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RECENT RESULTS ON THE PERFORMANCE OF Cs_3Sb PHOTOCATHODES IN THE PHIN RF-GUN

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Abstract

For the CLIC drive beam a photoinjector option is under study at CERN as an alternative to the thermionic electron gun in the CLIC baseline design. The CLIC drive beam requires a high bunch charge of 8.4 nC and 0.14 ms long trains with 2 ns bunch spacing, which is challenging for a photoinjector. In particular the required long and high intensity laser pulses cause a degradation of the beam quality during the frequency conversion process, which generates the ultra-violet laser beam needed for standard Cs_2Te photocathodes. To overcome this issue Cs_3Sb cathodes sensitive to green light have been studied at the high-charge PHIN photoinjector since a few years. In this paper recent measurements of fundamental properties of Cs_3Sb photocathodes such as quantum efficiency, cathode lifetime and dark current from summer 2014 will be presented, and compared with previous measurements and with the performance of Cs_2Te photocathodes.

INTRODUCTION

The Compact Linear Collider (CLIC) is a future e^+e^- collider, which is currently under study by a worldwide collaboration led by CERN [1]. It is based on a novel two-beam acceleration scheme, which requires a high peak and average current drive beam accelerator for generating 12 GHz RF power needed to accelerate the main beam. In the baseline design, the drive beam is foreseen to be produced by a thermionic electron gun and a sub-harmonic bunching system [2]. However, the bunching system generates parasitic satellite pulses, which get lost during the acceleration process. This can create radiation issues and will reduce the system power efficiency.

These limitations can be avoided if a photoinjector is used as a drive beam source and the required time structure for the CLIC beam combination scheme [1] is already produced on the laser side. Such a photoinjector option for the CLIC drive beam is currently under study at the high-charge photoinjector PHIN [3], which was originally developed and constructed to study its feasibility as drive beam source for the CLIC Test Facility 3 (CTF3). Practically satellite-free beam production with the required time structure has been demonstrated at PHIN [4].

However, the CLIC drive beam parameters are challenging for a photoinjector (Table 1) and efforts are on-going to improve the PHIN parameters towards CLIC requirements [5]. In particular the combination of 140 µs long trains, 8.4 nC bunch charge, 2 ns bunch spacing and 50 Hz macro-pulse repetition rate for CLIC is beyond the parameters of any existing photoinjector. This unique parameter set has a strong impact on the photocathode lifetime and also on the laser system: The required long and high-intensity laser pulses cause a degradation of the beam quality during the 4^{th} harmonics frequency conversion process, which generates the ultra-violet laser beam needed for standard Cs_2Te photocathodes. Since the 2^{nd} harmonics conversion process to produce green light is not affected by this problem, a potential solution is to use photocathodes sensitive to green light such as Cs_3Sb or K_2CsSb instead of Cs_2Te cathodes. For the CLIC photoinjector studies Cs_3Sb has been chosen because the existing production setup for Cs_2Te could be used, which made it possible to extensively profit from the experience gained with Cs_2Te. In this paper the latest results of the Cs_3Sb photocathode studies at PHIN will be presented. In parallel, R&D work on the surface characterization of photocathodes [6] and further development of the laser system are also on-going at CERN.

Table 1: PHIN and CLIC Design Parameters

Parameter	PHIN	CLIC
Charge / bunch (nC)	2.3	8.4
Train length (µs)	1.2	140
Bunch spacing (ns)	0.66	2.0
Bunch rep. rate (GHz)	1.5	0.5
Number of bunches	1800	70000
Macro pulse rep. rate (Hz)	5	50
Charge / train (µC)	4.1	590
Beam current / train (A)	3.4	4.2
Bunch length (ps)	10	10
Charge stability	<0.25%	<0.1%
Cathode lifetime (h) at QE > 3% (Cs_2Te) or QE > 0.5% (Cs_3Sb)	>50	>150
Norm. emittance (µm)	<25	<100

PHIN PHOTOINJECTOR

Layout

The PHIN photoinjector is installed at an off-line test stand at CTF3 (Fig. 1). It consists of a 2.5 cell RF cavity operated at 3 GHz and two solenoids, which provide the focusing of the electron beam. A test beam line is available with various diagnostic elements for beam measurements. The electron beam is produced by illuminating a Cs_2Te or Cs_3Sb photocathode with an ultra-

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violet (UV) or green laser beam respectively, which is generated by a powerful Nd:YLF laser system [7].

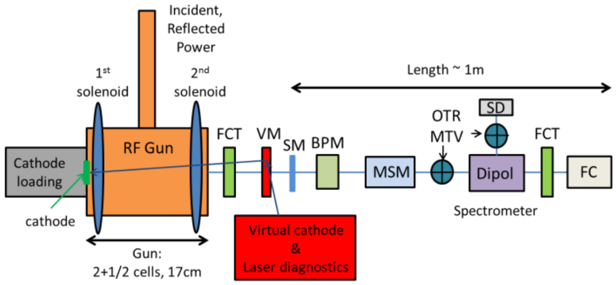

Figure 1: Layout of PHIN. Fast current transformers (FCT), vacuum mirror (VM), steering magnet (SM), beam position monitor (BPM), multi-slit mask (MSM), optical transition radiation screens (OTR), gated cameras (MTV), segmented beam dump (SD), Faraday cup (FC).

Photocathodes

The photocathodes for PHIN are produced in a dedicated photoemission laboratory at CERN using the co-deposition technique [8] and transported to PHIN in an ultra-high vacuum (UHV) vessel. Furthermore, a DC gun is available in the photoemission laboratory, which is used to characterize the photocathodes prior to their usage at PHIN.

Cs_3Sb PHOTOCATHODE STUDIES

Quantum Efficiency

One of the most important photocathode parameters is the quantum efficiency (QE), especially for high-current operation. While quantum efficiencies for Cs_3Sb cathodes have been measured in the DC gun of the photoemission laboratory of up to 7.5%, there have been issues to recover these values in the PHIN gun during the 2013 run. Only significantly less initial QE values of the order of 1% have been measured at that time (Table 2).

Table 2: Photocathodes Used During PHIN Runs 2013 (#186 - #194) and 2014 (#198 - #200)

Cathode	Material	QE in DC gun	QE in PHIN	Cu surface treatment*
#186	Cs_2Te	9.0%	6.5%	DPP
#191	Cs_3Sb	7.5%	1.0%	DT
#193	Cs_3Sb	5.8%	1.0%	DT
#194	Cs_3Sb	4.5%	1.3%	DPP
#198	Cs_2Te	14.8%	10%	DPP
#199	Cs_3Sb	5.2%	4.9%	DPP
#200	Cs_3Sb	5.5%	3.9%	DPP

*DPP=diamond powder polishing, DT=diamond turning

As a potential source of this problem a bad surface finishing of the cathode substrate had been identified, assuming that the subsequently deposited photoemissive layer does not smooth the surface. While in the past diamond powder polished oxygen-free copper substrates had been used with excellent results, in 2013 diamond turned copper substrates were used for cathode #191 and #193. Microscope images taken after usage revealed the presence of a concentric ring structure on the surface (Fig. 2a), which could likely cause a higher breakdown activity under the high electric field in the PHIN gun (85 MV/m), which leads to a deterioration of the photoemissive coating. This effect was obviously less critical under the lower electric field in the DC gun (7 MV/m). This problem has been solved during PHIN run 2014, by using again diamond powder polished substrates. No ring structure is visible (Fig. 2b) and the measured QE in the PHIN gun was only slightly less than the values measured in the DC gun (Table 2), which is the usual case.

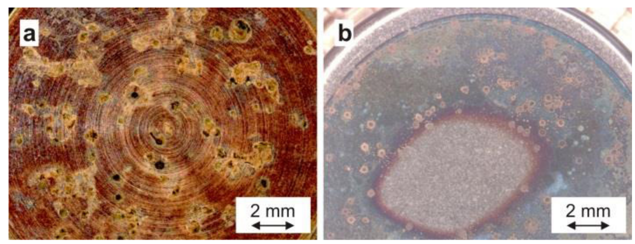

Figure 2: Optical microscope images of Cs_3Sb cathode #193 (a) and Cs_2Te #198 (b) after usage. A concentric ring structure of the substrate of cathode #193 is clearly visible. The spot in the center of cathode #198 is due to ion sputtering during XPS studies [6].

In 2013 a further cathode (#194) showed a low initial QE in the PHIN gun, which however was produced on a diamond powder polished substrate. This can be explained by the possible cathode surface contamination due to the fact that this cathode was transferred too rapidly to the gun without sufficient pump-down time of the gate chamber.

Cathode Lifetime

Strongly related to the QE is the operational cathode lifetime, which is defined as the period in which the gun can be operated with the nominal beam current for which the QE must be above a certain threshold. This threshold is different for Cs_2Te and Cs_3Sb (Table 1) due to the differences in wavelength of the driving laser beam and available laser energy. A better accessible parameter for measurements is the 1/e lifetime obtained by a single or double-exponential fit.

To increase the cathode lifetime the vacuum conditions at PHIN have been improved in two steps from initially 4e-9 to 7e-10 and 2e-10 mbar [5]. Step 1 resulted in an improvement of the lifetime by a factor 7 [5]. The impact of step 2 on the lifetime has been studied during PHIN run 2014 for Cs_2Te and Cs_3Sb cathodes.

While the lifetime of Cs_2Te cathode #198 was measured to be ~300 h and therefore similar to previous measurements with worse vacuum conditions [9], the

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results for Cs_3Sb were not so clear: Part of the data measured with the fresh cathode #199 with 2.3 nC per bunch and 350 ns train length could be well represented by a double-exponential fit (Fig. 3) yielding a lifetime τ_2 of ~150 h similar to a previous measurement from 2012 under slightly worse vacuum conditions [10].

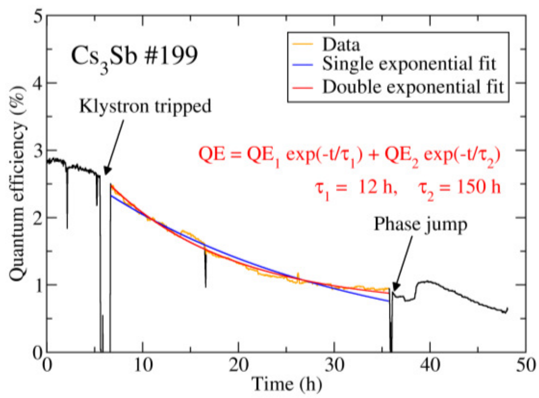

Figure 3: Lifetime measurement of fresh Cs_3Sb cathode #199 with 2.3 nC/bunch and 350 ns train length.

Another measurement was performed with the already used Cs_3Sb cathode #200 with a bunch charge of 1 nC and a train length of 800 ns. The data could be well represented with a single-exponential fit (Fig. 4) as expected for a used cathode. However, the obtained lifetime was only 48 h and a factor 4 less than during a previous measurement with the same beam parameters and worse vacuum conditions [10].

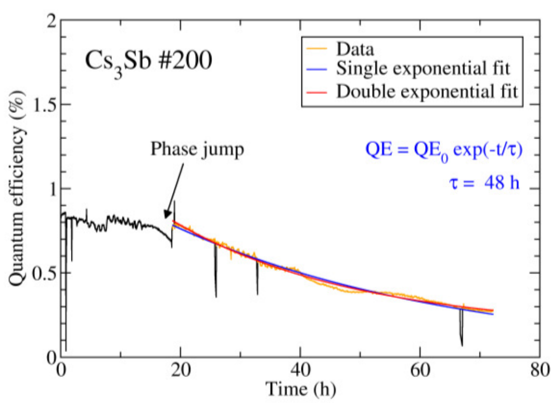

Figure 4: Lifetime measurement of used Cs_3Sb cathode #200 with 1 nC/bunch and 800 ns train length.

The reason for this discrepancy is not fully clear, but could possibly be explained with the fact that during both measurements several jumps of the gun RF field phase relative to the laser train of 220 degrees occurred, which usually caused strong RF breakdowns. In some cases indicated in Figs 3 and 4 the slope of the curve changed drastically after a phase jump. This can have a strong impact on the lifetime if the phase jump occurs at the beginning of the measurement, as it was the case for cathode #200 (Fig. 4).

According to these results it seems that the recent improvement of vacuum conditions did not measurably increase the cathode lifetime. However, for a conclusion more measurements are needed, as well for understanding the impact of the phase jumps.

Dark Current

Within the scope of the present studies dark current produced by Cs_3Sb, Cs_2Te and Cu cathodes has been measured (Fig. 5). The dark current from Cs_3Sb cathodes was higher by a factor 4 to 7 than the one from Cs_2Te cathodes, which is due to the lower work function of Φ_{Cs3Sb} = 2.05 eV compared to Φ_{Cs2Te} = 3.5 eV [11]. The low dark current from the Cu cathode confirmed that the major contribution is coming from the cathode itself and not from the gun cavity. The higher dark current of Cs_3Sb is itself not an issue for the CLIC drive beam since it is still less than one per mill of the average current in the train. However, the higher dark current could lead to higher breakdown activity with negative impact on the cathode lifetime.

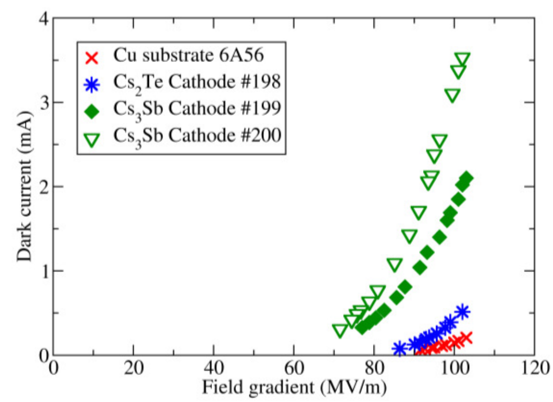

Figure 5: Dark current measured with Cs_3Sb, Cs_2Te and Cu cathodes.

CONCLUSION AND OUTLOOK

The parameters of Cs_3Sb photocathodes have been studied after the recent improvement of the vacuum conditions at PHIN. While measurements of the initial QE and the dark current are within expectations, an improvement of the lifetime could not be measured. For a conclusion more statistics and longer measurements would be needed, which however is difficult to achieve with present mode of operation of PHIN of only a few weeks per year. This limitation is due to fact that PHIN shares the klystron with the CTF3 probe beam photoinjector, which needs to be in operation for CTF3 most time of the year.

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