A HIGH VOLTAGE EXTRACTOR WITH PHOTOCATHODES

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Abstract

We describe a system designed for photocathode testing and beam dynamics studies which is based on a high voltage extractor and a sub–ps drive laser. The system's distinctive characteristics are the ability to run in the short bunch regime — where the dynamics are not governed by the Child–Langmuir law — and the anticipated availability of both transverse and longitudinal beam diagnostics to determine the full beam distribution. The system consists of a pseudo parallel plate 100 kV DC gun with a removable cathode and a cathode–anode gap of 8 mm, yielding a cathode field of up to 10 MV/m. The drive laser is a Nd:Glass system capable of producing over 200 µJ at 264 nm with a pulse length adjustable from approximately 250 fs to over 1 ps. The goals of the system, described in this paper, are to support ongoing photocathode studies, including measuring high current density extraction from prepared cathodes and investigating the effect of surface variation of the quantum efficiency. Additional studies foreseen include parameterizing the effect of surface variations on the transverse emittance, and exploring beam dynamics such as the short bunch blow out regime which has recently been proposed as a way to produce uniform ellipsoidal charge density distributions[1].

1 BACKGROUND

A DC high voltage extractor with photocathodes driven by a sub–ps laser has been designed to explore various issues surrounding short beams and cathodes. The experimental test stand takes advantage of existing equipment and facilities as well as the group's ongoing cathode material studies. The combination of a simple and reliable high voltage extractor with a short pulse laser allows for cathode testing under conditions closer to those found in a RF photoinjector than previously available, as well as the possibility to study novel beam dynamics of relevance to high brightness devices.

This report describes the new laboratory and related equipment as well as provide a status report on the project. A brief description of the cathode testing program is given. Additionally, some future scientific studies under consideration are mentioned.

The High Voltage Extractor laboratory — The Hive — will serve to extend the ongoing cathode research at LASA. The cathode program includes the design and fabrication of cathode preparation chambers, the testing and characterization of present (Cesium Telluride) as well as future cathode materials. The majority of the cathode research is in support of the TESLA collaboration. In this frame, a cathode preparation chamber has been installed at LASA (in Milan, Italy), with finished cathodes transported (under vacuum) to the Tesla Test Facility at DESY (in Hamburg, Germany). In order to increase reliability and quality control, it has been desired to have a means of testing the cathodes prior to transportation and insertion into the RF photoinjector. At present, testing capabilities are limited to low voltage (~10 kV) test chambers. A high voltage device more closely simulates the accelerating gradients of an RF photoinjector, and allows for beam diagnostics distributed along a beamline.

2 THE EXPERIMENTAL TEST STAND

The test stand, which consists of a DC "gun" arranged in a pseudo parallel–plate geometry with a removable photocathode, followed by a solenoid to focus the electrons, and a short beamline with various diagnostics, is constructed atop an optical table. The solenoid employs an iron yoke to reduce the effective lens thickness and focal length. Along the beamline, "picture frame" steering magnets are available to correct the beam trajectory and angle. The DC high voltage extractor itself is based on a CERN design[2], with modifications made primarily to the cathode and anode in order to accommodate cathode substrates used in the existing preparation chamber, and in order to increase the accelerating gradient while maintaining fixed the peak surface fields. The cathode preparation system[3] consists of a cathode substrate loading and transportation system, and a deposition chamber with surface analysis and vacuum monitoring equipment. A variety of cathode types can be fabricated, but the first investigation will be devoted to Cesium Telluride (Cs_2Te) on a Molybdenum substrate. A cathode transportation system which is able to move a set of cathodes (1 to 5) through the system and into a load–lock unit for removal, under vacuum, is also part of the system. Cathodes can be loaded into the DC gun using either the load–lock unit or by direct connection.

Initially, a minimal set of diagnostics will be implemented including a charge collecting Faraday cup, a current integrating transformer (pickup coil) and florescent beam profile screens (see Figure 1). Accommodations have been made to add emittance measurement slits, an energy spectrometer bend magnet, and a bunch length measurement system.

The drive laser to be used on the Hive is an existing TWINKLE sub–ps frequency–quadrupled Nd:glass device and produces over 100 µJ at 263 nm (UV) in sub–ps (around 250 fs) pulses at 10 Hz. The pulse length is adjustable through tuning of the novel "crossed path" non–linear compression scheme. The laser pulses impinge on the cathode at near normal angles, and with an adjustable transverse size.

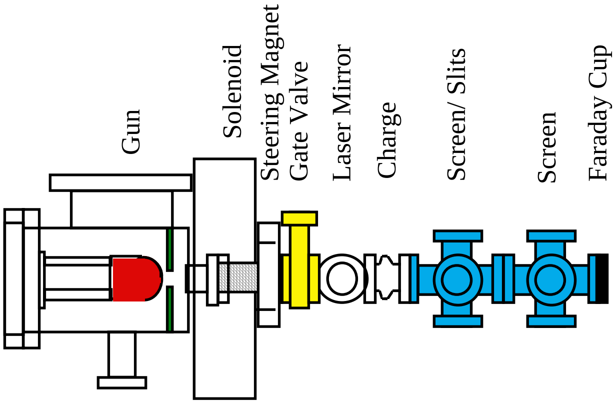

Figure 1: A sketch of the initial beamline with the gun, solenoid, key beamline components and diagnostic ports.

In addition to the laser, the vacuum devices form another critical sub–system. The Cesiated cathodes to be used and tested in the Hive require ultrahigh vacuum levels (~ 10^{-10} mbar) in order to have lifetimes of some weeks. The vacuum system consists of a large (~400 l/s) ion pump with Titanium sublimator connected through a short bellows to gun chamber. Additional pumping along the beamline and in the cathode loading section is provided by small (~30 l/s) ion pumps. A bake-out system, instrumentation and a turbo pumpdown cart complete the system.

The salient system parameters are listed in Table†1.

Table 1: The expected operating parameters of the high voltage extractor. The laser pulse length can range from 250 fs to nearly 2 ps. The 50 mm distance (from the cathode) is the anticipated location of the first diagnostic. Due to longitudinal space charge forces, the bunch length expands rapidly.

Cathode–Anode Voltage (Max.)	100 kV
Cathode–Anode Gap	8 mm
Nominal Accelerating Gradient	10 MV/m
Single Bunch Repetition Rate	5-10 Hz
Nominal Laser Pulse Length	0.3 ps
Cathode Spot Size	1.4 mm
Final Current at gun exit	14 A
Final Current at 50 mm	3 A
Beam Length at gun exit	0.7 ps
Beam Length at 50 mm	3.2 ps
Energy Spread at 50 mm	0.4 %

3 GUN MODIFICATIONS

The original CERN geometry on which the gun design was based has been modified by using an elliptical curvature around the beam extraction hole and an elliptical cathode edge shaping. The modifications were made to reduce the peak surface fields, that could limit the extraction energy, and to improve the beam dynamics by creating a larger linear region for the transverse (radial) field. The elliptical contours yielded a reduction of about 6% in the Kilpatrick ratio over the original circular contour. Thus allowing an increase in the maximum accelerating gradient. The high gradients achievable allow for cathode tests of relevance to RF photoinjectors.

4 CATHODE CHARGE EXTRACTION

One of the goals of the Hive is to provide a test stand for high charge extraction from the photocathodes developed in the cathode laboratory. In order to extract charge densities comparable to the ones measured in radio frequency (RF) guns, it is necessary to operate the Hive with the short pulse of the TWINKLE laser.

Electrostatic guns operated in the long bunch regime are limited by the Child–Langmuir law, which states that the maximum extracted current density (for a parallel plane configuration) is given by

$$J_{Child}\left[A/cm^2\right] = 2.34\times 10^3 \frac{\Delta V^{3/2}[MV]}{d[cm]^2} \qquad (1)$$

where ΔV is the relative potential between the electrodes and d is the electrode spacing.

The Hive will operate at ΔV = 100 kV, with a cathode–anode spacing of 8 mm. Using these parameters, and under the long bunch regime, a current density of nearly 116 A/cm^2 is possible. Assuming a laser transverse spot size of 2 mm, the extracted current could be 15 A. Due to the loss of perveance of the actual gun geometry with respect to the ideal Pierce configuration, the numbers quoted here represent an overestimate of the gun performance. Nevertheless, photocathodes in RF guns operate at much higher current densities than the ones provided by a Child–Langmuir device. This can be understood because of the RF gun's higher applied fields and operation in the short bunch regime.

To operate a DC gun in a regime not limited by the Child–Langmuir law, it is necessary to operate with a laser pulse much shorter than both the anode–cathode gap and than the transverse spot size (as is the case for the TWINKLE laser). In this regime the Child–Langmuir law does not hold, because the gap is not filled by the bunch, and the extracted charge from the cathode can be approximated as a charge sheet. The electric field generated by this thin charge sheet can be written as

$$E_0 = \frac{\sigma}{\varepsilon_0} \qquad (2)$$

where σ is the surface charge density of the sheet.

The extraction process stops when the charge density is high enough to mask the electric field between the gun plates. Since the Hive is operating at a cathode field of 90 kV/cm (as indicated by simulations), this leads to a current density in the laser pulse of 25 kA/cm^2, a current of more than 3 kA and a single bunch charge of 1 nC. Of course, it would be impossible to measure such a current in the beamline, since the beam would be subject to a strong longitudinal expansion due to the space–charge forces. The fields in the gun are not sufficiently high to counteract to these forces. In any event, the measure of the total emitted charge would "testify" to the operation of the cathode at these initially high current densities. By performing a series of measurements of the extracted charge as a function of input laser intensity, spot size and pulse length, it should be possible to place a lower limit on the maximum current density a given cathode can support. Since the lower limit theoretically achievable in the Hive is generally above the highest values needed for cathodes in RF guns (at least for collider and FEL applications), such validation is both relevant and interesting.

As a final remark for this section, it should be noted that the intermediate region between the Child–Langmuir limit and the short pulse regime has been studied analytically as well as numerically, and may be of interest for this experiment[4]. Next we present two scientific investigations which are considered at the same time important and feasible: tests of emittance and the effects of quantum efficiency variations along the cathode surface, and beam dynamics in the short bunch blowout regime.

5 ADDITIONAL STUDIES

A DC gun can serve well as a cathode test stand, and this alone can justify the need for such a device. However a DC gun can also serve to address issues relevant to free electron lasers and colliders, and specifically on physics relevant to the production of bright beams in RF photocathode guns.

5.1 Reproducing RF gun transverse beam dynamics with laser driven DC guns

The effects of cathode surface variations on beam quality are poorly understood. Recent simulations indicate that a smooth variation of 30% in the quantum efficiency over the cathode surface is sufficient to cause a relevant growth in the beam emittance.

Performing studies of cathode effects in RF guns can be difficult for different reasons:

– such facilities are few and time dedicated to fundamental studies is limited
– the RF field can cause changes over time to the cathode surface
– rapid replacement of the cathode can be hindered by the need to recondition the gun (although this may be an equal problem in a relevant DC gun)
– beam dynamics in a RF gun are more complicated.

A DC gun seems to be a suitable candidate for performing systematic studies of cathode surface variations versus beam quality. In order to use a DC gun in place of a RF gun, two conditions must be met: the beam dynamics of the DC gun must closely simulate those found in a RF gun, and relevant diagnostics to analyze the beam quality in the regime of interest must be available. The envelope shape typical of a RF gun can be reproduced almost exactly by the non–relativistic laminar beam of a laser driven DC gun, to the extent that the extracted charge, the laser pulse shape, and the location of the solenoid lens can be properly adjusted. Duplication of RF gun beam dynamics in a DC gun allows for reproducing the emittance correction process — that occurs in the beam dynamics of a Radio–Frequency photoinjector — by properly scaled operation of a laser driven DC gun in the ultra–short bunch regime.

5.2 Short Bunch Blow–out Regime

Recently, it has been suggested that rather than negate the effects of longitudinal space charge, the effects should be used to produce a brighter beam (at equilibrium)[5]. By accessing the so–called short bunch blow–out (SBBO) regime, it may be possible to produce a beam that, while several times longer than the drive laser pulse, has an equilibrium brightness which is higher than might otherwise result.

The SBBO regime has yet to be tested experimentally, and it may be advantageous to first study this regime on a DC high voltage extractor, rather than a RF gun. A SBBO experiment would entail studying the beam bunch length as a function of charge (laser intensity), laser pulse length and laser beam radius. The experiment faces a severe complication from the need to distinguish between the pulse lengthening caused by the blow–out, and that caused by the subsequent space charge lengthening in the drift from the gun exit to the first diagnostic. The final distribution of the beam should allow the experimentalists to distinguish between a "blown–out" beam, and one that is not.

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