MINCOR - Minimisation of crystal oscillator cosmic radiation effects

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INTRODUCTION

Quartz crystal oscillators for Space applications, due to their specific features, give high signal spectral purity, very good short-term and long-term frequency stabilities. These features are required in Navigation systems, science but also radar and telecom applications. As "timekeeper", quartz crystal oscillators are designed to minimize their sensitivity to the environment and one of them is the ionizing radiation which generates frequency drift (short-term and long term).

To ensure that the quartz crystal oscillators are achieving the required level of performance for every space application and remain in its specifications during the duration of the satellite mission, resonators are manufactured using specific processes. These processes may add additional costs or delays.

In the traditional space sector, mainly in GEO with long missions, the heritage and the reliability of the components are the drivers of their selection process. However, with the emergence of New Space, low-cost LEO satellites are now designed. The selection of the components is a key driver and it is required to design oscillators using quartz crystal resonators manufactured at the right cost while achieving the targeted performance.

It is in this frame that the project MINCOR, funded by ESA, was started. It aims to bind the real needs and the right processes. It aims also to identify potential improvement paths for reducing the radiation sensitivity.

This paper presents the work achieved up-to-now on the project.

RADIATION REQUIREMENTS

The radiation may affect the resonator and oscillator performance in different manner considering Dose Rate, Total Ionization Dose (TID) or Total Non-Ionizing Dose (TNID). In the study, a quite exhaustive analysis of the space environments was done with different missions. Several orbits and durations were considered based on existing space projects. Table 1 summarizes the mission's parameters:

Table 1 : Mission profiles

Type	Comments	Altitude	Inclination	Mission duration	Solar active period	Confidence interval
Telecom GEO	Standard telecom	35784 km	0°	18 years	14 years	85%
Telecom LEO	OneWeb, Vantage	1200 km	87.9°	12 years	8 years	90%
EO (SAR) LEO	SSO	800 km	98°	5 years	5 years	95%
Navigation GNSS MEO	Galileo, BeiDou	23222 km	56°	15 years	11 years	85%
MEO	O3B	8000 km	0°	7 years	7 years	90%
Deep Space	L2, Mars, Moon	-	-	15 years	11 years	85%

Based on these mission profiles, radiations were simulated using OMERE software, a tool developed by TRAD with the support of the CNES (National Center for Space Research). The models used for the calculations are compliant with the European Cooperation for Space Standardization ECSS-E-ST-10-04C Rev.1, 15/06/2020. It includes trapped electron (AE8), trapped proton fluxes (AP8 min) and average solar fluxes (ESP). Dose rate could be evaluated over the whole mission's lives permitting to evaluate the Total Ionization Dose.

Note that the solar activity is 11-year-periodical. For TID calculations, the date and time of launch were set to maximize the solar active period (worst-case). The solar fluxes are averaged over all the mission duration (total fluence provided by the ESP model). The confidence interval is defined in consistence with the duration of the mission.

TNID was also evaluated using OMERE 5.4 software. For each mission, the environment model was defined according to the recommendations from ECSS-E-ST-10-04C. For each mission, the Displacement Damage Equivalent Fluence (DDEF) was calculated considering 1 MeV neutrons. The Non-Ionizing Energy Loss (NIEL) data considered for the calculations are SILICON (Nemo-ONERA), which includes neutrons contrary to Summers93 model.

As an example, a representation of the path for the GNSS MEO mission profile and the corresponding dose rate is presented in Fig. 1.

Distribution and cumulative distribution could be evaluated as presented in Fig. 2.

To be noticed, that a thickness of 3mm of aluminum was used as a standard shielding of the device. Complete calculations are available as a function of this aluminum thickness. For instance, Total Dose received for GNSS MEO mission as function of aluminum thickness is presented on Fig. 3.

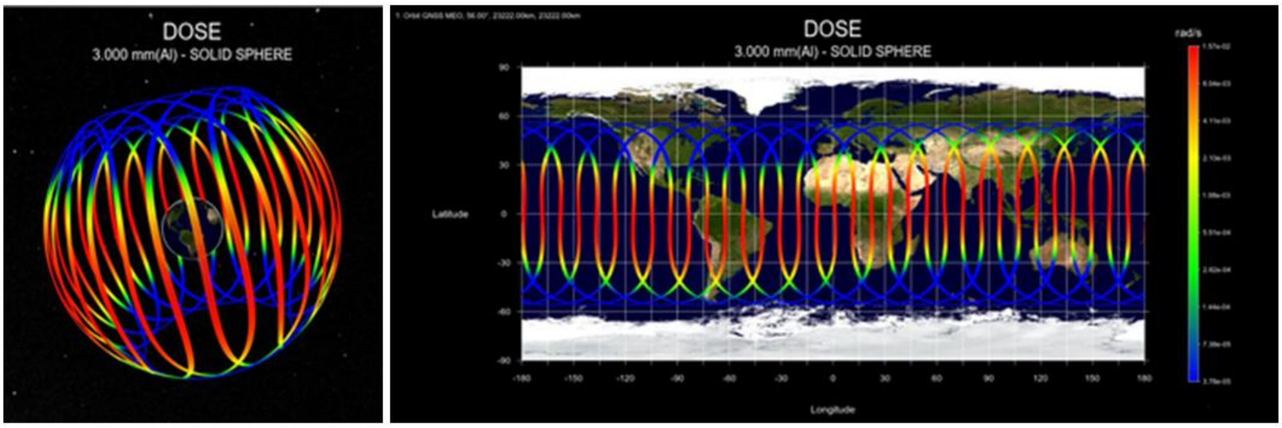


Fig. 1: Path and dose rate of the GNSS MEO mission

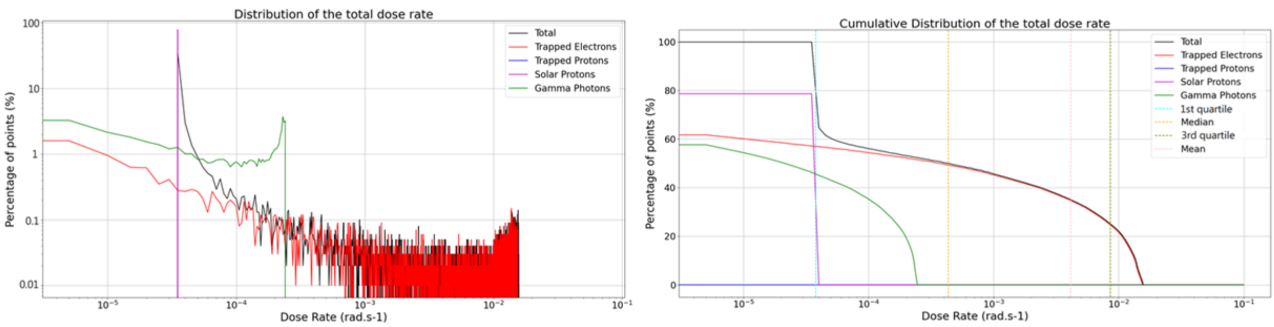


Fig. 2: distribution and cumulative distribution of the GNSS MEO mission

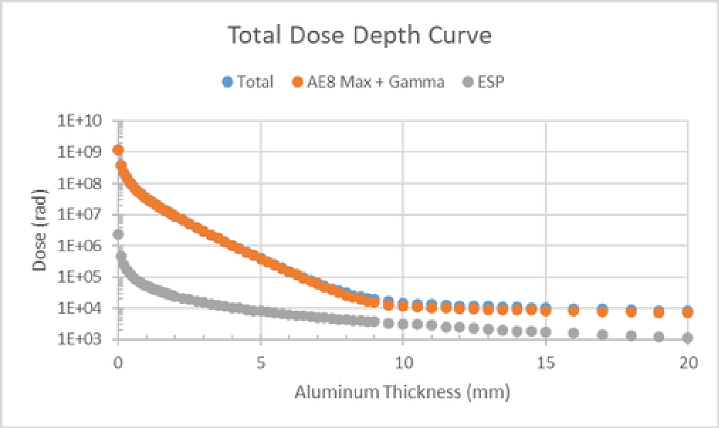


Fig. 3: Total dose received for GNSS MEO as a function of aluminum thickness

These calculations permitted to assess the Total Ionization Dose, dose rate and DDEF for all the missions.
For reference, TID values are ranging from 1.47e4 to 2.94e6 rad, dose rate from 7.33e-14 to 1.57e-2 rad.s-1 and DDEF from 1.22e11 to 6.11e12 n/cm2.

TECHNOLOGY AND PROCESS REVIEW

In order to understand the possible impact of radiations on the frequency of a resonator, a presentation of the technology is done. Quartz resonator structure is presented in Fig. 4.

Quartz material is an anisotropic crystal that presents an electromechanical coupling through its piezoelectric property. By placing electrodes on both sides of a quartz plate it is possible to excite its mechanical eigen resonances.
Quartz resonators are of interest because their crystalline structure gives them a very high Q-factor and allow to have very low physical evolution during the life of the product. Furthermore, it exists different quartz cut presenting low dependency to temperature. All other elements constitutive of the resonator and the corresponding manufacturing processes are chosen and optimized with highest care to have no physical evolution over time.

Main physical phenomena affecting the frequency are the following:

- Mass loading: additional weight on the quartz lens will decrease the frequency. This phenomenon can occur through oxidization of the electrode for instance. The order of magnitude of this phenomenon is 1ppm frequency drift per atomic layer. Resonators are especially sealed under secondary vacuum level to avoid further evolution.
- Mechanical stress: the stress will affect the frequency through the change of the effective elastic constant driving the mechanical wave. Temperature gradient, barometry or acceleration for instance may change the stress of the vibrating part. For acceleration sensitivity the order of magnitude is 1ppb per g.
- Quartz material: as the velocity of the wave depends on the material constants change in material will affect the frequency. Material used are synthetic materials that present very low level of defects and very low impurities (typically <1ppm).

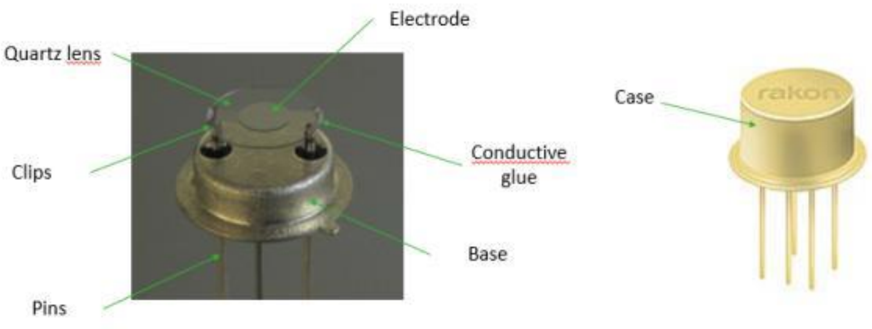


Fig. 4: Quartz resonator structure

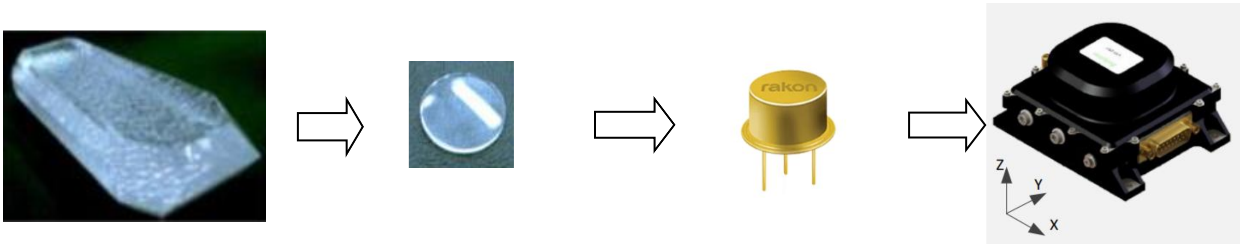
In conventional applications, mass loading and stress are the main points of interest for quartz resonator however, for space applications, material is also a concern because radiation may induce changes in the material.

The manufacturing of quartz resonator and oscillator (cf. Fig. 5) is a quite long process.

It involves different kind of technologies and know-how in different environment (synthetic production of quartz bar, sawing, lapping, polishing, etching, cleanroom processes, evaporation, vacuum technology, chemical and electrochemical processes, plasma, sealing technics, measurement technics, electronic-, mechanic- and thermo-mechanic-design…)

A schematic flow for the production of an Ultra Stable Oscillator (USO) is presented in Fig. 6 .

This process was developed over the decades since World War II and the continuous demand on precision and stability has led to mastering of the processes where very subtle elements may have an impact on the performance.



Quartz bar　　Quartz lens　　Resonator　　Oscillator

Fig. 5 : From Quartz bar to Oscillator

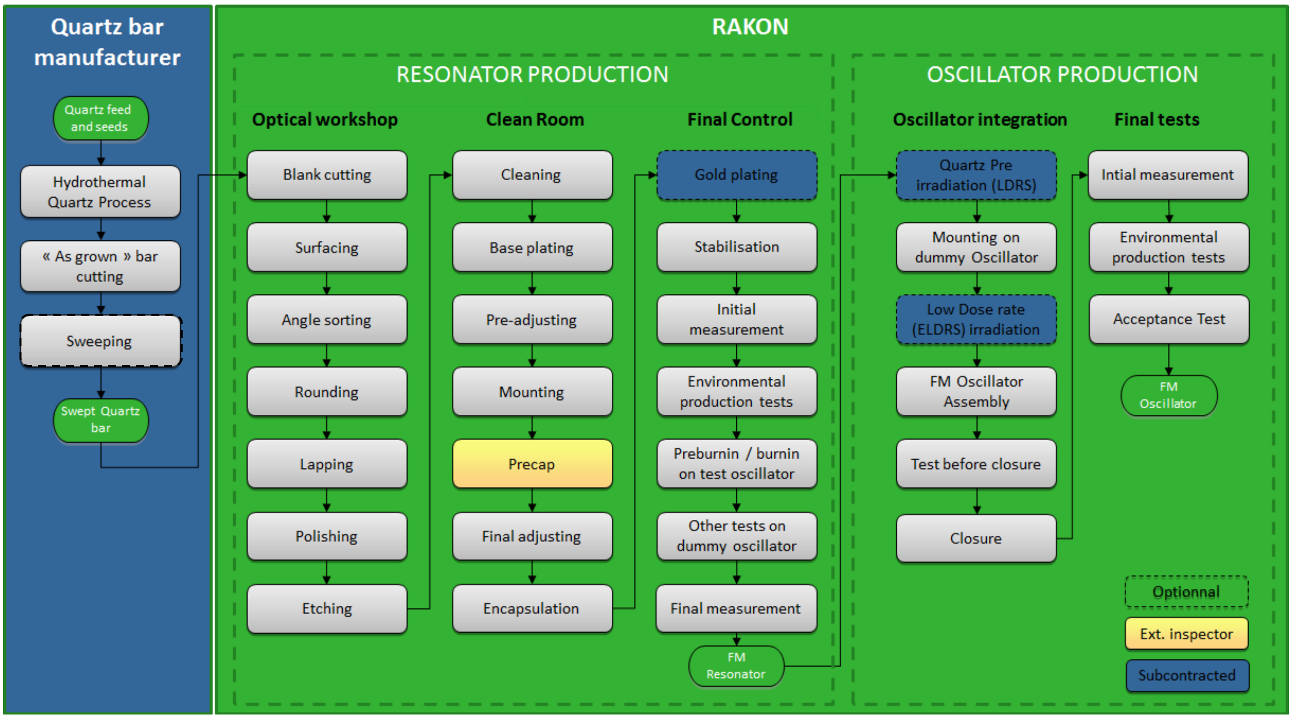


Fig. 6: Manufacturing flowchart of an Ultra Stable Oscillator

Within the MINCOR project, a deep bibliographic analysis was done permitting to place or re-place on the table the main contributors to the radiation sensitivity.

Numerous studies have been performed on the effect of irradiation on quartz material for more than 100 years since the discovery of X-ray in 1895 and later of radioactivity in 1896. As early as 1898, discoloration of crystal material and especially quartz submitted to radiation has been reported [1][2].

In the first half of the 20th century, with the invention of quartz crystal oscillator by Cady in 1921, studies started on the impact of irradiation on frequency of quartz resonator. In 1945, BT cut, AT-cut and Y-cut could already be compared, and the use of radiation was even at that time considered for the adjustment of quartz plate frequencies [3].

Later, with the development of nuclear weapons and then, with the development of space activities, the study of the effects of radiation has been increasingly important [4] [5] [6] [7].
Importance of raw material, especially impurities, was early detected. At the beginning natural quartz was used but since its invention in 1845 the hydrothermal growth of crystal (and especially quartz) the process has then been extensively developed after World War II especially because of the shortage on electronic grade material that was essentially from Brazil.

In 1956, Sawyer a US company introduced the first commercial process for growing quartz bar. This led to further reductions of imperfection in quartz material compared to natural crystal.
During following years, electro diffusion of ions (sweeping) was studied as a method to reduce quantities of impurities in the quartz. This process consists, after growing the quartz bar, in applying an intense electric field to the material to "sweep" the ions inside the bulk material at the external portion of the bar and then remove the impurities by cutting this portion.

Process was studied during these years with the target to improve the acoustic absorption (i.e., improve the Q factor) especially using different atmosphere during the sweeping (air sweeping in 1963 [8], vacuum sweeping in 1967 [9]. Nevertheless, the reduction of the radiation sensitivity was also of interest, and it led, in 1976, to its introduction in quartz bar production as a process to reduce the sensitivity of quartz to pulse radiation [10].
Since the late 70's, the low dose radiations effects have been then a continuous subject of interest especially because of the non-well understood mechanisms [11] [12] [13] [14] [15] [16] [17] [18] [19] [20] [21].

In this research effort, for decades RAKON has participated into numerous studies of the quartz material with CNES, other French agencies and SICN/GEMMA (a French quartz manufacturer). It permitted to support SICN/Gemma in the development of very high-quality material. This led also to numerous articles in 2001, 2003 and 2006 [22] [23] [24] [25].

This development permits today to Rakon to propose USOs with guaranteed radiation sensitivity of 2.10-12/rad tested up to 100krad with low dose rate specification. For this, very high Level of quartz quality, pre-irradiation and screening at low dose rate are required.

To be noticed that, in the years 2010s, GEMMA quartz – the last producer of very high-quality quartz in Europe - stopped its quartz synthesis production line. As this material is strategic for European supply, this activity was relaunched by Cristal Innov platform -close to Grenoble-, based on the best skills still existing in Europe and with the support of CNES and other French agencies.

For the MINCOR project the bibliographic analysis led RAKON to consider the following technical elements: quartz material, electrode material, surface and subsurface preparation.

Ultra Stable Resonator were excluded from the study as their exigences are far higher than LEO New Space requirements, and, as mentioned earlier, they do not suffer as strongly as New Space market from the time and cost constraints. Furthermore, their study is continuously done with CNES support.

Considering the New Space market and the technical aspects, RAKON chose to study:

- 3 enclosures : T807, T1507 and SMD
- 2 cuts: AT-cut and SC-cut
- 3 frequencies: 10, 50 and 100MHz
- 4 different materials: THQ, HQ SW, HQ, SQ. The THQ material is the Cristal Innov material considered as a reference material for the study. HQ and HQ SW are respectively High Quality and High Quality Swept material, SQ is Standard Quality material.
- 3 electrodes materials: aluminum, silver, gold
- 2 kinds of sub-surfaces preparation
- 2 kinds of cleaning

Given the number of possible combinations the most meaningful combinations were chosen leading to:

- 6 variants for T1507 10MHz SC-cut resonators
- 8 variants for T807 100MHz AT- and SC-cut resonators
- 1 variant for SMD 50MHz AT-cut resonators

TEST PLANS

Since the main interest is LEO orbits the radiation profile has a very strong periodic profile consisting of exposure period followed by non-exposure. This causes a strong interest in the Low Dose rate behaviour. Indeed, frequency may shift quite strongly during the period of exposure and come back during the non-exposure period. Because the levels are very low, it is needed to measure the resonator into an oscillator during the cycle.
To this aim, Rakon designed test oscillators that have specific structure permitting to expose only the resonator to the radiation (cf. Fig. 7 and Fig. 8). A movable wall made of lead permits to simulate the periodic exposure while the frequency is continuously monitored (Fig. 9)
At last, as the objective of the study is to avoid the pre-irradiation and because of the known stabilization with increased radiation, the project did not concentrate on the TID. Nevertheless, two strong radiation deposition were added to confirm the stabilization phenomenon (cf. Fig. 10) with intermediate Low Dose rate study.
Because the electronic may suffer from the high dose radiation, the resonator are removed from the oscillator during these parts of the radiation profile.

Fig. 7: Test oscillator structure (left) and shielding principle to expose only the resonator to radiation (right)

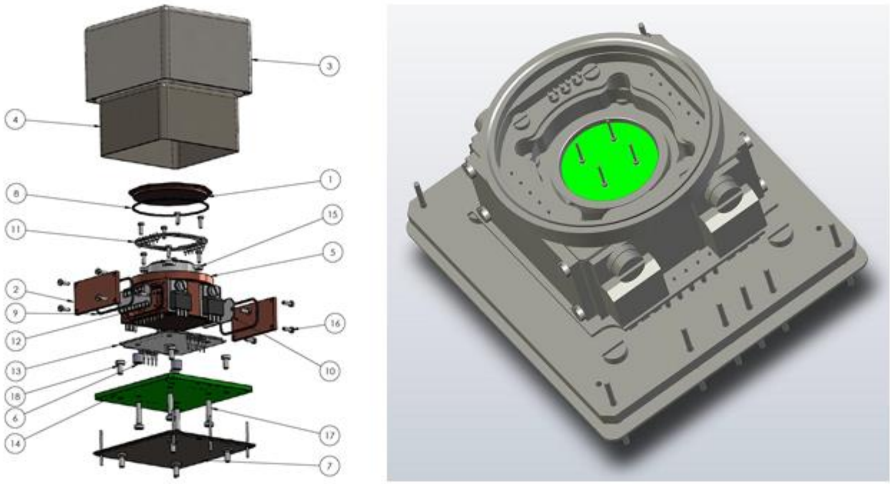


Fig. 8: Exploded view of the test oscillator (left) and mounted oscillator (right)

Fig. 9: Lead shield with holes with the movable wall (top left), oscillators on the lead wall from behind (top right), gamma source (bottom left), measurement system (bottom right)

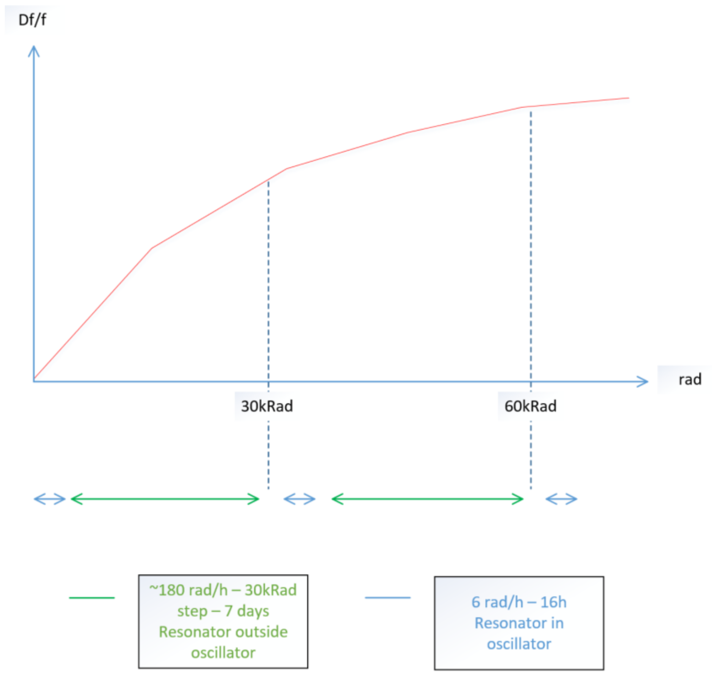


Fig. 10: Radiation profile

MANUFACTURING OF CRYSTAL RESONATORS

Resonators were manufactured on the ESCC3501 Space Qualified production line with all necessary documentations and traceability. They were measured, screened, aged and, at the end, for each 15 variants, 4 resonators were identified to be representative of their corresponding group and with an ageing characteristic stabilized permitting to detect the frequency change during the further Low Dose rate measurement. They are now ready for the first Low Dose evaluation (Fig. 11).

In the meantime, the different materials were sent, in blind test for comparison, to two different laboratories (from which Cristal Innov).

To be noticed that a specific measurement method at cryogenic temperature was developed at Cristal Innov for this project. This permitted to see specificities of swept material (Fig. 12).

Fig. 11: Resonators from 1 of the 15 groups.

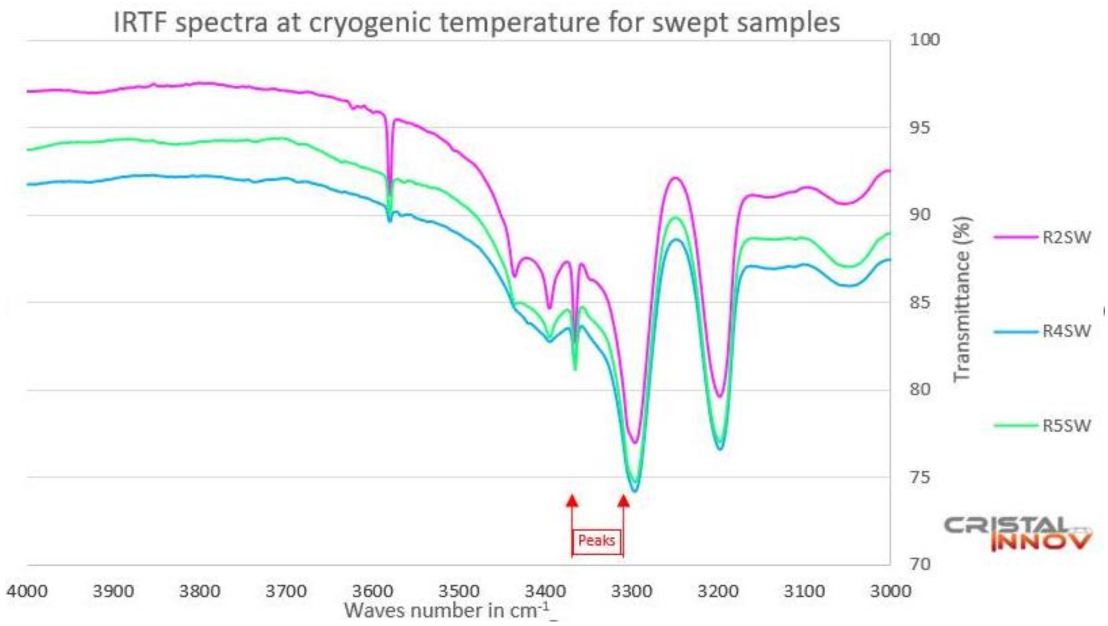


Fig. 12: Characterization of the transmittance as a function of wave number

All materials were presenting a very good Q factor (Infrared Absorption Coefficient α) down to 0.018 for two bars (from which Cristal Innov material) up to 0.031 (which remains quite good).

For inclusions all materials were measured from Ia class, for etch channel all from class 1 and the etch pits density ranges from 3.2 to 14.6 /cm² with the lowest value for Cristal Innov.

For impurities, the tests showed that the material were with impurities lower than 1ppm.

Nevertheless, tests confirmed the state-of-the-art level of Cristal Innov material with impurities down to 0.03ppm for Al and below 0.05ppm (the measurement limit of the system) for Li, Na, Mg, K, Ca and Fe ions.

CONCLUSION

In this paper we presented the objective of the MINCOR project, and the work done up-to-now. We determined the resonator and oscillator types relevant for the study, we determined the mission profiles and their corresponding radiation level over mission life, we determined the different material and process variants to be studied , we analysed the different quartz materials confirming the state of the art level of Cristal Innov material, we produced, screened, tested all the resonators needed for the irradiation study and we proposed a suited method and a test plan for assessing resonator performance without perturbation by the oscillator. Next steps are ongoing with the measurement of the Low Dose rate behaviour of the 60 resonators. First results are expected in last quarter of 2024.

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