A comparative study of oxygenated and un-oxygenated Si diodes, miniature and large area microstrip detectors.

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OUTLINE:

- Oxygenation technique of silicon wafers by High Temperature Diffusion from a SiO_2 layer
- Results of N_{eff} (V_{FD}) vs fluence for control and oxygenated diodes.
- Results in term of CCE for control and oxygenated diodes.
- Results of oxygenated and control diodes from Micron Semiconductor.
- Feasibility of large area microstrip detectors with HTD oxygen enriched silicon: ATLAS SCT detectors made by Micron.
- Results after irradiation in term of I-V, C-V and interstrip capacitance: large area and miniature detectors.
- Results in term of CCE, from light spot (1064 nm laser) and fast electrons (^{106}Ru source).
- Comparison of CCE between oxygenated, control and thin Hamamatsu irradiated detectors. Normalisation to the preirradiation value.

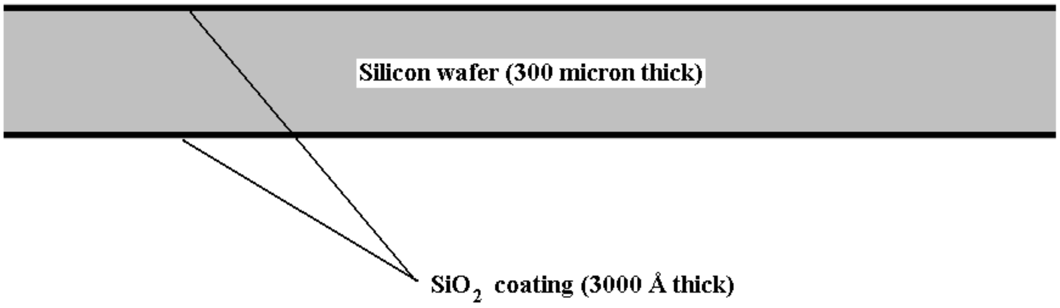
Oxygenation technique of silicon wafers by High Temperature Diffusion from a SiO_2 surface layer.

The isotropic diffusion process is described in term of diffusion coefficient D, as defined by the first Fick's law: $\bar{j} = -D\nabla N$

where N is the impurity concentration. The silicon devices are plane and parallel structures, therefore the analysis can be limited to the simple one dimensional case. $\frac{\partial N}{\partial T} = D\frac{\partial^2 N}{\partial x^2}$

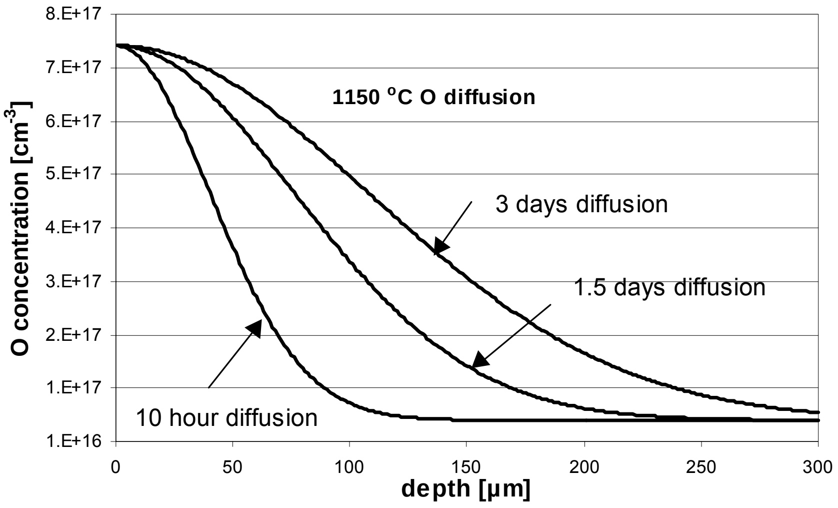
Solution in the case of diffusion from a surface layer of Oxygen acting as an infinite source: $N(x,t) = \frac{N_0}{2}\left[erfc\left(\frac{x-h}{2\sqrt{Dt}}\right) - erfc\left(\frac{x+h}{2\sqrt{Dt}}\right)\right]$.

where h is the depth of the initial impurity distribution.



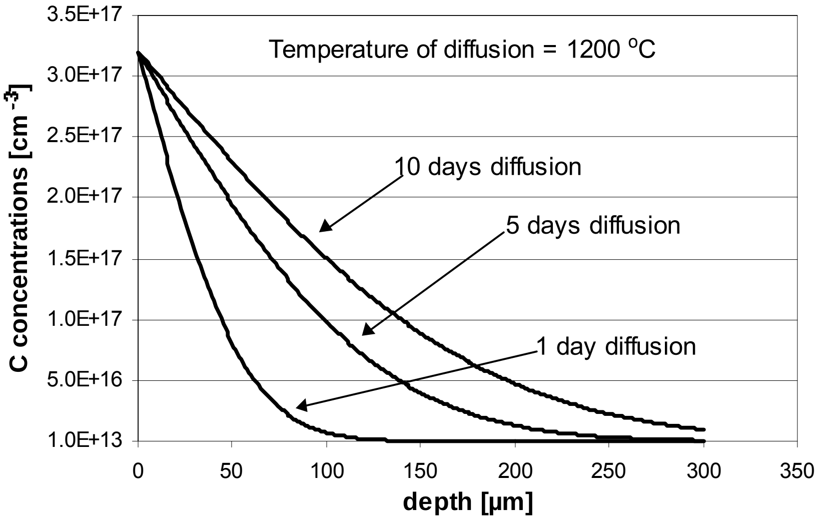
Diffusion atmosphere: N_2 or O_2 (no advantages using O_2)

Calculated oxygen diffusion profile @ 1150 °C using the diffusion coefficient: $2.25 \cdot 10^{-10}$ cm^2 s^{-1} (obtained from fit on SIMS profile, Ref. G. Casse, 1998).



CARBON diffusion

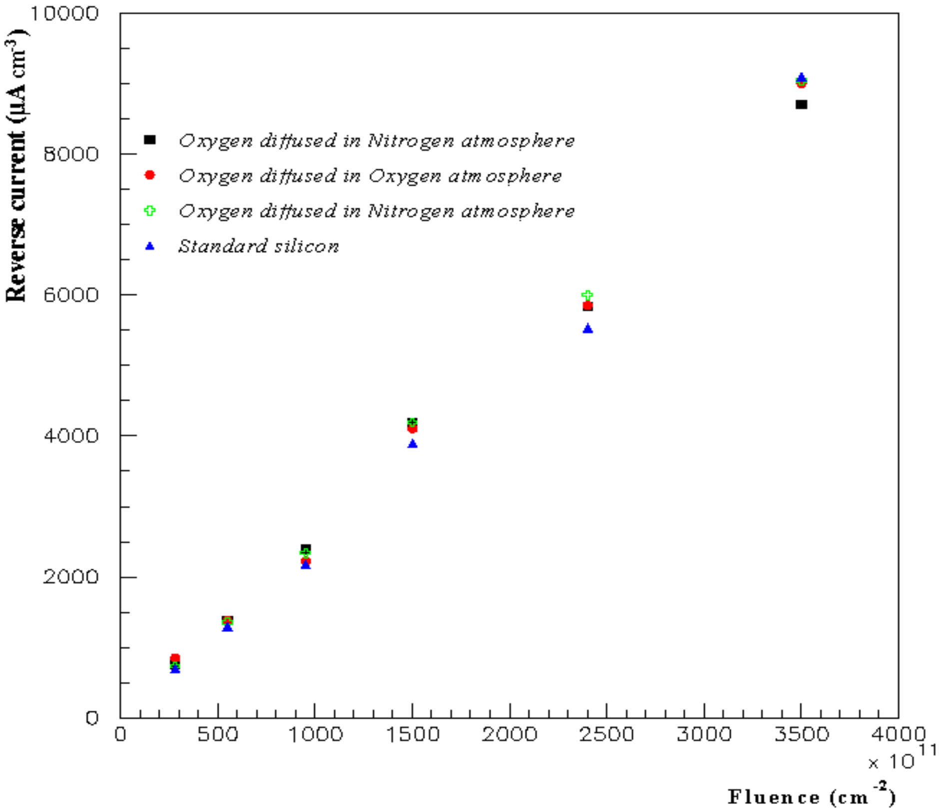
Carbon is in competition with oxygen in term of beneficial effects on radiation hardness of silicon detectors.
The diffusion of carbon is ~ 10 times slower than oxygen (carbon diffusion coefficient is $3.38 \cdot 10^{-11}$ cm^{2} s^{-1} (from Properties of silicon, INSPEC, The Institution of electrical Engineers, London and New York, 1998. The same source compiles oxygen diffusion coefficients ranging from $1.60 \cdot 10^{-10}$ to $5.60 \cdot 10^{-10}$ cm^{2} s^{-1})



Leakage current versus fluence for oxygenated and un-oxygenated silicon diodes.

The increase of the leakage current is a linear function of the fluence. The current is proportional to the concentration of radiation induced defects. The reverse volume current is measured using irradiated diodes biased above full depletion. Silicon materials with different (deliberately introduced) impurity concentrations do not show differences in the slope of the volume current with fluence. In the LHC experiments, these high currents will be reduced by cooling the detectors.

Normalised to 20 °C



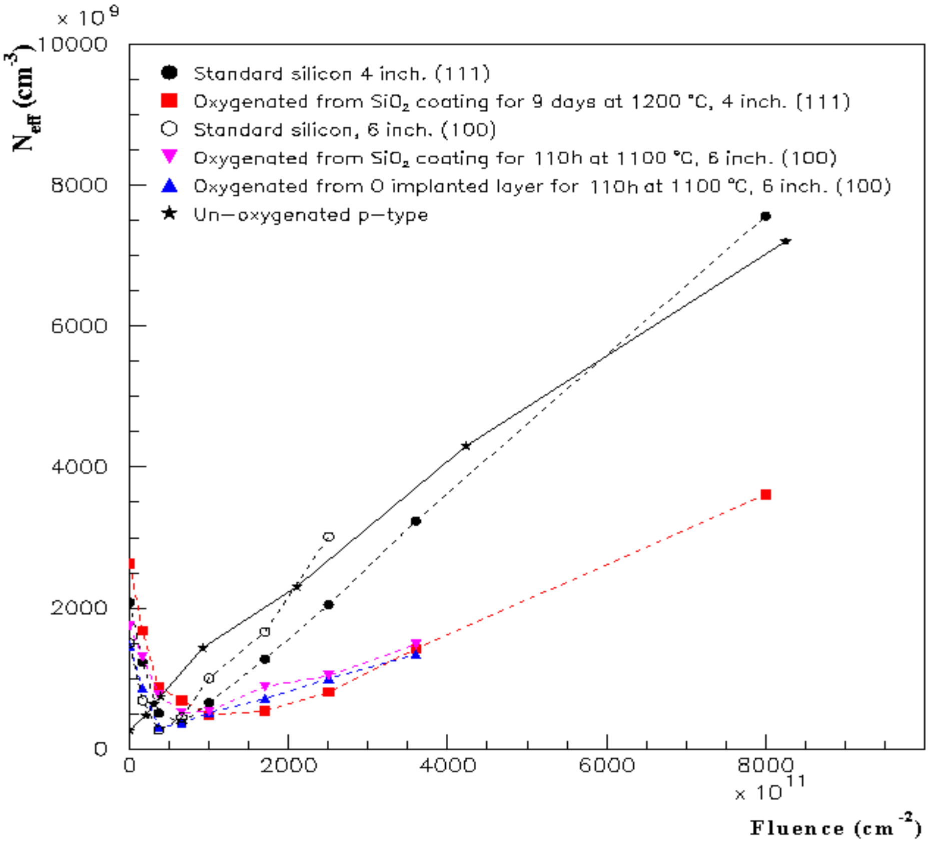
The introduction of high oxygen concentrations in the silicon bulk does not affect the increase of the leakage current with fluence

The effective doping concentration (N_{eff}) versus fluence for oxygenated and un-oxygenated silicon diodes.

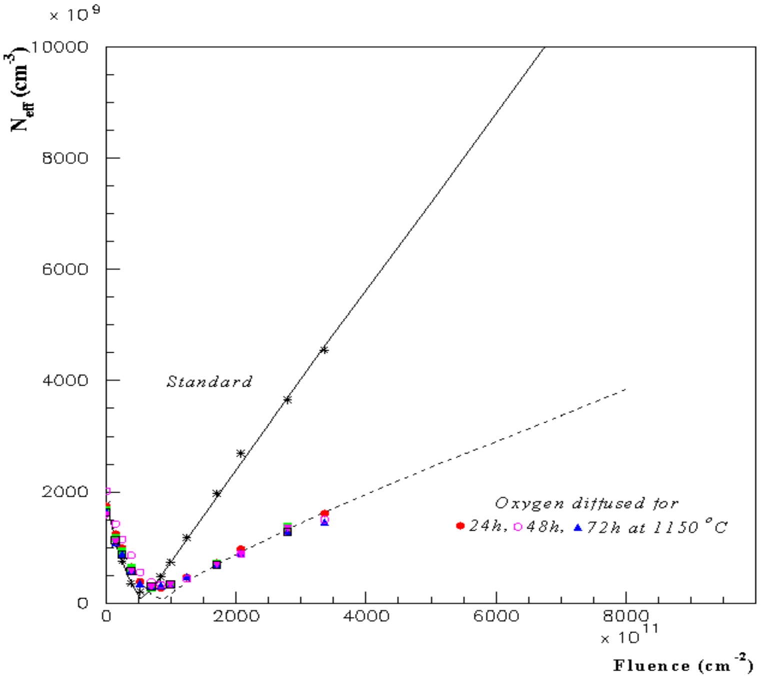
p-in-n detectors must be operated above full depletion to allow good signal/noise ratio. The full depletion voltage of silicon detectors is proportional to the effective doping concentration, which becomes more p-type as a consequence of the hadron irradiation. After heavy doses, N_{eff} is dominated by the concentration of the radiation induced p-type defects.

A high oxygen concentration ($>10^{17}$ cm^{-3}) in the silicon bulk reduces the effective introduction rate of acceptor-like defects and therefore the required detector bias after high doses.

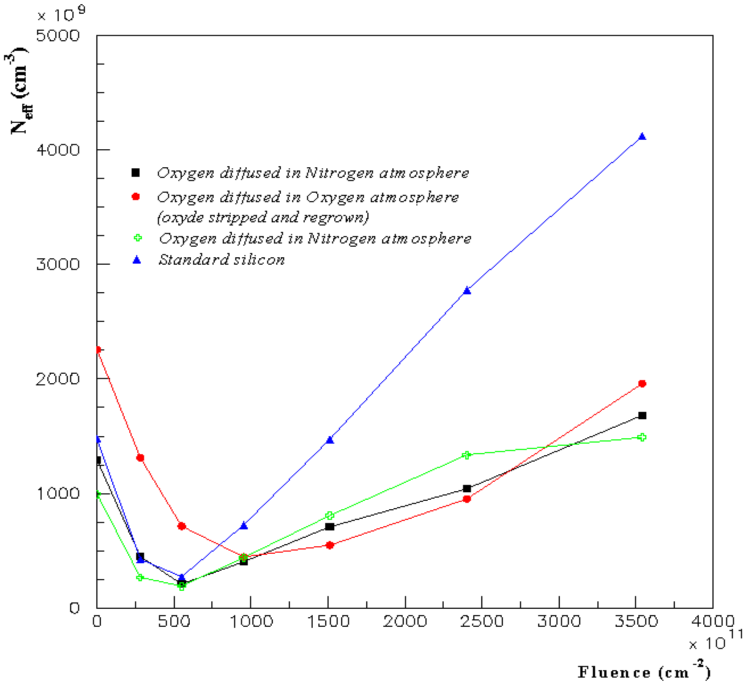
In all the following figures the diodes have been annealed at 80 °C for 4 minutes to just complete the beneficial annealing phase.



At high doses, N_{eff} is similar for un-oxygenated p-type or n-type starting materials, being dominated by the radiation induced defects. The oxygenated n-type silicon diodes show a substantially lower N_{eff} after high doses.



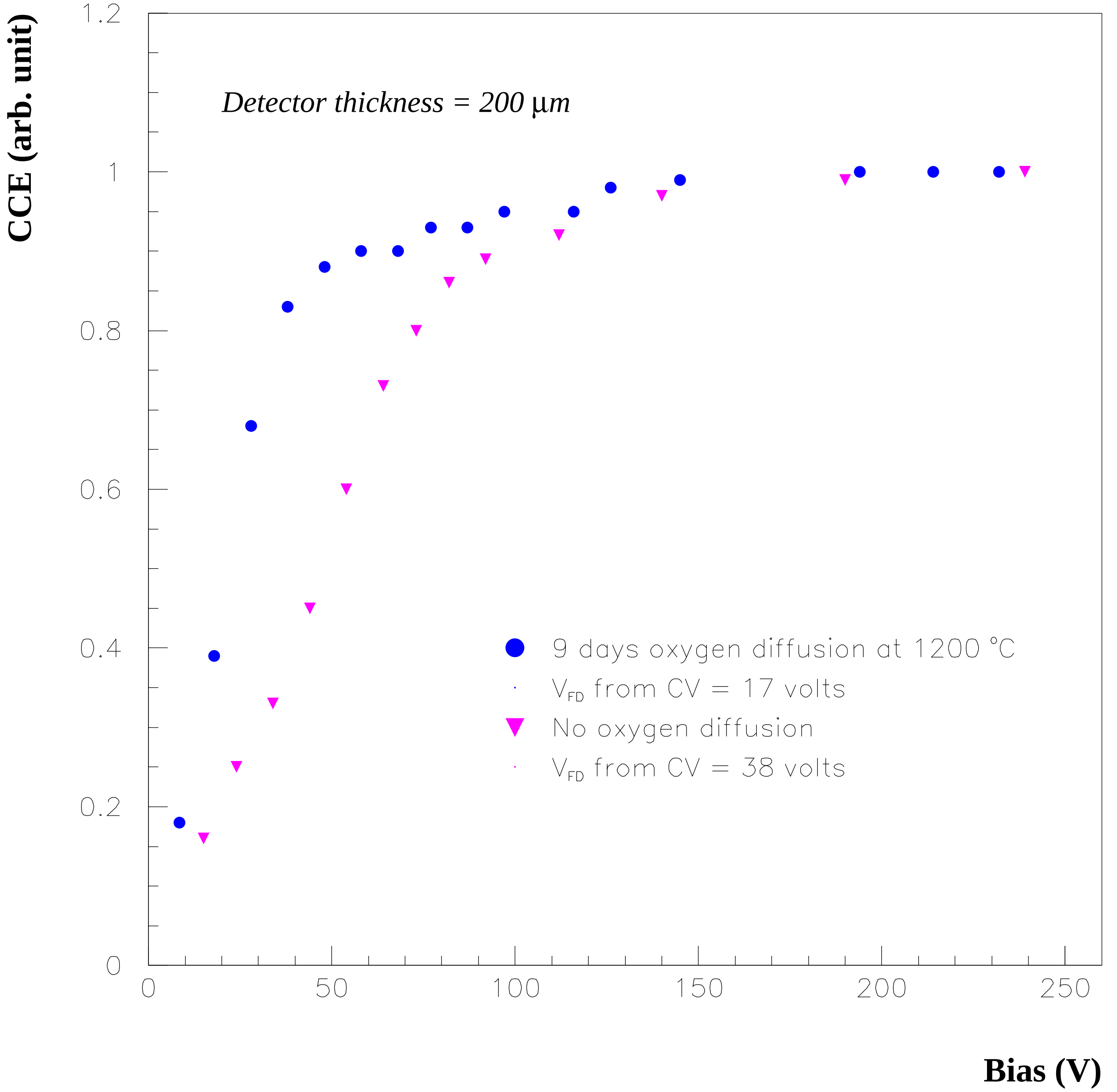
Diodes produced with silicon wafers submitted to high temperature oxygen diffusion for different times show very similar behaviours. They are here compared with diodes made from an un-oxygenated silicon wafer from the same ingot.



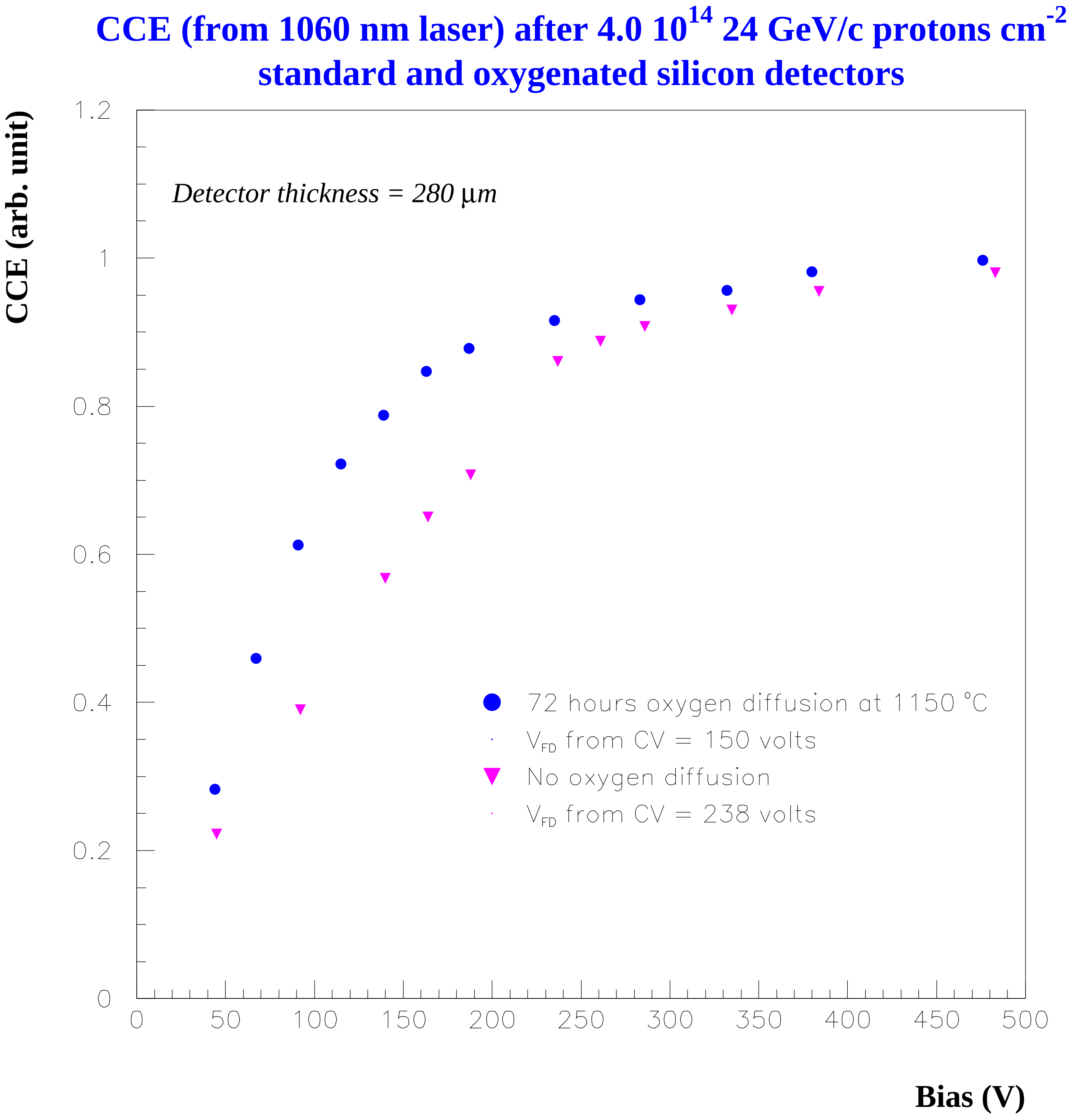
N_{eff} as a function of fluence for un-oxygenated and oxygenated n-type diodes with oxygen diffusion in different atmospheres.

BNL diodes. CCE normalised to the value @ 250 V.

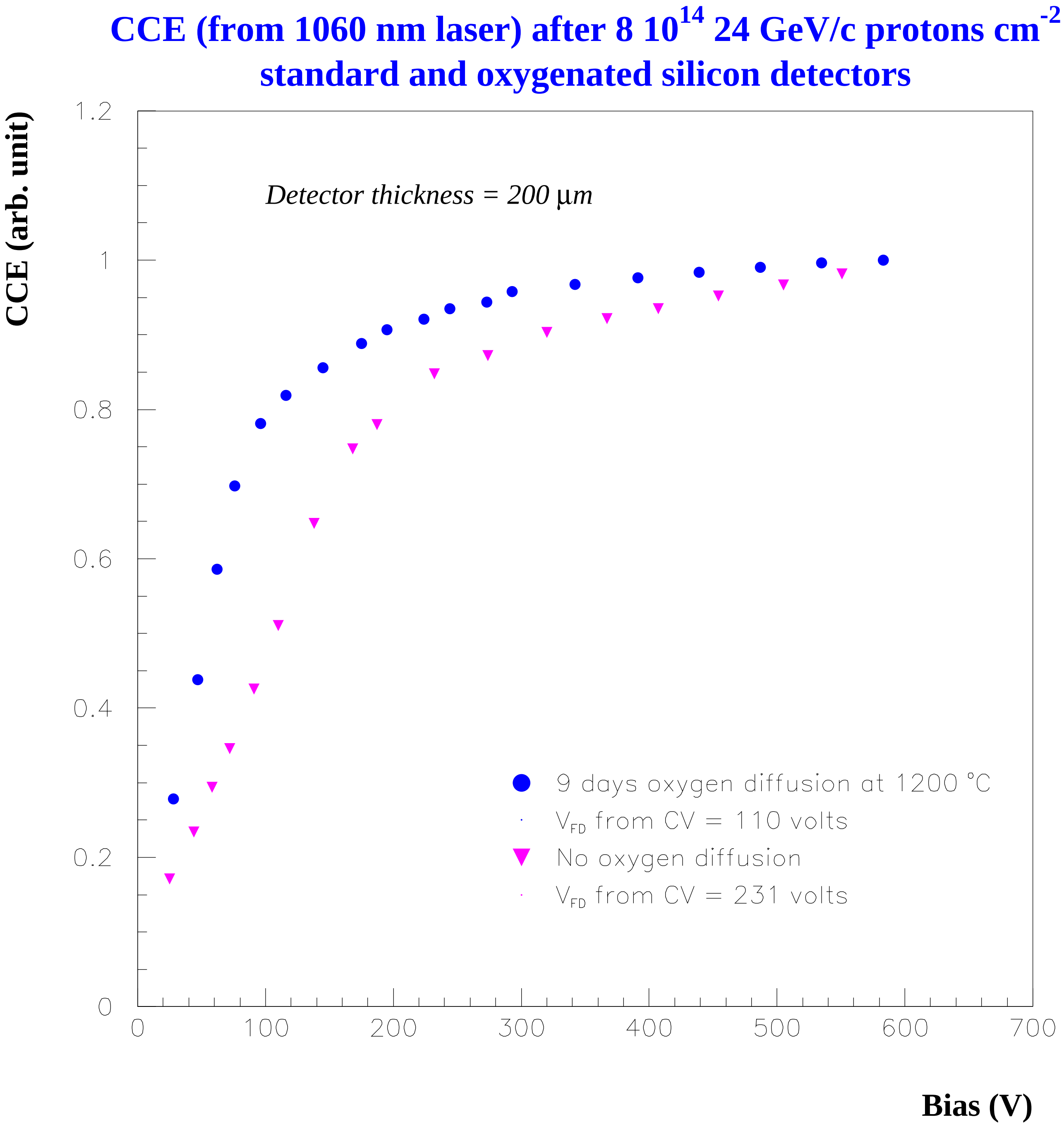
CCE (from 1060 nm laser) after 1.7 10^{14} 24 GeV/c protons cm^{-2}
standard and oxygenated silicon detectors

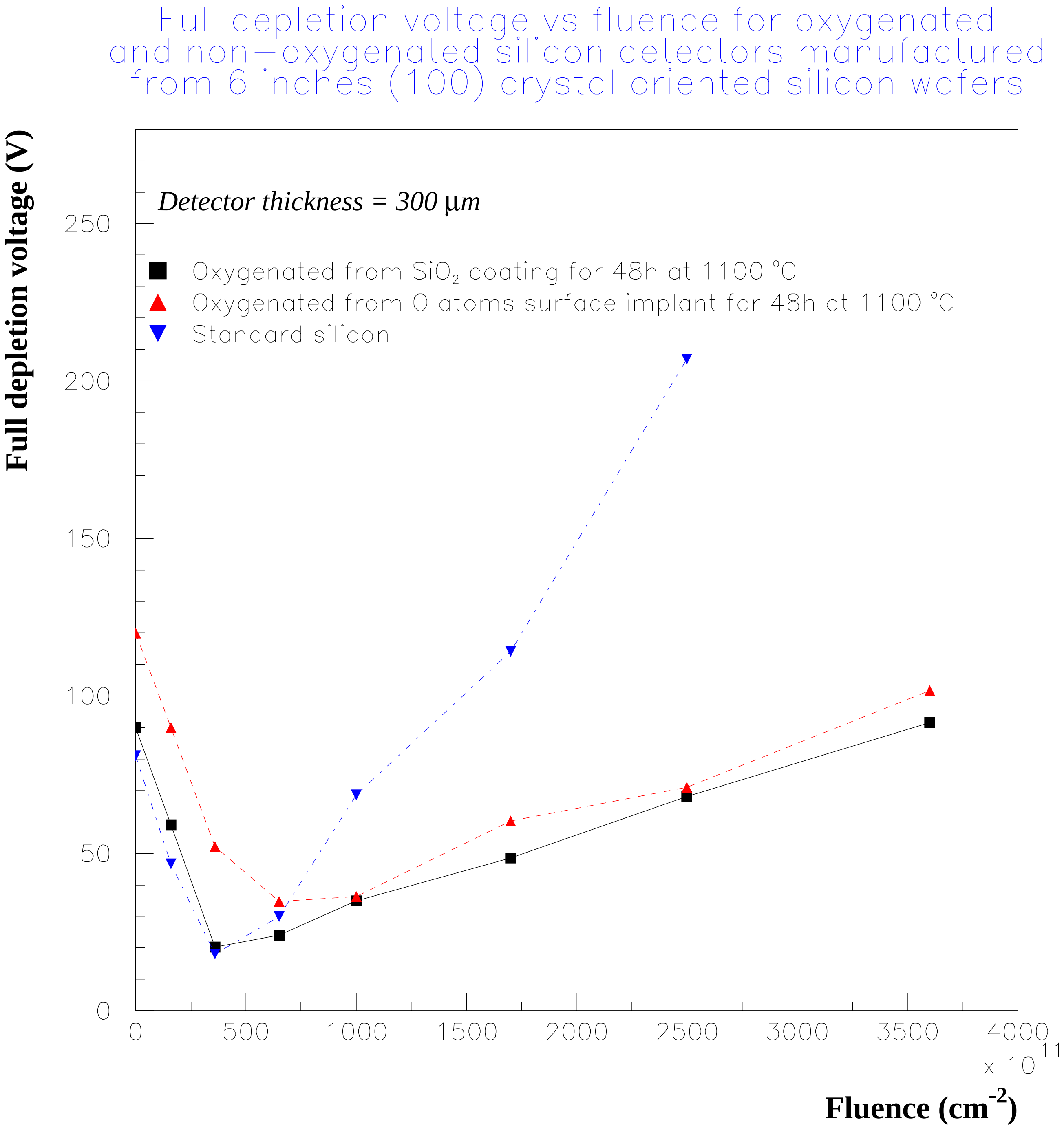


ITME diodes. CCE normalised to the value @ 500V.



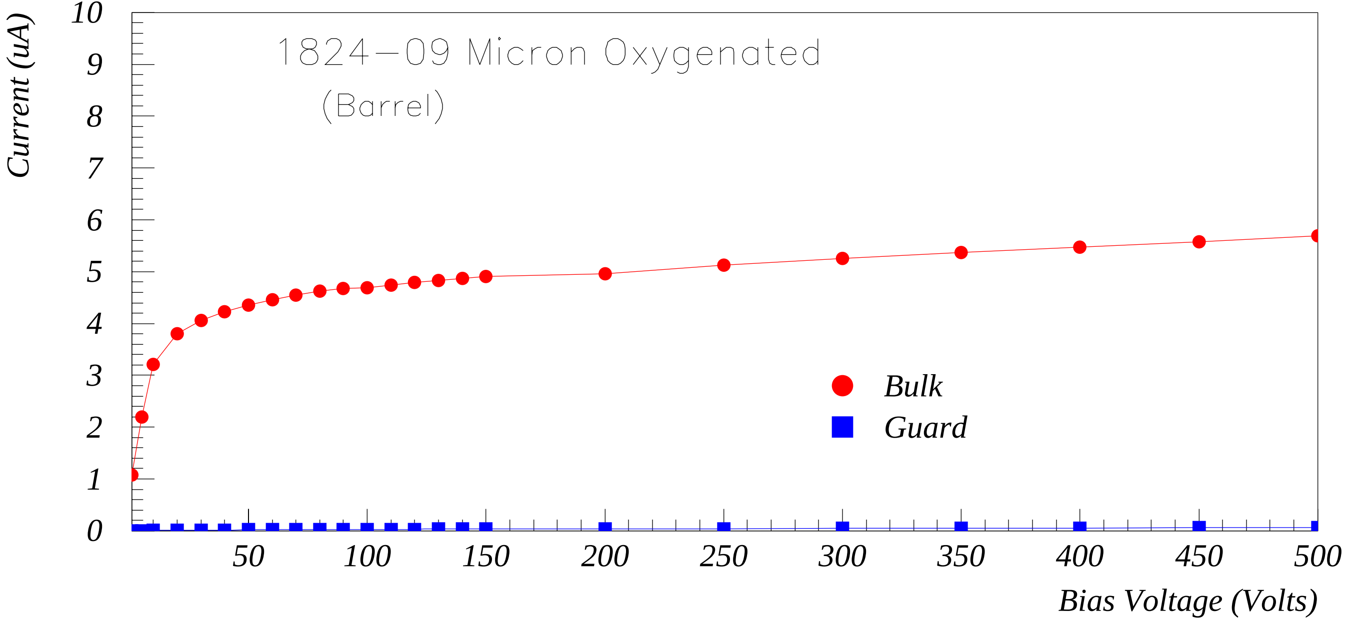
BNL diodes. CCE normalised to the value @ 600 V

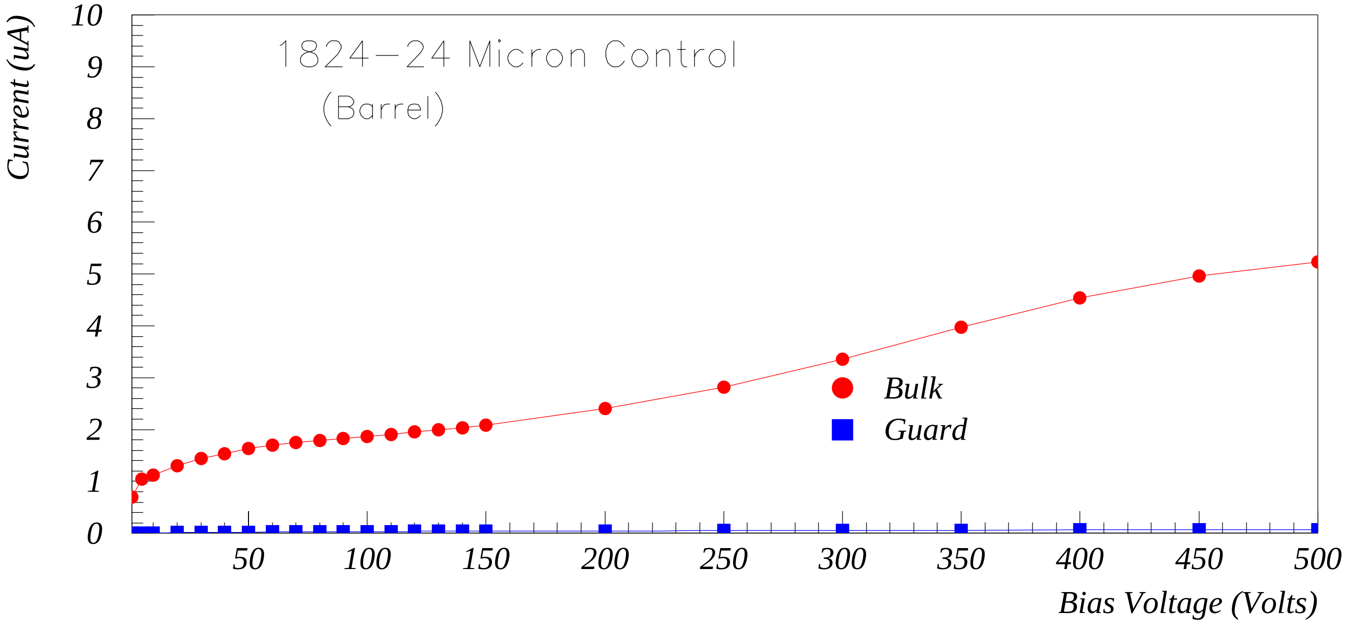


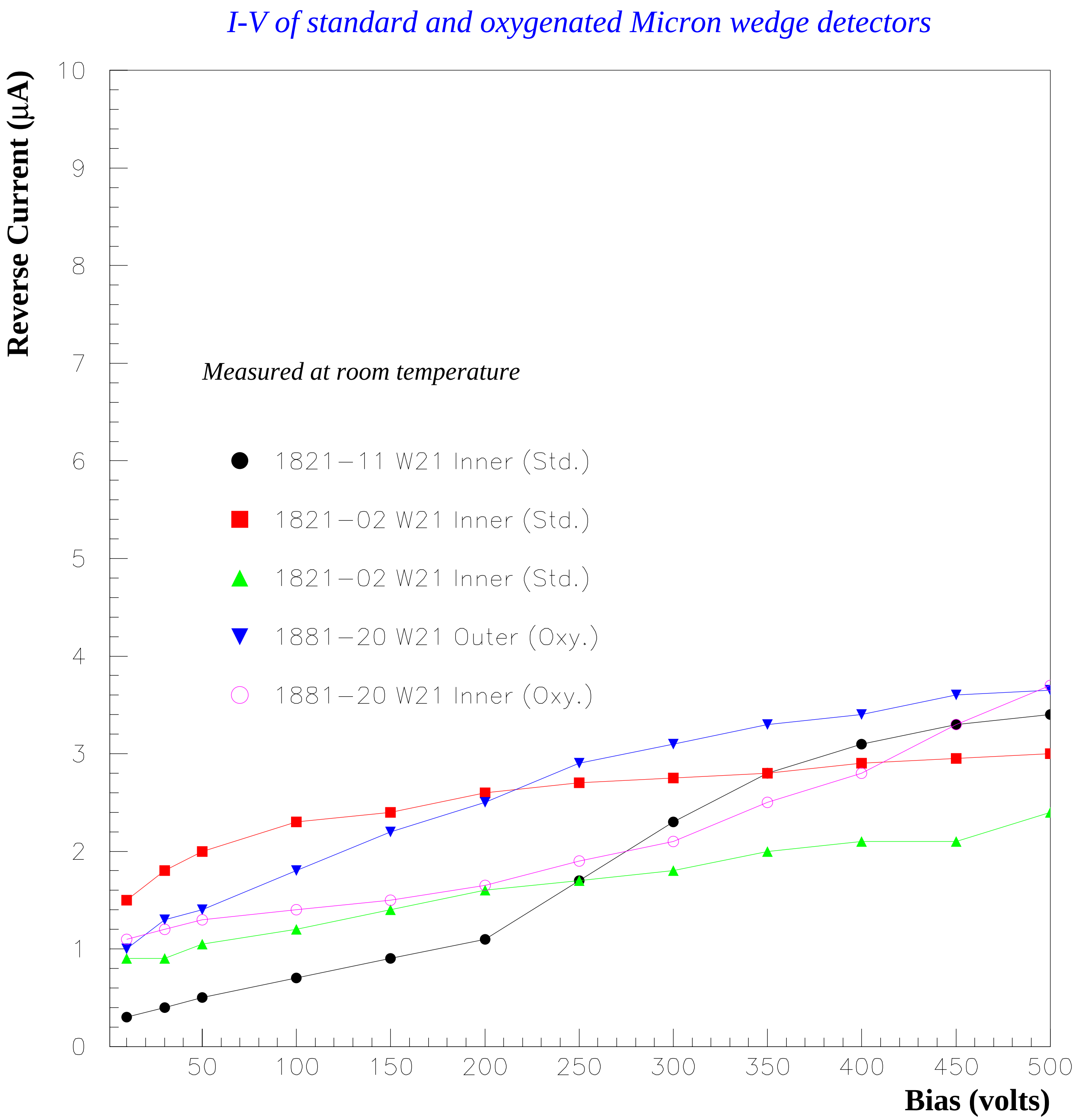


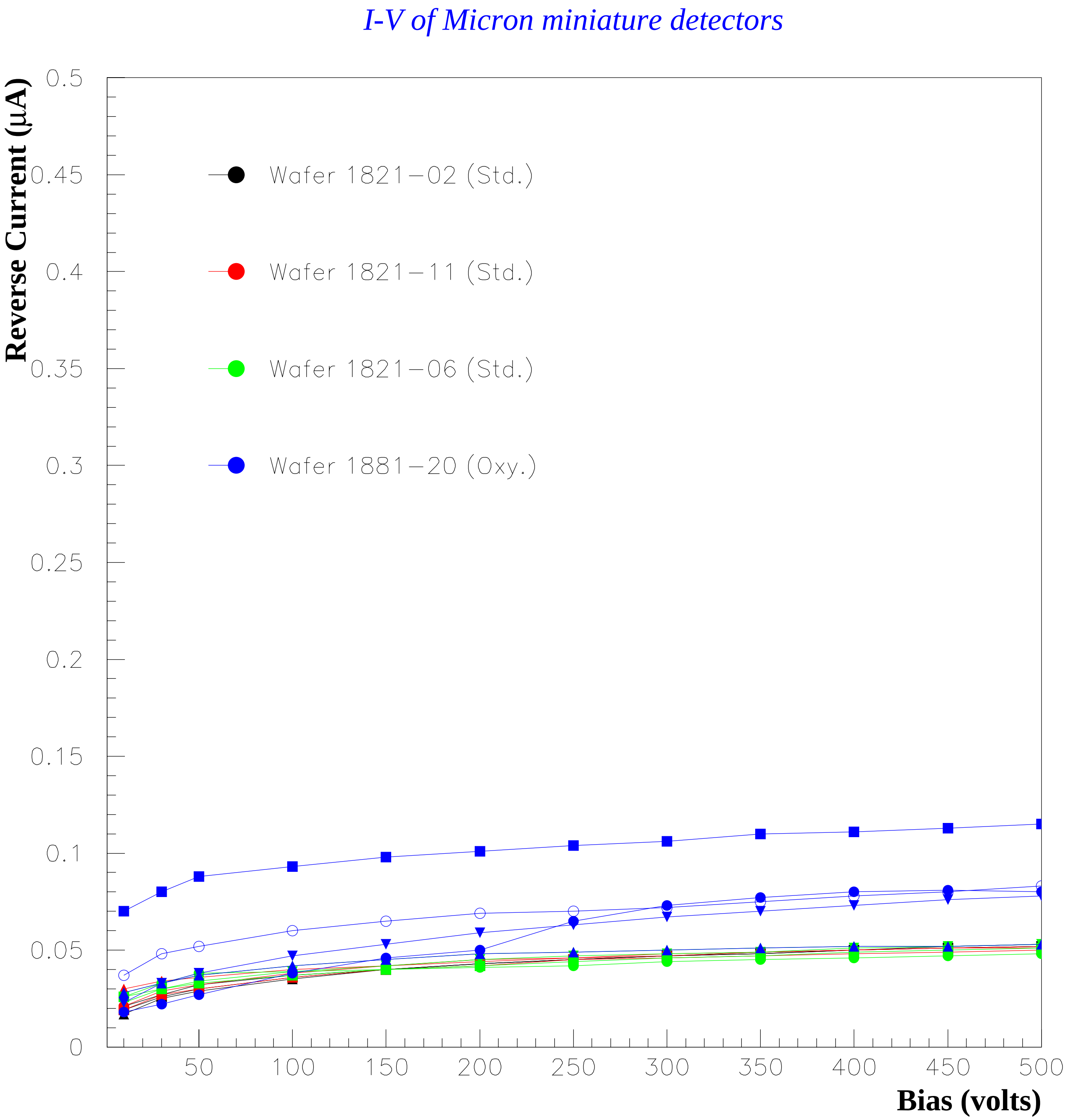
Full depletion voltage vs fluence for oxygenated and non–oxygenated silicon detectors manufactured from 6 inches (100) crystal oriented silicon wafers

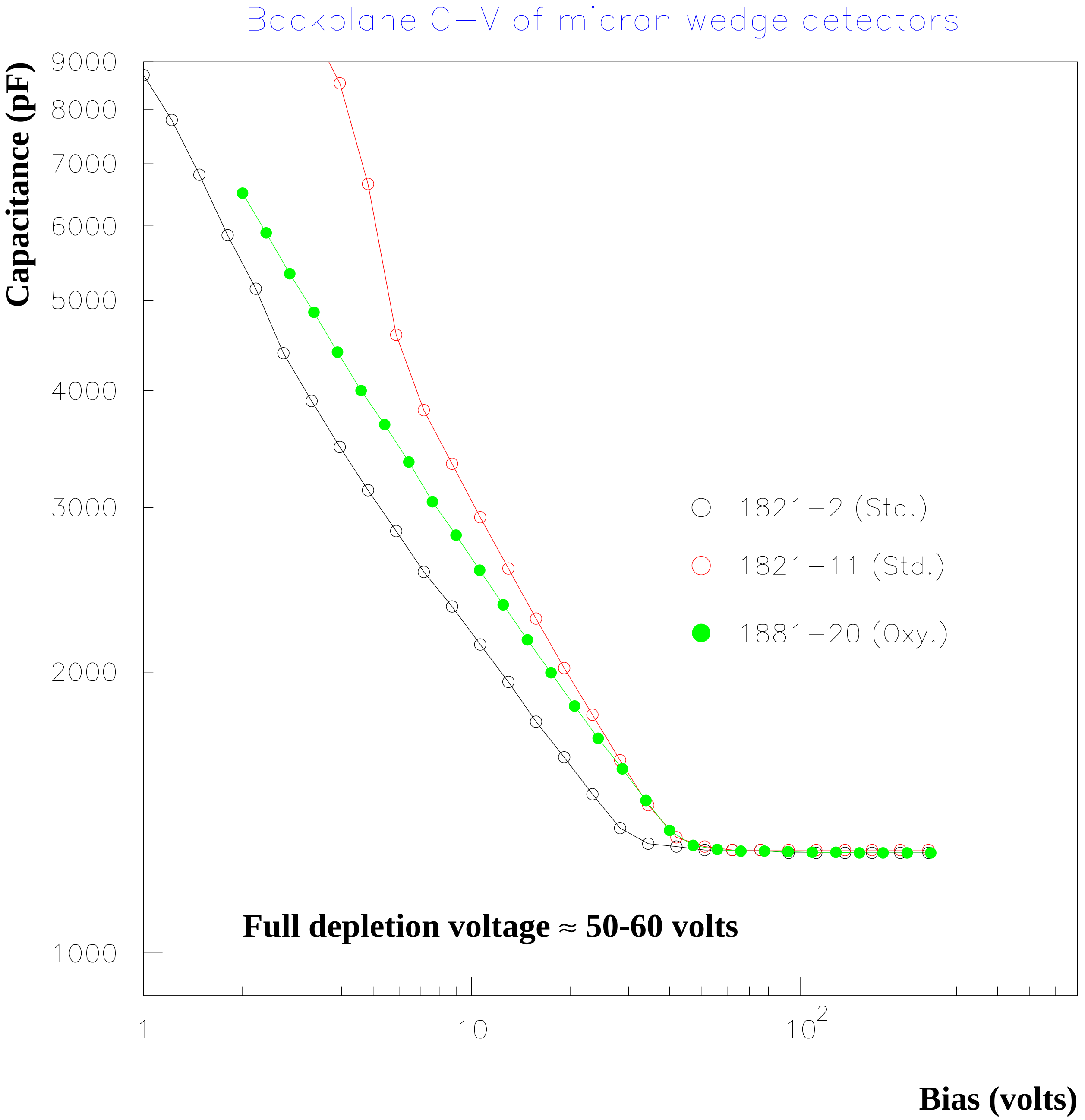
Micron Oxygenated Barrel

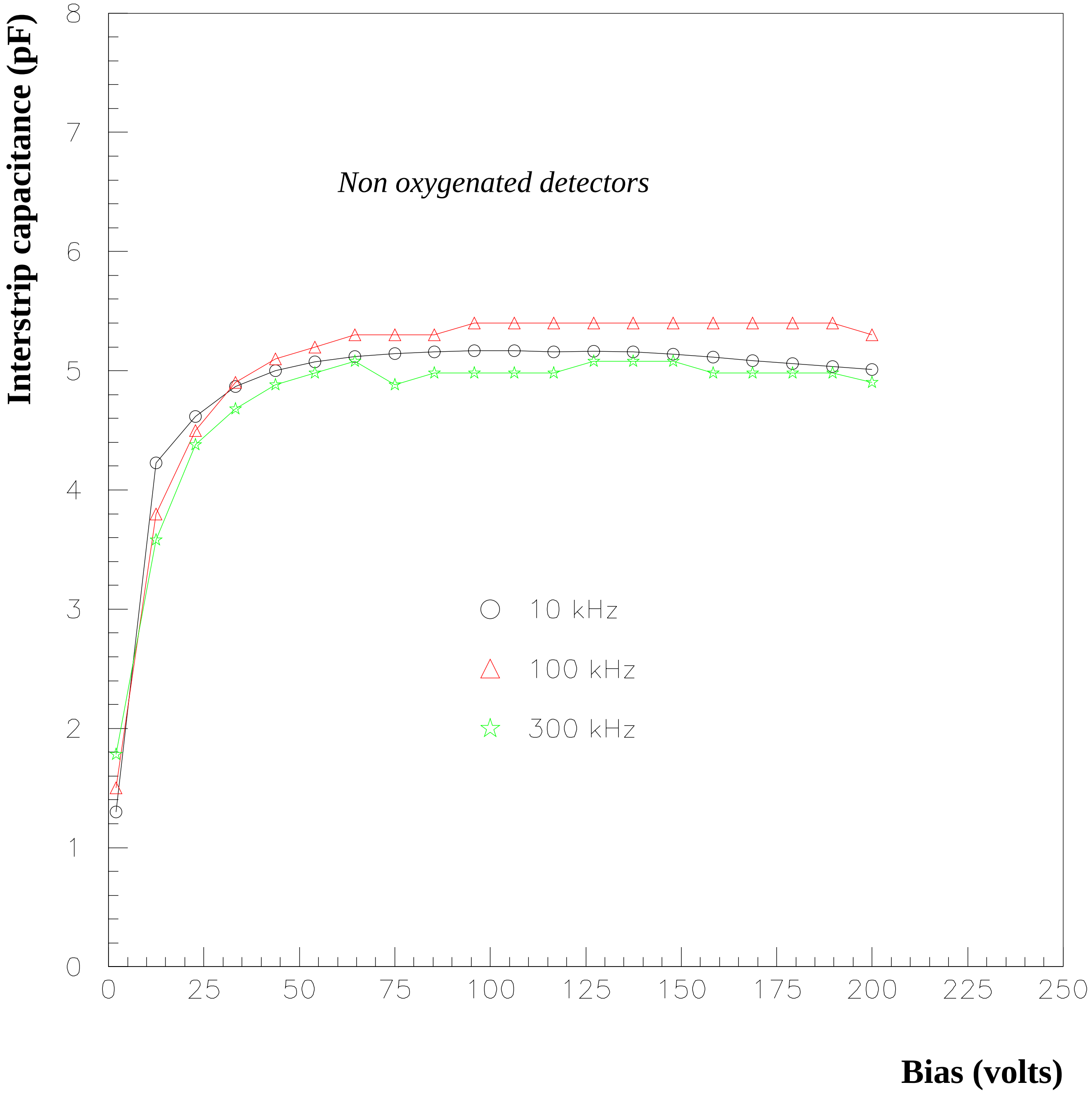





I-V of standard and oxygenated Micron wedge detectors
Reverse Current (μA)
0
1
2
3
4
5
6
7
8
9
10
Measured at room temperature
● 1821–11 W21 Inner (Std.)
■ 1821–02 W21 Inner (Std.)
▲ 1821–02 W21 Inner (Std.)
▼ 1881–20 W21 Outer (Oxy.)
○ 1881–20 W21 Inner (Oxy.)
50
100
150
200
250
300
350
400
450
500
Bias (volts)

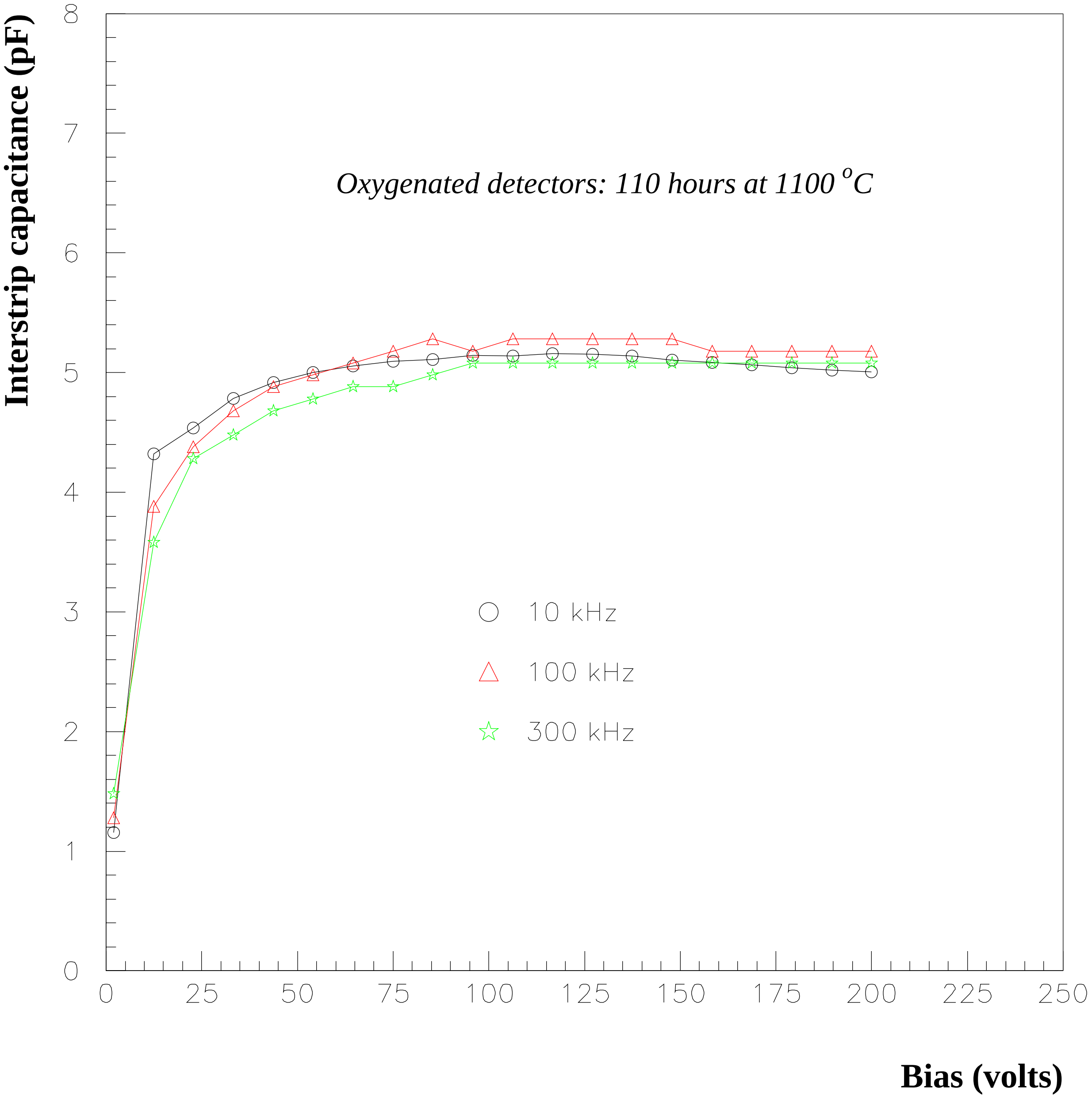

I-V of Micron miniature detectors
Reverse Current (μA)
Bias (volts)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
50
100
150
200
250
300
350
400
450
500
Wafer 1821−02 (Std.)
Wafer 1821−11 (Std.)
Wafer 1821−06 (Std.)
Wafer 1881−20 (Oxy.)


Backplane C–V of micron wedge detectors
Capacitance (pF)
9000
8000
7000
6000
5000
4000
3000
2000
1000
1
10
10^2
Bias (volts)
○ 1821–2 (Std.)
○ 1821–11 (Std.)
● 1881–20 (Oxy.)
Full depletion voltage ≈ 50-60 volts

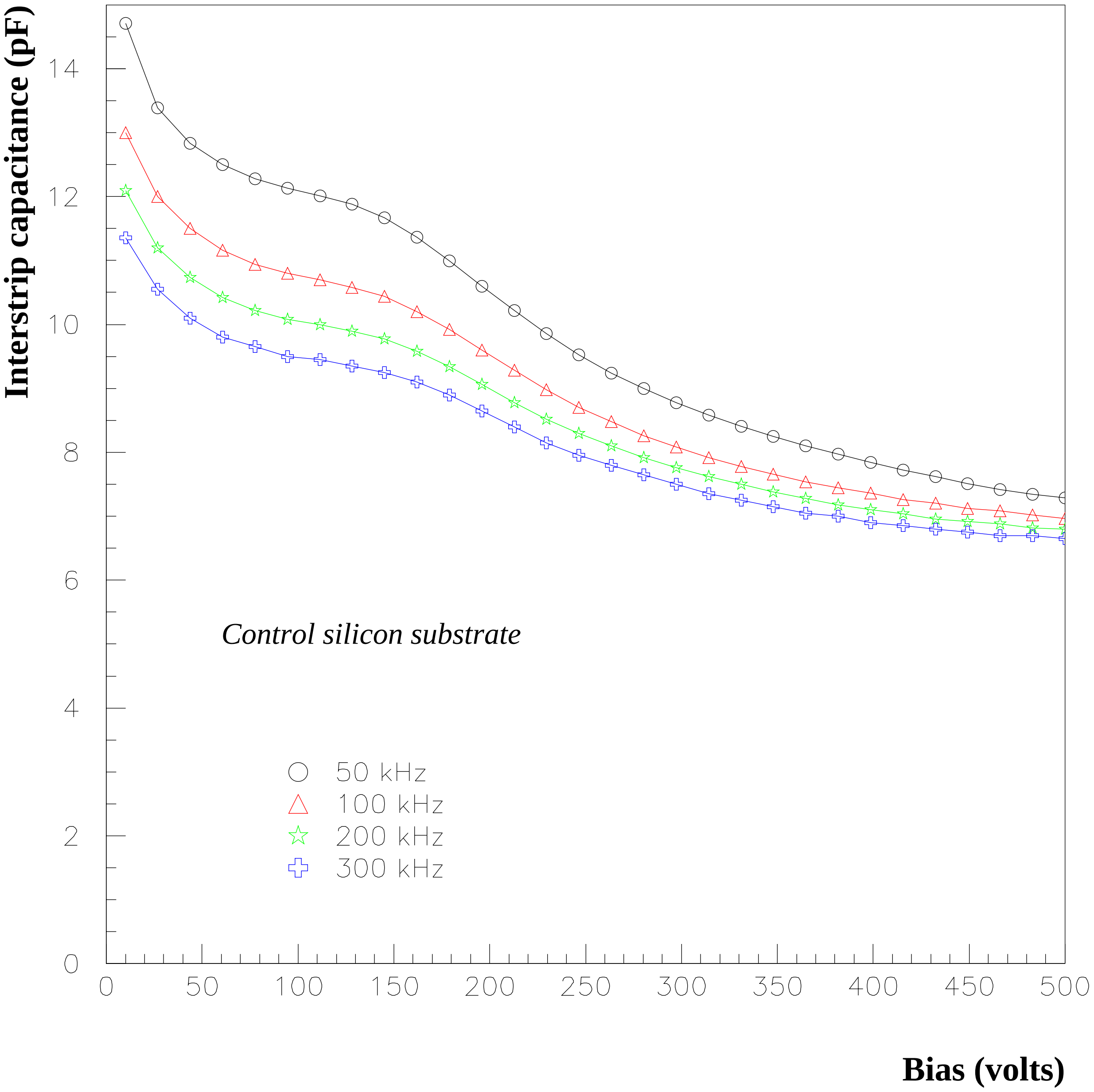


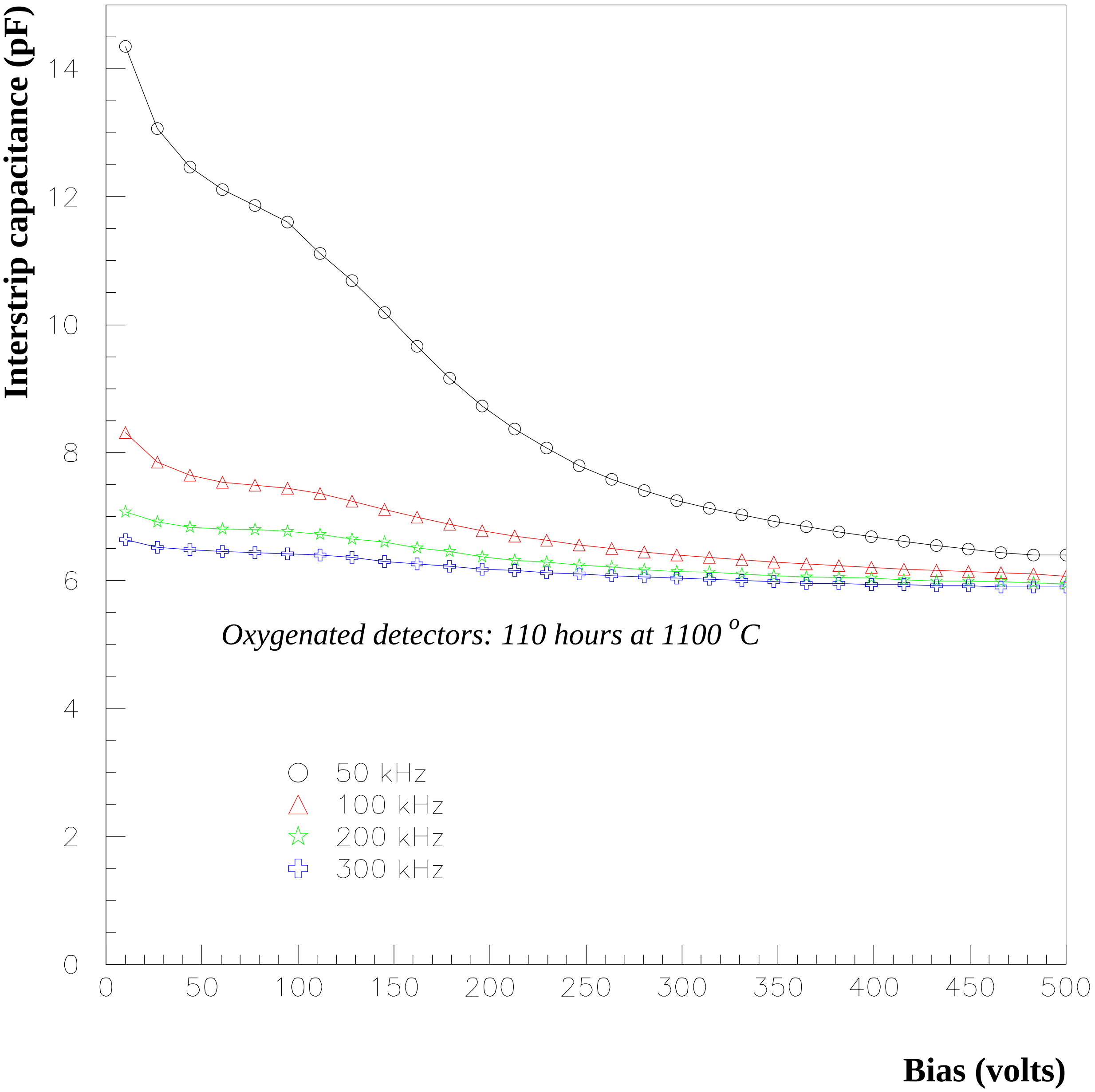
Interstrip capacitance (1st and 2nd neighbours each side) non irradiated detectors, 4 inch. (111) wafers

Interstrip capacitance (1st and 2nd neighbours each side) non irradiated detectors, 4 inch. (111) wafers



Interstrip capacitance (1^{st} and 2^{nd} neighbours each side)
after 3 10^{14} p cm^{-2}, non-oxyg. detectors, 4 inch. (111) wafers

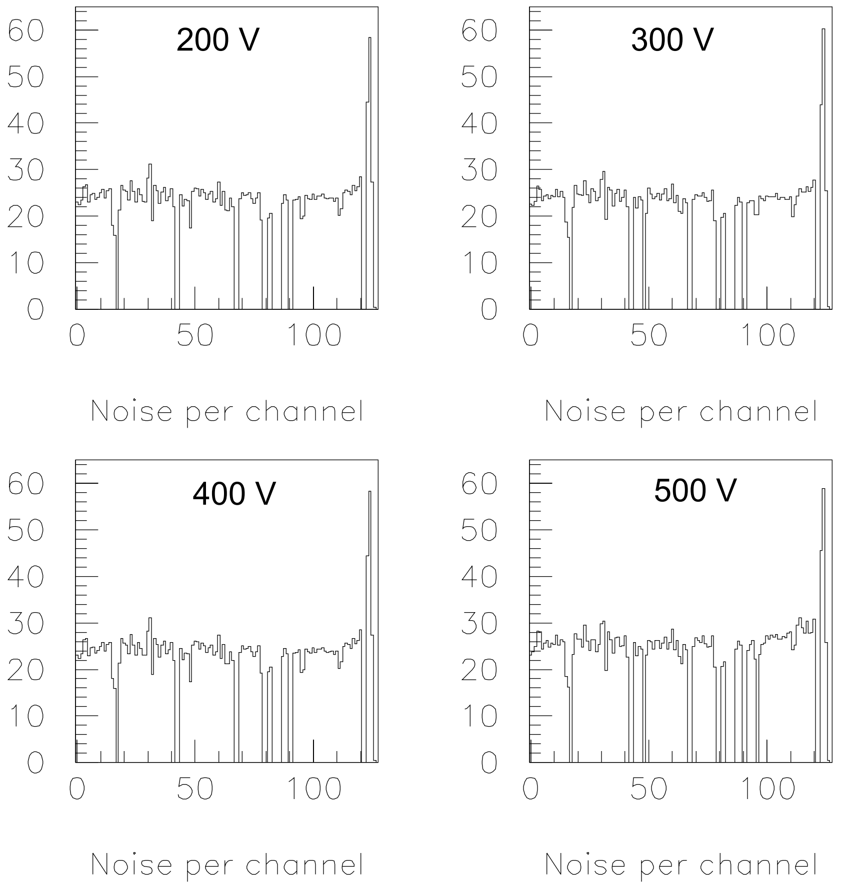




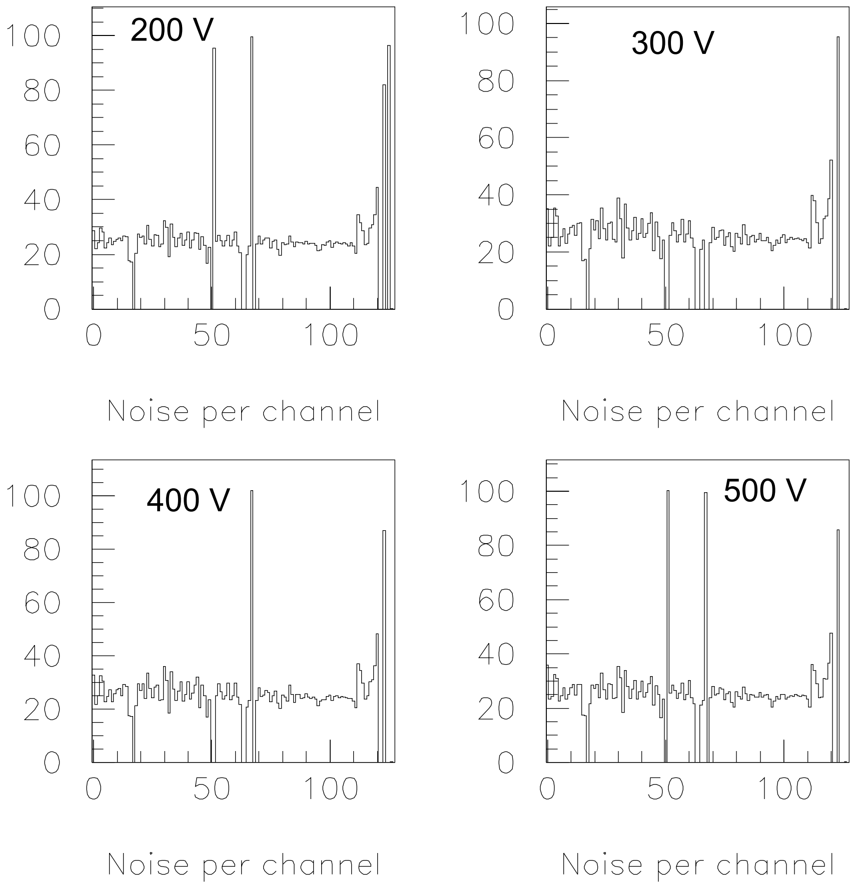
Interstrip capacitance (1^{st} and 2^{nd} neighbours each side) after $3\ 10^{14}$ p cm^{-2}, oxy. detectors, 4 inch. (111) wafers

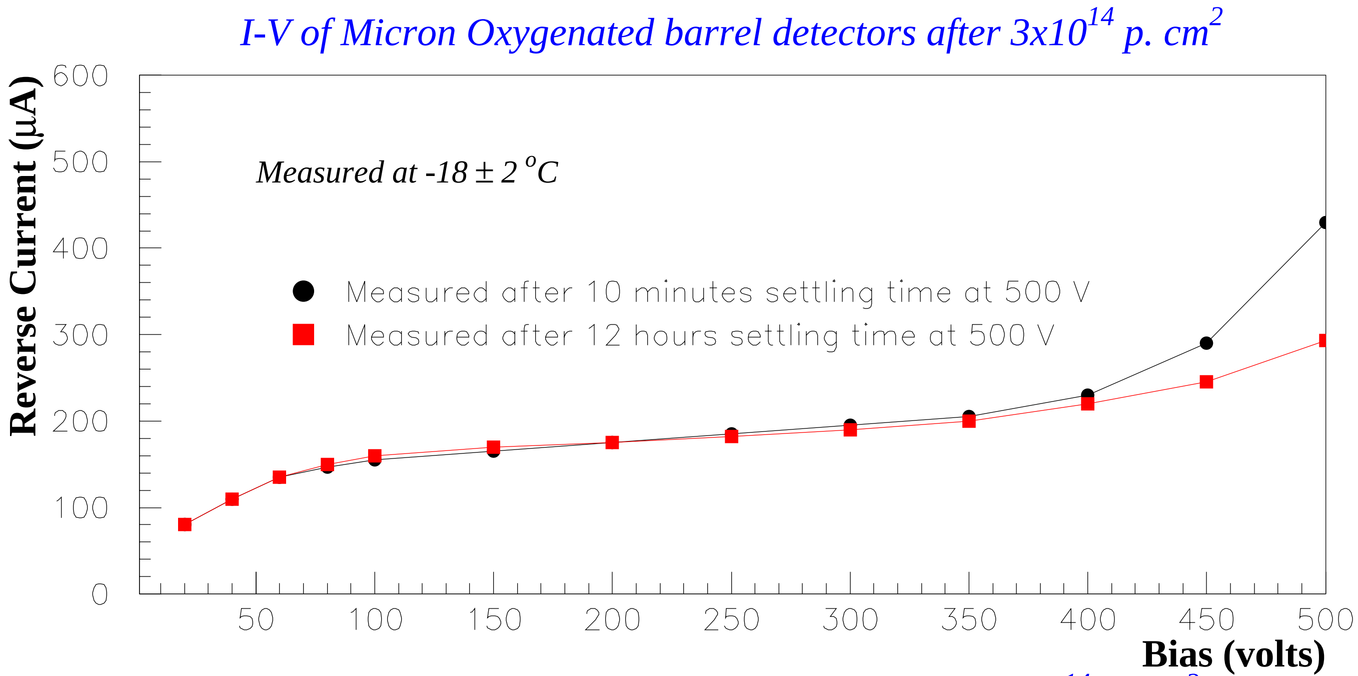
Oxygenated detectors: 110 hours at 1100 ^{o}C

Non-oxygenated

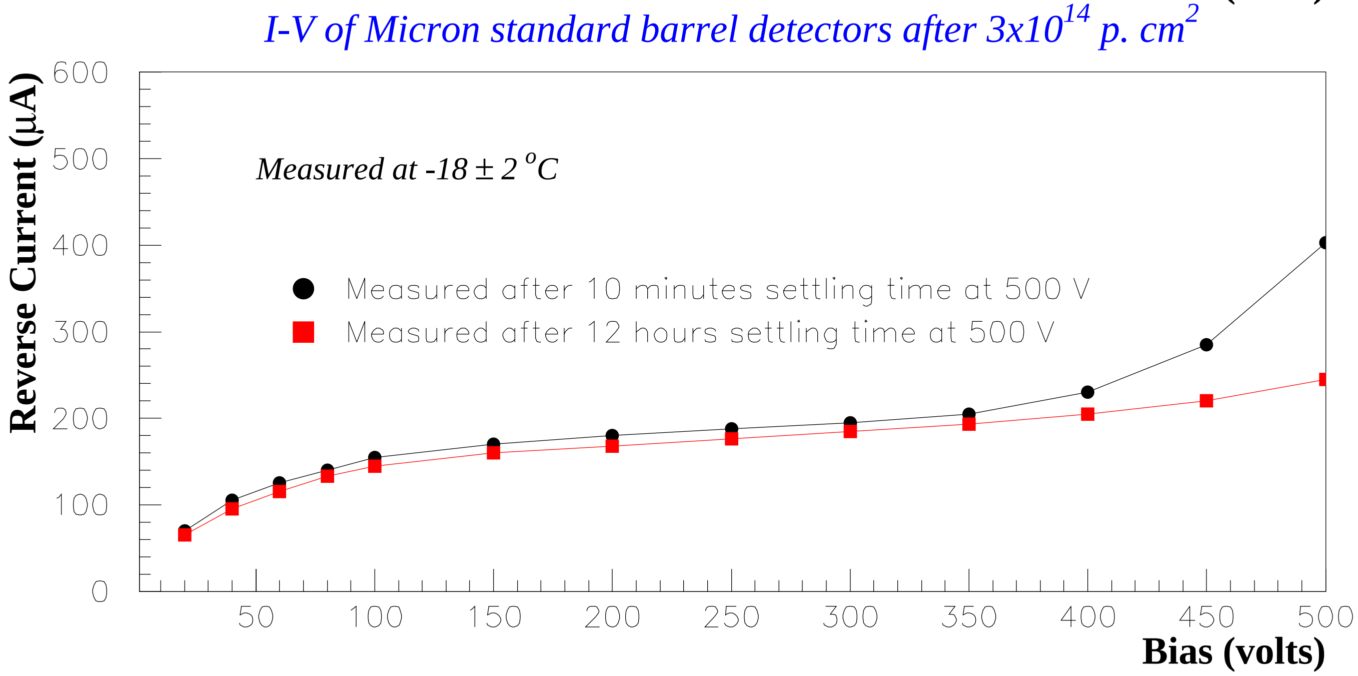


Oxygenated

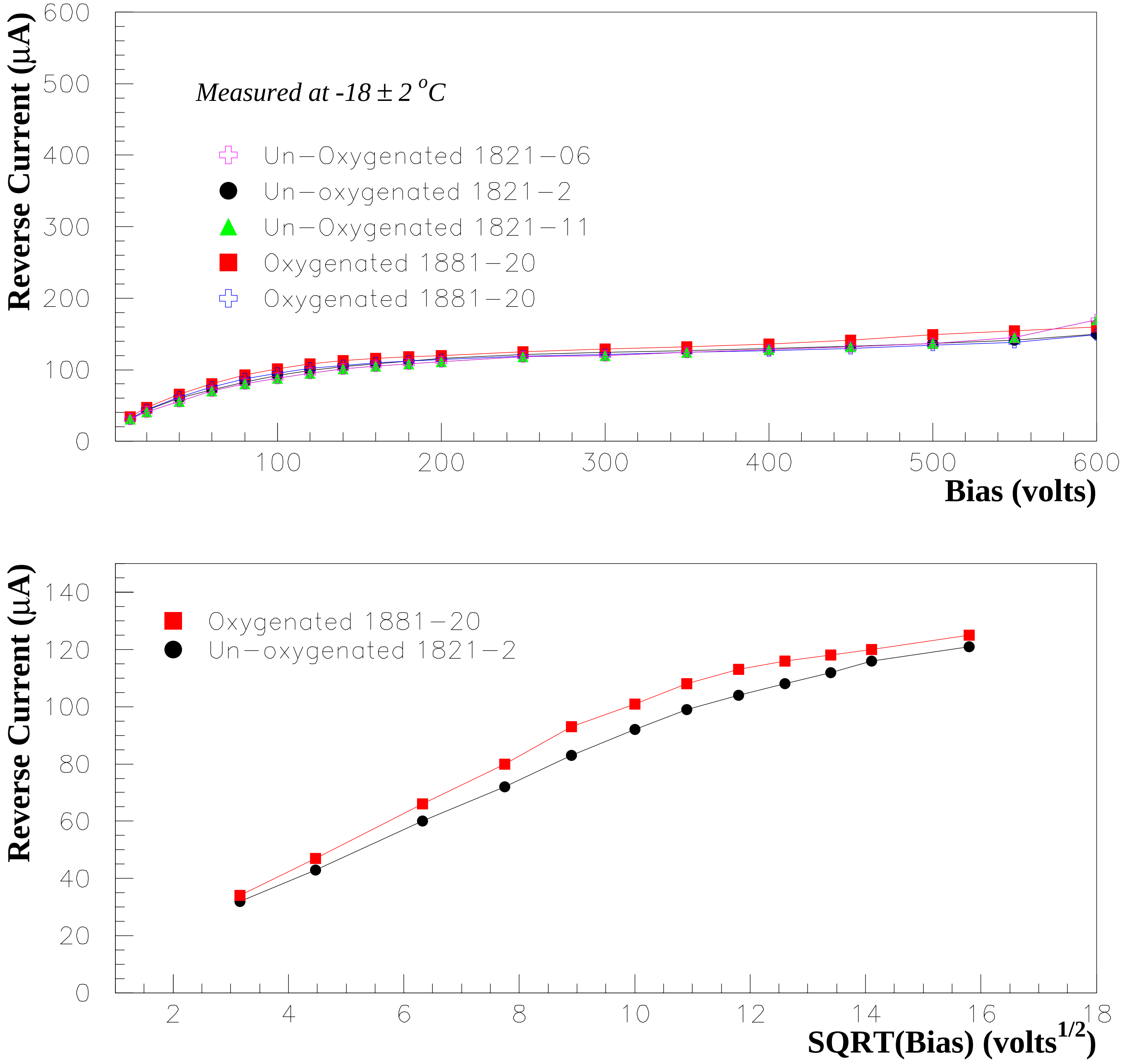




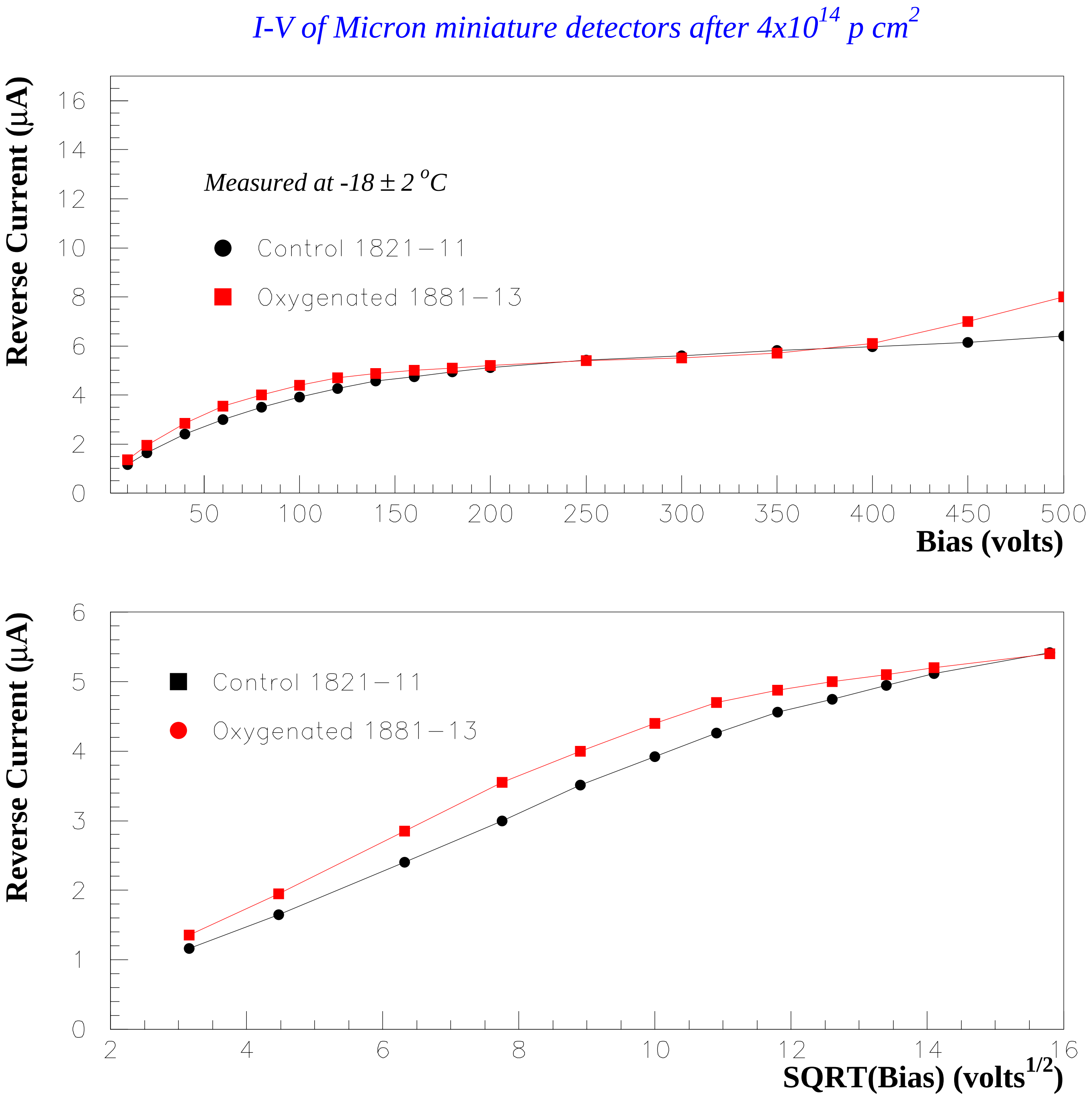
I-V of Micron Oxygenated barrel detectors after 3x10^14 p. cm^2
Reverse Current (μA)
600
500
400
300
200
100
0
Measured at -18 ± 2 °C
● Measured after 10 minutes settling time at 500 V
■ Measured after 12 hours settling time at 500 V
50
100
150
200
250
300
350
400
450
500
Bias (volts)

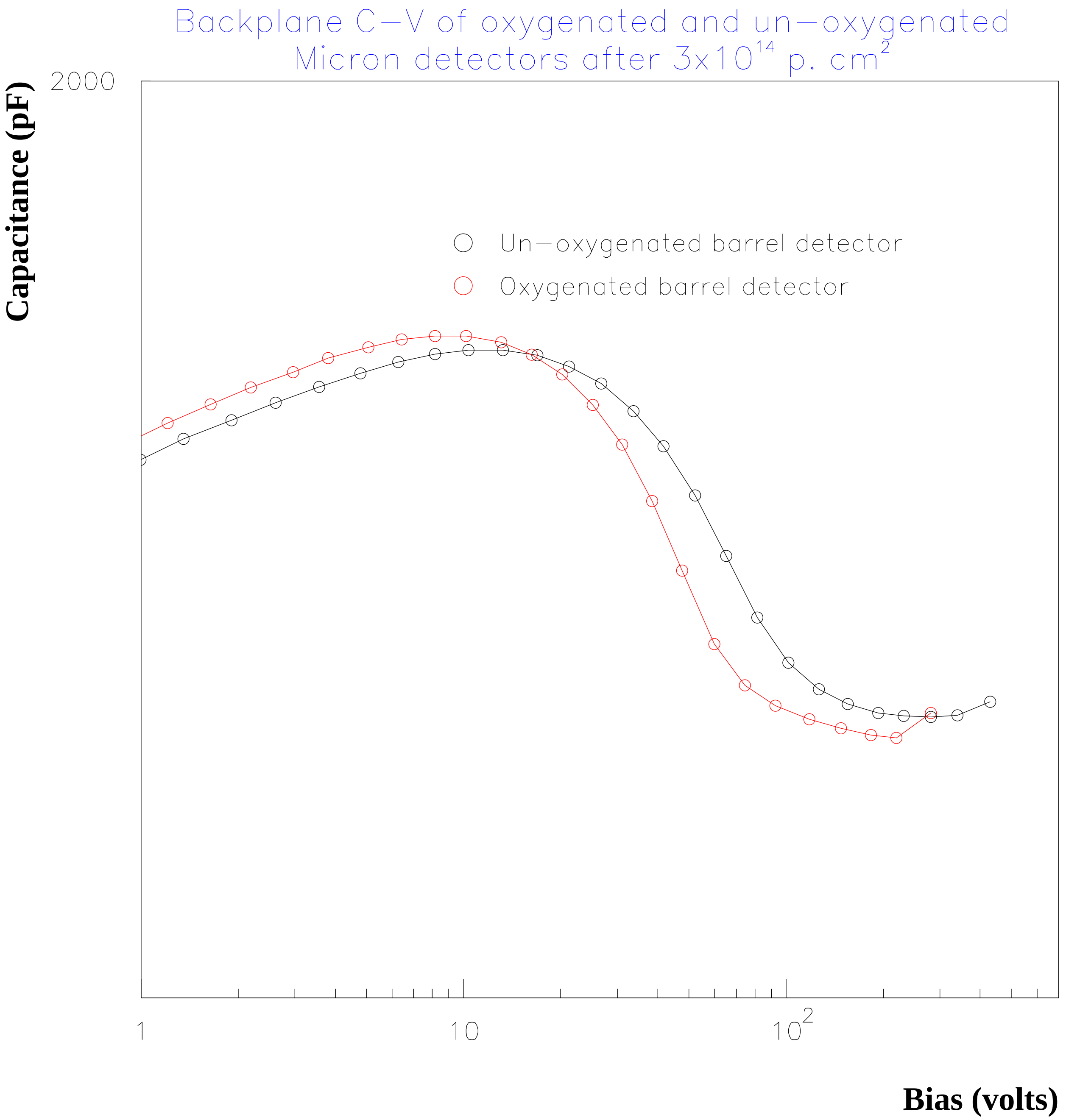


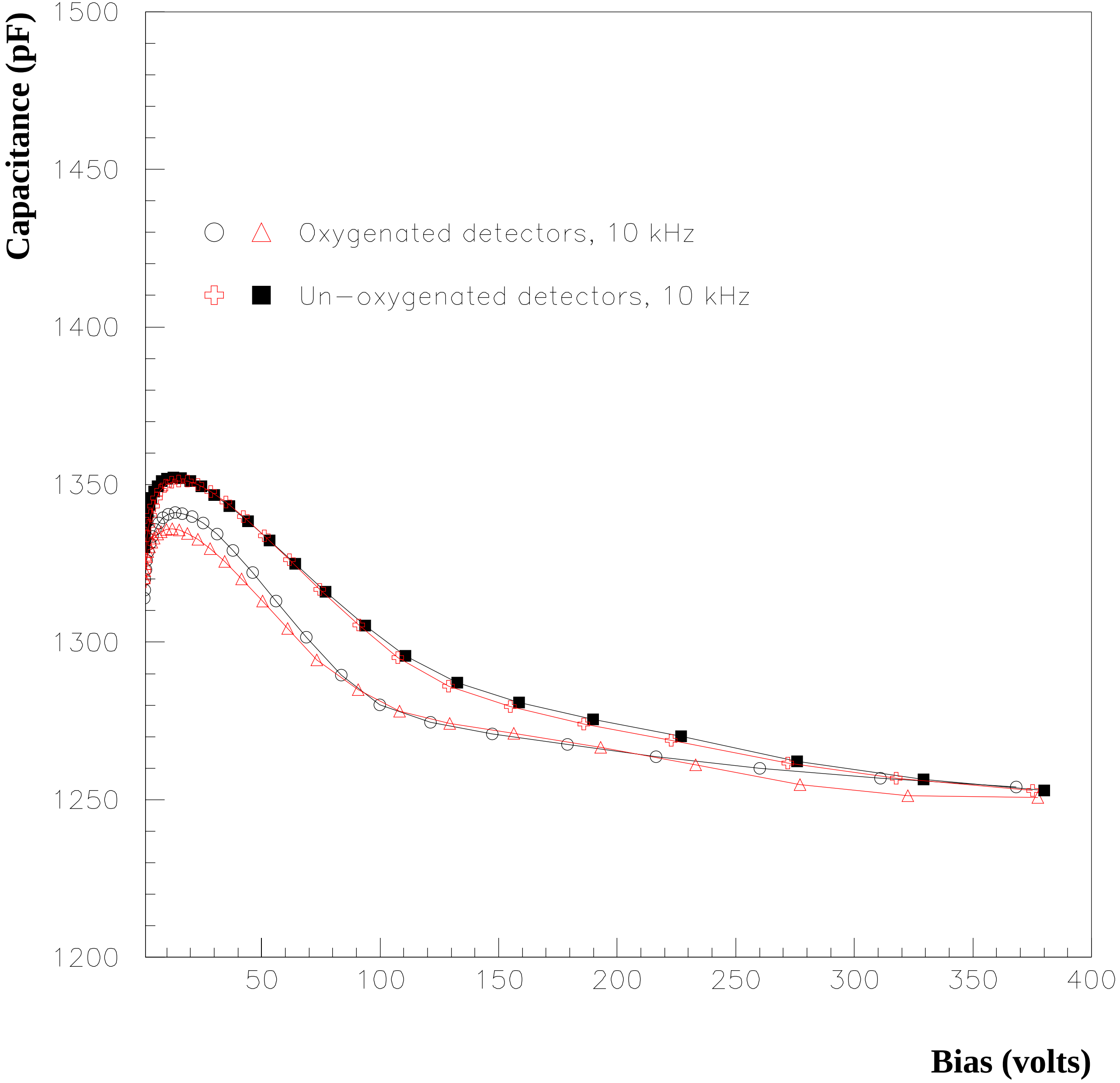
I-V of Micron standard barrel detectors after 3x10^14 p. cm^2
Reverse Current (μA)
600
500
400
300
200
100
0
Measured at -18 ± 2 °C
● Measured after 10 minutes settling time at 500 V
■ Measured after 12 hours settling time at 500 V
50
100
150
200
250
300
350
400
450
500
Bias (volts)



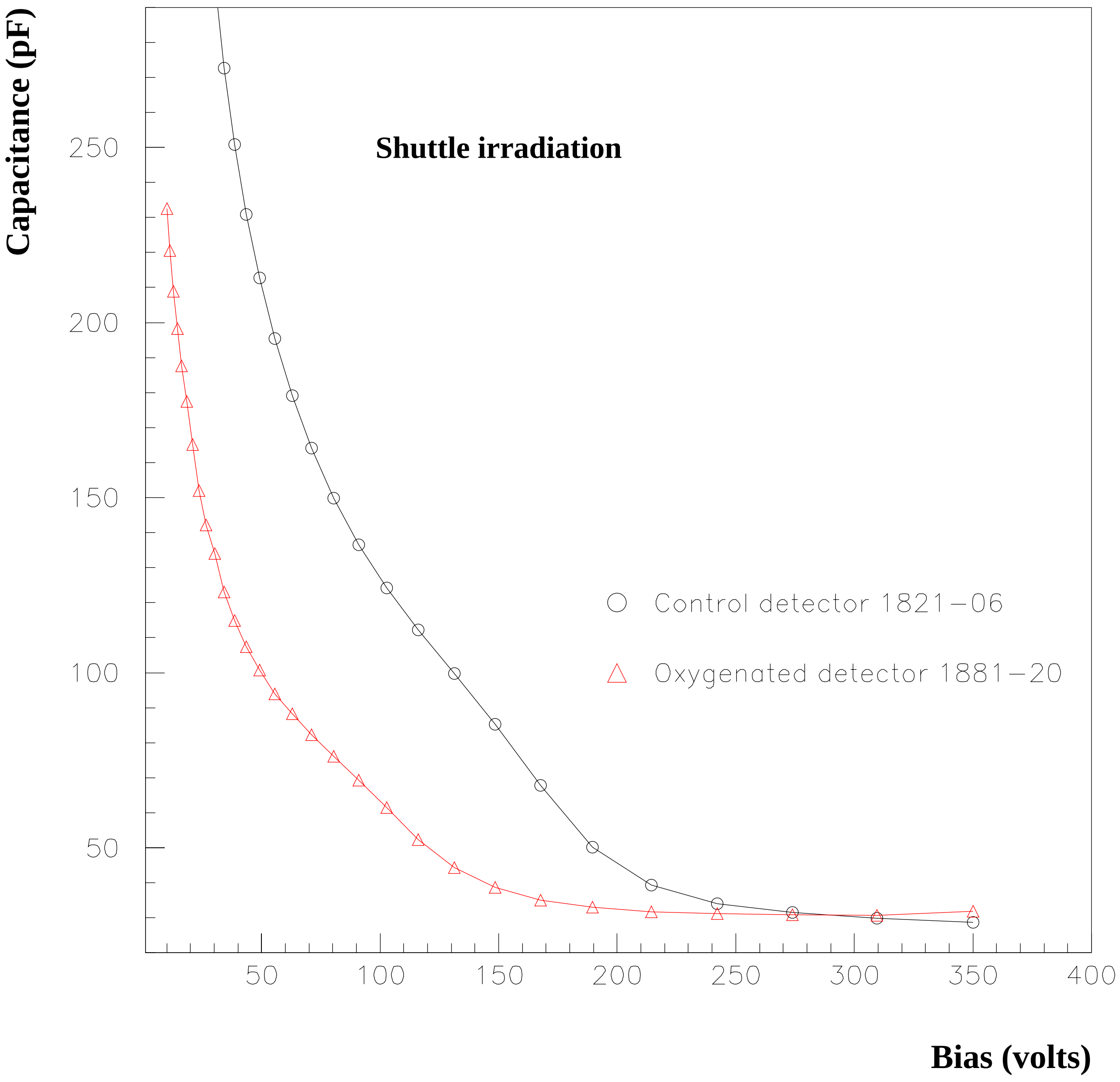
I-V of Micron wedge detectors after $3x10^{14}$ p cm^2


I-V of Micron miniature detectors after 4x10^{14} p cm^{2}
Reverse Current (μA)
0
2
4
6
8
10
12
14
16
Measured at -18 ± 2 °C
● Control 1821−11
■ Oxygenated 1881−13
50
100
150
200
250
300
350
400
450
500
Bias (volts)
Reverse Current (μA)
0
1
2
3
4
5
6
■ Control 1821−11
● Oxygenated 1881−13
2
4
6
8
10
12
14
16
SQRT(Bias) (volts$^{1/2}$)


Backplane C–V of oxygenated and un–oxygenated
Micron detectors after 3x10^14 p. cm^2
Capacitance (pF)
2000
○ Un–oxygenated barrel detector
○ Oxygenated barrel detector
1
10
10^2
Bias (volts)

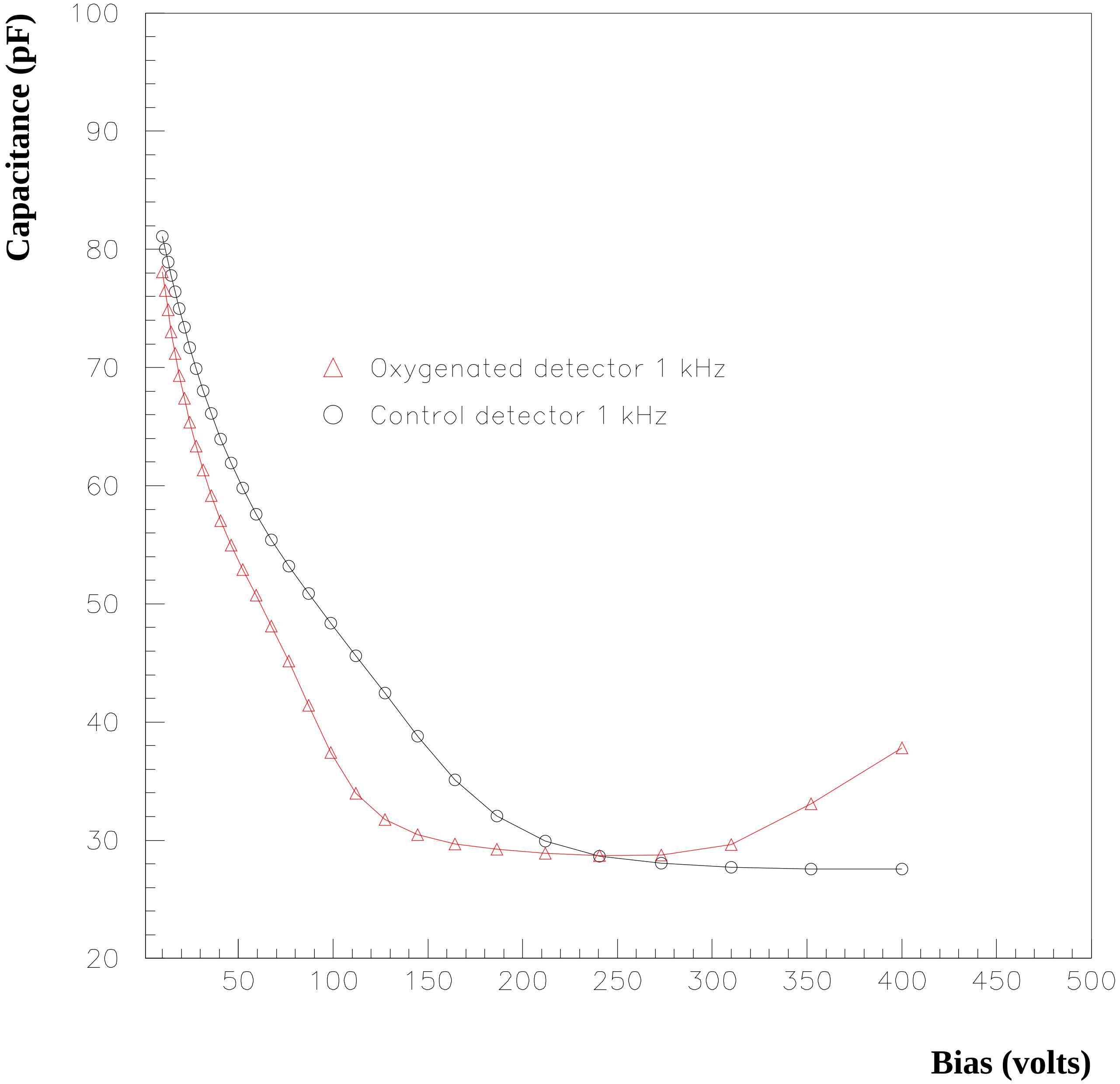


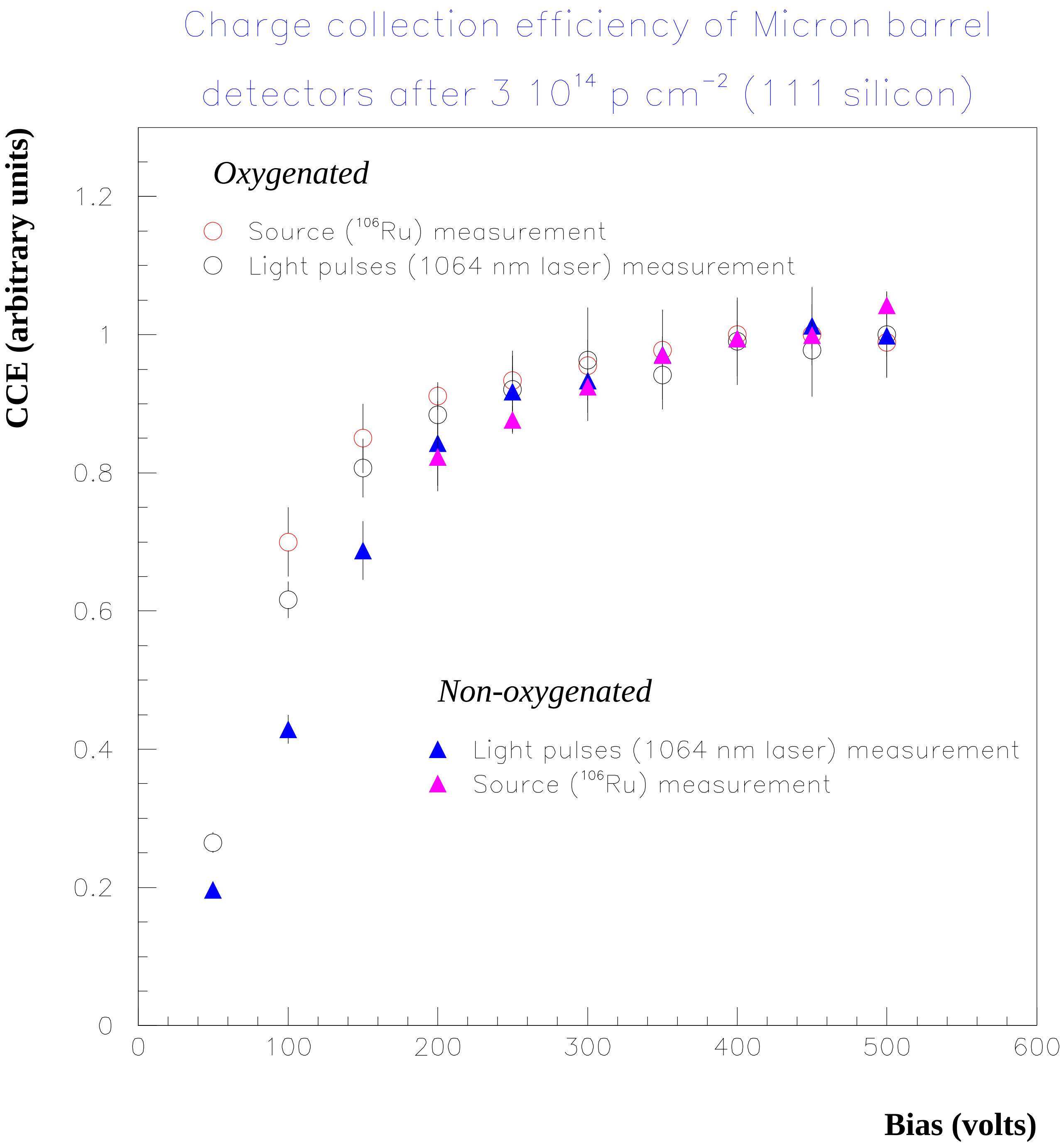
Backplane C-V of oxygenated and un-oxygenated Micron wedge detectors after 3×10^{14} p cm^2

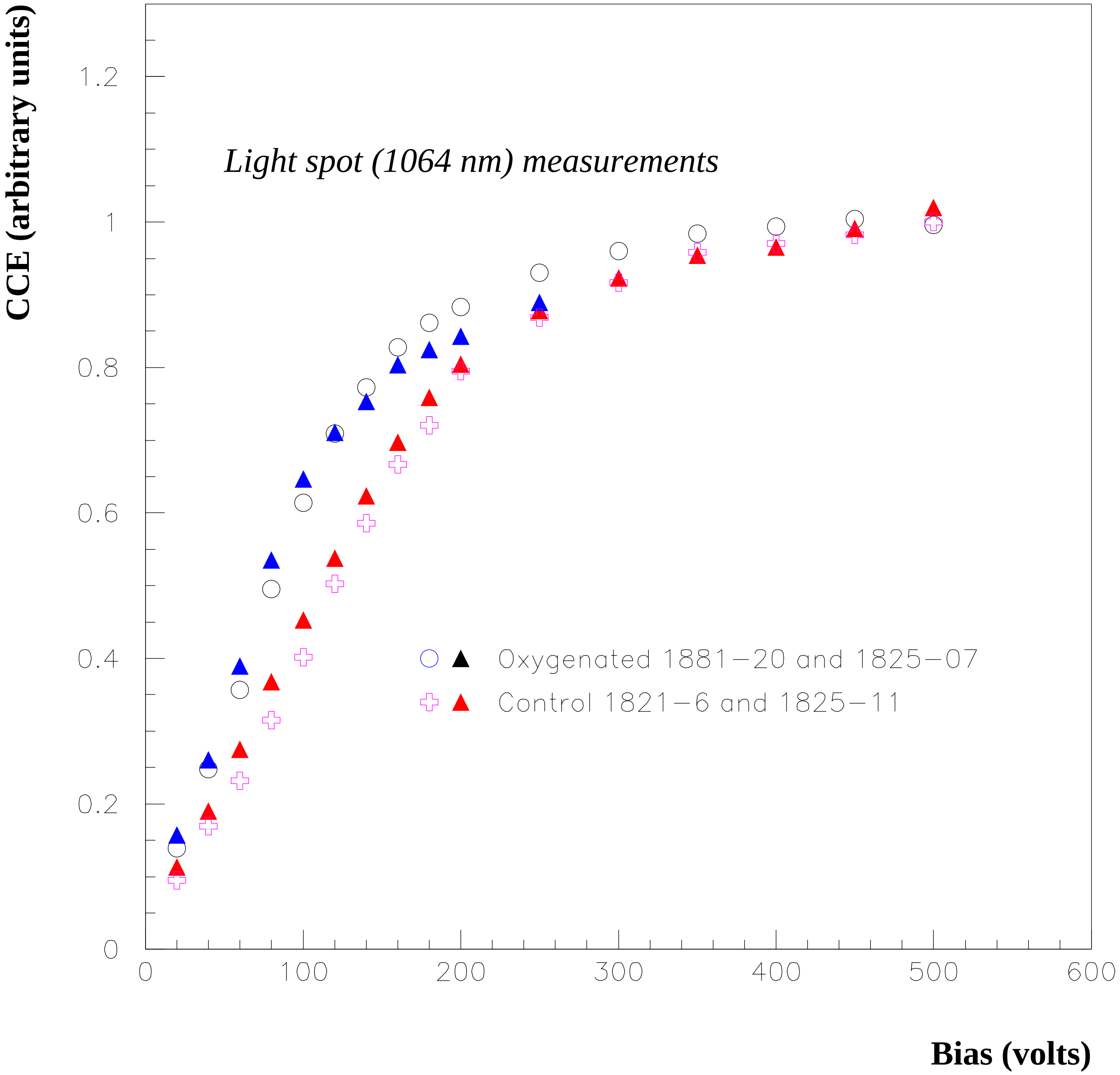


Backplane C-V of oxygenated and un-oxygenated Micron miniature detectors after 3×10^{14} p cm^{2}

Backplane C-V of oxygenated and un-oxygenated Micron miniature detectors after 4×10^{14} p. cm^2

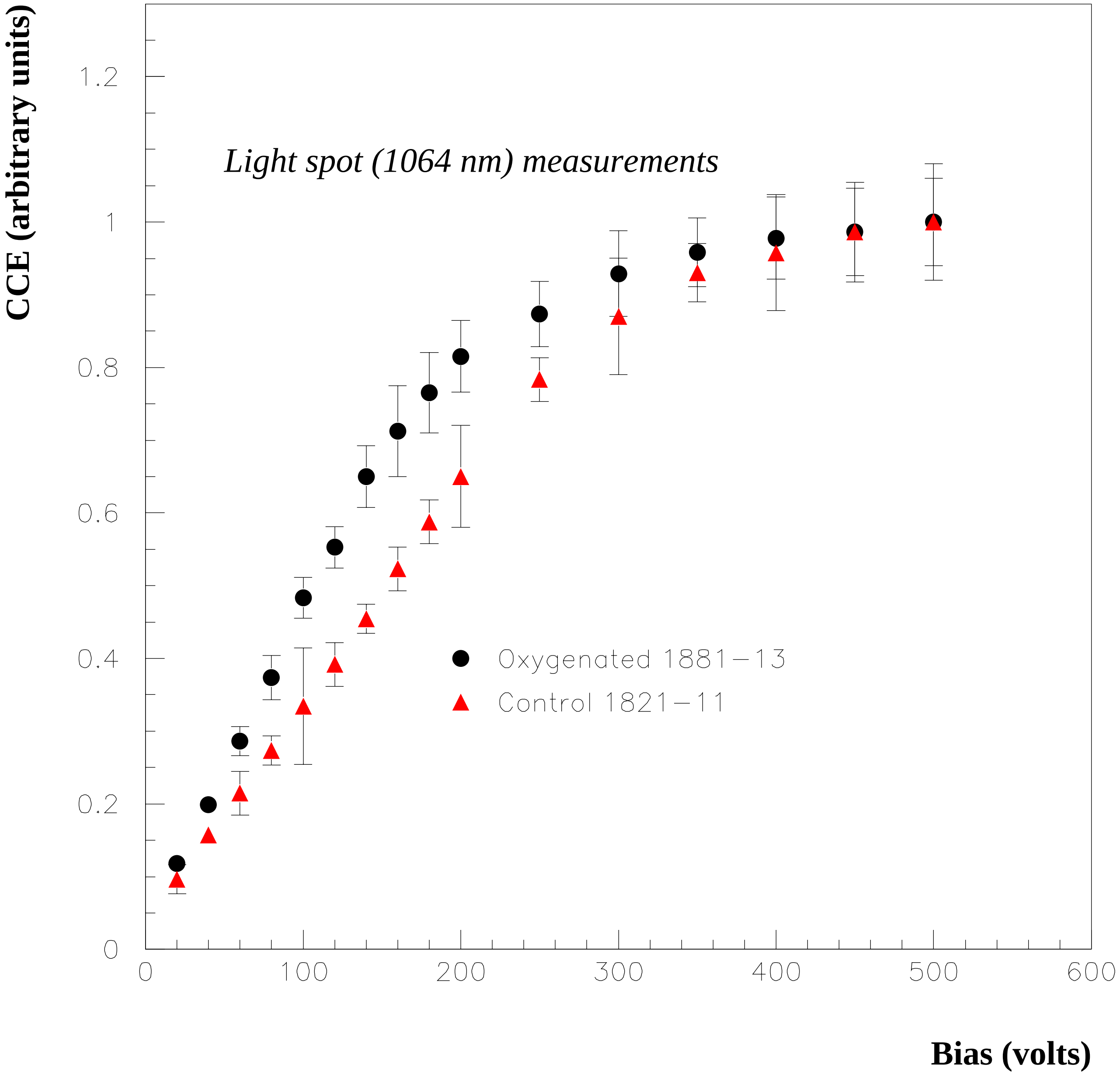


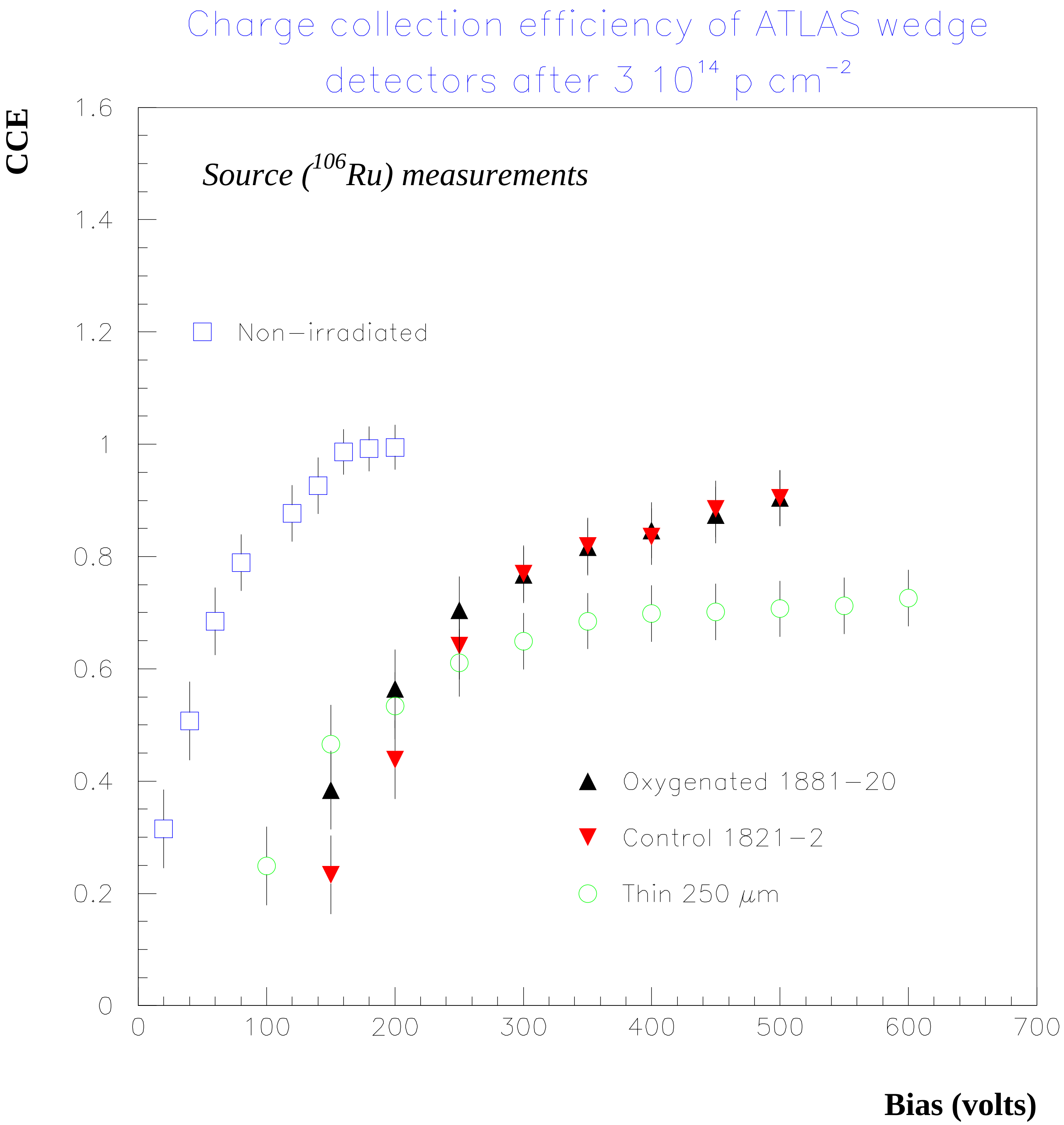

Charge collection efficiency of Micron barrel detectors after 3 10^{14} p cm^{-2} (111 silicon)
CCE (arbitrary units)
Bias (volts)
Oxygenated
Source (^{106}Ru) measurement
Light pulses (1064 nm laser) measurement
Non-oxygenated
Light pulses (1064 nm laser) measurement
Source (^{106}Ru) measurement
0
0.2
0.4
0.6
0.8
1
1.2
0
100
200
300
400
500
600



Charge collection efficiency of oxygenated Micron miniature detectors after 3 10^{14} p cm^{-2}

Charge collection efficiency of oxygenated Micron miniature detectors after 4 10^{14} p cm^{-2}




Charge collection efficiency of ATLAS wedge detectors after 3 10^{14} p cm^{-2}
CCE
Source (^{106}Ru) measurements
□ Non−irradiated
▲ Oxygenated 1881−20
▼ Control 1821−2
○ Thin 250 μm
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
100
200
300
400
500
600
700
Bias (volts)

CONCLUSIONS

- Oxygenated (with high temperature diffusion technique) silicon substrates are suitable for production of segmented detector (good results from oxygenated large area and miniature detectors). No evidence of oxygen induced relevant deterioration of the electrical properties of the detectors in term of reverse current, capacitance and noise measurements.
- Silicon detectors made from oxygenated substrates show better radiation hardness properties (when irradiated with high energy charged hadrons) than “standard” substrates. In term of CCE of microstrip detectors, the benefit is lower than expected (form CV measurements of silicon pad diodes).
- The use of oxygenated substrate is suitable in high charged particle radiation environment and still slightly beneficial (and not harmful) in lower radiation environment. Future investigation of this substrate are planned in Liverpool, especially for the applications in the LHCb experiment tracker environment. Use of oxygenated substrate for *standard* p-in-n, but also n-in-n and n-in-p diode geometry will be investigated.