DarkSRF: Using Accelerator Technology to Search for a Dark Photon

A. Romanenko, R. Harnik, A. Grassellino, R. Pilipenko, Y. Pischalnikov, Z. Liu, O. S. Melnychuk, B. Giaccone, O. Pronitchev, T. Khabiboulline, D. Frolov, J. Isaacson, S. Posen, A. Hook, A. Berlin

Fermi National Accelerator Laboratory

NAPAC'2022

Acknowledgements

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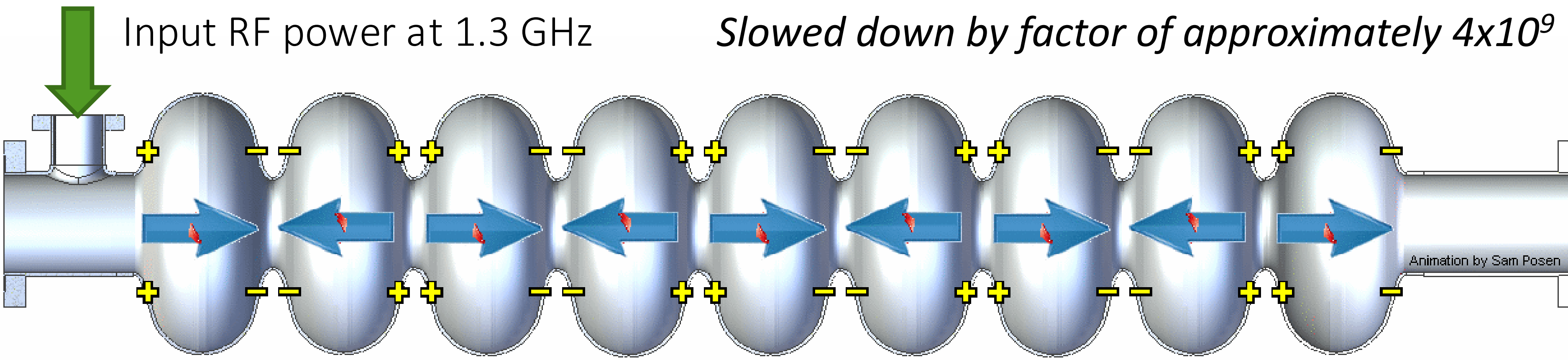
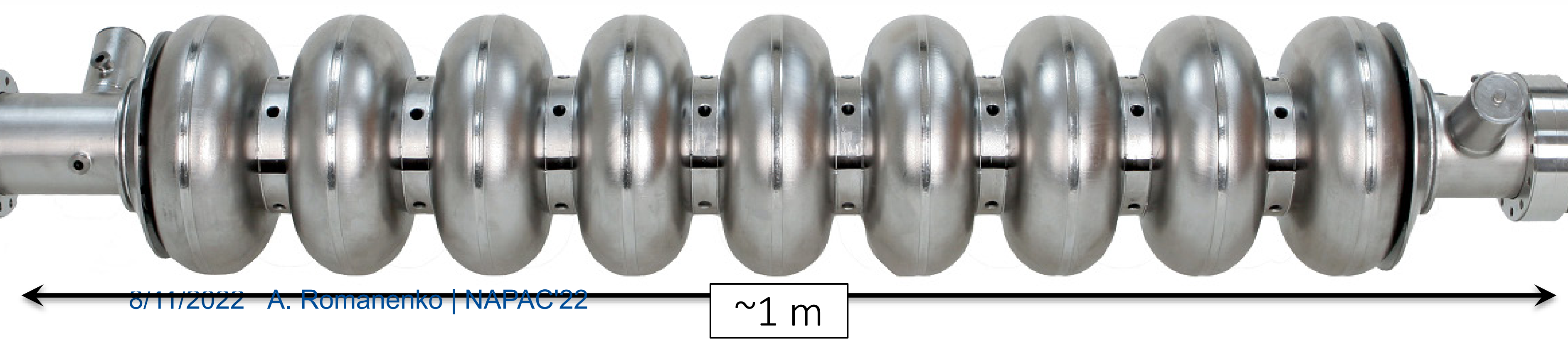
How are Particles Accelerated in Modern Machines?

- **Superconducting radiofrequency (SRF) cavities**
- High quality EM resonators: $Q_0 > 10^{10}$
- Over billions of cycles, large electric field generated (>$\mathbf{10^{25}}$ photons stored)
- Particle beam gains energy as it passes through

Input RF power at 1.3 GHz

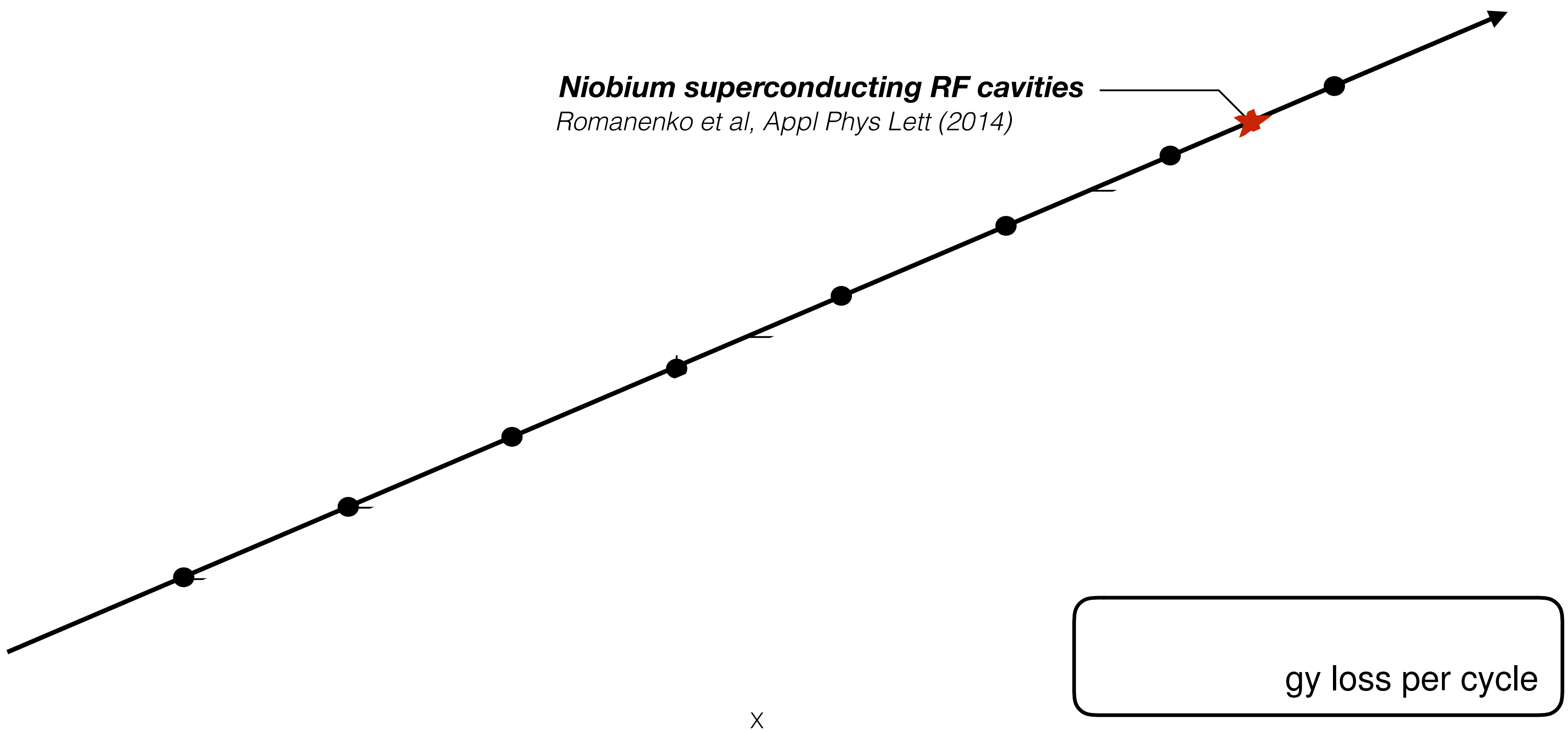
Slowed down by factor of approximately 4×10^9





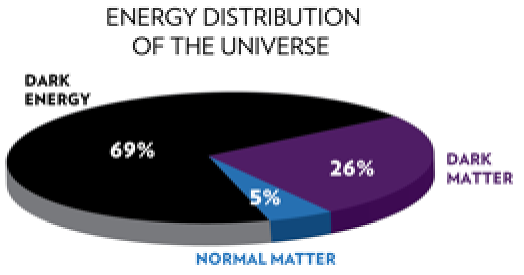
Why SRF cavities for quantum sensing?

SRF cavities are the most efficient engineered oscillators



Longer Range Interactions and Wave-like Dark Matter

- New light particles are theoretically well motivated. e.g.
  - Axion like particles (including the QCD axion)
  - Dark photons



- For such light particles two hypotheses can be tested:

New particle:

$\mathcal{L} \supset$ dark photons?
axions?
long range force?

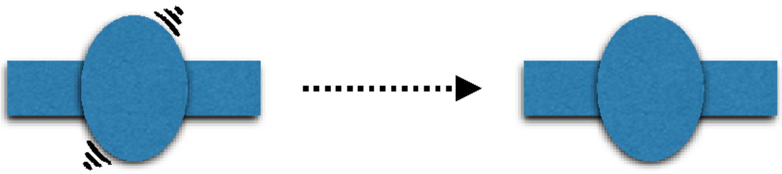
Dark matter (and new particle):

$\supset$ dark photons?
axions?

Basic search schemes

Light Shining through wall:

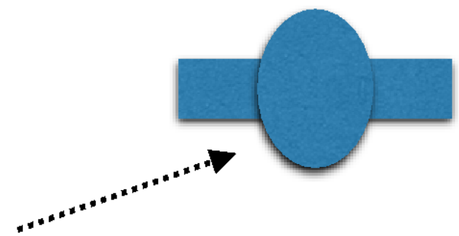
Emitter Receiver



a search for a mediator.

A dark matter search:

Receiver



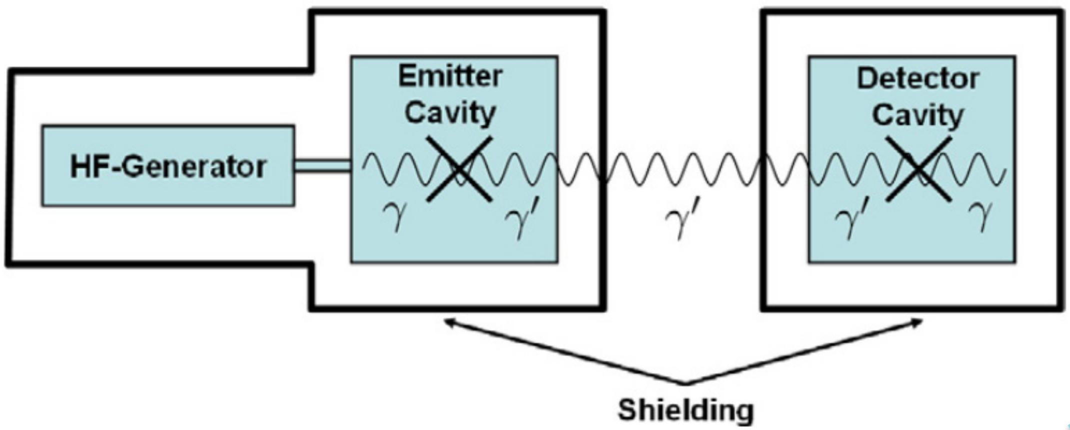
the DM filled Universe
is the emitter

Dark sector search

S. R. Parker *et al*, Phys. Rev. D 88, 112004 (2013)
J. Hartnett *et al*, Phys. Lett. B 698 (2011) 346
J. Jaeckel and A. Ringwald, Phys. Lett. B 659, 509 (2008)

Q_{DET}, Q_{EM} < 10^5 so far used

Looking for hidden paraphotons

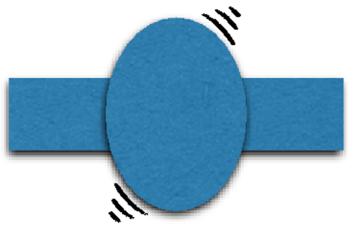


$$\frac{P_{DET}}{P_{EM}} = \chi^4 Q_{DET} Q_{EM} \left(\frac{m_{\gamma'} c^2}{\hbar \omega_\gamma}\right)^8 |G|^2$$

Q_{DET}, Q_{EM} > 10^{10} SRF can offer several orders of magnitude improvement in sensitivity to c

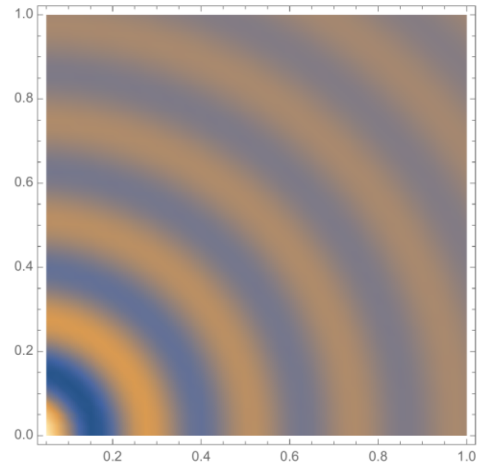
Dark Photon Search

Q> 1e9



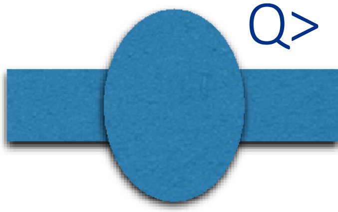
Emitter Cavity

Frequency of 1.3 GHz, excited to ~ 35 MV/m. Thats ~ 10^{25} Photons!



a dark photon field is radiated at 1.3 GHz.

Q> 1e10

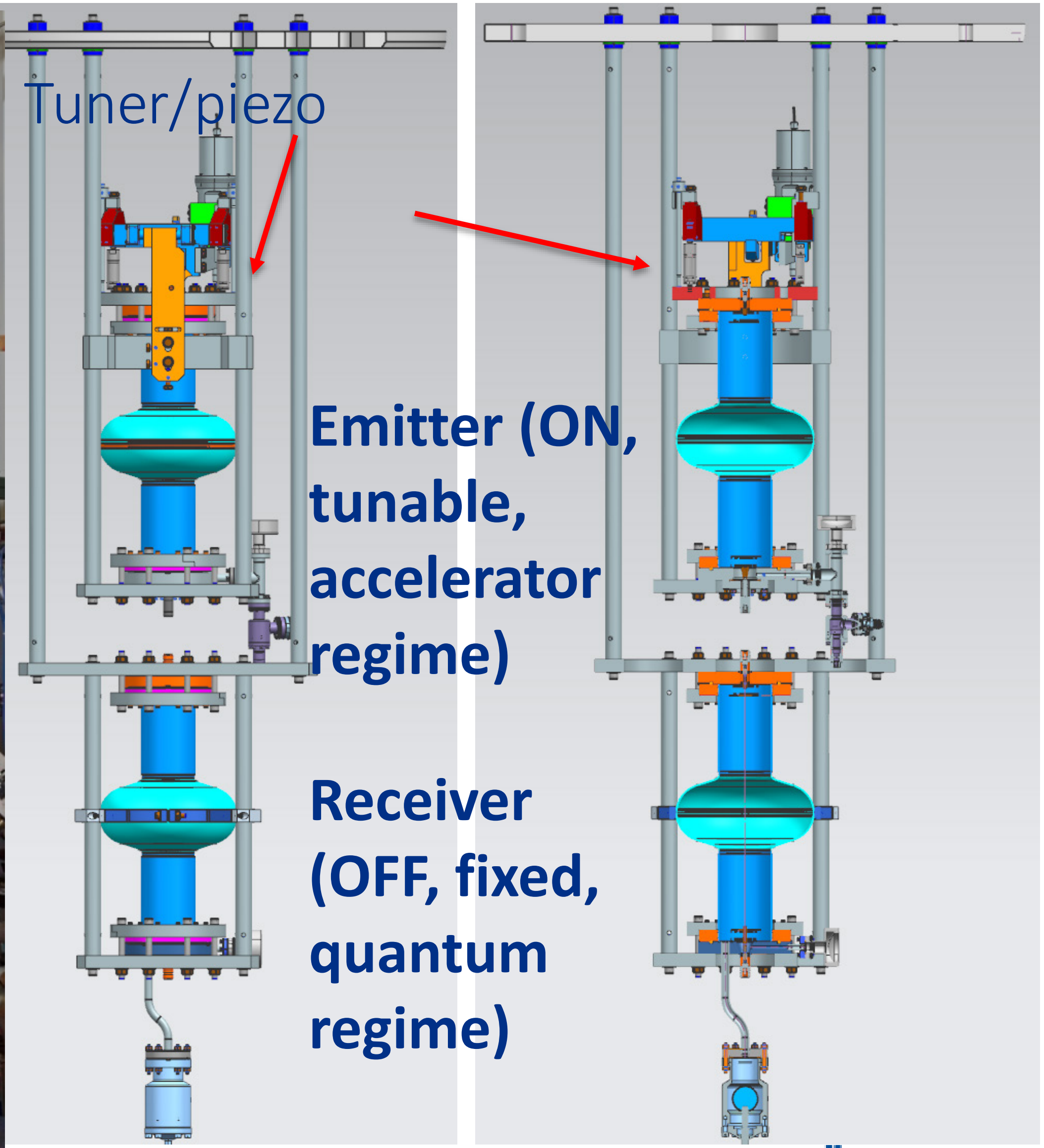


Receiver Cavity

Tuned to 1.3 GHz. Responds to dark field. Contains only thermal noise (T=1.4 K).

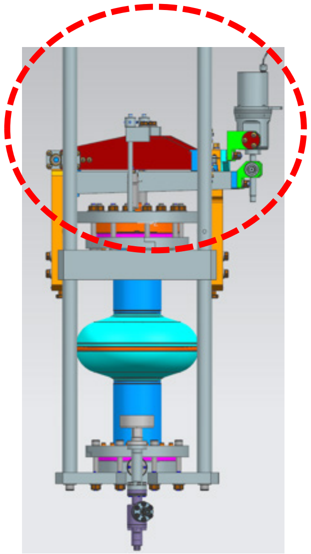
For correct cavity positioning $P_{rec} \propto G^2 \left(\frac{m_{\gamma'}}{\omega}\right)^4 Q_{rec} Q_{em} P_{em}$

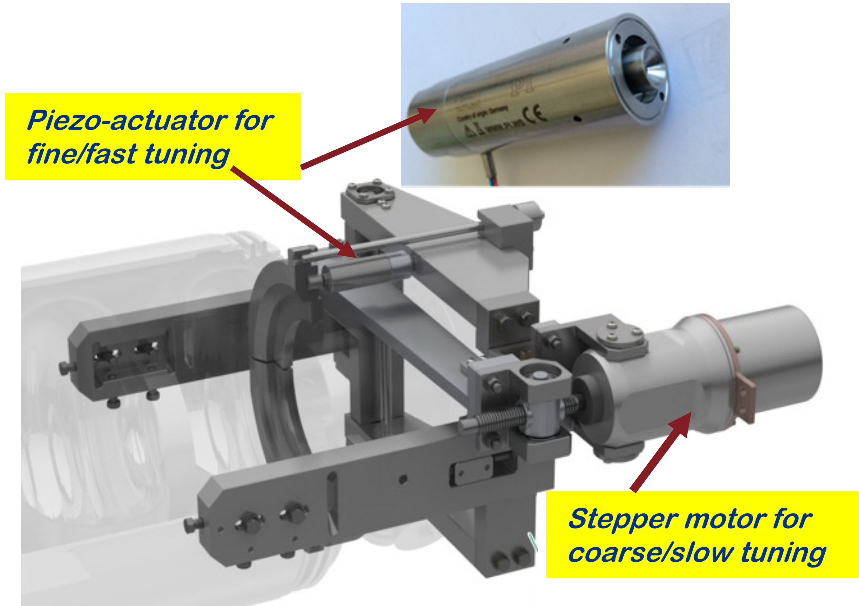
DarkSRF experiment



Controlling cavity frequency with sub-Hz resolution

SRF Cavity Tuner (LCLS II double lever tuner) to tune “transmitter” cavity





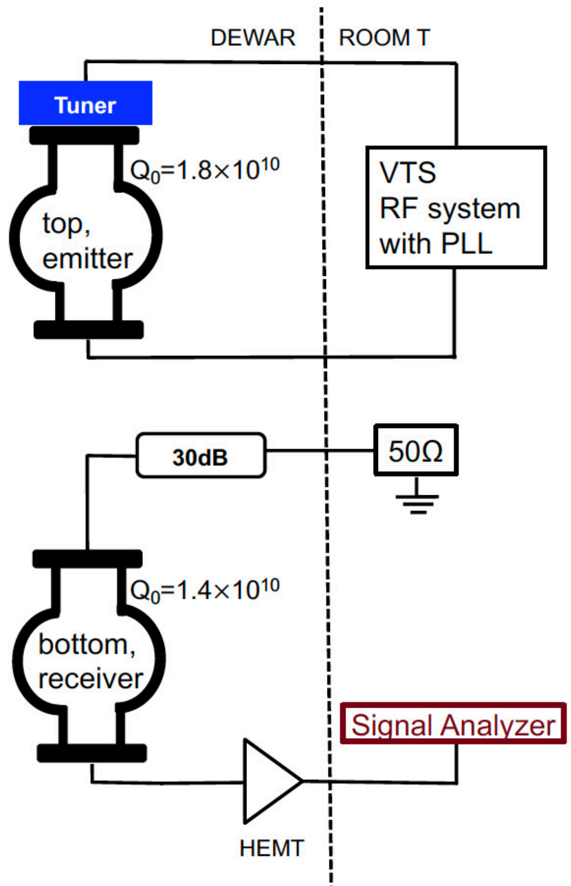
Coarse Tuner
- Range up to DX=2mm or DF=5MHz
- Resolution dx=5nm or dF=12Hz
- Hysteresis ~ 300Hz

Fine/Fast Tuner
- Range up to DX=3um or DF=8kHz
- Resolution dx=0.05nm or dF=0.1Hz (*)

(resolution will be limited by electrical noise of the piezo amplifier)

(*) Piezo tuner resolution measured with LCLS II cavity ~0.15Hz was limited by noise at HTS

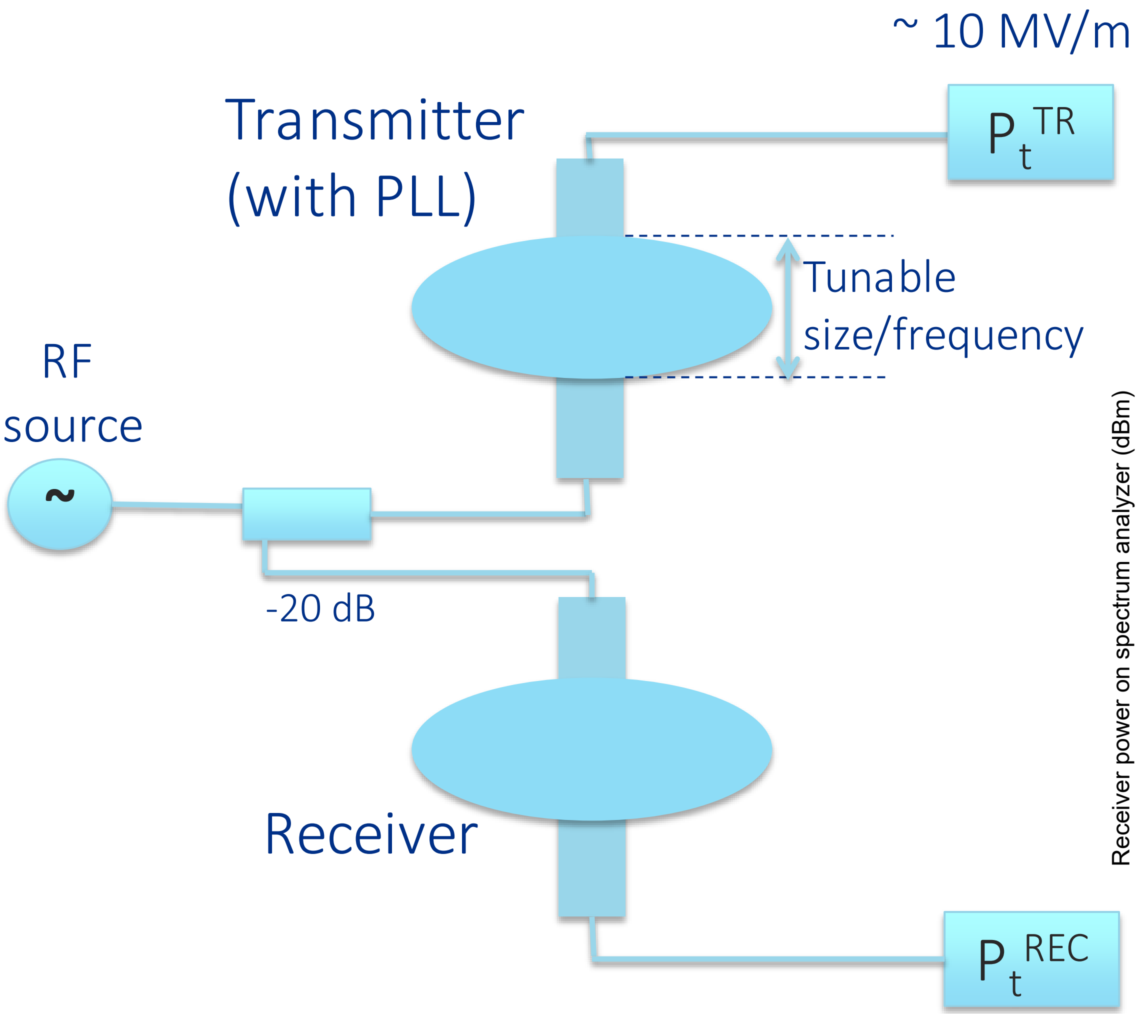
Y. Pischalnikov et al

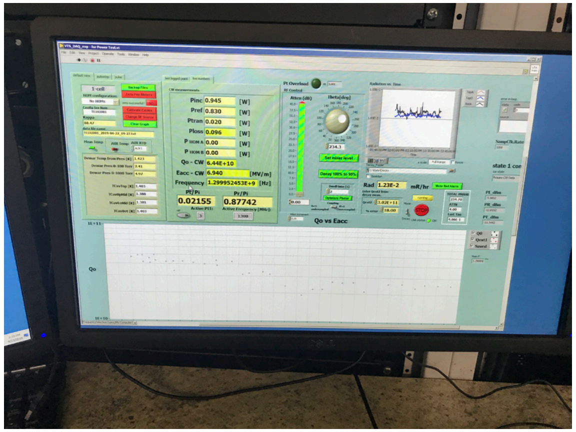

DEWAR
ROOM T
Tuner
Q_0=1.8×10[10]
top, emitter
VTS RF system with PLL
30dB
50Ω
Q_0=1.4×10[10]
bottom, receiver
Signal Analyzer
HEMT

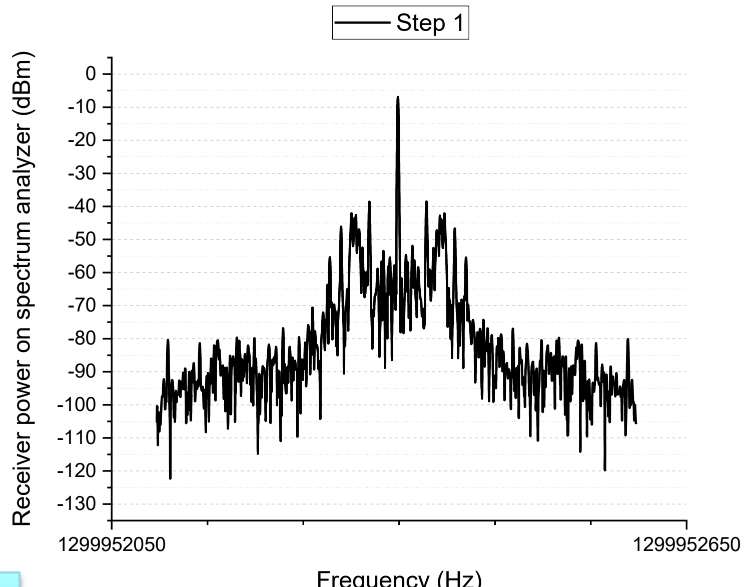
Happy people right before run zero

Fermilab

Cavity frequency matching – Step 1

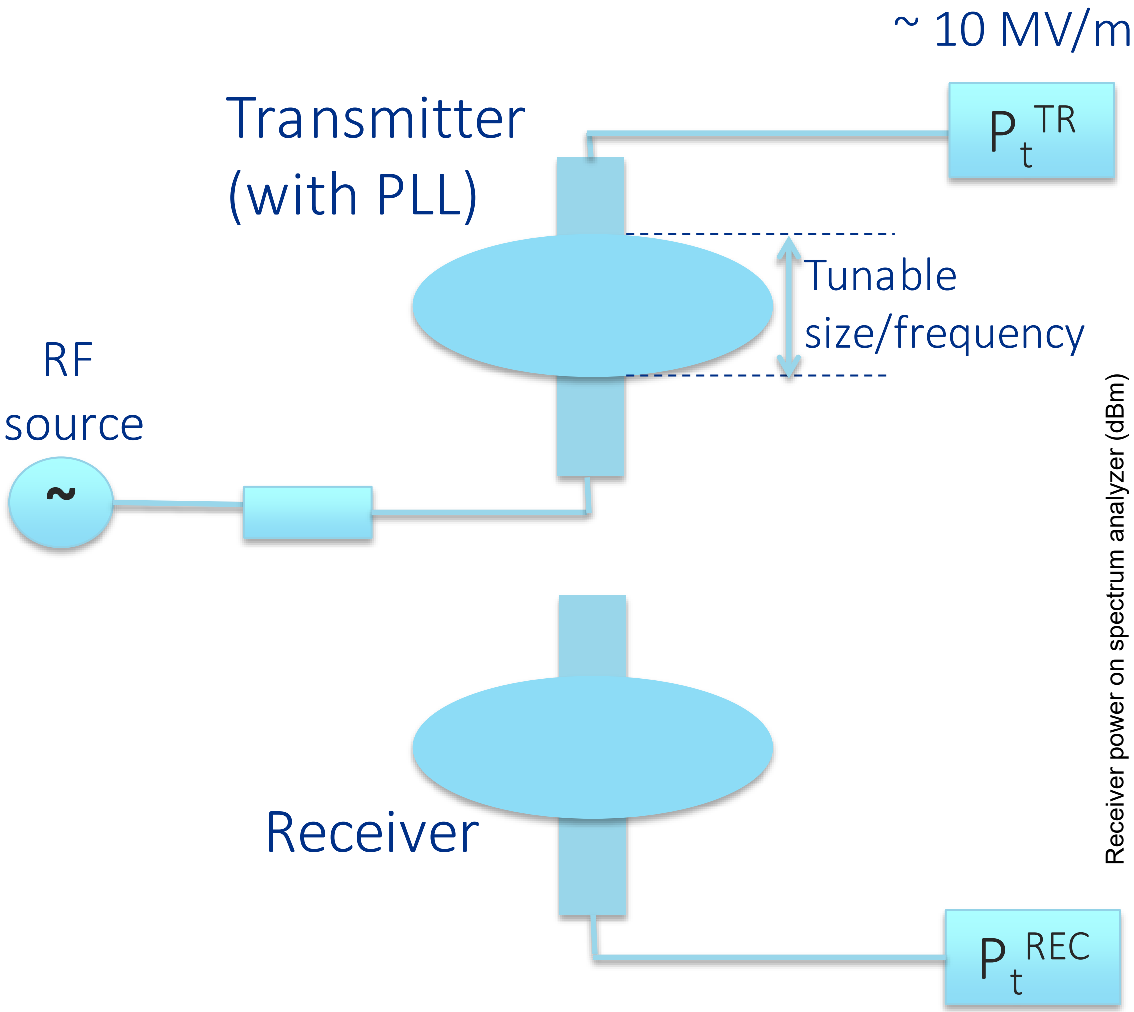


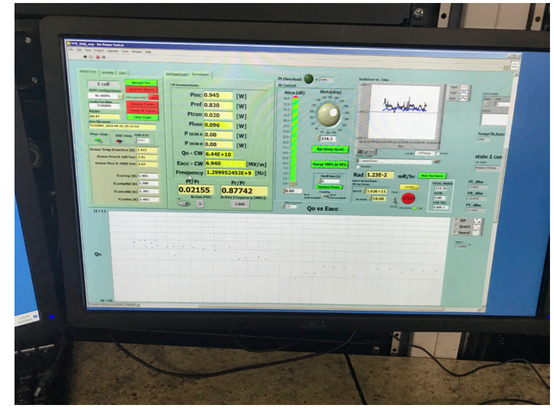


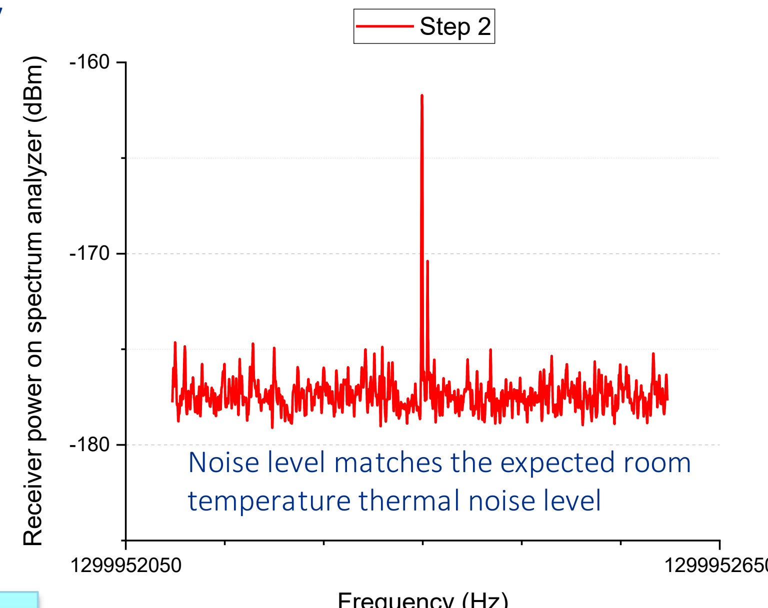


On spectrum analyzer

Dark Photon search! – (Step 2)





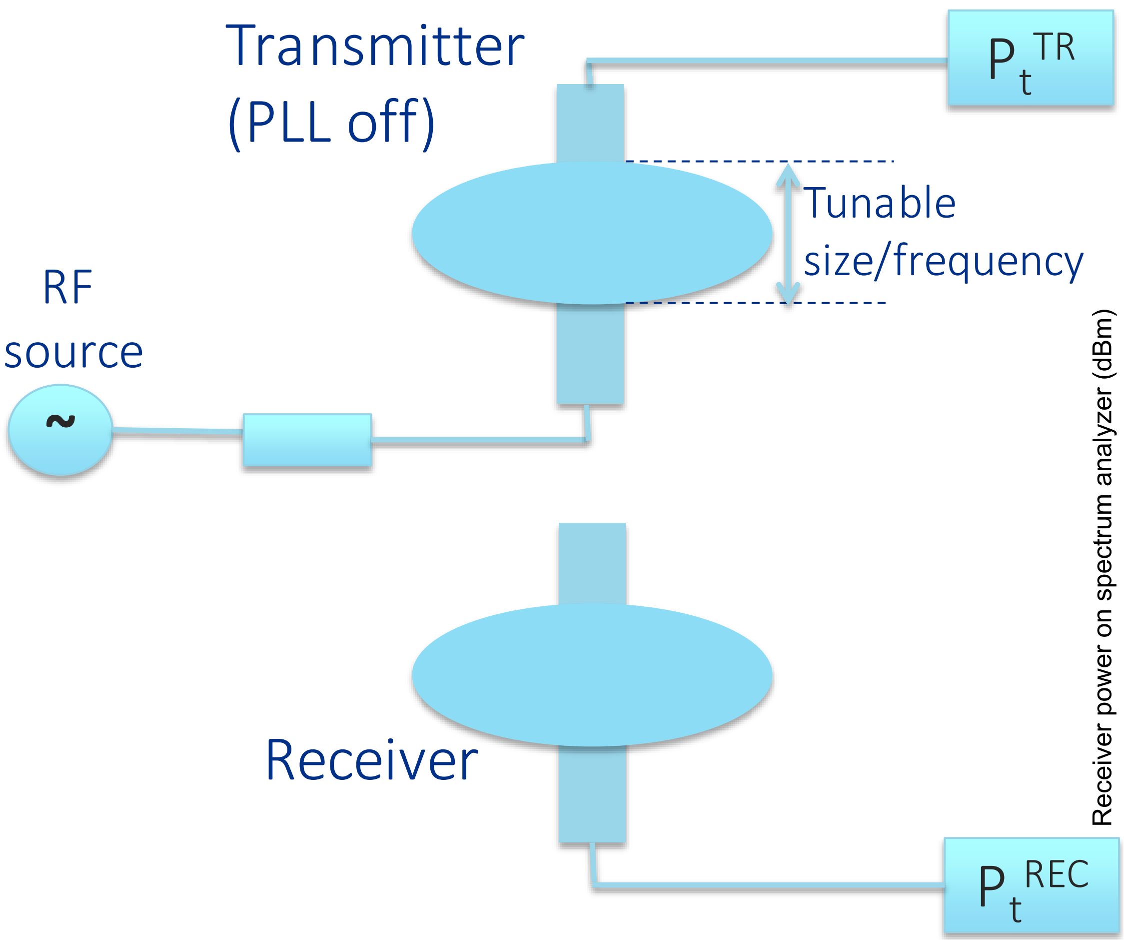


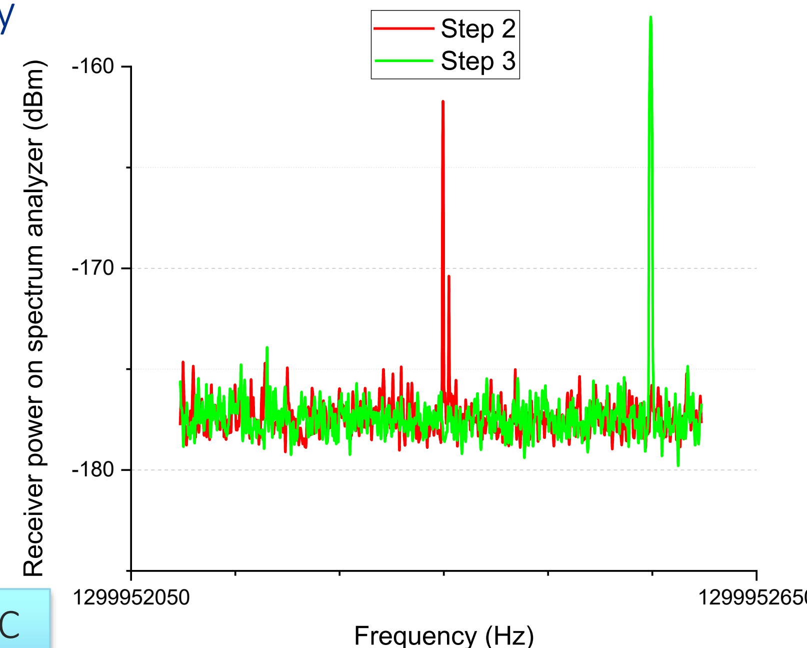
On spectrum analyzer

Bandwidth = 1 Hz

Cross-talk check - Step 3

No stored power = no dark photons



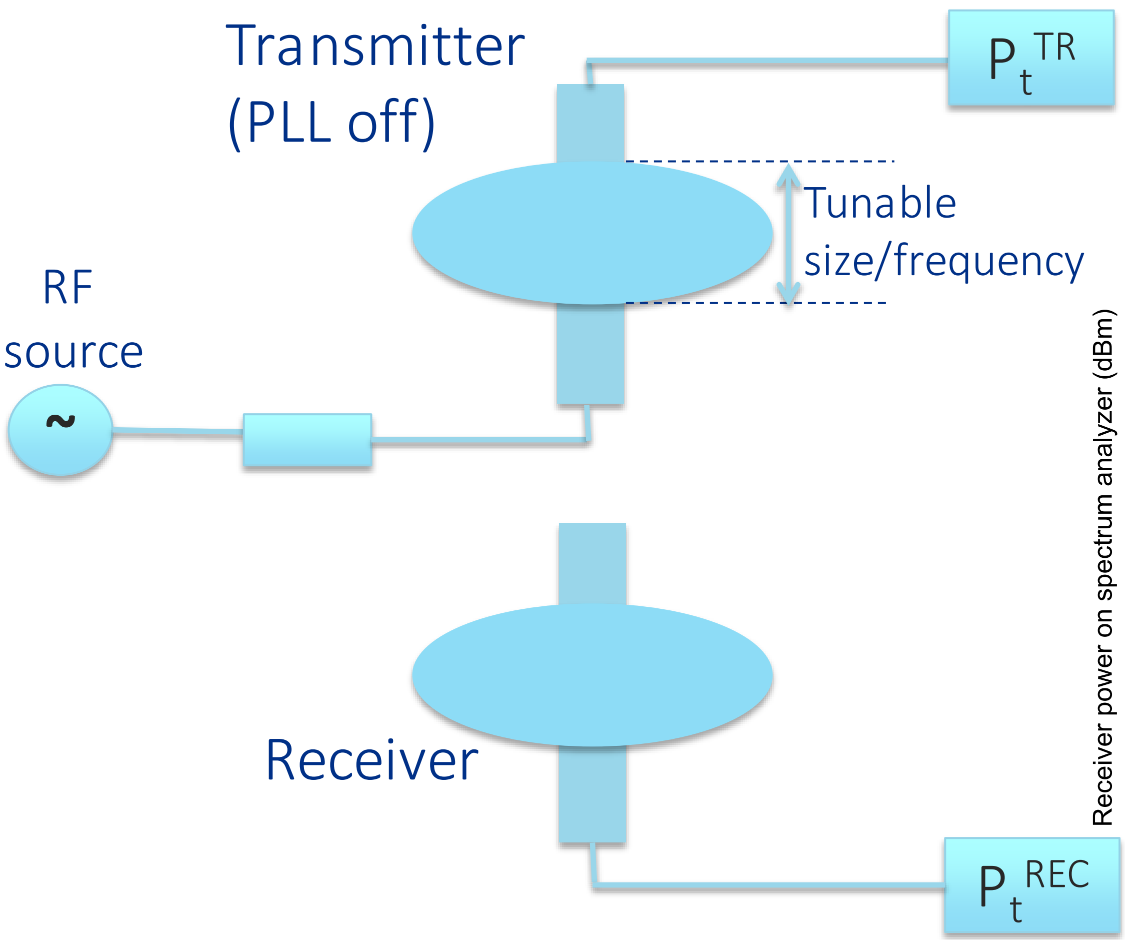


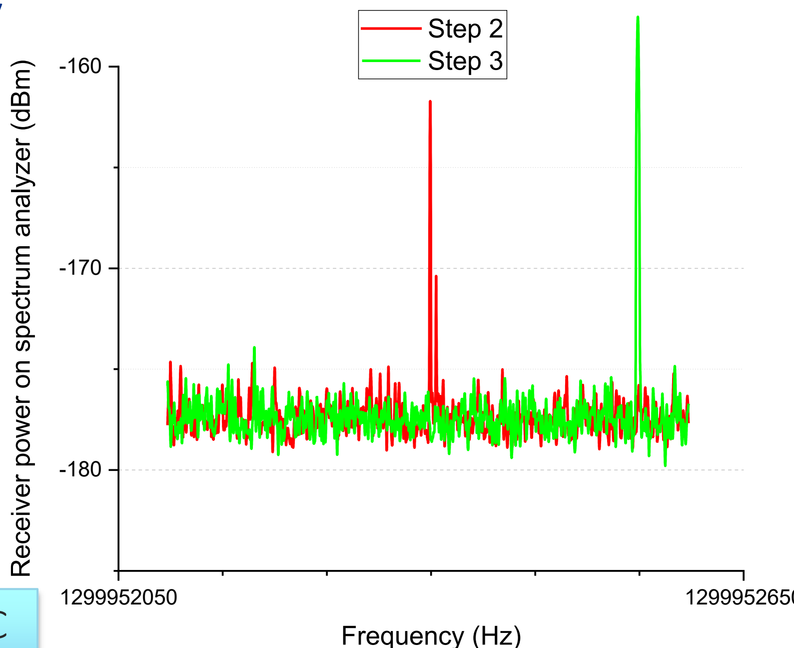
On spectrum analyzer

Cross-talk check - Step 3

No stored power = no dark photons

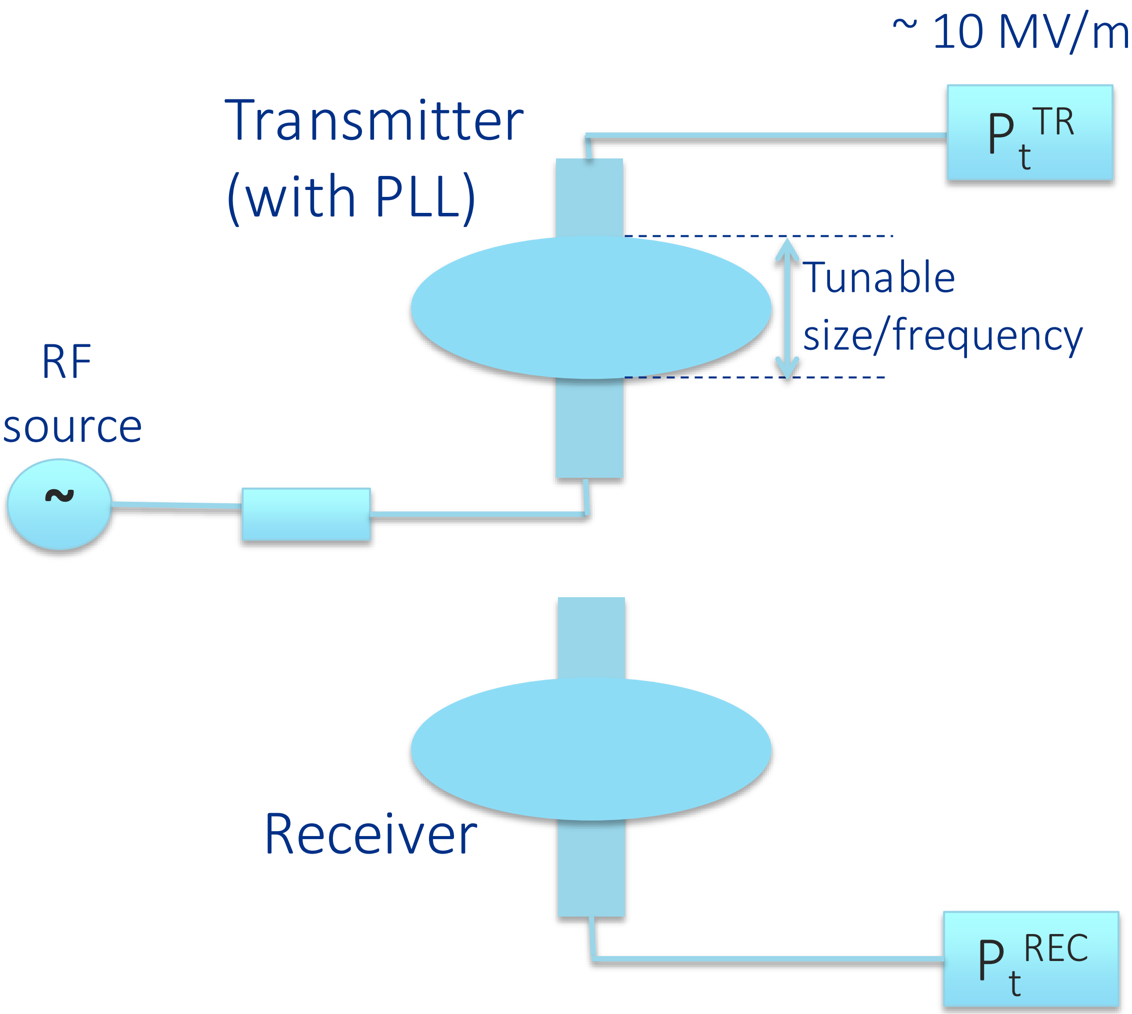
Don't see the dark photon signal (yet) beyond cross-talk

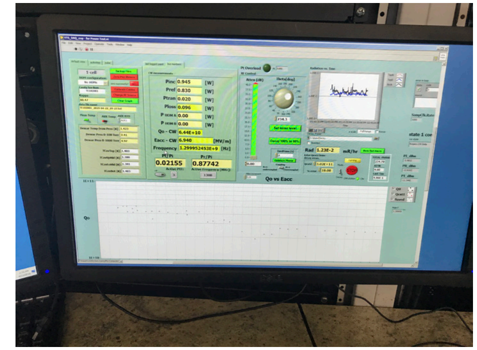


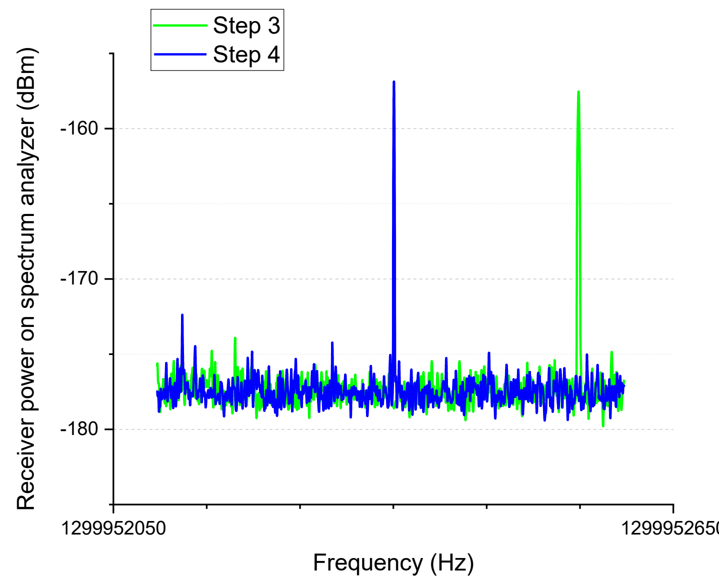


On spectrum analyzer

Back to dark photon search - Step 4 = Step 2

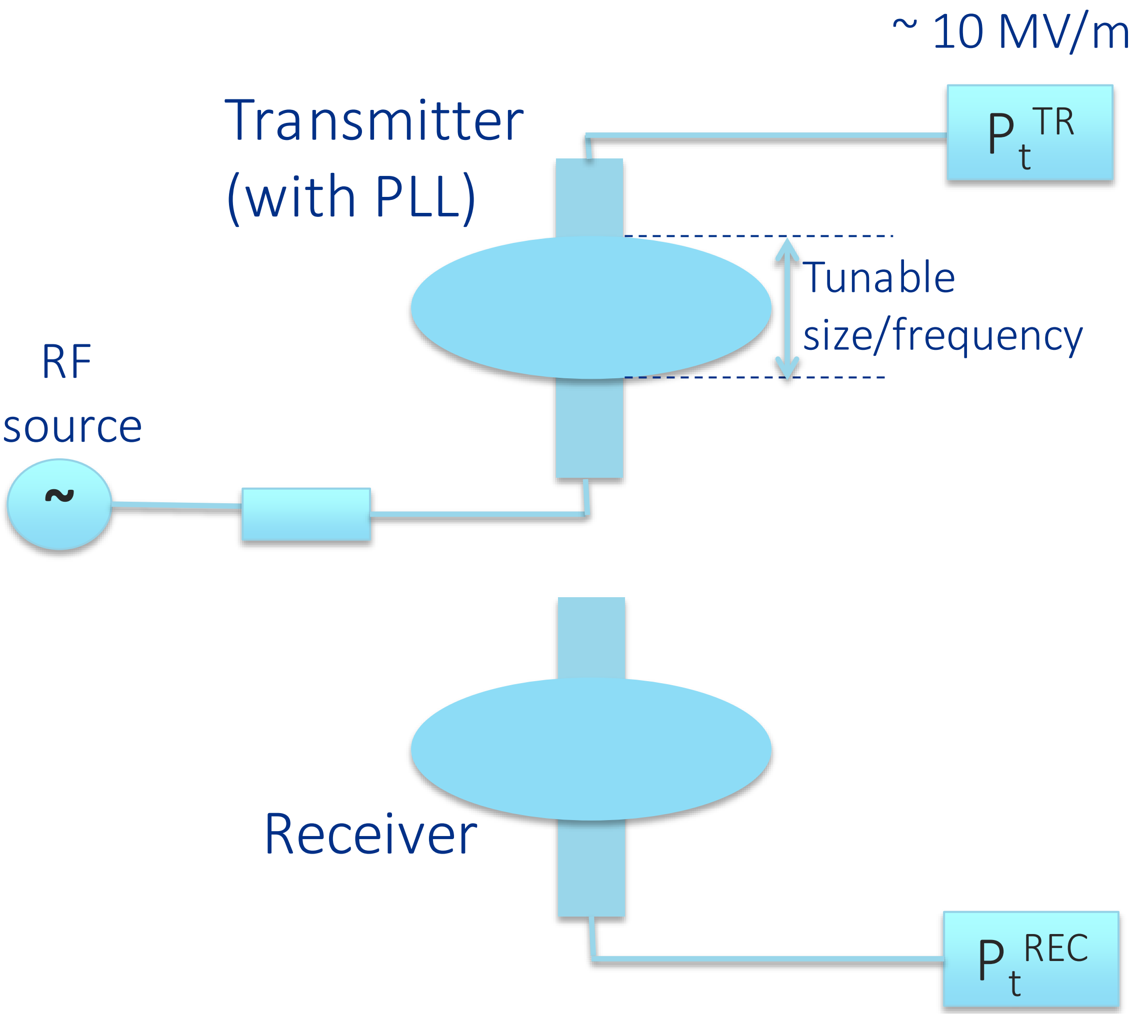


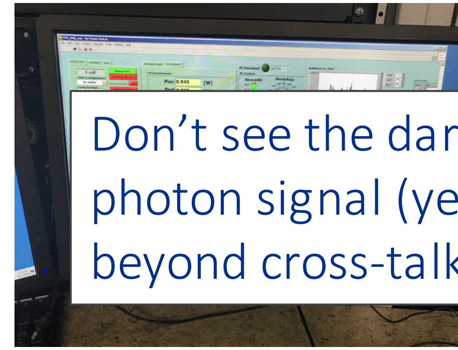




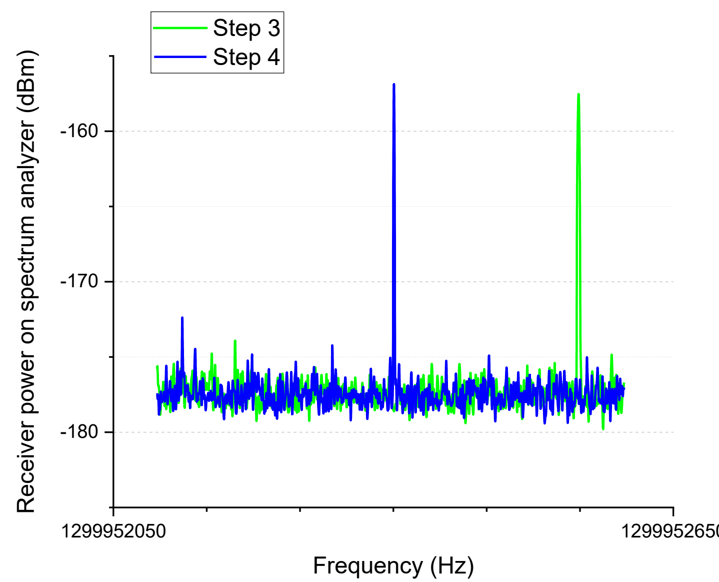
On spectrum analyzer

Back to dark photon search - Step 4 = Step 2



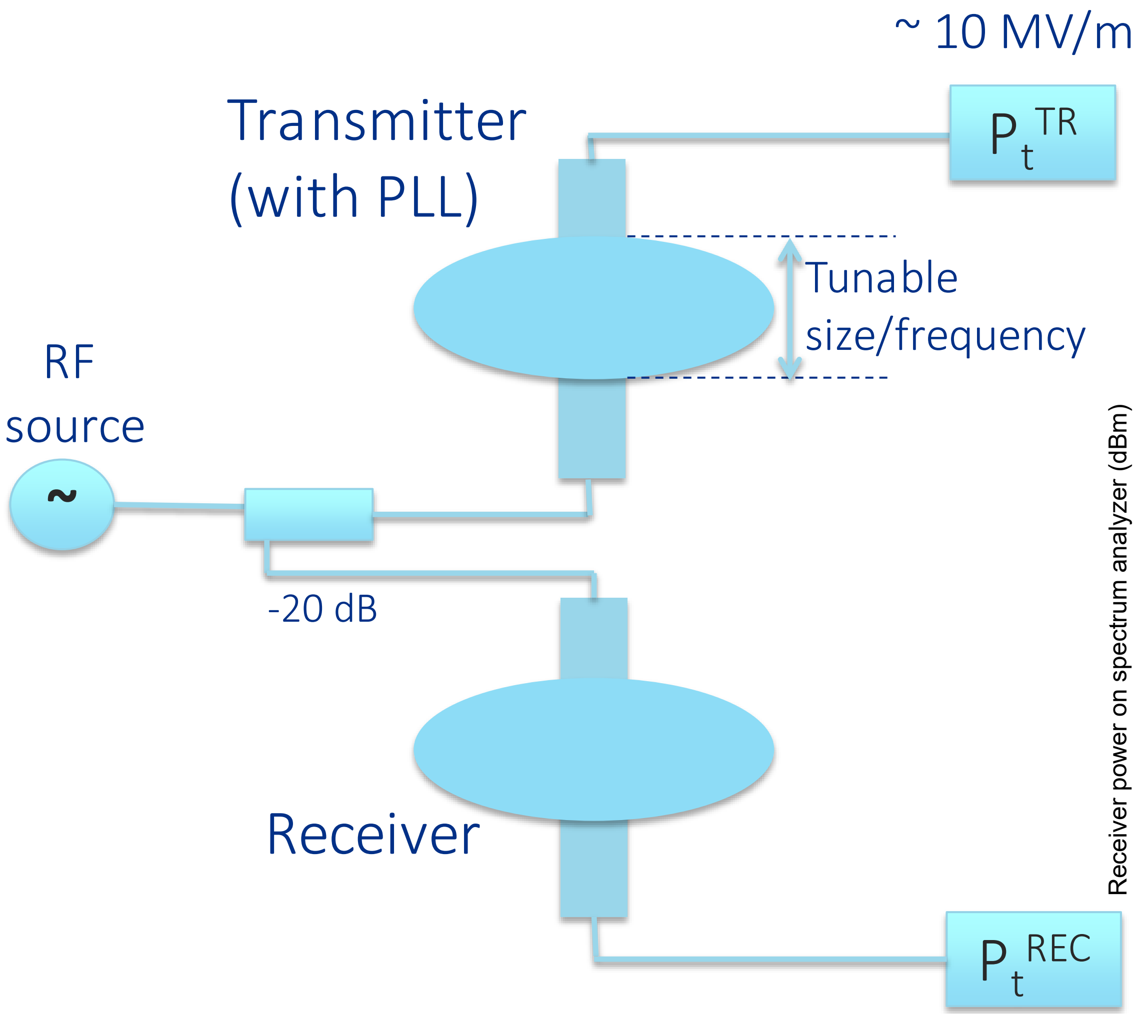


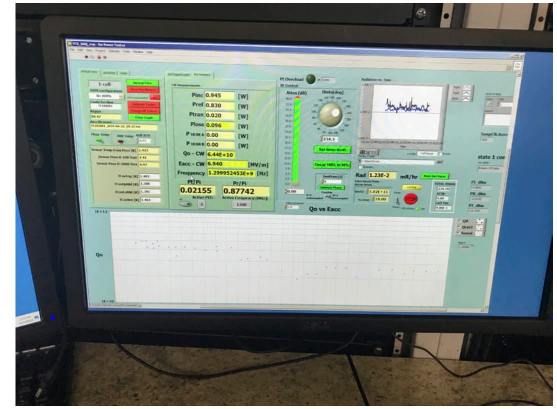
Don't see the dark photon signal (yet) beyond cross-talk

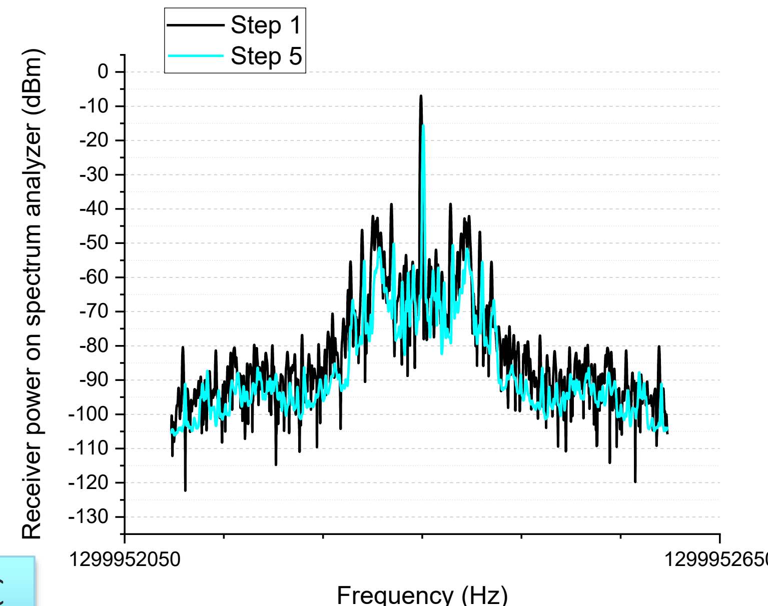


On spectrum analyzer

Back to Step 5 = Step 1 – all is still in tune



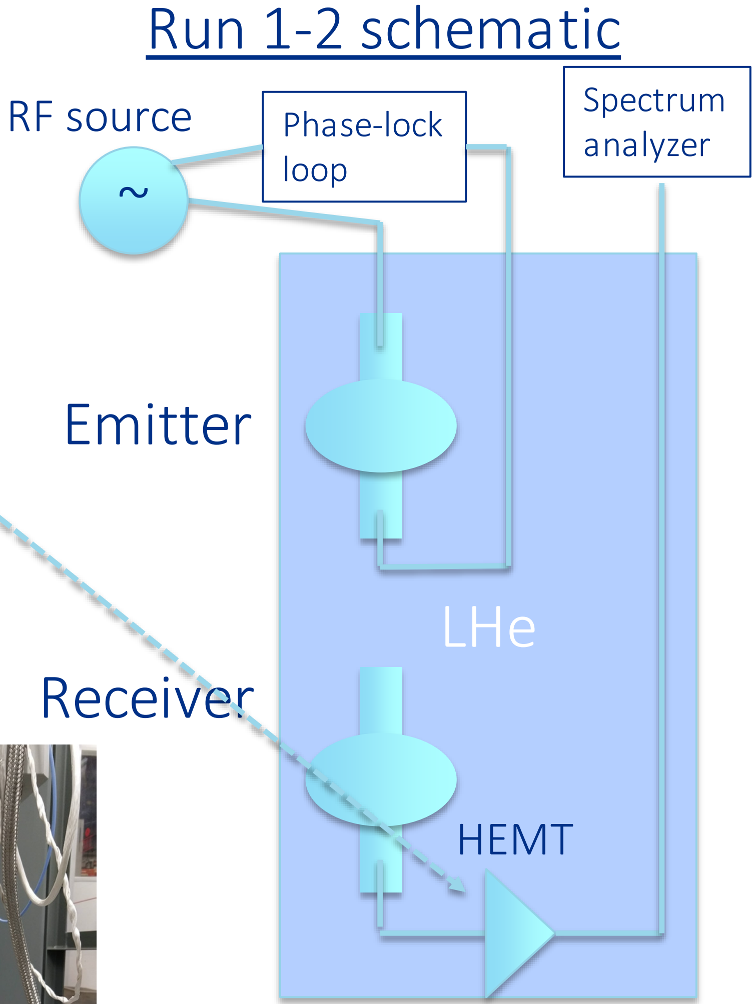




On spectrum analyzer

Run 1 and 2 improvements

- Added cryogenic (~40 dB) low-noise amplifier (HEMT) right at the pickup antenna of the receiver
- Identified and suppressed the main cross-talk sources
  - DC power and current bias wires for HEMT
  - Better isolated cables, connectors etc



Data acquisition runs – medium power

- Emitter:
  - E_{acc} = 6.2MV/m, stored energy U = 0.6 J ⇔ 7e23 photons, Q_0 ~ 4.5e10, Qloaded = 1.6e9, freq jitter rms ~ 1 Hz,

- Receiver:
  - Q_0 ~3e10, Qloaded = 6e9, freq jitter rms ~ 1 Hz

- Limitation: thermal excitation of the receiver cavity: ~5500 stray photons

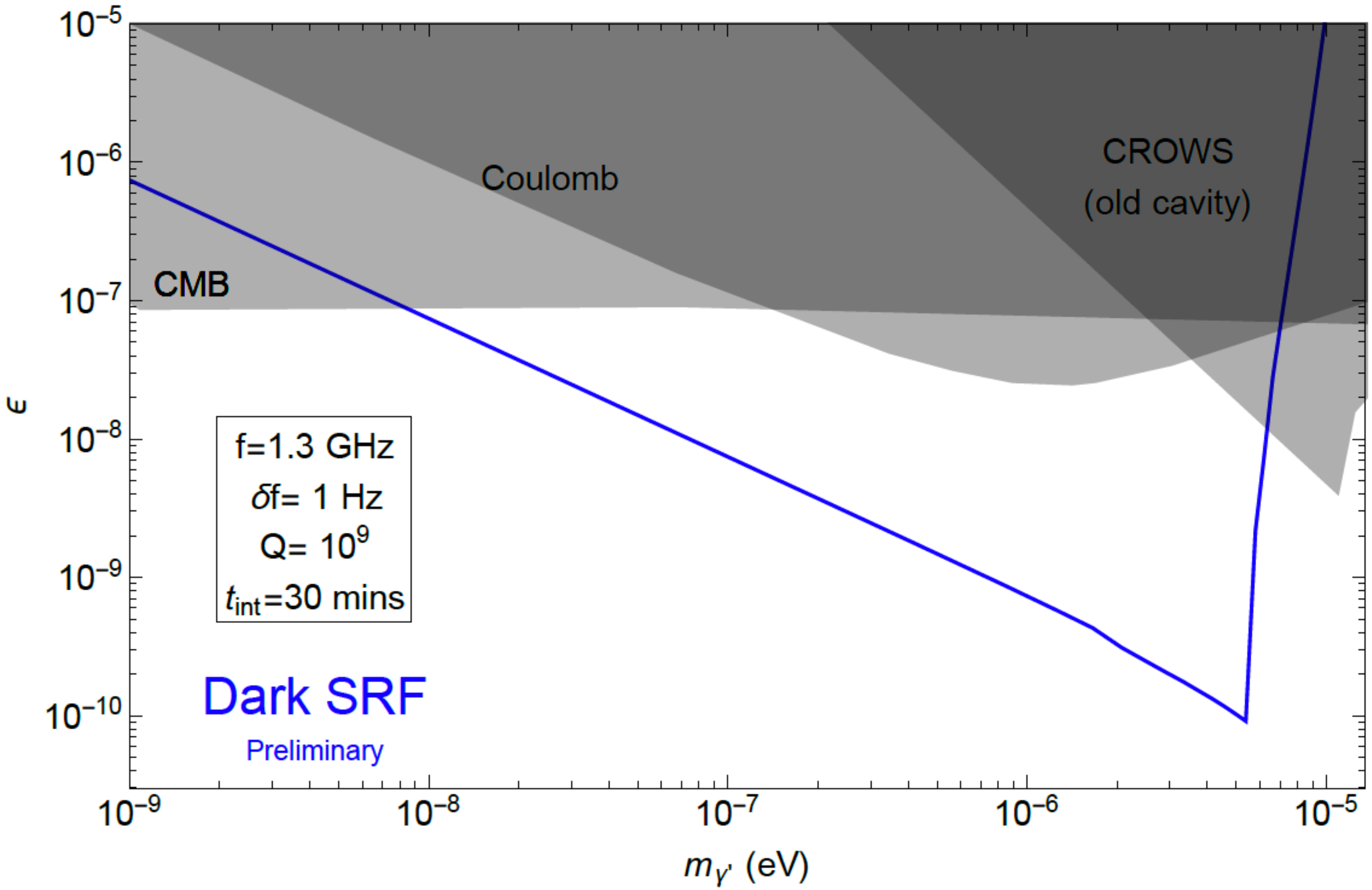
Data acquisition runs – high power

- Emitter:
  – Eacc = 40 MV/m, stored energy U = 26 J ⇔ 3e25 photons, Q_0 ~ 2e10, Q_{loaded} = 1.6e9, freq jitter rms ~ 1 Hz,

- Receiver:
  – Q_0 ~3e10, Q_{loaded} = 6e9, freq jitter rms ~ 1 Hz

- Limitation: some remaining cross-talk

Results from run 2 – exclusion boundary pushed up to 3 orders of magnitude compared to state of the art



Lots of new exciting ideas on very high Q SRF cavities for axion searches and more – we need to implement

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Probing Axionlike Particles and the Axiverse with Superconducting Radio-Frequency Cavities

Zachary Bogorad, Anson Hook, Yonatan Kahn, and Yotam Soreq
Phys. Rev. Lett. **123**, 021801 – Published 9 July 2019

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covering particles, fields, gravitation, and cosmology

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Axion production and detection with superconducting rf cavities

Ryan Janish, Vijay Narayan, Surjeet Rajendran, and Paul Riggins
Phys. Rev. D **100**, 015036 – Published 23 July 2019

Axion Dark Matter Detection by Superconducting Resonant Frequency Conversion

Asher Berlin
Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, NY 10003, USA.

Raffaele Tito D'Agnolo
Institut de Physique Théorique, Université Paris Saclay, CEA, F-91191 Gif-sur-Yvette, France

Sebastian A. R. Ellis, Christopher Nantista, Jeffrey Neilson, Philip Schuster, Sami Tantawi, Natalia Toro, and Kevin Zhou
SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA 94025, USA

Searching for Millicharged Particles with Superconducting Radio-Frequency Cavities

Asher Berlin[1] and Anson Hook[2]
[1] *Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, NY 10003, USA*
[2] *Maryland Center for Fundamental Physics, University of Maryland, College Park, MD 20742, USA*

SQMS

Led by FNAL, $115M
Awarded August 2020

Superconducting Quantum Materials and Systems Center

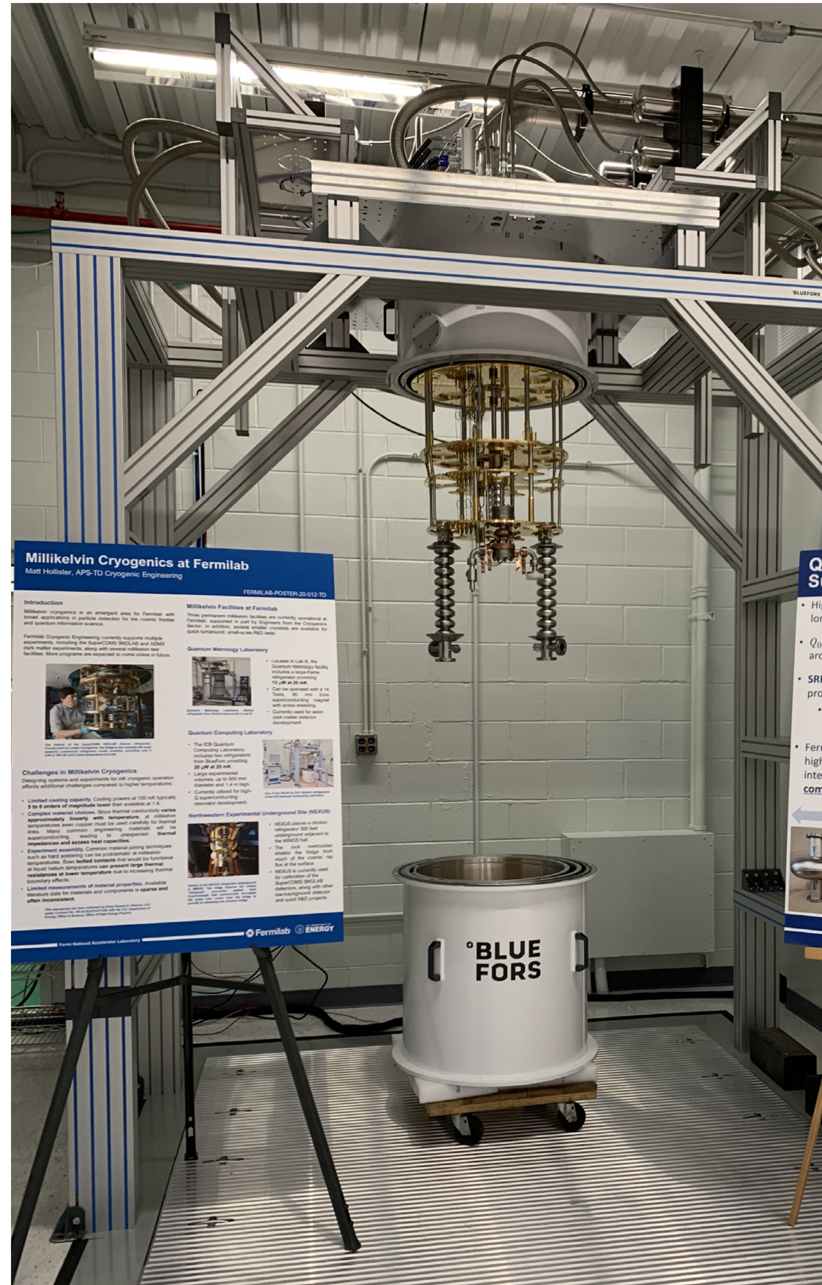
A DOE National Quantum Information Science Research Center

23 Institutions
> 350 Researchers
> 100 students/postdocs

Fermilab | rigetti | Northwestern University | Ames Laboratory (Creating Materials & Energy Solutions, U.S. Department of Energy) | NASA Ames Research Center
NIST | INFN Istituto Nazionale di Fisica Nucleare | Stanford University | University of Illinois Urbana-Champaign | Rutgers | Università di Pisa
University of Colorado Boulder | Illinois Institute of Technology | Johns Hopkins University | Temple University | Colorado School of Mines | The University of Arizona
University of Minnesota | NYU | Goldman Sachs | Lockheed Martin | JANIS | Unitary Fund

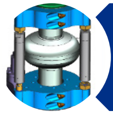
SRF Bluefors-2

- Designed to sustain several Watts at 2K stage
- Working on transferring the light shine through wall setup to this DR (tuner, piezo, rad shielding…)
- Should be able to run in DR in the next few months

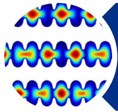


SQMS - Physics and Sensing 5-year Roadmap

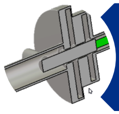
Year 1 | Year 2 | Year 3 | Year 4 | Year 5



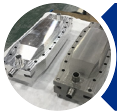
DarkSRF
- Measure in LHe, 1st DarkSRF publication
- Phase sensitive readout
- Implement in DR, quantum regime!
- Improve Q_0 towards 1e12



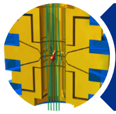
Multimode Cavity Axion Search
- Nonlinearity studies
- 2-cavity multimode design
- 2-cavity 1st test
- 2- and 3- mode 1-cavity design
- 2- and 3- mode 1-cavity 1st test



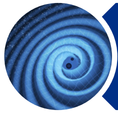
Tunable Dark Photon Search
- Design and fabricate cavity
- Trial runs, feedback
- Study heterodyne vs photon counting
- Data taking runs



High B-Field Axion Search
- Co-design w/ materials & devices
- Searches w/ best cavities and qubits
- Evaluate Nb_3Sn, NbTi Q_0 in high B
- Evaluate search w/ AC B-field



Single Particle Penning Trap
- Design high Q cavity geometry
- Testing optimized cavities/squids
- Prototype cavities & squids
- 1st next gen e- μ/μ_B measurements



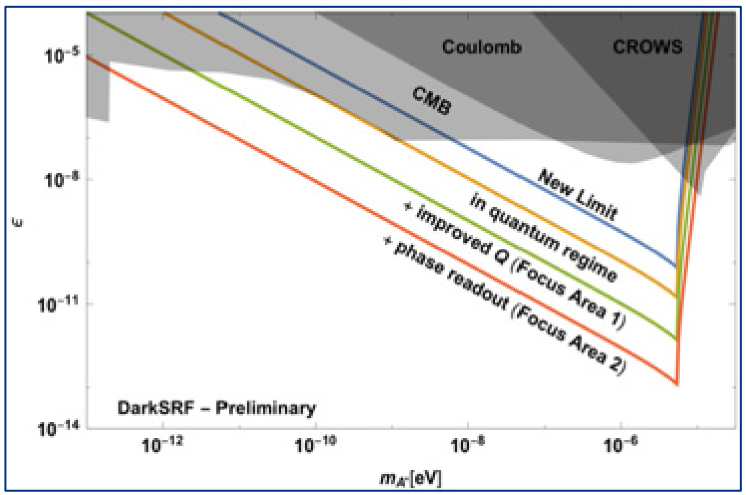
Other Quantum Sensing Schemes
- Theory study of QIS for dark radiation detection, Quantum Sensor Network,
- Evaluate SRF cavities for gravitational wave detection, DM with traps.

Science Thrust, Focus Area Physics and Sensing

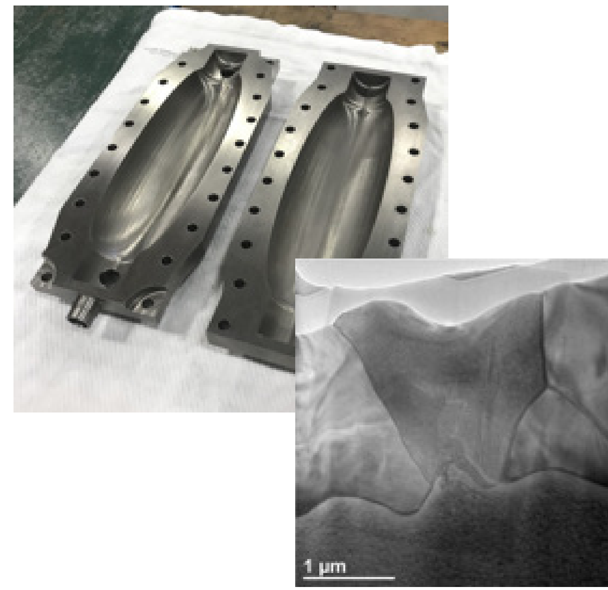
Goal: Exploit the center technological advancements for fundamental physics

Deliverables/metrics: develop and deploy search schemes with detection sensitivity orders of magnitude compared to state-of-the-art

DarkSRF experiment: A dark photon search



Orders of magnitude in sensitivity reach improvement via the SQMS advancements



Cavity and Nb_3Sn materials advancements for axion searches

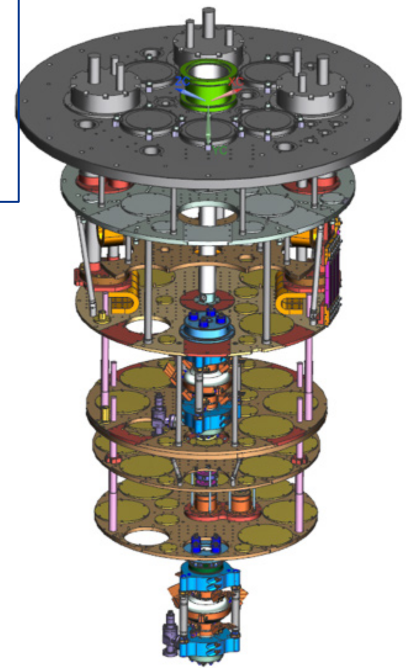
Progress in record-breaking materials, devices and platforms for quantum sensing

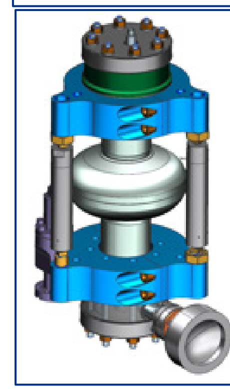
SQMS physics/sensing testbeds

Axion Search Platform

First measurements ever performed of Nb3Sn high Q cavities in Tesla magnetic fields; new cavity geometry optimized for minimizing flux losses demonstrated record Q in multi Tesla fields

Dark Photon Search Platform





Completed design for DarkSRF experiment in mK refrigerator at FNAL; parts in fabrication; Cavities, piezos, frames to be delivered this summer, commissioning to follow

Summary

- Exciting new opportunities with SRF cavities for QIS and dark sector searches
- First results exclude existence of dark photons in mass range 10^{-8}-10^{-5} eV by > 3 order of magnitude form previous searches
- Lots more progress to come - Very rich SQMS program exploring fully the advantage of high Q SRF in quantum regime