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ION IRRADIATION EFFECTS ON LITHIUM NIOBATE ETALONS FOR TUNABLE SPECTRAL FILTERS

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ABSTRACT

Solar Orbiter is a mission dedicated to solar and heliospheric physics. It was selected as the first medium-class mission of ESA's Cosmic Vision 2015-2025 Programme. Solar Orbiter will be used to examine how the Sun creates and controls the heliosphere, the vast bubble of charged particles blown by the solar wind into the interstellar medium. One of the scientific payload elements of Solar Orbiter is the Polarimetric and Helioseismic Imager (PHI). The PHI instrument consists of two telescopes, a High Resolution Telescope (HRT) that will image a fraction of the solar disk at a resolution reaching ~150 km at perihelion, and a Full Disk Telescope (FDT) to image the full solar disk during all phases of the orbit. PHI is a diffraction limited, wavelength tunable, quasi-monochromatic, polarisation sensitive imager. These capabilities are needed to infer the magnetic field and line-of-sight (LOS) velocity of the region targeted by the spacecraft. For the spectral analysis, PHI will use an order-sorting filter to isolate a bandpass of the order of 100 mÅ. The FilterGraph (FG) contains an etalon in single pass configuration as tunable spectral filter located inside a temperature stabilized oven. This filter will be made by means of a z-cut LiNbO3 crystal (about 300 microns thick) and multilayer coatings including a conductive one in order to apply a high voltage (up to 5 kV) and induce the required electric field to tune the filter.

Solar Orbiter observing mission around the Sun will expose the PHI instrument to extreme radiation conditions, mainly dominated by solar high-energy particles released during severe solar events (protons with energies typically ranging from few keV up to several GeV) and the continuous isotropic background flux of galactic cosmic rays (heavy ions, from Z=1 to Z=92). The main concerns are whether the cumulated radiation damage can degrade the functionality of the filter or, in the worst case, the impact of a single highly ionizing particle, coupled with the HV field, could trigger a dielectric breakdown in the Lithium Niobate.

In this paper we present the electro-optical results obtained when exposing a set of LN samples and a low-quality full size etalon to different radiation conditions. In a first irradiation campaign, performed at the Centre for Micro Analysis of Materials (CMAM-Madrid) facilities, we were mainly focused on the long-term degradation effects with a series of high flux (10^9 cm^{-2} s^{-1}) proton tests at an energy of 10 MeV. In order to study the possibility of a single ion breakdown, a second campaign was carried out, at the Texas A&M University (TAMU), exposing Lithium Niobate to high LET ion species (^{78}Kr, ^{40}Ar, ^{129}Xe, ^{197}Au) accelerated to the GeV energy range to penetrate or even pass through the entire Lithium Niobate thickness.

I. INTRODUCTION

PHI (Polarimetric Helioseismic Imager) is designed to carry out solar photospheric intensity, velocity and magnetic field measurements [1]. The measurement principle of PHI is based on imaging spectropolarimetric observations of a photospheric absorption line in the solar visible-light spectrum. Therefore PHI is a diffraction limited, wavelength tunable, quasi-monochromatic and polarisation sensitive imager.

The PHI instrument consists of two telescopes, a High Resolution Telescope (HRT) that will image a fraction of the solar disk at a resolution reaching ~150 km at perihelion, and a Full Disk Telescope (FDT) to image the full solar disk during all phases of the orbit (distances from 1 to 0.28 AU). The two telescopes can work sequentially and their selection is made by the Feed Selection Mechanism (FSM), which feeds one filtergraph (FG), the camera optics and one focal plane array (FPA). The FG provides for a very narrow passband filter centered at a wavelength of λ=617 nm. The polarimetric analysis is performed by one polarization modulation package (PMP) [2] in each of the telescopes. The modulation scheme is the same as the one used in the IMaX instrument of the Sunrise mission [3].

The radiation environment for the Solar Orbiter mission [4, 5] foresees two major components:

- Energetic protons (with energies typically below 1 GeV) coming from the solar wind and from individual Solar Particle Events. They represent the main contribution to the cumulative degradation of components and/or materials along the mission, but will have a low impact, in terms of a direct single-ion induced breakdown, due to their low LET.

- The continuous isotropic background flux of Galactic Cosmic Rays (GCR), consisting of ion species from Z=1 to Z=92 covering almost all the energy spectral range. Although the GCR predicted fluxes are low compared to the solar proton component, there exists a significant possibility for a heavy ion to pass through the S/C outer shielding structure and reach internal parts with extremely ionizing LET values (see fig.1.).

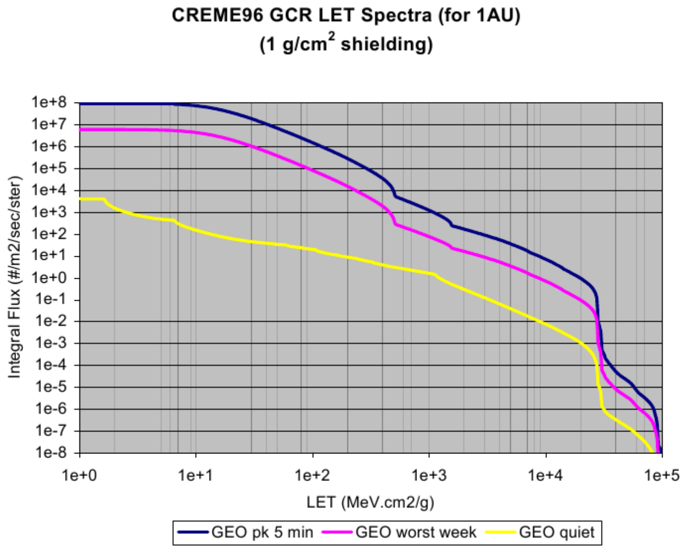

Fig. 1. Galactic Cosmic Ray LET Spectra predicted by CREME96 at 1 AU for nominal solar quiet conditions, worst week/worst case, and peak 5 minute. Fluxes are slowed-down by generic aluminium shielding of 1 g/cm2.

II. EXPECTED DIRECT DAMAGES UNDER ION IRRADIATION

Due to the harsh ionizing radiation environment during the SO mission and the particular operating conditions of PHI Lithium Niobate (LN) Etalons, it is necessary to test this technology under representative conditions that simulate the environment in order to verify the fulfilment of all the mission requirements.

Lithium niobate (LN) - stoichiometric formula $LiNbO_3$ - is a compound of niobium, lithium and oxygen. It is a dielectric material; in fact, it is characterized by large pyroelectric, piezoelectric, nonlinear and electro-optic (EO) coefficients. For example, in the case of LN, the extraordinary index changes when the electric field is applied along the crystal symmetry axis (z-axis). LN is classified as a negative uniaxial crystal, having two different refractive indices for ordinary and extraordinary polarized light, no and ne respectively, with ne<no, which depend slightly on the stoichiometry of the crystal and on temperature [6,7]. There are some phenomena well described of damage of LN under heavy ion irradiation [8-10], either considering just one impact or the accumulation of several impacts in the same area.

LN Etalons have the advantage to provide high resolution performances when used as a tuneable spectral filter, an essential requirement to complete the polarization measurements and spectroscopic analyses PHI is expected to carry out. However, to achieve such performances and allow a dynamic wavelength tuning range, the Etalons require to be polarized with a considerable High Voltage field between their surfaces (typically varying from -5 to +5 kV) with the consequent risk of inducing an electrical discharge in the case of a shortcut. In normal conditions, no short-circuits are expected to occur if Etalon electrodes are correctly isolated and inside of an effective isolating atmosphere, but the situation could dramatically change if a highly ionizing particle reaches the Etalon, passes through it and deposits significant amounts of energy along its track, what eventually could induce an electron-ionized plasma connecting the HV electrodes. In this scenario, the risk of creating a conducting path through the Etalon, with potentially destructive consequences, cannot be neglected. It should be observed that the dielectric breakdown voltage for LN approximately is 26 kV/mm while PHI Etalons are required to operate with voltages up to 5 kV along their 350 μm thickness, which is equivalent to ~14 kV/mm (54% of the breakdown voltage).

Therefore, by impact accumulation in operations conditions an effective medium is generated in the crystal with the embedded tracks, whose refractive index is shifted progressively towards lower values than the virgin substrate. This would generate a bias in the etalon response. Moreover, the amorphized volume will lose its EO coefficients, thence limiting the effective electro-optic response of the device progressively as a function of the cumulated fluence. This would be a more severe problem, since there is no way to compensate it. However, this extreme case seems not to be the most probable case given the spectra of ions present is space and the fact that the higher stopping power of heavy ions allow to stop them in the shields/layers of the instrument.

II. SUMMARY OF IRRADIATION TESTS.

By the above, a series of tests by irradiating different areas of a single etalon and on samples obtained from a wafer of the same type as the etalon (LN z- cut, thickness 350 µm) realized from CSIRO LTD. Company. In the test conduced at CMAM facilities we were mainly focused on the long-term degradation effects with a series of high flux ($10^9 cm^{-2}s^{-1}$) proton tests at energy of 10MeV. These tests were carried out in vacuum conditions and with a rectangular beam size of 2x2mm. In order to study the possibility of a single ion breakdown, a second campaign was carried out, at the Texas A&M University (TAMU), exposing LN to high LET ion species (^{78}Kr, ^{40}Ar, ^{129}Xe, ^{197}Au) accelerated to the GeV energy range to penetrate or even pass through the entire LN thickness. The tests were in room conditions with a circular beam size the diameter 6.35mm.

CMAM

Ion	**Sample**	**Fluence (cm^{-2})**	**Δt (s)**	**HV (4.5kV)**
^{1}H Energy 10 MeV	P1	1012	128	ON
	P2	$1.65\cdot10^{11}$	33	ON
	P3	1012	200	ON
	P4 (SPOT 1)	$1.5\cdot 10^{13}$	2935	ON
	P4 (SPOT A)	1012	200	OFF
	P4 (SPOT B)	1011	20	OFF
	P8 –1A	$6.3\cdot10^{9}$	1	OFF
	P8 – 1B	1010	1.6	OFF
	P8 – 2C	1011	16	OFF
	P8 – 2D	$1.1\cdot10^{12}$	160	OFF
	ETALON C1	$6.3\cdot10^{9}$	1	ON
	ETALON C2	1010	1.6	ON
	ETALON C3	1011	16	ON
	ETALON C4	$1.1\cdot10^{12}$	160	ON

TAMU

Ion	**$LET_{Surface}$ in Si ($MeVcm^2mg^{-1}$)**	**Sample**	**Fluence (cm^{-2})**	**Δt (s)**	**HV (2.5kV)**
^{78}Kr Energy 2979 MeV	14.7	TAMU-01	$1.0\cdot10^{6}$	94	ON
		TAMU-01	$2.0\cdot10^{6}$	264	ON
		TAMU-02	$5.0\cdot10^{6}$	637	ON
		TAMU-03	$5.0\cdot10^{6}$	860	ON
		ETALON C1	$5.0\cdot10^{6}$	651	ON
^{40}Ar Energy 1561 MeV	3.9	TAMU-04	$2.0\cdot10^{7}$	512	ON
		TAMU-05	$2.0\cdot10^{7}$	464	ON
		TAMU-06	$2.0\cdot10^{7}$	331	ON
		ETALON 02	$2.0\cdot10^{7}$	274	ON
^{129}Xe Energy 2814 MeV	40.3	TAMU-07	$4.98\cdot10^{6}$	427	ON
		TAMU-08	$4.98\cdot10^{6}$	510	ON
		TAMU-09	$5.0\cdot10^{6}$	571	ON
		TEST-01	$6.18\cdot10^{5}$	59	ON
		TEST-01	$6.79\cdot10^{5}$	60	ON
		TEST-01	$5.76\cdot10^{5}$	59	ON
		ETALON 03	$1.0\cdot10^{7}$	921	ON
^{197}Au Energy 2172 MeV	86.3	ETALON 05	$1.8\cdot10^{7}$	1171	ON

Table.1. Samples under test

In test performed at TAMU was found that the Etalon suffered a non-destructive electrical discharge at about ~3300V, when an electrical arc was observed between one of the contacts and the Etalon border, likely due to a defect in the contact together with the high ionization of the surrounding air. It was decided, in order to preserve the Etalon integrity, to lower the nominal HV to a conservative value of 2500V. This value ensured no electrical discharge was triggered and it was still enough representative of the actual Etalon operational conditions

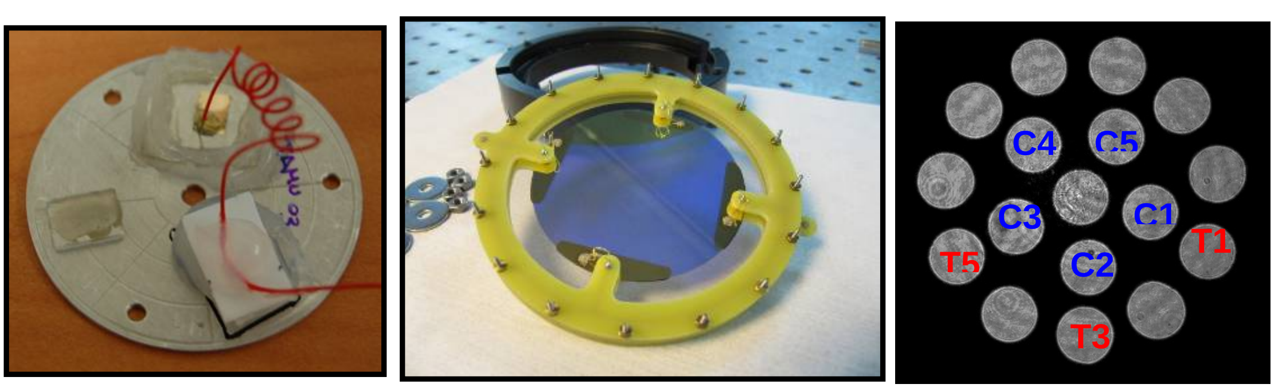

Fig. 2. Wafer Sample, raw etalon & Irradiation Mask.

III. ELECTRICAL RESPONSE.

For each irradiation test, the monitoring of the sample current in real time has allowed us the detection of a possible electrical disruption inside the sample, which supposes a dielectric breakdown in the device.

The Electric field will be applied between the + z-side and –z-side through High Voltage (HV) power supply (5 kV).The measurement and acquisition on-time of the sample holder current (Is) during the irradiation was performed using a Pico Ammeter (Keithley Mod. 6485) following the electrical schematic shown in Fig. 3.

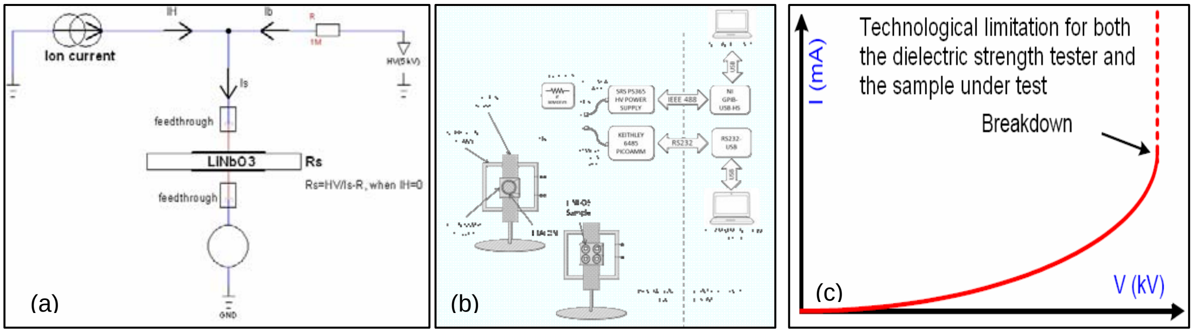

Fig. 3. (a) Schematic electrical diagram. (b) Acquisition and monitoring set-up. (c) Dielectric breakdown test.

The proton ion beam produces an ion current (*IH*). When beam off, *IH* = 0, and, thus, *Is* = *Ib*. In order to protect the picoammeter of a possible huge amount of current '*Is'* as a consequence of a shortcut induced in LN sample by a disruption event, a resistor is placed. Thus, if a significant change is appreciated in '*Rs'* after ion beam irradiation, it should be considered as a consequence of the ion induced damage being a fingerprint of creation of conduction channels by disruption events inside the LN sample, connecting both isolated faces and increasing the drift current between them, producing in the worst case, the total shortcut and the structural breaking of the sample. For the wafer samples a thin film of 40-50 nm Au will be deposited on the +z-cut LN face up to the ion beam playing the role of an active electrode, so the ions beam pass completely through the samples. They were individually mounted on Aluminium disks. The etalon has its own electrodes and coatings.

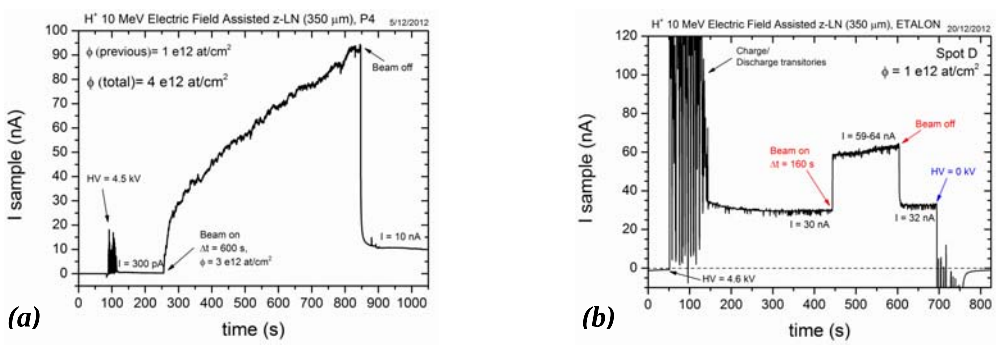

Fig.4. (a) Test 04 – Sample P4 (Spot 1/Step 2) electrical response to HV with H+ irradiation beam ON. (b) SPOT D current monitoring of the CSIRO Etalon (Area C4). Fluence 1012 cm-2, HV = 4.6 kV.

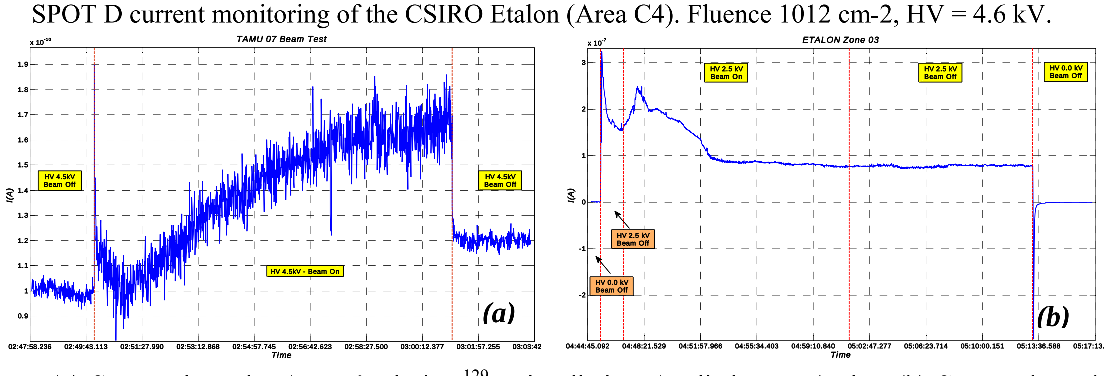

Fig.5. (a) Current through TAMU-07 during ^{129}Xe irradiation. Applied HV = 4.5 kV. (b) Current through Etalon Area T3 as function of applied HV=2.5 kV before, during and after irradiation.

In none of the tests carried out shows that a dielectric breakdown caused by the ion beam occurs. In the above figures it can be observed some results obtained on samples or the etalon.

IV. OPTICAL RESPONSE.

If radiation has somehow affected the physical properties of the etalon should see these reflected in their optical behaviour. The equations describing the performance of a single pass through an etalon are well-known [11-14]. The Airy formula describing the intensity distribution of the light passing through the etalon is:

$$I_t = \frac{\tau}{1 + F\sin^2(\delta/2)} \cdot I_i \tag{1}$$

Where I_i and I_t represent the incident and transmitted light intensity respectively, τ is the etalon peak transmission related to the fraction of light absorbed, *A*, by the combined effect of the etalon and the coatings. The parameter F is primarily related to the etalon surfaces reflectivity R.

$$\tau = \left(1 - \frac{A}{1-R}\right)^2; \qquad F = \frac{4R}{(1-R)^2} \tag{2}$$

The phase difference is given by:

$$\delta = \frac{4\pi}{\lambda} n' h \cos(\theta') \tag{3}$$

With λ representing the wavelength, *n'* the refractive index of the etalon, *h* is the thickness of the etalon (with a nominal value of h_0 for the reference wavelength λ_0) and the propagation angle inside the etalon, *θ'*.

For LN the refractive index changes with wavelength (dispersion). These changes have been included in the results presented in this work by taking into account the dependence of the refractive index with wavelength and temperature. The maximum transmittance occurs when δ is equal to zero or π. Hence the wavelength of maximum transmittance can be tuned by varying n', h, or θ'.

A. Transmittance

The LN is not totally transparent and this results in a reduction of the total transmittance of the etalon that need to be taken into account. Changes in the parameters described before can change the spectrum transmitted by the etalon. Mainly three effects on the etalon optical response could happen:

- Shift in the tuned wavelength: due to changes in thickness or the refraction index of the LN substrate. This shift could be correct during the mission with a proper method of calibration during the flight by applying another voltage different from the nominal one.
- Broadening of the transmission peak: due to changes in the thickness or the complex refractive index of the coatings, and, therefore changing the reflectivity of the dielectric multilayer mirrors. Changes on the coatings can be a since a small reduction of the reflectivity of the coatings produce a large decrease of the effective finesse and therefore, broadening of the peak tuned by the etalon. It could be critical for PHI and it cannot be corrected.
- Reduction of the transmission peak: the grown of colour centers would produce absorption peaks in the material (coatings or/and LN substrate). It could imply a reduction of the etalon transmission, being critical for the SO/PHI operation if the throughput requirement is not fulfilled.

The transmittance measurements were carried out with the ellipsometer VASE to guarantee the normal incidence. Although the same position before and after irradiation is not possible guarantee by mechanical positioners. All the measurements indicate that the etalon is very inhomogeneous.

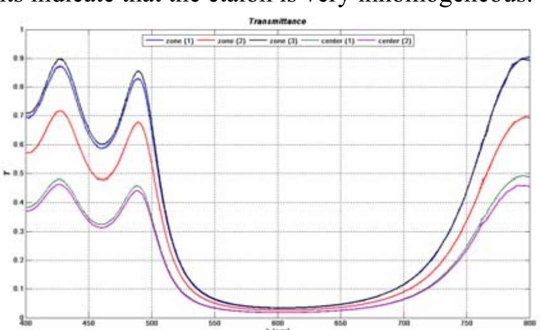

Fig.6. Transmittance in the same zones

The fig.6 shows two measurements very close to the centre of the etalon and other three measurements at inside a same area very close to each other. The location and magnitude of the transmission peaks change, so it the thickness and/or refraction index are changing. For the zones C1 to C5 were measured the transmittance before and after irradiation.

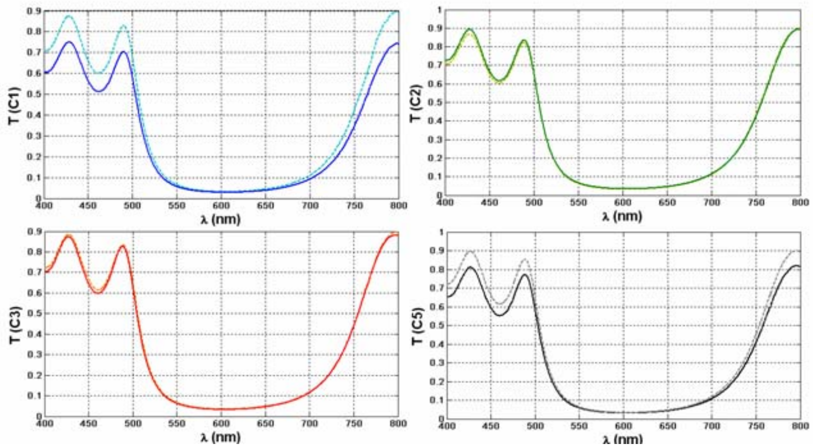

Fig.7. Transmittance Before (solid) & After (dash) Irradiation

We can not assert that the transmittance changes are due to irradiation and not to the inhomogeneity of the etalon, since we can not guarantee that we measure at exactly the same point.

B. Thickness Map.

The thickness of the etalon defines the Free Spectral Range (FSR: separation between two successive etalon peaks) of the spectrum transmitted by the etalon and it is directly related with the Full Width at Half Maximum (FWHM) that defines how broad is the peak tuned by the etalon. The etalon effective finesse which is usually measured empirically, contains information about all the parameters that can produce broadening and/or shift of the wavelength peak tuned by the etalon: defects, reflectance, aperture, and depending on the place situated along the optical instrument, tilt and relationship between the diameter of the beam entering the etalon and the beam from the telescope. We are going to try to get information about these two parameters measurement the transmittance in different angels and try to fit to an Airy function.

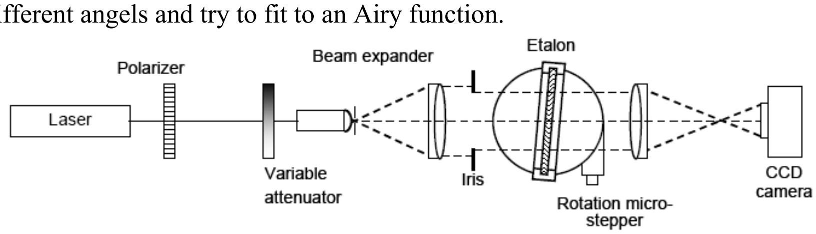

Fig.8. Thickness Map. Optical Set Up

If we represent the mean value of image for each angle and the images where we find a maximum, we can see that the etalon tuning in different zones, so the homogeneity (thickness, reflectance, refraction index, etc) is not right. This representation of the mean value versus the rotated angle should be similar to the Airy function for a given wavelength, and is very far from reality.

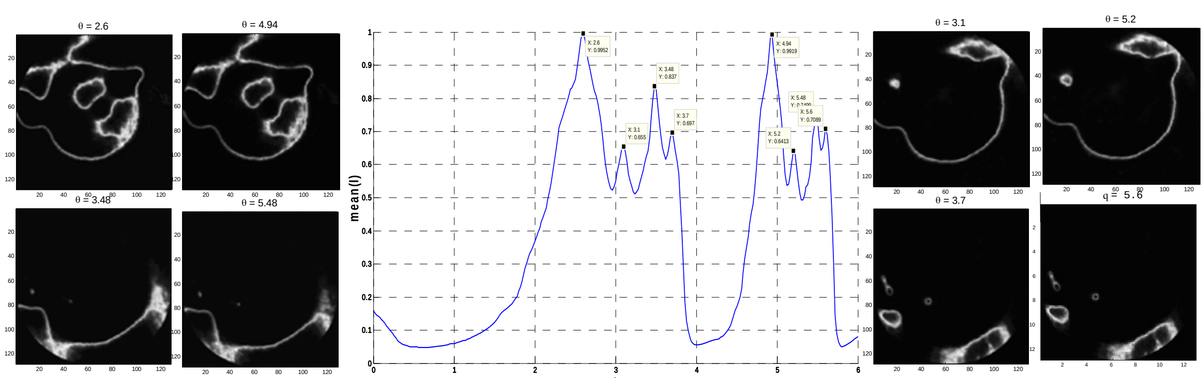

Fig.9. Behaviour Raw etalon

To these conditions we can not make an ideal flat-field and correct sampling for all the etalon. We had tried to find local solutions for different areas irradiated. For each local solution we found that the algorithm converges in very distant from each other solutions or even not converge. We have no exact coefficients tuning the etalon respect to temperature, so we represent the dispersion of the data on a relative value.

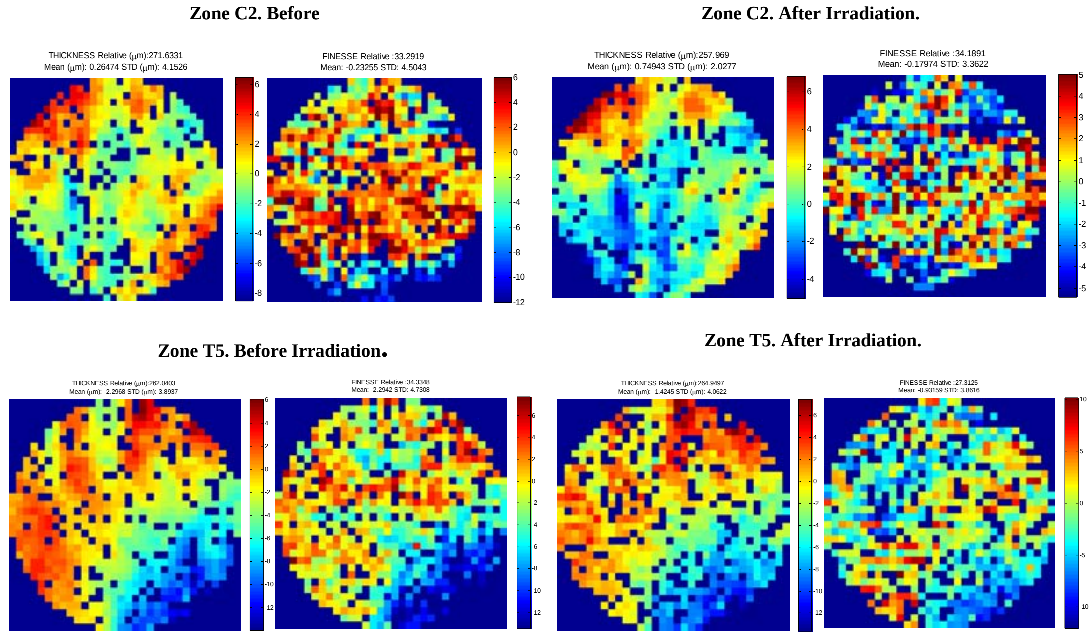

Fig.10. Relative Thickness Map

V. DISCUSION.

The etalon effective finesse (*Fe*), which is usually measured empirically, contains information about all the parameters that produce broadening of the wavelength peak tuned by the etalon. *Fe* can be written as follows:

$$\frac{1}{F_e^2} = \sum \frac{1}{F_i^2} = \frac{1}{F_R^2} + \frac{1}{F_d^2} + \frac{1}{F_a^2} + \frac{1}{F_{tilt}^2} + \frac{1}{F_{dif}^2} + \dots \tag{4}$$

Where F_d is the defect finesse, F_R is the reflectance finesse, F_a is the aperture finesse, F_{tilt} is the tilting finesse and F_{dif} is the diffraction finesse. If the effective fineness required for the instrument is greater than or equal to 30, so each factor of finesse must be greater than this value ($F_e > 30 \rightarrow F_i > 30$). Usually the most significant is the reflectance finesse.

$$F_R = \frac{\pi\sqrt{R}}{(1-R)} \quad \rightarrow \quad F_R > 30 \quad \Rightarrow \quad R > 90.1\%; \qquad \Delta R_0 = \frac{2\sqrt{R_0}\cdot(1-R_0)^2}{\pi\cdot(1+R_0)} \cdot \Delta F_{R0} \tag{5}$$

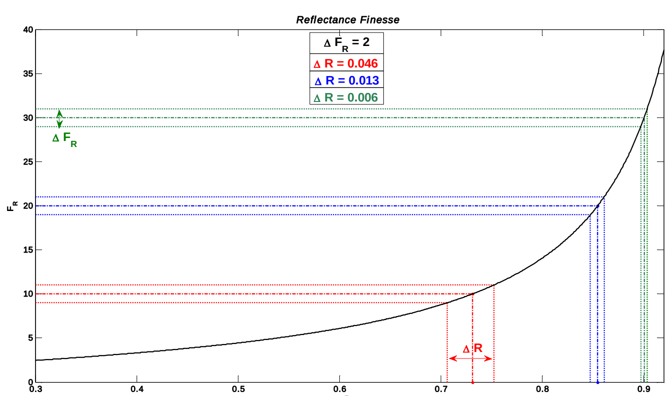

Fig.11. Reflectance Finesse for an Ideal Etalon.

So whether, if we see changes in the finesse of a high quality etalon, we should be able to appreciate changes of less than 0.6% reflectance. However, a low finesse etalon reflectance changes in this order of magnitude do not translate into significant changes in fineness (as in our case). So it the effects due to radiation may not be reflected in measurements of thickness or finesse.

VI. CONCLUSIONS.

In all wafer samples, when polarizing the LN with 4.5 kV an increase in the electrical current through the sample of up to few tens of nA was measured, corresponding to an average resistivity of around ~1014 Ohm-cm, in full agreement with the expected value for a common LN crystal. When turning the beam on with the HV still applied, different current results were obtained depending on the specific tested sample and the environment conditions. Even in the case of sample TEST-01, the polarization field was increased up to 7500V during the irradiation with ^{129}Xe. No dielectric breakdown was observed for any sample. Moreover, it was also observed that no permanent damaged in the LN electrical properties was induced.

The full size Etalon was also irradiated with the most penetrating ion species (^{78}Kr, ^{40}Ar, ^{129}Xe and ^{197}Au) under high voltage (4.5-2.5kV) without observing any electrical breakdown or resistivity change. It can be concluded that the LN etalon doesn't exhibit sensitivity to ion induced dielectric breakdown, for the mission representative ion species tested, and therefore it can be safely operated at the nominal high voltages required by PHI instrument.

With respect to the optical response, we have not been able to obtain true conclusions. Due to the in homogeneity of the etalon and no possibility to ensure the same position, transmittance measurements are not considered representative to identify whether changes are the result of irradiation. We have tried to make a measurement of the etalon thickness map. The behaviour of the etalon does not show the optimum conditions for such measures (in homogeneity. different temperatures, saturation or bad contrast at the images. Errors of fineness and thickness are so high that could hide any effect due to irradiation.

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