FERMILAB-SLIDES-24-0098-TD

High Q Cavities for Accelerators and Detectors

Sam Posen
Cornell LEPP Journal Club
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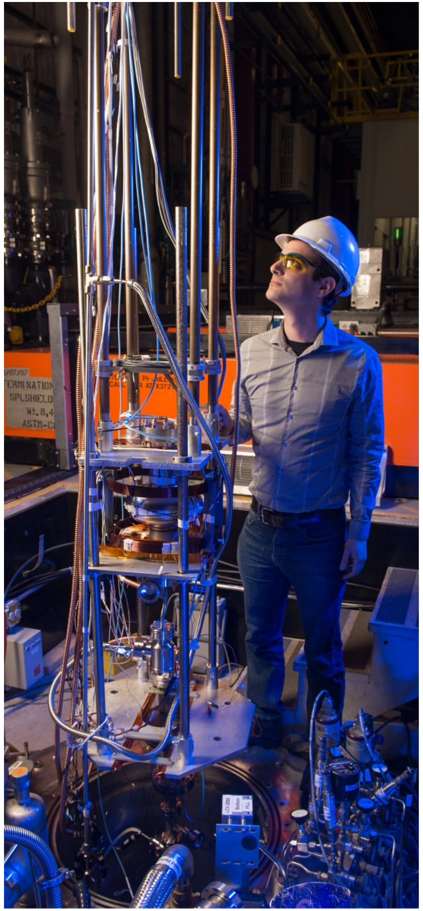
About Me

Sam Posen

Current Roles at Fermilab:

- Senior Scientist
- Interim Associate Lab Director in charge of the Applied Physics and Superconducting Technology Directorate (APS-TD)
  - Org of ~280 people: SRF, magnets, cryogenics, machine shop
- Focus Area co-Leader for Physics and Sensing in SQMS Quantum Center

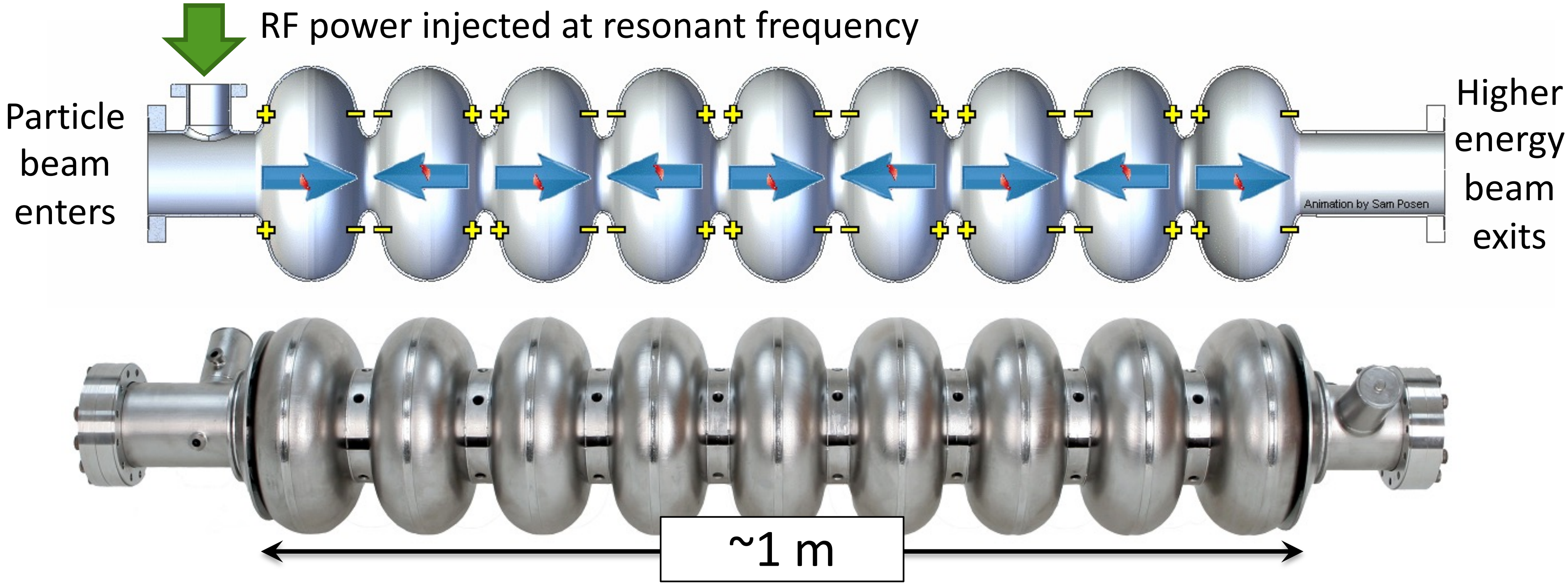
PhD at Cornell Physics Dept 2014 under Matthias Liepe:
Understanding and Overcoming Limitation Mechanisms in Nb_3Sn Superconducting RF Cavities



Fermilab

1. **Superconducting RF (SRF) Cavities**
2. SRF for Accelerators at Fermilab
3. SRF for Detectors at Fermilab
4. Summary

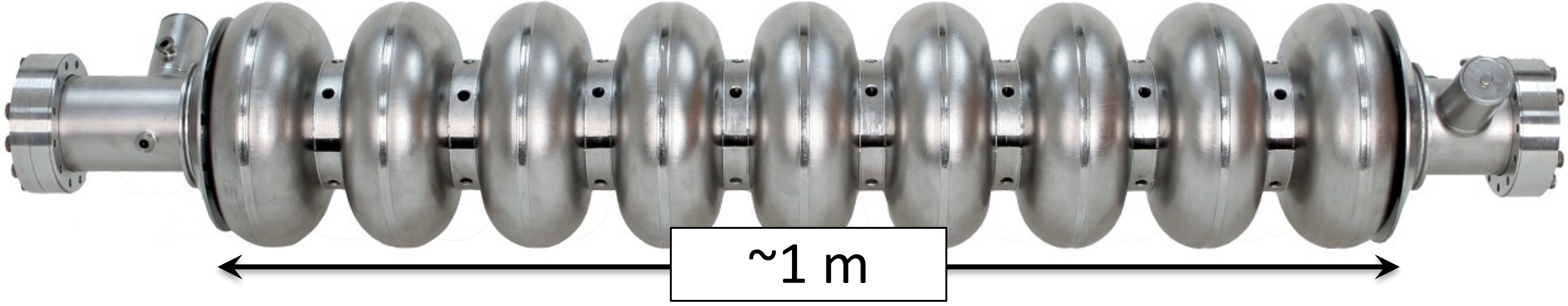
Superconducting Radiofrequency Cavities



Fermilab

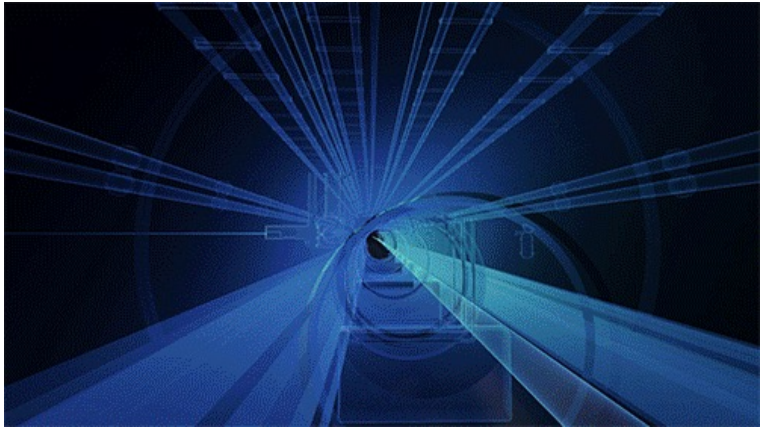
Why SRF Cavities for Accelerators?

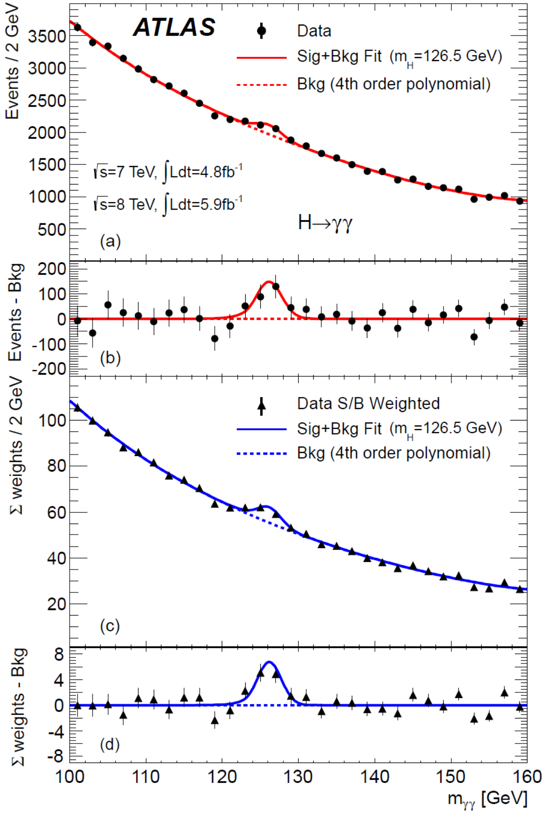
- **RF** – compared to DC, RF allows extremely high electric field gradients and avoids ground issues (e.g. giant insulators)
- **Superconductors** – unlike copper cavities, SC cavities allow for high gradients with high duty factors (e.g. copper may need very short pulses to avoid melting)

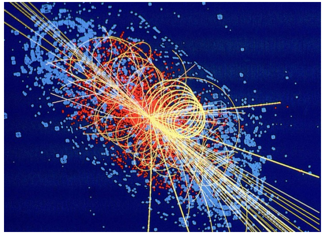


Colliders

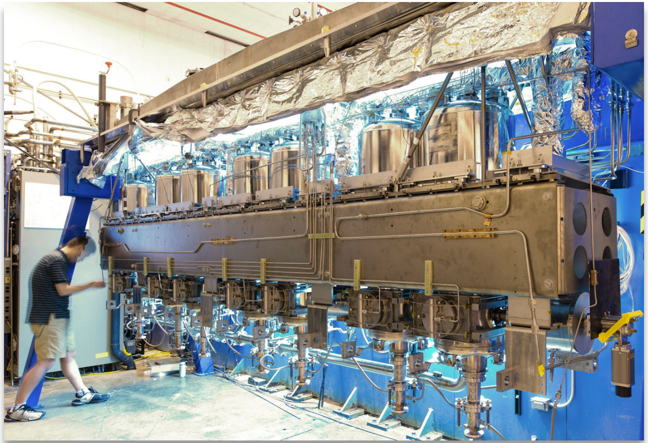
The Large Hadron Collider (LHC)
The Large Electron-Positron Collider (LEP)

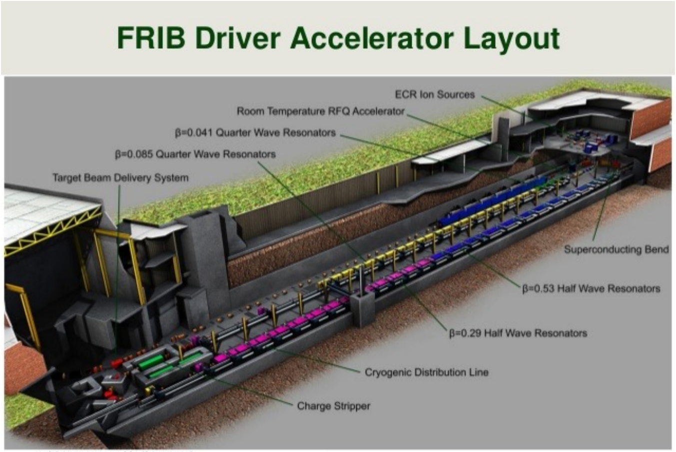


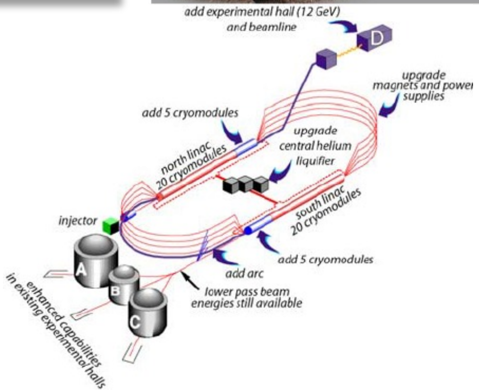


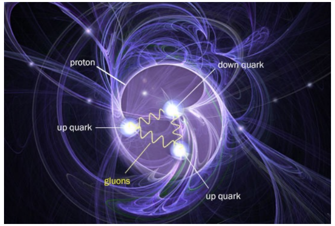


Nuclear Physics



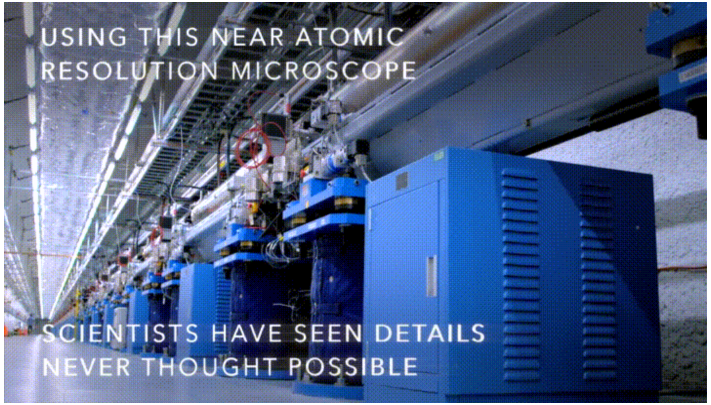


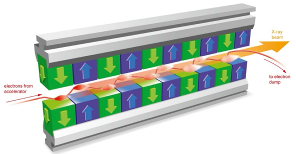


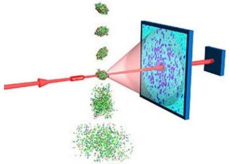


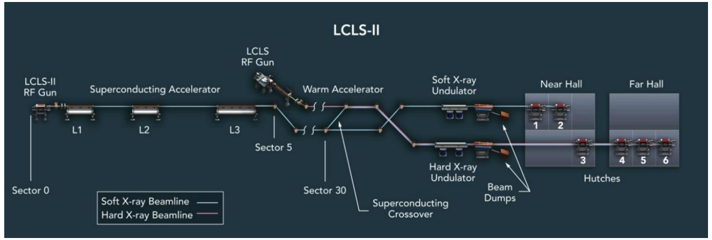
Images from ATLAS (ANL), FRIB (Michigan State University), CEBAF (Jefferson National Laboratory, Virginia), Brookhaven National Laboratory, New York)

Photon Sources







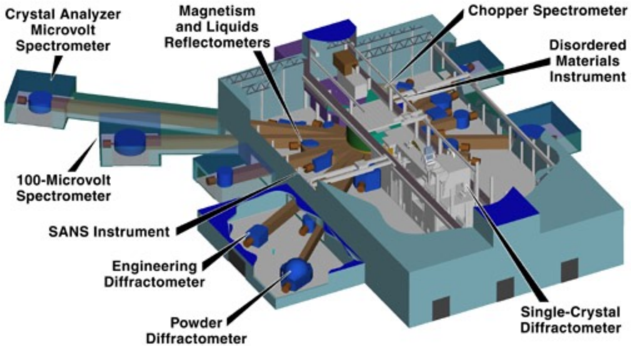


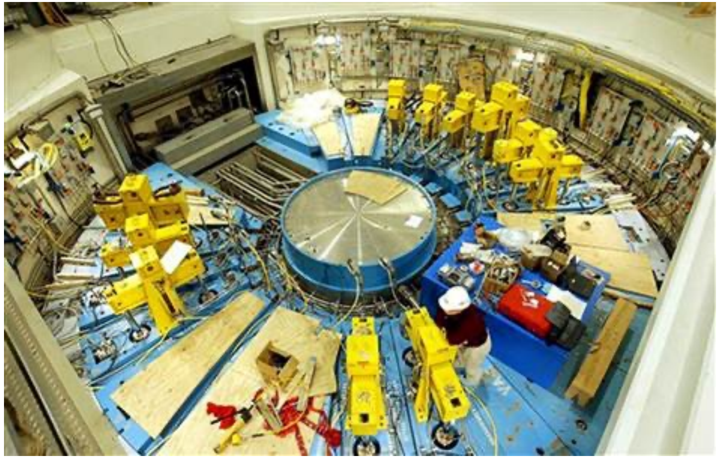
Images from LCLS-II and the European XFEL
youtu.be/t7jUZwhZdd0

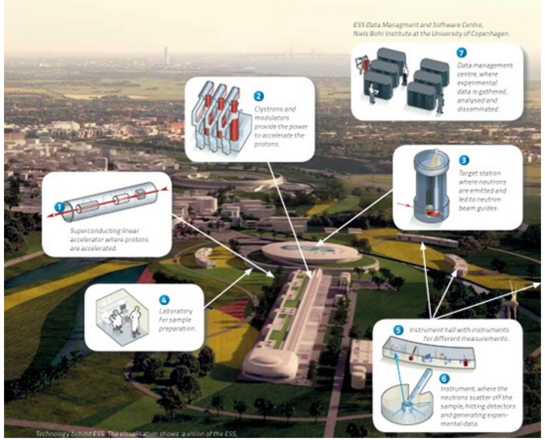
Fermilab

Neutron Sources

EUROPEAN SPALLATION SOURCE



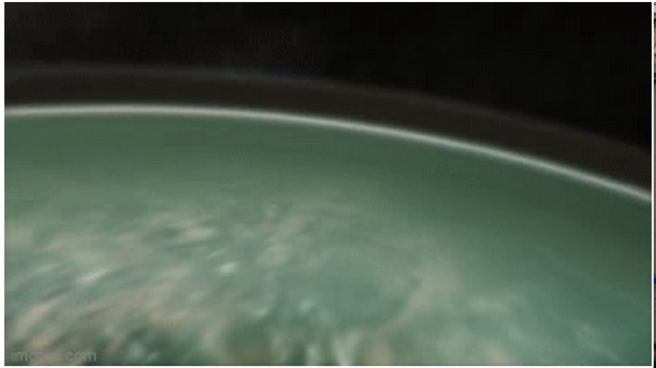


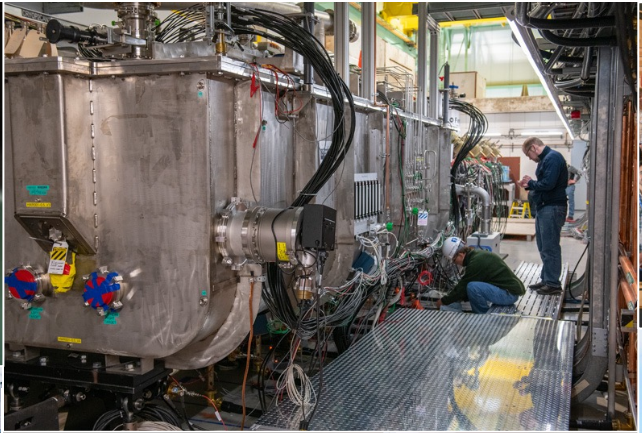


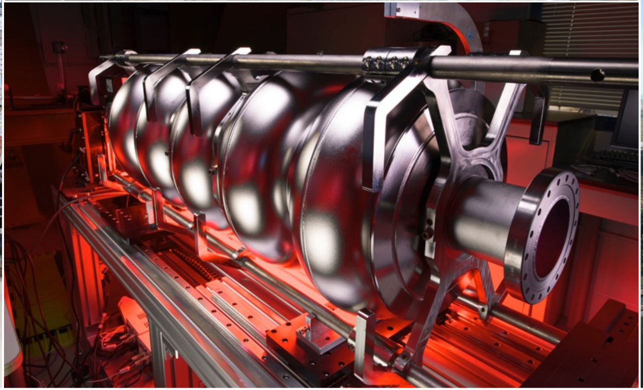
Images from Spallation Neutron Source, Oak Ridge National Laboratory and European Spallation Source

Neutrino Physics

LBNF DUNE PIP-II Fermilab

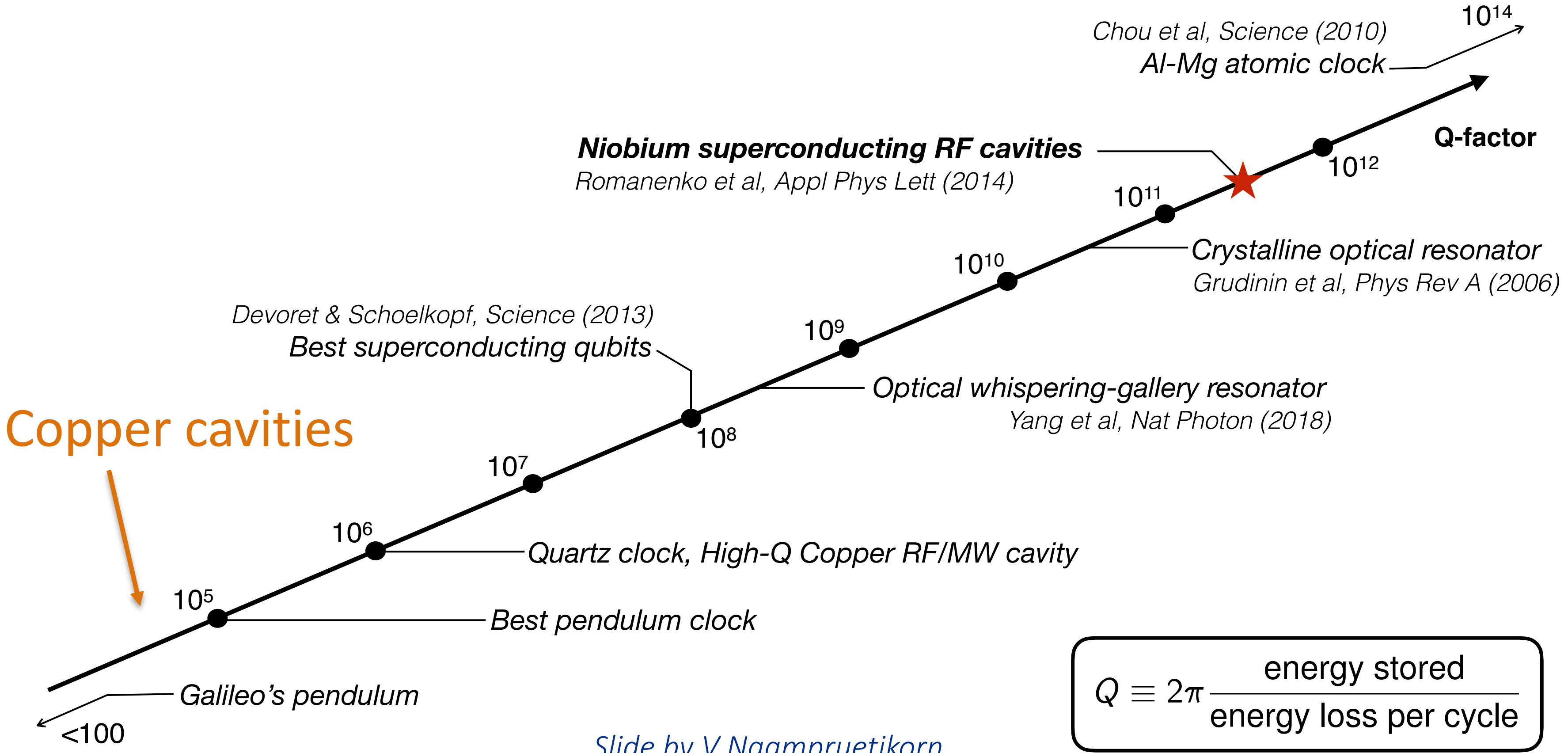






Images from LBNF/DUNE and PIP-II Collaborations

SRF cavities are the most efficient engineered oscillators



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

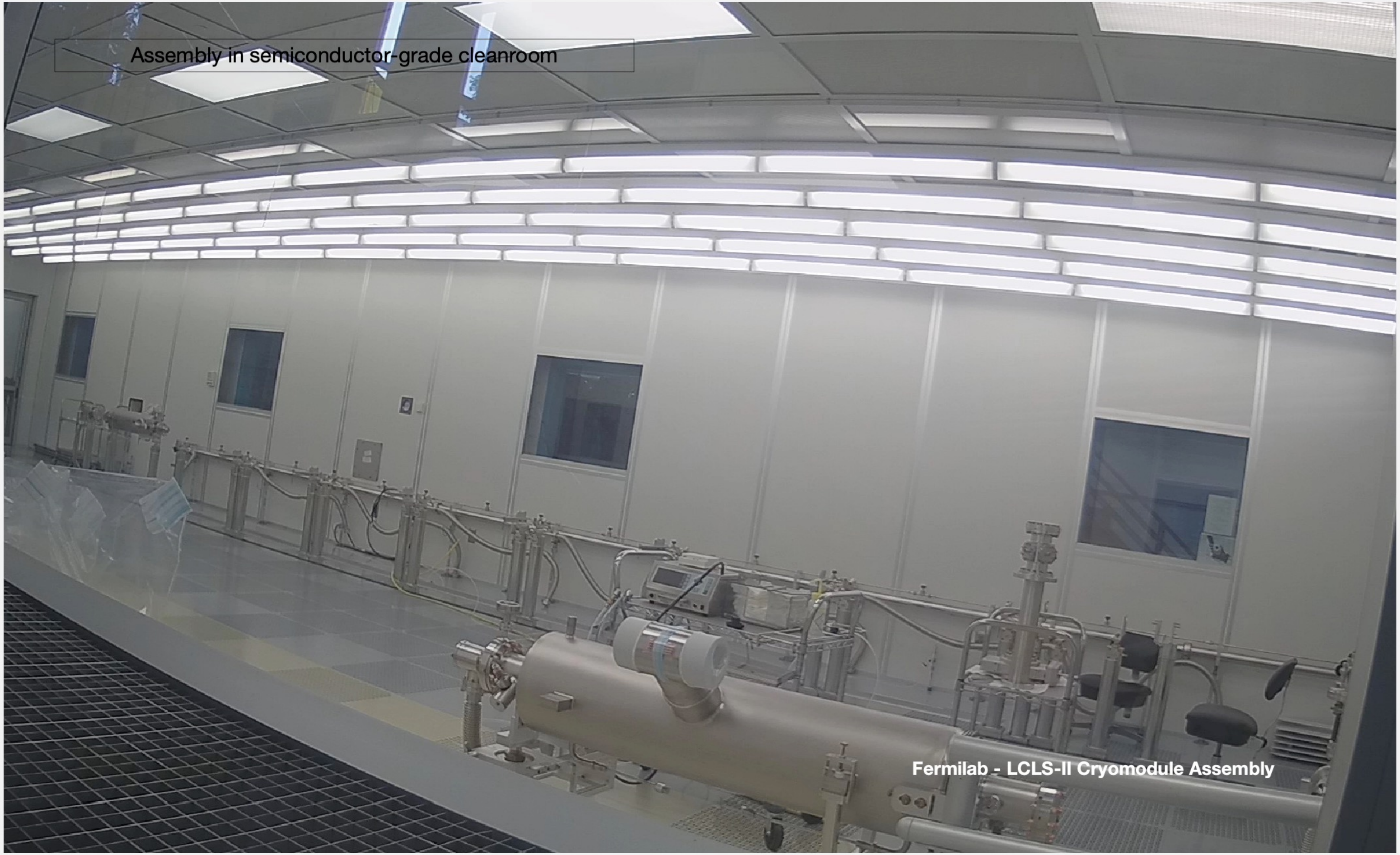
Slide by V Ngampruetikorn

1. Superconducting RF Cavities
2. **SRF for Accelerators at Fermilab – Present**
3. SRF for Detectors at Fermilab
4. Summary

LCLS-II

- X-ray free electron laser at SLAC based on SRF with 1 million pulses per second – previous copper linac had just 120 pulses per second
- Leverages new advances in high Q SRF technology
- Fermilab scope included design, assembly, and test of cryomodules, together with partners
- Successful production meeting ambitious specifications

Fermilab



Builds on designs, efforts, and facilities from ILC development

Key Enabling SRF Technologies Developed at Fermilab

- **Nitrogen doping** – add nitrogen interstitials to niobium to increase efficiency by a factor of ~3

- **Flux expulsion** – cooling of cavity with spatial thermal gradient to expel ambient magnetic fields that can otherwise degrade efficiency

- **Flux depinning** – thermal treatment to reduce tendency of niobium bulk material to trap flux

Superconductor Science and Technology

FAST TRACK COMMUNICATION

Nitrogen and argon doping of niobium for superconducting radio frequency cavities: a pathway to highly efficient accelerating structures

A Grassellino[1], A Romanenko[1], D Sergatskov[1], O Melnychuk[1], Y Trenikhina[2], A Crawford[1], A Rowe[1], M Wong[1], T Khabiboulline[1] and F Barkov[1]

Published 22 August 2013 • © 2013 IOP Publishing Ltd

Superconductor Science and Technology, Volume 26, Number 10

Citation A Grassellino *et al* 2013 *Supercond. Sci. Technol.* **26** 102001

DOI 10.1088/0953-2048/26/10/102001

Applied Physics Letters

RESEARCH ARTICLE | DECEMBER 10 2014

Ultra-high quality factors in superconducting niobium cavities in ambient magnetic fields up to 190 mG

A. Romanenko; A. Grassellino; A. C. Crawford; D. A. Sergatskov; O. Melnychuk

Check for updates

Appl. Phys. Lett. 105, 234103 (2014)

https://doi.org/10.1063/1.4903808

Journal of Applied Physics

RESEARCH ARTICLE | JUNE 03 2016

Efficient expulsion of magnetic flux in superconducting radiofrequency cavities for high *Q* applications

S. Posen; M. Checchin; A. C. Crawford; A. Grassellino; M. Martinello; O. S. Melnychuk; A. Romanenko; D. A. Sergatskov; Y. Trenikhina

Check for updates

J. Appl. Phys. 119, 213903 (2016)

https://doi.org/10.1063/1.4953087

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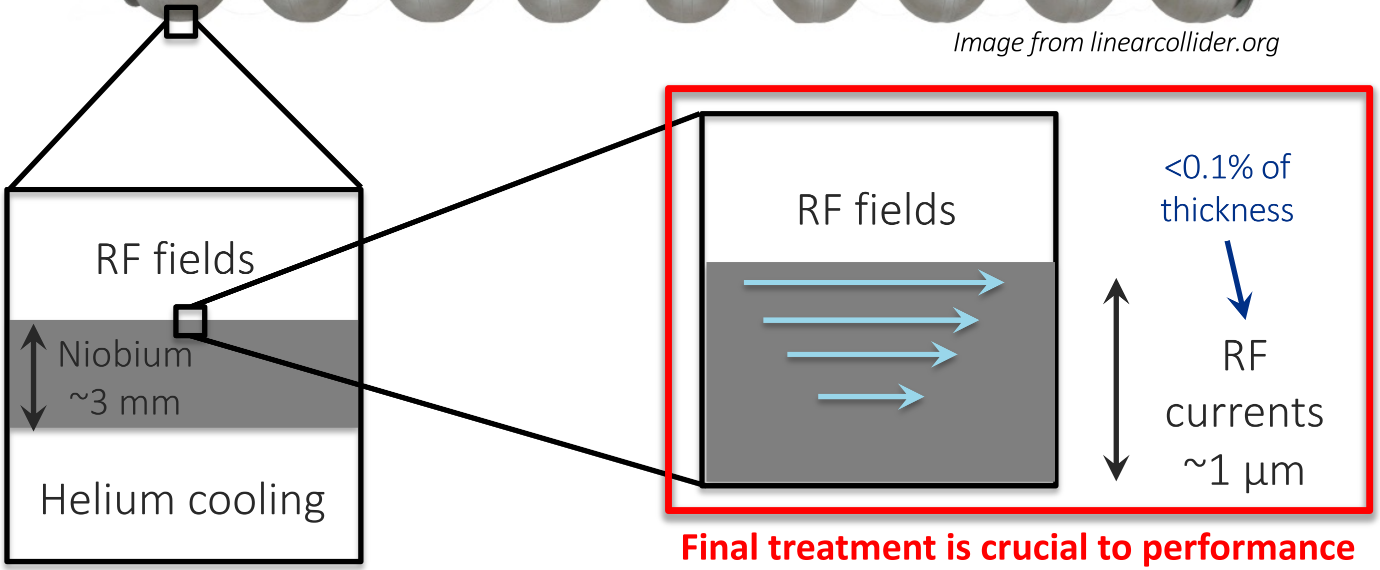
Crucial Role of Surface Layer

Image from linearcollider.org

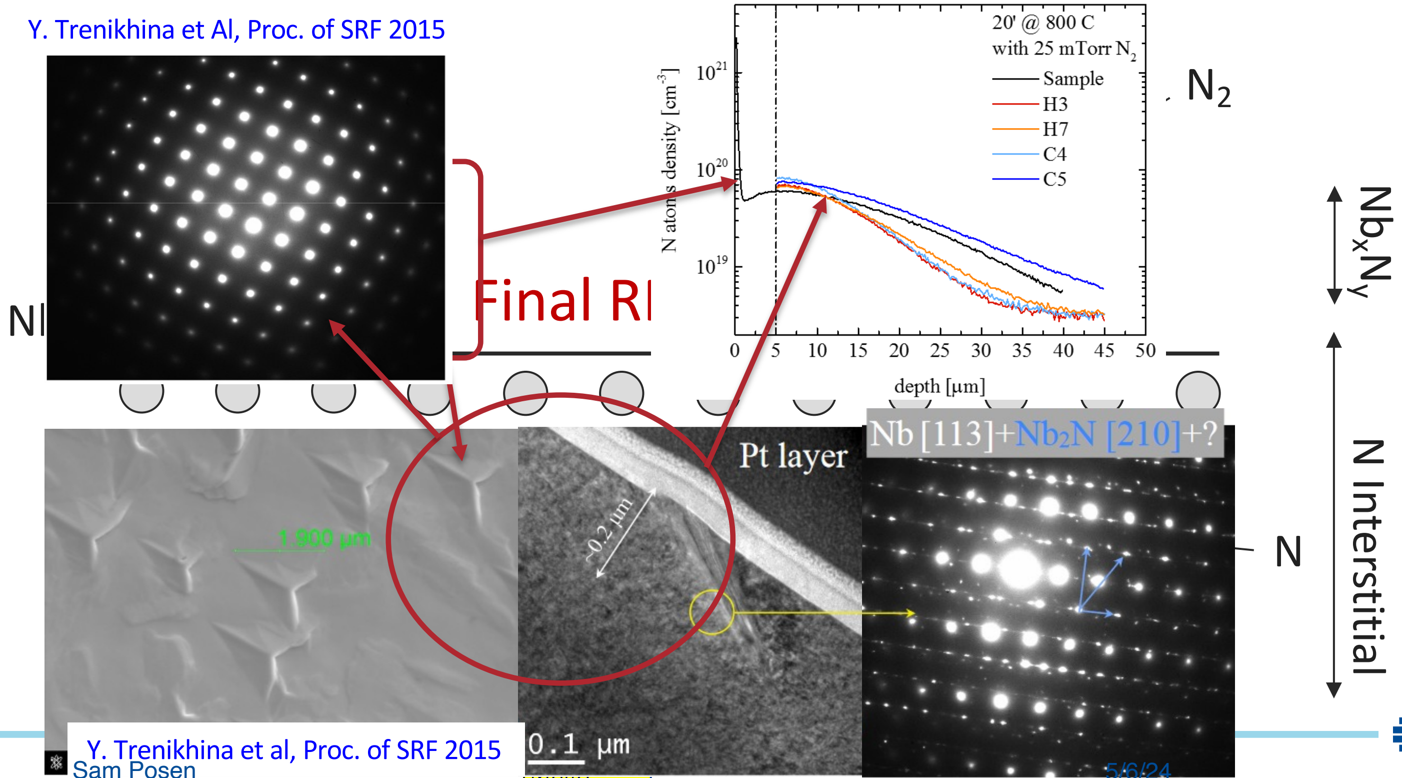


Final treatment is crucial to performance

Nitrogen Doping Treatment

800C UHV, 3 hours → 800C N_2 p = 25 mTorr 2 minutes → 800C UHV, 6 minutes → UHV cooling → 5 um EP

Y. Trenikhina et Al, Proc. of SRF 2015

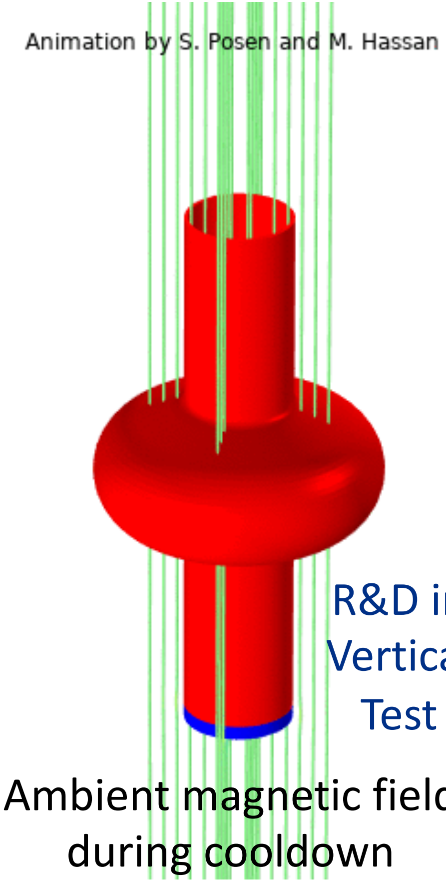


Y. Trenikhina et al, Proc. of SRF 2015

Slides adapted from M. Martinello

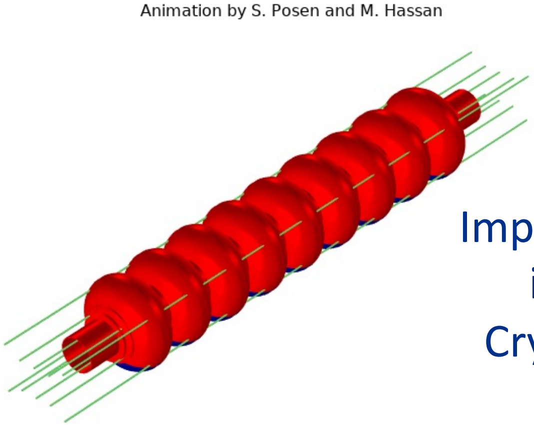
Magnetic Flux Expulsion

- Meissner Effect – well below T_c, niobium tends to expel applied magnetic flux
- However, flux can become trapped in superconductor during cooldown
- Only recently has R&D made it possible to reliably achieve strong expulsion during cooldown



R&D in Vertical Test

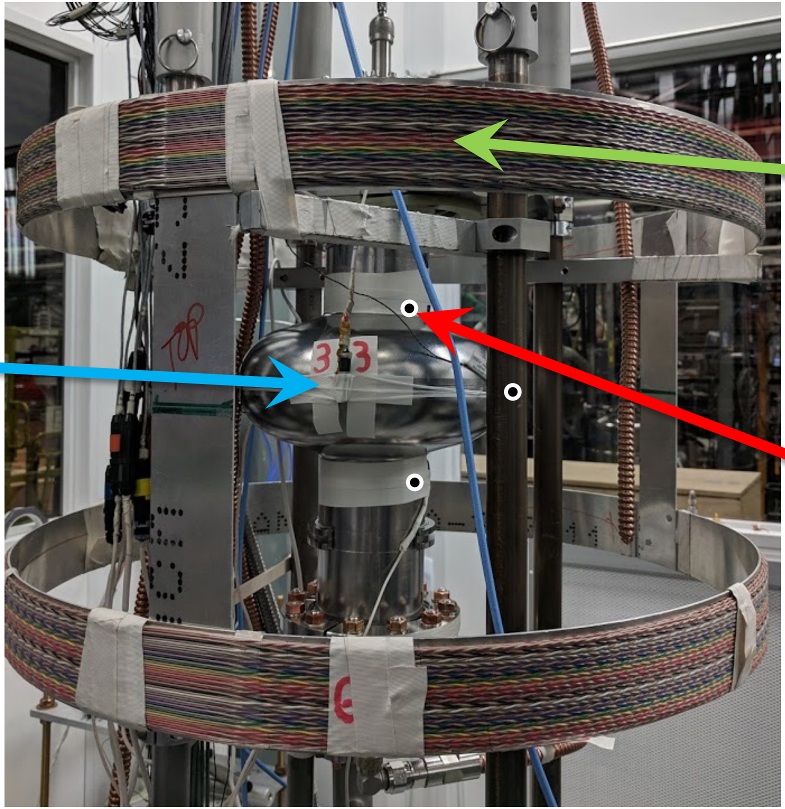
Ambient magnetic field during cooldown



Implementation in LCLS-II Cryodmodule

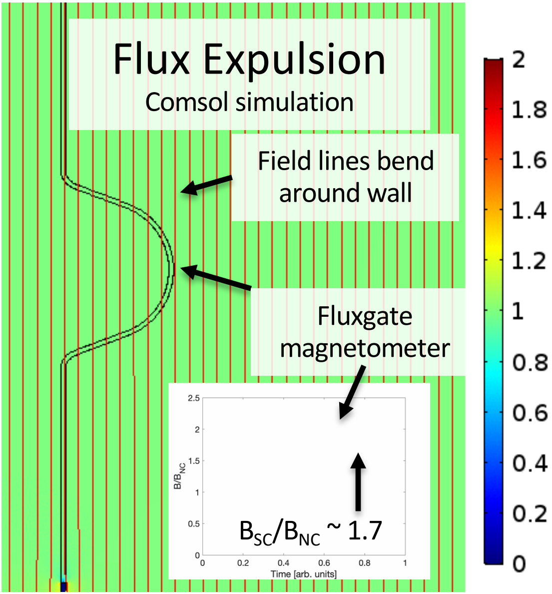
Measuring Flux Expulsion in Vertical Dewar Test

Fluxgate magnetometers
(3 around cell of cavity)

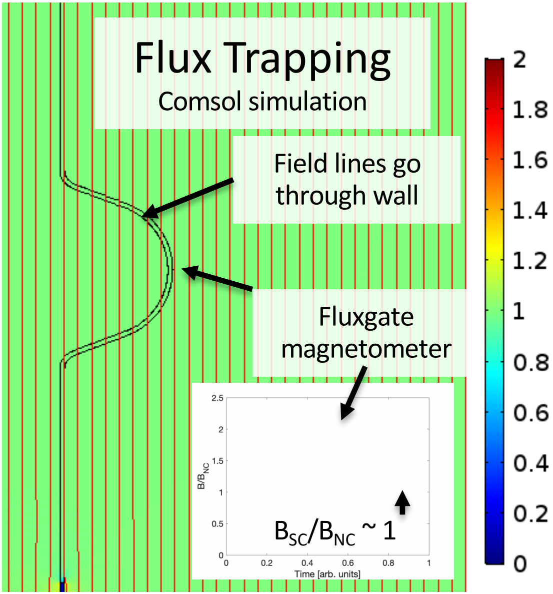


Magnetic field coils
(tens of mG applied field)

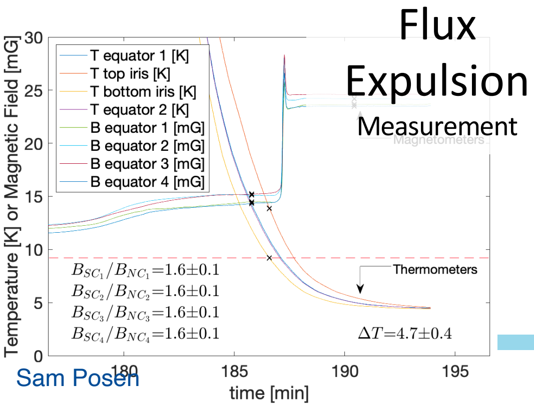
Temperature Sensors
(Top, middle, bottom of cell)



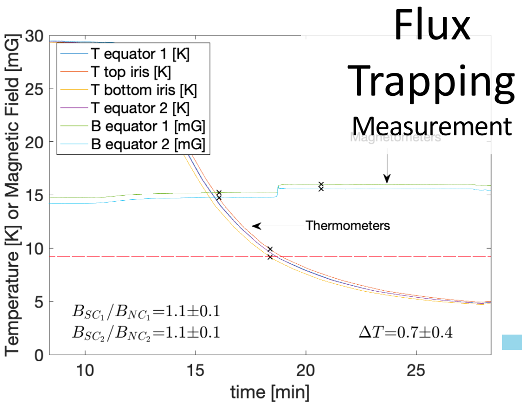
Flux Expulsion
Comsol simulation
Field lines bend around wall
Fluxgate magnetometer
B_SC/B_NC ~ 1.7
Time [arb. units]
B/B_NC



Flux Trapping
Comsol simulation
Field lines go through wall
Fluxgate magnetometer
B_SC/B_NC ~ 1
Time [arb. units]
B/B_NC



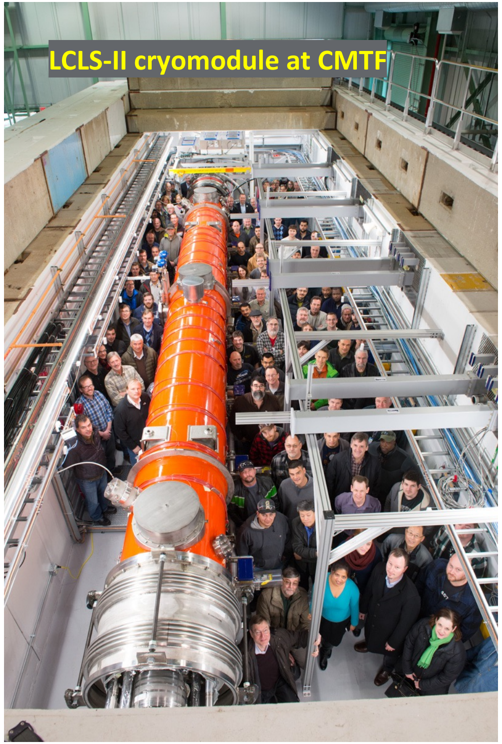
Flux Expulsion Measurement
T equator 1 [K]
T top iris [K]
T bottom iris [K]
T equator 2 [K]
B equator 1 [mG]
B equator 2 [mG]
B equator 3 [mG]
B equator 4 [mG]
Magnetometers
Thermometers
B_{SC_1}/B_{NC_1}=1.6±0.1
B_{SC_2}/B_{NC_2}=1.6±0.1
B_{SC_3}/B_{NC_3}=1.6±0.1
B_{SC_4}/B_{NC_4}=1.6±0.1
ΔT=4.7±0.4
Temperature [K] or Magnetic Field [mG]
time [min]



Flux Trapping Measurement
T equator 1 [K]
T top iris [K]
T bottom iris [K]
T equator 2 [K]
B equator 1 [mG]
B equator 2 [mG]
Magnetometers
Thermometers
B_{SC_1}/B_{NC_1}=1.1±0.1
B_{SC_2}/B_{NC_2}=1.1±0.1
ΔT=0.7±0.4
Temperature [K] or Magnetic Field [mG]
time [min]

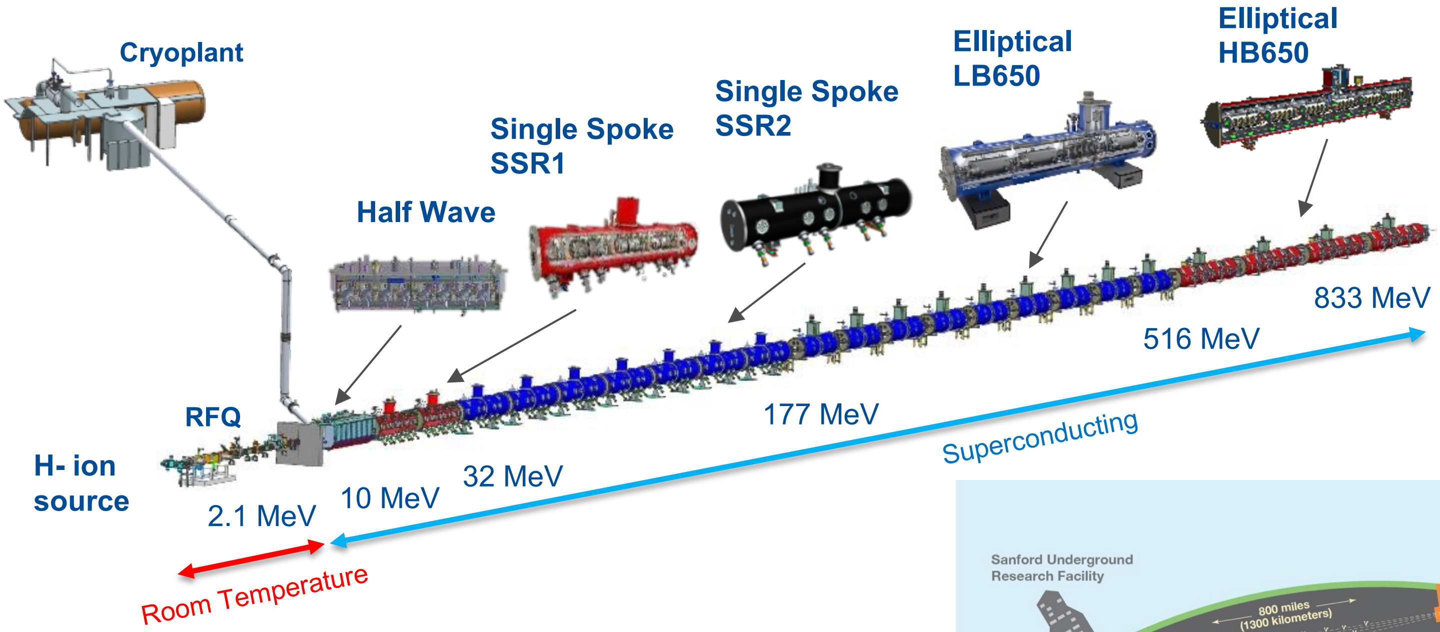
LCLS-II-HE

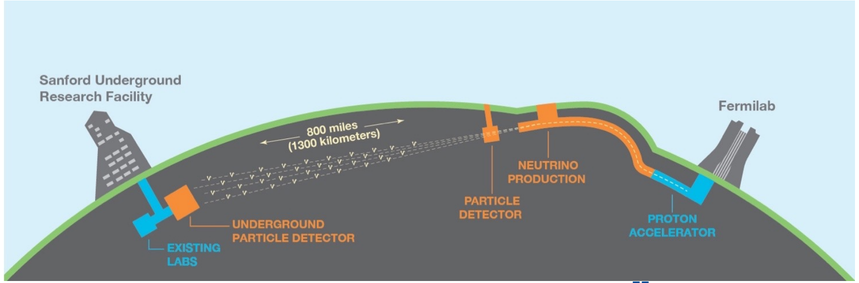
- LCLS-II was the first large-scale SRF CM production for Fermilab
- Fermilab designed, built, tested, and delivered 20 cryomodules
  - (17) 1.3 GHz cryomodules: average energy gain/CM = 158 MV (spec 128 MV), average $Q_0 = 3x10^{10}$ (spec $2.7x10^{10}$)
  - (3) 3.9 GHz cryomodules: average energy gain/CM = 46.5 MV (spec 41 MV), average $Q_0 = 3.45x10^9$ (spec $1.5x10^9$)
- **LCLS-II-HE: ~14 more CMs from FNAL** (plus more from JLab), new R&D was critical to achieve even more challenging specifications
- Production has been going well, 8 FNAL cryomodules qualified and delivered to date
- LCLS-II-HE was enabled by the success of high Q for LCLS-II: only 1 cryoplant is needed for operations so the second is available for the high energy upgrade



PIP-II superconducting CW linac

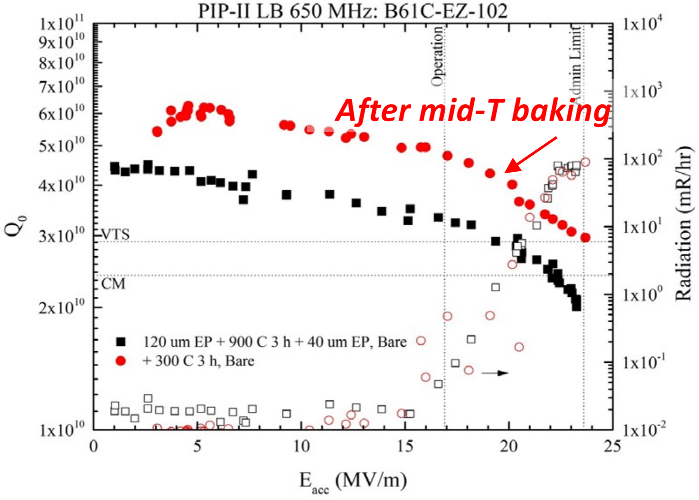
- PIP-II linac is technically complex, state of the art superconducting RF accelerator

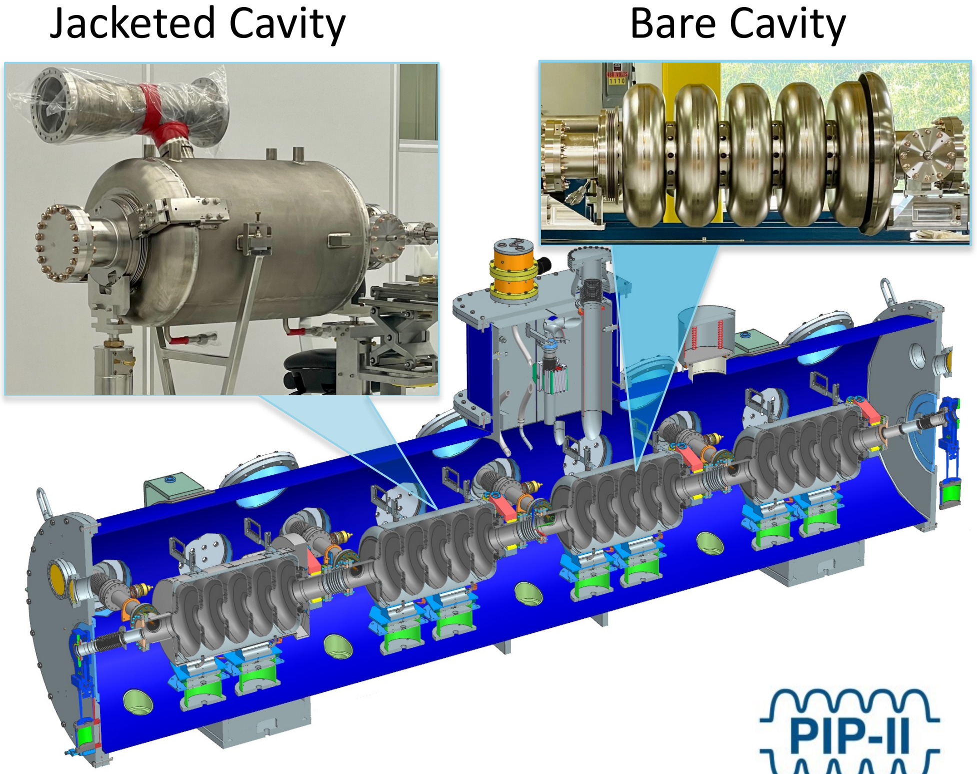




SRF Innovations Applied to PIP-II

- PIP-II LB650 cryomodules will use the mid-T bake, a simple process to improve Q developed at Fermilab that has been widely adopted by SRF community
- Impurity diffusion using native oxide as opposed to added nitrogen

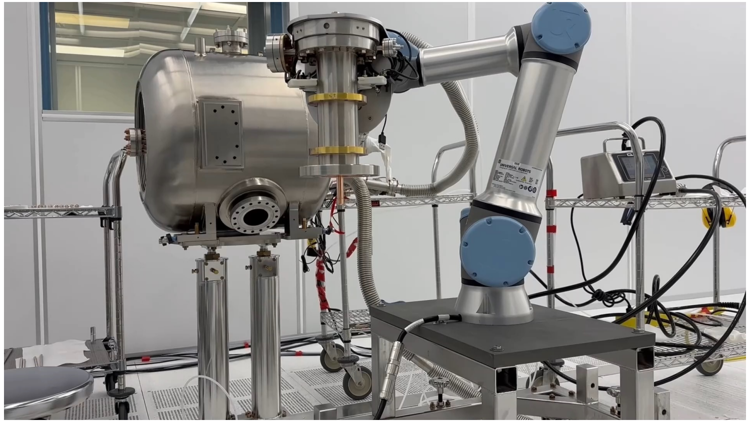




SRF Innovations Applied to PIP-II

PIP-II

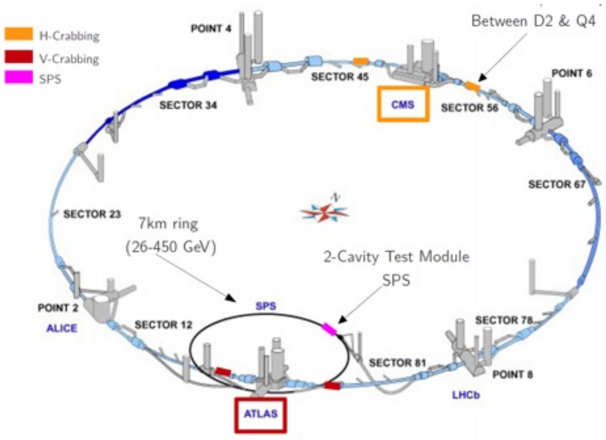
- Cleanroom robotics used to install RF power couplers for PIP-II SSR2 cavities
- Precise alignment and smooth movement of heavy coupler
- Cavity qualified in cold test after assembly
- Benefits vs conventional methods:
  - Improved ergonomics, reduced risk of particulate contamination
  - Milestone step towards cleanroom automation of certain steps to reduce costs, reduce risk, increase throughput

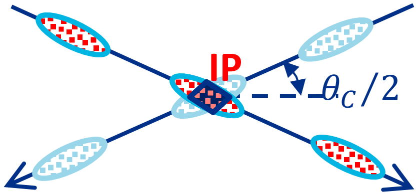


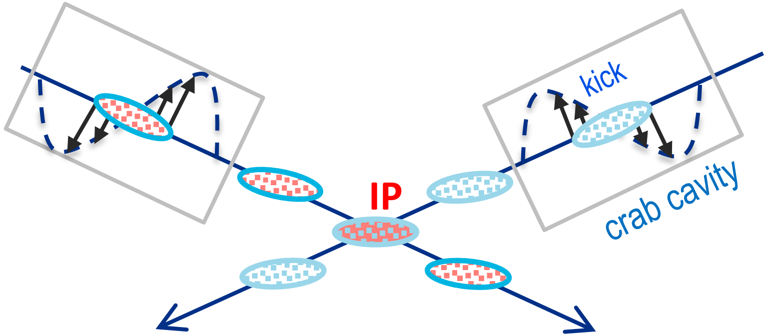
Video sped up 5x

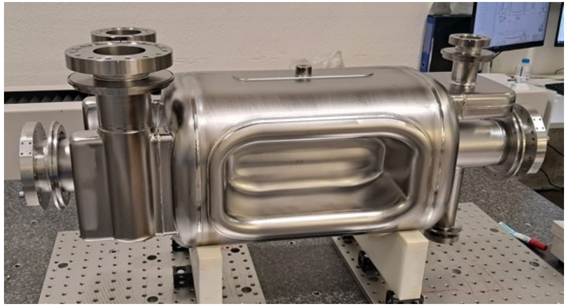
HL-LHC Accelerator Upgrade Project (AUP)

- Fermilab is leading US HL-LHC Accelerator Upgrade Project (AUP)
- Includes production of 10 crab cavities which will rotate the bunches to allow for more collisions per unit time at interaction regions
- Prototyping was successful and production has started







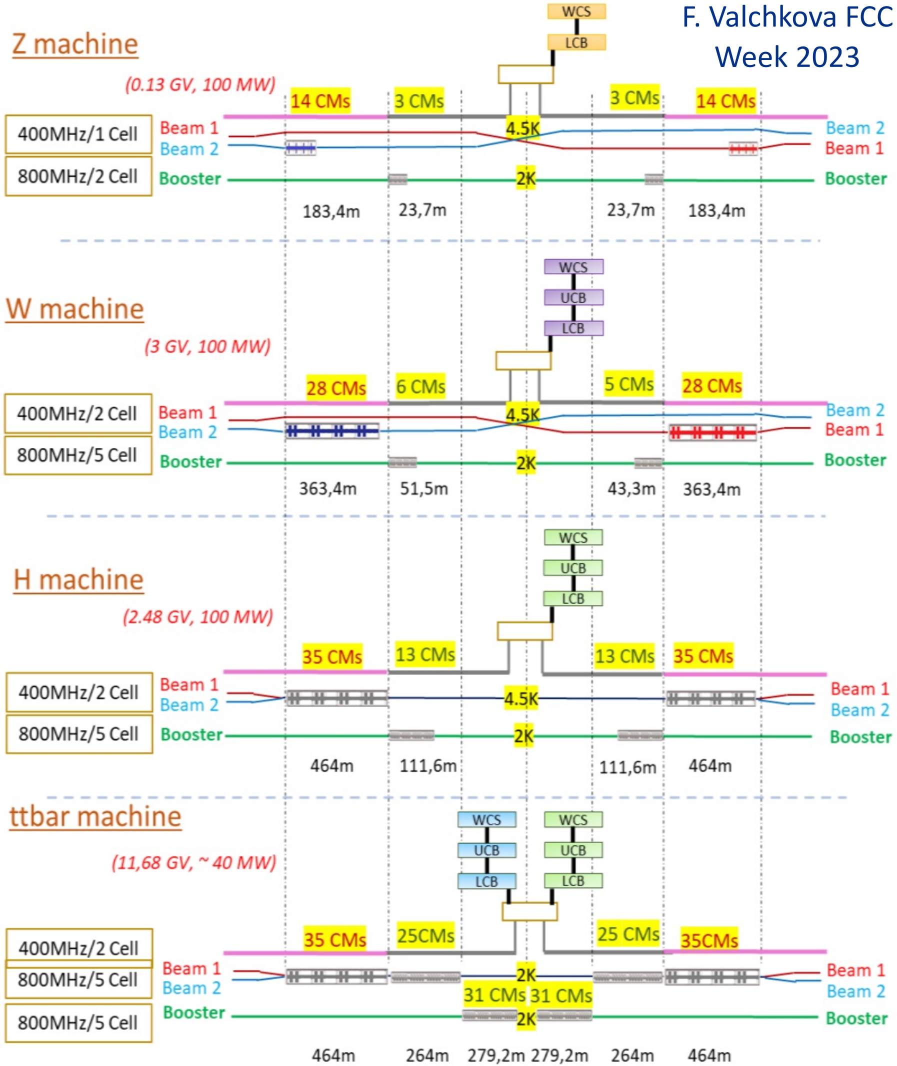


1. Superconducting RF Cavities
2. **SRF for Accelerators at Fermilab – Future**
3. SRF for Detectors at Fermilab
4. Summary

FCC-ee

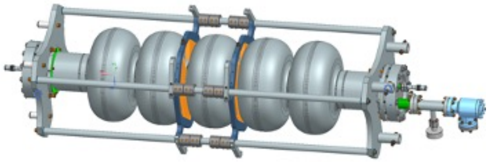
- Next big collider under study at CERN
- Highest energies require substantial RF to make up for synchrotron radiation
- FCC-ee involves stages over years, and later stages involve many 800 MHz cryomodules ~150 CMs overall
- High Q advances can be greatly impactful for power costs and sustainability

F. Valchkova FCC Week 2023

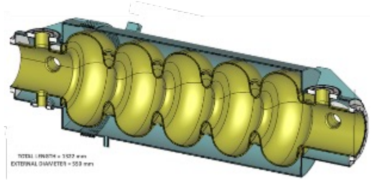


FCC-ee

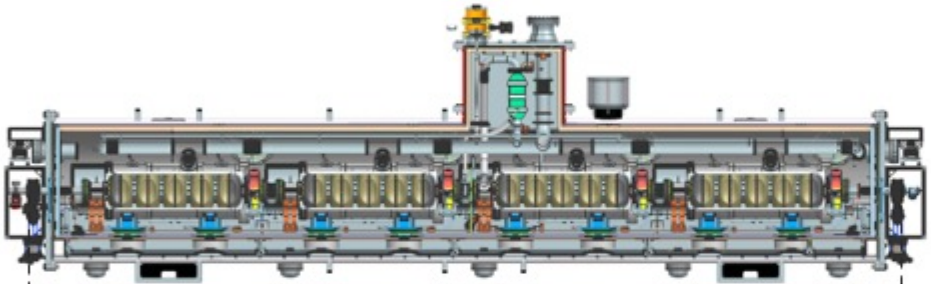
- Great opportunity for US involvement in SRF for FCC-ee
- Collaborative R&D is underway with CERN, including high Q treatment studies on prototype 800 MHz cavities
- Cryomodule design studies are starting as well



5-cell cavity with testing fixtures



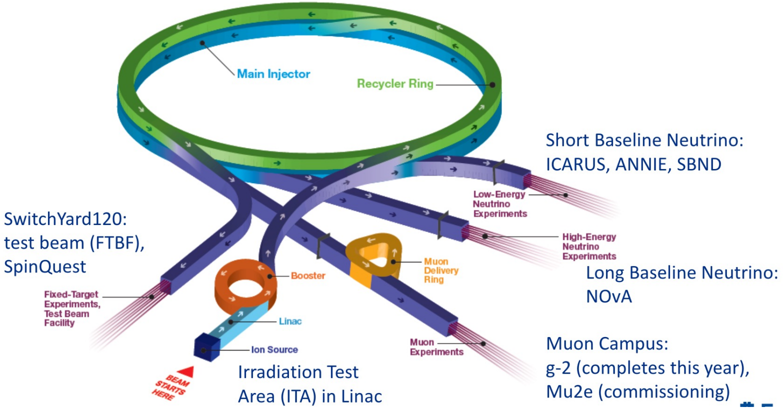
Concept of jacketed cavity

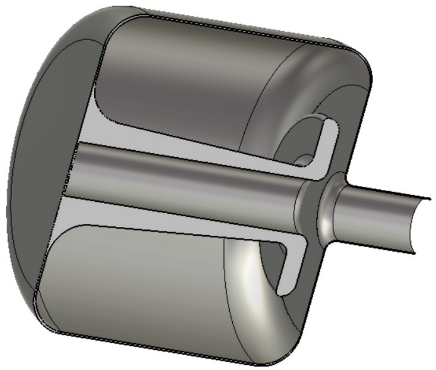


Segmented cryomodule concept with 800 MHz cavities

Widely Tunable SRF Cavity

- To deliver more proton power to Fermilab’s neutrino experiment LBNF/DUNE, plan to reduce the cycle time of the Main Injector ring from 1.3 s to 0.7 s
- Requires faster ramping magnets and more RF power
- Now performing conceptual R&D for widely tunable SRF cavity – a few SRF cavities could achieve similar voltage to ~20 normal conducting cavities
- Starting collaboration with Cornell



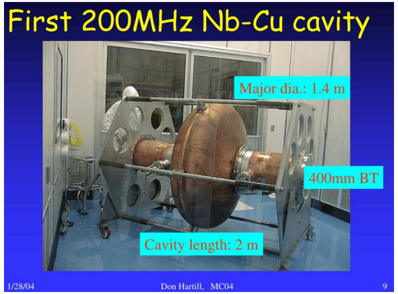


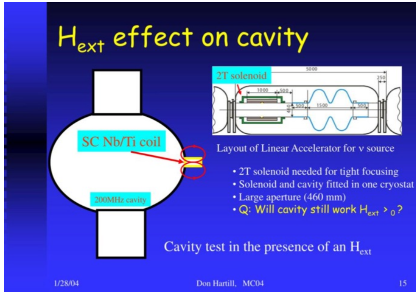
ACE-MIRT tunable SRF cavity concept

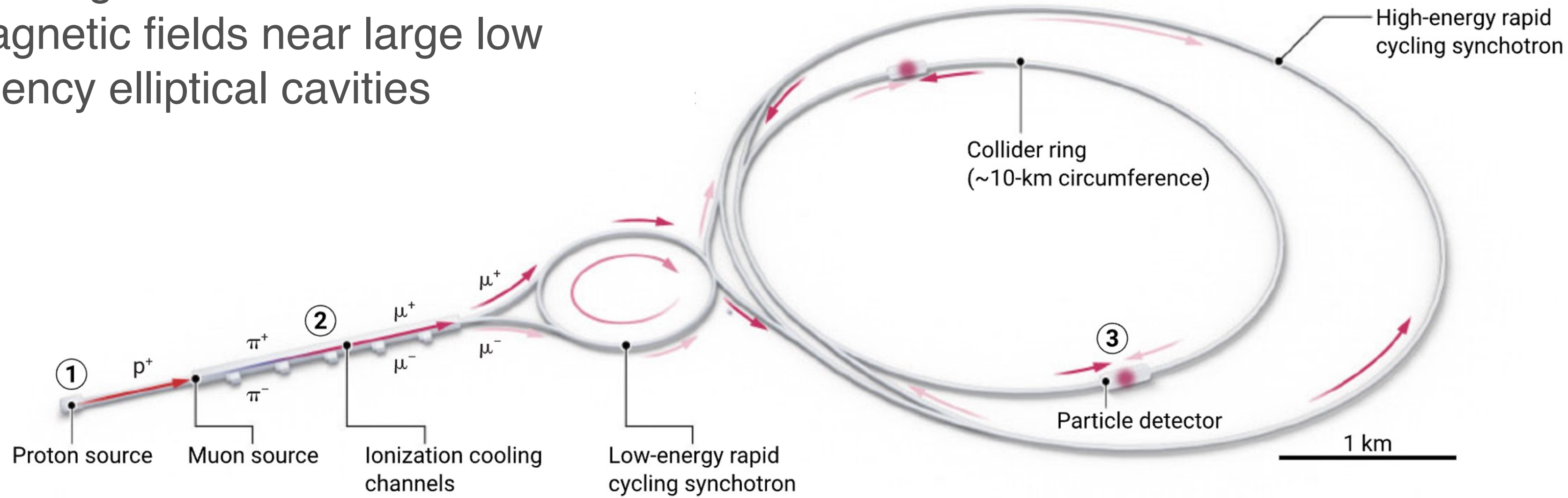
Fermilab

The Path to a Muon Collider

- Potential large SRF installations in muon collider scheme include driver, early stages of accelerator (recirculating linear accelerator)
- Pioneering work at Cornell studies effects of magnetic fields near large low frequency elliptical cavities







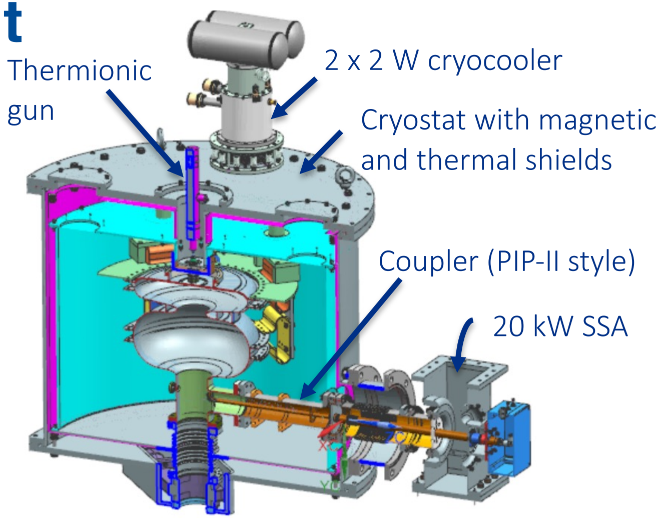
Images from Science Magazine, Don Hartill

Other SRF Accelerators Under Development

- **Compact SRF accelerators using Nb_3Sn** – applications in wastewater treatment, isotope production, cargo scanning, electron microscopy and more

- **Electron Ion Collider (BNL)**

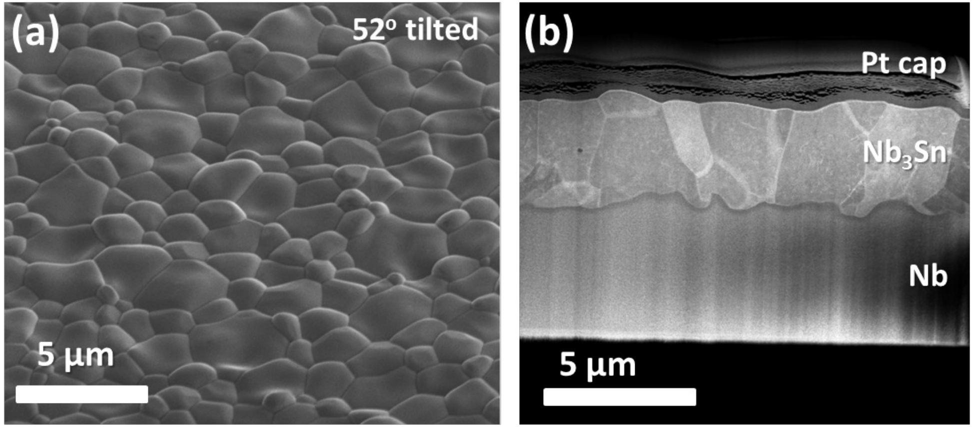
- **xLight** – partnership with industry to develop SRF ERLs for semiconductor lithography



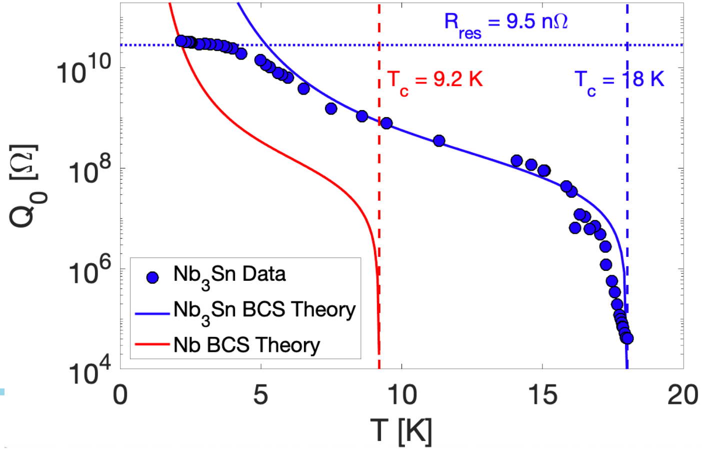
https://news.fnal.gov/2024/04/new-collaboration-sheds-bright-light-on-advancing-semiconductor-production-in-the-u-s/

Nb_3Sn SRF Coatings

- Nb_3Sn has substantially higher T_c than Nb (18 K vs 9 K)
- High Q_0 at relatively high temp.
  - Potential for high $Q_0 > 10^{10}$ in ~4.5 K operation in liquid helium
  - Potential for replacing cryoplant with cryocoolers
  - Even eliminating liquid helium via conduction cooling
- Impacts for high duty factor applications, especially small and medium-scale
- Predicted potential for maximum fields higher than Nb



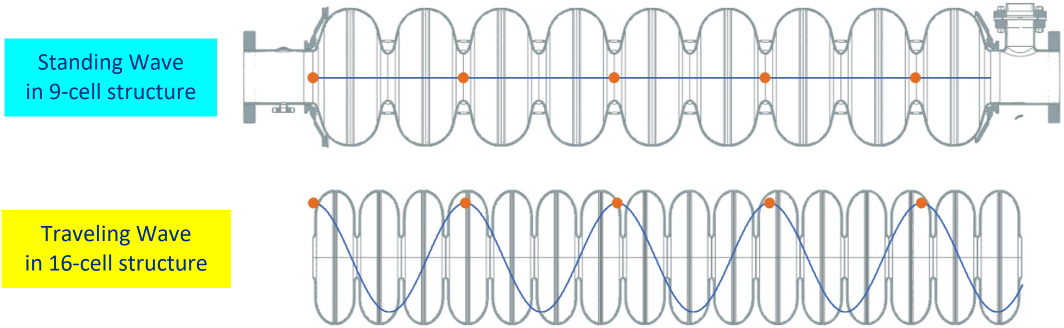
SEM images of Nb_3Sn film coated on Nb: a) surface, b) cross section



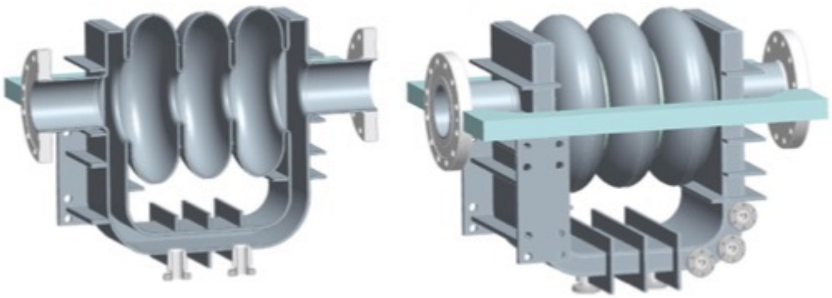
Travelling Wave SRF for future accelerators

Traveling Wave (TW) SRF cavity development

- Why TW? $\rightarrow > 20\%$ increase in acceleration per cryomodule
- Still a lot to do before this technology can be applied to accelerators.
- 3-cell prototype cavity currently undergoing experimental studies



Cavity on high pressure rinse stand

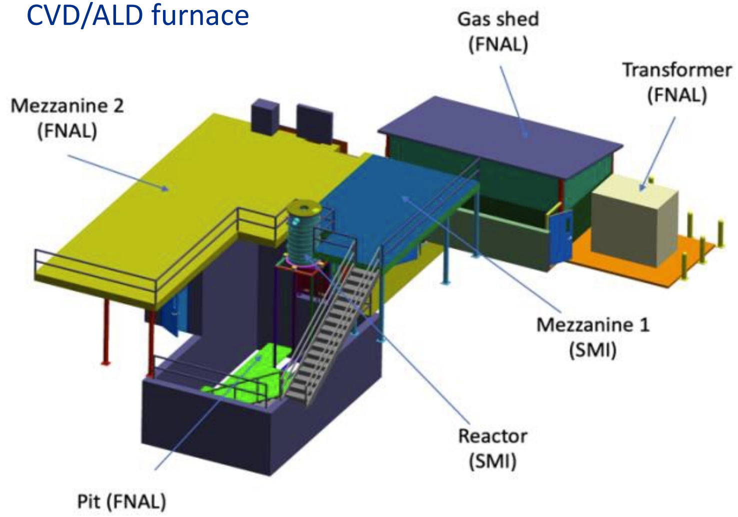


3D model of proof-of-principle cavity

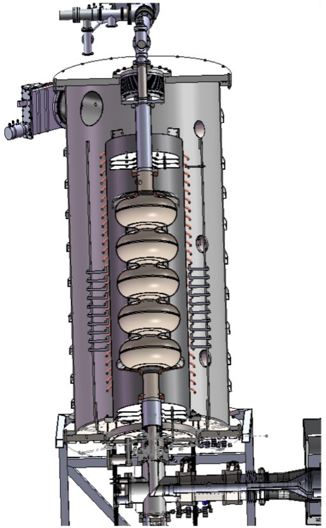
New furnace for advanced SRF materials and treatment

- Will be used to study new SRF materials, new ‘capping’ layers, multi-layered structures, novel heat treatments
- 2 configurations to achieve up to 1400℃
- 150 kW induction heating, two independent vacuum volumes, base pressure $< 10^{-7}$ Torr, capacity for large cavities

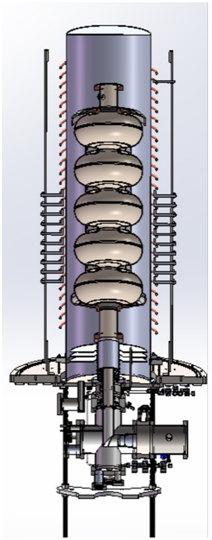
CVD/ALD furnace



Up to 400℃ (ALD)



Up to 1400℃



1. Superconducting RF Cavities
2. SRF for Accelerators at Fermilab
3. **SRF for Detectors at Fermilab**
4. Summary

SQMS

28 Partner Institutions

>450 Collaborators

A DOE National Quantum Information Science Research Center

Fermilab | Northwestern University | rigetti | AMES National Laboratory, Creating Materials & Energy Solutions | NASA Ames Research Center | NIST

Colorado School of Mines, Earth • Energy • Environment | FormFactor™ | Goldman Sachs | Illinois Institute of Technology | INFN | Jefferson Lab

Johns Hopkins University | Lockheed Martin | LSU | NPL National Physical Laboratory | NYU | Royal Holloway University of London

Rutgers, The State University of New Jersey | Stanford | Temple University | Unitary Fund | The University of Arizona | University of Colorado Boulder

University of Illinois Urbana-Champaign | University of Minnesota, Driven to Discover® | Università di Pisa | University of Waterloo | IQC Institute for Quantum Computing

A rich **ecosystem**, multi-institutional and multidisciplinary collaboration **leveraging investments** at DOE national labs, academia, industry and several other federal and international entities

SQMS Physics and Sensing Team

Fermilab

Northwestern University

University of Minnesota
Driven to Discover®

The University of Arizona

LSU

Johns Hopkins University

University of Illinois Urbana-Champaign

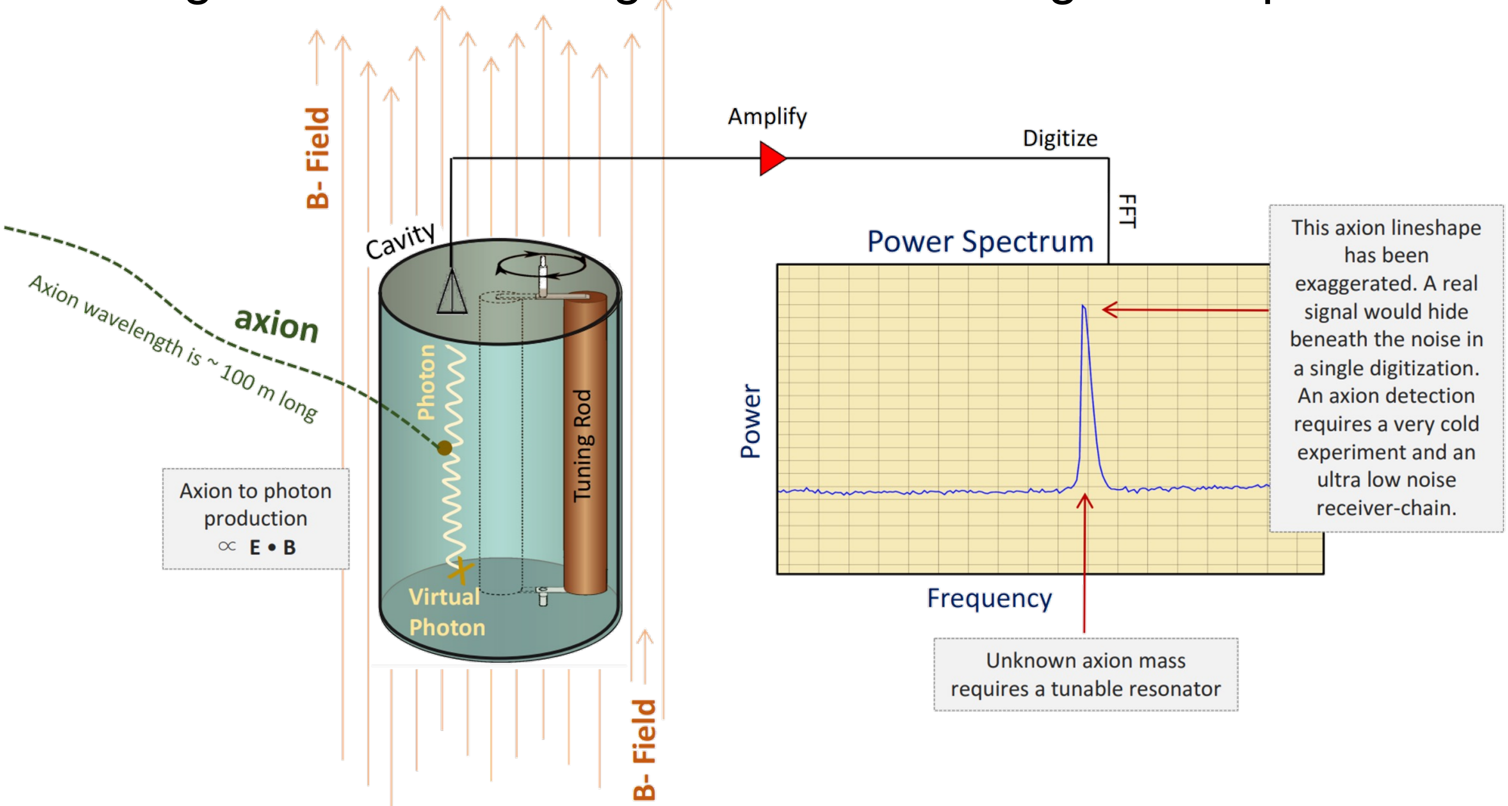
INFN

Stanford

Theorists and experimentalists working closely. Experts in HEP, materials, SRF, sensing, QIS, RF engineering.

Haloscope Searches for Dark Matter

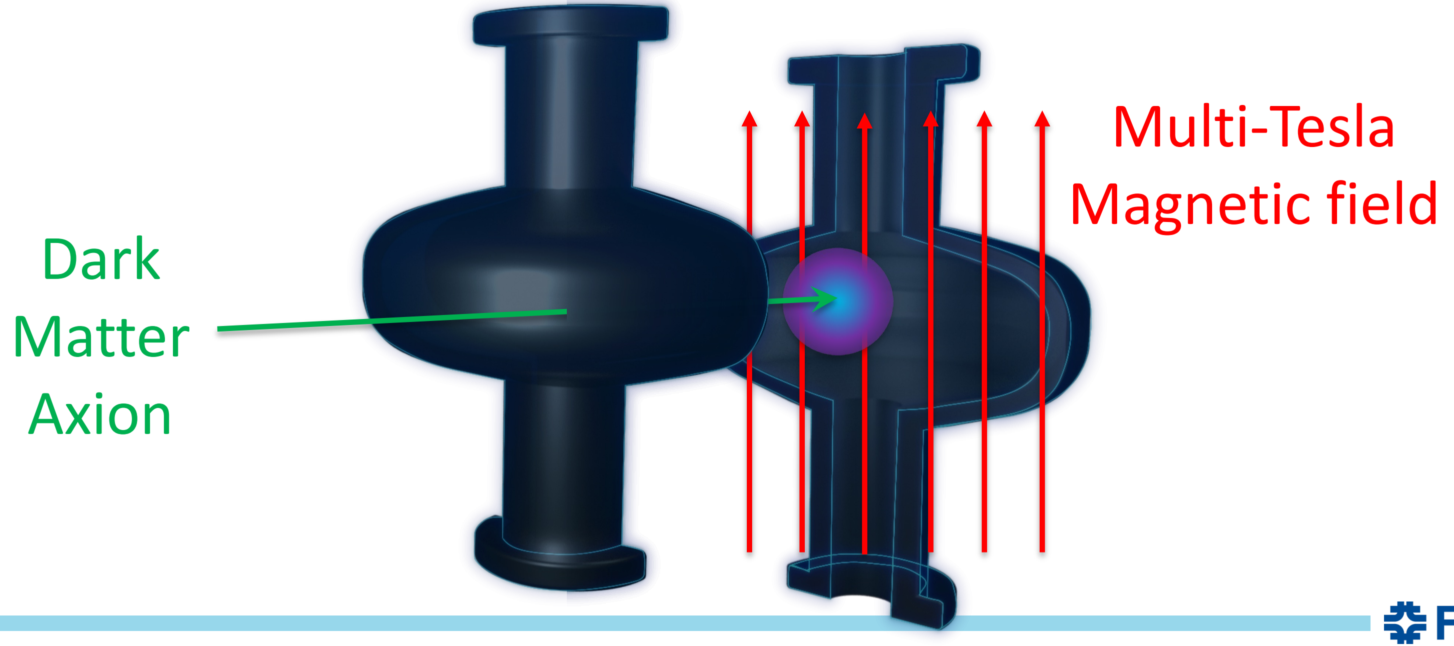
Looking for $< 10^{-24}$ W signal over wide range of frequencies.



Boutan, "A piezoelectrically tuned RF-cavity search for dark matter axions" (2017)

Nb_3Sn SRF for Quantum (part of SQMS Quantum Center)

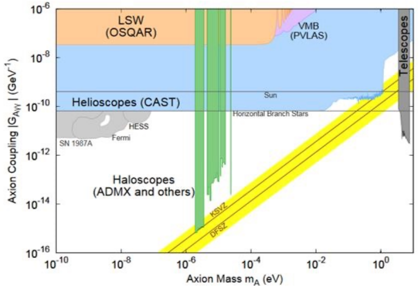
- **Haloscope**: dark matter axion conversion to microwave photon in magnetic field
- Cavity frequency must match axion mass to be sensitive to it
- Sensitivity improves with higher magnetic field, higher cavity Q_0

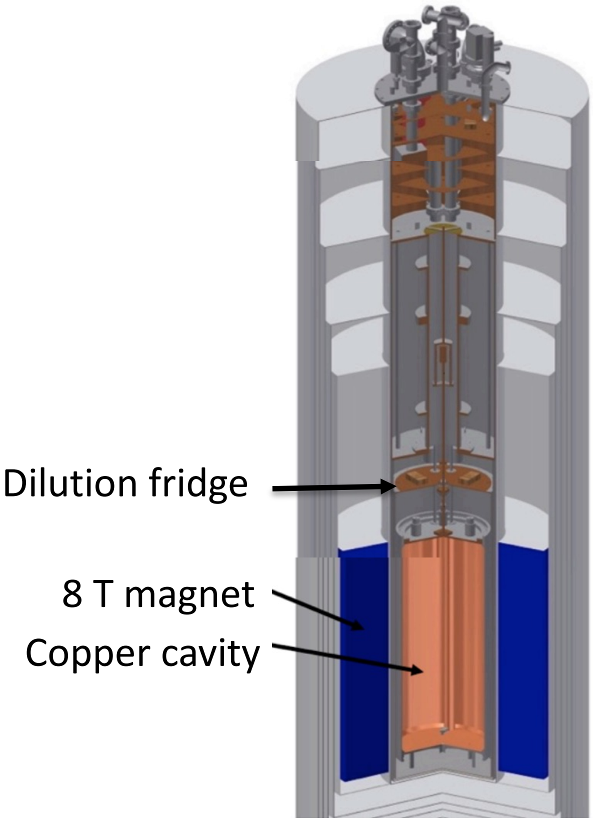


Fermilab

Current State of the Art Axion Searches

- Operating haloscopes like ADMX use normal conducting cavities (typically copper)
- They have reached desired exclusion limit for a small range of masses, but a very wide mass range remains
- Scan rate scales as $d\nu/dt \propto B^4V^2Q/2T_{sys}$
  - B (magnetic field), V (cavity volume), Q (cavity quality factor), T_{sys} (system noise temperature)
- Q improvement is promising path to improving rate of scanning substantially
- **Nb_3Sn is well suited due to its very high upper critical field, ~30 T** (for comparison: Nb ~0.4 T, NbTi ~15 T)



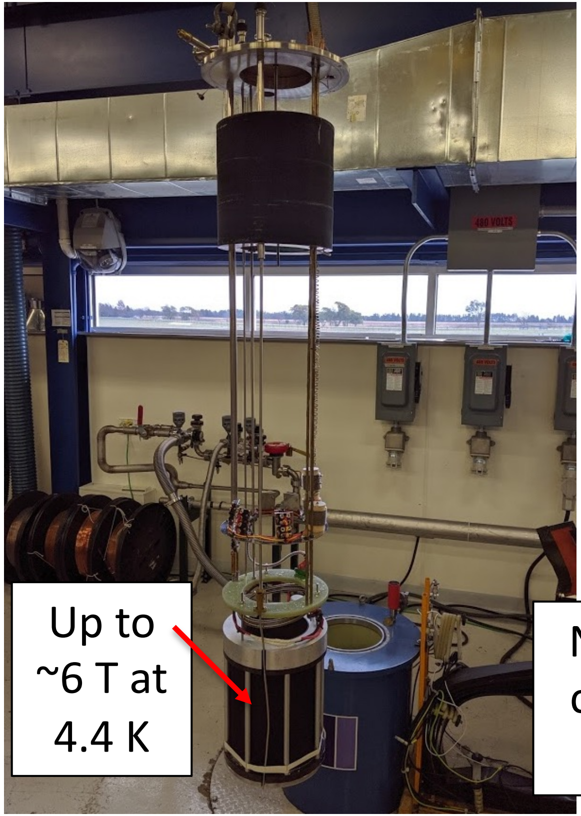


From ADMX

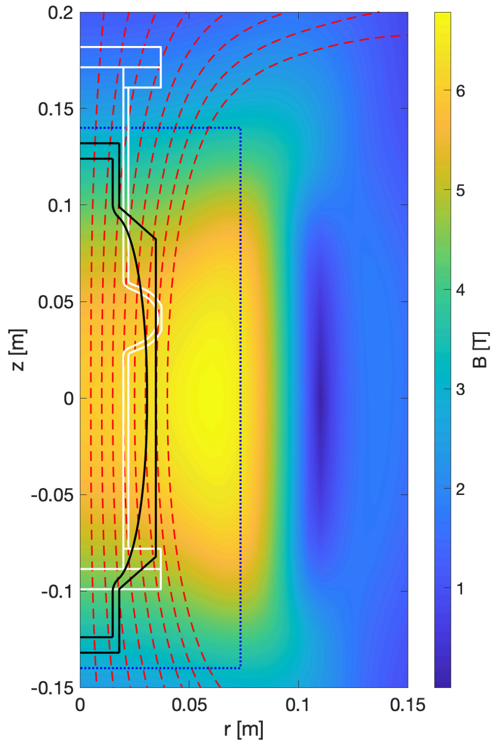
https://arxiv.org/pdf/1405.3685.pdf & https://indico.cern.ch/event/606690/contributions/2655459/attachments/1498473/2332791/Axion_Overview_TAUP_2017_Final.pdf

Evaluation of Nb_3Sn for Haloscopes

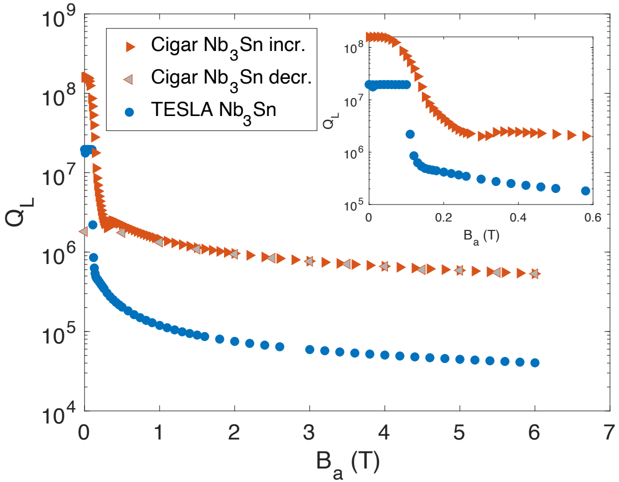
- First evaluation of Nb_3Sn SRF cavity in vortex state – test on 3.9 GHz cavity that was originally coated for accelerator cavity studies
- Use existing test stand typically used to evaluate magnet wires at multi-telsa fields
- In parallel, fabricating cavity with improved geometry for operating in magnetic fields

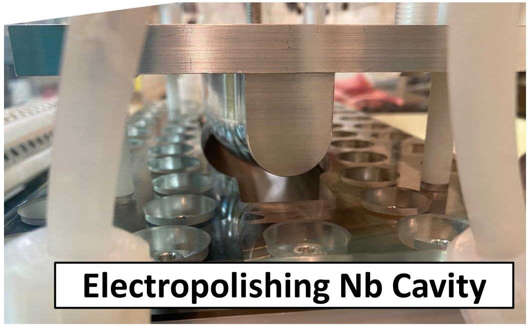


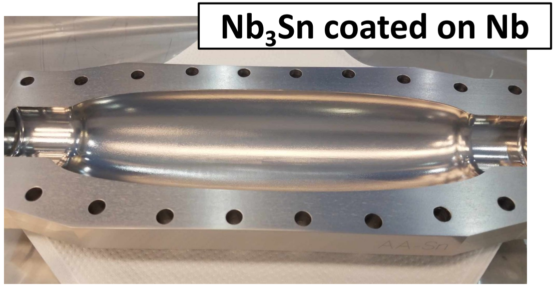
High Q Nb_3Sn SRF Cavity in Multi-Tesla Field

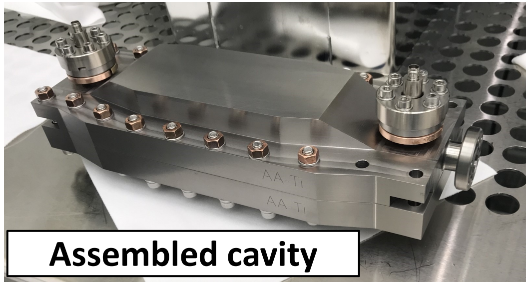


- Quality factor of $5x10^5$ in 6 T field at 4.2 K – substantial improvement over copper
- Exciting for speeding up axion dark matter search



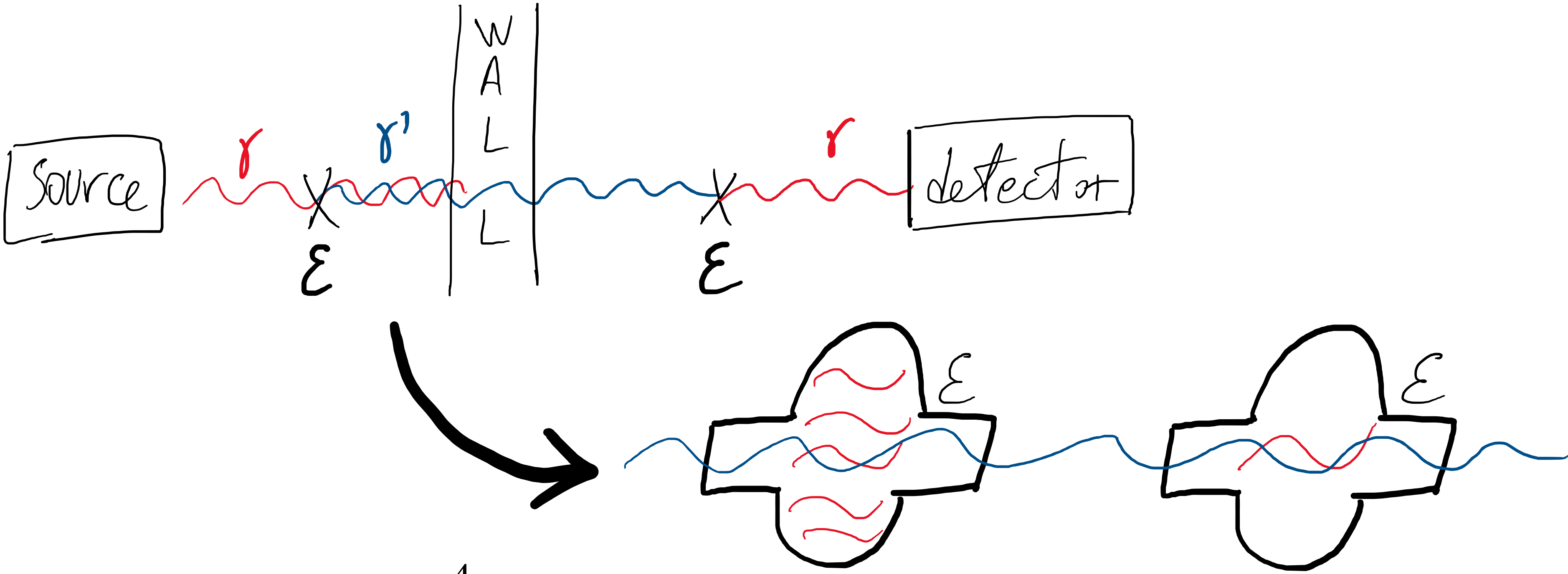






Posen et al., "Measurement of high quality factor superconducting cavities in tesla-scale magnetic fields for dark matter searches" Phys. Rev. Applied 20, 034004 (2023)

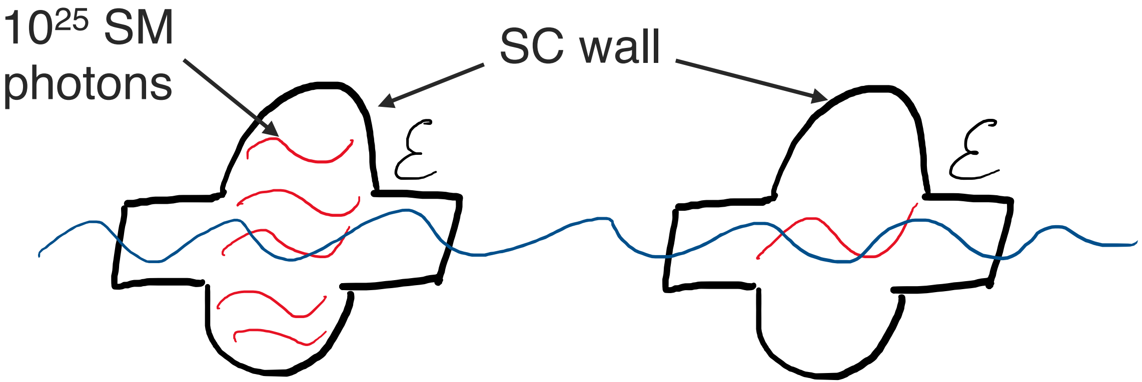
Light-Shining-through-Wall searches



$$P_{rec} = \epsilon^4 \left(\frac{m_{\gamma'}}{\omega}\right)^4 |G|^2 \, \omega \, Q_{rec} \, U_{em}$$

Graham et al., Phys Rev D90, 075017 (2014)
Romanenko et al., Phys. Rev. Lett. 130, 261801 (2023)

Advantage of using high Q cavities



Emitter cavity, in the accelerator regime, high field

Receiver cavity, in the low field regime

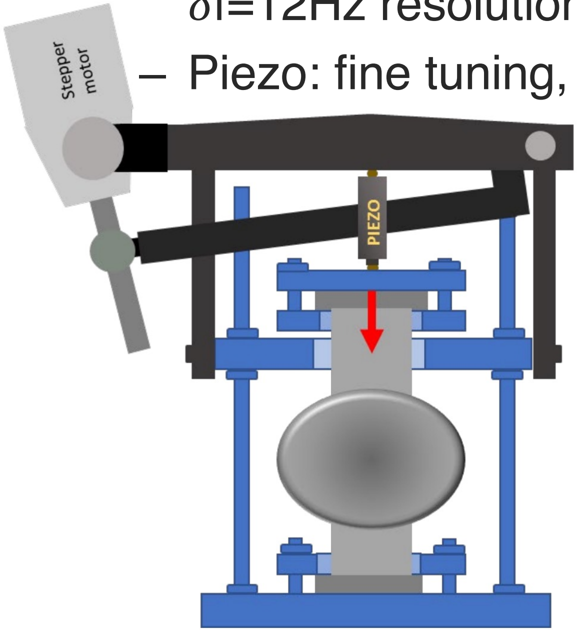
bility

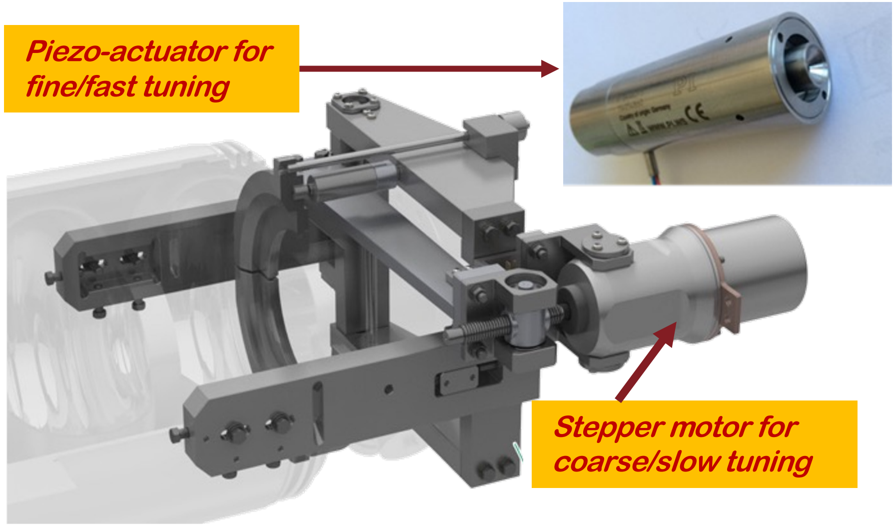
ss

Necessary to match cavities frequency!

Cavity tuning

- LCLS II double lever tuner to tune “transmitter” cavity
- Tuner mounted on emitter cavity and preloaded
  - Stepper motor: coarse tuning with Δx=2mm or Δf=5MHz, and δx=5nm or δf=12Hz resolution
  - Piezo: fine tuning, Δx=3um or Δf=8KHz, and δx=0.05nm or δf=0.1Hz resolution



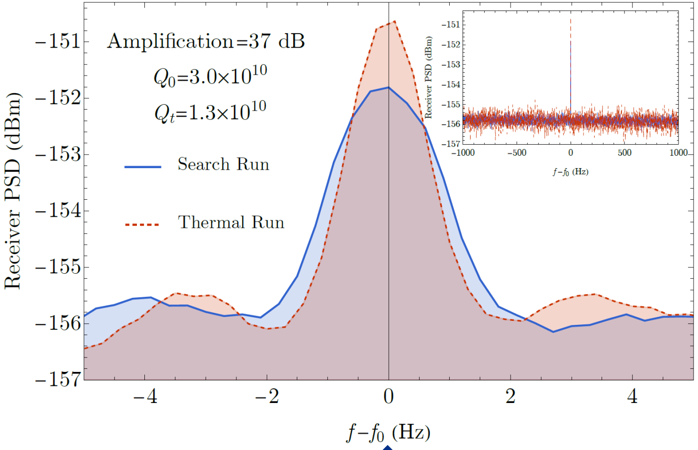


Pischalnikov et al., doi:10.18429/JACoW-SRF2019-TUP085

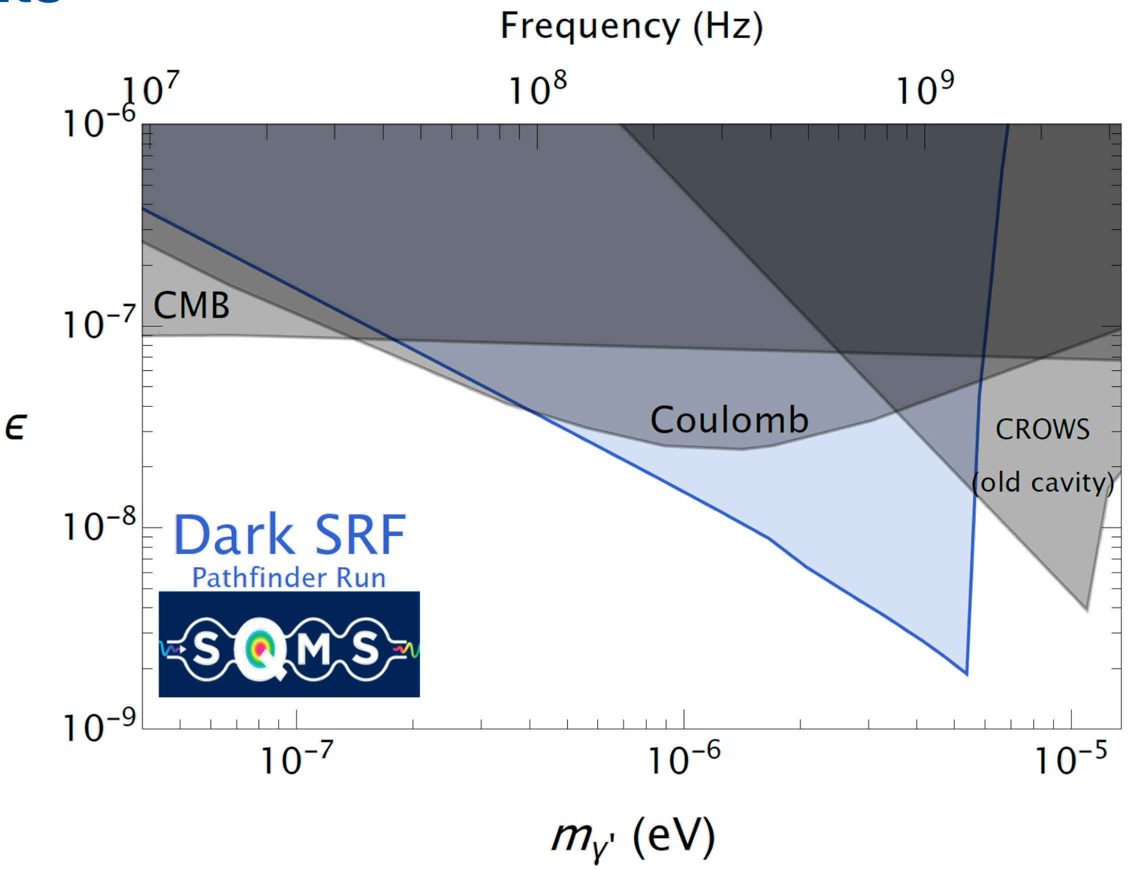
Dark SRF: phase 1 → results

Thermal run vs Search run

Search run conducted at
6.2 MV/m (= 0.6 J stored energy)



Leak of thermal photon
from receiver input line



Romanenko et al., Phys. Rev. Lett. 130, 261801 (2023)

Fermilab

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Search for Dark Photons with Superconducting Radio Frequency Cavities

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

Phys. Rev. Lett. **130**, 261801 – Published 26 June 2023

More

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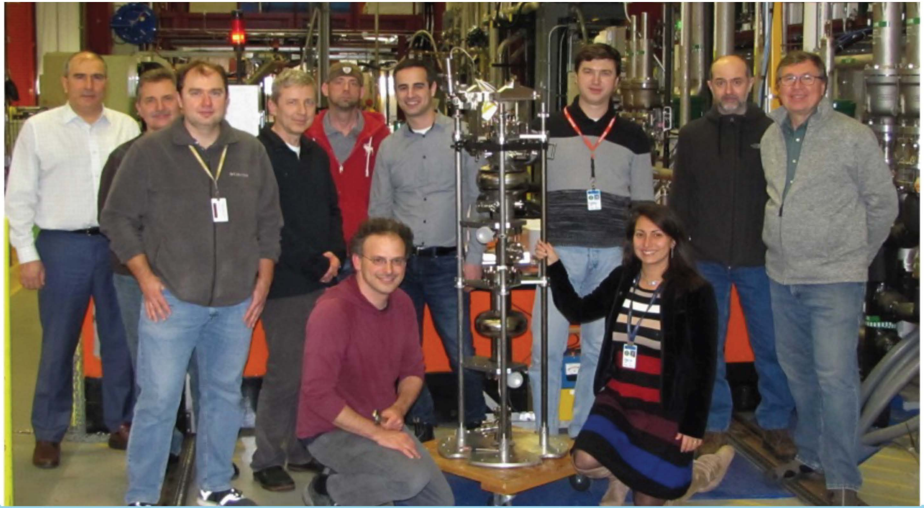
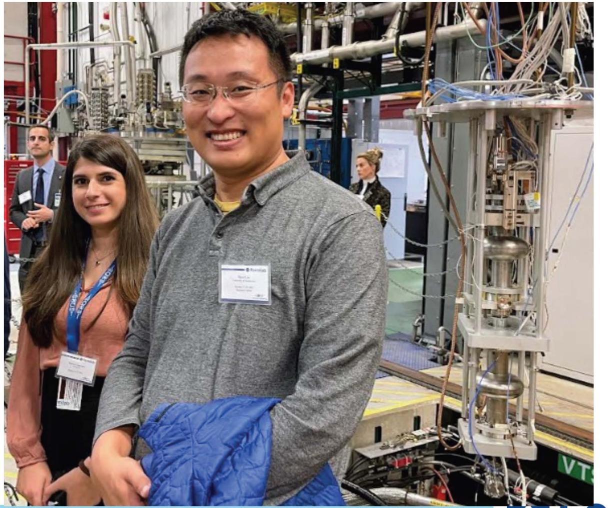
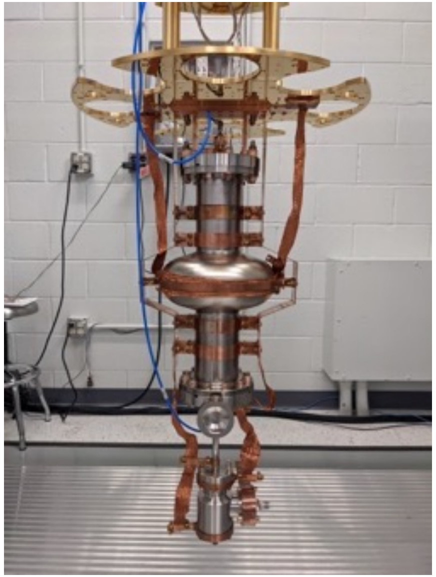




SRF Cavities for Dark Matter Searches



SQMS $\rightarrow Q \approx 10^{10}$

Compared to state-of-the-art

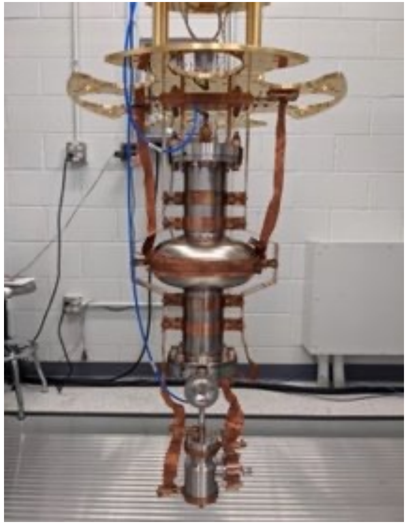
Credit: N. Du

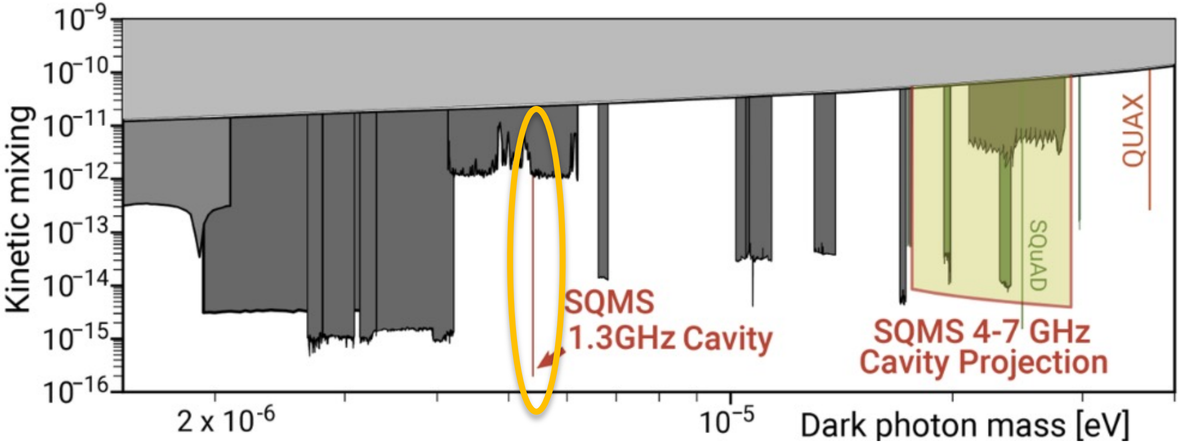
ADMX $\longrightarrow Q \approx 8 \times 10^4$

High Q allows for larger signal and lower noise floor.

Possibly factor 10^5 increase in instantaneous scan rate.

Deepest sensitivity: Ultrahigh Q for Dark photon DM





Cervantes et al., arXiv:2208.03183v3 (2022)

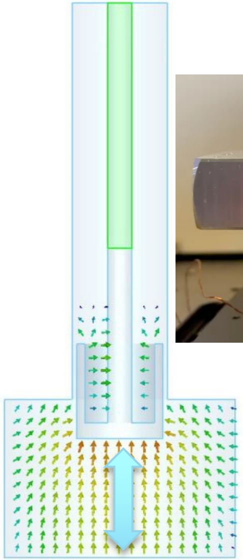
DPDM search with 1.3 GHz cavity with $Q_L \approx 10^{10}$.

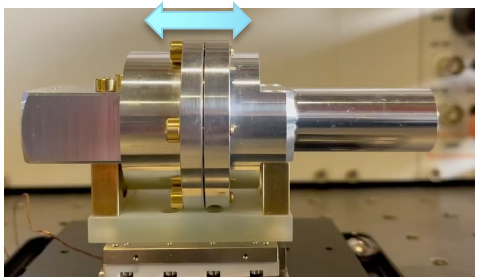
Deepest exclusion to wavelike DPDM by an order of magnitude.

Next steps:

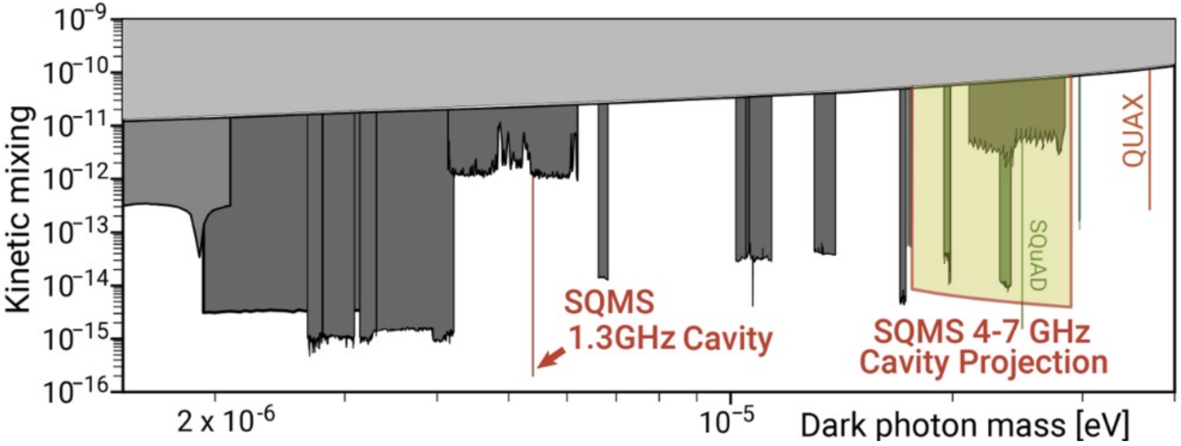
- Tunable DPDM search from 4-7 GHz ("low hanging fruit")
- Implement photon counting to subvert SQL noise limit.

Deepest sensitivity: Ultrahigh Q for Dark photon DM





"plunger" cavity
4-7 GHz



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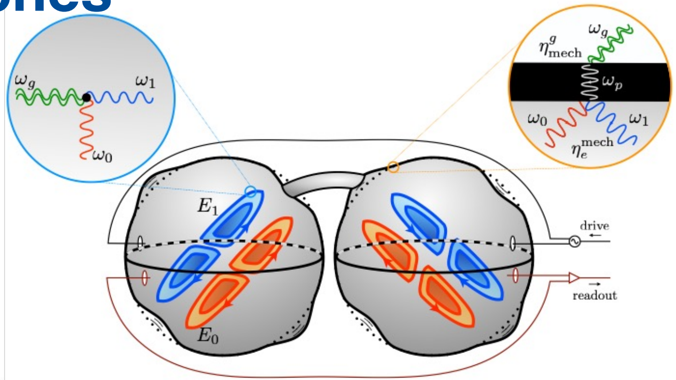
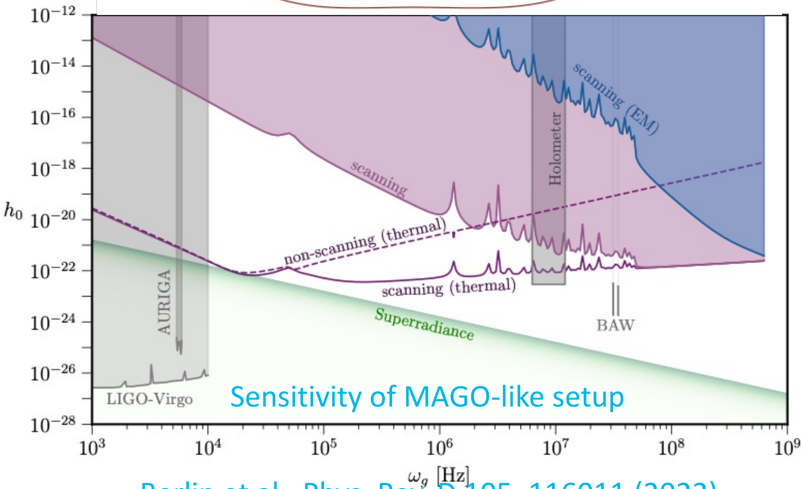
Fermilab

SRF cavities for gravitational waves searches

- SQMS theorists have laid the formalism for GR-EM cavity interaction.
- Two types of signals: EM and mechanical.
- Current axion experiments have sensitivity to GHz Gravity waves [1].
- A dedicated cavity experiment, e.g. MAGO, has significant reach at MHz [2].
- **New collaboration with INFN and DESY to revive MAGO**

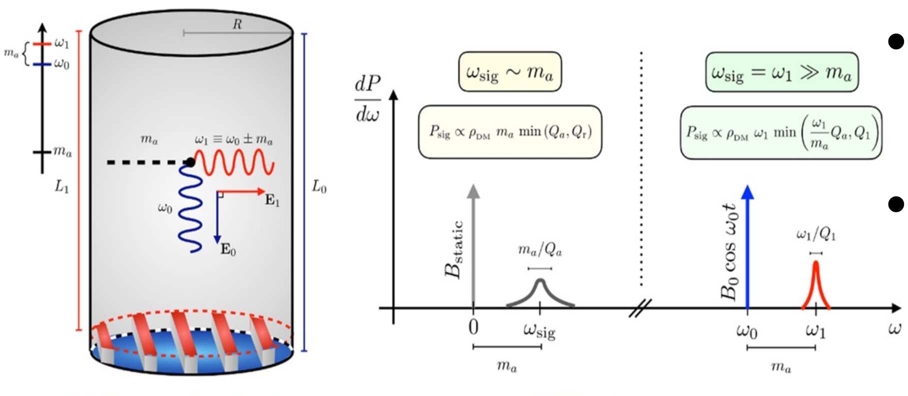
Ballantini et al., Class. Quantum Grav. 20,2003, 3505–3522 (2003)
Ballantini et al., arXiv:gr-qc/0502054 (2005)





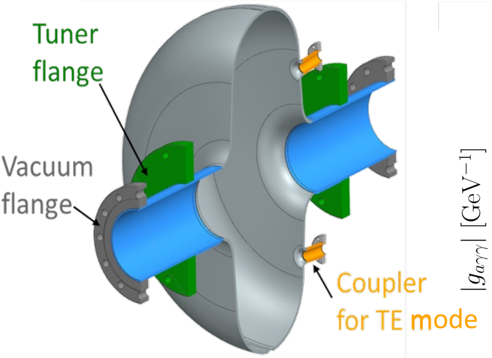
Berlin et al., Phys. Rev. D 105, 116011 (2022)
Berlin et al., arXiv:2303.01518v1 (2023)

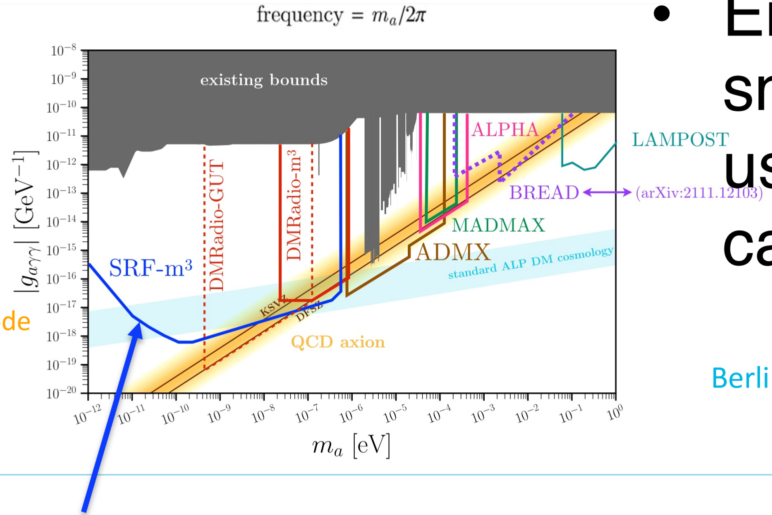
Heterodyne Axion DM search



(a) Cartoon of cavity setup.

(b) Signal parametrics.





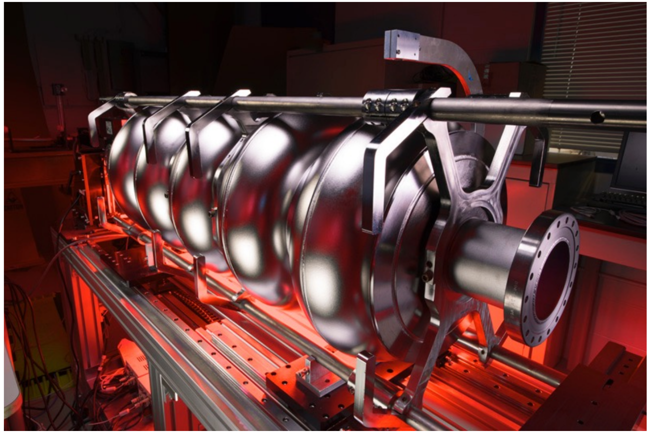
- One SRF cavity, no applied $\vec{B}$
- Modes TE_{011} and TM_{020} used to search for axion DM $\rightarrow m_{axion} \approx \Delta f$
- Enables to search for small masses without using prohibitively large cavities!

Berlin et al., Journal of High Energy Physics 2020.7 (2020)
Giaccone et al., arXiv:2207.11346 (2022)

1. Superconducting RF Cavities
2. SRF for Accelerators at Fermilab
3. SRF for Detectors at Fermilab
4. **Summary**

Summary

- SRF cavities are enabling to HEP mission of Fermilab
  - Accelerators to enable DUNE, future colliders
  - Detectors for dark sector, gravitational waves
- SRF R&D has brough substantial performance improvements and enabled new applications
- Many exciting future opportunities



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- Sincere thanks to Matthias Liepe, Nigel Lockyer, Alex Romanenko, Anna Grassellino, Sergey Belomestnykh, Hasan Padamsee, and huge number of other mentors for their strong support