Review of quantum related projects within the INFN framework

Andrea Giachero
University & INFN of Milano-Bicocca

Proposta esperimento CSN5:

Local Detection of OAM Entangled Photons
ADAMANT

Sezioni coinvolte: **Milano**
Coordinatore Nazionale: **Bruno Paroli (INFN-MI)**
Durata**: 2 anni**

Obiettivo Esperimento:

Studio e realizzazione sperimentale di un metodo innovativo per la trasmissione e la rivelazione locale di informazione quantistica facendo uso del momento angolare dei singoli fotoni.

Scopo principale del progetto

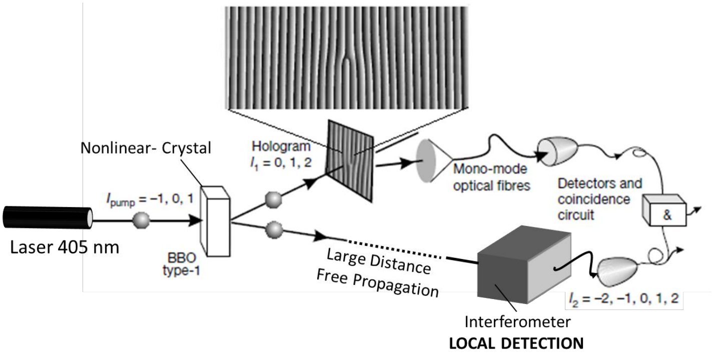
Il nostro fine è quello di sviluppare un protocollo di comunicazione quantistico che utilizzi il momento angolare dei fotoni come grado di libertà dove codificare l'informazione e rivelare **localmente** gli stati quantistici

Quindi abbiamo due punti da mettere in evidenza:

1) La radiazione deve essere quantistica per fare in modo che il protocollo sia sicuro rispetto all'attacco di una spia.
2) Il momento angolare ci permette di non tenere conto dell'orientamento relativo tra trasmettitore e ricevitore, cosa molto utile nel caso il trasmettitore e il rivelatore stiano a grande distanza (ad esempio il rivelatore potrebbe essere su un satellite). Inoltre si può sfruttare una molteplicità illimitata di stati per trasmissioni ad elevata densità.

Inoltre, punto fondamentale:
Il sistema di rivelazione del momento angolare che proprionamo in questo esperimento è innovativo e ci permette di rivelare L senza accoppiare tutta la radiazione nel rivelatore (cosa che sarebbe praticamente impossibile con metodi tradizionali nelle trasmissioni a grande distanza a causa della diffrazione).

Schema sperimentale proposto



Obiettivi Specifici

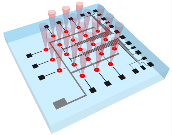
- **Fornire un sistema di comunicazione robusto che implementi protocolli quantistici** e quindi permetta il trasferimento intrinsecamente sicuro dell' informazione.

- **Fornire un sistema di comunicazione a lunga distanza** che sfrutta la radiazione con momento angolare orbitale per trasferire informazione ad alta densità. L'alta densità si ottiene grazie al' elevato numero di stati OAM rispetto a sistemi standard che sfruttano la polarizzazione.

- **Fornire un sistema di comunicazione indipendente dall'orientamento relativo tra il trasmettitore e il ricevitore**. Un punto debole dei sistemi quantistici che sfruttano gli stati di polarizzazione.

- **Dimostrare per la prima volta la fattibilità della misura locale della radiazione quantistica con momento angolare orbitale**. Verrà sviluppato un metodo interferometrico innovativo per la rivelazione locale degli stati quantistici di momento angolare orbitale capace di lavorare anche lontano dalla singolarità.

Fabrication of single-photon sources in diamond

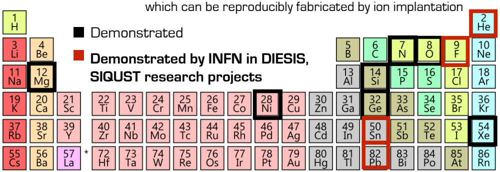


Diamond
- **5.5 eV** energy gap can host several defects with optical transitions
- **Point defects**: individual optical transitions → single-photon emission
- Operation at **room temperature; stable** (no photobleaching) **fluorescence**

Single photon sources
- Optically- (laser excitation) or electrically-stimulated quantum systems
- **One** photon **on-demand** with **given properties** (energy, polarization)
- **Encode** information in the **quantum state** of photons

Ion beam fabrication
- Formation of selected defects by impurity introduction
- Control individual ions' position (goal: <100 nm) and the number (goal: single-ion detection at <50 keV)
- Key advantages: 1. Reproducibility and scalability of sources
  2. Integration in electronic/photonic structures with high spatial density

INFN-TO: Demonstration of a significant fraction of the currently known emitters in diamond which can be reproducibly fabricated by ion implantation



nature COMMUNICATIONS
https://doi.org/10.1038/s41467-019-13332-w OPEN

Quantum nanophotonics with group IV defects in diamond

Carlo Bradac[1*], Weibo Gao[2], Jacopo Forneris[3], Matthew E. Trusheim[4] & Igor Aharonovich[1]

ACS Photonics Article
Cite This: ACS Photonics 2018, 5, 4864–4871 pubs.acs.org/journal/apchd5

Single-Photon Emitters in Lead-Implanted Single-Crystal Diamond

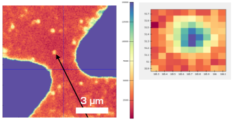
S. Ditalia Tchernij,[†,‡,¶] T. Lühmann,[§,¶] T. Herzig,[§] J. Küpper,[§] A. Damin,[∥] S. Santonocito,[†] M. Signorile,[∥] P. Traina,[⊥] E. Moreva,[⊥] F. Celegato,[⊥] S. Pezzagna,[§] I. P. Degiovanni,[⊥] P. Olivero,[†,‡] M. Jakšić,[#] J. Meijer,[§] P. M. Genovese,[‡,⊥] and J. Forneris[*,‡,#]

Forneris - INFN Sez. Torino 2/4

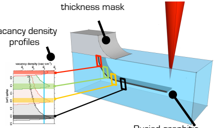
Applications of single-photon sources in diamond

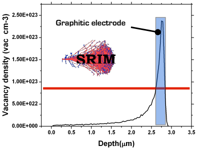
Integrated opto-electronic devices: Deep Ion Beam Lithography

Exploitation of **MeV** ion nuclear energy loss
Cumulation of **damage** at the **end of ion range**
Amorphization of buried diamond layer
Thermal treatment: **Conductive channels** embedded in **insulating diamond**



Confocal microscopy mapping of individual defects embedded in integrated graphite-diamond-graphite junctions



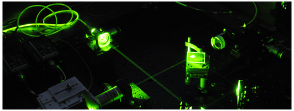


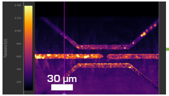
Integrated electrode pairs for the stimulation of single-photon emission (electroluminescence)

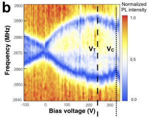
Scientific Reports 5 (2015) 15901
Carbon 113 (2017) 76

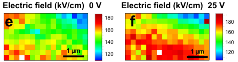
Field sensing at the nanoscale diamond-based sensors

Optical readout of local electric and magnetic field using nitrogen-vacancy defects in diamond. Spatial resolution: point defects!
Dedicated experimental setups at INFN-Sez. Torino









Direct observation of space charge build-up and **memory effects** in diamond
Spatial mapping of the internal electric field of a graphite-diamond junction
Phys. Review Applied 10 (2018) 014024

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Funded research projects

CNS5 Young Researcher Grant Call 2015:

DIESIS: DIamond-based Electrically controlled SIngle-photon Sources
2016-2017 - INFN Torino Section. National Coordinator: J. Forneris. Budget: 110 k€

Scientific output

12 papers on peer reviewed ISI-indexed journals
> 5 invited talks at international conferences
>15 oral contribution at international conferences
6 B.Sc and M. Sc. theses, 1 Ph.D thesis

Facility development @ INFN sez. TO

Dedicated single-photon-sensitive confocal microscope
Cleanroom for samples processing and fabrication

Collaboration with UniTO and INRiM in shared laboratories
- Optical cryostat at T≥4K
- Installation of multi-elemental ion implanter

EURAMET - EMPIR Fundamental scheme

EURAMET: European Association of National Metrology Institutes, i.e. **EU Regional Metrology Organization**
EMPIR European Metrology Programme for Innovation and Research: integrated in and co-funded by H2020
joint research projects involving metrological institutes, industrial organisations, academia

SIQUST: Single-photon sources as new quantum standards
2018-2021 - INFN Torino Section. Coordinator: J. Forneris. Consortium budget: 1.8 M€

Project Leader: Physikalisch-Technische Bundesanstalt (D)
6 **National Metrological Institutes**
8 **External Partners**

INFN-TO role:
- Fabrication of novel colour centers in diamond
- Electrical excitation of color centers
- Field sensing with new color centers

SEQUME: Single- and entangled-photon sources for quantum metrology
2021-2023 - INFN Torino Section. Coordinator: J. Forneris. Consortium budget: 1.8 M€

Project Leader: Physikalisch-Technische Bundesanstalt (D)
7 **National Metrological Institutes**
10 **External Partners**

INFN-TO role: **WP2 leader**
- Development and test of novel quantumness quantifiers for single-photon sources

Forneris - INFN Sez. Torino - Oct 15th, 2021

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Electron Electric Dipole Moment: Search for New Physics

Long Electron Spin Coherence Time in Paramagnetic Molecules

1) Probing Physics Beyond Standard Model & Fundamental Symmetries

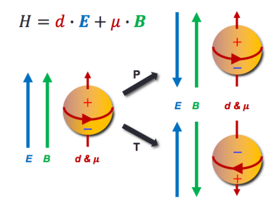
2) Electron EDM measurements

3) Reactive Paramagnetic Molecules with e-SPIN Long Coherence Time & Large Debye Moment

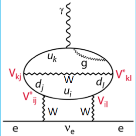
4) Isotopic Molecular Beam Production and Doping in Para-Hydrogen @ Low Temperature

5) Conclusions

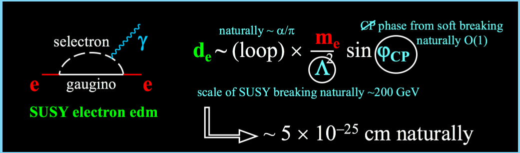
EDM Searches



- The EDM is an asymmetric charge distribution along the particle spin
- The EDM violates time reversal symmetry through CPT conservation – CP violation
- CP violation is required to generate a cosmological matter-antimatter asymmetry.
-
- It is present in the SM, through the complex phase in CKM matrix, however many order of magnitude below what is necessary
- EDM's in SM are tiny ($d_e < 10^{-38}$ ecm), but most SM extensions include new CP violating phases that contribute to EDM's.



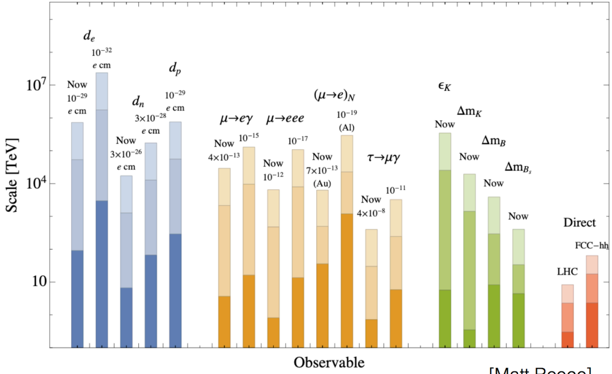
four-loop level in perturbation theory



THIS MAKES EDM's an ideal probe for detecting NEW PHYSICS associated with CP violation and a powerful window on energy scales much larger than those that can be probed directly at LHC

Bounds on scale of NP for various indirect precision observables (current and future)

Bounds on Λ (scale of NP) for dimension six (4-fermion) operators O_i : $\sum_i \frac{C_i}{\Lambda^2} o_i$



[Matt Reece]

M.Pepe Altarelli - CPAD 2021

5

BARYON ASYMMETRY IN OUR UNIVERSE

ELECTROWEAK SM EXPECTATION vs **OBSERVED**

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 10^{-18} \quad \text{vs} \quad \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 10^{-10}$$

Digitare l'equazione qui.

Connection Between Cosmology and SM of Particle Physics

Sahkarov Criteria for Baryogenesis in the early Universe JTEP Lett. 5, 24 (1967)

- **1) Baryon number violation**
- **2) CP Violation**
- **3) Thermal non-equilibrium**

MEASURING ELECTRON EDM ON MOLECULES: ACTUAL APPROACH

$$H = -\mu_B \frac{\mathbf{S}}{\mathrm{S}} \cdot \mathbf{B_0} - \mathrm{d_e} \frac{\mathbf{S}}{\mathrm{S}} \cdot \mathbf{E_0}$$

$$\omega_S = \gamma_e B_0 + \frac{\mathrm{d_e}}{\hbar} \mathrm{E_0} = \omega_L + \omega_d$$

$$\omega_d = 2\pi \times 2.4 \times 10^{-5}\mathrm{Hz} \left(\frac{E}{10^{10}\mathrm{V/cm}}\right) \left(\frac{d_e}{10^{-29}\mathrm{e\,cm}}\right)$$

Fasci Molecolari Freddi tempo coerenza elettrone lungo

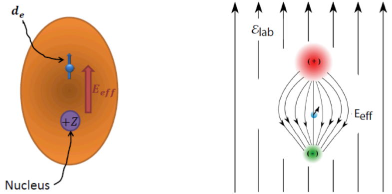
Misura di sfasamento su singola molecola

$$\phi \propto \omega\tau = (\mu B + dE)\tau$$

Gabrielse

Why Use a Molecule?

→ To Make Largest Possible Electric Field on Electron



Tl atom (best EDM limit till YbF)

$E_{lab} = 123$ kV/cm $\rightarrow$ $E_{eff} = 72$ MV/cm

ThO molecule

$E_{lab} = 100$ V/cm $\rightarrow$ $E_{eff} = 100$ GV/cm

Molecule can be more easily polarized using nearby energy levels with opposite parity (not generally available in atoms)

PREPARAZIONE INIZIALE STATO $\Psi(0)$ E SUA EVOLUZIONE $\Psi(T)$

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Conceptual EDM Measurement

B E

ThO

$$|\Psi\rangle = \frac{|{+}^1\!/_2\rangle + |{-}^1\!/_2\rangle}{\sqrt{2}}$$

make superposition of the polarized edm states

B E

ThO

$$|\Psi\rangle = \frac{|{+}^1\!/_2\rangle + e^{i\phi}|{-}^1\!/_2\rangle}{\sqrt{2}}$$

$$\phi \propto \omega\tau = (\mu B + dE)\tau$$

detect phase of evolved state

$$P_\Psi = \frac{1+\cos\phi}{2}$$

B E

look for changes as E is reversed

time evolution →

Gabrielse

Still, the EDM Gives Tiny Shift of Energy Levels

2 mHz

$$\Delta E = 7\times10^{-18}\ eV$$
$$= 7\times10^{-27}\ GeV$$
$$= 7\times10^{-30}\ TeV$$

Not so easy to resolve

To detect → let a prepared wave function evolve for time T

large as possible

$$|\Psi(0)\rangle = |1\rangle + |2\rangle \quad \rightarrow \quad |\Psi(T)\rangle = |1\rangle + e^{-i\phi}|2\rangle$$

$$\phi = \frac{\Delta E}{\hbar}T$$

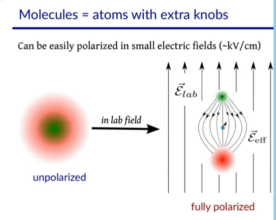
$$T = 1.1\,ms \quad \rightarrow \quad \phi = 11\times10^{-6} = 0.6\times10^{-3}\ \text{degrees}$$

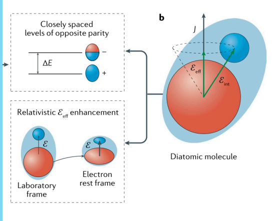
Example is for an electron edm equal the ACME upper limit.

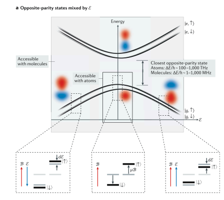
ACTUAL LIMIT "ACME" EXPERIMENT $d_e = 10^{-29}$ ecm

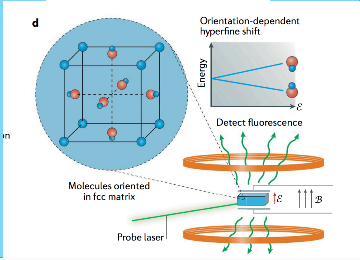
FROM MOLECULAR BEAM TO MOLECULAR DOPED CRYSTALS A NEW APPROACH

Probing 10^{18} BaF Molecules into ParaHydrogen Matrix Host









2 Possible measuring methods:

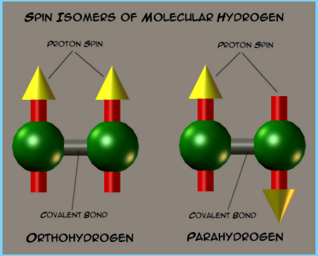
1) Weak Magnetization appearence under **E** modulation (see note) $d_e \sim 10^{-30}$ ecm

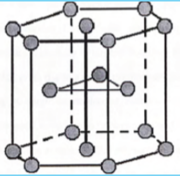
2) Optical Fluorescence Approach(see articles) $d_e \sim 10^{-34}$ ecm

PARAHYDROGEN ADVANTAGES

Almost a Quantum Solid

I=0 → *J* pari
simmetria sferica→ assenza di momenti di multipolo permanenti
Le interazioni sono interazioni di dispersione (molto deboli VDW)
Alta distanza tra le molecole: *a=3.783 Å*





Il cristallo di p-H_2 ha una struttura Hcp (Hexagonal closed packed).
Per la grande distanza intermolecolare, consente di ospitare un atomo senza deformazioni significative della struttura cristallina.

QuOT Lab @ UniBA

- Group leader: **Milena D'Angelo**
- Researchers:
  - Francesco Scattarella
  - Francesco V. Pepe
- Post-docs:
  - Francesco Di Lena
  - Sergii Vasiukov
- Students :
  - Davide Giannella
  - Gianlorenzo Massaro
  - Alessio Scagliola

INFN funded projects (Coordinator: Milena D'Angelo – INFN Bari)

TOPMICRO – TOward the Prototype of a correlation plenoptic MICROscope Feb. '21-Aug. '22

PICS4ME - Plenoptic Imaging with CorrelationS for Microscopy Enhancement Jul. '19 – Dec. '22

Partners:

M. Genovese, I. P. Di Giovanni (INRIM, Torino - IT) - INFN Torino

J. Forneris, P. Olivero (Università di Torino - IT) - INFN Torino

Qu3D – Qunatum 3D imaging at high speed and high resolution Mar. '20 – Dec.

Partners:

E. Charbon, C. Bruschini (EPFL - CH)

B. Stoklasa, Z. Hradil, J. Rehacek (Olomouc University - CZ)

M. Iacobellis, F. Santoro, L. Amoruso (Planetek Hellas - GR)

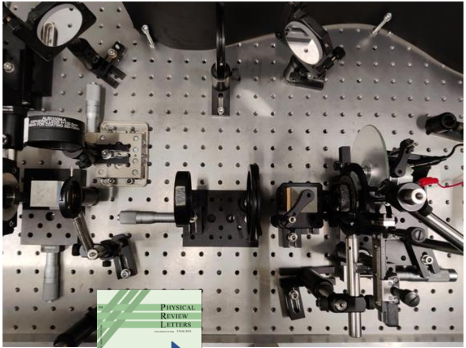
QUANTERA

http://www.ba.infn.it/qu3d/index.html

PICS4ME*

Plenoptic Imaging with Correlations for Microscopy and 3D Imaging Enhancement

1. Design, development and characterization, and optimization of a Correlation Plenoptic Microscope CPM
2. Comparison of CPM with 3D microscopy systems to demonstrate its effectiveness in several applicative scenarios
3. Optimization of the refocusing and 3D reconstruction algorithms
4. Develop novel protocols for SNR optimization (e.g., Differential CPI)
5. CPM with low-coherence sources, in view of its application in fluorescence microscopy

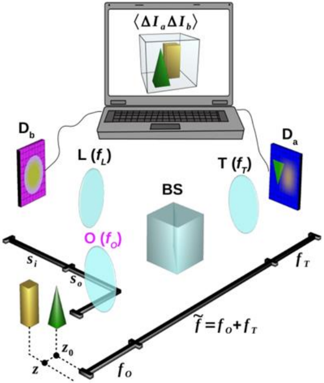


MISE-UIBM: Intellectual property award 2019

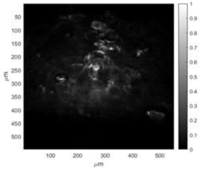
*Legacy of the Project PICS (young researcher grant CNS5 2017-2019, PI: Francesco Pepe)

PICS4ME

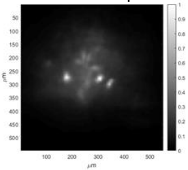
Correlation Plenoptic Microscope

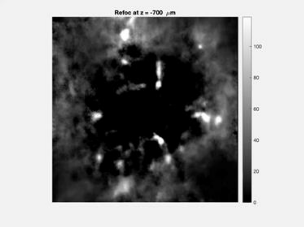


Acquired image at focus plane: z = 0



CPM refocus at z = 360 μm



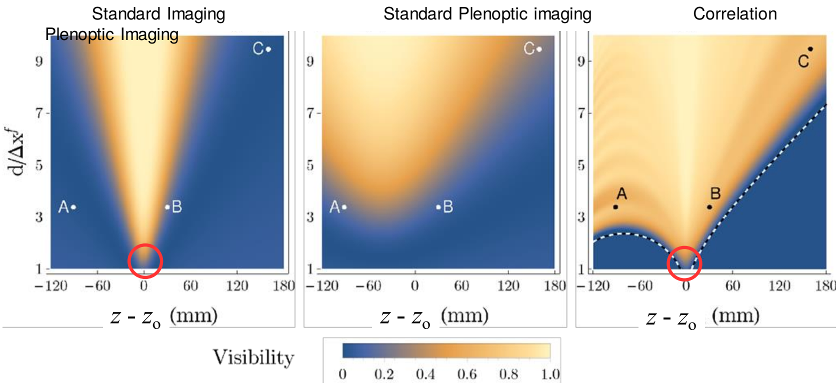


CPM allows scanning-free refocusing of different planes within a 3D sample (starch in gel)!

- Patent 2017 (Cina, Japan, Europe, USA)
- A. Scagliola, et al., Physics Letters A, p. 126472 (2020)
- G. Massaro et al., arXiv:2110.00807 (under consideration for pubblication)

PICS4ME

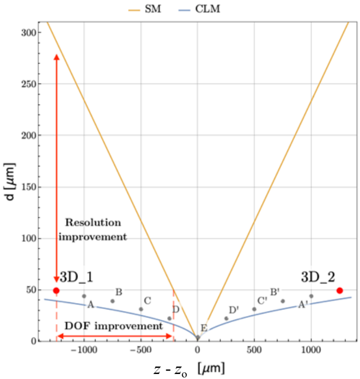
DOF vs. resolution trade-off



CPM enables refocusing over a much wider depth of field than standard imaging and standard plenoptic imaging, while preserving the maximum resolution (diffraction limit)

PICS4ME

DOF vs. resolution trade-off



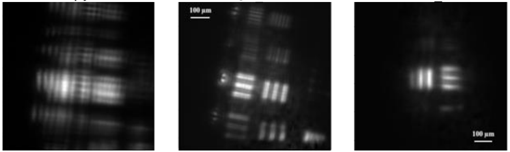
3D sample: 2 planar test targets 2.5mm apart

Standard Microscopy

Correlation Plenoptic Microscopy

3D_1

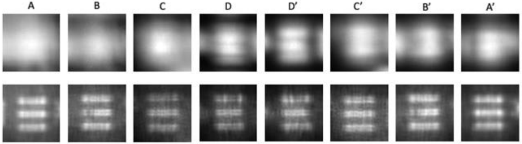
3D_2



2D samples

SM

CPM



CPM enables refocusing over a much wider depth of field than standard imaging and standard plenoptic imaging, while preserving the maximum resolution (diffraction limit)

Quantum 2022 - Summer School on Quantum Optical Technologies in Apulia

Trani (Bari), 18-24 Sept. 2022

The school is oriented to PhD students, master students and young researchers, and aims to provide **a privileged vision of quantum optical technologies** from both a theoretical and an experimental perspective. The lecture topics will include: quantum imaging; quantum information; quantum cryptography; quantum simulation; quantum communication in space; detectors, sources and measurements for quantum technologies.

Lecturers: Gunnar Björk, Edoardo Charbon, Maria Chekhova, Milena D'Angelo, Ivo Pietro Degiovanni, Paolo Facchi, Daniele Faccio, John Howell, Zdenek Hradil, Simone Montangero (to be confirmed), Ivano Ruo-Berchera, Fabio Sciarrino, Bohumil Stoklasa, Paolo Villoresi, Hugo Zbinden

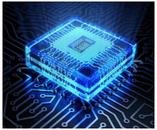
Scientific Committee: Milena D'Angelo, Paolo Facchi, Augusto Garuccio, Saverio Pascazio (UniBA and INFN), Marco Genovese (INRIM), Fabio Sciarrino (Sapienza Roma)

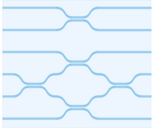
https://agenda.infn.it/e/quantum2022

QUANTEP

QUANtum Technologies Experimental Platform

- INFN **CSN5** project - Three years **(from 2021 to 2023)**
- Principal Investigator: A. Salamon (RM2)
- INFN Sections and Laboratories involved: LNL (V. Rigato), MI (V. Liberali), Camerino/PG (R. Gunnella), PI (F. Spinella), PV (V. Bellani), RM2 (A. Salamon), SA (C. Attanasio), TO (J. Forneris)
- Interest and support from: LNGS (LUNA-MV), LABEC (DEFEL), UNIPI (S. Saponara), UNITO, TYNDALL, Institut Ruđer Bošković (RBI), Micro Photon Devices (MPD), University of Leipzig, Chalmers University of Technology, Physikalisch-Technische Bundesanstalt (PTB).
- 15-17 FTE/year, ~ 1 MEuro budget
- Creation of a common **Silicon Photonics** platform for
  - linear optics quantum computing circuits;
  - single photon sources;
  - single photon detectors;
  - polarization control circuits.





October 2021 QUANTEP 1

Universal Quantum Gates

1 qubit: $\alpha_0|0\rangle + \alpha_1|1\rangle, \; |\alpha_0|^2 + |\alpha_1|^2 = 1$

Some 1 qubit elementary gates

$$X = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad Z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \quad R_\phi = \begin{pmatrix} 1 & 0 \\ 0 & e^{i\phi} \end{pmatrix} \quad H = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$$

Pauli-X (NOT) gate — Pauli-Z gate — Phase shift gate — Hadamard gate

2 qubits: $a|00\rangle + b|01\rangle + c|10\rangle + d|11\rangle \quad |a|^2 + |b|^2 + |c|^2 + |d|^2 = 1$

The prototype 2 qubits gate is the Controlled NOT (CNOT) gate

control bit

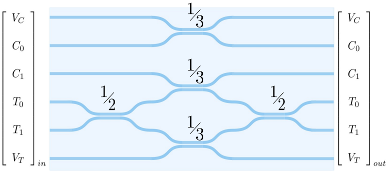
$$\mathrm{CNOT} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

target bit

- the control bit is left unchanged
- the output target bit is the XOR of the input control and target bits
- but of course it does much more: it works on the wave function

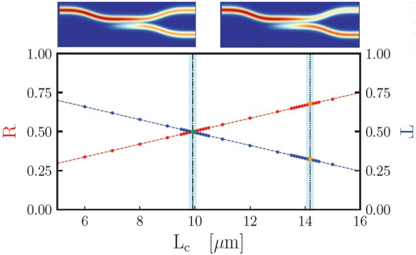
$$a|00\rangle + b|01\rangle + c|10\rangle + d|11\rangle \rightarrow a|00\rangle + b|01\rangle + c|11\rangle + d|10\rangle$$

Linear optical CNOT gate in the coincidence basis

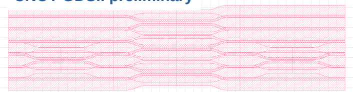


- Directional couplers used as beam splitters
- Coincidence basis: (C_0T_0, C_1T_0, C_0T_1, C_1T_1)
- Postselected probabilistic gate: P=1/9
- Optimal operation with directional couplers (1/2-1/2) and (1/3-2/3)

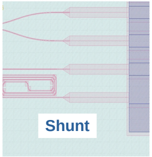
Silicon on Insulator 450 nm x 220 nm waveguides



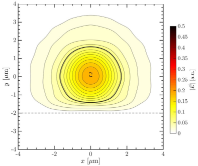
CNOT GDSII preliminary λ = 1550nm



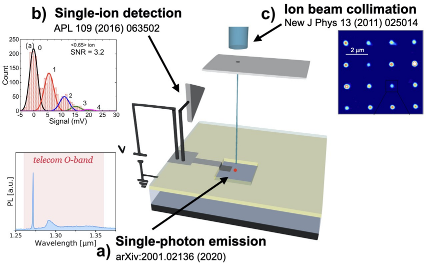
Spot size converter

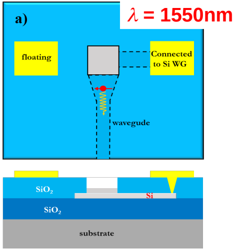


Output mode field



Si-based single-photon sources at telecom wavelengths





Vastly unexplored research field!

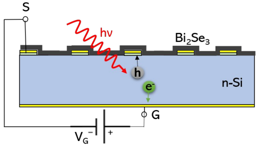
Emitters identification

- screening of luminescent centers fabricated by ion implantation (group-IV, transition metals, halogens, He, …) at Leipzig Uni, Ruđer Bošković Inst, LNGS (LUNA), LABEC
- F[2 MeV], Ge[3 MeV], C[4 MeV],V[6 MeV], Ag[7.2 MeV] implanted, characterization ongoing
- development of a custom telecom confocal microscope (TO)
- identification and characterization of suitable single photon emitters (TO)

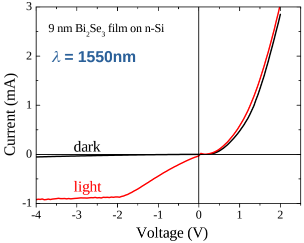
Emitters fabrication

- ion implantation with sub-µm accuracy (collimation)
- single-ion delivery capability: the Si circuit is exploited as particle detector
- development of a custom irradiation chamber at the TO ion implanter
- exploitation of a custom irradiation chamber at the AN2000 LNL beamline

Single Photon Detectors (Bi_2Se_3/n-Si and other 2D materials)

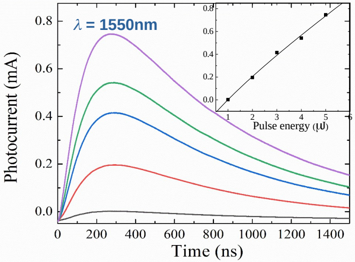


Sketch of Bi_2Se_3/n-Si junction



I-V characteristics of Bi_2Se_3/n-Si heterojunctions in dark and illuminated conditions (9 nm film).

Bi_2Se_3 deposited on n-Si substrates shows rectification, photovoltaic response and linearity at λ = 1550 nm

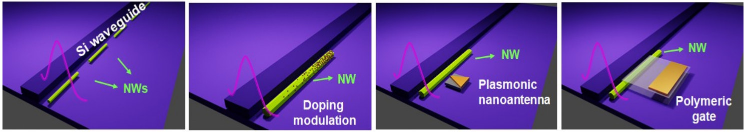


Bi_2Se_3/n-Si response to fs laser pulse.
Inset: photocurrent vs. laser pulse energy

M. Salvato et al. **Nanscale DOI: 10.1039/d0nr02725a (2020).**

Polarization control

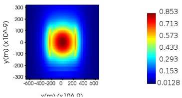
with nanowires, graphene and other 2D materials



An example: array of nanowires

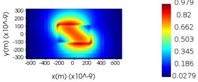
- Si-wg= 450x220 nm
- NW length= 5um
- NW radius= 60nm
- Material= InP
- Number of NWs= 10
- NW separation (d) = 500nm
- TE -> TM conversion
  - %51.5 (@1.54 um)
  - %60 (@1.55um)
  - %65 (@1.56um)

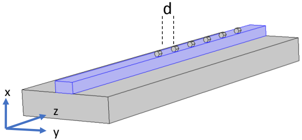
Input E-field



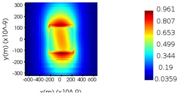
Output E-fields

wl = 1.54 um





wl = 1.56 um

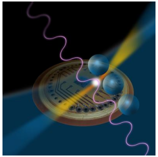


October 2021 QUANTEP PV, NEST, UNIMORE 6

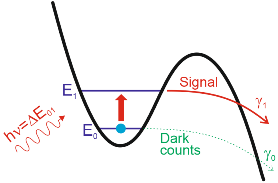
SIMP: Single Microwave Photon Detection

Development of single microwave photon counter (10-100 GHz) with two technologies:

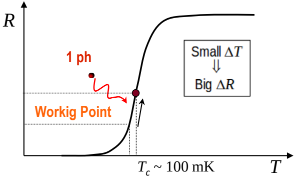
1. Current Biased Josephson Junction (LNF, Salerno, CNR-IFN)
2. Transition Edge Sensor (INFN-Pi, CNR Nano-NEST, TIFPA-FBK, INRIM)



When a photon is absorbed:



1) In a CBJJ a sudden variation of voltage (400 μV) appears across the junction (frequency range ν=5-20 GHz).



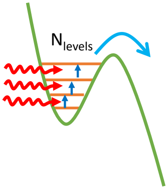
2) In a TES a steep variation of resistance causes a current drop detected by a SQUID (frequency range ν=50-100 GHz).

Units
LNF (RN C Gatti)
INFN Pi
INFN Sa
TIFPA-FBK
CNR Nano NEST
CNR IFN
INRIM

3 years project approved in CSNV in 2018

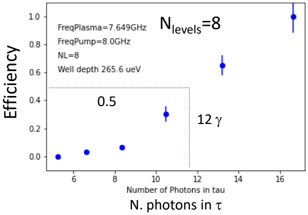
SIMP Single Microwave Photon Detection

Microwave Photon Detector Based on CBJJ

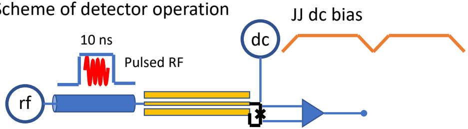


Simulations show single-photon sensitivity of an isolated JJ. The first test was done with a JJ coupled to a transmission line. In this configuration the device has a short relaxation time $\tau \sim 50\ ps$ loosing single-photon sensitivity and switching approximately when the number of photons reaching the JJ in a time τ is close to the number of levels in the potential well. The isolated-JJ limit will be reached adding a coplanar resonator (fabrication ongoing). Dark counts at mHz expected.

A. Rettaroli et al, Instruments **2021**, 5(3), 25

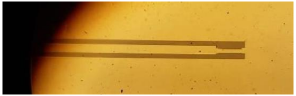


Scheme of detector operation



$$\tau = Z_0 C \simeq 50\ ps$$

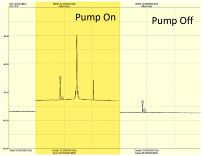
JJ coupled to a transmission line



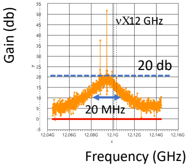
SIMP: Collaboration with CNR-IFN

SIMP Single Microwave Photon Detection

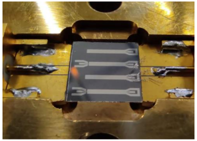
Josephson Parametric Amplifier



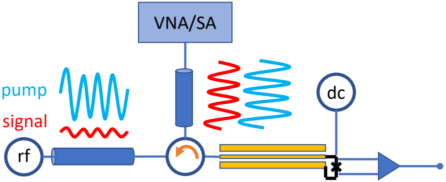
20 db Gain and 10 MHz bandwidth

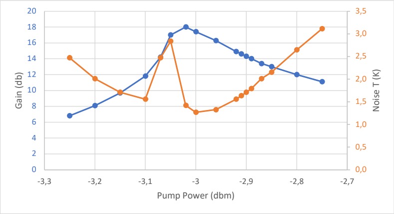


JJ-device operated as a JPA: the non-linear inductance of the JJ mixes Pump and Signal amplifying the second one. Gain close to 20 db was observed in a 10 MHz bandwidth with a noise reduction from 8K of HEMT amplifier to 1.3K.



SIMP: Collaboration with CNR-IFN





Noise reduced from 8K (HEMT) to about 1.3K

SIMP Single Microwave Photon Detection

3

Nanowire Transition Edge Sensors

- Nanowire TES (1µm×50nm×100 nm) with Tc 120 mK fabricated at INRiM and CNR-Nano/NEST.
- First characterization shows sensitivity to 100 GHz single photons and NEP 50 zW/√Hz.
- RF test in preparation.

Conditions needed to reduce TES noise fluctuations:

1. Small volume → use micro/nano fabrication
2. Low critical temperature → use bilayer made of superconductir and normal metal.

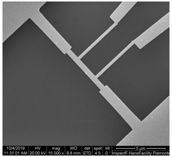
$$\sigma_E \propto \sqrt{k_B C T^2}$$

Lower the critical temperature

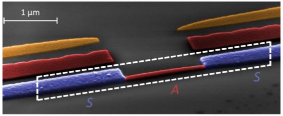
$$C = \gamma V T$$

Reduce the volume

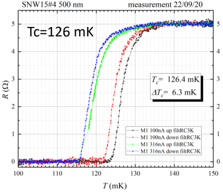
TiAu sample from INRiM

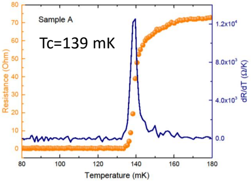


AlCu sample from CNR-Nano/NEST



F. Paolucci et al., J. Appl. Phys. **128**, 194502 (2020)



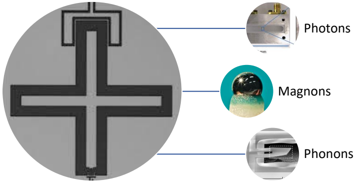


SIMP: Collaboration with INRIM and CNR-Nano/NEST

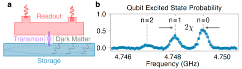
SIMP Single Microwave Photon Detection

Qub-IT Quantum Sensing with SC Qubits

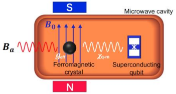
Units
LNF (RN C Gatti)
INFN Pi
INFN Sa
TIFPA
INFN Fi
INFN Fe
INFN Mi
INFN MiB
CNR IFN
FBK



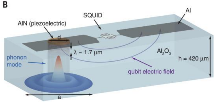
Superconducting qubits constitute a fundamental building block of quantum sensing. These are used in experiments for sensing single photons, magnons and phonons opening the way to new physics experiments. Qub-IT objective is the development of single photon detector based on SC qubits exploiting its quantum properties like state superposition and entanglement.



A V Dixit et al., "Searching for Dark Matter with a Superconducting Qubit," Phys. Rev. Lett. 126, 141302 (2021).



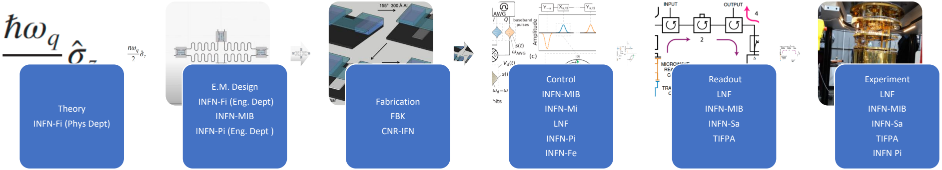
T Ikeda et al. "Axion search with quantum nondemolition detection of magnons," arXiv:2102.08764.



Chu et al, "Quantum acoustics with SC qubits," Science 358, 199 (2017)

3 years project approved in CSNV in 2021

Qub-IT Quantum Sensing with SC Qubits



Qub-IT puts together the entire knowledge chain necessary for developing superconducting quantum devices. This is a complex process requiring different skills going from theoretical modelling to electromagnetic design, multi-step fabrication with optical and electron lithography, control of qubits with RF pulses and single-shot readout of qubit state with quantum amplifiers, all cooled down in a dilution refrigerator to 10 mK.

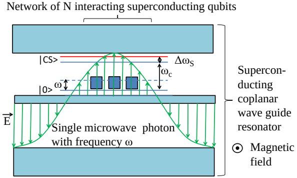
During the project, circuits with up to 2 qubits coupled to coplanar or 3D resonators will be designed, fabricated and tested and photon-sensing experiments will be carried out in the cryogenic labs of the collaboration.

SUPERGALAX

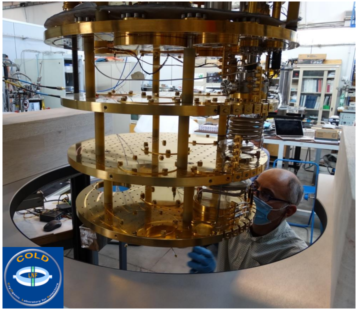
FET OPEN SUPERGALAX
CNR (IT, PI, exp)
INRIM (IT, exp)
INFN (IT, axion exp, RN C Gatti)
KIT (DE, exp)
Leibniz IPHT (DE, exp)
RUB (DE theory)
LU (UK, theory)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 863313. Grant amount 2 456 232.50 Euro.

https://supergalax.eu



The project objective is to develop a single microwave-photon detector for axion search with QUAX experiment with an array of SC qubits. The collective response of qubit array to single-photon excitation modifies the transmission properties of a coupled resonator. This change in transmission is used to detect the photon.



Supergalax SC qubit array for Axion detection

DEMETRA

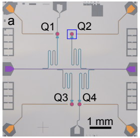
DEcoherence Mitigation through EnvironmenTal Radioactivity Abatement

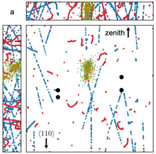
- Progetto finanziato dall'INFN con starting grant per neoassunti - commissione 5 ma non formalmente una sigla
- PI: Laura Cardani (INFN - Roma)
- Principali attori: INFN Roma, INFN - LNGS, Karlsruhe Institute of Technology (Germania).
- Scopo: studiare gli effetti della radioattività su qubit superconduttori
- Giugno 2018 - Giugno 2021

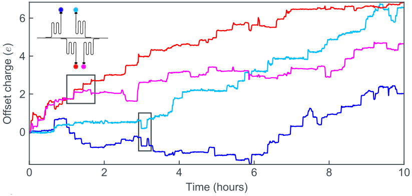
1

Radioactivity Effects

[Wilen et al, Nature 2021]





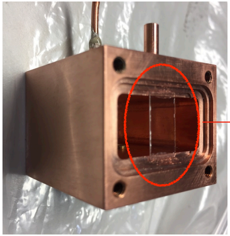


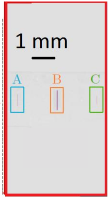
- Measurement of charge jumps in a 4-qubits matrix
- Proved that environmental radioactivity induces:
  - Many **simultaneous** jumps in 2-qubits:
    - 54% correlation prob. for $\Delta L = 340\ \mu m$
    - Diminishes for more distant qubits
  - Decrease of the **coherence** of single qubits
- Detrimental effect of radioactivity recently confirmed by a similar study done with the Google Sycamore

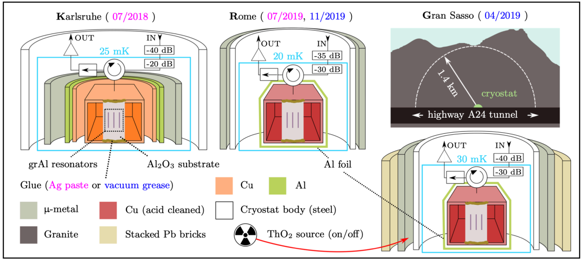
2

A possible solution

[Cardani et al, Nat. Comm. 2021]







3

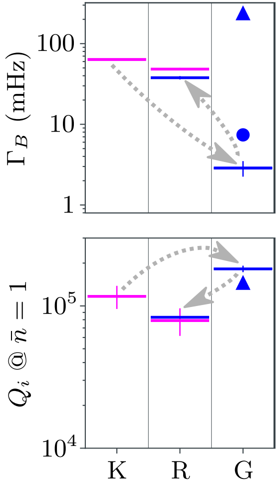
A possible solution

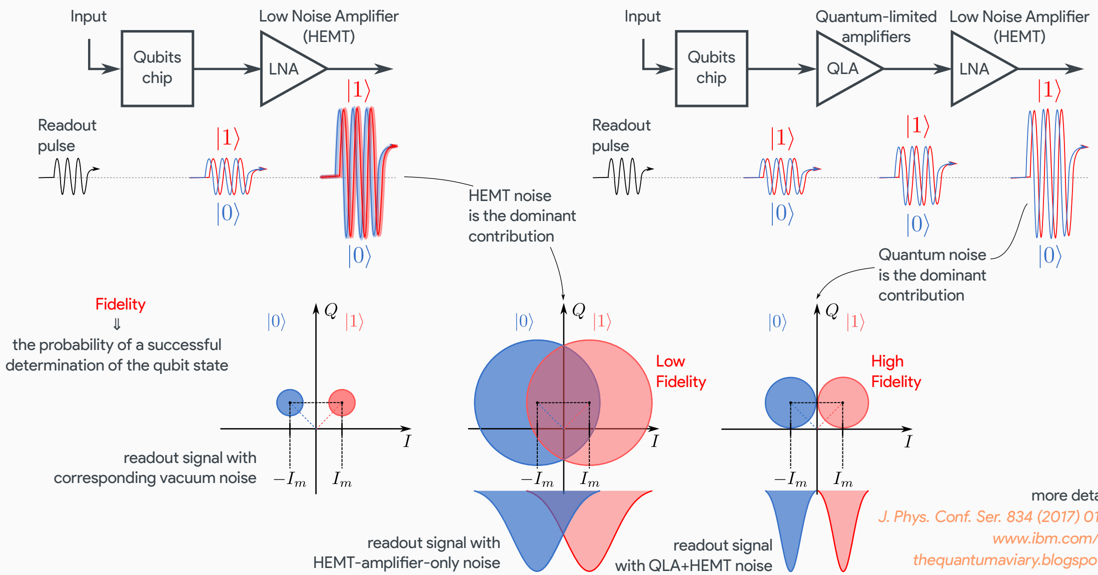
[Cardani et al, Nat. Comm. 2021]

Rate of impacts [= “errors”] reduced by ~30

Coherence can be improved by 2-4*

* if the loss is dominated by phonons, this is not the case for all superconducting qubits





more details on
J. Phys. Conf. Ser. 834 (2017) 012003
www.ibm.com/blogs
thequantumaviary.blogspot.com

DARTWARS: Detector Array Readout with Traveling Wave AmplifieRS

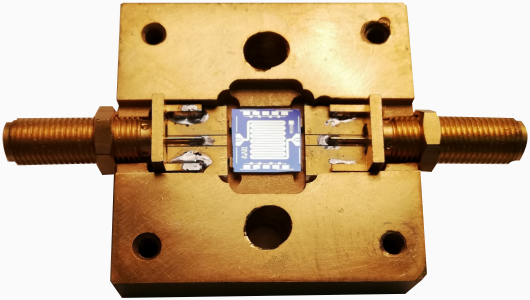
The principal objectives of DART WARS are

1. The practical development of high performing parametric amplifiers following two different promising approaches (KI-TWPA, TWJPA) and exploring new design solutions, new materials and advanced fabrication processes;

2. The read out demonstration of various detectors/components (TESs, MKIDs, microwave cavities and qubits) with improved performances due to a parametric amplification with a noise at the quantum level;

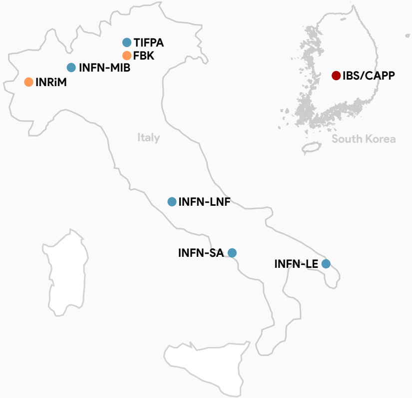
The technical goal is to achieve

- a gain value around 20 dB, comparable to HEMT;
- a high saturation power (around -50 dBm);
- quantum limited or nearly quantum limited noise (noise temperature < 600 mK)
- reduction of the gain ripple and yield improvement.



INFN units involved:

- The **INFN-MIB** coordinates the whole project and works specifically on the design and on characterization of the developed devices (mainly KI-TWPA);
- The **INFN-LNF COLD** (CryOgenic Laboratory for Detectors) supervises the device's fabrication and participates in the characterization (mainly TWJPA);
- The **INFN-LE** Cryo-Spintronics focuses on investigating magnon-cavity polaritons for quantum computation and quantum sensing applications.
- The **INFN-SA** group coordinates the design and simulation of the TWPAs and performs mounting (bonding and package) and initial testing of TWJPA devices;
- The **INFN-TIFPA** group supervises the device's production at FBK and participates in the characterization (mainly KI-TWPA);



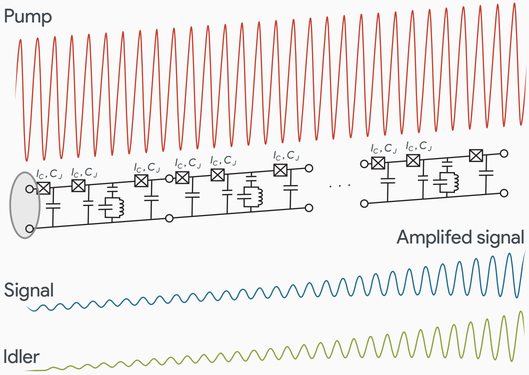
Other institutions involved:

- Fondazione Bruno Kessler (FBK) Micro System Technology group (MST) of Centre for Materials and Microsystems (CMM) is be in charge of the fabrication of the KI-TWPA prototypes;
- Istituto Nazionale di Ricerca Metrologica (INRiM) designs and fabricates the TWJPA prototypes in Al technology;
- Institute for Basic Science Center for Axion and Precision Physics Research (IBS-CAPP), co-finances the parametric amplifiers production and participates in the characterization.

- JPA has typically been used only for single frequency measurements due to lower bandwidth and saturation power;
- New approach: microwaves travelling along a transmission line with embedded non-linear elements;
  Phys. Rev. B 87, 144301
- The nonlinear reactive element can be implemented by Josephson Junction (JJ) or Kinetic Inductance (KI) of superconductors. The relationship is, at the first order,

$$L(I) = L_0 \left[1 + \frac{I}{I_c}\right]^2$$

I_c is the superconductor critical current for KI
I_c is the junction critical current for JJ
At $I < I_c$ junctions are dissipationless and act as a nonlinear inductor.

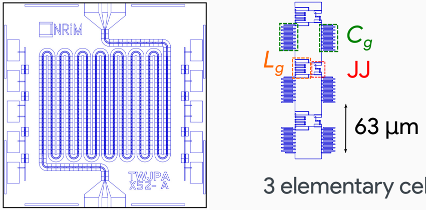


A large pump tone modulates this inductance, coupling the pump (f_p) to a signal (f_s) and idler (f_i) tone via frequency mixing;

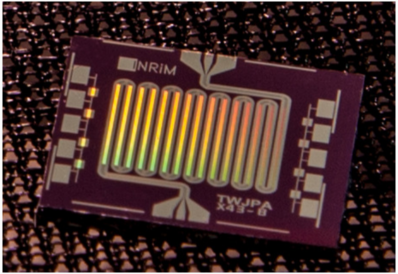
4-wave mixing	**3-wave mixing**
$2f_p = f_s + f_i$ (4WM)	$f_p = f_s + f_i$ (3WM)

- TWJPA are classically designed for operating only in the 4-wave mixing mode (4WM);
- Recent studies suggest that a three-wave mixing (3WM) JTWPA should increase the power handling, and decrease the ripple in the gain versus frequency dependence;
- New design: 3WM TWJPA based on microwave transmission line formed by a serial array of non-hysteretic one-junction rf-SQUIDs;
- The non-linearity of the inductance associated to the JJ (L_J) gives rise to the mixing process;
- JJs created as Al/Al-Ox/Al tri-layer exploiting the Niemeyer-Dolan technique;
- Design and production in collaboration with the Istituto Nazionale di Ricerca Metrologica (INRiM, Torino);

TWJPA chip fabricated at INRiM

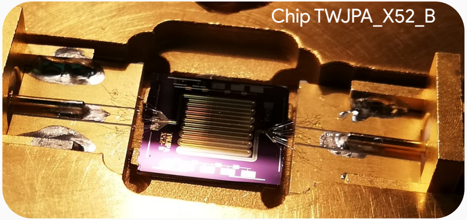


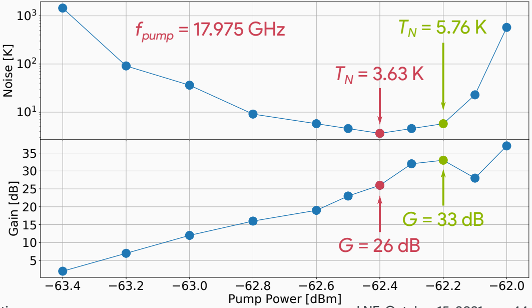
3 elementary cells



DARTWARS: first TWJPA characterizations

- In the first semester of 2021 chips with TWJPA produced at INRiM were tested at LNF and at IBS-CAPP;
- Measurements showed clear evidence of parametric amplification but with an non-homogeneous behavior in frequency probably due to a non-homogeneous fabrication of the about 900 Josephson junctions of the device;
- Gain up to 30 dB was observed at particular frequencies and with a minimum noise temperature of 3.63 K;
- Measurements on array of Josephson junctions with the goal to test the Josephson junction reproducibility foreseen before the end of 2021;
- New design with a modified dispersion relation following a new approachea (Resonant Phase Matching) in developement with the goal to avoid power leakage into higher frequency tones;



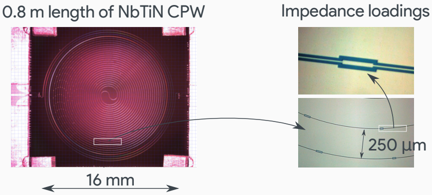


- Two different approaches for the transmission line:
  - classical CPW
  - artificial transmission line with lumped element
- The advantage of the lumped element approach a shorter transmission line: 20 cm vs. 1-2 m;
- The goal is to lower the device heating with a consequent reduction of the gain ripple and yield improvement;

  $\Rightarrow$ different materials will be considered to lower the T_c: multilayer of Titanium and Titanium Nitrate (Ti/TiN) and Tungsten Silicide (WSi);
- Transmissions implemented with a different layout: microstrip transmission lines with ultra-low-loss single-crystal silicon dielectrics fabricated on a silicon-on-insulator (SOI) wafer;
- Production in collaboration with the Fondazione Bruno Kessler (FBK, Trento).

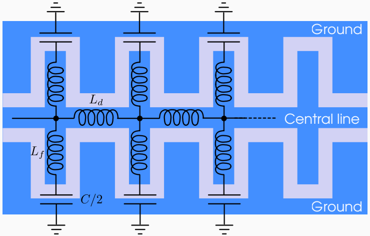
CPW transmission line

arranged in a double spiral with periodic impedance loadings



Artificial transmission line

that uses lumped-element inductors

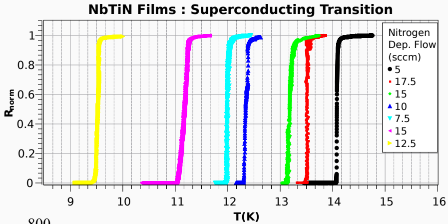


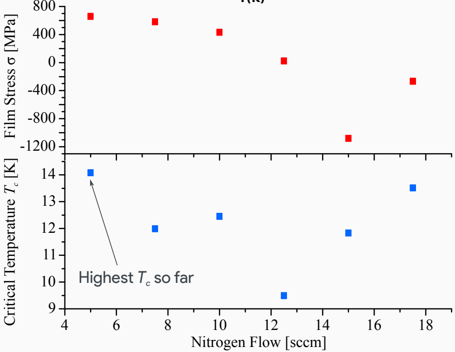
Preliminary depositions of NbTiN at FBK

- Co-sputtering with separate targets (Nb and TI)
  - 700 W(Nb), 150 W(Ti), 400 °C, $3 \cdot 10^{-3}$ mbar, Ar 50 sccm, N_2 15 sccm
  - $T_c = 13.19\,K$ 😐
  - $RRR = 0.71$ ☹

- Sputtering from a single target $Nb_{0.66}Ti_{0.34}$
  - 700 W, 400 °C, $3 \cdot 10^{-3}$ mbar, Ar 50 sccm, N_2 (5 – 17.5) sccm
  - $T_c = 14.08$ K 😐 $RRR = 0.99$ 🙂 @5 sccm N_2
  - $T_c = 13.52$ K 😐 $RRR = 1.10$ 🙂 @17.5 sccm N_2

To improve T_c and RRR new tests will be made using crystalline Si as substrate and larger N_2 flow





DART WARS: possible impact for the INFN projects

Qubit	Microwave cavities	MKIDs	TESs
SQMS Superconducting Quantum Materials and Systems at FNAL **SUPERGALAX** Quantum network of superconducting qubits for searching galactic axions **DEMETRA** Effects of Radioactivity on Superconducting Quantum Bits	**QUAX** Cosmological Axion Detection	**CALDER** Neutrinoless Double Beta Decay **BULLKID** Coherent elastic neutrino-nucleus scattering **MoBiKID** Cosmic Microwave Background **KIDS_RD** X-ray spectroscopy	**HOLMES** Neutrino Mass Measurement **PTOLEMY** Relic Neutrino Detection **CRESST** Dark Matter Search **NUCLEUS** Coherent elastic neutrino-nucleus scattering **SIMP** Single Microwave Photon Detection **STAX** Axion-like particle searches with sub-THz photons