

Gallium Arsenide photocathodes used in high electric fields

Results of experiment from November 1997 to January 1998

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1. Introduction

This paper summarises the work done from November 1997 to January 1998 in the collaboration between SLAC and CERN to test GaAs Photocathodes in the RF gun of the CERN CLIC Test Facility. The interesting property of GaAs is as a source of polarised electrons, for which the optimum wavelength of the illumination is about 850nm. No suitable light source at this wavelength was available, the measurements were made at 532, 266 and 213 nm, at which wavelengths the quantum efficiency is greater, but the electrons produced have very low polarization. The trials concentrate on the procedure to produce GaAs cathodes activated by cesium and oxygen and study their behaviour in the high electric field of the RF gun.

2. Preparation of the Gallium Arsenide Photocathode

The Gallium Arsenide (GaAs) samples and the assembly set were supplied by the Stanford Linear Accelerator Centre (SLAC). In this way a GaAs sample can be mounted inside the body of a Photocathode plug used in the RF gun of the CTF drive beam at CERN (fig. 1). The Mo retaining ring was omitted in the final design.

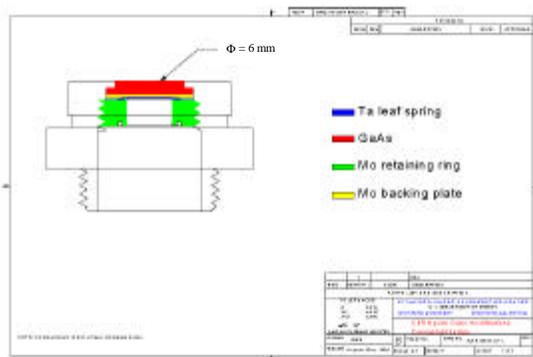


Figure 1-a

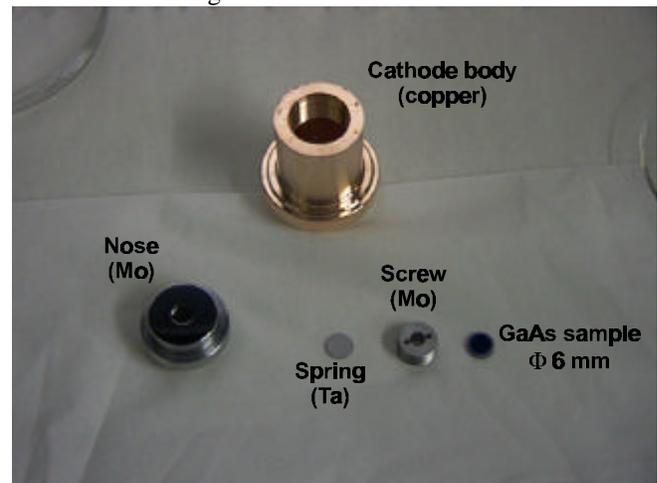


Figure 1-b

Two sets of samples were supplied, the first set of four were used to test the assembly and cleaning procedures and for familiarization with the equipment, then a second set of four with precise machining, which could be inserted into the CTF source without detuning the RF cavity.

2.1. Chemical cleaning

The GaAs sample is protected by an anodized surface which must be removed before mounting. The SLAC Anodisation Removal Procedure was followed : Immersion for thirty seconds in Ammonia hydroxide (NH_4OH), rinsing with a steady stream of deionised water (H_2O), followed by a rinse in a steady stream of methanol (CH_3OH) and finally blown dry with Nitrogen (N_2). The pictures 2a, 2b show the GaAs photocathode ready to be placed in the preparation chamber.



Figure 2-a : Sample for test

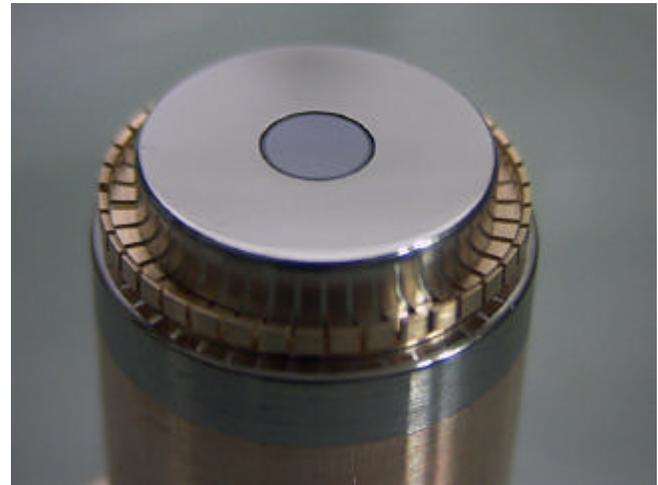


Figure 2-b : Sample for CTF RF gun

2.2. Cleaning by Argon ion bombardment (Etching)

The CERN Photocathode preparation chamber cannot provide the high temperatures (600°C) needed to clean the GaAs photocathode for Ultra High Vacuum (UHV) in the usual way. The cleaning process used is by argon ion bombardment, Ionic Controlled Etching (ICE). The argon pressure is kept constant at close to 75×10^{-3} mbar (50×10^{-3} mbar N_2 equivalent). The plasma voltage is about 400V for a current flow of $1 \mu\text{A}$ and 700V for $10 \mu\text{A}$. We define an Arbitrary Etching Unit (EAU) which is used to quantify the erosion process. The EAU is equal, in the domain of pressure described above, to the product of the plasma voltage by the current in the plasma and by the time interval during which the plasma is fired. $1 \text{ EAU} = 1 \text{ V} \times 1 \text{ A} \times 1 \text{ s}$ at a 75×10^{-3} mbar of argon pressure. The plasma voltage is monitored with a $10 \text{ M}\Omega$ resistor connected at output of the power supply. The plasma voltage is then defined as $U_{\text{HT}} - 10^7 \times I$. The ICE furnace is built so that, for the above set of pressure and voltage, the plasma etches only the front face of the photocathode. The Argon pipes are pumped out by the primary pumping system shown at picture 3. The vacuum quality is good so that the purity of argon N70 (99.99990%) is maintained in the preparation chamber.

2.3. Activation

The activation process consists firstly of an evaporation of Cesium, which is monitored online so as to identify the maximum quantum efficiency. The Cesium quantity is very small, in the order of one or two atomic layers (the radius of the atom of cesium is about 0.33 nm). This is followed by a low pressure oxidization of the surface, the O_2 pipes having been previously pumped out (Fig. 3) in order to maintain the Oxygen's purity (99.998%). Quantum efficiency measurements could be done at 3 different wavelengths : 213 nm, 266 nm and 532 nm (Fig. 4).

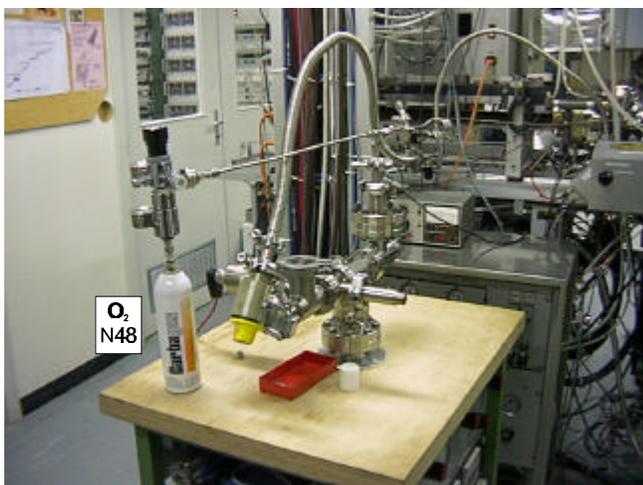


Figure 3 : oxidation system and pumping group

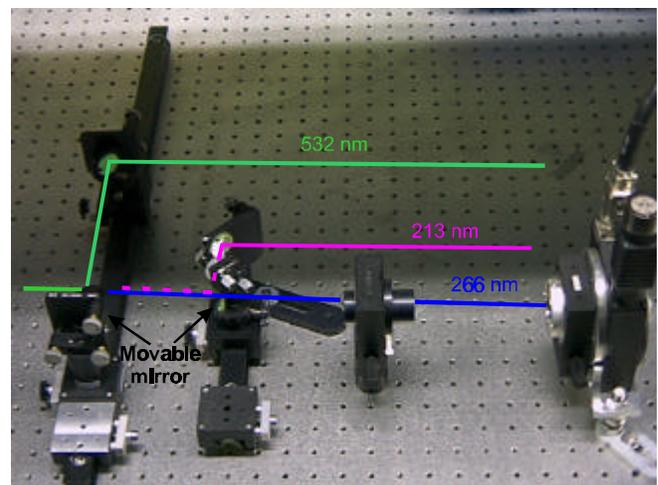


Figure 4 : Set-up for 3 wavelength measurements

Figure 5 shows the species analysis in the preparation chamber, before and after the oxidation process.

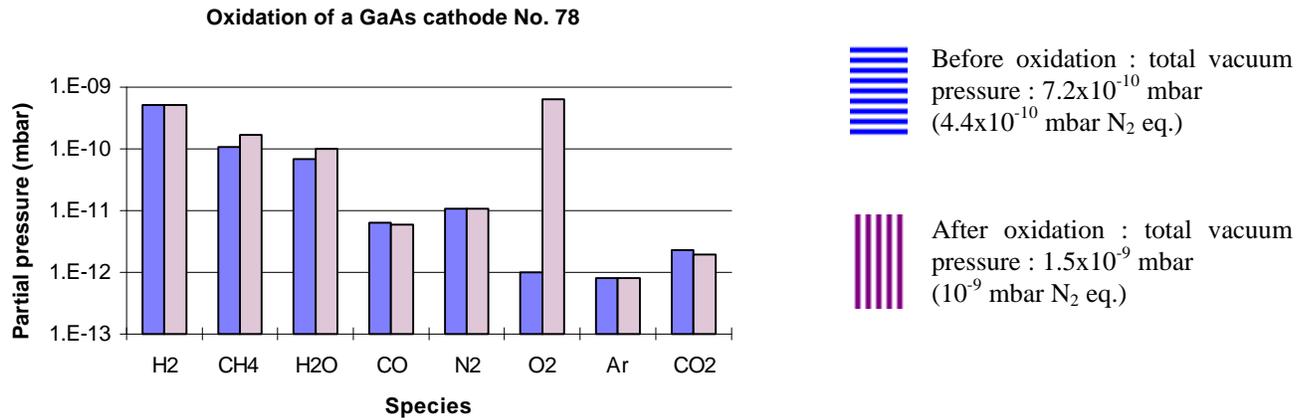


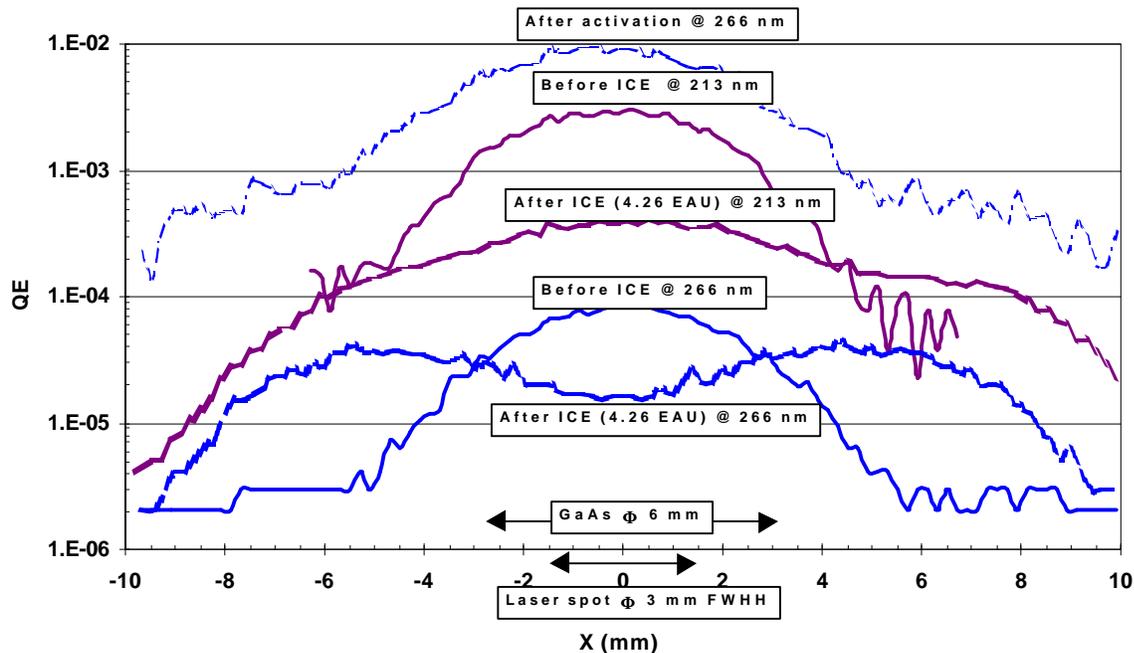
Figure 5 : Vacuum analysis before and after oxidation

3. Photocathode No 75

This Photocathode plug was fitted with a test sample from the first set. It can be seen in picture 2a that the GaAs sample was clearly set back from the plane of the front face of the photocathode.

The sample was cleaned using 4.26 EAU (710 V, 10 μ A, 10 minutes) at 75×10^{-3} mbar of Argon pressure. For comparison, the rejuvenation of a Cesium/Rubidium/Tellurium cathode after exposure to atmospheric pressure needed 90 EAU. The quantum efficiency measurement done after ICE shows a clear decrease at 213 and 266 nm wavelengths, with a value close to the typical value for “clean” GaAs material (typically less than 2×10^{-4} at 213 nm).

Figure 6 : QE distribution on photocathode No 75

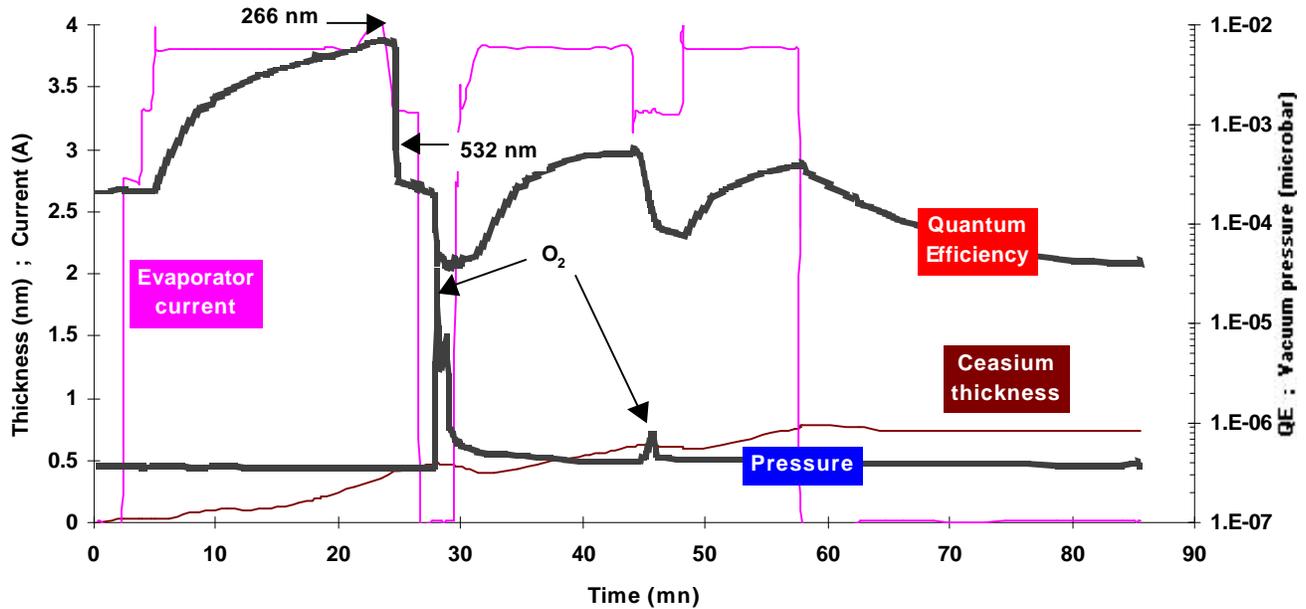


The effect of cleaning on the molybdenum substrate may be seen in figure 6. Note that QE increased by more than a factor 10 at 266nm wavelength. The quantum efficiency at 532nm wavelength was very low and could not be measured before or after cleaning by ICE.

The activation sequence for the GaAs sample is shown in figure 7. The first oxidation suffered from a poor control of the oxygen pressure which reached up to 3.3×10^{-8} mbar, which probably polluted the surface.

Figure 7 : GaAs activation on the photocathode No 75

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The cathode was then exposed to a 7 MV/m DC electric field. The activation produced a strong dark current emission. Figure 8 shows the dark current and the photo emission current measured at the Faraday cup with a 1MΩ load and the photocathode illuminated by 532nm light from a Nd:YAG laser.

The laser energy on the photocathode was estimated to be 21 μJ. The charge measured by the wall current monitor was 0.3nC which gave a quantum efficiency of 3.2×10^{-5} .

With no light on the photocathode, a voltage of 1.6V was measured on the Faraday cup with its 1MΩ load, indicating a dark current of 1.6 μA.

The activation process increased the dark current from less than 2 nA (the limit of resolution for this measurement) to 1.6 μA for an electric field value of 7 MV/m.

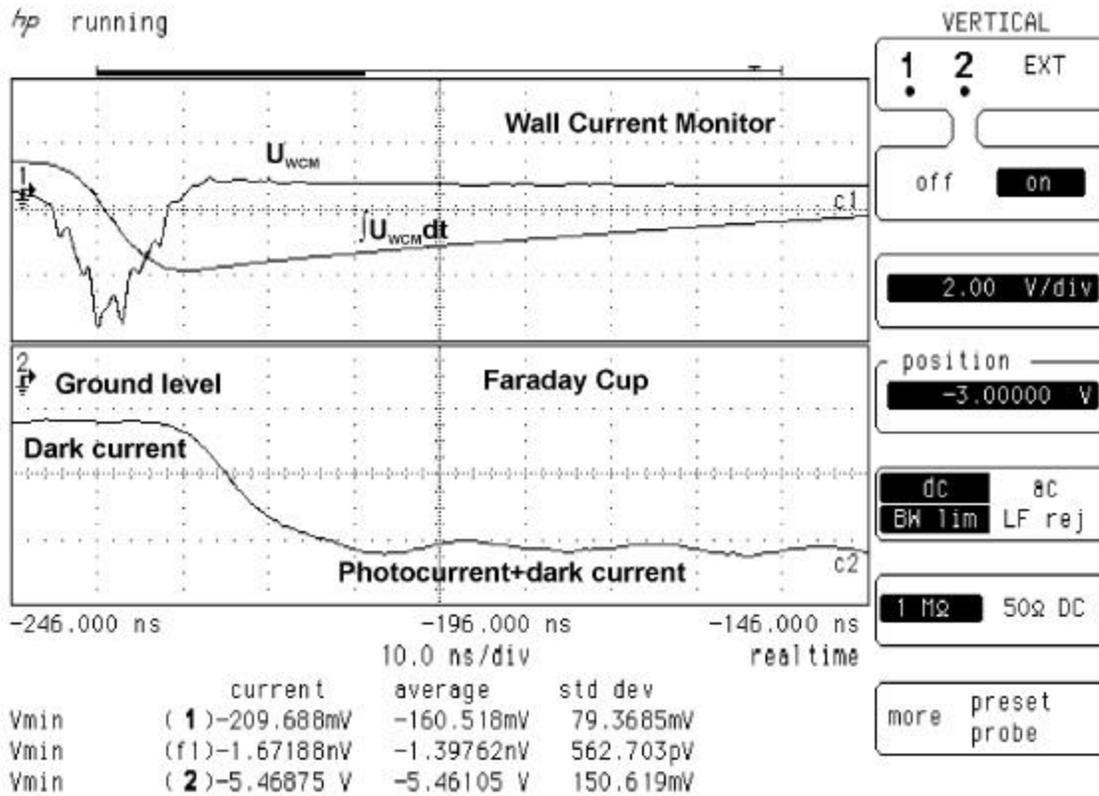


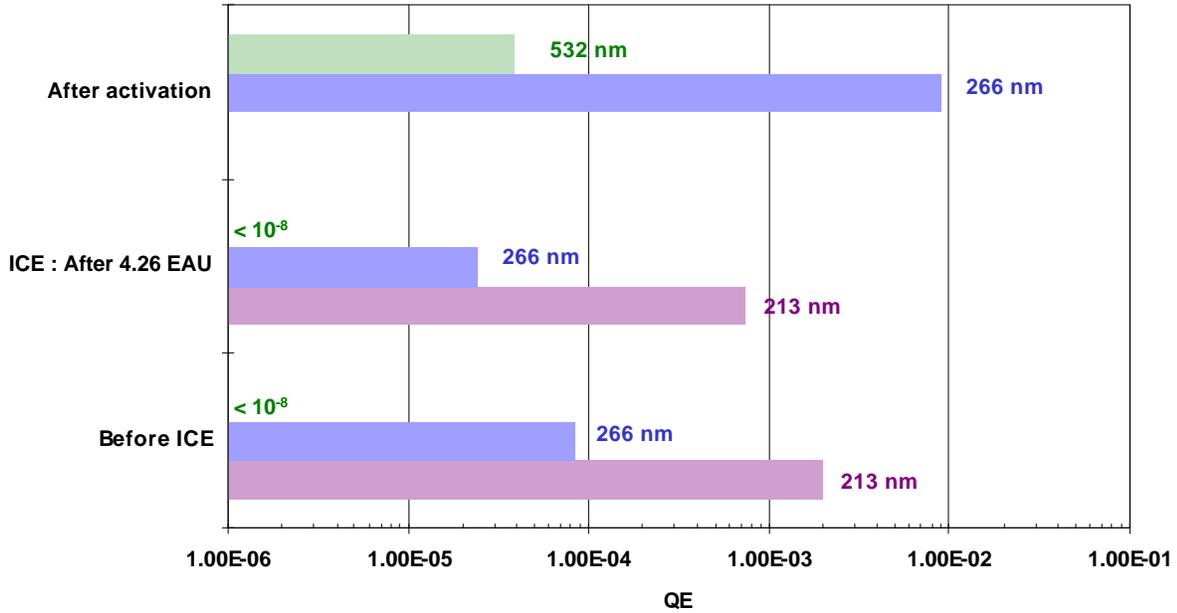
Figure 8 : Measurement of the charge induced by a 532 nm laser pulse at 7 MV/m electric field

Table 1 and figure 8 summarize the performance obtained with this photocathode.

Table 1 : Cathode No 75

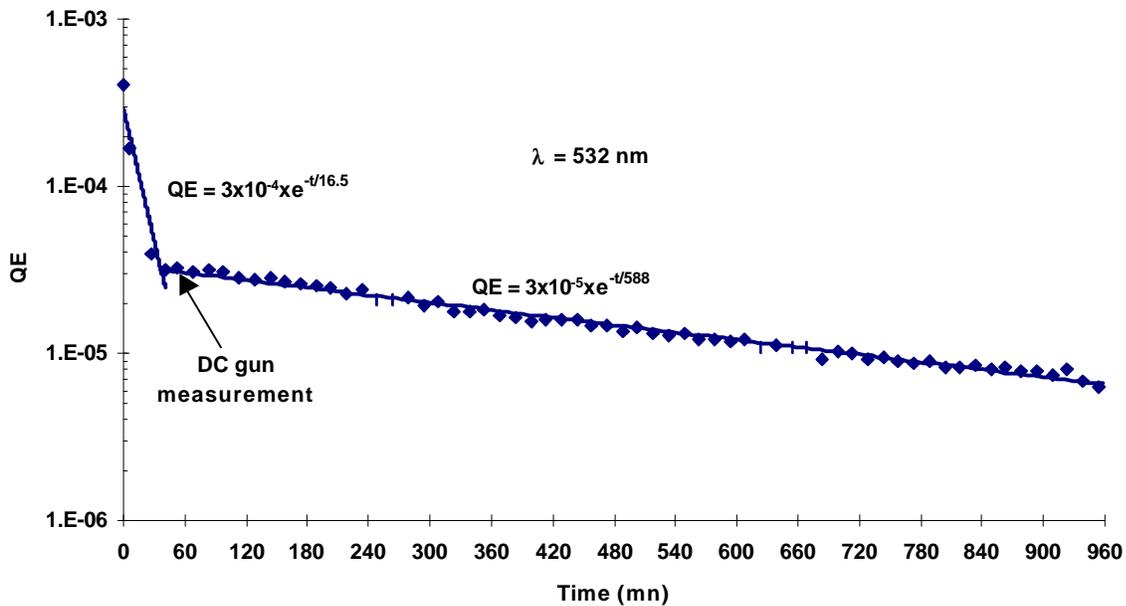
	before ICE	after ICE	after activation
QE at $\lambda = 213$ nm	2×10^{-3}	7.5×10^{-4}	
QE at $\lambda = 266$ nm	8.4×10^{-5}	2.4×10^{-5}	9×10^{-3}
QE at $\lambda = 532$ nm	below measurement resolution	below measurement resolution	3.2×10^{-5}
Dark current at 7 MV/m	< 2 nA	< 2 nA	1.6 μ A

Figure 8 : QE of GaAs photocathode No 75



The photocathode life time has a two slope characteristic very similar to those of alkali photocathodes. The first slope is of 17 minutes time constant for the first period of 50 minutes, this is followed by a steady decrease in QE with a time constant of about 10 hours for the next 10 hour period. The performance of this photocathode is shown at figure 9.

Figure 9 : Lifetime of the GaAs photocathode No 75



4. Photocathode No 76

The photocathode 76 was fitted with a GaAs sample which was not mechanically compatible with the CTF RF gun and was used to test the cleaning process by ICE. The argon pressure was 75×10^{-3} mbar. Figures 10 and 11 show the cleaning effect on this cathode at 213, 266 and 532 nm wavelengths. Unlike the cathode No 75, no dark current was observed, either before or after cleaning. The measurement resolution was 2 nA.

Figure 10 : QE distribution of GaAs photocathode No.76

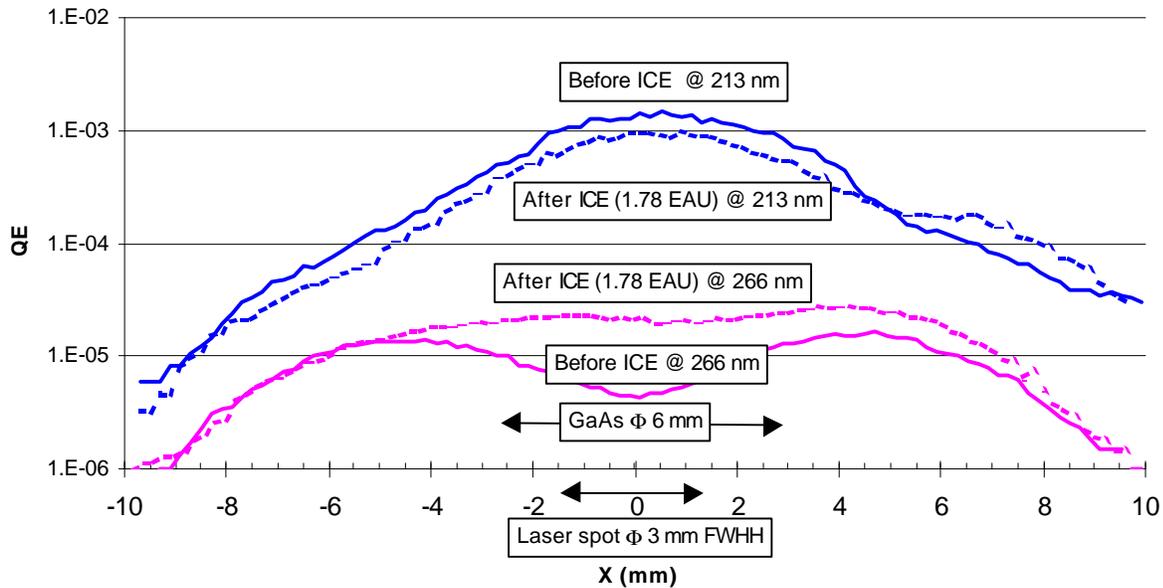
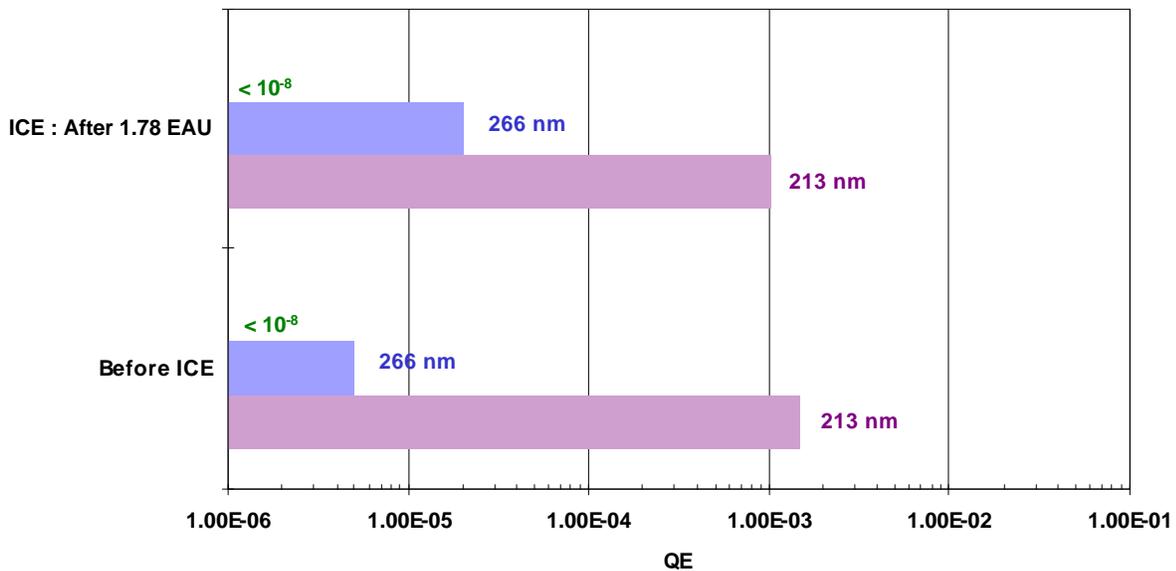


Figure 11 : QE of GaAs photocathode No 76



5. Photocathode No 77

This cathode was compatible with the CTF RF gun. Unfortunately, after two ICE cleaning cycles, the cathode plug became blocked in the clamp of the transfer arm. The preparation chamber had to be returned to atmospheric pressure to fix the mechanical blockage and also to change the scratched photocathode copper plug which was the origin of the problem.

6. Photocathode No 78

The starting point for this photocathode was photocathode 77 with a new copper plug. The history of the substrate was as follows:

a) photocathode 77:

- Cleaning with ammonia.
- Badly controlled ICE cleaning : about 0.03 EAU at 75×10^{-3} mbar of argon pressure.

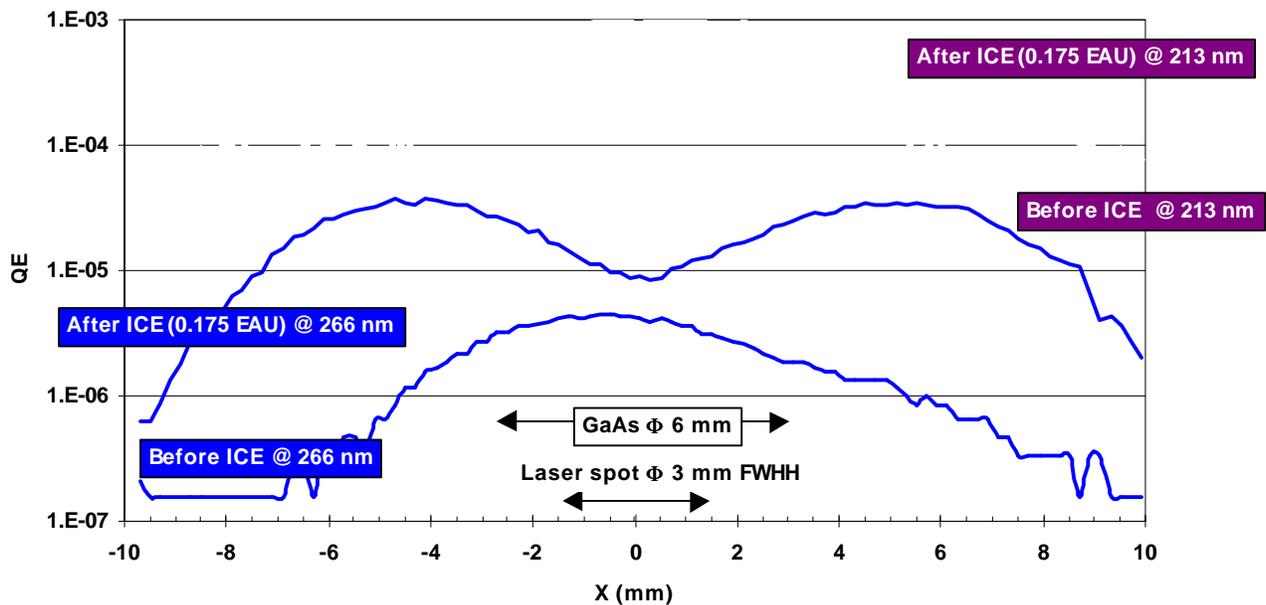
b) photocathode 78:

- Preparation chamber raised to atmospheric pressure for the repair, replaced in new plug.
- ICE cleaning : 0.17 EAU at 75×10^{-3} mbar of argon pressure.

ICE cleaning was done carefully in order to prevent the destruction of the crystalline structure at the surface of the GaAs sample. The EAU quantity was chosen to get close to the typical QE of clean GaAs material.

Figure 12 shows the effect of ICE cleaning on this photocathode.

Figure 12 : QE distribution of GaAs photocathode No.78



In order to obtain a signal well above the noise floor, the QE was monitored at 266 nm wavelength at the beginning of the cesium evaporation. The QE was also checked at 532nm after the first two cesium evaporation and was found to be below the measurement threshold. Figure 13 shows that after third evaporation, the QE at 532nm is decreasing, indicating that the maximum had been passed. Activation with O_2 does not return to this maximum value. It seems that the activation process failed, due to a dirty GaAs surface (the oxygen-phobia phenomenon).

In the DC gun, measurements were made at 7 MV/m before activation and at 5 MV/m after. Unlike the photocathode 75, no dark current was observed before or after activation. The quantum efficiency measurements are reported in table 2 and figure 14.

The photocathode was then tested in the RF gun of the CTF drive beam, about 24 hours after its activation. This is the time needed to obtain a vacuum pressure low enough to transfer the photocathode into the gun. A quadratic dependence of

the emitted charge versus the laser energy was observed, which suggests two photon emission and therefore a work function greater than 4.6eV. A slight dependence of the quantum efficiency with the electric field was observed. As with the DC gun the dark current was very low, its value was lower than that of a Cs₂Te photocathode measured a few minutes before for comparison purposes. This is again an indication of a high work function and of the failure of the activation process. However the radiation generated by the gun with the GaAs photocathode 78 is higher than that of the Cs₂Te photocathode used for comparison (figure 15). All other parameters being supposed similar, this measurement seems to contradict the dark current measurement. For these measurements, the RF gun was the only load receiving 3 GHz RF power, and was therefore the only possible source of this radiation.

Figure 13 : Activation of GaAs photocathode No 78

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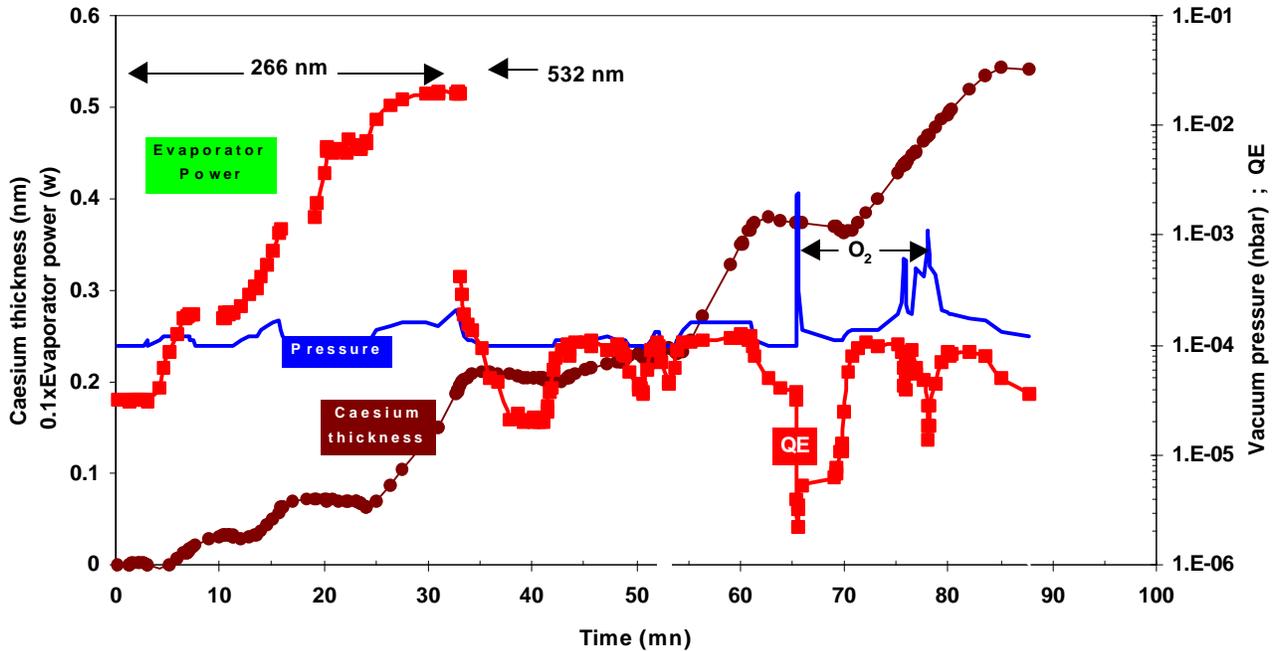


Table1 : cathode No 78

The DC gun measurements at 5 MV/m. At this level the dark current was below 2 nA.

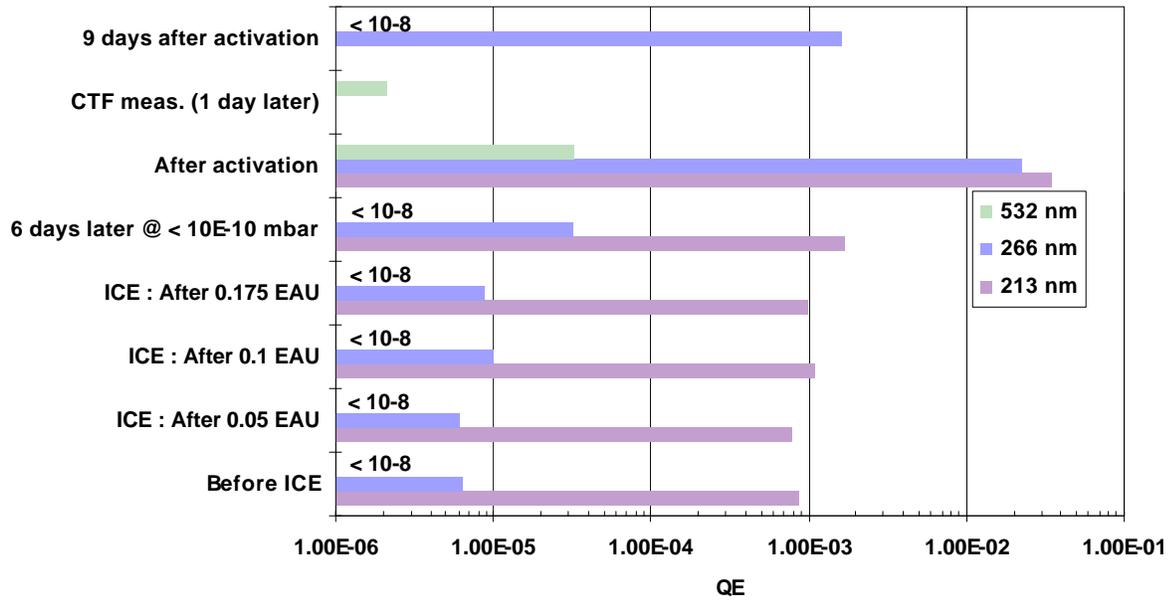
	QE à $\lambda = 213$ nm	QE à $\lambda = 266$ nm	QE à $\lambda = 532$ nm
Before ICE	9×10^{-4}	6.4×10^{-6}	$< 10^{-8}$
ICE : 0.05 EAU	7.7×10^{-4}	6×10^{-6}	$< 10^{-8}$
ICE : 0.1 EAU	1.1×10^{-3}	10^{-5}	$< 10^{-8}$
ICE : 0.175 EAU	9.8×10^{-4}	8.8×10^{-6}	$< 10^{-8}$
6 days later ^{a)}	1.73×10^{-3}	3.2×10^{-5}	$< 10^{-8}$
After activation ^{b)}	3.48×10^{-2}	2.3×10^{-2}	3.3×10^{-5}
CTF @ 73 MV/m ^{c)}			2.1×10^{-6} (2 photon effect)
9 days later		1.6×10^{-3}	$< 10^{-8}$

^{a)} The photocathode was kept in a vacuum pressure better than 10^{-10} mbar

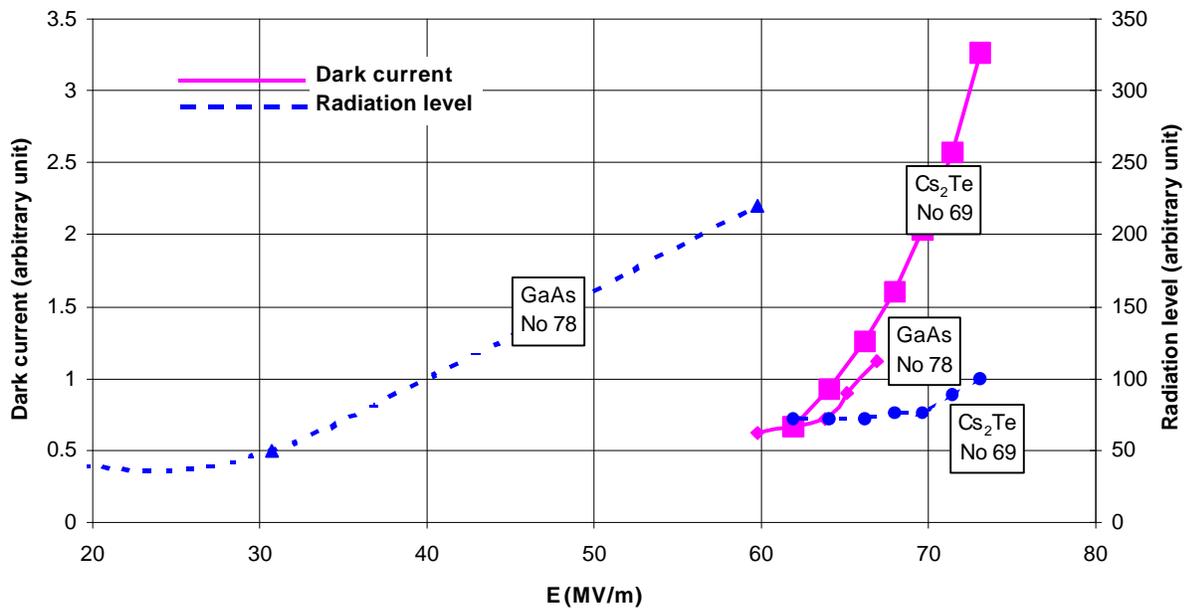
^{b)} Deposition of 0.54 nm of cesium , then oxidation at about 10^{-9} mbar oxygen pressure

^{c)} About 24 hours after cathode activation

Figure 14 : QE of GaAs photocathode No 78



Dark current produced by photocathodes in the Drive Beam RF gun



7. Photocathode No 79

The starting point for this photocathode was cathode 78 which was kept under vacuum. It was then well etched by ICE cleaning using 30.7 EAU instead of 0.175 EAU for the preparation of the previous cathode.

It was then activated by depositing 1.6 nm of cesium and an exposure to oxygen. All the process monitored online at 532 nm wavelength. As seen before, the optimum quantum efficiency was obtained by a thin cesium layer, about 0.05 nm. Figure 16 shows the activation attempt for this photocathode

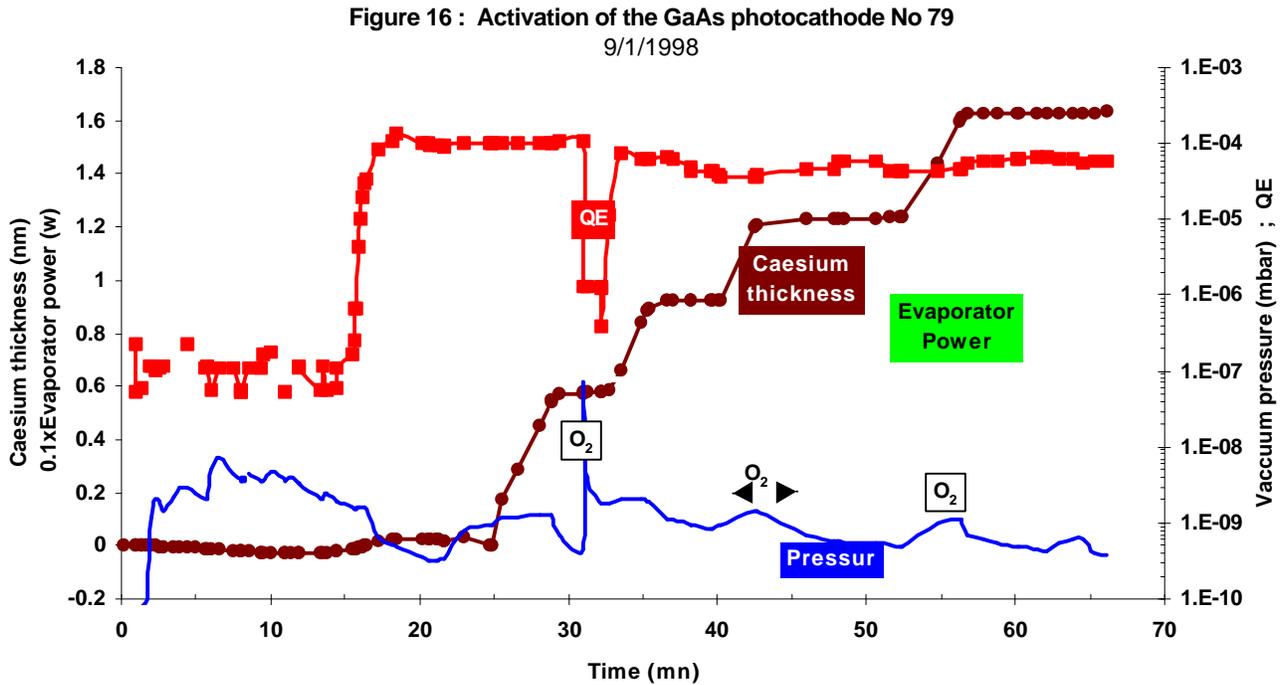


Table 3 and figure 17 summarize the main characteristics of this photocathode.

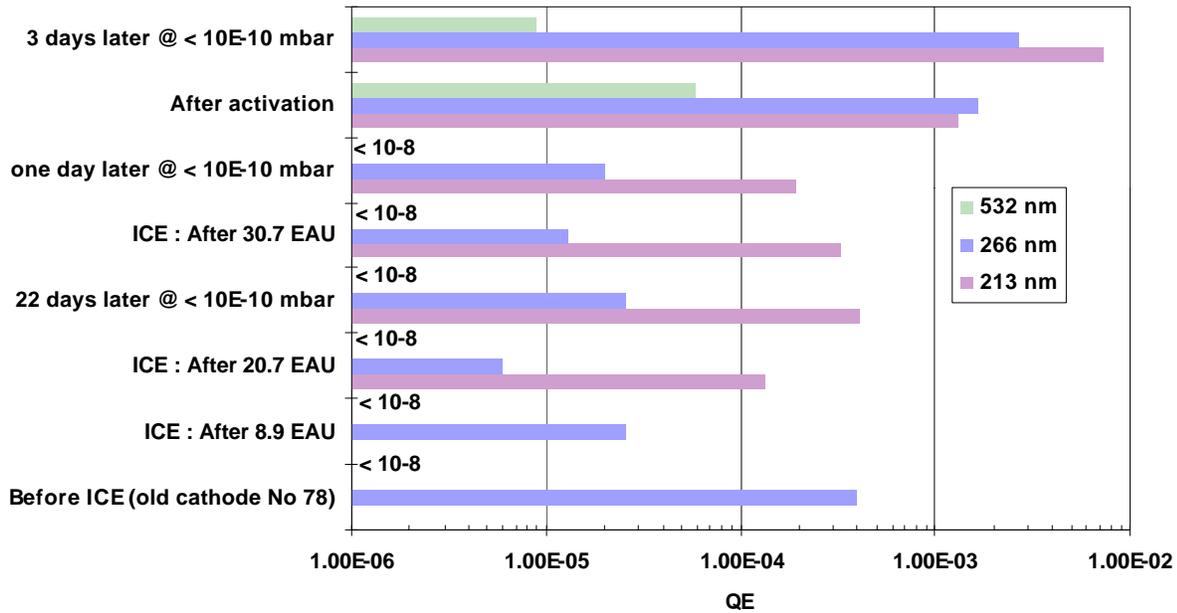
Table 3 : cathode 79

	QE at $\lambda = 213 \text{ nm}$	QE at $\lambda = 266 \text{ nm}$	QE at $\lambda = 532 \text{ nm}$
Before ICE (cath. 78)		4×10^{-4}	$< 10^{-8}$
ICE : 8.9 EAU		2.6×10^{-5}	$< 10^{-8}$
ICE : 20.7 EAU	1.3×10^{-4}	6×10^{-6}	$< 10^{-8}$
22 days later ^{a)}	4.1×10^{-4}	2.6×10^{-5}	$< 10^{-8}$
ICE : 30.7 EAU	3.3×10^{-4}	1.3×10^{-5}	$< 10^{-8}$
one day later ^{a)}	1.9×10^{-4}	2×10^{-5}	$< 10^{-8}$
After activation ^{b)}	1.33×10^{-3}	1.65×10^{-3}	5.9×10^{-5}
3 days later ^{a)}	7.3×10^{-3}	2.7×10^{-3}	9×10^{-6}

^{a)} The cathode is stored inside a vacuum pressure better than 10^{-10} mbar

^{b)} Deposition of 1.64 nm of cesium under about 10^{-9} mbar of oxygen pressure

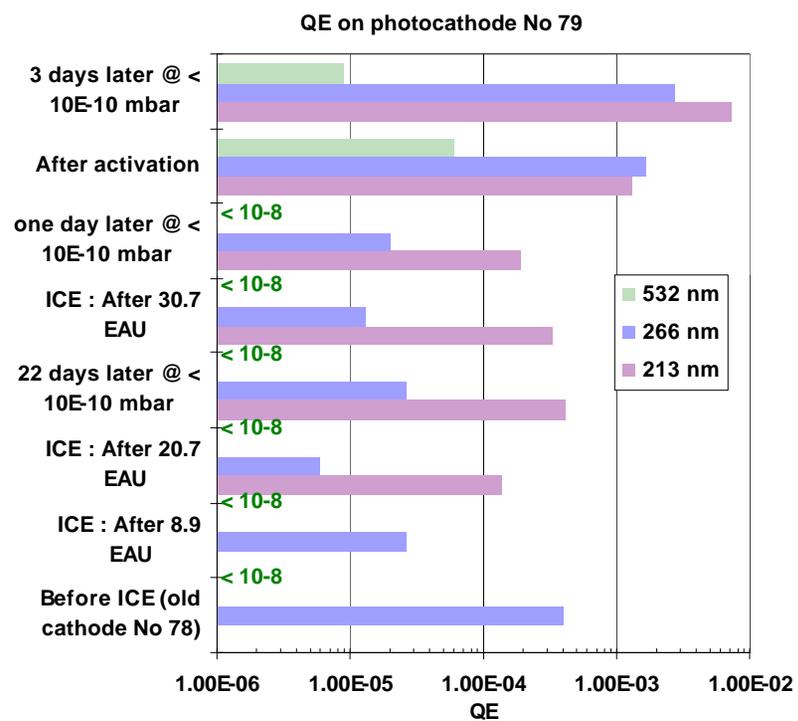
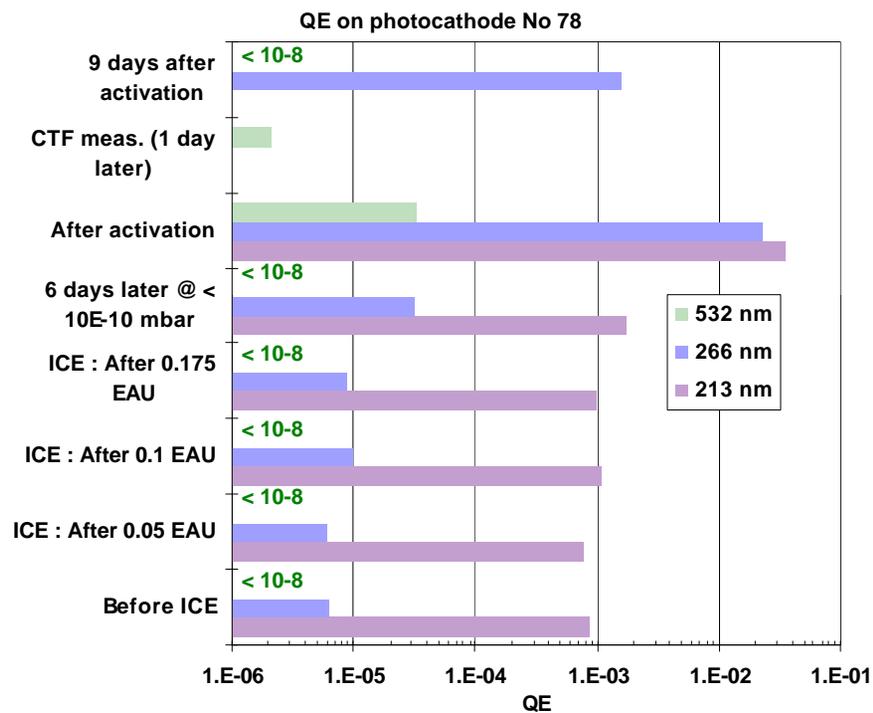
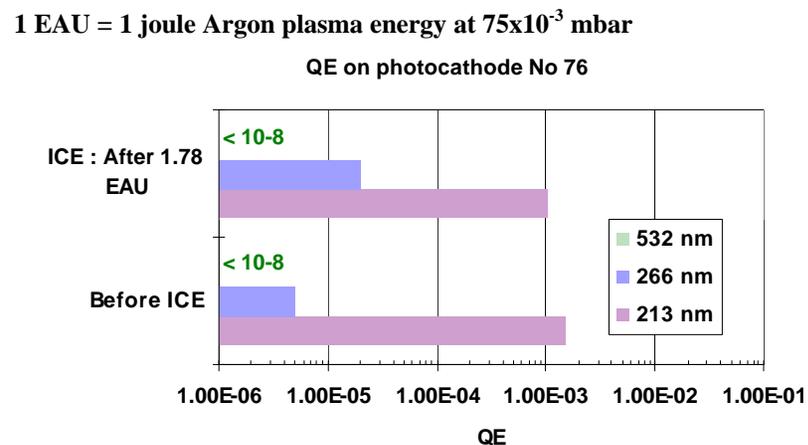
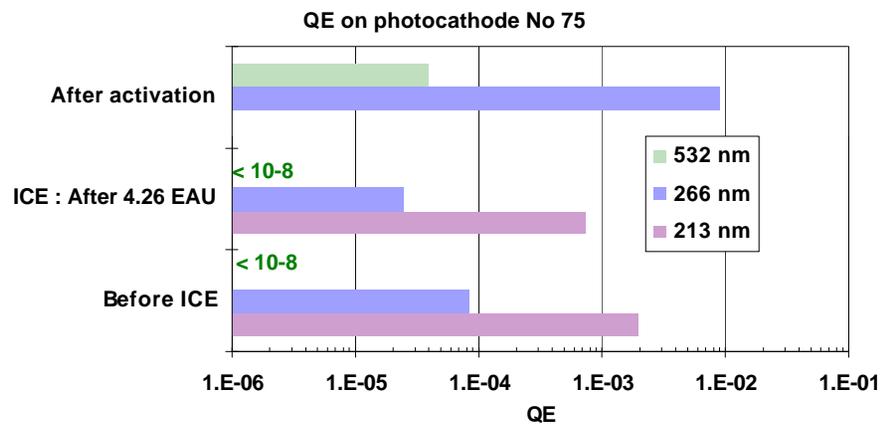
Figure 17 : QE of GaAs photocathode No 79



8. Summary of tests done with GaAs photocathodes

	No44	No 45	No 46	No 75	No 76	No 78	No 79
Date	22/11/95	27/11/95	27/11/95	26/11/97	28/11/97	2/12/97	18/12/97
Type	Cs ₂ Te	GaAs	GaAs	GaAs	GaAs	GaAs	GaAs
Anodization	no	?	?	yes	yes	yes	yes
Ammonia cleaning	no	no	no	yes	yes	yes	yes
Methanol cleaning	yes	yes	yes	yes	yes	yes	yes
ICE	no	no	no	4.26 EAU	1.78 EAU	0.175 EAU	30.7 EAU
Cesium layer	11 nm	0	10 nm	0.8 nm	0	0.5 nm	1.6 nm
Oxidation	no	no	no	yes	no	yes	yes
I _{dark_curr.} @ 7 MV/m	9 pA		0.3 nA	1.6 μA	< 2 nA	< 2 nA	< 2 nA
I _{dark_curr.} @ 8 MV/m	45 pA		2.7 nA		< 2 nA	< 2 nA	< 2 nA
I _{dark_curr.} @ 9 MV/m		< 2 nA	9 nA		< 2 nA	< 2 nA	< 2 nA
QE @ 532nm	DC gun	< 10 ⁻⁸	3.6x10 ⁻⁶	3.2x10 ⁻⁵	< 10 ⁻⁸	3.3x10 ⁻⁵	5.9x10 ⁻⁵
	RF gun					2.1x10 ⁻⁶	
QE @ 266 nm	DC gun	3.7x10 ⁻²	2.6x10 ⁻³	9x10 ⁻³	2x10 ⁻⁵	2.3x10 ⁻²	1.6x10 ⁻³
	RF gun		1x10 ⁻⁶	5.7x10 ⁻⁵			
QE @ 213 nm					10 ⁻³	3.5x10 ⁻²	1.3x10 ⁻³
E _{max} MV/m		87	60	7	9	73	9

Ion bombardment cleaning and activation on GaAs photocathodes



9. Conclusion

GaAs requires different techniques compared to the Cs₂Te preparation with which we are familiar. We were not able with the available equipment to overcome the lack of:

- heating up to 600 °C with temperature control for UHV bake out.
- monitoring online using red or infra red light during cesium evaporation and oxidation.
- transferring the GaAs photocathode within a short time (< half an hour) from the photo-emission lab to the CTF RF gun.

However, the injection of low pressure oxygen inside the preparation chamber was finally achieved.

Electronic microscope observation of the test samples reveals no damage on the surface of the GaAs material, damage attributable to the ICE cleaning process or the 7 MV/m electric field in the DC gun.