FIRST MEASUREMENT RESULTS OF THE PSI 500KV LOW EMITTANCE ELECTRON SOURCE

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Abstract

The Paul Scherrer Insitut (PSI) is presently developing a low emittance electron source for the PSI-XFEL project. The target beam parameters at the source are I=5.5 A, Q=0.2 nC and a slice emittance below 0.2 mm.mrad. The gun concept consists of a high gradient „diode“ stage followed by a two-frequency two-cell cavity to allow fine tuning of the longitudinal phase space. This paper reports on the first experimental results obtained with the PSI 500 kV test stand. The facility consists of a 500 kV diode stage followed by a diagnostic beam line including an emittance monitor. An air-core transformer based high voltage pulser is capable of delivering a pulse of 250 ns FWHM with amplitude up to 500 kV. The diode gap between two mirror polished electrodes is adjustable to allow systematic gradient studies. The electrons are produced by a 266 nm UV laser delivering 4 micro Joules on the Cu-cathode.

FACILITY LAYOUT

Diagnostics

The (diagnostic) beam line includes five solenoid magnets, an emittance monitor, an additional YAG screen for the measurement of transverse beam sizes as well as a wall current monitor and a Faraday cup for bunch charge measurements (see Fig. 1).

To cover the wide range of beam charges and energies a dedicated emittance monitor (E-meter) [1] was developed for this test facility. Given the constraints of a space-charge dominated, low-energy electron beam with possibly significant shot-to-shot fluctuations the "pepperpot" measurement method has been selected. In this method, a space-charge dominated beam hits a pinhole array ("pepperpot mask") leaving emittance-dominated beamlets for determination of their transverse beam sizes on a scintillating screen downstream of the pinhole mask. The broadening of the beamlets along the drift between the mask and the screen is a measure for the uncorrelated divergence, whereas the beamlet centroids give information on the correlated beam divergence.

In our setup, the retractable pepperpot mask is a laser-beam machined tungsten disk of 0.5 mm thickness. The holes cover an area of 5x5 mm and have a diameter of 20 µm at a distance of 250 µm. The beamlets are imaged by a 50 µm thick YAG screen, whose light is deflected by an outcoupling mirror under an angle of 90° into a telescope equipped with a firewire CCD camera (PointGrey Flea). The optical resolution of the imaging system is about 10 µm. Both mask and screen are mounted on stainless steel sliders inside a 900 mm UHV chamber and can be moved individually over a distance of 600mm along the beam axis, allowing for a wide range of experimental setups.

The first images from this device were obtained with a beam charge of around 10 pC.

A preliminary, straight-forward analysis based on rms values indicates uncompensated transverse emittances of around 1 mm mrad in both x and y. Unfortunately, the substantial level of beam-correlated background between the beamlets complicates the detailed analysis. A comprehensive analysis taking full account of the background is in progress.

The YAG screen of the E-meter can also be used for other measurements of the transverse beam properties (e.g. beam envelope scans).

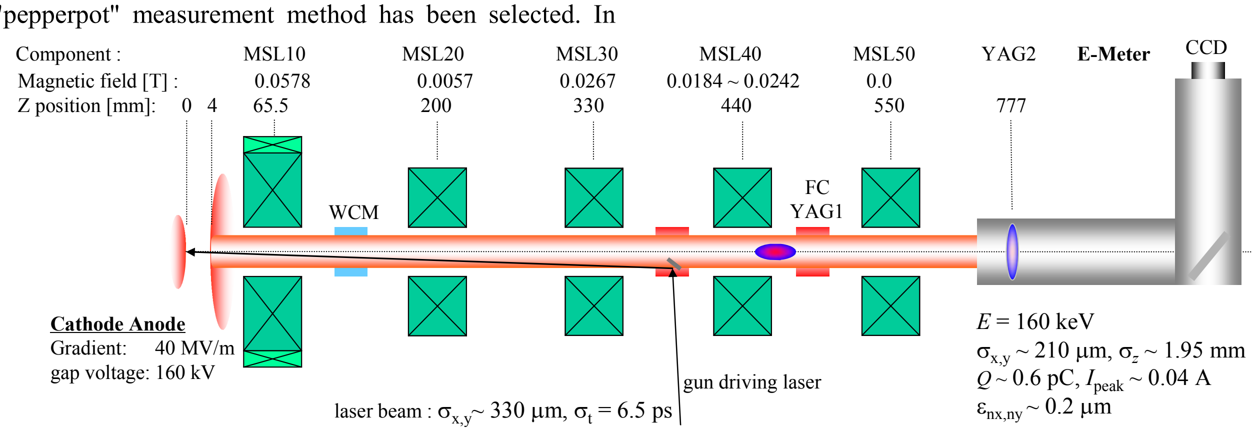

Figure 1: Machine layout for thermal emittance measurements with a copper cathode. MSL are shielded solenoids, WCM and FC resp. wall current monitor and a Faraday cup. YAGs are screens. The pepperpost mask was retracted.

A second 50 µm thick YAG screen is mounted for adjustment of the beam optics and determination of beam position under an angle of 45° directly in front of the emittance monitor. The camera optics for this screen is designed to cover the full screen of 20 mm diameter and gives a resolution of 50 to 100 µm.

For fast charge measurements a coaxial Faraday cup with a bandwidth of more than 4 GHz can be inserted into the beam path. The minimum measurable bunch charge is about 0.2 pC. Further upstream a wall current monitor (WCM) is installed for non-destructive charge measurement

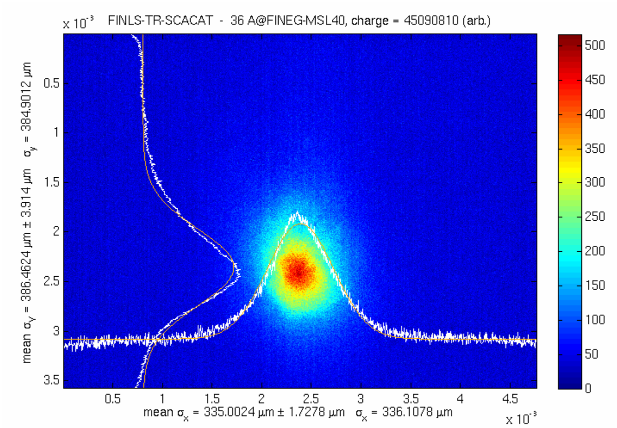

Figure 2: Laser spot transverse profile measured at the virtual cathode position.

Laser System

The metallic cathode is illuminated by laser pulses when the applied voltage across the anode cathode gap is at maximum. The laser consists of a Nd:vanadate (Nd: VAN) passively mode locked picosecond system (long. Gaussian $\sigma_{t,laser}$ = 6.5 ps rms, λ = 266 nm) [2]. The energy per pulse can reach 12 µJ at laser exit and decrease to 4 µJ (± 0.1 µJ) at the pulser viewport entrance after ten meters of transport through an evacuated pipe and various optical components. The laser transverse profile is Gaussian as represented in Fig. 2, with a rms width $\sigma_{r,laser}$ controlled via a two lens telescope assembly. The laser enters the electron beamline from a side viewport and a 5 mm square mirror finally sends the light towards the cathode. The mirror edge is at least 5 mm away from the electron beam axis. A reflexion from the entrance viewport is monitored on a small optical table beside the beamline, at a distance equal to the viewport to cathode distance. The laser pointing stability at this virtual cathode position was measured to be around 10 µm rms.

QUANTUM EFFICIENCY MEASUREMENTS

As represented on Fig. 2, the quantum efficiency (QE) increases with the applied electric field due to the Schottky effect. Indeed analytical formulas [3] based on the three steps model (absorption, excitation and emission of electrons) [4] reproduce quite well the measured data points. The only parameter that has been adjusted is the work function which depends mainly on the surface material and crystal orientation. The difference between the two copper measurements can be interpreted as a cleaning (contaminants removal) of the surface after one month of operation. The maximum QE for copper was measured to be around 2.10^{-5} at 25 MV/m, which is in agreement with copper based RF photogun [5]. Stainless steel (316L) is a promising material to withstand high electric field, and the QE is still comparable to copper around 10^{-5} (see Fig. 3).

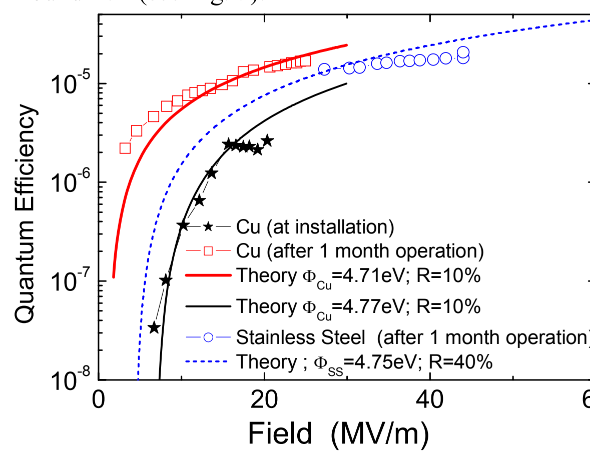

Figure 3: Measured and theoretical [3] quantum efficiency versus applied electric field.

THERMAL EMITTANCE MEASUREMENTS

To characterize the minimum achievable slice emittance, we first concentrated our efforts on thermal emittance measurements with a diamond-turned copper cathode and a hand-polished stainless steel one. Many laboratories already reported similar measurements with various cathodes types [6]-[8]; but the measured values were somewhat higher than theoretically expected probably due to nonlinear RF field effects in the RF-gun cavity, space charge effects, and the image noise and resolution limitation in the slit or pin-hole based measurement system. In this test facility we do not have any RF field affecting longitudinally the bunch phase space similarly the non linearity of the 250 ns (FWHM) sinusoidal pulse with respect to the laser pulse (6.5 ps rms) plays a negligible role. The expected energy spread along a bunch is only 0.067 eV at 500 keV. To minimize space charge effects, we reduced the bunch charge down to about 0.6 pC by attenuating the driving laser. Furthermore, to solve the image noise and resolution limitation in the pin-hole based E-meter, we used solenoid scan instead of the pepperpot method. The E-meter telescope and YAG2 screen with the point-spread function of 11.8 µm were used to measure small beam sizes with a good resolution. Machine parameters and optics layout during thermal emittance measurements with the copper cathode are shown in Fig. 1. A more detailed description of these measurements will be reported in another paper [9]. After optimizing the optics to get a small round beam image on YAG2, we recorded the beam size while scanning the solenoid current of MSL40. From the quadratic fitting of the square of the beamsize σ^2 and the solenoid focusing strength k_{sol}, we estimated the emittance [9]. With stable operation at 40 MV/m and using the copper cathode as shown in Fig. 4 we could reproducibly obtain about 0.2 µm.rad thermal emittance. Here the laser spotsize on the cathode was about 330 µm (RMS). The expected theoretical value should range around 0.17 µm.rad.

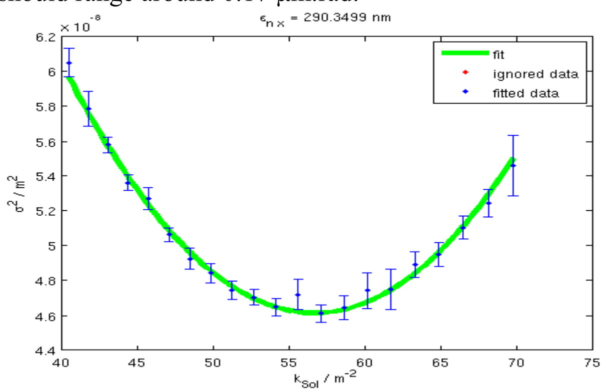

Figure 4: typical thermal emittance measurement result on the horizontal plan with a copper cathode.

With the stainless steel cathode, the gun was optimized at a higher gradient of about 50 MV/m (400 kV at 8 mm gap), and the laser spotsize reduced to 300 µm (RMS). In that case, the measured emittance was about 0.45 µm.rad [9].

HIGH GRADIENT EXPERIMENTS

An important milestone for the PSI-XFEL electron source is to achieve 125 MV/m at 4 mm gap in presence of a few µJ of UV laser beam.

Stable High Gradient (HG) operation depends on good preparation not only of the photocathode, but also of the anode. The first electrodes used were diamond turned Cu OFHC; firstly used at large gap (10mm) with voltage up to 350 kV, and 4 µJ of UV laser power. Cu was first chosen as it is rather resistant to breakdown damage (craters size) and its quantum efficiency is among the best for pure metal. Dark current and arc indicator X-ray activity was monitored using a NaI scintillator signal.

The gap was then closed to 4mm, and stable operation was achieved up to 40 MV/m with 0.2% amplitude stability over days and when switching ON or OFF the high voltage. At 41 MV/m a breakdown occurred, permanently affecting the emittance measurements reported here above.

Test series of electrodes of different materials are currently performed. From literature [10,11], it is well known that suitable materials are stainless steel 316L (SS), Ti, or Ti alloys and other refractory materials. Aluminium is also a very good candidate. However, due to its low melting point, damage (size of craters) when breakdown occurs is more severe than for refractory materials, with the risk that Al droplets could coat some sensitive ceramics.

Hand polished SS electrodes routinely reached 70 MV/m at 4mm gap with 4 µJ UV laser. Reproducibility at higher gradient for a given material is dependant upon the person doing the polishing. The best result achieved at 4 mm was 110 MV/m. without laser and 95 MV/m with laser. Results, without laser, obtained after many cycles of HG testing with hand polished TiVAl alloy, were similar to SS. The best values were 130 MV/m at 2.5 mm gap without any spark; the first and irrecoverable breakdown occurred at 140 MV/m at 2.5 mm gap.

The Nb electrodes achieved 63 MV/m at 5 mm gap in presence of ~4 µJ of laser energy. They were vacuum fired at 900 °C for 2 hours and chemically buffered polished. Grains were ~10mm and surface was much rougher upon visual inspection than was achieved with the previously cited metals.

CONCLUSIONS

Our intrinsic emittance measurements show values appreciably lower than those reported by other laboratories and probably approaching the thermal threshold. The first HG results with polished cathodes indicate that operation at gradient exceeding 130 MV/m with relatively long pulses should be achievable with a diode configuration. To exceed this value we are exploring new cathode preparation methods and materials. Long term stability studies at voltage below breakdown and manufacturing reproducibility must be performed as well to ensure a reliable operation. Finally replacing the photo cathode with photo assisted field emission emitters, presently under development at PSI, should improve the gun performance [12].

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