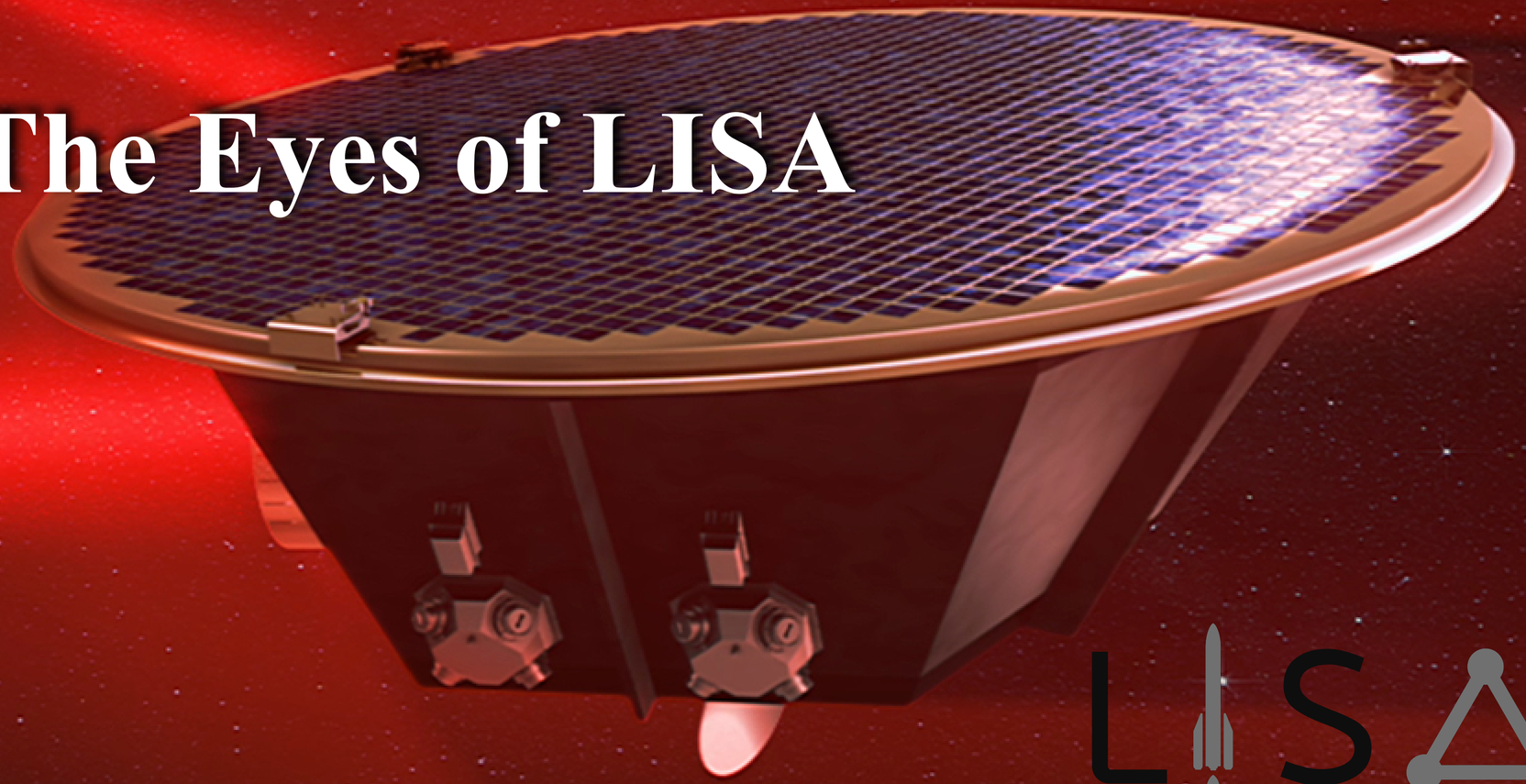
Nikhef

SRON
Netherlands Institute for Space Research

The Eyes of LISA



Observatoire de la CÔTE d'AZUR

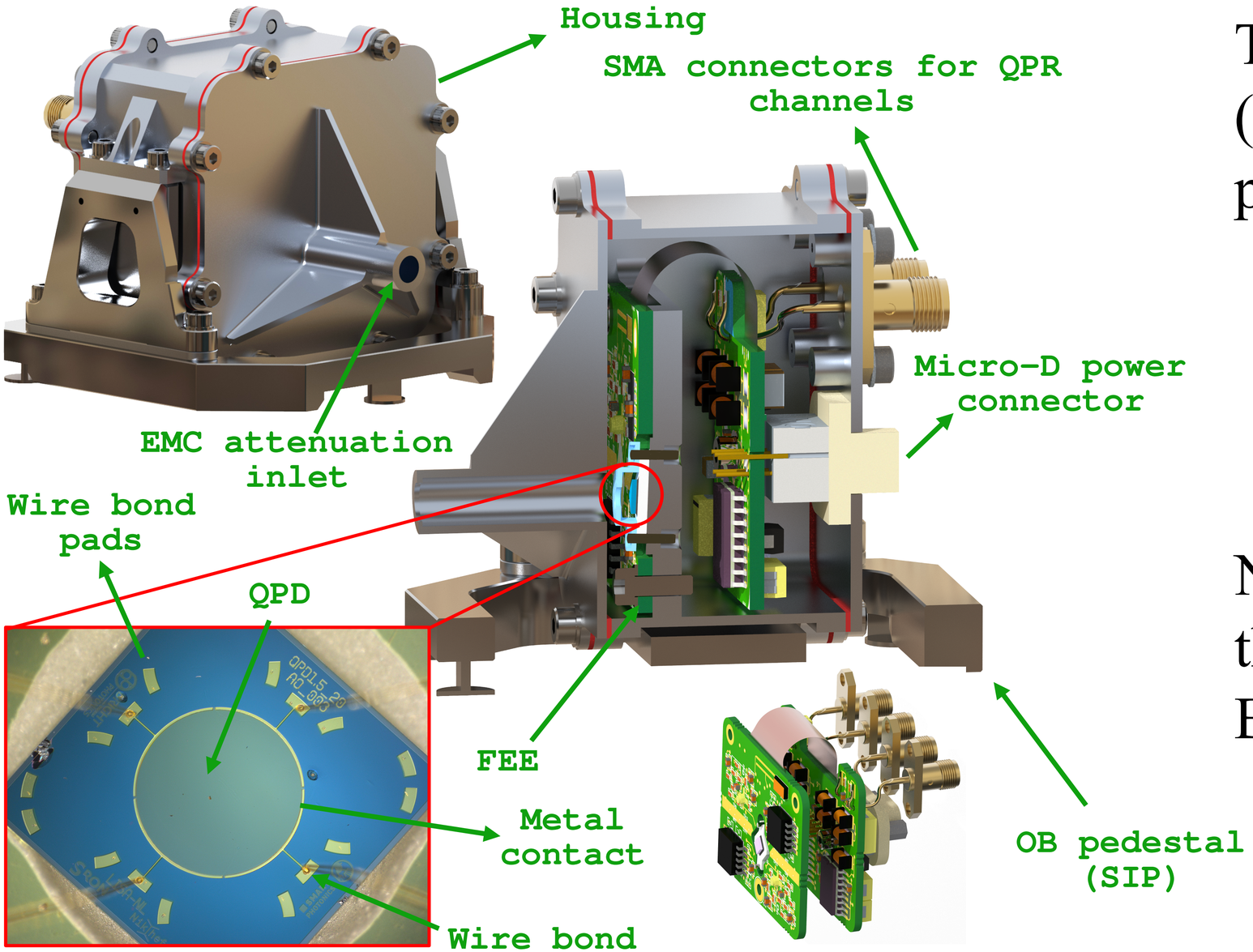
ESA | NASA lisa

NWO

LISA CONSORTIUM

T. Mistry, M.v. Beuzekom, N.v. Bakel, R. Cornelissen, M. Adams, G. Visser, J. in 't Zand, M. Frericks, P. Laubert, R. Wanders, L. Dubbeldam, G. Aitink, G. de Lange

WHAT IS THE LISA QPR



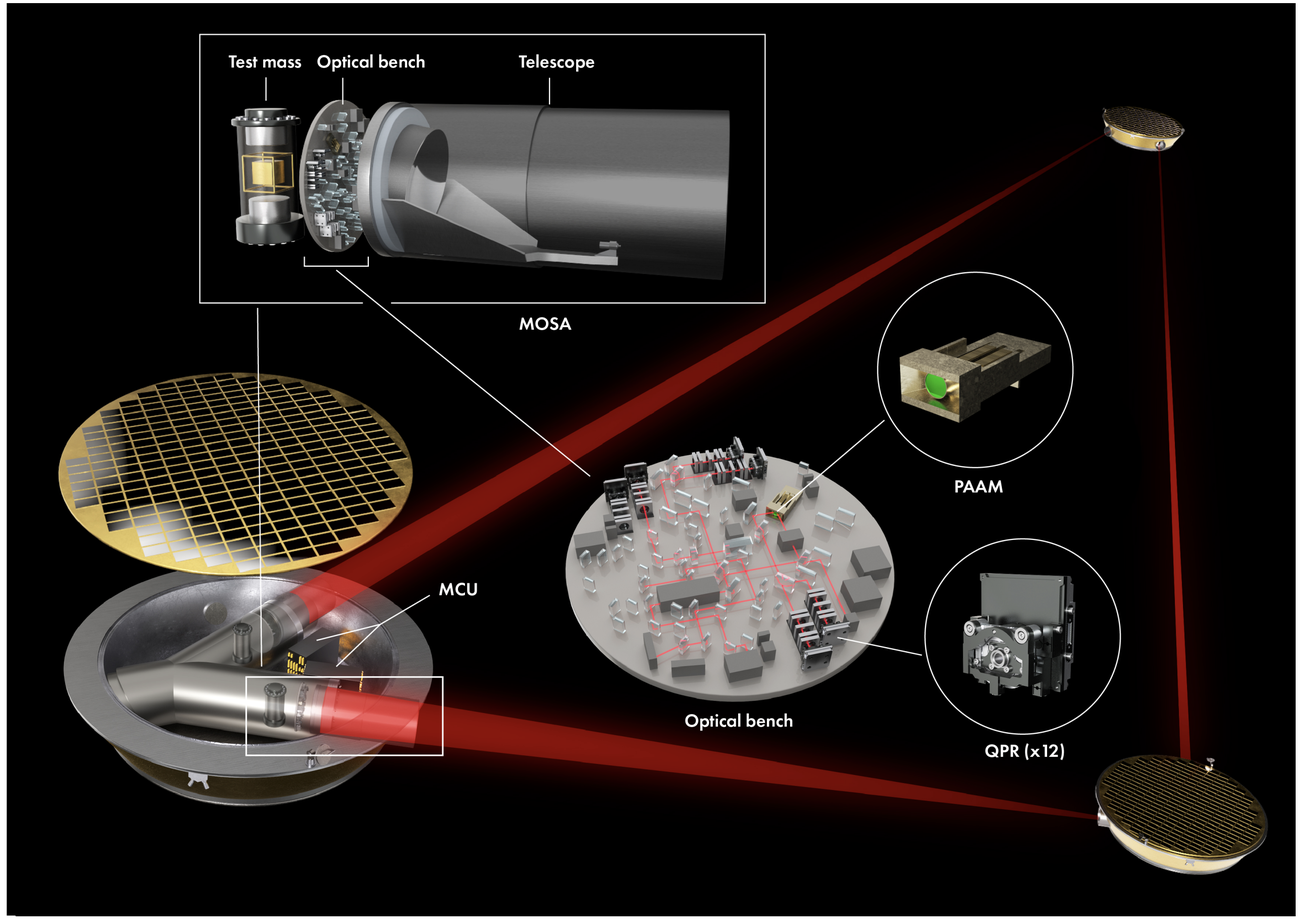
The **Q**uadrant **P**hoto-**R**eceiver (QPR) is made of the following parts:

- The **Q**uadrant **P**hoto**d**iode (QPD)
- The mechanical housing
- The **F**ront **E**nd **E**lectronics (FEE)

Nikhef + SRON responsible for the QPD and housing with Belgium supplying the FEE

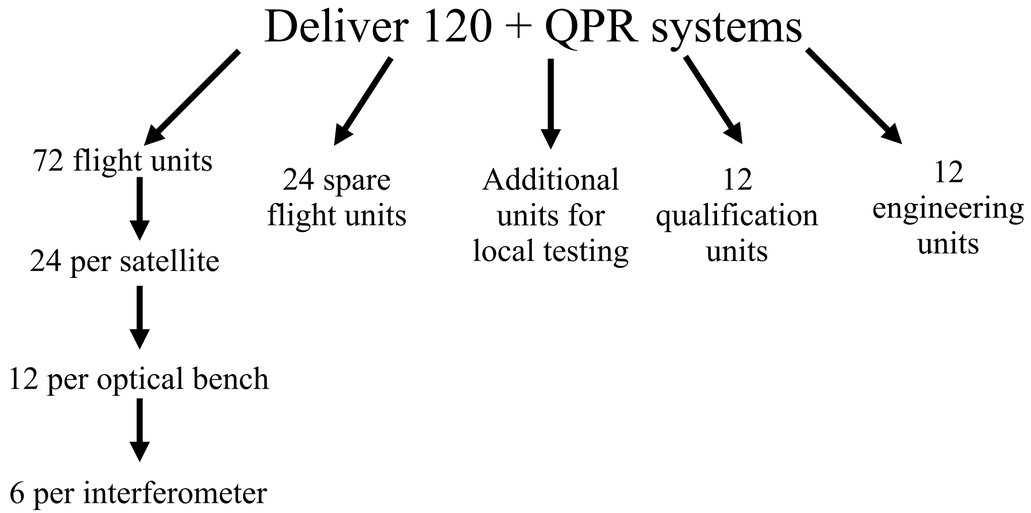
QPR REQUIREMENTS

We develop bespoke QPD for LISA since the requirements cannot be met with commercial devices.



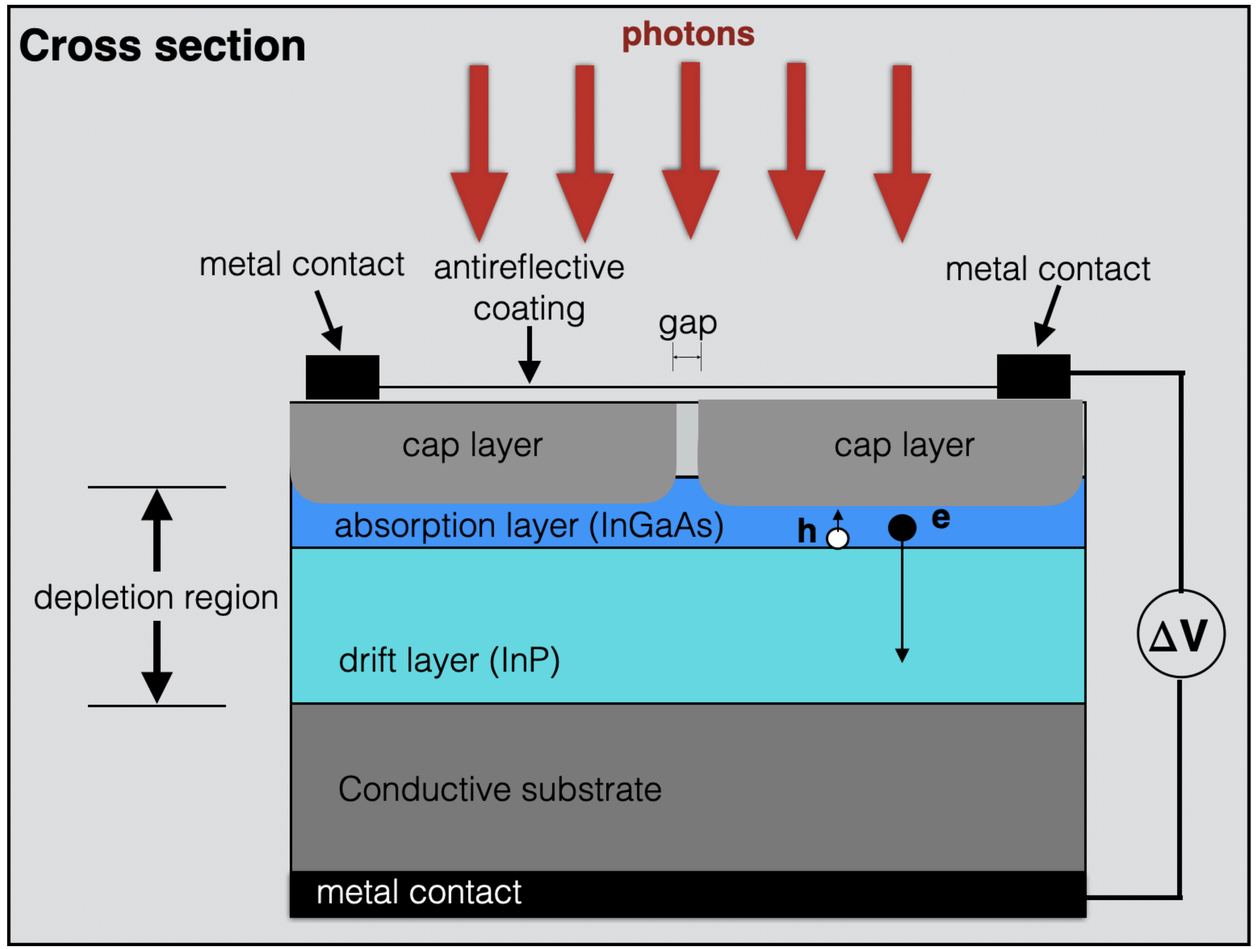
Dutch hardware contribution to LISA. Nikhef and SRON to deliver the QPR, PAAM delivered by TNO and MCU

Name	Value	Validation Method
Operating wavelength	1064 nm	Laser used for measurements
Responsivity	0.8 A/W	DC Carrier to noise measurement and DC uniformity
Active diameter	1.5 mm	Mask design and QPD foundry
Quadrants	4	Mask design and QPD foundry
Gap between quadrants	20 μm	Mask design and QPD foundry
RF Bandwidth	3 - 30 MHz	White light measurement
Capacitance	$\leq$ 5 pf	C/V and I/V measurements
Equivalent input current noise density	$\leq 2\ \mathrm{pA}/\sqrt{Hz}$	White light measurement
Phase stability over temperature	$\leq$ 5 mrad/K	Phase over tempearture measurement
Anti-reflection coating	$\leq$ 2 % at 1064 nm	Anti-reflective foundry
Spatial DC uniformity	TBC	DC response from rasterised QPD scan
Spatial RF uniformity	TBC	RF response from rasterised QPD scan
Leakage current	$\leq$ 1 μA TBD	C/V and I/V measurements
Crosstalk	$\leq$ - 40 dB	Optical and electrical measurements



LOW NOISE LARGE AREA QPD

Low noise requires low capacitance



Simplified cross-section of LISA QPD indicating key features such as the cap layer that forms the quadrants, the absorption and drift layer as well as the gap between the quadrants. Features are not to scale.

Permittivity (dielectric constant) of the material

Capacitance

QPD area

$$C = \frac{\varepsilon A}{d}$$

Depletion region width

Low capacitance

Reduce ε

Semiconductors have close values of ε thus, material changes will have little impact

Reduce A

Large area required for beam alignment and larger area eases OB beam (waist) compression.

Increase *d*

Higher (reverse) bias voltage required to fully deplete the diode (requirement specifies 24 V supplied voltage).

Reduce absorption and drift layer doping

LOW NOISE LARGE AREA QPD

Elementary charge

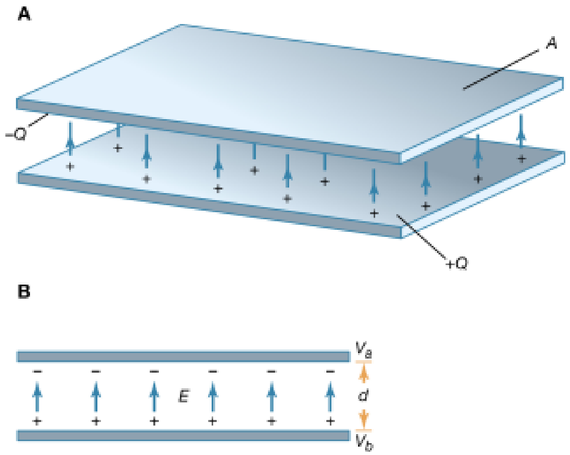
Doping concentration → Purity of InGaAs / InP

$$V = \frac{qNd^2}{2\varepsilon}$$

Depletion region width

Full depletion voltage

Permittivity (dielectric constant) of the material



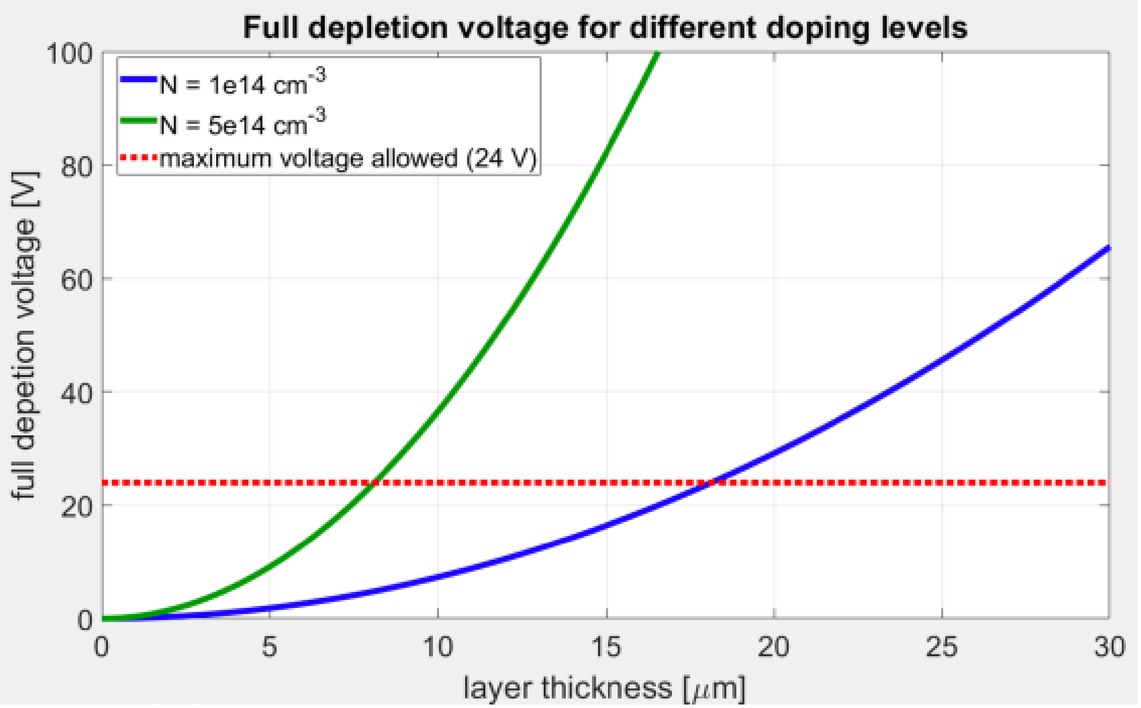


Figure shows how the bias voltage required to fully deplete device varies as a function of the device thickness and doping concentration. For the LISA requirement of 24 V, the device thickness changes quadratically thereby emphasising the need for low doping.

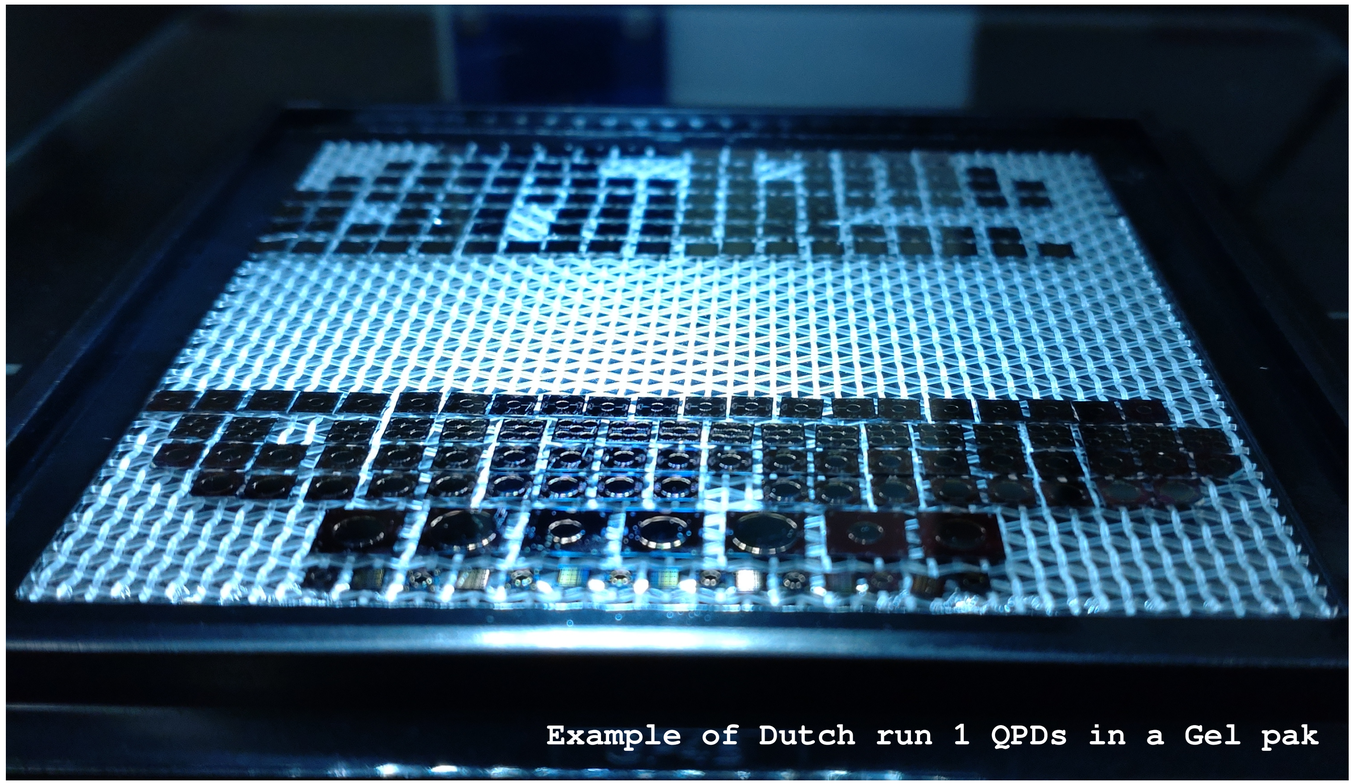
Doping concentration target value:
$N \leq 1x10^{14}$ cm^{-3}

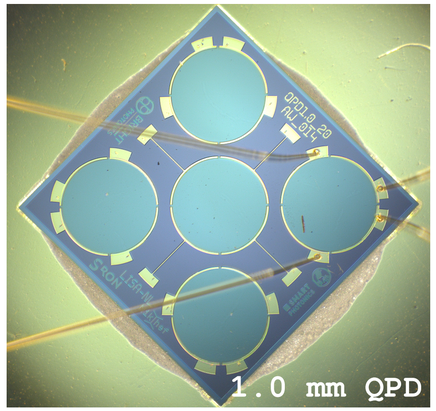
Typical sensitivity of doping concentration measurement techniques:
$N \sim 1x10^{14}$ cm^{-3}

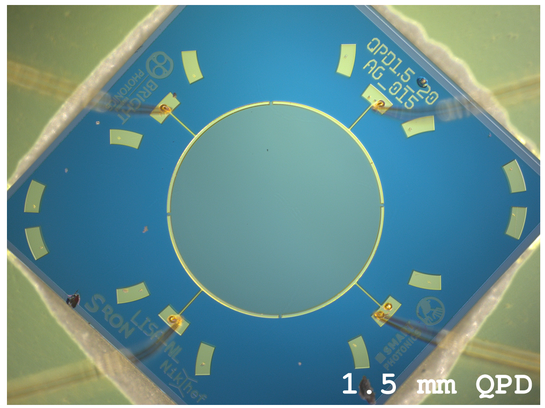
Number of InGaAs atoms/molecules in a crystal lattice volume:
$\sim 4x10^{22}$ cm^{-3}

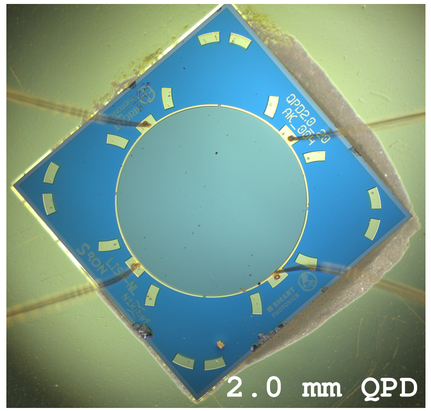
TIMELINE OF LISA QPDS

P. Colcombet et al., "Radiation Tolerance of Low-Noise Photoreceivers for the LISA Space Mission," in IEEE Transactions on Nuclear Science, doi: 10.1109/TNS.2024.3401047.


Example of Dutch run 1 QPDs in a Gel pak


1.0 mm QPD


1.5 mm QPD


2.0 mm QPD

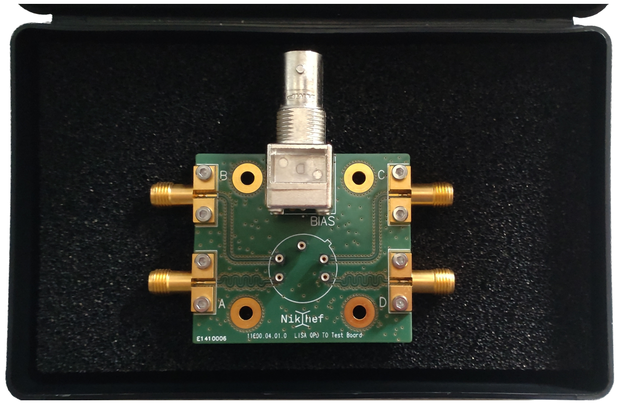
Expected to be two ‘runs’ of QPD development.

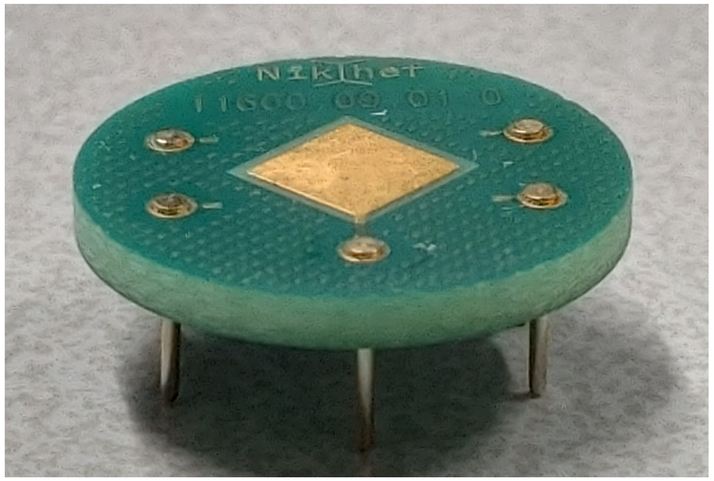
- Run 1 (2019)
  - First prototypes (not intended for flight)
  - Designed with Dutch industry (Bright Photonics)
    - One wafer can accommodate many different types of QPD.
  - Wafer produced in Poland (VIGO).
  - Processing and dicing by Dutch industry (Smart Photonics).
  - Delivered to Nikhef/SRON in GelPaks for bonding to various packages.
- Run 2 (2024)
  - Modifications made from the Run 1 QPD.
    - Layer stack modifications.
    - Fiducials for alignment when glueing.
    - Dedicated die for the QPD (see slide 12).
  - Wafer produced and processed in Poland (VIGO)
    - Front-side processing (involves lithography, diffusion, coating; back-side processing includes G&P [thinning], metallisation [anode])
  - Back-side processing, thinning and dicing by Helia
  - Anti-reflective coating by VIGO

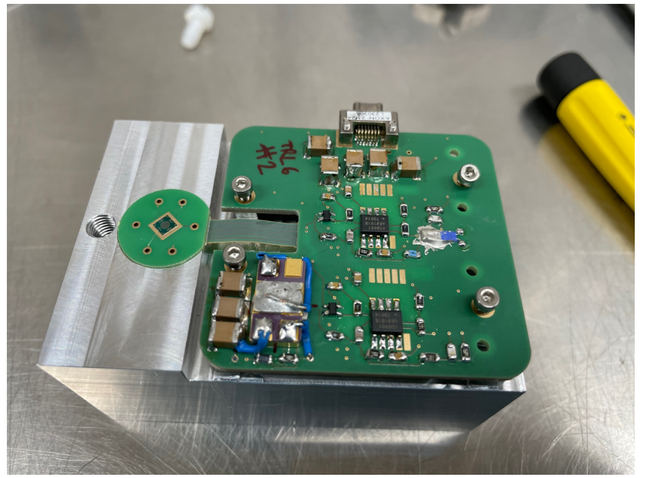
RUN 1 PERFORMANCE – TESTS AT NIKHEF

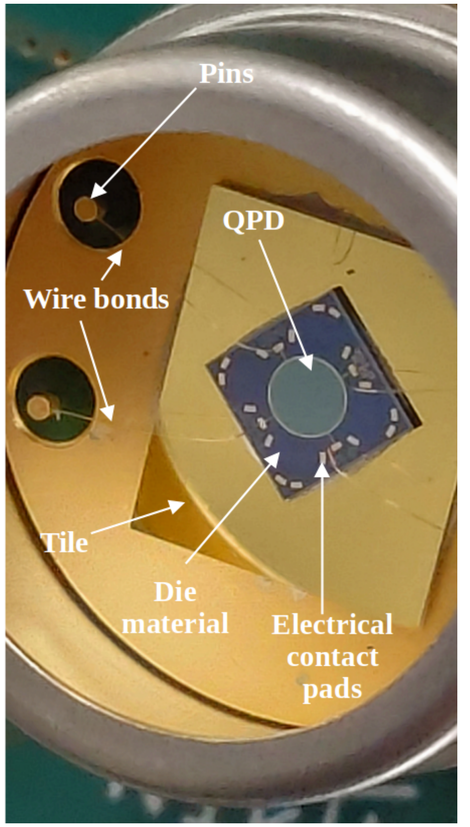
Wide variety of QPD packages and test readout electronics.

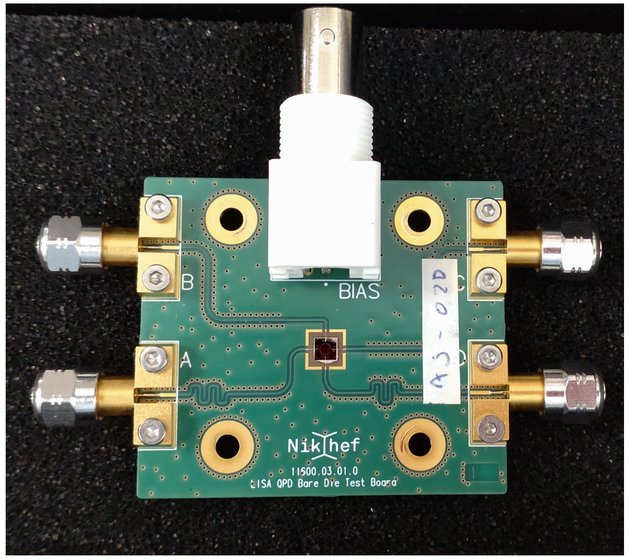
- Tests conducted around the beatnote frequency (1 – 30 MHz)

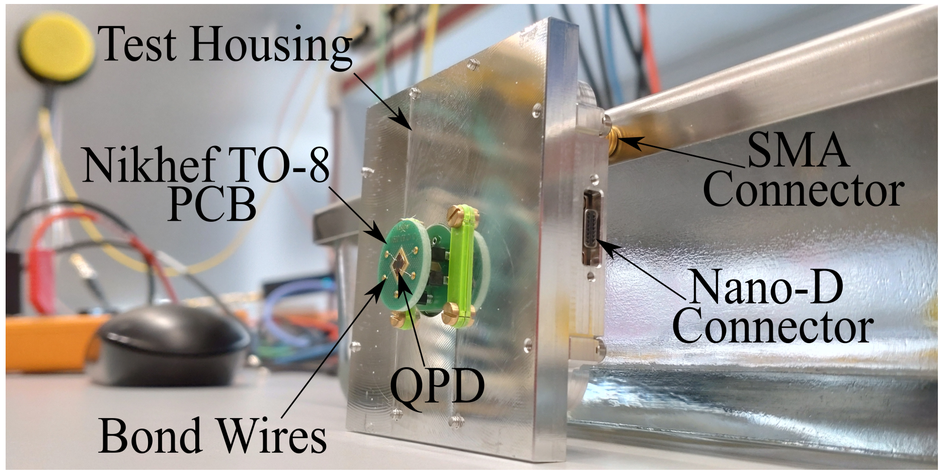


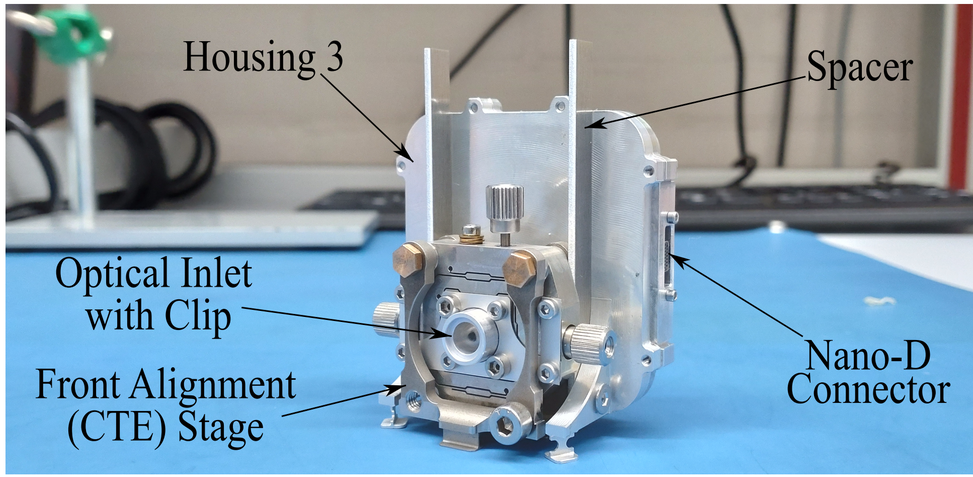




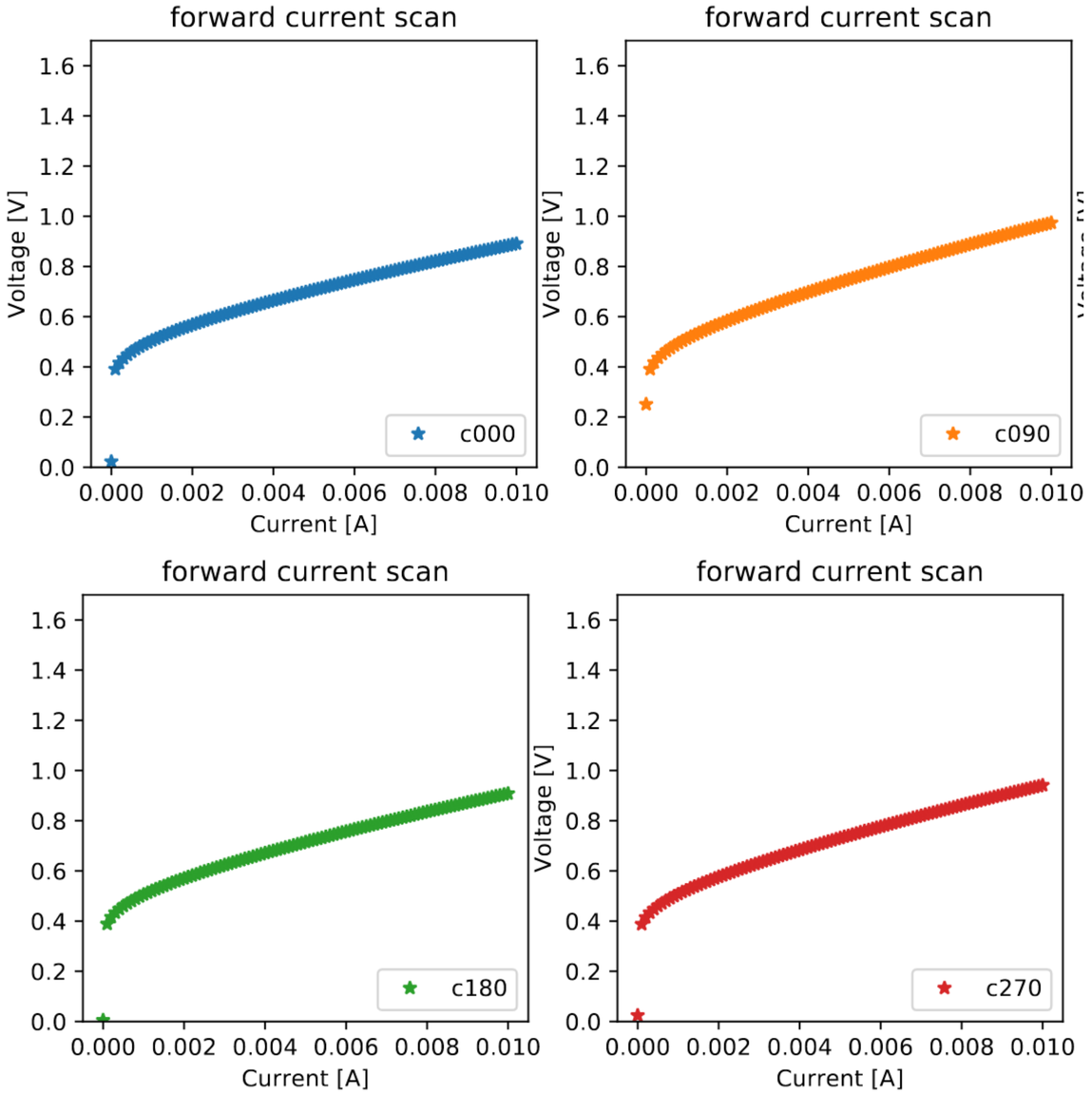








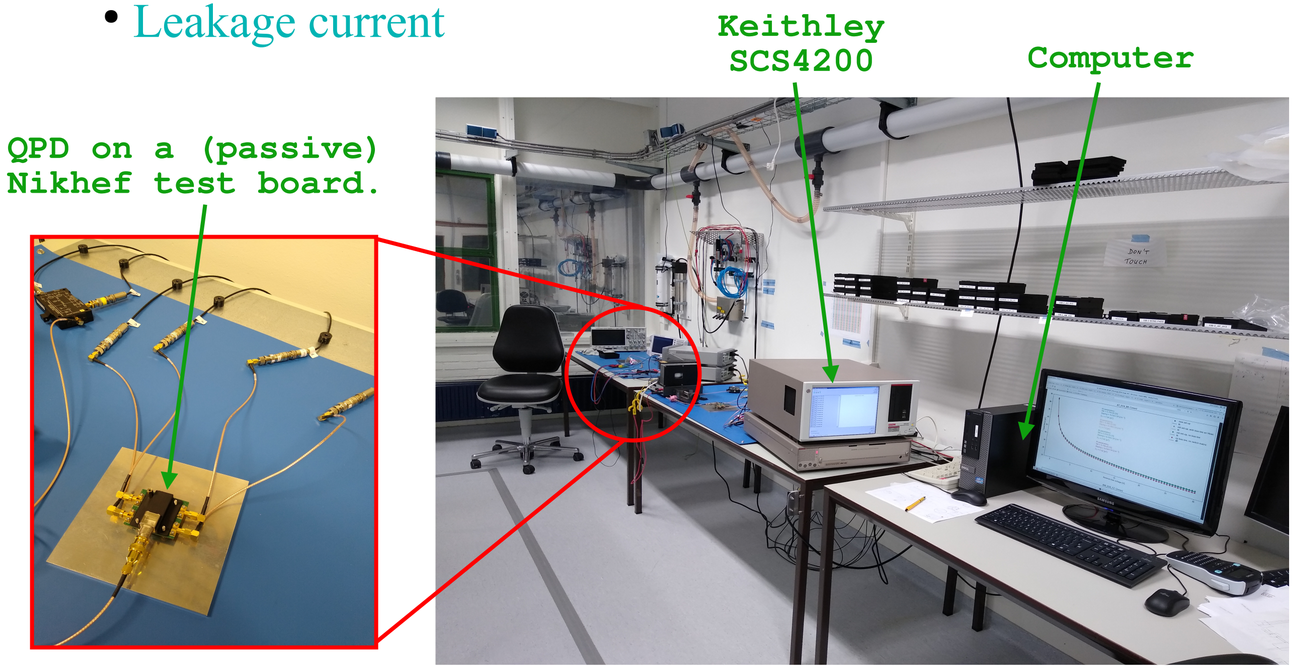
RUN 1 PERFORMANCE – CV AND IV SCANS



Example of forward I-V measurement from each of the QPD segments (channels).

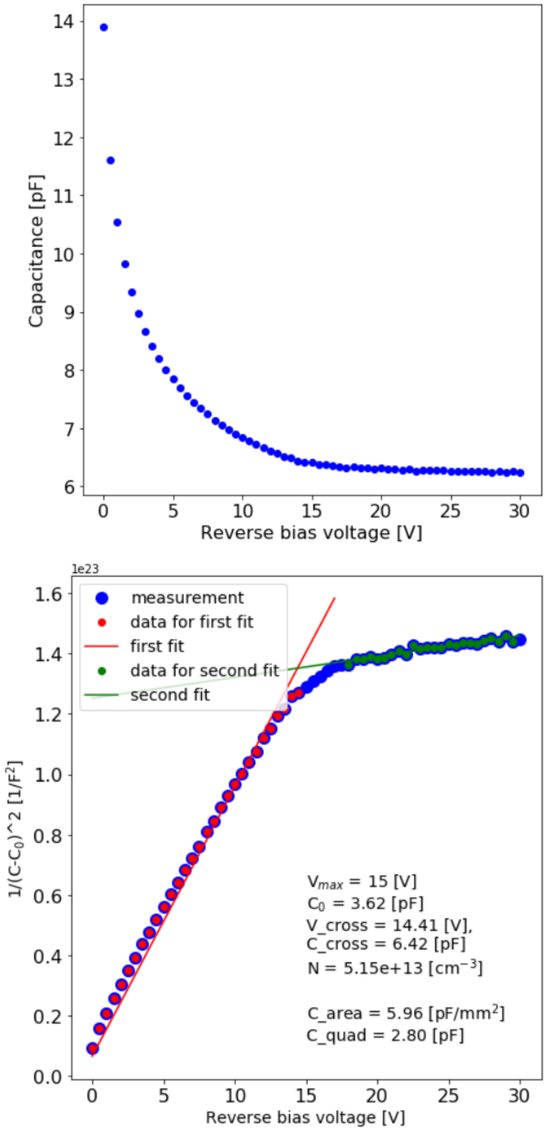
Current voltage (I-V) measurements at diode level

- Forward I-V
  - Push current though the device and measure the voltage.
  - (Contact) resistance
- Reverse (bias) I-V
  - Leakage current



C-V and I-V lab setup at Nikhef

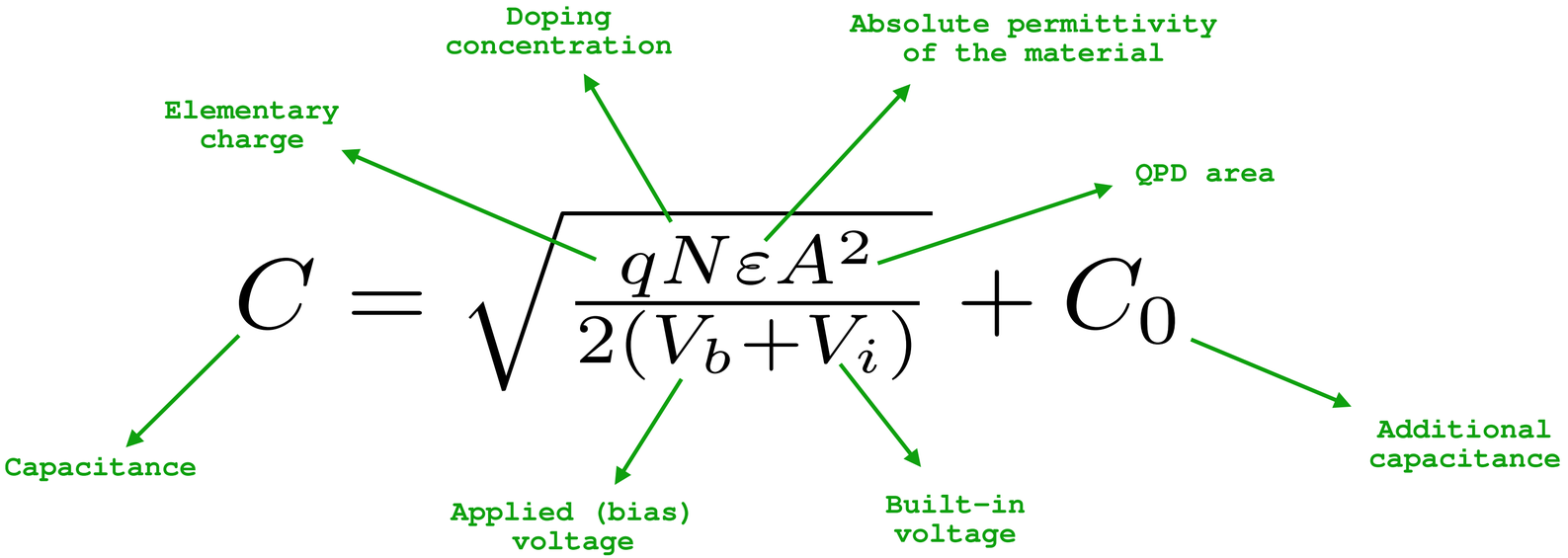
RUN 1 PERFORMANCE – CV AND IV SCANS



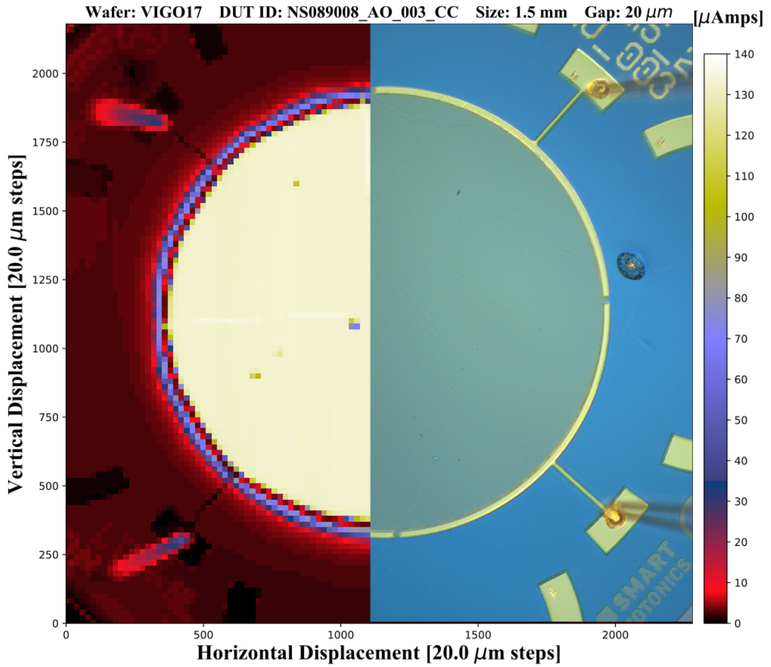
Top: Reverse bias C-V measurement.
Bottom: Fitting to extract diode parameters

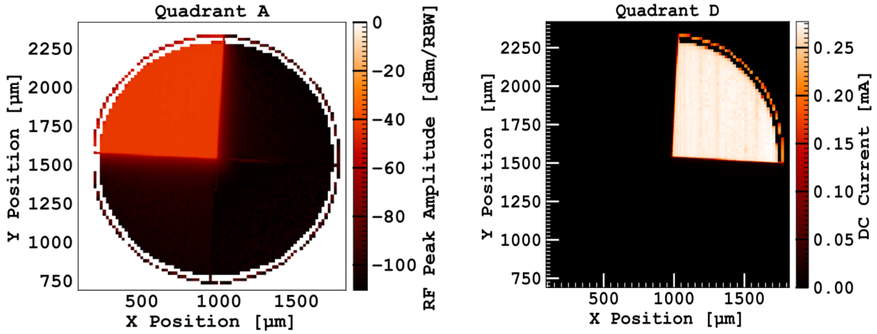
Capacitance voltage (C-V) scans measure the capacitance of the QPD

- Overall diode capacitance reduced with increasing (reverse) bias voltage.
  - Effect reduces after diode is fully depleted (15 V).
- Estimate the doping level of the InGaAs
  - Due to such low doping levels, not possible to directly measure the doping.



RUN 1 PERFORMANCE – UNIFORMITY





Top: Split image of DC uniformity measurement and real image of the same QPD.
Bottom: Left is the RF response at 15 MHz and right is an individual quadrant DC response.

Spatial measurement of the uniformity of the QPD by rasterising over the QPD area with a laser.

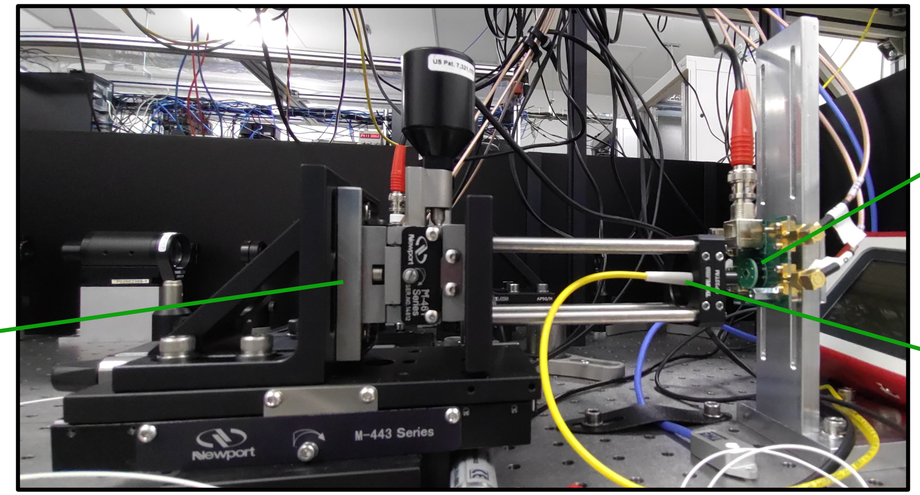
- Performed on bare QPD with passive readout electronics.
  - No amplification of the raw photocurrent from each quadrant/channel.

Measure the DC and RF response of each quadrant

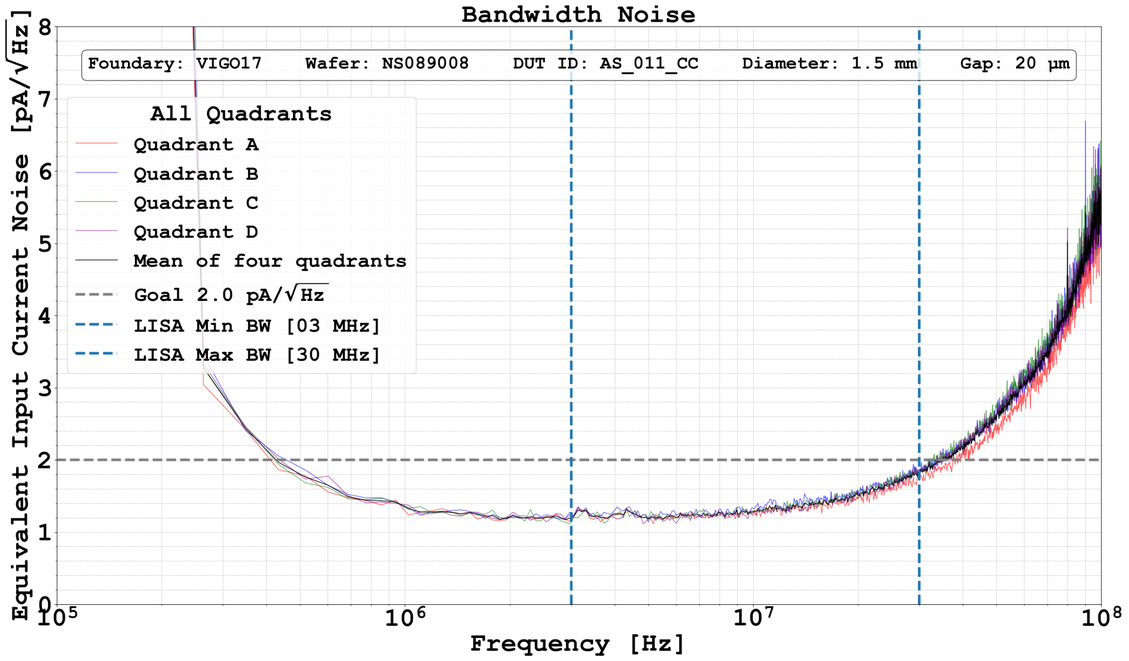
- RF measured with spectrum analyser.
- DC measured with a multimeter.

Measurement is limited by instrument systematics

- Stripes in the scans are from laser power fluctuations and not from the QPD.
  - Planning on adding power meter to track the laser output power when taking scans.
- See imperfections in the AR coating and other features.



RUN 1 PERFORMANCE – INPUT NOISE



Equivalent input current noise for a 1.5 mm QPD on a TRL6 AEI FEE

Use the ‘white light’ method

- Requires the full QPR (FEE with the QPD).
- Take a dark and light measurement then divide the measurements.
  - Gives the input noise and transimpedance amplifier (TIA) gain (not shown).

Baseline Run 1 QPD already meets the LISA requirement.

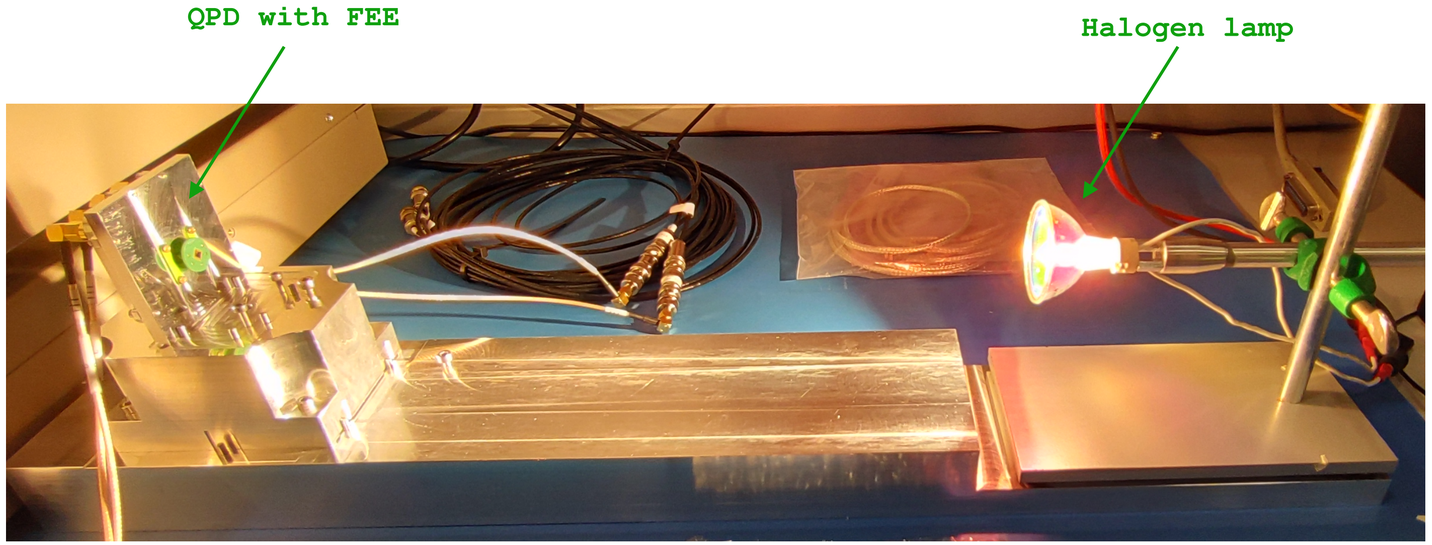
- Run 2 QPD expected to have reduced noise.
  - Reduction of overall device capacitance.

Equivalent input current noise

Shot noise of the DC photocurrent

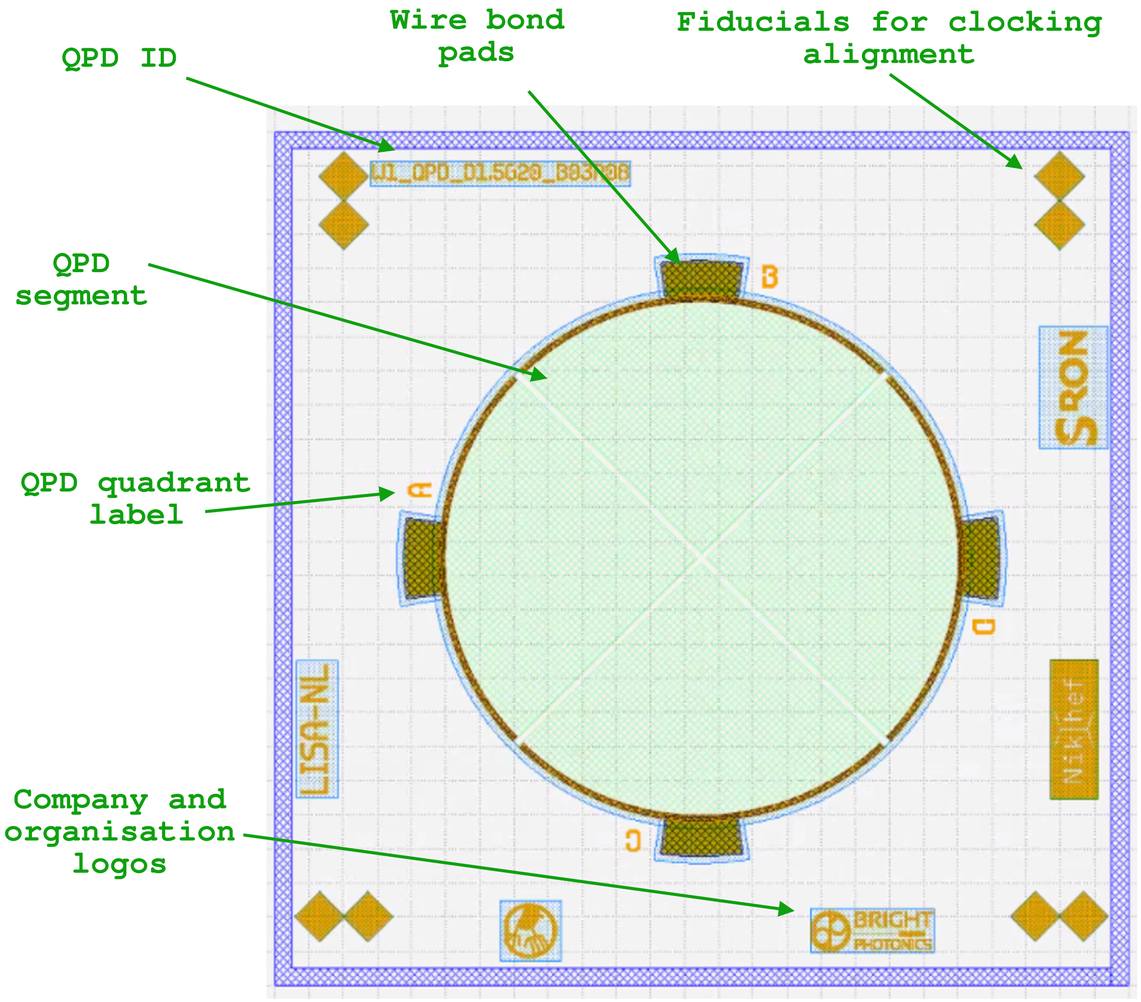
$$i_{en} = \frac{i_{sn}}{\sqrt{\left(\frac{v_n}{v_{en}}\right)^2 - 1}}$$

Voltage noise of the TIA with light



Germán Fernández Barranco (2018). Photodetection in intersatellite laser interferometers. doi:https://doi.org/10.15488/3866.

THE RUN 2 QPD



Mask design of the Run 2 LISA-NL QPD that will be used by the VIGO foundry to make the QPDs.

Expected to be the flight QPDs

- First delivery in July
  - C-V and I-V tests to gauge initial performance.

12 wafers ready for QPD processing

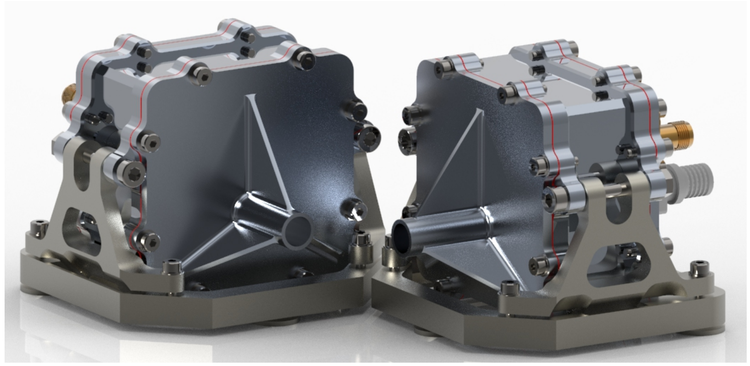
- Four will be used for first batch
- > 200 diodes per wafer

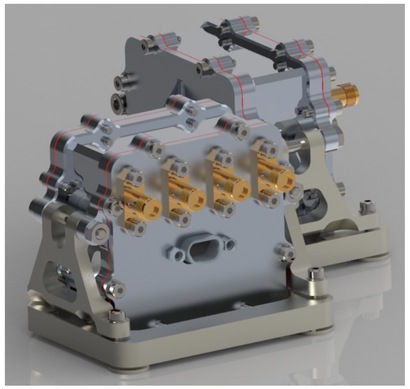
Variety of QPD sizes will be delivered

- Baseline for LISA is a 1.5 mm QPD with 20 µm gap.
- Additional test structures for probing layer stack.

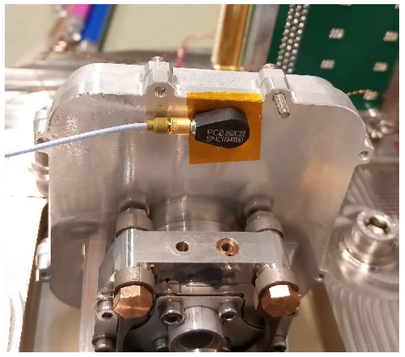
DEVELOPMENTS ON THE QPR HOUSING

QPR assembly on the OB

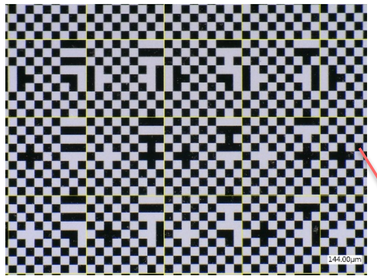




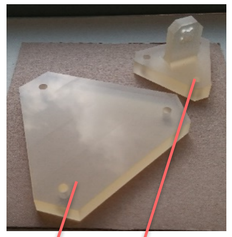
Accelerometer



RASNIK mask

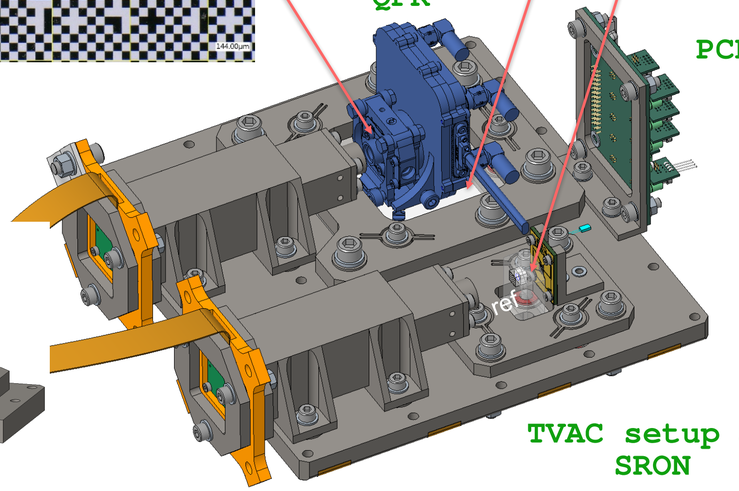


Invar (in-place of zerodur)

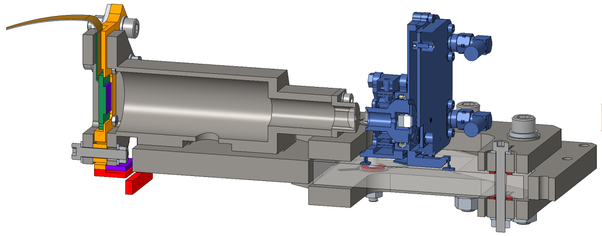


QPR

PCB



TVAC cross-section



TVAC setup at SRON

Housing has gone through many iterations.

- Catering for OB interface, FEE size and performance.
  - FEE is still being finalised so housing developments are currently paused.

Housing challenges include:

- Ensuring QPD remains at the same height above the OB over temperature range.
  - Thermal hysteresis (OB/satellite temperature environment)
  - CTE compensation QPR housing design
    - Validated with RASNIK measurement with a previous housing design.
- EMC shielding.
  - Isolate the QPR electronics from external EM-fields.
    - Such as X-band high gain antenna.
- Precise alignment on the OB.
  - Pedestal style interface (much like most of the hosted units on the OB).
  - Precise shims for fine adjustments.
- Stiffness
  - Positional stability (i.e. during launch)
  - Validated with vibration tests.
    - Thermal vacuum (TVAC) setup at SRON.
  - Resonant mode of QPR assembly.
- Heat dissipation
  - Coating (vacuum safe) for heat transfer.

CONCLUSION AND OUTLOOK

Run 1 QPD already meets the performance requirements for LISA.

- For 1.5 mm diode with 20 um gap.

Developed an array of lab tests to validate the performance of the LISA QPD and QPRs.

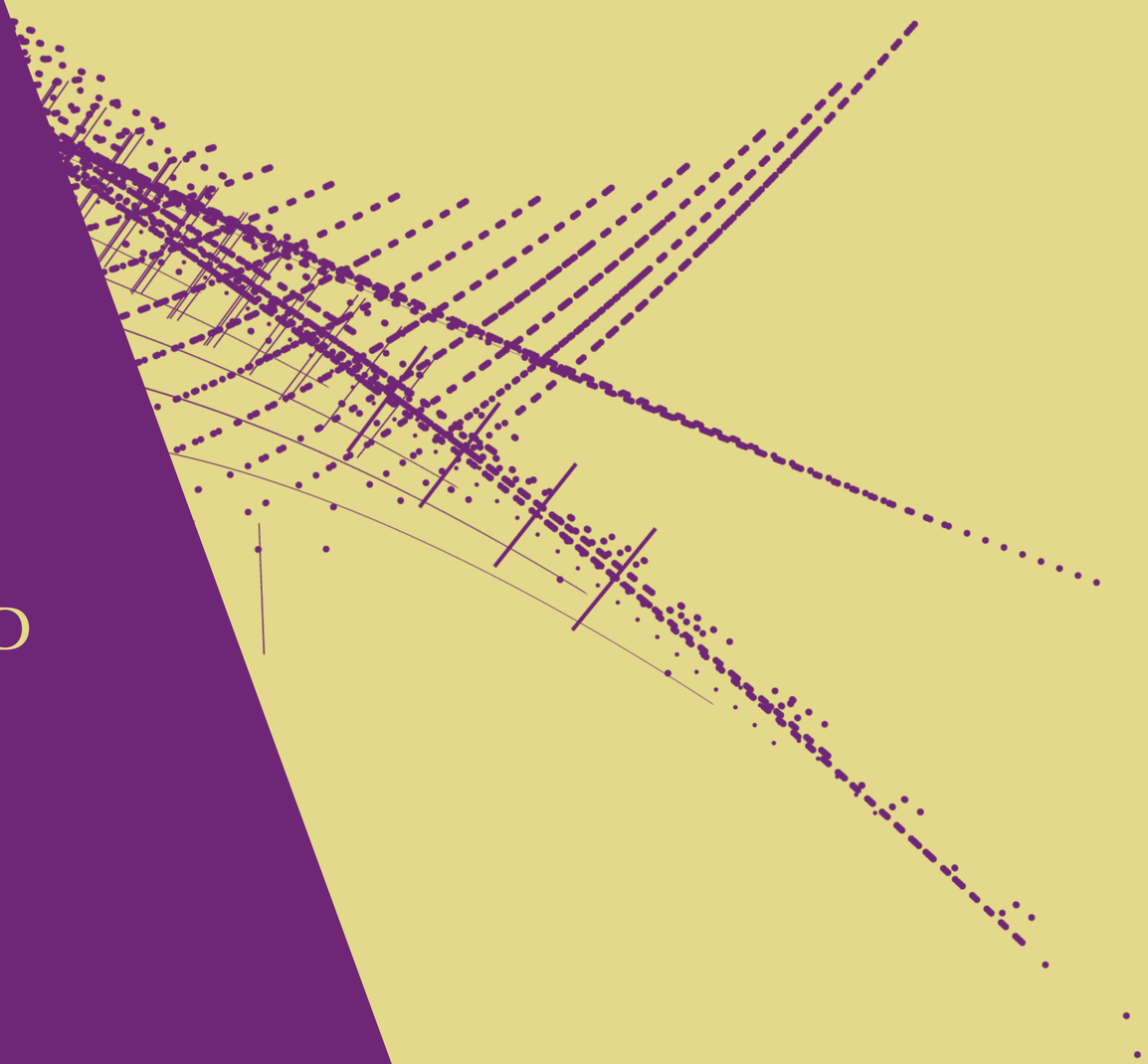
Identified areas where the QPDs can be improved thus next generation QPDs is expected to have lower noise.

Simulations ongoing to integrate and understand the impact of measurements on LISA performance.

Busy preparing dedicated LISA lab for QPR production.

- Adjustments to the test setups
  - Including vacuum chambers
  - Contamination control (clean room)
  - Buying equipment and building permanent setups.

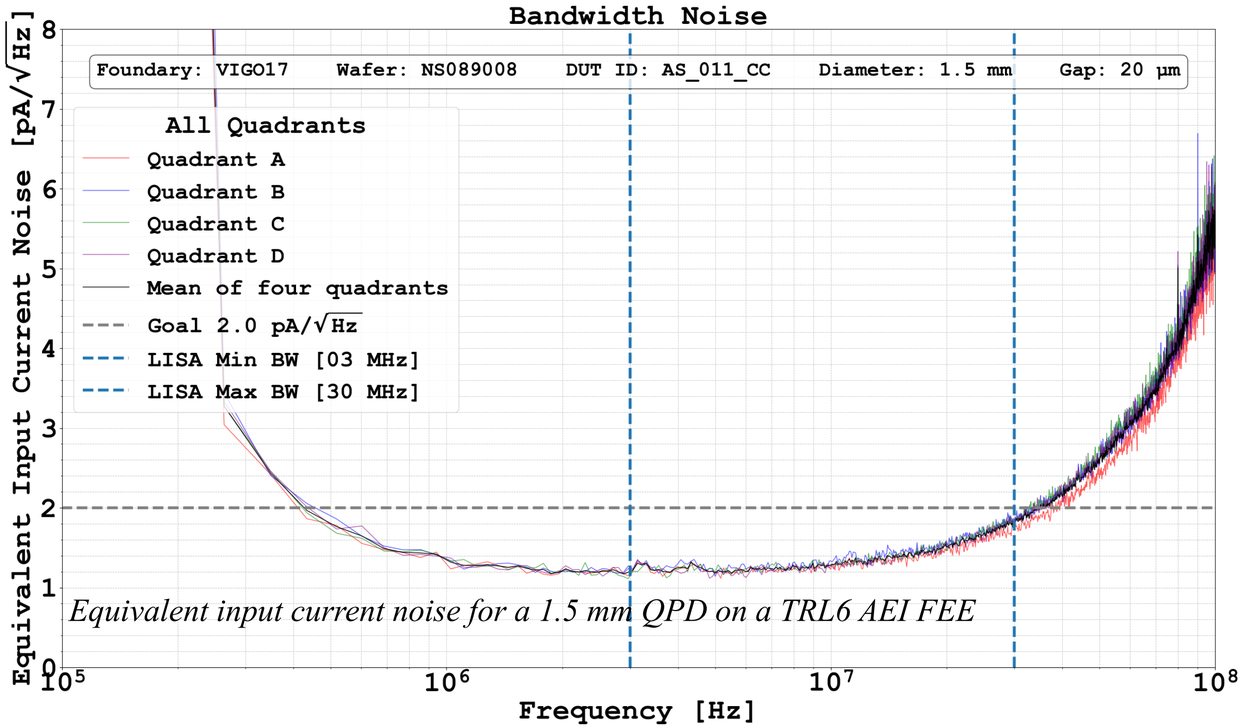
Nikhef



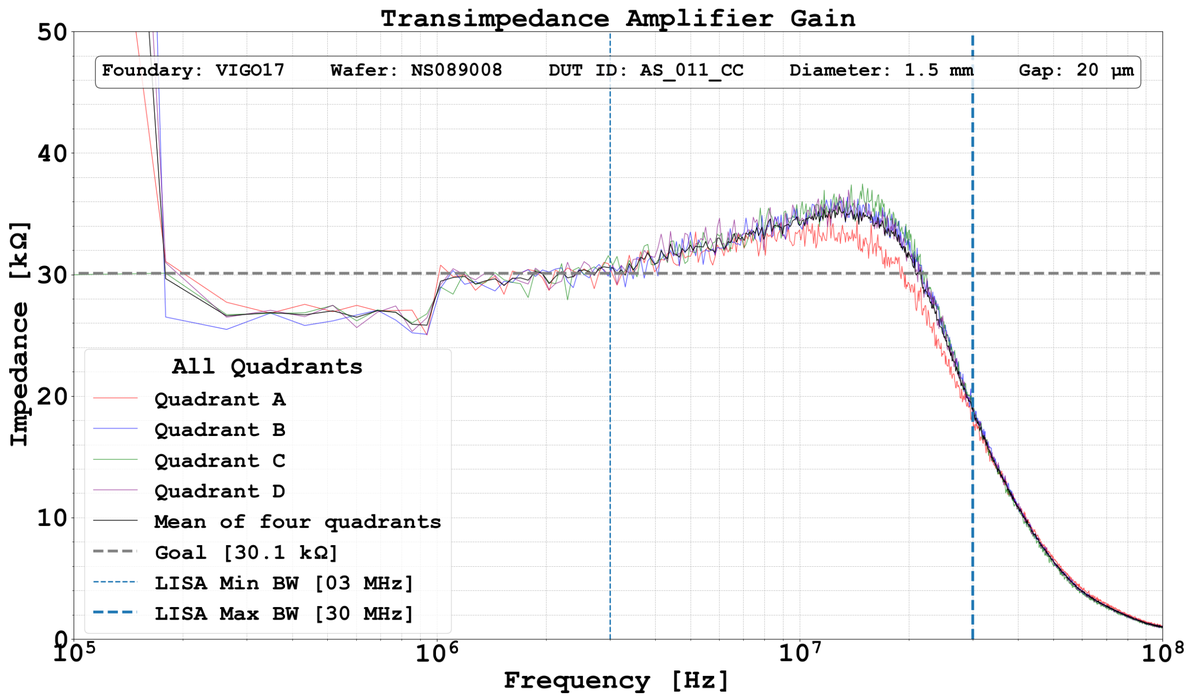
LISA SYMPOSIUM 2024 – DUBLIN IRELAND

THE EYES OF LISA – BACK-UP SLIDES

RUN 1 PERFORMANCE – INPUT NOISE



Equivalent input current noise for a 1.5 mm QPD on a TRL6 AEI FEE



Equivalent input current noise

Shot noise of the DC photocurrent

$$i_{en} = \frac{i_{sn}}{\sqrt{\left(\frac{v_n}{v_{en}}\right)^2 - 1}}$$

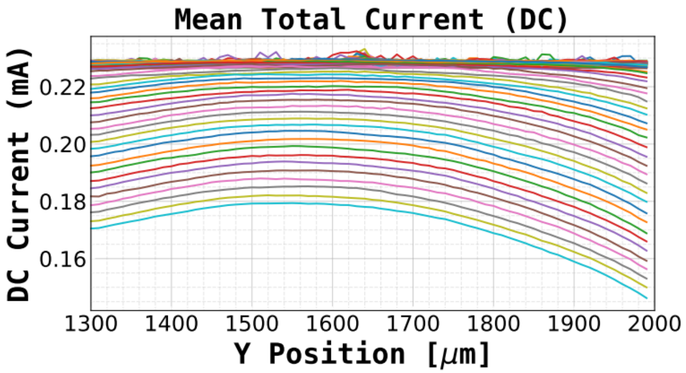
Voltage noise of the TIA with light

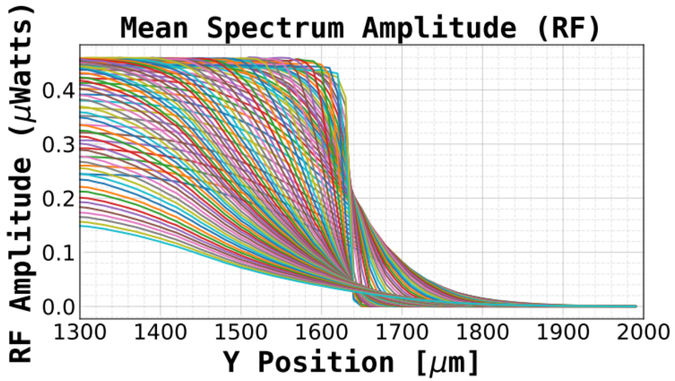
TIA gain

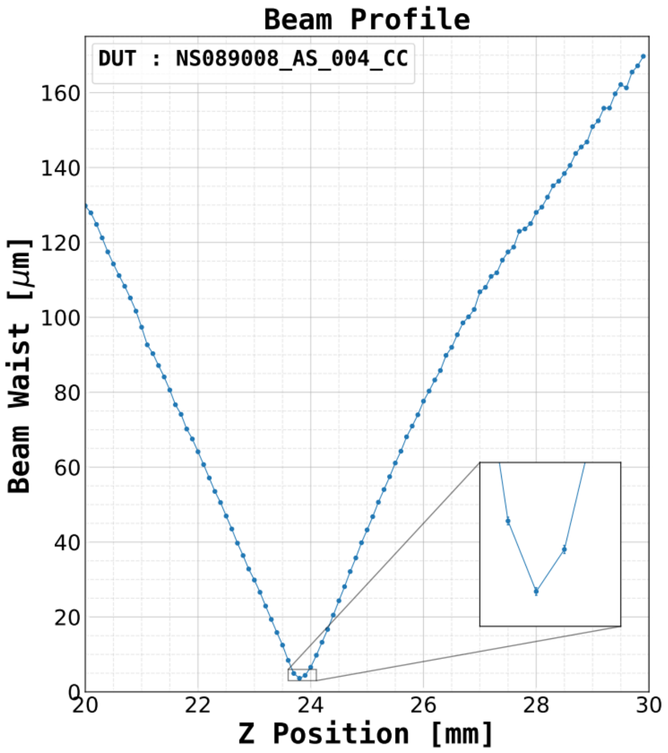
Voltage noise of the TIA without light

$$G_{TIA} = \frac{v_{en}}{i_{en}}$$

FOCUSING THE LASER USING THE QPD





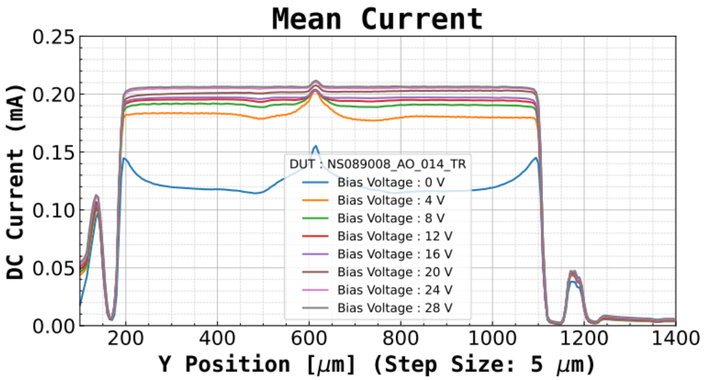


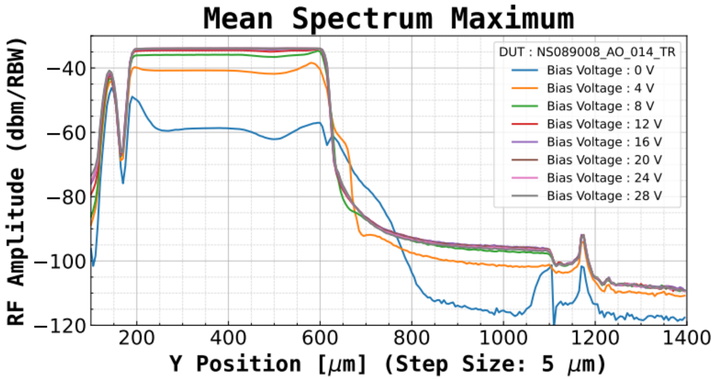
Exploit the gap as a ‘knife edge’.

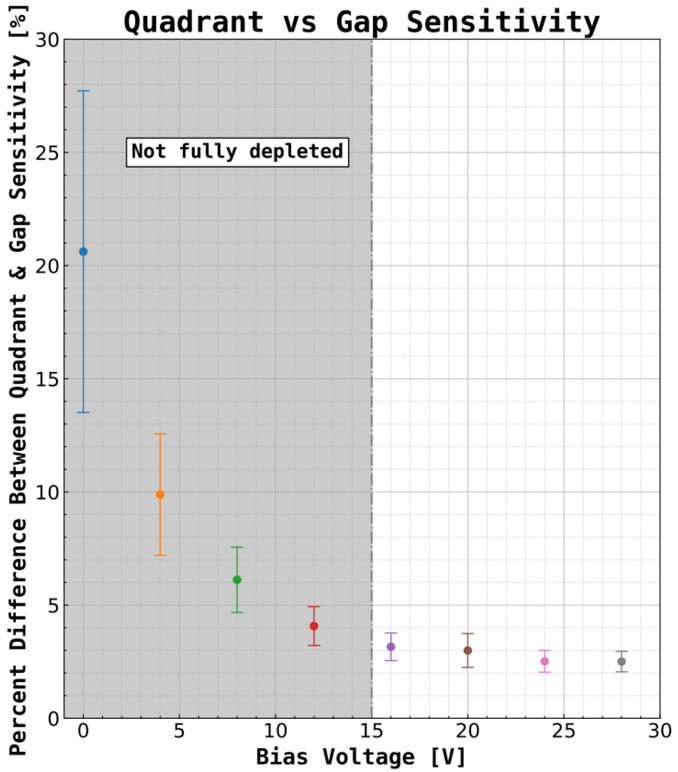
- Scan across the gap and measure the single quadrant response.
- Assume beam is Gaussian so use the error function to fit the step response.

Beam waist ~ 4 um.

RUN 1 PERFORMANCE – QPD GAP RESPONSE







We see an increase in the measured current in the gap between the QPD quadrants.

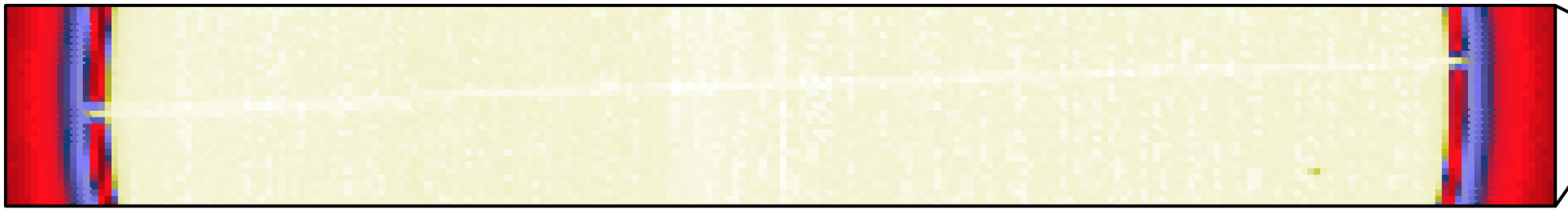
- Perform line scans at different bias voltages.

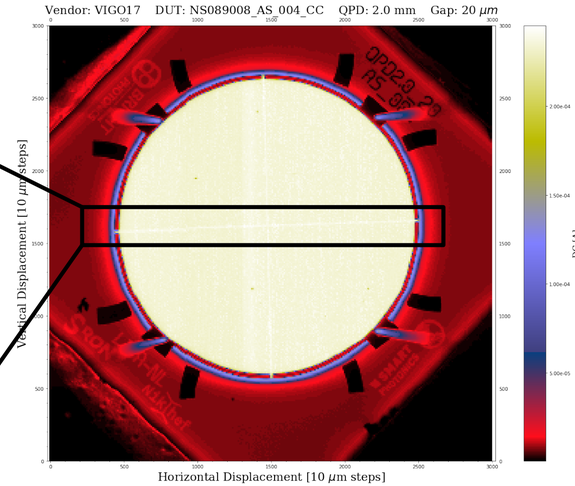
The current LISA QPD model assumes no response in the gap.

- A 100-104% response in the gap increases the total signal by about 10%

Results has significant impact on electronics chain after QPR.

- Current LISA assumes gap has a -7 % loss in the gap.





IMPACT OF QPD ON LISA PERFORMANCE

The challenge is to integrate the lab measurements into LISA performance model.

- LISA performance model
- Simulators?
  - LISA Node
  - LISA Instrument

Currently, only a basic model of the QPD is implemented

- Two parameters
  - Input current noise and responsivity.

Nikhef and SRON is collaborating with the IDS team to update the model and provide a more realistic QPD model.

