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PHOTO-CATHODE TESTING AT LOW ACCELERATING FIELD LABORATORY: A NEW R&D ACTIVITY AT INFN-LNF

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Introduction

In the framework of EuPRAXIA project [1] a high peak current and low emittance electron beam is required to obtain a high brightness electron beam, or in other word, quasi-"monochromatic" electrons, concentrated in very short bunches, with small transverse size and divergence, that is high particles density 6D phase space. The brightness, B, is defined as:

$$B[{}^{A}/_{m^2}] = \frac{Q}{\varepsilon_{nx}\varepsilon_{ny}\sigma_t\sigma_\gamma} \qquad (1)$$

where Q is the beam charge, ε_{nx} and ε_{ny} are respectively the normalized xx' and yy' transverse trace space emittances, σ_t is the bunch length and σ_γ is energy spread.
In this scenario the electron photo-injector, based on a laser excited photo-cathode immersed in a high accelerating field gun, is used. The performance of the photo-cathode, in terms of high quantum efficiency (*QE*), response time, emission uniformity and long lifetime, is essential to increase the brightness of the electron beam. For this reason, a R&D activity on photo-cathodes is essential to understand and characterize each stage of the photo-cathode's life cycle, with the aim of improving its capability in terms of quantum efficiency and more generally, of emission processes.
Presently, an international solid network focused on photo-cathodes R&D still exists based on the activities of INFN-LASA. The photocathodes produced by this laboratory are installed, and at present used, in different facilities (XFEL, FLASH). Beside the photocathode production, a whole environment for a better exploitation of the device has been developed including characterization, transportation, plug system and cleaning procedures.
A local Cathode Laboratory at INFN-LNF can be the place for the developing of a local know-how about the assembling, the maintenance and quality tests for the existing photo-cathodes and, in the next future, a place for R&D activities.
The strategy could be defined to orient the laboratory forward the integration into the already existing European Network in which are included Research Institutes currently partners of LNF in other research programs.
In first approximation, this means a first period dedicated to the setup of a laboratory available for the characterization of "basic" properties of photo-cathodes providing standards similar to those of the other facilities in terms of vacuum level and quality, sample holder/transportation system, cleanliness, sample manipulation and accuracy of data acquisition.

1. Scientific case

The quantum efficiency (*QE*) is a key parameter whose high value is demanded to any photo-cathode. In the photoemission process, the quantum efficiency, *QE*, is defined as the ratio of the number of photoemitted electrons (N_e) to the number of incident photons (N_φ), as expressed in the following equation:

$$QE = \frac{N_e}{N_\varphi} = \frac{\left(\frac{q}{e}\right)}{\left(\frac{E_L}{h\nu}\right)}, \qquad (2)$$

where q is the emitted charge, e is the electron charge, E_L is the incident radiation energy on the photo-cathode and $h\nu$ is the photon energy. Since the photoelectric effect involving the interaction between photons and electrons it is probabilistic in nature, the *QE* concerns the probability that incident photons of energy hν above the effective work function (φ_{eff}) of the cathode material, are absorbed by electrons near the Fermi energy which then move to the surface and escape [2,5]. The equation (2) is used for the experimental *QE* measurements in a photoinjector, where the collected charge (electron beam charge) is function of the laser energy, at fixed applied RF field.
In several facilities many experimental and computational studies are in progress to produce more efficient photo-cathodes. This approach looks at the photo-cathode like a "variable" and sensitive object in terms of surface modifications due to laser radiation, RF fields breakdown and contaminations due to quality vacuum variation of its environment.
Among the different materials that can be used as photocathode, metals have been defined as the preferred choice, particularly a Cu photo-cathode, for their fast response time (10^{-16}s < τ < 10^{-14}s), useful for the laser pulse shaping, and for their robustness and lifetime. The required electron beam distribution defines the characteristics of the laser system to be used for the photoemission. In general the photoemission process in metal photo-cathodes require photon in range of UV light, that can be obtained using the 3rd or 4th harmonic conversion from the fundamental wavelength of an IR laser. Cu photo-cathodes are minimally reactive with respect to other materials, they require about 10^{-9}Torr vacuum level and they are compatible with the environment of the RF cavity, whose walls are typically made of copper (Cu) too [2].
In this regards we want to start investigating the behaviour of different photo-cathode materials with respect to the conventional Cu, in particular the photoemission properties respectively of yttrium (Y) and magnesium (Mg). The Y is a transition metal that has a work function value of about φ_{work} = 3.1 eV (QE @ λ ~ 266 nm is about 5x10^{-4}) [9]. This value is very interesting because it gives, in principle, the possibility of illuminating the photo-cathode with an incident radiation of λ ~ 400 nm, (lower wavelength in the visible range). This wavelength can be obtained, for example, as second harmonic of Ti:Sa laser, thus giving the possibility to generate the linear electron photoemission with metals by means of visible radiation. This opportunity avoids the use of higher harmonic conversions and, giving an increase of the laser energy per pulse, contributes to the realization of high repetition rate photoinjectors by using conventional laser sources [3].
The Mg is a lightweight metal that has a work function value of about φ_{work} = 3.66 eV. Due to its work function, at λ ~ 266 nm and at the same applied RF field, it has a higher quantum efficiency (QE~ 10^{-3}) with respect Cu (QE~ 10^{-5}) [4,5].
It's important to stress that the material choice depends on the robustness (response to vacuum arc deposition due to RF breakdown), lifetime and uniformity of emission.

Many experimental studies have shown that the Cu photo-cathode is the best option in terms of robustness and long lifetime (many years). One of the issues related to an alternative material with respect to Cu is compatibility with the environment of the RF cavity, whose walls are made of Cu. Any rough and steep boundary between the two different metals would trigger arcs, with a resulting cathode damage and/or limiting the maximum RF field amplitude [6]. To avoid this problem a thin and central film photo-cathode (Mg and Y) on a Cu substrate would be the better solution. Different materials and deposition techniques have been tested, though, from the state of art, the greatest choice is the pulsed laser deposition technique (PLD) [7,8,9]. To study and to perform experimental analysis on these types of photocathodes it is important to understand which could be the best choice given the beam machine parameters requirements.
Regarding the uniformity of the emission, possible problem could also be due, besides to a not perfect laser uniformity, also to the quality of the cathode surface, since both the surface roughness and the contamination could cause a degradation of the homogeneity of the QE due to the modification of the working function.
To evaluate the quality of the photo-cathode surface, it is necessary, before and after photocathode operation, to analyze the surface by Scanning Electron Microscopy (SEM) to study the surface condition and Energy Dispersive Spectroscopy (EDS) to analyze the chemical composition of surface. In addition, it is essential to measure the surface roughness by using the AFM analysis. In other word, it is important to characterize the photo-cathode's surface through the morphology, chemical and roughness analysis to estimate the issues that could affect the electron beam quality.
To limit this degradation it has been proposed a thin protection layer deposition on photo-cathode's surface to guarantee long-term high quality. The state of the art is represented by a thin layer of graphene deposited on a Cu cathode [10]. Understanding the photoemission from this kind of photo-cathodes is one of the key points of our experimental program.

2. Previous Results and Experimental set up

A Cathode Laboratory at LNF-INFN has been active until 2009 [11] performing R&D on metallic photo-cathodes: Cu and Cu covered with Mg or Y thin films. QE measurements and surface activation, by mean of laser cleaning, were performed in a photo-cathode testing chamber. The experimental apparatus (Fig.1) consisted of a UHV photodiode test chamber, a metal thin film on Cu as cathode, a vacuum system providing residual pressure levels of about $2 \cdot 10^{-9}$ mbar and a laser optical transport line to illuminate the cathode's surface. An accelerating DC electric field up to about 1.7 MV/m were applied to the diode to extract the emitted electrons. The emitted charge (electrons) was detected by a coaxial cable connected to the cathode. The current output was read by a high sensitivity charge amplifier and a sampling scope.
The Optical and Source systems were composed by:

- Laser Nd:YAG Q-switch mode-locked with a longitudinal pulse of about tens ps and 30mJ of energy.
- An optical transfer line. The 4th harmonic of the laser beam was reflected by a mirror mounted on a gimbal for fine alignment; a variable aperture iris was used to select the central part of the beam and to align it. A beam splitter was used to sample the beam energy by means of a calibrated fast photodiode. When needed, a series of neutral density filters was used in order to decrease the laser energy down to a fraction of nanojoule. A couple of cylindrical lenses were used to transversely shape and collimate the beam in order to obtain a circular laser spot on the cathode. The laser beam was, when necessary, focused with a fused silica plano-convex lens (focal length 30 cm) mounted onto an *xyz* translational stage driven by stepper motors controlled by a computer (*x* and *z* movements

were linked in order not to change the chosen distance between the lens and the illuminated area of the cathode). Another variable aperture iris was used for laser beam alignment prior the vacuum chamber quartz window. A triggered CCD camera was used to observe the laser spatial distribution over the cathode surface. The laser energy measurements were performed by integrating the signal of the calibrated fast photodiode, while the charge measurements were done using a charge integrator. Another beam splitter sampled out the laser beam in order to illuminate a Ce doped YAG screen used as a virtual cathode [11].

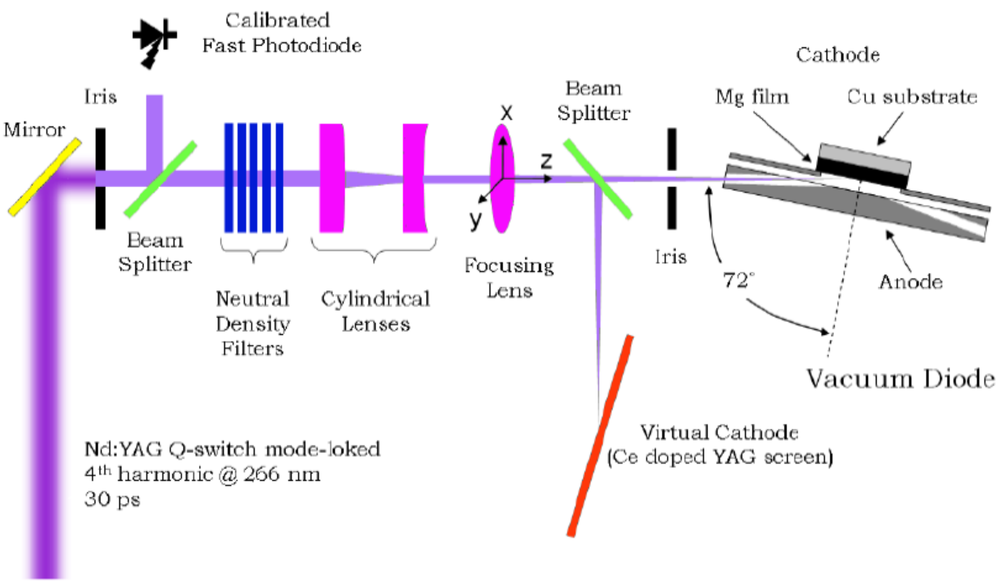

Figure 1: Layout of the experimental setup with the optical beamline [11].

The vacuum System (Fig.2) was composed of:

- A UHV chamber. On this chamber different windows allow the entrance of laser beam illuminating the cathode from different incident angles. The upper closure presents electrical feedthroughs for the signal acquisition.
- Hot cathode vacuum gauge
- Ion Pump
- Quadrupole RGA
- All metal gate valve for the separation between measurement chamber and the rough vacuum group.
- Rough vacuum group composed of turbomolecular pump and diaphragm pump.
- Resistors cable, and related control unit, for bakeout process.

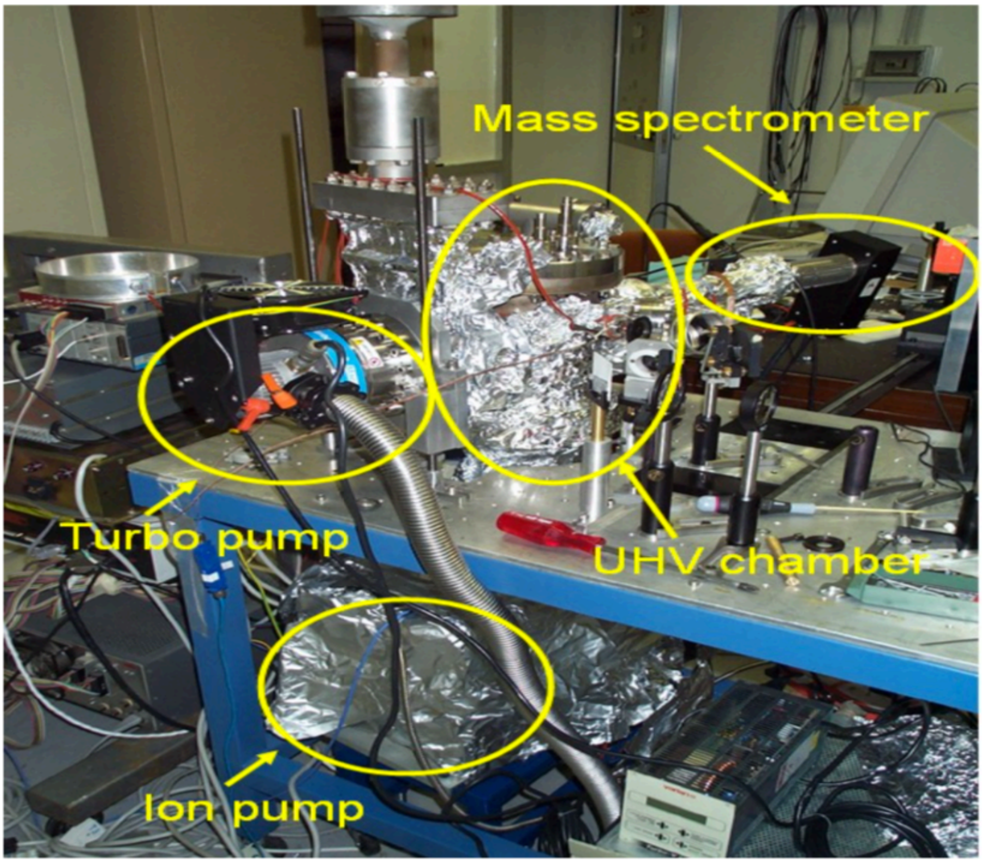

Figure 2: Vacuum system [12].

The HV system and the acquisition chain (Fig.3) were composed by:

- HV Generator: an accelerating electric field of about 1.7 MV/m is obtained by means of a 5kV voltage applied across the cathode and the anode placed at a distance of 3 mm.
- A coaxial cable directly connected on the cathode to collect the emitted charge. This allows reading precisely the current even if the electrons are not collected by the anode, which is very important at low charges regimes.
- A high sensitivity charge amplifier and an oscilloscope, or only a fast oscilloscope to read the current output.

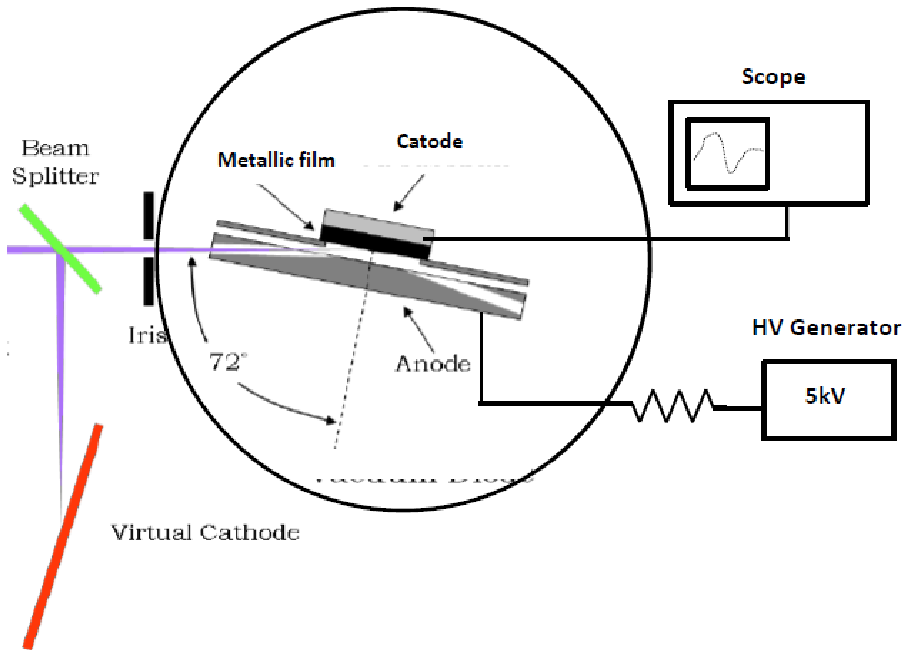

Figure 3: Low field applied and acquisition system.

The measured QE values resulted to be similar to those published by other laboratories, with critical factors inherent the surface or thin film conditions, the contamination and the cleanliness procedures.
At present, the whole system needs to be inspected, refurbished and tested. In the short term a cautious revamping design of some acquisition chain devices and of the vacuum system is expected to improve the facility performances. The optical system requires a new source and the suitable laser system could be a Laser Nd:YAG Q-switch mode-locked, with a longitudinal pulse of about tens ps and 30mJ of energy, in other word the same system as the previous.

3. Short and Long Terms Goals

The short terms goals (the objectives for the first year of activity) are listed below:

- Setup of the experimental station:
  - Installation, alignment and test of the laser source device;
  - Installation and test of vacuum system;
  - Installation and validation of the acquisition chain (Hardware and Software);
  - Installation of HV generator;
- Test of the availability of a local or an external laboratory for the morphology characterization;
- Activation of a partnership for the production of a new set of photo-cathodes;
- Installation of instrumentation for the sample manipulation;
- Presentation of the activities by an LNF internal seminar;

All of these goals can be considered fulfilled with the first complete characterization campaign of a new set of photo-cathodes

The long terms goals (objectives to be achieved in two years of activities) are:

- Upgrade of the experimental chambers to made the system compatible with laboratories, RF Guns' systems of the other partner Institutes;
- Draft of a research program for the successive years of activities;
- Presentation of the activities to an international conference;
- Request of a PhD position;

4. Conclusions

In the RF photo-gun the photo-cathode is subject to surface modification and contamination due to laser radiation, RF fields breakdown and low vacuum pressure.
In this contest and in the framework of EuPRAXIA project, to produce high brightness electron beam it is essential to carry on a R&D activity on photo-cathodes, in terms of surface analysis, estimation of lifetime and evaluation of QE value. Indeed, the fundamental constraint of high brightness electron beam sources is the cathode.
The photo-cathode testing at low accelerating field will give the possibility to have a full characterization of each stage of the photocathode "life" and to have a complete overview of the photoemission properties relevant for high brightness photo-injectors.

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