RF Superconductivity

Part2 : reality and applications

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CERN Summer Student Lecture 2024

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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

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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

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Yesterday: idealized model

Perfect vacuum

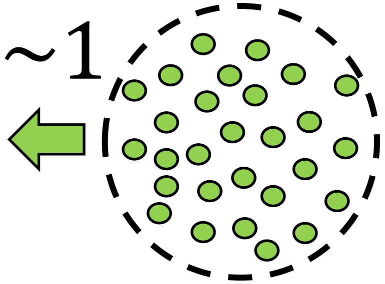
Perfect superconductor
→ Higgs + RF + phase transition

Constant temperature

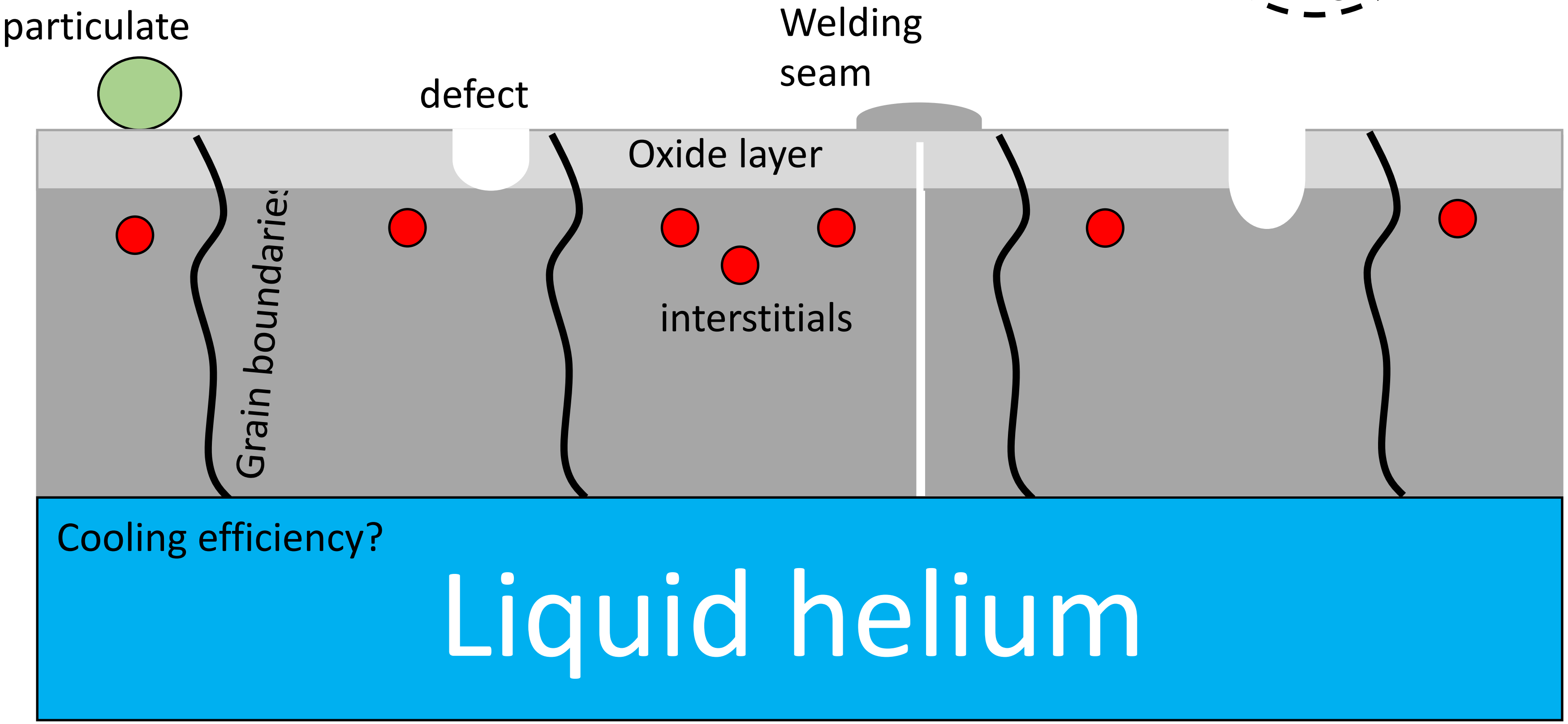
Today: real superconducting cavities

$0 \ll$ Vacuum $< 1\times10^{-8}$ mbar

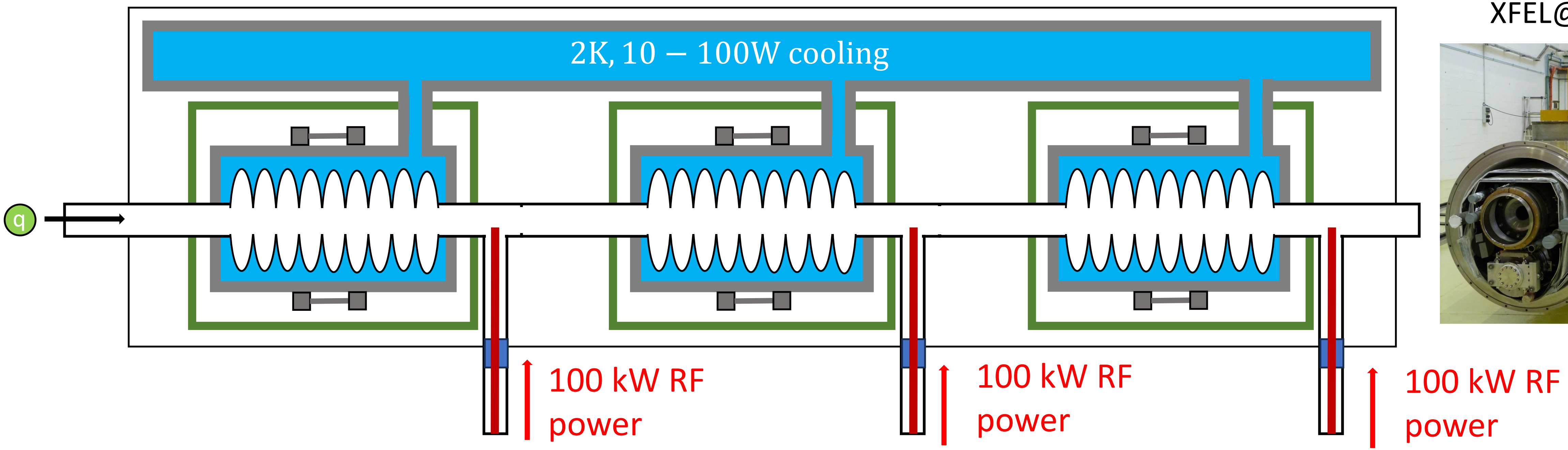
$\frac{v}{c} \sim 1$



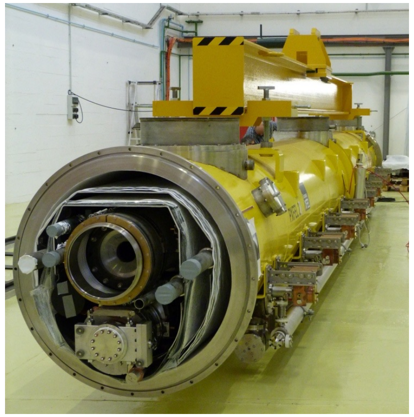
10^{10} charged particles



Cryomodule: SRF cavity cryostat in accelerators



XFEL@DESY



Contact: Vittorio Parma

<u>Technical challenges</u>

- What determines the shape of the cavities?
- How to fabricate and prepare perfect cavities? Typical surface resistance is only $10\ n\Omega$!
- 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 (1×10^{-10} mbar), etc, etc

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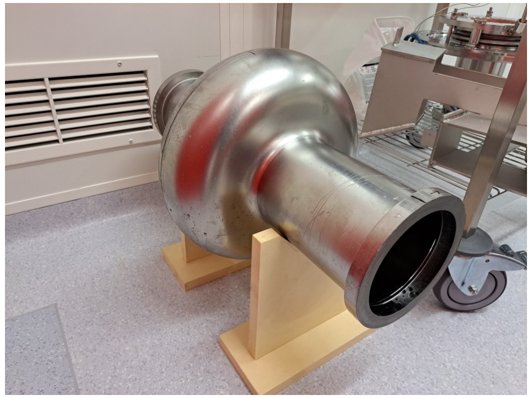
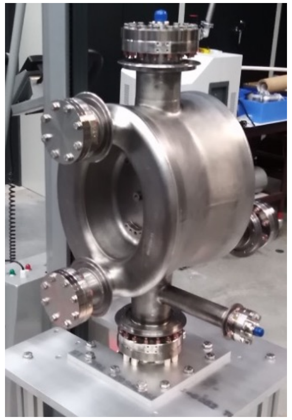
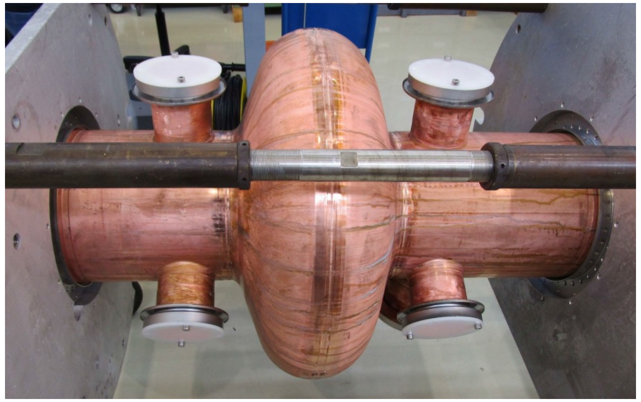
Various structures of SRF cavities

Bulk niobium cavities: standard

Nb/Cu: CERN's specialty



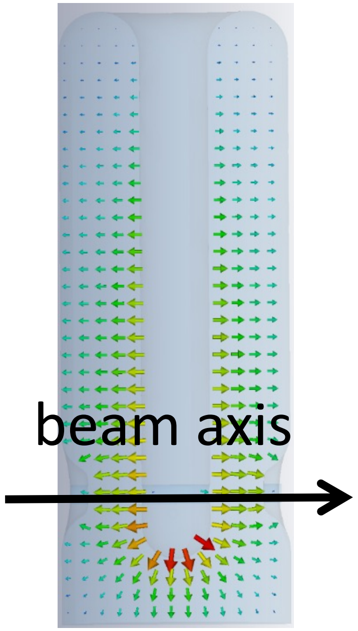




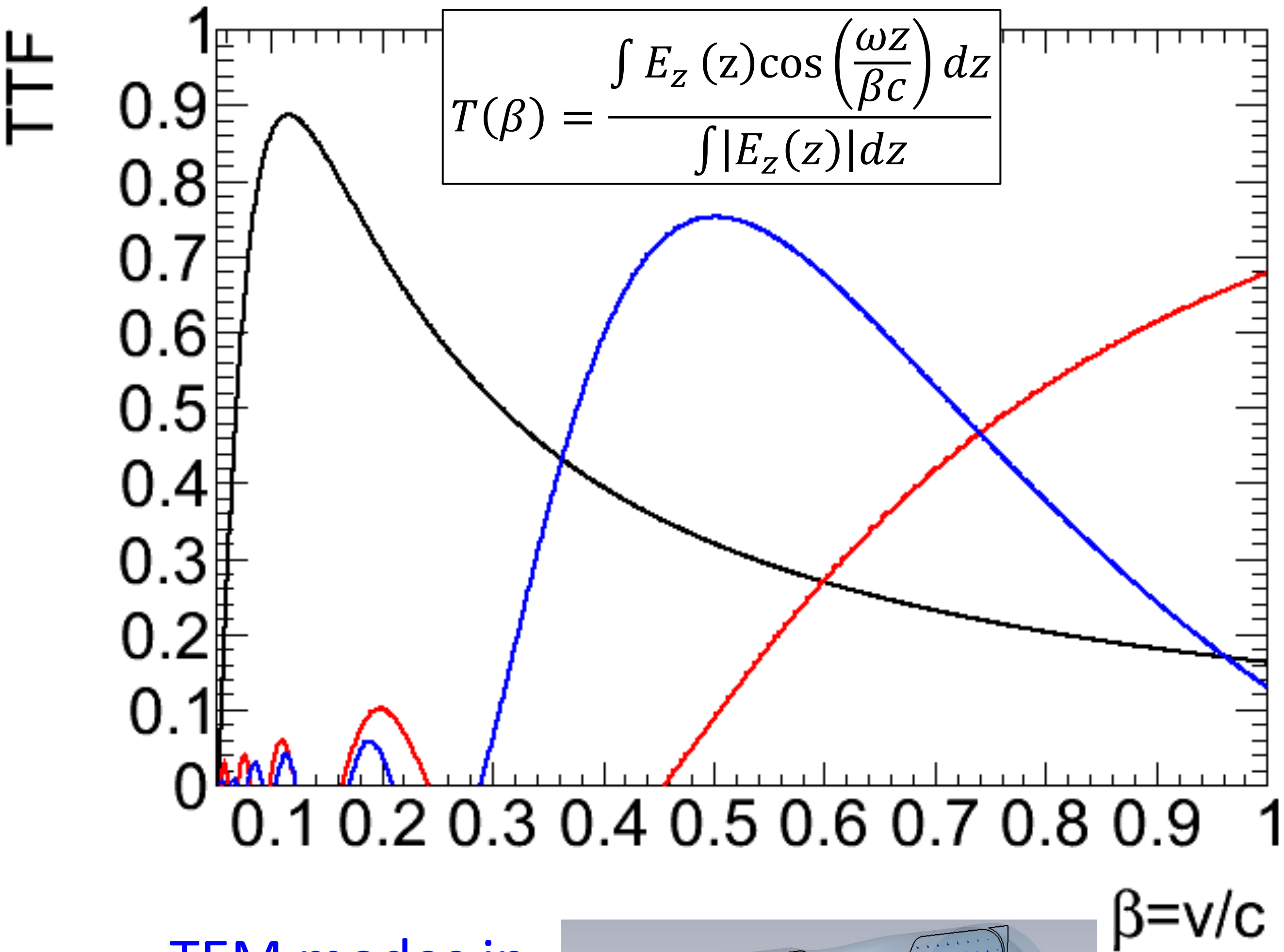
→ Why so many different structures?

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

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

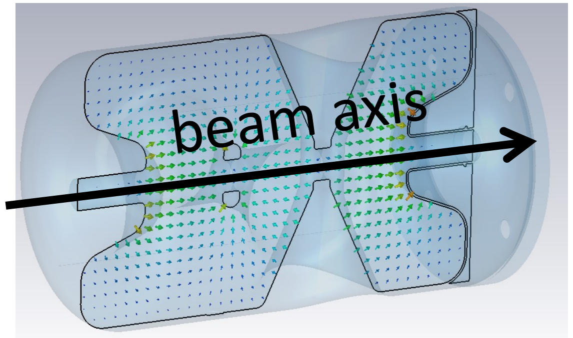


- p+ upstream (<1GeV)
- Heavy ion
- **HIE-ISOLDE at CERN**



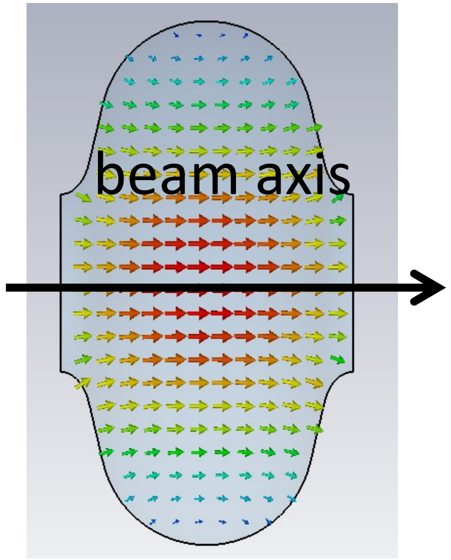
$$T(\beta) = \frac{\int E_z(z)\cos\left(\frac{\omega z}{\beta c}\right) dz}{\int |E_z(z)| dz}$$

TEM modes in a spoke cavity



- p+ (<1GeV)
- Not at CERN ☹

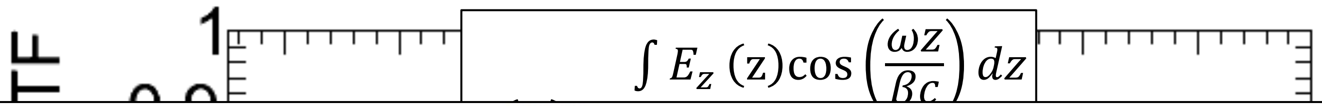
TM$_{010}$ modes in an elliptical cavity



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

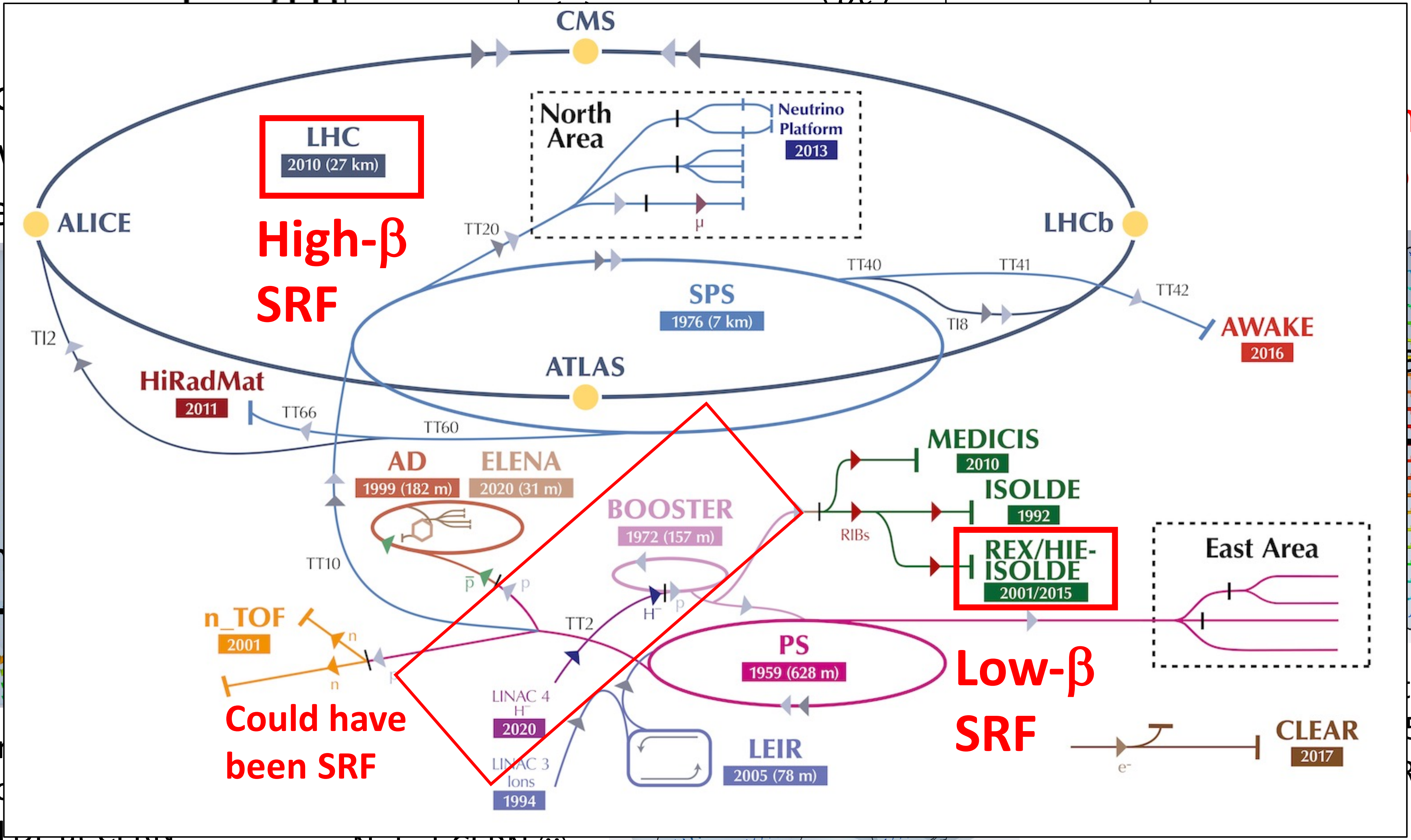
Contact: Franck Peauger

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



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

modes in
tical cavity



am axis

bean

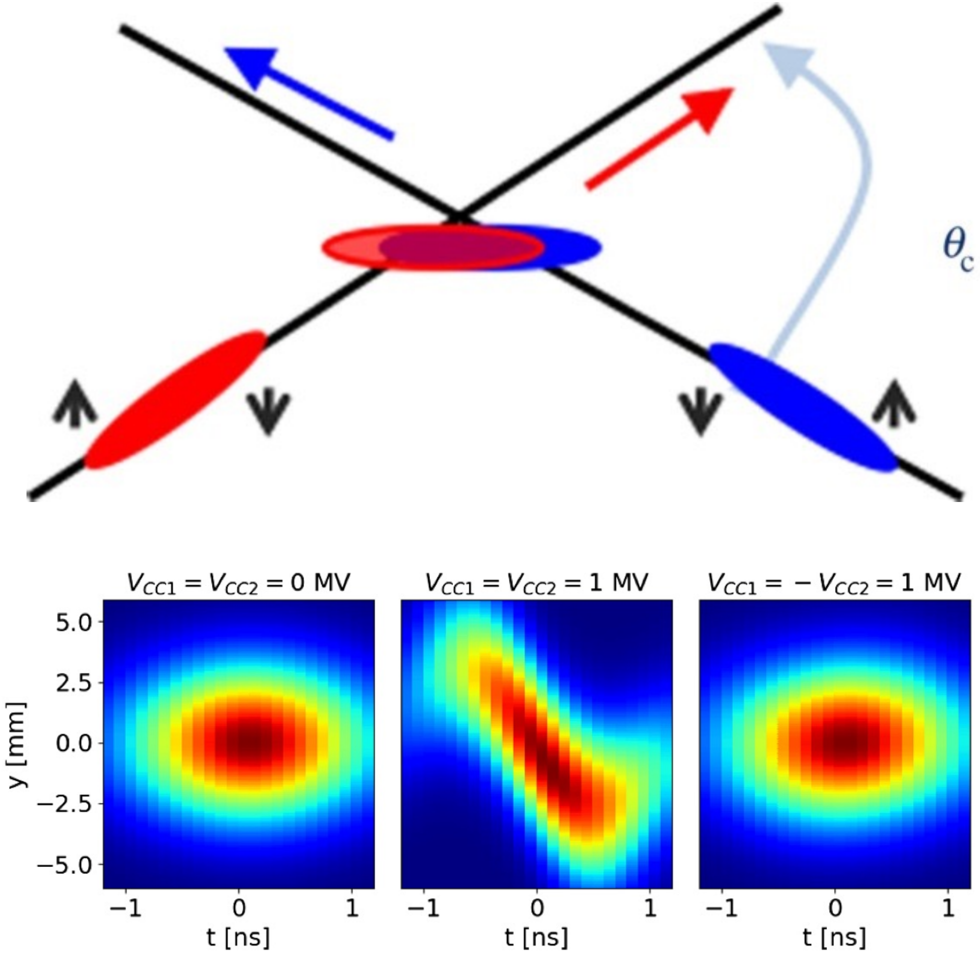
- p+ upstr
- Heavy io
- HIE-ISOLDE at CERN

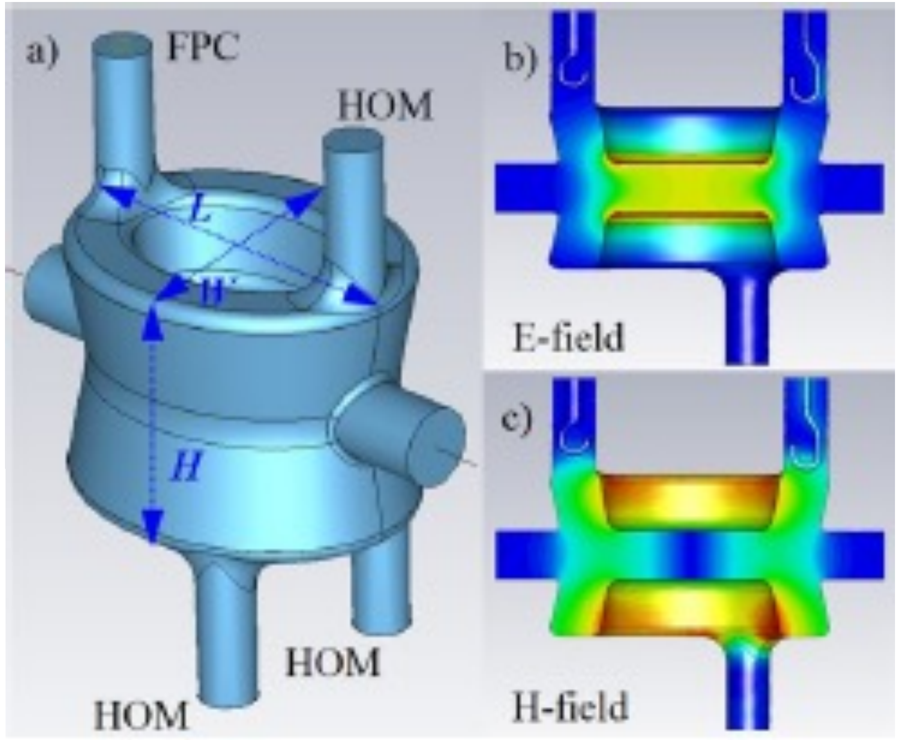
tream (>1GeV)
5MeV)
RN

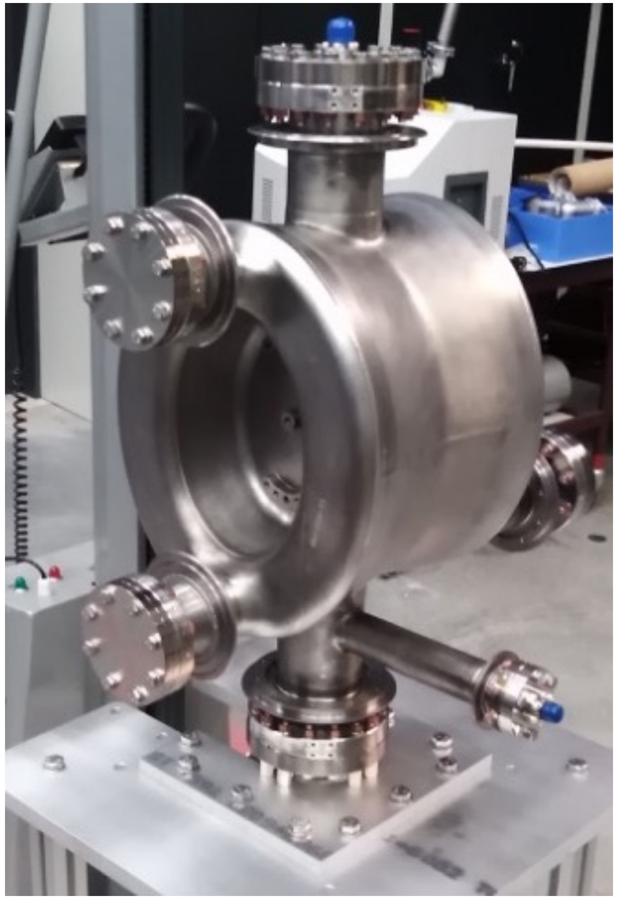
- Not at CERN ☹

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

For better luminosity





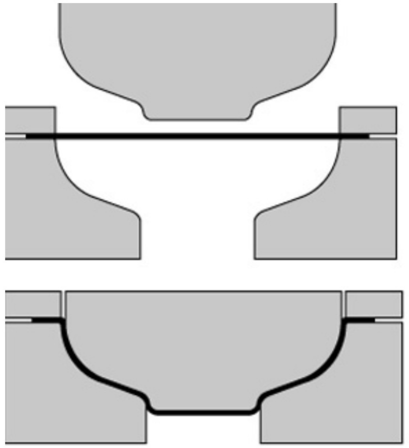


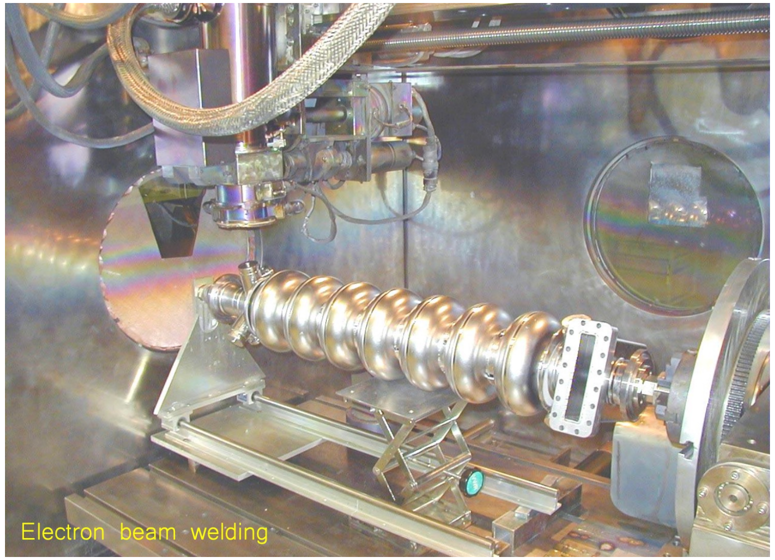
Phys. Rev. Accel. Beams 24, 062001 2021

Contact: Rama Calaga

Fabrication processes

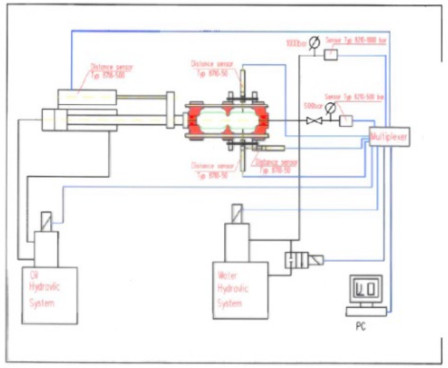
Deep drawing + electron beam welding

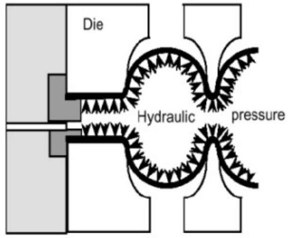




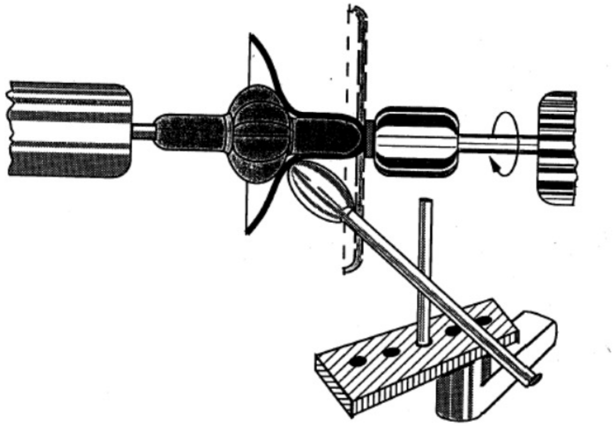
Seamless cavity fabrication

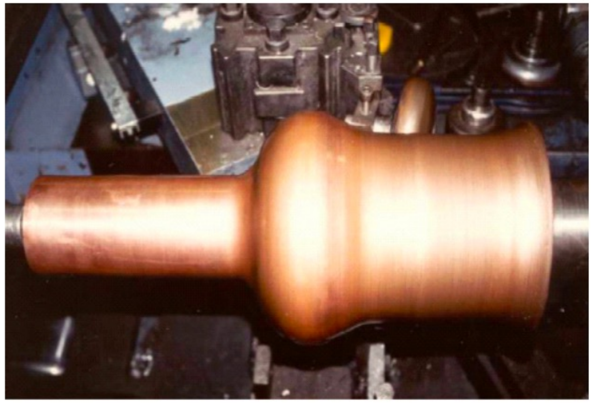
Hydro forming （W.Singer,DESY）





Spinning （V.Palmieri,INFN Legnaro）

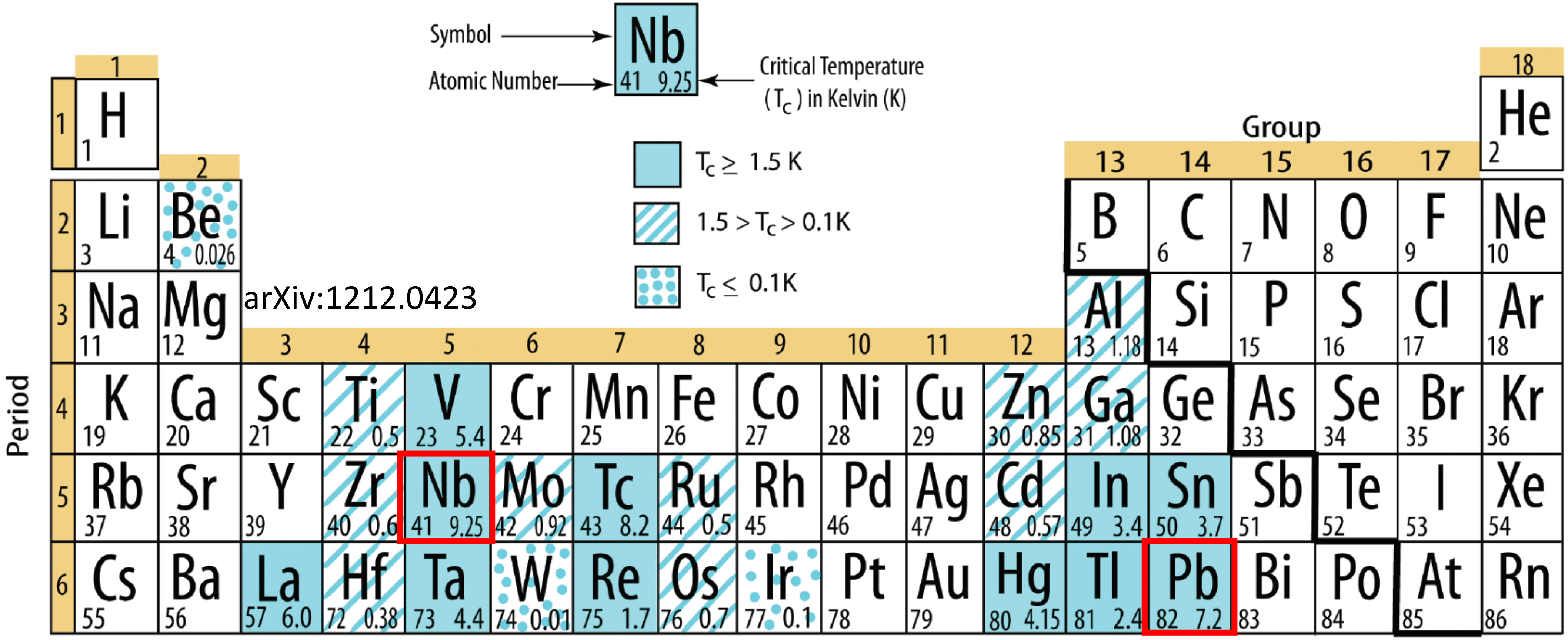




Courtesy: Rong-Li Geng

CERN is also working on seamless cavities
Contact: Said Atieh

Table of superconductors of pure elements



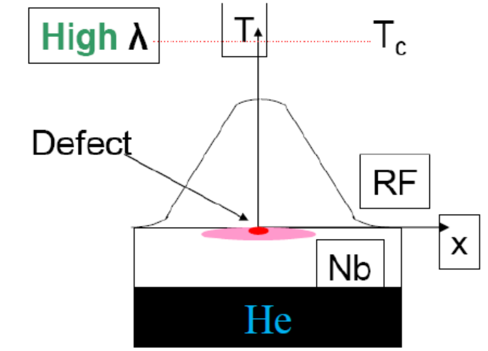
arXiv:1212.0423

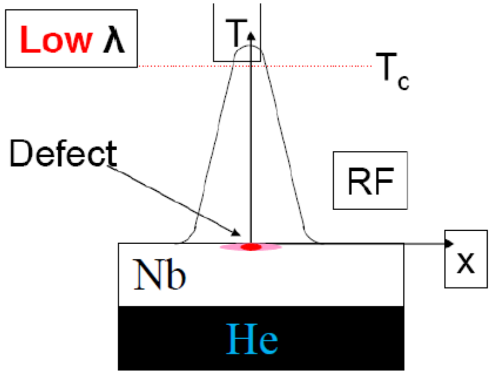
[a]Period 7, and the ***f*** elements in period 6, with the exception of lanthanum, La, are not shown.

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

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

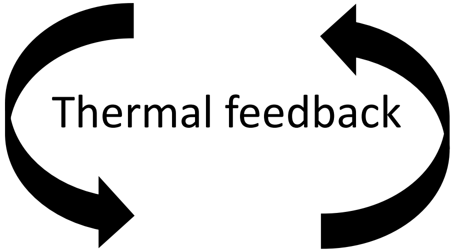
Defects enhance thermal breakdown





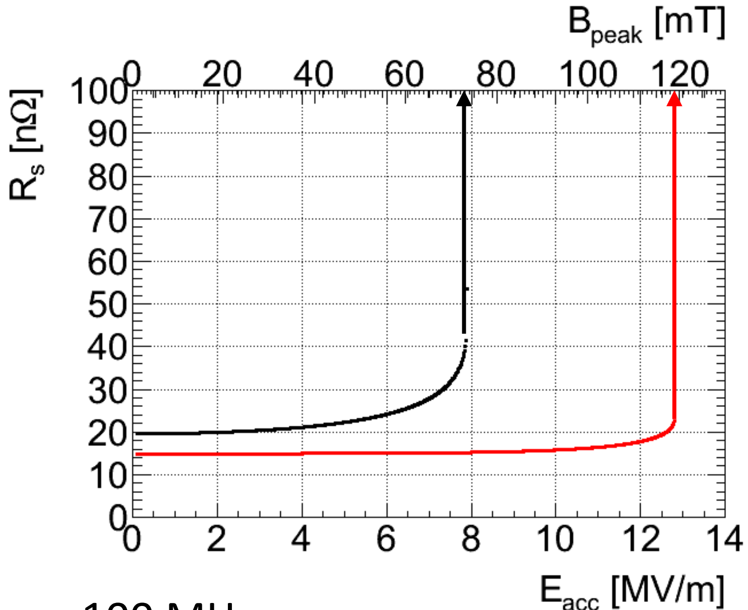
BCS resistance

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

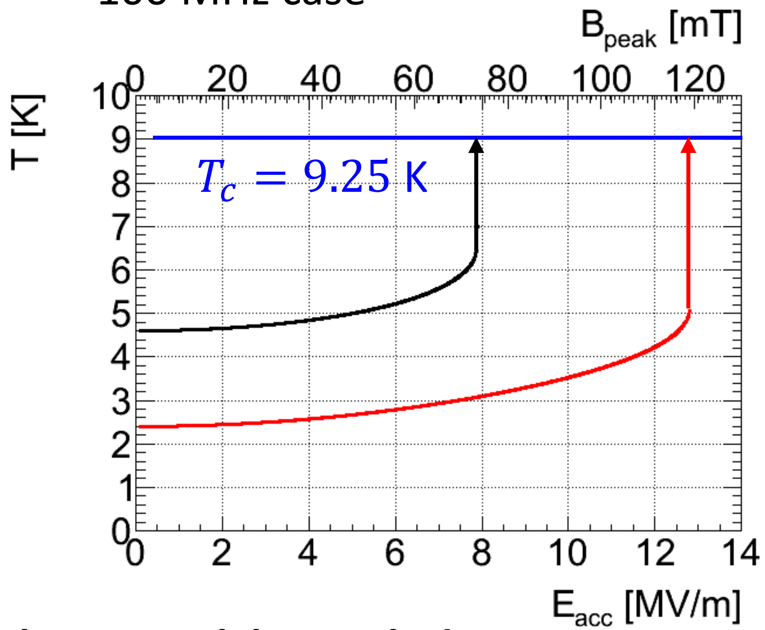


Joule heating: $P = \frac{1}{2} R_s H^2$

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



100 MHz case

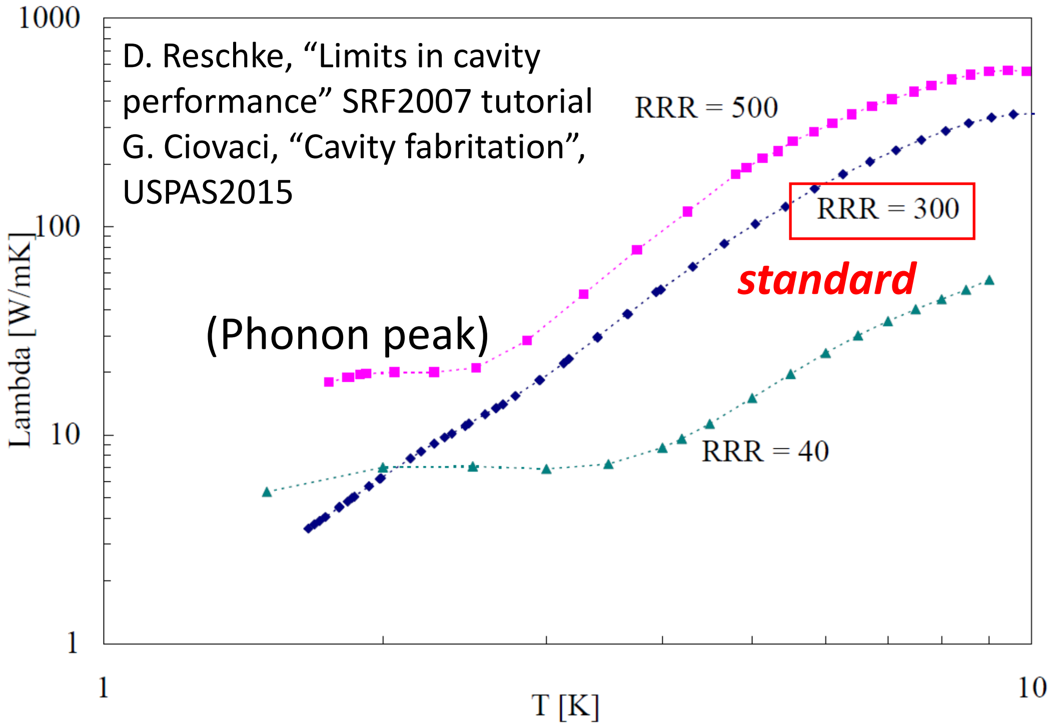


Defect, bad thermal resistance $R_{th} \propto 1/\lambda$ can enhance thermal breakdown

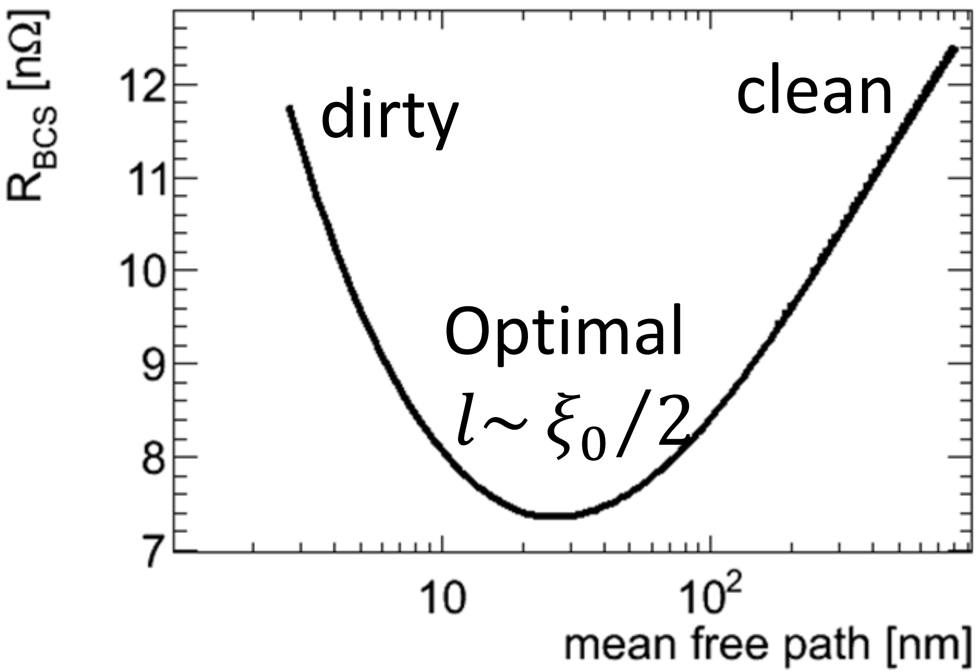
→ **defect-free and good thermal conductance is a key of SRF cavities**

Issue of Nb: thermal conductivity vs surface resistance

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



l nm

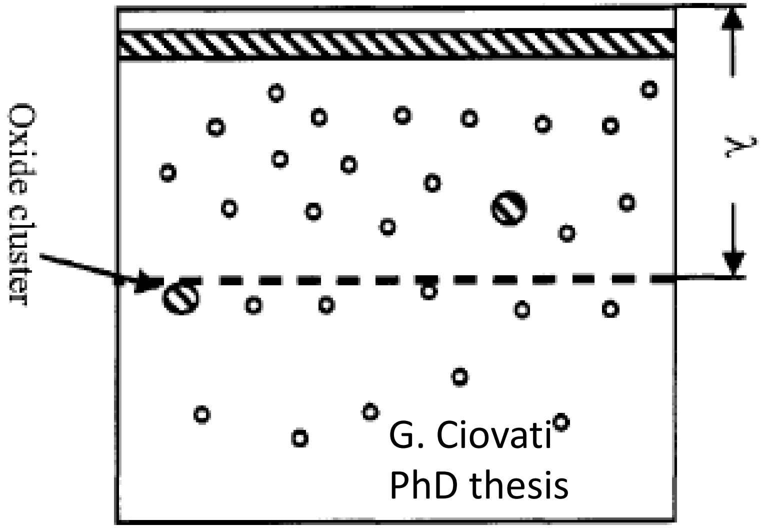


1. **Clean** bulk for thermal conductivity
   - RRR~300: 700 EUR/kg (price in 2024 spring)
2. Sufficiently **dirty** surface for lower BCS resistance
   - R_{res} can be worse

These two requirements contradict with each other

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

Heat treatment, doping,…

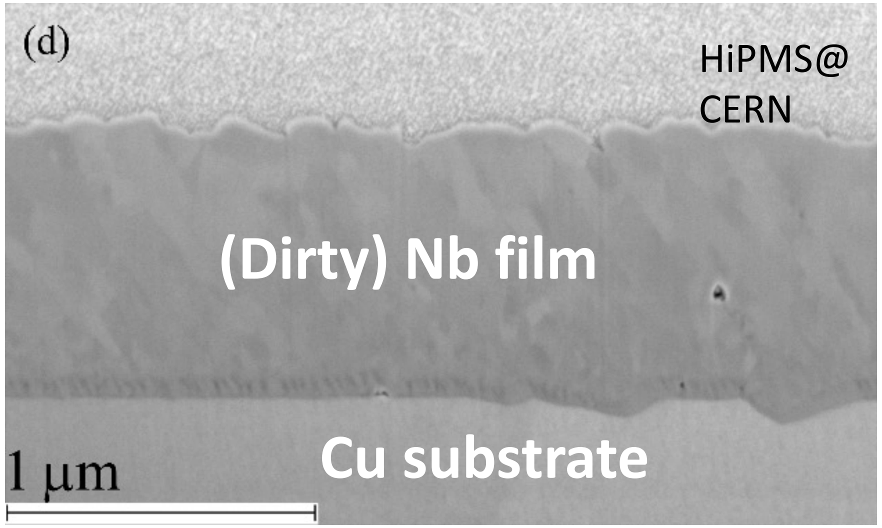


Hyper-low R_{BCS}, sensitive R_{mag}, anti-Q-slope, a lot of mysteries

Nb film

CERN's specialty

Contact: Guillaume Jonathan Rosaz



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

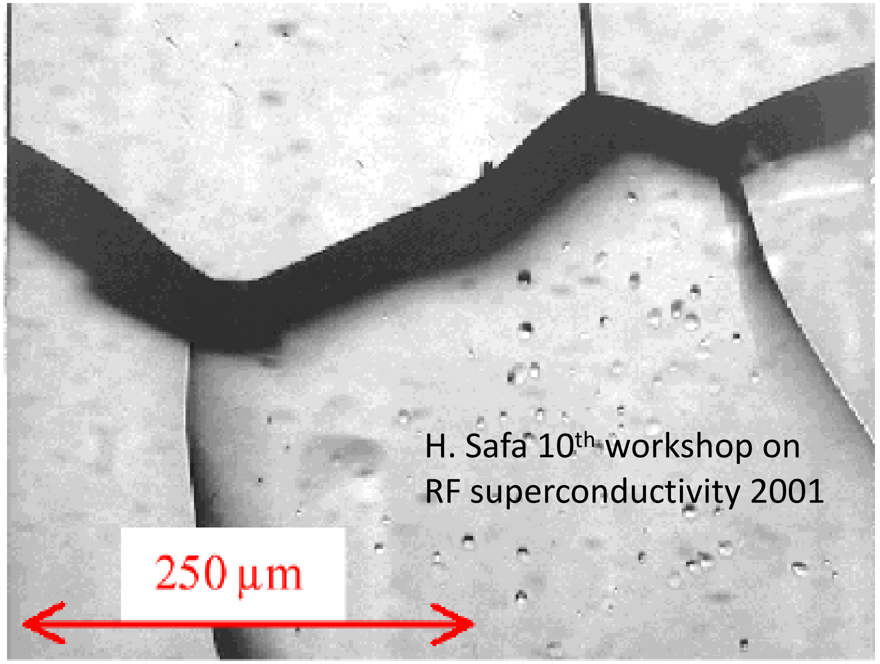
We have been developing **recipes** but why and how are generally missing

One of the research frontiers for new SRF cavities

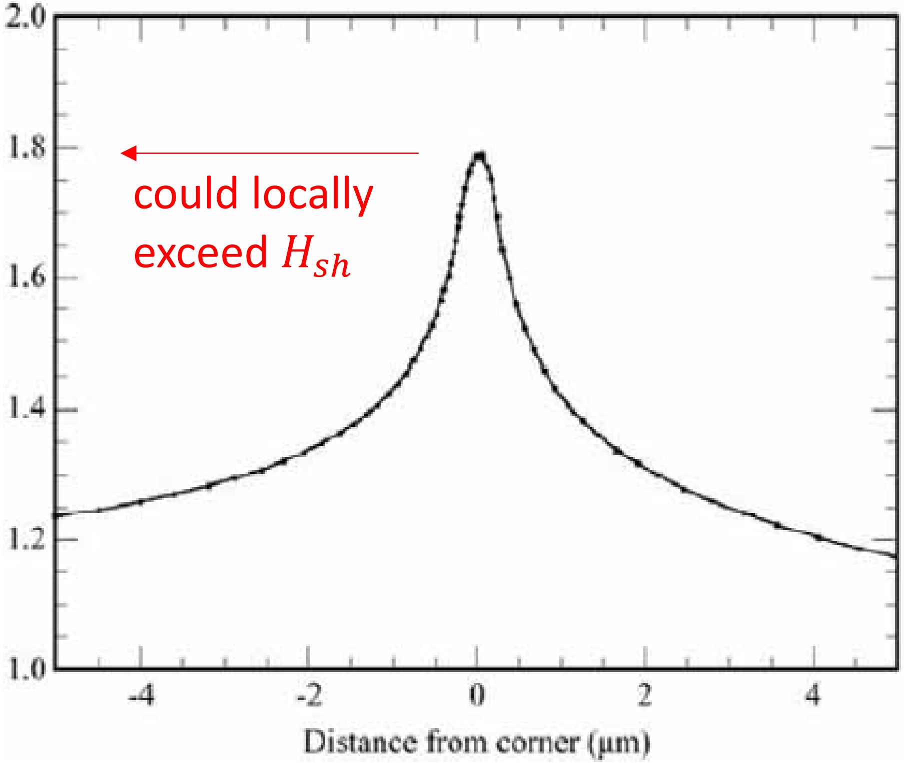
Importance of surface roughness: one example

Local defect or field enhancement

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



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



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

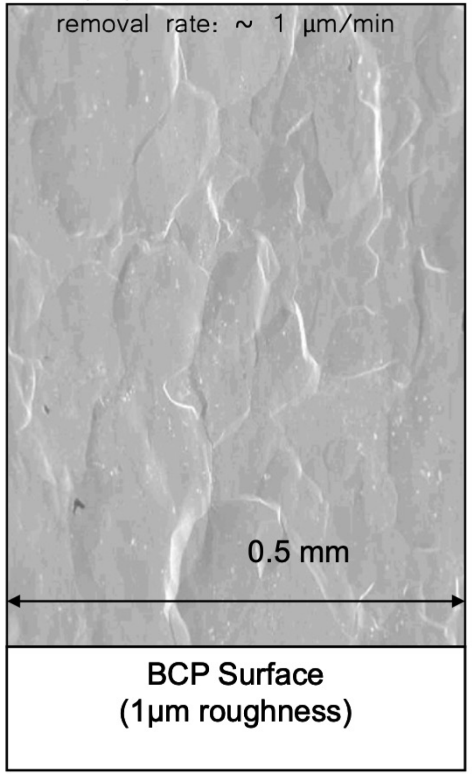
Quench limit and high-field Q-slope is an open research area

Two methods of surface etching

Contact: Marc Thiebert

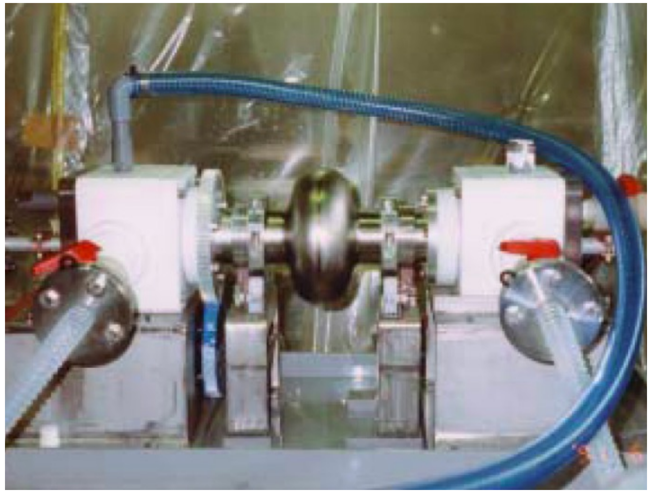
Buffered Chemical Polishing (BCP)

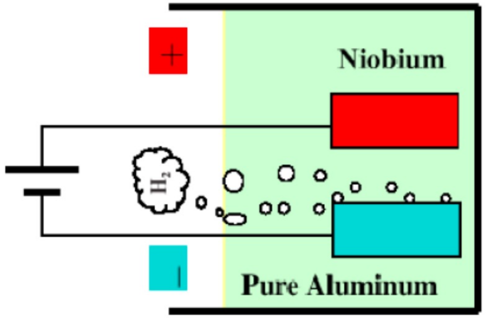
HF + HNO_3 + H_3PO_4

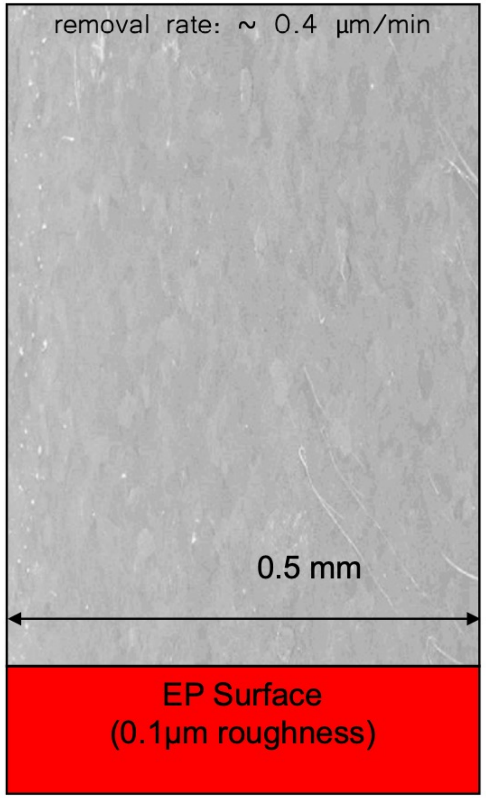


Electropolishing (EP)

HF + H_2SO_4 + voltage





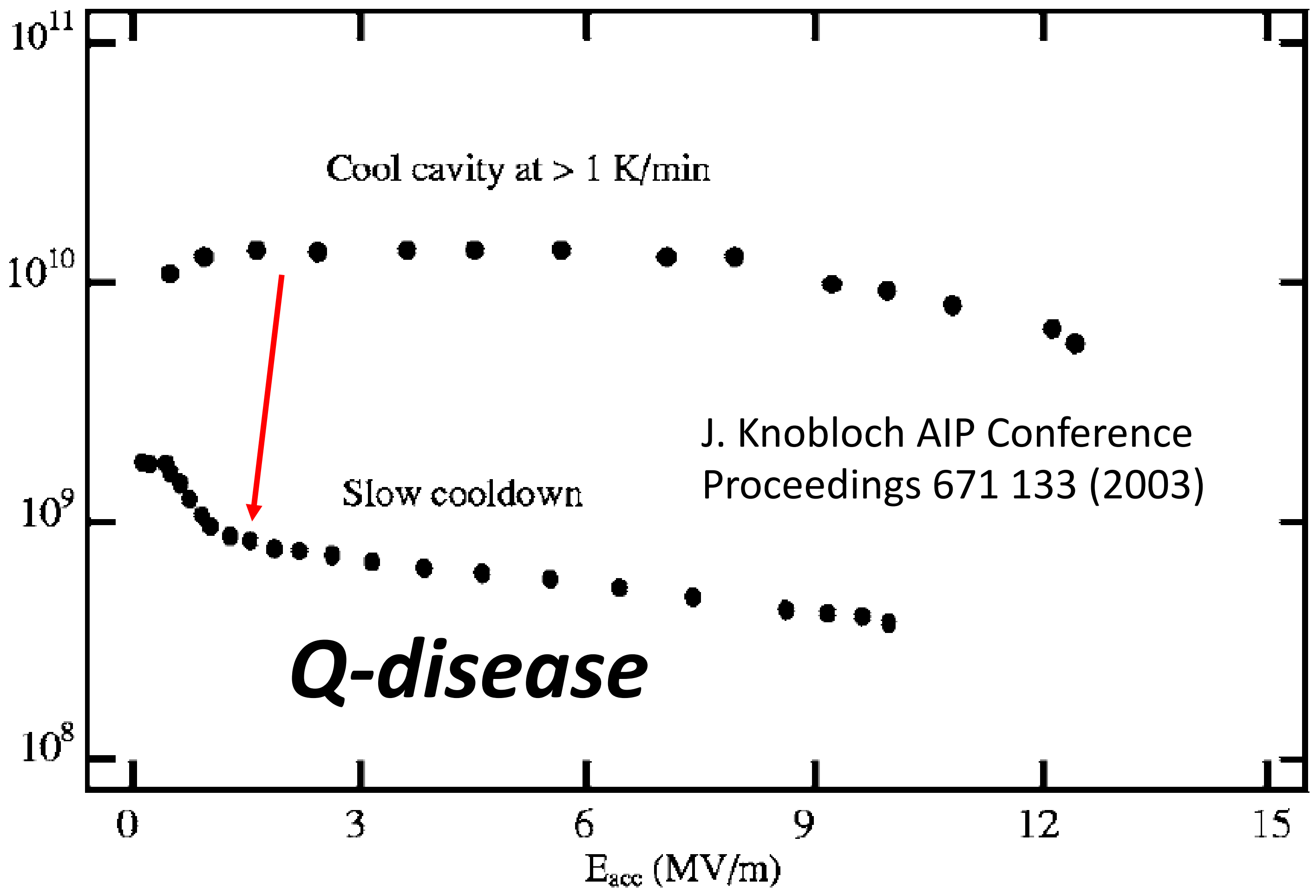


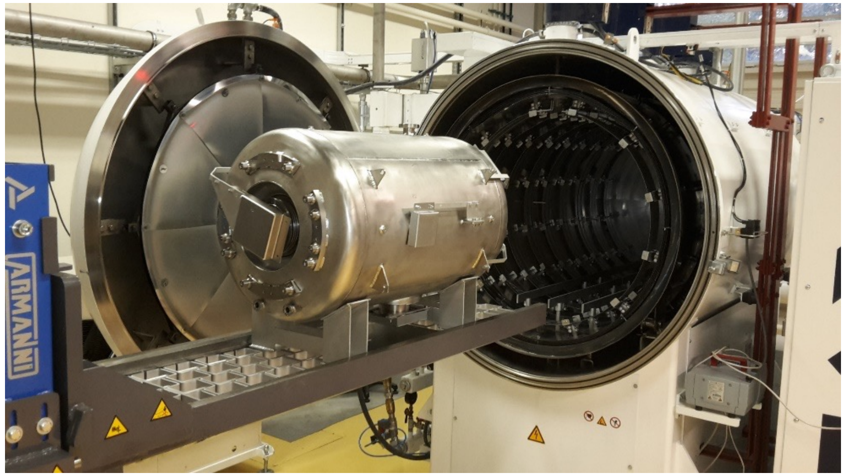
Courtesy: Rong-Li Geng

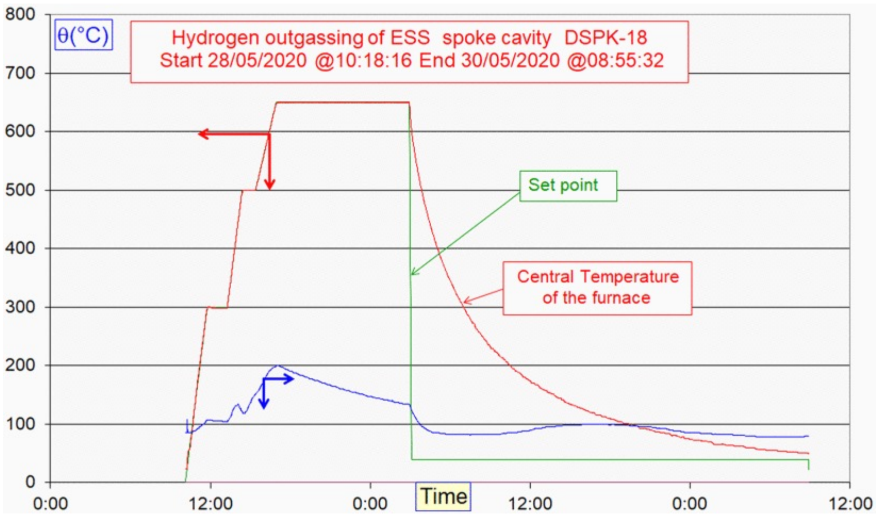
EP is known to be better but more complex and expensive

→ BCP may be enough depending on the performance requirement

Hydrogen from HF acid → Nb hydride





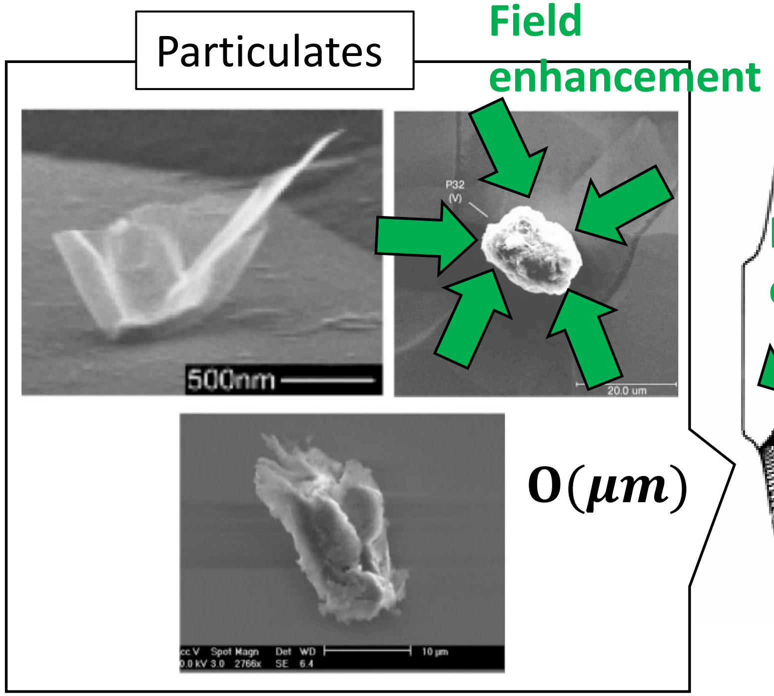


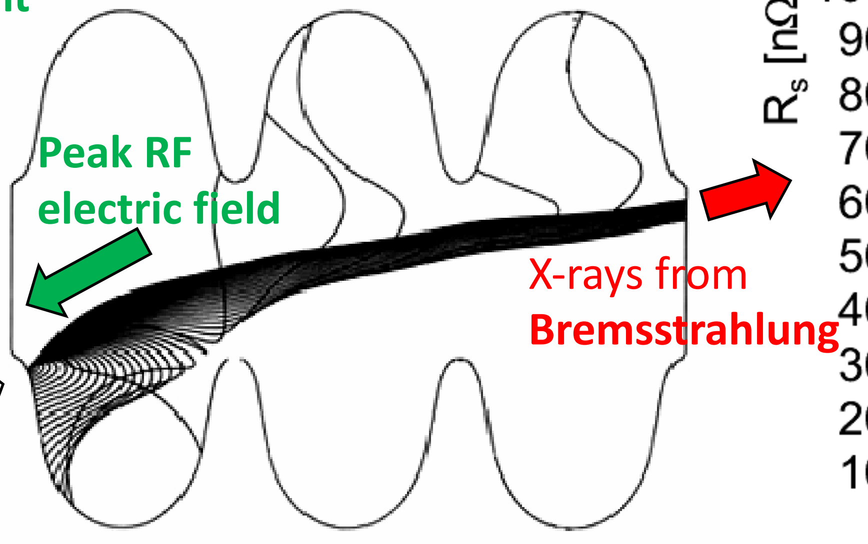
M. Fouaidy et al., IEEE Transactions on Applied Superconductivity, 31, 5, pp. 1-8, 2021, 3500508

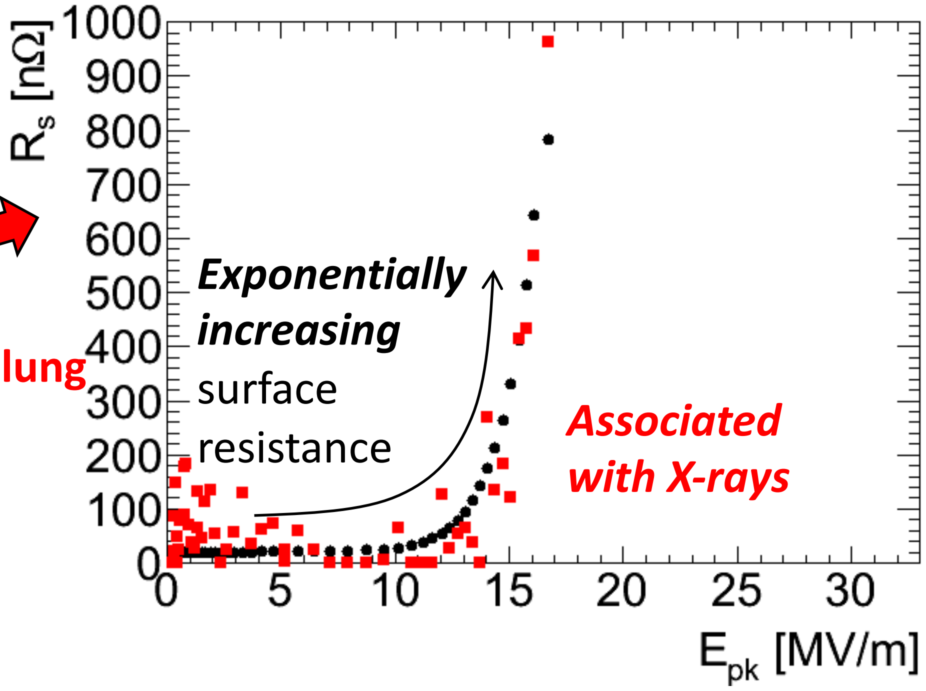
Solutions

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



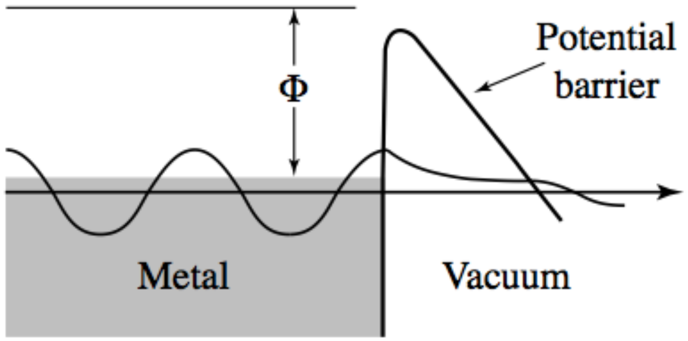




Tunneling current by Fowler-Nordheim

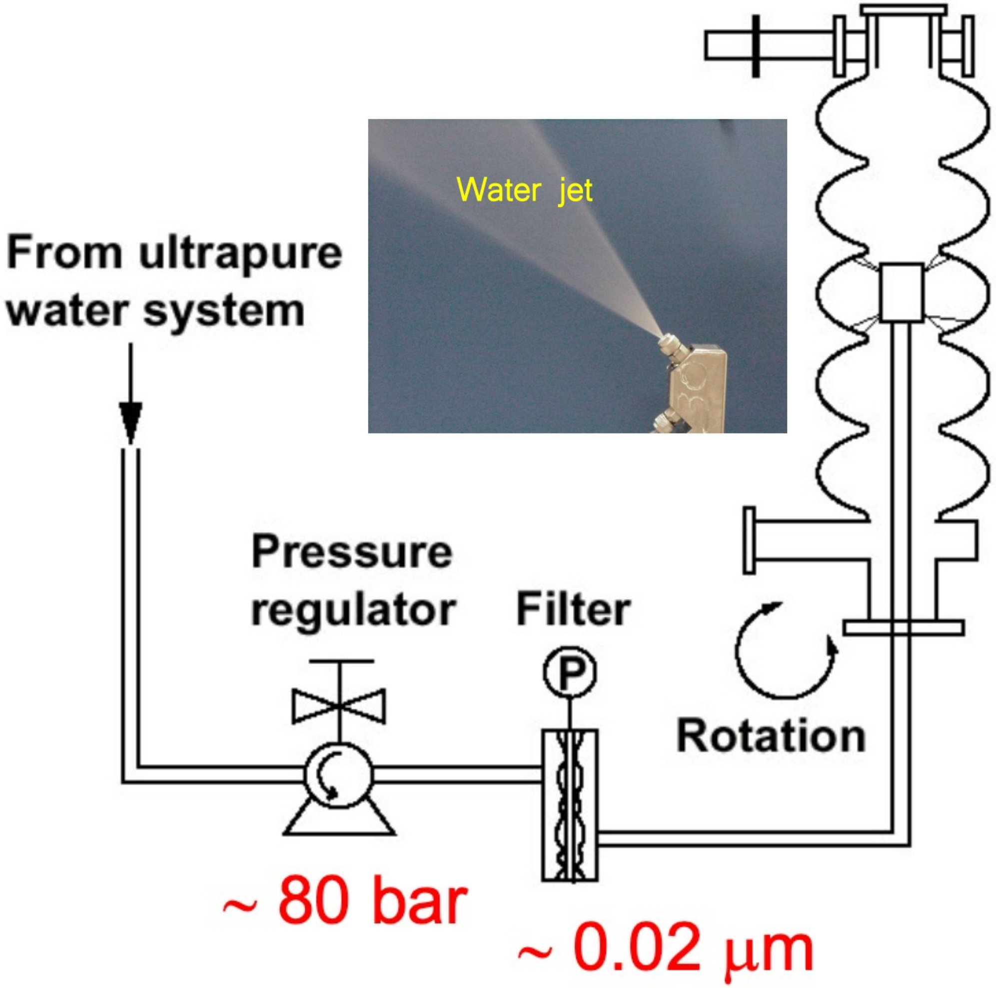
$$J \propto \exp\left(-6.53\times10^{6}\frac{\phi^{3/2}}{\beta E}\right)$$

1. work function ϕ~4-5 eV
2. peak electric field
3. field enhancement



Practical challenge in SRF projects with a large number of cavities

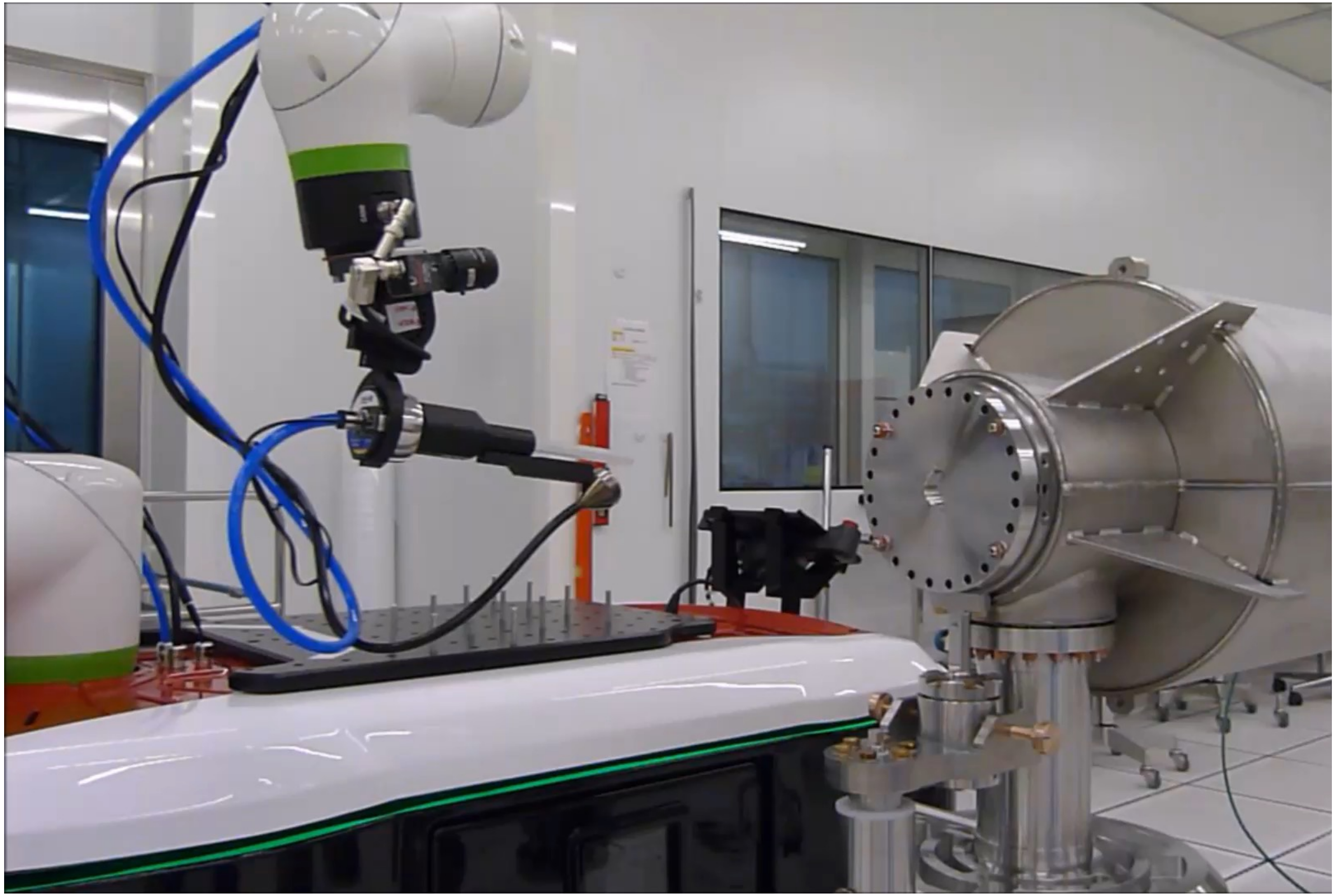
Mitigate FE: High Pressure Water Ringing & clean room assembly



Contact: Mathieu Therasse

Working in a clean room is tough business

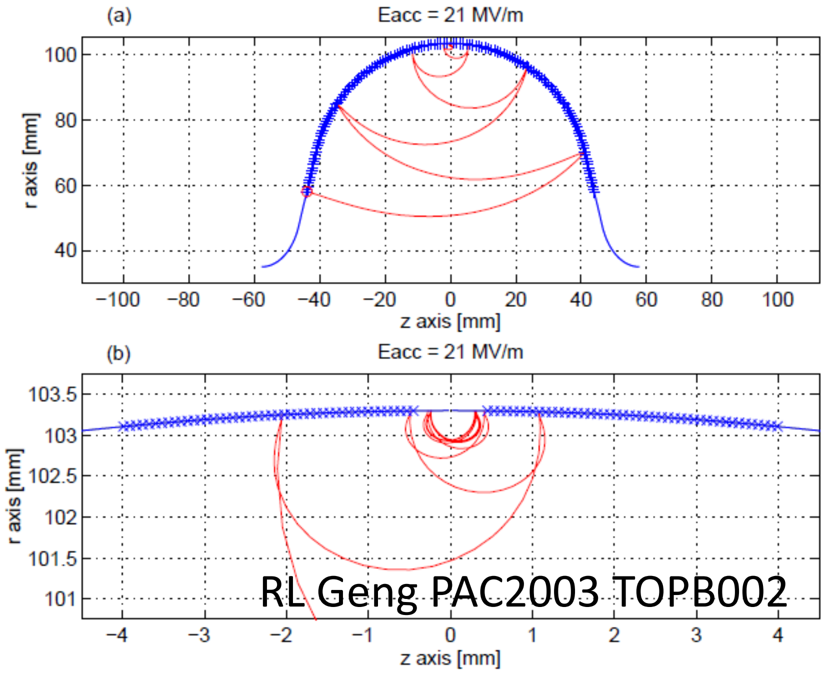
Introduction of robotics is one research direction



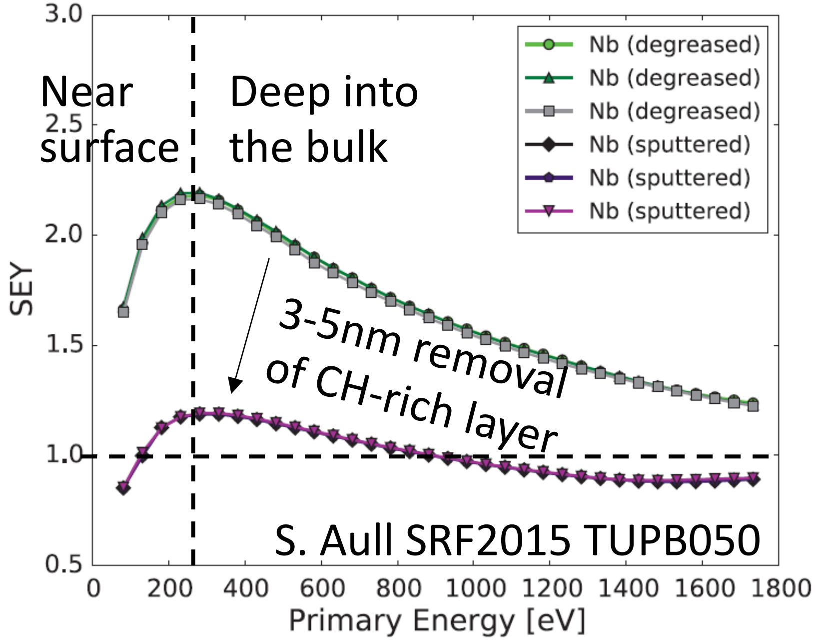
Courtesy:
Julien Drant
CEA Saclay

Multipacting: resonant avalanche of secondary electrons

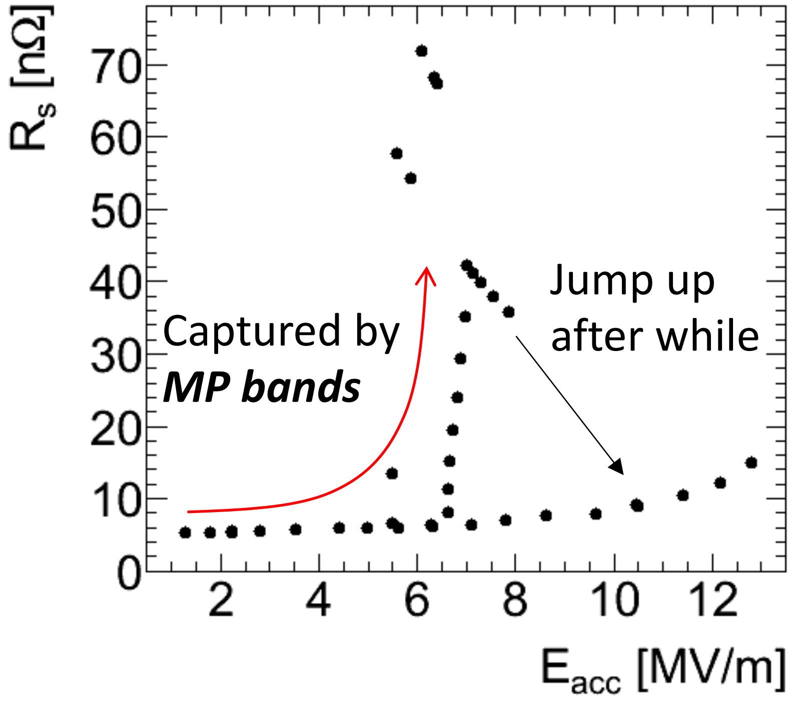
Resonance and geometry



Secondary Electron Yield



Example: ESS double spoke



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

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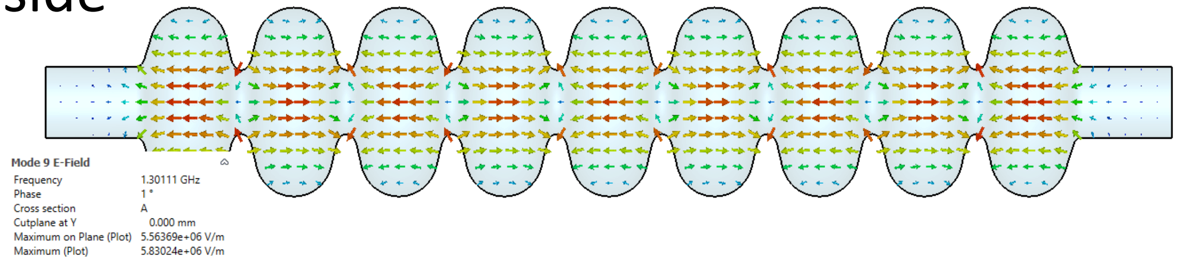
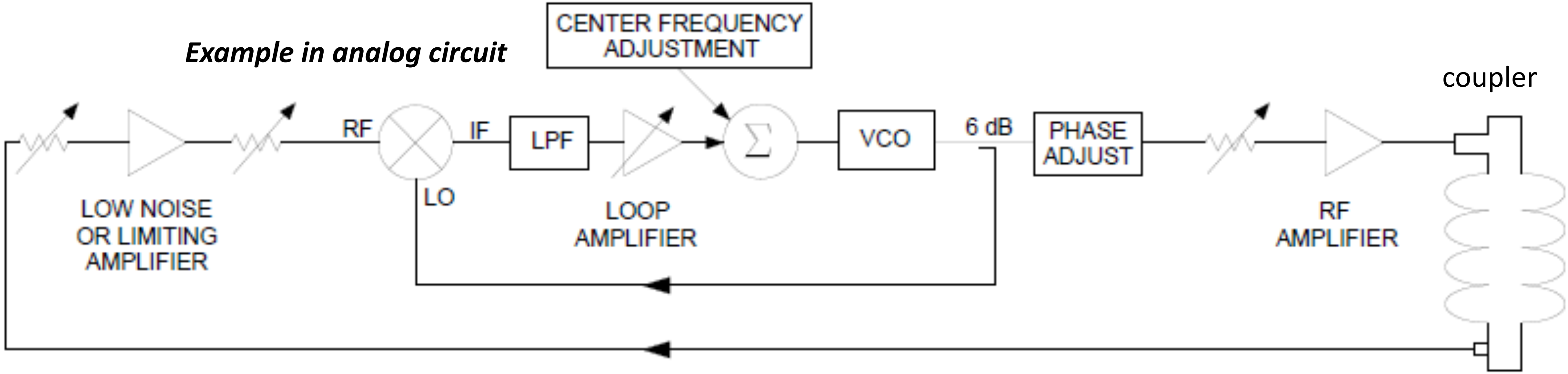
A lonely empty cavity is useless at all ☹

We need RF inside



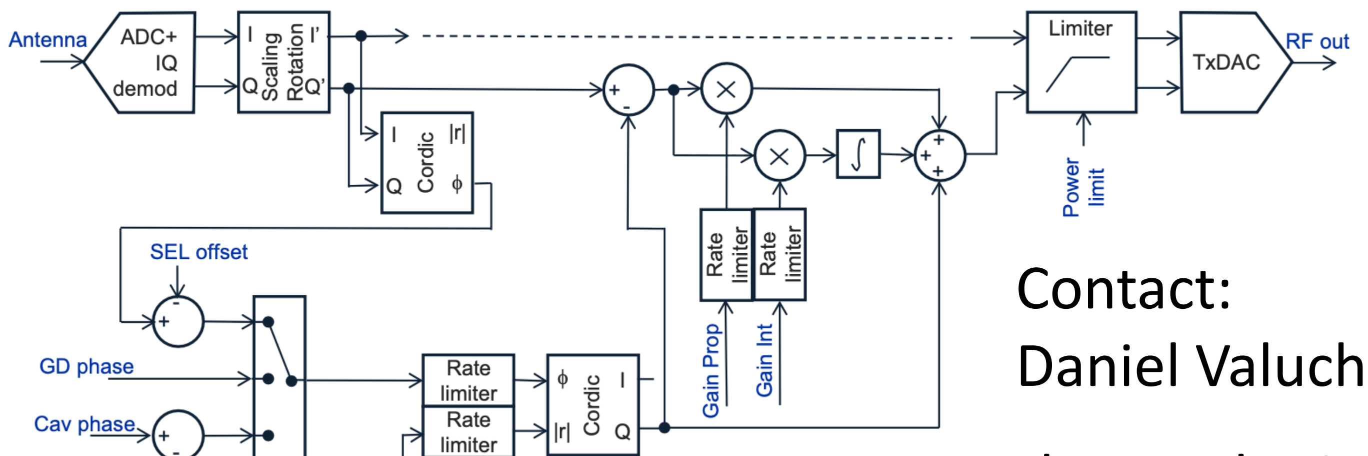
Example in analog circuit

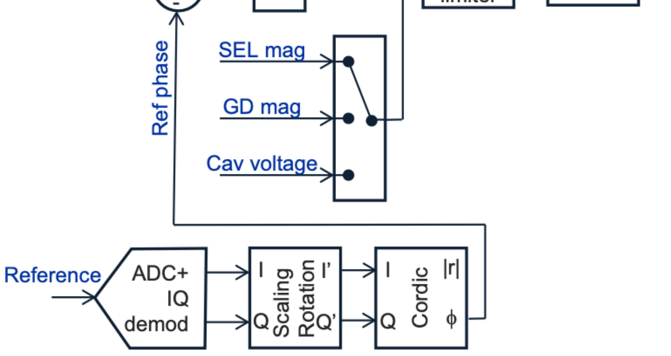


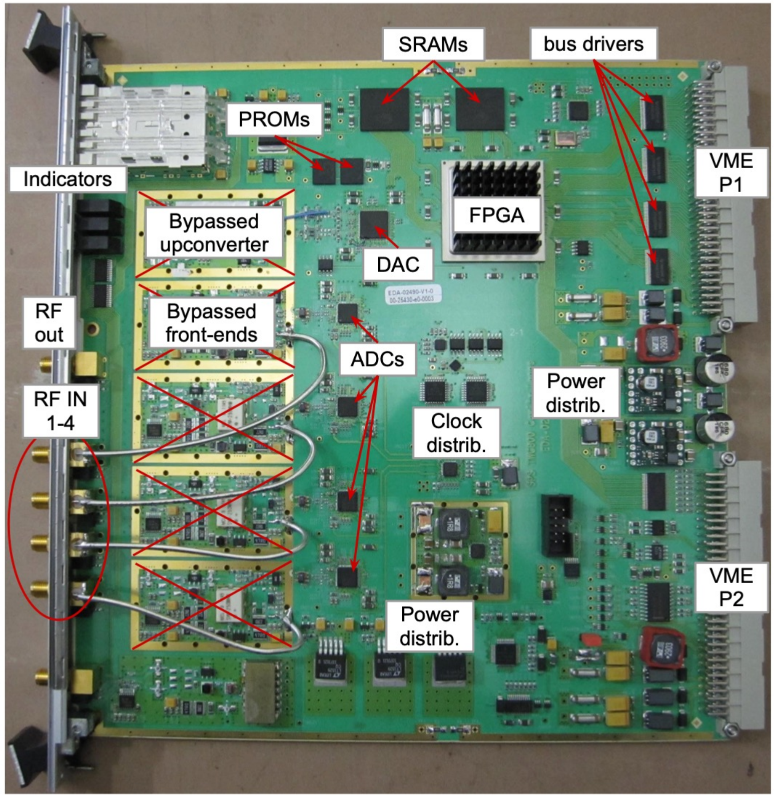
- An low-power RF circuit locks frequency, phase, and amplitude of the superconducting cavity
- An RF amplifier generates useful power level
- A power coupler feeds RF to the cavity
- Tuner controls resonant frequency of the cavity

LLRF: digital system and control algorithm

M. Elias master thesis



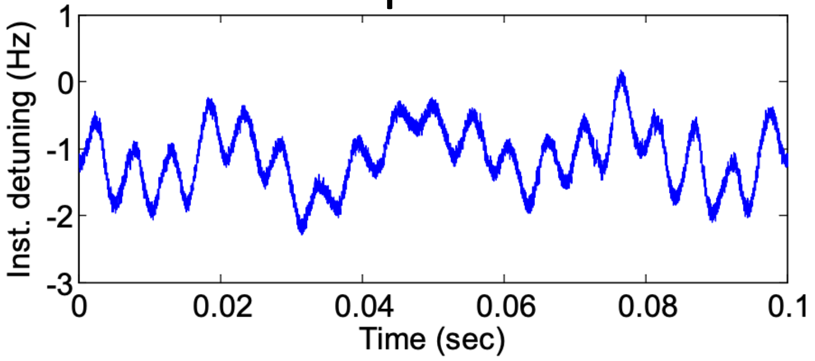




Contact:

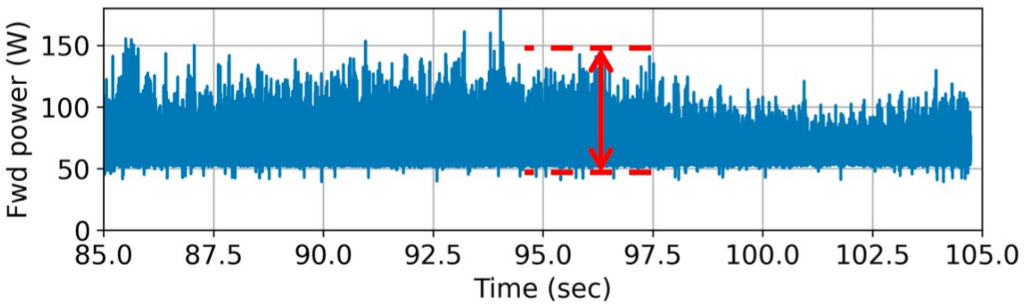
Daniel Valuch

External perturbation



- 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

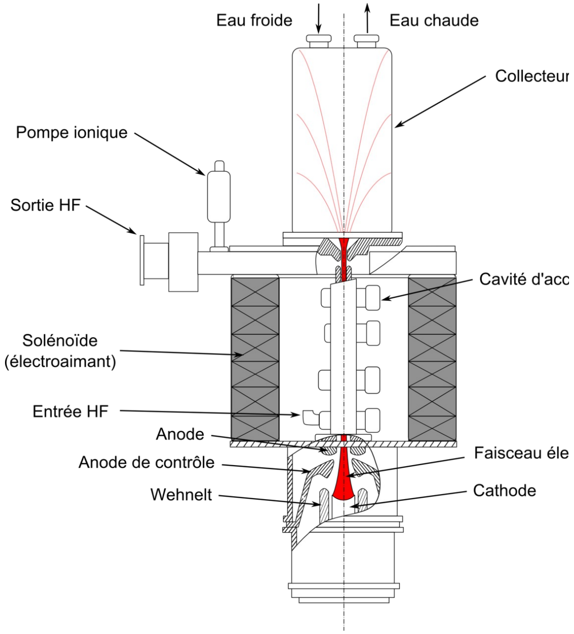
FB to keep cavity field constant



High-power amplifiers

Vacuum tubes / klystrons

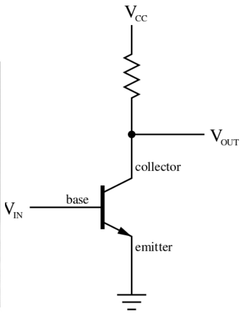
Amplification via the RF & DC beam interaction

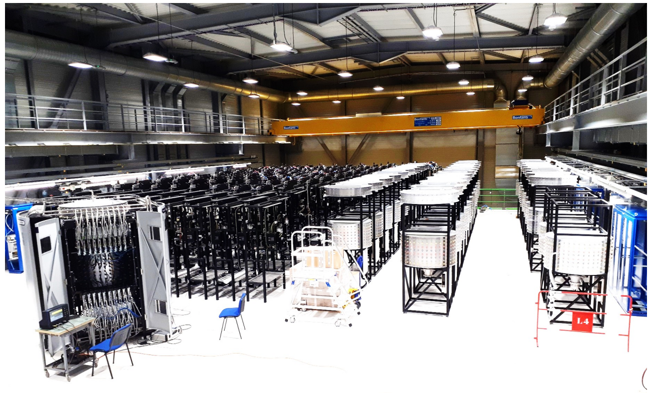


Transistor-based solid-state amplifiers

Amplification via
the tunneling effect

Shockley Bardeen Brattain



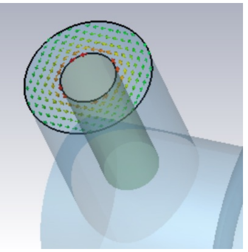


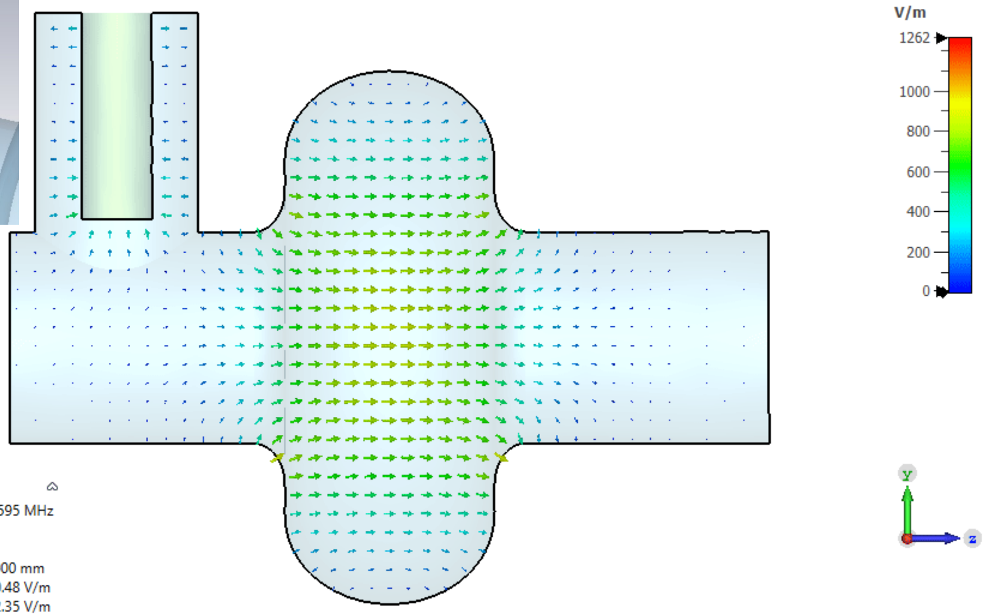
Courtesy: Eric Montesinos

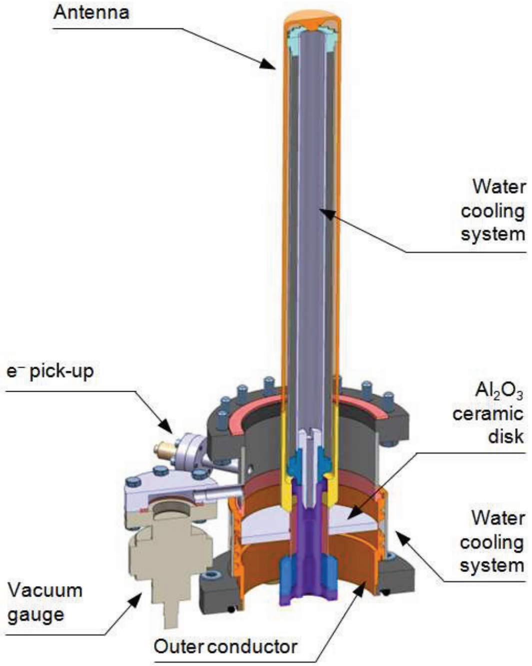
Recent research directions at CERN

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

RF power coupler to feed RF







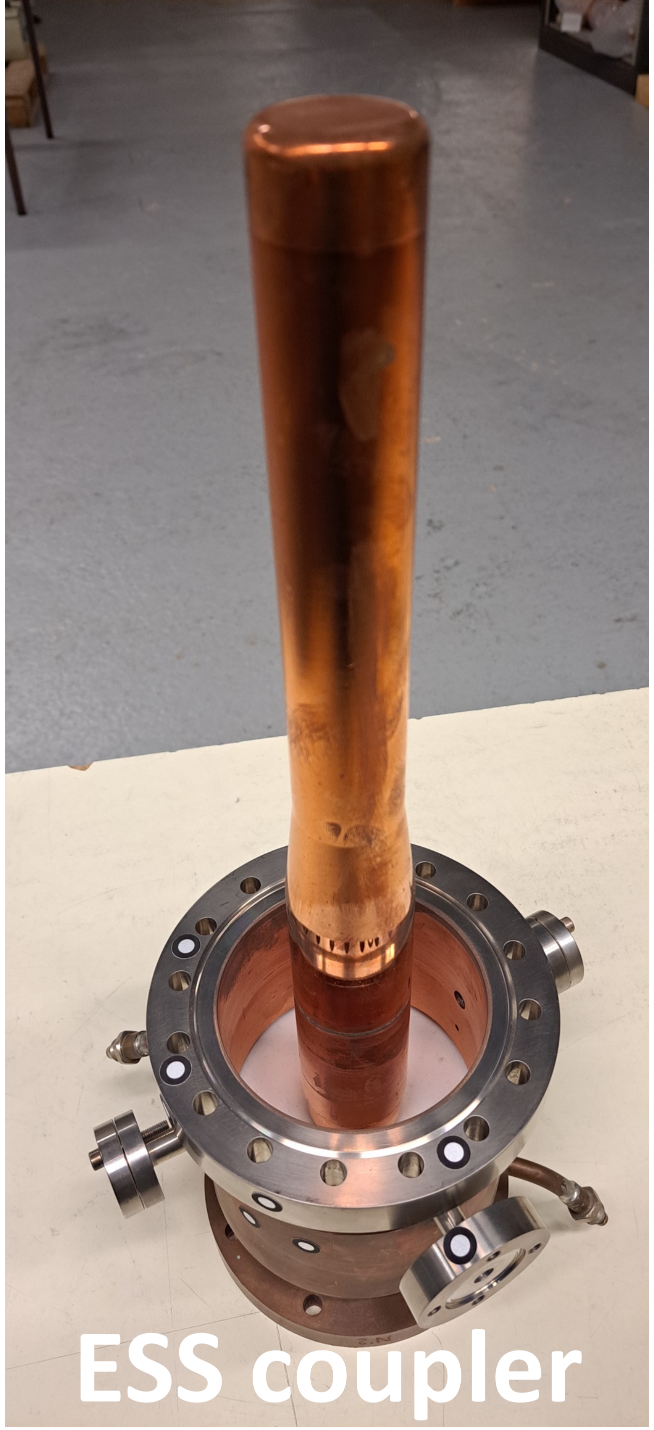
Power flow (Poynting vector) through the port gives coupler Q

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

Total Q of the cavity is thus shifted from unloaded Q_0

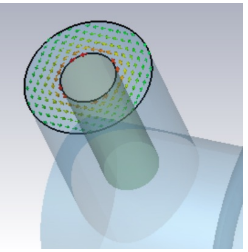
$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_{ext}}$$

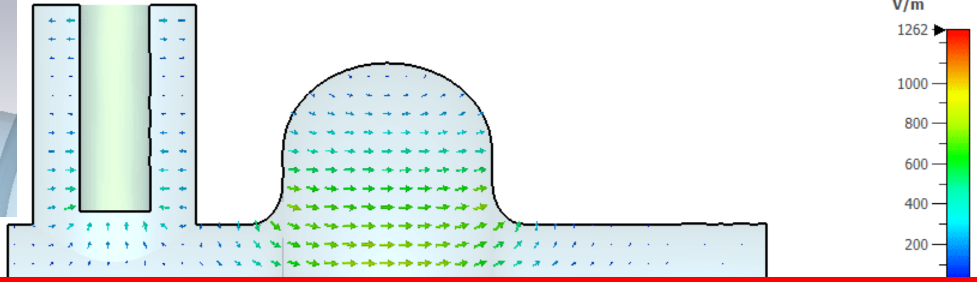
Contact: Eric Montesinos

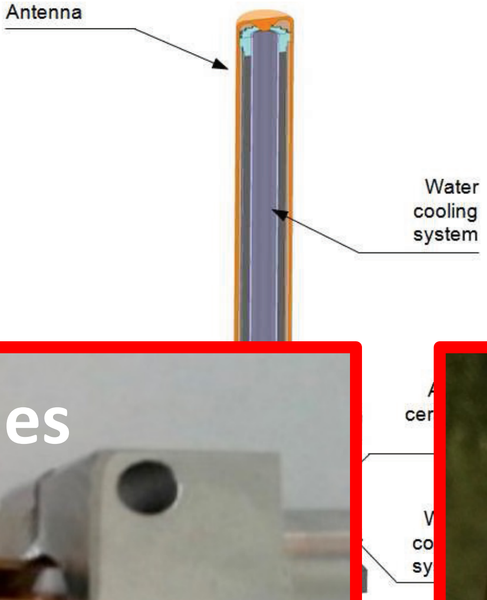


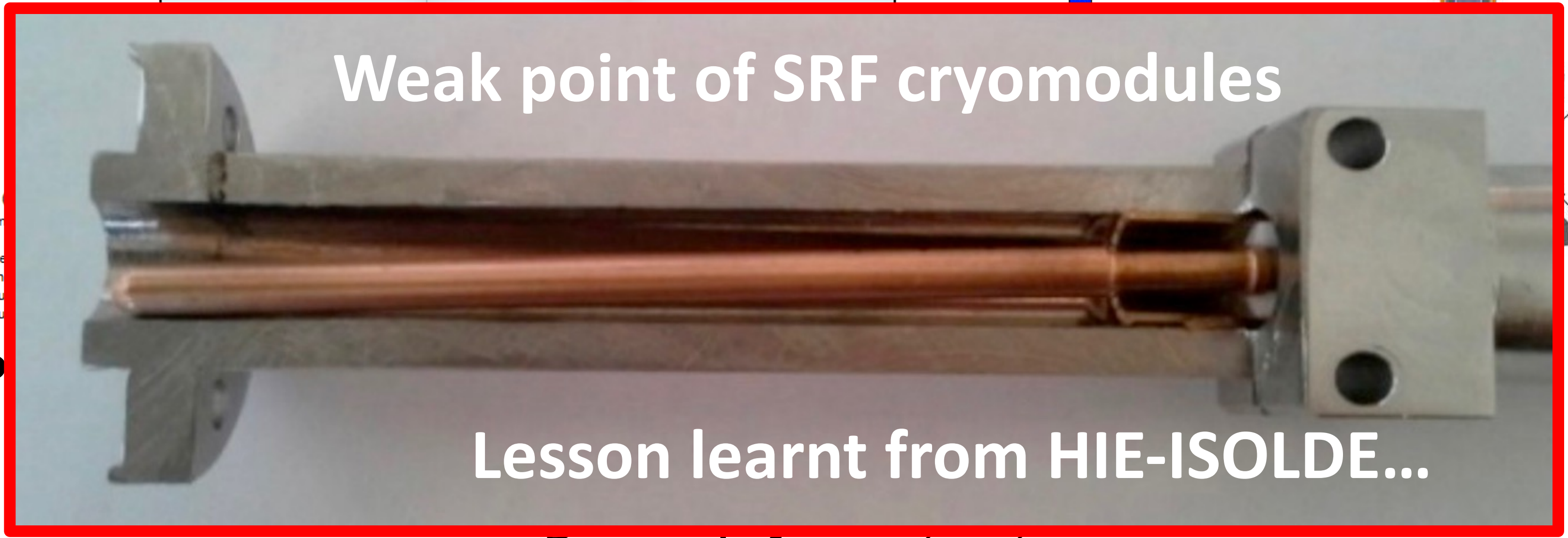
RF power coupler to feed RF

port









P

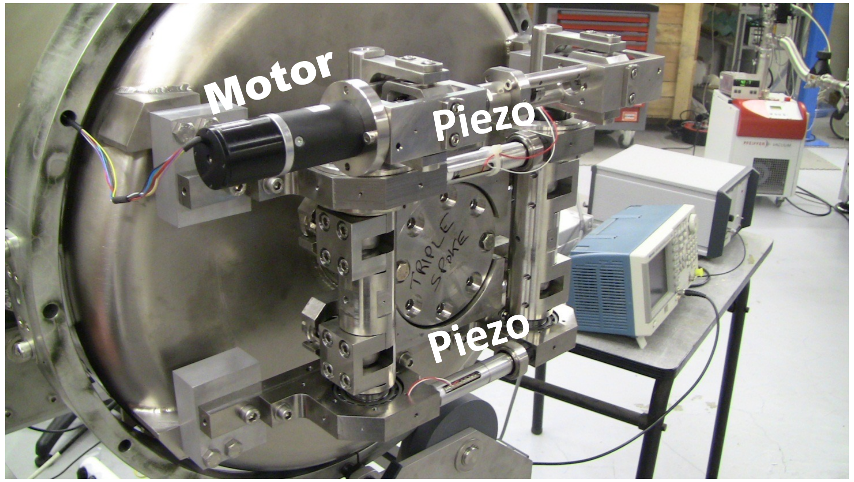
$$P_e \quad \frac{1}{2}\int_{S_{port}} E\times H dS$$

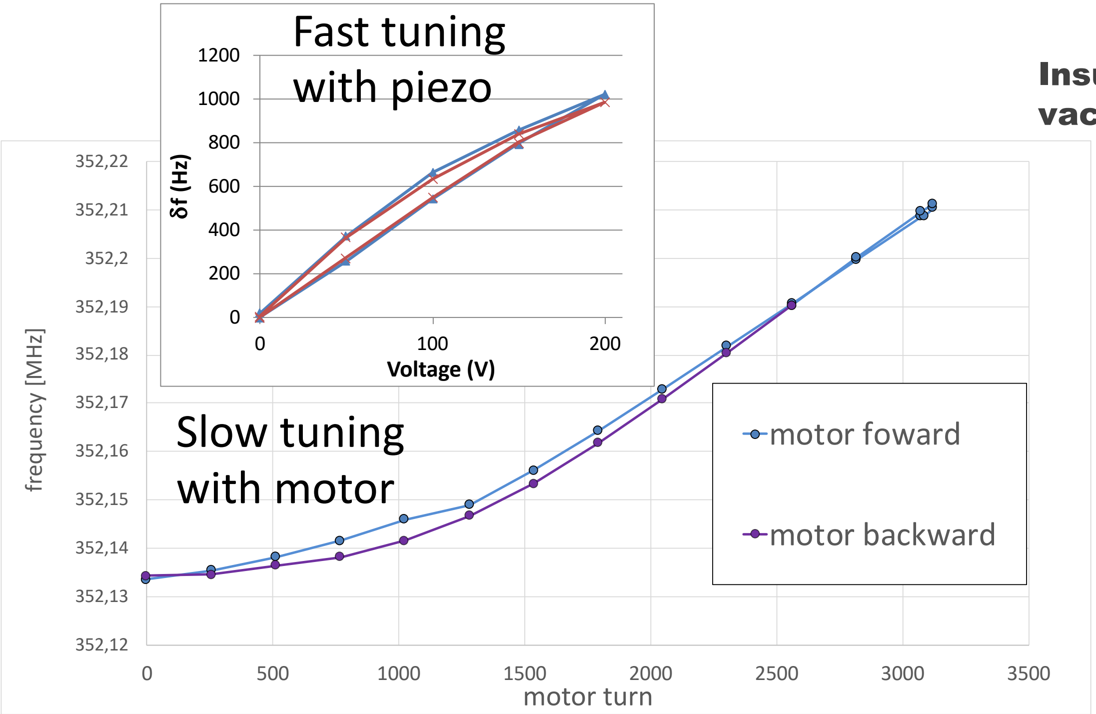
Total Q of the cavity is thus shifted from unloaded Q_0

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

Contact: Akira Miyazaki

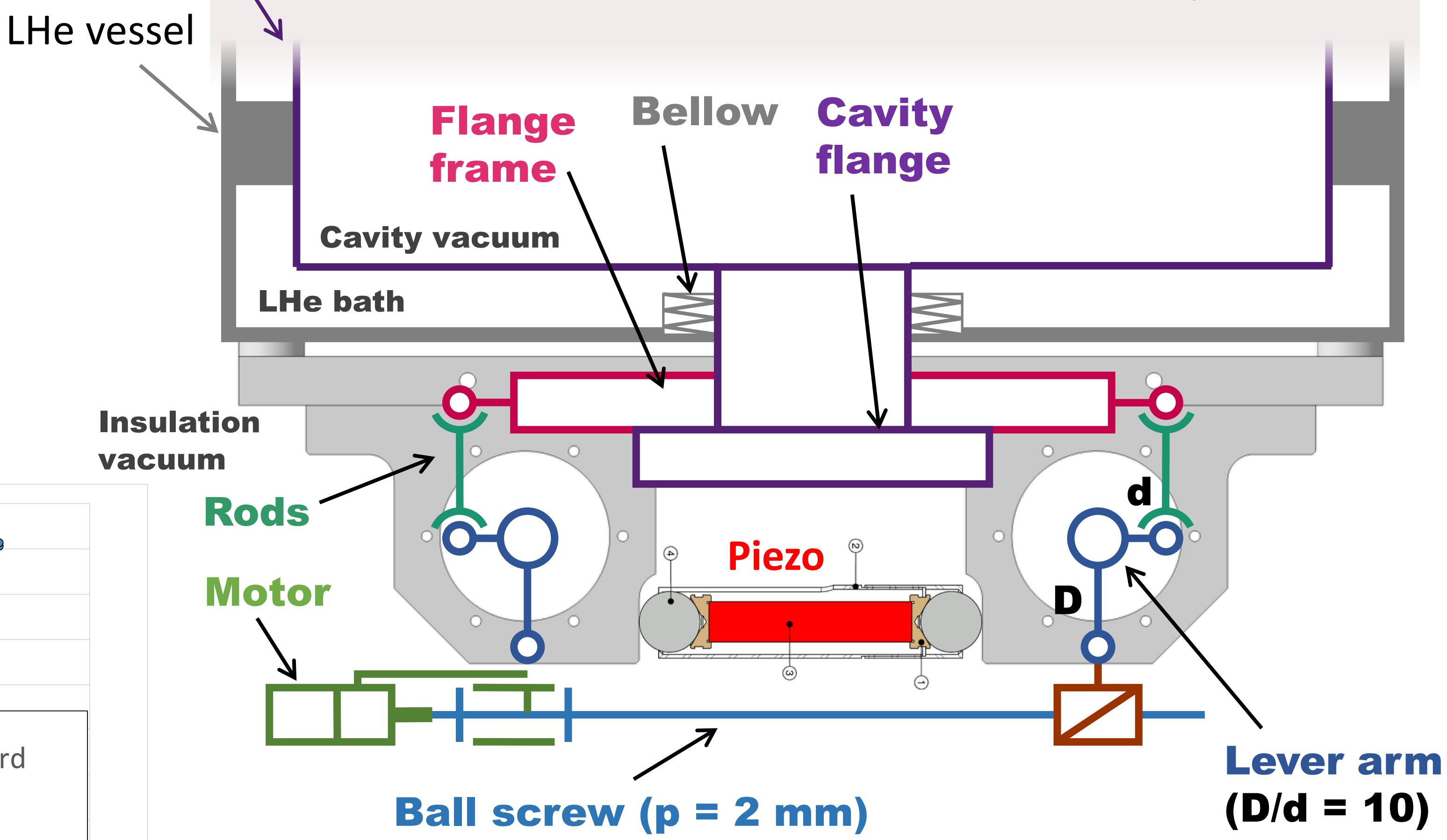
Tuner to control resonant frequency of cavities





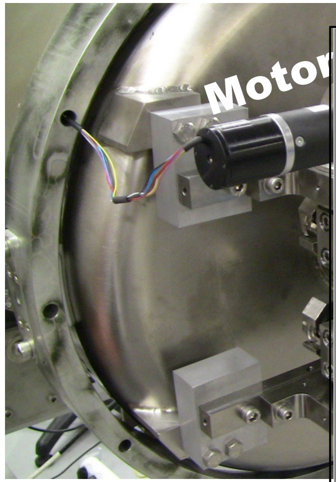
Example in ESS spoke cavities

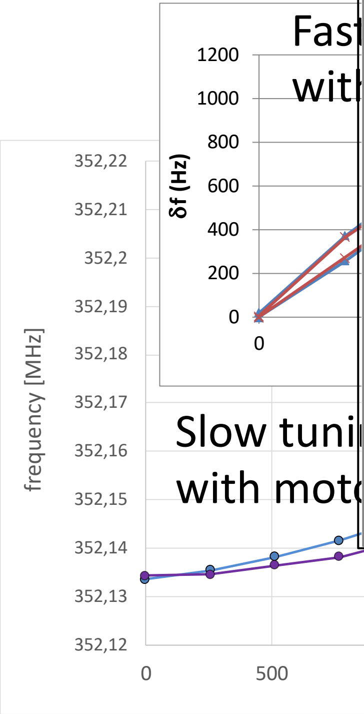
Courtesy: N. Gandolfo

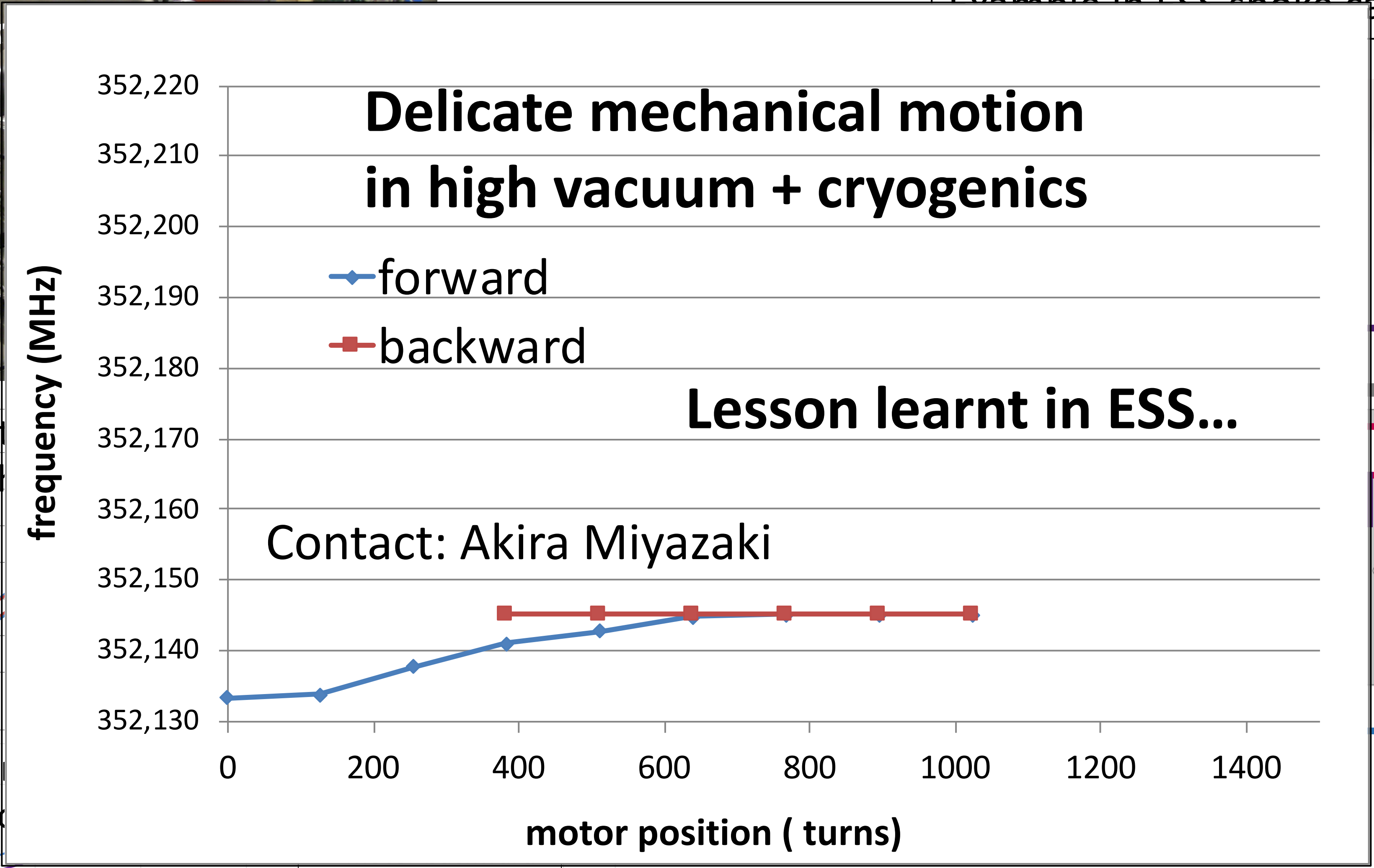


- Motor → course tuning before accelerator operation
- Piezo → active tuning against vibration & pulsed operation

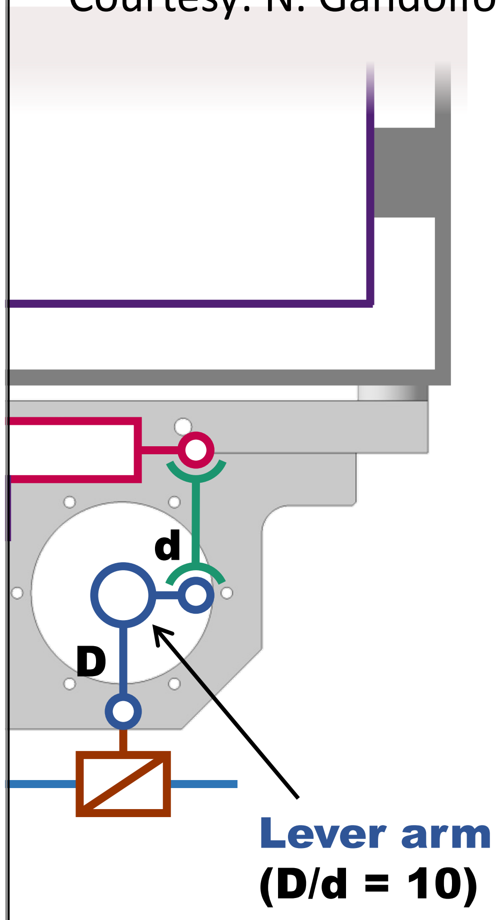
Tuner to control resonant frequency of cavities





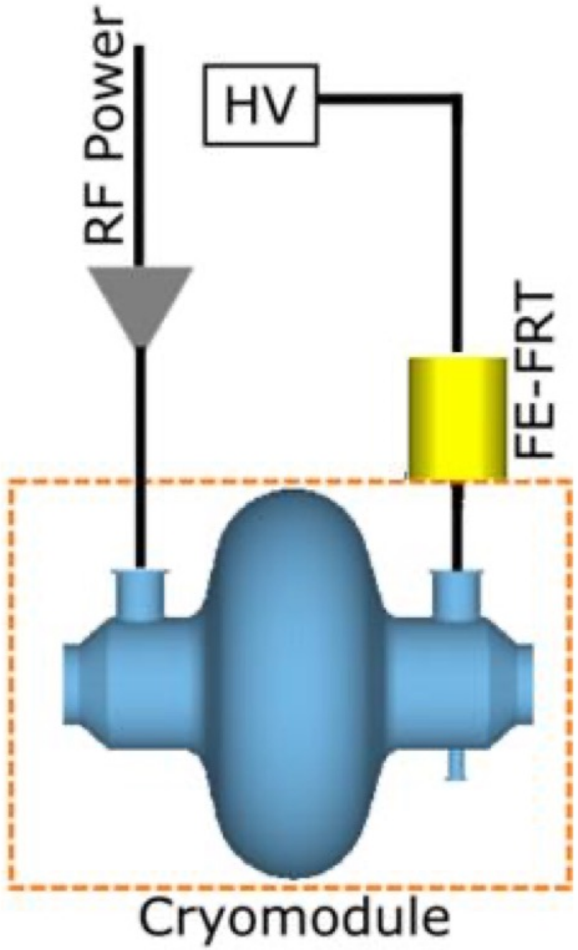


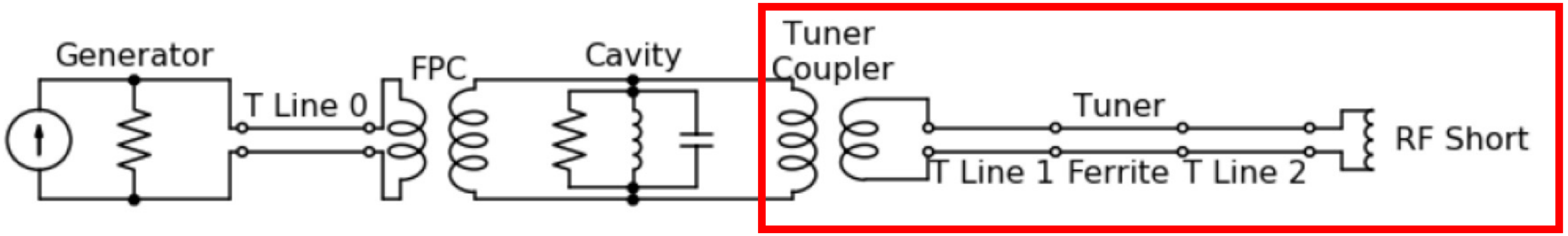
Courtesy: N. Gandolfo



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

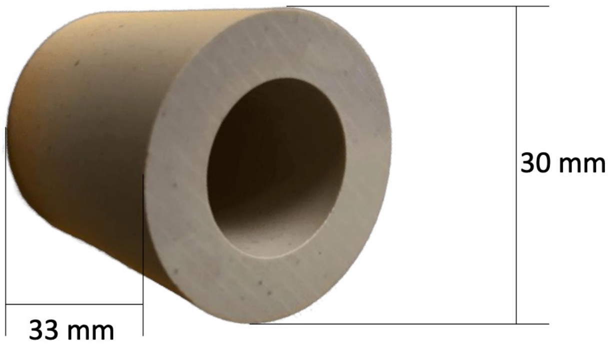
Non-mechanical fast reactive tuner





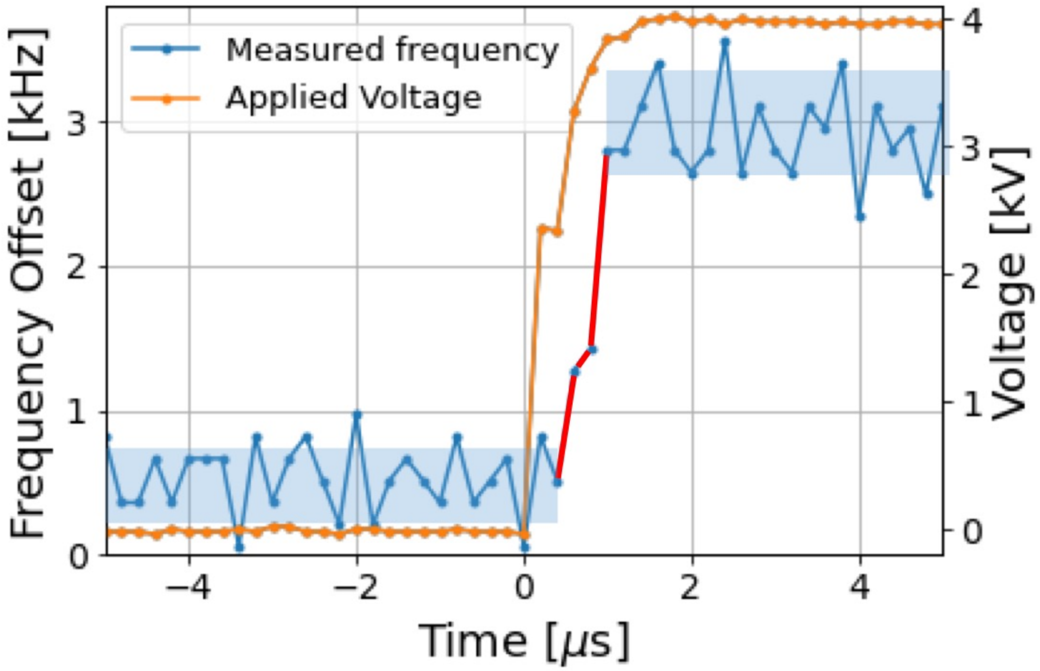
Courtesy: N. Shipman

$BaTiO_3$-$SrTiO_3$



A BST(M) Ferroelectric Sample

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

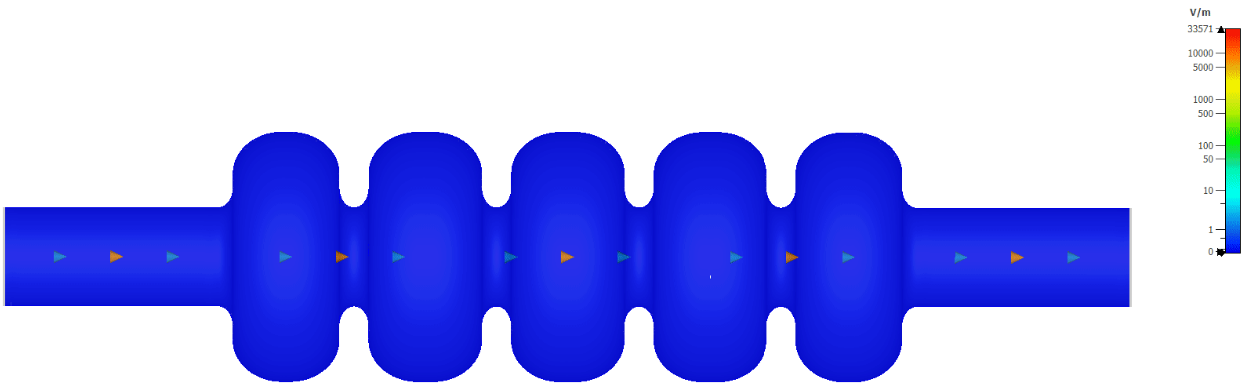


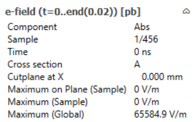
Active R&D is on-going at CERN

Contact: Alick Macpherson

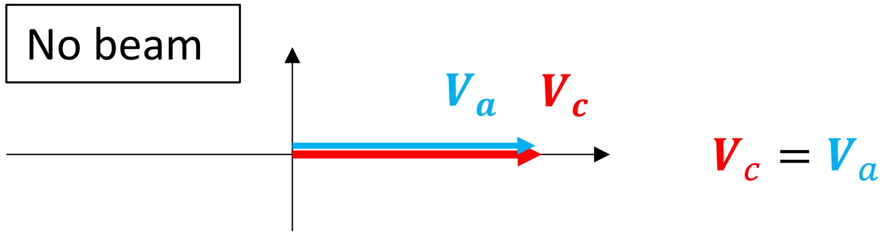
Contact: Rama Calaga

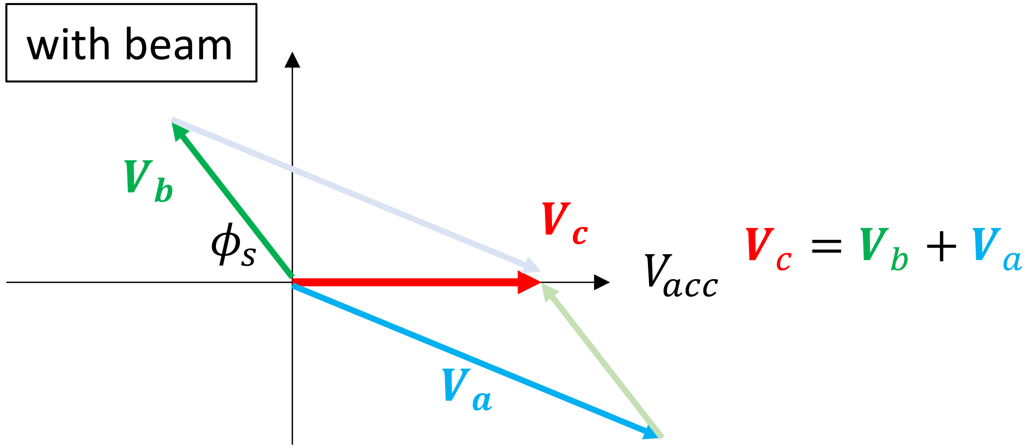
Beam → RF excitation





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





Beam loading

Accelerating mode V_b is excited in another phase

→ Overhead in the amplifier V_a to compensate it

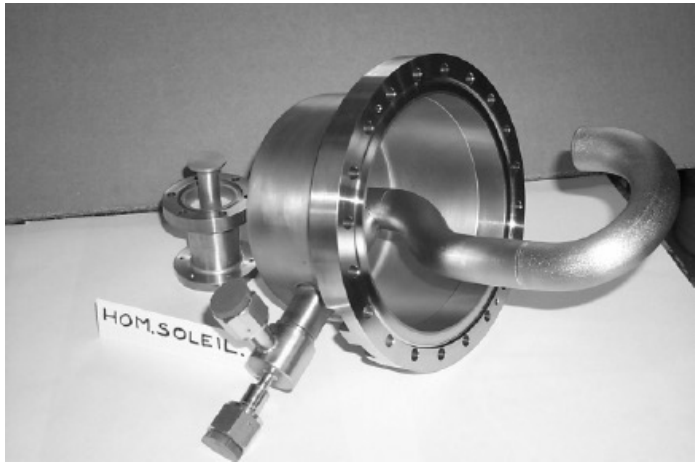
→ Optimum detuning trick (see LHC)

Higher Oder Modes

Non-accelerating modes are excited

→ Perturbation to beam (challenge in circular machines)

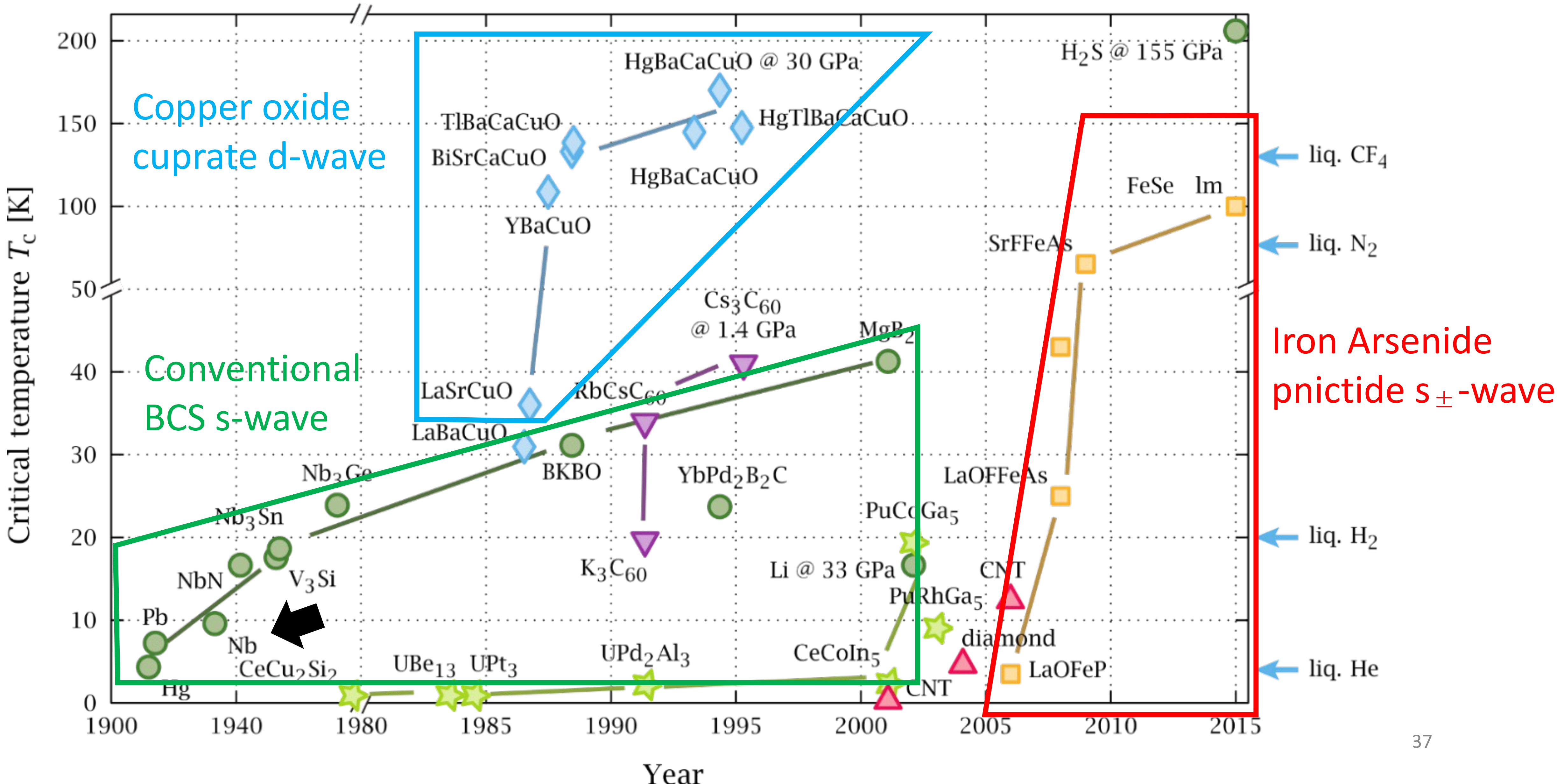
→ HOM couplers / dampers to mitigate them



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



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

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

<u>Mechanically brittle</u>

Difficult to fabricate cavity structures → coating?

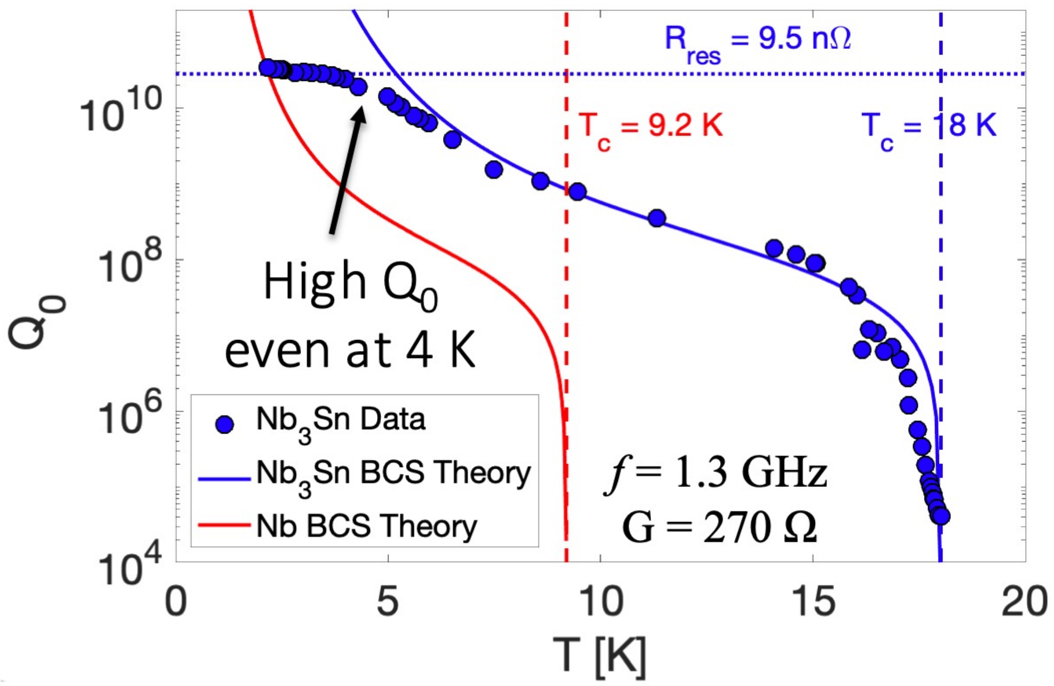
<u>Thermal conductivity</u>

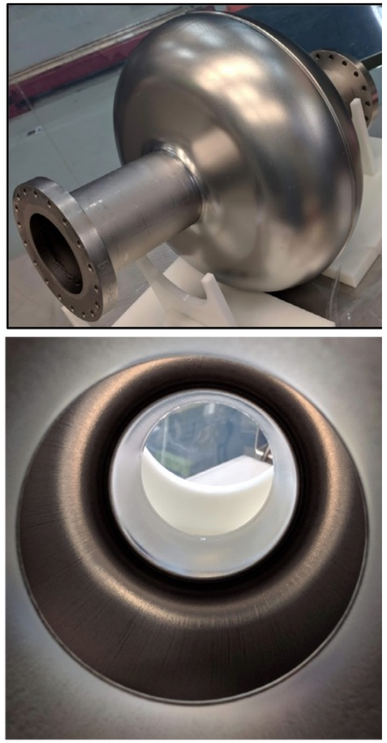
Much worse than Nb → Just a film?

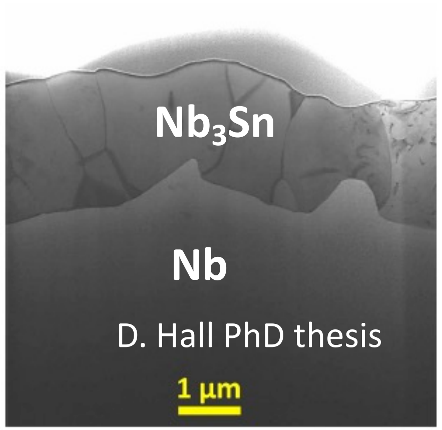
<u>Short ξ_0</u>

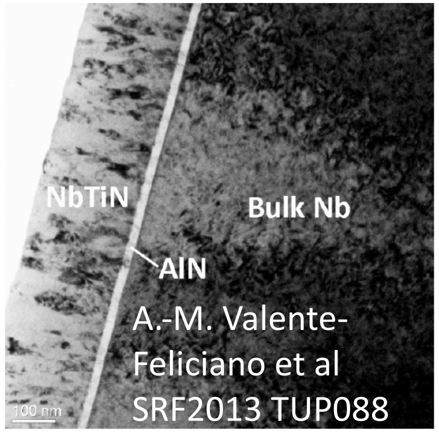
Flux penetration through grain boundaries → Protective layer?

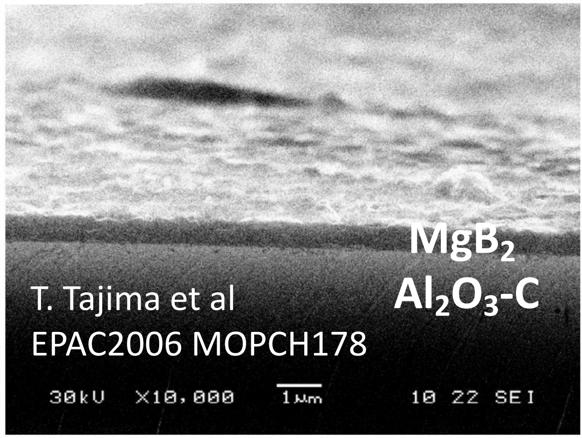
Courtesy S. Posen





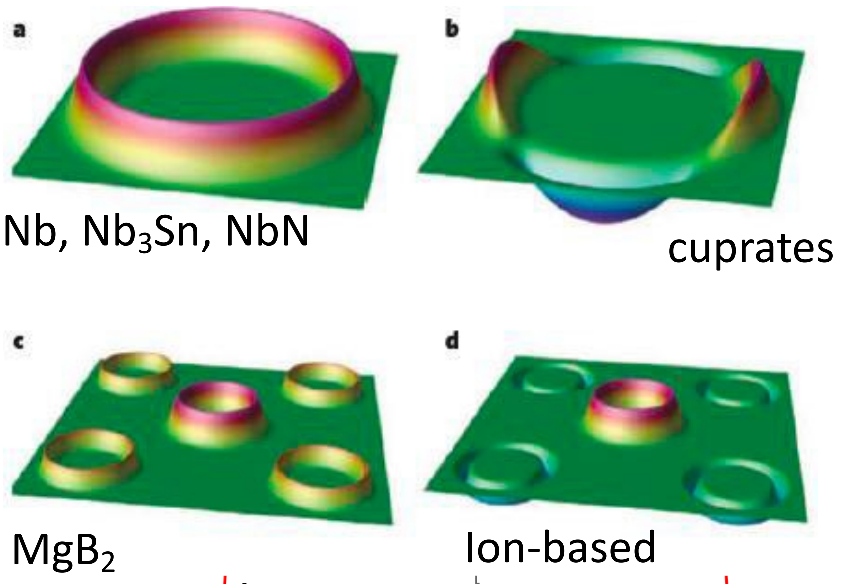


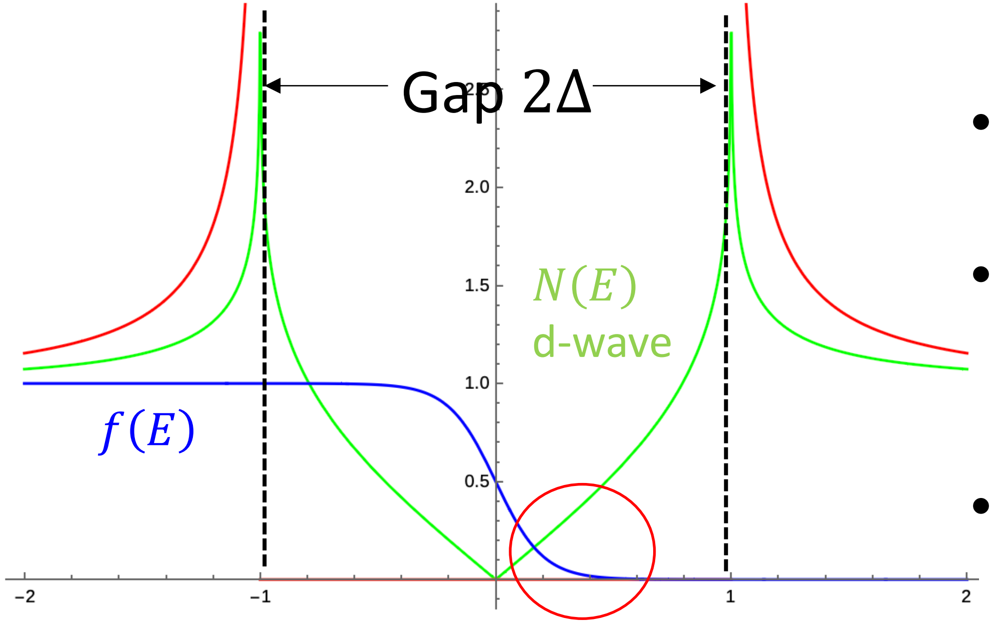




Contact: Guillaume Jonathan Rosaz

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





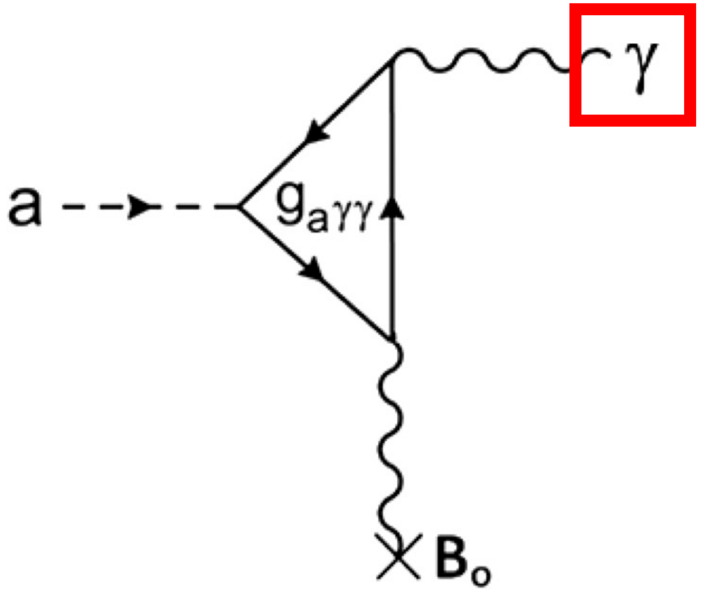
$$R_s \propto \hbar\omega \int_{\Delta}^{\infty} dE\, [f(E) - f(E+\hbar\omega)] \times N(E)N(E+\hbar\omega)$$

- 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

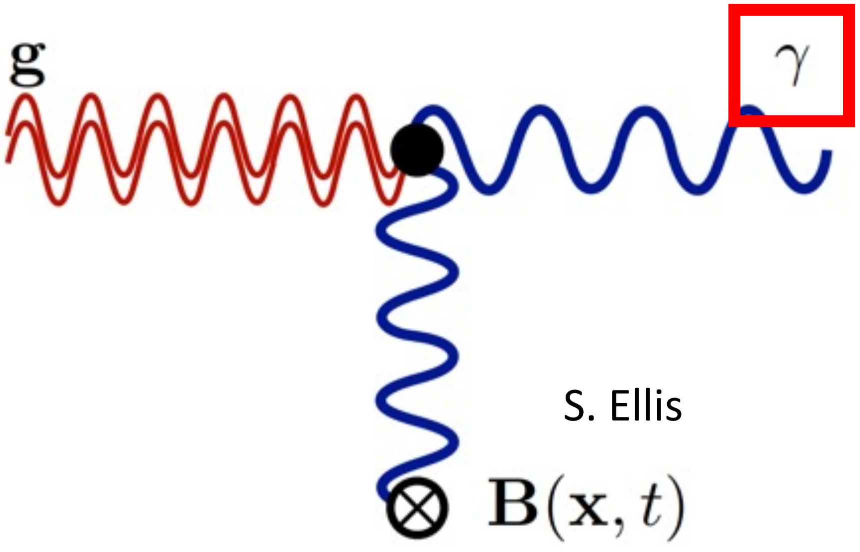
Axions



Inverse Primakoff effect

Minimal extension of SM

Gravitational waves

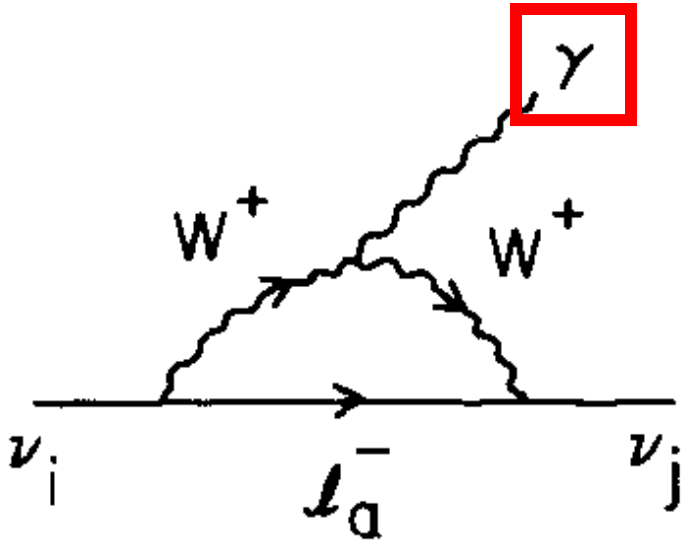


S. Ellis

Inverse Gertsenshtein effect

Solution of general relativity

Neutrinos

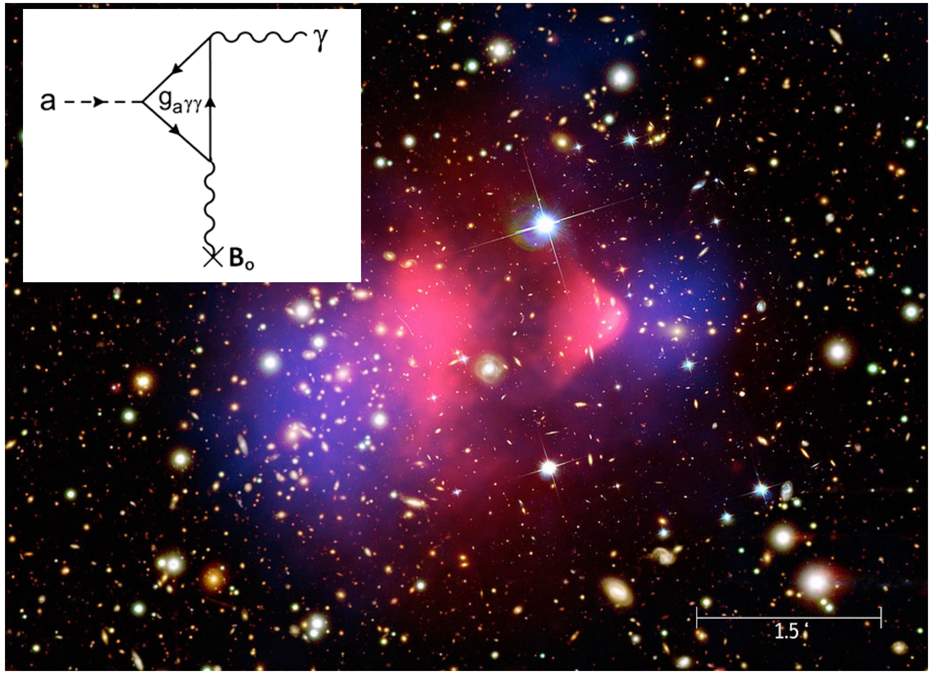


Cosmic neutrino background

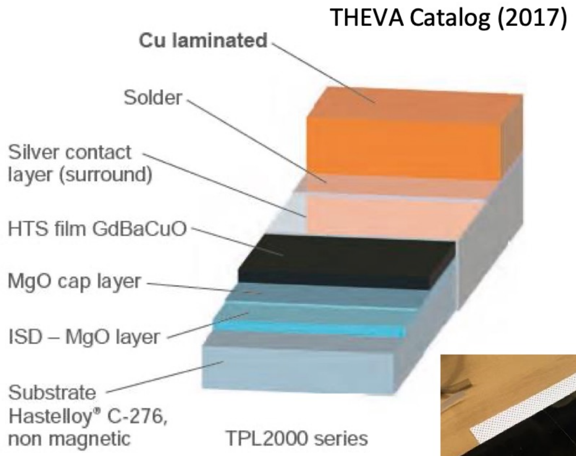
Extension of SM and/or SM

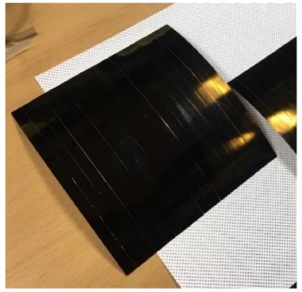
Contact: Akira Miyazaki

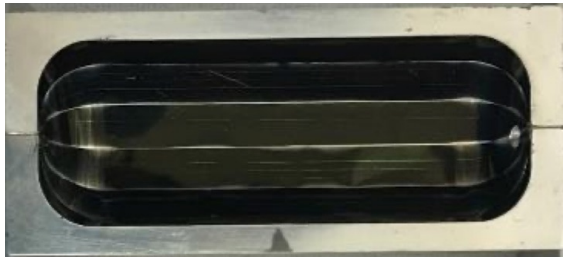
HTS SRF cavities under static magnetic field



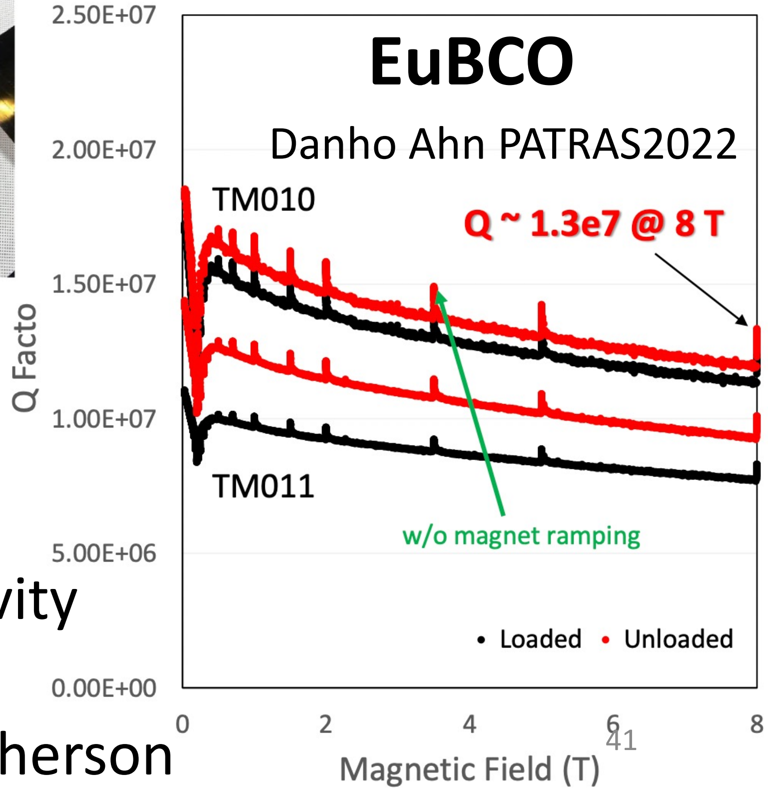
cuprate tapes on copper cavities







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

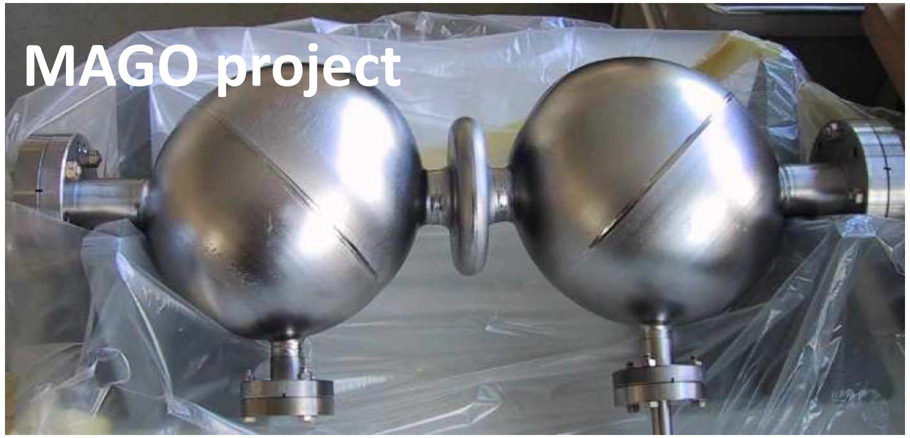
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

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

Mechanical deformation of a cavity wall

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

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

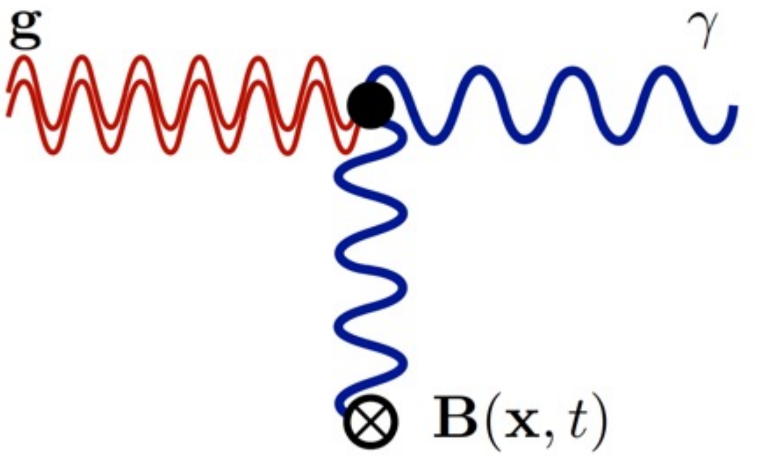


arXiv:gr-qc/0502054

Coupling to microwaves under static B

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

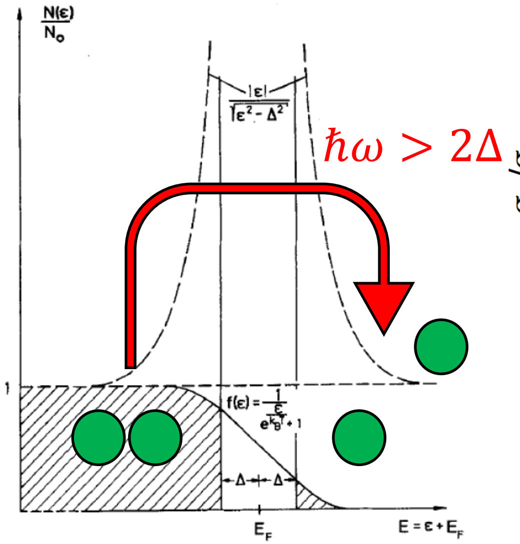
$$4\pi T_{\mu\nu} = F_{\mu\alpha}F_{\nu}{}^{\alpha} - \frac{1}{4} g_{\mu\nu} F_{\alpha\beta}F^{\alpha\beta}$$

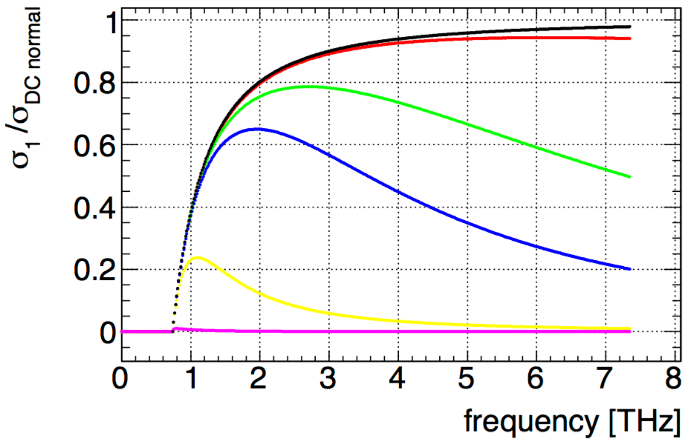


M. E. Gertsenshtein JETP 41 113 1961

Single microwave photon sensors

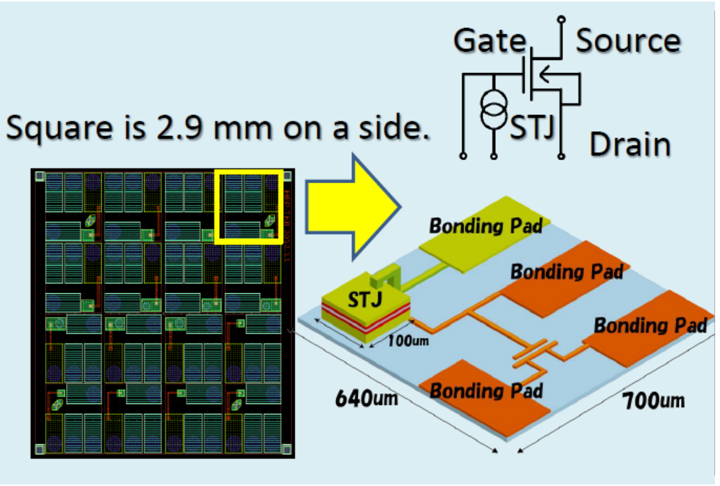
Superconducting Tunnel Junction (STJ)





Al STJ

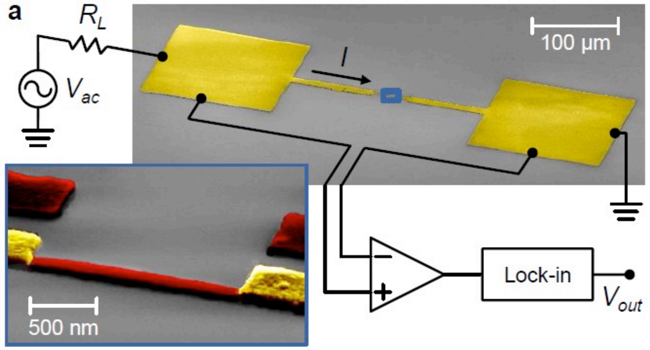
Hf STJ

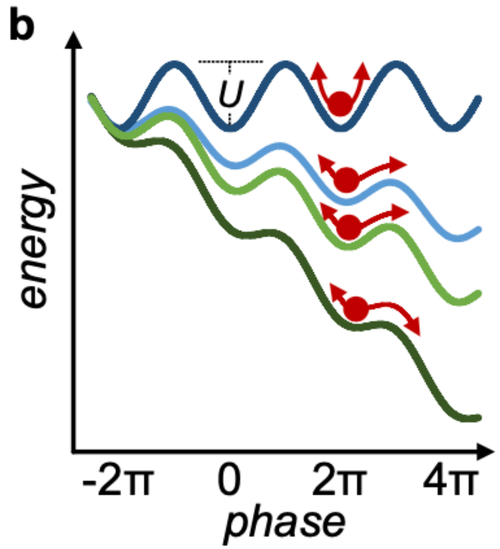


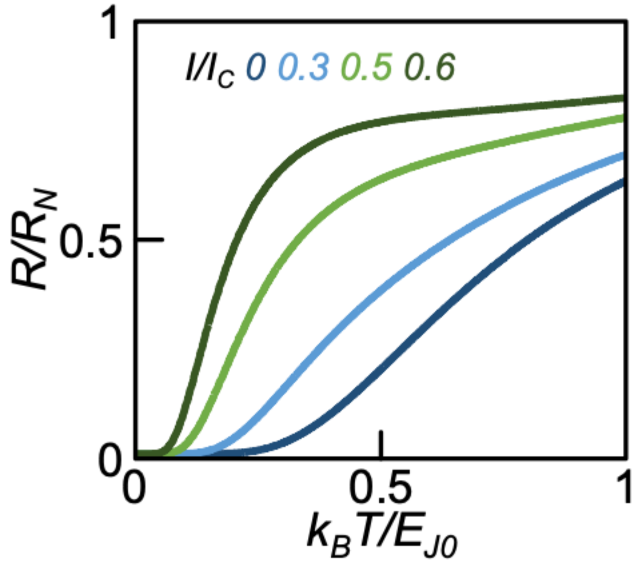
S.-H. Kim et al, JPS Conf. Proc. 1 013127 2014

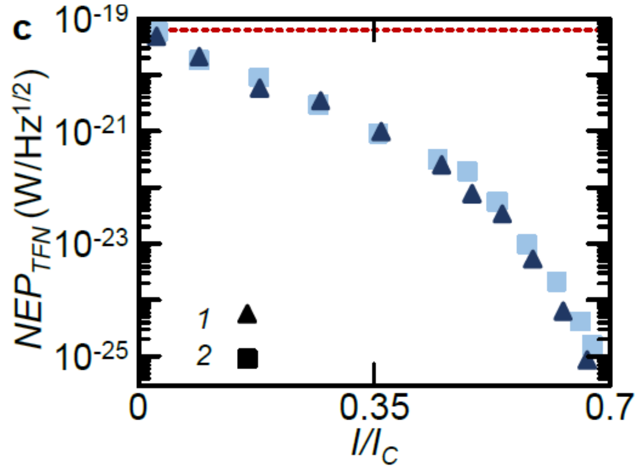
Current-biased Josephson Junction TES (JES)

Bolometer/calorimeter





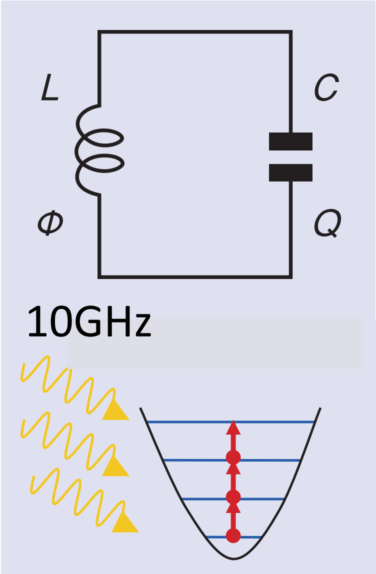


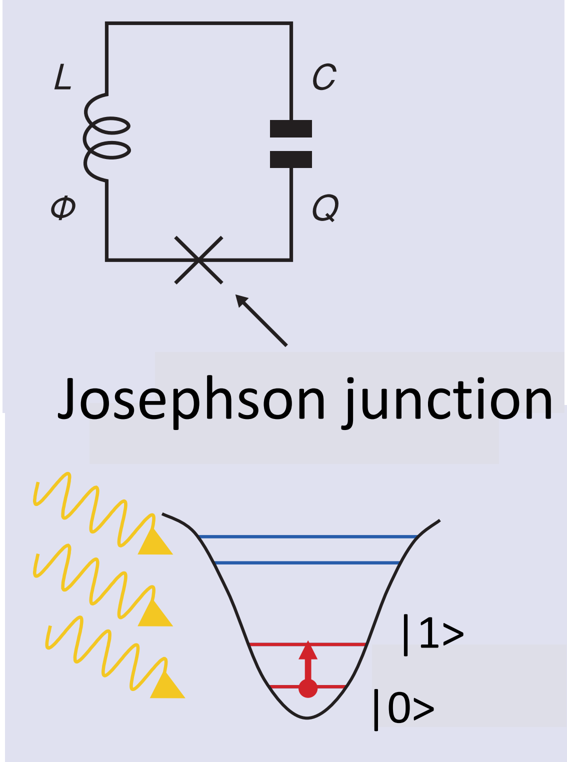


F. Paolucci et al Phys Rev Appl. 14 034055 (2020)

Superconducting qubit based on SRF cavities (?)

Key: quantized LC circuit

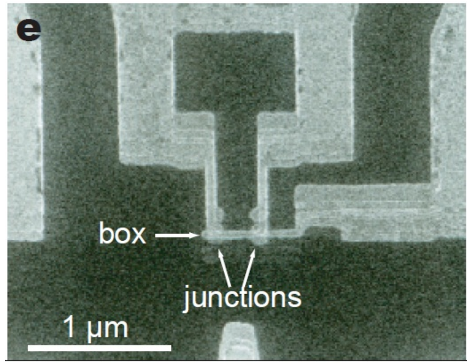




Harmonic oscillator has equally spaced many states
→ Not useful as qubit

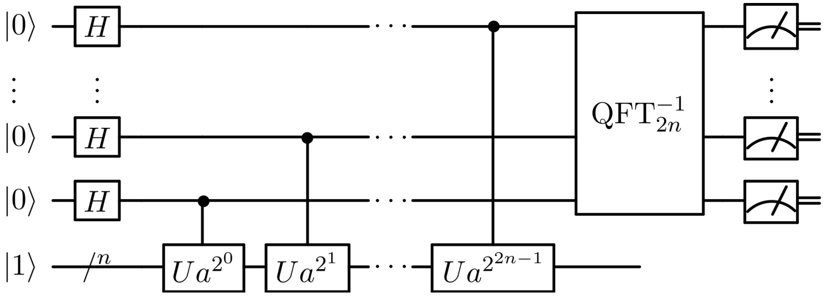
JJ → anharmonic potential
→ selective |0> & |1>

transmon

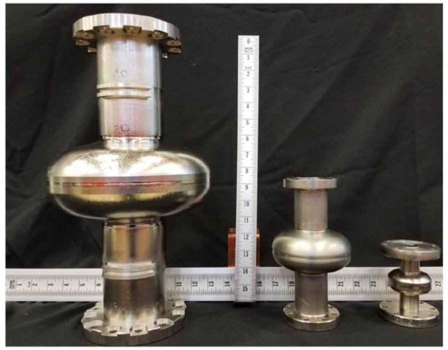


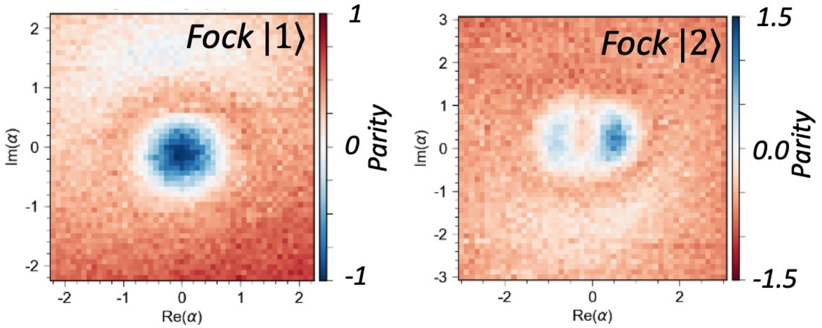
Shor's algorithm

finding the prime factors



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

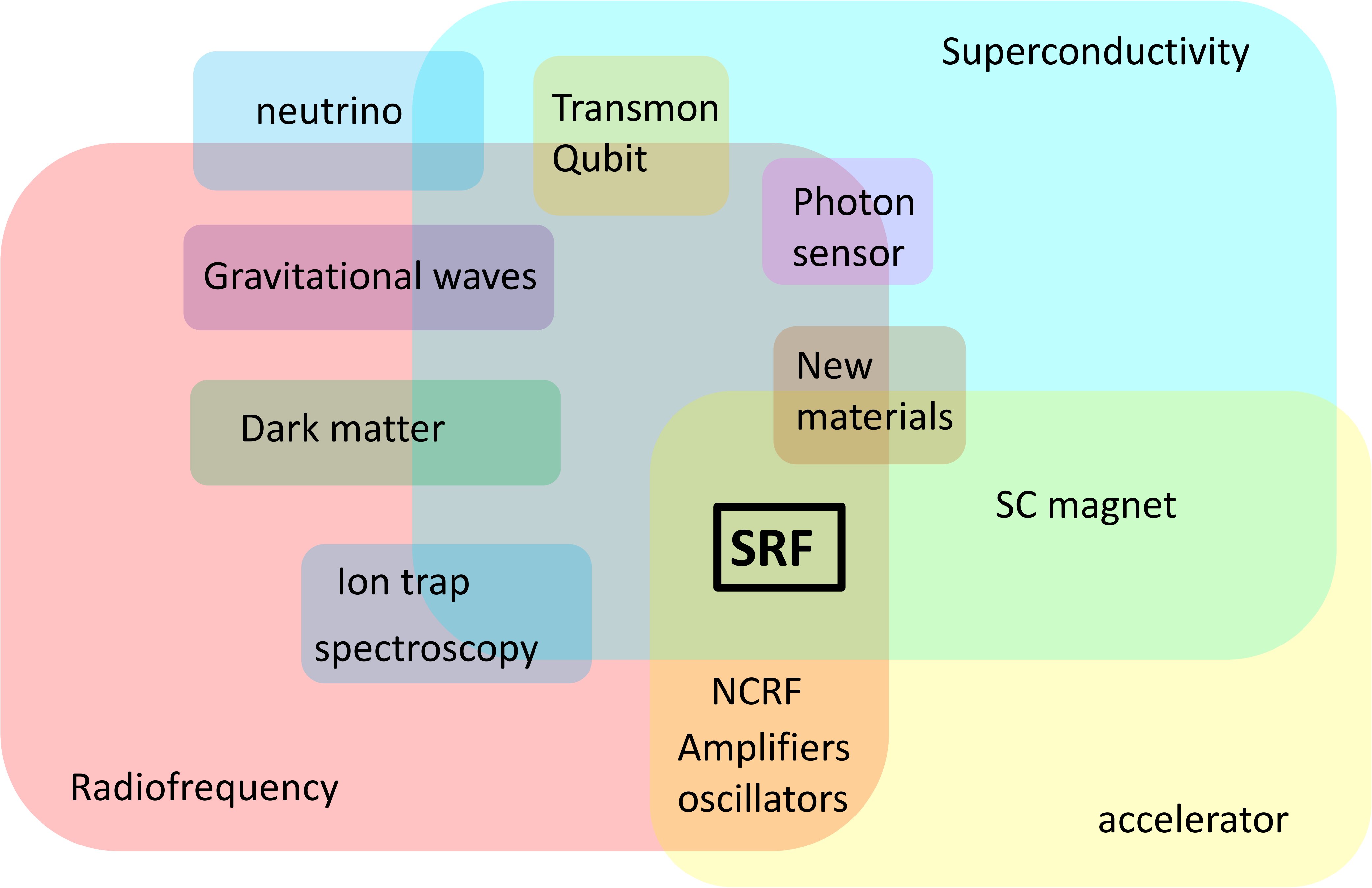




T. Roy "Advances in SRF Qubit Architectures for Quantum Computing" SRF2023

- 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

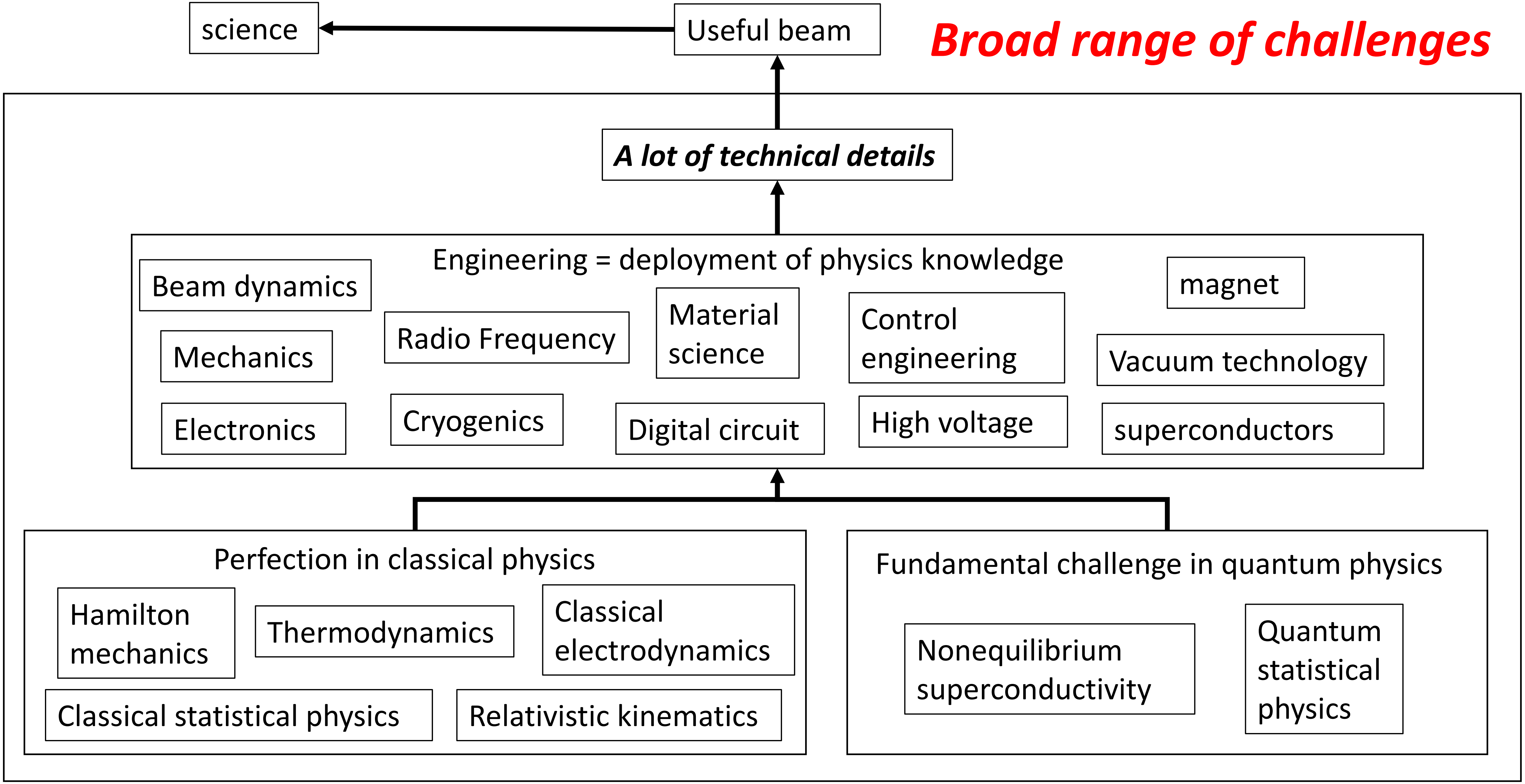
- Fundamental aspects of SRF cavities are interesting but can be hidden by practical challenges
  - Practicality requires extremely broad range of expertise of state-of-the art science and engineering
  - Recent progress in technology gives us almost ideal SRF cavities → chance to further validate and 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

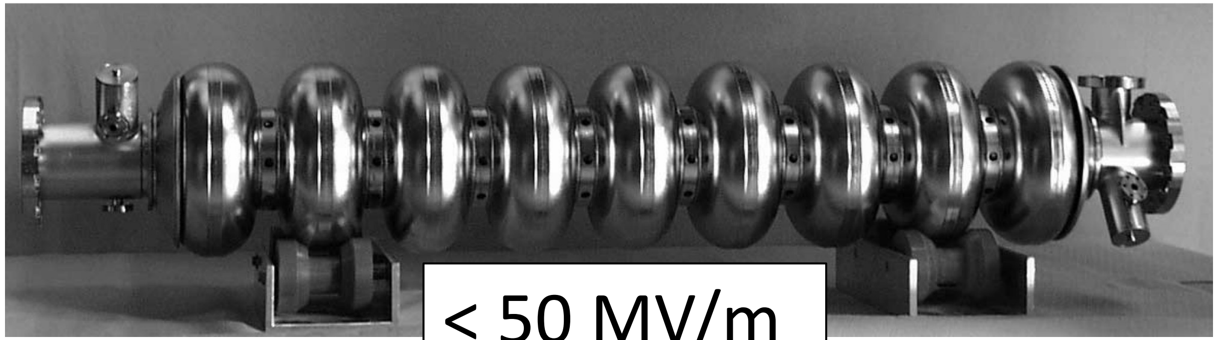
backup

Broad range of challenges

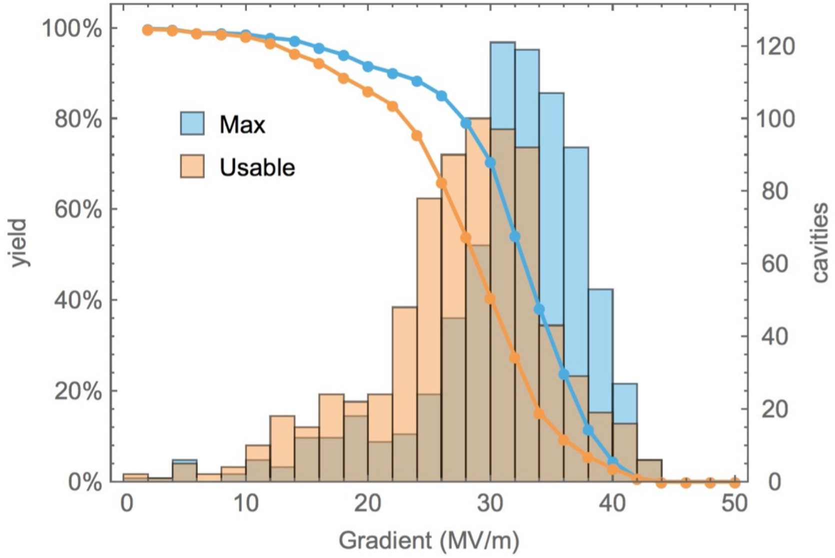


Accelerating cavities

<u>Superconducting niobium cavities (TESLA)</u>



< 50 MV/m

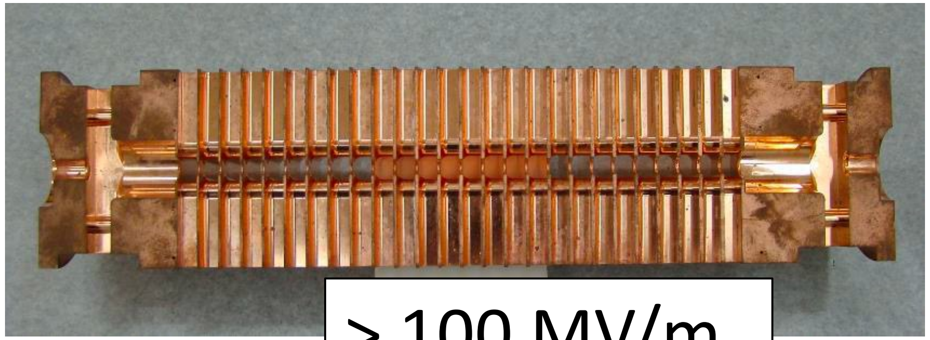


PHY REV ST - ACCEL BEAMS, **3**, 092001 (2000)

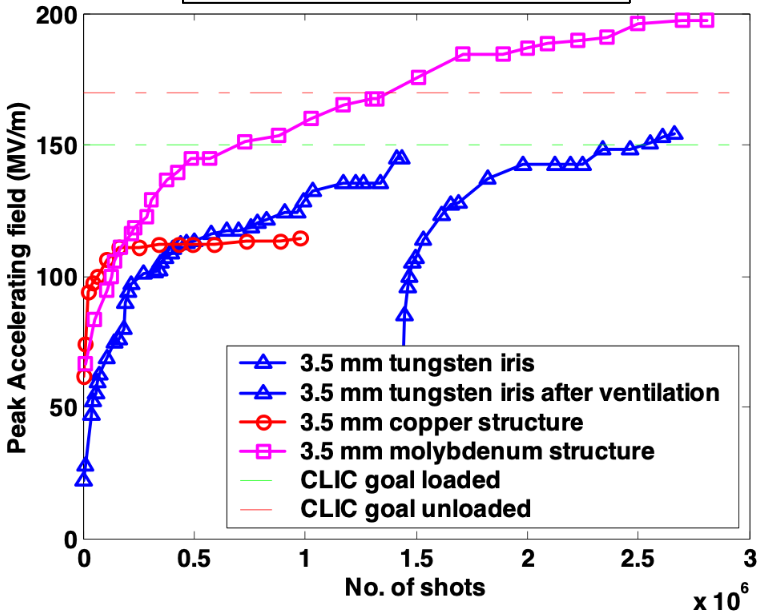
PHY REV ACCEL BEAMS 20, 042004 (2017)

>×2

<u>Normal conducting copper cavities</u>



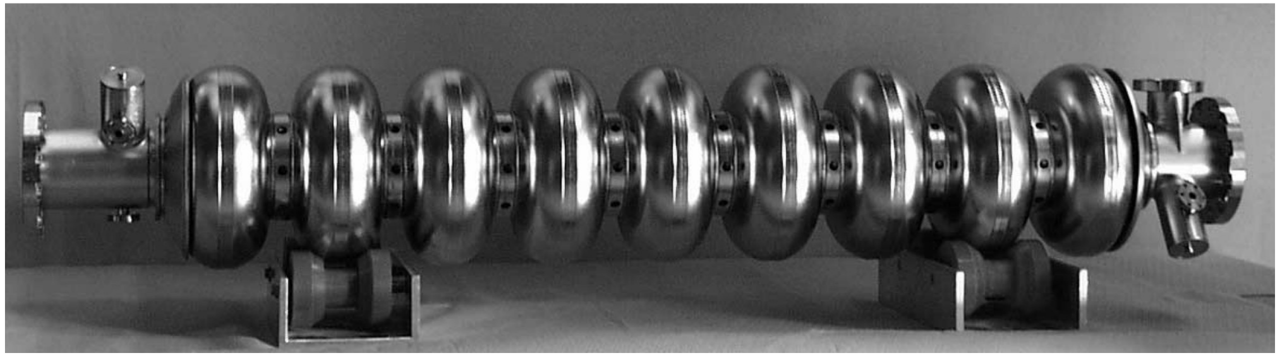
> 100 MV/m

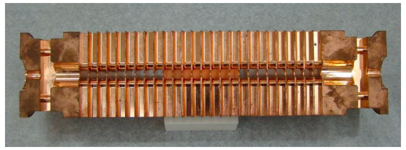


Courtesy: Walter Wuensch

Superconducting vs normal conducting

Aperture

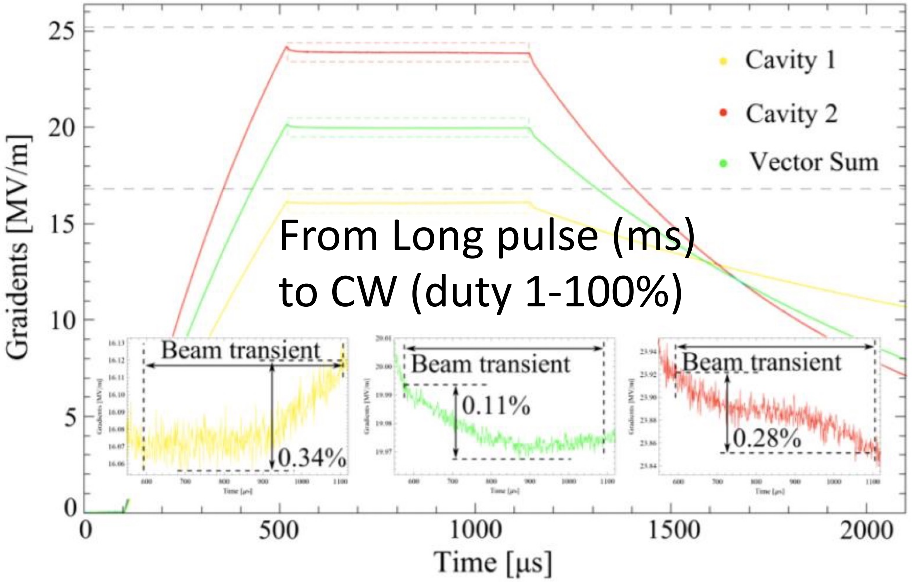




Superconducting cavities can keep high gradient at low frequency
→ large aperture (ILC: ϕ70 mm)

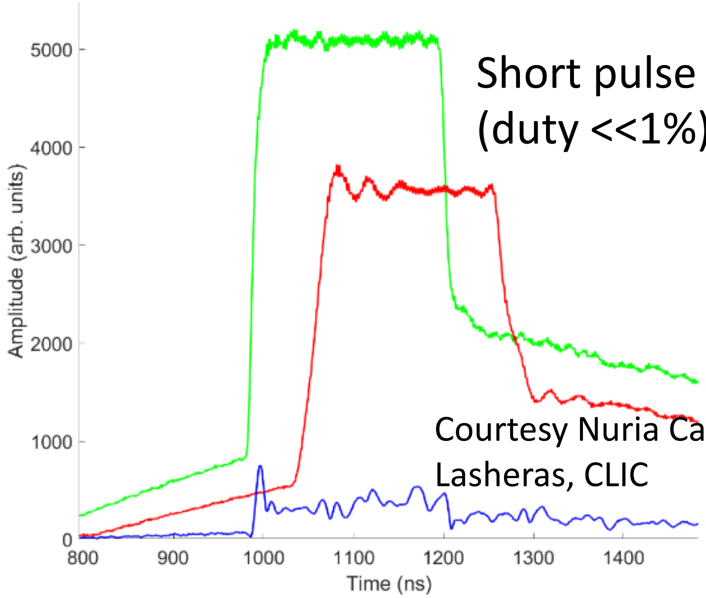
Normal conducting cavities are efficient at high frequency
→ small aperture (CLIC X-band: around ϕ3 mm)

Pulse length and duty cycle



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

M. Omet
SRF2021
lecture

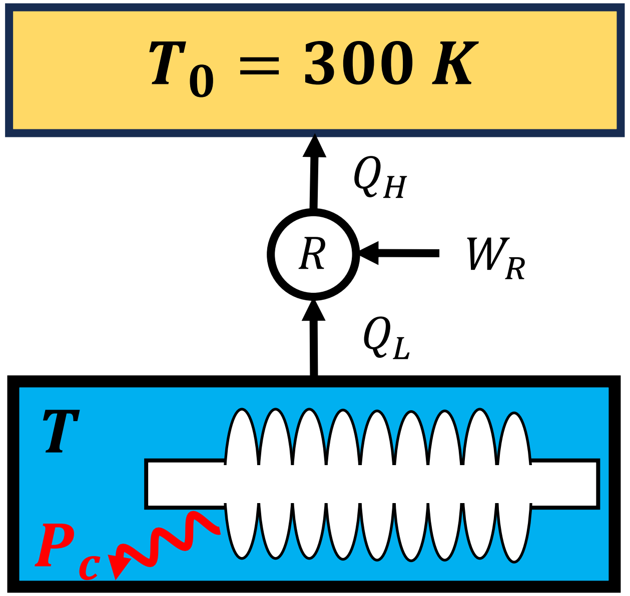


Short pulse (μs)
(duty <<1%)

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



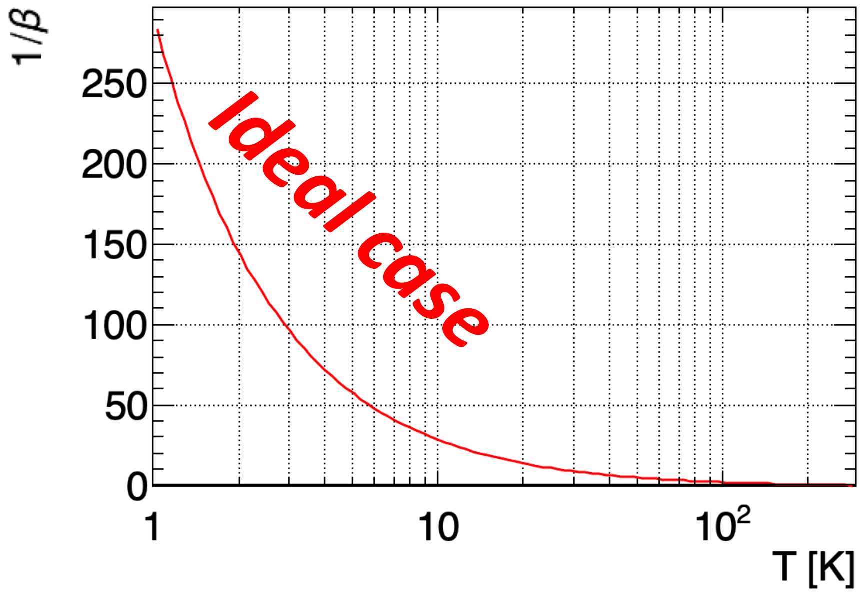
Carnot's theorem

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

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

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

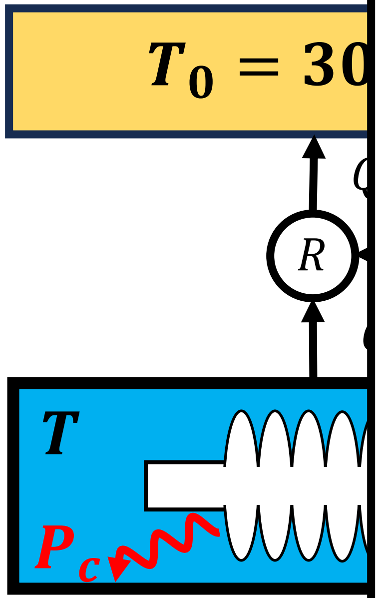
NC cavities

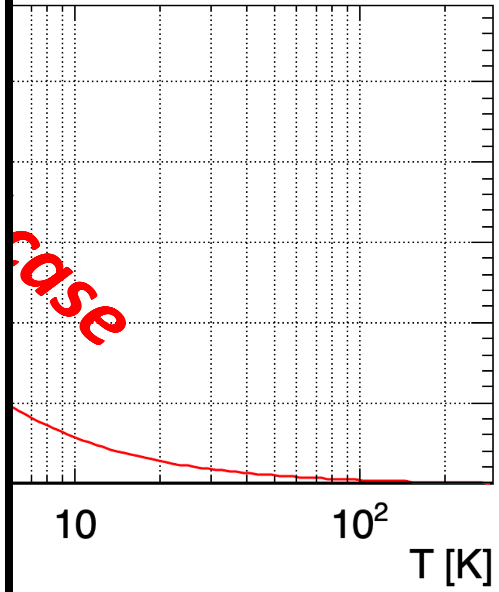
$P_c = 10$ MW (CW)
Duty cycle 10^{-5}
Water cooling

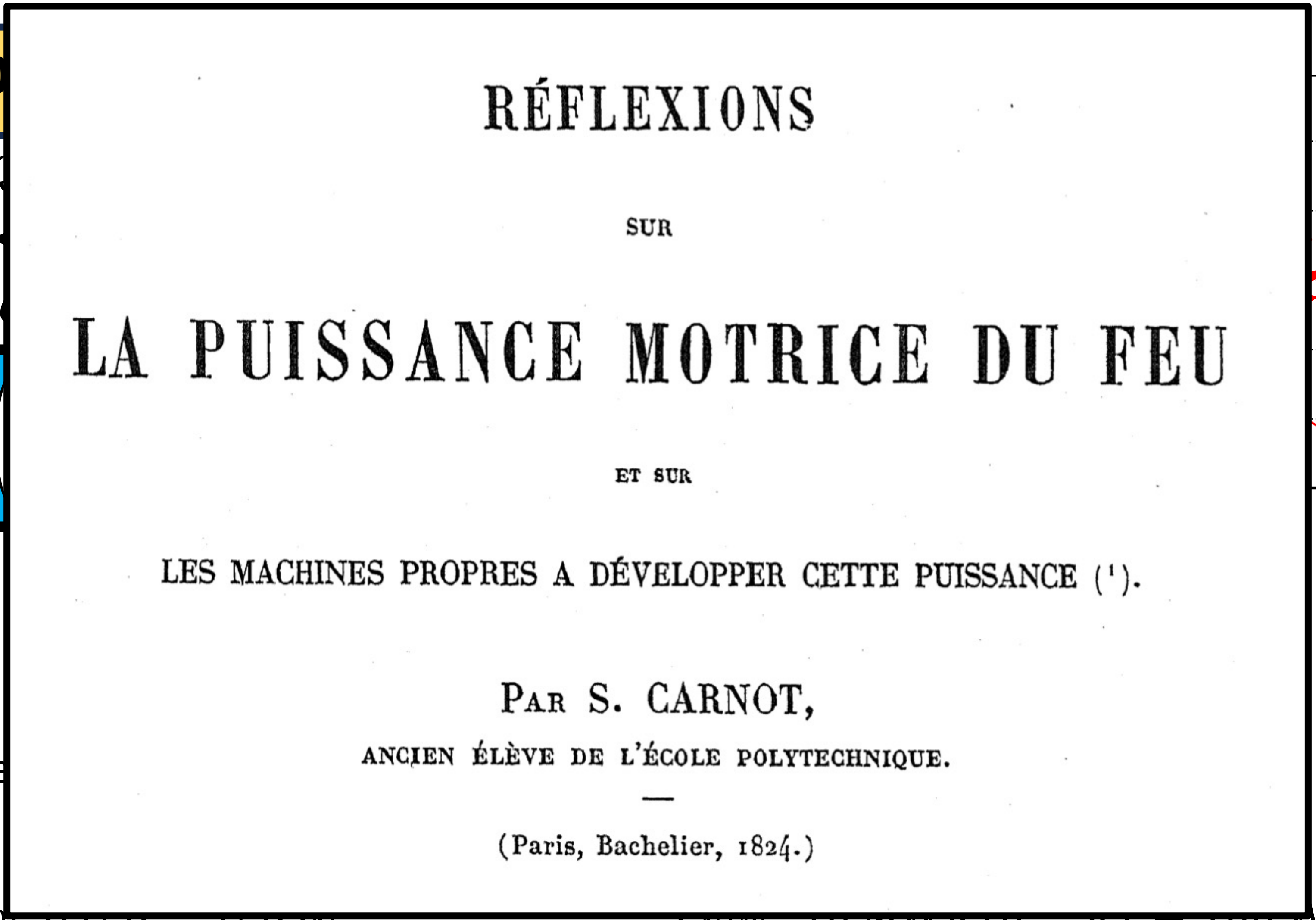
$$P_{NET} \sim 10\ \text{MW} \times 10^{-5} \times 1 = 100\ \text{W}$$

→ 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

$T = 2\,\mathrm{K}$

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

P_{NET} … $= 100\ \mathrm{W}$

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