Large Charge Extraction from Metallic Multifilamentary Nb₃Sn Photocathode

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The current density limit for photoemission from metals was measured in an rf photogun to be below 10^9 A/m². We have achieved 1.6×10^{11} A/m² by photofield emission from a new type of photocathode made from a metallic-composite, multifilamentary Nb₃Sn wire driven by a 266 nm picosecond laser pulse and a 2 ns, 50 kV accelerating voltage. This cathode has a micrometer arrayed structure with tens of thousands of Nb/Nb₃Sn filaments embedded in a bronze matrix. Our measurements revealed the existence of a new electron emission regime at high laser fluence (100 mJ/cm²). We have extracted stably, and without any surface ablation, up to 4800 pC of charge. This corresponds to 0.9% quantum efficiency, 100 times larger than what is measured from conventional metallic photocathodes. The unexpected large and stable charge extraction cannot be explained by the 3-step model. Thanks to the small emitting area, the measured emittance (0.6 mm · mrad) is low in spite of the high current density and space charge effects. This cathode will be of benefit for many applications based on short and bright electron bunches.

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Short and ultrashort electron bunches with high brightness are of great benefit for ultrafast electron diffraction, electron holography, linear-accelerator-based THz sources, for modern particle accelerators and compact free electron lasers (FEL) as well as other scientific and industrial applications [1]. These electron sources require cathodes with high quantum efficiency (QE), fast response time, a small emittance, and they have to be resistant to adverse vacuum conditions.

In principle, for the above mentioned applications, well-polished technical metallic photocathodes are superior to semiconductor-type cathodes since they provide the fastest response time upon laser excitation, the lowest electron beam emittance, the shortest electron bunches, and they are less sensitive to vacuum conditions. Unfortunately, they deliver, without an extensive preparation or cleaning procedure, low QE compared to semiconductor-type cathodes [2–5]. This is a drawback, in particular, when high-charge extraction (e.g., for FELs) or high-repetition rate (MHz) electron bunches (e.g., for ultrafast electron diffraction) are needed as it demands high peak and average power lasers.

When, in order to increase the brightness, the emittance is reduced by reducing the area of the laser spot, ablation and damage of the cathode surface will occur. In the past, carbide based single tips were investigated in the quest for low-emittance electron emitters using field or laser-assisted field emission [6–8]. Recently, new properties have been reported from the micro- and nanostructuring of metals. In such structures, surface plasmon-polaritons (SPPs) form at the metal-dielectric interface as a result of the interaction between the metallic surface charges and the electromagnetic field [9]. Because of their confinement to the metal-dielectric interface, SPPs are able to produce strong near-field enhancements which can be used to

increase the QE of photocathodes. Following these developments, we have investigated, for the first time, electron emission properties of metallic-composite, multifilamentary wires used in the superconductor magnet technology, as potential candidates for a brilliant electron source. These micro-structured wires contain tens of thousands of very fine metallic filaments (2–5 μ m in diameter), grouped in bundles, uniformly distributed, and embedded in a bronze matrix surrounded by a Ta ring and a pure Cu jacket (Fig. 1). The main idea behind this investigation is to take advantage of the presence of these fine filaments and their arrayed microstructure to improve the coupling of the laser field to the cathode and to use the SPPs and the photofield effect to enhance photoelectron emission.

FIG. 1 (color online). A close-up view of a typical bronze-route strand before the test. The 0.8 mm diameter wire has 14 326 filaments, $\phi = 3.8$ μ m, grouped in 754 bundles with 19 filaments. The inset shows a scanning electron microscope of the wire with a magnification of $\times 1000$. Two laser spots, 50 and 160 μ m in diameter, are shown, corresponding to fluences of 100 and 10 mJ/cm² for a constant laser energy of 2 μ J.

It turns out that the investigated metal structured surface allows for 2 orders of magnitude higher QE and charge, and withstands unexpected high laser fluence compared to conventional metal cathodes, while keeping low-emittance and prompt electron emission properties of the metal.

In this Letter, we study electron emission from Niobium-Tin (Nb-Sn) multifilamentary composite wires. The wires can be used in two forms: reacted and nonreacted. In the reacted wires the filaments contain the low- T_c superconductor Nb₃Sn while in the nonreacted wires the filaments are of pure Nb. By abuse of language we call both variants simply Nb₃Sn. The reacted wires are prepared using a special heat treatment procedure [10]. The Sn from the bronze matrix diffuses in the Nb filaments generating the superconducting intermetallic compound Nb₃Sn with a critical temperature of $T_c = 18.5$ K and critical field $B_{c2} = 24.5$ T. Although there is no structural difference between the reacted and nonreacted wires, the reacted ones are interesting in view of their superconducting properties. It should be mentioned that pure Nb is also superconducting but with a much lower critical temperature ($T_c = 9.46$ K) and critical field ($B_c = 0.2$ T) as the Nb₃Sn compound [10].

We use the experimental setup shown in Fig. 2 to test our multifilamentary wires. A Nd:VAN mode locked picosecond laser system (longitudinal Gaussian distribution with $\sigma_t = 6.2$ ps, $\lambda = 266$ nm) is synchronized with a fast, high voltage pulser to extract electrons from the wires at a repetition rate of 10 Hz. The laser energy per pulse can reach up to 5 μ J at the wire. The laser incidence is close to normal (5 deg off) and the spot size on the wire (FWHM of a Gaussian beam) is between 50 and 500 μ m. The fluence is changed by varying the spot size at a constant laser energy. The pulser produces negative voltage pulses of

2 ns FWHM with amplitudes up to 50 kV, a rise or fall time of 1 ns, and a time jitter of 200 ps from pulse to pulse. The UHV chamber hosts a sample holder [aluminum support, Fig. 2(c)] placed at $d = 8$ mm away from the anode, a phosphor screen, a vacuum ladder with a tungsten pinhole array [pepperpot, PPT in Fig. 2(a)] to measure the emittance, and a yttrium aluminium garnet (YAG) screen [SCR in Fig. 2(a)]. A Faraday cup [FC in 2(a)] is used to measure the charge emitted by the cathode. Located near the cathode, a movable focusing solenoid can produce a magnetic field up to 110 mT. The chamber is pumped by a 50 l/s turbopump down to 10^{-6} Torr. The system allows a fast exchange of the cathode and is usually not baked. Short wire pieces, ~ 30 mm long, reacted and nonreacted, were cut from a spool and polished at one end. Before polishing, the wire tip was carefully finished on a lathe in order to remove the cut traces. Some wire samples were etched ~ 100 μ m deep in HNO₃ acid solution. This removes the copper jacket and the bronze matrix surrounding the filaments and liberates tens of thousands of micron-sized tips (Fig. 1). The Ta ring is not affected and keeps the filaments together. We investigated electron emission from differently treated samples: #10 and #13 (nonreacted, etched), #12 (nonreacted, nonetched), #20 (reacted, etched), and #23 (reacted, nonetched). A pure copper sample, #15, is used as reference. At the beginning, we scanned the charge emission as function of the laser fluence for sample #13 by changing the spot size at constant laser energy. The typical behavior is shown in Fig. 3 and shows two stable regimes: one with low-charge emission and QE of the order 10^{-5} for laser fluences below 10 mJ/cm² and one with high-charge emission and QE of the order of 10^{-3} for laser fluences

FIG. 2 (color online). (a) Experimental setup. (b) The cathode and (c) the multifilamentary wire in the aluminum support.

FIG. 3 (color online). Charge and QE for sample #13 (etched, nonreacted) as a function of laser fluence. The sample tip is 1.3 mm above the aluminum support, the applied voltage is 37 kV, and the laser energy is 3.55 μ J. The fluence is increased by reducing the spot size from 500 to 50 μ m. The line is a guide for the eye. The error is 60% for the last stable point of the low-charge regime. Between the last point of the low-charge and the first point of the high-charge regime, the measurements are very unstable with the error larger than 100%.

around 100 mJ/cm^2 . A factor of 10 increase in the fluence produces an increase of 2 orders of magnitude in the charge and QE. Between the last point of the low-charge and the first point of the high-charge regime shown in Fig. 3, the measurements are very unstable with errors larger than 100%. The two regimes are unveiled for all investigated Nb_3Sn samples. In the first regime, the maximum charge extracted is less than 30 pC and the electron beam shape is circular. In the second regime, the charge extracted increases to values up to 3800 pC for sample #12 (non-reacted, nonetched) and to 4800 pC for sample #20 (reacted, etched). A slightly higher charge is extracted from the etched samples as compared to nonetched ones while the highest charge is measured from an etched and reacted sample. A maximum peak current of $I_p = Q/\sigma_t\sqrt{2\pi} = 310 \text{ A}$ is achieved. This corresponds to a current density of $1.6 \times 10^{11} \text{ A/m}^2$ considering a laser spot size of $50 \text{ }\mu\text{m}$ in diameter on the cathode. The highest photoemission current density reported for a photocathode in an rf photogun is below 10^9 A/m^2 [7,11]. In the high-charge regime, the electron beam shape recorded on the YAG screen after 310 mm propagation is no longer circular (Fig. 4) indicating a not fully symmetric, space charge dominated beam. One could envision several mechanisms for this including a nonuniform laser spot and nonuniform quantum efficiency across the wire surface.

For single tip photocathodes, the high-charge regime is usually attributed to the explosive electron emission (EEE). On a ZrC tip, studied in our experimental setup, the EEE regime starts for laser power densities above 1 GW/cm^2 [8]. The EEE is reported to erode a ZrC tip after a few hours of operation. With 10 mJ/cm^2 and a laser pulse with $\sigma_t = 6.2 \text{ ps}$, we are already close to this limit. In the second regime (100 mJ/cm^2) the power density is 6.45 GW/cm^2 , well above the limit. In spite of this, we did not observe any EEE-typical damage on our samples. Even after many (up to 60) hours of operation in the high-charge

regime, the only effect was a slight blackening of the surface and a localized melting of only a few filaments, but no degradation of QE. The charge delivered after 60 h of operation at 10 Hz with 2 nC/pulse was $\sim 4 \text{ mC}$. The fact that the destructive effect of the EEE is not seen but the charge emission increases dramatically needs further investigation. At this time we expect that a combination of surface plasmonic effects, photofield enhancement, and fast dynamics in the electronic bands at the ps time scale imposed by the laser pulse, could be responsible for this effect. Laser irradiation with the right polarization can excite plasmons. In the multifilamentary structure of the investigated wires, surface plasmon could be formed at the metal interface, as a result of the interaction between the surface charges and the electromagnetic field. Because of their confinement to the interface these SPPs are able to produce strong near-field enhancements and by consequence an enhanced photoelectric effect which could explain the observed increase of the QE. A characteristic of plasmon resonance is a sudden increase of the quantum efficiency associated with a change of reflectivity at the surface [12], which has been observed during the laser alignment procedure.

The role played by the pulser electric field was investigated by varying h , the height of the wire tip relative to the aluminum support [see Fig. 2(c)]. As h increases, the distance D between the tip and the anode decrease. Using the same notations as in [13], the average electric field is given by $F_0 = V_0/D$ and the enhancement factor is $\beta = F/F_0 = 3.5 + h/r$. For h in the range 1.3 to 3.5 mm, as in our measurements, we get field enhancements from 6.75 to 12.25. Increasing the height of the wire tip over the aluminum support will increase the local electric field on the tip, $F = \beta F_0$; the Schottky barrier will be lowered and the charge emission will increase. The reduction of the metal work function Φ due to the Schottky effect is given by $\Phi_{\text{eff}} = \Phi - \sqrt{e^3 \beta F / 4\pi\epsilon_0}$ [14], where e is the electron

FIG. 4 (color online). Images of the beam in the low-charge 8.56 mJ/cm^2 (left panel) and high-charge 124 mJ/cm^2 (right panel) regimes. Sample #13, $h = 3.5 \text{ mm}$, $U = 32.65 \text{ kV}$.

FIG. 5 (color online). Extracted charge as a function of the pulser voltage for all investigated samples with the wire tip at 3.5 mm relative to Al support. Samples #10 and #13 (nonreacted, etched), #12 (nonreacted, nonetched), #20 (reacted, etched), #23 (reacted, nonetched). Sample #15 (pure copper) is used as a reference.

charge and ϵ_0 the dielectric constant in vacuum. The QE has a weak dependence on the work function Φ and photon energy $E_{\text{phot}} = h\nu$ and is given by $QE = 1 - [1 + (\Phi_{\text{eff}} - h\nu)/E_F]^{3/2}$ [15], where E_F is the Fermi energy of the cathode material.

We observed the maximum charge emission for $h \sim 3.5$ mm for all applied voltages. Pure field emission (no laser) was observed only at a maximum field (50 kV) with an emitted charge of ≤ 10 pC. Plots of emitted charge and QE as a function of voltage are presented in Figs. 5 and 6. In the first regime (low laser fluence), the photofield emission is the dominant mechanism as evidenced by the monotonic increase of charge and QE with the voltage. This behavior is well described by the 3-step model [16], as shown by the thick line in Fig. 6. In the second regime (high laser fluence), we observe a similar monotonic increase with voltage but the charge and QE are ~ 100 times larger. The reacted and etched sample #20 has the highest charge emission of all wires while sample #23 (reacted, nonetched) the lowest. The nonreacted samples produce charge with values in between these two extremes. We have compared the emission of our multifilamentary wires with the emission from a bare polished Cu wire (sample #15) of the same diameter. In the first regime, the charge emission of the copper wire was comparable to that of the multifilamentary wires while in the second regime it became unstable and nonreproducible. This fact indicates the stabilizing role played by the presence of Nb_3Sn filaments at high laser fluence irradiation.

The high-charge emission of Nb_3Sn in the high fluence regime is accompanied by a strong space charge effect which can, in principle, lead to a large bunch expansion in the radial and axial directions. In order to check that the electron bunch can pass through the small 3 mm aperture

FIG. 6 (color online). QE as function of the pulser voltage for all investigated samples with the wire tip at 3.5 mm relative to Al support. The thick line is a 3-step model calculation with $\Phi = 4.65$ eV, $\beta = 5.4$, and $T = 300$ K. Sample #20 (reacted, etched), sample #23 (reacted, nonetched), #13 (nonreacted, etched), #12 (nonreacted, nonetched), and #15 (pure copper).

in the anode, a series of particle in cell (PIC) simulations have been performed. The simulations show that there is an optimum position of the wire tip relative to the anode ($D \sim 2$ mm) for which the whole electron bunch passes through the anode hole in spite of the space charge effect. A snapshot of the electron bunch at $t = 80$ ps after emission is shown in Fig. 7 for the optimal wire position. The calculated maximum energy of the electrons, 71.74 keV, is higher than the expected 50 keV due to the strong axial charge repulsion within the bunch. Preliminary measurements on the transverse rms electron beam emittance have been performed by sending the electrons through a pinhole array (hole spacing of 250 μm , hole

FIG. 7 (color online). PIC simulation result showing the passage of an 3800 pC electron bunch at $t = 80$ ps through the 3 mm small anode aperture under a 50 kV accelerating voltage. The microbunching is a PIC artifact of the discretization of the charge emission algorithm.

FIG. 8 (color online). (Left panel) Typical pepperpot beamlets recorded on a YAG screen. (Right panel) Cross section used for emittance calculation with XANAROOT [17].

diameter $50\text{ }\mu\text{m}$) onto the YAG screen where the beamlets are recorded (Fig. 8). Assuming the pepperpot intercepts all emitted electrons, a minimum normalized emittance of $\epsilon_n = 0.6\text{ mm} \cdot \text{mrad}$ for a charge of 2500 pC was measured for sample #12 at the pepperpot position using XANAROOT [17]. The emittance at the cathode is expected to be even lower due to the small electron emission area of the filaments. The strong contribution of space charge forces increases the emittance during beam transportation from the cathode to the pinhole array, as the low beam accelerating voltage ($\sim 50\text{ kV}$) is not enough to freeze the beam emittance. The transverse brightness calculated with the formula $B_{\perp} = I_p / 4\pi^2 \epsilon_n^2$ [1] is $B_{\perp} = 1.13 \times 10^{13}\text{ A}/(\text{rad}^2 \text{m}^2)$, where I_p is the peak current at the cathode and ϵ_n is the measured emittance (300 mm away from the cathode). This value is an order of magnitude higher than the state of the art rf photogun performance [18]. This corroborates the potential of our novel electron source for demanding applications. The use of a reacted multifilamentary cathode (superconductive form), at liquid He temperature, for example, could allow the extraction of even larger currents or the DC operation of an electron source.

In conclusion, we presented a new type of metallic photocathode made of multifilamentary Nb_3Sn superconductor wires as a bright electron emitter. This new type of cathode combines, for the first time, the advantages of metal cathodes (fast response, low-emittance, ultrashort electron bunches) with the advantages of semiconductor-based cathodes (high QE). We have extracted, by laser-assisted emission, 4800 pC from this multifilament wire cathode using a short UV laser pulse at a fluence of $100\text{ mJ}/\text{cm}^2$ and a moderate accelerating voltage up to 50 kV . The charge emission and the QE (0.9%) in this regime is 2 orders of magnitude higher than what is measured on conventional polished and flat metal cathodes. The most striking effect is connected, in our opinion, with the way we changed the fluence, i.e., by reducing the area of the laser spot at constant energy. This shows that the reason for the high-charge emission is localized at the filament level, at a scale of several μm and is absent at a scale of $100\text{ }\mu\text{m}$ or larger. The 3-step model of photoemission [16] cannot describe this regime but it describes well the emission behavior at fluence below $\sim 10\text{ mJ}/\text{cm}^2$, pointing to the different photoemission mechanisms involved in the two regimes. We could not observe any relevant erosion on the

wires after 60 hours of operation at 10 Hz and the complete absence of ablation seems to eliminate any hot plasma assisted models as a possible explanation. Our emittance measurements indicate that the use of this new type of cathode is paving the way toward high brightness electron sources opening novel opportunities in accelerator physics, FELs, accelerator-based THz sources, and high-repetition rate ultrafast electron diffraction.

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