First results of DarkSRF: a dark photon search using SRF cavities

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Outline

Introduction on SRF

SRF Cavities “towards” the Quantum Regime

DarkSRF Experiment at 1.4K and first results

DarkSRF stage 2 search in dilution fridge: SRF cavities in the true quantum regime

Extending the search scheme to axions
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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 ($>10^{25}$ photons stored)
- Particle beam gains energy as it passes through

Input RF power at 1.3 GHz

Slowed down by factor of approximately $4 \times 10^9$
Why SRF cavities for quantum sensing?

SRF cavities are the most efficient engineered oscillators

- **Niobium superconducting RF cavities**

- **Crystalline optical resonator**

- **Optical whispering-gallery resonator**

- **Quartz clock, High-Q Copper RF/MW cavity**

- **Best pendulum clock**

- **Best superconducting qubits**
  Devoret & Schoelkopf, Science (2013)

- **Al-Mg atomic clock**

\[ Q \equiv \frac{2\pi}{\text{energy loss per cycle}} \]
Nanometric RF Penetration Layer drives the performance

Characterization and nano-engineering the surface layer is crucial to performance

RF fields

Helium cooling

Niobium
~3 mm

RF currents

~100 nm

<0.1% of thickness

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Major SRF infrastructure and expertise at Fermilab, enabling highest Q ever achieved, in low and high photon count regimes.
Material science and superconducting characterization

- Cavity surface undergoes a series of delicate chemical and heat treatments
- Material science tools are essential to understand the surface nanostructural changes that lead to dramatic changes in performance

At the present day, we know

Dirty Nb Clean Nb

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Modern large scale accelerators: large and complex high coherence SRF systems

European XFEL
~1000 cavities
Specification:
$Q > 10^{10}$ @ 2K, 23.6 MV/m

LCLS-II at SLAC
Fermilab is building half (30+) of cryomodules
Specification:
$Q > 2.7 \times 10^{10}$ @ 2K, 16 MV/m

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Extending the search scheme to axions
Taking SRF cavities “towards” the quantum regime

Fermilab Vertical cavity test Facility at APS-TD (VTS)

\[ T = 1.4K \]

\[ \sim 1000 \text{ photons} \]

Dilution Fridge at Fermilab APS- TD Quantum Lab (QCL)

\[ T \sim 6mK \]
RF Surface resistance is highly nonlinear

Where does $Q$ go at very low fields?

$Q = \text{const} / R_s$

$T = 2K$

Average surface resistance

$B_{\text{peak}} \approx 160 \text{ mT}$

Increase $Q$ => decrease required power

Increase $\max E_{\text{acc}}$ => decrease accelerator length

Surface magnetic field $B$
First experiment: extend the measured fields to record low fields.

Good news: low field Q saturates at $Q > 3 \times 10^{10}$.

Now measured down to $<N> < 1000$ photons.

First clear proof that growing natural Nb oxide degrades low field Q: confirmation of TLS losses

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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:**
- dark photons?
- axions?
- long range force?

**Dark matter** (and new particle):
- 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


Looking for hidden paraphotons

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

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

\( Q_{DET}, Q_{EM} > 10^{10} \) SRF can offer several orders of magnitude improvement in sensitivity to \( \chi \)
Dark Photon Search

Q > 1e9

Emitter Cavity

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

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

\[
P_{\text{rec}} \leftarrow G^2 \frac{m_{\gamma^0}^2 \sigma_{\gamma^0}}{!} Q_{\text{rec}} Q_{\text{em}} P_{\text{em}}
\]
DarkSRF experiment

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Controlling cavity frequency with sub-Hz resolution

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

Coarse Tuner
- Range up to $\Delta X=2\text{mm}$ or $\Delta F=5\text{MHz}$
- Resolution $\delta x=5\text{nm}$ or $\delta F=12\text{Hz}$
- Hysteresis $\sim 300\text{Hz}$

Fine/Fast Tuner
- Range up to $\Delta X=3\text{um}$ or $\Delta F=8\text{kHz}$
- Resolution $\delta x=0.05\text{nm}$ or $\delta F=0.1\text{Hz}$ (*)

(*) Piezo tuner resolution measured with LCLS II cavity
$\sim 0.15\text{Hz}$ was limited by noise at HTS

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Happy people right before run zero
Cavity frequency matching – Step 1

Transmitter (with PLL)

Receiver

RF source

-20 dB

PfTR

PfREC

~ 10 MV/m

On spectrum analyzer

Receiver power on spectrum analyzer (dBm)

0

-10

-20

-30

-40

-50

-60

-70

-80

-90

-100

-110

-120

-130

Frequency (Hz)

1299952050

1299952650

-130

-120

-110

-100

-90

-80

-70

-60

-50

-40

-30

-20

-10

0
Dark Photon search! – (Step 2)

Transmitter (with PLL)

~ 10 MV/m

Receiver

Noise level matches the expected room temperature thermal noise level

Bandwidth = 1 Hz

Receiver power on spectrum analyzer (dBm)

Frequency (Hz)

Step 2

-180
-170
-160

On spectrum analyzer

1299952050 1299952650

-180
-170
-160

Receiver power on spectrum analyzer (dBm)

Frequency (Hz)

1299952050 1299952650
Cross-talk check - Step 3

No stored power = no dark photons

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

Transmitter (PLL off)

RF source

Receiver

Tunable size/frequency

$P_{t_{TR}}$

$P_{t_{REC}}$

On spectrum analyzer

2/26/2020  A. Romanenko | Dark SRF Meeting
Back to dark photon search - Step 4 = Step 2

Transmitter (with PLL) ~ 10 MV/m

Receiver

Tunable size/frequency

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

On spectrum analyzer

Step 3

Step 4

1299952050 1299952650

Receiver power on spectrum analyzer (dBm)

1299952050 1299952650

Frequency (Hz)

-180

-170

-160
Back to Step 5 = Step 1 – all is still in tune

Transmitter (with PLL)

RF source

~ 10 MV/m

Tunable size/frequency

Receiver

$P_t^{TR}$

$P_t^{REC}$

Receiver power on spectrum analyzer (dBm)

Frequency (Hz)

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:**
  - $E_{\text{acc}} = 6.2\text{MV/m}$, stored energy $U = 0.6\text{ J} \leftrightarrow 7\times 10^{23}\text{ photons}$,
  - $Q_0 \sim 4.5\times 10^{10}$, $Q_{\text{loaded}} = 1.6\times 10^{9}$, freq jitter rms $\sim 1\text{ Hz}$,

- **Receiver:**
  - $Q_0 \sim 3\times 10^{10}$, $Q_{\text{loaded}} = 6\times 10^{9}$, freq jitter rms $\sim 1\text{ Hz}$

- **Limitation:** thermal excitation of the receiver cavity: $\sim 5500$ stray photons
Data acquisition runs – high power

• **Emitter:**
  – \( E_{\text{acc}} = 40 \text{ MV/m} \), stored energy \( U = 26 \text{ J} \) \( \leftrightarrow \) \( 3 \times 10^{25} \) photons, \( Q_0 \sim 2 \times 10^{10} \), \( Q_{\text{loaded}} = 1.6 \times 10^9 \), freq jitter rms \( \sim 1 \text{ Hz} \),

• **Receiver:**
  – \( Q_0 \sim 3 \times 10^{10} \), \( Q_{\text{loaded}} = 6 \times 10^9 \), freq jitter rms \( \sim 1 \text{ Hz} \)

• Limitation: some remaining cross-talk
Results from run 2 – exclusion boundary pushed up to 3 orders of magnitude compared to state of the art

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~1000 photons

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T ~ 6 mK

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Record high Q in quantum regime at first run

Material treatment to suppress TLS dissipation

Material treatment to suppress TLS dissipation

\[ \text{Nb}_2\text{O}_5 \]

5 nm

\[ \text{Nb} \]

\[ \text{Nb} \]

Record high photon lifetimes achieved

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
New limit vs future potential reach in DR

[Graph showing results for different scenarios:]

- **Blue:** new limit 1.4K
- **Yellow:** DR one week run
- **Green:** DR, Q ~5e10
- **Orange:** DR, Q~5e10, one week phase sensitive readout

**Legend:**
- **Coulomb**
- **CMB**
- **New Limit**
- **CROWS**

*Grassellino- First results of DarkSRF*
First measurements in quantum regime

- Exclusion of dark photons floating around in the galaxy at one specific frequency
- Could extend experiment by scanning

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

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

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’Aguolo
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
Extending DarkSRF to axions searches

**Emmitter Cavity**

Excite *two* modes, with a non-zero (oscillating) \( E_1 \cdot B_2 \)

or

search for cosmic DM.

**Receiver Cavity**

an axion field is radiated at \( (f_1 \pm f_2) \).

Several possibilities to explore:

- One excited and one quiet mode.
- Inserting a region of static B field.
- .... R&D is required

- **Harnik, Romanenko, Grassellino, PAC 2018 DarkSRF presentation, Fermilab**
- Rajendran et al: Suggestion for light-shining-through-wall axion search using a quiet receiver cavity and a static B-field adjacent to the cavity.
SRF Cavities for Axion Searches in Tesla fields?

- FNAL SRF group has an active research program in Nb₃Sn and other new materials
- World record Nb₃Sn cavities in the range 650MHz - 4 GHz with Q ranging from $1e9$ to $1e11$
- Will now test them in Tesla fields
- Nb₃Sn is excellent candidate – $H_{c2} \sim 30$ T and we know how to make high quality films
- Optimize geometry for parallel fields to minimize Lorentz force ($F \sim IxB$)
- Several other new materials to be studied with our new CVD/ALD furnace
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