# RF Superconductivity

## Part2 : reality and applications

Akira Miyazaki
CNRS/IN2P3/IJCLab Université Paris-Saclay

CERN Summer Student Lecture 2024

Akira.Miyazaki@ijclab.in2p3.fr / Akira.Miyazaki@cern.ch

# Answer to the first three questions yesterday

1. What is the superconductivity?
    1. A finite attractive interaction between independent electrons form a Cooper pair that obeys nonrelativestic U(1) Higgs mechanism
    2. Photons gain mass in superconductors due to spontaneous symmetry breaking, which leads to the Meissner effect
2. What are the fundamental origins of finite RF loss in SRF cavities?
    1. Thermally activated quasi-particles at finite temperature act like normal conducting electrons and cause a loss in RF
    2. Even at absolute zero temperature, residual resistance exists due to several different mechanisms, such as flux oscillation and subgap state’s effect, whose ultimate origins are not wholly understood
3. What are the fundamental limitations of the field inside SRF cavities?
    1. Superheating field, which exceeds thermodynamic critical fields in equilibrium state, would give a fundamental limitation
    2. The dynamic calculation of the superheating field is still an open field of fundamental research

# Answer to the first three questions yesterday

1. What is the superconductivity?
    1. A finite attractive interaction between independ[illegible]ectrons form a Cooper pair that obeys nonrelativestic U(1) Higgs [illegible]
    2. Photons gain mass in superconduct[illegible]us symmetry breaking, which leads to the Meissner [illegible]
2. What are the funda[illegible]SRF cavities?
    1. Thermally a[illegible]like normal conduc[illegible]
    2. Even at [illegible]tance exists due to several different [illegible] and subgap state’s effect, whose ultimate [illegible]stood
3. What are the [illegible]imitations of the field inside SRF cavities?
    1. Superheating [illegible]ich exceeds thermodynamic critical fields in equilibrium state, would g[illegible]e a fundamental limitation
    2. The dynamic calculation of the superheating field is still an open field of fundamental research

Forget!

# Outline

- Introduction: from theory to reality *cryomodule*
- Cavity engineering
  - Mechanical structure
  - Material
  - Surface physics
- Ancillary of cavities
  - RF couplers & tuners
  - Digital LLRF
  - High power amplifiers
- New research directions
  - New materials
  - Applications for fundamental physics
- Conclusion

I will give you contacts to experts at CERN

# Outline

- Introduction: from theory to reality *cryomodule*
- Cavity engineering
  - Mechanical structure
  - Material
  - Surface physics
- Ancillary of cavities
  - RF couplers & tuners
  - Digital LLRF
  - High power amplifiers
- New research directions
  - New materials
  - Applications for fundamental physics
- Conclusion

# Yesterday: idealized model

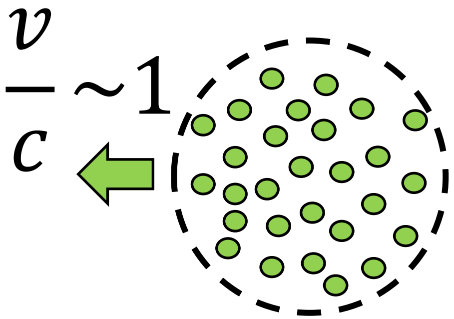
Perfect vacuum

Perfect superconductor
→ Higgs + RF + phase transition

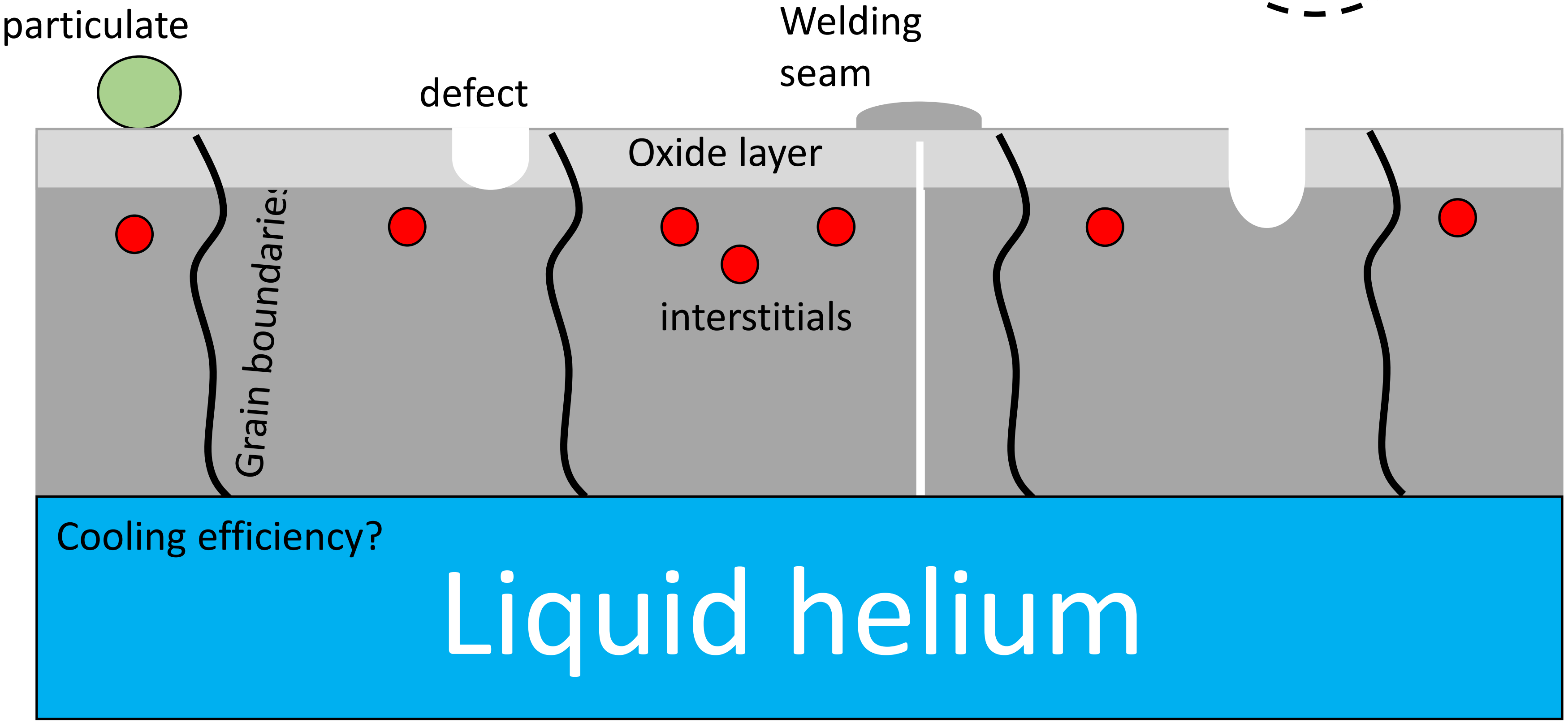
Constant temperature

# Today: real superconducting cavities

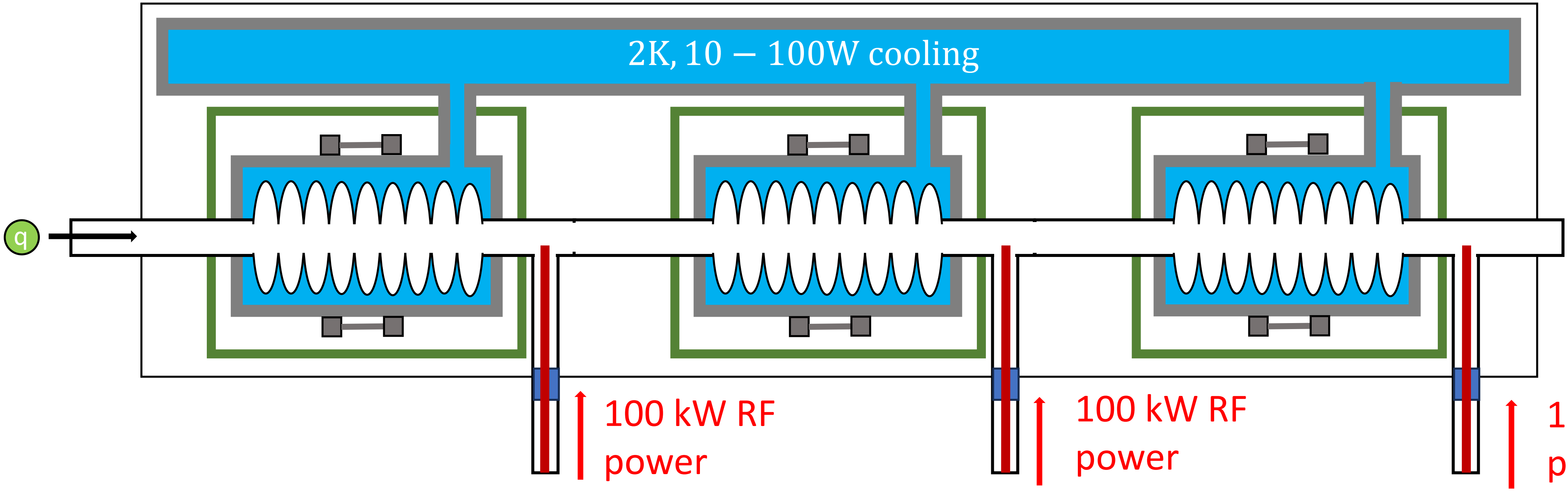
$0 \ll \text{Vacuum} < 1 \times 10^{-8}$ mbar



$10^{10}$ charged particles



# Cryomodule: SRF cavity cryostat in accelerators



XFEL@DESY

Contact: Vittorio Parma

Technical challenges

- What determines the shape of the cavities?
- How to fabricate and prepare perfect cavities? Typical surface resistance is only $10\ \mathrm{n\Omega}$!
- How to feed RF to the cavities? 100 kW to 100 W cooled 2K system!
- How to control RF to be very precise? Better than 0.1% fluctuation in field and 1 deg in phase
- Cryogenics (2-4K), ultra-high vacuum ($1 \times 10^{-10}$ mbar), etc, etc

# Outline

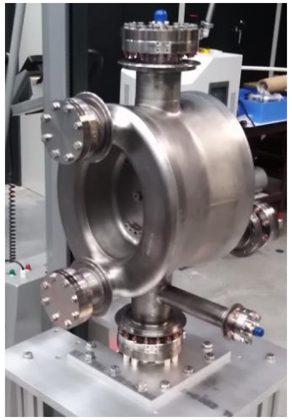
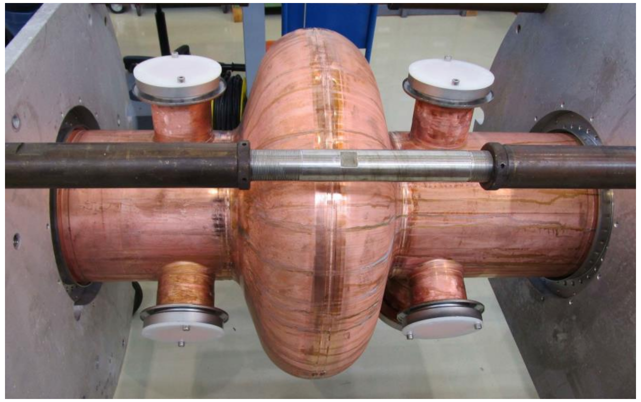
- Introduction: from theory to reality *cryomodule*
- Cavity engineering
  - Mechanical structure
  - Material
  - Surface physics
- Ancillary of cavities
  - RF couplers & tuners
  - Digital LLRF
  - High power amplifiers
- New research directions
  - New materials
  - Applications for fundamental physics
- Conclusion

# Various structures of SRF cavities

Bulk niobium cavities: standard

Nb/Cu: CERN’s specialty

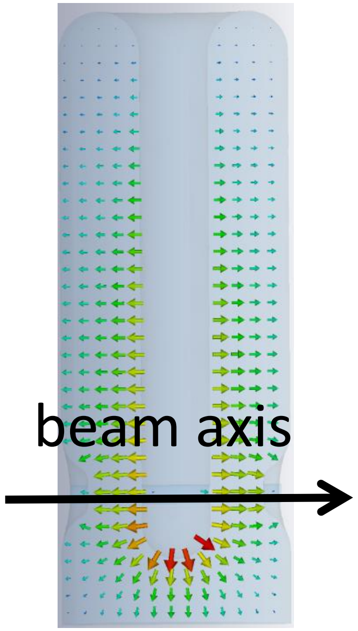


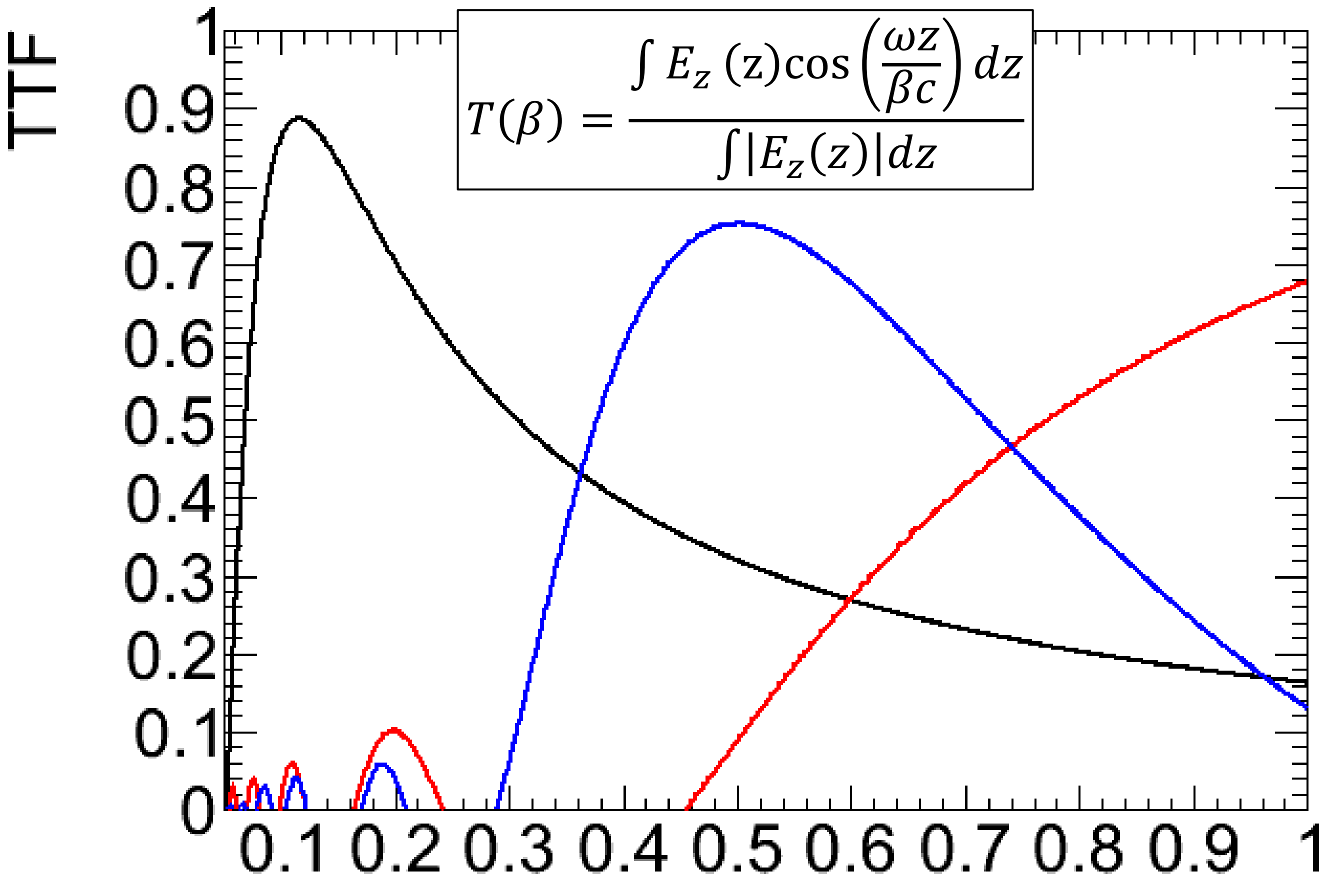

→ Why so many different structures?

# Geometrical consideration: low-β , middle-β, and high-β

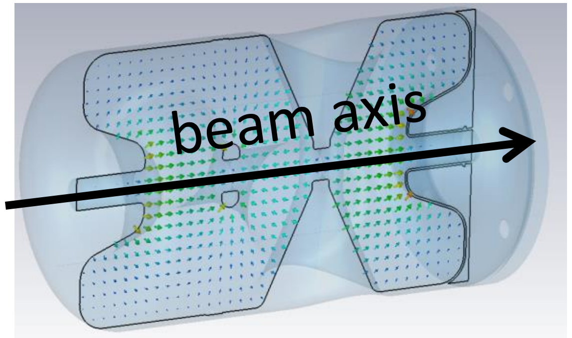
$TEM_{00}$ modes in a quarter-wave or half-wave cavity



- p+ upstream (<1GeV)
- Heavy ion
- **HIE-ISOLDE at CERN**

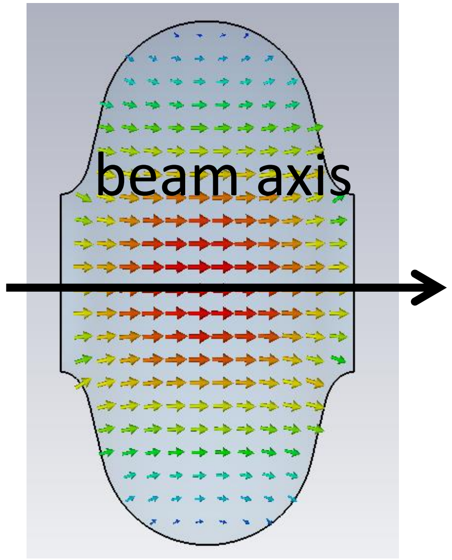

$$T(\beta) = \frac{\int E_z\,(\mathrm{z})\cos\left(\frac{\omega z}{\beta c}\right) dz}{\int |E_z(z)|dz}$$

TEM modes in a spoke cavity



- p+ (<1GeV)
- Not at CERN ☹

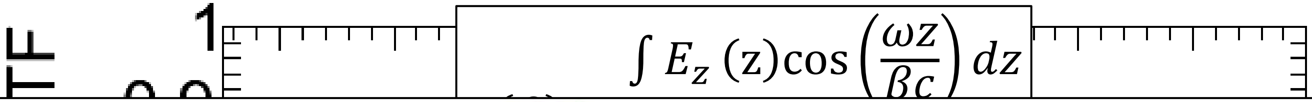
$TM_{010}$ modes in an elliptical cavity



- p+ downstream (>1GeV)
- e-, e+ (>0.5MeV)
- **LHC at CERN**

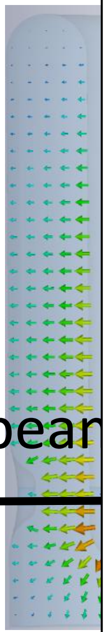
Contact: Franck Peauger

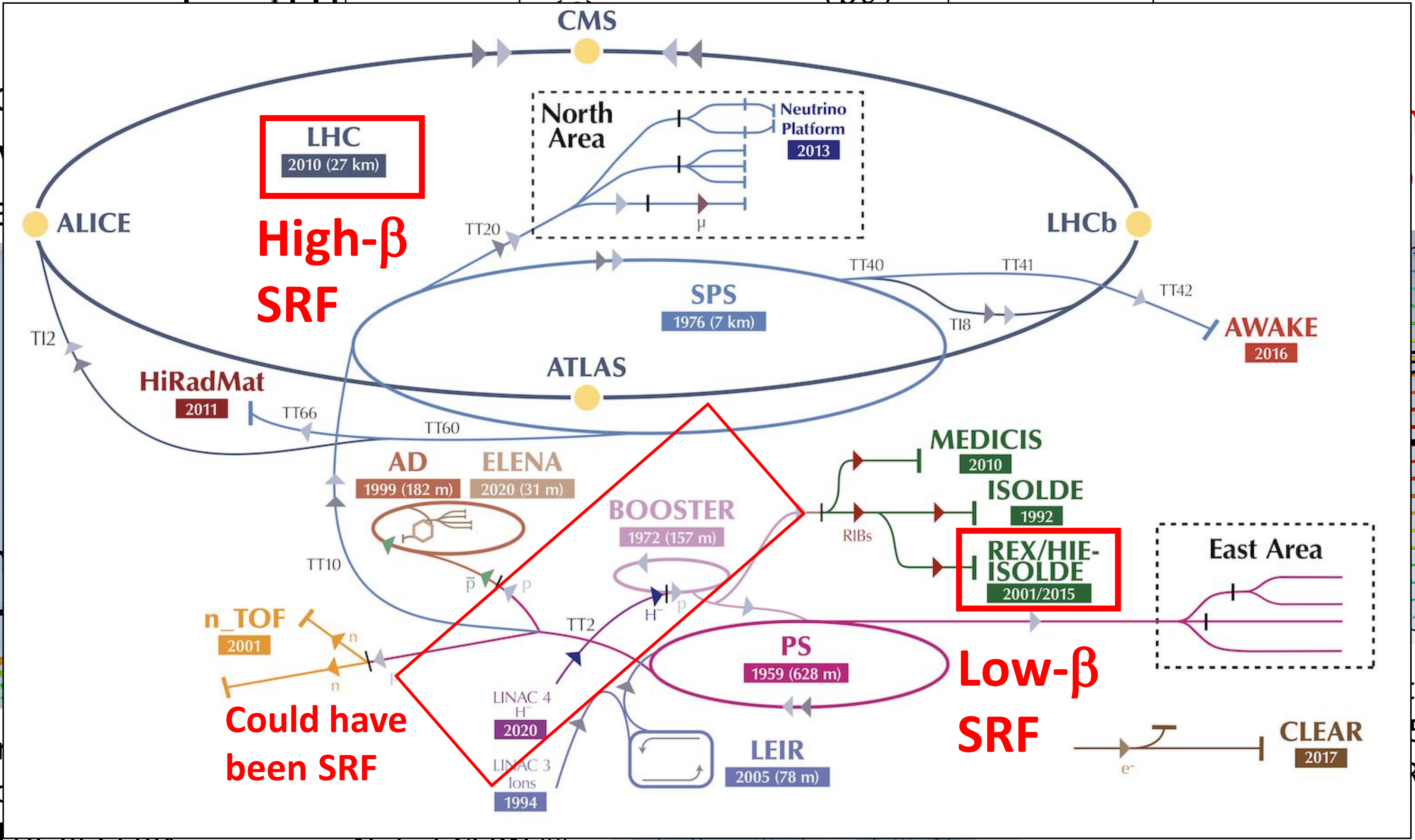
# Geometrical consideration: low-β , middle-β, and high-β



$\int E_z\,(\mathrm{z})\cos\left(\frac{\omega z}{\beta c}\right) dz$

TEM$_{00}$ mo
quarter-w
half-wave



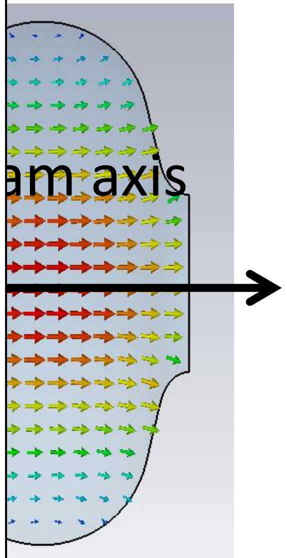


High-β SRF

Low-β SRF

Could have been SRF

modes in
tical cavity



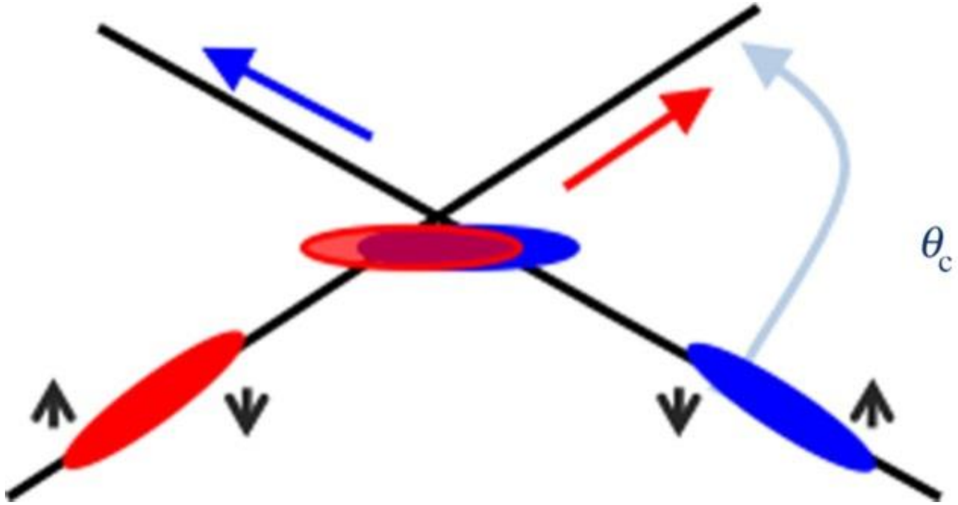
- p+ upstr
- Heavy io
- HIE-ISOLDE at CERN

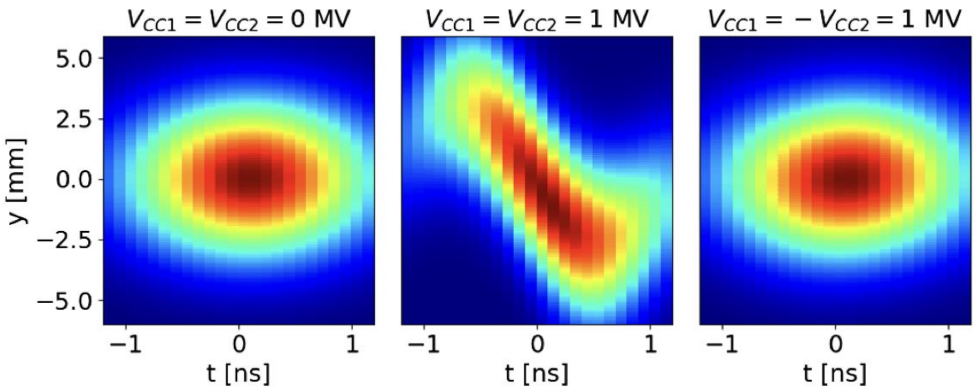
tream (>1GeV)
5MeV)
RN

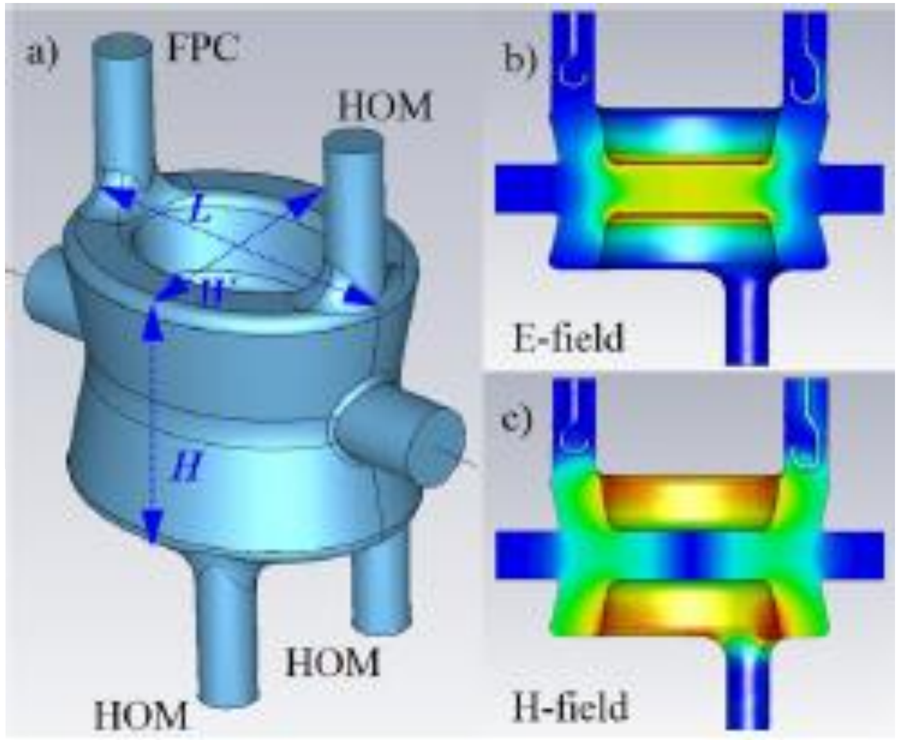
- Not at CERN ☹

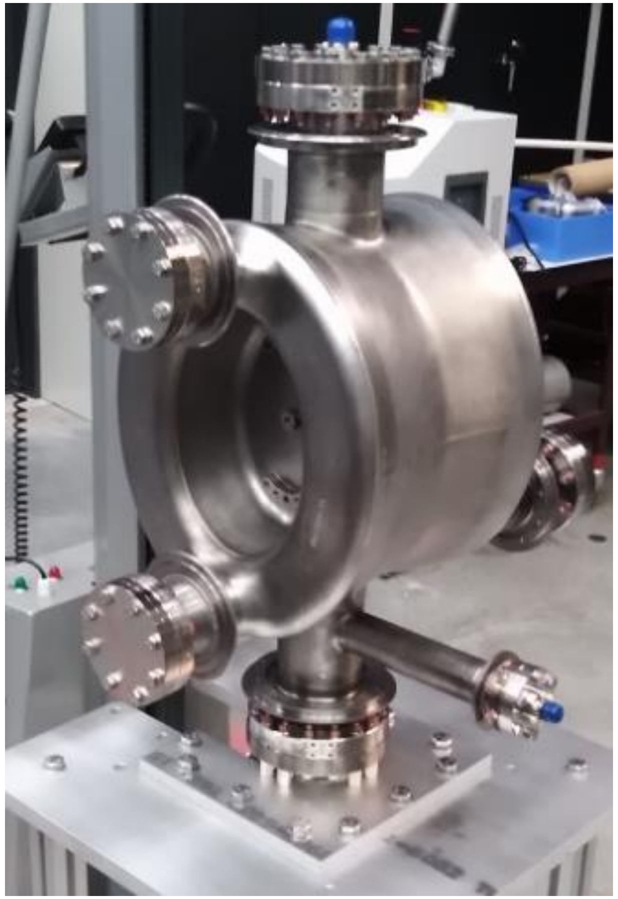
# Exception: deflecting cavity (eg HL-LHC crab cavity)

## For better luminosity







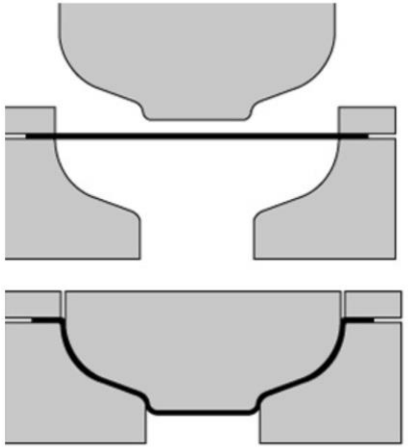


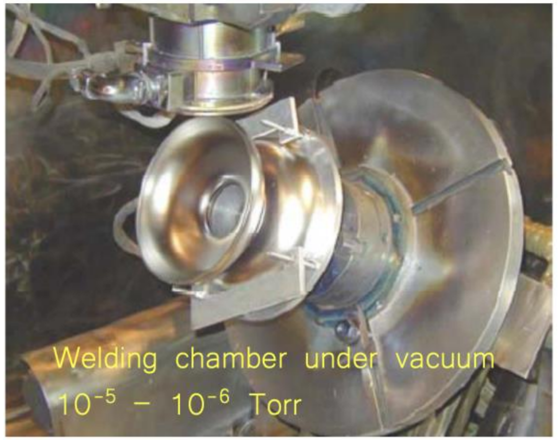
Phys. Rev. Accel. Beams 24, 062001 2021

Contact: Rama Calaga

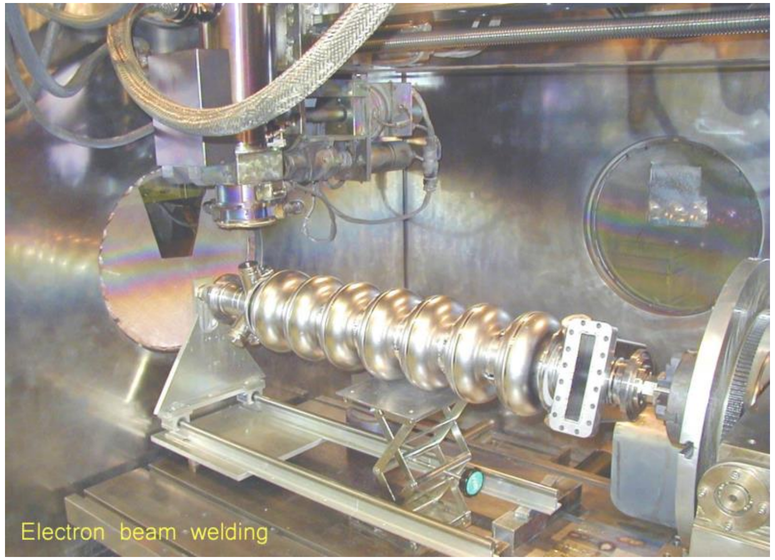
# Fabrication processes

## Deep drawing + electron beam welding





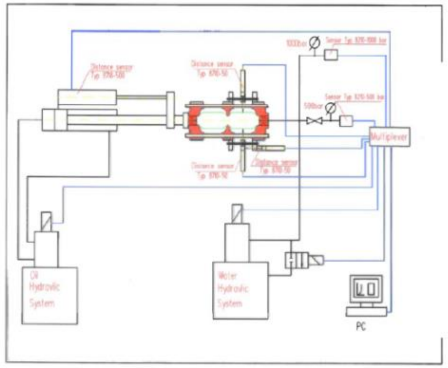
Welding chamber under vacuum $10^{-5}$ – $10^{-6}$ Torr

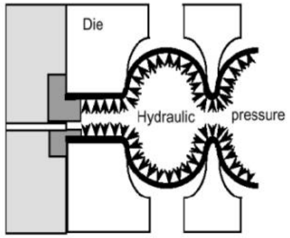


Electron beam welding

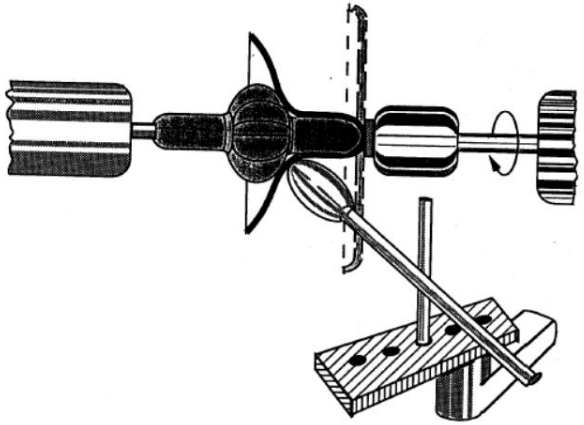
## Seamless cavity fabrication

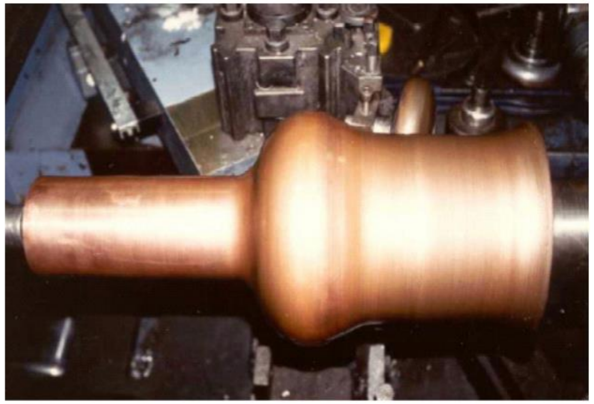
Hydro forming （W.Singer,DESY）





Spinning （V.Palmieri,INFN Legnaro）

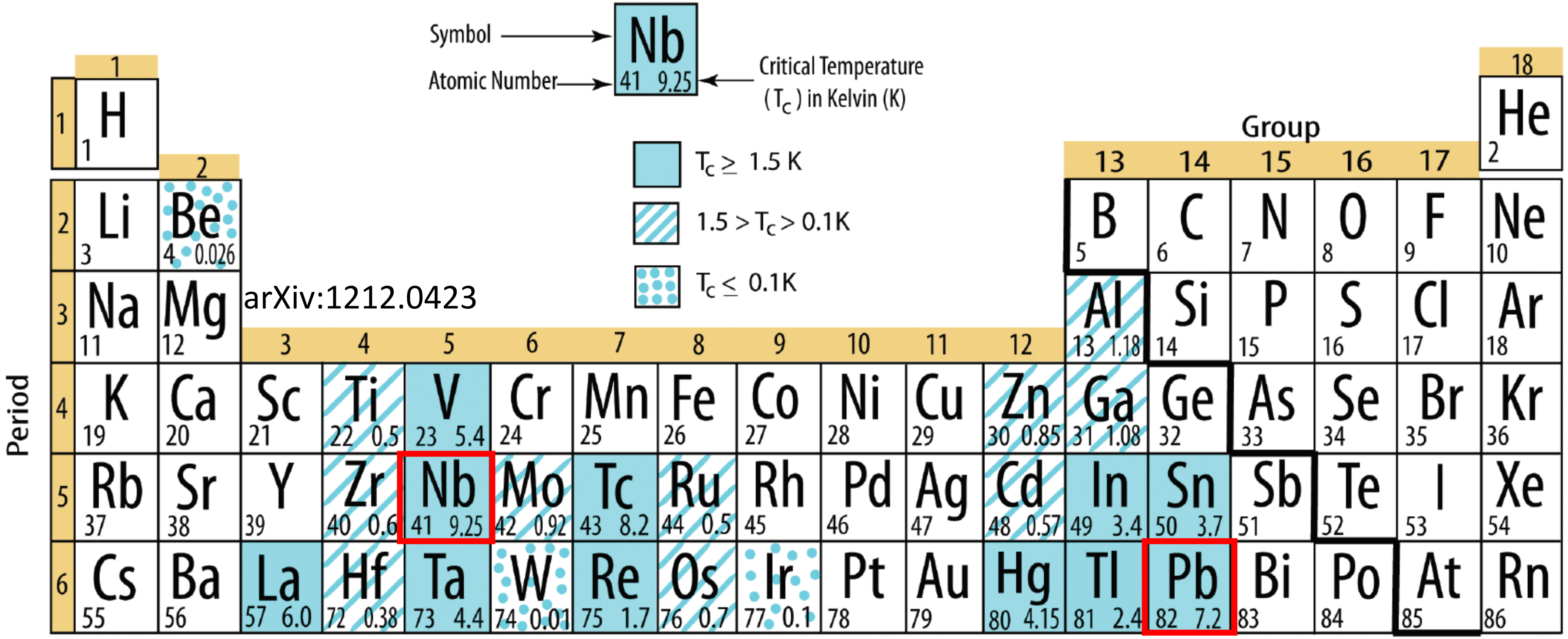




Courtesy: Rong-Li Geng

CERN is also working on seamless cavities
Contact: Said Atieh

# Table of superconductors of pure elements



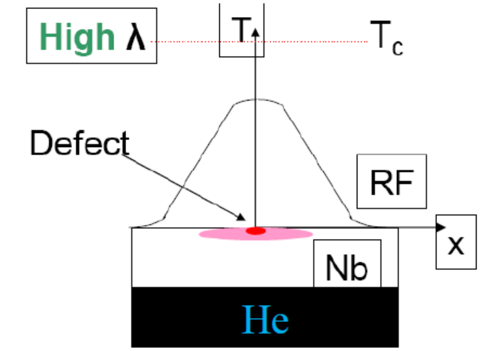
arXiv:1212.0423

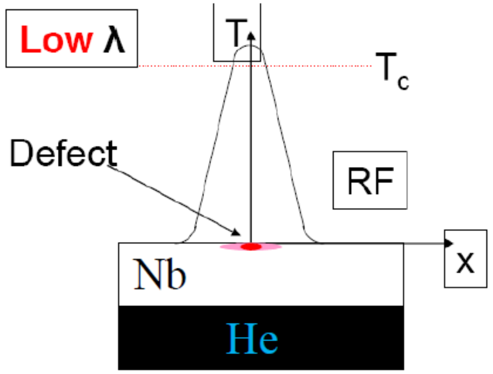
[a] Period 7, and the ***f*** elements in period 6, with the exception of lanthanum, La, are not shown.

Pb is toxic and soft → Nb is the standard for SRF cavities

Nb: $T_c = 9.25$ K, $B_c = 200$ mT

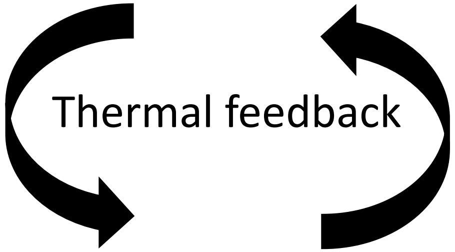
# Defects enhance thermal breakdown





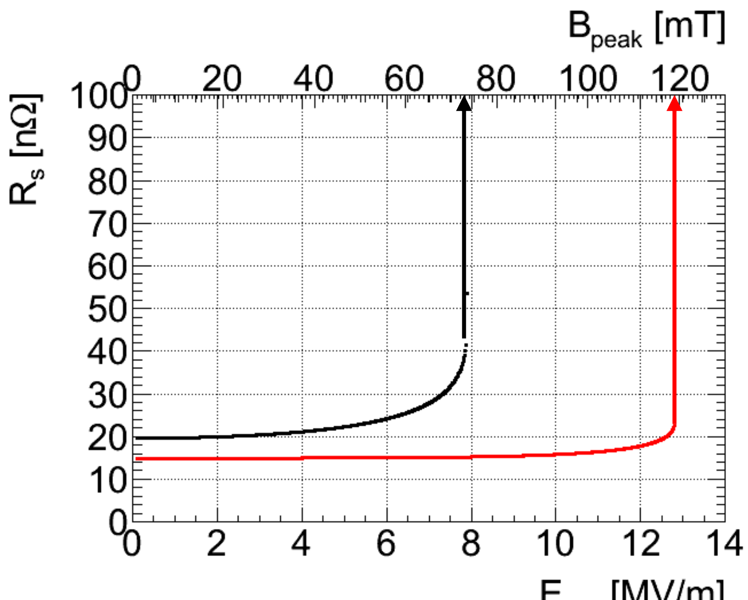
BCS resistance

$$R_s \sim \frac{A\omega^2}{T}\exp\left(-\frac{\Delta}{k_B T}\right)$$

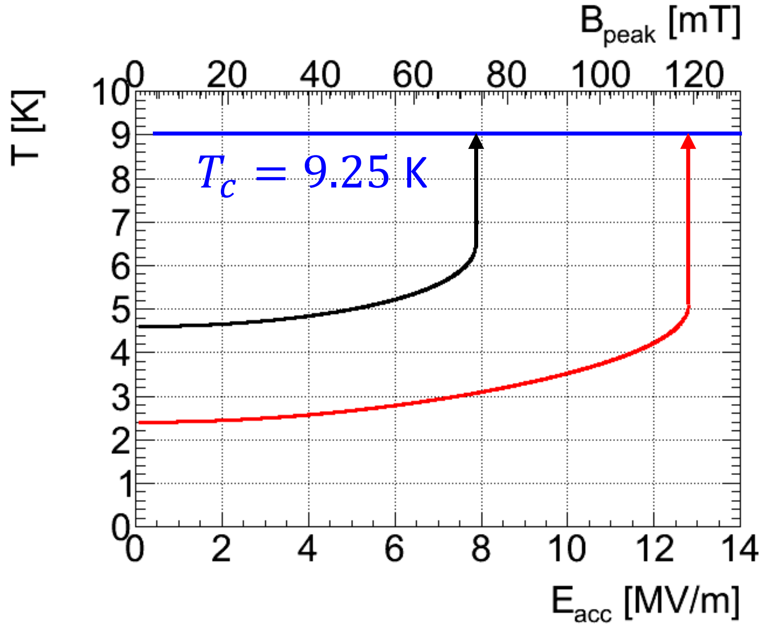


Joule heating: $P = \frac{1}{2} R_s H^2$

$$\Delta T = R_{th} P$$



100 MHz case



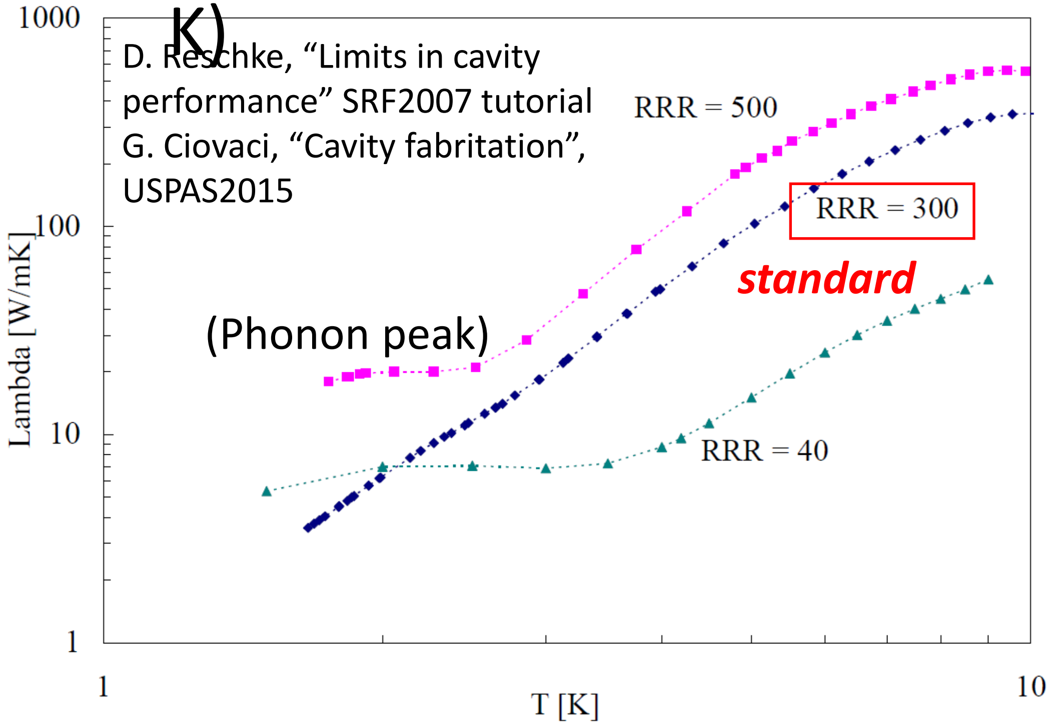
***Defect***, bad thermal resistance $R_{th} \propto 1/\lambda$ can enhance thermal breakdown

→ **defect-free and good thermal conductance is a key of SRF cavities**

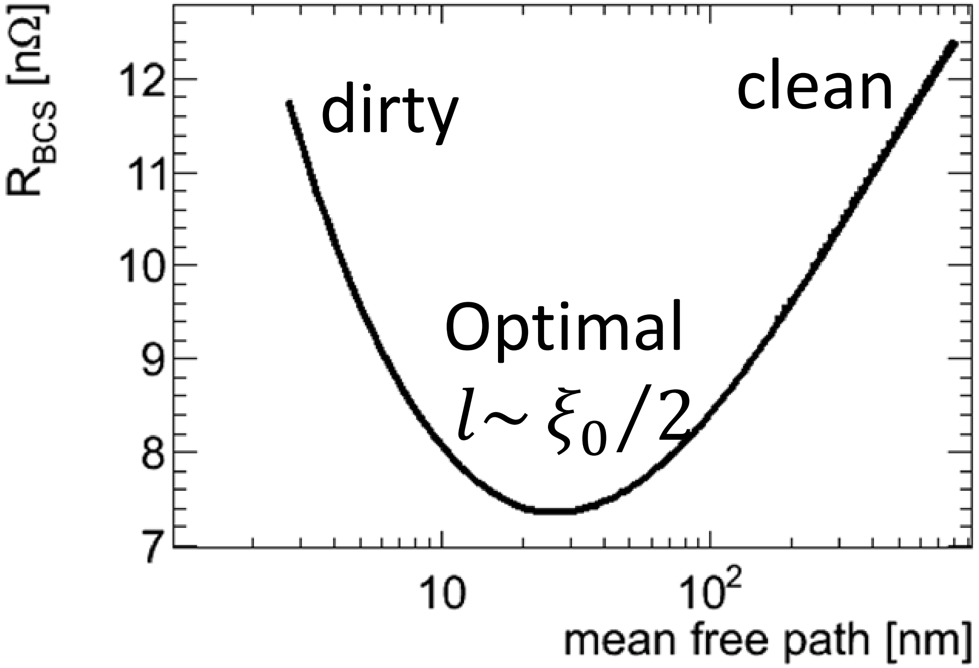
# Issue of Nb: thermal conductivity vs surface resistance

$\lambda(4.2\mathrm{K})\sim 0.1\times l$ W/(m K)

$l$ nm



D. Reschke, “Limits in cavity performance” SRF2007 tutorial
G. Ciovaci, “Cavity fabritation”, USPAS2015

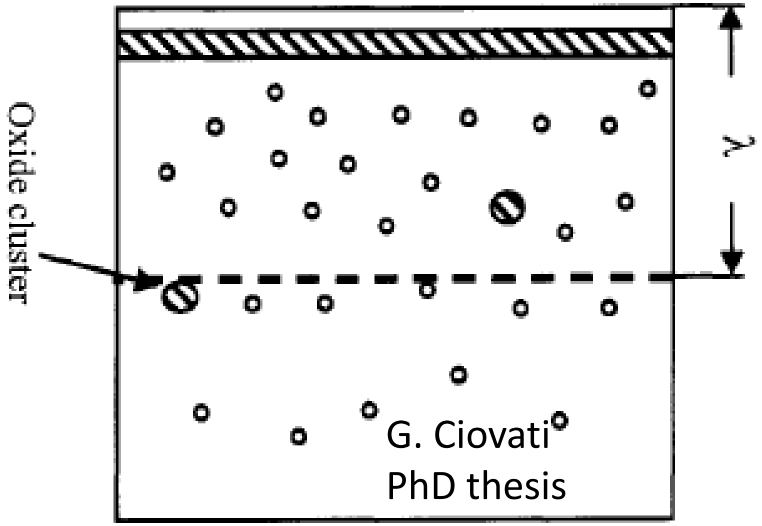


1. **Clean** bulk for thermal conductivity
   - RRR~300: 700 EUR/kg (price in 2024 spring)
2. Sufficiently **dirty** surface for lower BCS resistance
   - $R_{res}$ can be worse

These two requirements contradict with each other

# How to achieve **clean** bulk and **dirty** surface

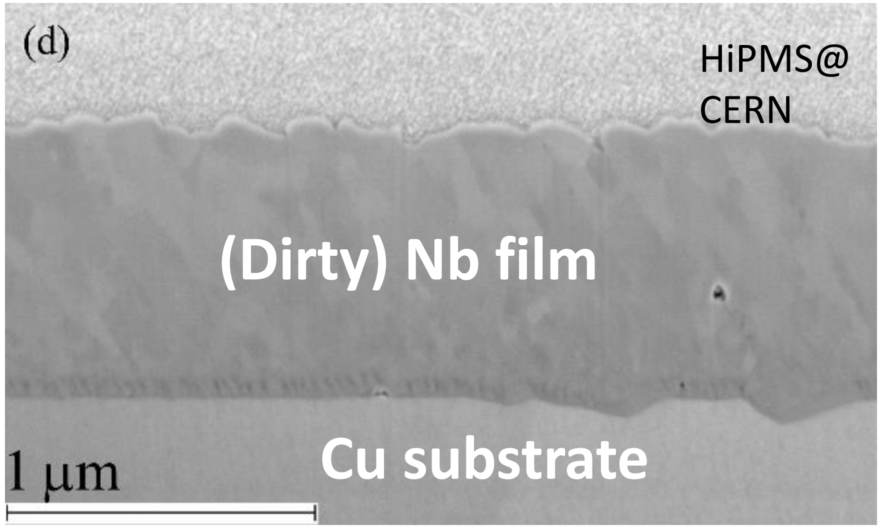
Heat treatment, doping,…



Hyper-low $R_{BCS}$, sensitive $R_{mag}$, anti-Q-slope, a lot of mysteries

Nb film

CERN's specialty
Contact: Guillaume Jonathan Rosaz



Very low $R_{BCS}$, insensitive $R_{mag}$, Q-slope, … a lot of mysteries

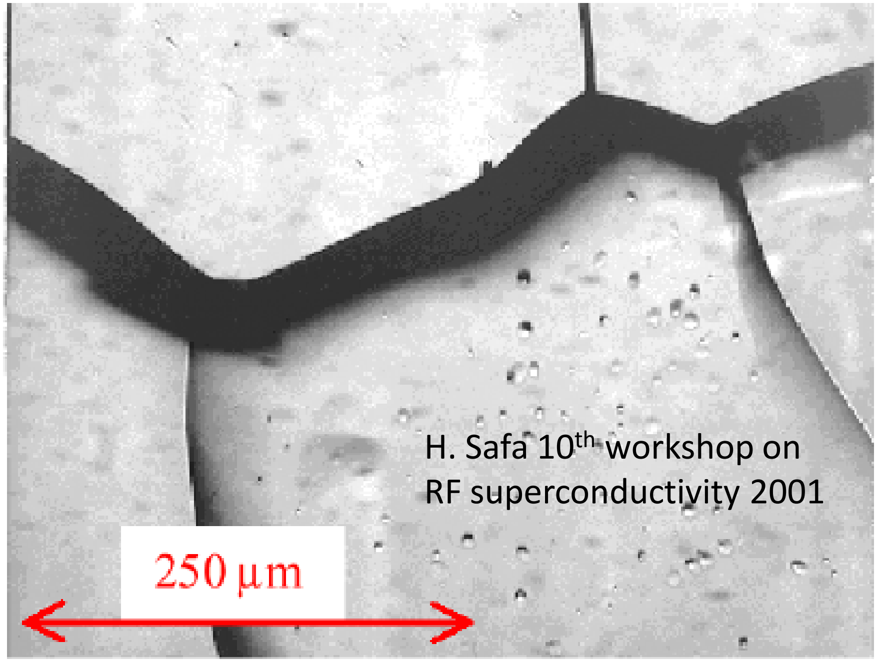
We have been developing **recipes** but why and how are generally missing

***One of the research frontiers for new SRF cavities***

# Importance of surface roughness: one example

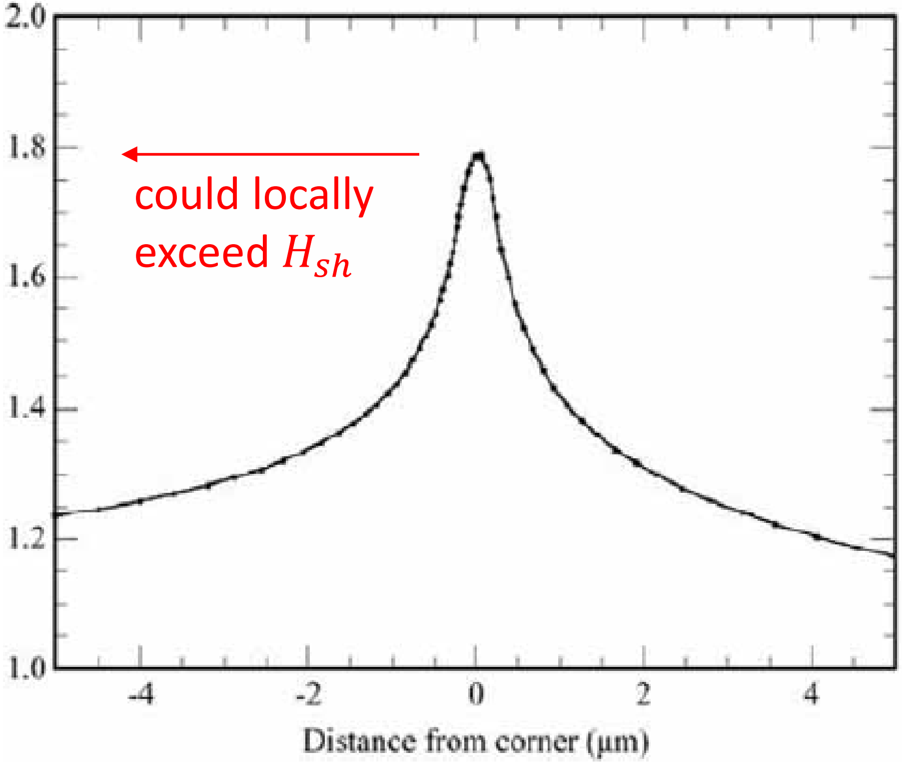
## Local defect or field enhancement

Standard BCP Chemistry on niobium :
Sharp boundary edges are clearly visible



H. Safa 10th workshop on RF superconductivity 2001

Calculated magnetic field enhancement
on a 100 µm x 10 µm step



could locally exceed $H_{sh}$

→ Choice of chmical etching method
(Buffer Chemical Polishing or Electro Polishing)

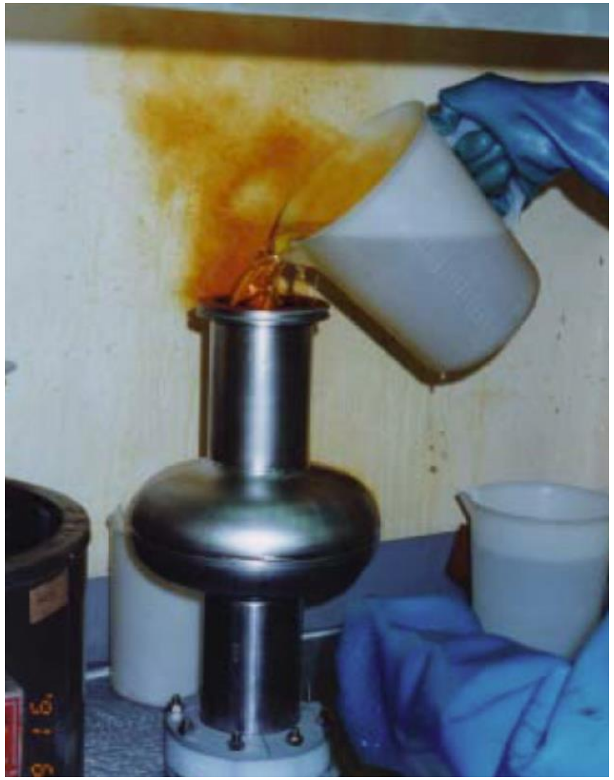
Quench limit and high-field Q-slope is an open research area

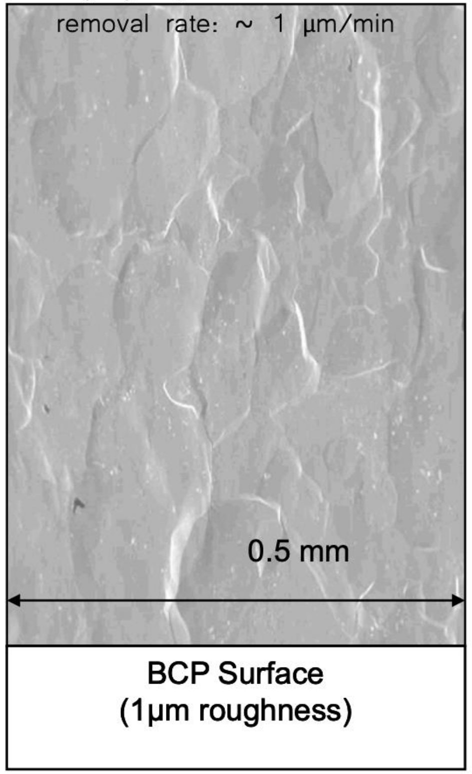
# Two methods of surface etching

Contact: Marc Thiebert

## Buffered Chemical Polishing (BCP)

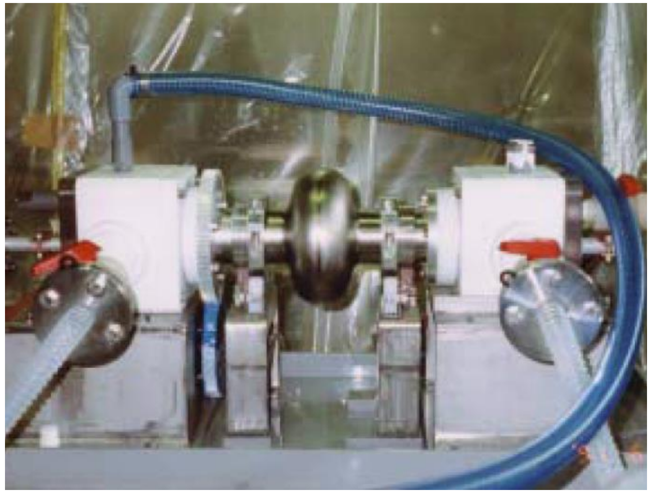
HF + $HNO_3$ + $H_3PO_4$

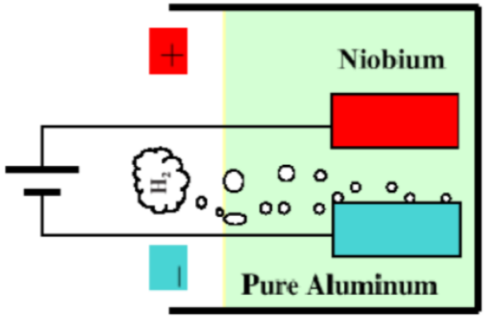


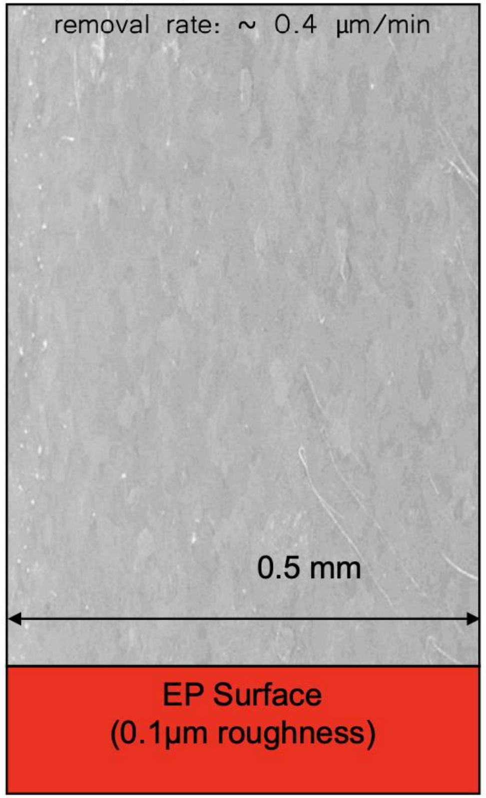


## Electropolishing (EP)

HF + $H_2SO_4$ + voltage





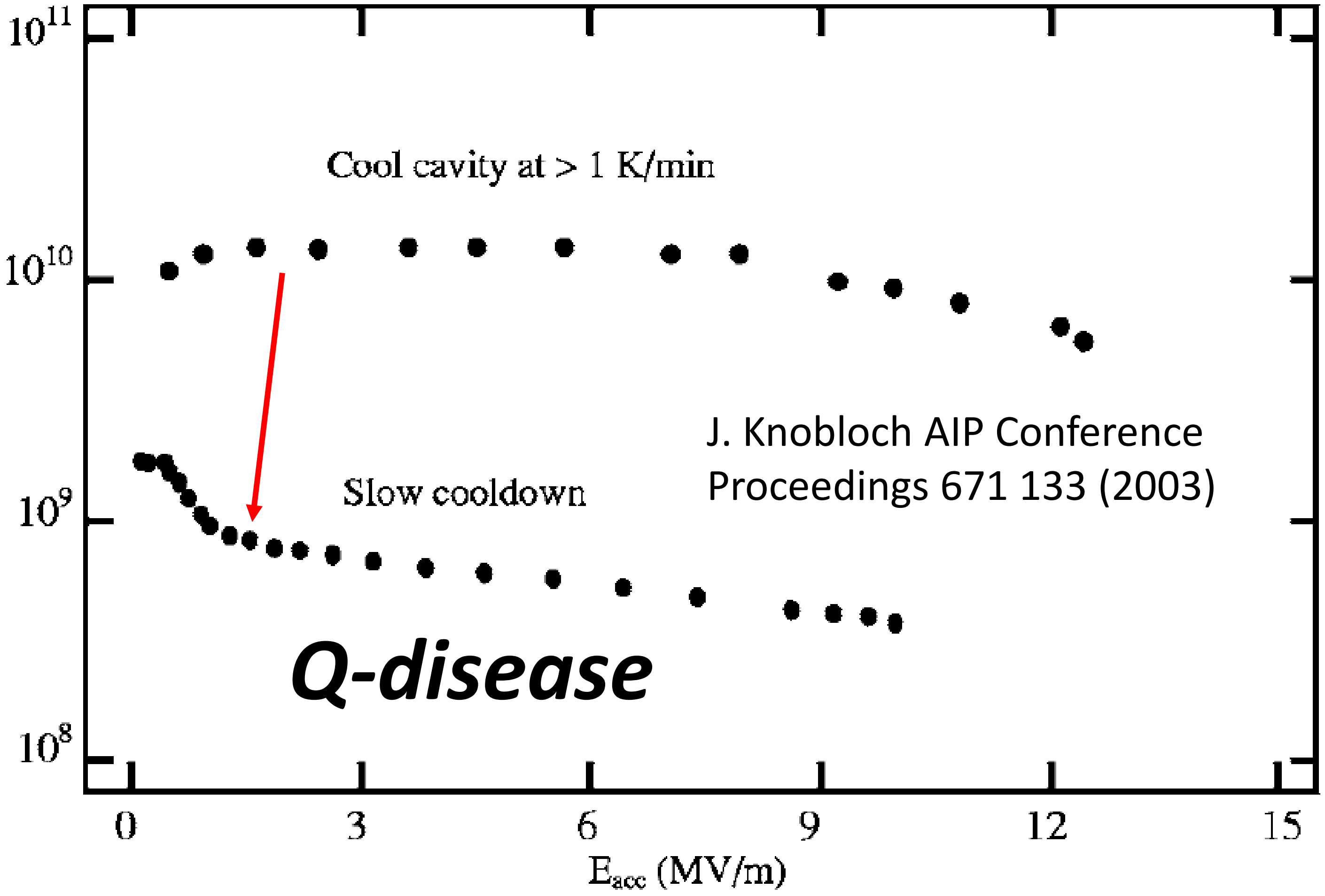


Courtesy: Rong-Li Geng

EP is known to be better but more complex and expensive

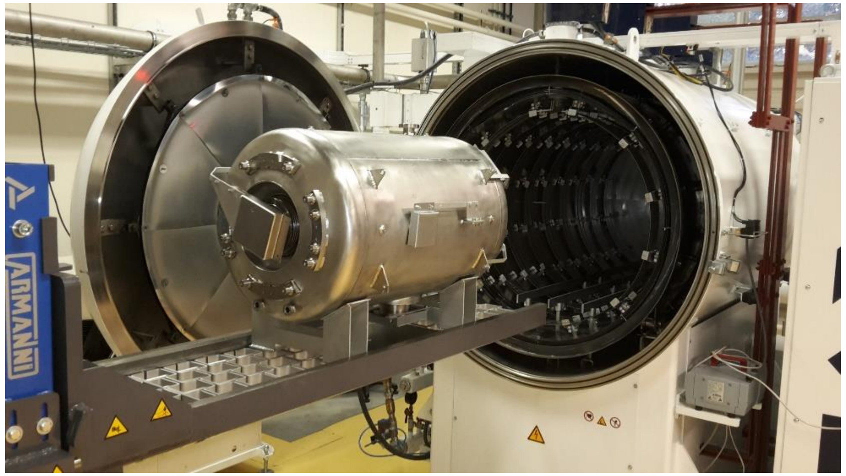
→ BCP may be enough depending on the performance requirement

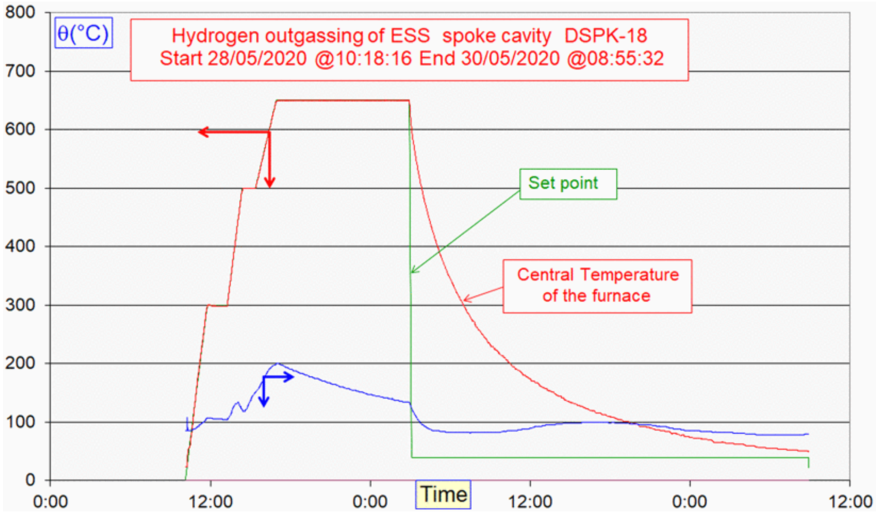
# Hydrogen from HF acid → Nb hydride



**Q-disease**

J. Knobloch AIP Conference Proceedings 671 133 (2003)



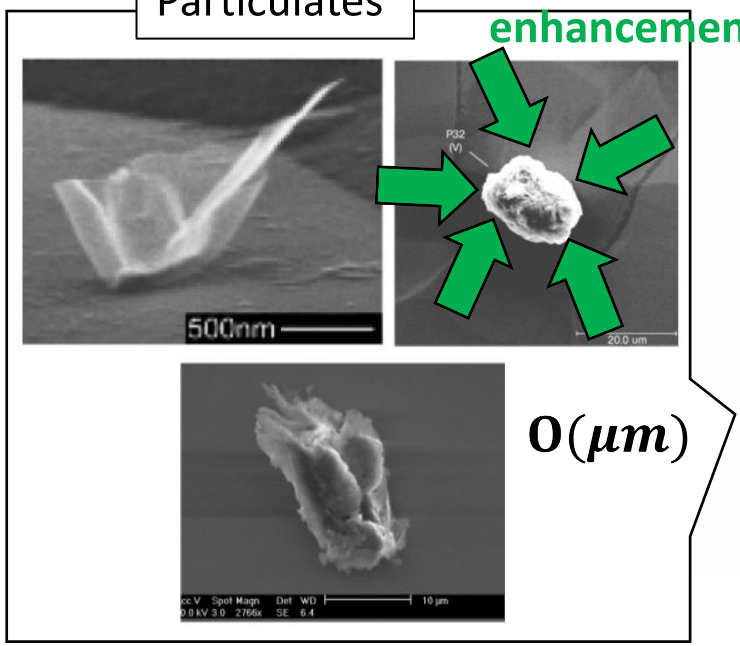


M. Fouaidy et al., IEEE Transactions on Applied Superconductivity, 31, 5, pp. 1-8, 2021, 3500508

<u>Solutions</u>

1. Anneal the cavity above 600C to degas hydrogen
2. Avoid slow cooling down around dangerous temperature 75-150K

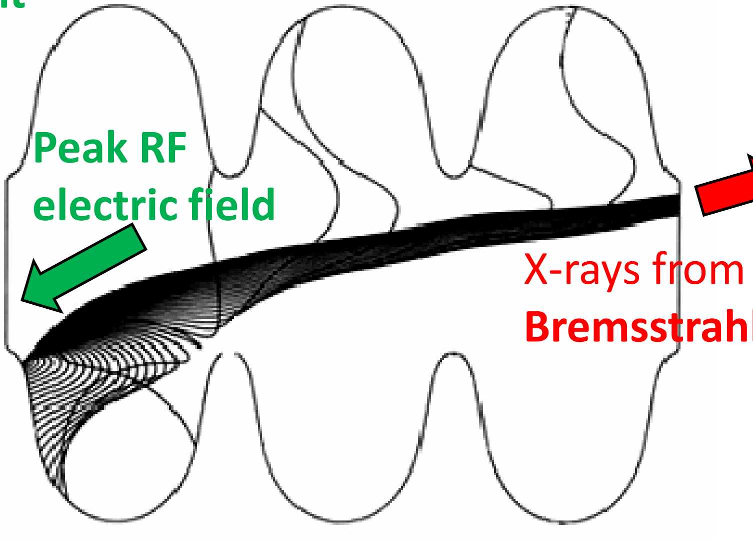
# Field Emission (FE): discharge due to electron tunneling



Particulates

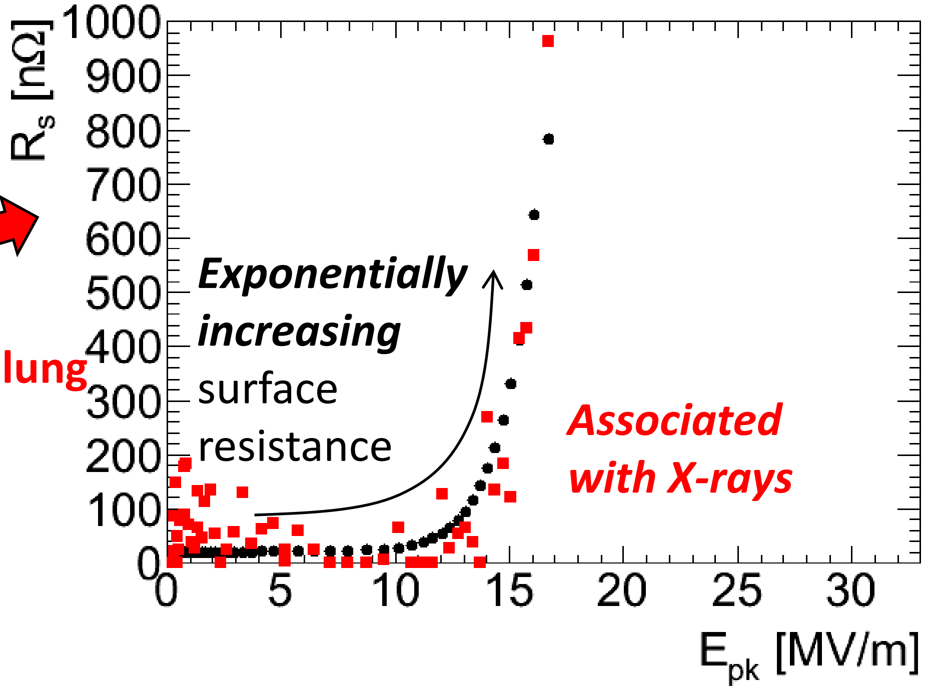
Field enhancement

$O(\mu m)$



Peak RF electric field

X-rays from **Bremsstrahlung**



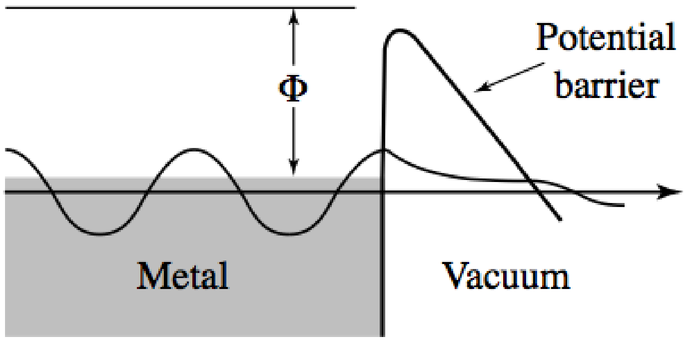
***Exponentially increasing*** surface resistance

***Associated with X-rays***

## Tunneling current by Fowler-Nordheim

$$J \propto \exp\left(-6.53\times10^{6}\,\frac{\boxed{\phi}^{3/2}}{\boxed{\beta}\boxed{E}}\right)$$

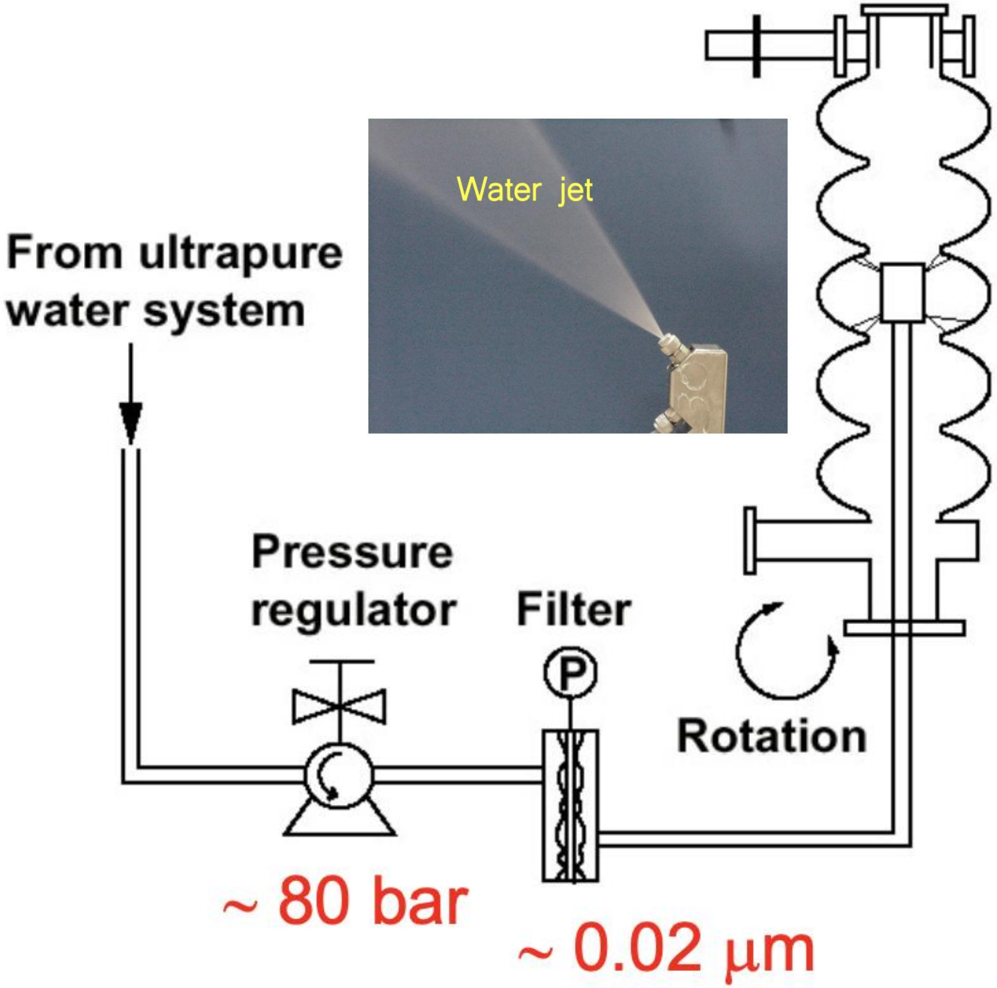
1. work function $\phi$~4-5 eV
2. peak electric field
3. field enhancement



**Practical challenge in SRF projects with a large number of cavities**

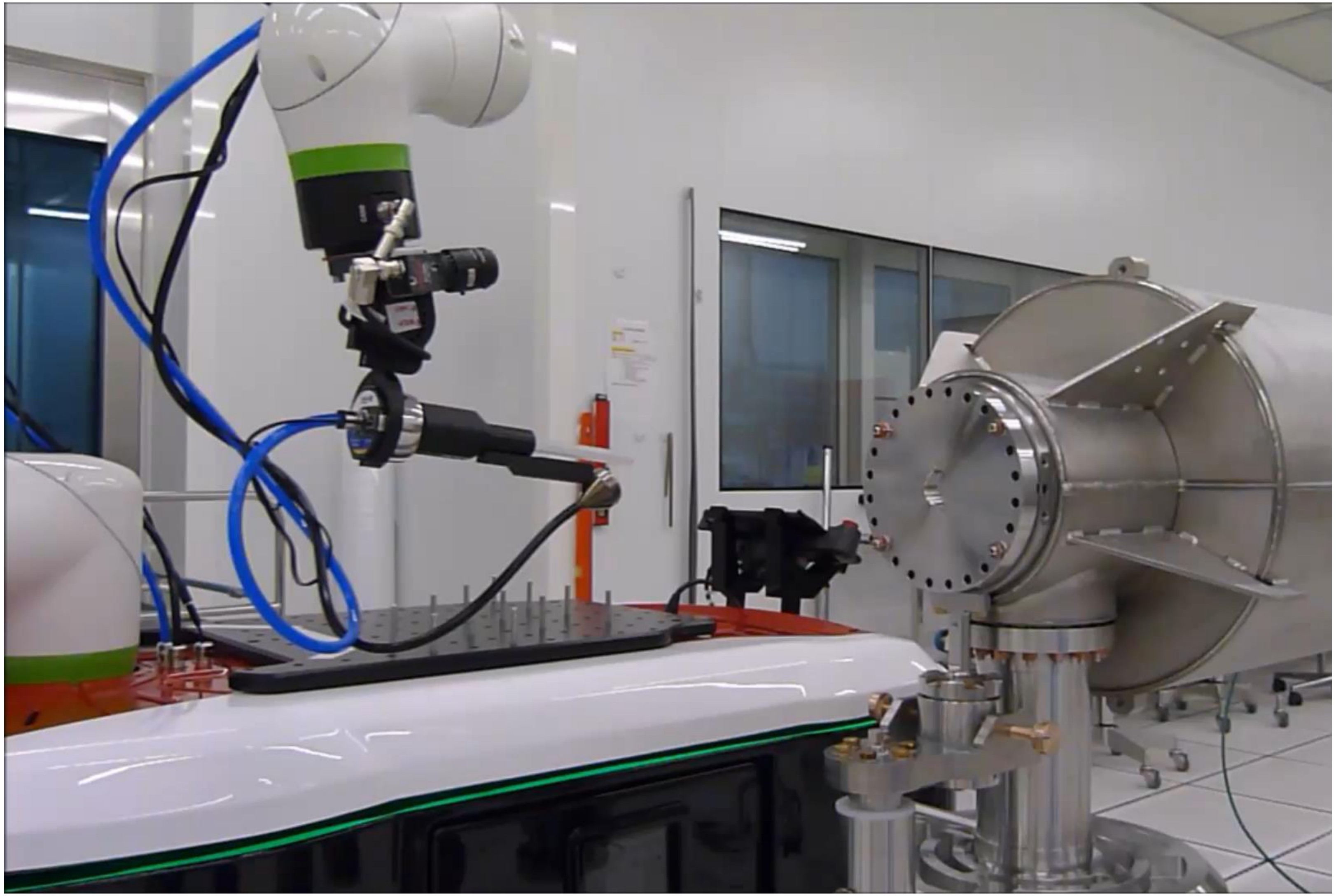
# Mitigate FE: High Pressure Water Ringing & clean room assembly

Contact: Mathieu Therasse



Working in a clean room is tough business

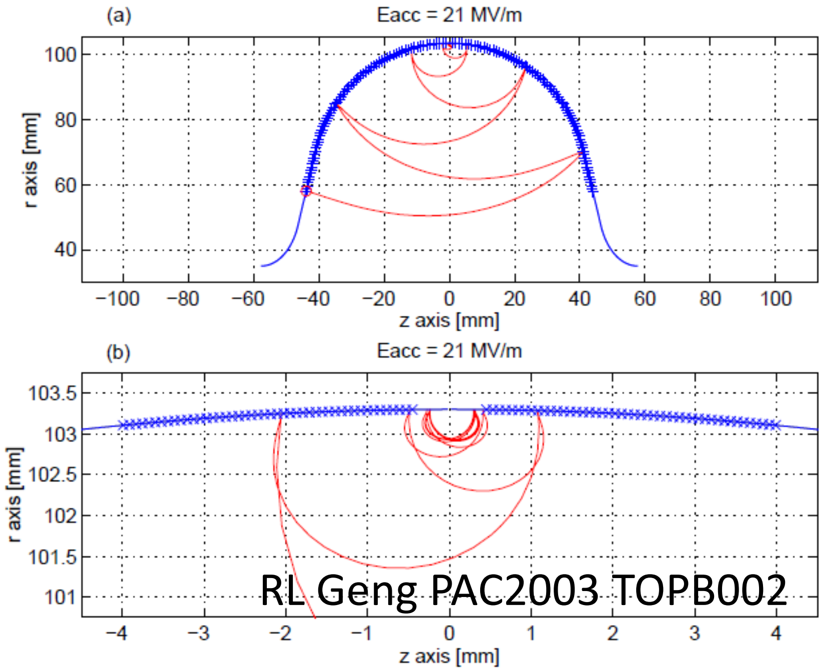
# Introduction of robotics is one research direction



Courtesy:
Julien Drant
CEA Saclay

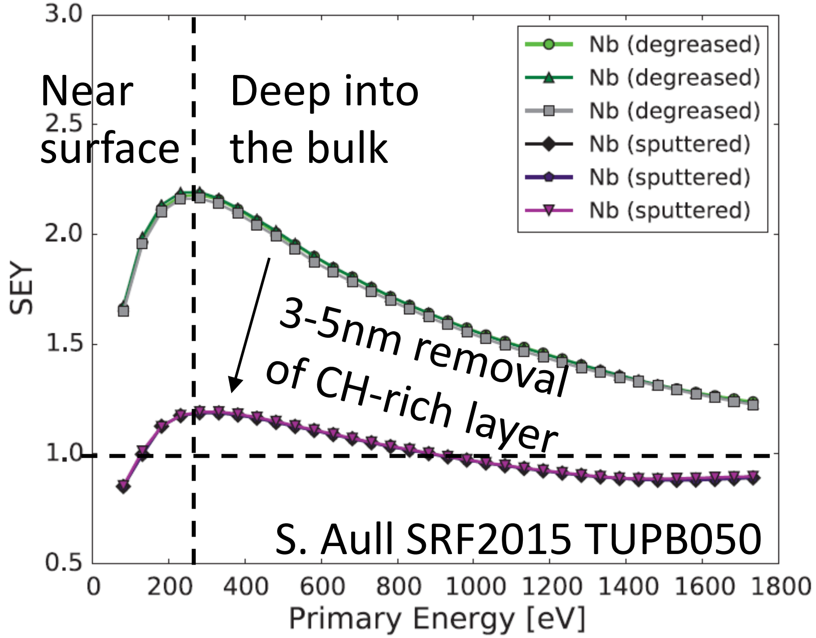
# Multipacting: resonant avalanche of secondary electrons

## Resonance and geometry



RL Geng PAC2003 TOPB002

## Secondary Electron Yield



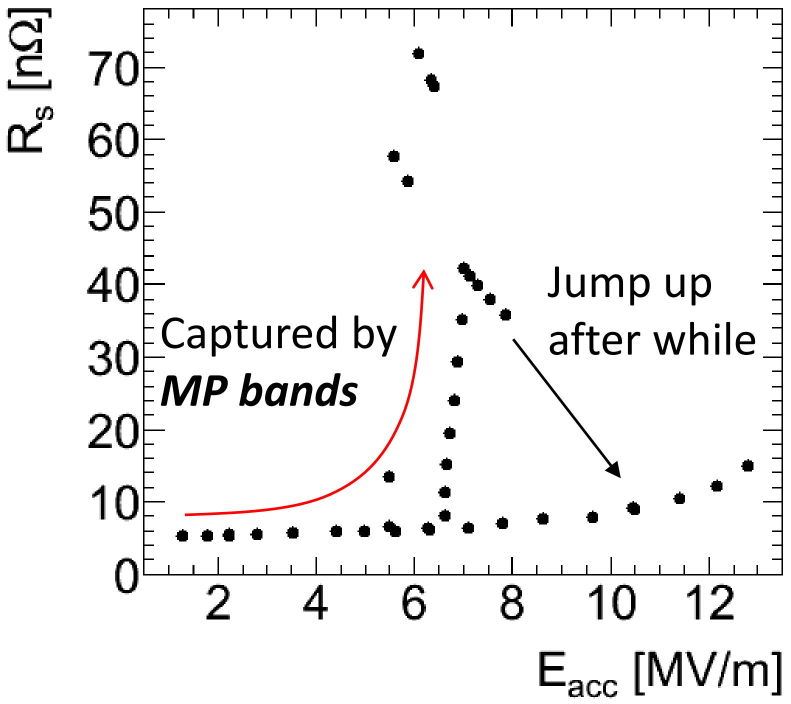
Near surface

Deep into the bulk

3-5nm removal of CH-rich layer

S. Aull SRF2015 TUPB050

## Example: ESS double spoke



Captured by ***MP bands***

Jump up after while

Multipacting is annoying but ***conditionable*** in properly designed Nb cavities

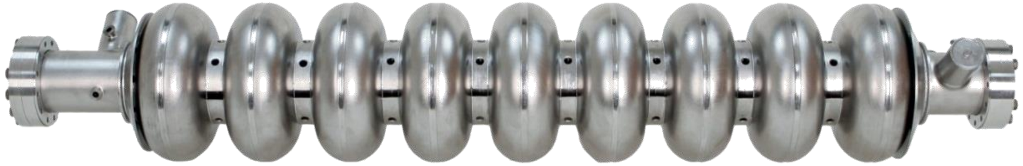
- Sending RF in the MP band
- Jump up to outside the band within a few hours or one day
- Repopulated after thermal cycles

Low-T baking is often performed to get rid of water from the surface

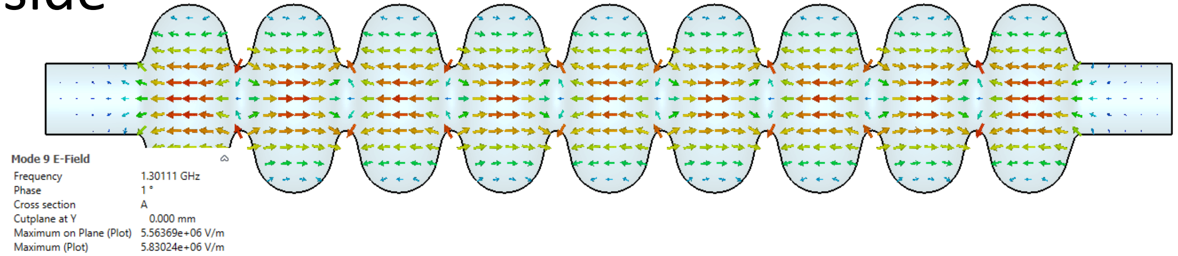
# Outline

- Introduction: from theory to reality *cryomodule*
- Cavity engineering
  - Mechanical structure
  - Material
  - Surface physics
- Ancillary of cavities
  - RF couplers & tuners
  - Digital LLRF
  - High power amplifiers
- New research directions
  - New materials
  - Applications for fundamental physics
- Conclusion

# A lonely empty cavity is useless at all ☹



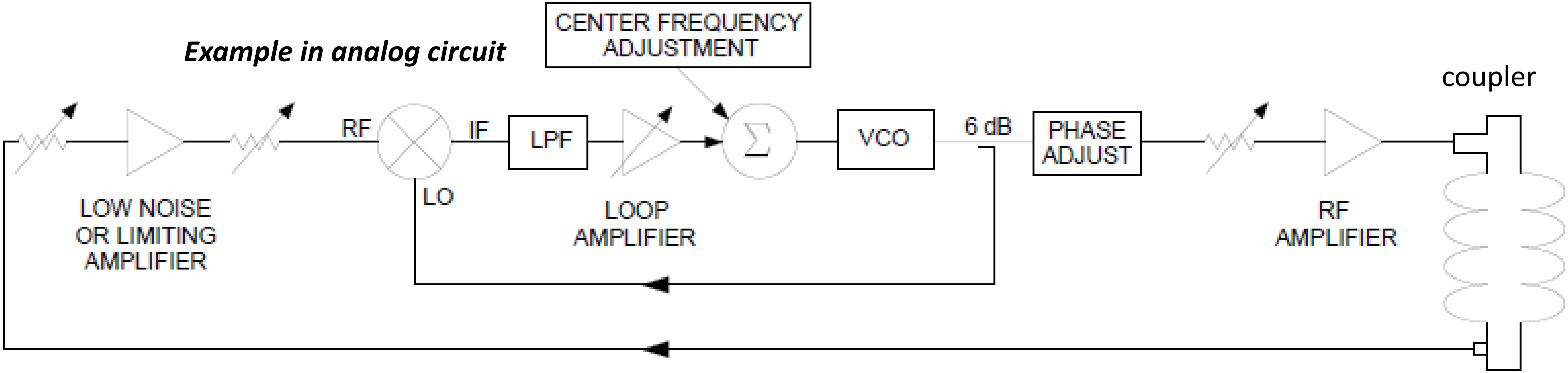
We need RF inside



Mode 9 E-Field

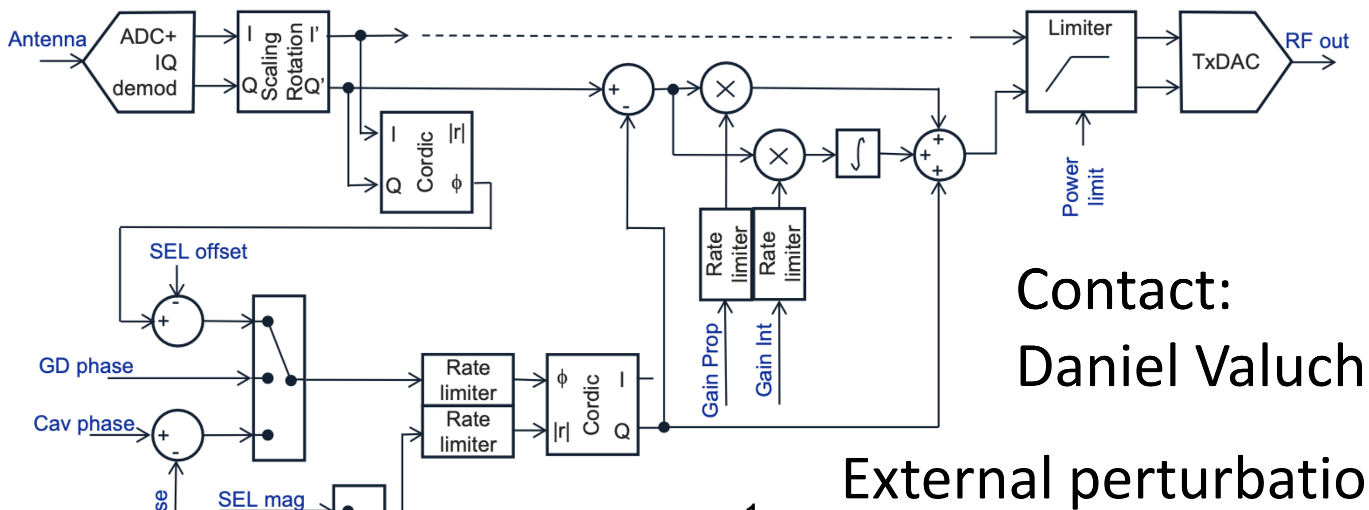
Frequency 1.30111 GHz
Phase 1 °
Cross section A
Cutplane at Y 0.000 mm
Maximum on Plane (Plot) 5.56369e+06 V/m
Maximum (Plot) 5.83024e+06 V/m

***Example in analog circuit***



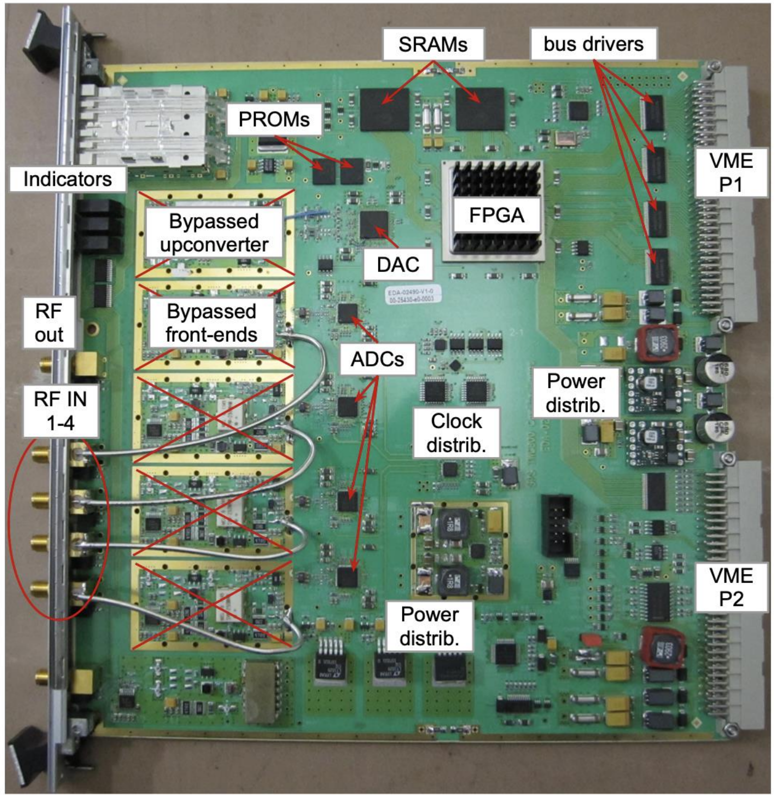
- An low-power RF circuit locks frequency, phase, and amplitude of the superconducting cavity
- An RF amplifier generates useful power level
- A power coupler feeds RF to the cavity
- Tuner controls resonant frequency of the cavity

# *LLRF*: digital system and control algorithm

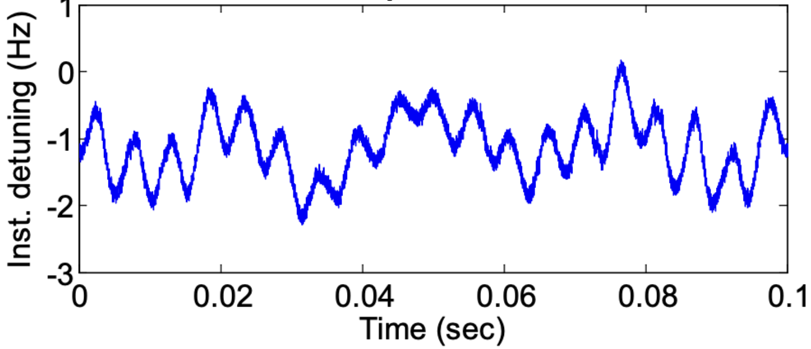


Contact:
Daniel Valuch

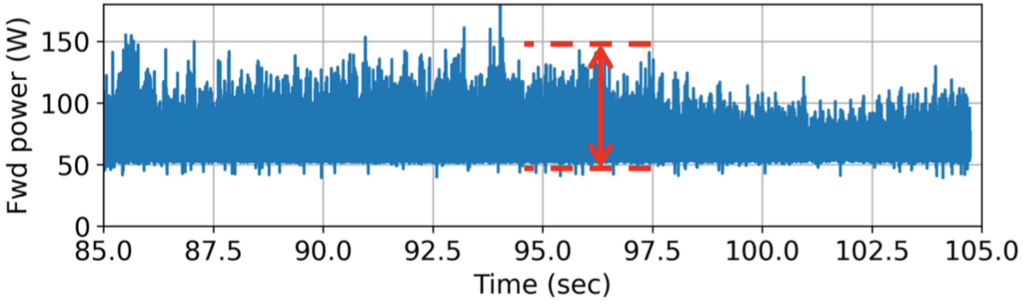
M. Elias master thesis



## External perturbation



## FB to keep cavity field constant

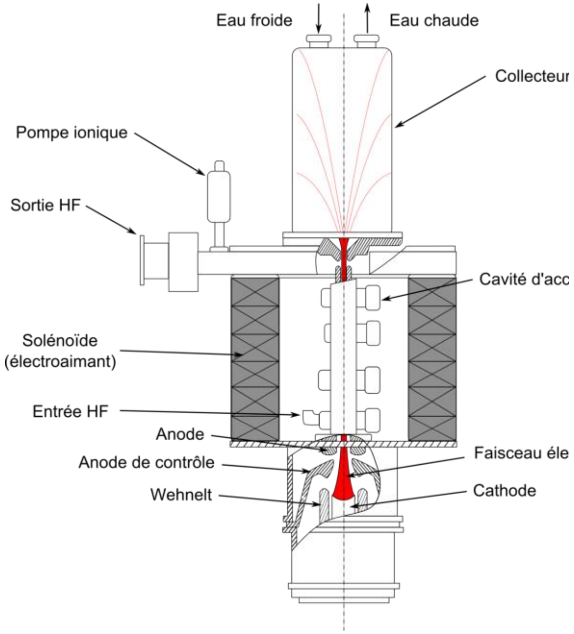


- Design analog and digital circuit to cope with various phenomena to keep cavity field stable
- Control theory and implementation in FPGA
- Directly handled power: 1 mW → needs amplifier

# High-power amplifiers

## Vacuum tubes / klystrons

Amplification via the RF & DC beam interaction



Par Julien Hillairet — Travail personnel, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=3165202

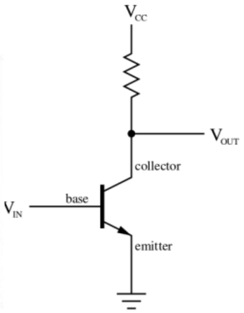
## Transistor-based solid-state amplifiers

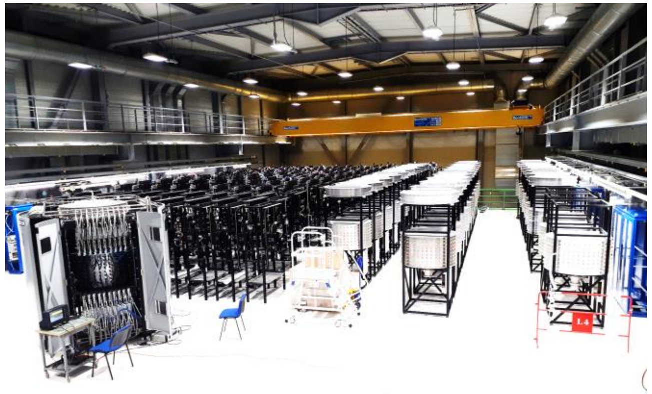
Amplification via the tunneling effect

Shockley

Bardeen

Brattain



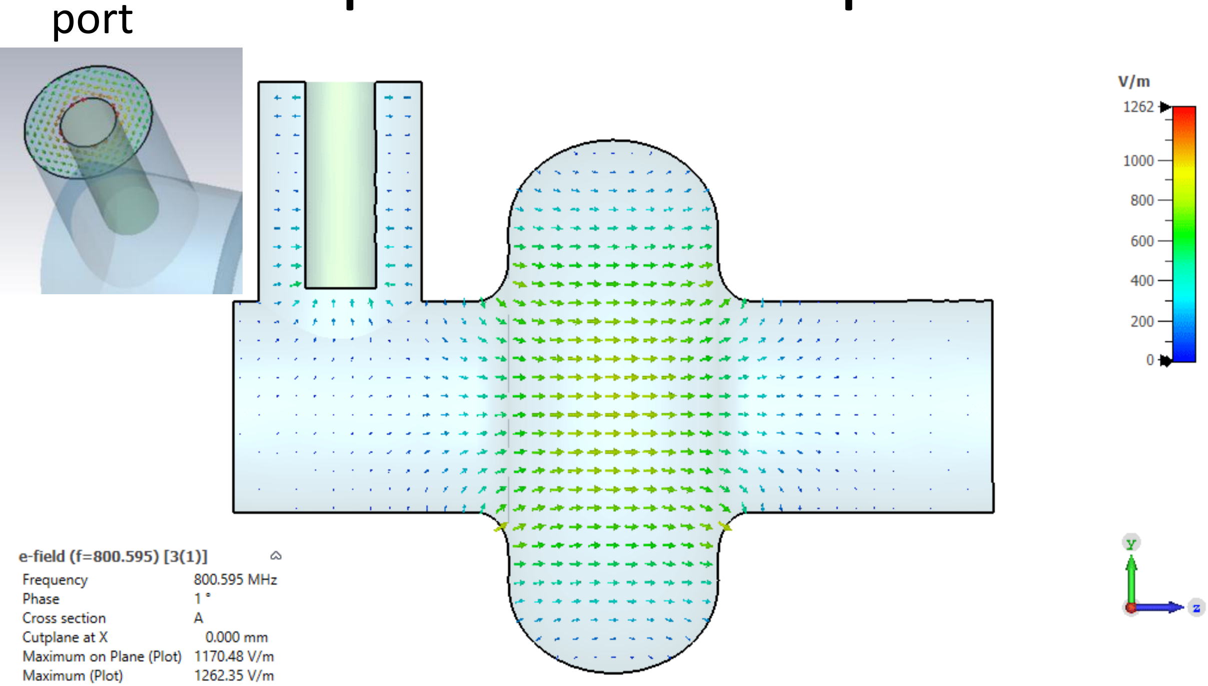


Courtesy: Eric Montesinos

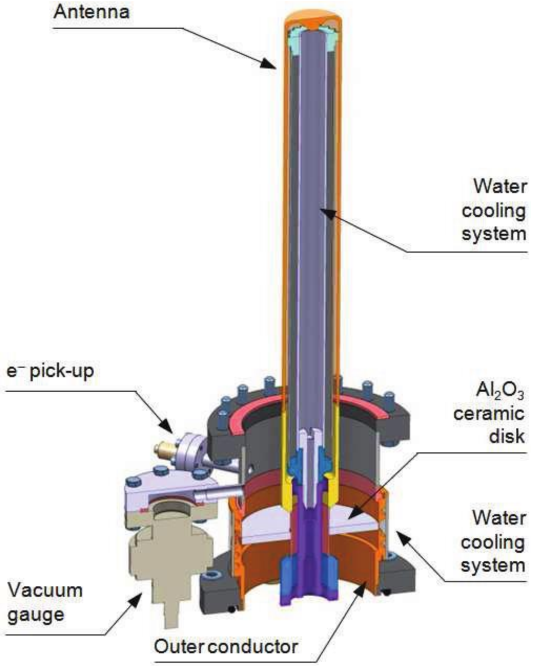
## Recent research directions at CERN

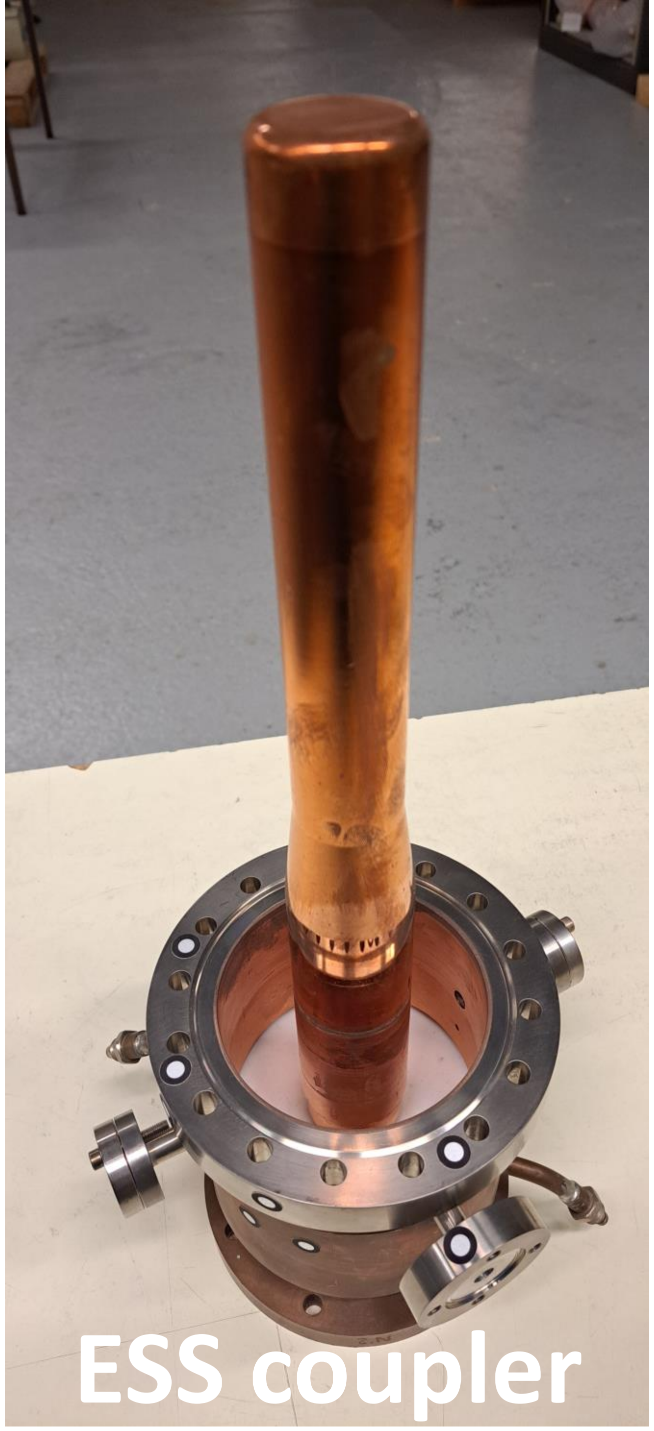
- Very efficient klystron design (contact: Igor Syratchev)
- Large combiner of a large number of transistors
- Sustainability & reliability

# RF power coupler to feed RF



e-field (f=800.595) [3(1)]
Frequency 800.595 MHz
Phase 1 °
Cross section A
Cutplane at X 0.000 mm
Maximum on Plane (Plot) 1170.48 V/m
Maximum (Plot) 1262.35 V/m





Power flow (Poynting vector) through the port gives coupler Q

$$Q_{ext} = \frac{\omega_0 U}{P_e} = \frac{\omega_0 U}{\frac{1}{2}\int_{S_{port}} \vec{E} \times \vec{H} dS}$$

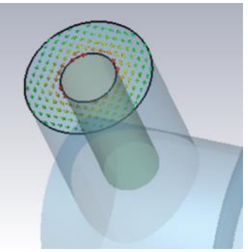
Total Q of the cavity is thus shifted from unloaded $Q_0$

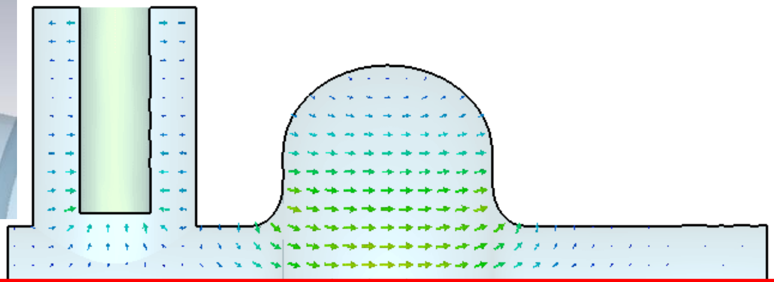
$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_{ext}}$$

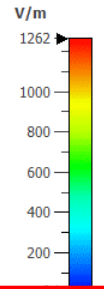
Contact: Eric Montesinos

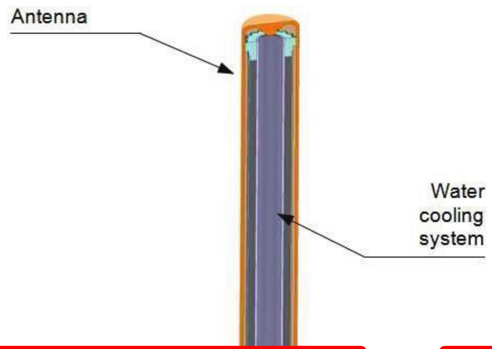
# RF power coupler to feed RF

port









**Weak point of SRF cryomodules**

**Lesson learnt from HIE-ISOLDE…**

**ESS coupler**

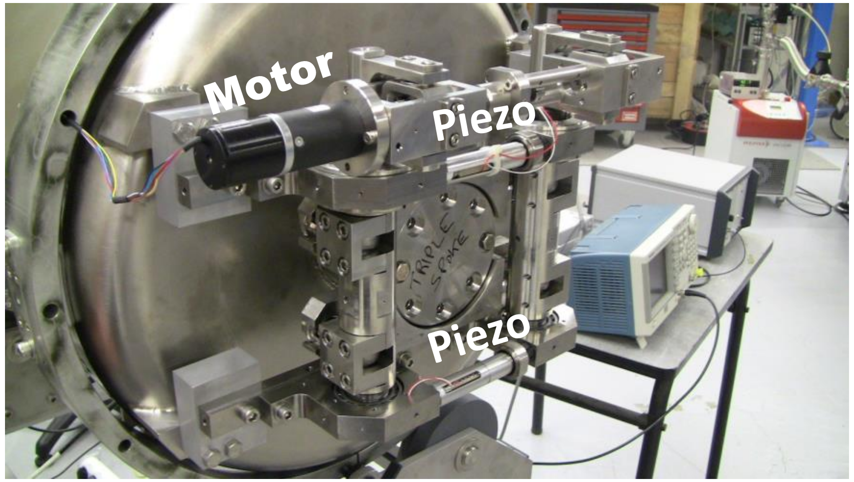
$$P_e \quad \frac{1}{2}\int_{S_{port}} \vec{E}\times\vec{H}\,dS$$

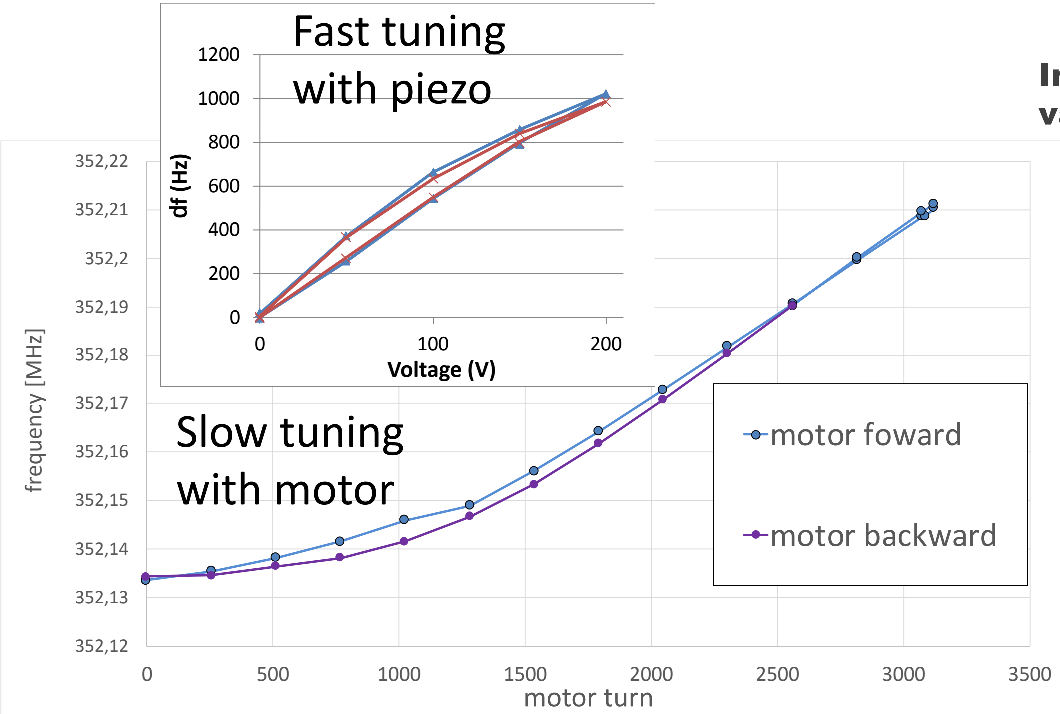
Total Q of the cavity is thus shifted from unloaded $Q_0$

$$\frac{1}{Q_L}=\frac{1}{Q_0}+\frac{1}{Q_{ext}}$$

Contact: Akira Miyazaki

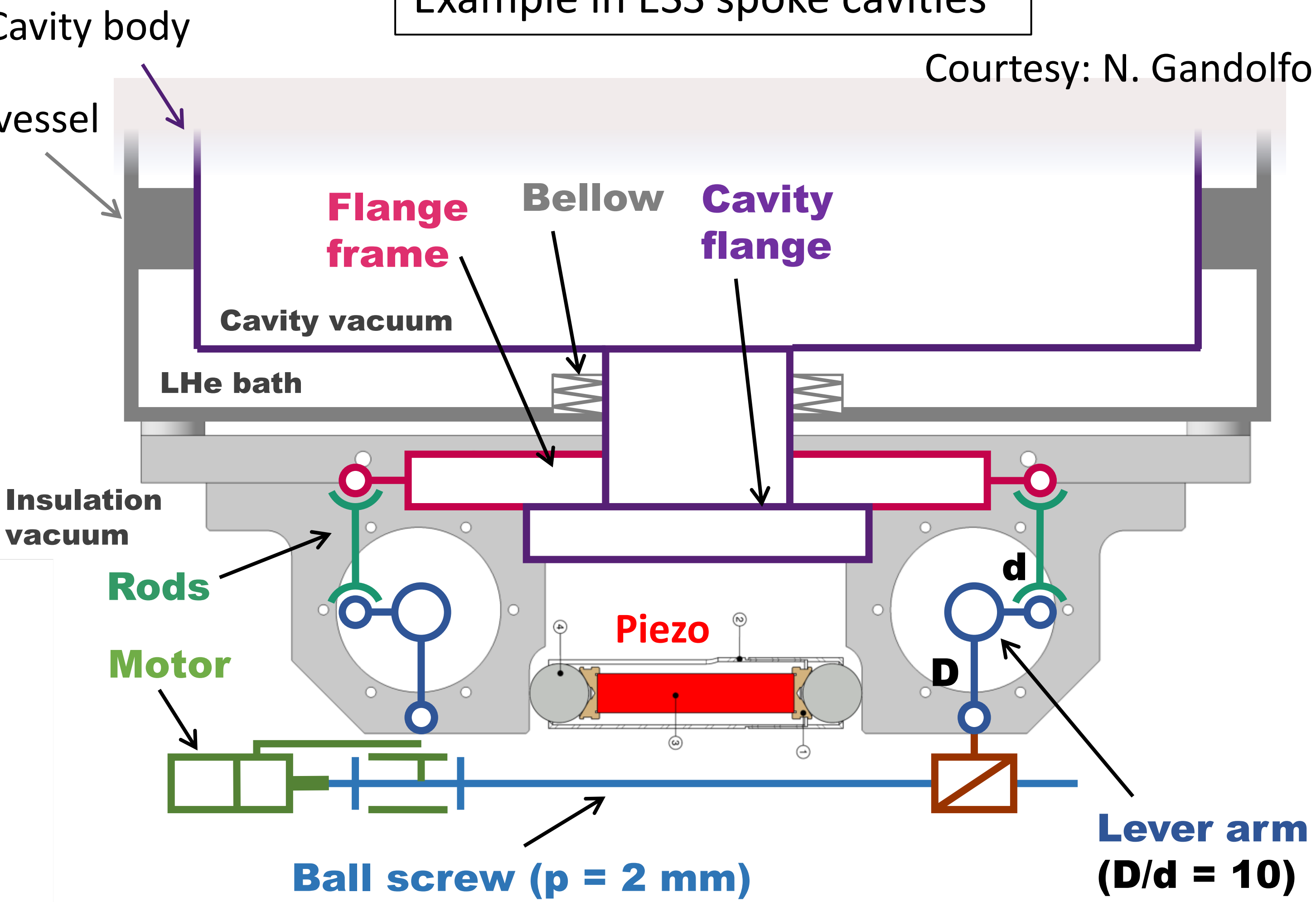
# Tuner to control resonant frequency of cavities





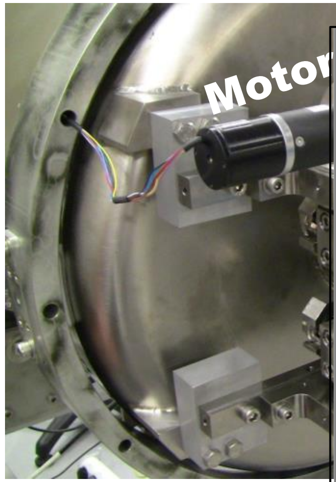
Example in ESS spoke cavities

Courtesy: N. Gandolfo



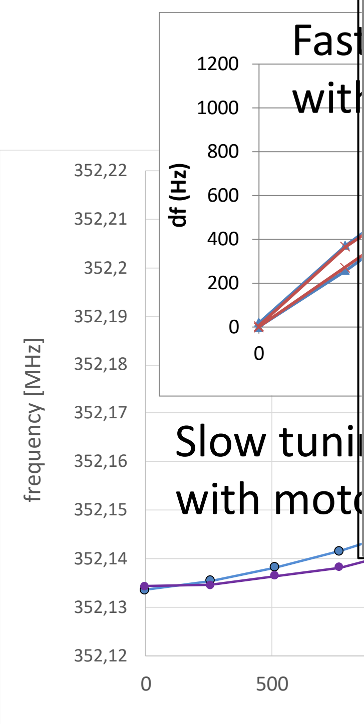
- Motor → course tuning before accelerator operation
- Piezo → active tuning against vibration & pulsed operation

# Tuner to control resonant frequency of cavities



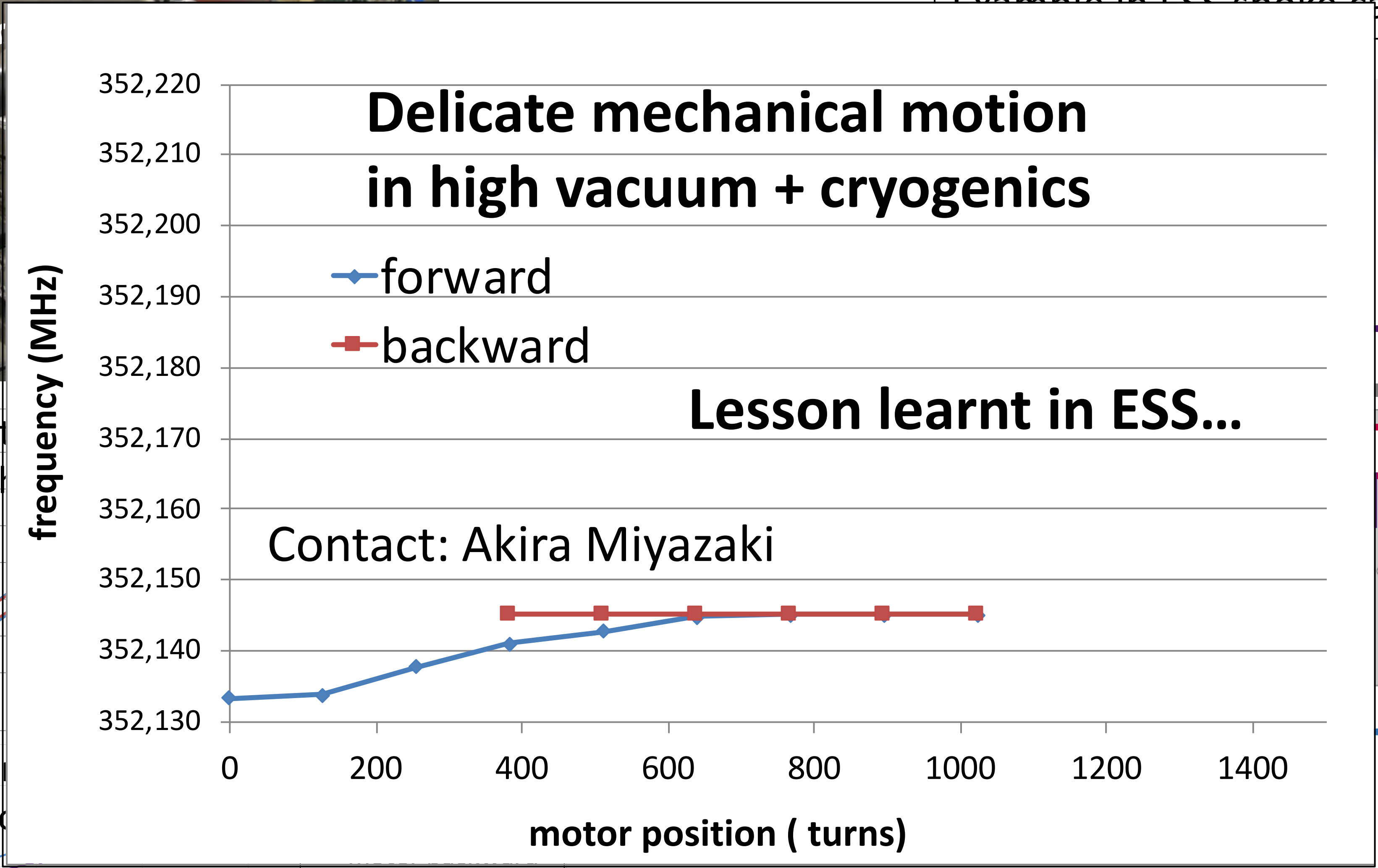
Example in ESS spoke cavities

Courtesy: N. Gandolfo



Fast
wit

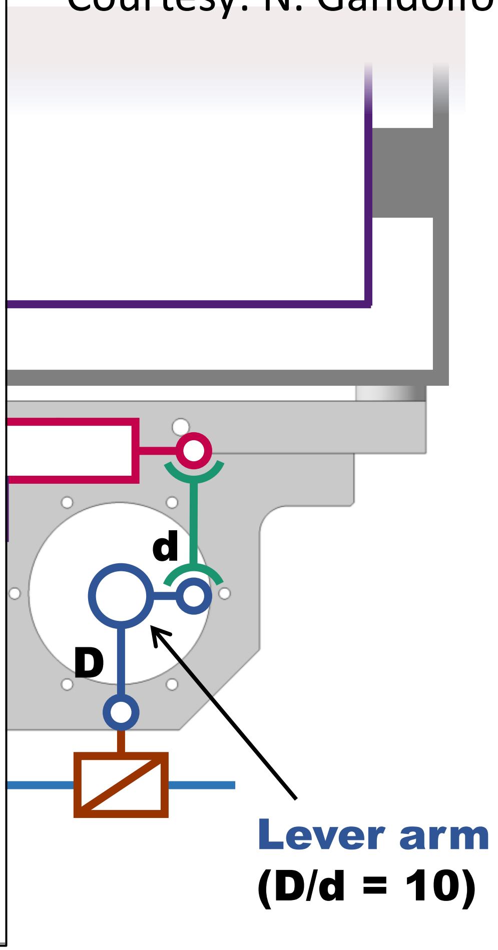
Slow tuni
with mot



**Delicate mechanical motion in high vacuum + cryogenics**

**Lesson learnt in ESS…**

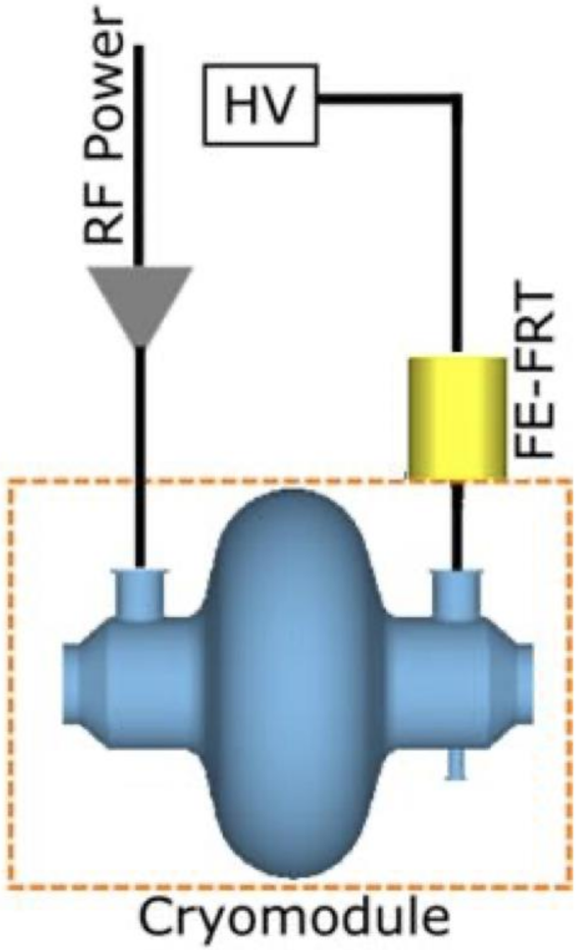
Contact: Akira Miyazaki

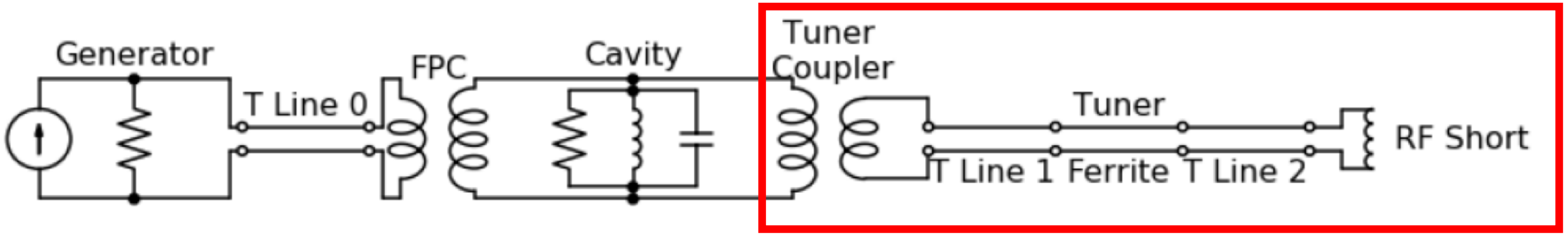


**Lever arm (D/d = 10)**

- Motor → course tuning before accelerator operation
- Piezo → active tuning against vibration & pulsed operation

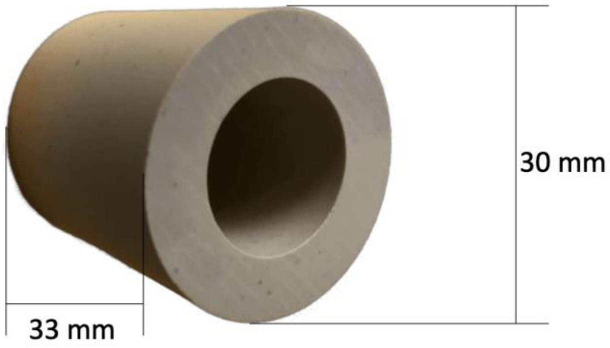
# Non-mechanical fast reactive tuner





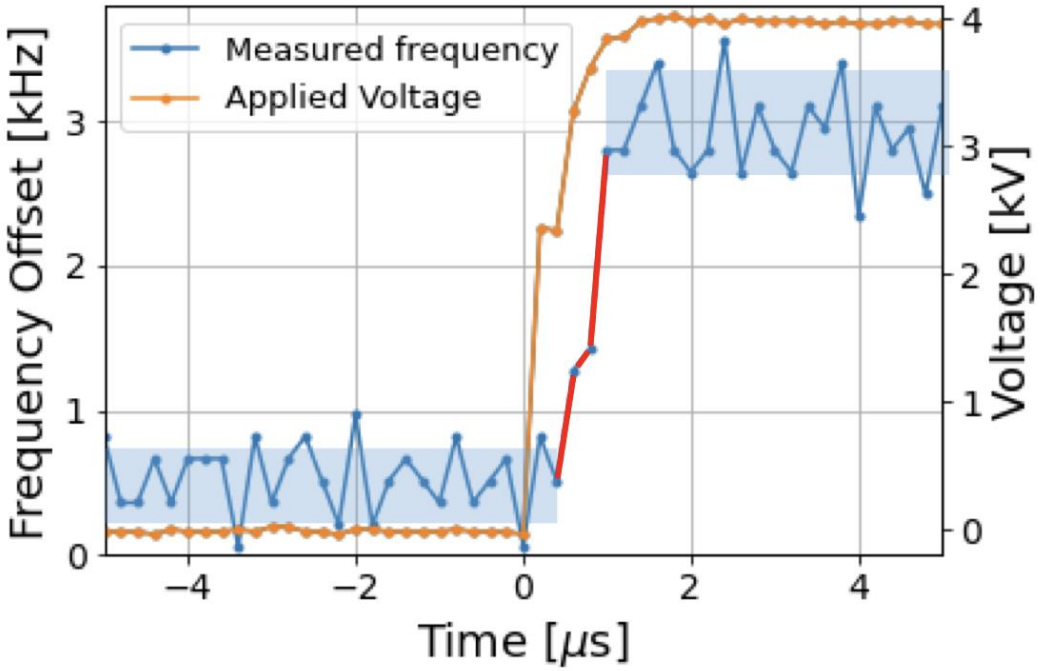
Courtesy: N. Shipman

$BaTiO_3$-$SrTiO_3$



A BST(M) Ferroelectric Sample

$$\epsilon = \epsilon(E) \rightarrow \Delta f$$

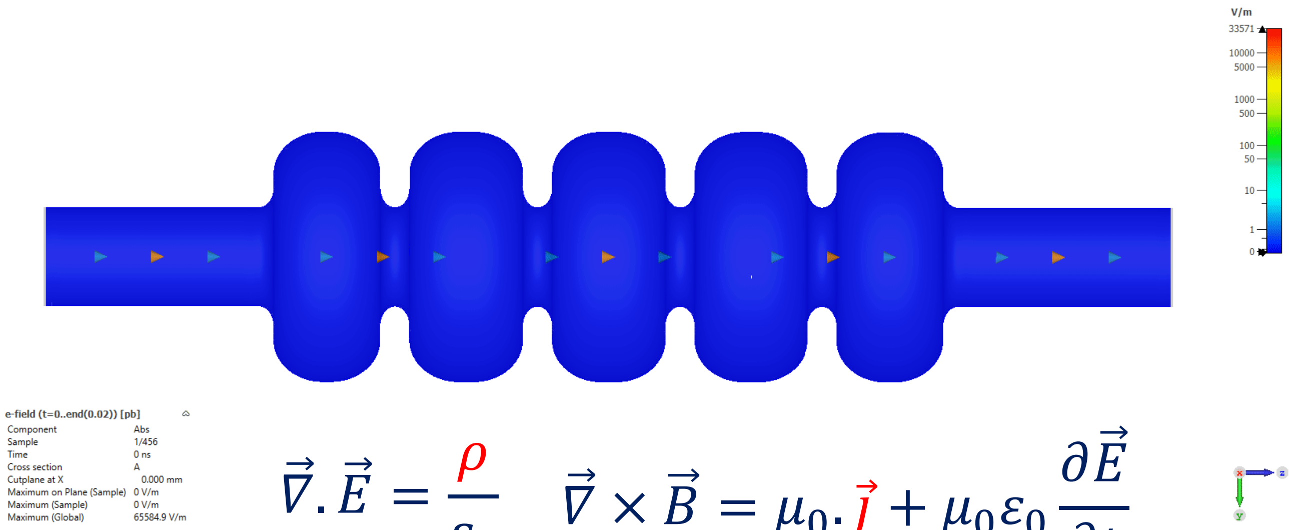


## Active R&D is on-going at CERN

Contact: Alick Macpherson

# Beam → RF excitation

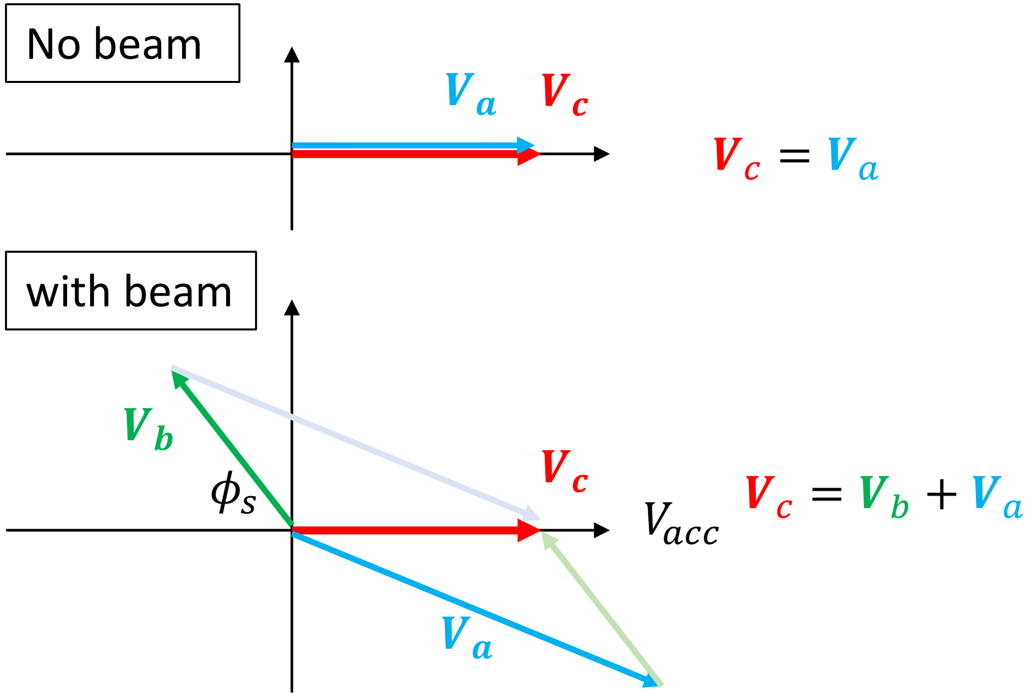
Contact: Rama Calaga



e-field (t=0..end(0.02)) [pb]

| | |
|---|---|
| Component | Abs |
| Sample | 1/456 |
| Time | 0 ns |
| Cross section | A |
| Cutplane at X | 0.000 mm |
| Maximum on Plane (Sample) | 0 V/m |
| Maximum (Sample) | 0 V/m |
| Maximum (Global) | 65584.9 V/m |

$$\vec{\nabla}.\vec{E} = \frac{\rho}{\varepsilon_0} \qquad \vec{\nabla} \times \vec{B} = \mu_0.\vec{j} + \mu_0\varepsilon_0\frac{\partial\vec{E}}{\partial t}$$



$$V_c = V_a$$

$$V_c = V_b + V_a$$

## Beam loading

Accelerating mode $V_b$ is excited in another phase

→ Overhead in the amplifier $V_a$ to compensate it

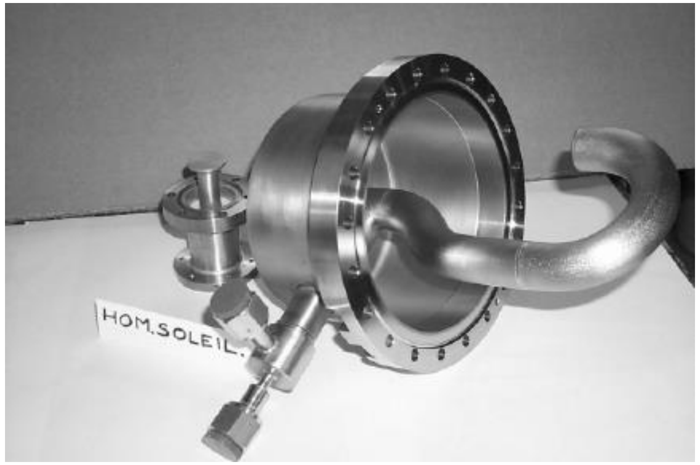
→ Optimum detuning trick (see LHC)

## Higher Oder Modes

Non-accelerating modes are excited

→ Perturbation to beam (challenge in circular machines)

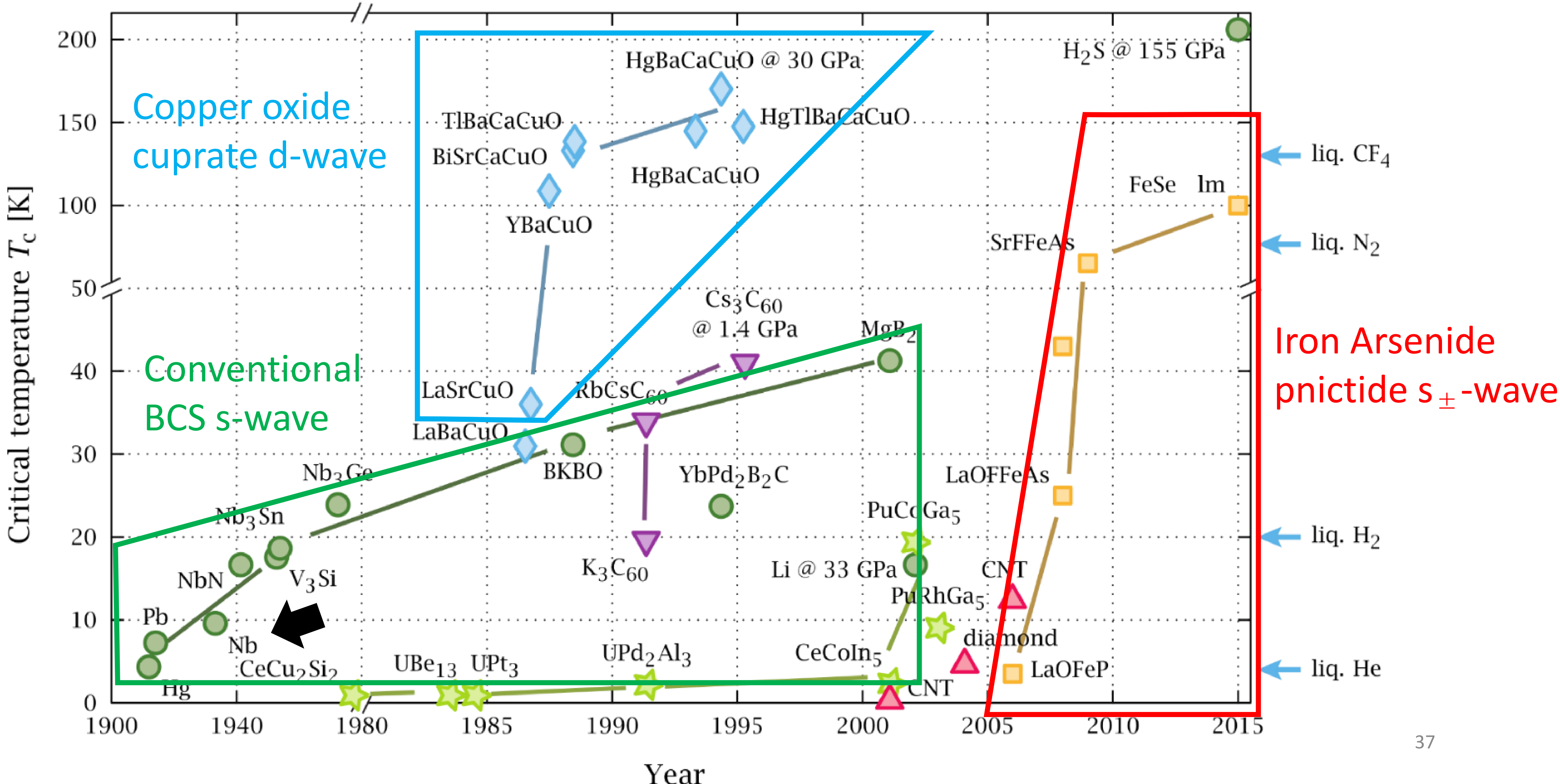
→ HOM couplers / dampers to mitigate them



# Outline

- Introduction: from theory to reality *cryomodule*
- Cavity engineering
  - Mechanical structure
  - Material
  - Surface physics
- Ancillary of cavities
  - RF couplers & tuners
  - Digital LLRF
  - High power amplifiers
- New research directions
  - New materials
  - Applications for fundamental physics
- Conclusion

# Three different families of superconductors

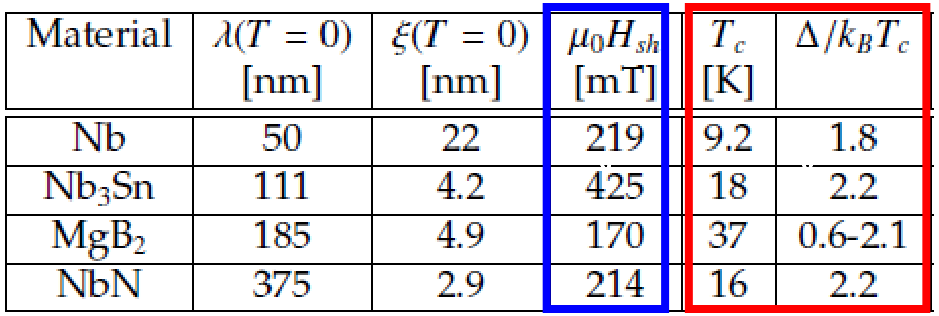


Copper oxide
cuprate d-wave

Conventional
BCS s-wave

Iron Arsenide
pnictide $s_{\pm}$-wave

# How about alloys?



| Material | $\lambda(T=0)$ [nm] | $\xi(T=0)$ [nm] | $\mu_0 H_{sh}$ [mT] | $T_c$ [K] | $\Delta/k_B T_c$ |
|---|---|---|---|---|---|
| Nb | 50 | 22 | 219 | 9.2 | 1.8 |
| $Nb_3Sn$ | 111 | 4.2 | 425 | 18 | 2.2 |
| $MgB_2$ | 185 | 4.9 | 170 | 37 | 0.6-2.1 |
| NbN | 375 | 2.9 | 214 | 16 | 2.2 |

$$R_{BCS}(T) = \frac{A}{T} \exp\left(-\frac{\Delta}{k_B T_c}\frac{T_c}{T}\right)$$

**Mechanically brittle**

Difficult to fabricate cavity structures
→ coating?

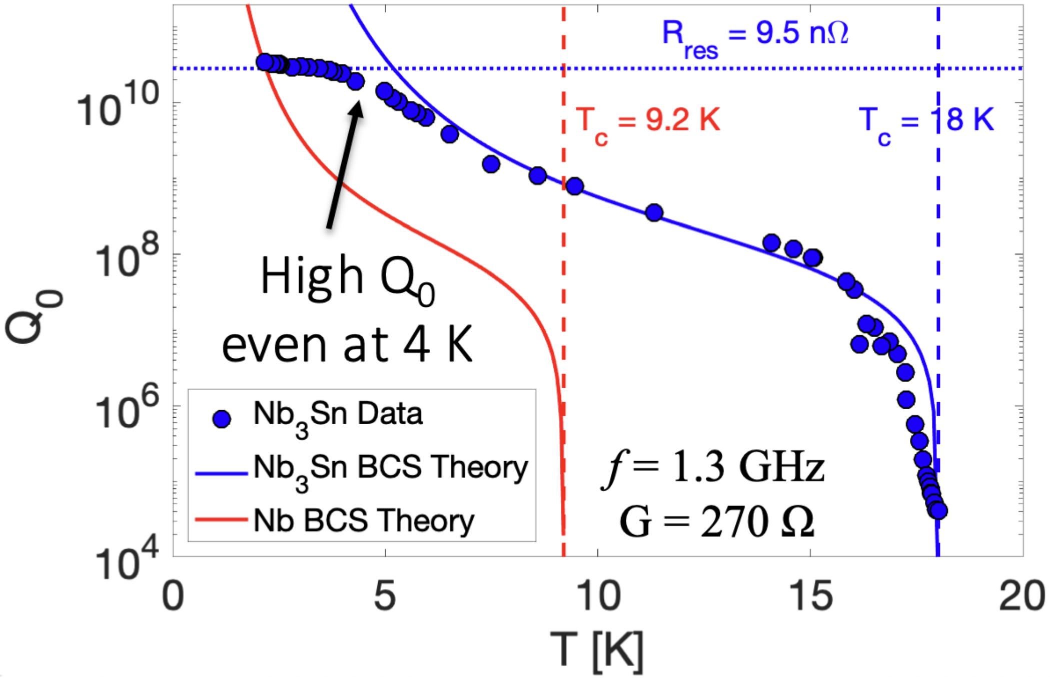
**Thermal conductivity**

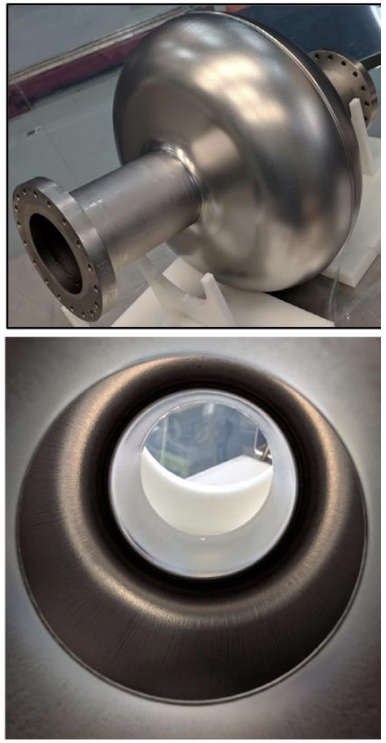
Much worse than Nb → Just a film?

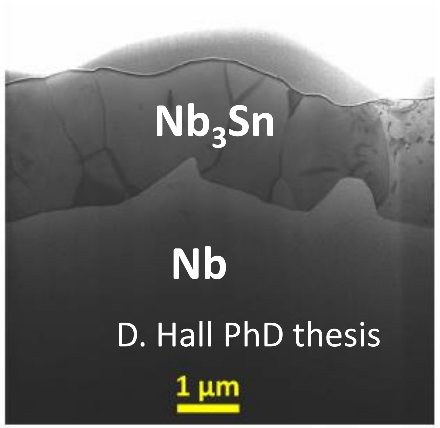
**Short $\xi_0$**

Flux penetration through grain boundaries → Protective layer?

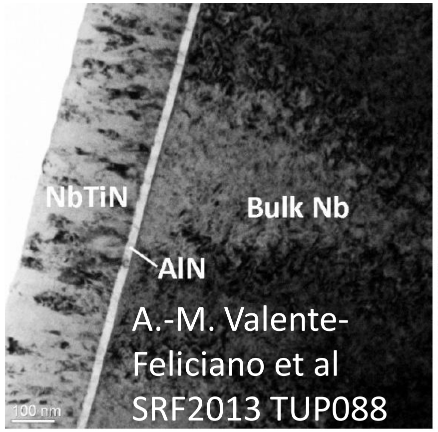
Courtesy S. Posen



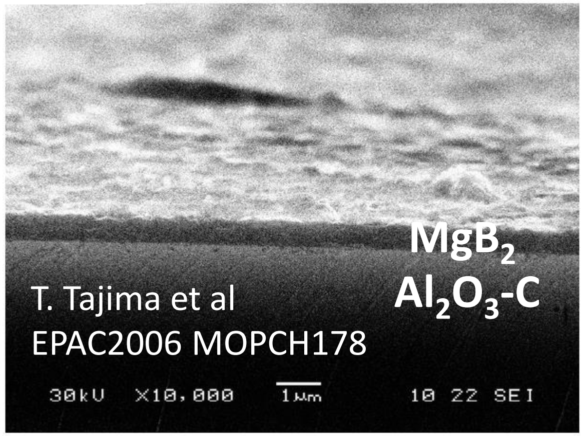




D. Hall PhD thesis



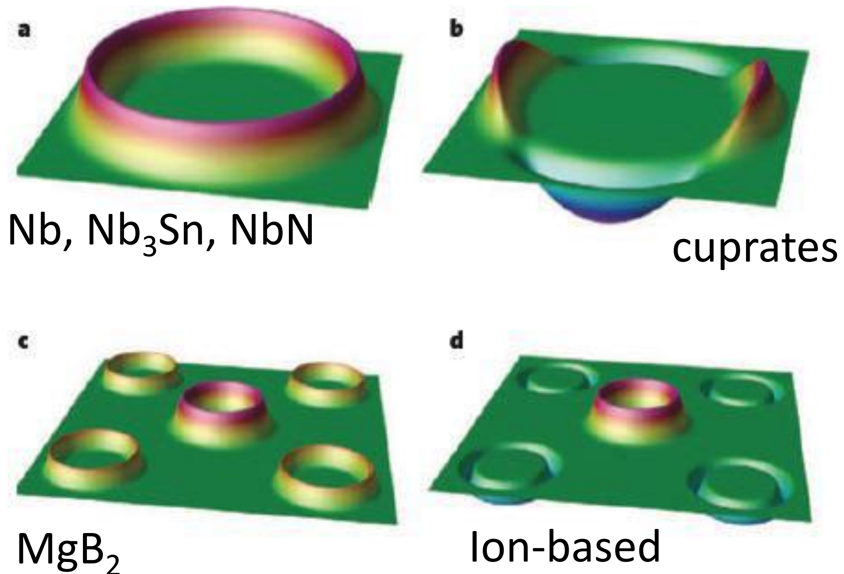
A.-M. Valente-Feliciano et al
SRF2013 TUP088

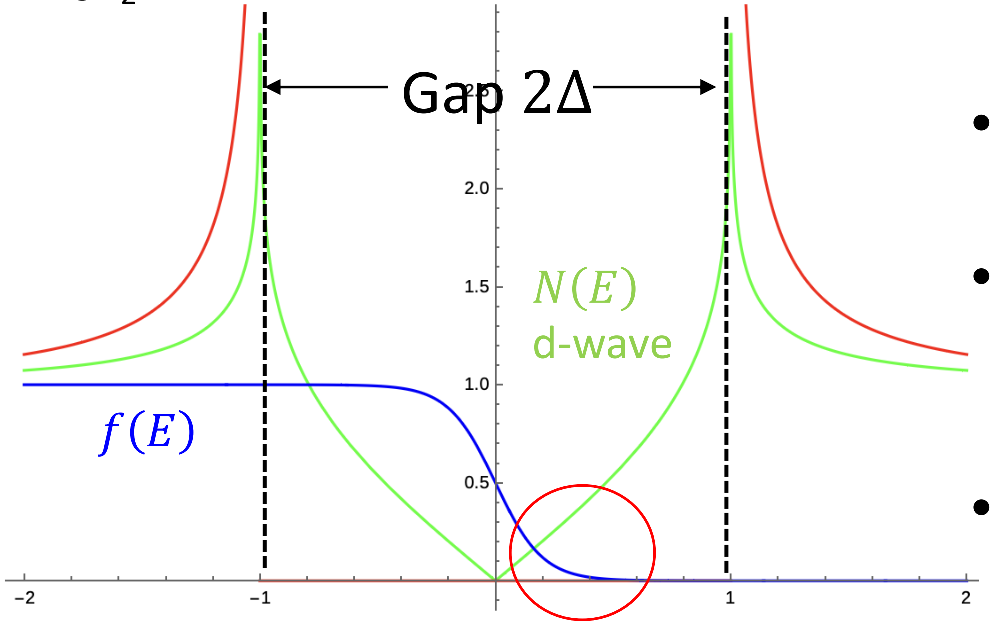


T. Tajima et al
EPAC2006 MOPCH178

Contact: Guillaume Jonathan Rosaz

# High-Tc SC→ Full gap may be important for high RF field





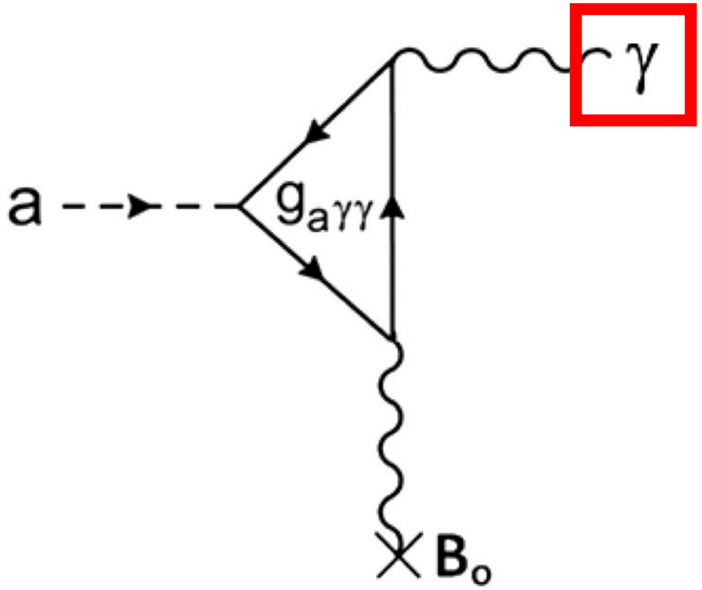
$$R_s \propto \hbar\omega \int_{\Delta}^{\infty} dE\, [f(E) - f(E+\hbar\omega)] \times N(E)N(E+\hbar\omega)$$

- One of the major sources of the SC surface resistance is thermally excited quasi-particles
- Conventional SC is s-wave and the full gap structure prevents the number of quasi-particles $\sim \exp(-\Delta/T)$
- Cuprate is gapless d-wave and many quasi-particles can be excited $\sim T^{\alpha}$
- Ion-based superconductors are gapful
  - Preliminary study by AM (arXiv:2311.17513)
  - $B_{c1}$&$B_{c2}$ enhancement was observed (SUST 34 015001 34)
- SLAC & CERN → YBCO with medium pulse length

Open question for the future generation

# Microwave photons may address fundamental physics

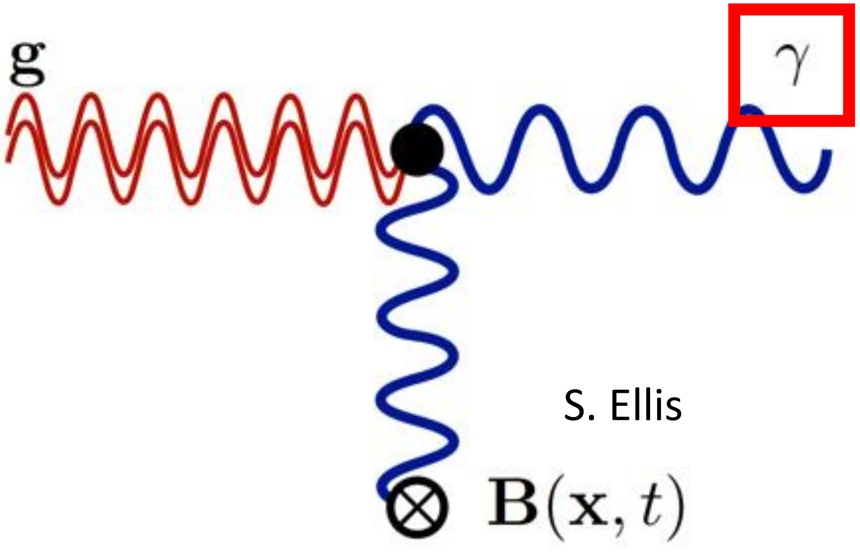
## Axions



Inverse Primakoff effect

Minimal extension of SM

## Gravitational waves

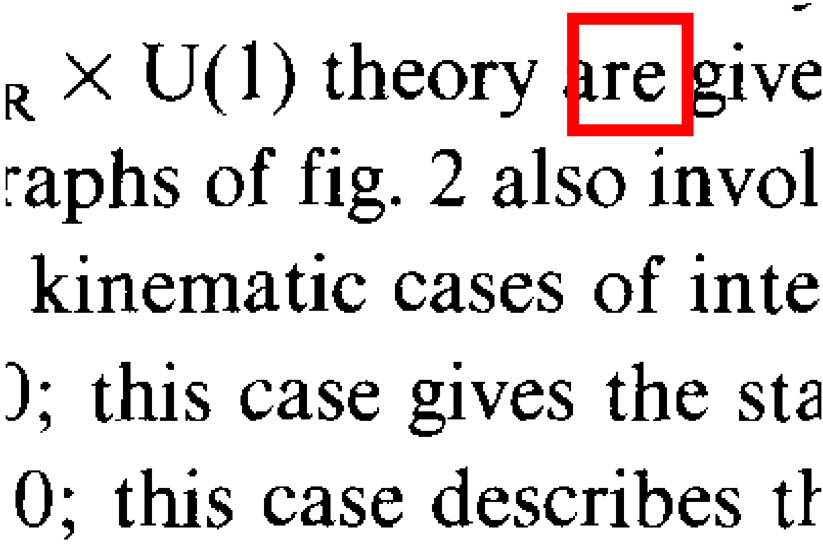


S. Ellis

Inverse Gertsenshtein effect

Solution of general relativity

## Neutrinos



R × U(1) theory are give
raphs of fig. 2 also invol
kinematic cases of inte
); this case gives the sta
0; this case describes th

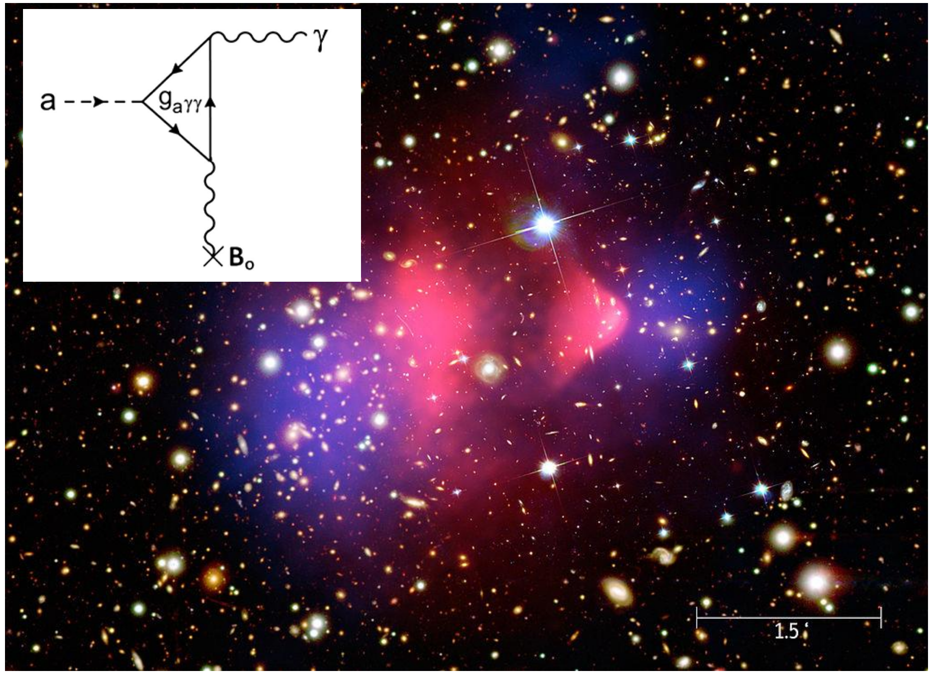
Cosmic neutrino background

Extension of SM and/or SM

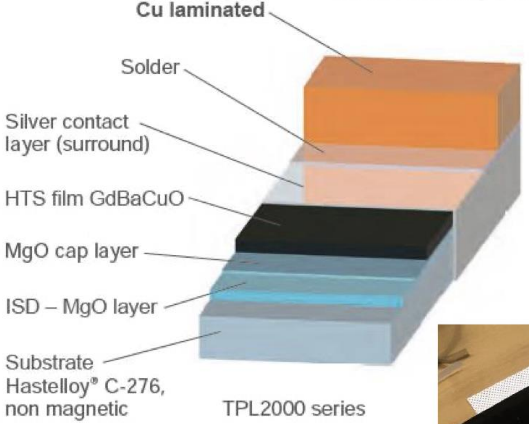
Contact: Akira Miyazaki

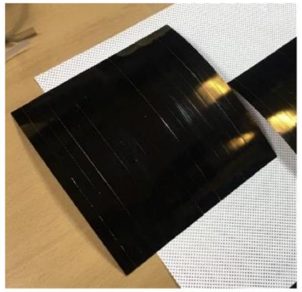
# HTS SRF cavities under static magnetic field

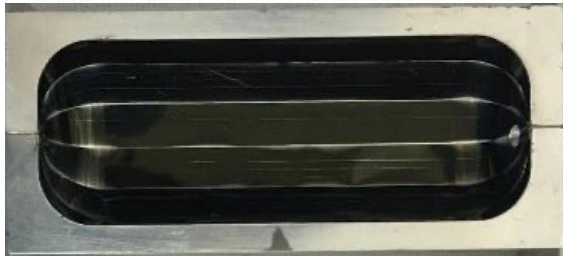
## cuprate tapes on copper cavities



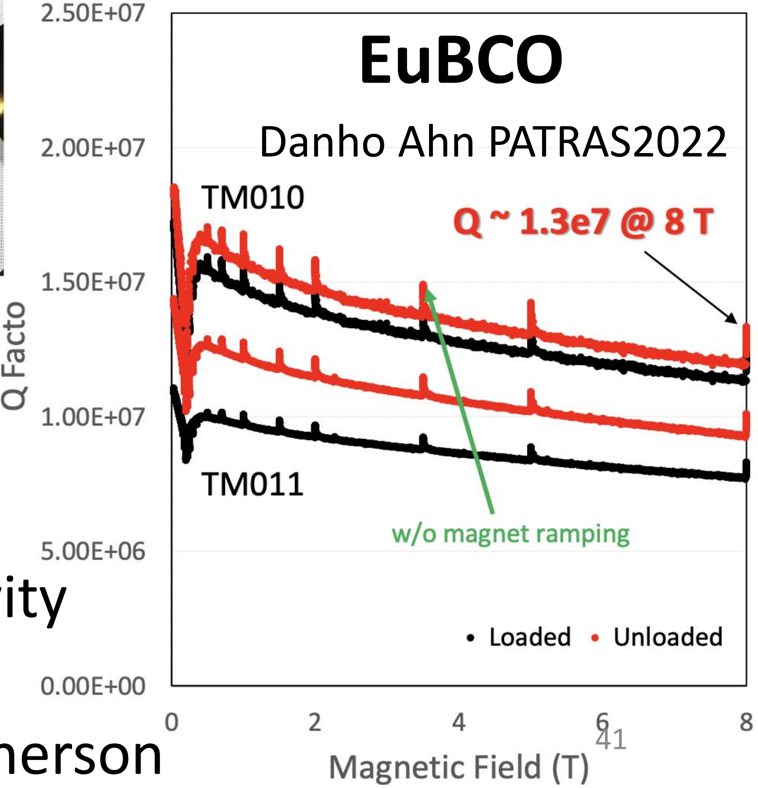
THEVA Catalog (2017)







Contact: Sergio Calatroni



- Excellent Q is obtained under strong **static** magnetic fields
  - Good application of cuprates for dark matter axion search
- New experiment at CERN: “axion heterodyne”
  - No magnetic fields → RF is applied in a conventional SRF cavity
  - Phys. Rev. D 104, L111701 2021
  - Maybe an opportunity for students?

Contact: Alick Macpherson

# Two Phenomena to address GW via microwaves

The Einstein equation

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

can be expanded to the linear order with small strain $h$

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

- Primodial blackhole merger →MHz-GHz signal
- GW from early universe

## Mechanical deformation of a cavity wall

$$\frac{d^2x}{dt^2} = -\frac{1}{2}\frac{d^2h_{xx}}{dt^2}x + \frac{1}{2}\frac{d^2h_{xx}}{dt^2}y$$

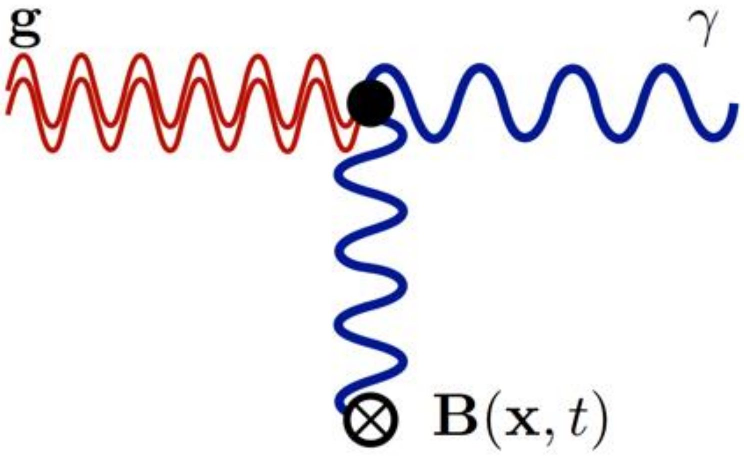
$$\frac{d^2y}{dt^2} = \frac{1}{2}\frac{d^2h_{xx}}{dt^2}x + \frac{1}{2}\frac{d^2h_{xx}}{dt^2}y$$

arXiv:gr-qc/0502054

## Coupling to microwaves under static B

$$\Box h_{\mu\nu} = -16\pi T_{\mu\nu}$$

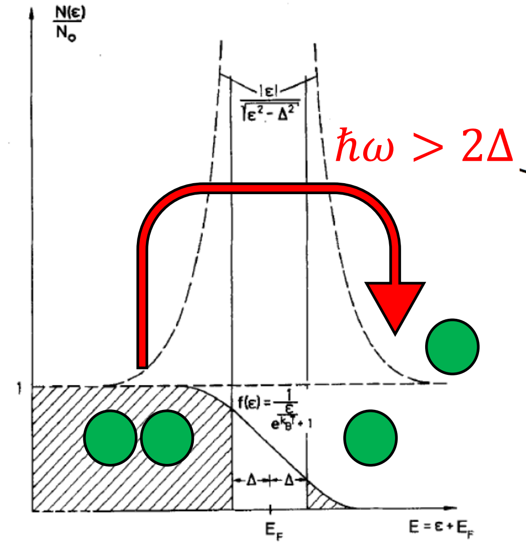
$$4\pi T_{\mu\nu} = F_{\mu\alpha} F_{\nu}{}^{\alpha} - \frac{1}{4} g_{\mu\nu} F_{\alpha\beta} F^{\alpha\beta}$$

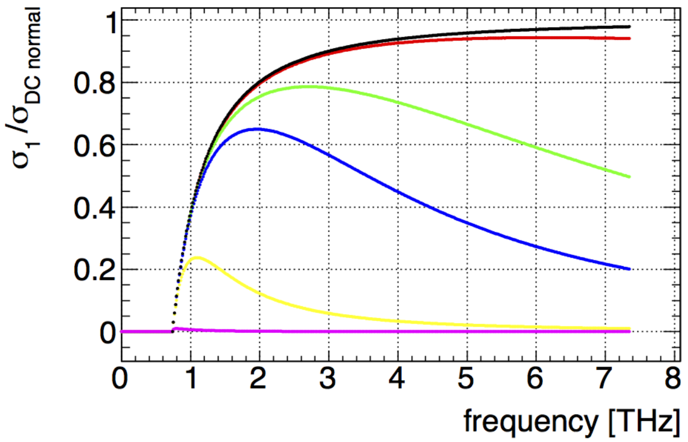


M. E. Gertsenshtein JETP 41 113 1961

# Single microwave photon sensors

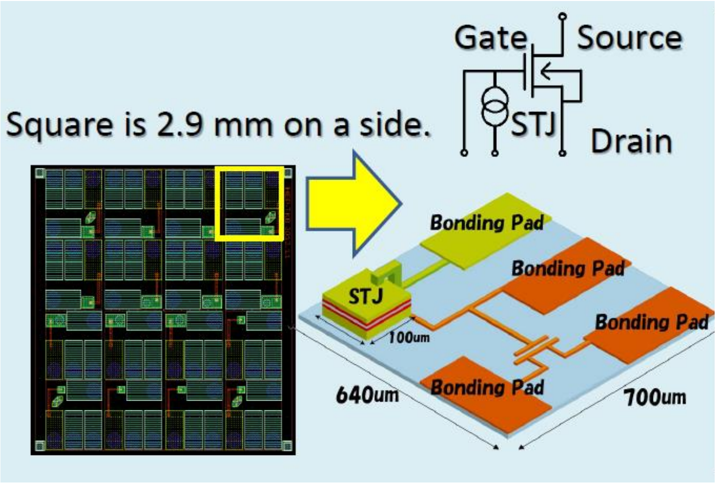
## Superconducting Tunnel Junction (STJ)





Al STJ

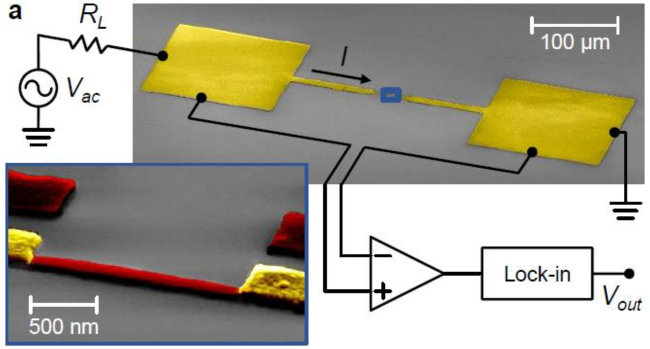
Hf STJ

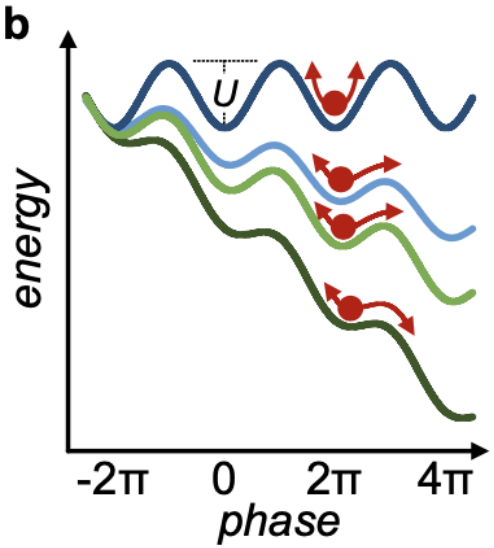


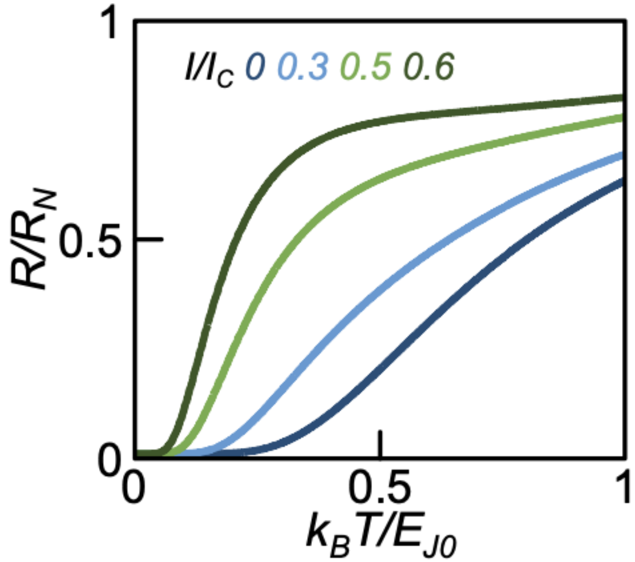
S.-H. Kim et al, JPS Conf. Proc. 1 013127 2014

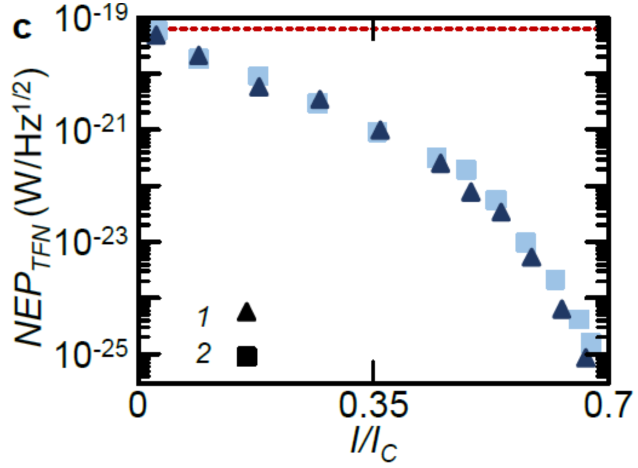
## Current-biased Josephson Junction TES (JES)

Bolometer/calorimeter





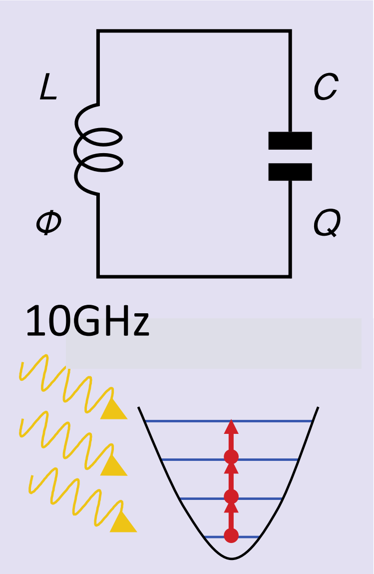


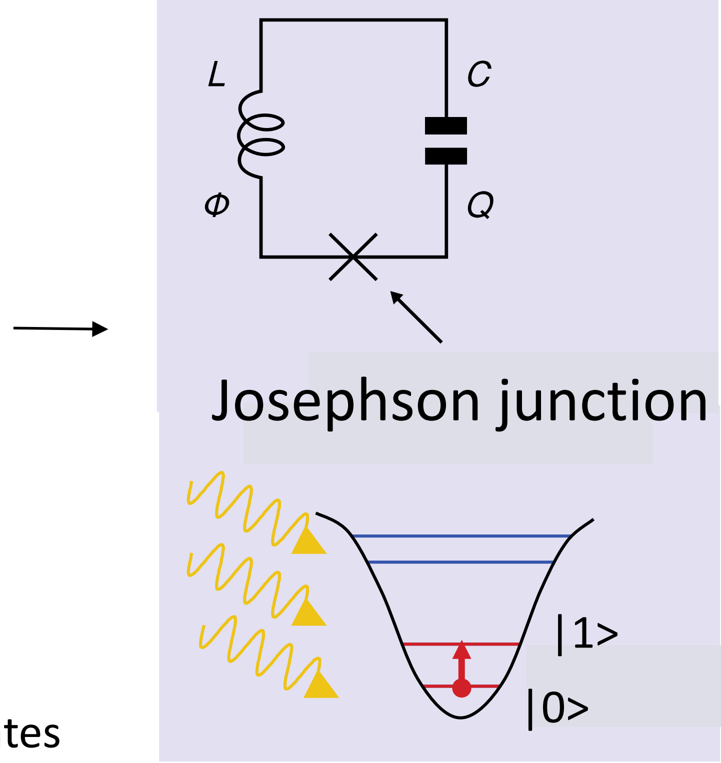


F. Paolucci et al Phys Rev Appl. 14 034055 (2020)

# Superconducting qubit based on SRF cavities (?)

## Key: quantized LC circuit

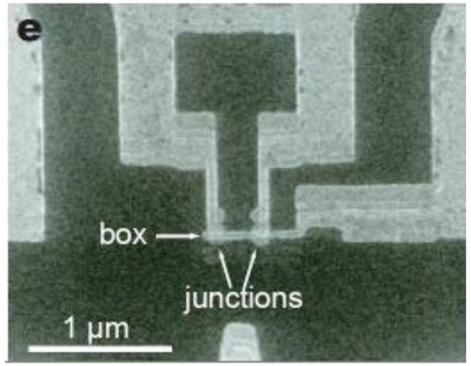




Harmonic oscillator has equally spaced many states
→ Not useful as qubit

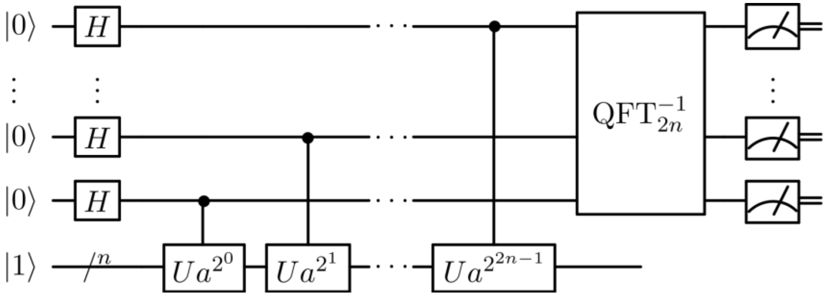
JJ → anharmonic potential
→ selective |0> & |1>

## transmon



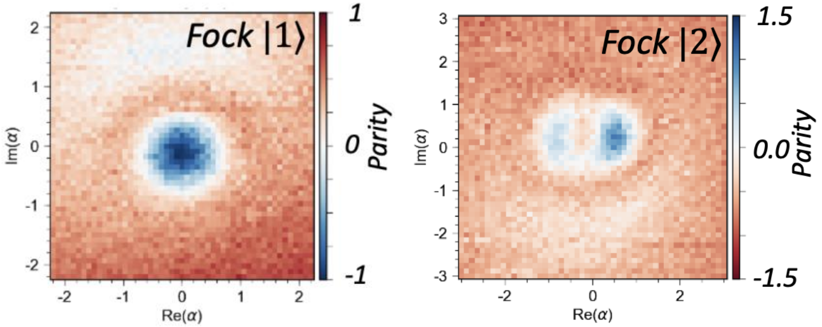
## Shor’s algorithm

finding the prime factors



By Bender2k14 - Own work. Created in LaTeX using Q-circuit. Source code below., CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=34319883

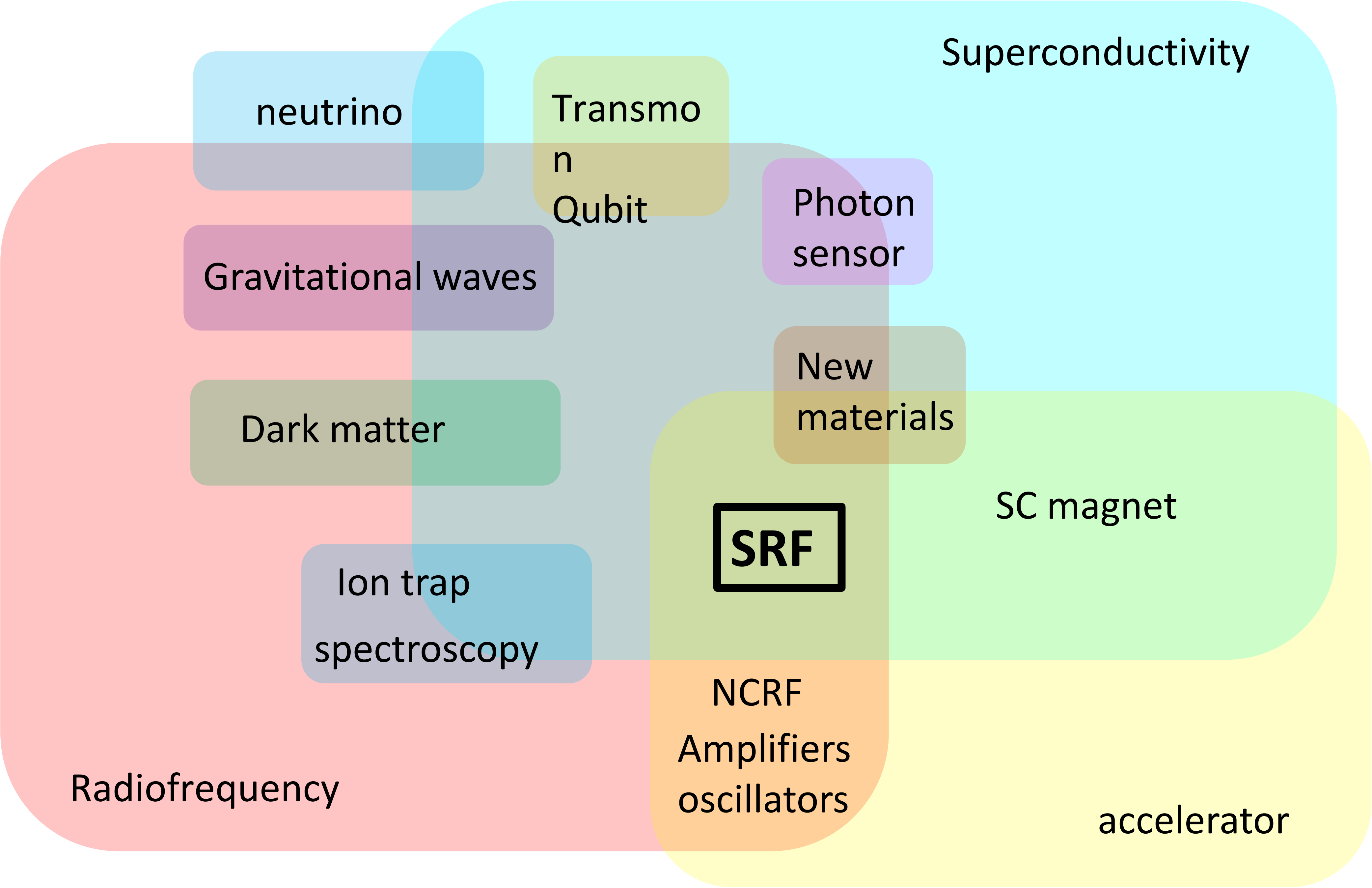
SRF cavity is also a (huge) LC circuit
→ Longer coherent length than existing qubits (qudits)



T. Roy “Advances in SRF Qubit Architectures for Quantum Computing” SRF2023

- 仙場 浩一 “超伝導量子ビットと単一光子の量子もつれ制御” NTT技術ジャーナル 2007.11 23
- 山本剛 “超伝導量子回路の集積化技術の開発” ムーンショット目標6 キックオフシンポジウム2021.3.11

**Quantum Initiative at CERN https://quantum.cern**



Superconductivity

neutrino

Transmon Qubit

Photon sensor

Gravitational waves

New materials

Dark matter

SC magnet

**SRF**

Ion trap spectroscopy

NCRF
Amplifiers
oscillators

Radiofrequency

accelerator

# Outline

- Introduction: from theory to reality *cryomodule*
- Cavity engineering
  - Mechanical structure
  - Material
  - Surface physics
- Ancillary of cavities
  - RF couplers & tuners
  - Digital LLRF
  - High power amplifiers
- New research directions
  - New materials
  - Applications for fundamental physics
- Conclusion

# Conclusions

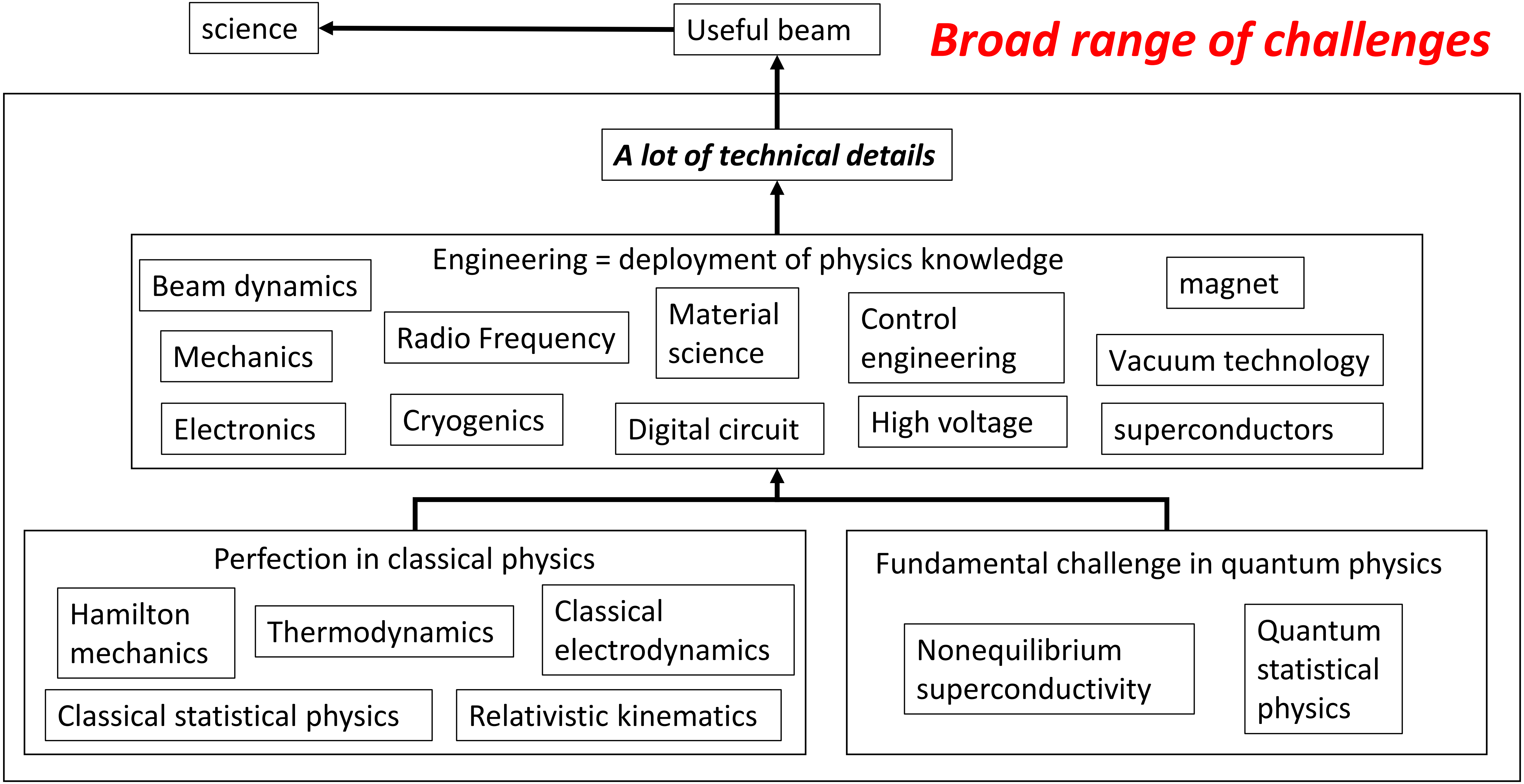
- Fundamental aspects of SRF cavities are interesting but can be hidden by practical challenges
  - Practicality requires extremely broad range of expertise of state-of-the art science and engineering
  - Recent progress in technology gives us almost ideal SRF cavities → chance to further validate and develop fundamental theory originally calculated but kind of stuck in the 1970s
- Cavity engineering is very delicate but finally matured today
  - Geometry and fabrication process
  - Bulk niobium material must be very pure → surprisingly expensive! → Nb/Cu cavities for CERN cavities
  - Surface cleaning and heat treatment (BCP, EP, HPR, HT) to avoid practical limitations (thermal breakdown, Field emission, Q-disease, multipacting), recently with robotics
- A cavity becomes useful only with ancillary RF components
  - LLRF digital circuit and control theory
  - High-power amplifier: vacuum tube vs solid state
  - High-power couplers → be careful! It can be broken
  - Tuner: stepper motor + piezo → New! Fast reactive tuner is being developed
  - Beam → RF excitation: beam loading and HOM handling
- New research opportunities are emerging in the SRF research domain
  - New SC materials: $Nb_3Sn$, NbN, $MgB_2$, cuprate (?), ion-based superconductors (??)
  - SRF is a mean to directly address fundamental physics: axion dark matter, gravitational waves, neutrino decay
  - RF photon sensor and even quantum computing applications
- SRF is an extremely exciting research field and you are more than welcome!

# References

- Standard textbooks on SRF
    - H. Padamsee et al "RF superconductivity for accelerators", 2nd edition, WILEY-VCH (2008)
    - H. Padamsee "RF superconductivity", WILEY-VCH (2009)
    - H. Padamsee "Superconducting Radiofrequency Technology for Accelerators: State of the Art and Emerging Trends", WILEY-VCH (2023)
- Tutorial lectures Series of International Conference on RF Superconductivity
    - https://srf2023.vrws.de/html/class.htm
    - https://indico.frib.msu.edu/event/38/page/357-tutorial-program
- CERN Accelerator Schools
    - https://cas.web.cern.ch
- Advanced topics today can only be found in journal publications and presentations

# backup

# *Broad range of challenges*



science

Useful beam

***A lot of technical details***

Engineering = deployment of physics knowledge

Beam dynamics

magnet

Mechanics

Radio Frequency

Material science

Control engineering

Vacuum technology

Electronics

Cryogenics

Digital circuit

High voltage

superconductors

Perfection in classical physics

Hamilton mechanics

Thermodynamics

Classical electrodynamics

Classical statistical physics

Relativistic kinematics

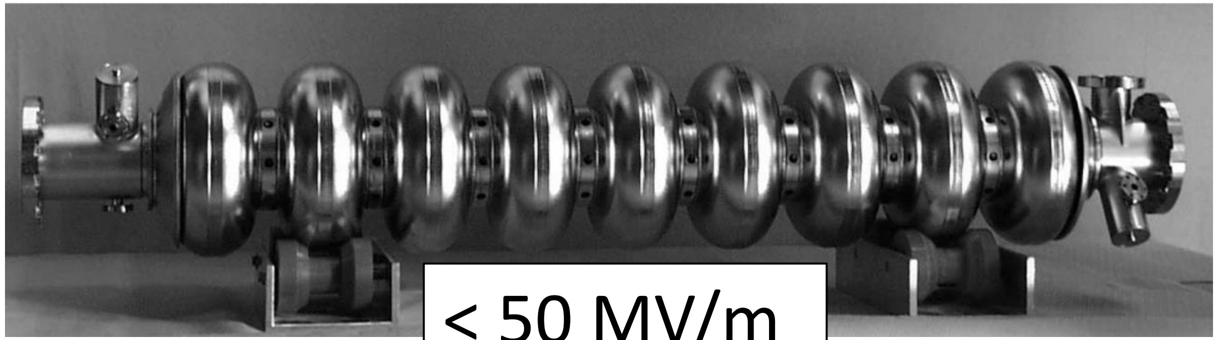
Fundamental challenge in quantum physics

Nonequilibrium superconductivity

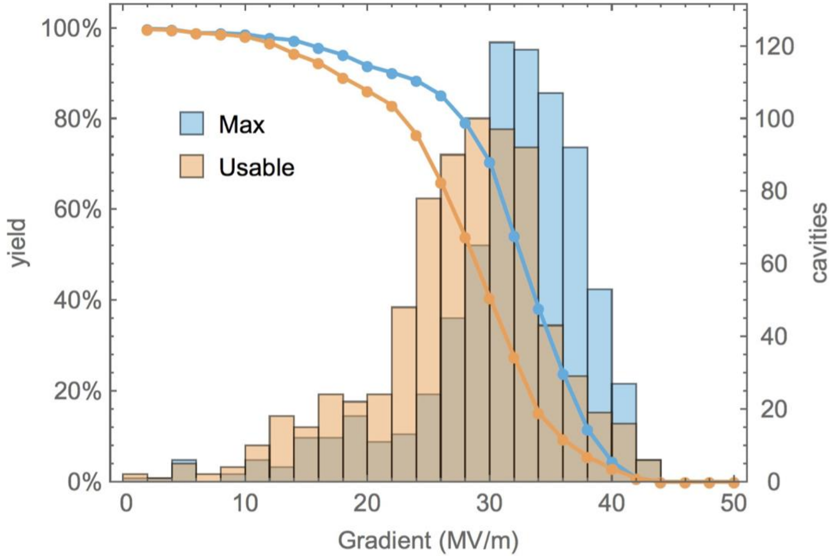
Quantum statistical physics

# Accelerating cavities

## Superconducting niobium cavities (TESLA)



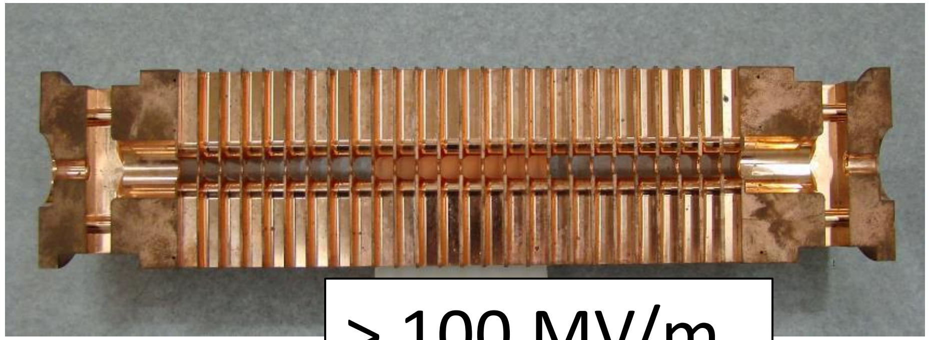
< 50 MV/m



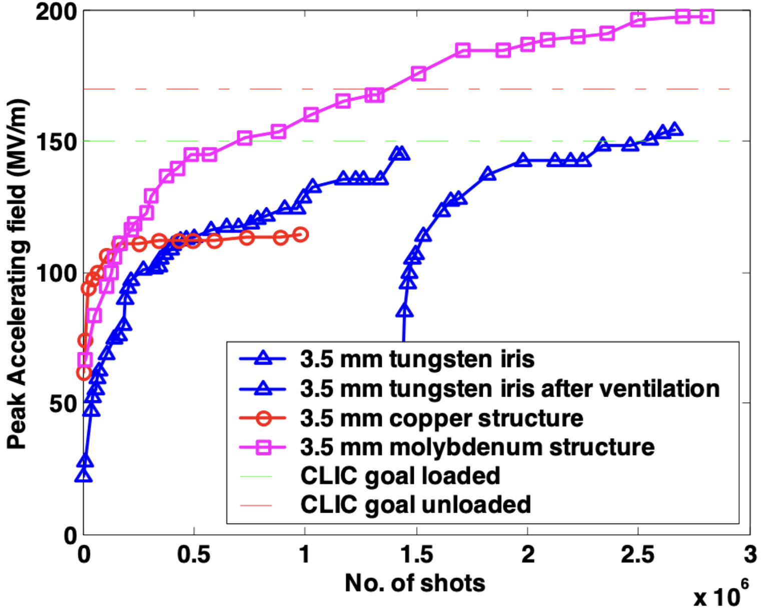
PHY REV ST - ACCEL BEAMS, **3**, 092001 (2000)
PHY REV ACCEL BEAMS 20, 042004 (2017)

$> \times 2$

## Normal conducting copper cavities



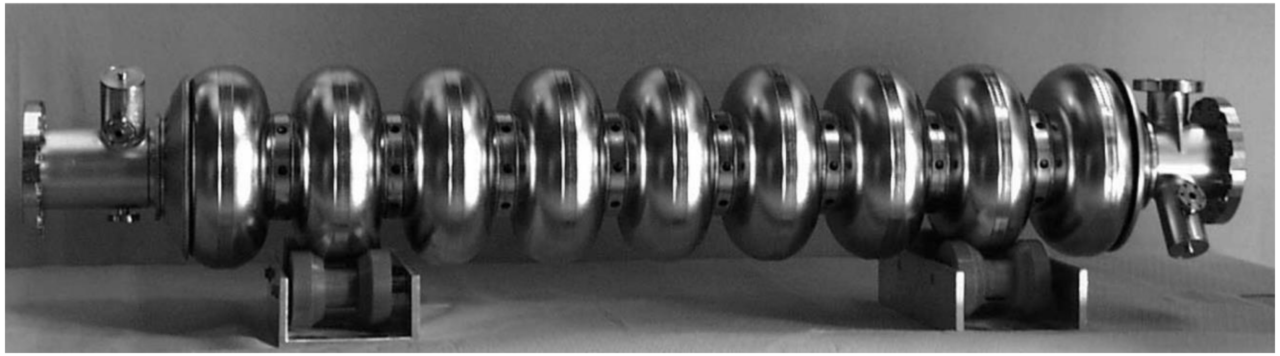
> 100 MV/m



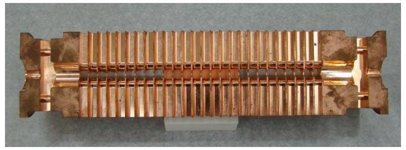
Courtesy: Walter Wuensch

# Superconducting vs normal conducting

## Aperture

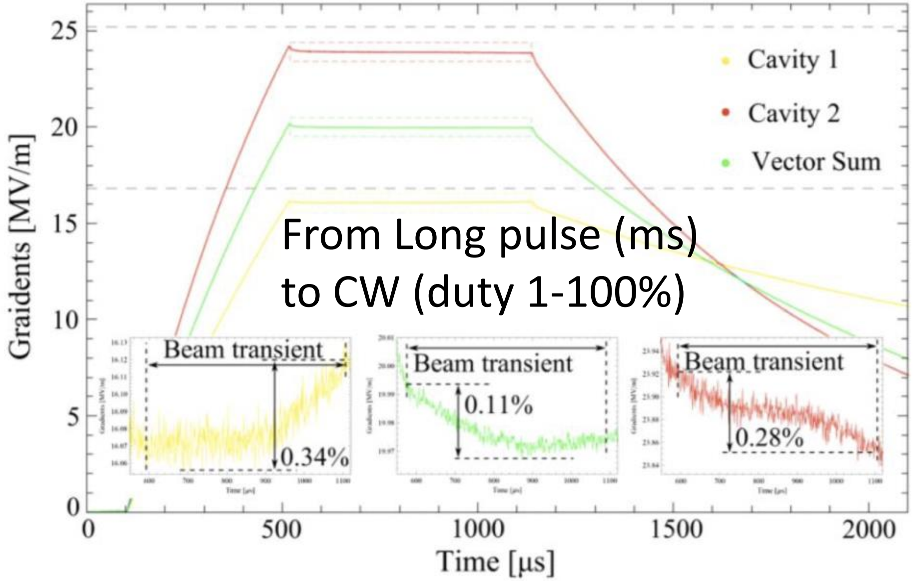


Superconducting cavities can keep high gradient at low frequency
→ large aperture (ILC: ϕ70 mm)



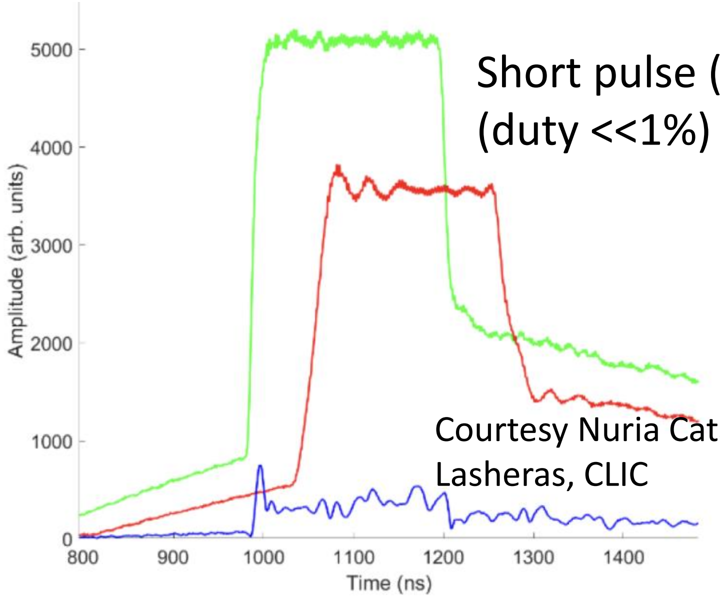
Normal conducting cavities are efficient at high frequency
→ small aperture (CLIC X-band: around ϕ3 mm)

## Pulse length and duty cycle



From Long pulse (ms)
to CW (duty 1-100%)

M. Omet
SRF2021
lecture

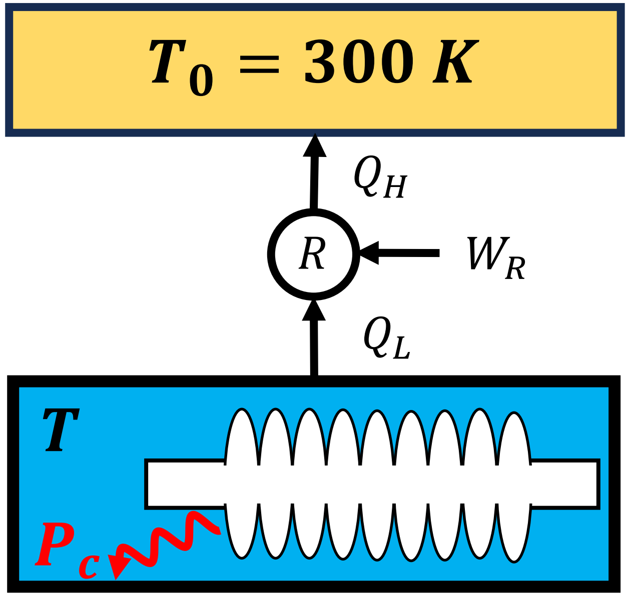


Short pulse (µs)
(duty <<1%)

Courtesy Nuria Catalan
Lasheras, CLIC

SC cavities' quality factor
$\times 10^{6}$
than copper cavities
→ power dissipation
$\times 10^{-6}$
but in ***cryogenics***!

# Cooling efficiency < Carnot cycle



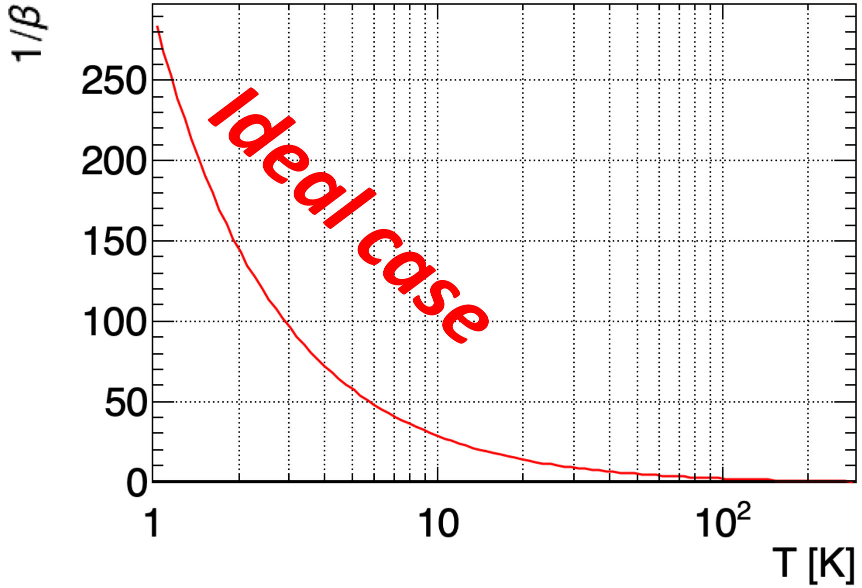
Carnot's theorem

$$\beta = \frac{Q_L}{W_R} = \frac{Q_L}{Q_H - Q_L} \overset{\downarrow}{=} \frac{T}{T_0 - T}$$

Required power

$$P_{cryo} > W_R = \frac{P_c}{\beta}$$

(typically 5 kW/W @ 2 K for AC plug)



SC cavities

$P_c = 100$ W (CW)
Duty cycle $10^{-2}$
$T = 2$ K

$$P_{NET} \sim 100\text{ W} \times 1\% \ \times 150 = 150\text{ W}$$

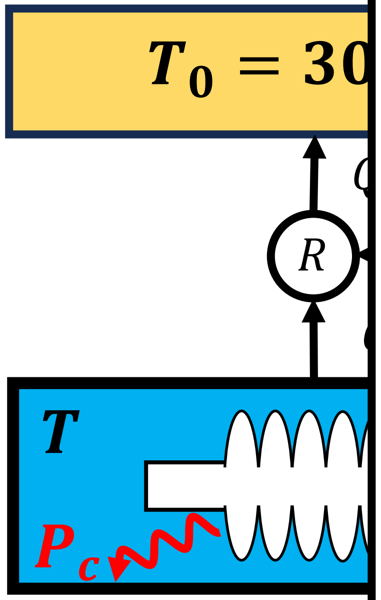
NC cavities

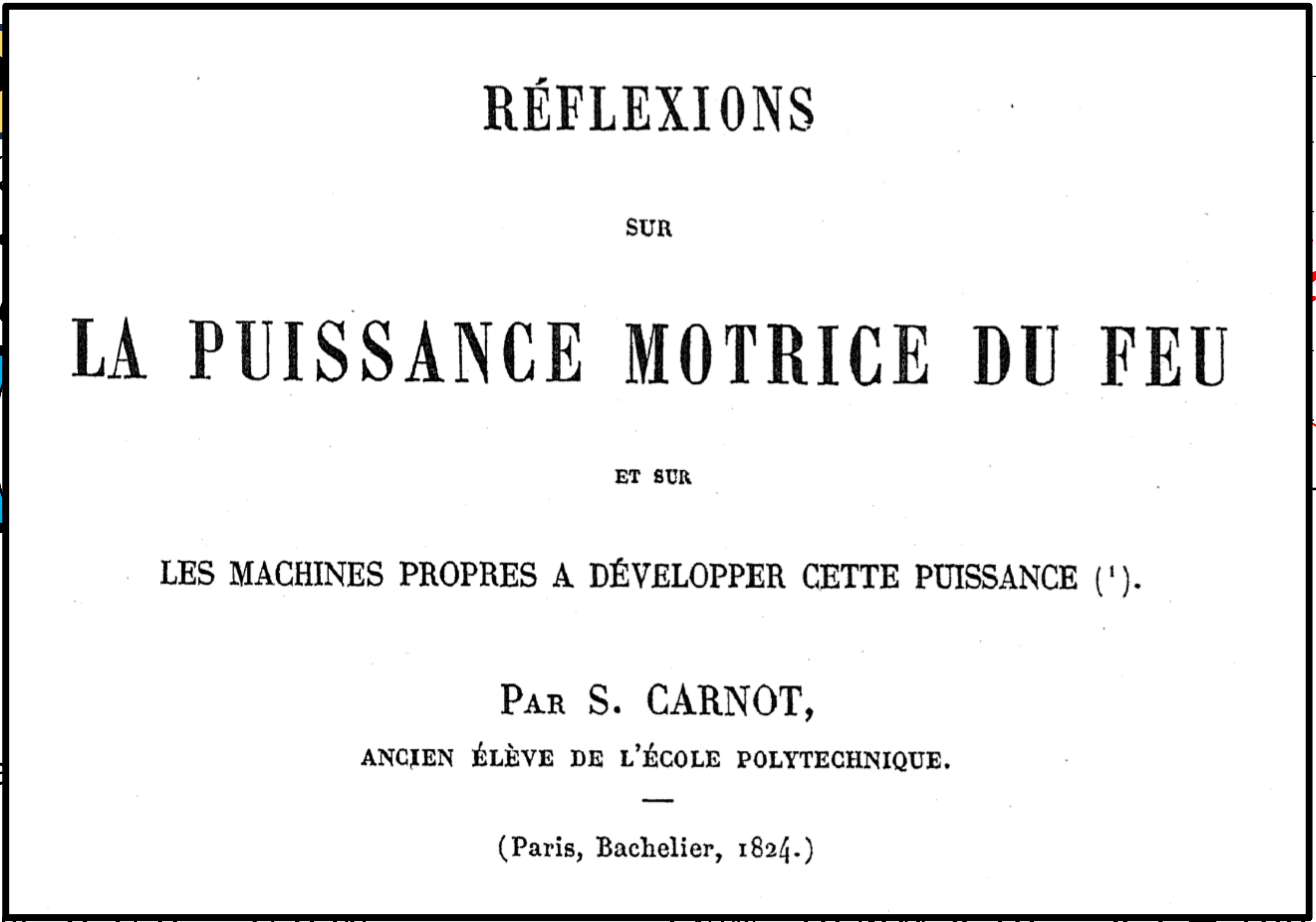
$P_c = 10$ MW (CW)
Duty cycle $10^{-5}$
Water cooling

$$P_{NET} \sim 10\text{ MW} \times 10^{-5} \ \times 1 = 100\text{ W}$$

→ Short pulsed NC cavities and long pulsed SC cavities are similar in power consumption

# Cooling efficiency < Carnot cycle





RÉFLEXIONS

SUR

LA PUISSANCE MOTRICE DU FEU

ET SUR

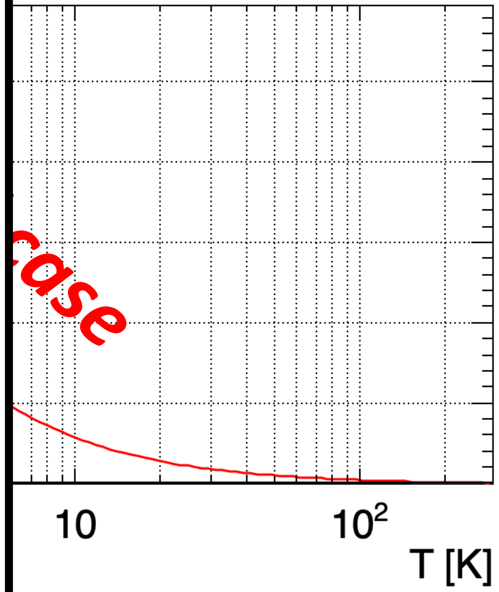
LES MACHINES PROPRES A DÉVELOPPER CETTE PUISSANCE (¹).

PAR S. CARNOT,

ANCIEN ÉLÈVE DE L'ÉCOLE POLYTECHNIQUE.

—

(Paris, Bachelier, 1824.)



SC cavities

$P_c = 100$
Duty cycle
$T = 2$ K

$P_{NET} \sim 100$ W × 1% × 150 = 150 W

$P_{NET}$ 10 MW × 10 × 1 = 100 W

→ Short pulsed NC cavities and long pulsed SC cavities are similar in power consumption