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Dark SRF - experiment

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for the **Dark SRF Collaboration**

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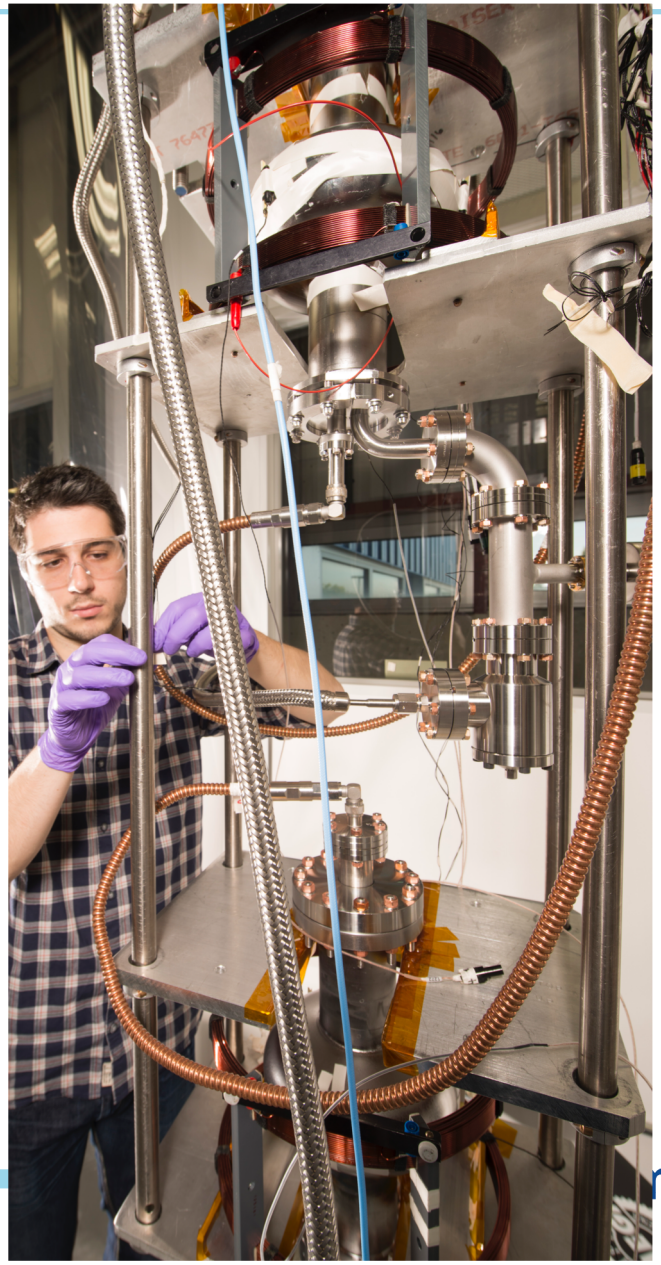
Zhen Liu (Theory), Joshua Isaacson (Theory).

Light Shine through the Wall – with SRF cavities

Pictured on the right:
Routine cavity test (dozens a week)
at the APS-TD SRF Vertical test
Facility

Takeaway message:

The experiment looks a lot like
what we already do.
We just need to iron out some
details.



Two options for where to run the experiment: VTS (T= 1.4K) or Dilution Fridge (T~20 mK)

Vertical cavity test Facility at APS-TD (VTS)

Ready now
T= 1.4K
~1000 photons

Dilution Fridge at APS- TD Quantum Lab (QCL)

More prep required
T~20 mK
NO thermal photons

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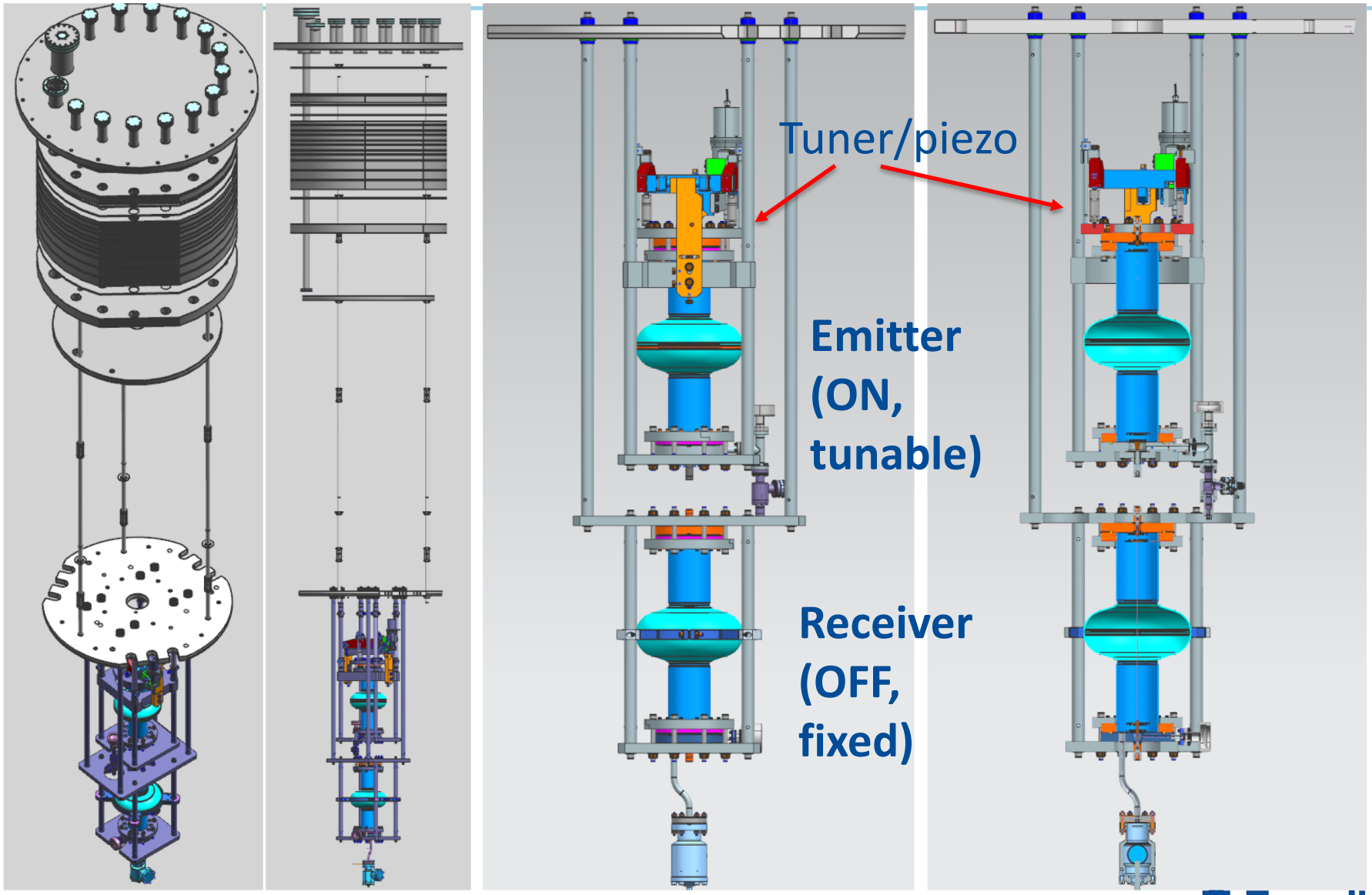
Light Shine through the Wall – for the first time in the world, realized with SRF cavities: VTS frames in fabrication



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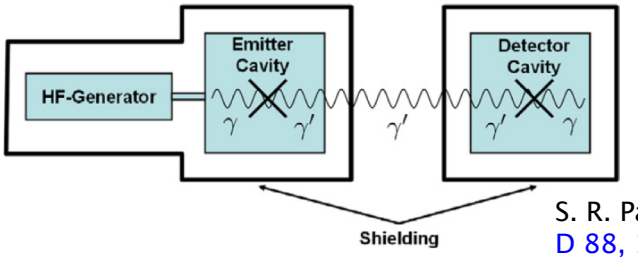
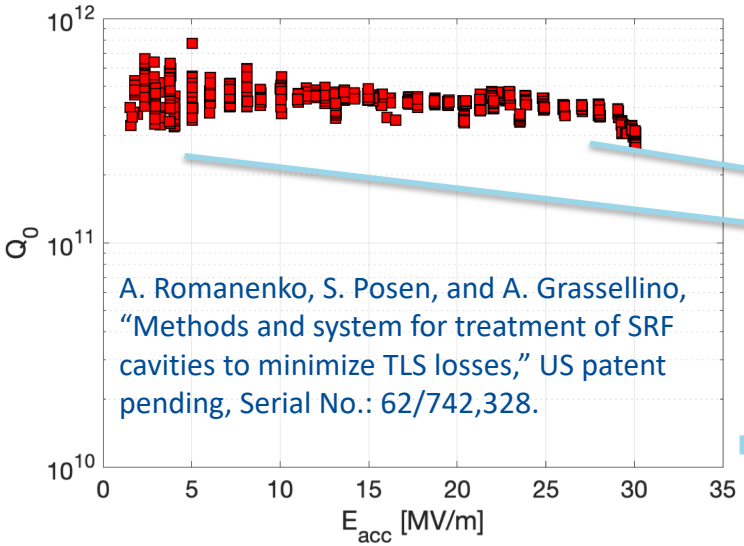
The enabling part: the extraordinary high Q

- SRF cavities (f < 3 GHz) can easily reach Q > 1e9 at T< 2K, vs > 5 orders of magnitude over copper cavities, combining E and R → > 10 order of magnitude gain
- Via deep knowledge of intricate niobium cavity surface treatments, the Fermilab SRF group has pushed the boundaries of Q to world records, reaching routinely among the highest quality factors in nature Q > 4e11
- Moreover, we have developed the expertise to manipulate the Q factor in the range from >10^{25} photons to the quantum regime (< 20 photons)

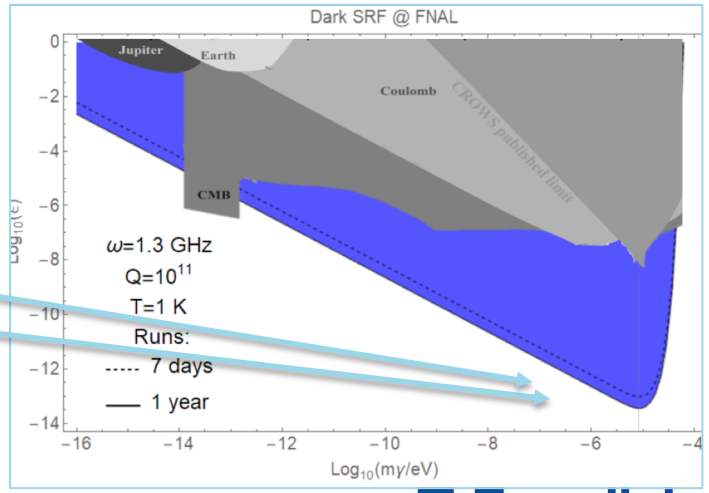


$$\frac{P_{DET}}{P_{EM}} = \chi^4 Q_{DET} Q_{EM} \left(\frac{m_{\gamma'} c^2}{\hbar \omega_\gamma}\right)^8 |G|^2$$

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)

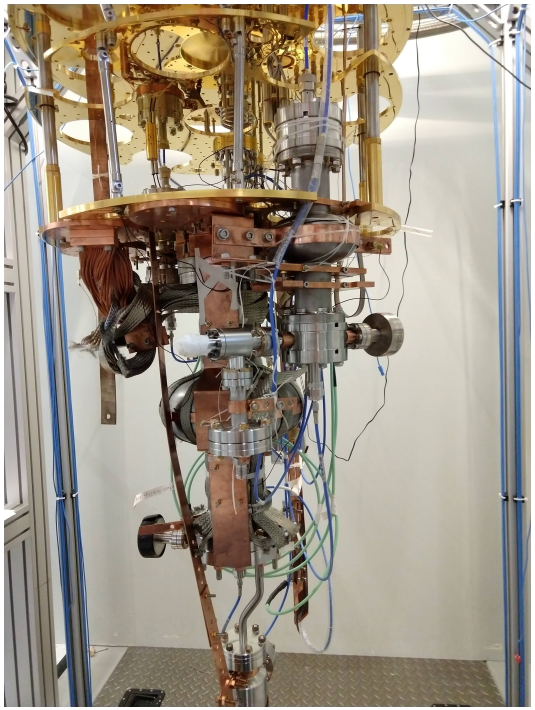


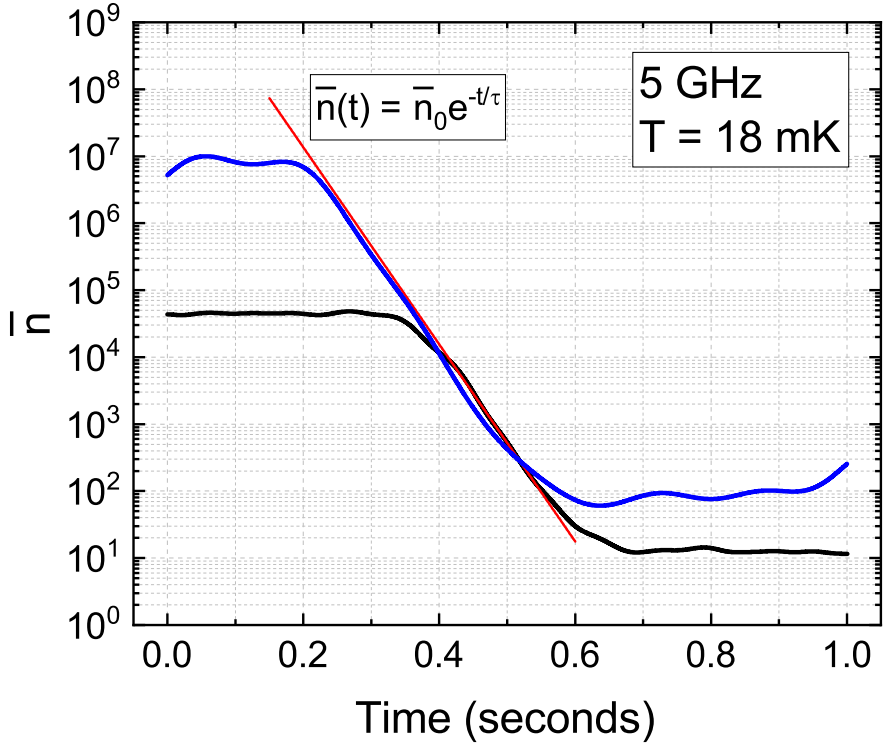
A. Romanenko, S. Posen, and A. Grassellino, "Methods and system for treatment of SRF cavities to minimize TLS losses," US patent pending, Serial No.: 62/742,328.



New enabling capability: SRF cavities in quantum regime

- First measurements in quantum regime demonstrate that high Q SRF cavities already have world-leading sensitivity to dark matter floating around in the galaxy





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

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

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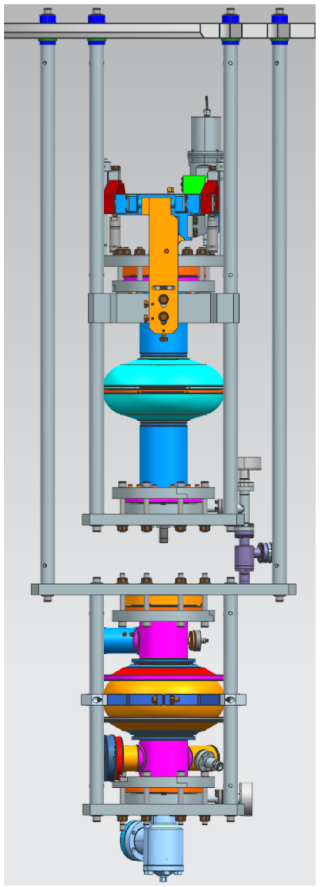
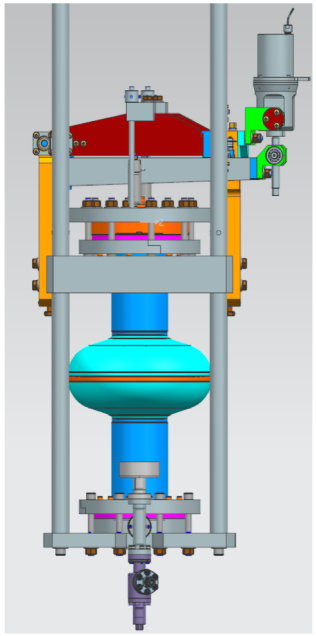
New challenges ahead: the “frequency precision” frontier

1. T = 1.4K (VTS) ~ 1000 photons background
2. T = 20 mK (Dil Fridge) < 10 photons background



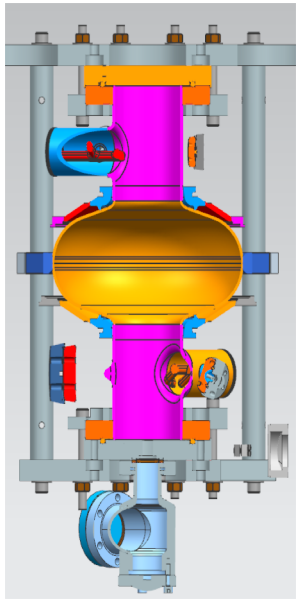
Emitter:

- > 30 MV/m (> 10^{25} photons)
- Q >10^{10} @ 1.3 GHz → Df < **0.1 Hz!**
- **Challenge: 0.1 Hz → controlling the cavity wall displacement with ~sub-nanometer precision**
- **Compensate in real time for He vibrations or other sources**



Receiver:

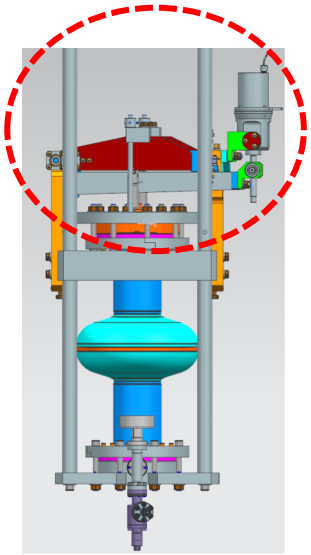
- OFF
- Q> 10^{10}
- Measure its frequency cold, then match emitter to it via tuner/piezo mechanism
- **Challenge: design/realize as stiff as possible cage to keep f stable to sub-Hz level**

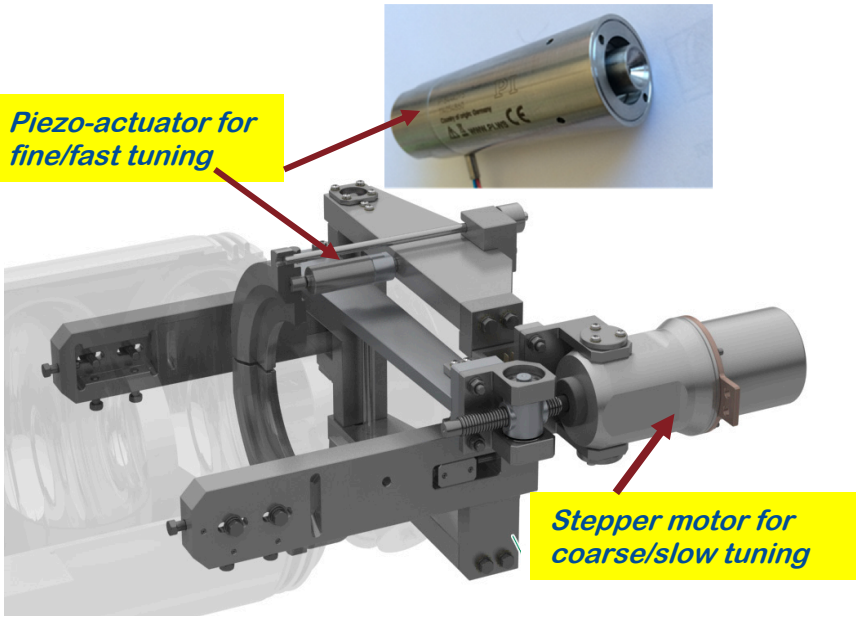


Stimulated emission: frequencies need to match!

Enabling tool: Tuner and Piezo (courtesy of Y. Pischalnikov and group)

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

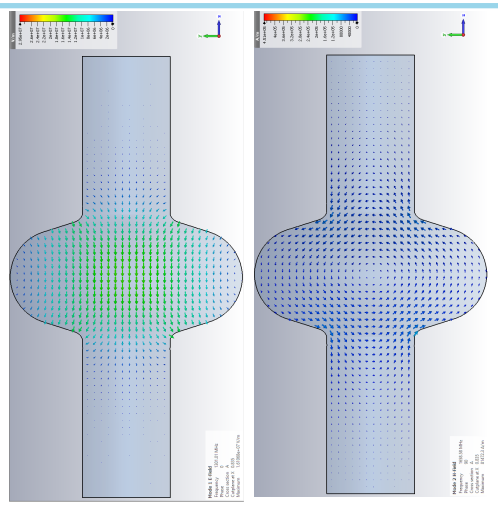
Fine/Fast Tuner
- Range up to ΔX=3um or ΔF=8kHz
- Resolution δx=0.05nm or δF=0.1Hz (*)

(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

Axion Searches – concept under development

- Axion detection typically bets on increasing B fields, with lower Q cavities (copper cavities)
- If however we bet on Q, with lower B field (compatible with SRF cavities, up to ~200 mT), we can gain orders of magnitude in sensitivity
- Two options:
  - Stimulated emission (multimode scheme or guide static B field in receiver)
  - Scan, but will require multiple frequency tunable cavities (can be developed, e.g. use in house cavities in range 650 MHz-9 GHz with Nb plunger)

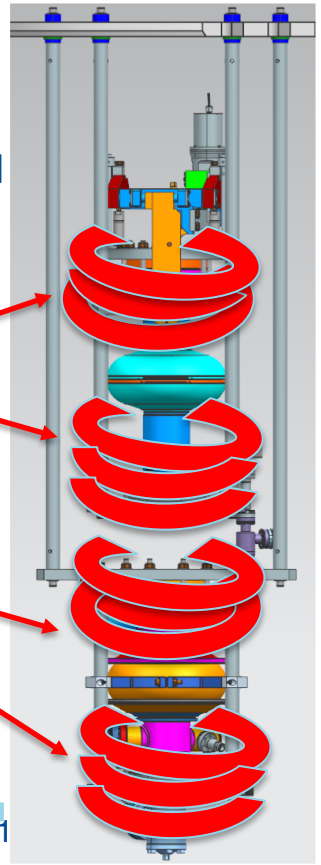


1.3 GHz E field

1.66 GHz B field

Multimode excitation gives non zero E.B in the cavity

Beampipe coils to guide static B field in the cavity parallel to beam axis and E_{RF} field ?



Conclusions

- Dark SRF experiment looking for dark photons is low hanging fruit, given the unique and world leading Fermilab SRF capabilities
- Will either discover or move exclusion boundary for dark photons existence by orders of magnitude compared to the state of the art
- World leading expertise in high Q SRF cavities is now further enhanced by the new quantum R&D activities
- Straightforward upgrade path: running in the dilution fridge
- Next: extend search to axions
- Upgrade path will bring enhanced and unprecedented sensitivity, but will require additional resources (technical and equipment)

Acknowledgements

- The awesome Dark SRF Group (group picture below)