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ACTIVITIES AT NCBJ TOWARDS DEVELOPMENT OF THE FUTURE, FULLY-SUPERCONDUCTING, XFEL-TYPE, RF ELECTRON GUN

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Abstract

Our group at NCBJ is working on upgrade of 1.6-cell, SRF, XFEL-type injector in collaboration with DESY and other laboratories. The work is focused on preparation of lead-on-niobium photo-cathode, its positioning in the gun cavity and on the UV laser system for photocurrent excitation. RF focusing effect was used to minimize the predicted emittance and the transverse size of accelerated e^- beam. Following beam dynamics computation, it has been proposed that the photocathode be recessed 0.45 mm into the back wall of the gun cavity. It helps focusing e^- beam in its low-energy part. Preparation of superconducting (sc) photocathodes of Pb layer on Nb plugs is reported, aimed at reaching clean, planar and uniform Pb films. The laser system will consist of commercially available Pharos laser and a 4-th harmonic generator. A gaussian, 300 fs long, 257 nm in wavelength pulse will be transformed in time by pulse stretcher/stacker and in space by pi-shaper. The planned optical system will generate cylindrical photoelectron bunch 2 - 30 ps long and 0.2 - 3 mm wide.

BACKGROUND

R&D program on low and medium current, fully-superconducting, RF electron photo-injector is a part of the task of performance improvement of E-XFEL [1 - 3] and similar facilities. The injector is expected to produce electron beam bunches of normalized emittance below $1{\cdot}\pi$ µrad with charges up to hundreds of pC. Long pulse and continuous wave (CW) operation modes are also anticipated [1, 3]. At the present state-of-the art, reaching an average current of 25 µA from XFEL SRF gun at CW operation is expected in a few years [3]. The concept of a SRF, hybrid Nb-Pb electron injector for linear, sc accelerators was proposed and developed [1,4-8]. This solution assumes the use of a fully sc photocathode in the form of a Pb film applied to niobium surface. Both metals are superconductors with similar critical temperatures but lead exhibits much higher quantum efficiency (QE) of photoemission.

Long-time collaboration between TJNAF, DESY, HZB, BNL, HZDR,, Stony Brook University, NCBJ and SLAC resulted in a concept and design of a 1.6-cell TESLA-type SRF cavity with a replacable photocathode of niobium plug with applied lead film as a photoemitting element. The plug is mounted to the rear cavity wall. This solution, was first proposed at TJNAF [8]. Early tests on such guns with Nb-Pb photocathodes were performed at TJNAF, DESY and HZB [8 - 10]. To emit photoelectrons the lead photocathode is typically excited with an UV beam of photon energy above 4 eV, synchronized with the phase of RF field. The amplitude of the electric field on the cathode surface is 40-60 MV/m [8]. This solution allowed avoiding the cathode contact with mixtures of acids used for chemical treatment of cavities. Nevertheless, high pressure water rinsing of the injector with the photocathode is needed to obtain sufficiently high RF field intensity in the cavity. This preparatory step imposes demands on the lead layer adhesion to the plug.

The work of our team on the optimization of the electron gun for the use of Polish Free Electron Laser (PolFEL) is concentrated on three areas:

1. Improvement of e^- beam focusing and reduction of it transverse dimensions, based on beam dynamics computations.
2. Development of an optimal technique of applying a Pb layer on the photocathode plug.
3. Development and implementation of laser and optical systems for photocurrent excitation from the cathode surface.

The above issues are addressed in the following subsections of this paper.

IMPROVEMENT OF e^- BEAM FOCUSING INSIDE SRF ELECTRON GUN, BASED ON BEAM DYNAMICS COMPUTATION

The main challenge in designing superconducting RF guns is to counteract the space charge forces, particularly in the non-relativistic, low energy e^- beam region immediately downstream of the cathode. Beam focusing in this region by using axial magnetic field from external solenoid is not possible for superconducting structures. Therefore, it was decided to focus the near-cathode electrons by generating a radial component of electric RF field that comes from retraction of the photocathode tip (terminated with the emissive surface) back into the rear cavity wall.

The geometry of 1.6-cell gun cavity with electric field lines is shown in Fig. 1. The field distribution has been computed by using Poisson Superfish code [11]. The radial field component distribution 0.5 mm off the cavity axis is depicted in Fig. 2 for accelerating field amplitude E_{acc} on the axis equal 40 MV/m. A short focusing field spike is visible next to the cathode surface. The spike amplitude grows with the distance from the axis.

The discussed plug retraction reduces the field value on the cathode surface which typically elongates life-time of the cathode. On the one hand it reduces photocurrent emission at high space charge. The latter effect, however, may

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be compensated by rising the accelerating field amplitude (E_{acc}) on the axis. Reaching E_{acc} of 54 MV/m as a result of a special cavity electro-polishing treatment has been reported at KEK.

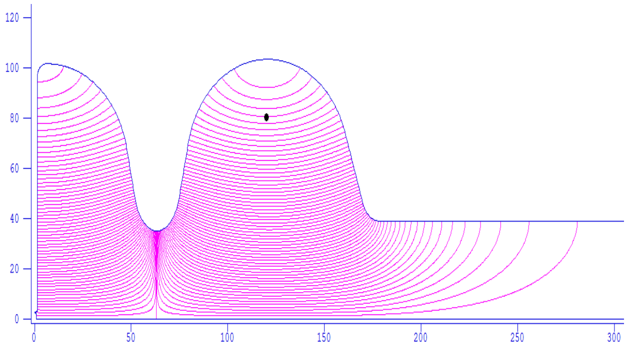

Figure 1: Geometry of 1.6 cavity RF gun with electric field contour lines.

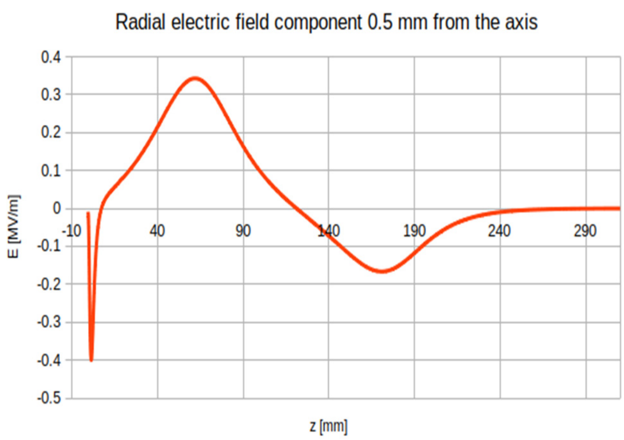

Figure 2: Radial electric field component 0.5 mm off the axis. A few mm wide spike of focusing field is present close to the cathode surface.

To simulate electron bunch dynamics, Astra code [12] was used (similar computations have been performed at DESY). Calculations were done for different positions of the cathode (in relation to the back cavity wall), using cylindrically symmetric algorithm that takes into account space charge field as well as mirror charges at the cathode. The reduction of transverse emittance at the gun cavity end (0.31 m downstream of the cathode), of a 100 pC e^- bunch, as a function of the cathode retraction distance is shown in Fig. 3. On the other hand this beam focussing is reached at the expense of bunch elongation and its energy spread (see energy spread at different plug positions and various beam diameters in Fig. 4). The choice of the cathode retraction distance is a matter of compromise between beam focussing and keeping bunch energy spread within acceptable limits. After carrying out many simulations for electron bunches with diameter up to 2.8 mm and charges from 20 to 250 pC it may be recommended that the cathode emitting surface be recessed by 0.45 mm into the back wall of the gun cavity.

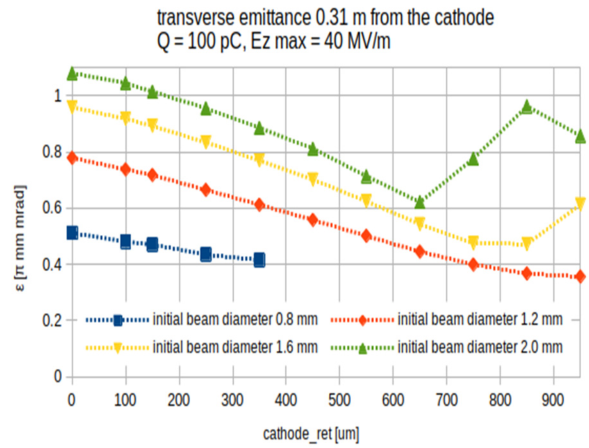

Figure 3: Normalised transverse emittance for 100 pC bunch, 0.31 m from the cathode. Different initial beam sizes at the cathode surface were taken into account.

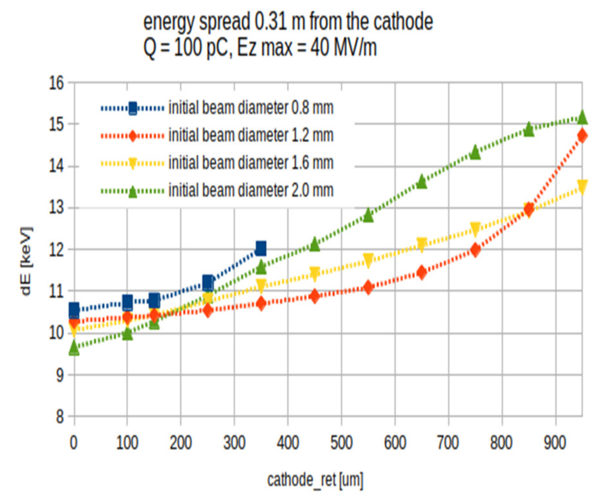

Figure 4: Energy spread rms for different initial beam sizes at the cathode and for different positions of the emission surface in relation to the back cavity wall.

PREPARATION OF A HYBRID, SC PHOTOCATHODE: SUMMARY OF THE WORKS DONE SO FAR AND IMPLEMENTATION OF A NOVEL Pb COATING METHOD

The selection of the correct procedure of Pb layer coating on Nb substrate is a prerequisite for preparation of an effective Nb-Pb photocathode for fully superconducting, RF electron gun. As shown in preliminary experiments, of all the available coating methods, lead deposition in cathodic arc is most promising due to the high QE of electron photoemission from Pb layers obtained in this way [4]. This type of arc generates pure metallic plasma by eliminating any support gas - the eroded metallic cathode material is used as a discharge medium [13]. To control the arc plasma propagation the cathode is immersed in a dc magnetic field of 10 – 20 mT, generated by external coils. High

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degree of Pb ionization (including multi-charged ions) and high ionic energy reached by applying negative dc bias of substrate, allow avoiding columnar structure and voids within a film. It also enables obtaining high layer density and shallow Pb ion implantation into Nb. The main disadvantage of using this coating method is the presence of Pb droplets in a stream of lead plasma. The droplets are by-products of activation of microscopic "cathode spots" on the arc cathode surface [13, 14] in which material erosion takes place. If the flow of droplets between the arc cathode and a substrate is not limited, they are incorporated into the layer which results in strong increase of its roughness.

Assuring a reproducible and proper operation of a photocathode requires uniform and smooth Pb layer and its sufficient adhesion. The film cleanliness, microstructure and surface morphology determine its real QE, thermal emittance of photocurrent and emission of parasitic electron dark current. On the other hand, reaching these features depend on deposition and post-processing used to prepare the film. So far our group has developed and published two procedures [15, 16] based on using cathodic arc, which allow the obtained lead layers to come close to the above requirements:

1. The first procedure is based on using an arc coating system equipped with a magnetic filter inserted between the arc cathode and the coated substrate to reduce droplets stream from the arc plasma. The filter guides plasma electrons and ions along a bended (by 30°) plasma duct whereas the massive lead droplets (sized 0.5-40 µm) are intercepted on a duct wall due to their huge mass to charge ratio.
2. As an alternative, a two-step procedure has been proposed and implemented, consisting of deposition of 15 – 20 µm thick Pb layer in an arc without droplets filtering, combined with ex-situ layer smoothing by surface treatment in a rod plasma injector by repeated melting with argon plasma pulses.

The details of the abovementioned coating systems and Nb-Pb photocathode preparation are given in [15 ,16]. The choice of these deposition methods (see Table 1 for arc parameters) was supported with the studies of lead layers' microstructure, their surface morphology, dark current emission and QE (the latter $2\cdot10^{-4}$ at 260 nm photon beam after laser cleaning of the emissive surface [16]). The main limitation of the layers obtained in the filtered arc is the presence of a small amount of residual surface extrusions with high aspect ratio coming from casual Pb droplets dissipation from the plasma duct walls. These extrusions became local field emission centres which resulted in a pretty high dark current at a surface field exceeding 14 MV/m [15]. It is relevant for the application in XFEL-type guns working at a maximum field value of up to 60 MV/m. Direct dark current measurement in a dc pulsed field of this amplitude revealed the peak value of ca 200 nA from a sample Nb-Pb photocathode, 1 cm^2 in area, after 30 min. conditioning in dc pulsed electric field [15]. A similar Nb-Pb sample reached by the two-step procedure showed dark current lower by a factor of 5 (ca. 40 nA).

Because of a widespread need for further reduction of thermal emittance of e$^-$ photocurrent, our group proposed a novel method of Pb coating with further improvement of a film surface flatness. In this procedure reduction of lead droplets in a layer is obtained by deposition via extracting lead plasma ions perpendicularly to the main arc plasma propagation direction (Fig. 5) in cathodic arc. This method is further referred to as "deposition with lateral ion extraction". The scheme in Figure 5 shows the system for lead deposition on the tip of a niobium photocathode plug. The plug is mounted in a stainless-steel capsule attached to a horizontal rod rotating at a speed of 3-5 turns per second. The rotation of the plug is aimed at reaching isotropic lead distribution on its surface. The capsule allows exposing to Pb coating only the planned photoemission area. The main arc plasma column propagates in vertical direction whereas a part of it is extracted by the negative dc bias towards the deposited target.

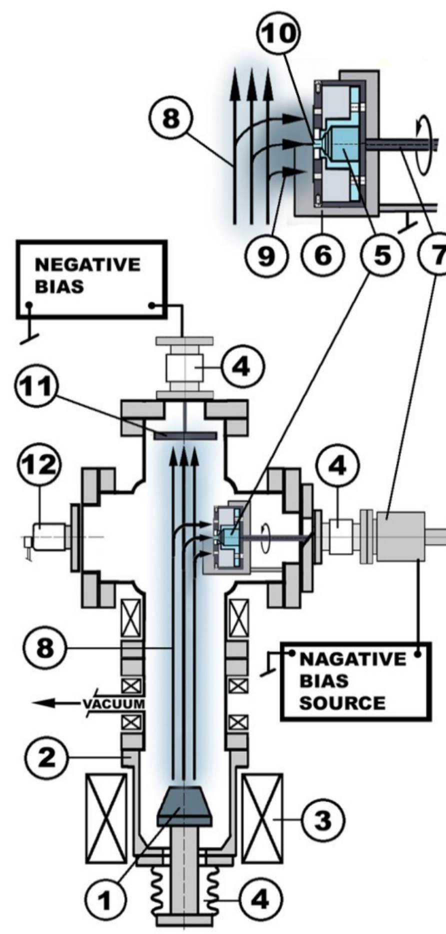

Figure 5: Pb arc coating system with lateral ion extraction: 1- arc cathode, 2- arc anode, 3- coils, 4- insulators, 5 - deposited photocathode plug, 6 - target shielding, 7 – target rotation system, 8 – arc plasma stream, 9 - Pb ion extraction towards the target, 10 – coated plug area, 11 – plasma ion collector, 12 – vacuum measuring gauge.

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Table 1: Pb coating parameters and surface morphology

Coating method	Arc voltage (V)	Arc current (A)	Deposition rate (µm/min.)	Film thickness (µm)	Substrate bias (V)	Film surface morphology (ref.)
Arc with 30º bent filter	≈22	25	0.2	1-5	-70	Planar film with few semispherical protrusions of high aspect ratio, sized up to 30 µm - the sources of dark current ([15, 16])
Arc coating + pulsed plasma treatment	≈22	25	3.0	15-20	-70	Complete, planar film with round, elongated surface forms (up to 2 µm high) of low aspect ratio.([15, 16])
Arc deposition with lateral ion extraction	≈17	≈18	0.07	0.6	-20	Smooth film with a small number of rounded protrusions of low aspect ratio (Fig. 6).

The target is protected from the lead droplets (which move upwards from the arc cathode) by a stainless-steel shielding which surrounds the bottom part of the capsule. Apart from the presence of droplets the deposited film may be contaminated with Pb debris removed from the shielding surface. These peeling products may also enhance field emission, dark current or photocurrent emittance. Since the lead peeling rate drops with decreasing arc current and target bias, the arc voltage and current were reduced comparing to the methods 1. and 2. (Table 1). The negative target bias value has been decreased down to -20 V. The optimal position of the capsule within the shield was adjusted experimentally. Smooth and continuous Pb layers on Nb have been reached (with negligible number of extrusions of low aspect ratio) by using this system (Fig. 6). They require, however, further tests to determine their QE, adhesion to the substrate and their impact on SRF gun performance.

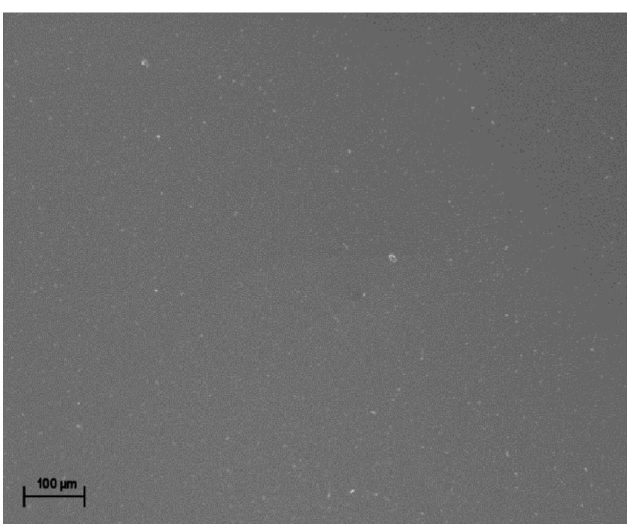

Figure 6: Scanning electron microscope (SEM) image of a 600 nm thick Pb layer on niobium, reached in the coating device shown in Fig. 5.

FUTURE LASER SYSTEM TO EXCITE PHOTOEMISSION IN THE PolFEL SRF ELECTRON GUN

Photocathode laser system will base on commercially available Pharos laser (Lithuanian company Light Conversion, UAB). The laser fundamental parameters after regenerative amplifier are: repetition rate of 50 kHz, Gaussian pulse duration FWHM ≈ 300 fs, wavelength of 1026 nm at a pulse energy of 400 µJ and ca. 3 mm beam diameter. A fourth harmonic generation module attached to this laser system will give a radiation pulse 256 nm in wavelength and of energy above 40 µJ. It takes 4 – 30 ps FWHM pulse duration (flat top both, in space and time) to excite and extract from the photocathode a perfect “cylindrical” e^- bunch. Converting Gaussian pulse shape in time requires two additional optical setups. The first one is needed to stretch the Gaussian pulses from 300 fs to 4 ps pulse duration at the most, by using double prism pulse stretcher. It will add negative Group Delay Dispersion. The second optical setup – pulse stacker – will divide the pulse and stack them together on polarizing beam cube splitter. As a final output of these conversions a flat top beam shape will be reached in time domain with FWHM pulse duration from 2.4 to 30 ps.

To convert the Gaussian spatial profile after passing the pulse stretcher and stacker, a commercially available pi-shaper module is to be applied, preceded by a telescope. The latter will convert the original 3 mm beam diameter to 6 mm or 12 mm ($1/e^2$) required by the pi-shaper. A pinhole is to be added into the telescope to reach a perfectly Gaussian spatial pulse profile at the entrance to the pi-shaper. This system should be placed in a low vacuum chamber to avoid UV beam focus power fluctuations and/or arc discharge which might happen in ambient atmosphere.

After the above described conversion of Gaussian pulses to “cylindrical” ones, a special “travelling” lens system will deliver UV beam to the photocathode with possible varying of its diameter on the cathode from 50 µm to 3 mm. It will give flexibility of choice between hundreds of pC electron bunches (at a large beam diameter) and “skinny”,

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low emittance bunches (for beam diam. 50 – 250 μm), required for different types of PolFEL's undulators: VUV, IR or Terahertz.

SUMMARY

We report the present state of preparation of the planned, fully-superconducting RF electron gun, based on the XFEL-TESLA technology. The following issues have been discussed: e^- beam focusing and optimal location of the photocathode plug inside the gun cavity, Nb-Pb cathode preparation and the concept of laser and optical systems destined for inducing photoemission.

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