Ultra-high Q superconducting cavities from accelerators for increased coherence of 3D quantum systems

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Intersections between Nuclear Physics and Quantum Information

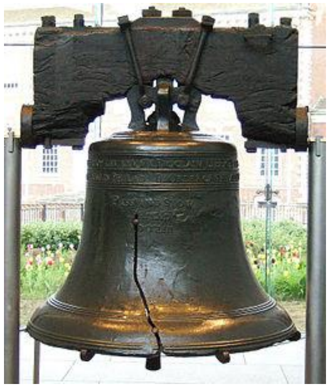
30 March 2018

Outline

- Superconducting RF (SRF) cavities in particle accelerators
- Appeal of SRF cavities for quantum systems
  - Ultra-high Q > 10^{10} factors are routine
  - Decades of expertise in surface engineering and underlying superconducting RF science
- Progress towards the “quantum” implementation at FNAL
  - Clarification of the TLS role
  - First measurements at T < 20 mK

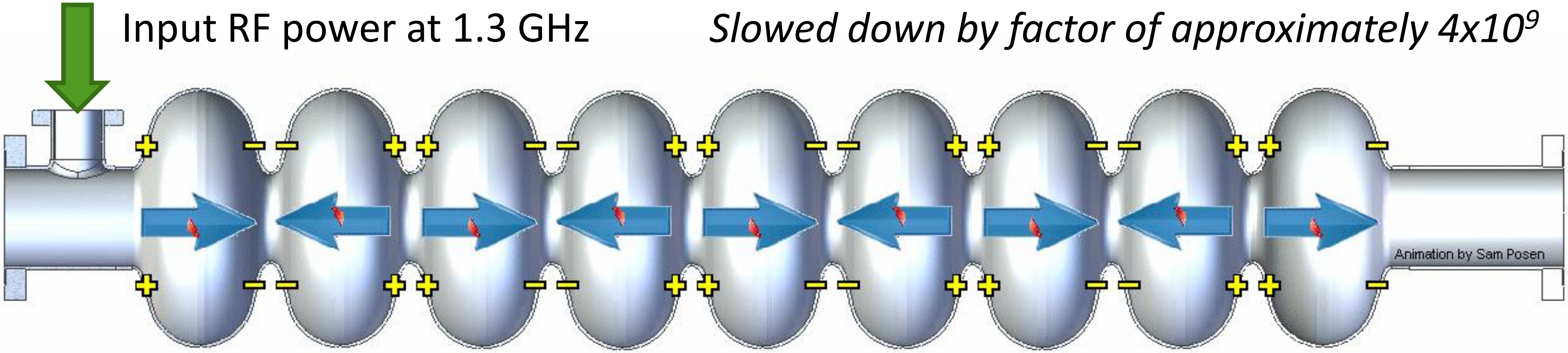
How are Particles Accelerated in Modern Machines?

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



Input RF power at 1.3 GHz

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



~1 m

Images from linearcollider.org, WIkipedia

Modern large scale accelerators are based on SRF

European XFEL

~1000 cavities

Specification:
Q > 10^{10} @ 2K, 23.6 MV/m

LCLS-II at SLAC

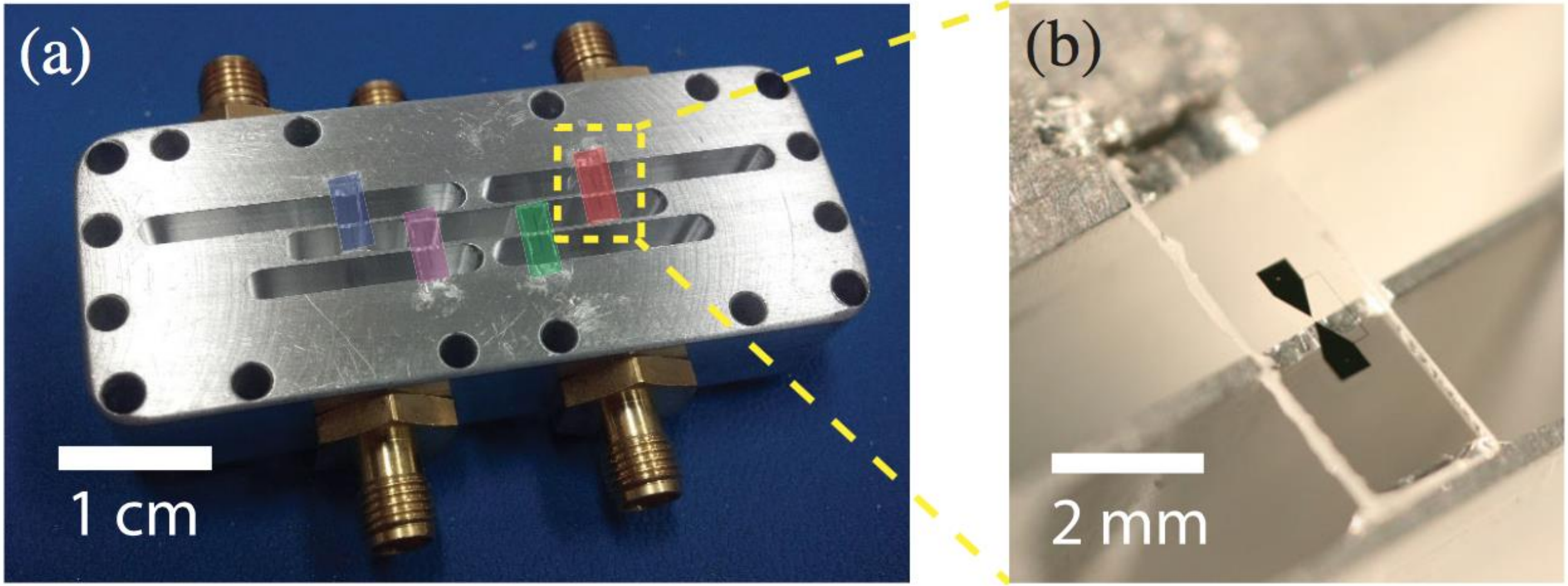
Fermilab is building half (17+) of cryomodules

Q > 2.7 x 10^{10} @ 2K, 16 MV/m

Quantum Computing: 3D circuit QED architecture

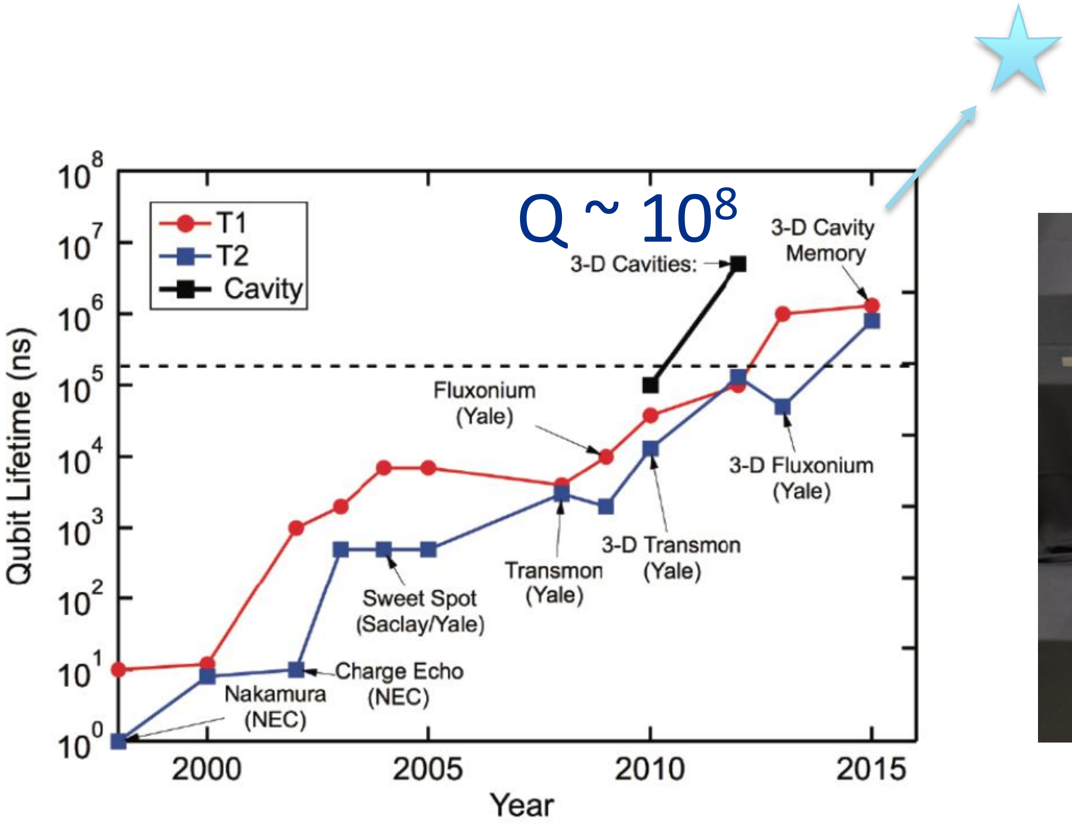
State-of-the-art quality factors Q in quantum computing are ~10^8

Machined Aluminum host cavity



H. Paik et al, Phys. Rev. Lett. 117, 251502 (2016)

High Q SRF cavities for improved coherence



$Q > 10^{11}$

Potential of up to ~10 <u>seconds</u> of coherence

M. H. Devoret and R. J. Schoelkopf, *Science* 339, 1169–1174 (2013)

1-cell Fermilab cavities of various frequencies

RF Penetration Layer drives the performance

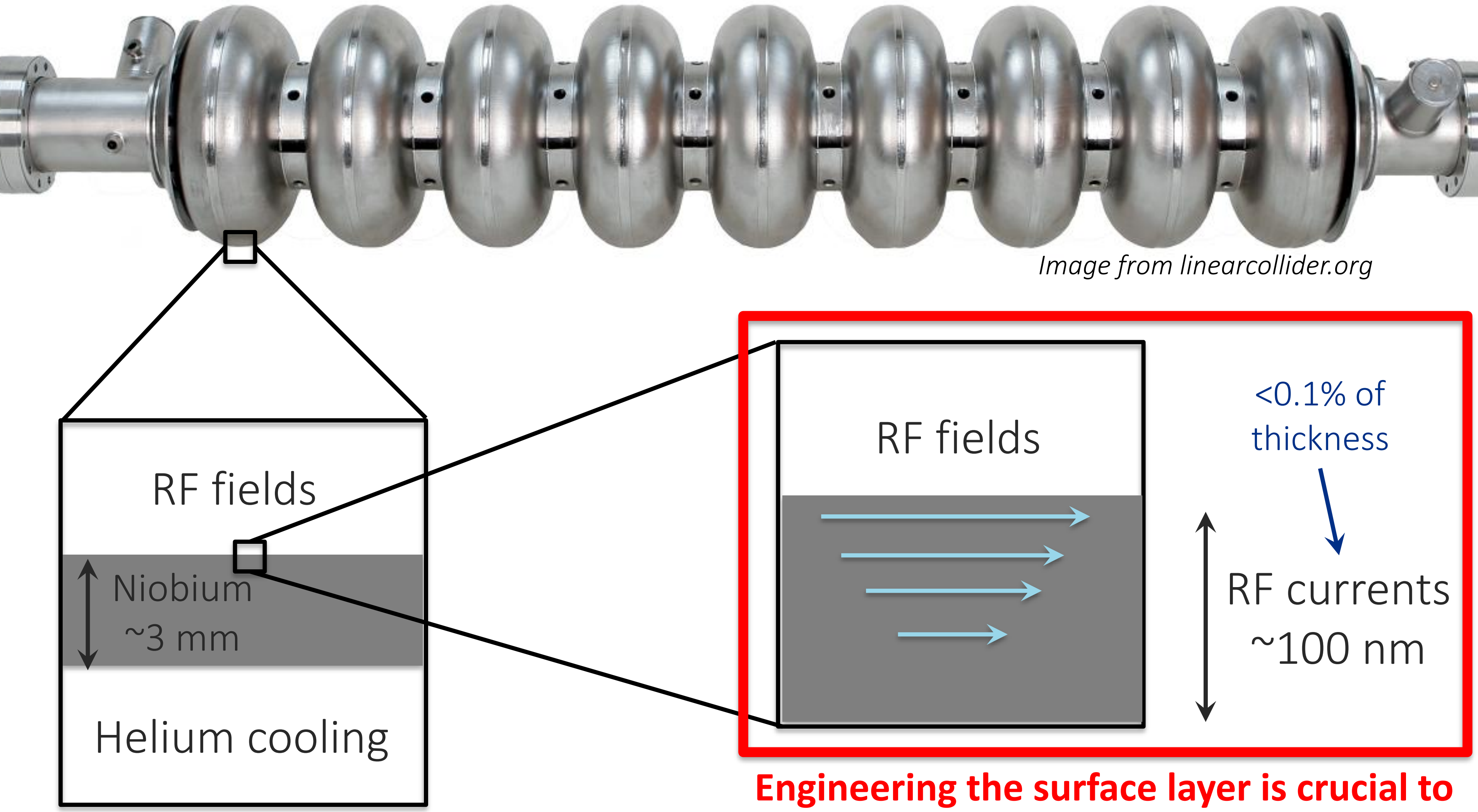


Image from linearcollider.org

RF fields

Niobium ~3 mm

Helium cooling

RF fields

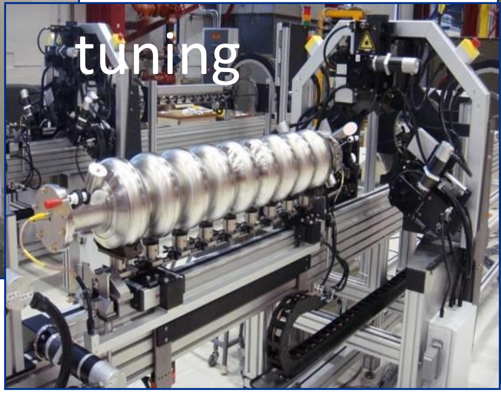
<0.1% of thickness

RF currents ~100 nm

Engineering the surface layer is crucial to performance

Major SRF Infrastructure at Fermilab (necessary to achieve high performance/high Q)

Class 10 clean room/high pressure water rinsing



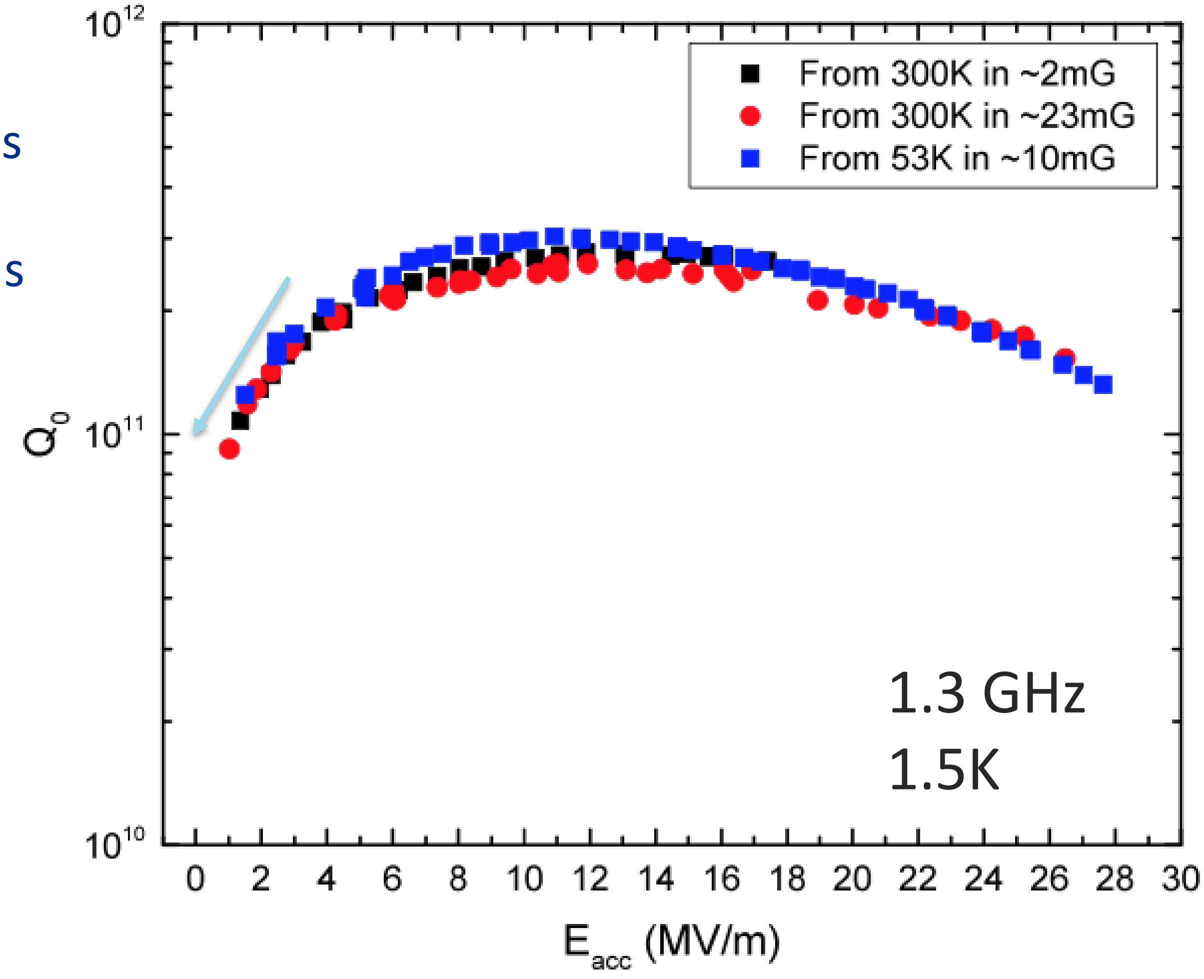
Can we translate high Q expertise in SRF cavities to ‘quantum regime’?

- First task: what is the cause of the low field Q slope and what happens with Q as we decrease the field further?
- Second task: what happens at lowest T < 20 mK?

Renewed importance of the low field Q slope

How will the best cavities we have behave at ultralow fields for various possible applications?

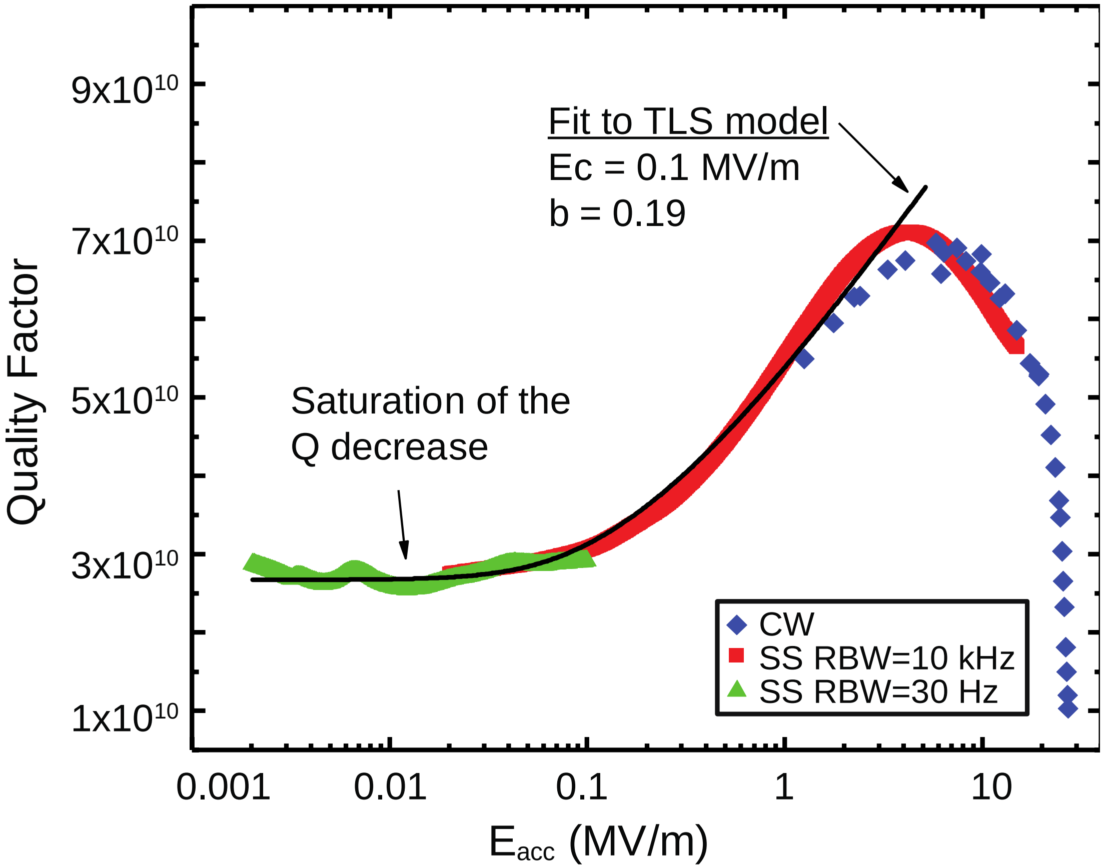
- Quantum computing/memory
- Dark sector searches
- Gravitational effects
- ….



A. Romanenko et al, Appl. Phys. Lett. **105**, 234103 (2014)

Saturation of Q decrease

1.3 GHz T=1.5K



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

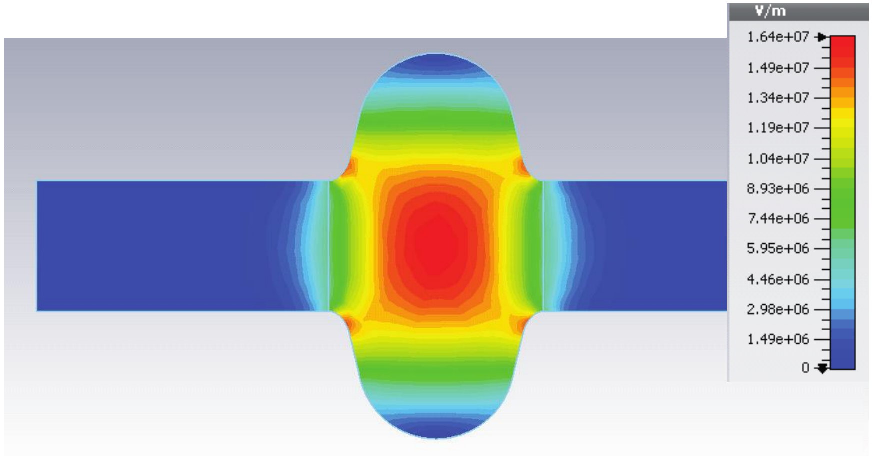
Good news: low field Q saturates at Q>**3×10^{10}**

Now measured down to <N> ~ 1000 photons

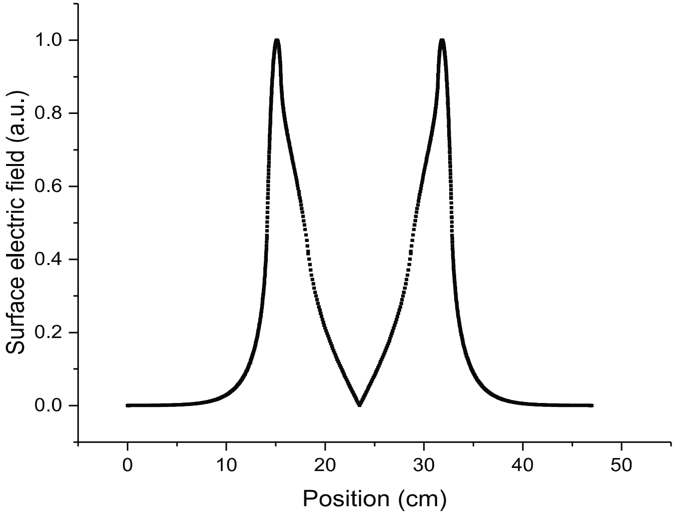
Direct probing in the new regime with single cell cavities

f = 1.3 GHz, TM_{010} mode

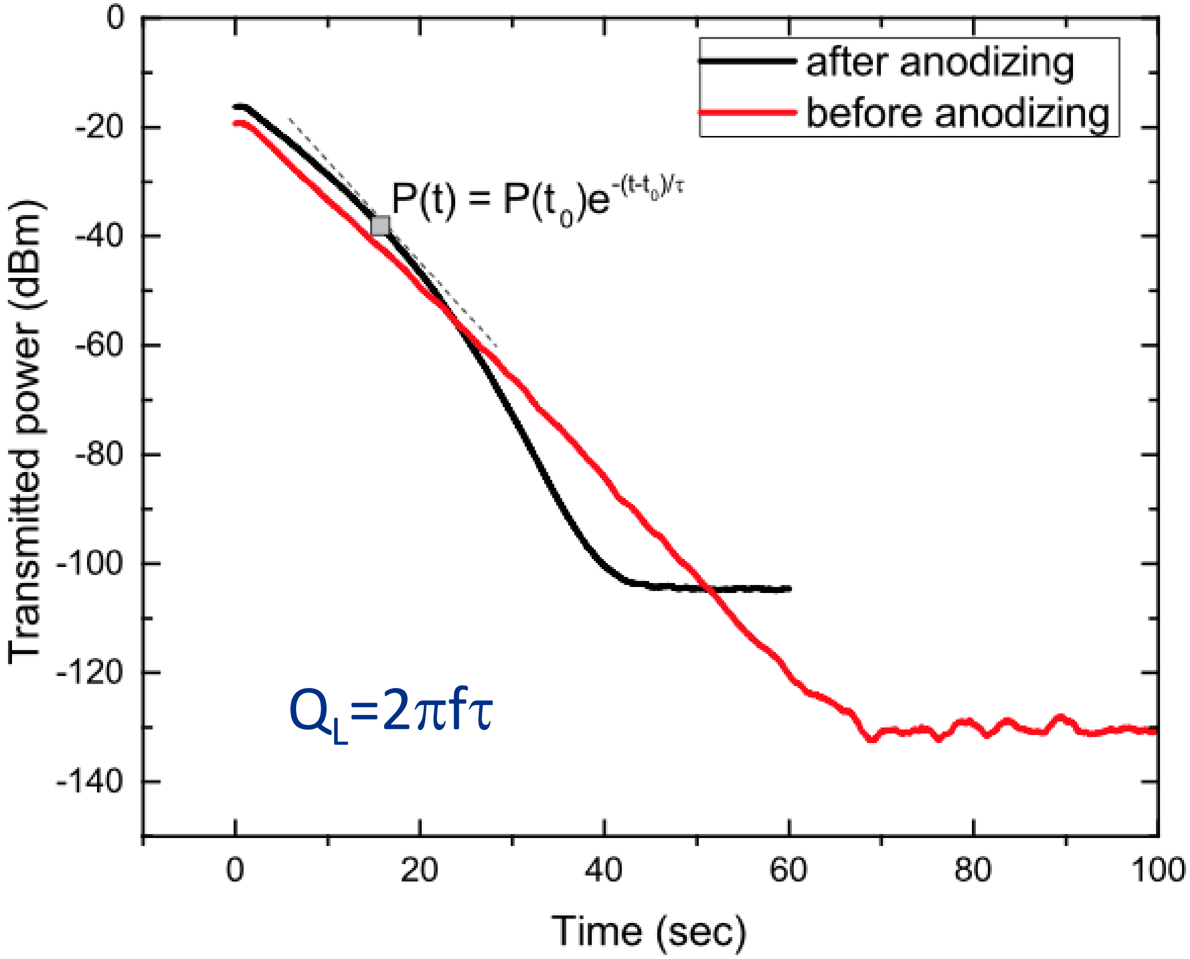
(a)



(b)



Single shot measurements



- $Q > 10^{10}$ cannot be measured using standard network analyzer techniques
- Instead -> decays from PLL state with bandpass filtering (10-1000 Hz around resonance) instead

Various cavities/surface treatments investigated

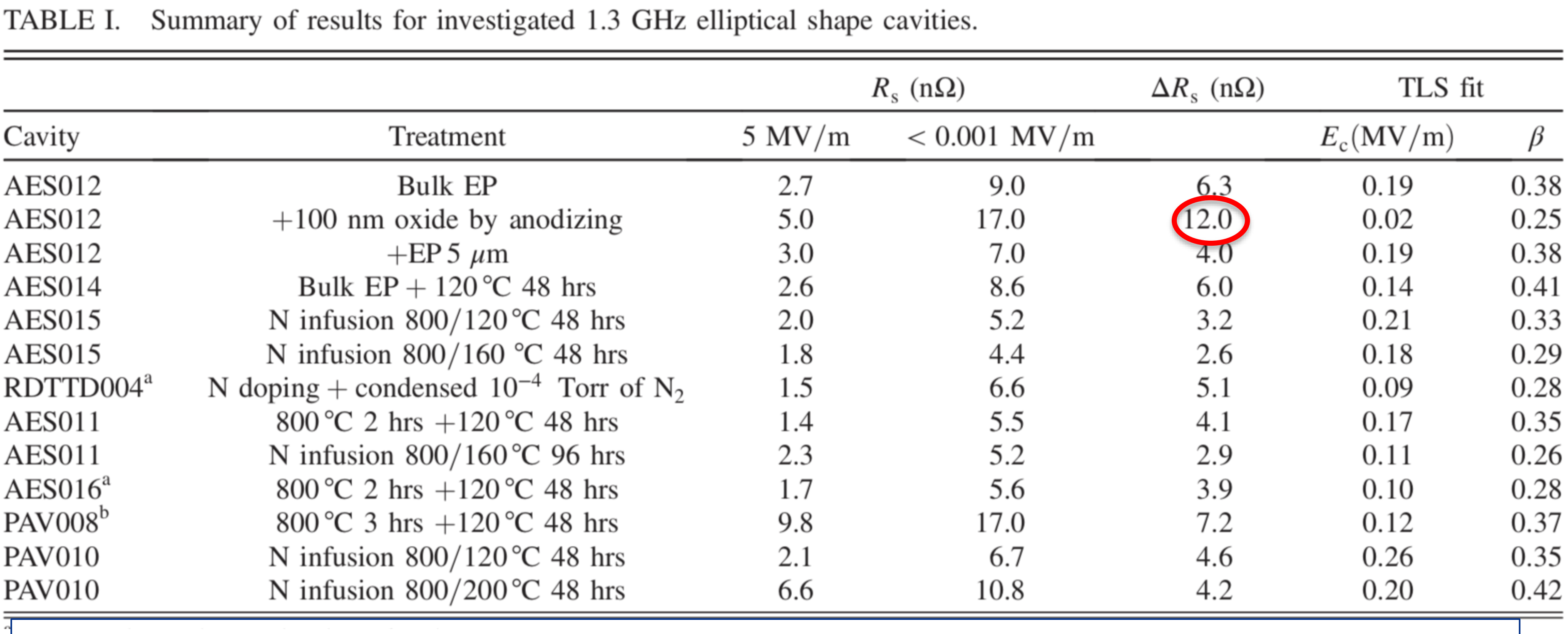


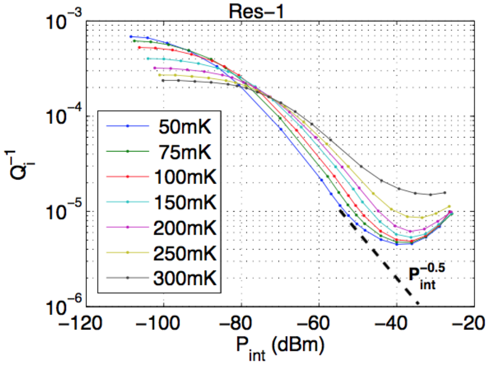
TABLE I. Summary of results for investigated 1.3 GHz elliptical shape cavities.

		R_s (nΩ)		ΔR_s (nΩ)	TLS fit	
Cavity	Treatment	5 MV/m	< 0.001 MV/m		E_c(MV/m)	β
AES012	Bulk EP	2.7	9.0	6.3	0.19	0.38
AES012	+100 nm oxide by anodizing	5.0	17.0	12.0	0.02	0.25
AES012	+EP 5 μm	3.0	7.0	4.0	0.19	0.38
AES014	Bulk EP + 120 °C 48 hrs	2.6	8.6	6.0	0.14	0.41
AES015	N infusion 800/120 °C 48 hrs	2.0	5.2	3.2	0.21	0.33
AES015	N infusion 800/160 °C 48 hrs	1.8	4.4	2.6	0.18	0.29
RDTTD004[a]	N doping + condensed 10^{-4} Torr of N_2	1.5	6.6	5.1	0.09	0.28
AES011	800 °C 2 hrs +120 °C 48 hrs	1.4	5.5	4.1	0.17	0.35
AES011	N infusion 800/160 °C 96 hrs	2.3	5.2	2.9	0.11	0.26
AES016[a]	800 °C 2 hrs +120 °C 48 hrs	1.7	5.6	3.9	0.10	0.28
PAV008[b]	800 °C 3 hrs +120 °C 48 hrs	9.8	17.0	7.2	0.12	0.37
PAV010	N infusion 800/120 °C 48 hrs	2.1	6.7	4.6	0.26	0.35
PAV010	N infusion 800/200 °C 48 hrs	6.6	10.8	4.2	0.20	0.42

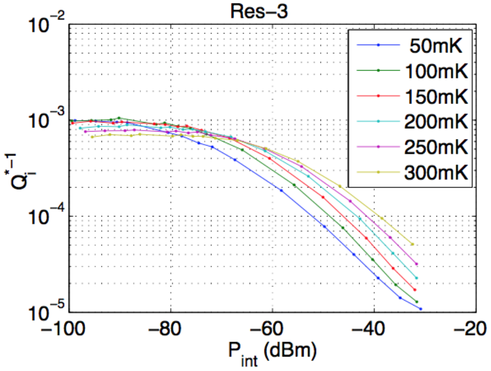
Changes within penetration depth have little effect

Oxide growth/change -> strong increase in very low field dissipation

From 2D resonator world

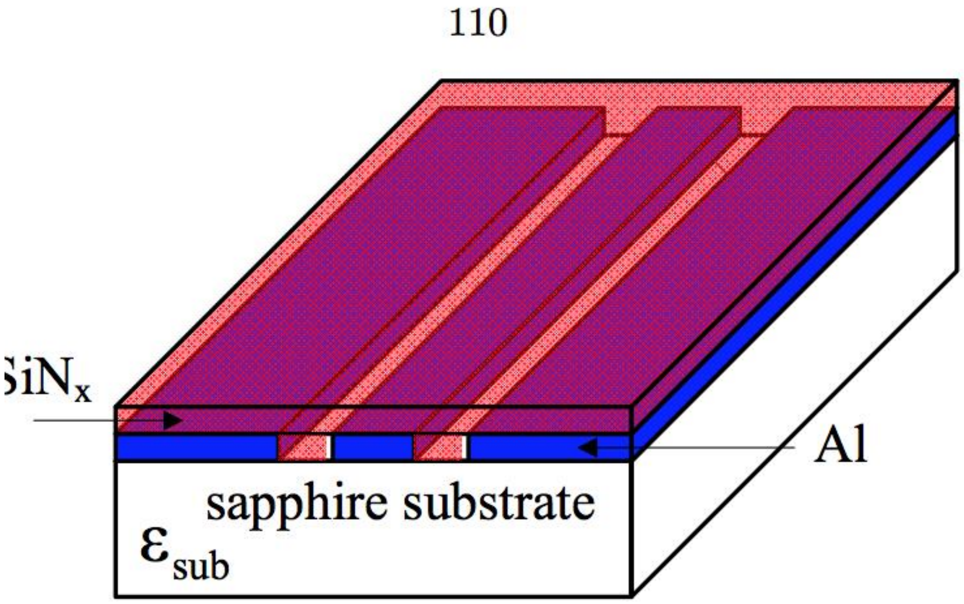


(a)



(c)

Two level systems in the dielectric as a cause

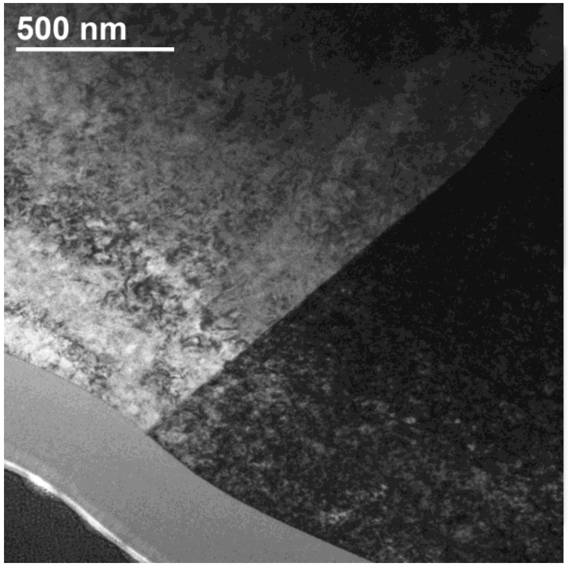


J. Gao, PhD Thesis, Caltech, 2008

J. Zmuidzinas, Annu. Rev. Condens. Matter Phys. 2012. 3:169–214

Two level systems in the natural niobium oxide?

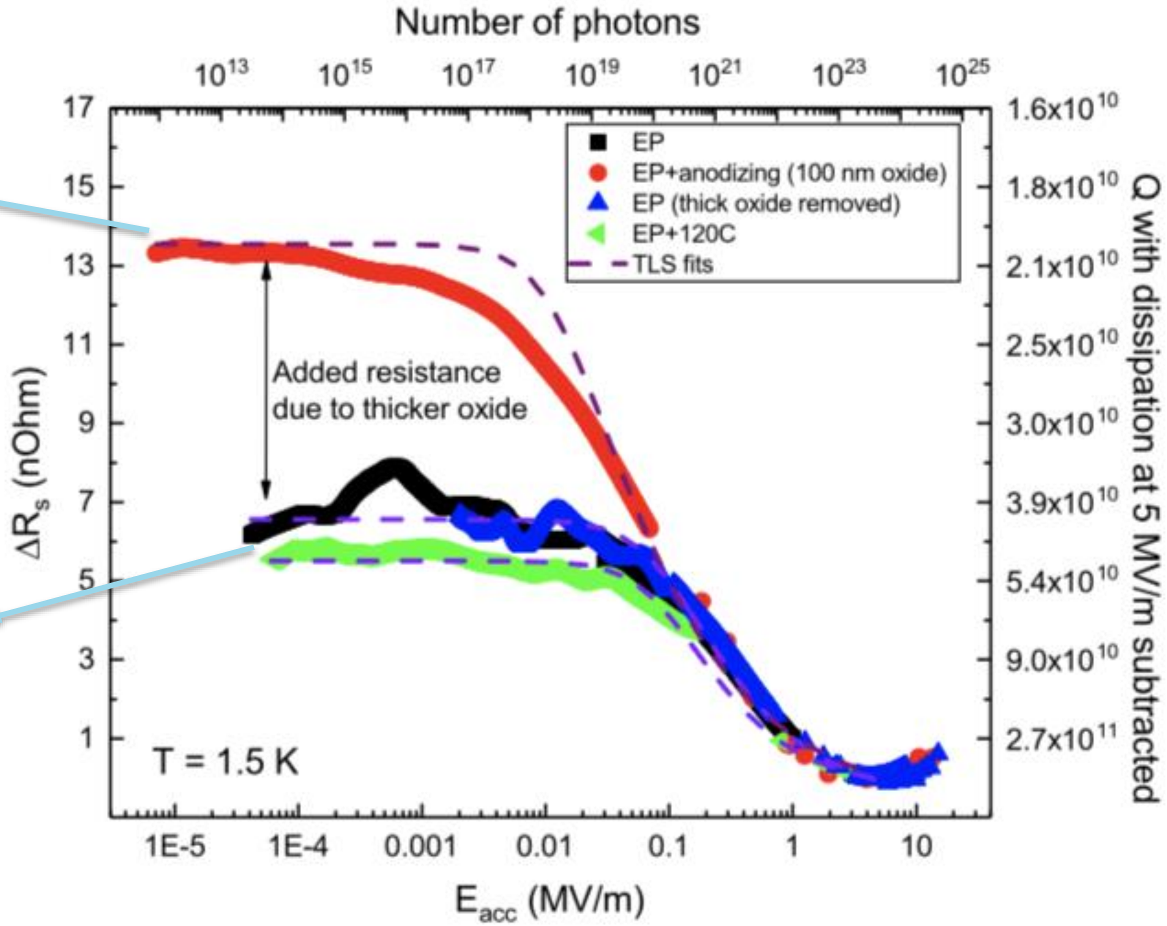
According to Martinis et al, Phys. Rev. Lett. 95, 210503 (2005) -> electric field effect



5 nm

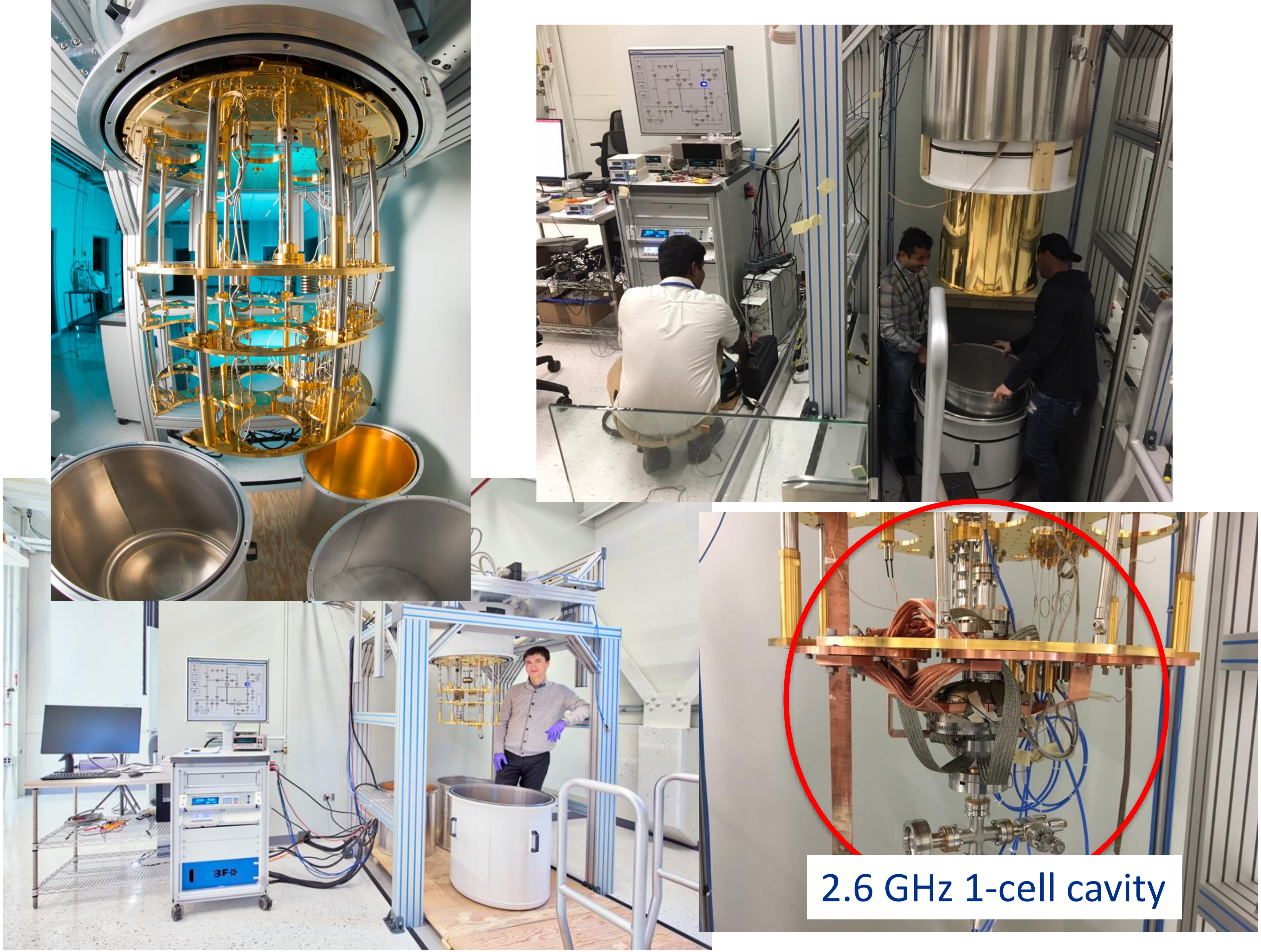
Nb_2O_5

Nb



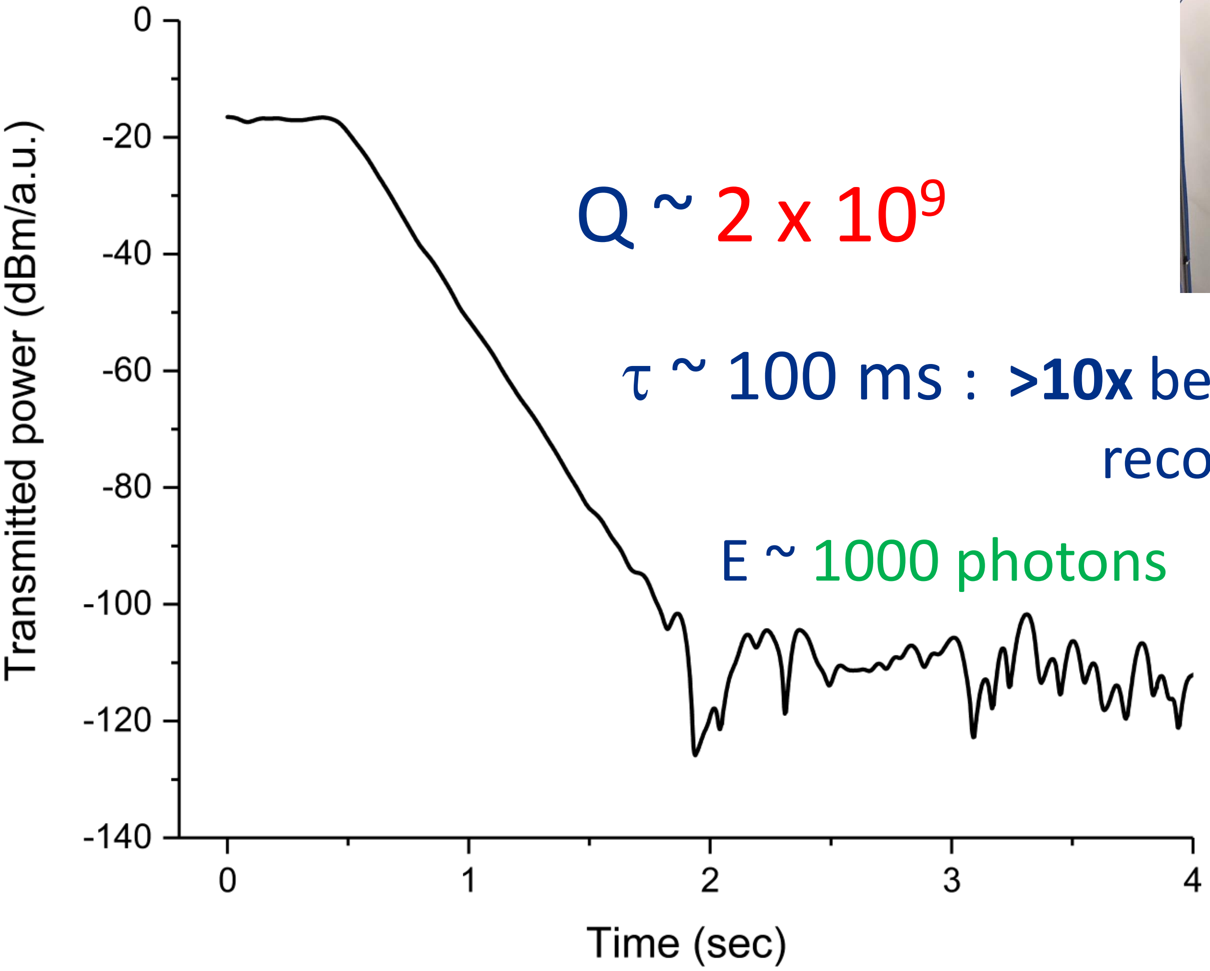
A. Romanenko and D. I. Schuster, Phys . Rev. Lett. **119**, 264801 (2017)

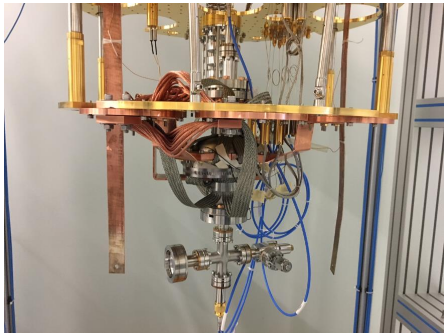
- What happens at lowest $T < 20$ mK, low powers?



2.6 GHz 1-cell cavity

First try: Q at T ~ 12 mK, down to ~1000 photons





Q ~ 2 x 10^9

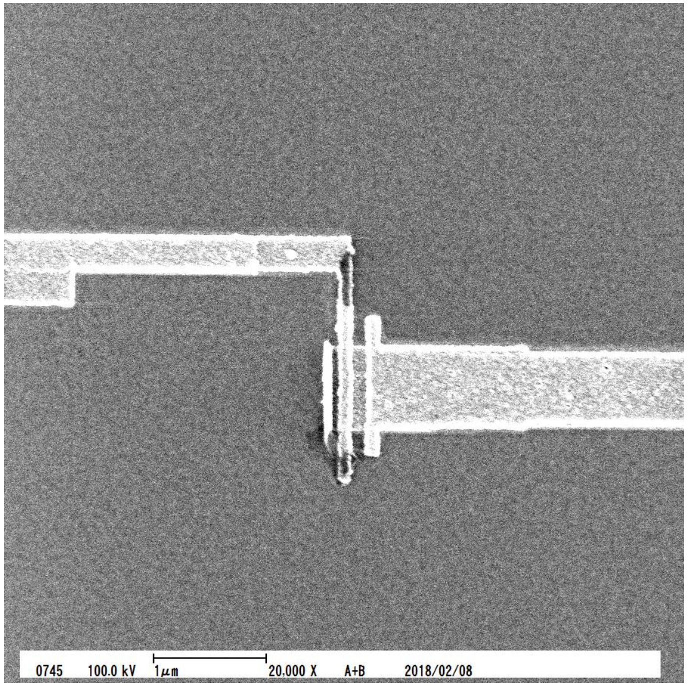
τ ~ 100 ms : **>10x** better than previous records

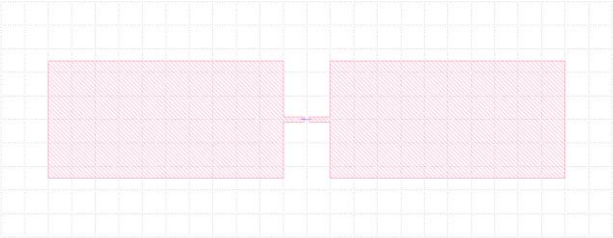
E ~ 1000 photons

Publication with full details in preparation

Immediate plans

- Couple a very high Q SRF cavity with the transmon qubit to probe the achievable coherence times





Collaborations with:

<u>Univ. of Wisconsin (Madison)</u>:
Prof. Robert McDermott
Chris Wilen

<u>NIST</u>: D. Pappas

Summary

- Accelerator ultra-high Q microwave 3D cavity expertise can enable a qualitative jump on achievable photon lifetimes/coherence
  - Complex accelerators with hundreds of Q > 10^{10} cavities are routine, Q >10^{11} is the state-of-the-art

- Very high Qs can be translated to ”quantum” regime
  - Demonstrated **Q ~ 2 x 10^{9}, τ ~ 100 msec** at 12 mK, 1000 photons at the first try

- First 3D-SRF qubits are to be tested shortly