Development of superconducting parametric amplifiers for quantum applications

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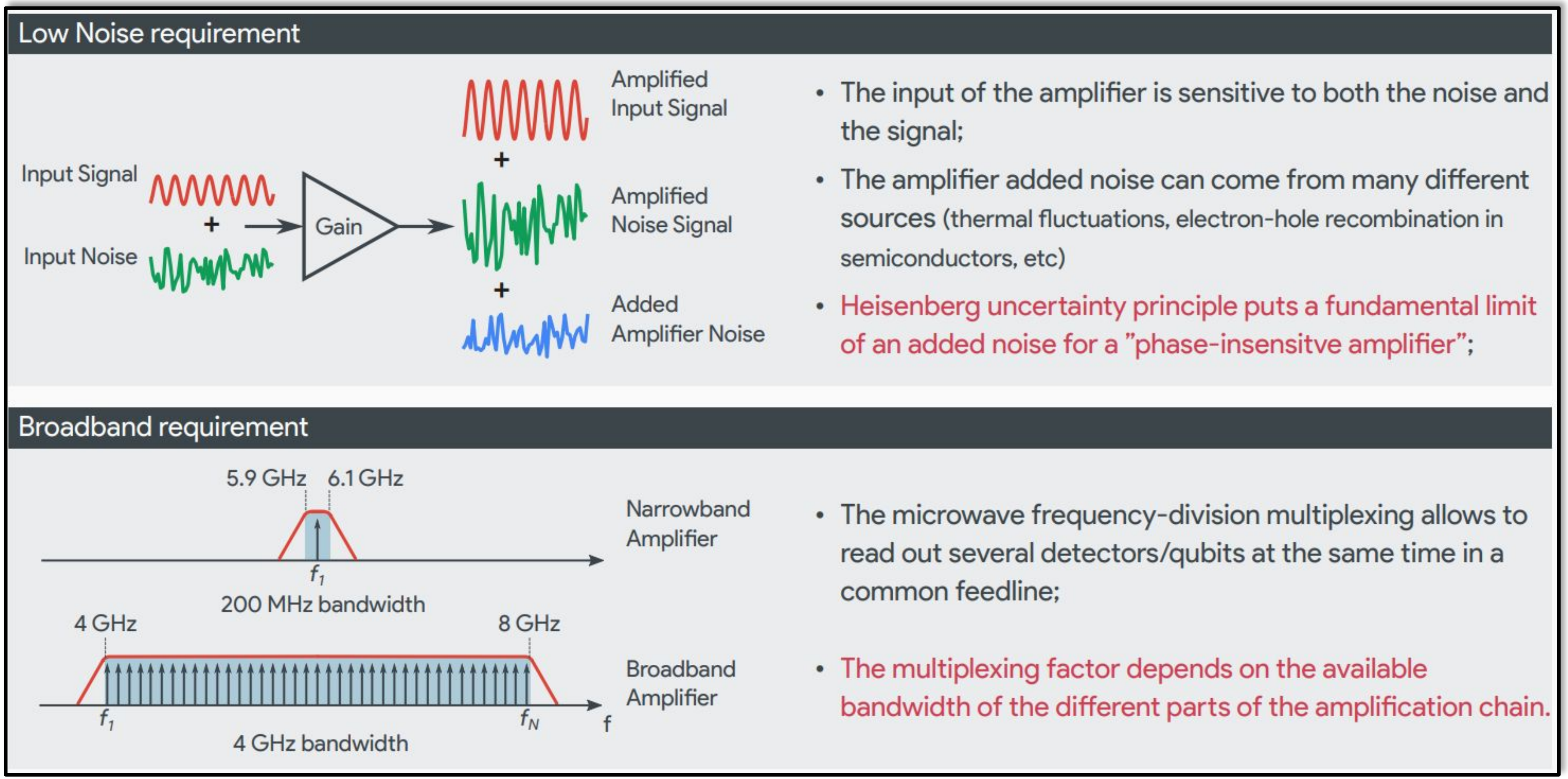
DIPARTIMENTO DI FISICA "E.R. CAIANIELLO"

Motivation

Ultralow-noise microwave detection plays a central role in different applications/experiments, such as: dark matter, axion, dark photons, neutrino, CMB, magnon, qubit read out, and quantum computing



Current technologies for ultra low noise amplification at MW

High electron mobility transistors (HEMTs)

- **Large bandwidth** and **high dynamic range** at very high microwave frequencies;
- Cooling gives an **improvement in noise temperature**, but it is negligible below 20-30 K;
- HEMT development has almost reached its physical limit in term of achievable noise;
- The current HEMT noise is 10–40 times above the fundamental limit imposed by quantum mechanics.

Used to read out array of TESs, MKIDs, and cQED devices

Qub-IT INFN experiment

Josephson Parametric Amplifiers (JPA)

- Power is transferred from a strong pump tone to a weak signal by exploiting an inductive or capacitive nonlinearity and the mixing process;
- Measured **noise** close to the **quantum limit**;
- **Very small instantaneous bandwidth**: < 100 MHz ⇒ read out of few detectors for line;
- **High gain**, but a fixed gain-bandwidth product;
- Very **small dynamic range**: < −100 dBm.

Used as a first stage of amplification for the readout of a superconducting qubits and RF cavities

DARTWARS INFN experiment

Traveling Wave Parametric Amplifiers (TWPAs)

- Microwaves travel along a transmission line with embedded non-linear elements, that can be implemented by **Josephson Junction** (JJ) or Kinetic Inductance (KI) of superconductors. A large pump tone modulates this inductance, coupling the pump (fp) to a signal (fs) and idler (fi) tone via frequency mixing;
- **Noise near to quantum-limited**;
- **High bandwidth**: over a 4 GHz centered at 5 GHz;
- **Limited gain**: < 20 dB, and gain profile with large ripple.

Potential use for reading large number of qubits or RF cavities

Qub-IT

https://coldlab.lnf.infn.it/experiments/qub-it/

The **Qub-IT** project aims to develop quan**tum sensing with superconducting qubits**, with the realization of an itinerant **single-photon counter** that surpasses present devices in terms of efficiency and low dark-count rates by exploiting repeated QND measurements of a single photon and entanglement in multiple qubits.

The project covers the years 2022-2024 and involves, as INFN partners: LNF, Ferrara, Firenze, Milano, Milano-Bicocca, Pisa, **Salerno**, TIPFA and, as external partners, FBK-Trento and CNR-IFN.

INFN SA Lines of activity:

- Modeling of the **Josephson parametric amplifiers (JPAs)** and optimization of the operational parameters
- Experimental test of superconducting circuit components to calibrate the fabrication process

Main equipment:
GPU powered workstations to perform computer intensive numerical simulations.
300 mK insert, microwave sources, spectrum analyzer, low noise microwave amplifier chain, wedge and ball bonder.

The INFN-Salerno group: Carlo Barone, Giovanni Carapella, Giovanni Filatrella, Claudio Guarcello, Sergio Pagano.

Local P.I.: Sergio Pagano, sergio.pagano@sa.infn.it

https://dartwars.unimib.it/home

The **DARTWARS** project is a research effort to **improve the performance and reliability of travelling wave parametric amplifiers (TWPA)** with the study of new materials and with improved microwave and thermal engineering. The long-term goal is to demonstrate, for the first time, the readout with different sensors (TESs, MKIDs, microwave cavities, and qubits) opening the concrete possibility to increase the sensitivity of the next generation particle physics experiments.
The project covers the years 2021-2024 and involves, as INFN partners: LNF, Lecce, Milano Bicocca, **Salerno**, Trento TIPFA and, as external partners, FBK-Trento and INRiM-Torino.

INFN SA Lines of activity:

- Modelling and simulations of the **Josephson TWPA** and optimization of the operational parameters.
- Perform initial tests of JTWPA.

Main equipment:
GPU powered workstations to perform computer intensive numerical simulations.
300 mK insert, microwave sources, spectrum analyzer, low noise microwave amplifier chain, wedge and ball bonder.

The INFN-Salerno group: C. Guarcello, G. Avallone, C. Barone, G. Carapella, G. Filatrella, V. Granata, C. Mauro, and S. Pagano

Local P.I.: Sergio Pagano, sergio.pagano@sa.infn.it

Travelling Wave Parametric Amplifier (TWPA)

parametric amplification = wave-mixing process based on parametric amplification

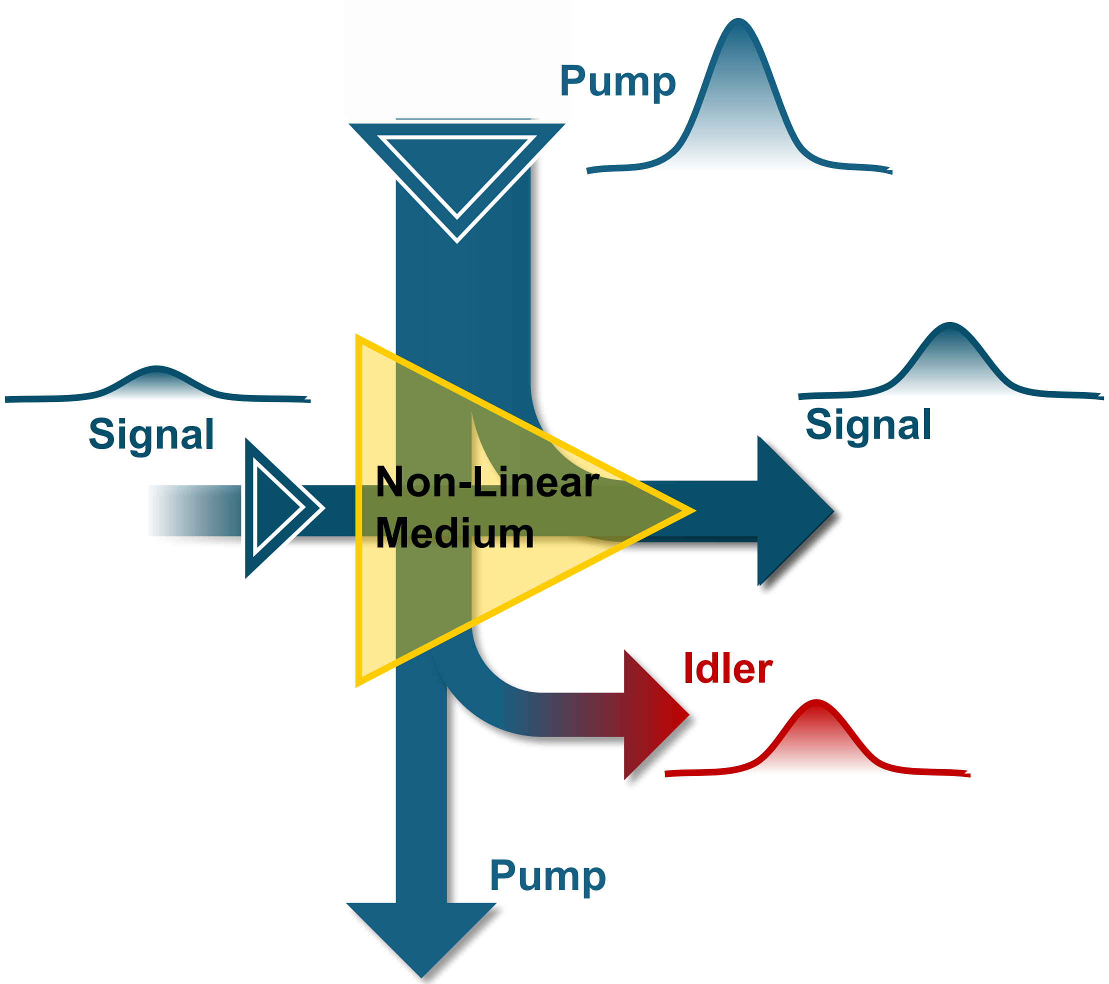
Superconducting Amplifiers

Within the **DARTWARS** project:

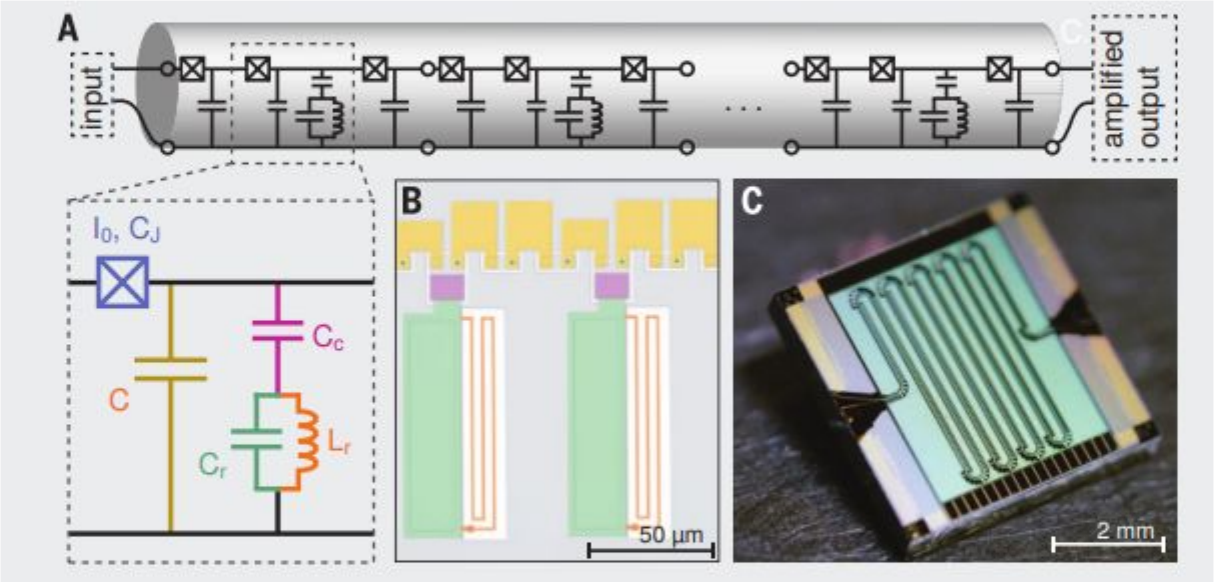
- kinetic inductance of a high-resistivity superconductor;
- **Josephson traveling-wave parametric amplifiers (JTWPA).**

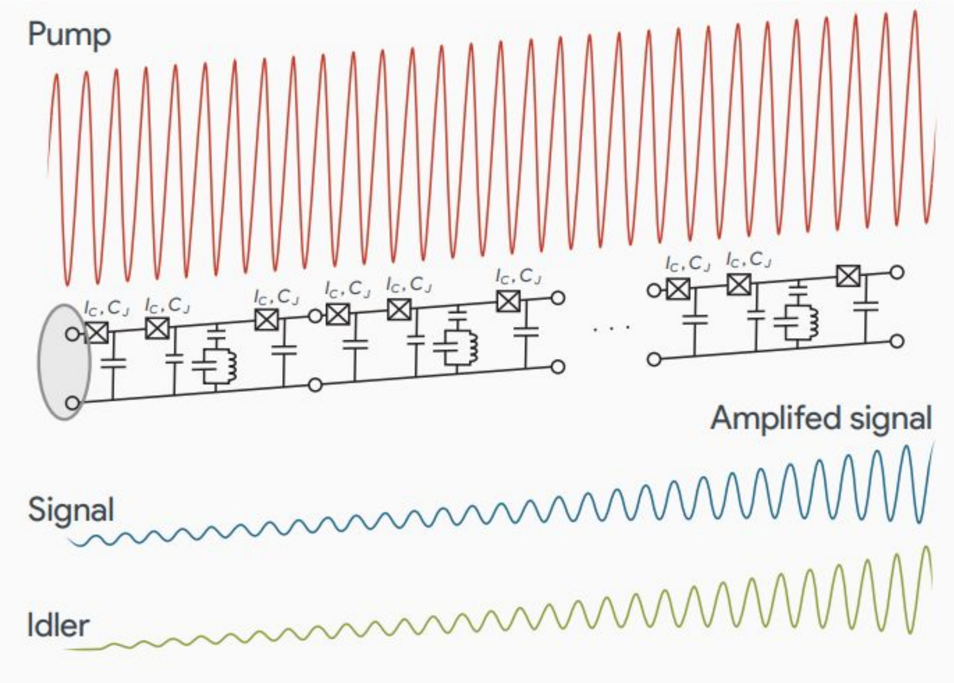
A Josephson junction can be considered as a ***non-linear inductance***

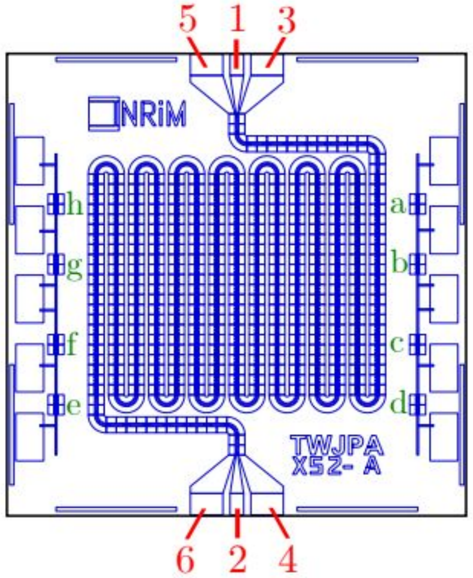
$$L_J = \frac{\Phi_0}{2\pi}\left(\frac{dI_J}{d\varphi}\right)^{-1}$$

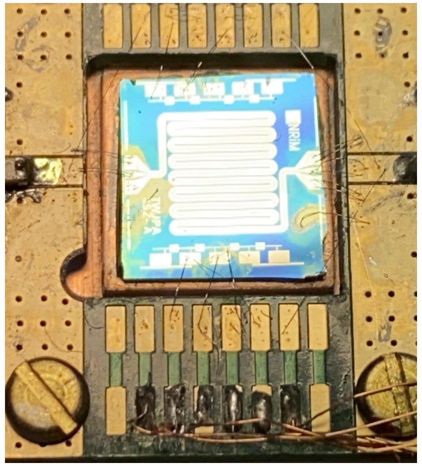


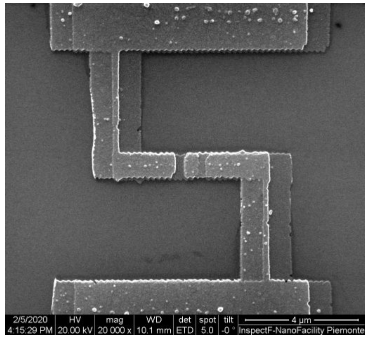
JTWPA

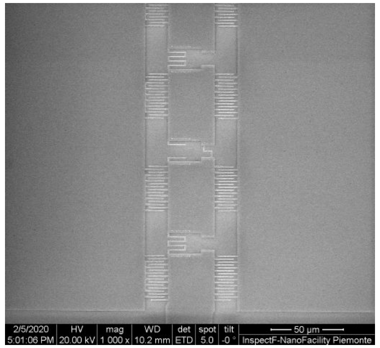

A
input
amplified output
I_0, C_J
C
C_c
C_r
L_r
B
50 µm
C
2 mm

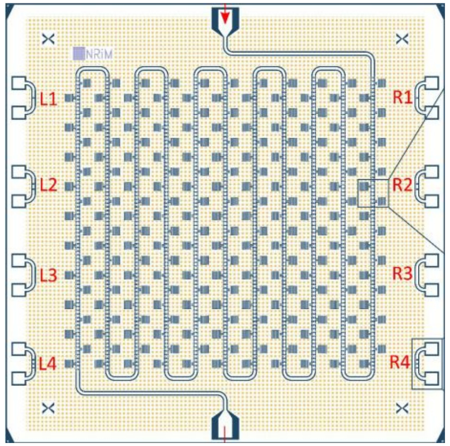

Pump
I_c, C_J
Amplifed signal
Signal
Idler

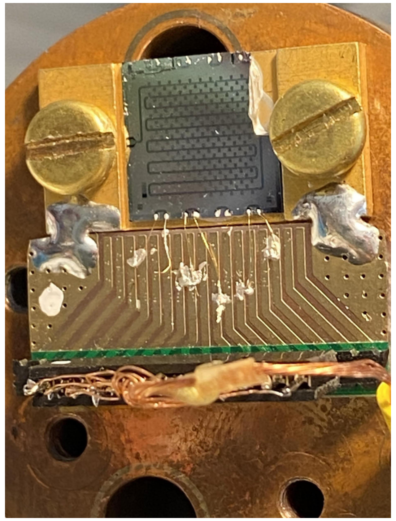

5 1 3
NRIM
h g f e
a b c d
TWJPA X52- A
6 2 4




4 µm
InspectF-NanoFacility Piemonte


50 µm
InspectF-NanoFacility Piemonte

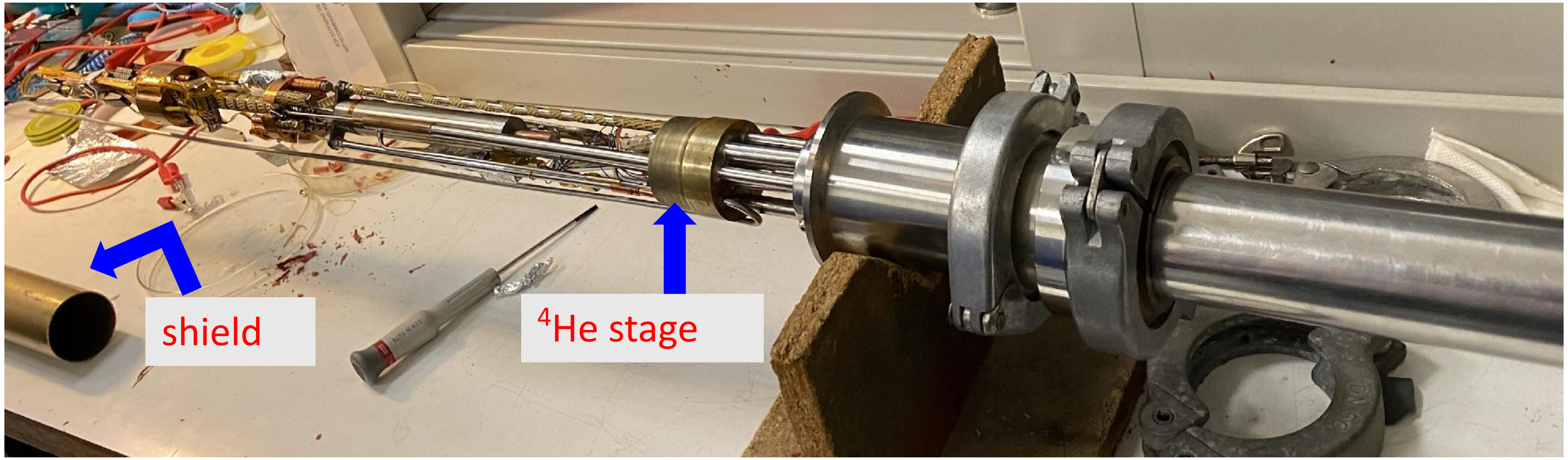

L1
L2
L3
L4
R1
R2
R3
R4

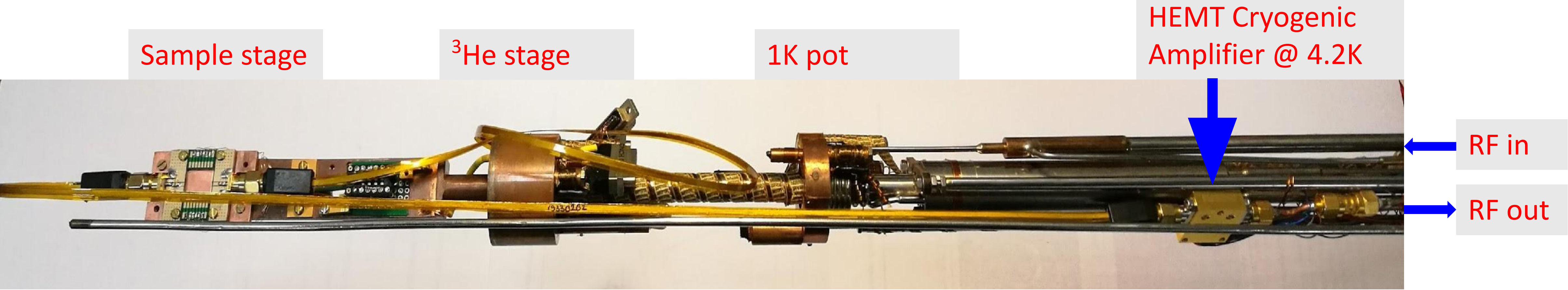


Old 300 mK cryostat

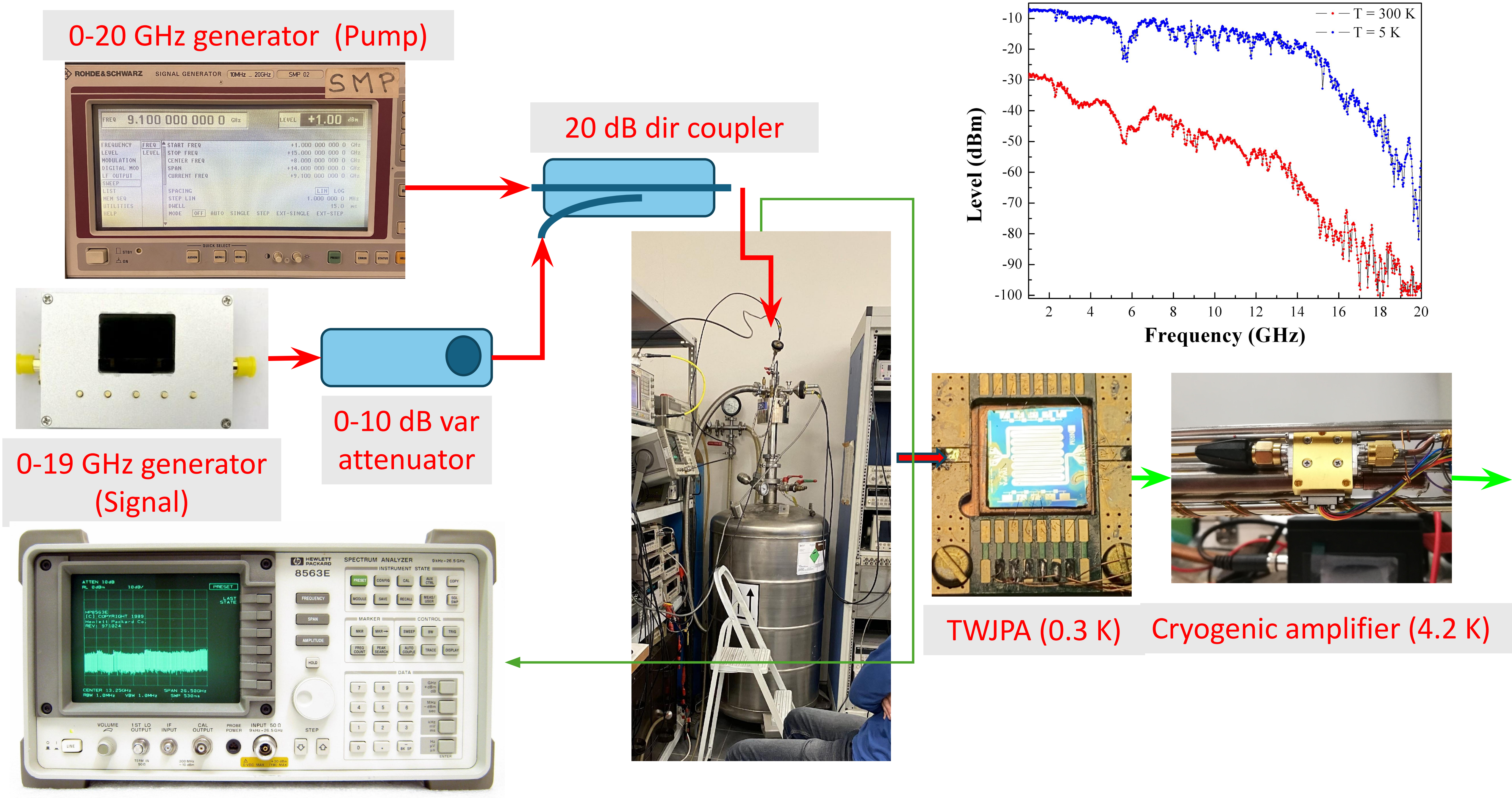
Oxford Heliox VL ^{3}He cryostat

OK for testing Al based junctions
Needed adaptations for MW signals



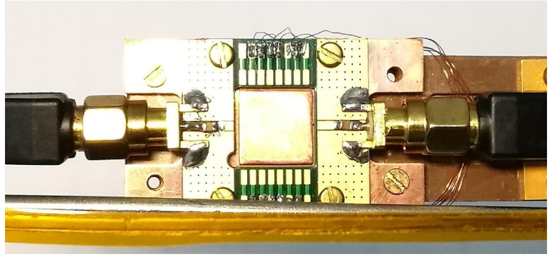


RF measurement setup



DC measurement setup

Sample holder

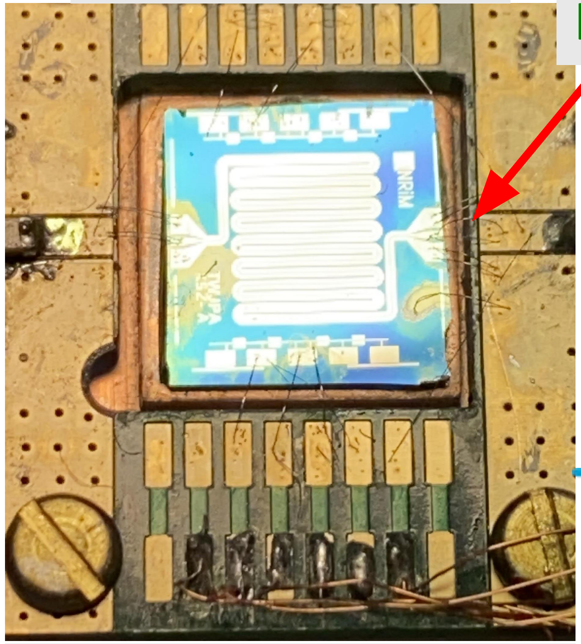


TWJPA X52-A

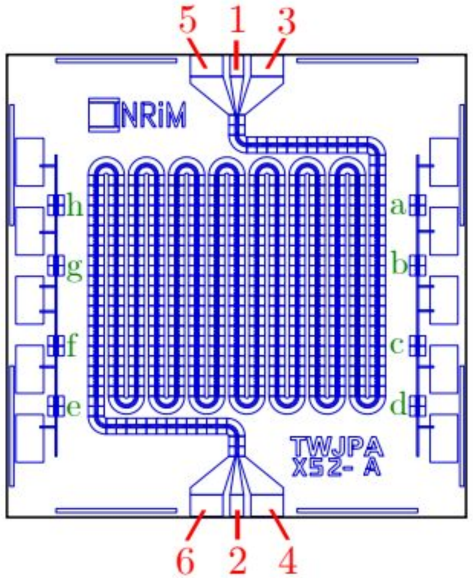
Ultrasonic bonding

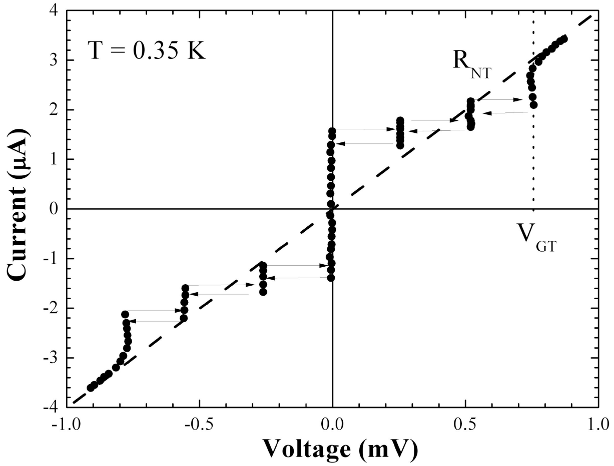
RF out

RF in

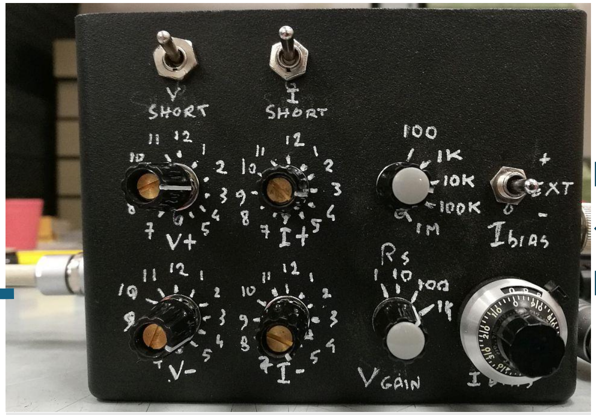


DC bias and test lines

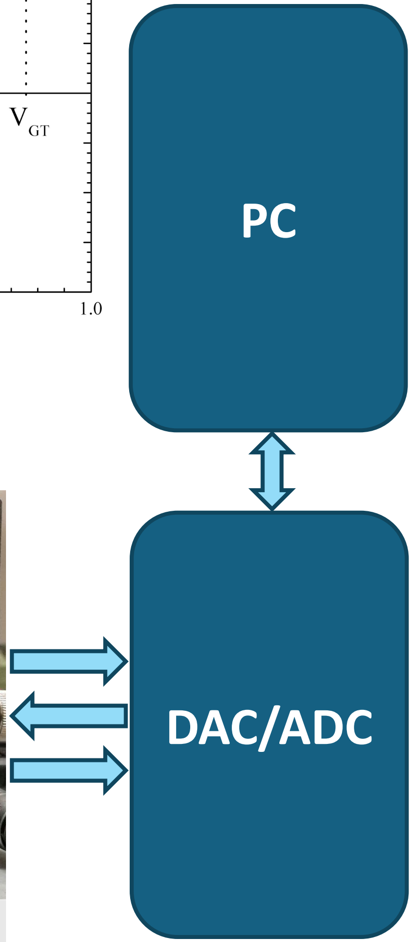




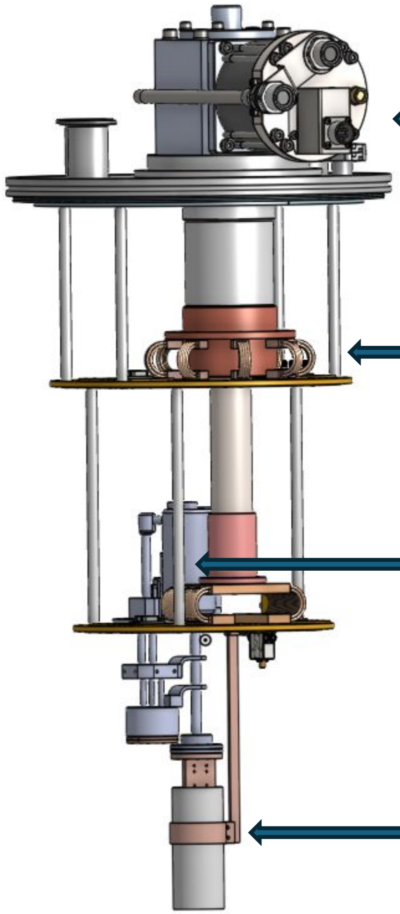
Filtering and grounding box



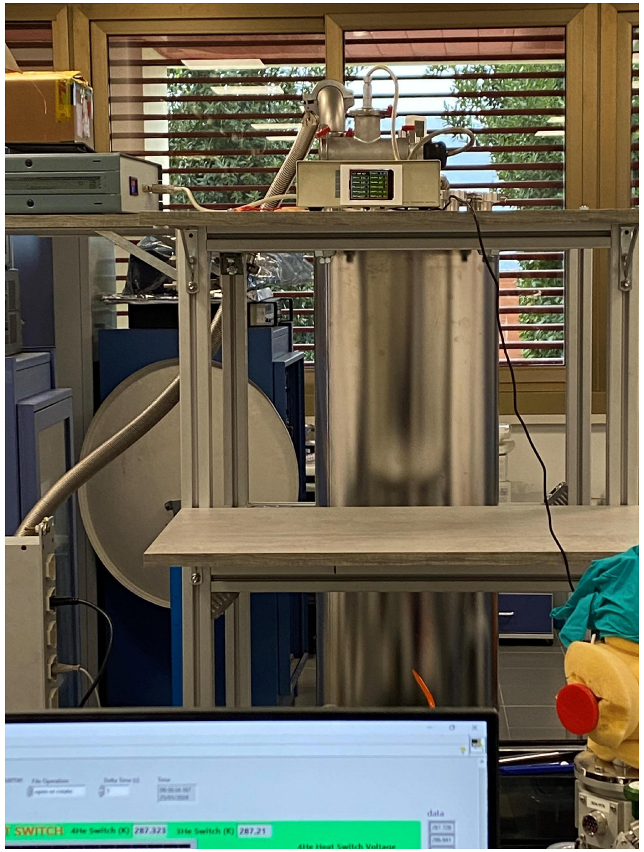
Low Noise DC readout



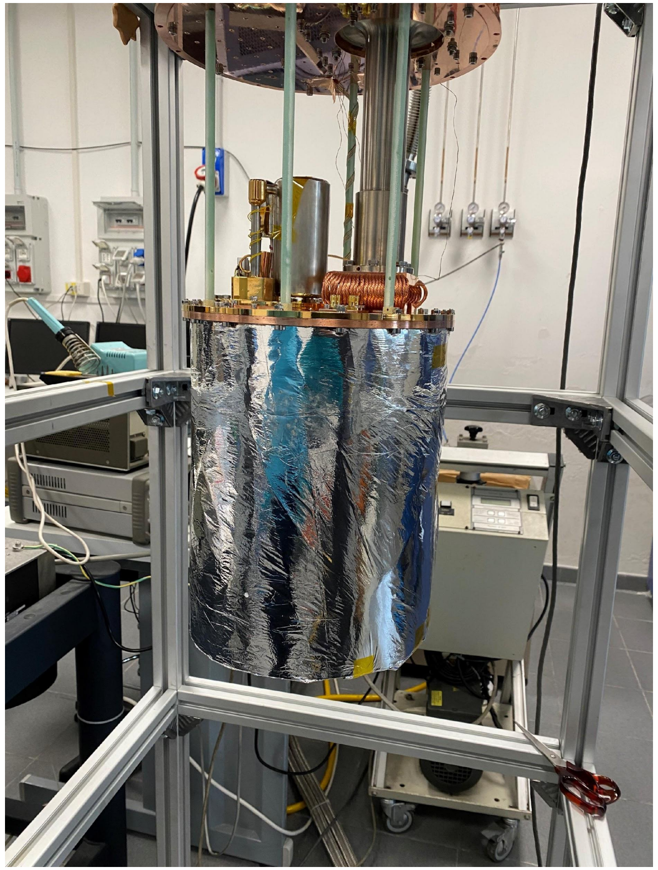
New 300 mK cryostat design



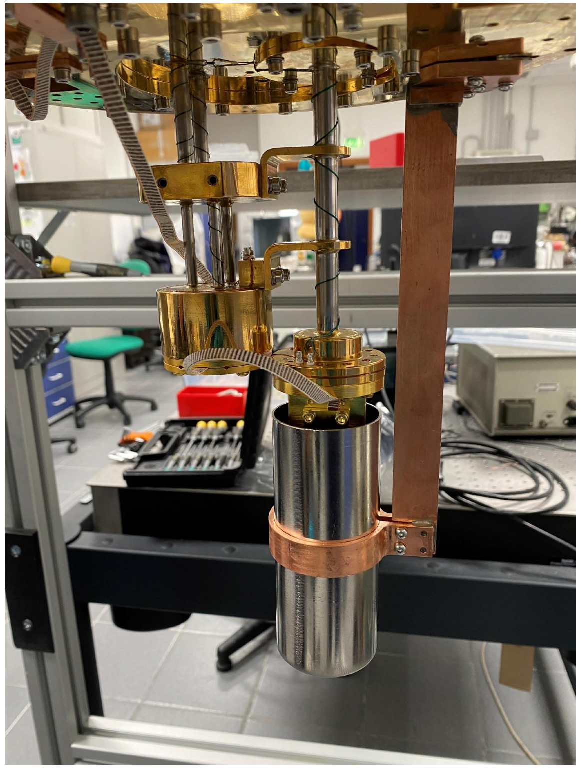
The new 300 mK cryostat



External view

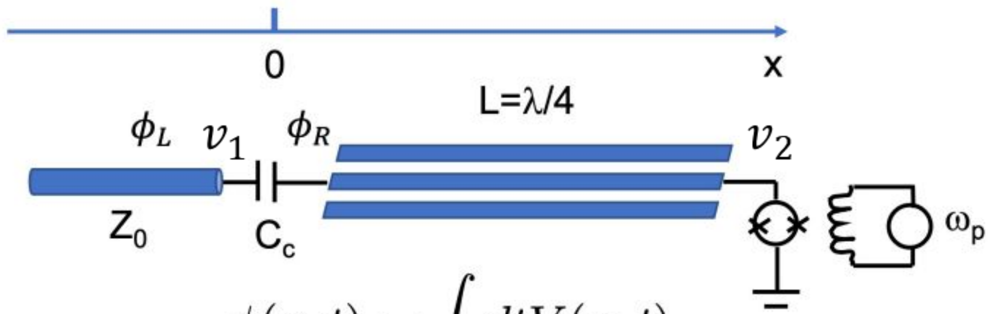


4K thermal shield



300 mK stage

JPA modeling



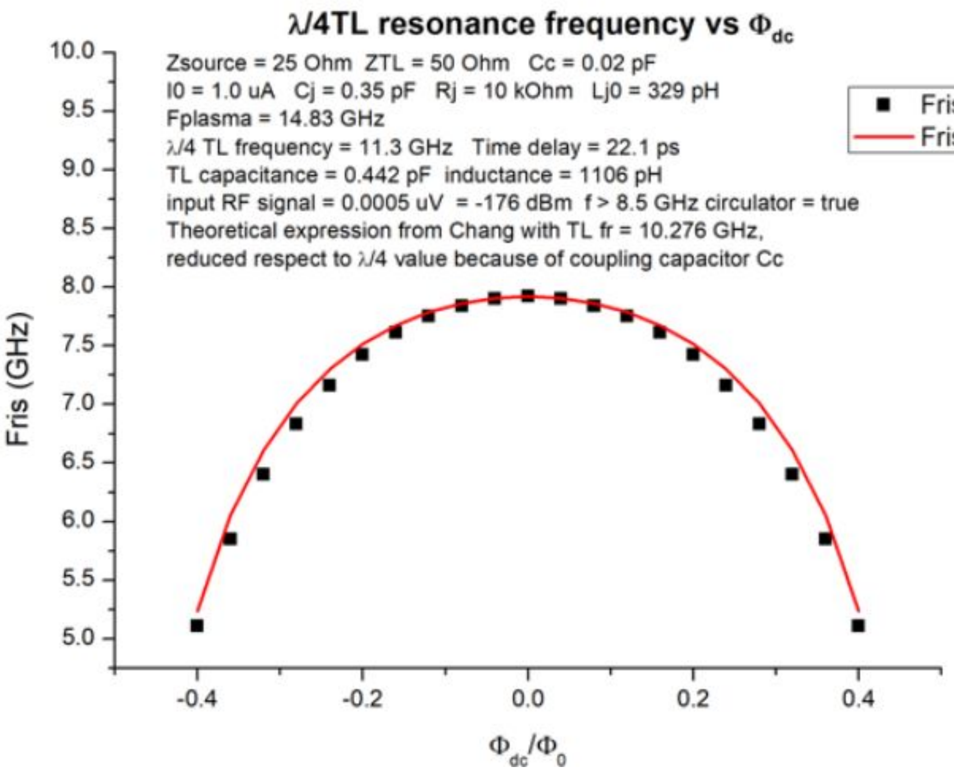
$$\phi(x,t) = \int dt V(x,t)$$

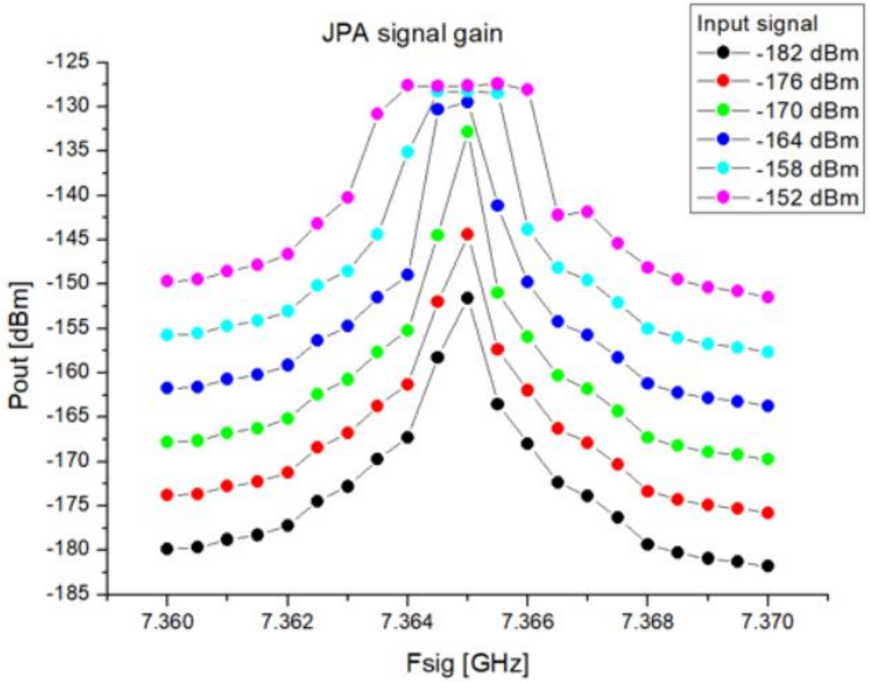
$$\dot{v}_1 = -\frac{1}{2C_cZ_0}v_1 + \frac{1}{2}\dot{v}_{rf}(t) - \frac{1}{2}\dot{E}_r(t-\tau) - \frac{1}{2C_cZ_0}E_r(t-\tau)$$

$$\dot{v}_2 = -(\frac{1}{C_jZ_0} + \frac{1}{C_jR_j})v_2 - \frac{2I_j}{C_j}cos(2\pi\frac{\Phi_{ext}}{\Phi_0})sin\phi - \frac{1}{C_jZ_0}E_i(t-\tau)$$

$$\dot{\phi} = \frac{2e}{\hbar}v_2$$

where: $\dot{v}_{rf}(t) = v_{rf}\omega cos(\omega t)$; $\phi_{ext}(t) = \phi_{ext}cos(\omega_p t))$; $Z_0 = 50\Omega$; $\tau = \frac{T}{4} = \frac{\pi}{2\omega}$.



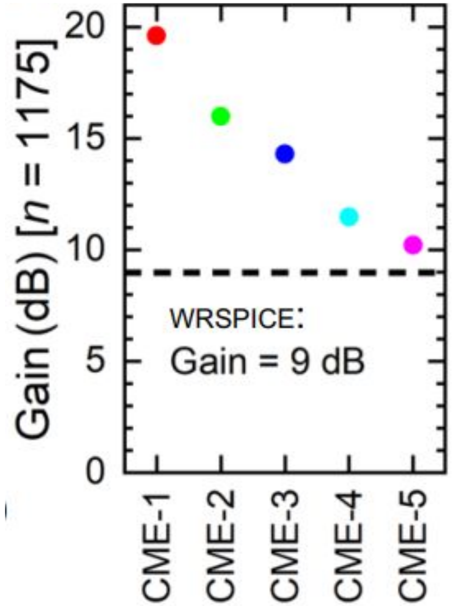


JTWPA modeling

Several models have been developed to account for JTWPA behavior.

- **Analytic approaches** are based on **low-order approximation of nonlinearities**, homogeneous systems and assume the presence of only Signal, Idle and Pump modes, impedance matching.
- **Semi-analytic approaches** consider also a limited number of **additional modes** and require numerical calculations (harmonic balance, …)
- **Dynamic numerical models** show full behavior and can be realized using different approaches (direct coding, scripting, wrspice,…)

A. B. Zorin, Phys. Rev. Appl., ***6****, 034006 (2016)*



T. Dixon et al. Phys. Rev. Appl. ***14****, 034058 (2020)*

V. Gaygamachenko et al. J. Appl. Phys. **132**, 154401 (2022)

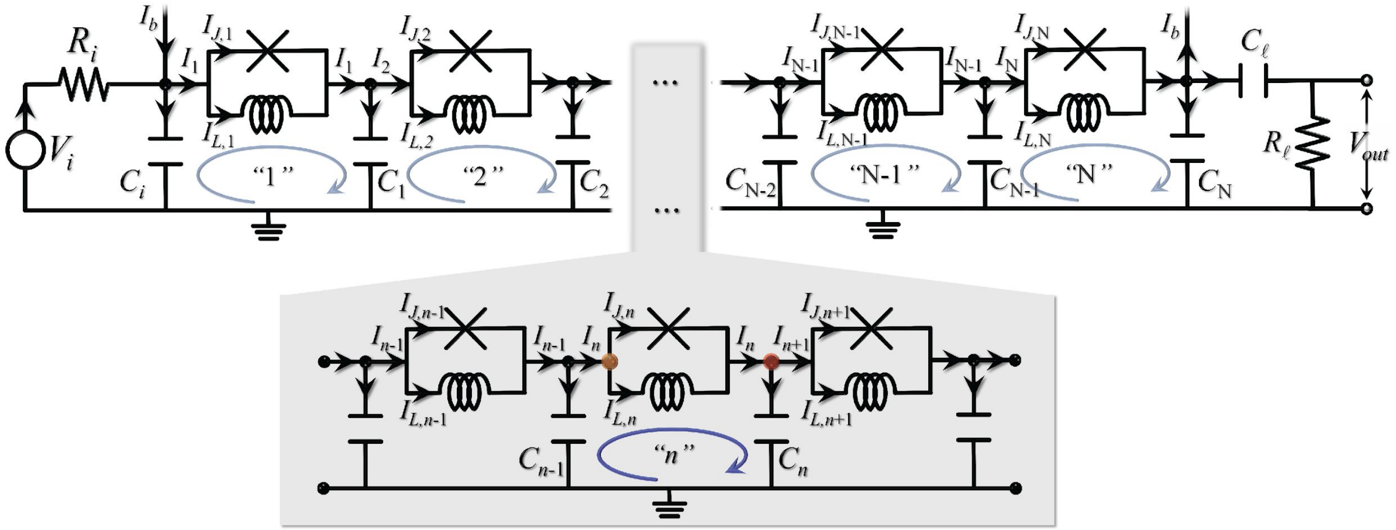
The real issue is Accuracy vs Computation time

Our approach is to **numerically solve the nonlinear system describing the JTWPA without approximations**. We use the device parameters extracted from design and experiments and investigate the dynamic behavior in different configurations.

JTWPA modeling

The model of our JTWPA is formed by 990 cells, each containing an RF SQUID in series and a capacitor to ground.

In the n^{th} cell the current I_n, the phase φ_n and the charge q_n are related by:



Equivalent circuit of the modelled JTWPA

$$I_n - I_{n+1} = \dot{q}_n \,;\, I_n = I_{J,n} + I_{L,n} = I_{J,n} + \frac{\hbar}{2e}\frac{\varphi_n}{L_{g,n}}$$

$$\frac{\hbar}{2e}\frac{d\varphi_n}{dt} + \frac{q_n}{C_{g,n}} = \frac{q_{n-1}}{C_{g,n-1}}$$

$$I_{J,n} = C_J \frac{\hbar}{2e}\frac{d^2\varphi_n}{dt^2} + \frac{1}{R_J}\frac{\hbar}{2e}\frac{d\varphi_n}{dt} + I_c \sin\varphi_n$$

The resulting Josephson plasma frequency is ≈ 27.7 GHz.

$N = 990$ JJs	$C_n = 24$ fF
$R_i = 50\ \Omega$	$L_g = 120$ pH
$C_i = 24$ fF	$R_J = 20$ kΩ
$R_\ell = 50\ \Omega$	$C_J = 200$ fF
$C_\ell = 1$ nF	$I_c = 2\ \mu A$

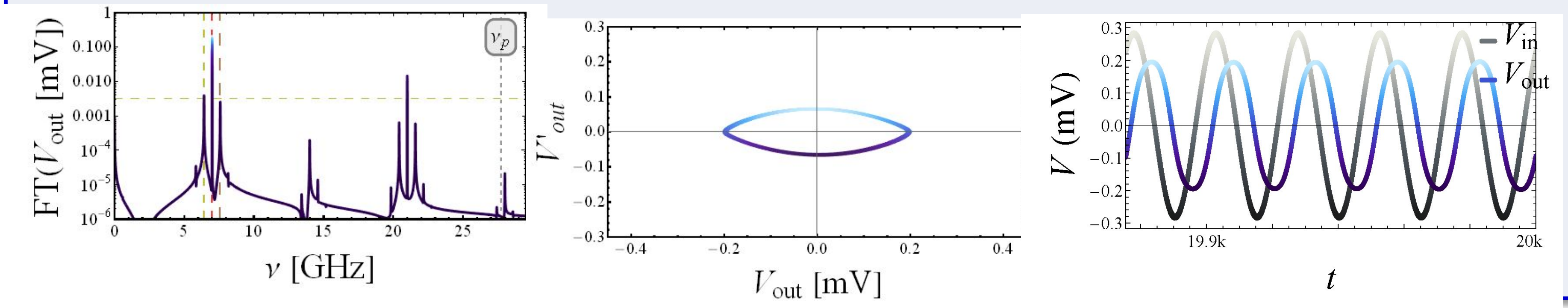
circuit parameters

The applied voltage is: $V_i = V_{pump}\sin(2\pi f_{pump} t) + V_{sign}\sin(2\pi f_{sig} t)$

The output Voltage is measured across a resistive load $R_\ell = 50\ \Omega$

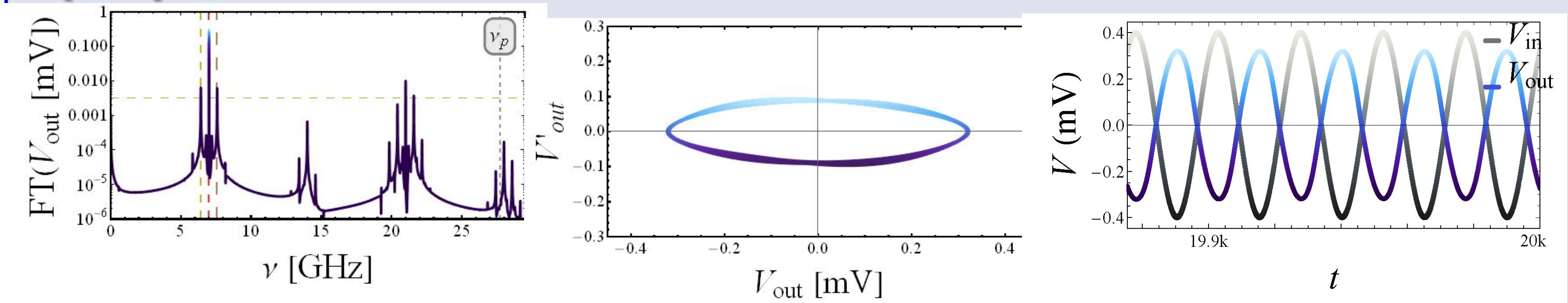
Results

$P_{pump} = -61$ dBm



The phase-space portrait shows a sort of elliptical limit cycle
The spectrum contains only pump, signal and idler (in 4WM) and their harmonics

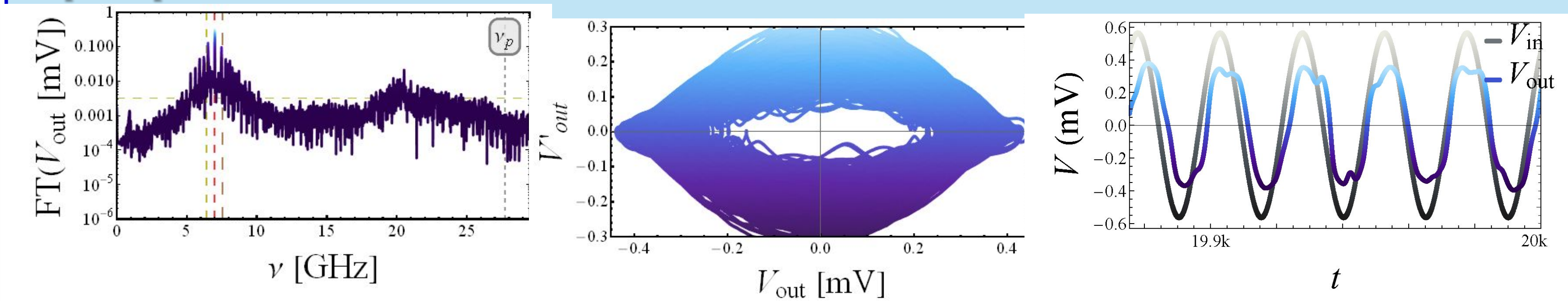
$P_{pump} = -58$ dBm



The limit circle is more complex

The spectrum contains many more mixing products

$P_{pump} = -55$ dBm



The dynamics becomes chaotic

The spectrum has a large noise background

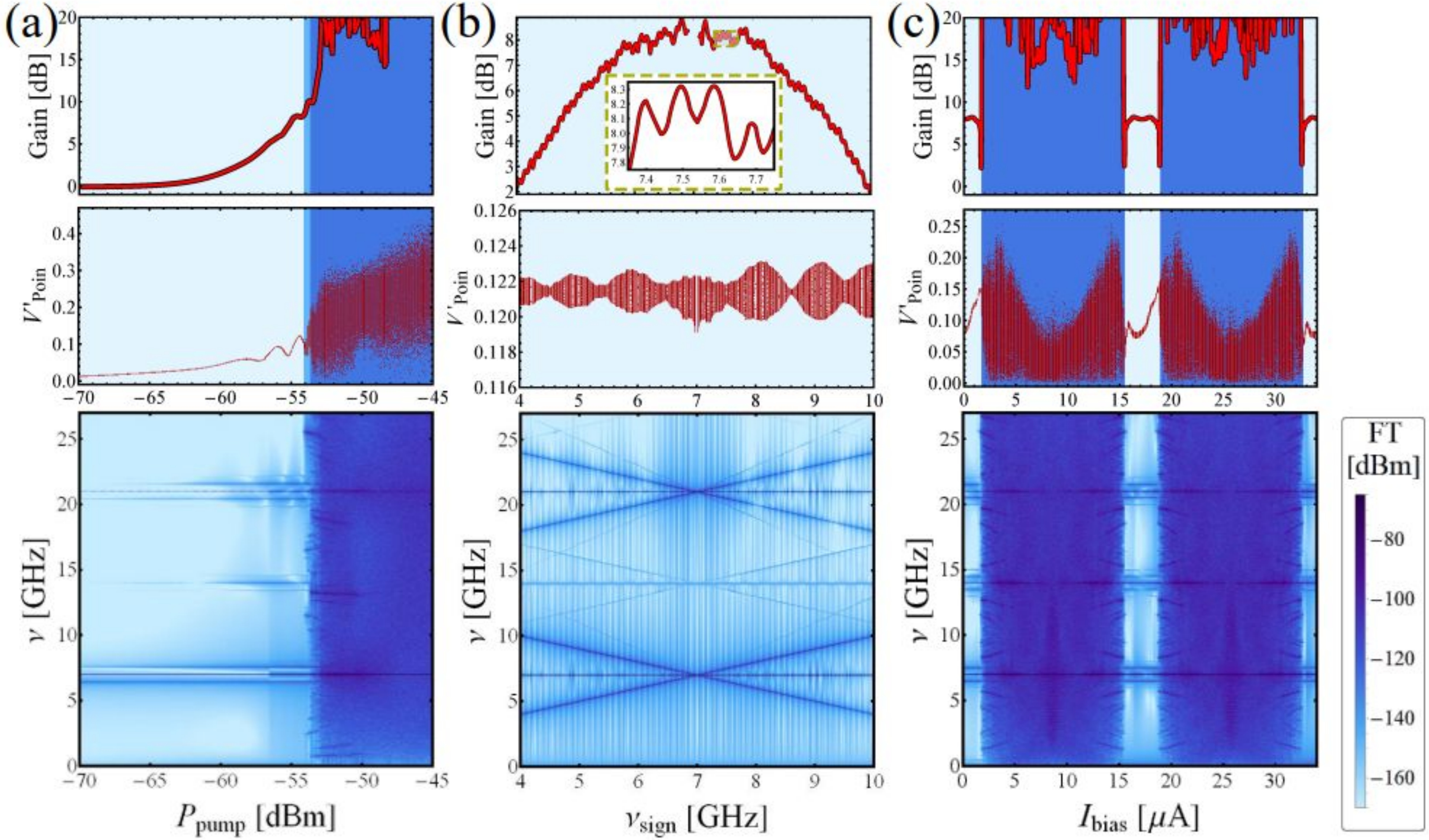
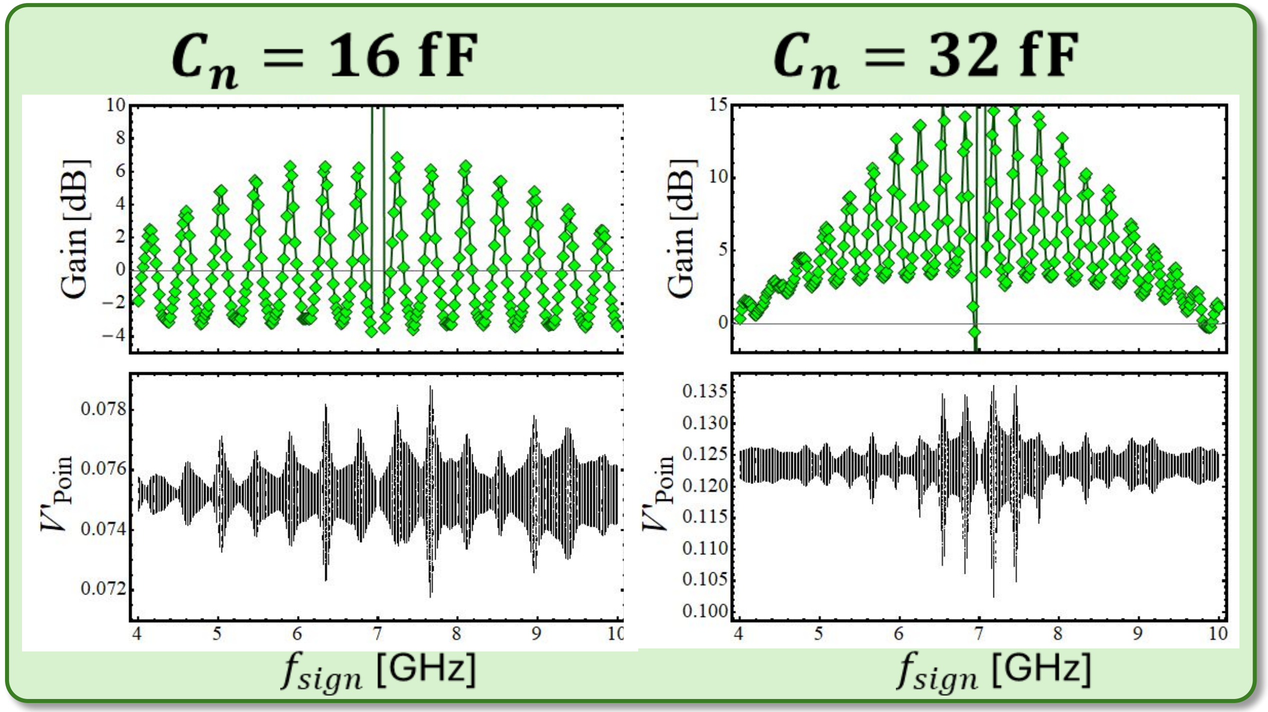


FIG. 2. Gain (top panel), Poincaré section (middle panel), and Fourier spectra of the output voltage (bottom panel) *versu* (a) pump power level, P_{pump}, at $\nu_{\mathrm{sign}} = 6.42$ GHz and $I_{\mathrm{bias}} = 0$; (b) the signal frequency, ν_{sign}, at $P_{\mathrm{pump}} = -54.5$ dBm ar $I_{\mathrm{bias}} = 0$; (c) bias current, I_{bias}, at $P_{\mathrm{pump}} = -55$ dBm and $\nu_{\mathrm{sign}} = 6.42$ GHz. In top and middle panels, different respons regimes are highlighted by regions shaded in different colors. In the density plots, the color intensity scale represents tl amplitude of the spectral components whose frequency can be read on the bottom-left vertical axis. The other parameters ar $\nu_{\mathrm{pump}} = 7$ GHz and $P_{\mathrm{sign}} = -100$ dBm.

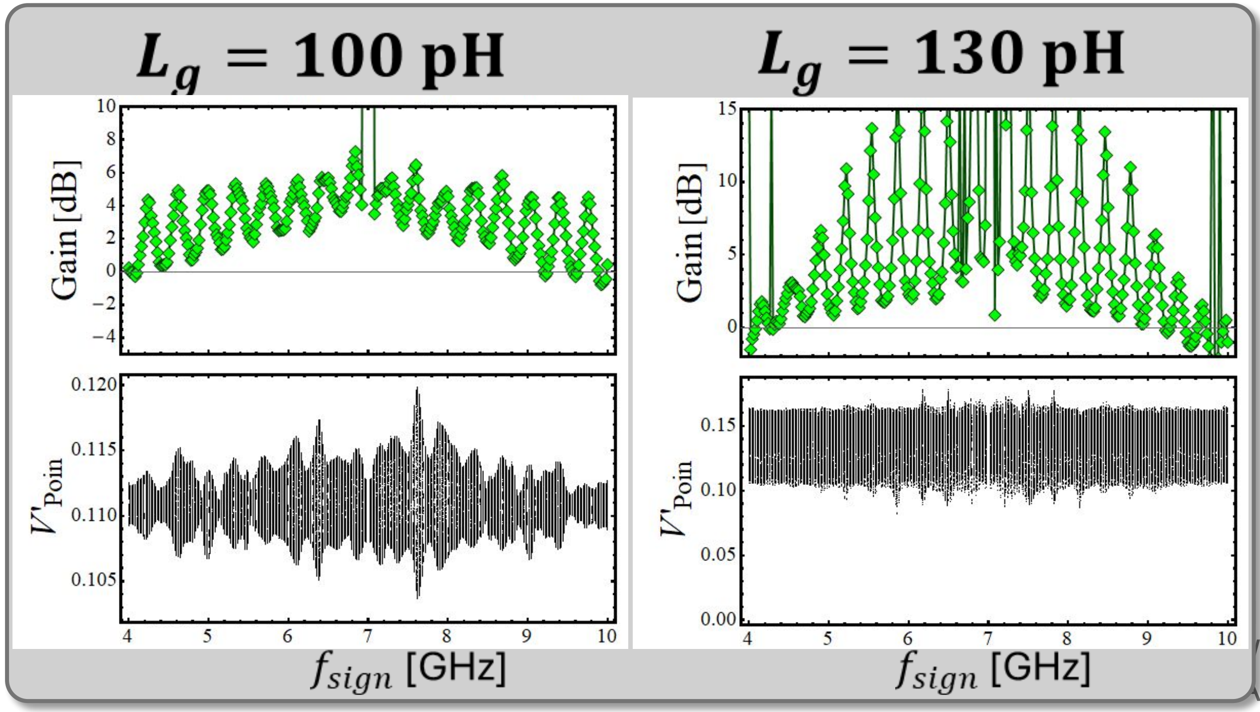
GAIN *vs* electrical parameters

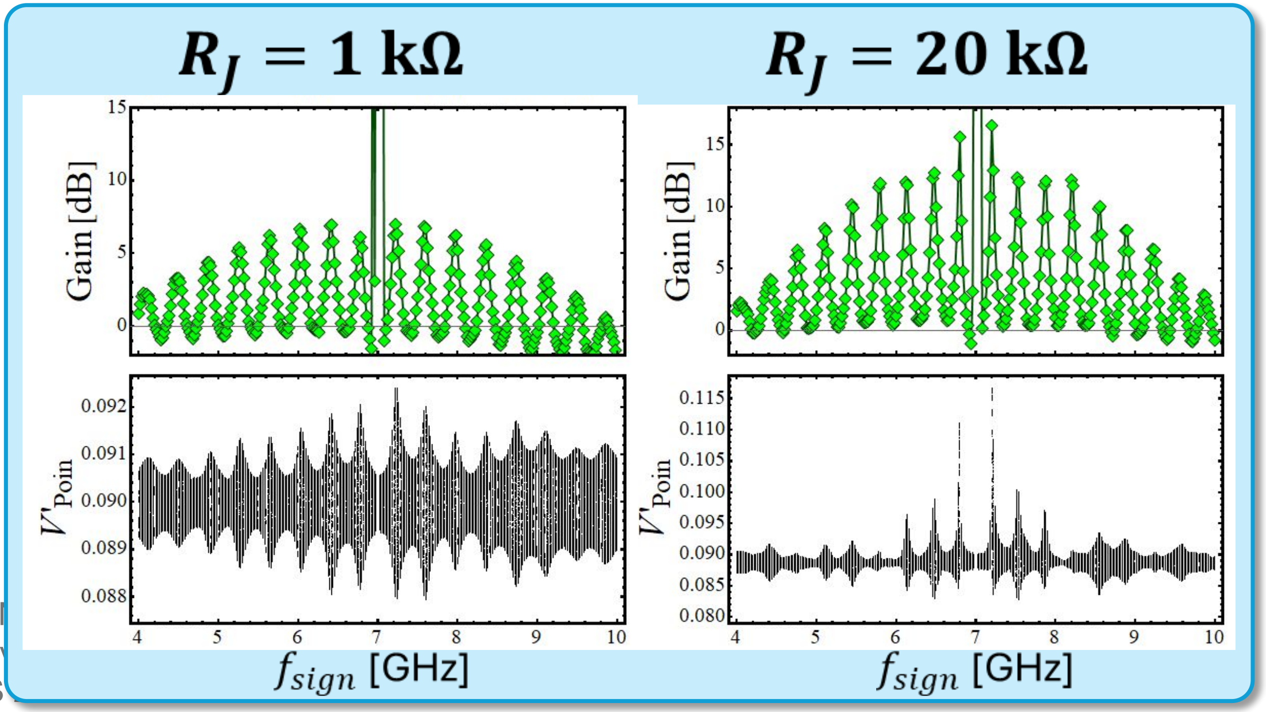


V'_{poin} represents a sort of *quality factor* of the amplifier:
A constant value means no gain (only the pump is present)

Some fluctation around the mean value is necessary but too much means **chaos**

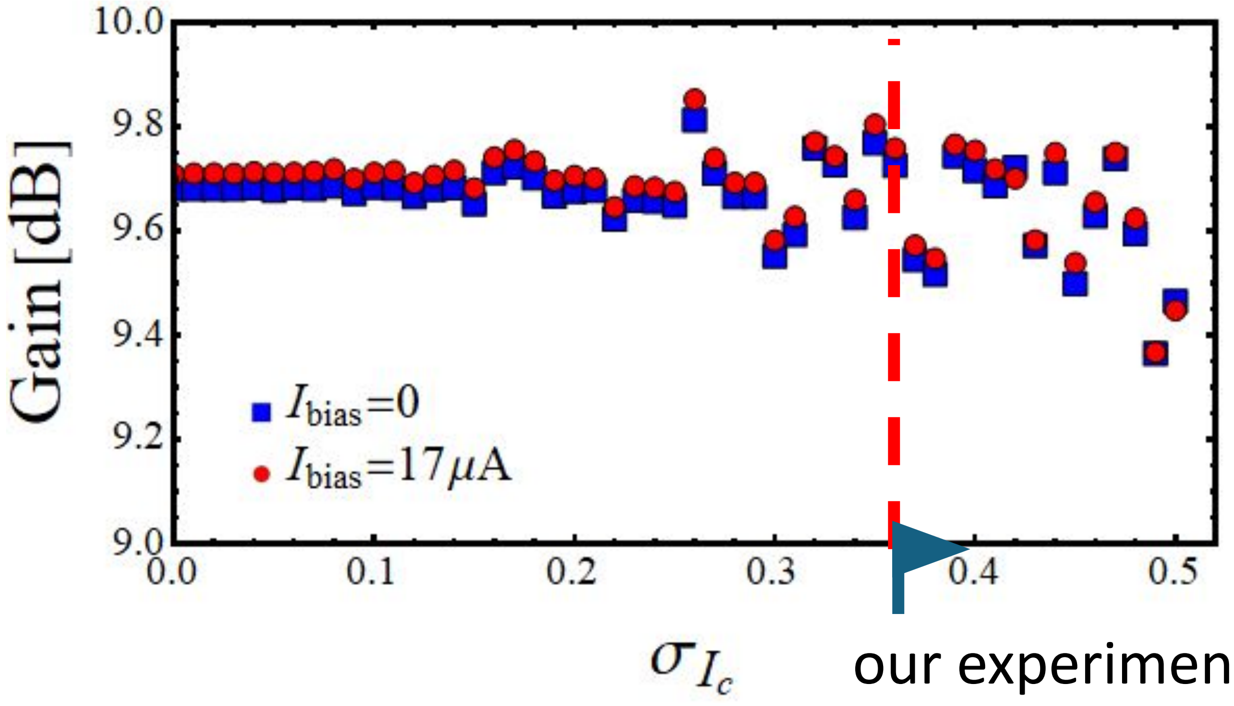
$N = 990$ JJs	$C_n = 24$ fF
$R_i = 50\ \Omega$	$L_g = 120$ pH
$C_i = 24$ fF	$R_J = 20$ kΩ
$R_\ell = 50\ \Omega$	$C_J = 200$ fF
$C_\ell = 1$ nF	$I_c = 2\ \mu A$



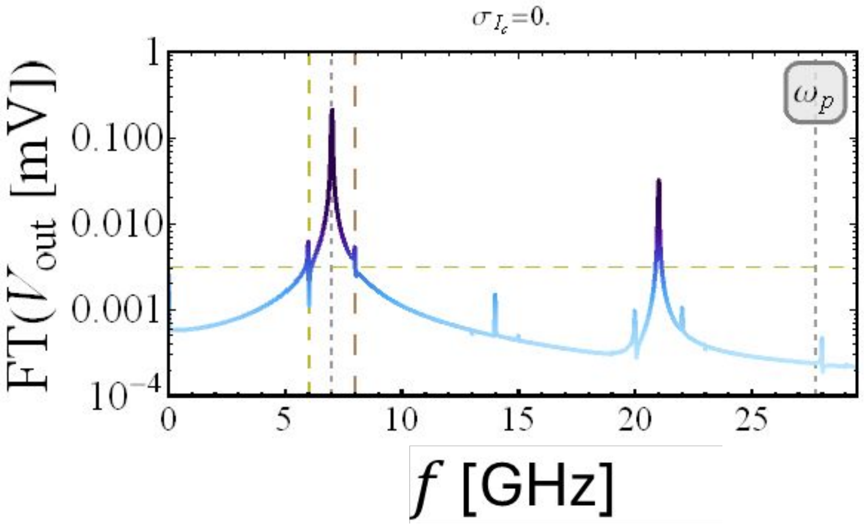


Effect of Ic variation along the TL

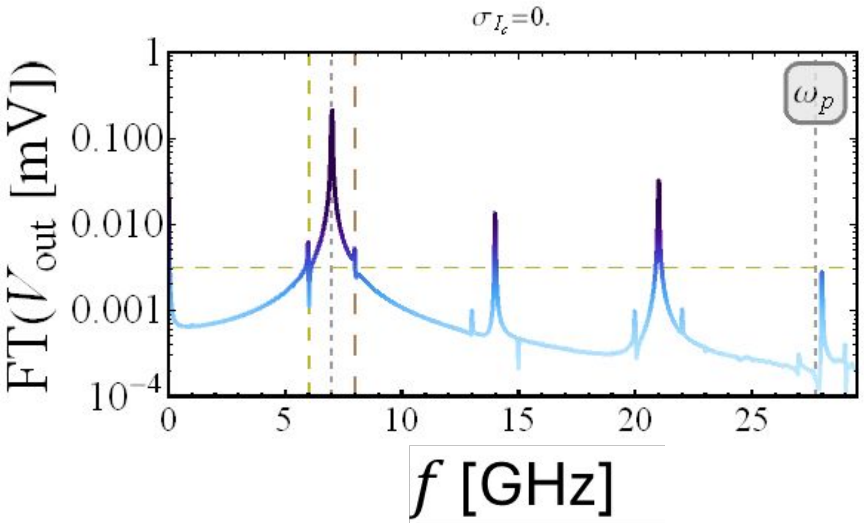
Here, we assume the JJ critical currents to be distributed according to $I_{c,n} = \overline{I_c}(1 + \delta I_c)$ with $\boldsymbol{\delta I_c}$ being Gaussian distributed with zero mean and variance $\boldsymbol{\sigma^2_{I_c}}$.



our experimental value



Spectral output for $I_{bias} = 0\ \mu A$



Spectral output for $I_{bias} = 17\ \mu A$

see also C. Kissling et al.,IEEE Trans.Appl.Sup., ***33****, 1700106 (2023)*

Conclusions and outcome

- We have developed a detailed know how for the modeling, simulation and experimental characterization of quantum limited Josephson junctions based amplifiers.

- Future activities, within INFN, are towards the realization of a quantum simulator

- Perspective development of experimental facilities for the realization and characterization of state of the art superconducting devices for quantum sensing, funded by NQSTI.