductor which offers this opportunity: Nb₃Sn known as low- T_c superconductor. The other known technological superconductor, NbTi has a similar multifilamentary structure and is under investigation. Recently, new superconductor compounds known as high- T_c are technologically available but their multifilamentary structure is less developed. Nevertheless, their investigation is of great interest due to the expected special photoemission properties of the basic materials associated to their 2D structure.

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