Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

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

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Acknowledgements

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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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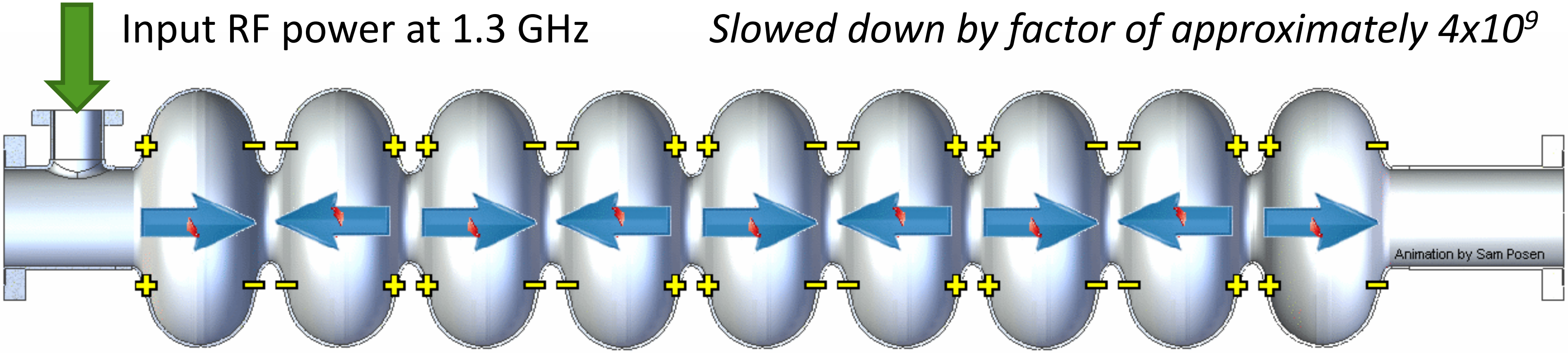
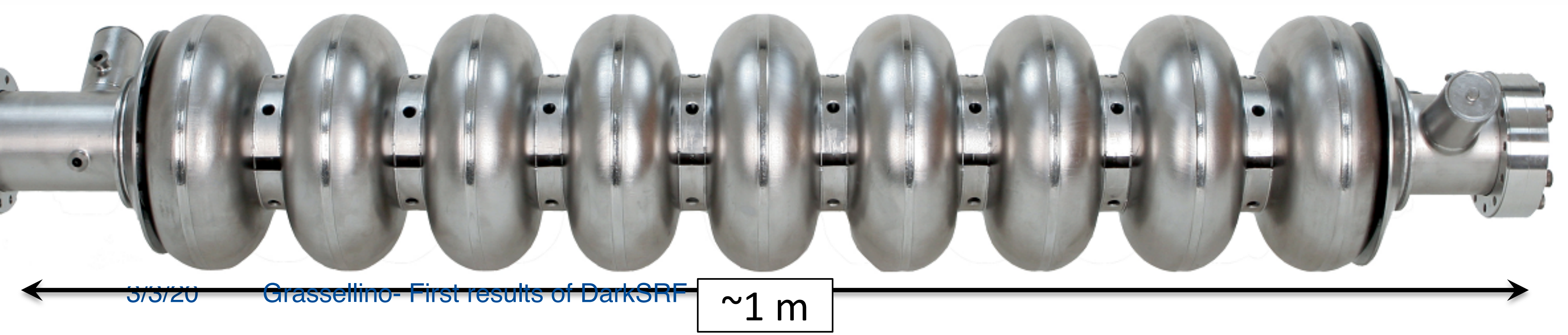
How are Particles Accelerated in Modern Machines?

- **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

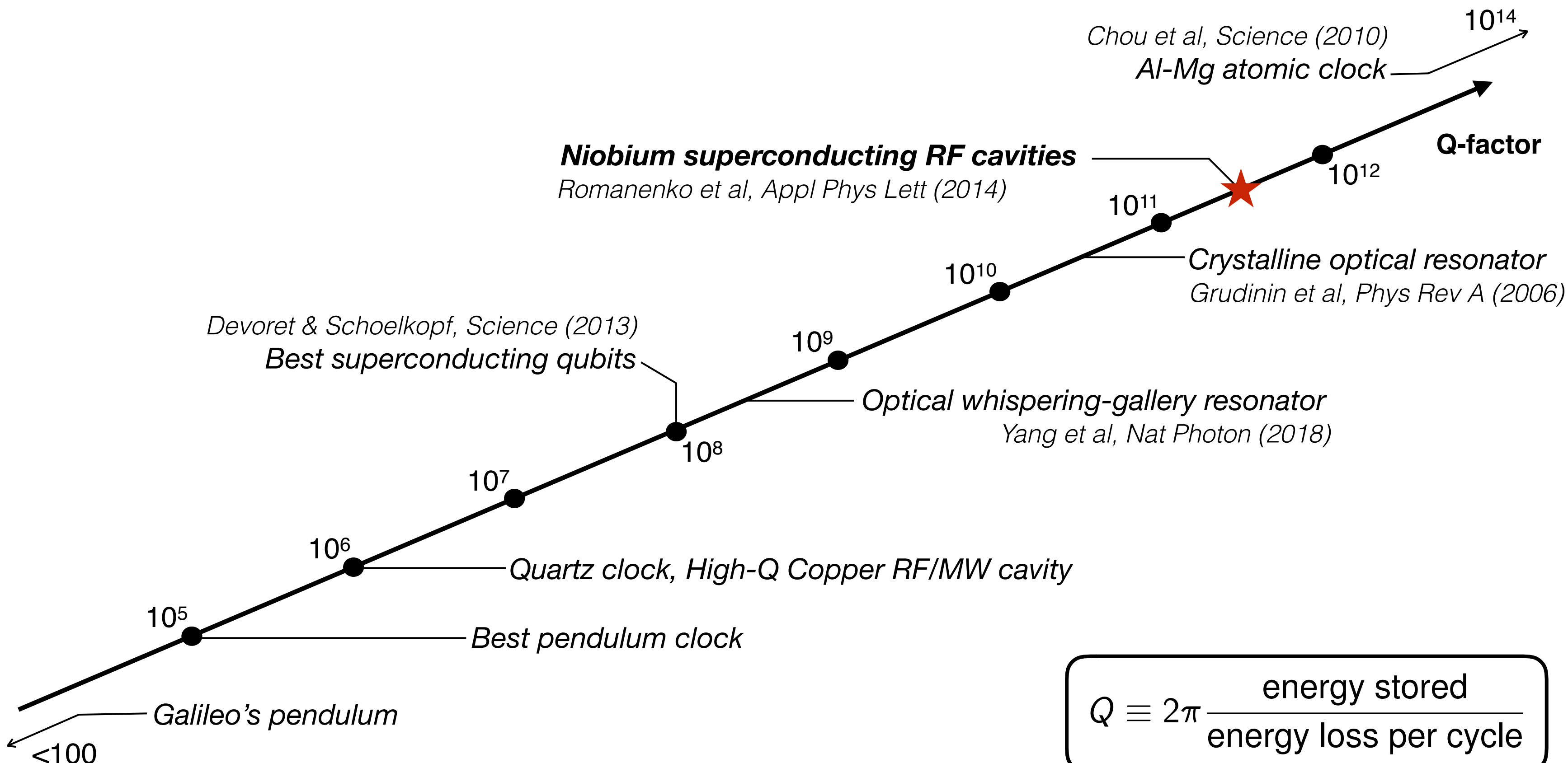
Slowed down by factor of approximately $4x10^9$





Why SRF cavities for quantum sensing?

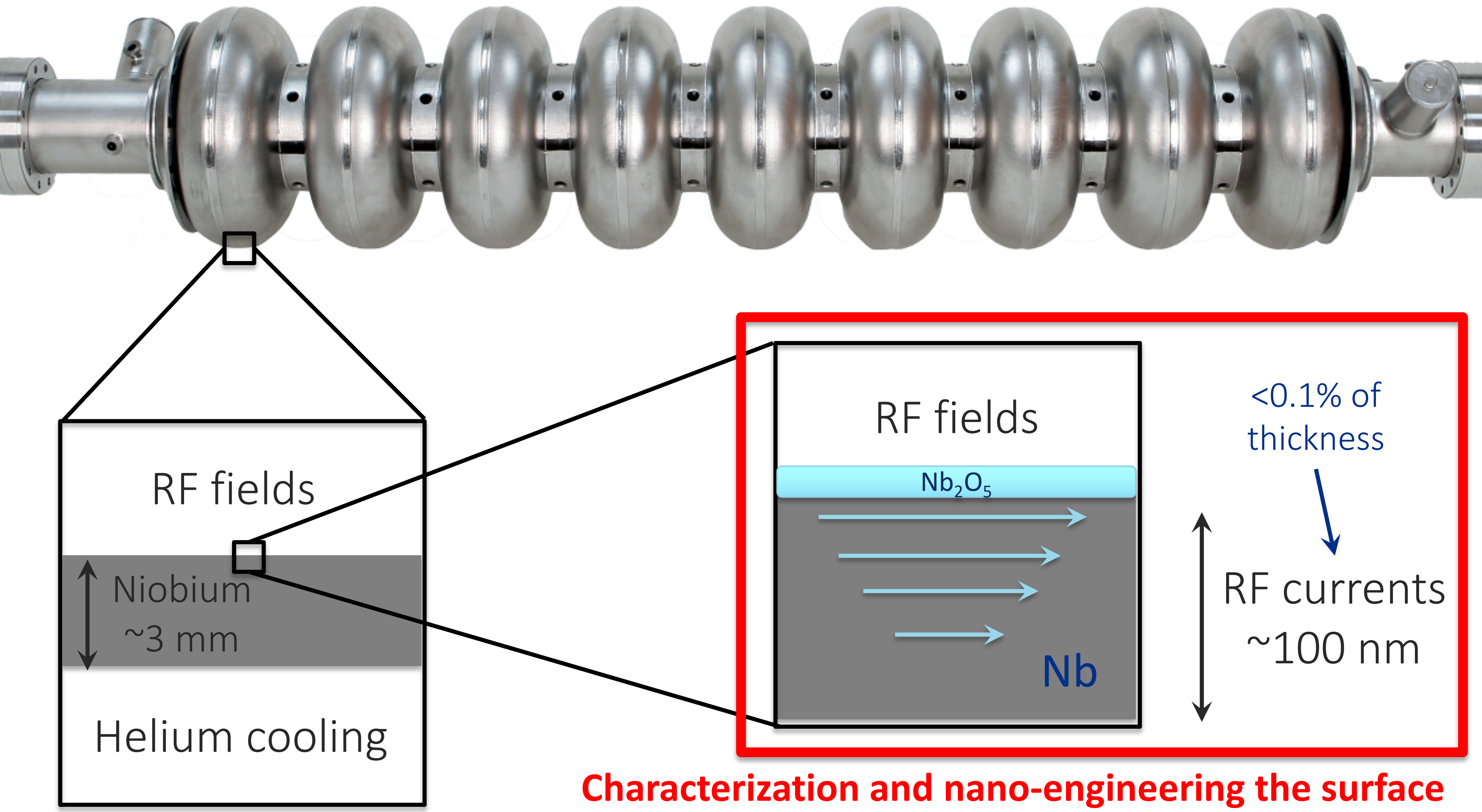
SRF cavities are the most efficient engineered oscillators



$$Q \equiv 2\pi \frac{\text{energy stored}}{\text{energy loss per cycle}}$$

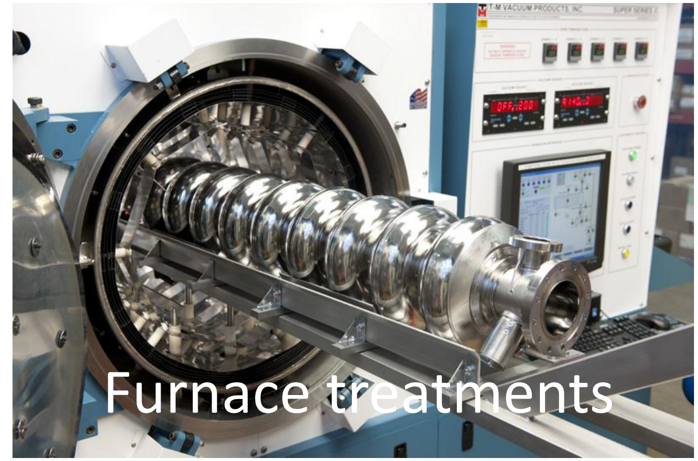
X

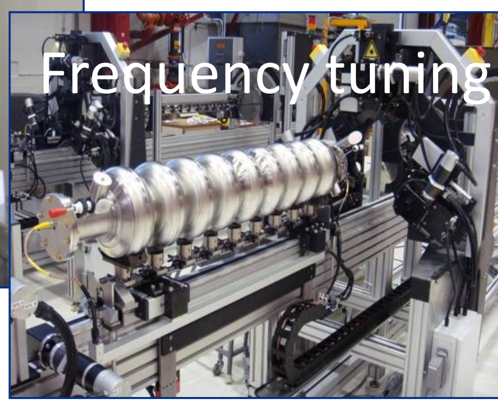
Nanometric RF Penetration Layer drives the performance



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

Major SRF infrastructure and expertise at Fermilab, enabling highest Q ever achieved, in low and high photon count regimes





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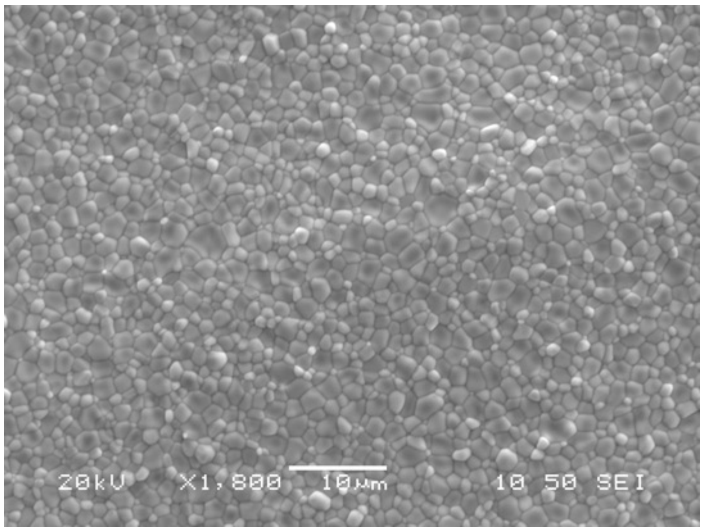
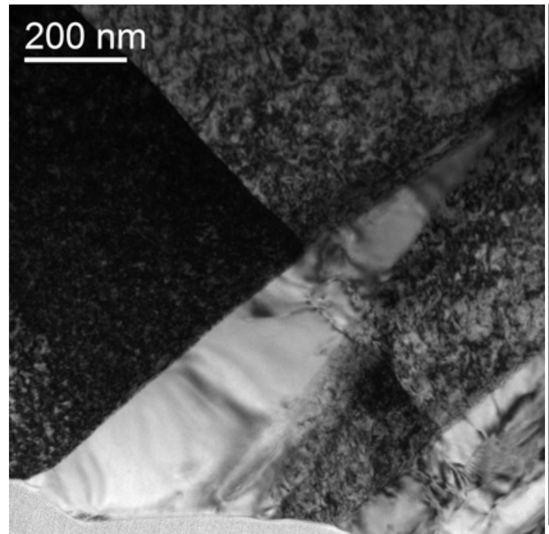
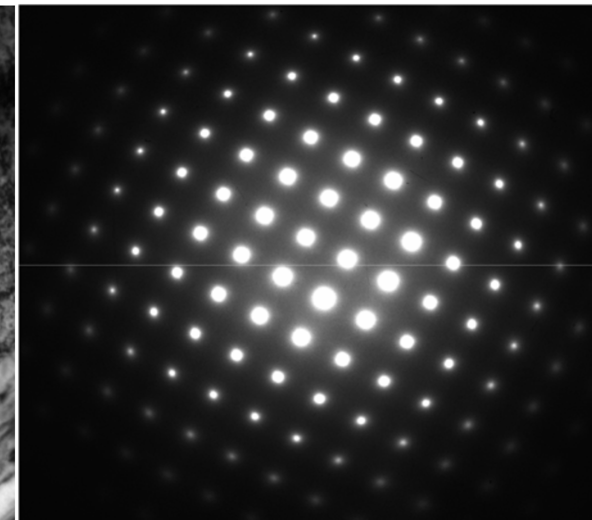
Material science and superconducting characterization

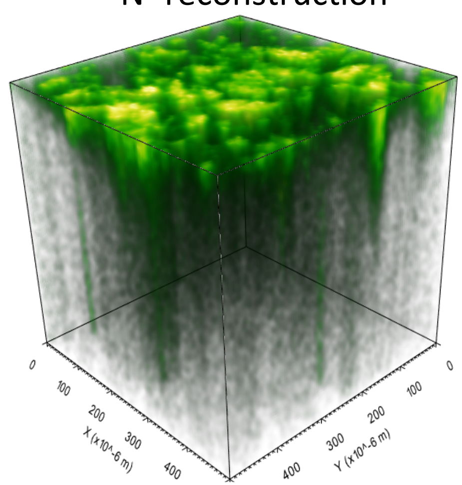
- Cavity surface undergoes a series of delicate chemical and heat treatments
- Material science tools are <u>essential</u> to understand the surface nanostructural changes that lead to dramatic changes in performance

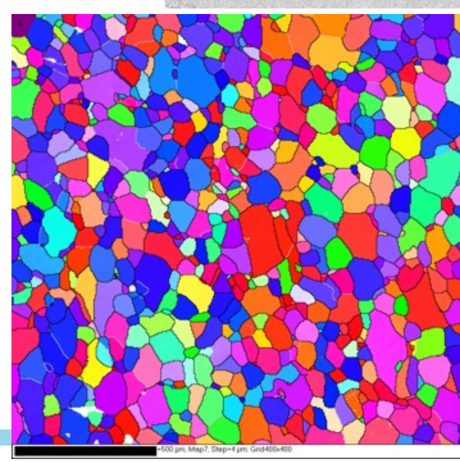




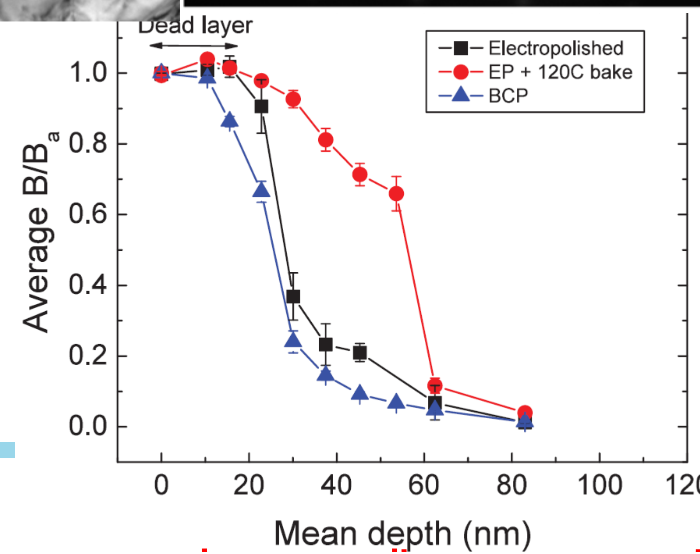


N- reconstruction





First results of DarkSRF



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

$Q > 2.7 \times 10^{10}$ @ 2K, 16 MV/m

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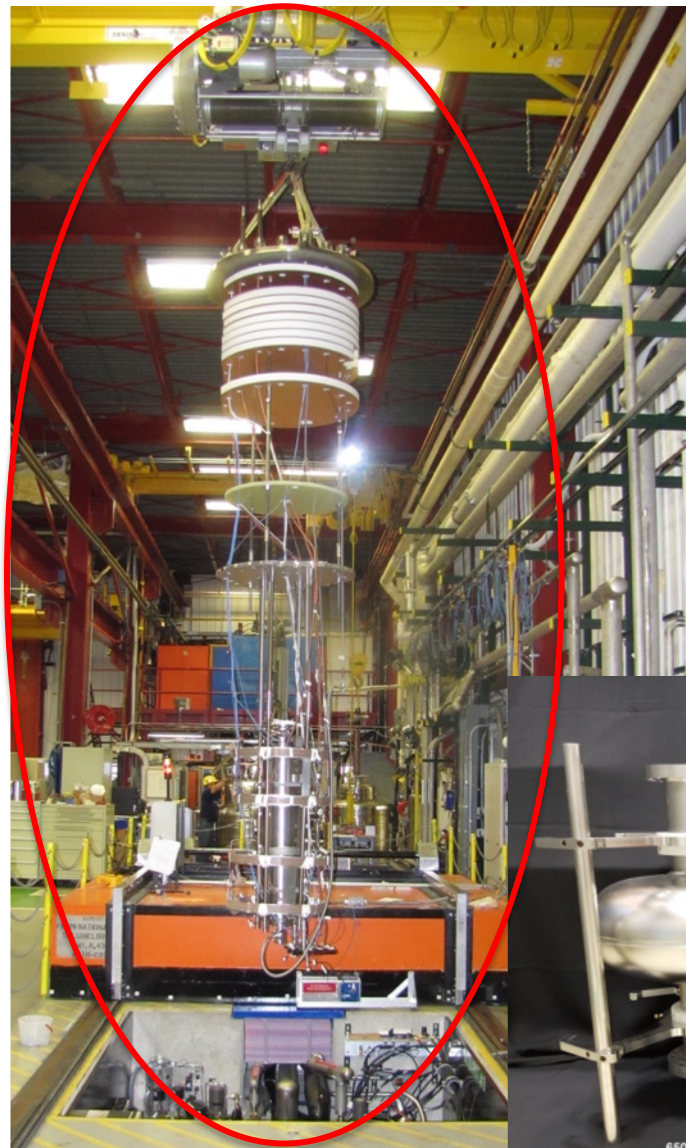
Taking SRF cavities “towards” the quantum regime



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

T= 1.4K

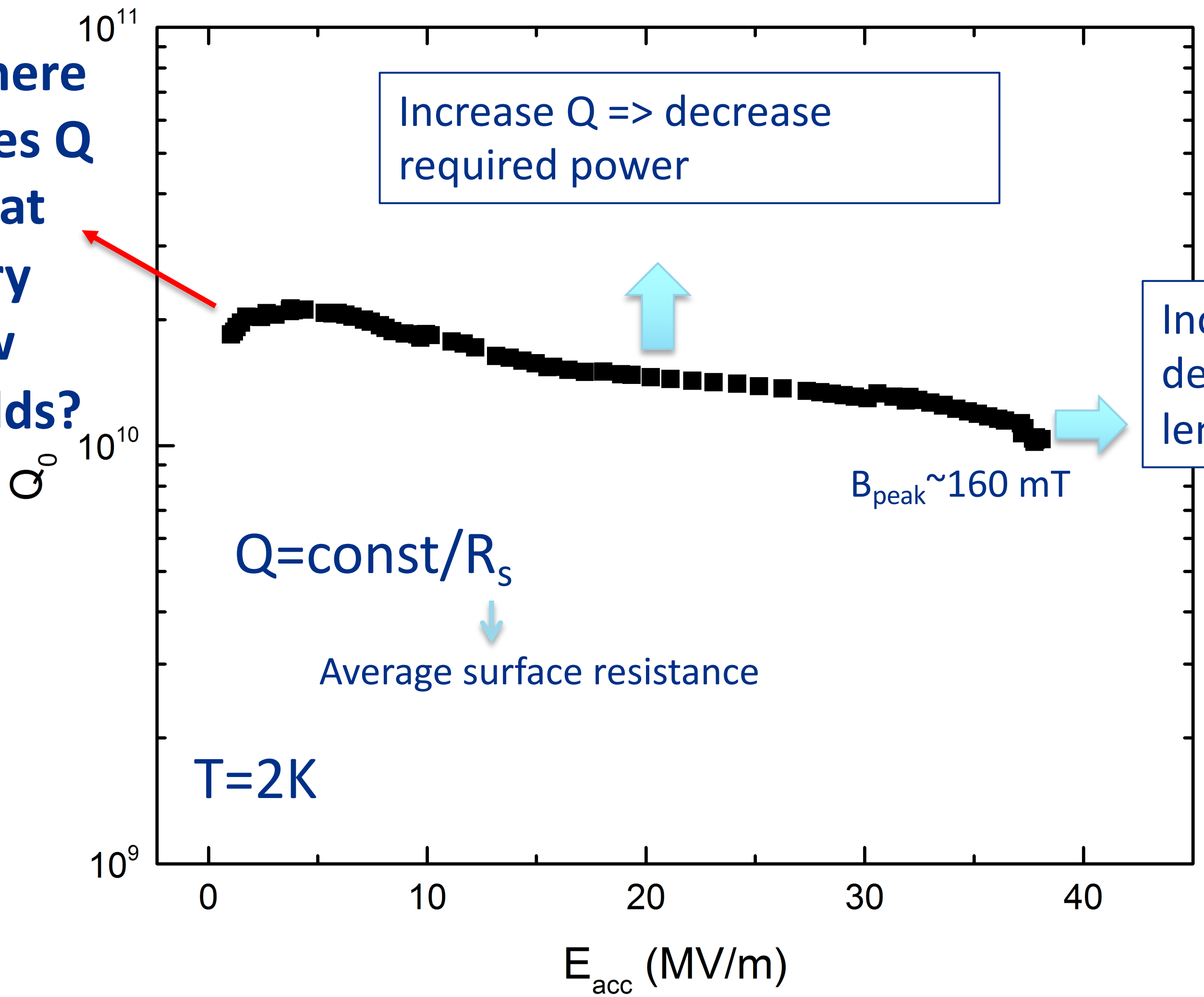
~1000 photons

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

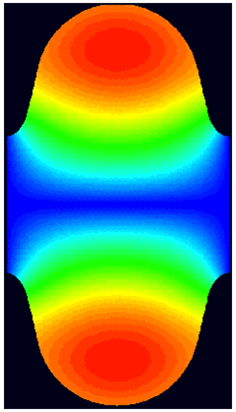
T~6mK

RF Surface resistance is highly nonlinear

Where does Q go at very low fields?

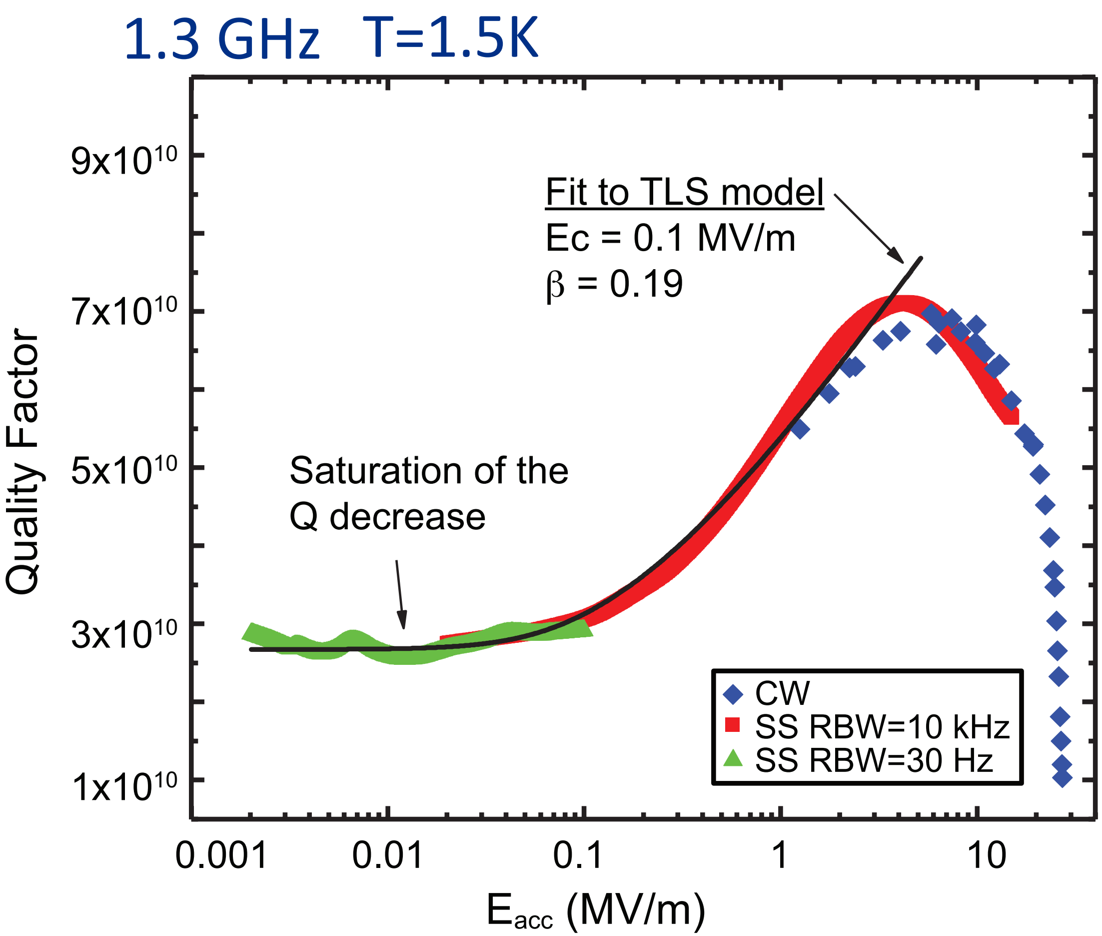


Increase max E_{acc} => decrease accelerator length



Surface magnetic field B

First experiment: extend the measured fields to record low

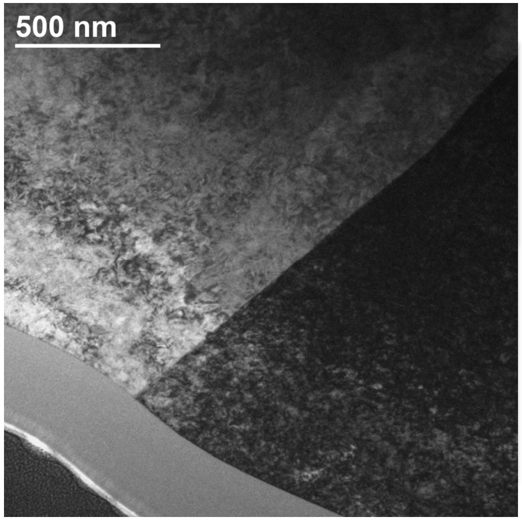


Good news: low field Q saturates at Q>**3 x 10^{10}**

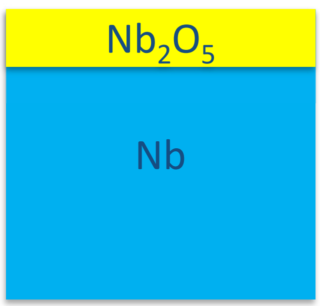
Now measured down to
<N> < 1000 photons

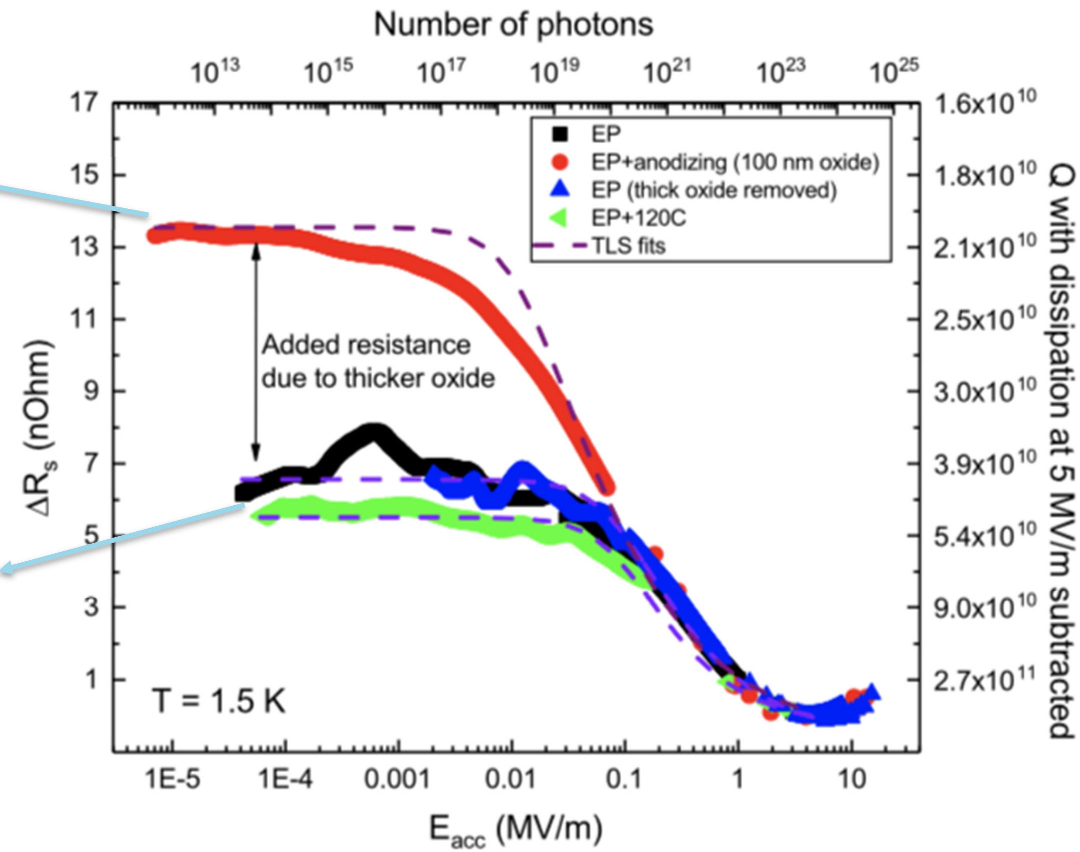
A. Romanenko and D. I. Schuster,
Phys . Rev. Lett. **119**, 264801 (2017)

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



5 nm





A. Romanenko and D. I. Schuster, Phys . Rev. Lett. **119**, 264801 (2017)

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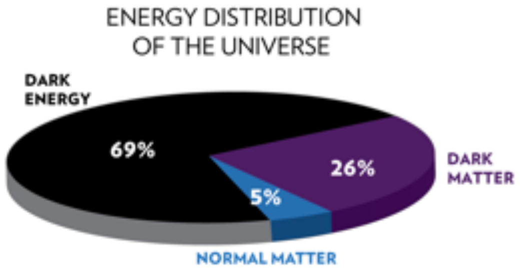
Longer Range Interactions and Wave-like Dark Matter

- 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?

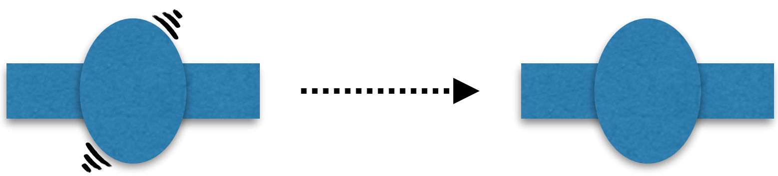
Dark matter (and new particle):

$\supset$ dark photons?
axions?

Basic search schemes

Light Shining through wall:

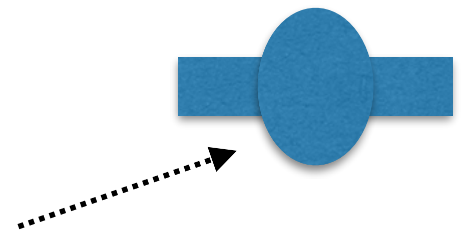
Emitter Receiver



a search for a mediator.

A dark matter search:

Receiver



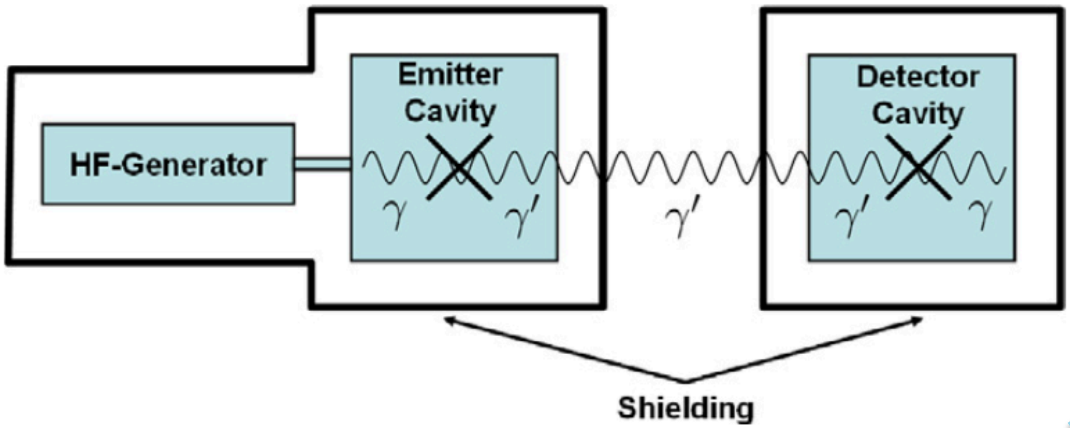
the DM filled Universe
is the emitter

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

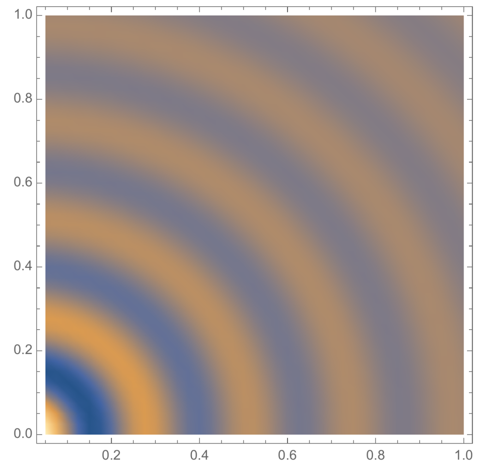
Looking for hidden paraphotons



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

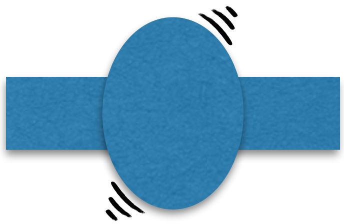
Q_{DET}, Q_{EM} > 10^{10} SRF can offer several orders of magnitude improvement in sensitivity to χ

Dark Photon Search



a dark photon field is radiated at 1.3 GHz.

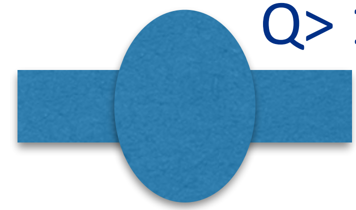
Q> 1e9



Emitter Cavity

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

Q> 1e10

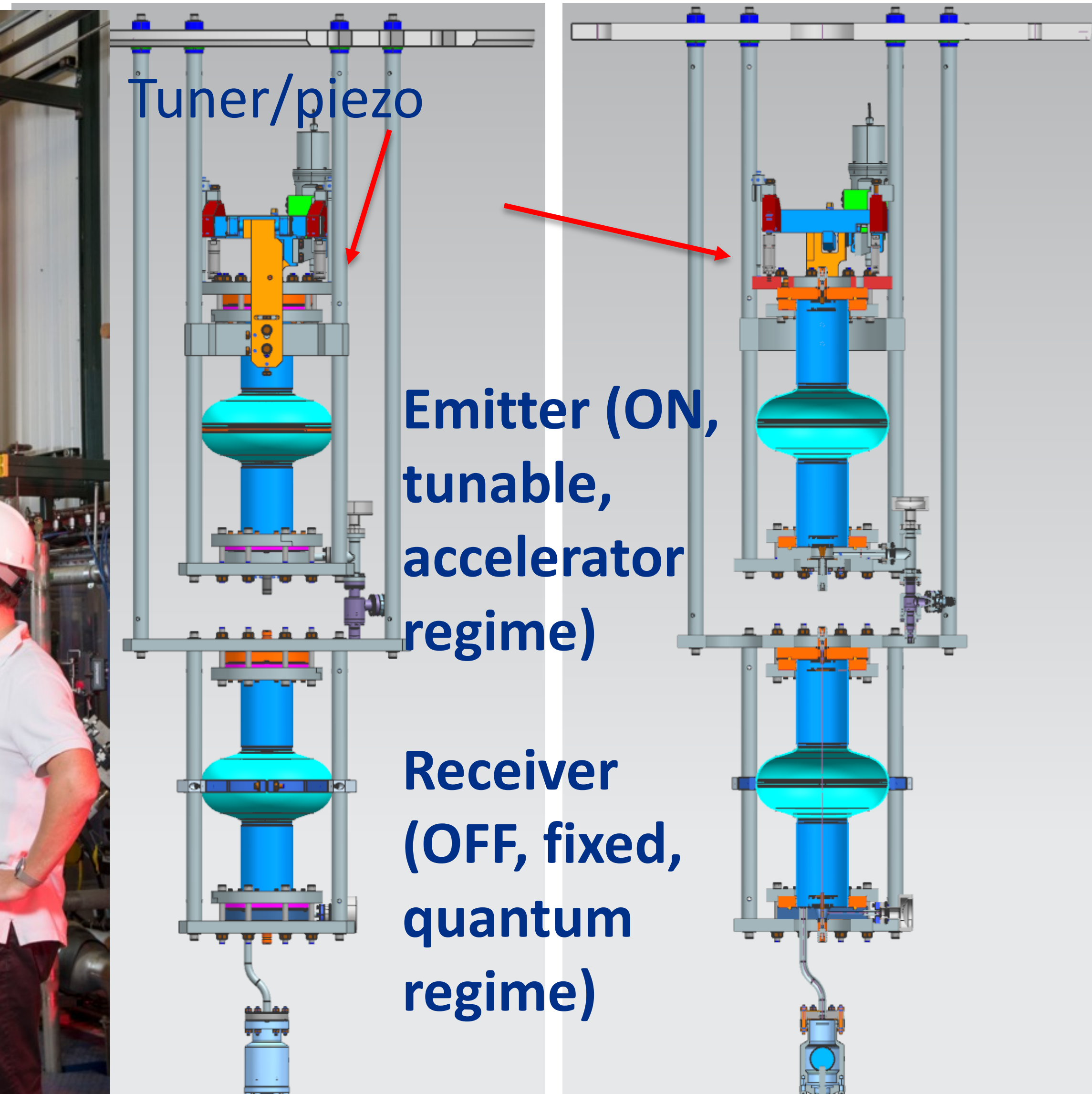


Receiver Cavity

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

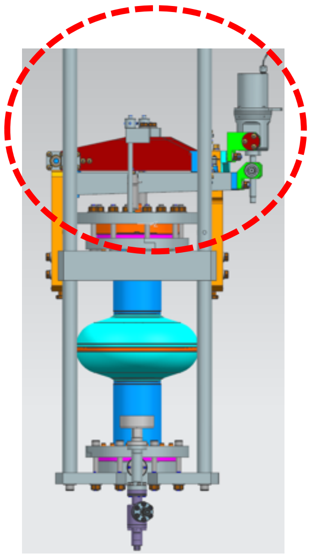
For correct cavity positioning $P_{\text{rec}} \sim G^2\,\epsilon^4 \left(\frac{m_{\gamma'}}{\omega}\right)^4 Q_{\text{rec}} Q_{\text{em}} P_{\text{em}}$

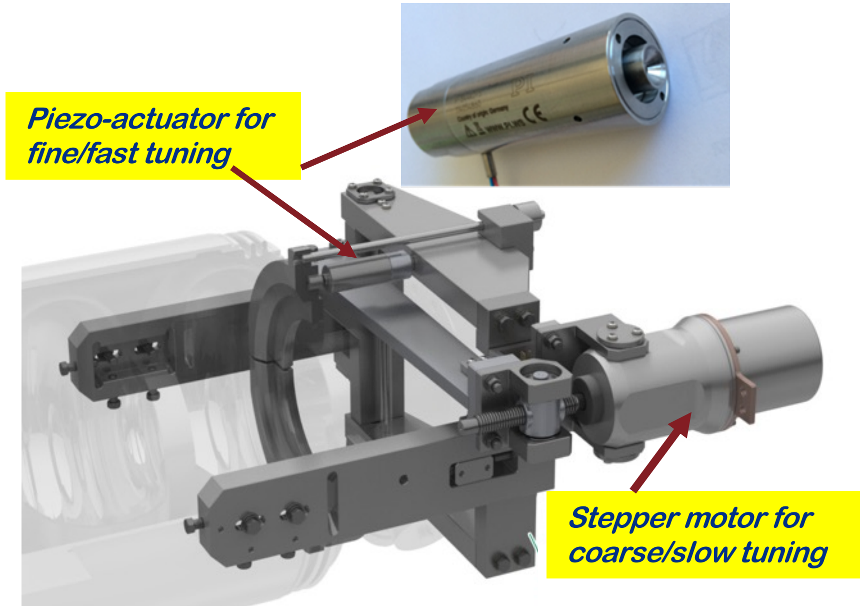
DarkSRF experiment



Controlling cavity frequency with sub-Hz resolution

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





Coarse Tuner

- Range up to ΔX=2mm or ΔF=5MHz
- Resolution δx=5nm or δF=12Hz
- Hysteresis ~ 300Hz

Fine/Fast Tuner

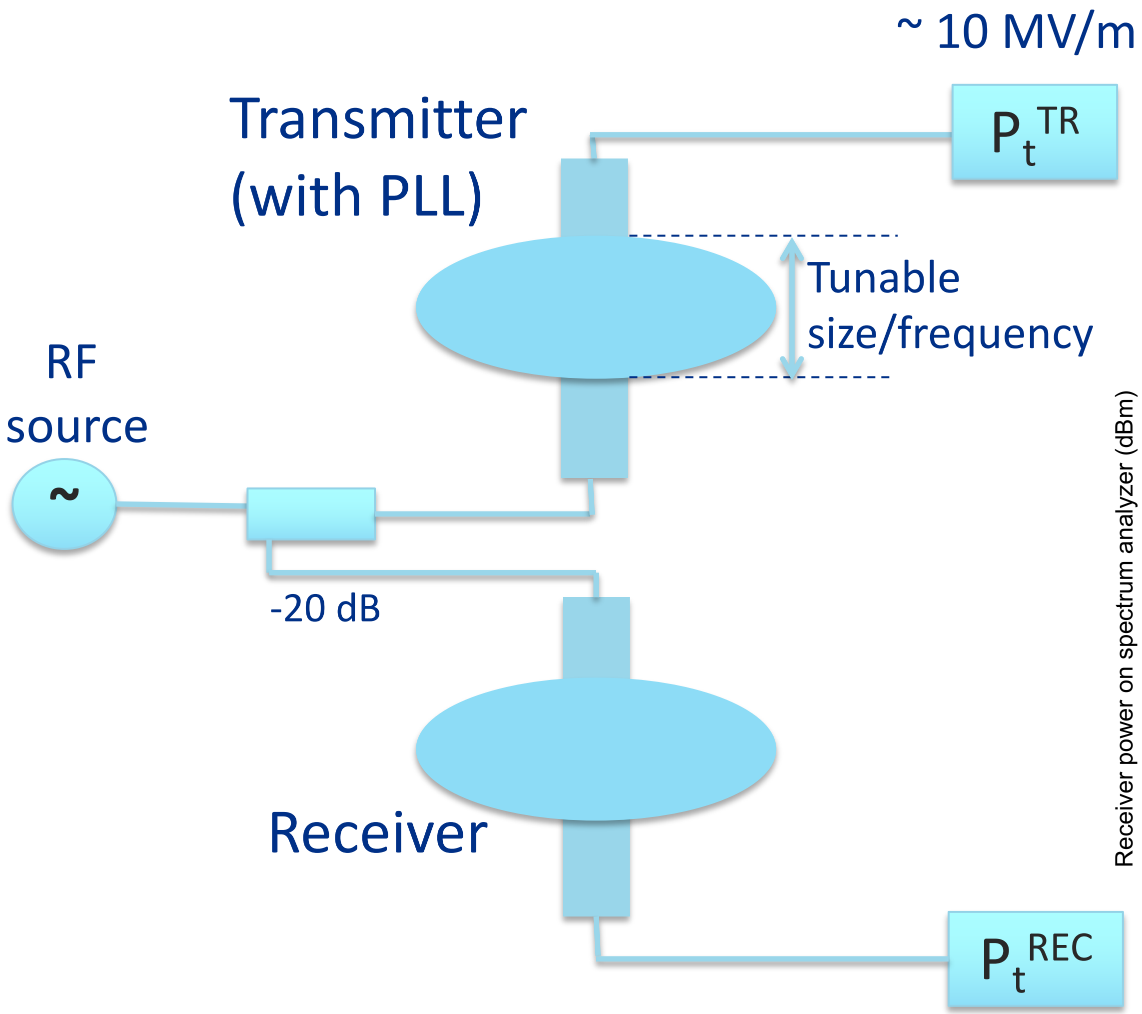
- Range up to ΔX=3um or ΔF=8kHz
- Resolution δx=0.05nm or δF=0.1Hz (*)

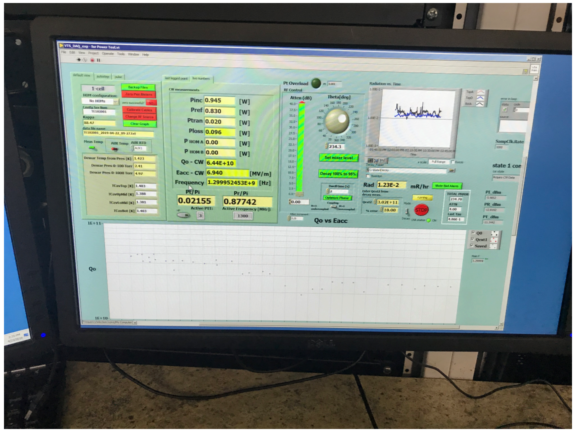
(resolution will be limited by electrical noise of the piezo amplifier)

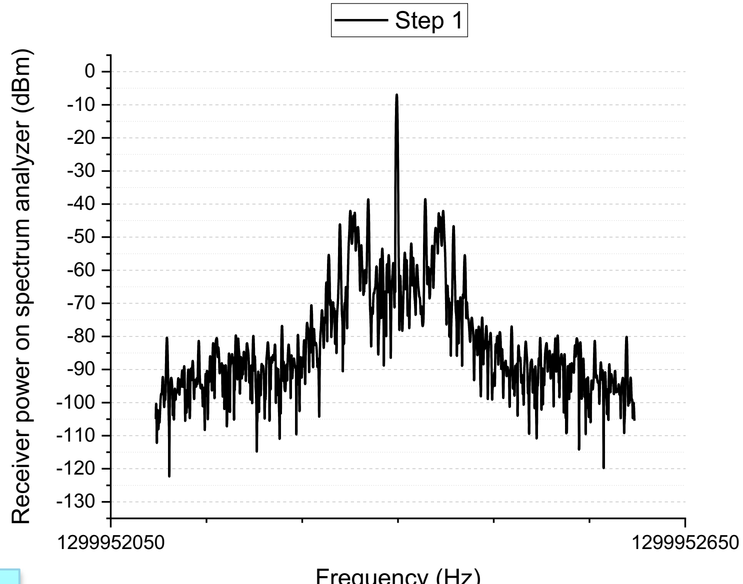
(*) Piezo tuner resolution measured with LCLS II cavity ~0.15Hz was limited by noise at HTS

Happy people right before run zero

Cavity frequency matching – Step 1



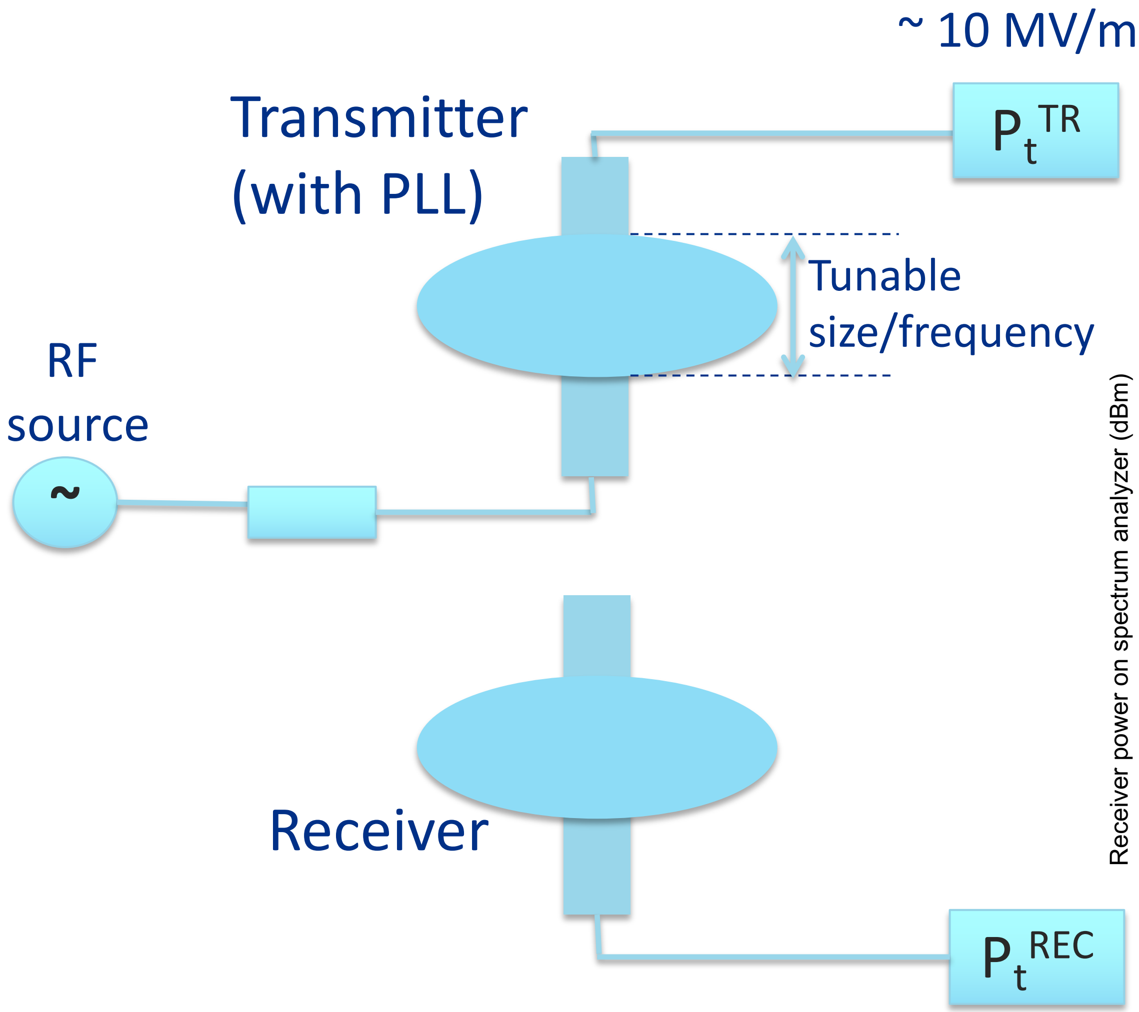


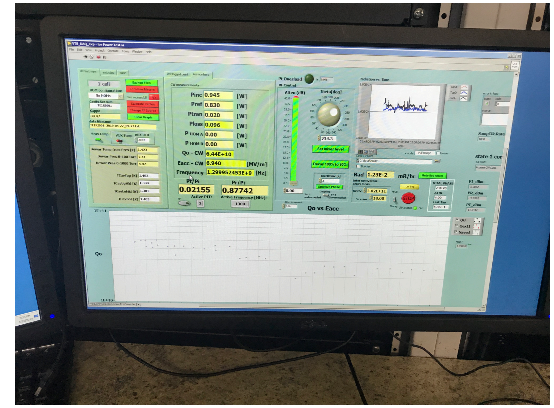


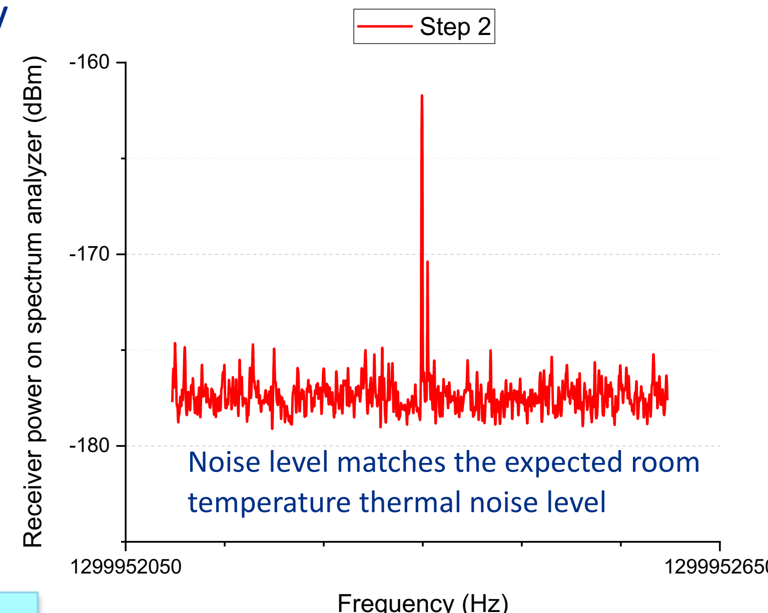
On spectrum analyzer

Fermilab

Dark Photon search! – (Step 2)





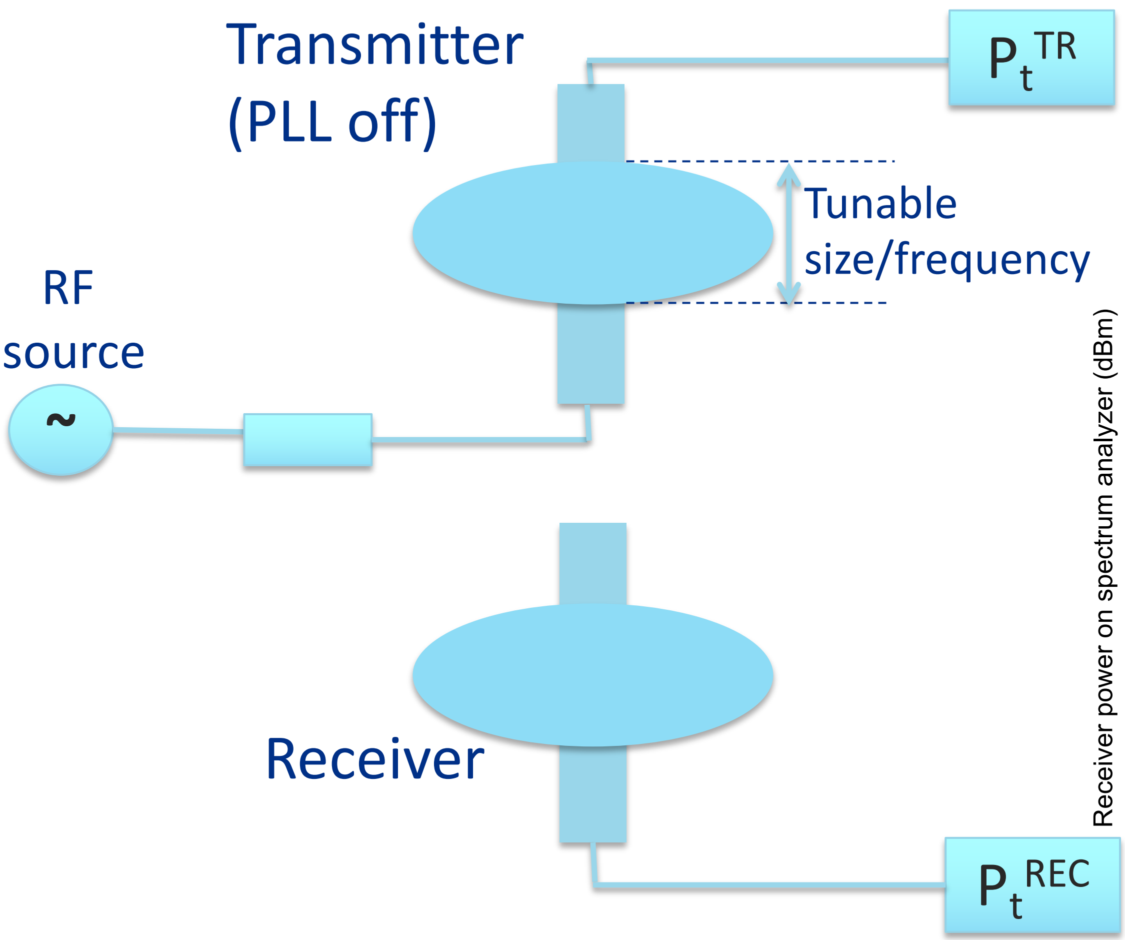


On spectrum analyzer

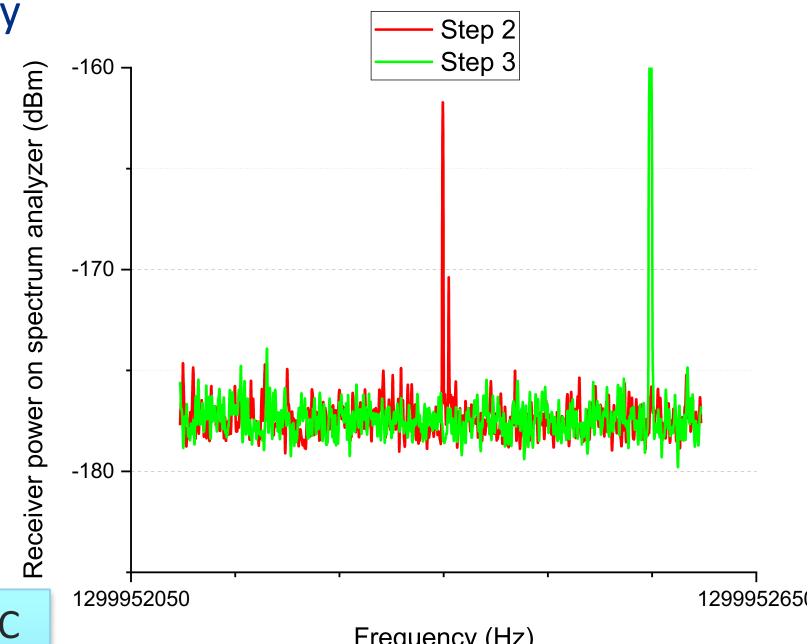
Bandwidth = 1 Hz

Cross-talk check - Step 3

No stored power = no dark photons

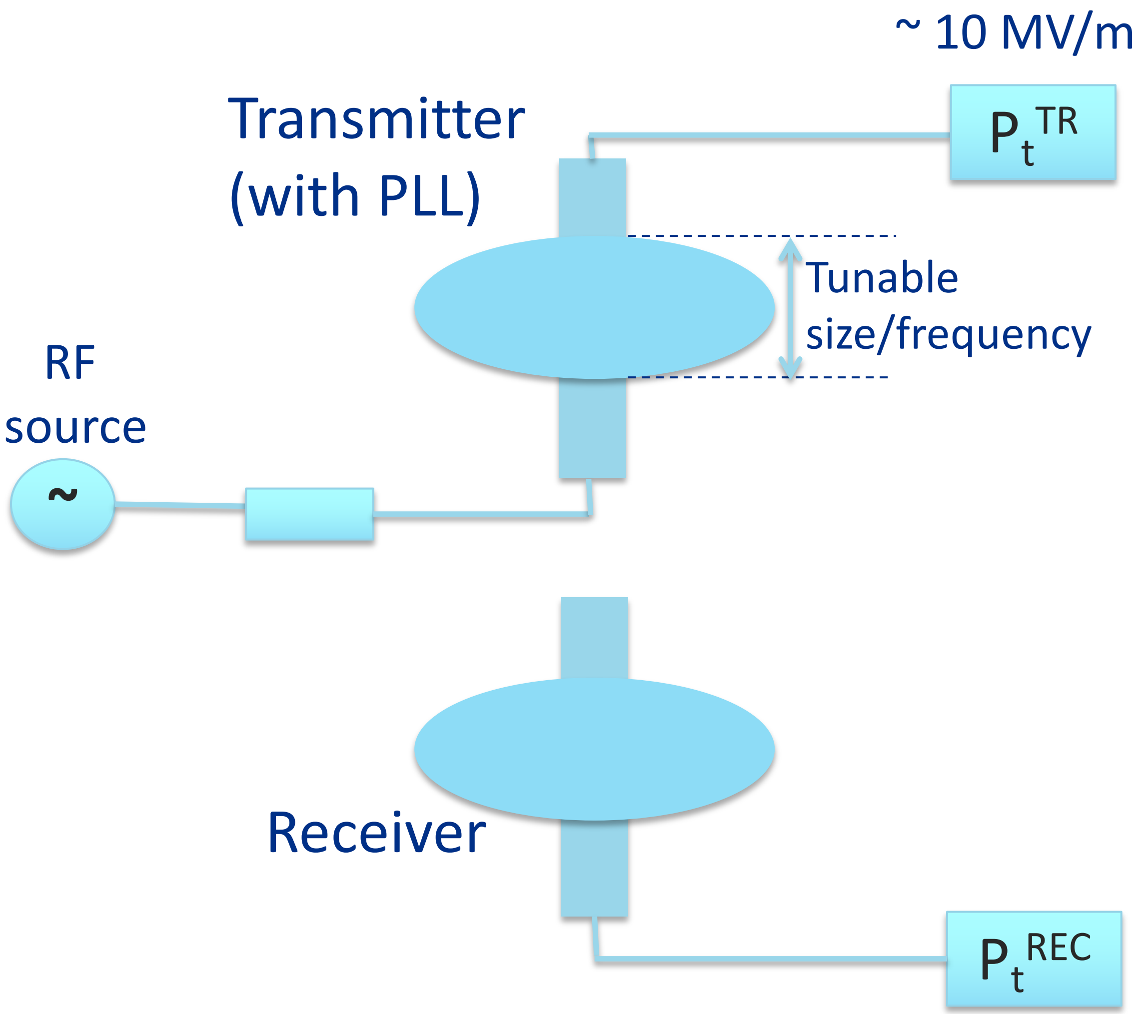


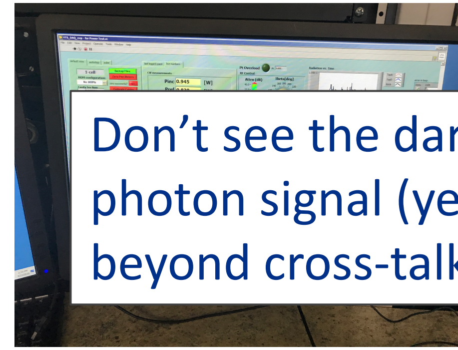
Don’t see the dark photon signal (yet) beyond cross-talk



On spectrum analyzer

Back to dark photon search - Step 4 = Step 2





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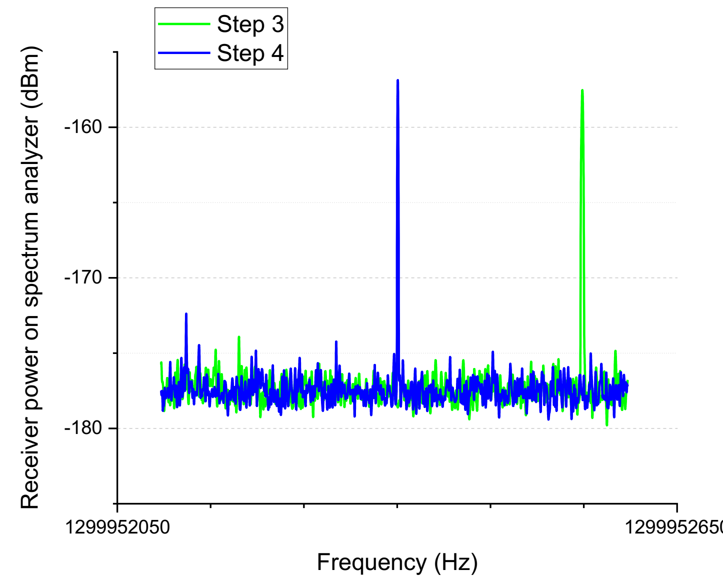
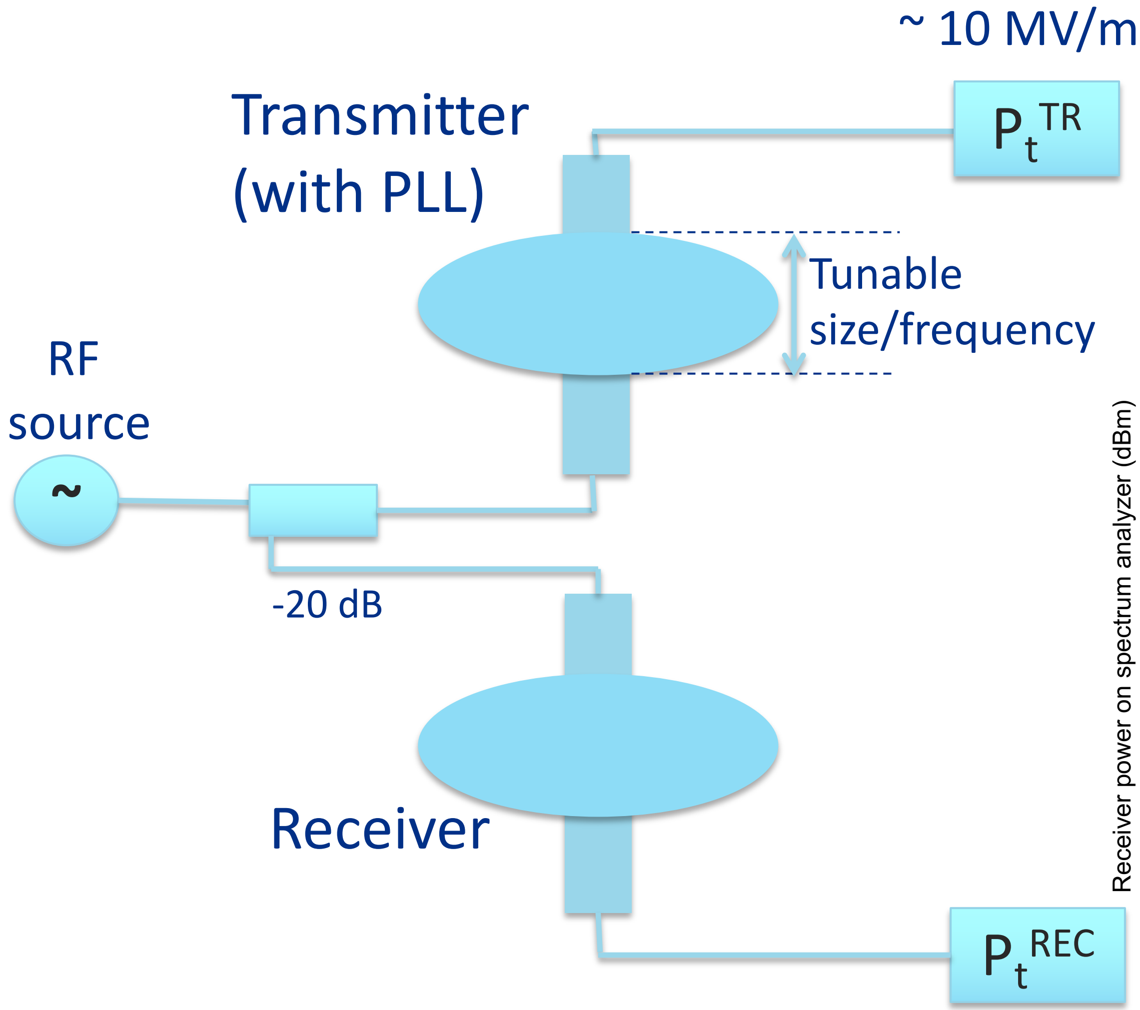
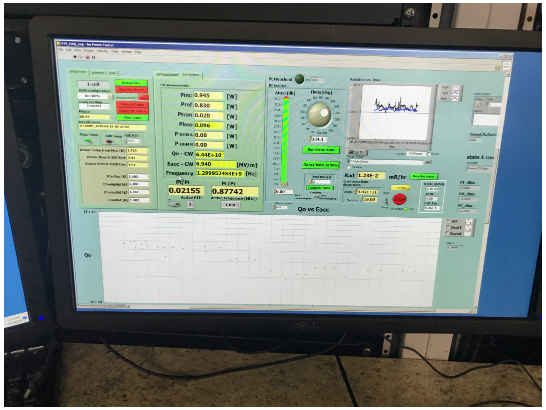
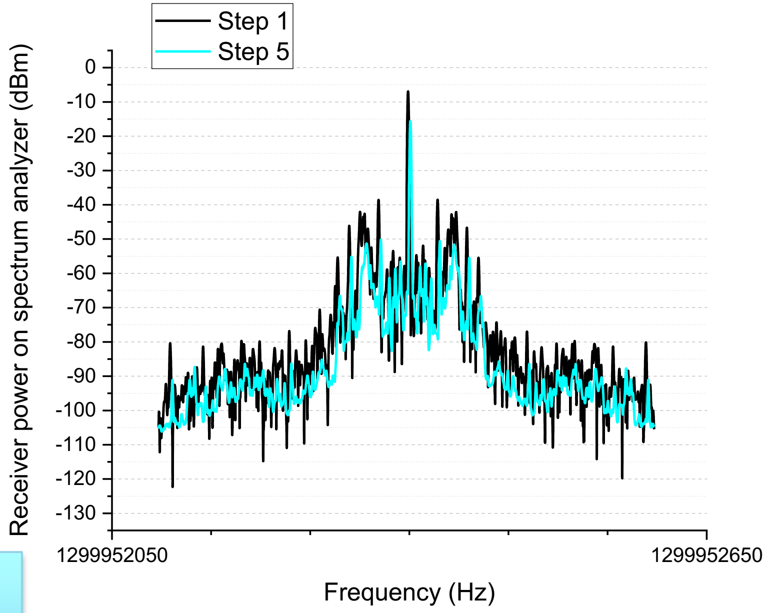


On spectrum analyzer

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





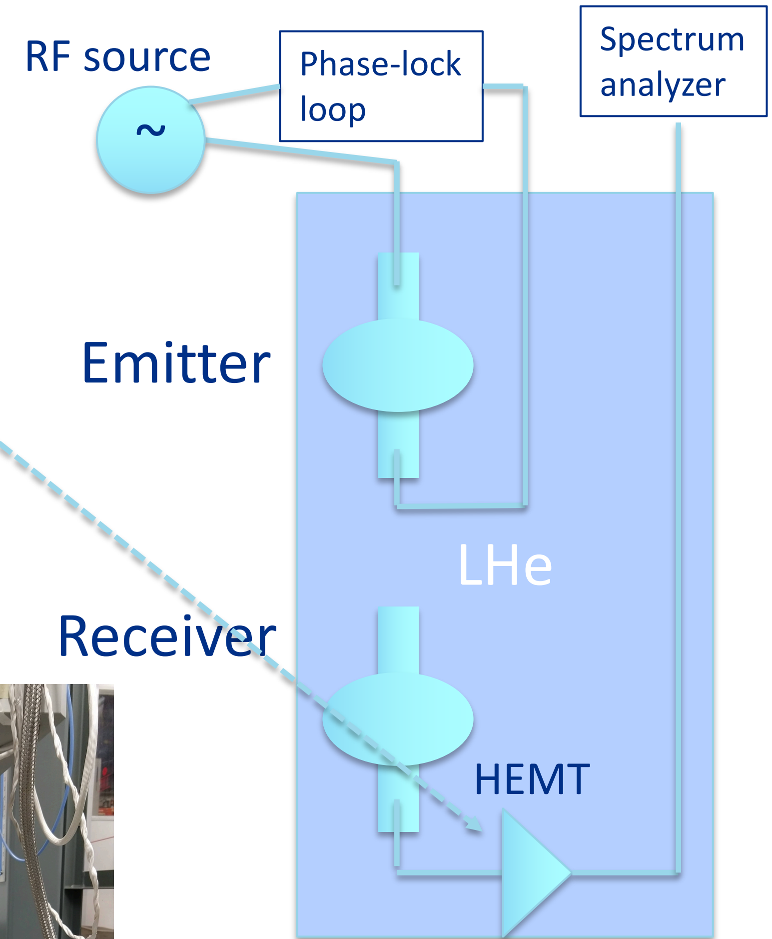


On spectrum analyzer

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

Run 1-2 schematic



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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

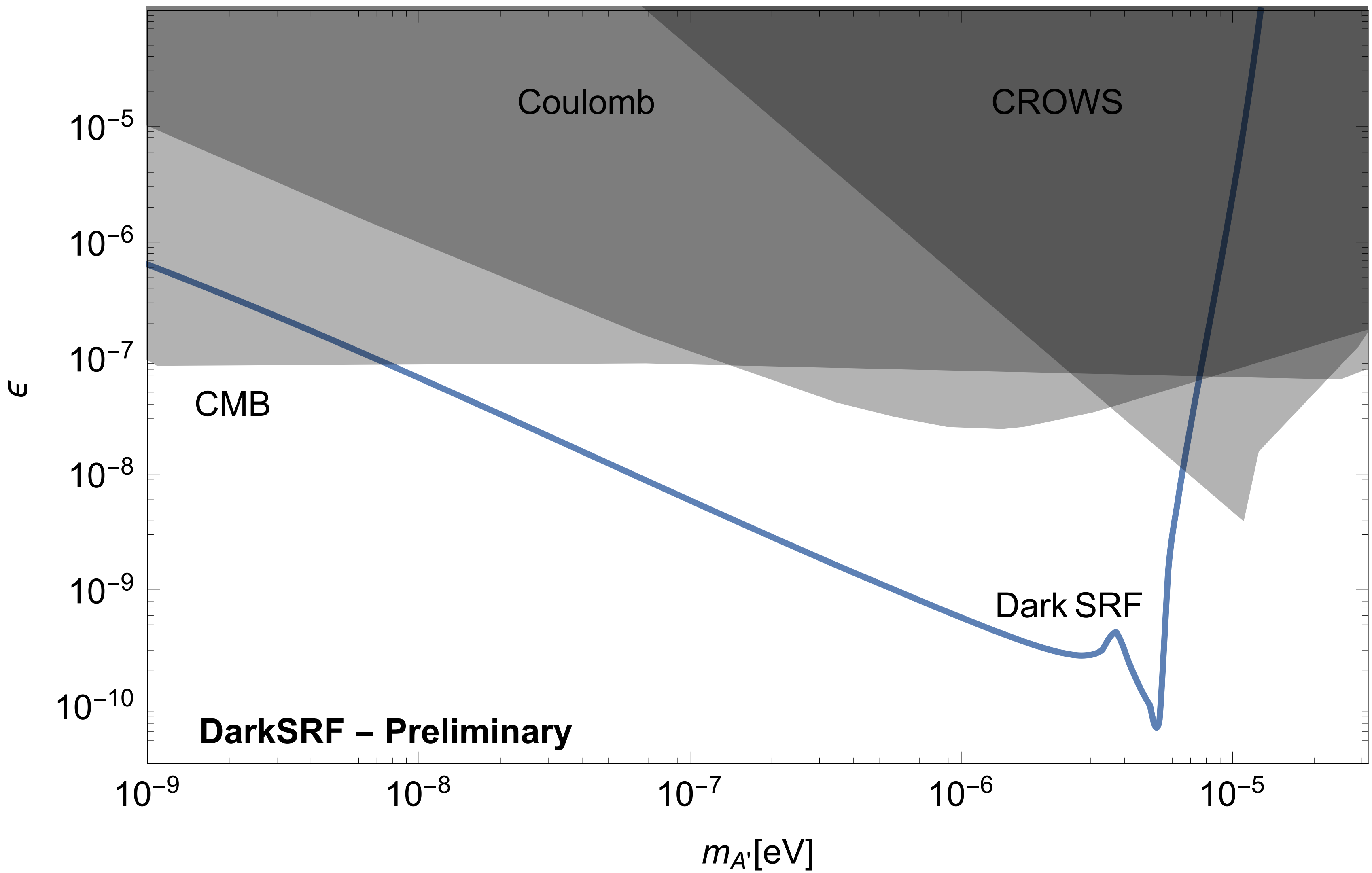
Data acquisition runs – high power

- 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



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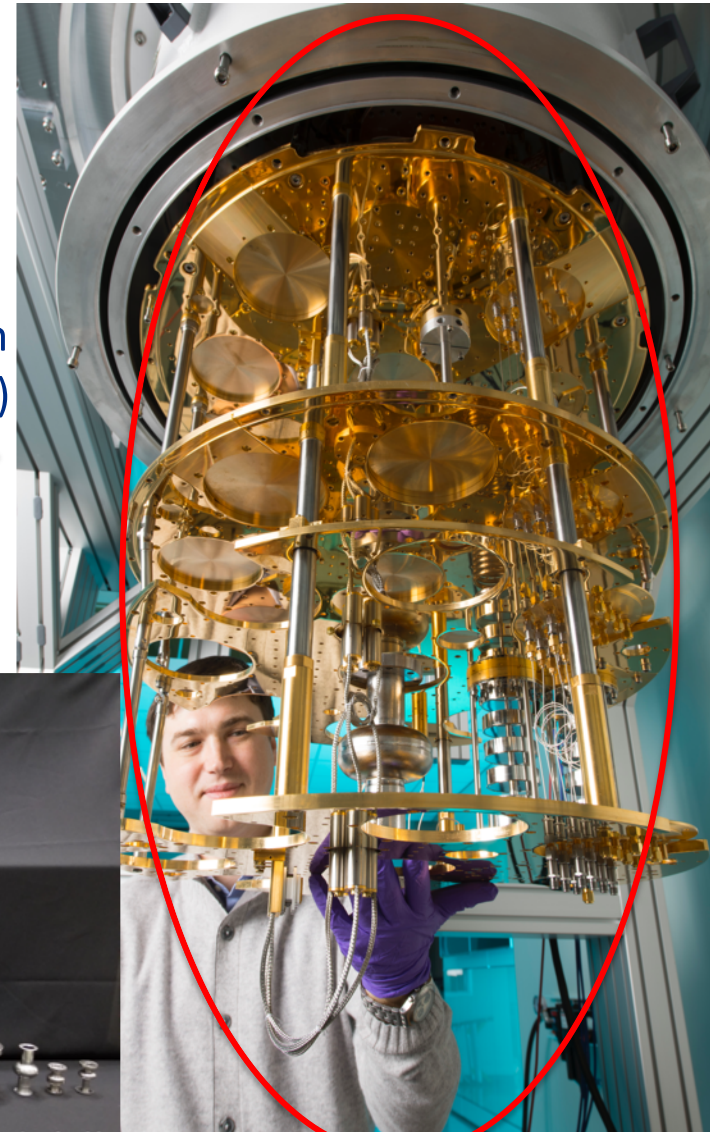
T= 1.4K

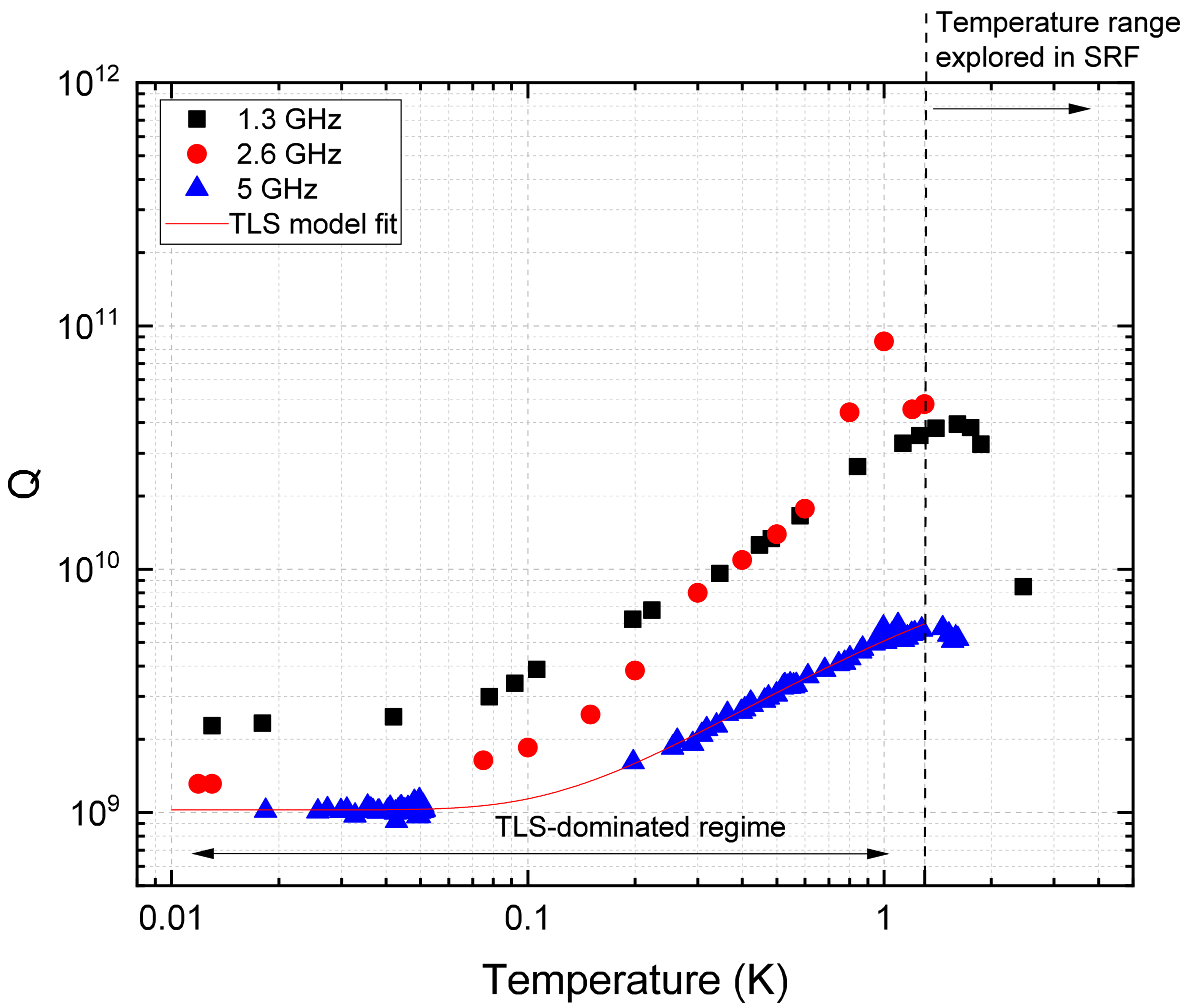
~1000 photons

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

T~6mK

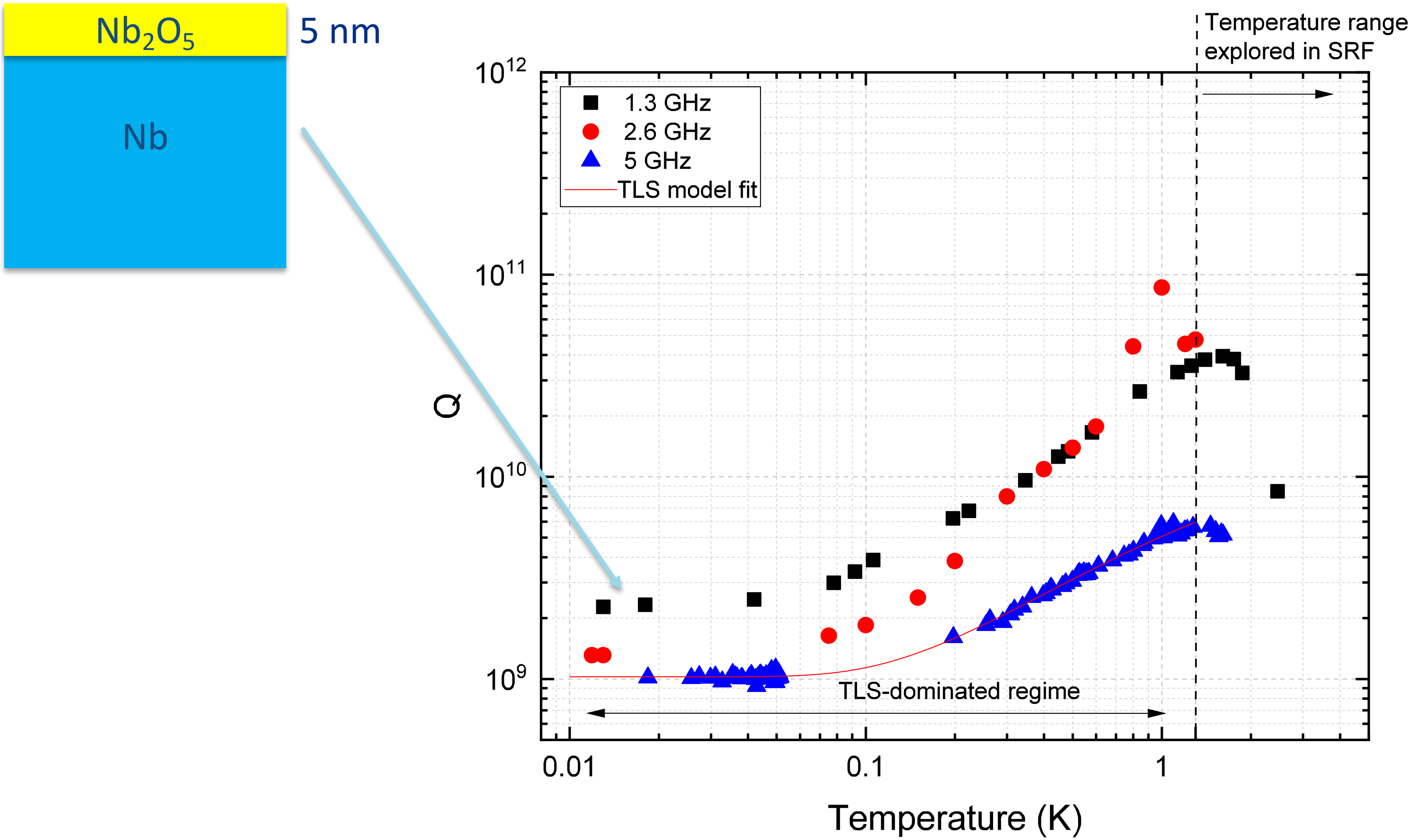


Record high Q in quantum regime at first run



A. Romanenko, R. Pilipenko, S. Zorzetti, D. Frolov, M. Awida, S. Posen, A. Grassellino, arXiv:1810.03703

Material treatment to suppress TLS dissipation



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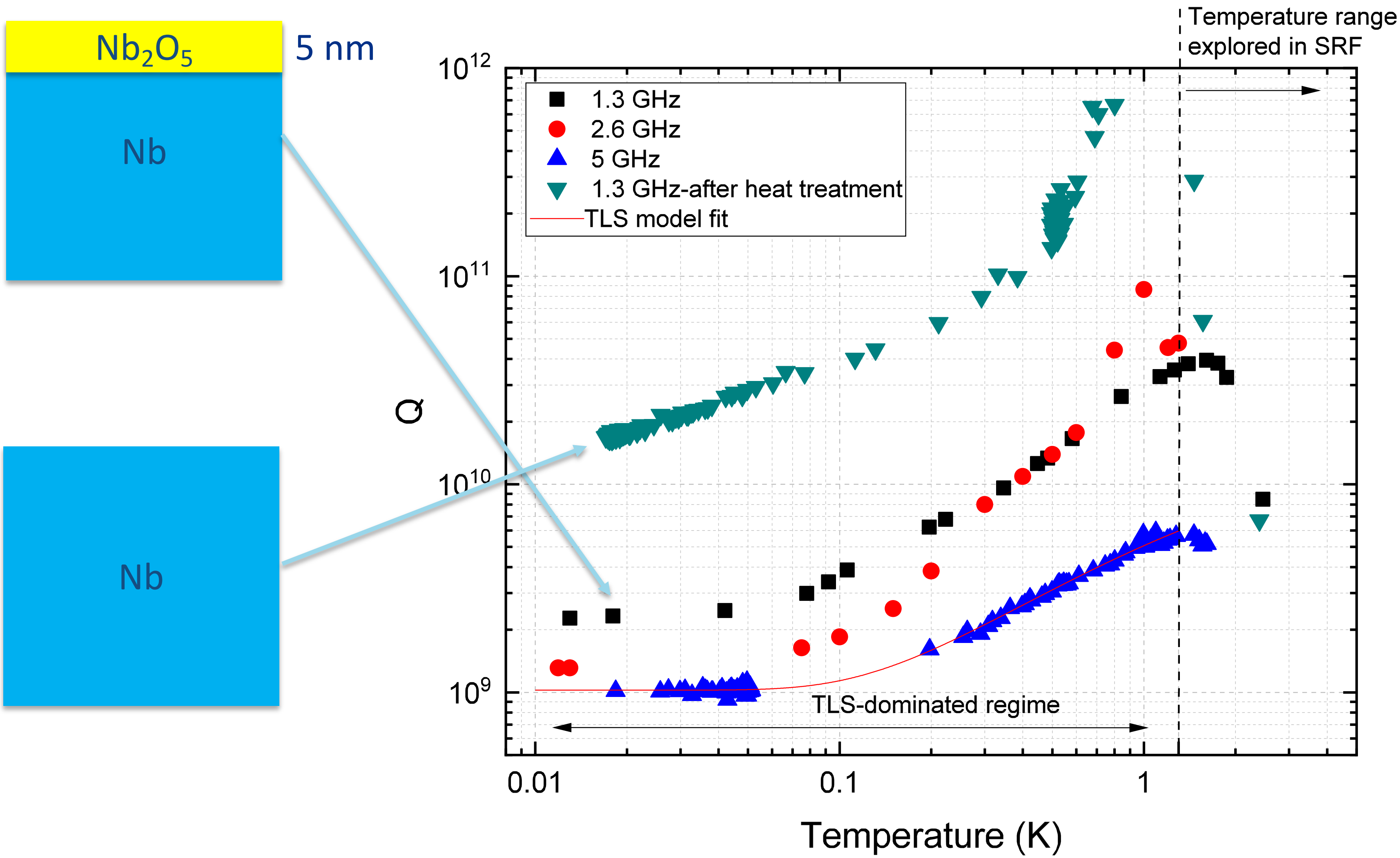
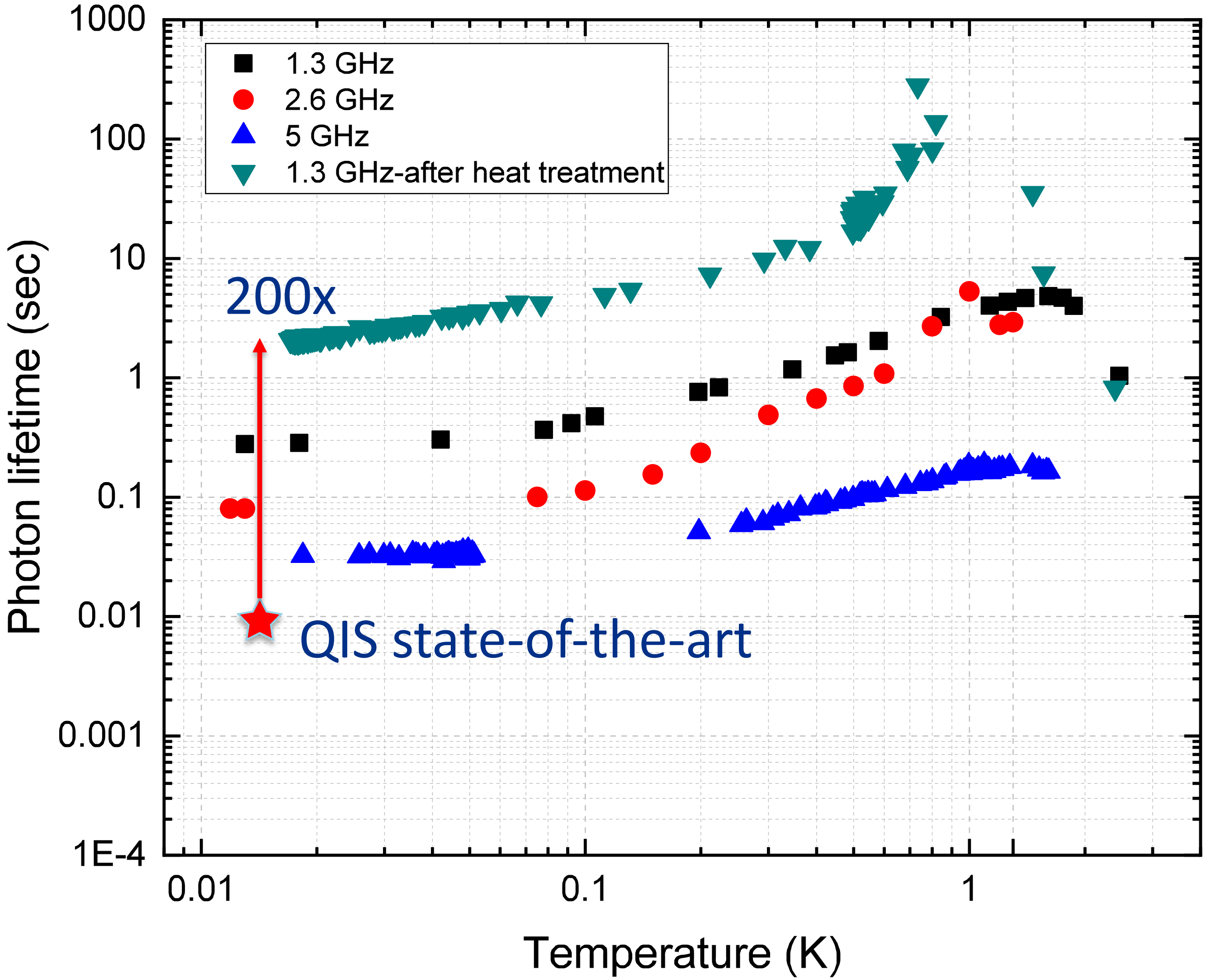


A. Romanenko, R. Pilipenko, S. Zorzetti, D. Frolov, M. Awida, S. Posen, A. Grassellino, arXiv:1810.03703

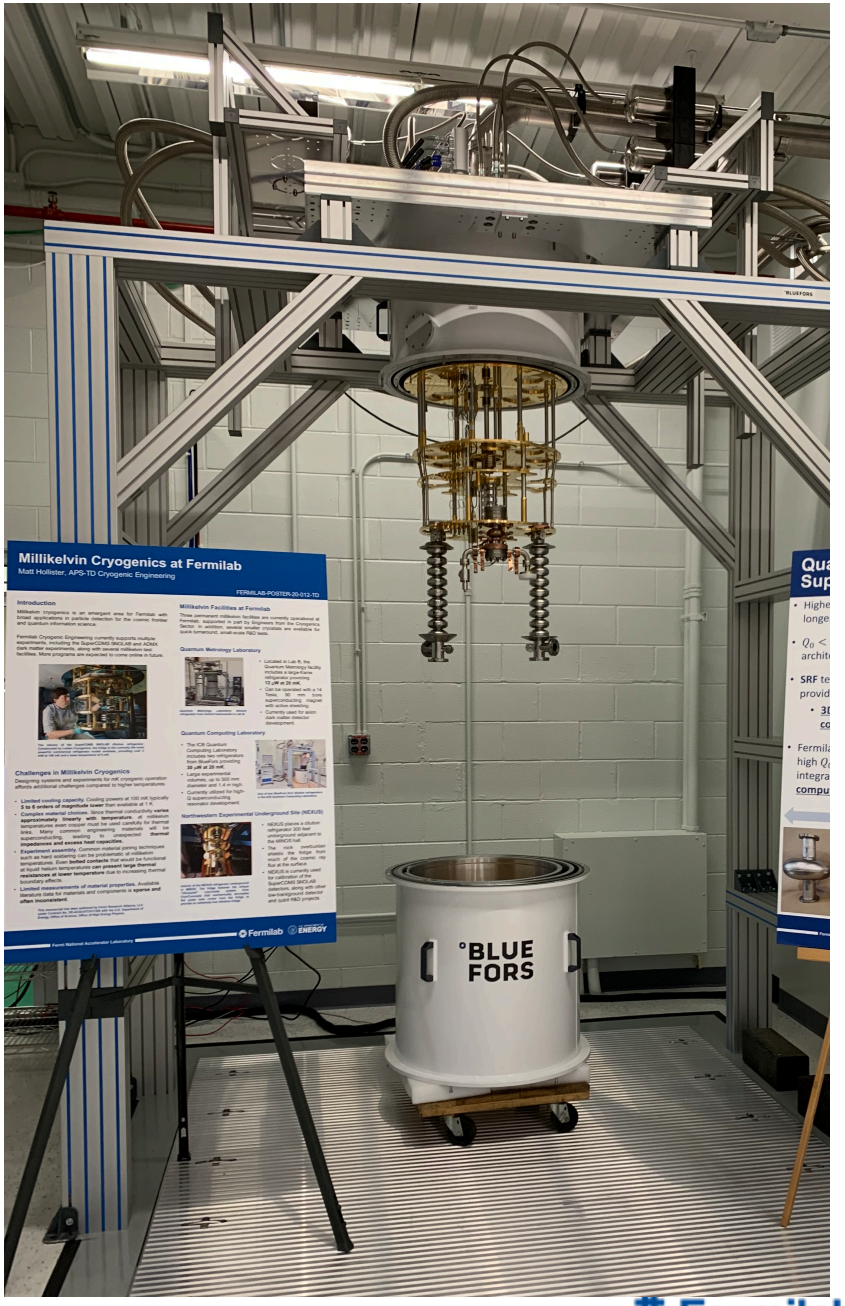
Record high photon lifetimes achieved



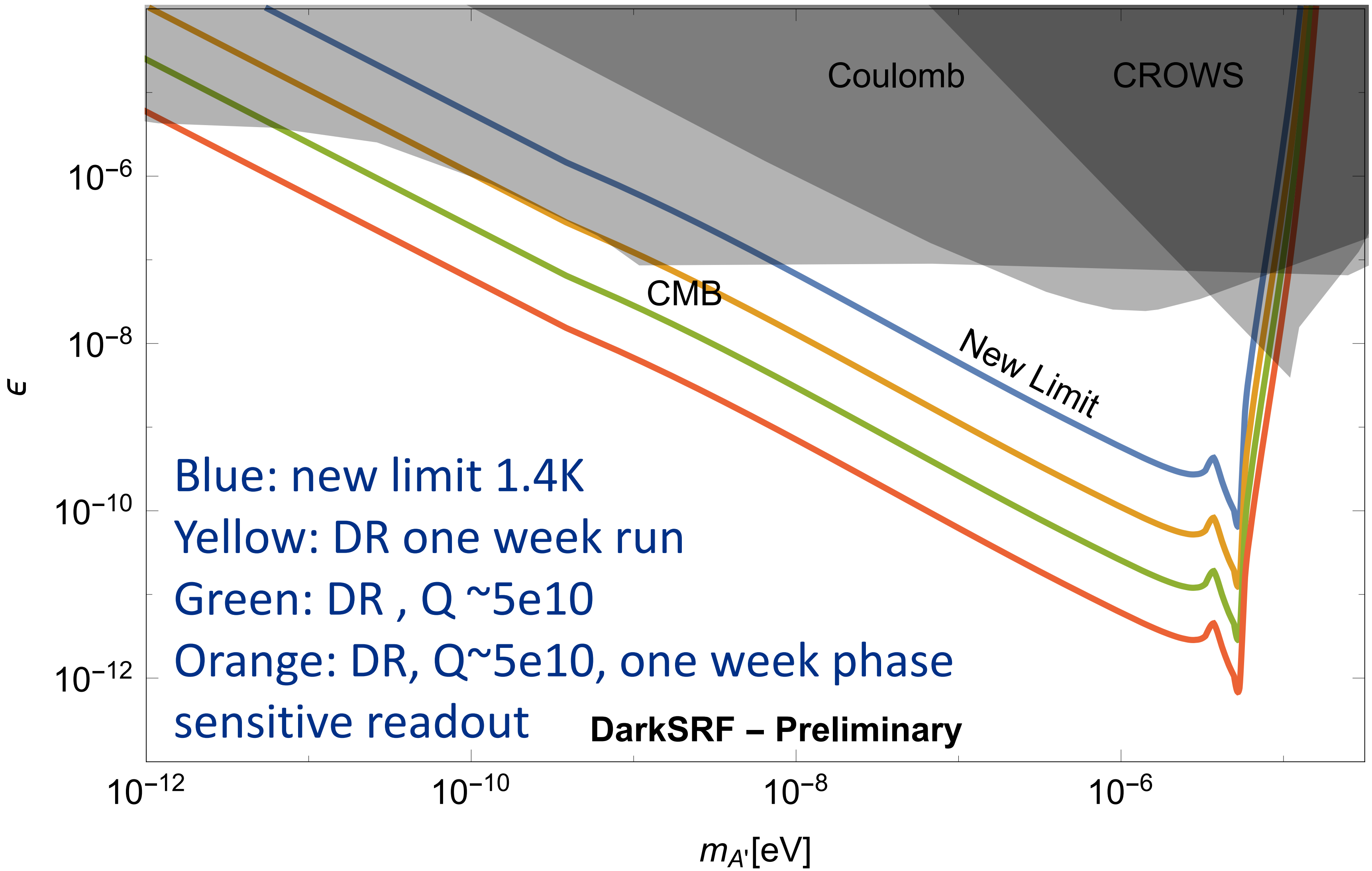
A. Romanenko, R. Pilipenko, S. Zorzetti, D. Frolov, M. Awida, S. Posen, A. Grassellino, arXiv:1810.03703

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

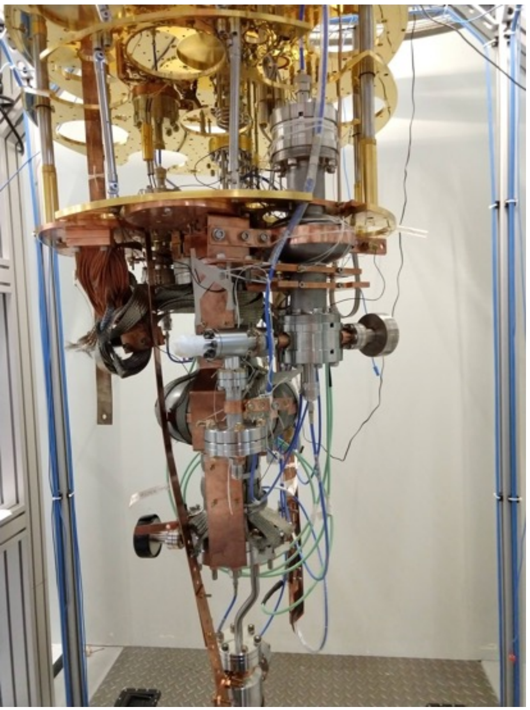


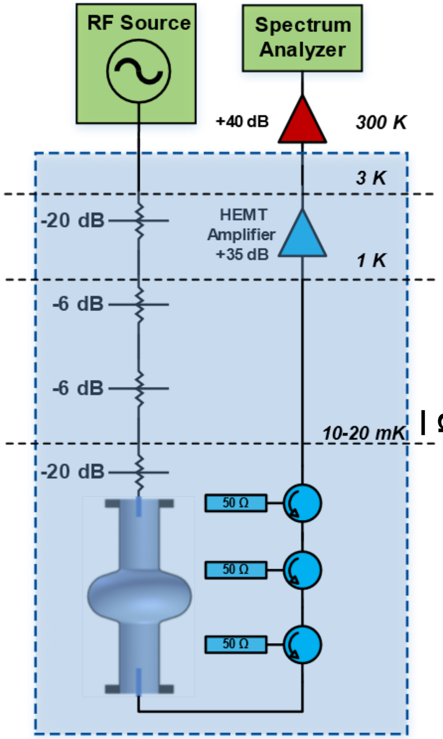
New limit vs future potential reach in DR

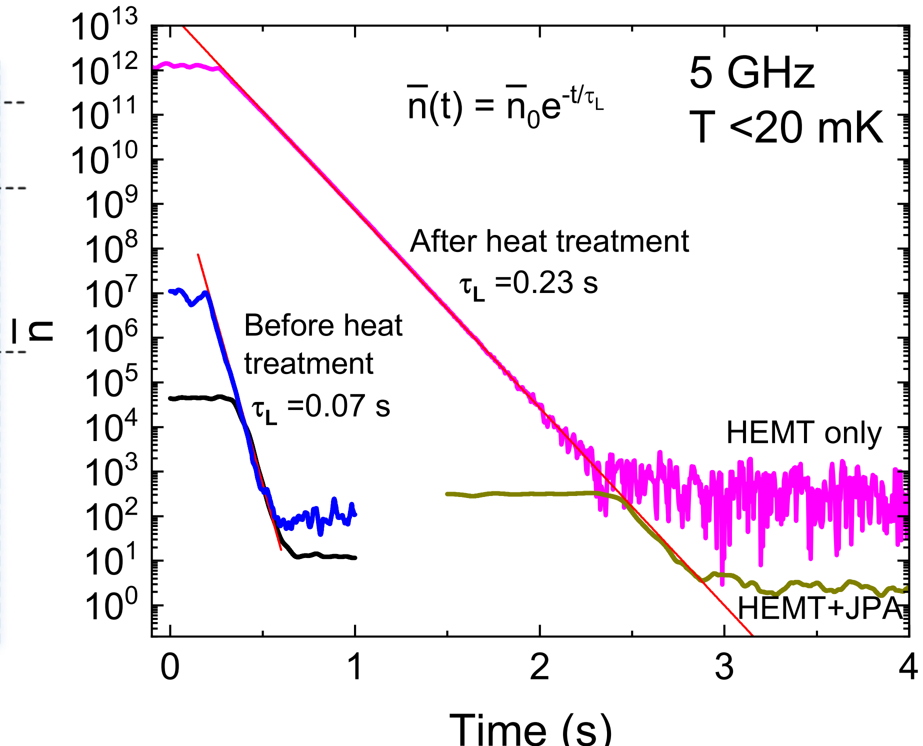


First measurements in quantum regime

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







A. Romanenko, R. Pilipenko, S. Zorzetti, D. Frolov, M. Awida, S. Posen, A. Grassellino, arXiv:1810.03703

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 and more

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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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

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Institut de Physique Théorique, Université Paris Saclay, CEA, F-91191 Gif-sur-Yvette, France

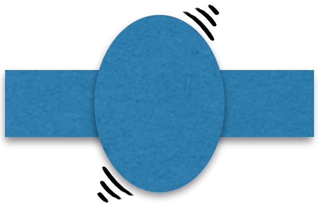
Sebastian A. R. Ellis, Christopher Nantista, Jeffrey Neilson, Philip Schuster, Sami Tantawi, Natalia Toro, and Kevin Zhou
SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA 94025, USA

Searching for Millicharged Particles with Superconducting Radio-Frequency Cavities

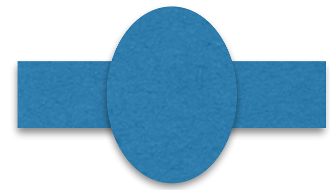
Asher Berlin[1] and Anson Hook[2]
[1] *Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, NY 10003, USA*
[2] *Maryland Center for Fundamental Physics, University of Maryland, College Park, MD 20742, USA*

Extending DarkSRF to axions searches

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



Emitter Cavity



Receiver Cavity

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

or

search for cosmic DM.

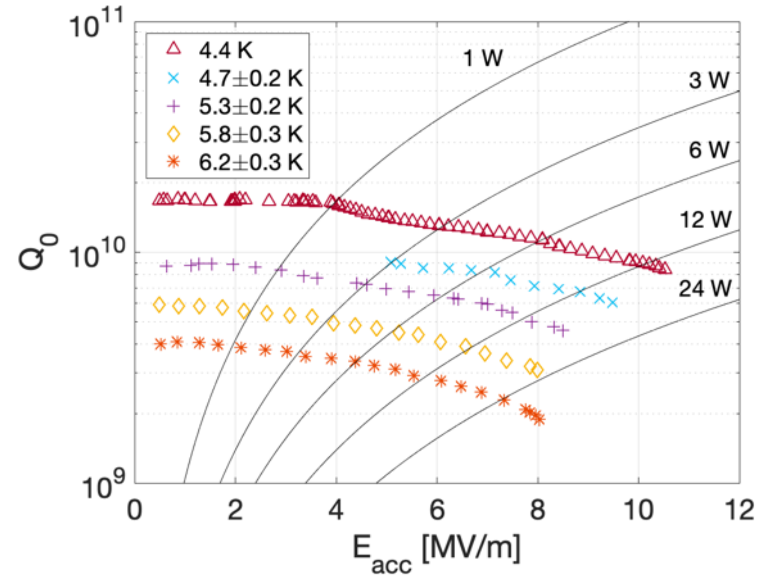
Several possibilities to explore:

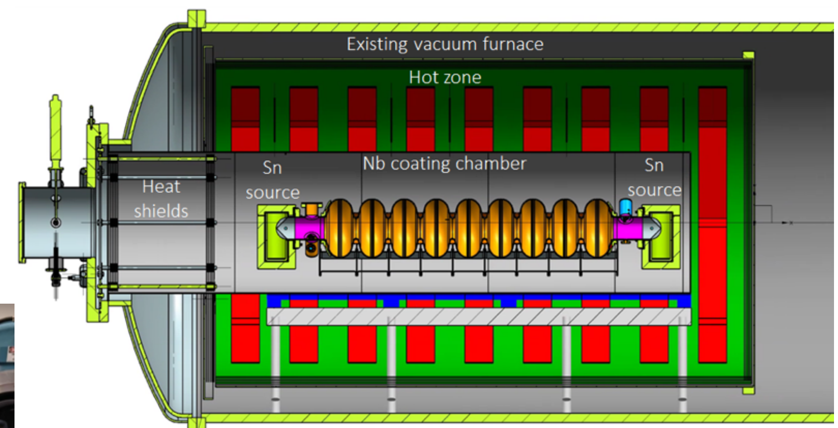
- One excited and one quiet mode.
- Inserting a region of static B field.
- .... R&D is required

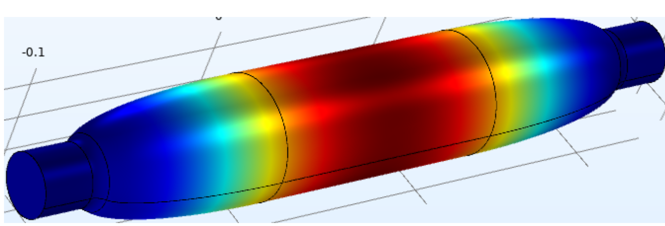
- Harnik, Romanenko, Grassellino, PAC 2018 DarkSRF presentation, Fermilab
- Kahn et al: Searching for axions and for the SM light-by-light interaction at low energies in a single cavity.
- Rajendran et al: Suggestion for light-shining-through-wall axion search using a quiet receiver cavity and a static B-field adjacent to the cavity.

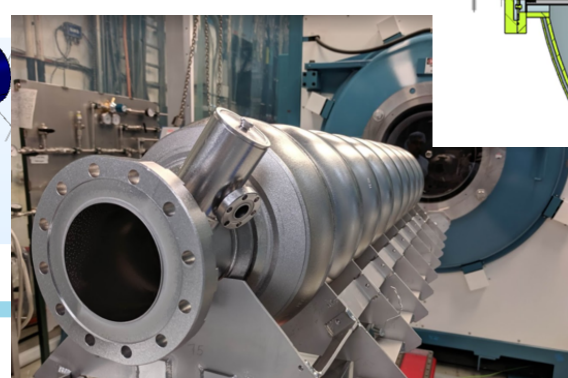
SRF Cavities for Axion Searches in Tesla fields?

- FNAL SRF group has an active research program in Nb_3Sn and other new materials
- World record Nb_3Sn cavities in the range 650MHz - 4 GHz with Q ranging from **1e9 to 1e11**
- **Will now test them in Tesla fields**
- Nb_3Sn is excellent candidate – H_{c2} ~ 30 T and we know how to make high quality films
- Optimize geometry for parallel fields to minimize Lorentz force (F~IxB)
- Several other new materials to be studied with our new CVD/ALD furnace









Sam Posen, FNAL

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