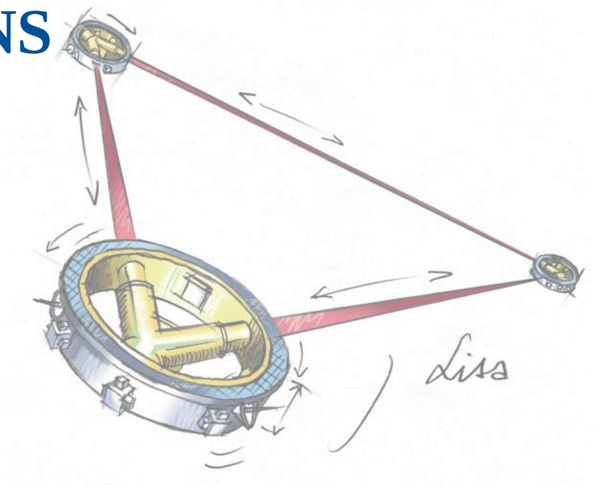
RADIATION TOLERANCE OF LOW-NOISE PHOTORECEIVERS FOR LASER INTERFEROMETRIC SPACE APPLICATIONS



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Outline

Introduction

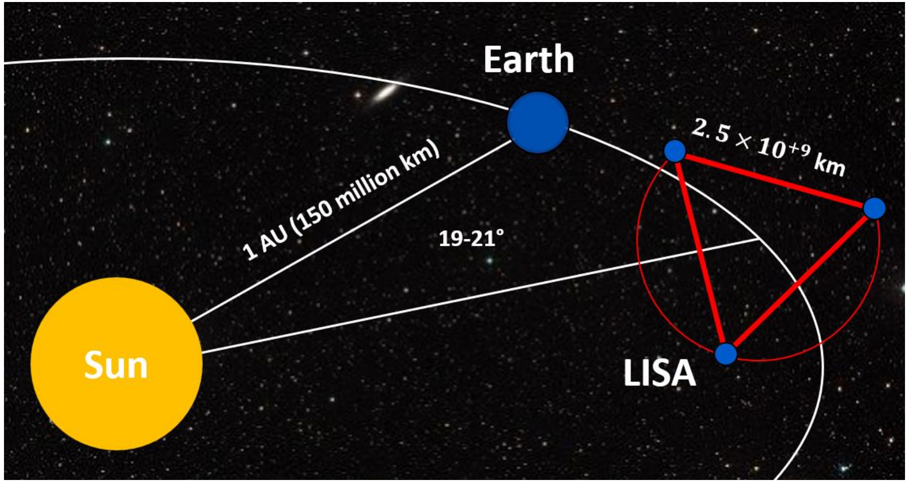
- LISA: Laser Interferometer Space Antenna
- LISA's Radiation Environment

Methods & Result

- Irradiation Campaign Overview & Test Procedure
- QPD Dark Current Damage Factor vs Irradiation
- QPD Quantum Efficiency vs Irradiation
- QPR Equivalent Input Current Noise vs Irradiation
- QPR Phase & Amplitude Response to an Interferometric Equivalent Signal

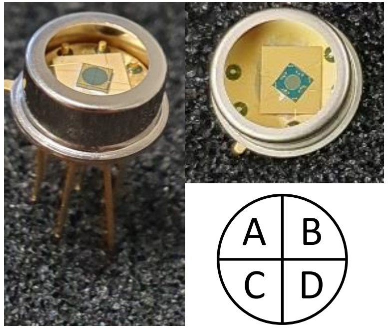
Conclusion

Laser Interferometer Space Antenna (LISA)



Quadrants Photoreceivers (QPR)

QPD InGaAs (JP&NL)
ϕ=1.0, 1.5 & 2.0 mm



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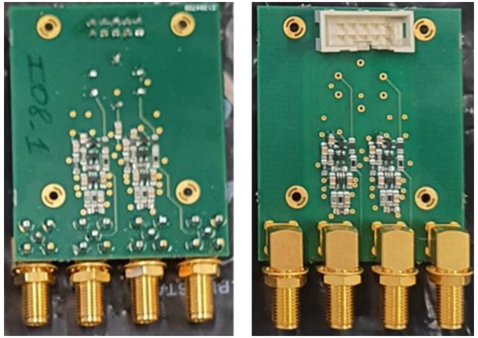
Double side FEE (DE)
Transimpedance Amplifier (TIA)



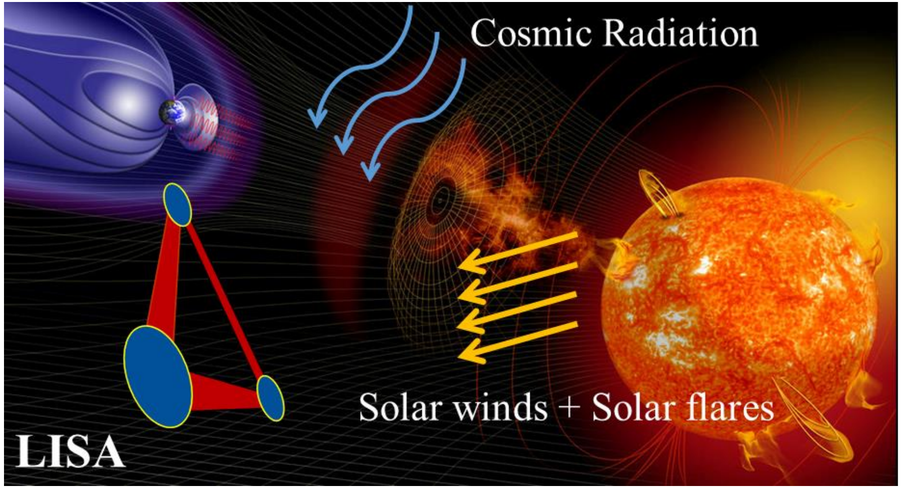
LISA objectives

- Gravitational waves detection
- Low-frequency range [0.1 mHz; 1 Hz]
- High precision interferometer (~pm/$\sqrt{Hz}$)

LISA QPR main requirements

- QPD Dark current < 1 µA
- QPD Quantum Efficiency > 81%
- QPR Input current noise < 2 pA/√Hz

LISA's Radiation Environment



GSFC Model (Protons)

- E = [0.1; 500 MeV]
- Fluence = [$6.0x10^{+07}$; $5.8x10^{+11}$ p/cm²]

Mission Conditions:

- Duration: 12.5 years
- Shielding: 3 mm Al
- Detector: InGaAs (QPD material)

Radiation main physical effect

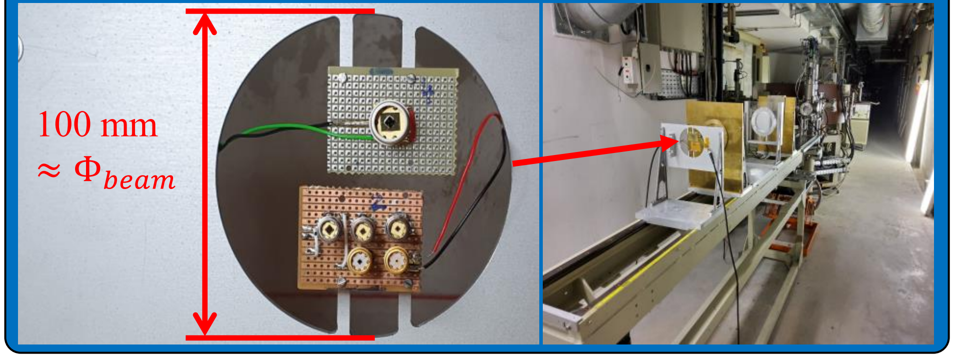
- Ionizing Damage (e.g., TID)
- Non-Ionizing Damage (e.g., DDEF, DDD)

Requirements (ESA L3-EST-MIS-SP-001)

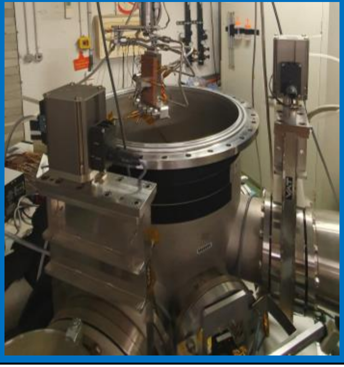
Particle type	Energy (MeV)	DDEF (#/p/cm²)	TID (krad)	DDD (MeV/g)
Proton	10	$1.01x10^{+11}$	101.7	$6.62x10^{+8}$
	20	$1.41x10^{+11}$	71.9	$6.62x10^{+8}$
	60	$1.80x10^{+11}$	38.5	$6.62x10^{+8}$
Gamma	1.25		40	

Irradiation Campaigns Overview

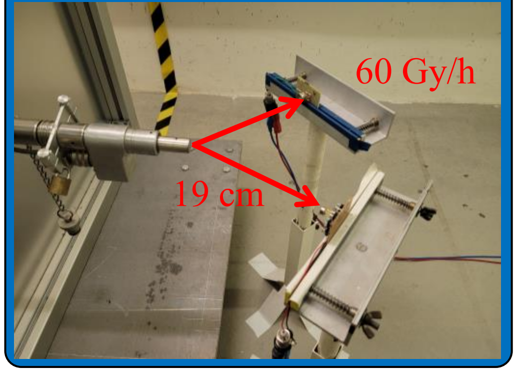
Proton @ CAL



Electron @ONERA



Gamma @ONERA



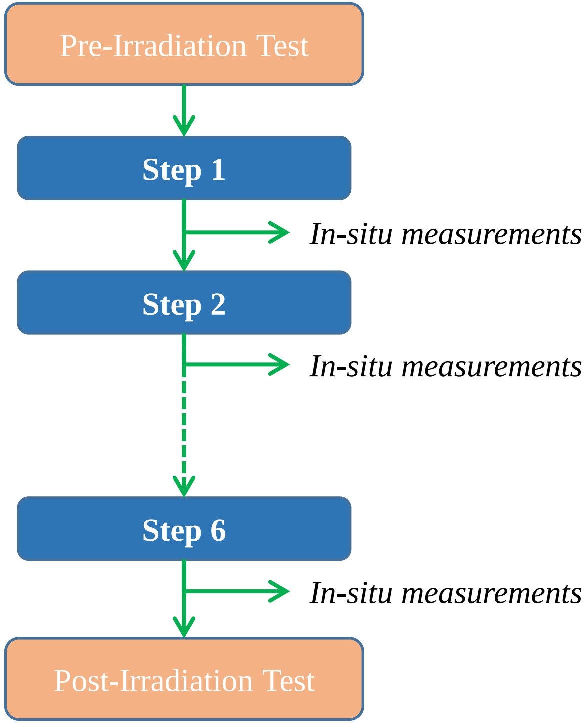
Experimental irradiation conditions

Particle type	**Energy (MeV)**	**Fluence (p/cm²)**	**TID (krad)**	**DDD (MeV/g)**
Proton (CAL)	20	$1x10^{+12}$	237	$4.9x10^{+9}$
	60	$1x10^{+12}$	104	$3.6x10^{+9}$
Electron (ONERA)	0.5	$5x10^{+12}$	105	$3.36x10^{+7}$
	1	$5x10^{+12}$	100	$9.71x10^{+7}$
Gamma (ONERA)	1.25		237	$\sim 7.6x10^{+7}$

~5 × LISA requirements

NOTE: irradiation applied only on QPDs

Irradiation Test Procedure



Pre & post irradiation tests

- ✓ QPD dark current vs V_{bias} vs temperature
- ✓ QPD capacitance vs frequency
- ✓ QPD quantum efficiency
- ✓ QPR input equivalent current noise vs frequency
- ✓ QPR phase & amplitude of AC signal vs frequency

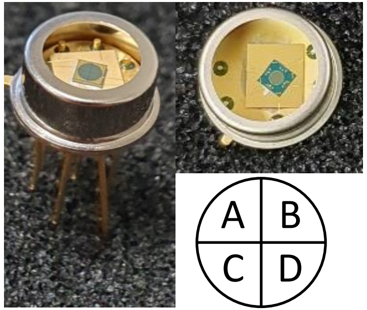
In-situ irradiation tests

- ✓ QPD dark current vs V_{bias} vs temperature
- ✓ QPD capacitance vs frequency
- ✓ QPR equivalent input current noise vs frequency

Effect of irradiation on the QPD performance

Quadrants Photodiode (QPD)

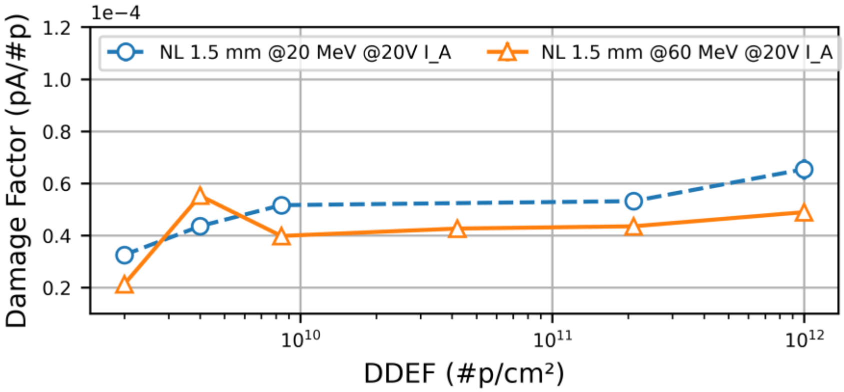
QPD InGaAs (JP&NL)
ϕ=1.0, 1.5 & 2.0 mm

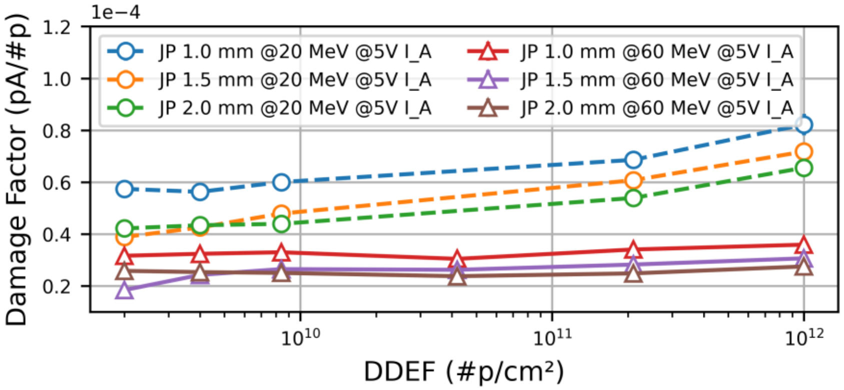


<u>Parameters</u>

- QPD Dark current
- QPD Quantum Efficiency

QPD Dark Current Damage Factor from Proton Irradiation

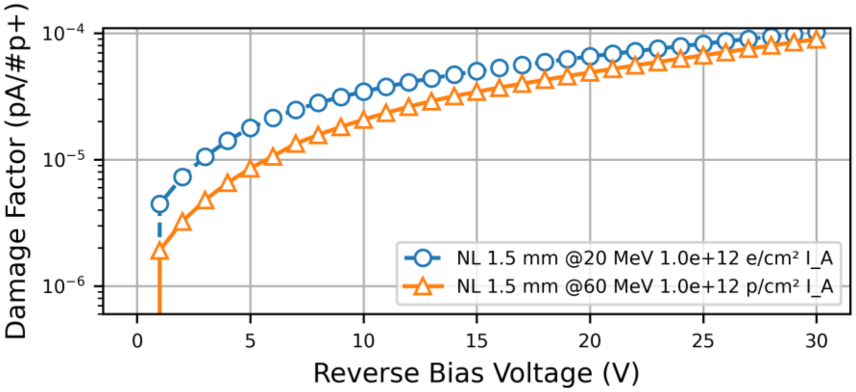


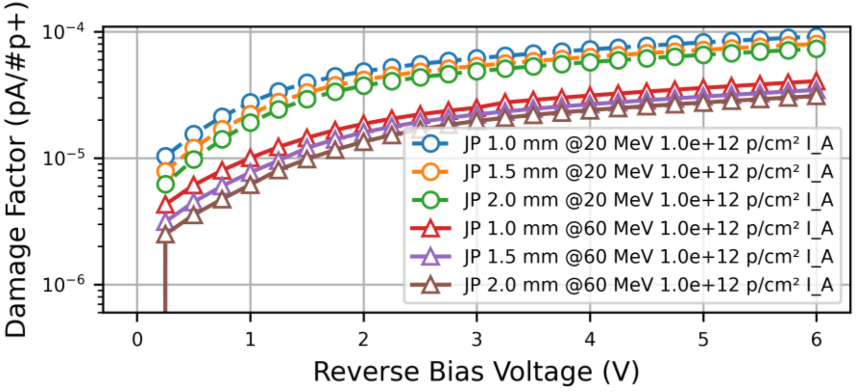


$$K_{Idark} = \frac{I_{dark}(\Phi) - I_{dark}(0)}{\Phi \cdot S}$$

- K_{Idark} increase with fluence
- K_{Idark} dependent of energy, techno & size

QPD Dark Current Damage Factor Dependance





- K_{Idark} increase with V_{bias}

➢ Reduce V_{bias} to limit degradation

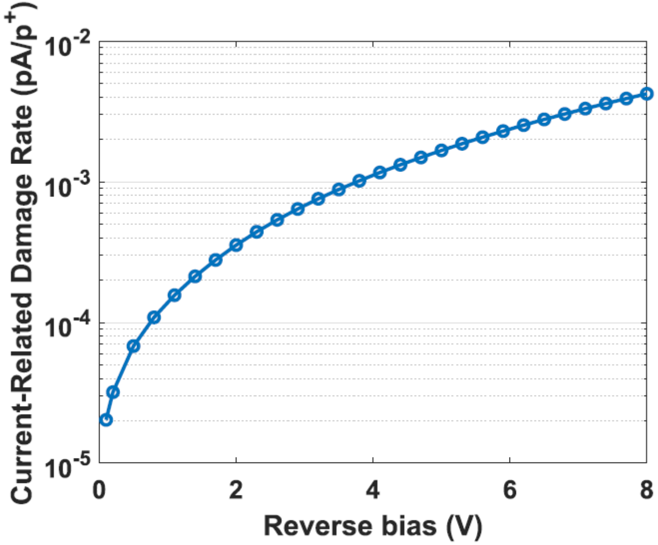
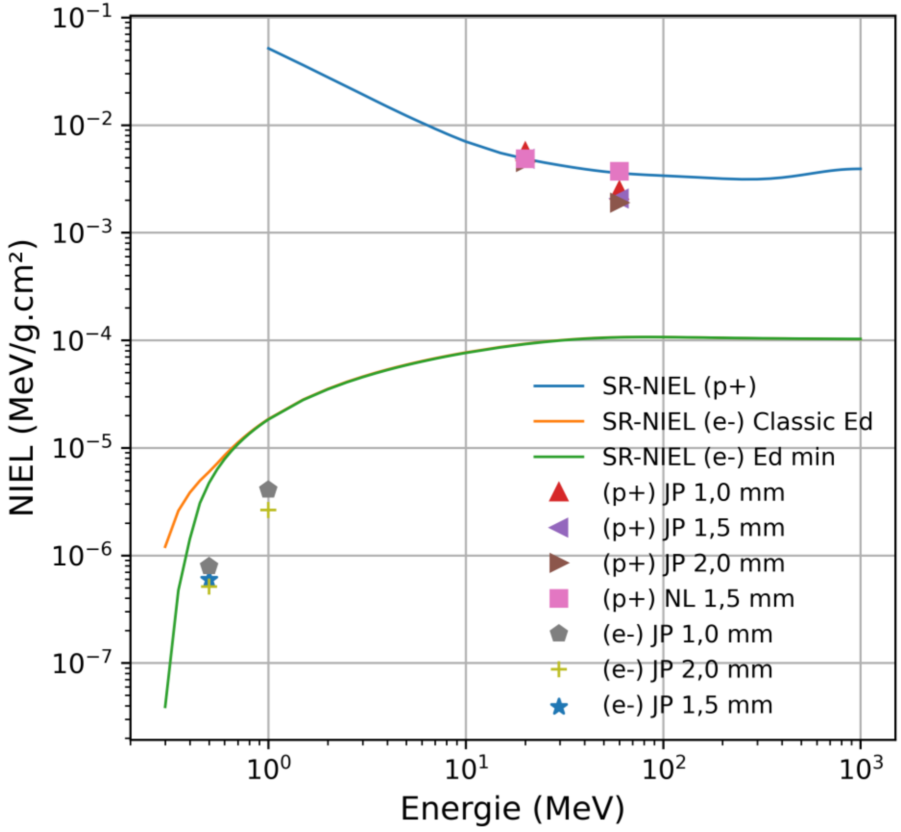


Fig. 6. Dark current-related damage rate for Diode5 as a function of the bias.

M. Benfante _et al._, « *Electric Field-Enhanced Generation Current in Proton Irradiated InGaAs Photodiodes* », _IEEE Transactions on Nuclear Science_, vol. 70, no 4, p. 523-531, avr. 2023, doi: https://doi.org/10.1109/TNS.2023.3244416

QPD Damage Factor vs NIEL (1/2)



$$K_{Idark} = \frac{I_{dark}(\Phi) - I_{dark}(0)}{\Phi \cdot S} \propto NIEL$$

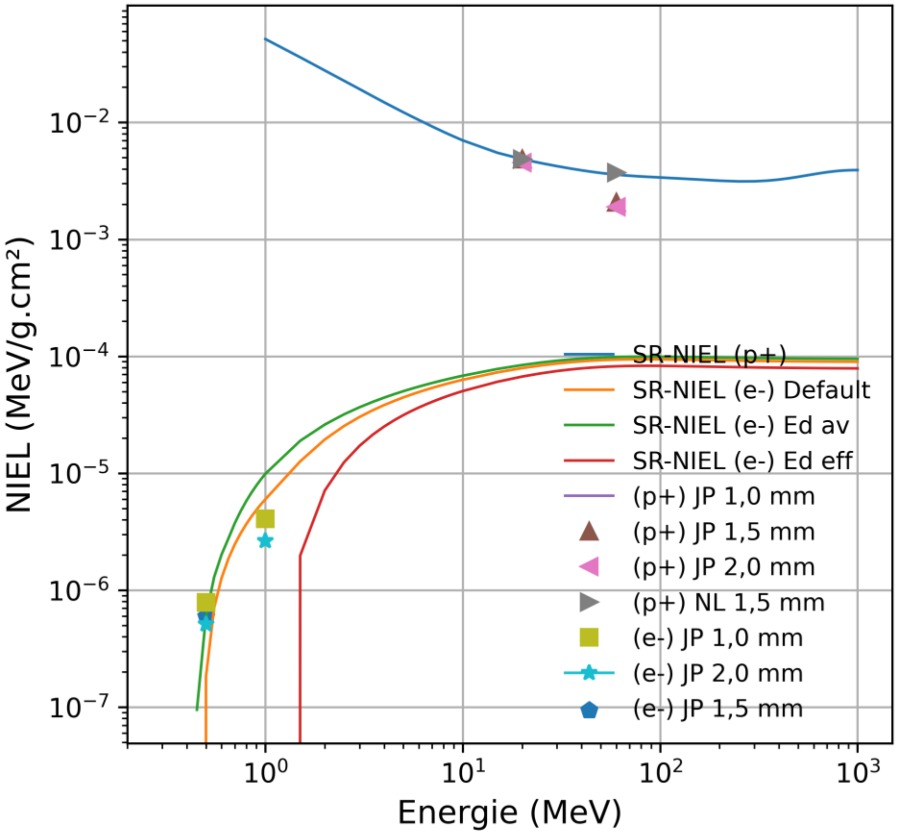
Parameter for SR-NIEL calculation (electron)

	Classic Ed	Ed min[1]
$In_{0.53}$	15	10
$Ga_{0.31}$	10	12
As	10	15

- ➢ Discrepancy with Electron NIEL values

[1] A. Yu. Konobeyev, U. Fischer, Yu. A. Korovin, et S. P. Simakov, « *Evaluation of effective threshold displacement energies and other data required for the calculation of advanced atomic displacement cross-sections* », _Nuclear Energy and Technology_, vol. 3, no 3, p. 169-175, sept. 2017, doi: https://doi.org/10.1016/j.nucet.2017.08.007

QPD Damage Factor vs NIEL (2/2)



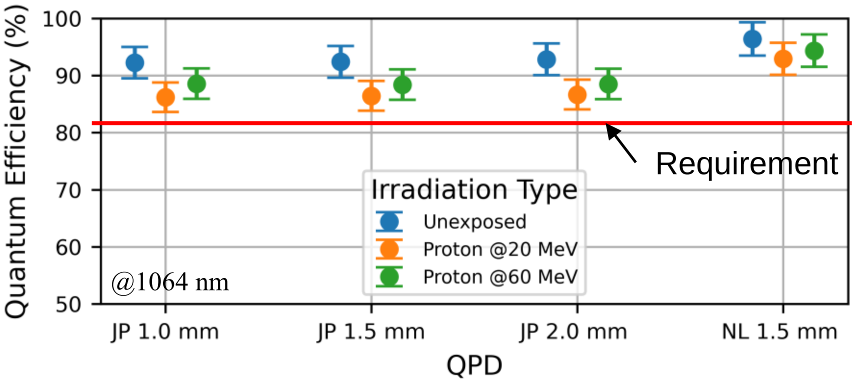
Parameters for SR-NIEL calculation (electron)

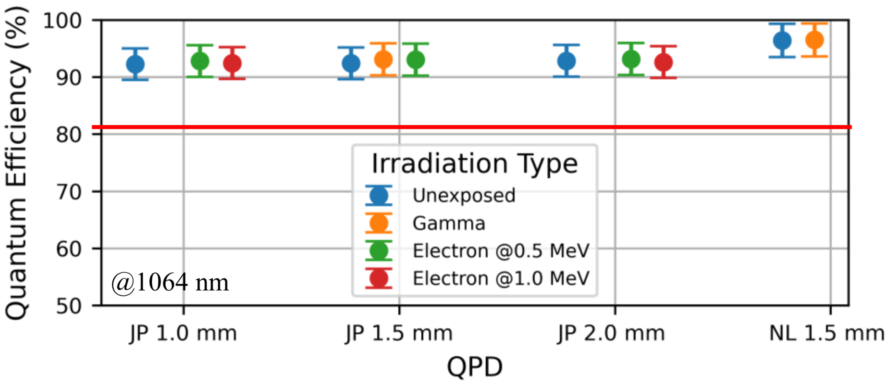
	Ed default[1]	Ed av[2]	Ed eff[2]
$In_{0.53}$	43.0 eV	12.0 eV	52.0 eV
$Ga_{0.31}$	21.5 eV	23.0 eV	70.0 eV
As	21.5 eV	31.0 eV	76.0 eV

[1] R. Campesato _et al._, « *NIEL Dose Analysis on triple and single junction InGaP/GaAs/Ge solar cells irradiated with electrons, protons and neutrons* », arXiv, Nov. 20, 2019. doi: https://doi.org/10.48550/arXiv.1911.08900

[2] A. Yu. Konobeyev, U. Fischer, Yu. A. Korovin, et S. P. Simakov, « *Evaluation of effective threshold displacement energies and other data required for the calculation of advanced atomic displacement cross-sections* », _Nuclear Energy and Technology_, vol. 3, no 3, p. 169-175, sept. 2017, doi: https://doi.org/10.1016/j.nucet.2017.08.007

QPD Quantum Efficiency vs Irradiation

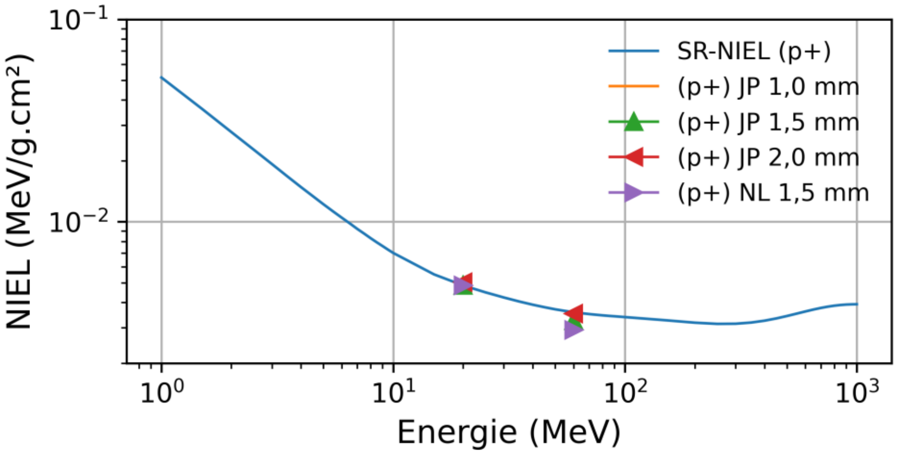




Quantum Efficiency Damage factor

$$K_R = -\frac{QE(\Phi) - QE(0)}{\Phi}$$

Comparison with NIEL



Effect of irradiation on the QPR performance

Quadrants Photoreceivers (QPR)

QPD InGaAs (JP&NL)
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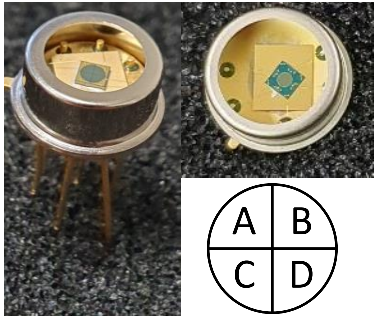

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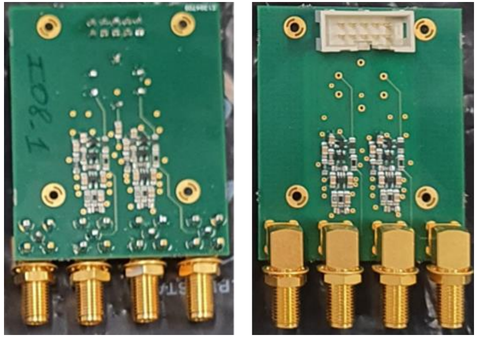
Transimpedance Amplifier or FEE (DE)

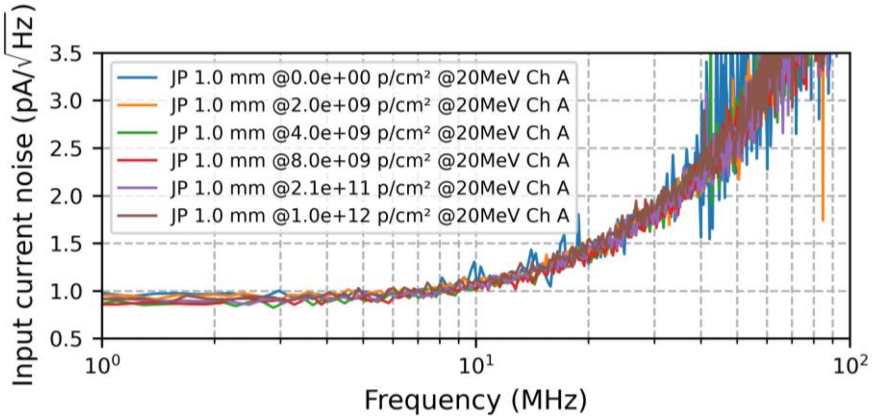


Parameters

- QPR Equivalent Input Current Noise
- QPR Phase & Amplitude to LISA Like Signal

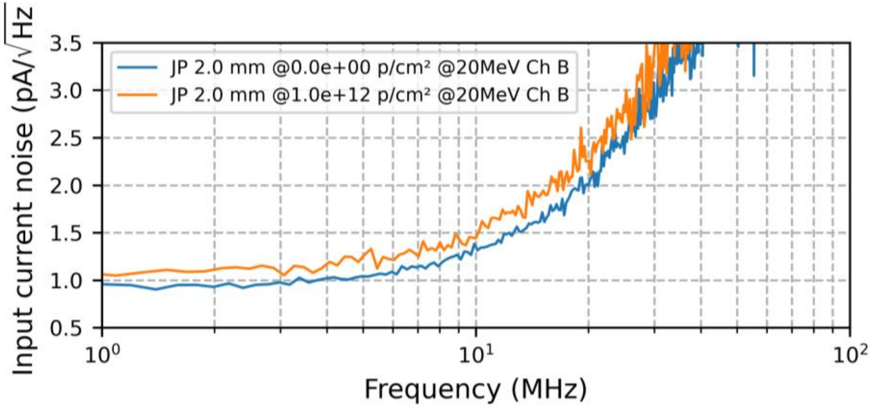
Only the QPD was irradiated

QPR Input Equivalent Current Noise vs Irradiation



No significative variation

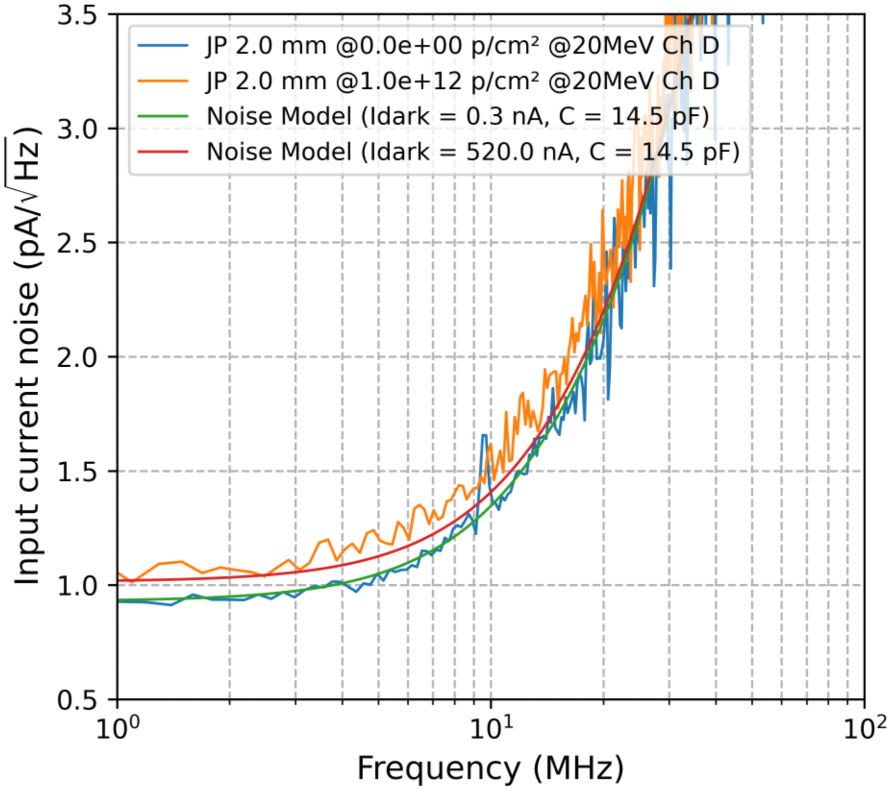
- Independent of QPD
- Independent of irradiation type



Exception 2,0 mm QPD irradiated @ 20 MeV

- Noise increase of 0.16 pA√Hz
- Bandwidth decrease of 2.0 MHz
  - ➢ Why ?

QPR Input Equivalent Current Noise Model



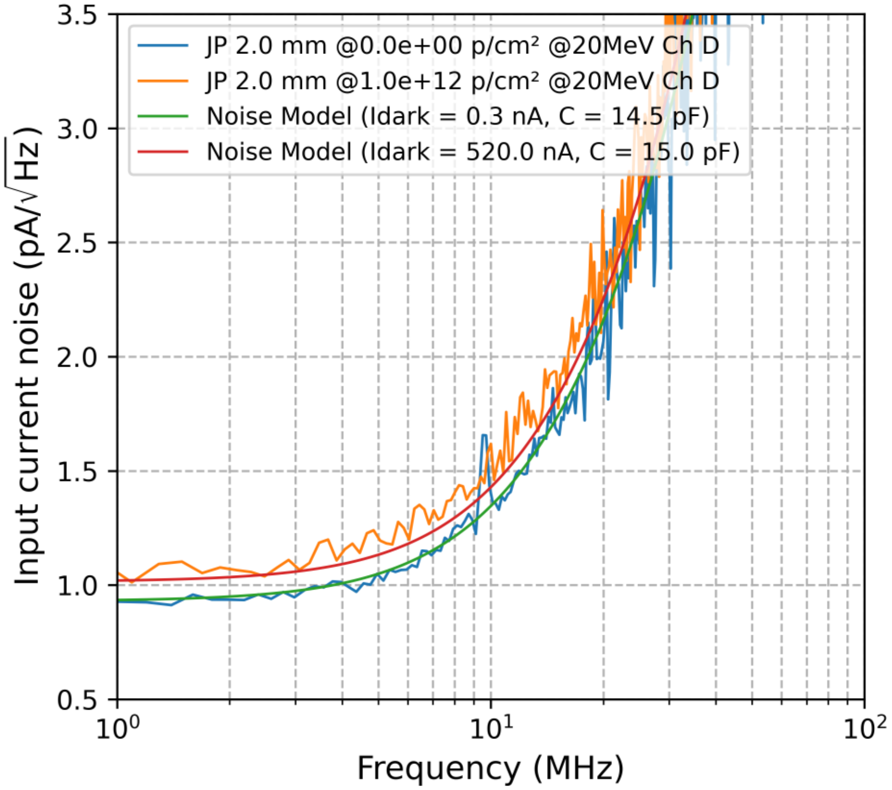
Noise Model

$$I_{Noise}^2 = I_{SN}^2 + I_{JN}^2 + I_{TIA}^2$$

- Shot noise: $I_{SN}^2 = 2q\left(I_{ph} + I_{dark}\right)$
- Johnson noise: $I_{JN}^2 = \frac{4kT}{R_f}$
- TIA op-amp noise: $I_{TIA}^2 = e_n \frac{\sqrt{1+\left(2\pi f R_f C_T\right)}}{R_f}$

F. G. Cervantes, J. Livas, R. Silverberg, E. Buchanan, et R. Stebbins, « *Characterization of photoreceivers for LISA* », _Class. Quantum Grav._, vol. 28, no 9, p. 094010, mai 2011, doi: https://doi.org/10.1088/0264-9381/28/9/094010

QPR Input Equivalent Current Noise Model



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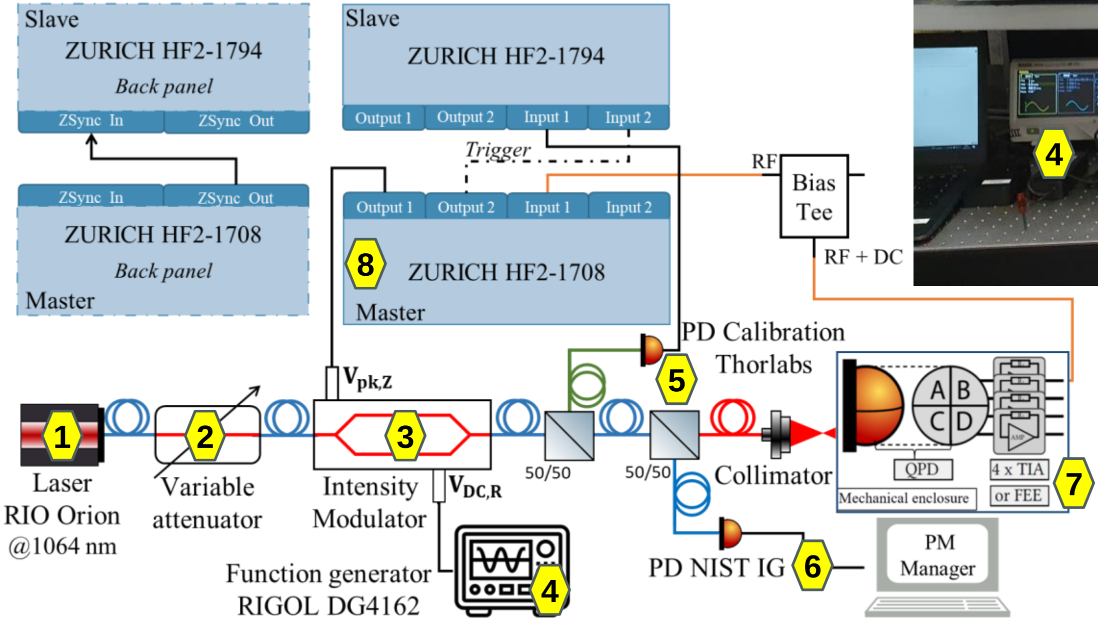
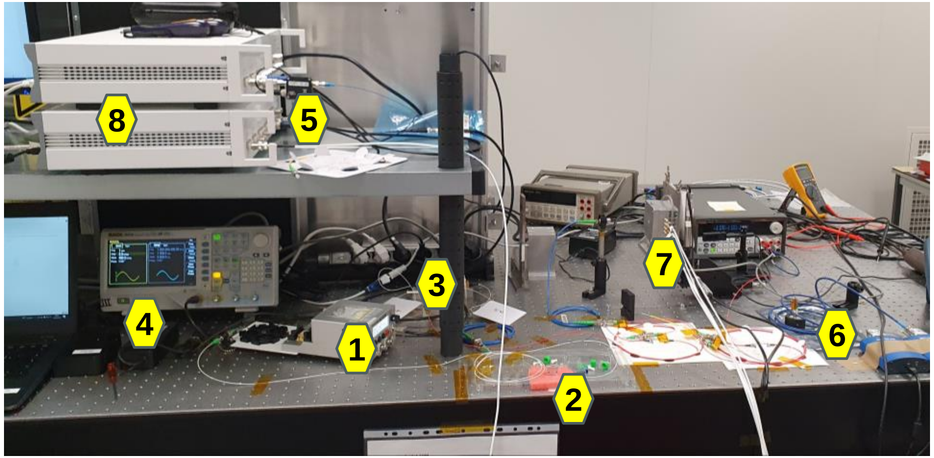
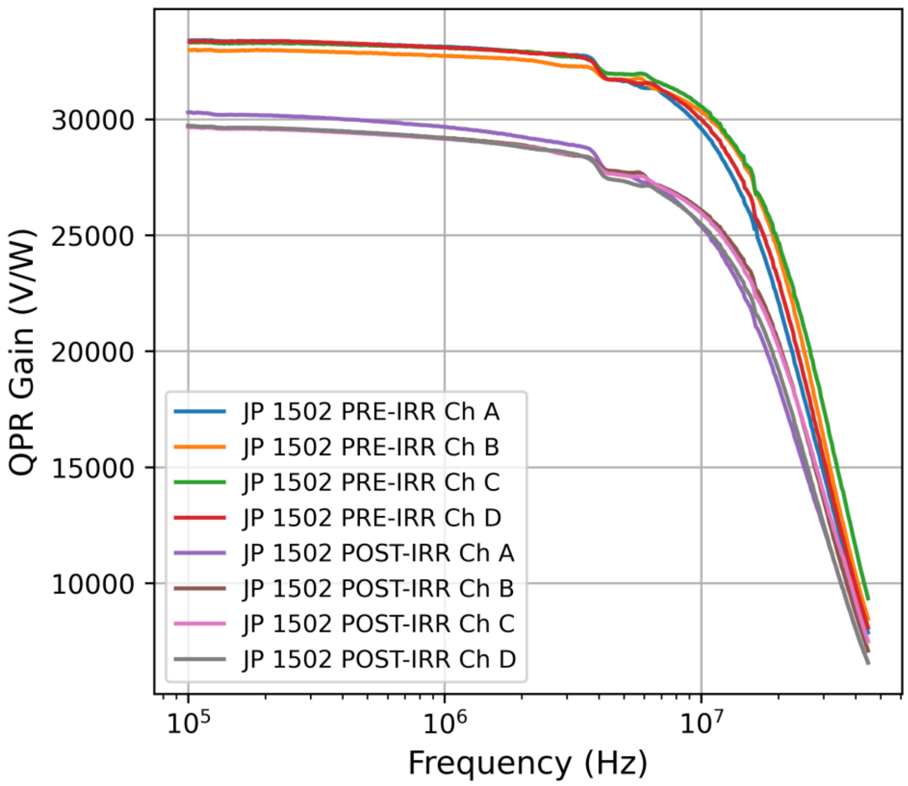
QPR Phase & Amplitude to LISA Like Signal





QPR Amplitude Signal vs Irradiation Conditions

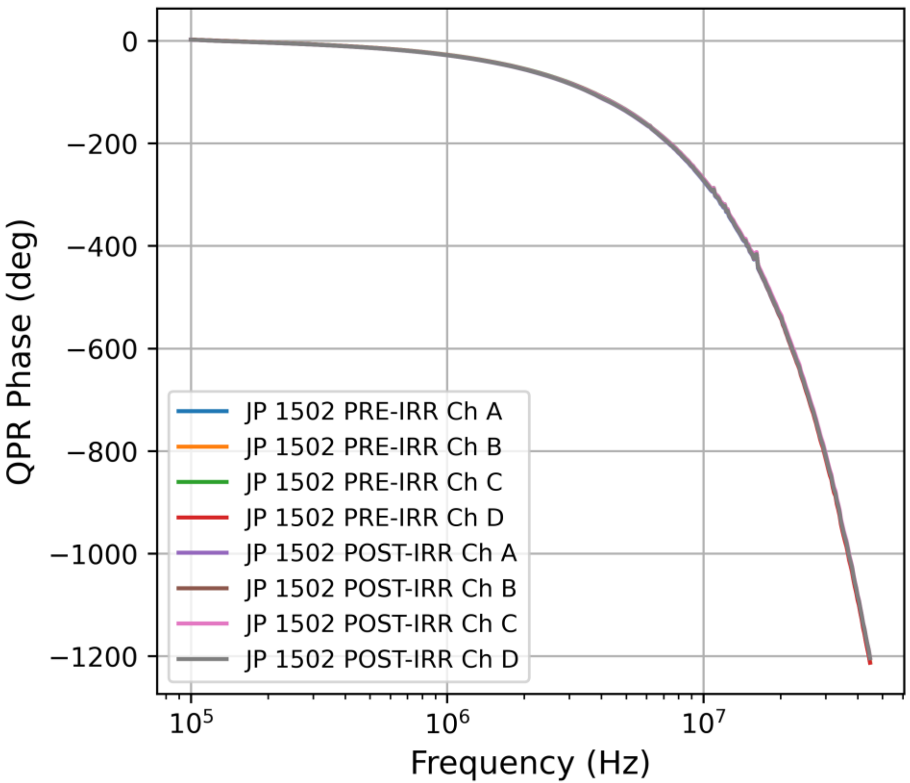


$$QPR_{Gain} = \frac{V_{pkpk,QPR}}{P_{pkpk,Opt}}$$

~9% Loss in amplitude

- Due 9% decrease of QPD quantum efficiency

QPR Phase Signal vs Irradiation Conditions



No variation observed

Conclusion

Overview of Experimental Irradiation Conditions

- LISA QPD of different size 1.0, 1.5 & 2.0 mm & technologies
- Protons, Electrons, Gamma rays @~5x LISA specification

Main Results

- QPD Dark current damage factor: techno, size, voltage dependent. NIEL: varies for electrons
- QPD Quantum efficiency : degradation see for proton. Damage factor correlates with NIEL
- QPD Noise: No effect except one QPD with increased noise linked to dark current
- QPR Phase: No variation
- QPR Amplitude: Amplitude 9% decrease due to quantum efficiency decrease
- InGaAs QPDs promising candidates for interferometric space applications such as LISA

Perspective

- Explore the increase of damage factor with the fluence