"Update of the empirical interpretative model of the γ-ray induced leakage current (LAriiLC)"

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Outline

- The LariiLC empirical model
  - ✓ Collection of positive and negative charge
- Validation of the model from literature
  - ✓ Charging of SiO_2
  - ✓ Understanding of how charge can affect SiO_2
- The most likely and reasonable mechanism to explain increase in SiO_2 conductivity
  - ✓ Interpretation of some experimental observations in terms of thism mechanism
- Results of the operation of the detector without any passivation layer.
- Summary and Conclusions

Empirical model of the γ-ray induced LC (LAriiLC)

GOAL: to explain the mechanism that drives the increase of LC observed during γ-irradiation

Basic points:

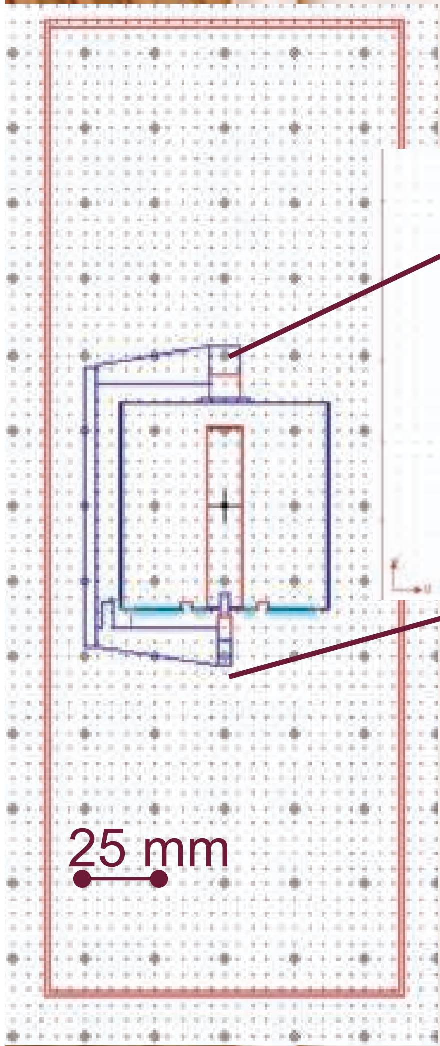
- LAr surrounding the detector, in case of both bias at +HV and at -HV, experiences a strong electric field
- When irradiating with a ^{60}Co source, ionization happens both in
  - a. Ge
  - b. LAr
- Concerning LAr volume, the electric field generated around the detector separates and drifts charges toward respective electrodes. e^-s survive in LAr ($[O_2]$ ~ppm) only few μs, then they are trapped to form O_2^-, OH^-, which are slowly (cm/s) drifted to +HV surfaces.
- The charge collected on the passivation layer (PL) results in an extra conductivity ($\rho \sim 10^{14-15}$ Ω/cm).

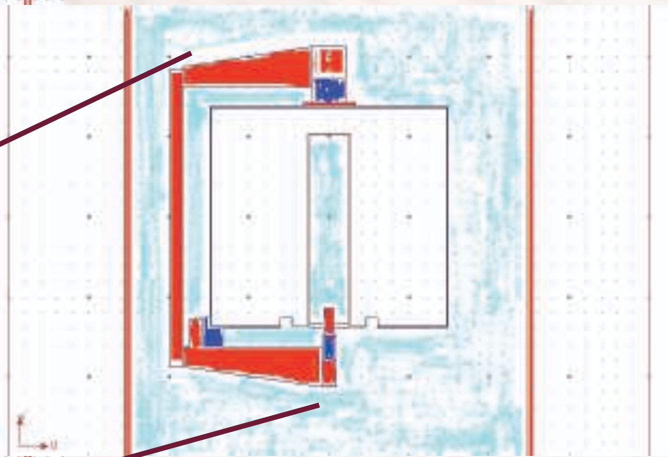
The model consists of 3 main parts:

1. Charge production;
2. Charge transportation and collection @ detector surfaces;
3. Effect of collected charge on SiO_2 conductivity.

E field numerical computation by Maxwell 2-D

- Crystal (Ge,Li,B,SiO), Cu holder, IR shield have been described with actual geometry e materials





Material (not in MAXWELL database)	Rel. Permittivity	Conductivity [siemens/m]
Doped Ge (n+ & p+)	16	$9 \cdot 10^{4}$
Intrinsic Ge (bulk)	16	$1.8 \cdot 10^{-4}$
Liquid Ar	1.5	0

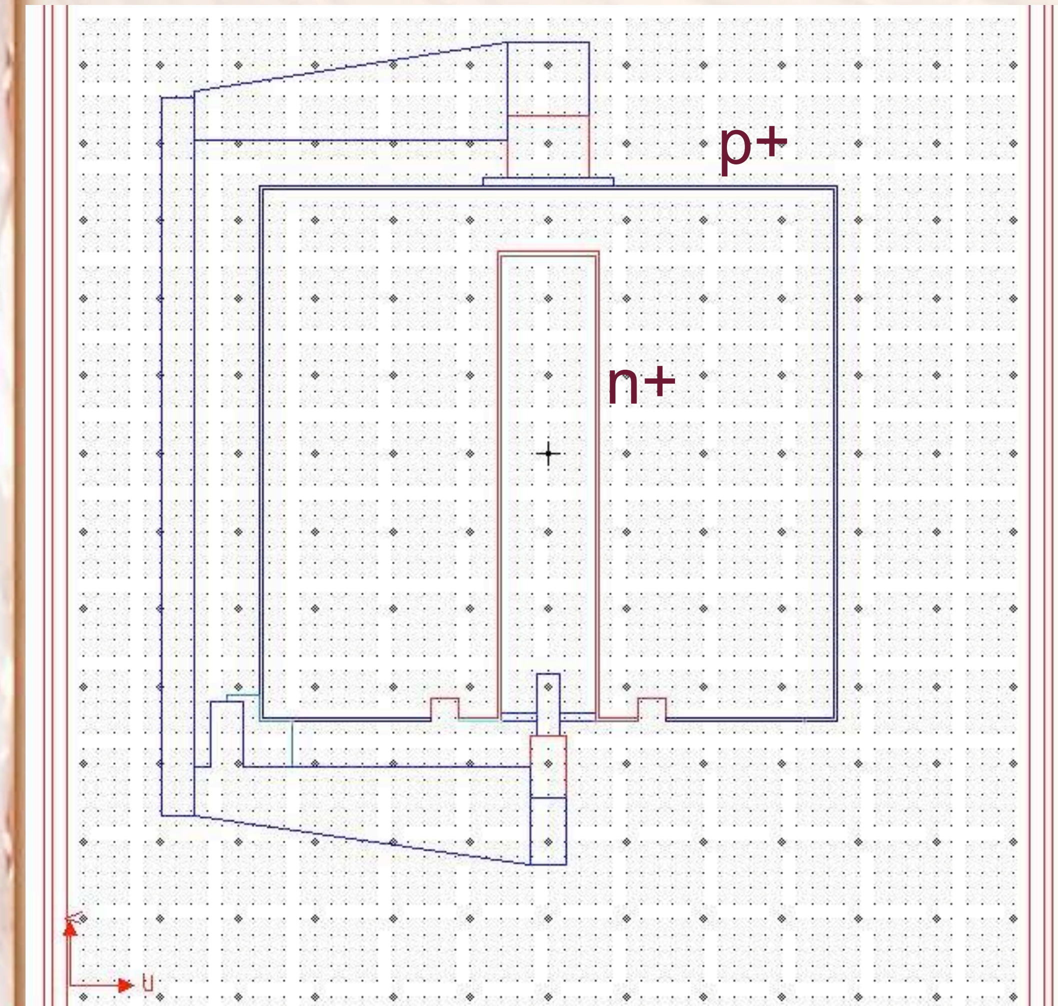
--> copper --> teflon

- The problem is solved at finite elements, after choosing the proper grid dimension

Output of numerical computation:

Values and direction of E field→ E_r and E_z

Potential configurations



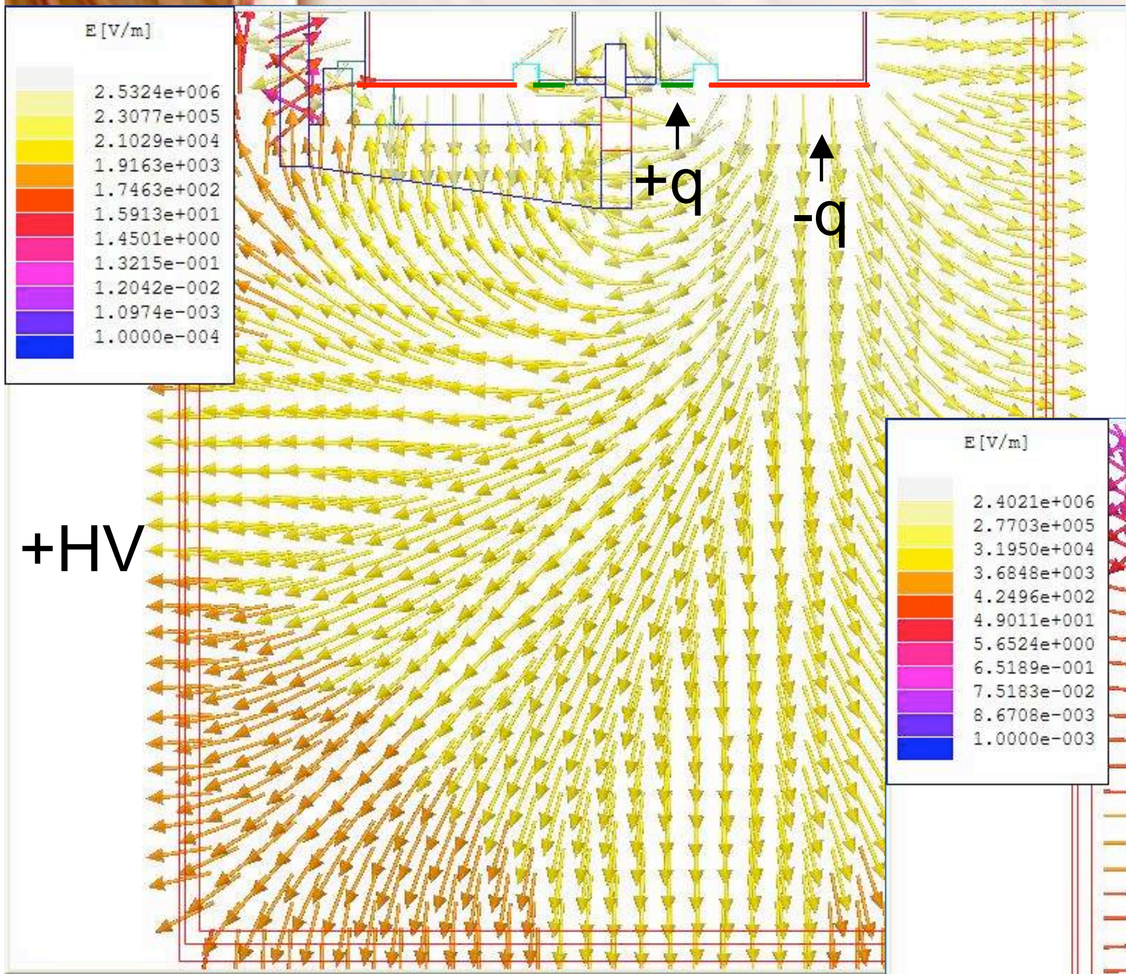
IR-shielding --> 0 V
Cu holder --> 0 V

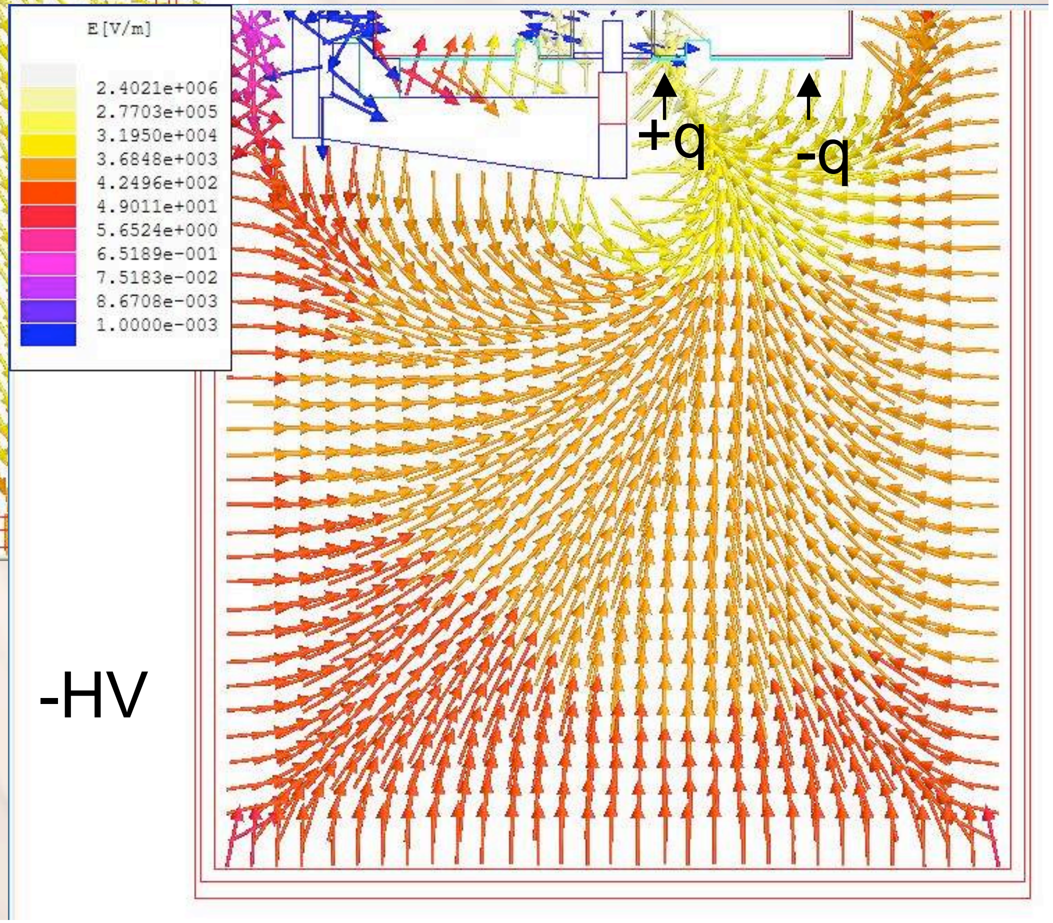
Configuration 1:
n+ --> 4000 V
p+ --> 0 V

Configuration 2:
n+ --> 0 V
p+ --> -4000 V

Charge collection on the SiO_2

In both cases:
positive charge collected on the inner part (between groove and borehole) negative charge in the outer part



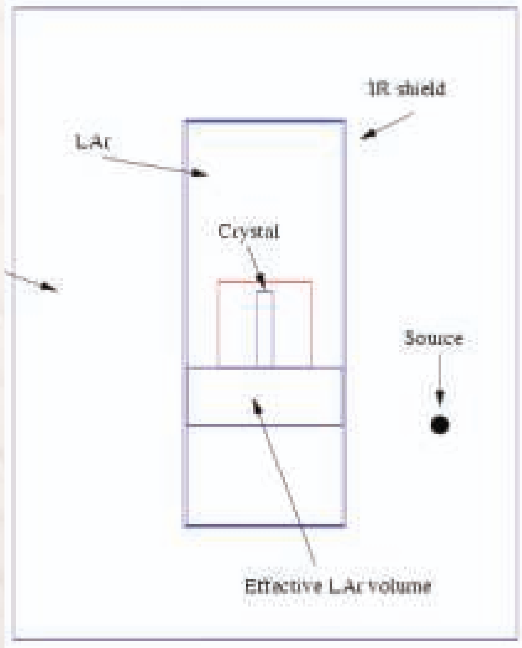


How estimate charge collected

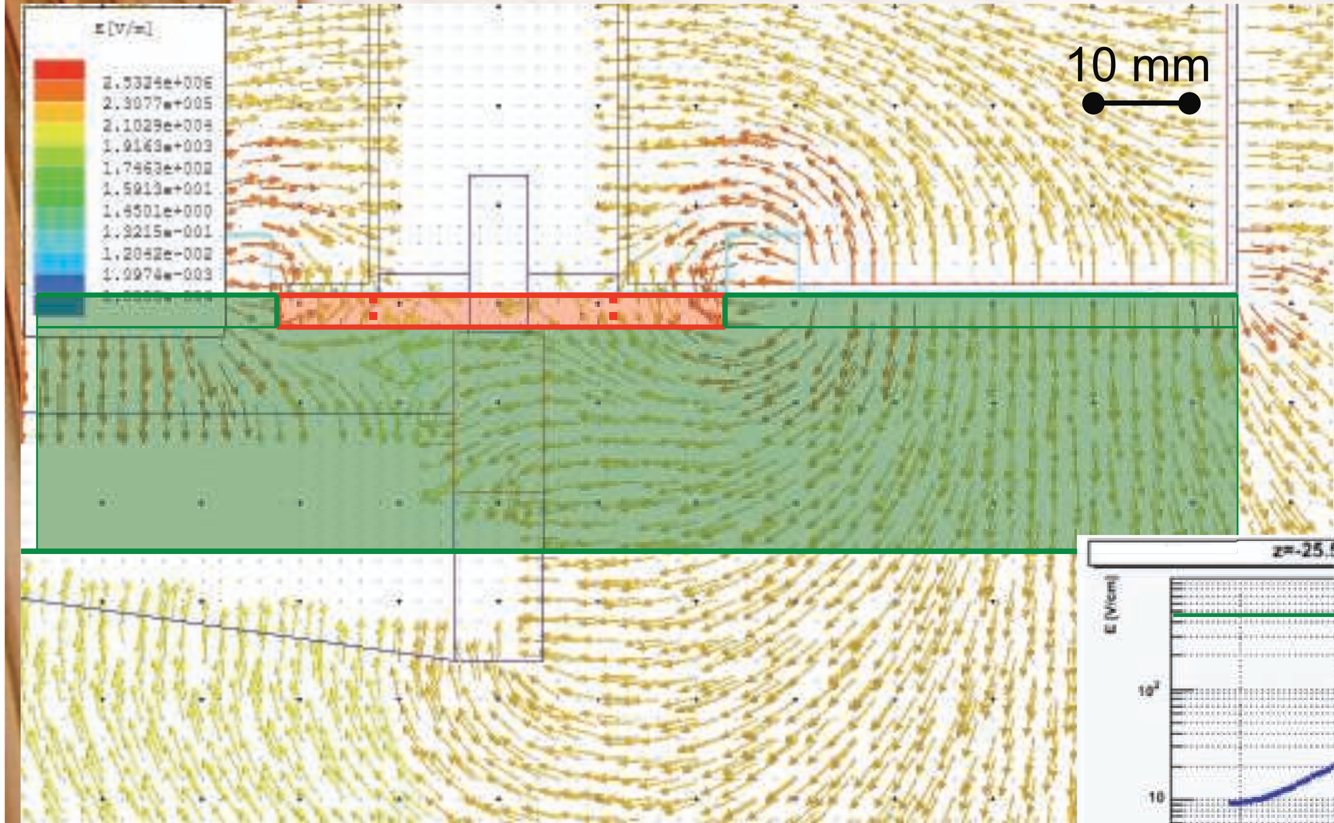
1. Evaluation of effective volume (E>500 V/cm and right direction) for collection of each charge (positive or negative);
2. From Monte Carlo simulation, determination of ionization rate in LAr and mean deposited energy in LAr

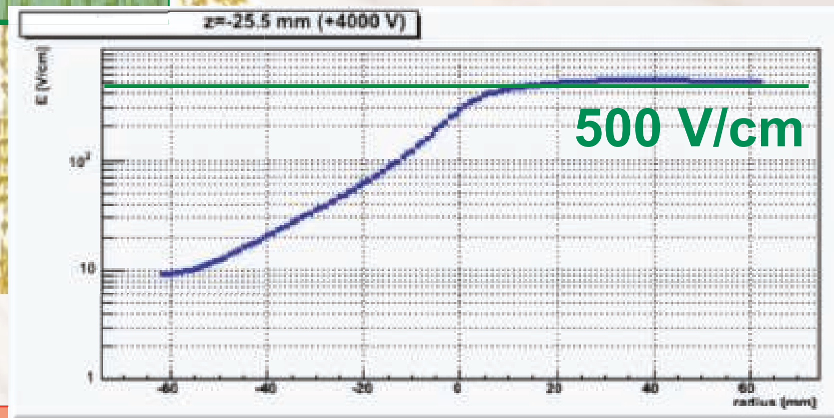
Source position	IR in Ge [kHz]	IR^{MC} in LAr [kHz]	IR^{MC} in effective LAr [kHz]
0	1.5	3.59	1.71

3. The volume considered as effective in the MC is the one below the crystal with height=4cm (E>500 V/cm with +HV)



Effective volumes for +HV configuration





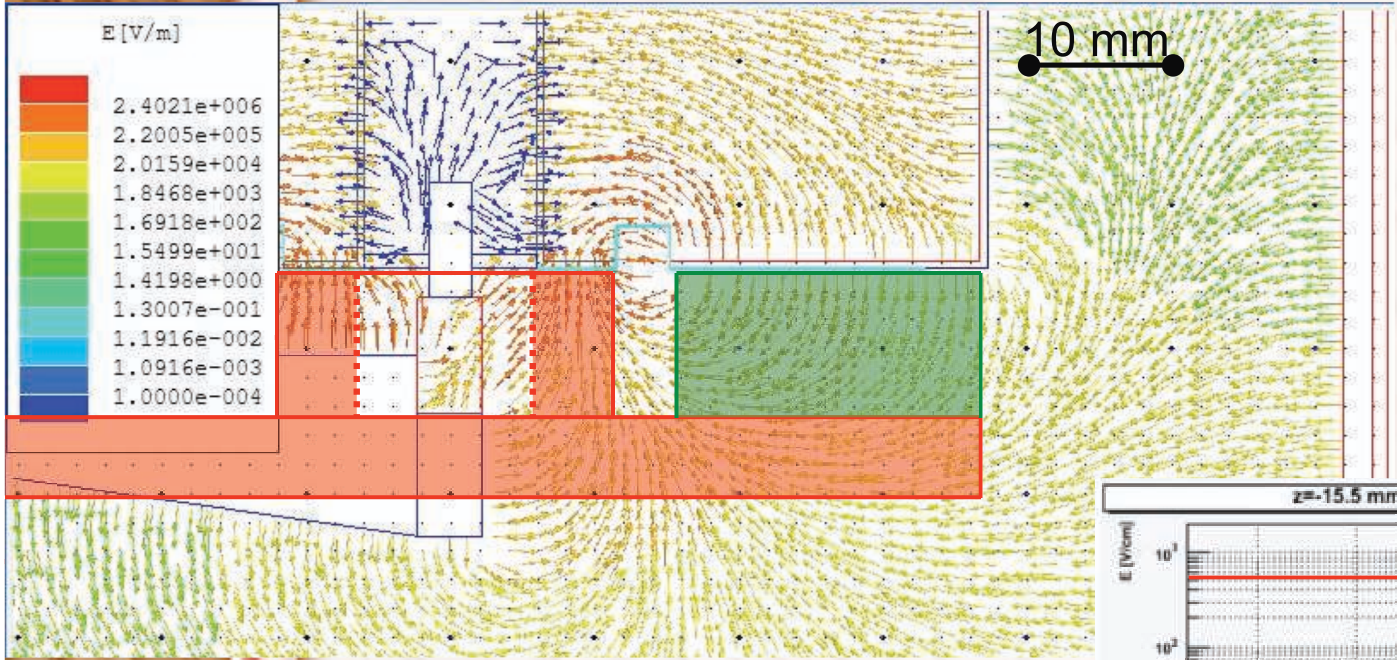
Effective V for +q collection

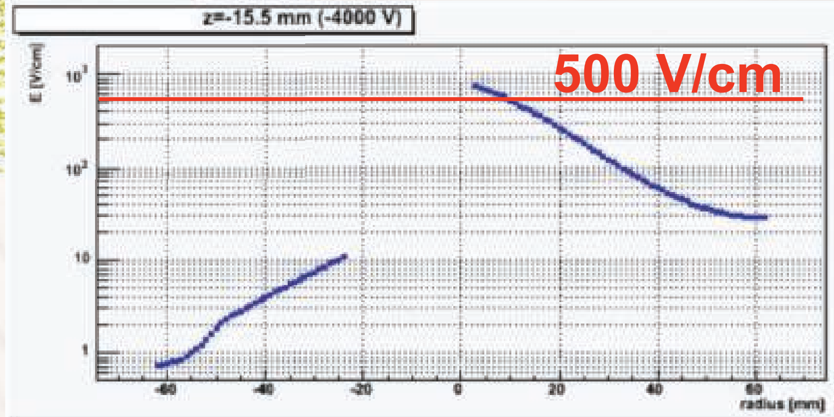
$\approx (r_{ig}^2 - r_{bh}^2)\pi$ 5 mm $\approx 1.3 \cdot 10^3$ mm^3

Effective V for -q collection

$\approx$remaining cilinder below PL with z=25 mm $\approx 1.05 \cdot 10^5$ mm^3

Effective volumes for -HV configuration





Effective V for +q collection ≈ $2.6 \cdot 10^4$ mm^3

Effective V for -q collection ≈ $3.8 \cdot 10^4$ mm^3

Charge density on the PL and E field built up as a consequence of charge pile up

	Positive charge (+q) [pC/d·cm^2]	ρ (+q) [ion/d·cm^2]	E [V/cm]	V [mV]	Negative charge (-q) [pC/d·cm^2]	ρ (+q) [ion/d·cm^2]	E [V/cm]	V [mV]
+HV	$2.4 \cdot 10^2$	$1.5 \cdot 10^9$	140	1.4	$2 \cdot 10^3$	$1.1 \cdot 10^{10}$	$2.5 \cdot 10^3$	0.25
-HV	$1.8 \cdot 10^3$	$1.1 \cdot 10^{11}$	$2.5 \cdot 10^4$	250	$6.5 \cdot 10^2$	$4 \cdot 10^9$	920	9.2

Assumptions for these evaluations:

- IR derived from MC is scaled at different effective LAr volumes.
- Mean energy deposited by ^{60}Co γ in LAr is ≈ 300 keV.
- All the charges produced by ionization in LAr effective volume are collected at the PL. e^-s recombine with impurities and produce negative ions.
- There is no charge recombination at the PL.
- E field is calculated by Gauss theorem ($\varepsilon_r(SiO_2)$=3.9, that is the value for thermal oxides, for CVD oxides like we have it can vary widely)
- Thickness of SiO_2 layer = 100 nm (the exact value is unknown but the layer could even be thicker)

Some important preliminary remarks

There are no analogous cases known from literature.

SiO_2s are widely studied in the field of microelectronics and increases of leakage currents are reported by many authors. Anyhow our conditions are very different from standard situation:

- the oxide layer is thicker than SiO_2 layers applied in semiconductor devices;
- SiO_2 is at LAr temperature;
- SiO_2 is deposited on n+ or p+ contacts where Ge is highly doped with metals, apart from the groove where the interface semiconductor/SiO_2 is present.

➔ LAriiLC doesn't claim to be able to explain quantitatively the experimental data or predictive.

➔ It can give a qualitative idea of what is happening.

➔ It has been and is helpful to address experiments in the direction of understanding of the phenomenon.

➔ The comparison with experimental data allows to reject some hypotheses that were put forward at the beginning.

Current experimental situation (see Marik talk)

3 detectors has been tested both in +HV and -HV configuration in LAr:

1. Prototype with passivation layer;
2. GTF1 with passivation only in the groove;
3. GTF2 without passivation layer.

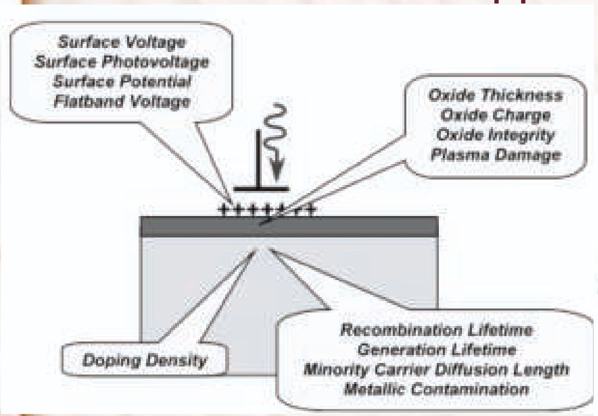
Overview on experimental observations

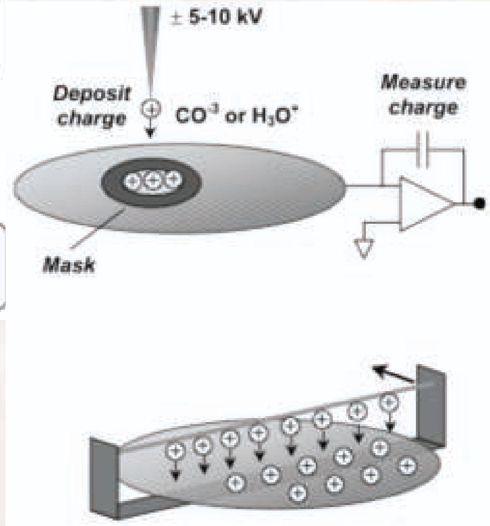
1) Increase of LC with irradiation with prototype
    a) Higher increase of LC with irradiation closer to the PL
    b) Increase of LC steeper with -HV than +HV
2) Much smaller LC increase with GFT1
3) Difference of steady LC (ΔLC_0) when switching from +HV to -HV configuration (and viceversa), both in prototype and in GTF1
4) Effect of previous irradiations with +/-HV configuration on results with opposite configuration
5) Unlinear behaviour of LC increase with γ-irradiation
6) Results of the detector without passivation layer.

Charging of SiO_2

Charging of SiO_2 by corona discharge is a known technique* to perform contactless surface charge for semiconductor characterization. Charge, in these measurements:

1) as a “gate” in MOS type measurements, where the charge replaces the metal or poly-silicon gate,
2) as a surface modyfing method where the charge controls the surface potential. It is measured as a function of probe voltage to determine oxide properties (oxide charge, oxide thickness, interface trapped charge).



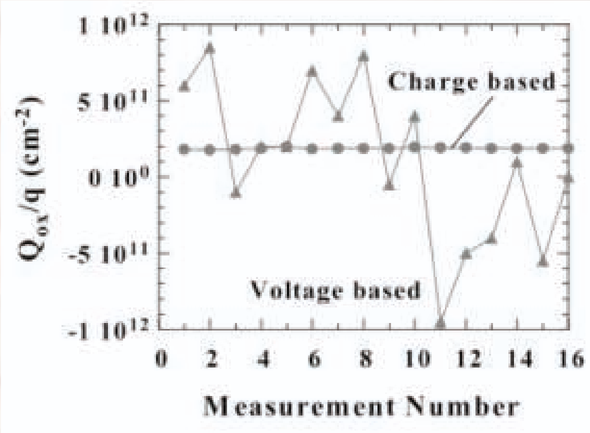


The situation is analogous to ours apart from temperature (T(room) vs T(LAr)) and the ionized medium (air vs LAr)

* “Contactless surface charge semiconductor characterization”
D.K. Schroder, *Material Science and Engineering B91-92 (2002) 196-210*

Charging of SiO$_2$ (II)

$$Q_{ox} = C_{ox}V_{ox} = \varepsilon_{Rox}\varepsilon_0 V_{ox} / t_{ox}$$



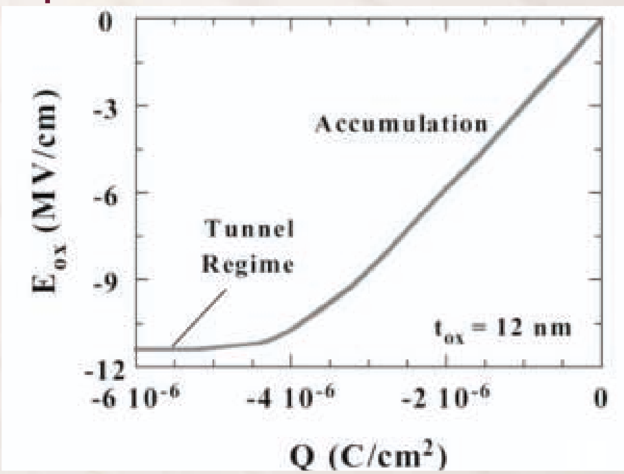
where a) t_{ox} is the oxide thickness
b) $Q_{ox} \approx 10^{10}$ charge/cm^2 the charge in the SiO$_2$.

This value is of the same order of the charge collected on the PL by collecting ionization charges in LAr.
Limit in the amount of charge that can be deposited on the oxide because the charge is related to the oxide electric field e_{ox}

$$Q = \varepsilon_{Rox}\varepsilon_0 \varepsilon_{ox}$$

Charge builds up --> the surface voltage increases, until charge density leaks through the oxide by Fowler-Nordheim or direct tunneling and the surface potential is clamped.

SiO$_2$ breaks at $\varepsilon_{0x} \approx 10$ MV/cm with
"breakdown" charge ≈ 4 · 10^{-6} C/cm^2
From LAriiLC estimations of built up E
$\varepsilon_{ox} \leq 30$ kV/cm



NO BREAKDOWN TAKES PLACE!

Understanding of the LC increase observation: how charge affects SiO_2 conductivity (I)

Charging of SiO_2 layers, even quite thick as our case (O(100nm)), through LAr ionization is known from literature and the estimated amount of charge collected is below the breakdown charge.

So:

✓ Collection of charge --> affect SiO_2 conductivity

✓ Higher increase of LC with irradiation closer to the PL--> effect depends on the rate of charge collected that depends on IR

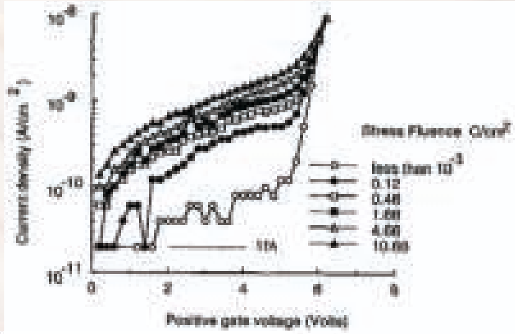
$$\frac{\Delta(LC)^{pos.1}_{after}}{\Delta(LC)^{pos.2}_{after}} = 3.5 \quad \frac{IR(LAr)^{pos.1}}{IR(LAr)^{pos.2}} = 3.5 \quad \frac{\Delta(LC)^{pos.2}_{after}}{\Delta(LC)^{pos.3}_{after}} = 2.6 \quad \frac{IR(LAr)^{pos.2}}{IR(LAr)^{pos.3}} = 3.3$$

$$\frac{\Delta(LC)^{pos.1}_{bulk}}{\Delta(LC)^{pos.2}_{bulk}} = 1.1 \quad \frac{IR(Ge)^{pos.1}}{IR(Ge)^{pos.2}} = 1.15$$

Understanding of the LC increase observation: how charge affects SiO_2 conductivity (II)

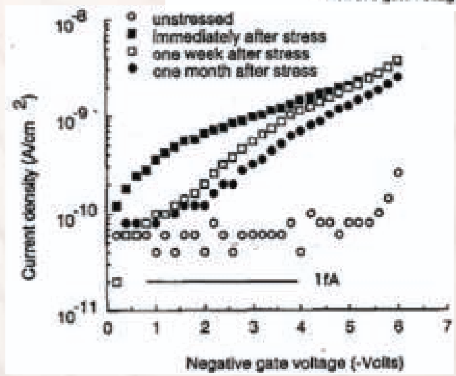
A possibile explanation--> low level pretunneling leakage currents due to charging and discharging of traps generated inside the SiO_2 by high voltage stress**

As in our case, ΔLC depends on time (fluence of charge) the stress is applied -->



but a) the rapid increase in the current is due to Fowler-Nordheim tunneling effect that requires E≈5 MV/cm that is not our case.

b) In known cases (thin SiO2, high E), a discharging of stress generated traps is observed



c) Trap density $\propto \sqrt[3]{\ }$ fluence (e^-)

And LC$\propto$trap density

$\Rightarrow$LC $\propto \sqrt[3]{\ }$ fluence (e^-)

But our observed increase is steeper

**"Correlation of Stress-Induced Leakage Current in Thin Oxides with Trap Generation Inside the Oxides"
D.J. Dumin & J.R. Maddux, *IEEE Tran Elec Dev, Vol 40 No 5 May 1993*

"Low-level leakage currents in thin silicon oxides films"
D.J. Dumin et al., *J. Appl. Phys. 76(1), 1 July*

Understanding of the LC increase observation: how charge affects SiO_2 conductivity (III)

Following what is available in the literature, the Fowler-Nordheim tunneling does not seem reasonably responsible for experimentally observed ΔLC since SiO_2 is too thick and the charge built up field is not strong enough.

⇒The 2nd hypothesis: either

a) The groove is the only region where a semiconductor (intrinsic Ge)/SiO_2 exists and an interface trapped charge could be present. In such a case tunneling can proceed indirectly with the assistance of interface traps. The magnitude of the current density associated with tunneling processes has been found to obey an *empirical relationship* given by

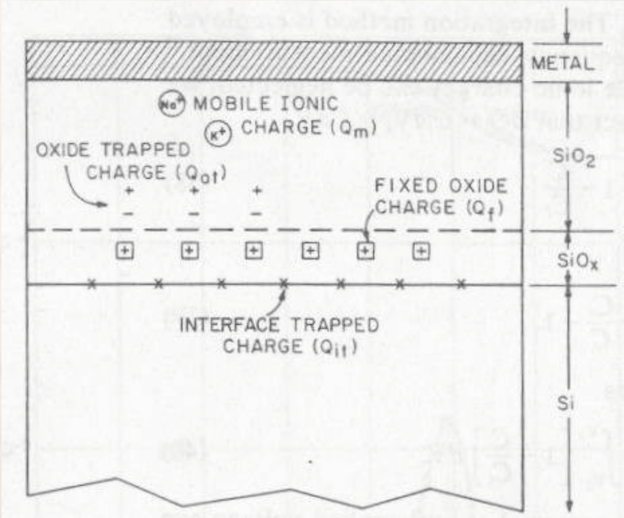
$J \sim F^2 \exp\{-K/F\}$

Where F-->E magnitude

K=19-23 MV/cm

empirical value for Si-SiO_2*

For Ge-SiO_2 ???????



(*Introduction to semiconductors devices, K.F. Brennan)

Understanding of the LC increase observation: how charge affects SiO_2 conductivity (IV)

…or

In deposited insulators which contain a high density of structural defects, these can cause additional energy states close to the band edge. This is the Poole-Frenkel emission, but it involves the field-enhanced thermal emission of electrons from trap states into the conduction band of the insultor. This phenomenon has been reported for 5 nm thick insulator (especially Si_3N_4)***

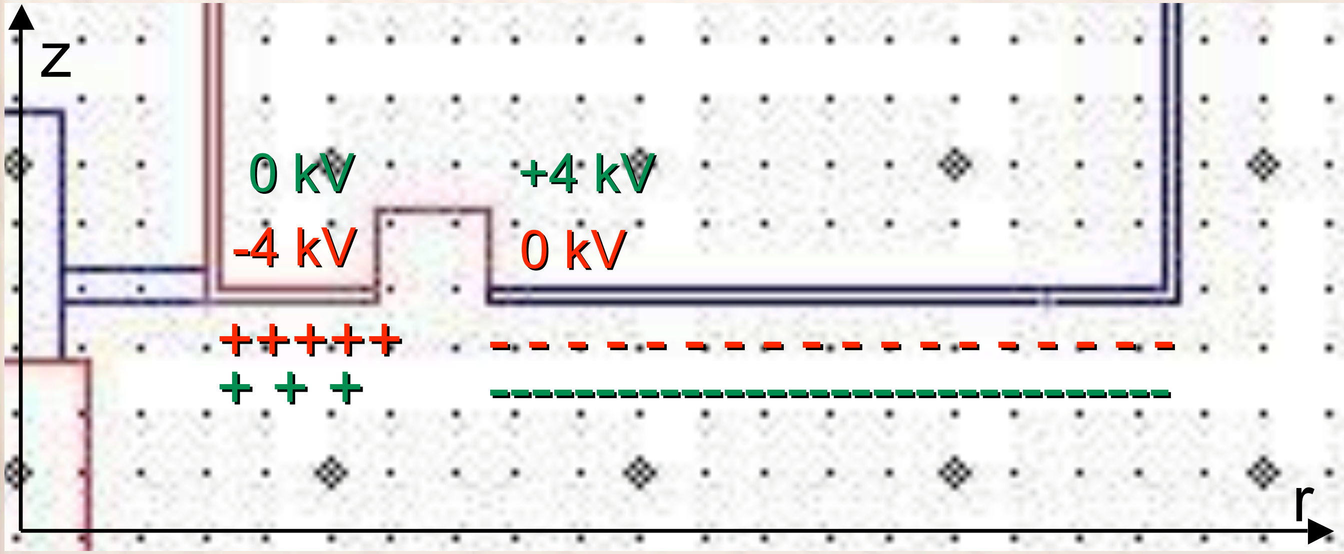
➔This phenomenon is not a good candidate to explain the observed radiation induced leakage current increase due to

a) Too low temperature (T(LAr))
b) Thickness of SiO_2

**"Trap-assisted conduction in nitrided-oxide and re-oxidized nitrided-oxide n-channel metal-oxide-semiconductor field-effect transistors"
S. Fleisher et al. J. Appl. Phys. 73 (12), 15 June 1993

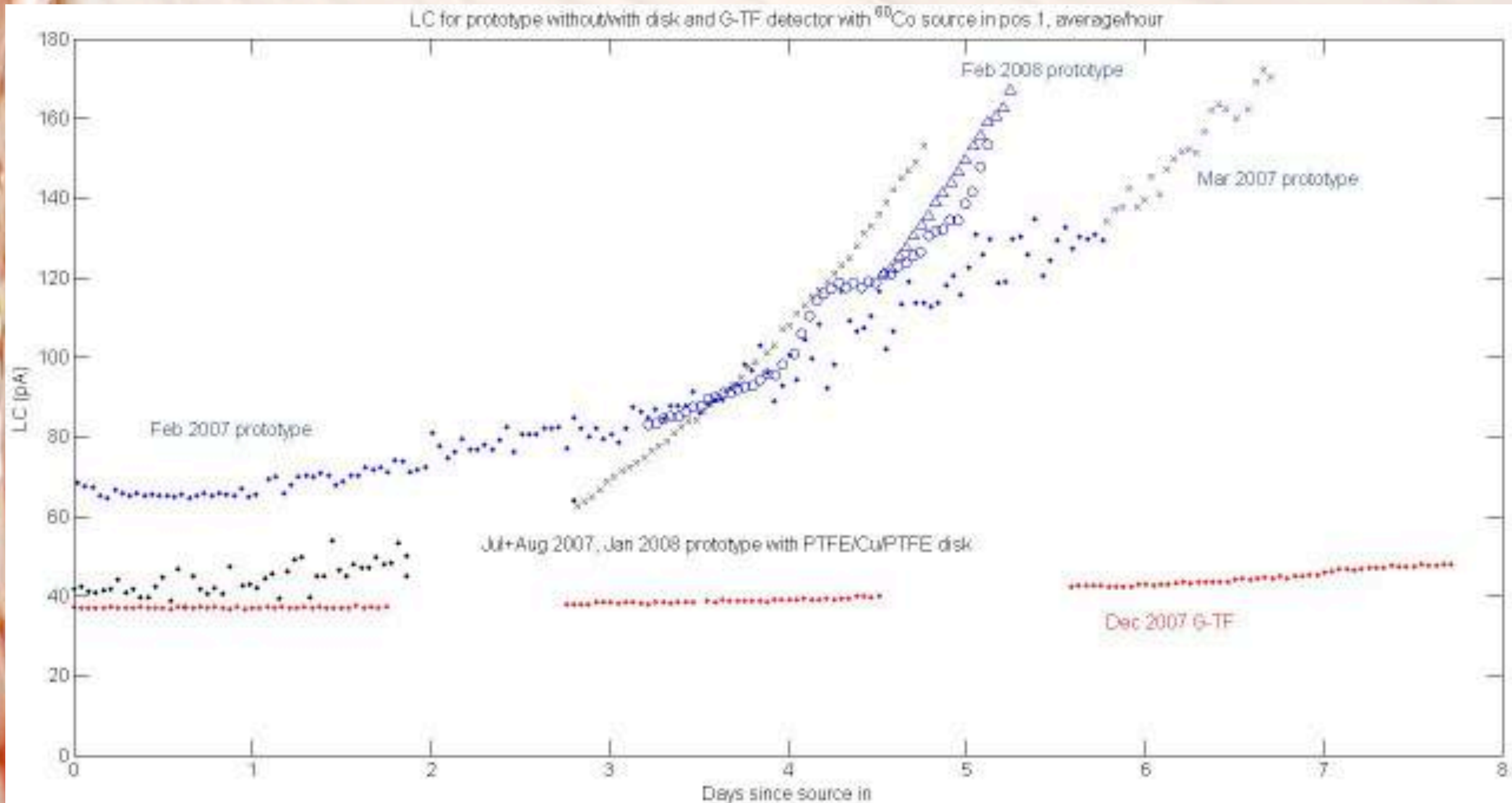
The most likely and reasonable mechanism to explain increase of SiO_2 conductivity

Browsing through what is available in literature (relative to experimental conditions quite different from our situation) and comparing some data, mainly the value of the E field generated by collected, we can likely exclude tunneling through SiO_2. The most reasonable explanation turns out to be a SURFACE CONDUCTIVITY (the driving potential difference being 0/+4 kV or -4 kV/0 between the opposite side of the groove).



Experimental indications for a surface conductivity of the PL (I)

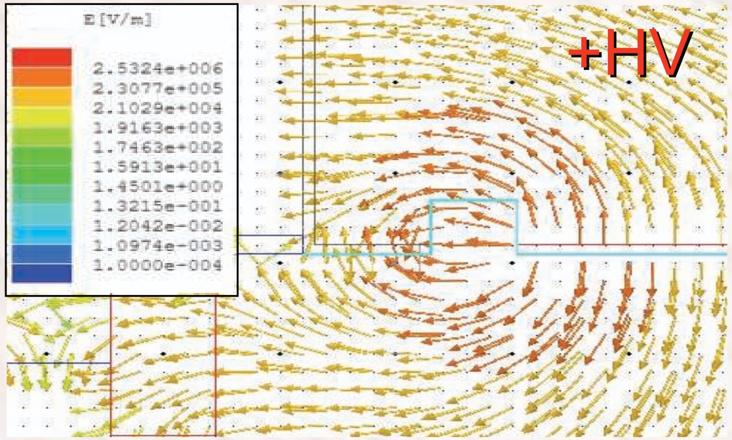
1. The ΔLC following γ-irradiation is much steeper for prototype (large PL) compared to GTF-1 (PL only in the groove).

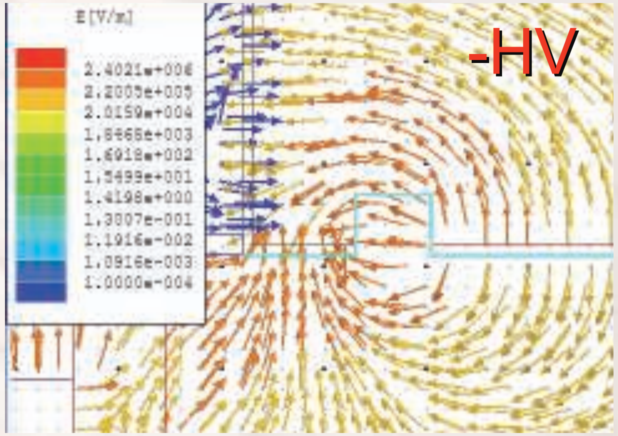


Comparison between rates of increase of γ-ray induced LC in prototype and in GTF-1 both in +HV configuration:
Prototype ➔ ΔLC= 40 pA/d
GTF-1 ➔ ΔLC= 1.4 pA/d ⇒a factor of ≈ 30 lower than in prototype!

Understanding of difference between γ-ray induced LC(+HV) and LC(-HV)

A possible explanation of this:
Since in the groove the charge is collected only from inside the groove





Our idea: conductivity (σ) depends on the radial distribution of charge collected @ PL and the σ in the groove is affected by the tails of charge distribution both on the internal and external surfaces of PL.
This could explain the faster increase of LC with -HV than with +HV observed with both detectors:

	+HV	-HV
Prototype	ΔLC= 40 pA**/d**	ΔLC=26 pA**/h**
GTF-1	ΔLC= 1.4 pA**/d**	ΔLC_0=3.5 pA**/h**

Difference in steady LC (ΔLC_0) between +HV and -HV configuration, both in prototype and in GTF1

✓ Prototype +HV irradiation

-HV ➔ +HV

LC_0= 265 pA ➔ LC_0=100 pA ⇒ ΔLC_0=165 pA

⬇ irradiation with ^{60}Co

LC_0= 340 pA 🡐 LC_0=145 pA ⇒ ΔLC_0=195 pA

✓ GTF-1 -HV irradiation

+HV ➔ -HV

LC_0= 9 pA ➔ LC_0=22 pA ⇒ ΔLC_0=13 pA

⬇ irradiation with ^{60}Co

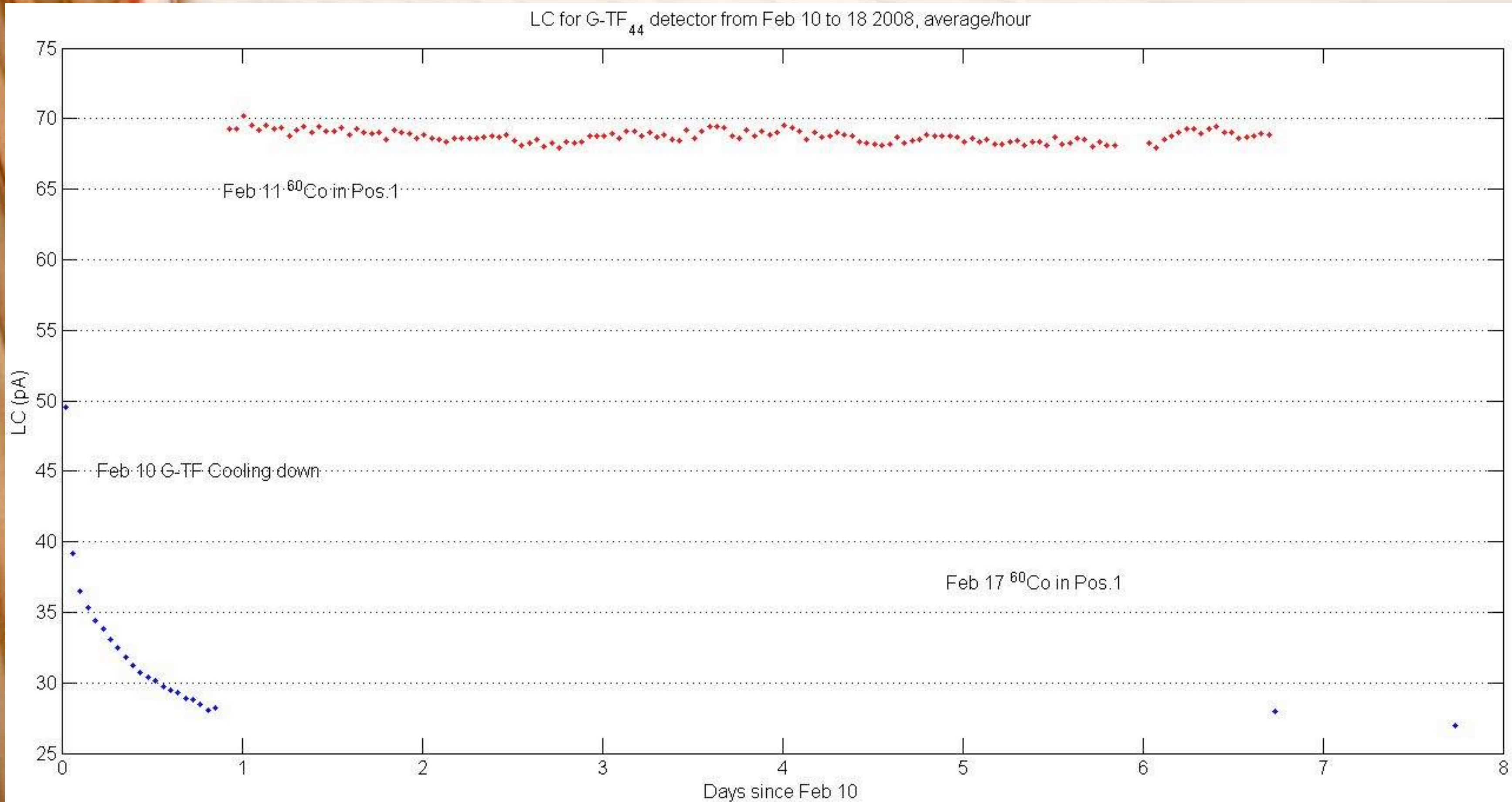
LC_0= 11 pA 🡐 LC_0=35 pA ⇒ ΔLC_0=24 pA

ΔLC_0 :

- is observed with both detectors (large PL and PL only in the groove);
- It is an istantaneous phenomenon that cannot depend on charge collection since that has no time to take place;
- $\Delta LC_0 \approx 1.5\ LC_0$(+HV) but it increases after irradiation --> depends on previous “history” of the detector.

A possible explanation: different dispersion of current through LAr between +/-HV configuration and/or effect of LAr polarization (ε_r=1.5)

The PL is responsible for γ induced ΔLC



Summary and Conclusions (I)

- LAriiLC consists mainly of three parts:
    1. Charge production by LAr ionization produced by γ-source;
    2. Charge transportation and collection at the detector surfaces;
    3. Effect of collected charge on SiO_2 conductivity

    → there is no available literature for similar cases. Anyhow from comparison between literature and data, a surface conductivity seem to be the most reasonable explanation for our ΔLC, but a more detailed description is still missing:
        a) How can charge built up in the PL surrounding the groove affect SiO_2 conductivity in the groove?
        b) Is really a surface phenomenon or could some kind of “trap assisted tunneling” take place?

- LAriiLC can qualitatively explain
    - γ-induced LC both in prototype and GTF-1 (operated naked in LAr)
    - Higher increase of LC with irradiation closer to the PL
    - ΔLC(+HV)< ΔLC(-HV)
    - ΔLC(GTF-1)<< ΔLC(prototype)

Summary and Conclusions (II)

Anyhow it cannot still explain

- difference in LC (ΔLC_0) between +HV and -HV configuration, both in prototype and in GTF1 --> this is probably due to a completely different electric mechanism related to different
- dispersion of current through LAr between +/-HV configuration and/or effect of LAr polarization (ε_r=1.5).
- Irradiation @ 2000V ≈ @ 4000V --> the only reasonable explanation could be an overestimation of effective volume for charge collection in case of bias at 4000 V. (???????)

- The LAriiLC is reversible and UV seems to be the curing agent.
- γ-induced LC is not observed when operating the detector in LAr without any passivation layer. Is the very preliminary result (2 day irradiation) on LN_2 starting to confirm that LAr, with its ionization, is responsible of ΔLC?
- Suggestions for a further understanding of the phenomenon and improving of the model:

  --> electrometric measurement of the SiO_2 charge;

  --> a new detector with PL apart in the groove to understand if the PL in the groove is responsible for γ-ray induced LC.