OPERATIONAL EXPERIENCE WITH THE Nb/Pb SRF PHOTOELECTRON GUN*

J. Völker[†], T. Kamps, W. Anders, R. Barday, A. Jankowiak, J. Knobloch, O. Kugeler,
A. N. Matveenko, A. Neumann, T. Quast, J. Rudolph, S. Schubert, HZB, Germany
V. Volkov, BINP SB RAS, Russia; J. Smedley, BNL, USA
J. Sekutowicz, DESY, Germany; J. Teichert, HZDR, Germany
P. Kneisel, JLab, USA; R. Nietubyc, NCBJ, Poland; I. Will, MBI, Germany

Abstract

The superconducting radio-frequency (SRF) photoinjector concept combines the advantages of photo-assisted production of high brightness, short electron pulses and high-gradient, low-loss continuous wave (CW) operation of a SRF cavity. A SRF photoinjector is under development by a collaboration between HZB, DESY, JLAB, BNL and NCBJ. The aim of the project is to understand and optimize the beam performance of a Nb SRF gun cavity coated with a small metallic superconducting Pb cathode film on the cavity backplane.

MOTIVATION

The choice of photocathode is of great importance for the SRF photoinjector and guided by the application of the electron source. The initial beam parameters like the intrinsic emittance, pulse length and average current are all determined by the photocathode and drive laser properties. FEL and THz application demand CW operation at repetition rates in the kHz range with average currents below 1 mA. For this class of electron source metallic photocathodes are well suited. Sekutowicz et al developed the idea of a hybrid Nb/Pb gun cavity [1], where a small spot of Pb is deposited on the center of the inner backwall of a Nb gun cavity. Pb has a quantum efficiency an order of magnitude higher than Nb. Several test cavities have been built and all cavity treatment and Pb depositon techniques have been optimized to achieve high QE of the Pb spot while not compromising the quality factor and the achievable peak gradient of the SRF cavity [2]. HZB joint the effort on the hybrid Nb/Pb cavity system and setup a complete SRF photoinjector including drive laser and diagnostics beamline for electron beam generation and characterization.

RESULTS FROM COMMISSIONING

The setup of the cold mass of the SRF photoinjector [3] and warm diagnostics beamline [4] was built to allow basic measurements of all relevant RF properties of the SRF cavity [5] and projected beam parameters. Typical setup and beam parameters obtained during the first run of the gun in 2011 are summarized in Table 1.

Table 1: Typical setup and beam parameters measured. The value for the bunch length represents the emission time of the electron pulse from the cathode.

Parameter	**Value**
Cathode material	Pb (SC)
Cathode QE$_{\mathrm{max}}$	$1 \cdot 10^{-4}$ at 258 nm
Drive laser wavelength	258 nm
Drive laser pulse length	2.5 ps fwhm
Repetition rate	8 kHz
Electric peak field in cavity	20 MV/m
Operation launch field on cathode	5 MV/m
Electron exit energy	1.8 MeV
Bunch charge	6 pC
Electron pulse length	2. . .4 ps
Average current	50 nA
Normalized emittance	2 mm mrad

EMITTANCE MEASUREMENTS

Solenoid Scan Technique

The transverse emittance of the electron beam was measured with the solenoid scan technique. The solenoid is positioned right after the SRF gun cavity inside the cryovessel. During data taking the focal length f of the solenoid is changed and the transverse beam sizes $\sigma_{x,y}$ are observed on a viewscreen some distance behind the solenoid. Figure 1 shows an example of such a solenoid scan. The transverse emittance can be reconstructed by fitting a linear beam optics model to the data. In Fig.1 we see the effect of solenoid lens astigmatism as the foci for the horizontal and vertical plane do not conicide. This can either be the result of a yaw error of the solenoid alignment or an angular and spatial offset error of the electron beam. The statistical error of the measurement is on the order of 3%. The systematic error is dominated by higher order effects of the solenoid lens like chromatic and spherical aberrations. These superimpose each other and result in an overestimate of the actual emittance. Both effects have been studied using simulations of the actual measurement with the ASTRA code. The overall resulting uncertainty is on the order of 10%. It is possible to reduce the systematic error by choosing a solenoid lens with a larger aperture and by allowing in-situ beam based alignment of the magnet by means of mechanical actuators.

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* The work at HZB is supported by BMBF and the State of Berlin. The Pb depositon activity is supported by EuCARD.

[†] jens.voelker@helmholtz-berlin.de

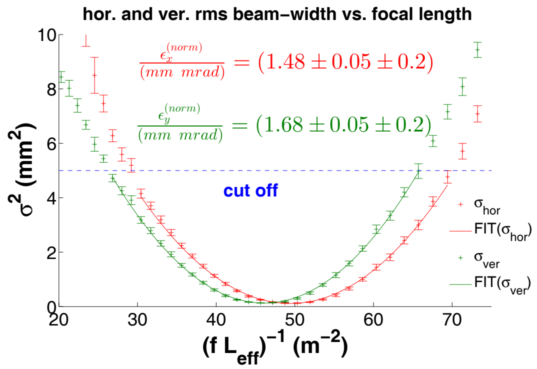

Figure 1: Example of a solenoid scan with a squared regression (L_{eff} as the effective magnetic length of the solenoid).

Emittance Contributions

The transverse emittance measured with the solenoid scan has contributions from the thermal (intrinsic) emittance of the emission process ε_{th}, the influence of the RF field of the gun cavity ε_{rf}, the higher order effects due to aberrations and astigmatism of the solenoid ϵ_{sol}, interparticle repulsion due to space charge ε_{sc}, and cathode surface roughness ε_{cat}. Under the assumptions that all contributions are not correlated the emittance measured can be expressed as the sum of squares of all individual contributions like

$$\varepsilon_{\text{meas}}^2 = \varepsilon_{\text{th}}^2 + \varepsilon_{\text{rf}}^2 + \varepsilon_{\text{sol}}^2 + \varepsilon_{\text{sc}}^2 + \varepsilon_{\text{cat}}^2 \qquad (1)$$

We include the cathode roughness because we found by microscopic measurements that the emission surface of the Pb film is not smooth but is covered with protrusions and droplets resulting in micrometer-sized features [6].

In order to investigate the magnitude of all contributions the scaling of the transverse emittance as function of bunch charge, launch phase and laser spot size on the cathode was investigated experimentally. The scaling of the emittance with the size of the emission area was studied by adjusting a transverse beam shaping aperture in the laser beam path between drive laser and photocathode. The beam shaping aperture plane is imaged with a relay lens on the cathode plane. Figure 2 shows the transverse emittance for different laser spot sizes. In good approximation the emittance is linearly correlated to the laser spot size with a slope of $\varepsilon_{\text{n}}/\sigma \approx 5\,\text{mrad}$. The intrinsic emittance, the lower floor for the minimum achievable emittance, scales linearly with the laser spot size and is for Pb $\varepsilon_{\text{th}}/\sigma = 0.8\,\text{mrad}$ [7].

The bunch charge can be manipulated by changing the intensity of the laser pulses hitting the cathode film. We found only a weak scaling of the emittance. Simulations support the assumption that with bunch charges below a couple of pC and spot sizes between 0.2 and $1\,\text{mm}$ the contribution of ε_{sc} to the overall emittance is on the order of 10% of the intrinsic emittance.

The influence of the RF field was studied by measuring the emittance for different launch fields in the gun cavity. For launch fields higher than 5 MV/m the transverse emittance does not change with increasing launch field. The bunch length is short compared to the RF cycle, being around 1 degL, the influence of the RF curvature is negligible.

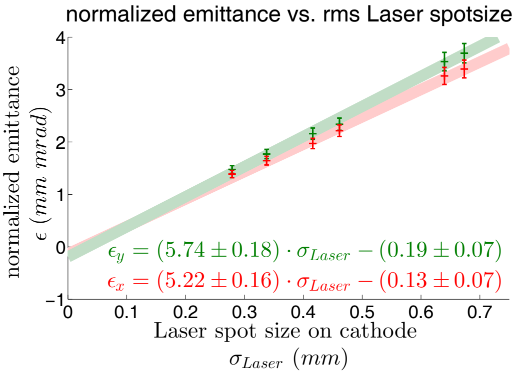

Figure 2: The measured normalized transverse emittances for different laser spot sizes on the cathode with a linear regression.

In the following we want to investigate the effects due to higher order effects in the solenoid ε_{sol} and the topology of the emissive surface ε_{cat} .

Higher Order Effects of the Solenoid

The astigmatism is a lens error of the solenoid with the effect that the foci of the horizontal and vertical planes do not coincide. The signature is that there are no sharp focal point but the beam is distorted to an ellipses in front and behind the focus. The orientation of the ellipse is turned by 90 deg while going through the focus. There are two distinct forms of astigmatism. One is a third-order aberration and occurs when the beam passes the solenoid off-axis and under an angle. This can be the result of a misalignment of gun cavity and solenoid. The second form is when the solenoid lens is not rotationally symmetric due to manufacturing errors. We studied third-order aberrations with simulations. For these studies the solenoid field is rotated in the horizontal and displaced in the vertical plane. For each misalignment setup a complete solenoid scan was simulated. In some cases the beam steeres extremely in the transversal plane during a scan, which was not observed during the experiment. Therefore only those setups were used which produced low steering. It is possible to obtain emittance values which are five times higher, but only as if the solenoid is rotated by $10\,\text{deg}$ and has an offsets of more than $15\,\text{mm}$. These large misalignments seem unrealistic with the present setup. We estimate values for offsets in the range of $3\,\text{mm}$, which consist of thermal expansion of the solenoid-bracket (up to $1\,\text{mm}$) and misalignments of the cavity (up to $2\,\text{mm}$). The cavity misalignment could produce rotation angles of 1 to $2\,\text{deg}$. Therefore the emittance increase due to astigmatism by misalignments of the solenoid are lower than 20% compared to the intrinsic emittance.

Effects due to Cathode Surface

An experimental indication of irregular emission from a non-uniform cathode area is shown in Fig. 3. Here the solenoid lens was used to relay image the emissive area on the viewscreen. The emission is not uniform, there are hot spots with increased electron emission present as well as dark areas with no significant electron population. This pattern can be reproduced with simulations modeling of a rough cathode surface with local field and QE variation.

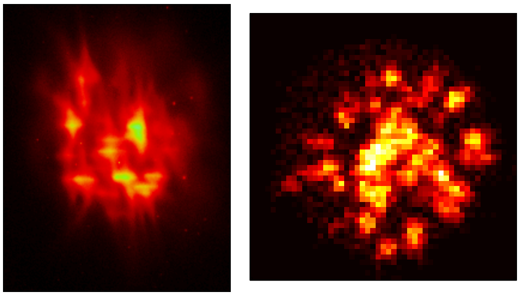

Figure 3: Measured (left) and simulated (right) image of the emissive area of the cathode. In both cases the diameter of the laser spot on cathode is approximately 1mm.

In the following we want to describe a model for the emission from the Pb cathode material. We can use this model to estimate the effect of an irregular surface, local QE variation and the presence of droplets and protrusions, on the transverse emittance. The emission process from metallic photocathodes can be described with the three-step-model for metal photocathodes [7]. The QE and the emittance depend strongly on the effective workfunction $\phi_{\rm eff}$, which is corrected by the Schottky enhancement due to the presence of an electric field E_o on the cathode surface like

$$\frac{\varepsilon_{\rm th}}{\sigma_{\rm l}} = \sqrt{\frac{\hbar\omega - \phi_{\rm eff}}{3m_e c^2}}\ , \ \phi_{\rm eff} = \phi_o + \sqrt{\frac{e^3\beta E_o}{4\pi\epsilon_o}} \qquad (2)$$

as a function of $\hbar\omega$ photon-energy and the field enhancement factor β. The electric field on the cathode surface during electron emission is in the range of 5 to 15 MV/m, depending on the actual launch phase. The field can be locally enhanced at the protrusions on the cathode surface (see Fig. 4). Images from microscope measurement reveal that the Pb film is densely covered with protrusions ($> 100/\mathrm{mm}^2$) with sizes from 1 to 10 μm [9]. These protrusions originate from Pb droplets hitting the cathode plane during arc-deposition. The protrusion modeled in Fig. 4 causes an increase of the longitudinal electric field by a factor of ten and an additional transverse electric field, at least five time higher than the uniform field, which defocuses the electrons during emission. With simulations we investigated the consequences for electron bunches, which are emitted by rough cathode surface covered with such protrusions. This was done in two directions: for cathodes with a couple protrusions and non-uniform electric fields, and for planar cathodes with many small areas with random field enhancement factors. Simulated solenoid scans with these distributions show that the transverse emittance is dominated by the transverse electric field due to the protrusions. The emission process plays a minor role. The transversal electric fields of four to eight protrusions with a field enhancment factor of five can increase the transversal emittance by 60% compared to the intrinsic emittance. Extrapolating this result to levels of droplet density (> 100) and field enhancement factors of ($\gg 10$) could explain the dominant effect of emittance measured and needs to be investigated. Systematical studies with the SLANS code indicate also that the transverse emittance is dominated by radial fields due to micro-droplets and other more complex features present on the cathode surface [10].

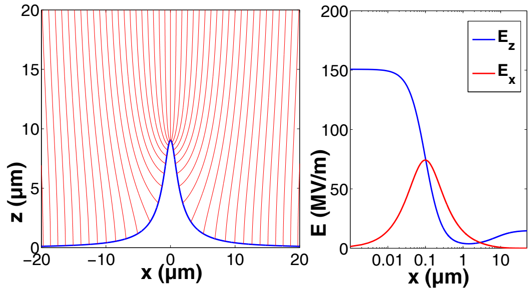

Figure 4: Left: Electric field (red) of a protrusion (blue) on a planar cathode in a uniform electric field of 15MV/m. Right: x and z components of the electric field along the protrusion surface (model according to [8])

SUMMARY AND OUTLOOK

The beam performance capabilities of an SRF photoinjector based on the hybrid Nb/Pb gun cavity have been studied experimentally. All basic beam parameters have been measured. The main areas for optimization include in-situ alignment capabilities for the solenoid magnet, a tuning mechanism for the cavity, and the coating procedure for the Pb cathode film. All these measures should lead to an improvement of the transverse emittance and quantum efficiency from the cathode.

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