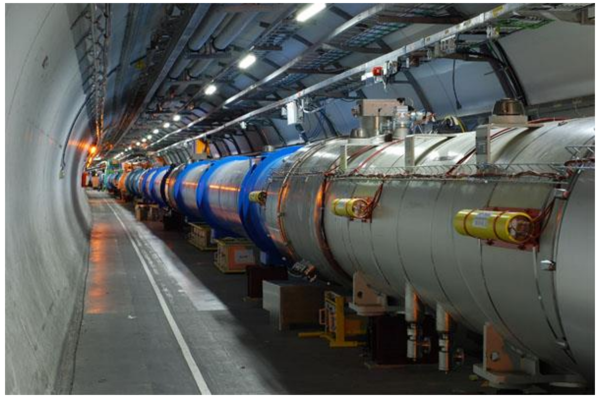
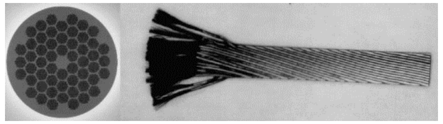
# Superconducting Radiofrequency research and development at TRIUMF and UVic

Tobias Junginger, Aveen Mahon, Daniel Hedji, Lucas Wallace, Noah Gorgichuk, Oliver Kester, Philipp Kolb, Robert Edward Laxdal, Rogério de Sousa, Ryan McFadden, William Stokes, Md Asaduzzman, Edward Thoeng

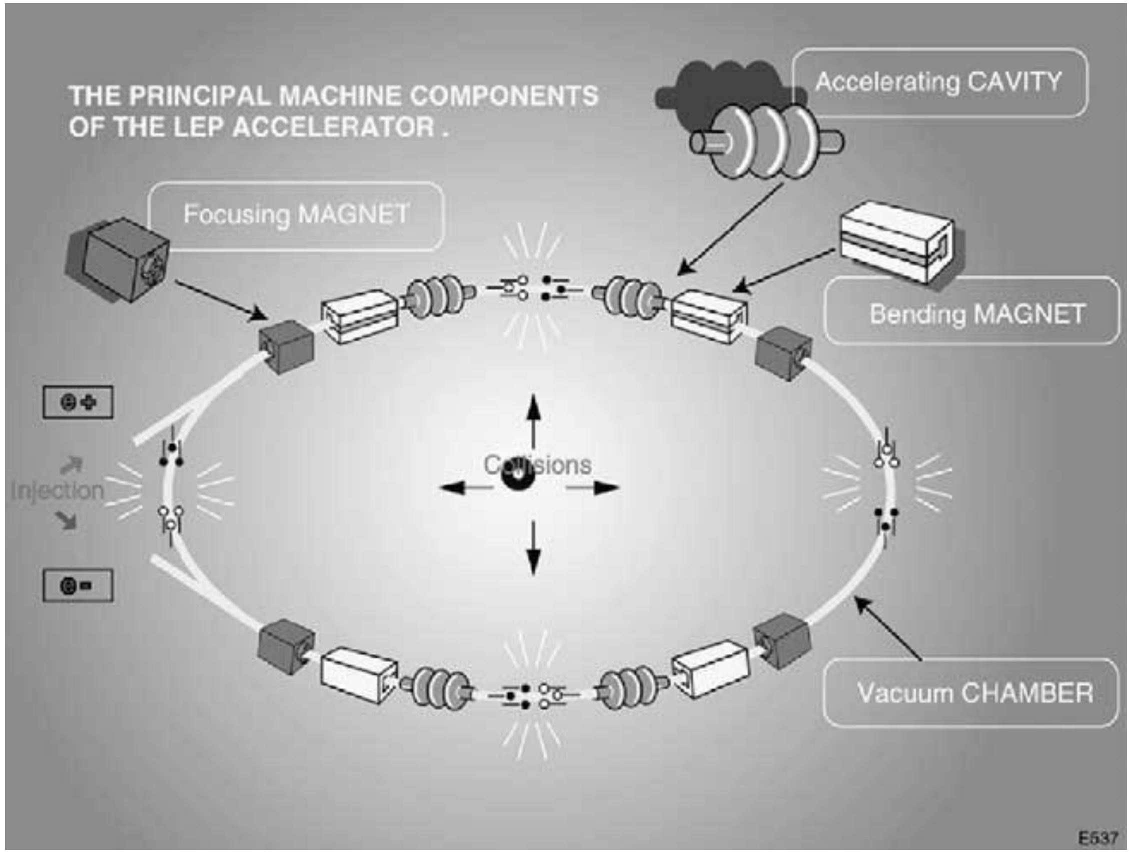
# Superconductivity for accelerators



*Bending Magnets of the LHC*



*Cross section of wire with NbTi filaments in a copper matrix*



*Superconducting Radiofrequency (SRF) cavities of the LHC*

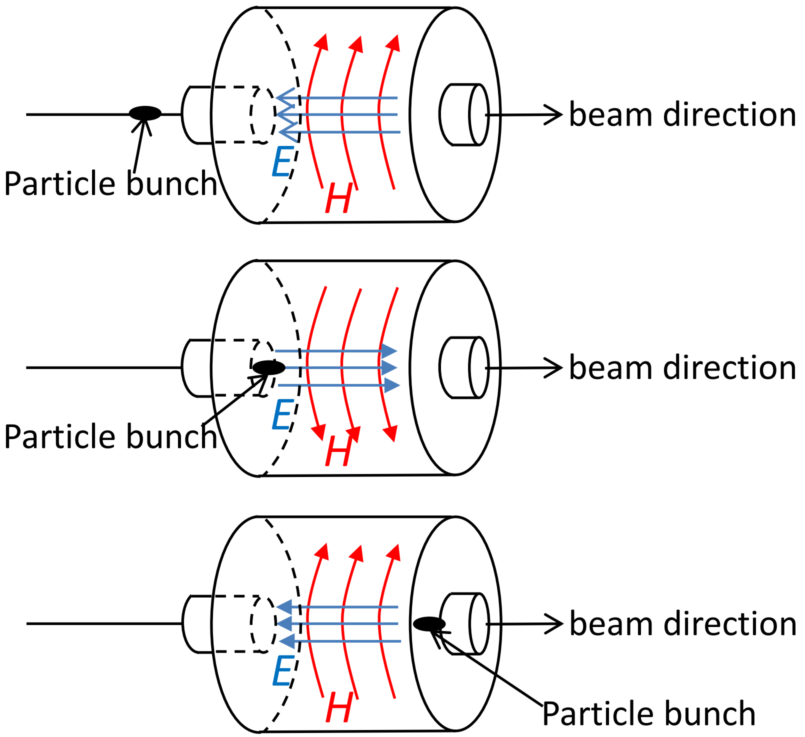
**Particle accelerators use superconductors to steer and increase the energy of charged particles**

# Particle Acceleration with cavities

1. Acceleration with radiofrequency cavities requires synchronization of particles and RF field. Outside of the cavity the approaching particle bunch does not experience the RF field

2. The particle bunch enters the cavity. The electric field is pointing in the direction of the beam axis → The particle is accelerated

3. The particle bunch leaves the cavity. The field direction has changed again



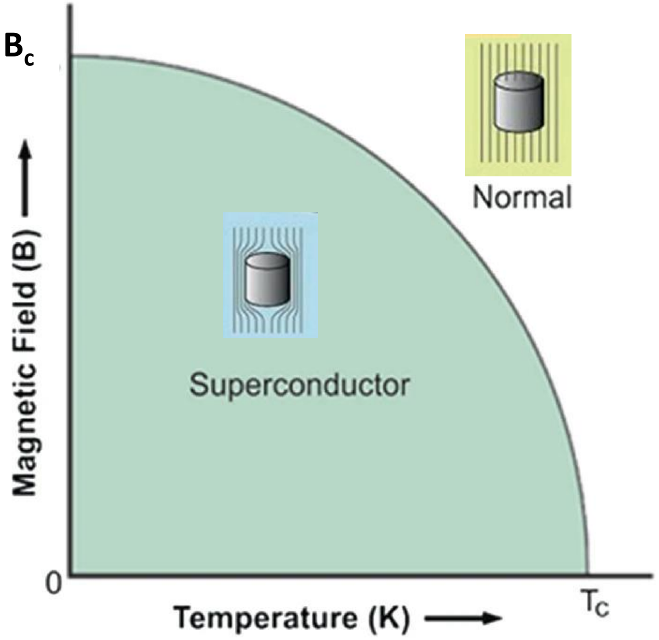
- Cavities are used to accelerate particles by an alternating electric field
- An oscillating electric field causes an oscillating magnetic field
- The cavity confines the electromagnetic fields by surface shielding currents
- These currents create losses (heating), which can be reduced by using superconducting materials

Why is niobium the material choice which requires costly helium cooling?

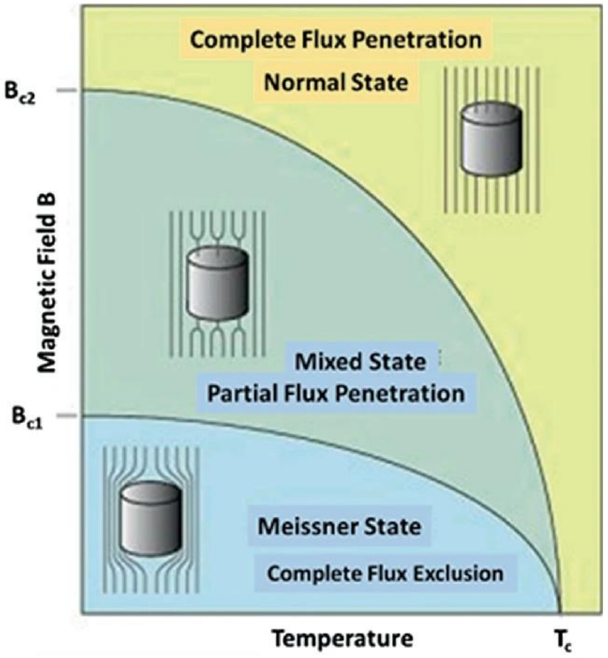
# Two types of superconductors

A type II superconductor can split into normal and superconducting areas to lower its energy

- Magnetic fields partially enters into the normal conducting areas in the form of flux tubes
- Under DC fields flux tubes can be pinned –> no dissipation
  - SC magnets are operated between $B_{c1}$ and $B_{c2}$
- Under RF fields flux tubes oscillate –> strong dissipation
  - RF cavities are operated in the Meissner state
  - For defect free surfaces the Meissner state can persist metastable up the superheating field $H_{sh}$



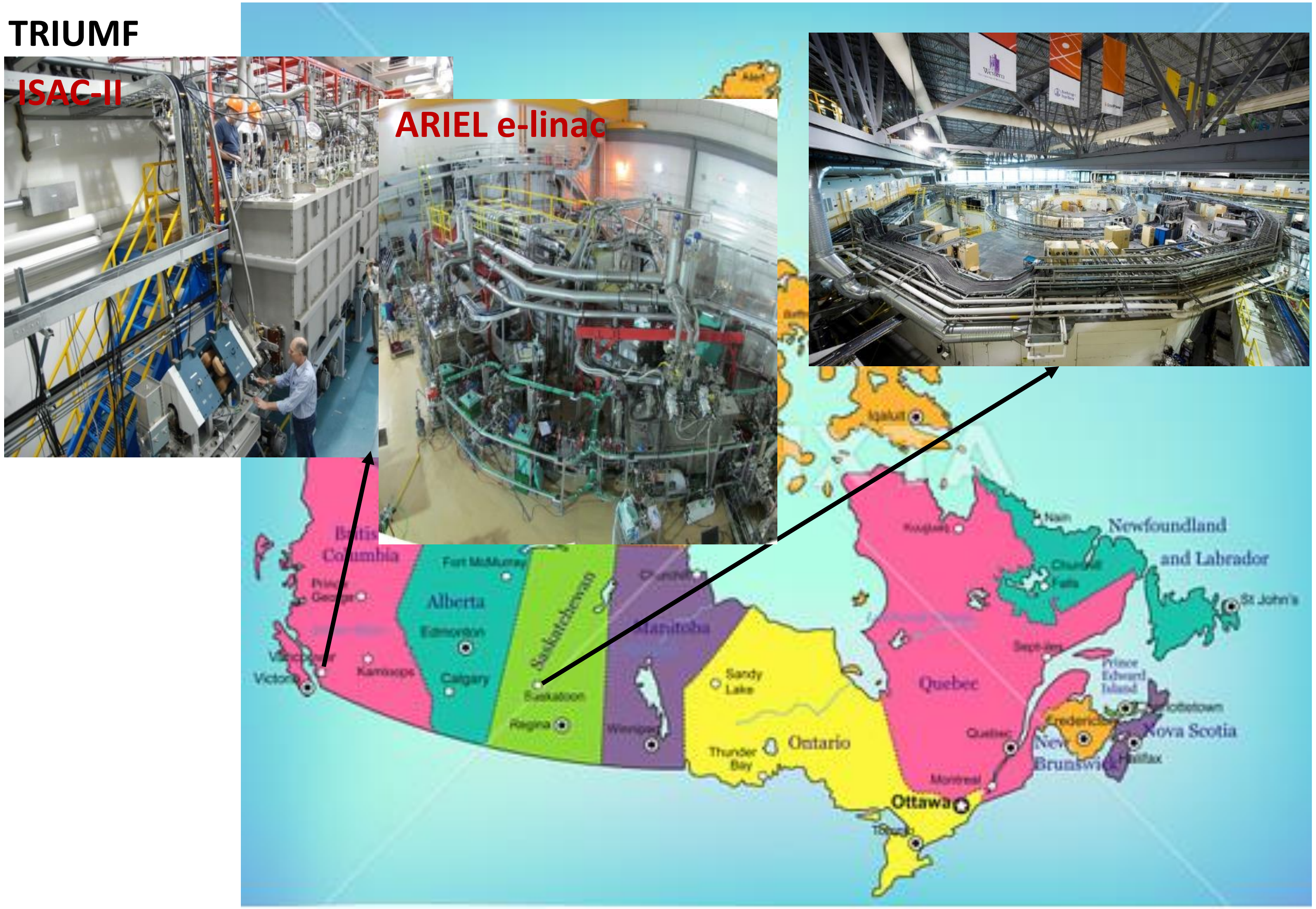
(a) Type I



(b) Type II

| Material | Lead | Nb | NbTi | Nb3Sn |
|---|---|---|---|---|
| $B_c$[T] | 0.07 | 0.2 | 0.2 | 0.52 |
| $B_{c1}$[T] | - | **0.17** | 0.01 | 0.05 |
| $B_{c2}$[T] | - | 0.24 | 11 | 28 |
| $B_{sh}$[T] | 0.08 | **0.24** | 0.16 | **0.44** |

# SRF Accelerators in Canada



**TRIUMF**

ISAC-II

ARIEL e-linac

**Canadian Light Source**

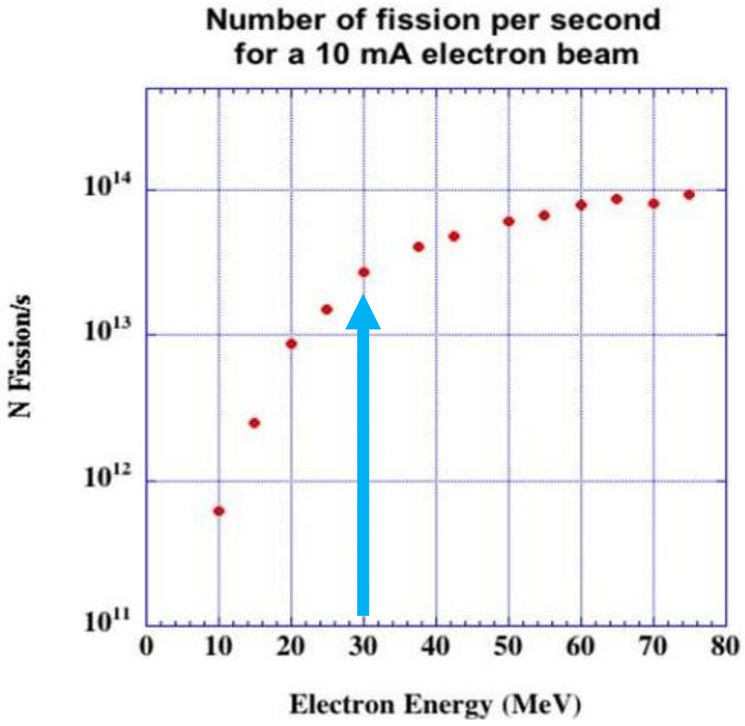
# TRIUMF ARIEL e-LINAC - Reliable 30MeV Operation

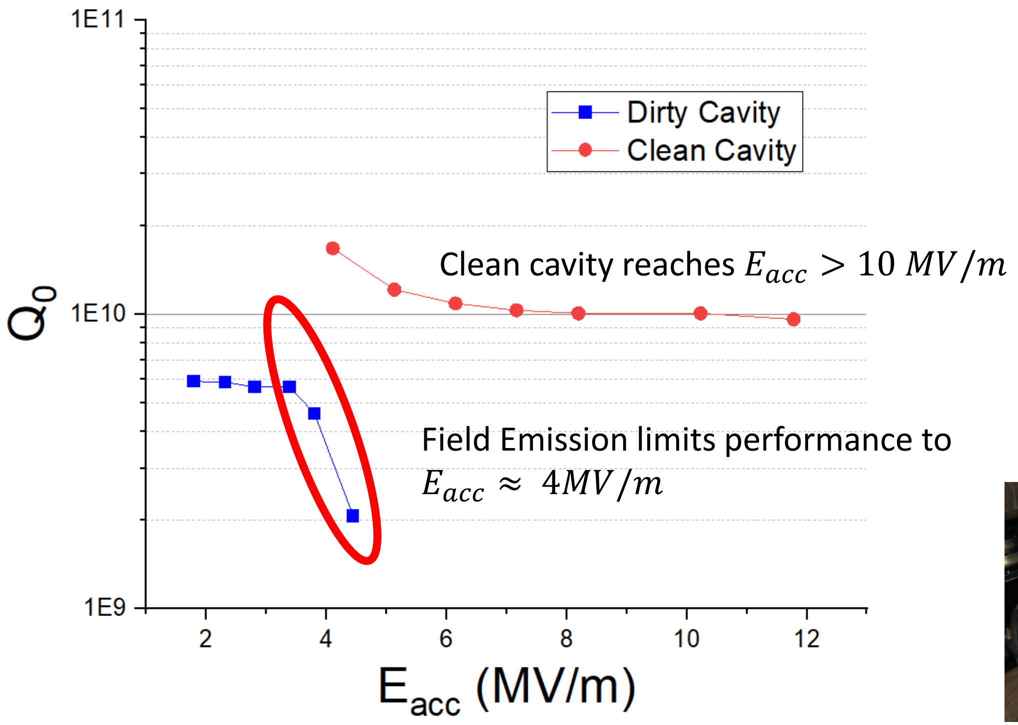
**Stable 30MeV operation is critical for Radioactive Ion Beam (RIB) production:**

- RIB yield is strongly dependent on beam energy
- TRIUMF is operating at 30MeV (3 cavities each delivering 10 MV/m) – at the lower end of the yield curve

**Field emissions from contaminants in the SRF cavity limit RF performance to lower $E_{acc}$**

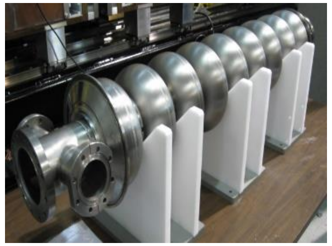
- Prevention and mitigation critical to keeping performance high, to keep RIB yield high





Clean cavity reaches $E_{acc} > 10\ MV/m$

Field Emission limits performance to $E_{acc} \approx\ 4MV/m$

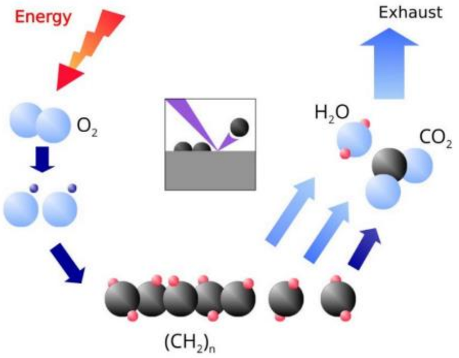


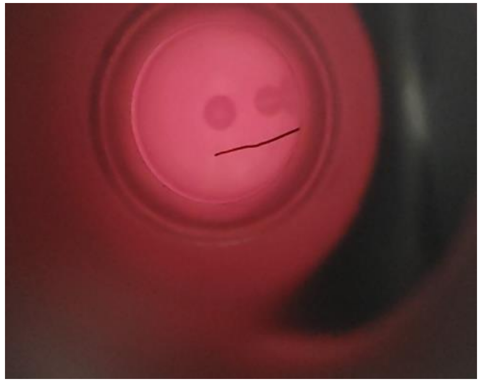
# TRIUMF ARIEL e-LINAC - Reliable 30MeV Operation

MSc. D. Hedji
P.I. R.E. Laxdal

**Plasma cleaning**

- Current cleaning procedures are done *ex-situ* (2-3 months).
- Plasma cleaning allows for an *in-situ* cleaning, which reduces cleaning time to ~1 week. MSc project D. Hedji





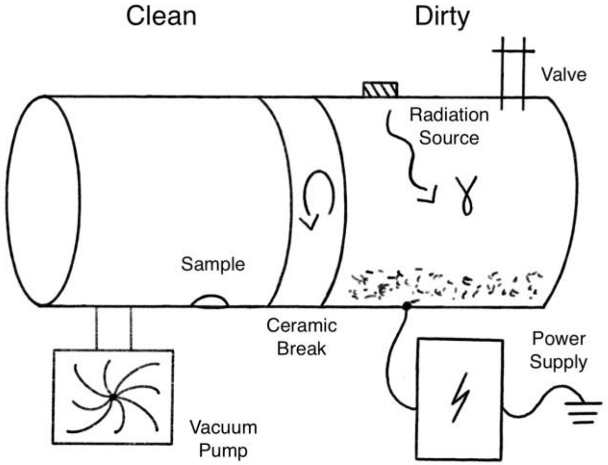
**What if we could avoid contamination in the first place?**

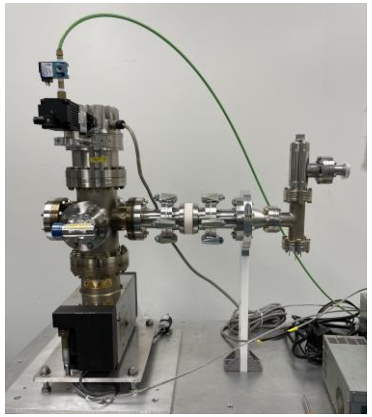
Emitters are µm to sub µm sized contaminants → dust

Previous studies indicate that dust migrates and is charged:

> A potential barrier could therefore suppress dust migration and tackle field emission problem at its source.

PhD A. Mahon
PI T. Planche

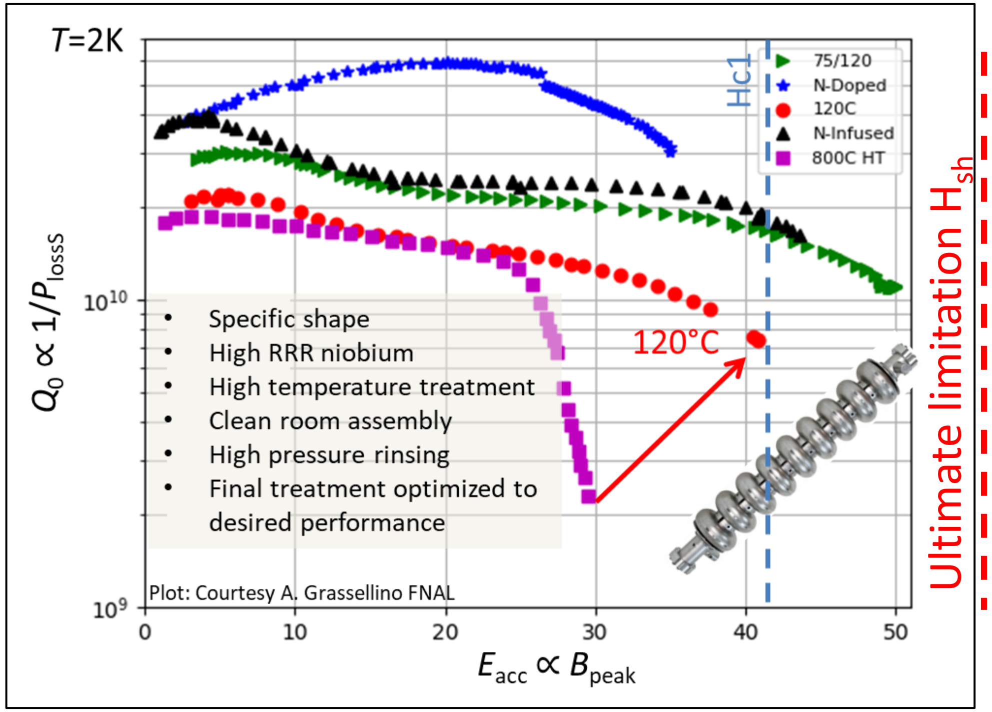




# SRF materials research

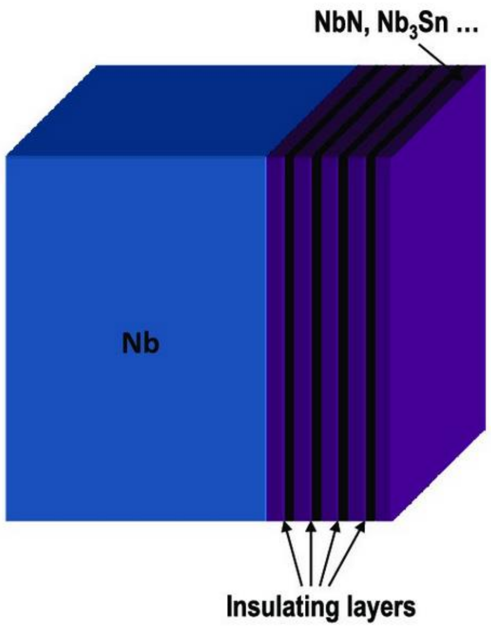
Current material of choice niobium is reaching fundamental limitations

- Subtle changes in heat treatments have significant influence
- Surface treatments have only been optimized for electron accelerators (elliptical cavities)
  - TRIUMF has dedicated program to optimize co-axial cavities for heavy ion accelerators
- **Accelerating gradients beyond 50 MV/m require new materials potentially as multilayers**

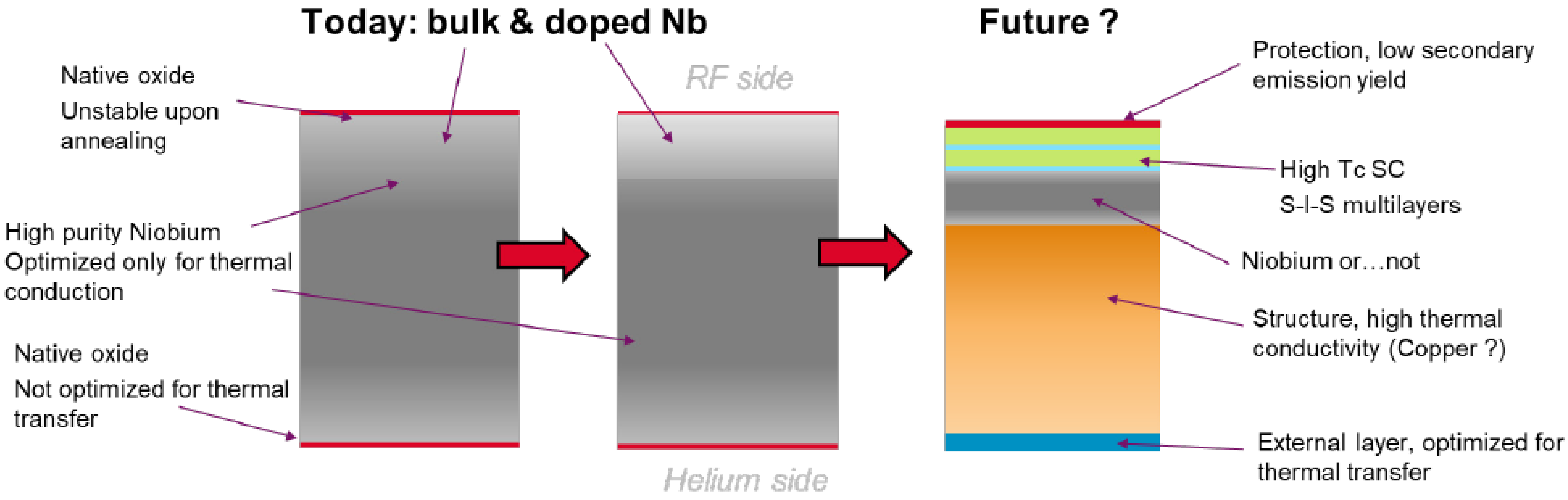


*State of the art niobium cavity performance*

*Co-axial test cavities*

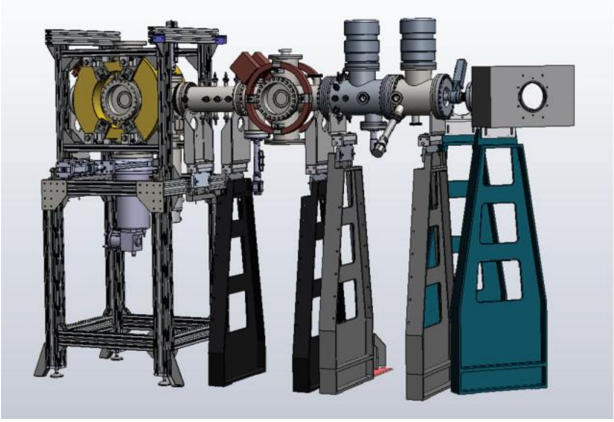


# SRF Material of the future

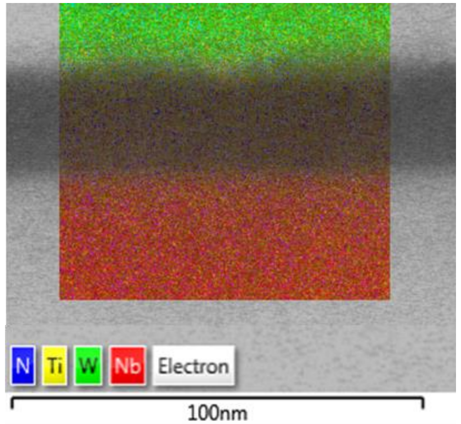


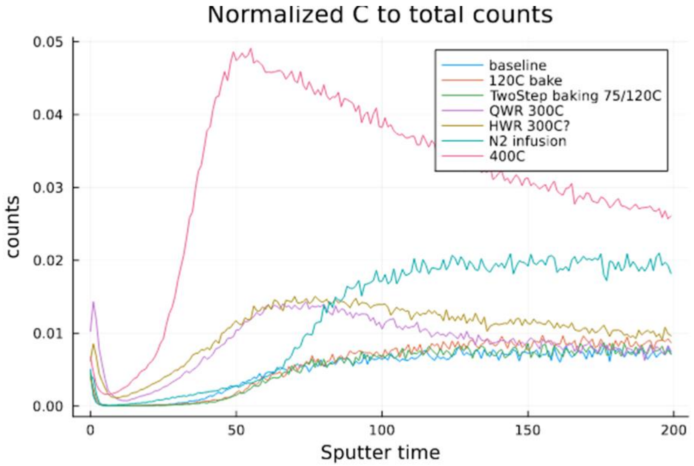
# SRF Material Science

- SRF material science is about engineering the outermost ~100nm of the material by coating or diffusion
- Our research focuses on detecting flux penetration with nanometer resolution and its correlation to material properties



*β-NMR (TRIUMF) enables flux penetration measurements with nanometer depth resolution*



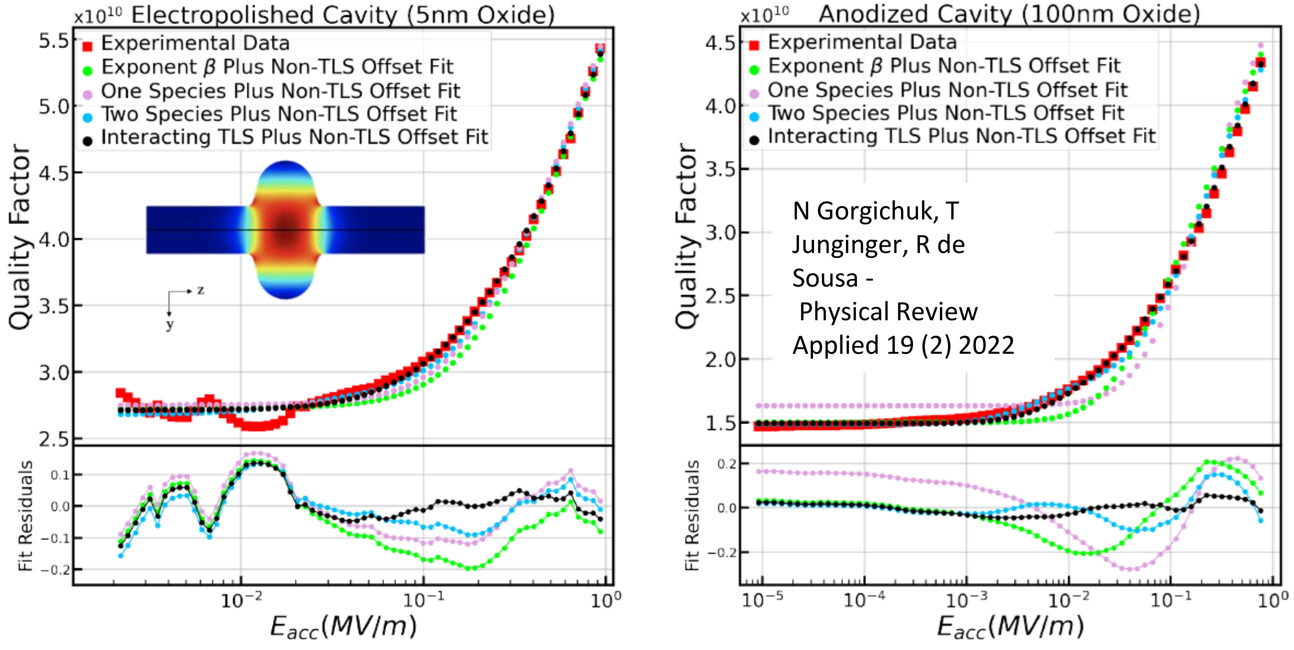


*Transmission electron microscopy (UVic) and secondary ion mass spectroscopy (Surface Science Western) reveal surface structure and elemental composition*

R. Laxdal, R. McFadden, E. Thoeng, Md Assaduzzaman, W. Stokes, L. Wallace

# SRF for Quantum Computing

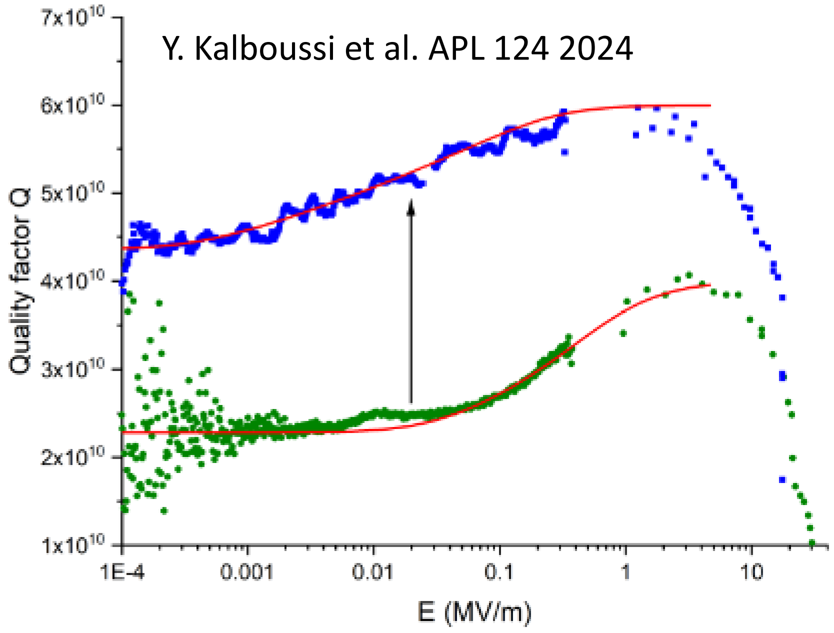
- Main mechanism for quantum decoherence in current quantum hardware are defect two level systems (TLS) in oxides
- SRF cavities can increase coherence times and be used as a testbed for theoretical models
- Re-analysis of literature data provides evidence that the TLSs present in niobium oxide are “atomic-like” (instead of “glass-like”) . Undergrad Project N Gorgichuk
- Replacing the oxide with another material can increase coherence times (recent results from CEA Saclay)



N Gorgichuk, T Junginger, R de Sousa - Physical Review Applied 19 (2) 2022

(a)

(b)



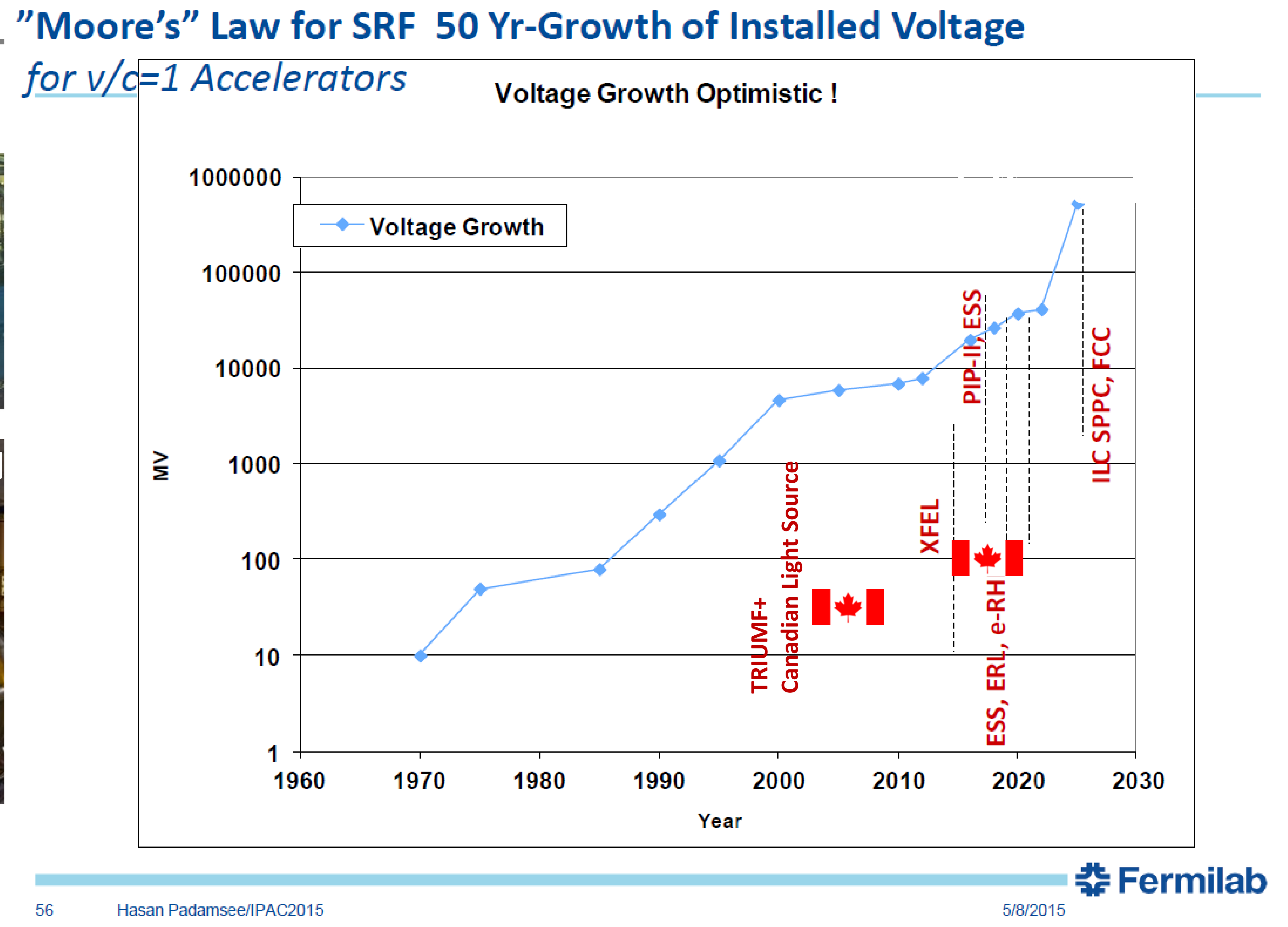
Y. Kalboussi et al. APL 124 2024

# Summary

- SRF cavities unlike DC magnets need to be operated in a flux free Meissner state
  - Current material of choice for SRF cavities is niobium (largest $H_{C1}$)
    - Performance close to fundamental limits in elliptical cavities
  - Meissner state can potentially be maintained above $H_{c1}$ using heterostructure coatings
- SRF technology is interesting for quantum applications

# Backup slides

# Examples of SRF accelerators

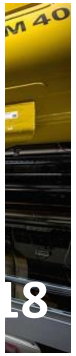


## ”Moore’s” Law for SRF  50 Yr-Growth of Installed Voltage
*for v/c=1 Accelerators*

Voltage Growth Optimistic !

56 Hasan Padamsee/IPAC2015 5/8/2015

Fermilab



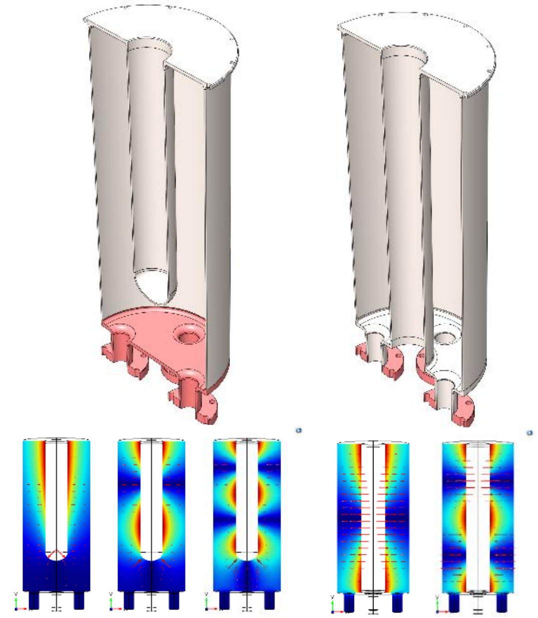
# Coaxial Research Cavities at TRIUMF

- Most SRF research done on high frequency, high beta, elliptical cavities.
- Ion accelerators need low frequency, low beta coaxial cavities.
- TRIUMF has dedicated coaxial cavities for fundamental SRF research

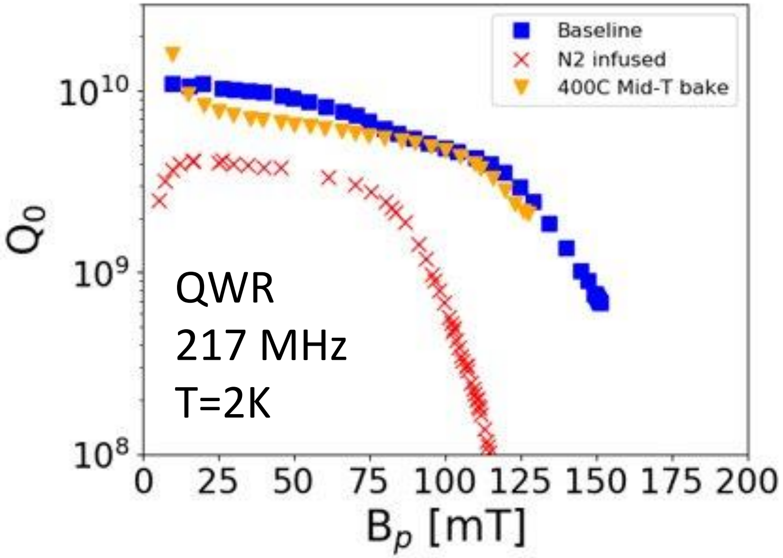
PI R. Laxdal, P. Kolb, MSc R. Gregory, MSc. McMullen

*QWR: Quarter Wave Resonator*
*HWR: Half Wave Resonator*

P. Kolb et al.
Phys. Rev. Accel. Beams 23, 122001



*Multiple modes (=multiple frequencies)*



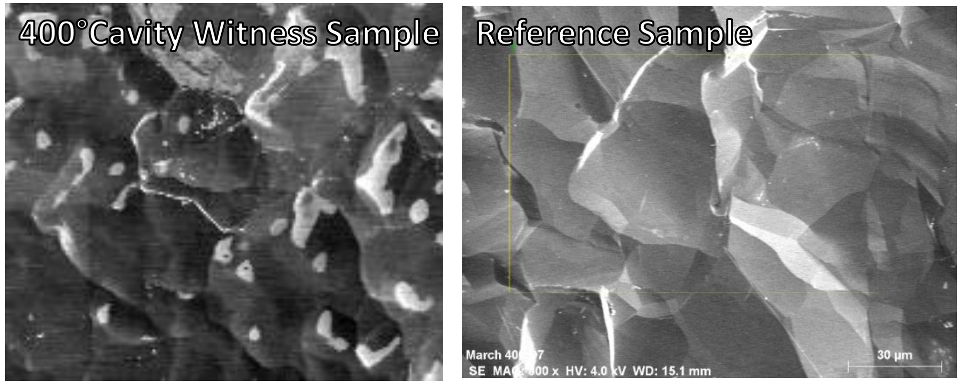
*New baking procedures tried for the first time on coaxial cavities*

*Encouraging results but below expectation (P. Kolb et al. SRF2021)*

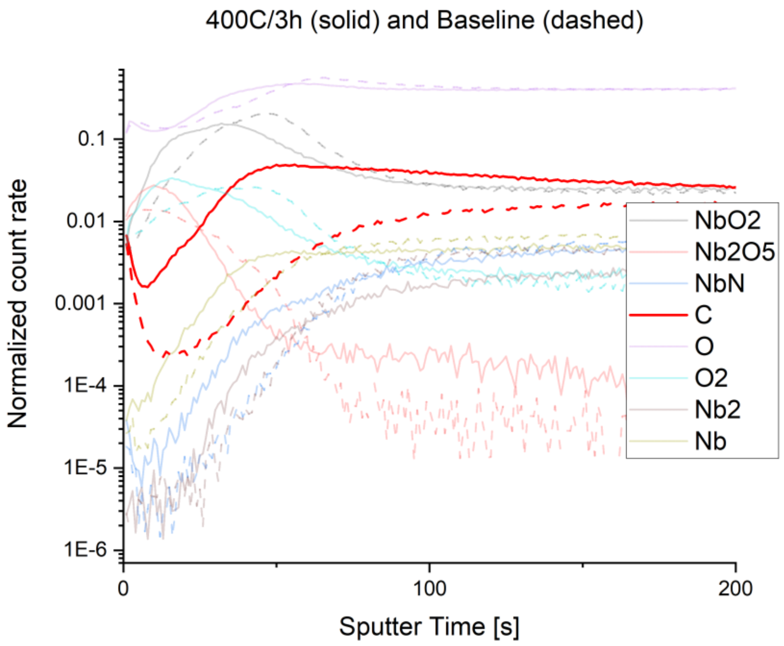
# Coaxial Research Cavities at TRIUMF

**Several new baking procedures tried for the first time on coaxial cavities**

- Unlike for traditional procedures there is no material removal (chemistry) after baking. Very clean environments required.
- Material analysis with SEM/EDX shows signs of carbon contamination. (Honors thesis project D. Hedji)
- TOF-SIMS depth profile shows that carbon contamination is most pronounced in relevant near surface region



SEM image before and after furnace cleaning

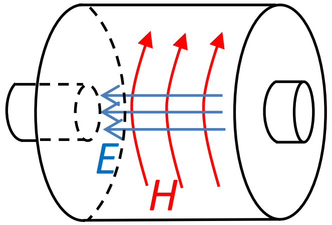


SEM: scanning electron microscopy, EDX: energy dispersive X-Ray spectroscopy, TOF-SIMS: Time-of-Flight Secondary ion mass spectroscopy

# When to use Superconducting Cavities

Dissipated power: $P_{\text{diss}} = \frac{1}{2} R_S \int |H|^2 \, dS$ $\quad H \propto E_{acc}$

Carnot Efficiency of refrigeration cycle: $\eta = \frac{T_{cavity}}{RT - T_{Cavity}} = \frac{4.2\text{K}}{300\text{K} - 4.2\text{K}} = 0.014$



Example: Isac-II CW 141 MHz cavity operated in CW $E_{\text{acc}}$=5 MV/m

| | **Super Conducting** | **Normal Conducting** |
|---|---|---|
| $R_S$ | ~100nΩ | 3mΩ |
| $P_{\text{diss}}$ | 7 W | 200kW |
| Grid Power | ≈1kW | ≈400kW |

⇩

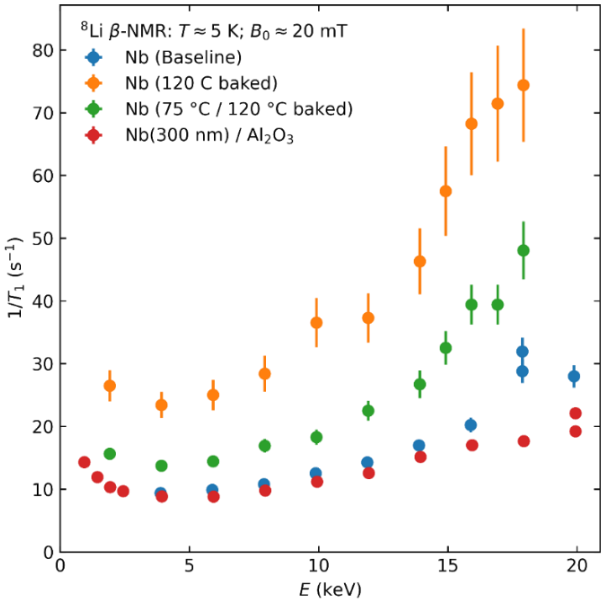
Strongest incentive to use SC cavities is for accelerators operated in CW or at high duty factors

In case of SRF systems grid power goes mainly to the cryoplant and the beam, for normal conducting machines mainly in the RF power source

# β-NMR + SRF @ TRIUMF

- Low energy muon spin rotation is limited to parallel field to about 25mT
- SRF cavities operate at 100-200mT
  - Steering in higher field difficult due to low muon mass
  - Higher mass of 8Li favors betaNMR with 8Li for SRF studies

R. Laxdal, R. McFadden, PhD E. Thoeng (UBC), PhD Md Assaduzzaman

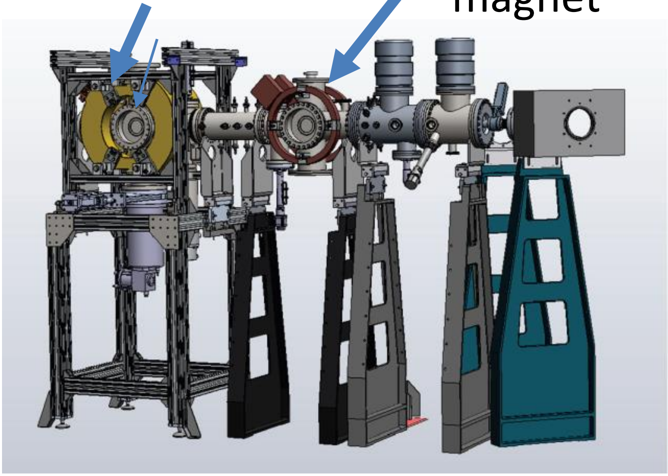


*Method is sensitive to changes by surface treatments*

*(E. Thoeng et al SRF2021)*

New high field magnet

Low field magnet

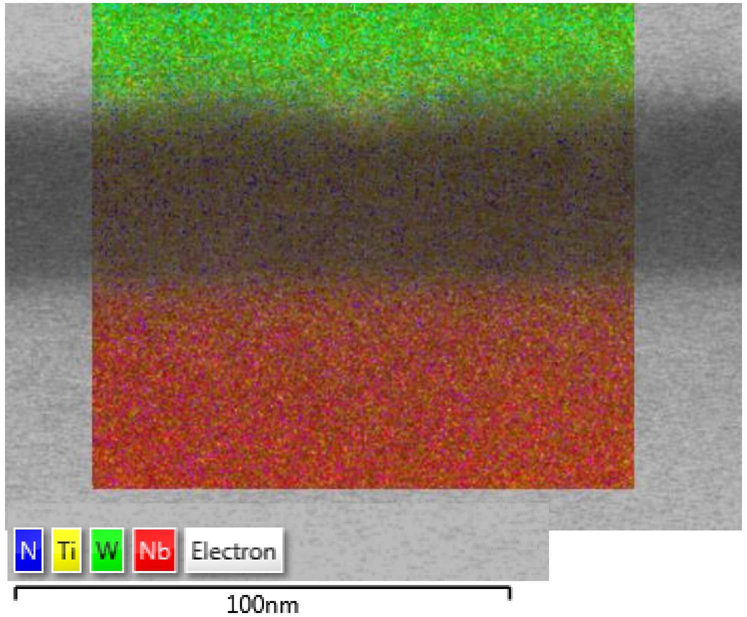


*High parallel field spectrometer. Successfully commissioned in summer 2021*

*Next studies will be on multilayer samples prepared by atomic layer deposition at CEA Saclay*

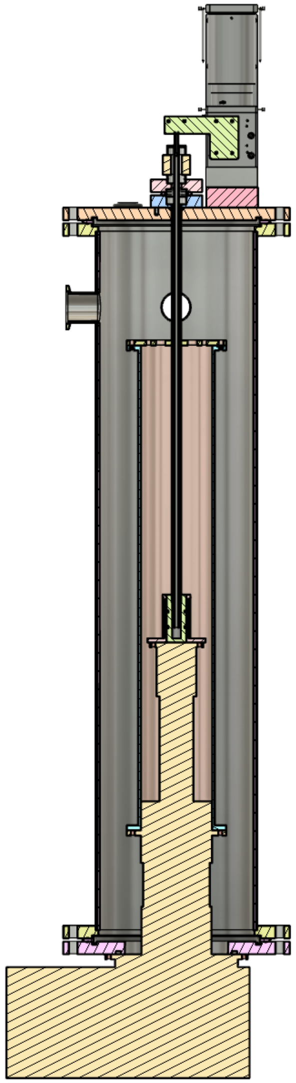
# Measurement of the vortex penetration field

- β-NMR studies will be coupled with measurements of superconducting bulk and material properties at UVic
- Vibrating sample magnetometry can be used to measure the substrate (niobium) vortex penetration field
  - Instruments are commercially available but the SRF parameter range (relatively low field at low temperature) favor a dedicated design which can be realized at a fraction of the cost
  - Status: Design finalized, construction started (MSc Lucas Wallace)

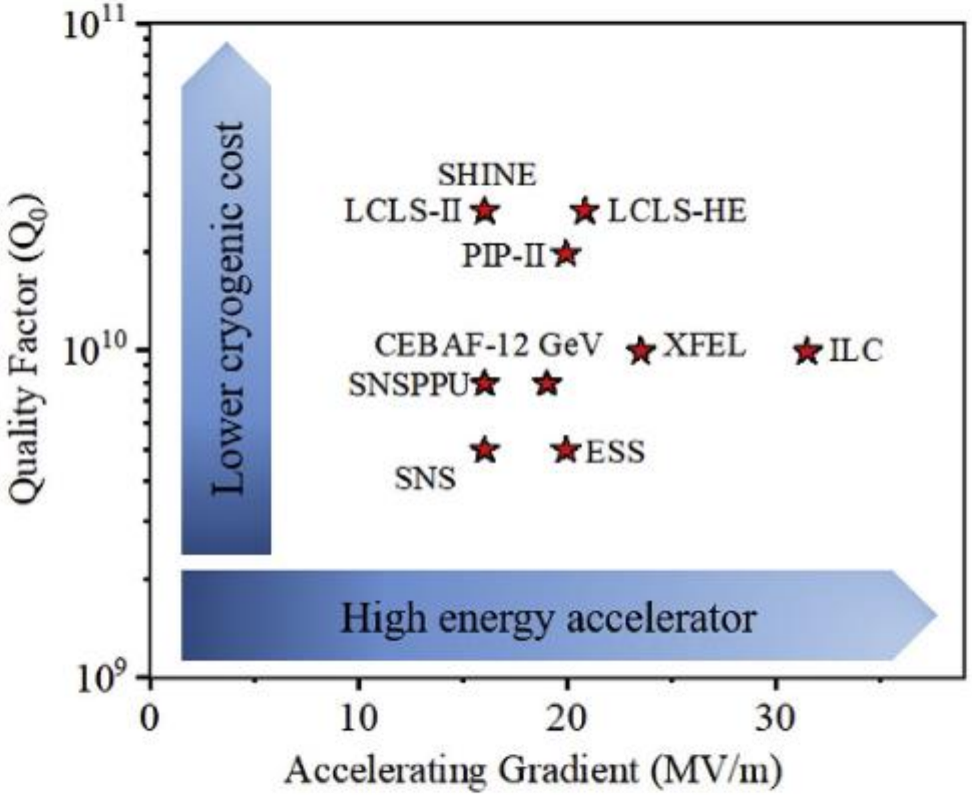


*TEM/EDX map of a NbTiN on Nb sample*

BSc Will Stokes



# Backup slide



Rongli Geng, SRF2023 Tutorial
6/22-24, 2023, MSU, East Lansing, MI

# UVic/TRIUMF Accelerator Research

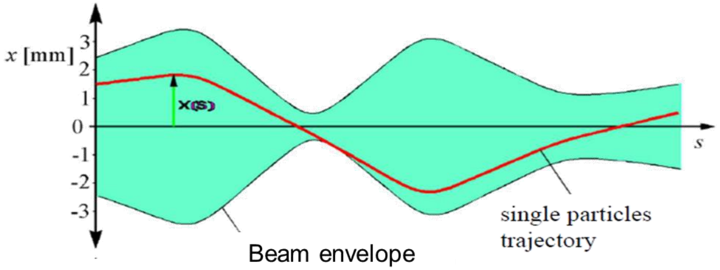
**Graduate Program**

- Currently 14 UVic graduate students in accelerator physics based at TRIUMF (11), UVic (2), D-Pace (1)
- Seven adjunct professors, six at TRIUMF, one at D-Pace

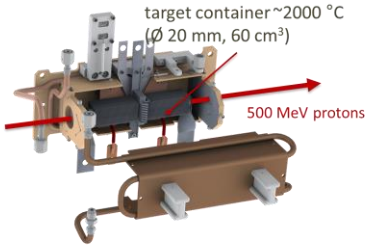
**Education**

- One graduate lecture course taught by adjunct faculty at TRIUMF each year and broadcasted nationwide
- Undergraduate lecture course, graduate + undergraduate projects offered at UVic

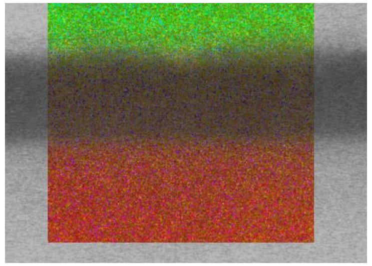
- There are no particle accelerators at UVic
- Accelerator Research does not necessary require accelerators on site. At UVic we focus on
  - Cryocooler based fundamental SRF studies
  - Surface and Materiel Science Studies at the Electron Microscopy Facility (A. Blackburn)
  - Application of SRF technology to quantum computing (R. de Sousa)
  - Beam Dynamics studies for polarized beams in SuperKEKB (M. Roney)



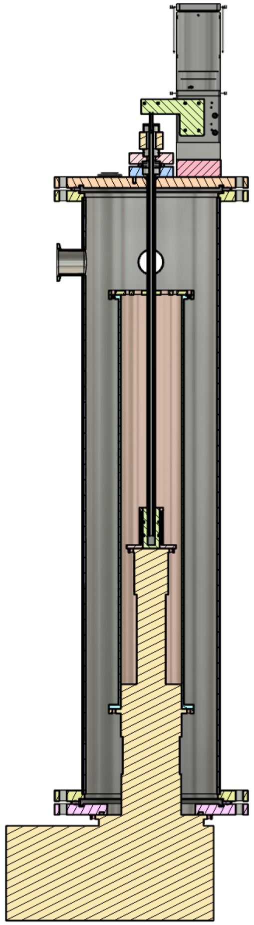
*Beam Simulations*



*Accelerator Systems Development*

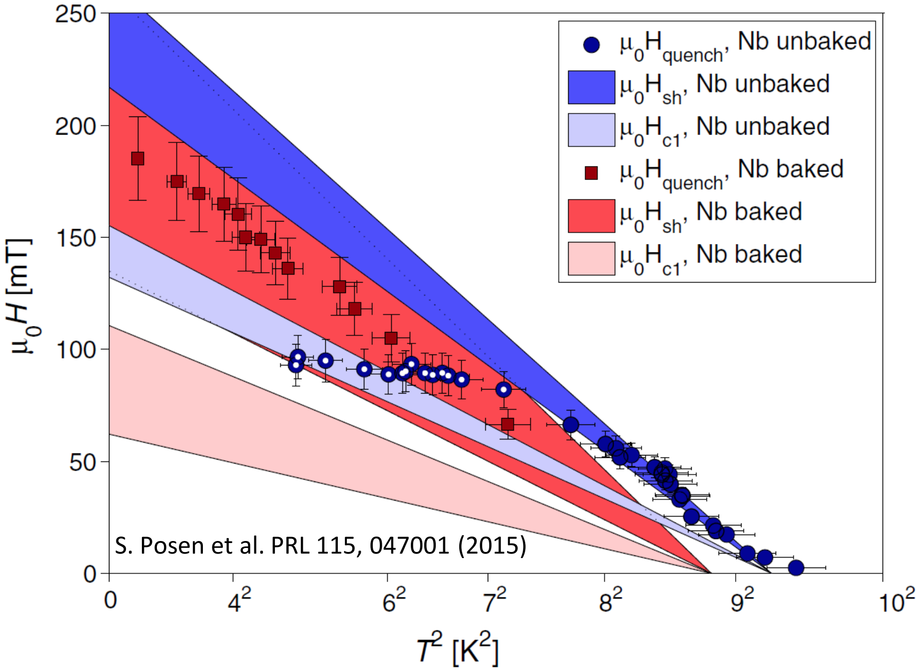


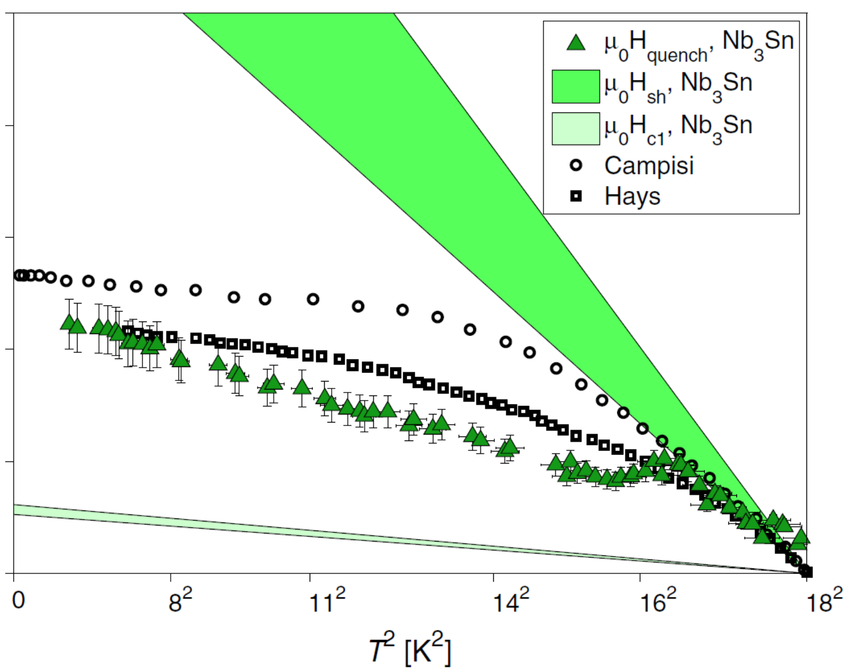
*Material Science*



*Fundamental SRF studies with purpose built instruments*

# The superheating field





Niobium:

- Close to $T_c$ $H_{entry}=H_{sh}$
- $T<<T_c$ usually $H_{entry}<H_{sh}$

$Nb_3Sn$:

- Close to $T_c$ $H_{entry}=H_{sh}$
- $T<<T_c$ $H_{entry}<<H_{sh}$

- RF heating proportional to $H^2$. Close to $T_c$ less power is dissipated. Flux entry less likely.
- Coherence length of $Nb_3Sn$ smaller than Nb. Flux entry at defects more likely.
- **The good news is $H_{c1}$ is not a general limitation!**