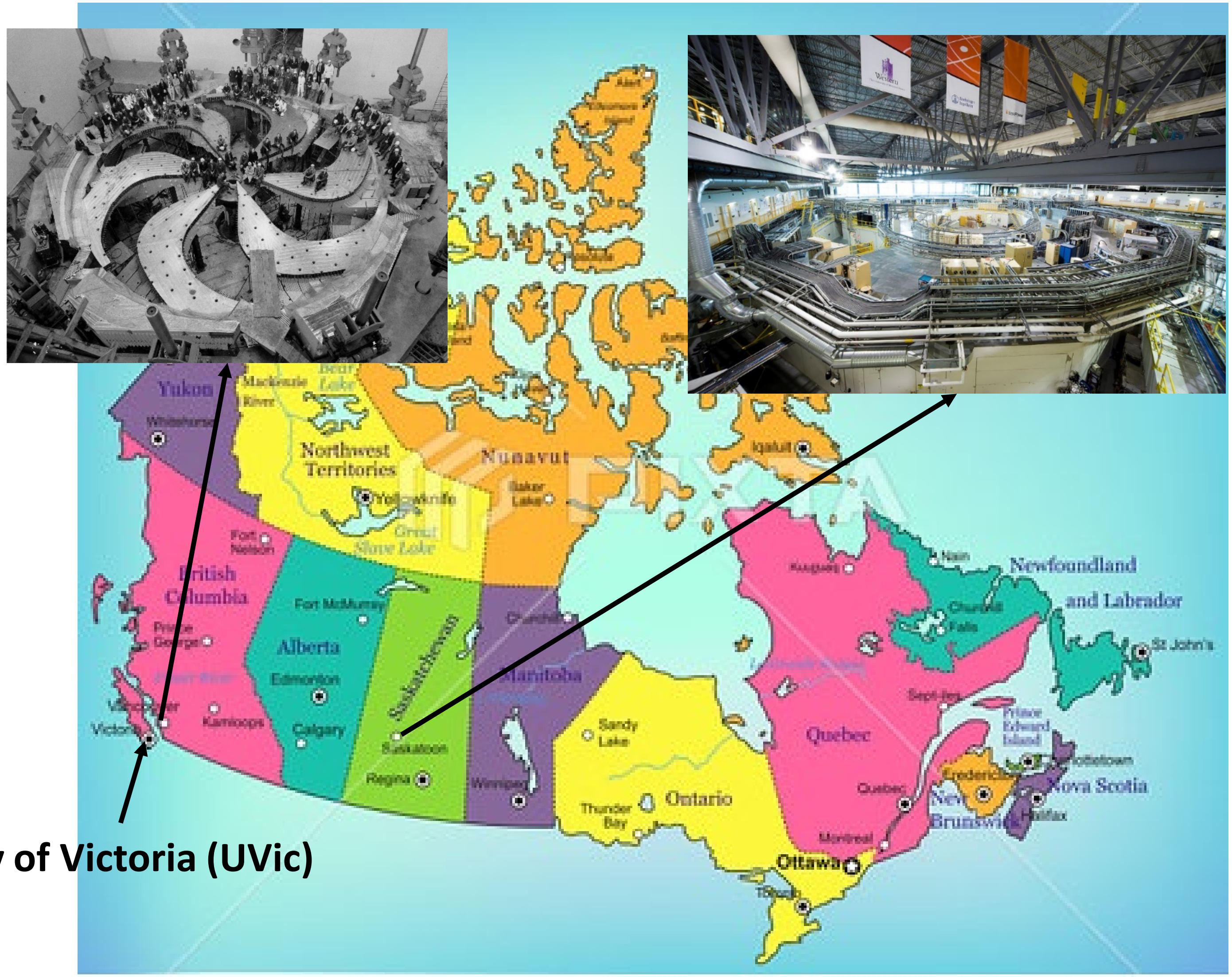
Particle Accelerator R&D at TRIUMF and the University of Victoria

Tobias Junginger

Accelerators in Canada

TRIUMF



Canadian Light Source

University of Victoria (UVic)

UVic/TRIUMF Accelerator Research

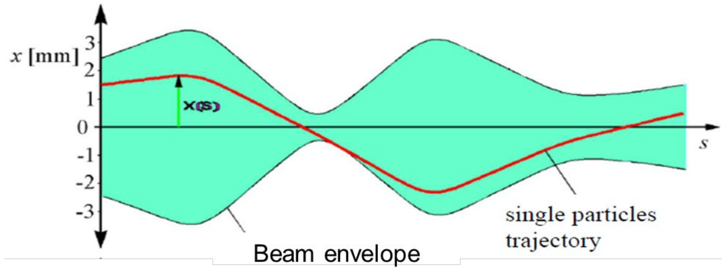
- UVic is the lead University of the ARIEL project
- Currently 14 UVic graduate students in accelerator physics at TRIUMF
- One graduate lecture course taught by the adjunct faculty each year at TRIUMF and broadcasted nationwide
- Undergraduate lecture course, graduate + undergraduate projects offered at UVic

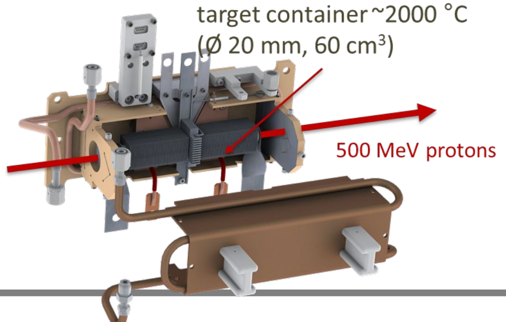
RESEARCH FOCUS at TRIUMF

- **Beam physics and instrumentation** (R. Baartman, O. Kester, T. Planche)
- **Superconducting RF** (R. Laxdal)
- **Ion Sources and Targets for secondary particle production** (A. Gottberg, O. Kester)

Projects at UVic

- 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 SuperKEKB (M. Roney)



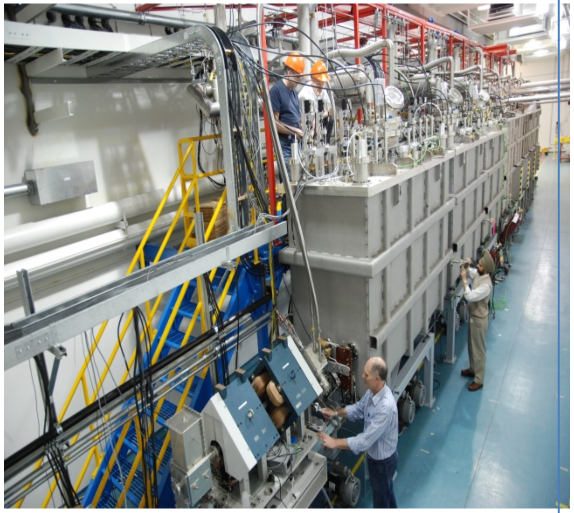


Content

- Nuclear Physics Accelerator Projects at TRIUMF
  - ISAC facility
    - Increase experiment time – Model based beam tuning
    - Reaching higher charge states – Two frequency heating of charge state booster
    - ISAC-II energy upgrade
    - ISAC Storage Ring
  - ARIEL e-linac
    - Status and future applications
- Fundamental SRF research
  - Coaxial cavity research
  - High accelerating gradient research for linacs like ILC – BetaNMR studies
- International Particle Physics Accelerator Projects
  - Cryomodule development for international projects
  - Polarized Beams for SUPERKEK-B
- Non subatomic physics accelerator projects with UVic and TRIUMF involvement

SRF Accelerators at TRIUMF

40MV ISAC-II SRF heavy ion linac @ 106MHz - operational since 2006

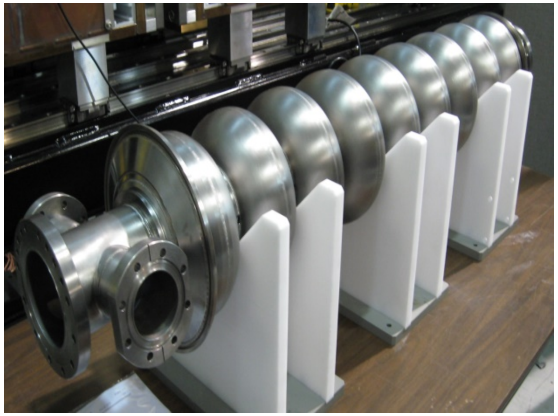


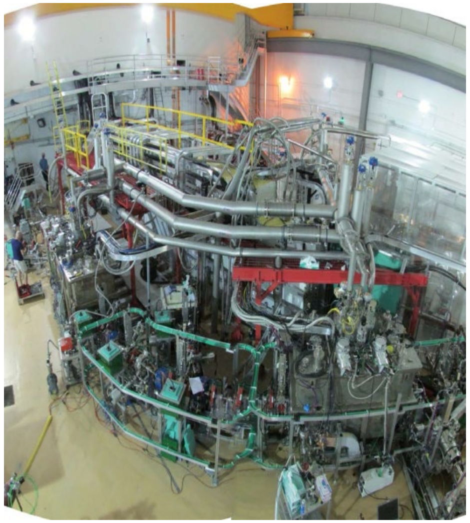
Bare cavities

Cryomodules

Accelerators

30MV ARIEL SRF 10mA electron linac @ 1.3GHz – first beam 2014





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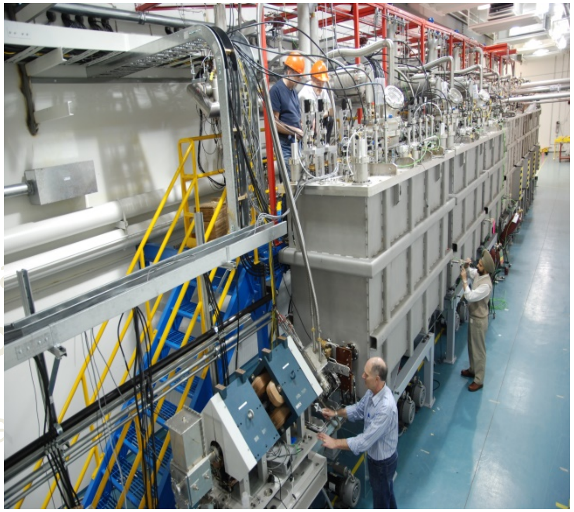
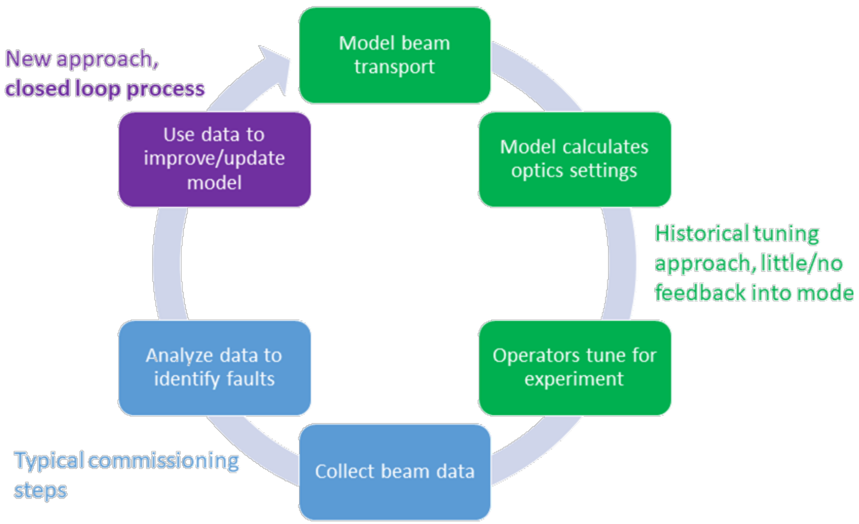


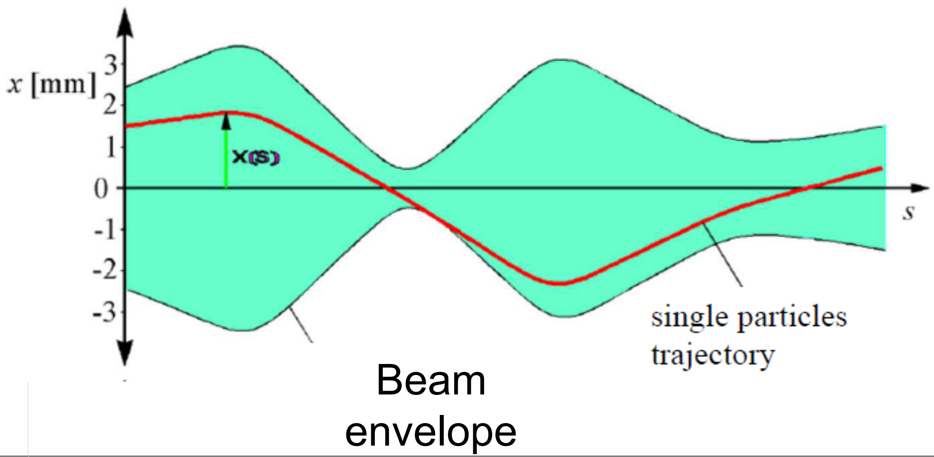
- Non subatomic physics accelerator projects with UVic and TRIUMF involvement

ISAC- Model based beam tuning

- Using beam physics models (usually used for design of accelerators) during beam operation
- Models rely on a code developed at TRIUMF (Rick Baartman) that describes the beam envelope throughout the entire accelerator instead of individuals particles
- Enables improved automation of various tuning processes



Ph.D. Olivier Shelbaya
M.Sc. Spencer Kiy



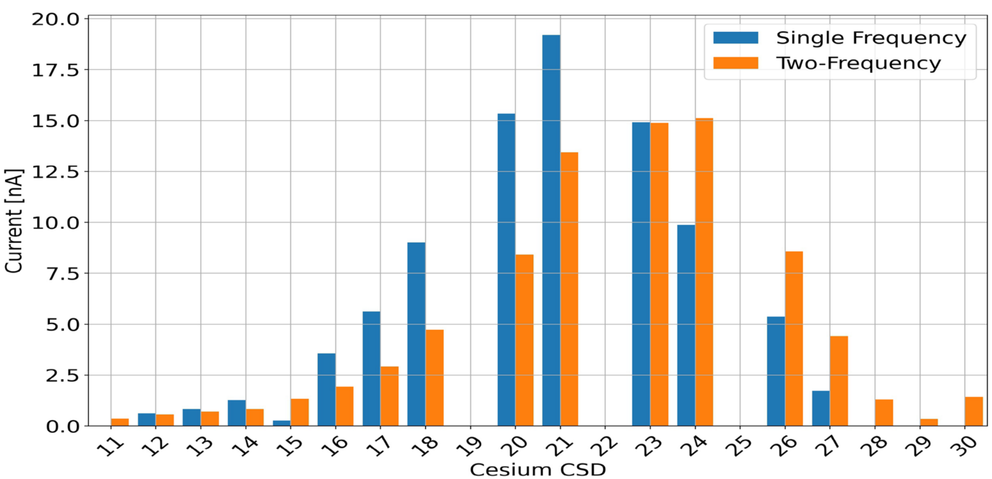
ISAC - Optimization of the Charge State Booster (CSB)

Fundamental problem: Beam properties provided by the particle source cannot be improved in the accelerator.

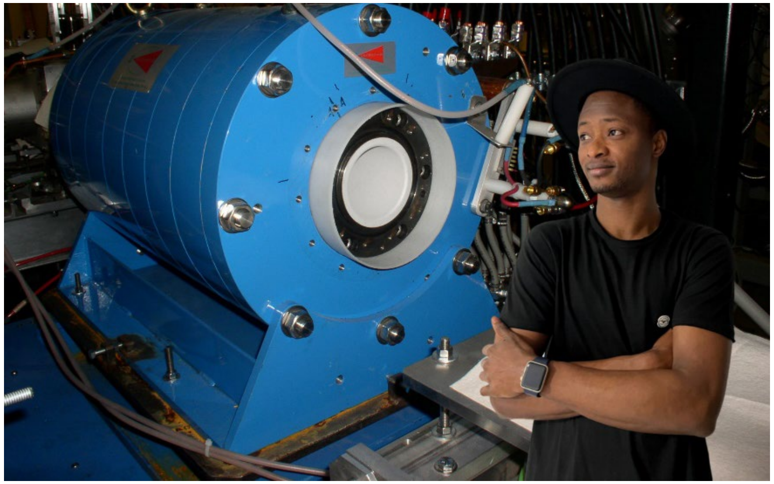
Research Goal: Improve beam quality, intensity and charge state of post-accelerated beams in the ISAC charge state booster

- Systematic investigation and optimization of the charge state booster extraction system
- Implement two-frequency heating of the ECRIS CSB

PhD student Joseph Adegun received the student poster price at the 2021 International Conference on ion sources (ICIS) for this work



Two frequency heating enables higher charge states



Joseph Adegun in front of the CSB

ISAC - Storage ring for neutron captures on radioactive nuclei

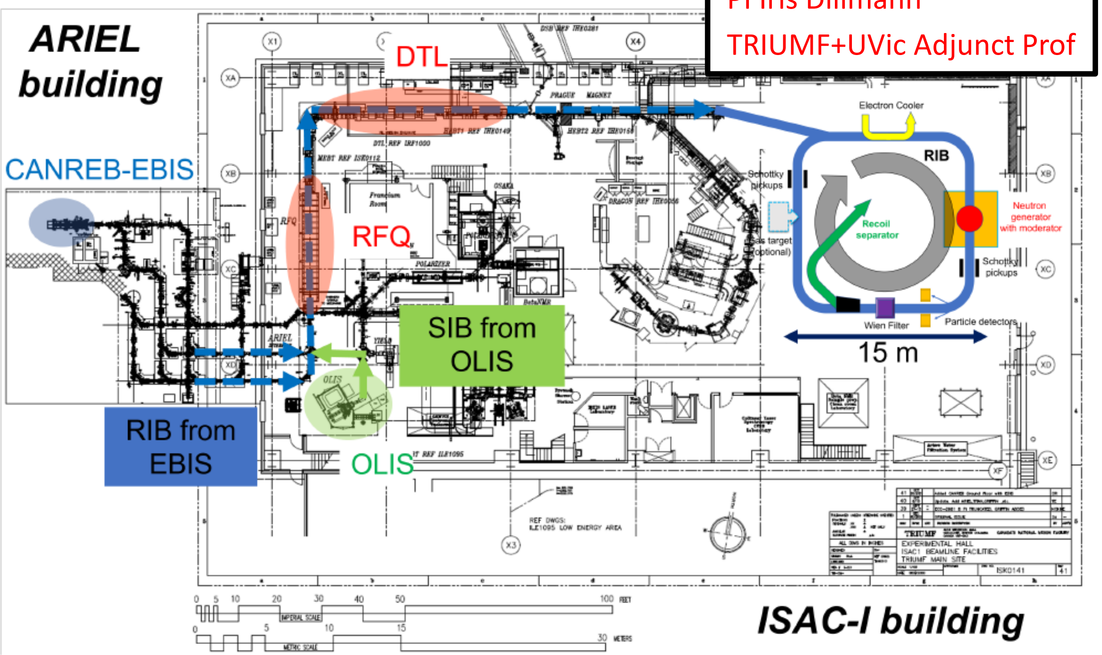
Motivation: Direct measurement of neutron capture cross sections of short-lived radionuclides down to seconds of half-lives.

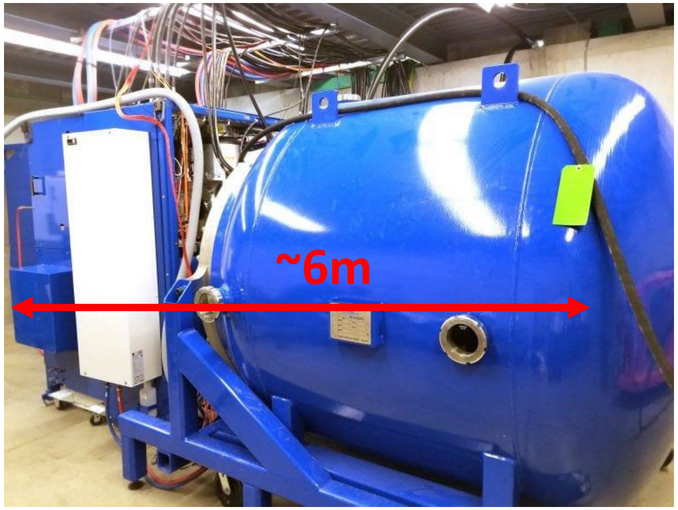
Requirement: ISOL Facility + Storage Ring + Neutron “Target”

- Several proposal exist – no facility world-wide
- Others have considered using a reactor (safety issues) or a spallation source (costly) as targets We consider using a commercial neutron generator as target

Timeline: Feasibility studies towards TDR in 2025 – First experiments in 2031

PI Iris Dillmann
TRIUMF+UVic Adjunct Prof

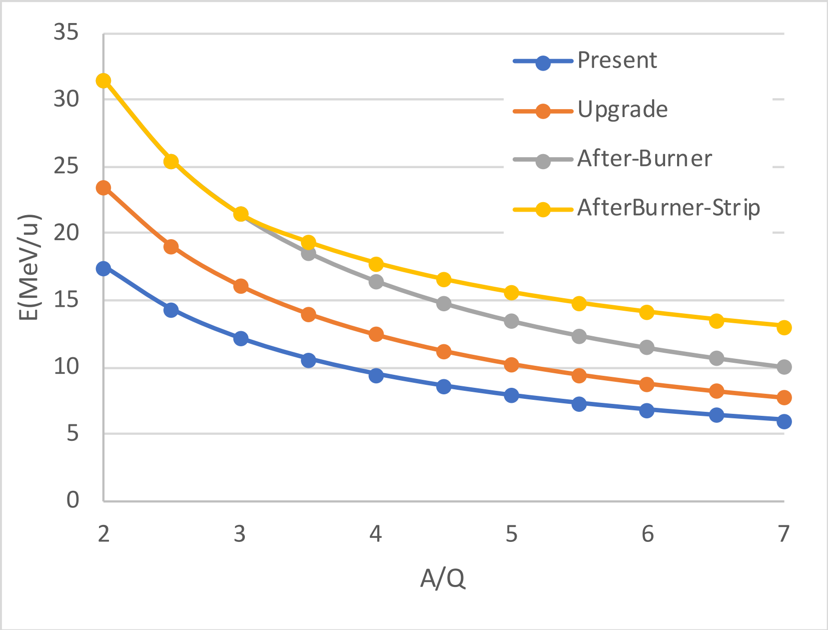


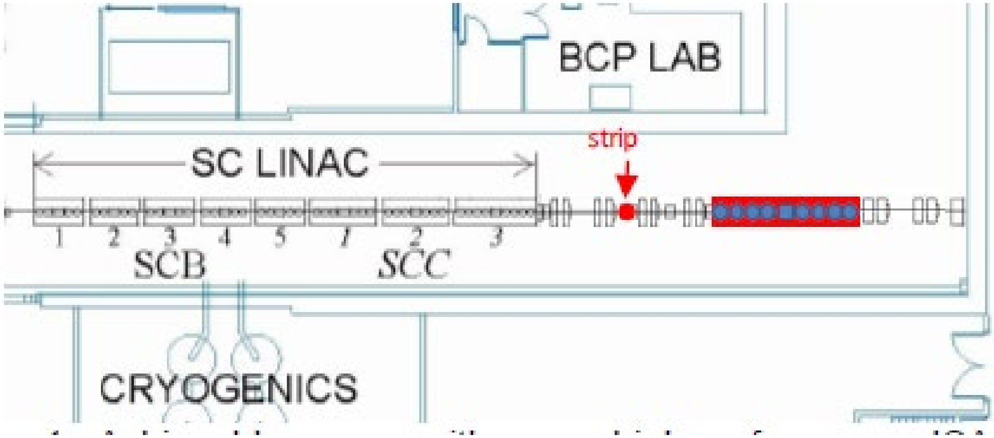


Alectryon 300T from Phoenix LLC: highest output gaseous target DT neutron generator on the market

ISAC-II - Energy Upgrade

- ISAC-II designed for 40MV but presently delivering 34 MV
- New SRF cavity processing infrastructure will permit ISAC-II performance upgrade to >=44 MV
- Afterburner cryomodule using state-of-the-art fabrication and processing would add 16 MV to result in 60 MV total
- Would restore world lead in RIB post-accelerator performance back to ISAC-II





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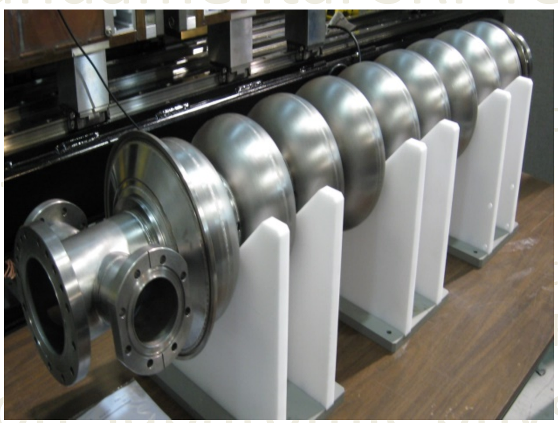
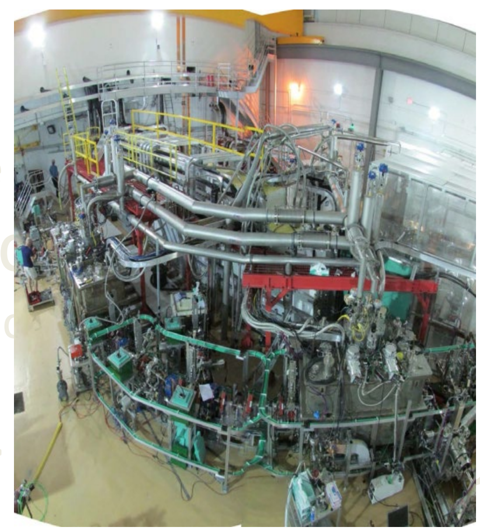


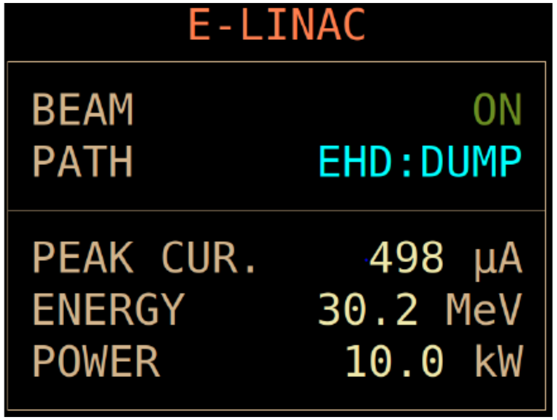


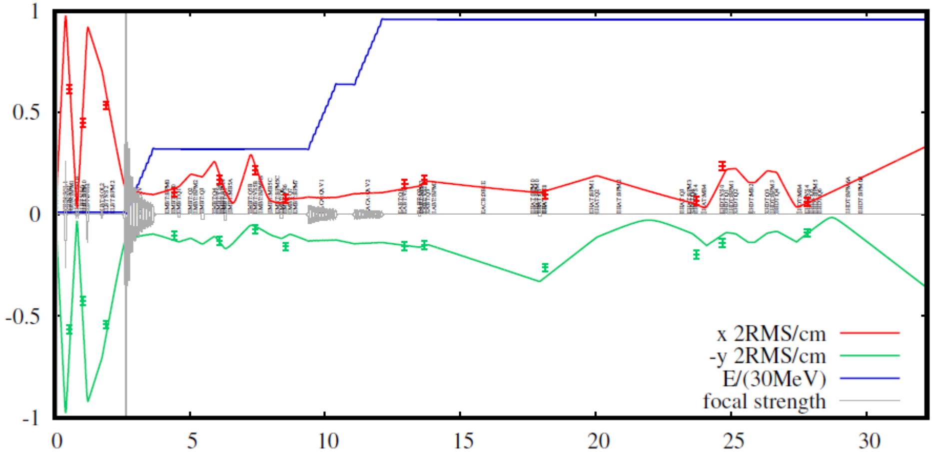
- Non-subatomic phys … UVic and TRIUMF involvement

ARIEL e-linac

Figures of merit in a linac – Energy, Beam Current, Reliability, Operability, and Beam Quality

- **Current and energy**: Reached 10 kW at 30MeV in September 2021 as required for first ARIEL science run
- **Operability**: Now relying entirely on the beam optics model to determine tunes
- Focus for 2022 is to increase **beam quality**, make linac reliable and **easily operable**
  - Demonstrate energy stability better than 0.1% (2RMS) – now at 0.3%
  - Hand over from experts to operators
- Before the ARIEL electron target is ready to take beam science focus is on
  - FLASH-MRT - Reducing side effects in radiotherapy by a combination of two novel treatment techniques, the ultra-fast (FLASH) radiotherapy with spatially fractionated microbeam therapy (MRT) – First beam delivered to experiment in February 2022
  - DarkLight project - Electron scattering experiment to search for particles beyond the standard model – Target chamber installed December 2021





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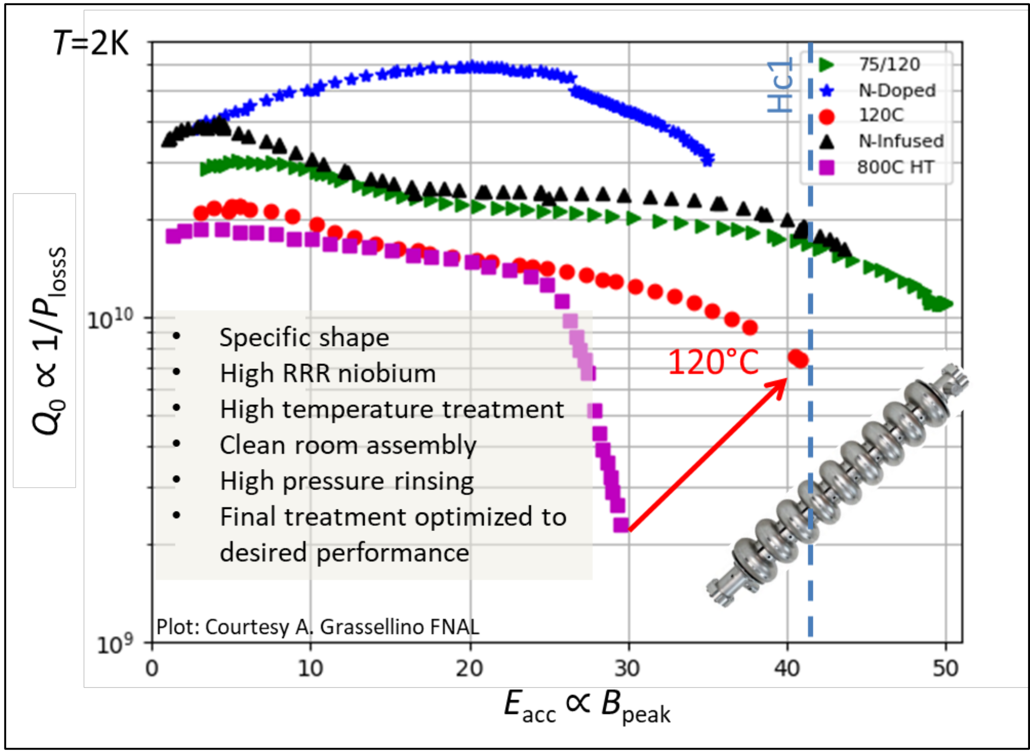
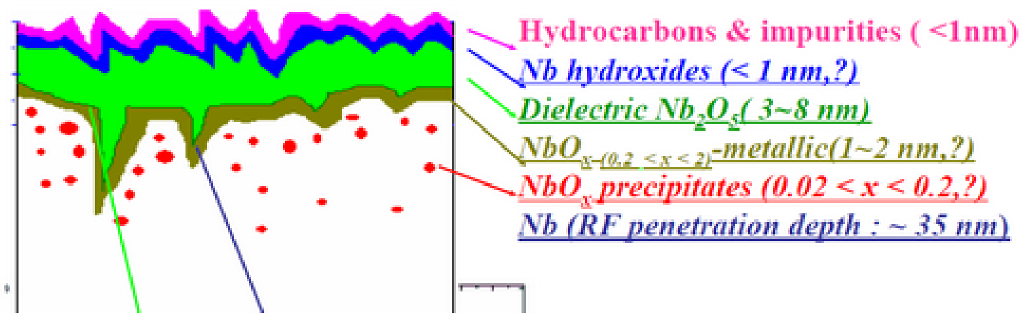
Motivation for fundamental SRF research

- SRF is highly efficient but complex technology
- Supercurrents only flow within a few tens of nanometres
  - Performance is very sensitive to near surface material properties which can be engineered by heat treatments in vacuum or low pressure gas atmosphere
- Maximum quality factor and accelerating gradient depend on surface treatment but also on RF frequency, cavity shape (surface field configuration), ambient magnetic flux in a correlated and not fully understood way

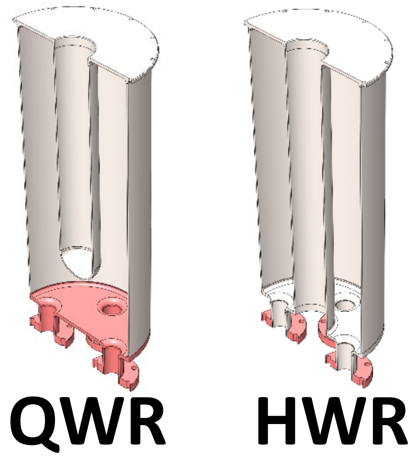




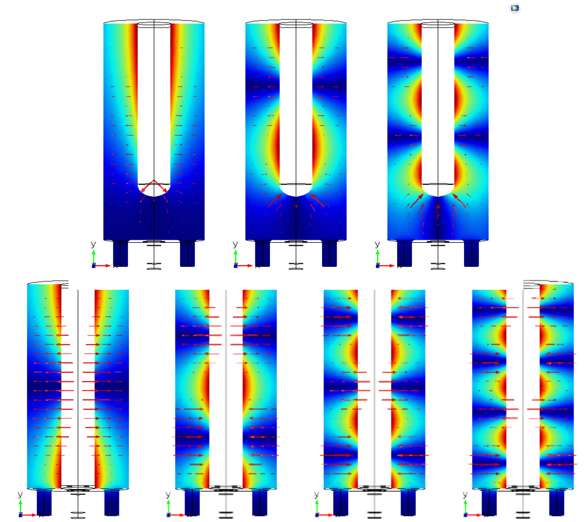
Coaxial Research Cavities at TRIUMF

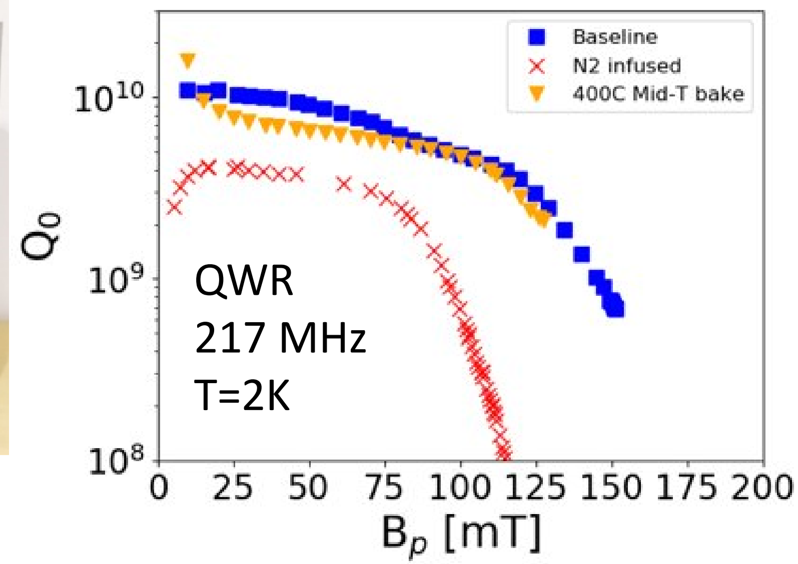
- Most SRF research done on high frequency, high beta, elliptical cavities.
- Ion accelerators need low frequency, low beta coaxial cavities
- TRIUMF has dedicated coaxial cavities for fundamental SRF research
  - Multiple modes (=multiple frequencies)
- Two new baking procedures tried for the first time on coaxial cavities
  - Encouraging results but below expectation (P. Kolb et al. SRF2021)

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



QWR: Quarter Wave Resonator
HWR: Half Wave Resonator

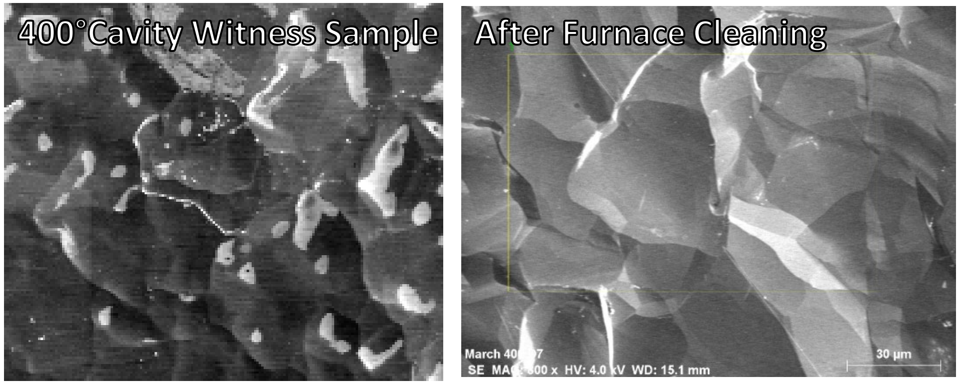




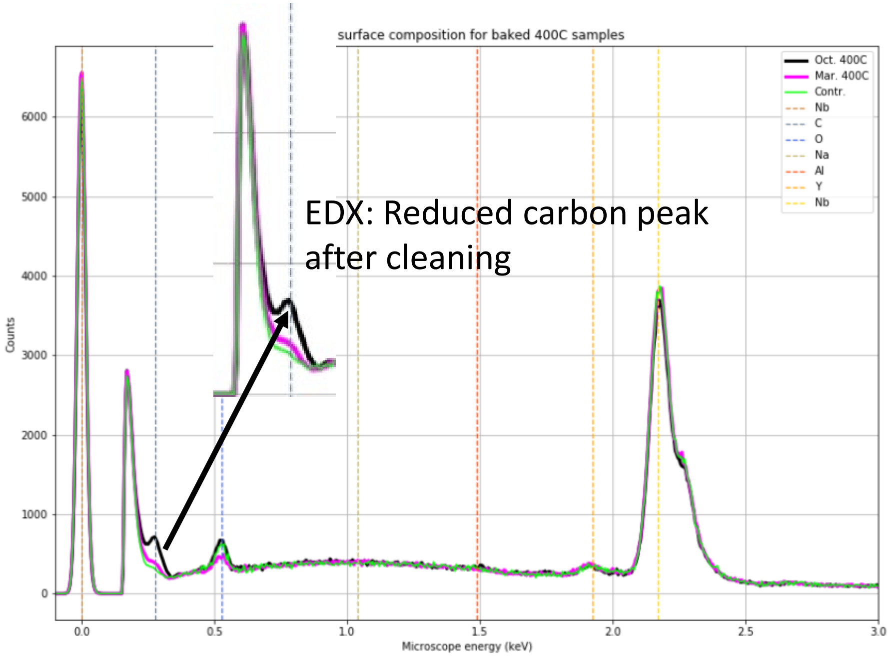
Coaxial Research Cavities at TRIUMF

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)
- SIMS depth profile shows that carbon contamination is most pronounced in relevant near surface region
- Furnace cleaning: Wiping down surfaces with methanol, cleaning burn-off at 100°C reduced carbon content



SEM image before and after furnace cleaning



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

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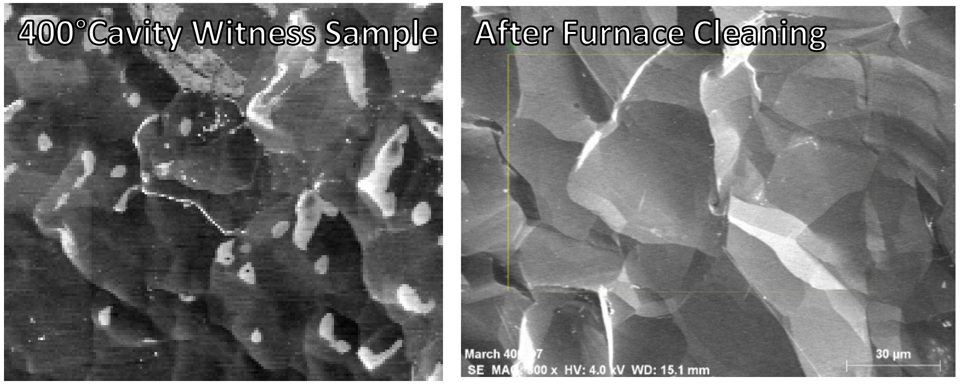

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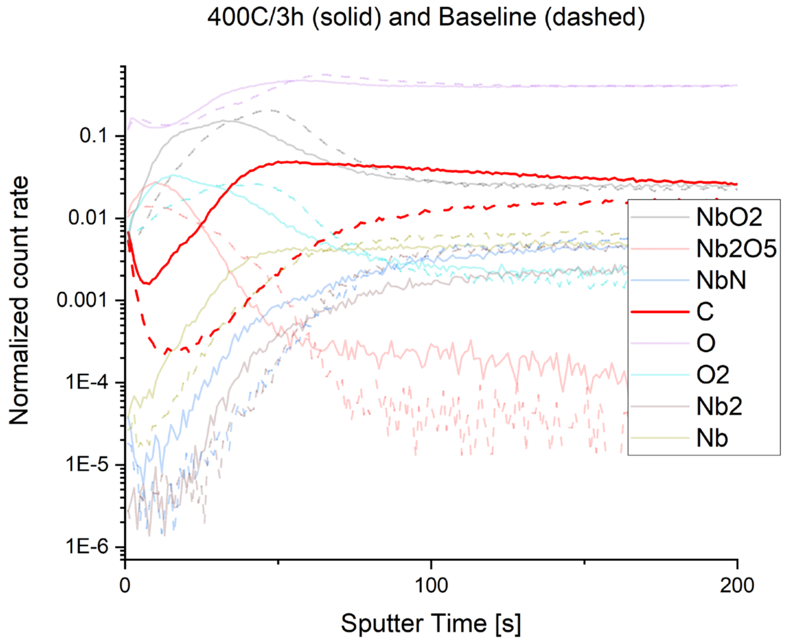

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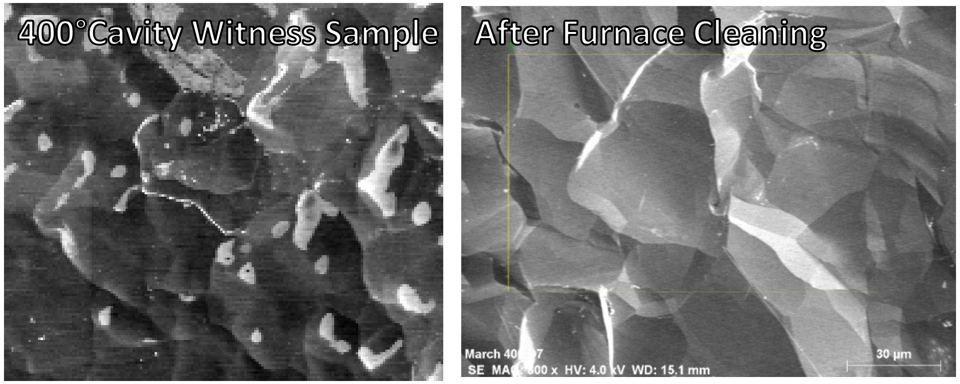

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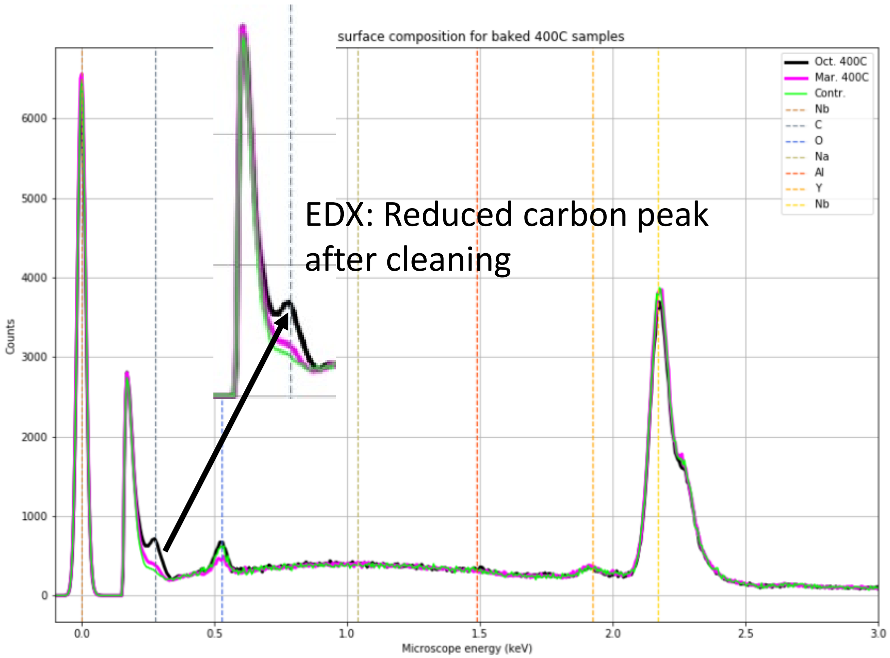

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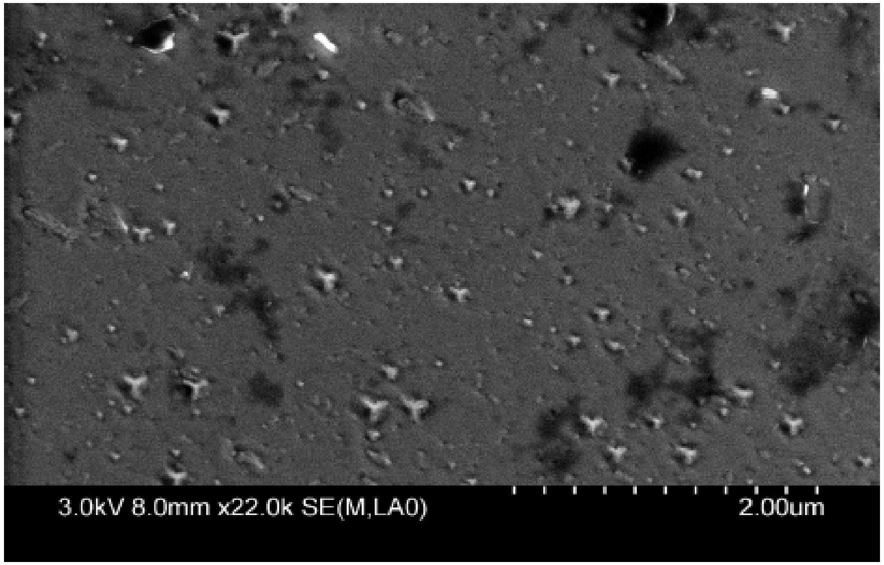
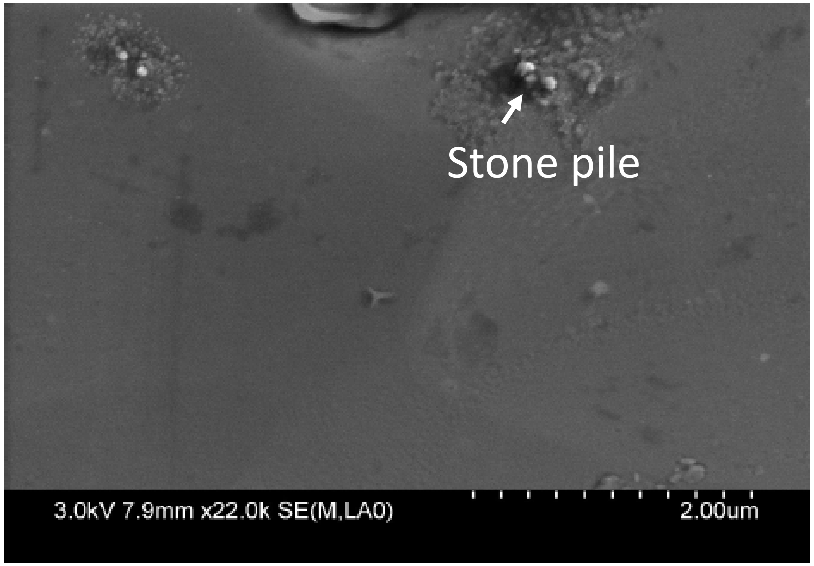
N-Infusion study

- The ”stone-pile” precipitate seen with the TRIUMF N2-infused sample is a formed oxide, while the star-shaped formations along the FNAL N2-infused sample are formed carbides.
- Only one instance of the star-shaped precipitate was found during the entirety of the TRIUMF N2-infused sample investigation period, while the formed ”stone” shaped oxides were found repeatedly throughout the measurement period.



FNAL



TRIUMF

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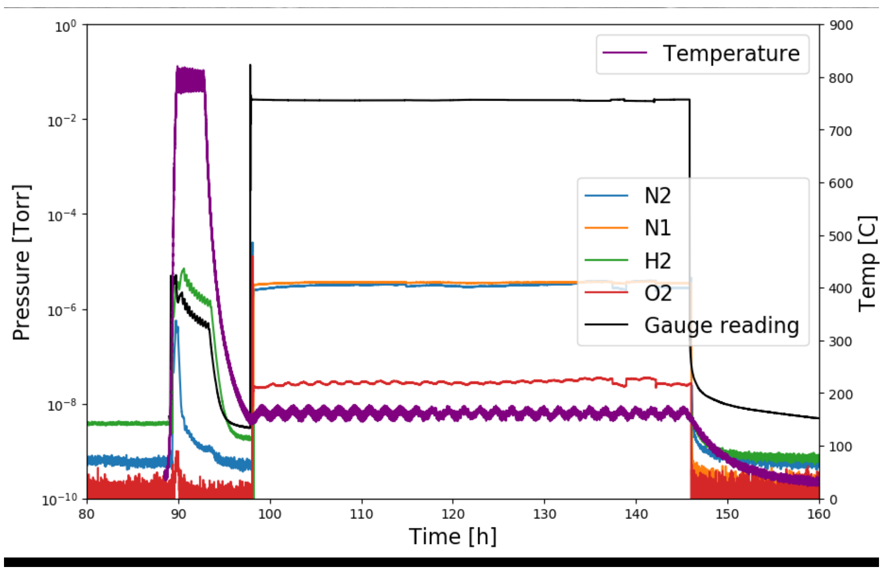

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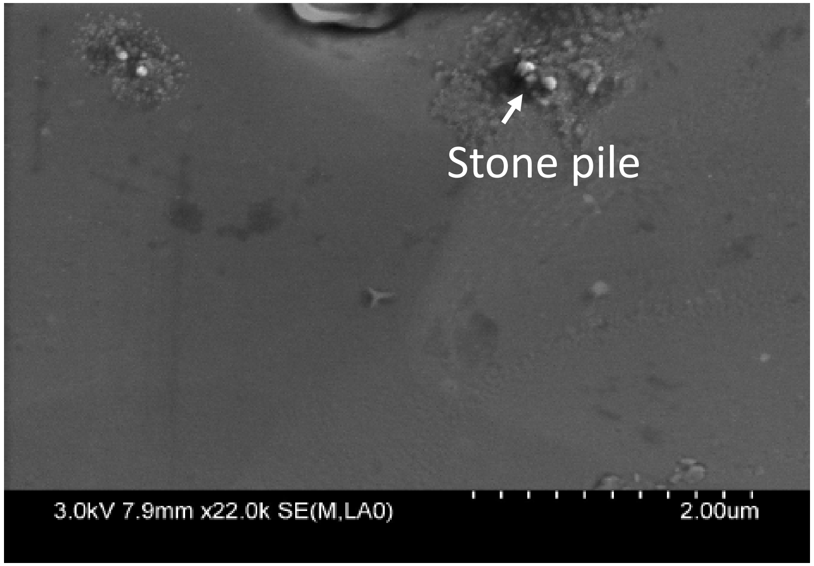
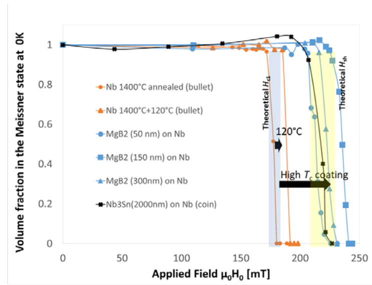


TRIUMF

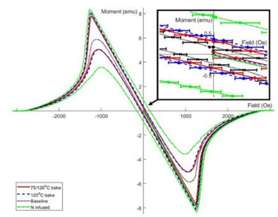
SRF sample studies

- Sample studies are done to optimize cavity treatments but also as predictive tools for SRF performance
  - e.g. field of first vortex penetration is indicative of maximum achievable accelerating gradient
- We use a wide variety of local and external methods including
  - SEM/EDX, TEM (UVic), SIMS (University of Waterloo)
  - muSR (TRIUMF, PSI), betaNMR (TRIUMF)
  - Neutron tomography (HZB)
  - Vibrating sample magnetometry (ISIS, UK; to be developed at UVic)

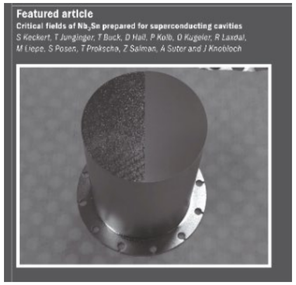


and W.Wasserman Superconductor Science and Technology 30 (12) 2017, 125012

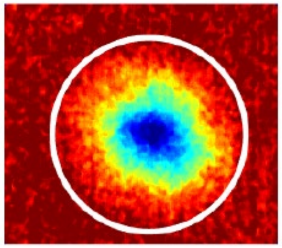
Layered superconductors increase DC field of first vortex penetration up to the superheating field
T. Junginger et al. Superconductor Science and Technology 30 (12), 125012 (2017)



Low temperature baking does not increase DC field of first vortex penetration but increases surface pinning
D. Turner, G. Burt, T. Junginger, Sci Rep 12, 5522 (2022)



Nb3Sn cavities can be operated in a metastable state above Hc1. Current limitations are not intrinsic.
S. Keckert, T. Junginger et al. Superconductor Science and Technology 32 (7), 075004 (2019)



Flux trapping depends on surface treatments and can be visualized with polarized neutron tomography.
W. Treimer, T. Junginger, O. Kugeler Applied Sciences 11 (14), 6308 (2021)

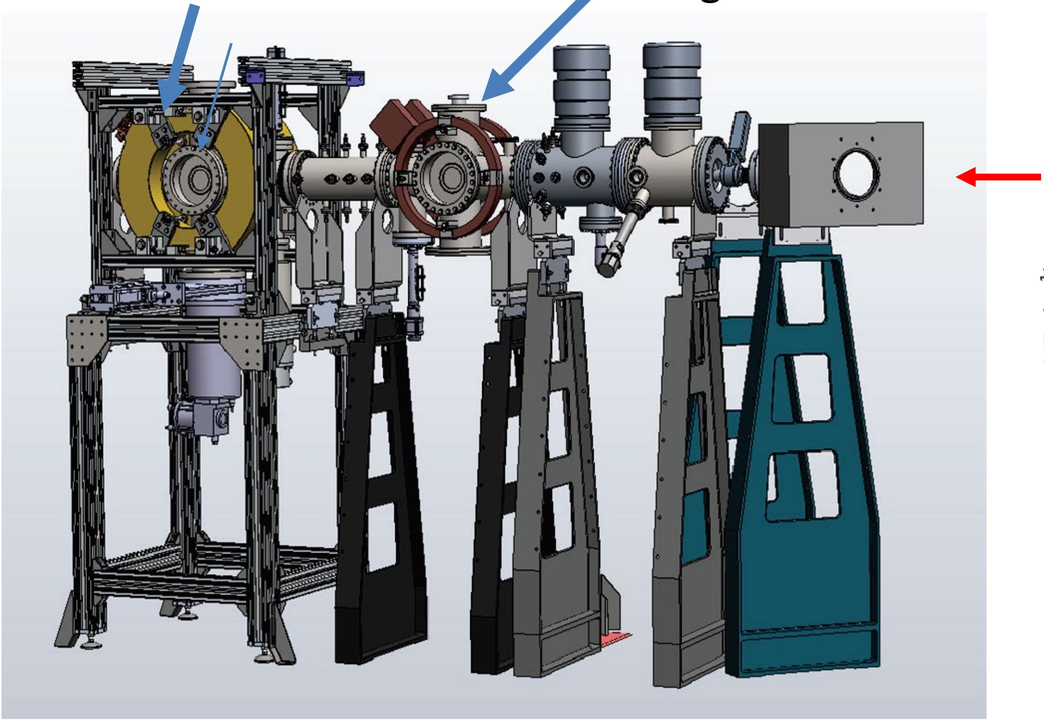
β-NMR + SRF @ TRIUMF

beta-NMR can probe magnetic fields with nanometric depth-resolution

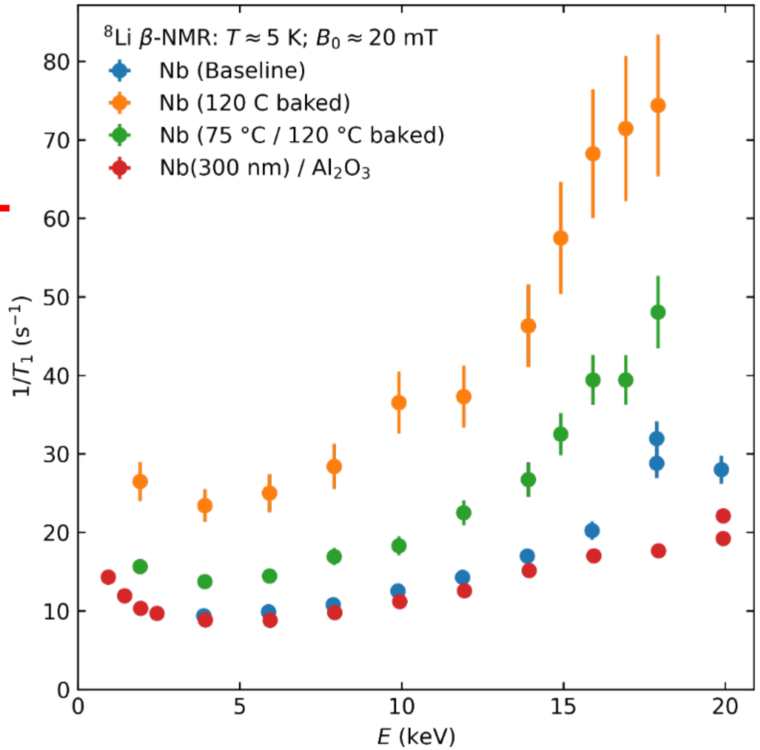
- With β-SRF we have added facility to test samples in high parallel field (200 mT). **Successfully commissioned Summer 2021 and now provides world-wide unique capability**
- Method is sensitive to changes by surface treatments (E. Thoeng et al SRF2021)

New high field magnet

Low field magnet



Extension of parallel field spectrometer



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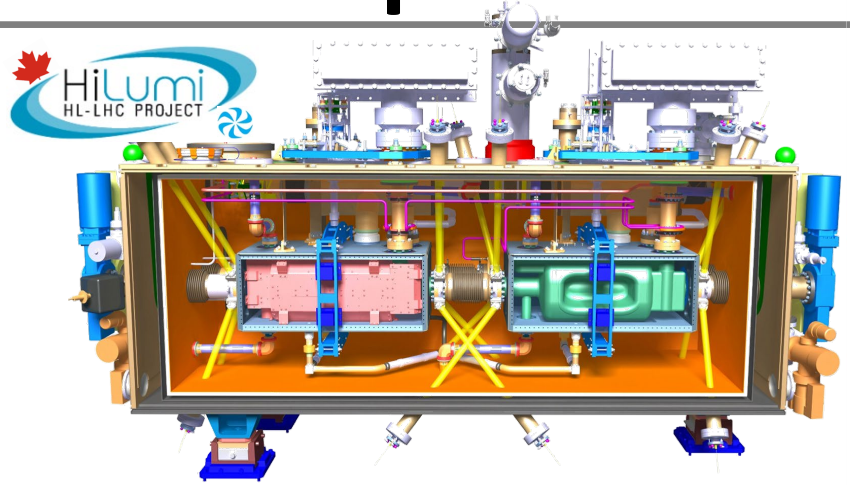
20 year vision - What will TRIUMF look like?

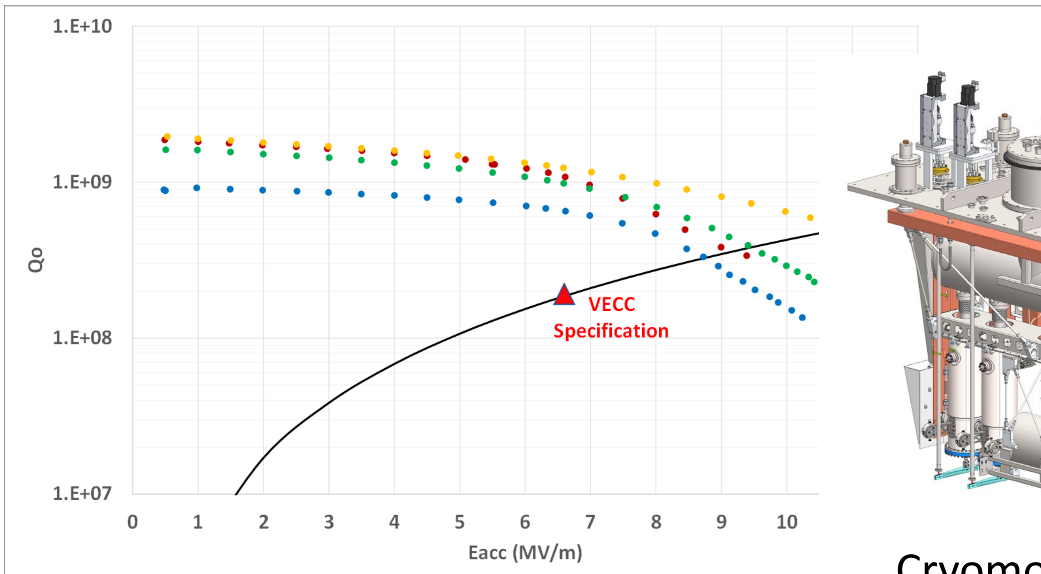
The major revolution will come from the expansion of TRIUMF outside of its physical boundaries, allowing us to play a key role in the forthcoming knowledge-based economy as the owner of Canada's accelerator-related expertise.

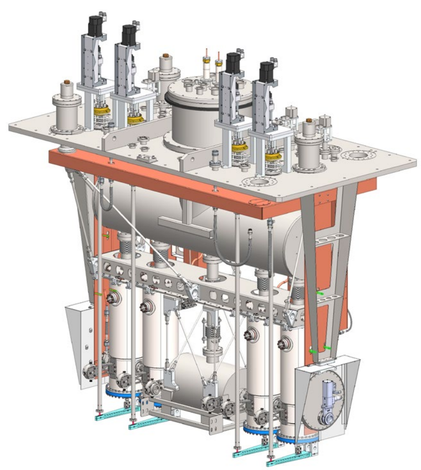
TRIUMF Cryomodule Development

TRIUMF SRF group produces cryomodules for the in-house linacs at ISAC-II and ARIEL as well as for external projects



Five HiLumi LHC crab cavity cryomodules will be assembled in 2022-24

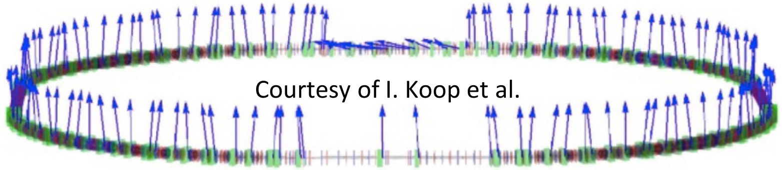


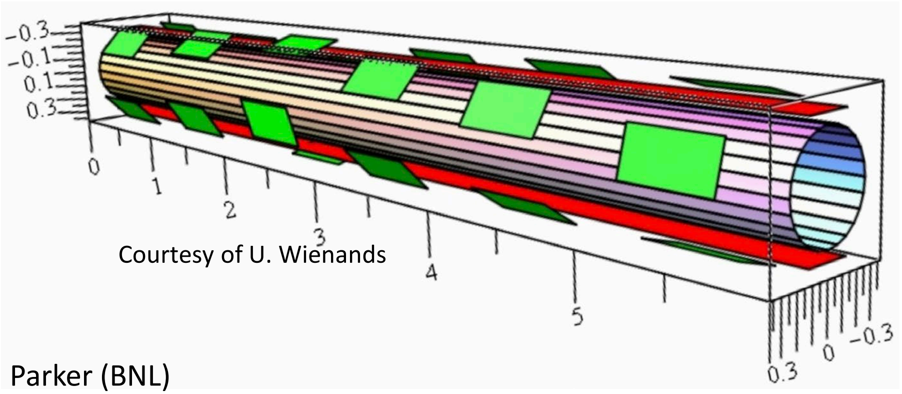


Cryomodule for VECC (Kolkata) successful cold test in Nov. 2021 with delivery in 2022.

Polarized Beams for SuperKEKB

- Polarized electron beams provide precise measurements of electro-weak parameters in the process $e^+e^- \rightarrow f\bar{f}$
  - Requires longitudinal polarization at the Intersection Point
- Space constraints in the ring require a combined function magnet for spin rotation and steering
  - U. Wienands proposed solenoid-dipole combined function magnets on both sides of the Intersection Point with 6 Skew-quadrupoles on top of each rotator magnet section to compensate for x-y coupling
- **MSc thesis Yuhao Peng** - Detailed study in BMad of the full SuperKEKB lattice including combined function magnet spin rotator. *Graduated Dec 2021*


Courtesy of I. Koop et al.



Courtesy of U. Wienands

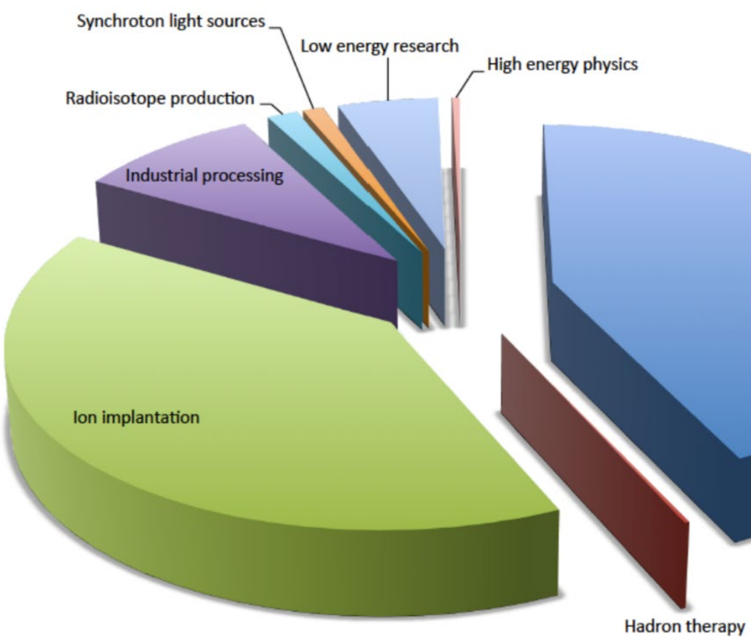
Collaborators: D. Zhou (KEK), U. Wienands (ANL), D. Sagan (Cornell), B. Parker (BNL)

Content

- Nuclear Physics Projects at TRIUMF
  - ISAC facility
    - Increase experiment time – Model based beam tuning
    - Reaching higher charge states – Two frequency heating of charge state booster
    - ISAC-II energy upgrade
    - ISAC Storage Ring
  - ARIEL e-linac
    - Status and future applications
- Fundamental SRF research
  - High accelerating gradient research for linacs like ILC – BetaNMR studies
  - Coaxial cavity research
- International Particle Physics Projects
  - Cryomodule development for international projects
  - Polarized Beams for SUPERKEK-B
- Non subatomic physics accelerator projects with UVic and TRIUMF involvement

Accelerators beyond subatomic research

Most of the approximately 30.000 accelerators world-wide are not built for subatomic physics research



National Research Council:
Nuclear Physics: Exploring the Heart of Matter
Washington DC (2012)

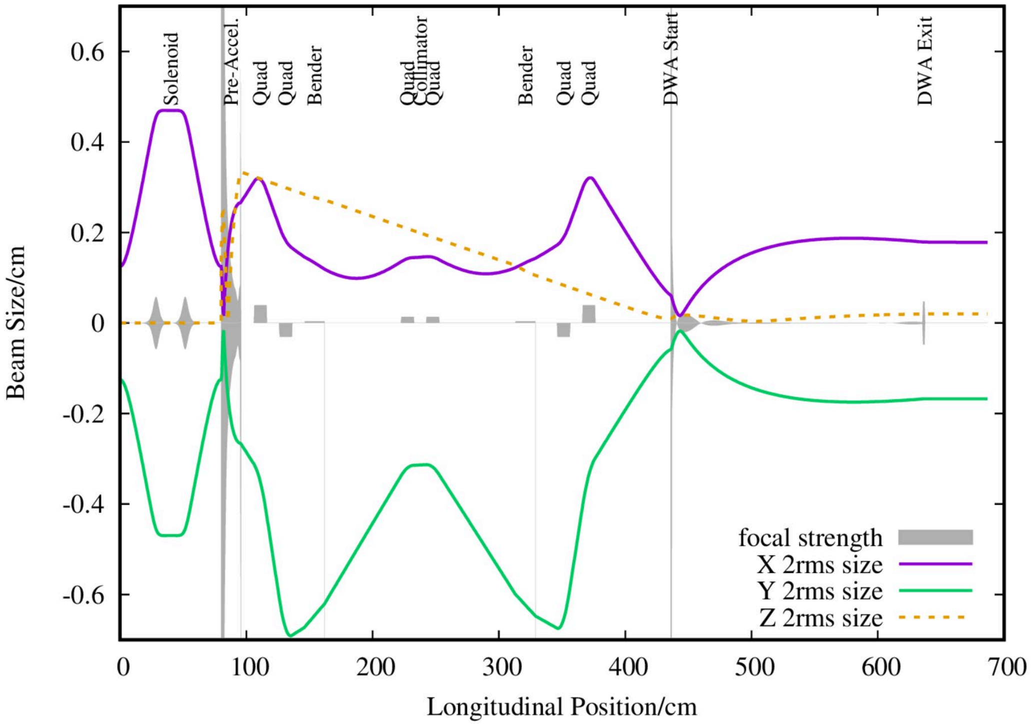
Non subatomic physics accelerator physics projects with UVic student involvement

- P. Jung - Cancer treatment with a dielectric wall accelerator
- A. Paul (D-Pace) – Creating He^- using H^- ion source for ion implantation
- M. Abbaslou – Development of a compact Canadian neutron source
- N. Gorgichuk - SRF technology for quantum computing application

Dielectric Wall Accelerator Design

A dielectric wall accelerator is a type of induction accelerator that can provide a technical solution for a compact variable energy accelerator

- Initially patented in 2001 but only recent developments in high gradient insulators and dielectrics promise technical feasibility
- Proposed by McGill Medical Physics Unit for proton therapy
- TRIUMF provided design in TRANSOPTR (R. Baartman's code) with custom subroutine.

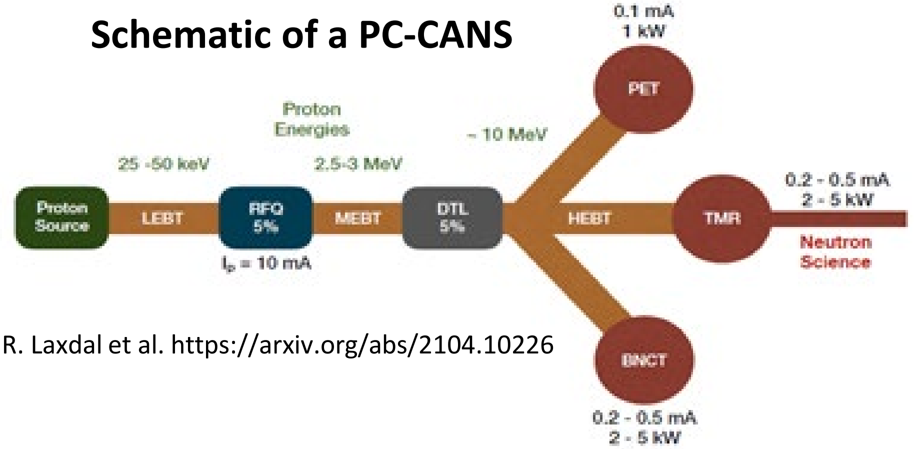


PhD work
Paul M. Jung

Compact Accelerator-based Neutron Source for Canada

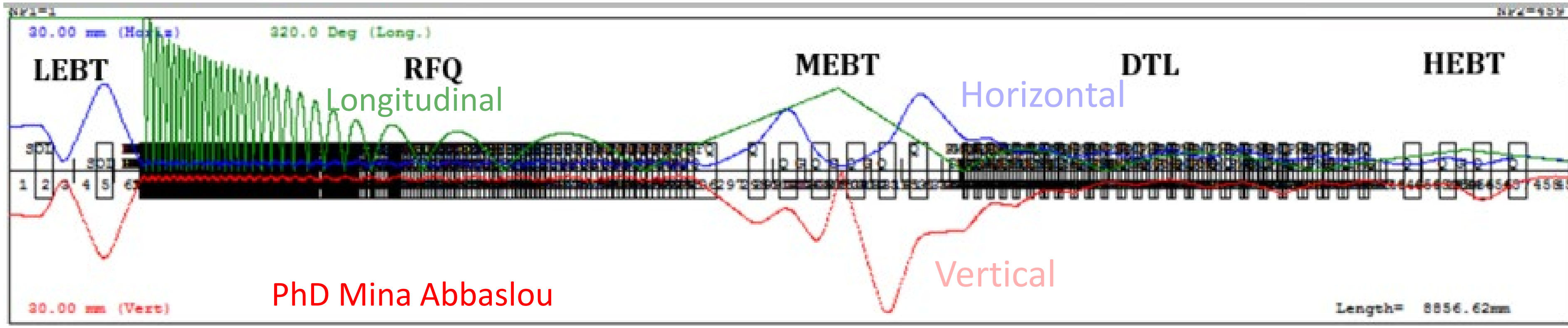
- **C**ompact **A**ccelerator-based **N**eutron **S**ources (CANS) can provide intense neutrons with a capital cost significantly lower than a spallation source
- TRIUMF is designing a **P**rototype **C**anadian CANS (PC-CANS) to be located at the University of Windsor
- PC-CANS is based on a high intensity linear proton accelerator (RFQ+DTL) and multiple target stations for science and medical purposes
- **Status**: Conceptual design studies towards a proposal for funding.

Schematic of a PC-CANS



R. Laxdal et al. https://arxiv.org/abs/2104.10226

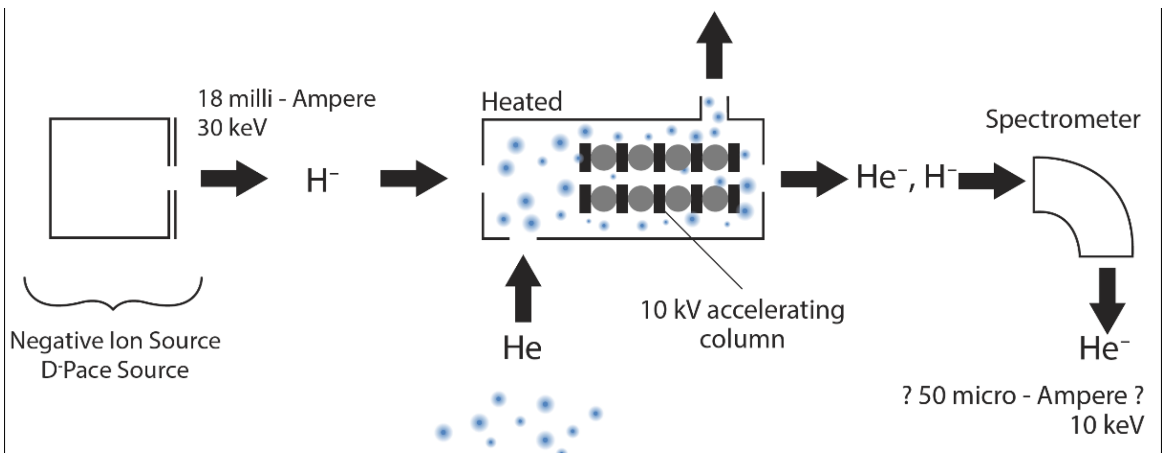
End to end simulation of p-LINAC in Trace-3D code



PhD Mina Abbaslou

Creating He- using H- ion source for ion implantation

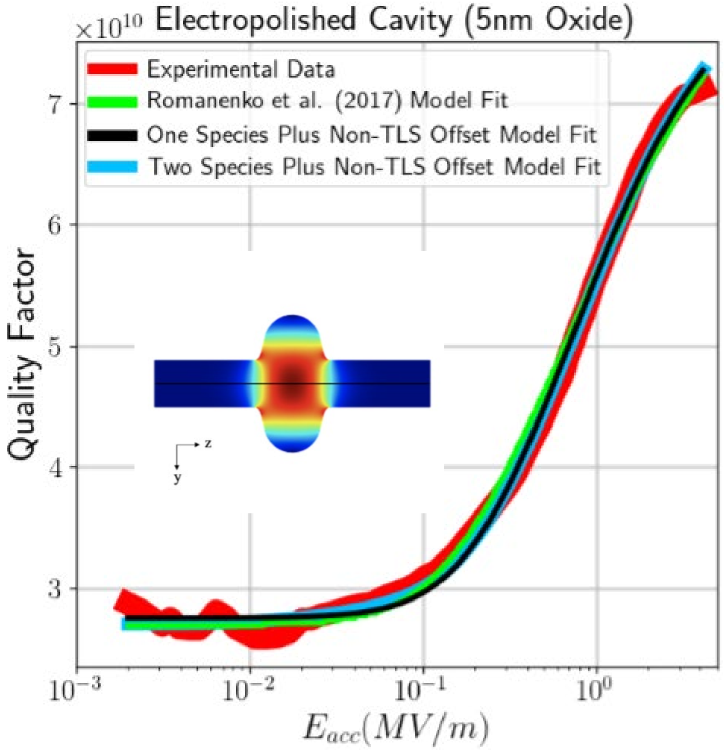
- Current manufacturing techniques for silicon based computer chips requiring negative ions are prone to alkali metal contamination
- TRIUMF spin-off company D-Pace brought forward the idea of producing He- through bombardment of neutral He gas with H- to avoid contamination
  - If a He- ion current of 20 microampere could be achieved this approach would be commercially viable
- Current Status: Gas cell accelerator has been manufactured and is ready for installation and initial tests

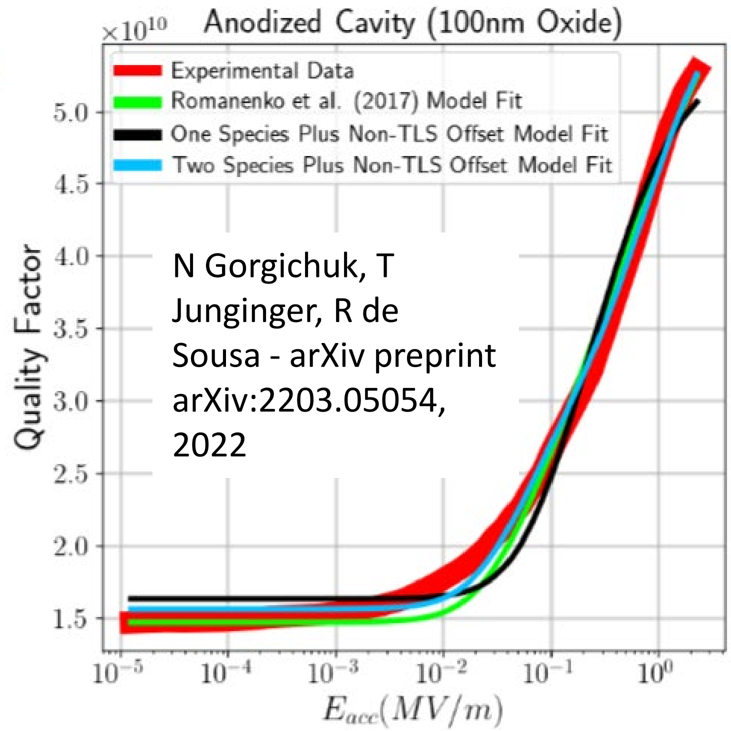


Collaboration of D-Pace, UVIC, and TRIUMF, PI Morgan Dehnel (D-Pace)

SRF for Quantum Computing

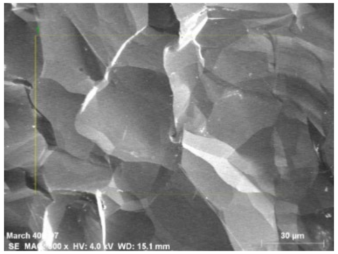
- Main mechanism for quantum decoherence in current quantum hardware are two level systems in amorphous oxides
- SRF cavites can increase coherence times and be used as a testbed for theoretical models
- Low field data is available in the literature but published analysis does not take into account the variation of the electric field on the cavity surface.
- We propose a new model for quantum decoherence based on the separation of oxide and interface losses

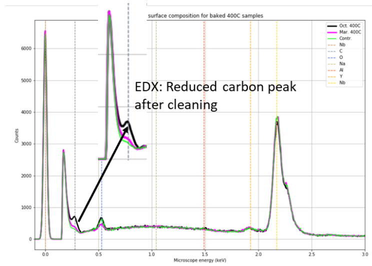


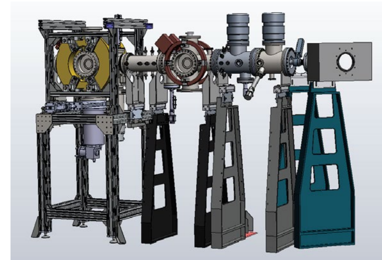


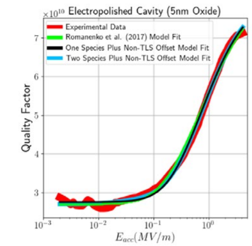
N Gorgichuk, T Junginger, R de Sousa - arXiv preprint arXiv:2203.05054, 2022

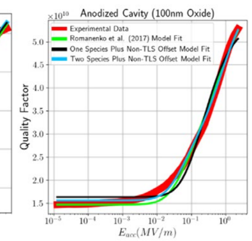
Thank you for your attention



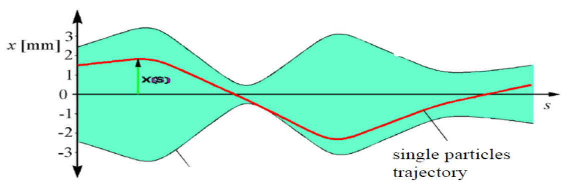


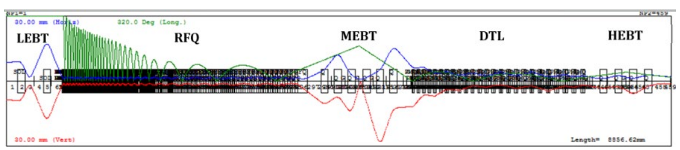


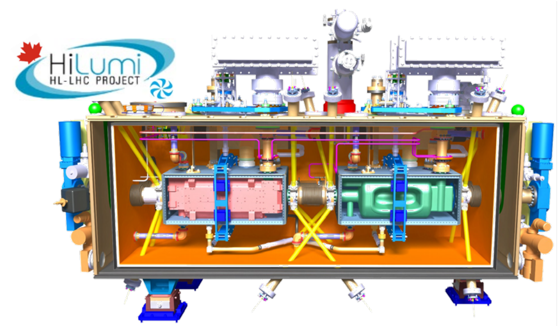


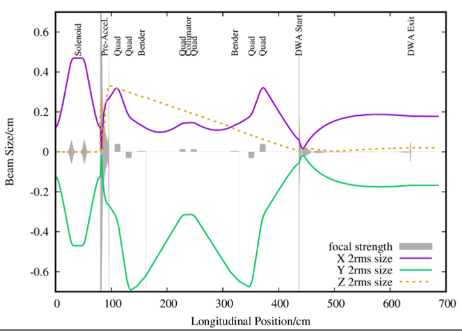


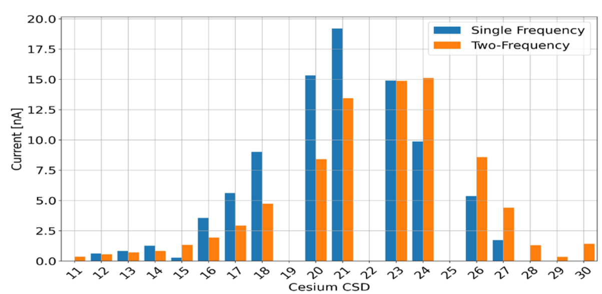
TRIUMF with UVic as key partner is the center for accelerator research in Canada

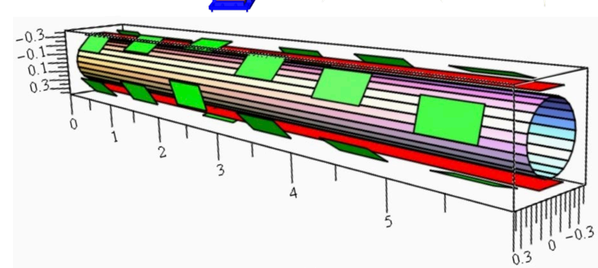












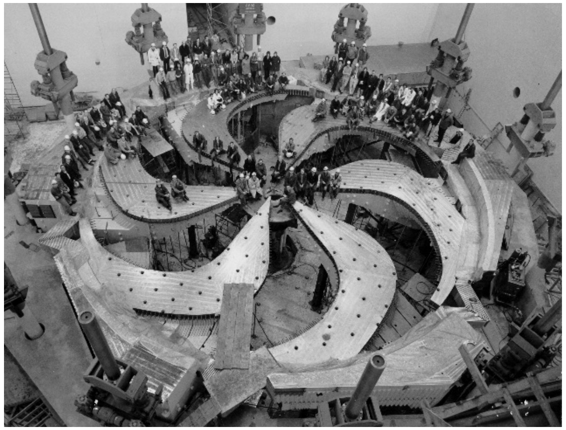
Backup slides

UVic adjunct faculty in Accelerator Division

- **ACCELERATOR DIVISION** – O. Kester
  - *Deputy* – *R. Laxdal*
  - **Admin. Assist.** – S. Bruckner
  - **Accelerator Operations** – *(O. Kester)*
    - **Beam Delivery & Development** – F. Ames
    - **Operations** – V. Toma
  - **Accelerator Systems** – Y. Bylinski
    - **Cryogenics** – A. Koveshnikov
    - **Diagnostics** – V. Verzilov
    - **High Power DC Systems** – D. Louie
    - **Vacuum** – D. Yosifov
  - **Beam Physics** – R. Baartman
  - **RF / SRF** – R. Laxdal
    - **Development & Projects** – (R. Laxdal)
    - **RF Operations** – V. Zvyagintsev
  - **Targets/Ion Sources** – A. Gottberg
    - **Laser Applications** – J. Lassen
    - **Production & Operation** – A. Mjos
    - **Remote Handling** – G. Minor
    - **Research & Development** – A. Gottberg

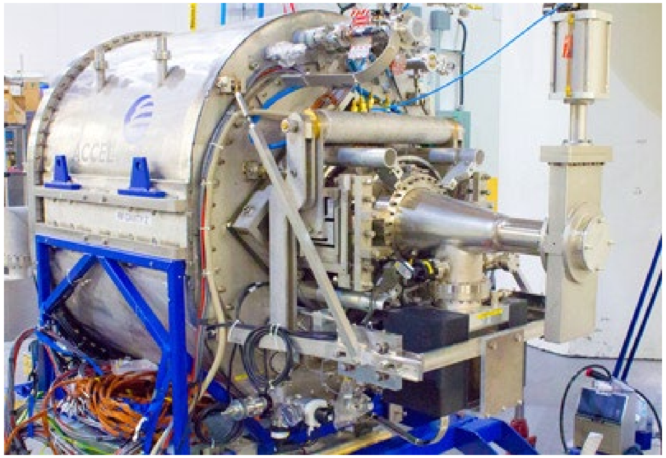
<u>TRIUMF Accelerator Research focus</u>

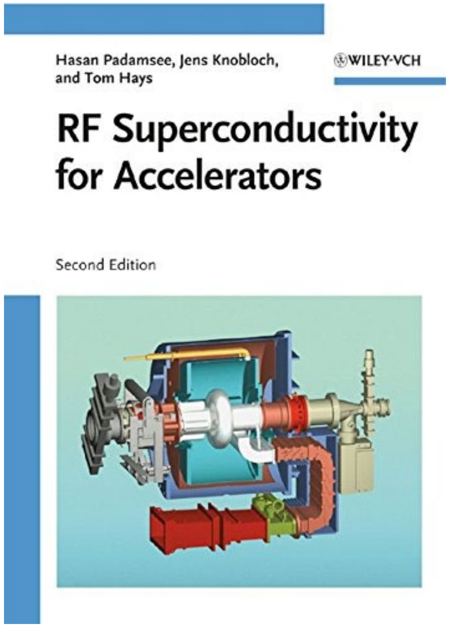
- **Beam physics and instrumentation** (O. Kester, R. Baartman, T. Planche)
  - Intense beams, Particle sources, beam diagnostics (including High Luminosity-LHC and AWAKE at CERN)
- **Superconducting RF** (R. Laxdal, T. Junginger)
  - Cavity and cryomodule engineering (including High Luminosity-LHC) and material research
- **Target Material and Target ion sources** (A. Gottberg)
  - Science and technology for the production, ionization, formation of secondary particle beams and handling of highly radioactive components



Canadian Light Source

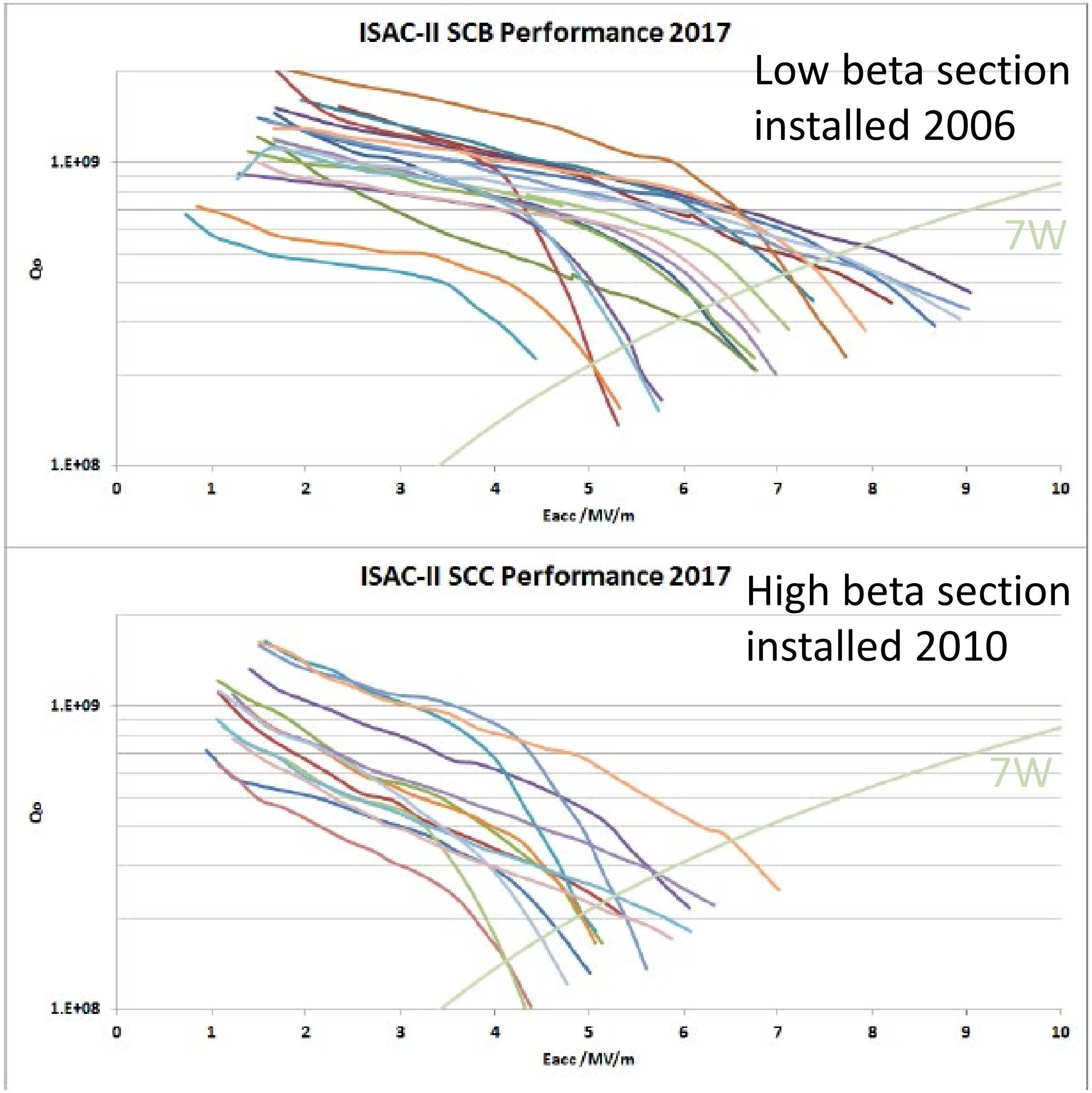
- First light source to use SRF technology from the beginning of operation in 2003
- CESR-B cavity developed at Cornell University and built at Research Instrument, Germany
- Operational experience
  - SRF system is generally reliable but complex
  - Repair times for cryomodules are long → Risk of significant downtime periods





ISAC-II performance and availability

- 40 cavities each operated at 7 W
- E_{acc} between 4 and 8 MV/m



Z. Yao et al. SRF 2017, Lanzhou TUPB064

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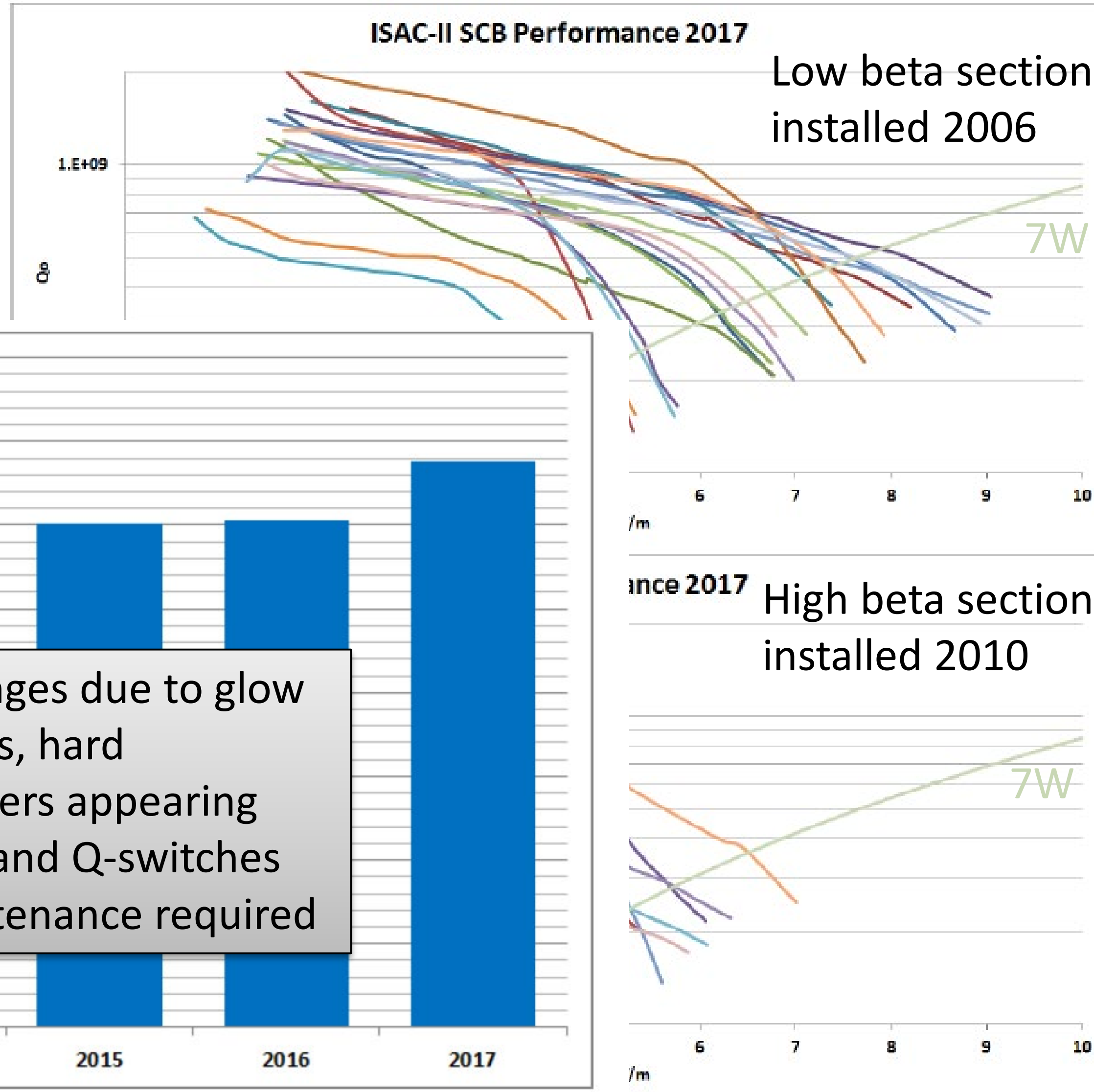
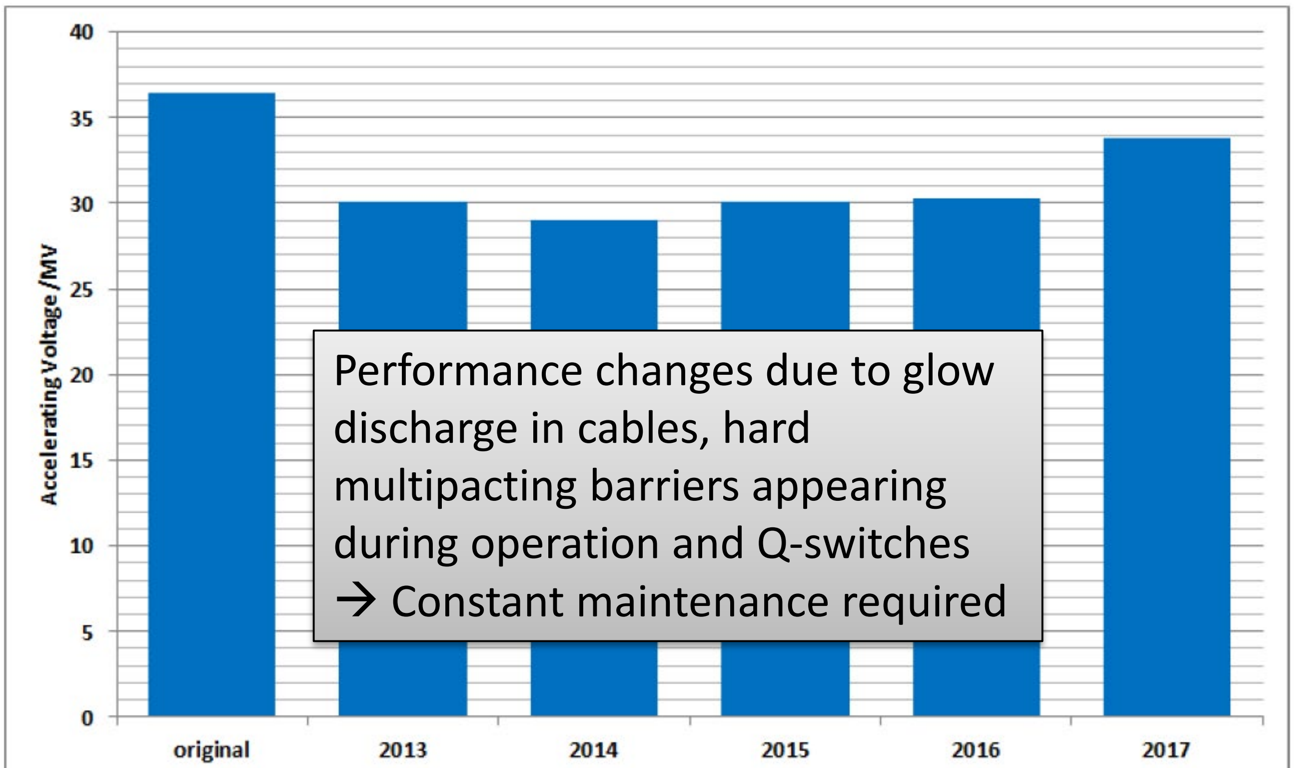
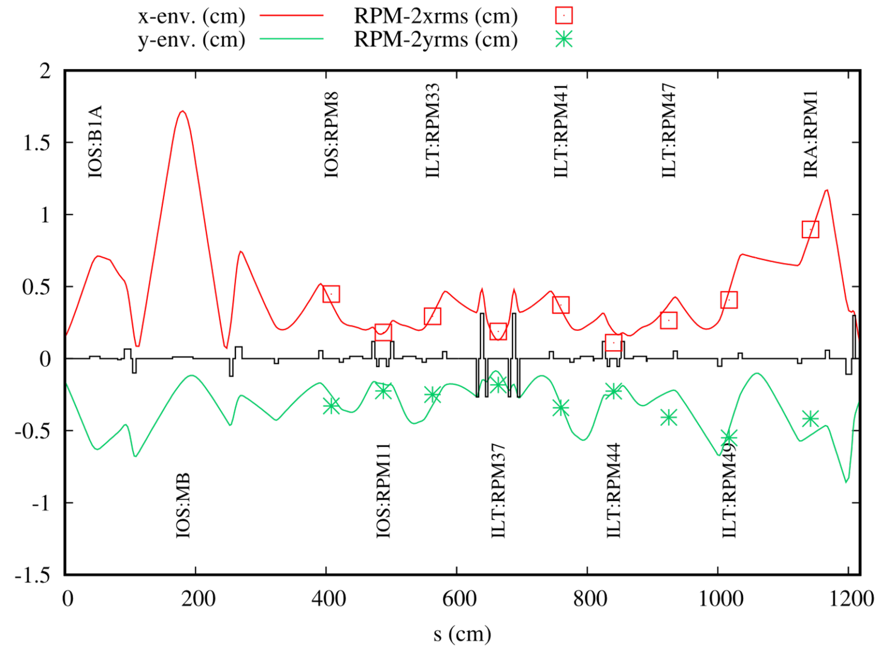


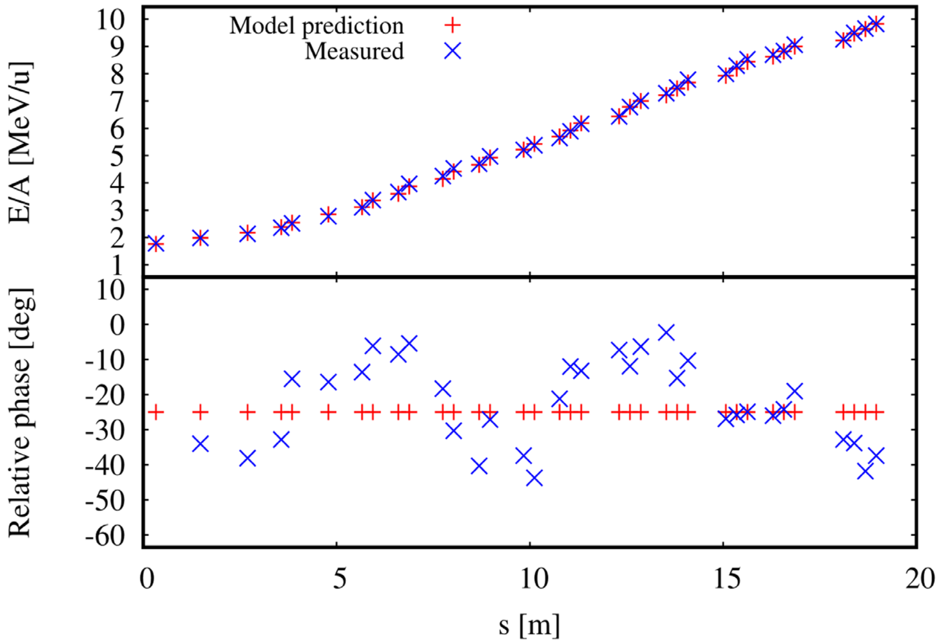


Performance changes due to glow discharge in cables, hard multipacting barriers appearing during operation and Q-switches
→ Constant maintenance required

Z. Yao et al. SRF 2017, Lanzhou TUPB064

ISAC - Model based beam tuning



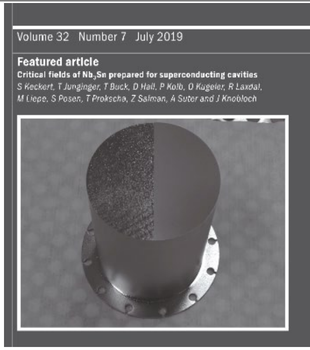


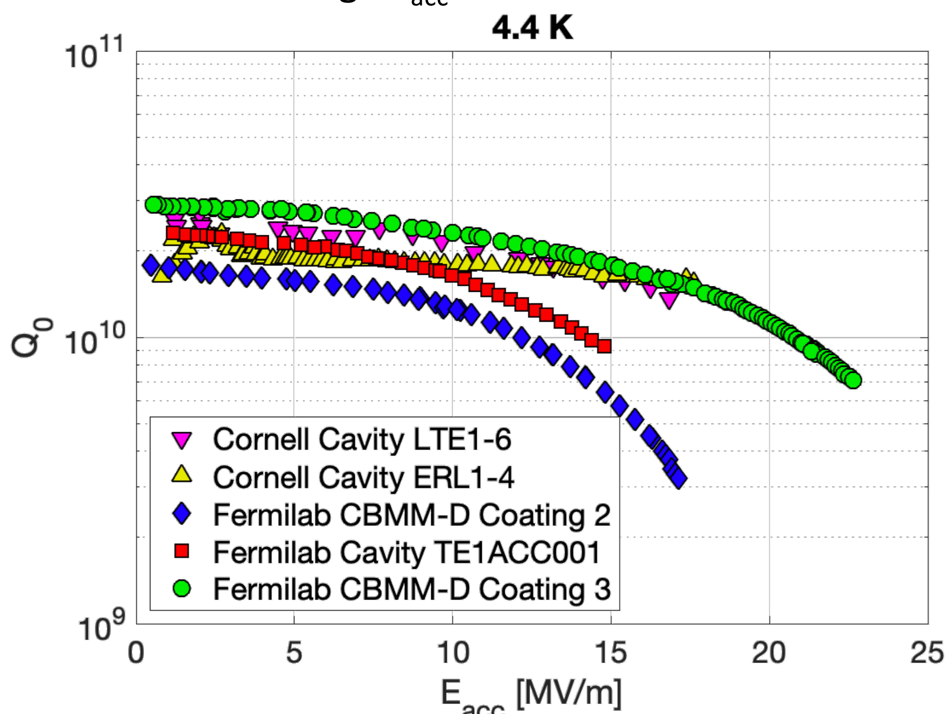
- 7Li from off-line ion source (OLIS) to the ISAC RFQ, simulated envelope vs measured beam size at profile monitors.
- Profile monitor data was used in a transoptr optimization to fit the initial beam conditions (O. Shelbaya).

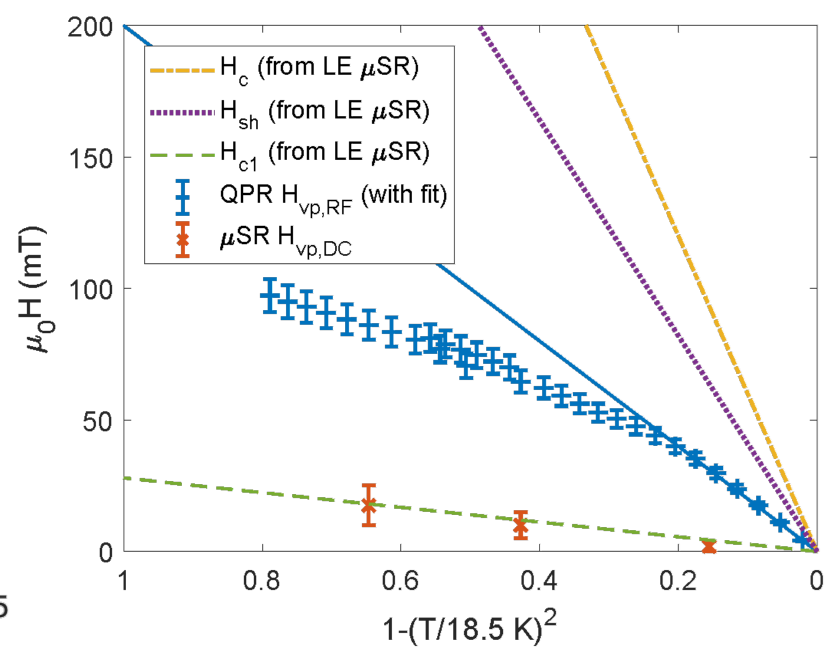
- Comparison of model calculated tune for the ISAC-II heavy ion linac to observations.
- Successfully delivered beam to an experiment (IRIS S1834) with model-set cavity phases for the first time (S. Kiy)

Beyond Nb - Critical Fields of Nb_3Sn

- Results from Cornell and FNAL show that Nb_3Sn 1.3 GHz cavities are reaching up to 22.5 MV/m (95 mT)
  - Quality factors at 4.2 K can be as high as for Nb at 2 K
- Measurements from both bulk µSR (TRIUMF) and LE-µSR (PSI), as well as RF measurements with a specialized sample test cavity to determine the DC and RF critical fields of Nb_3Sn prepared for SRF application
  - Potential for high E_{acc} still needs to be demonstrated



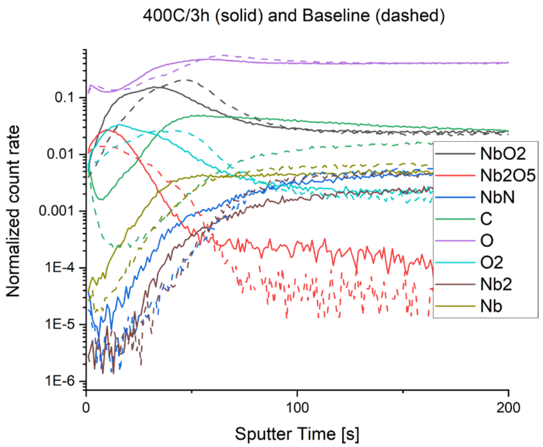




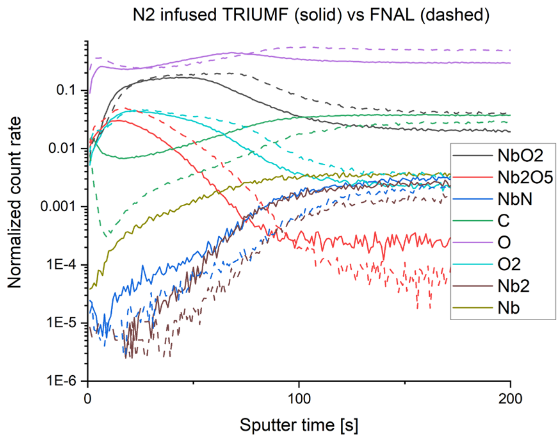
S Keckert, T Junginger, T Buck, D Hall, P Kolb, O Kugeler, R Laxdal, M Liepe, S Posen, T Prokscha, Z Salman, A Suter and J Knobloch, "Critical fields of Nb3Sn prepared for superconducting cavities", SUST, Volume 32 Number 7 July 2019

SIMS + SEM sample study

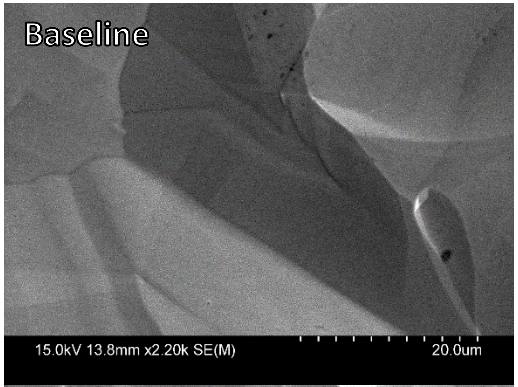
- EDX generally only gives the elemental composition for a fixed depth
- Secondary ion mass spectroscopy (SIMS) can provide depth can provide depth resolved elemental composition
- Most SIMS traces are very similar, except Carbon.

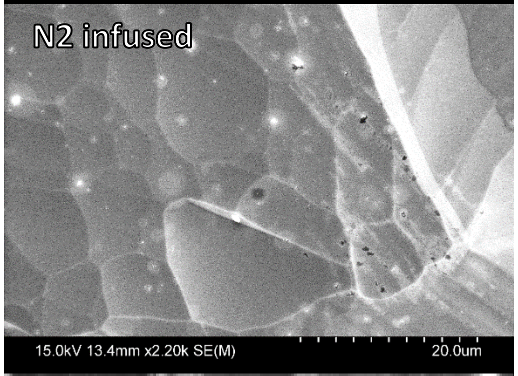


Witness samples for baseline test and 400°C treatment



Witness samples for N2 Infusion compared with a sample from Fermilab (High performing)





SIMS analysis performed at U Western Ontario

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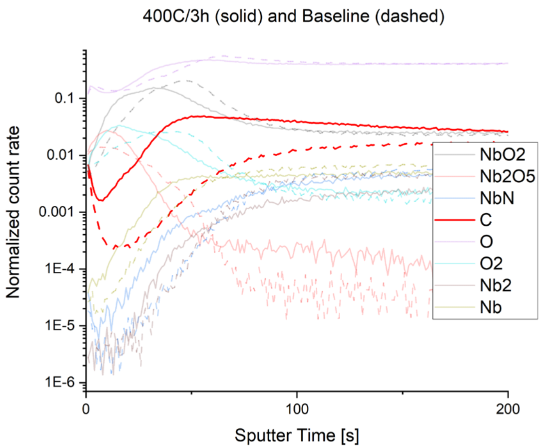

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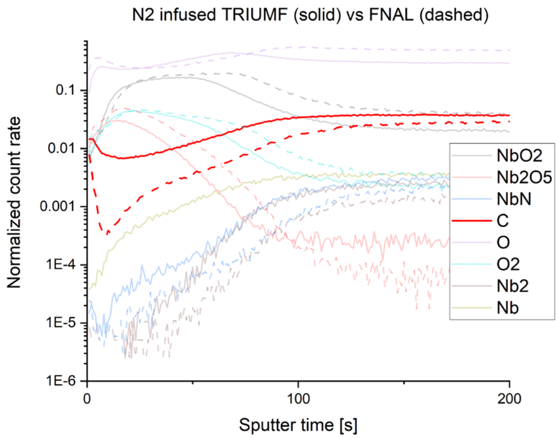

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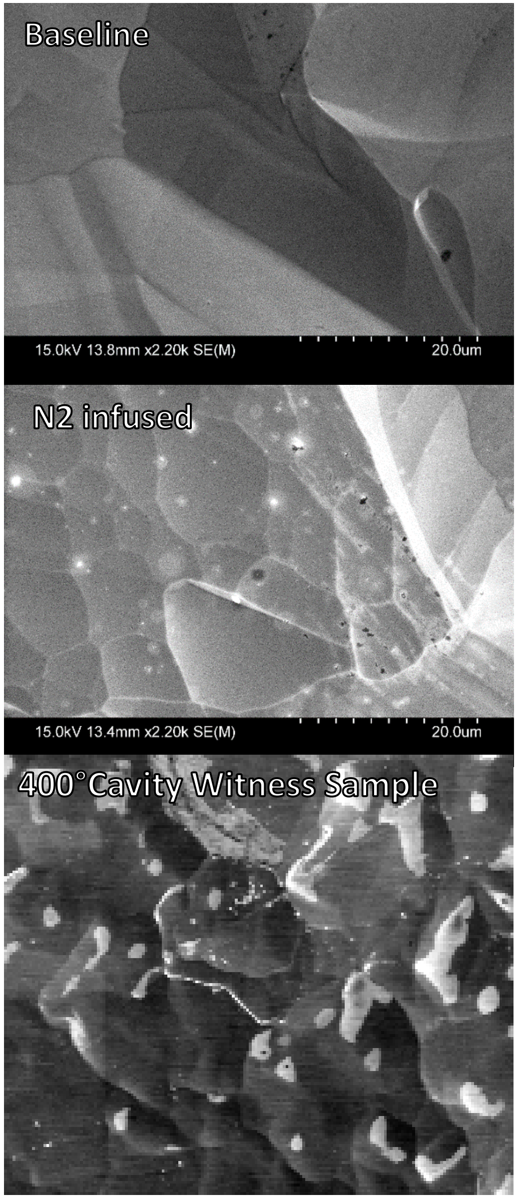
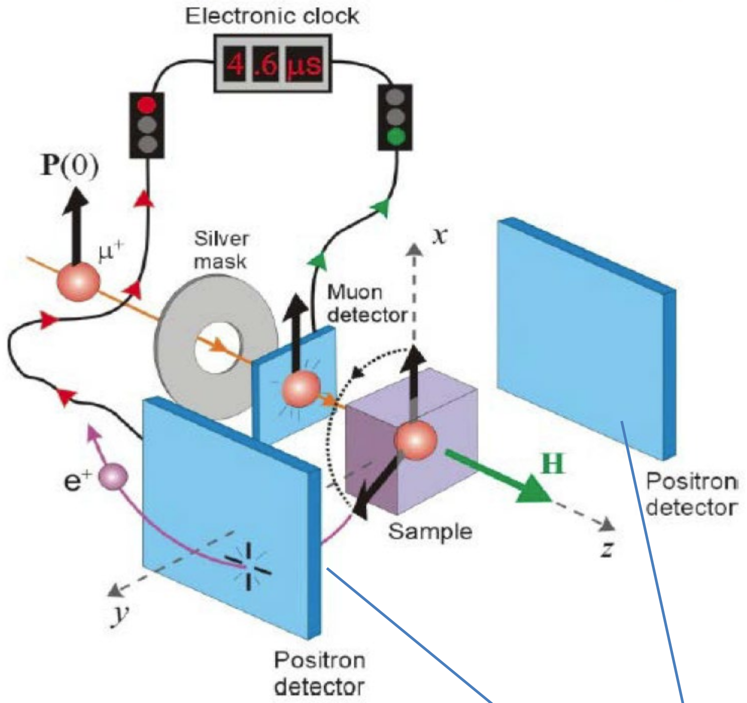


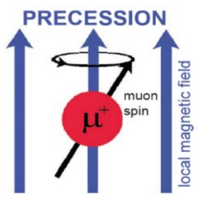
SIMS analysis performed at U Western Ontario

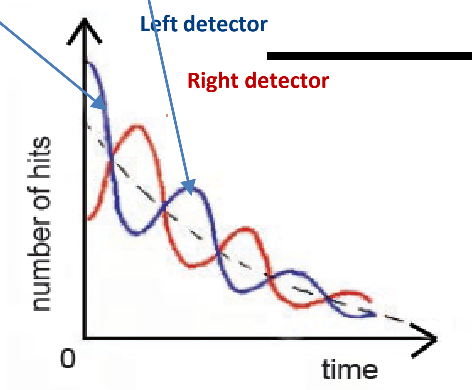
Muon Spin Rotation (µSR)

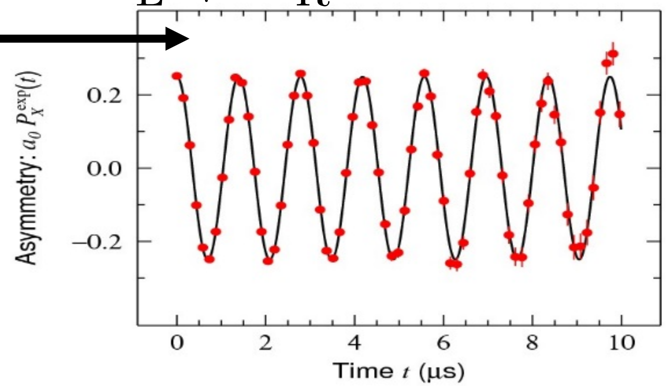


- Muons are deposited one at a time in a sample
- Muon decays emitting a positron preferentially aligned with the muon spin
- Right and left detectors record positron correlated with time of arrival
- The time evolution of the asymmetry in the two signals gives a measure of the local field in the sample

$$a_0 P_y(t) = \frac{N_L - N_R}{N_L + N_R}$$







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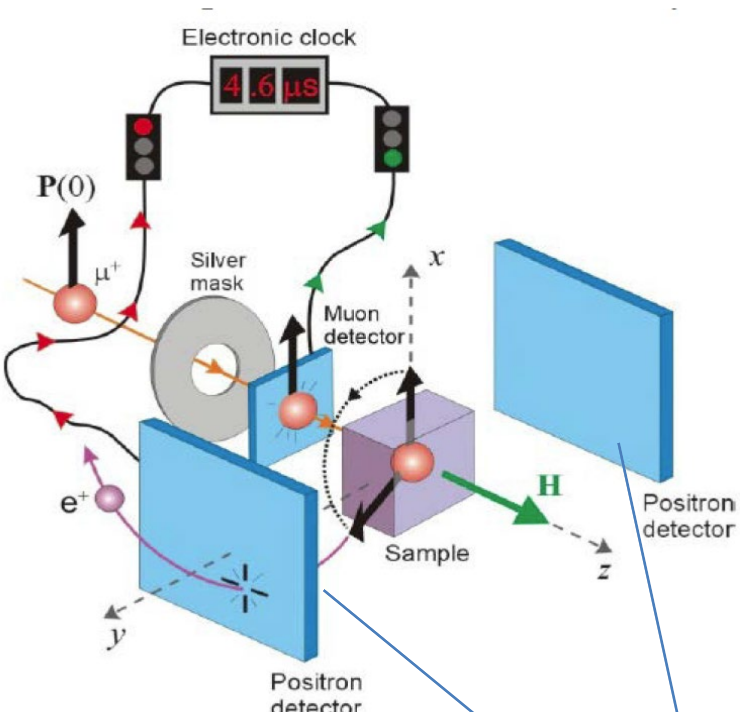

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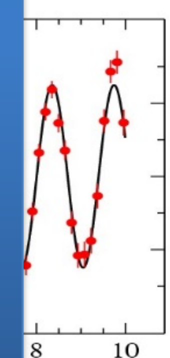
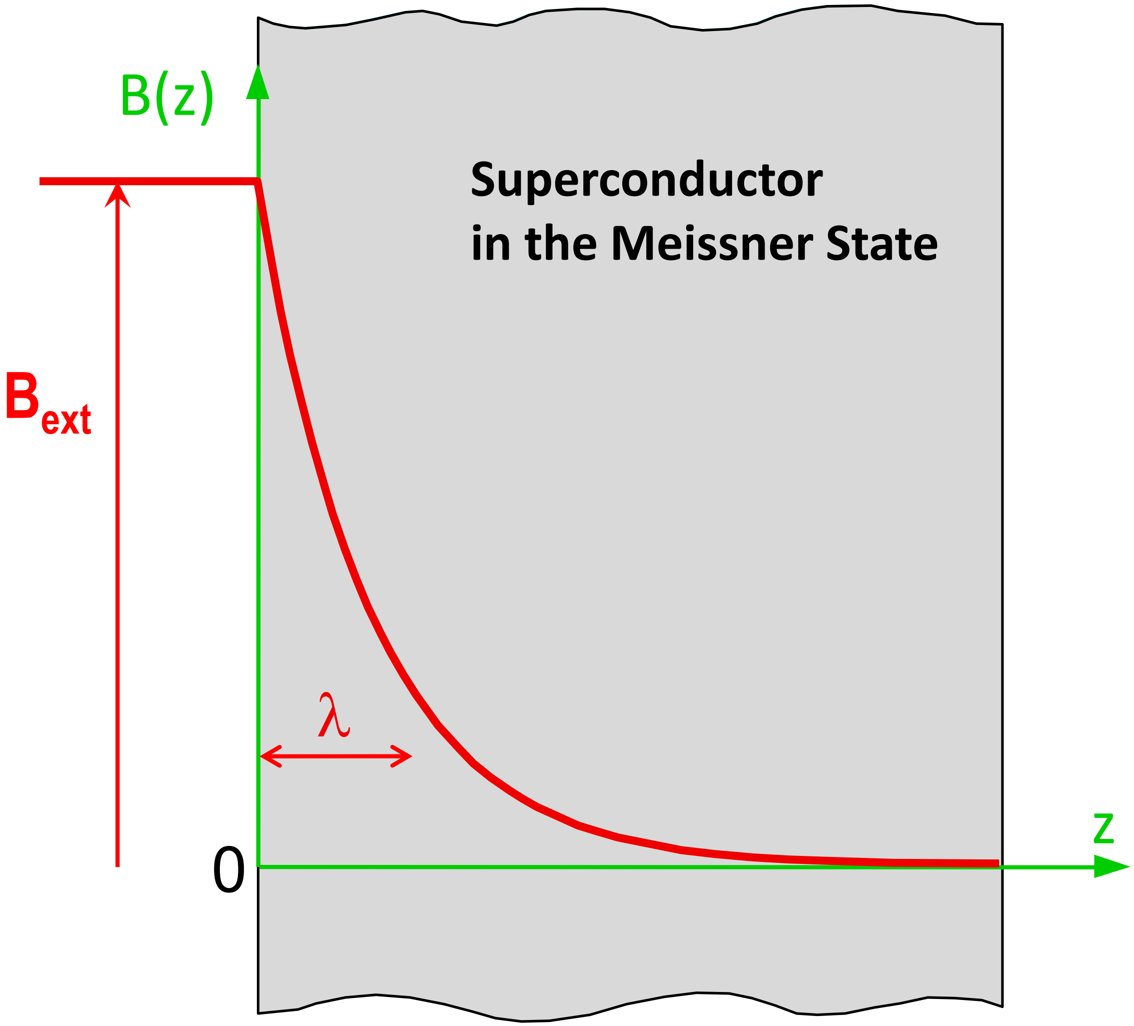
$$a_0 P_\mu(t) = \frac{N_\mathrm{L} - N_\mathrm{R}}{\cdots}$$

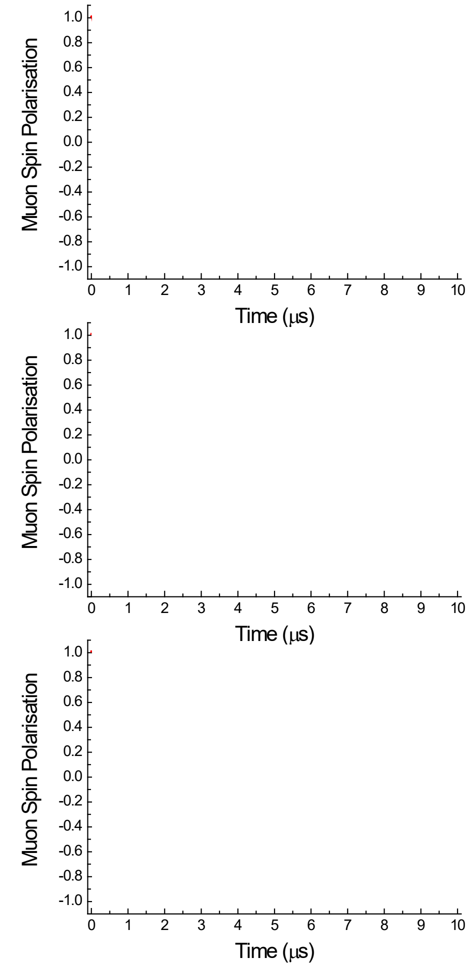


- µSR is a sensitive probe for the detection of the presence of local magnetic field and can thus be used to detect the transition from the Meissner to a vortex state
- µSR has been used for SRF studies since 2010
- We have established a techniques to measure the **pinning strength** and the **field of first flux entry** using different spectrometers and sample shapes

T. Junginger et al. PRAB 21, 032002 (2018)

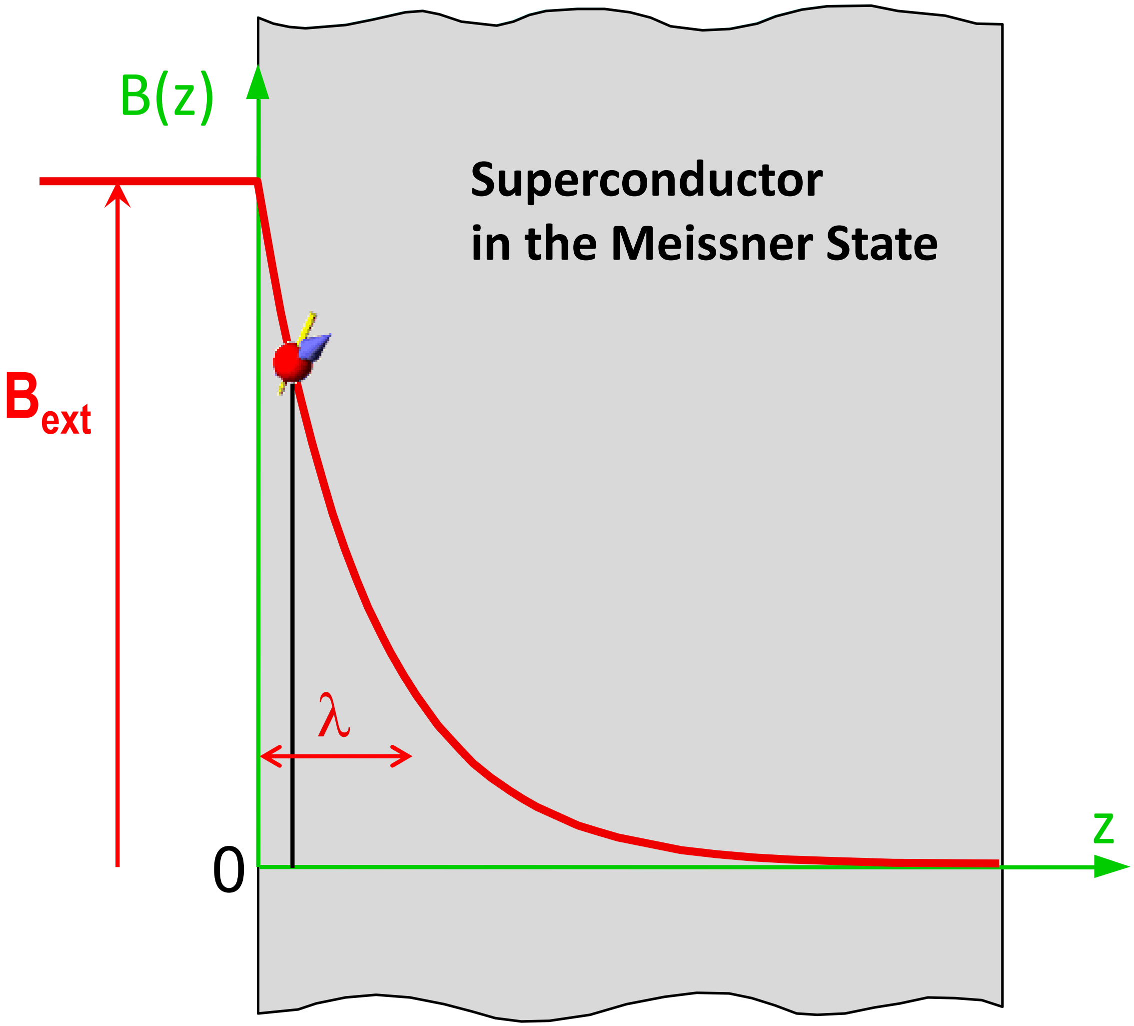
Low energy μSR (PSI)

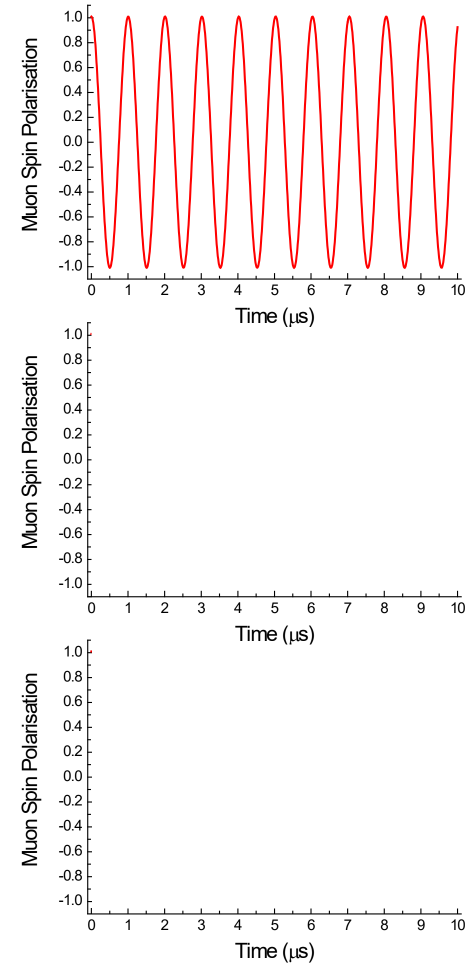




$$\omega_\mu(z) = \gamma_\mu B_{\mathrm{loc}}(z)$$

Low energy μSR (PSI)





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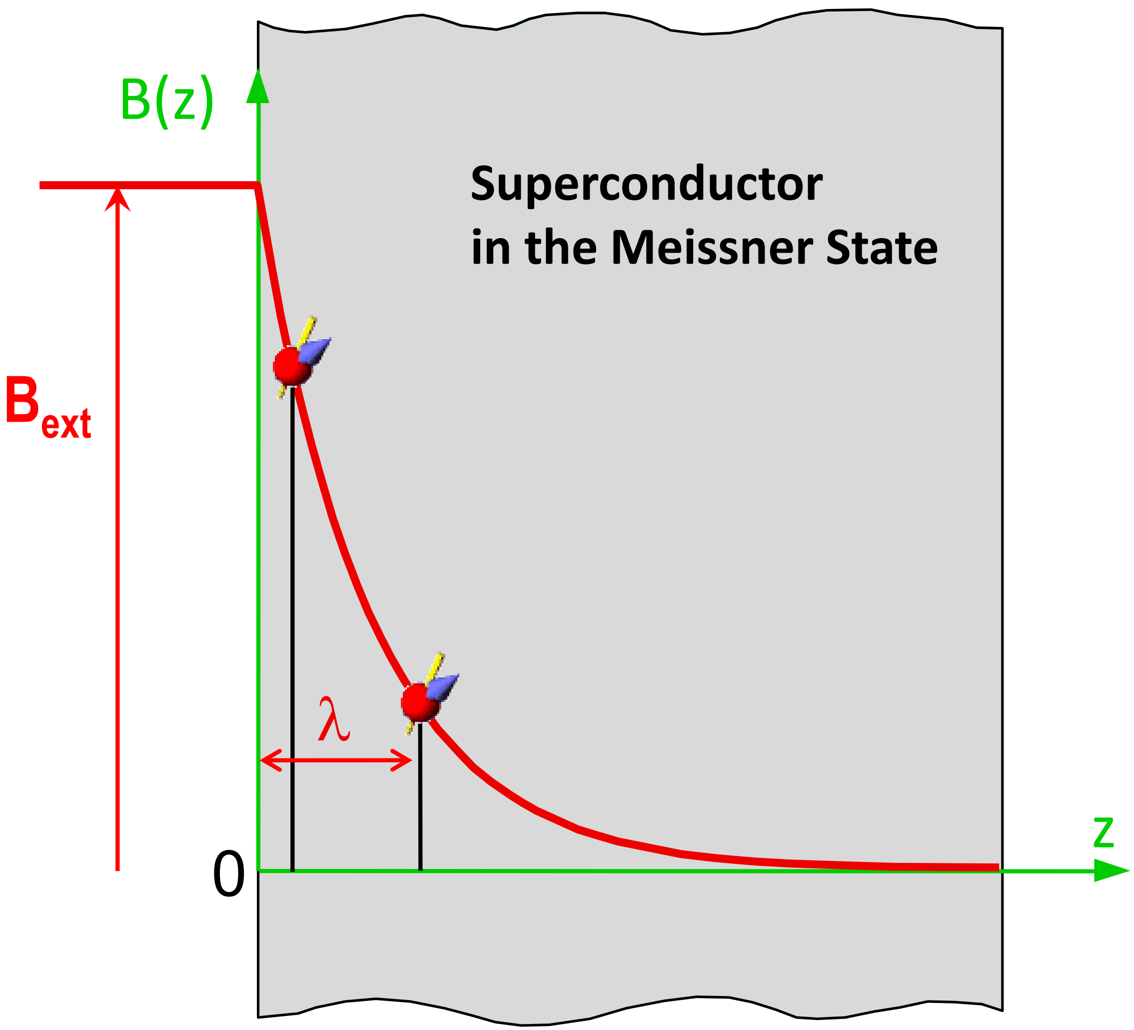

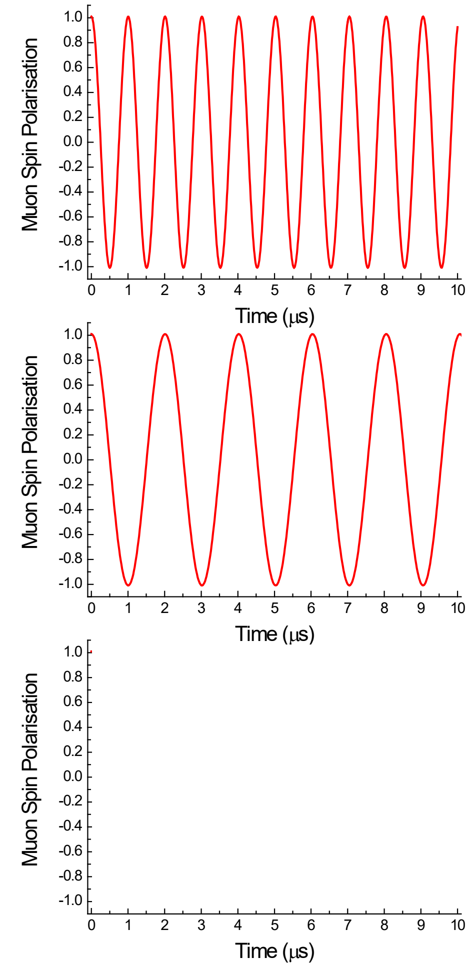

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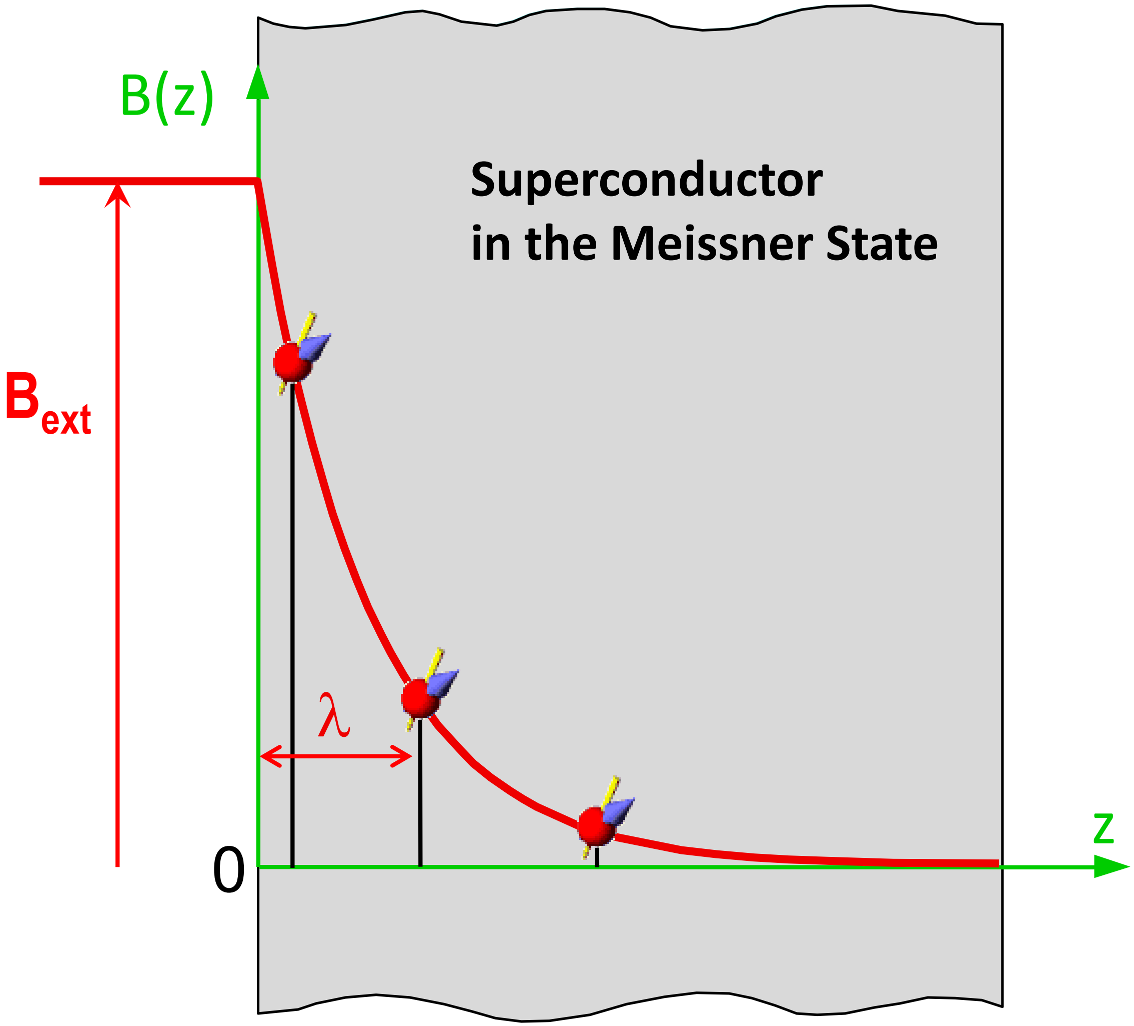
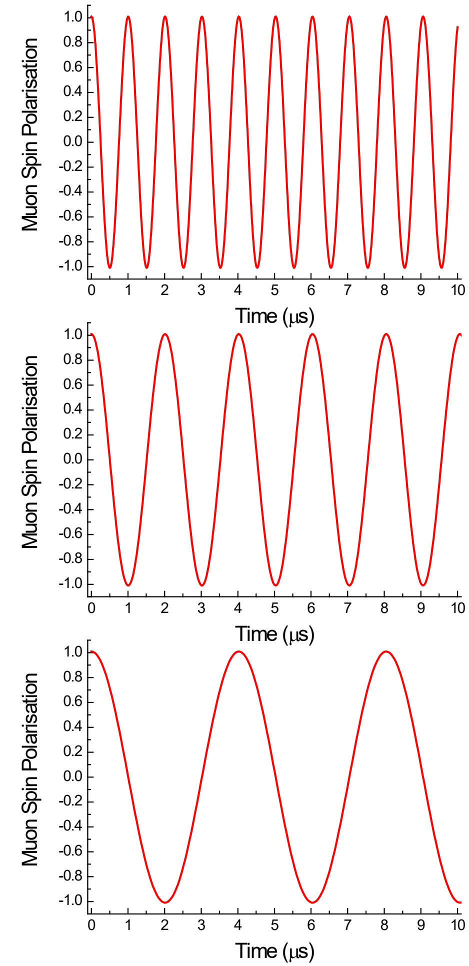
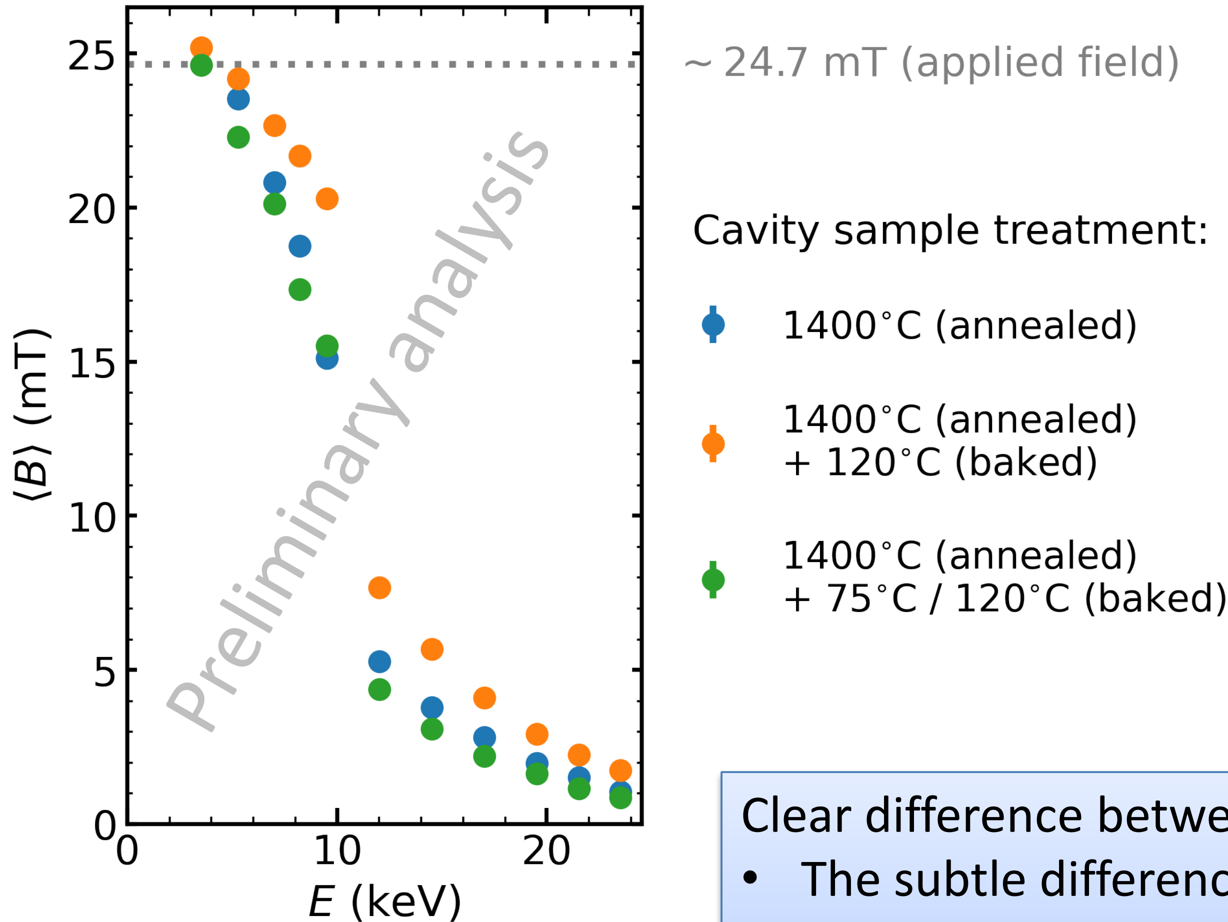




$$\omega_\mu(z) = \gamma_\mu B_{\mathrm{loc}}(z)$$

Low energy µSR results



Non-exponential decay for all samples

- Superconductors generally have a **non-local** current-voltage relation
- Clear change in screening for 120°C baking in the near surface area (confirmation of previous results)

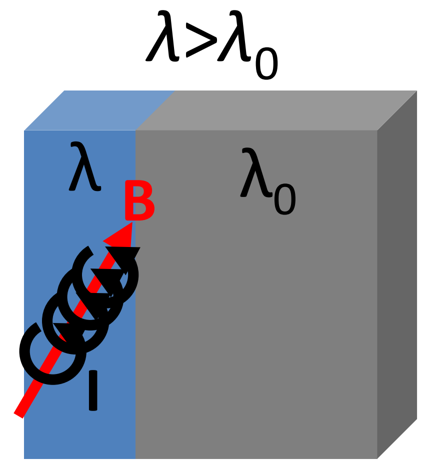
Clear difference between 120°C and 75/120°C

- The subtle difference in treatment has a strong effect in cavity performance and screening current
- Complex ongoing analysis

Origin of performance increase

Two possible effects

1. **Reduction in surface current** prevents quench
   - Ampère's law without Maxwell's correction $\nabla \times \boldsymbol{B} = \boldsymbol{\mu_0 J}$
2. **Effective bilayer with penetration depth λ larger in outermost layer**
   - Vortex at the SC/vacuum boundary
   - Magnetic field is parallel to the surface
   - Modelled by image vortex
   - Attractive force →Bean-Livingston barrier
   - If λ>λ0 there is second energy barrier at the interface between the layer and the substrate



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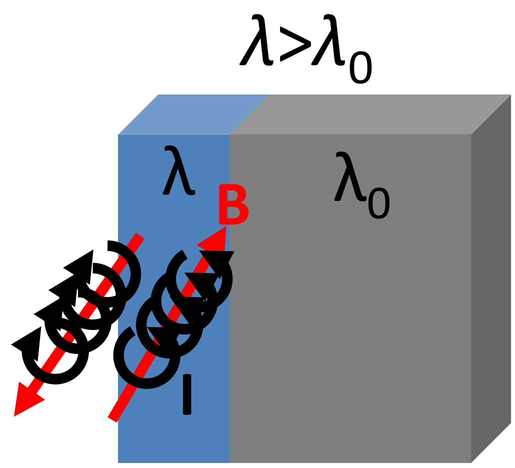

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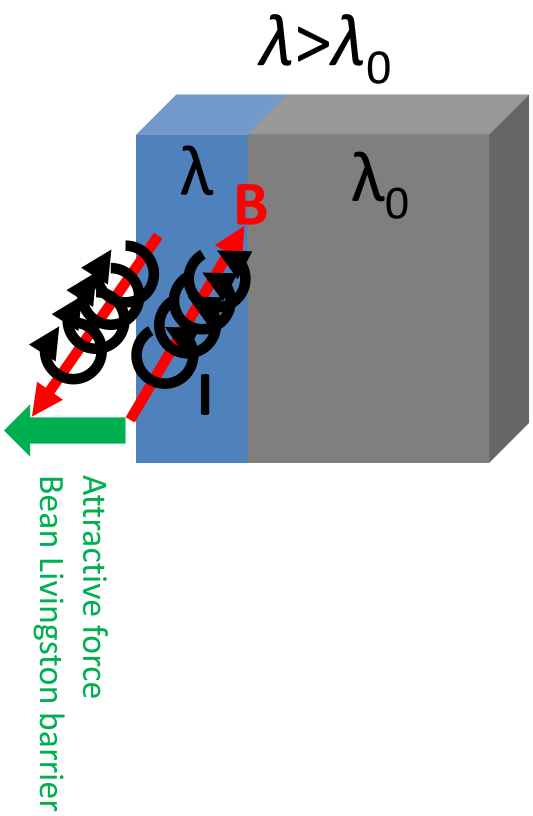

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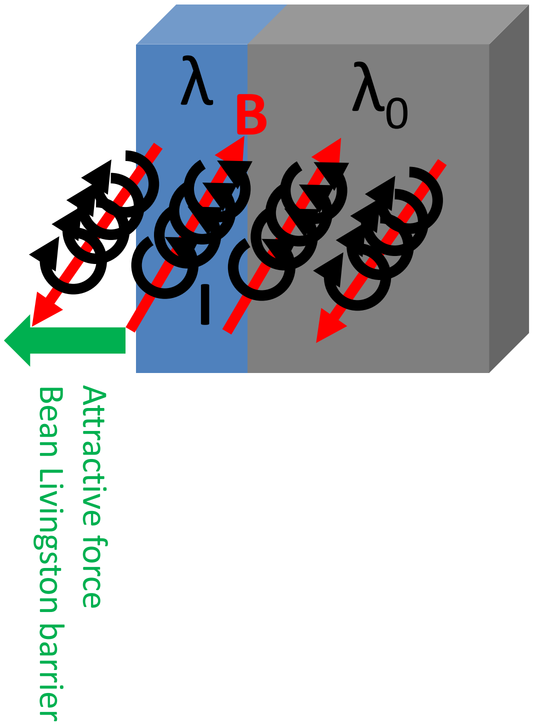
$\lambda > \lambda_0$



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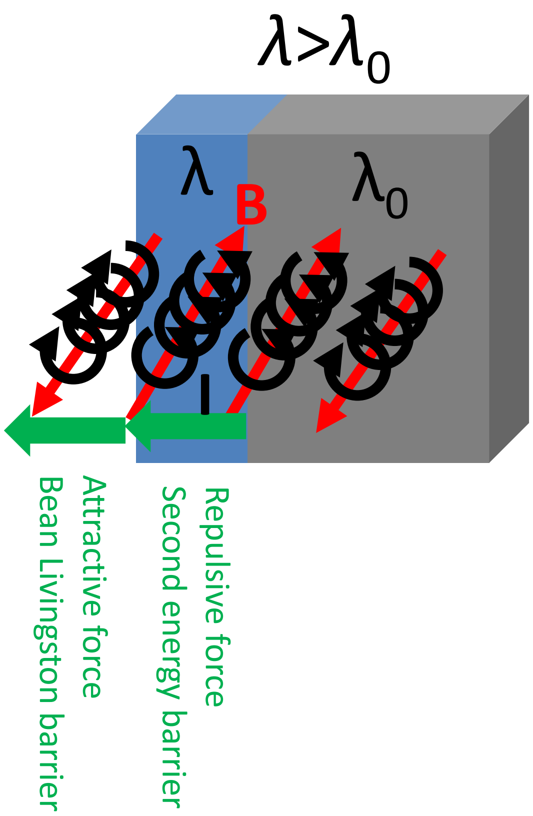
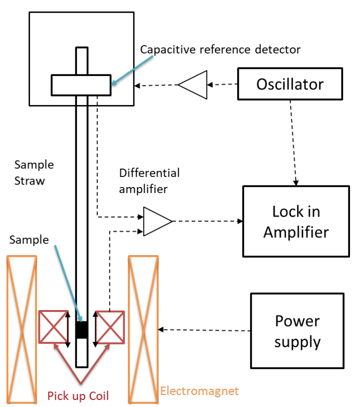
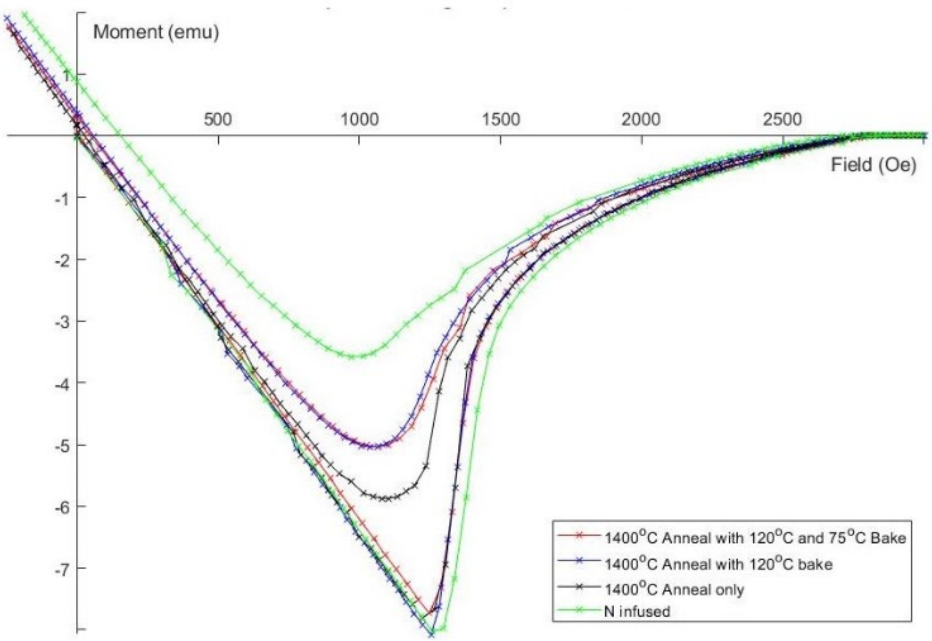


Field of first vortex penetration

Superconducting sample in external magnetic below H_{c1} or H_{sh} will repel field by surface currents (Meissner effect)

- Sample gets magnetized
- Sample is vibrated and the magnetization is measured with a lock-in amplifier tuned to the vibration frequency
- Magnetization *M* of the sample is measured with a lock-in-amplifier tuned to the vibration frequency. From the *M* vs *H* curve the field of first vortex penetration is measured
- Commercial vibrating sample magnetometer has been used





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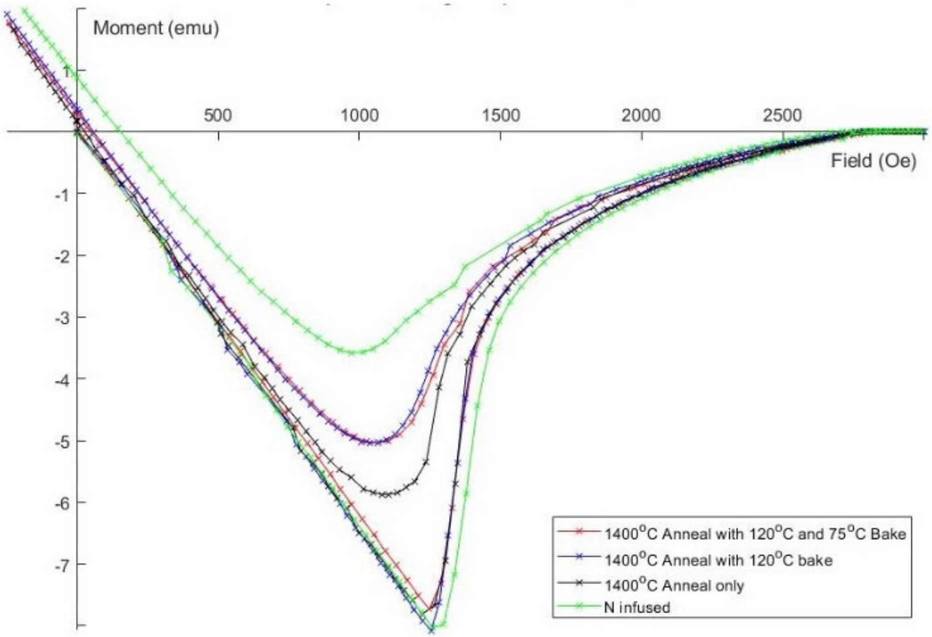
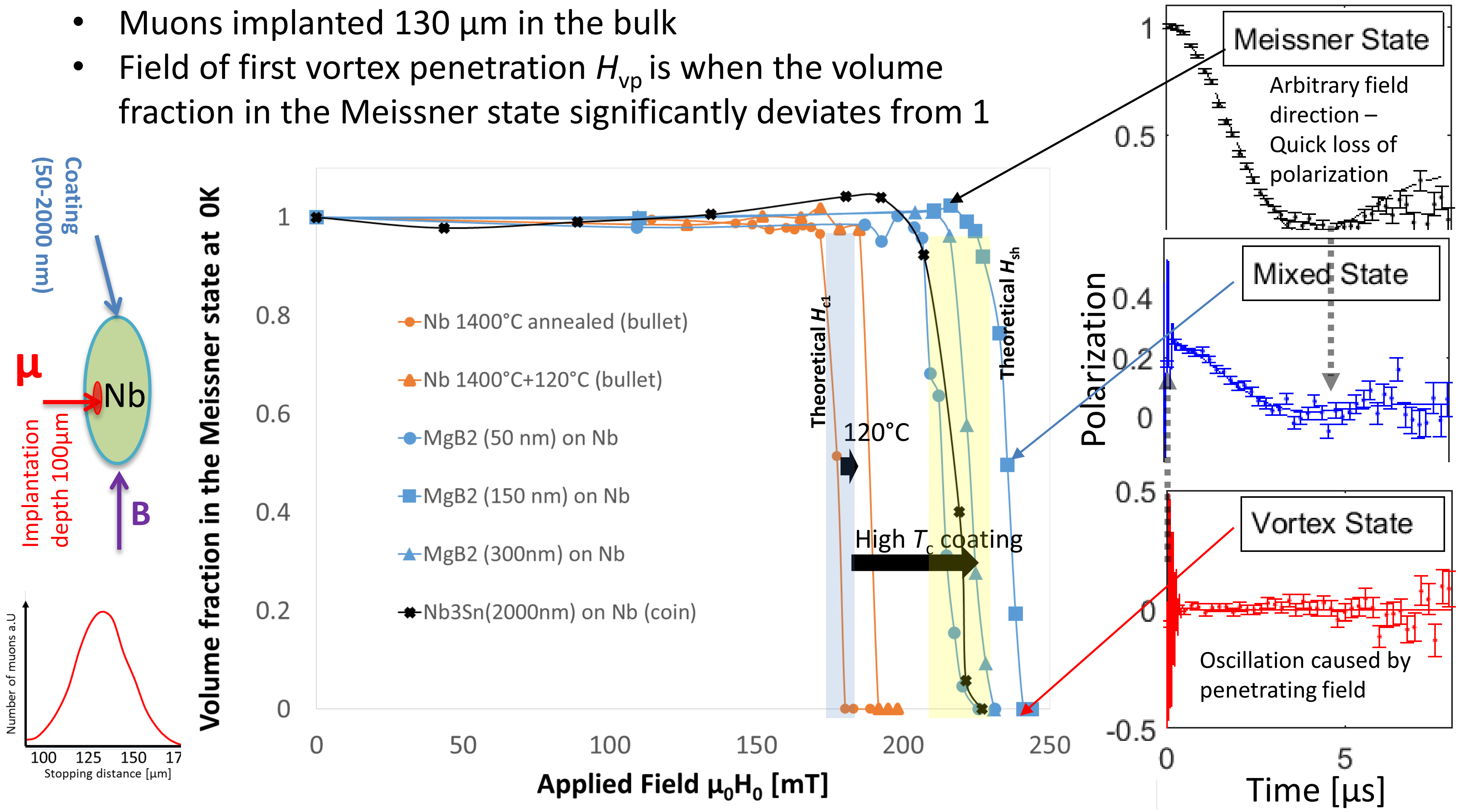
The **DC** field of first vortex penetration is not enhanced for low temperature baked niobium.
What if we can use a real bi-layer of two superconductors? The lack of elliptical samples required to use a local probe - µSR



μSR - Field of first flux entry measurements

- Nb_3Sn and MgB_2 with 50-2000 nm thickness on niobium
- Muons implanted 130 μm in the bulk
- Field of first vortex penetration H_{vp} is when the volume fraction in the Meissner state significantly deviates from 1



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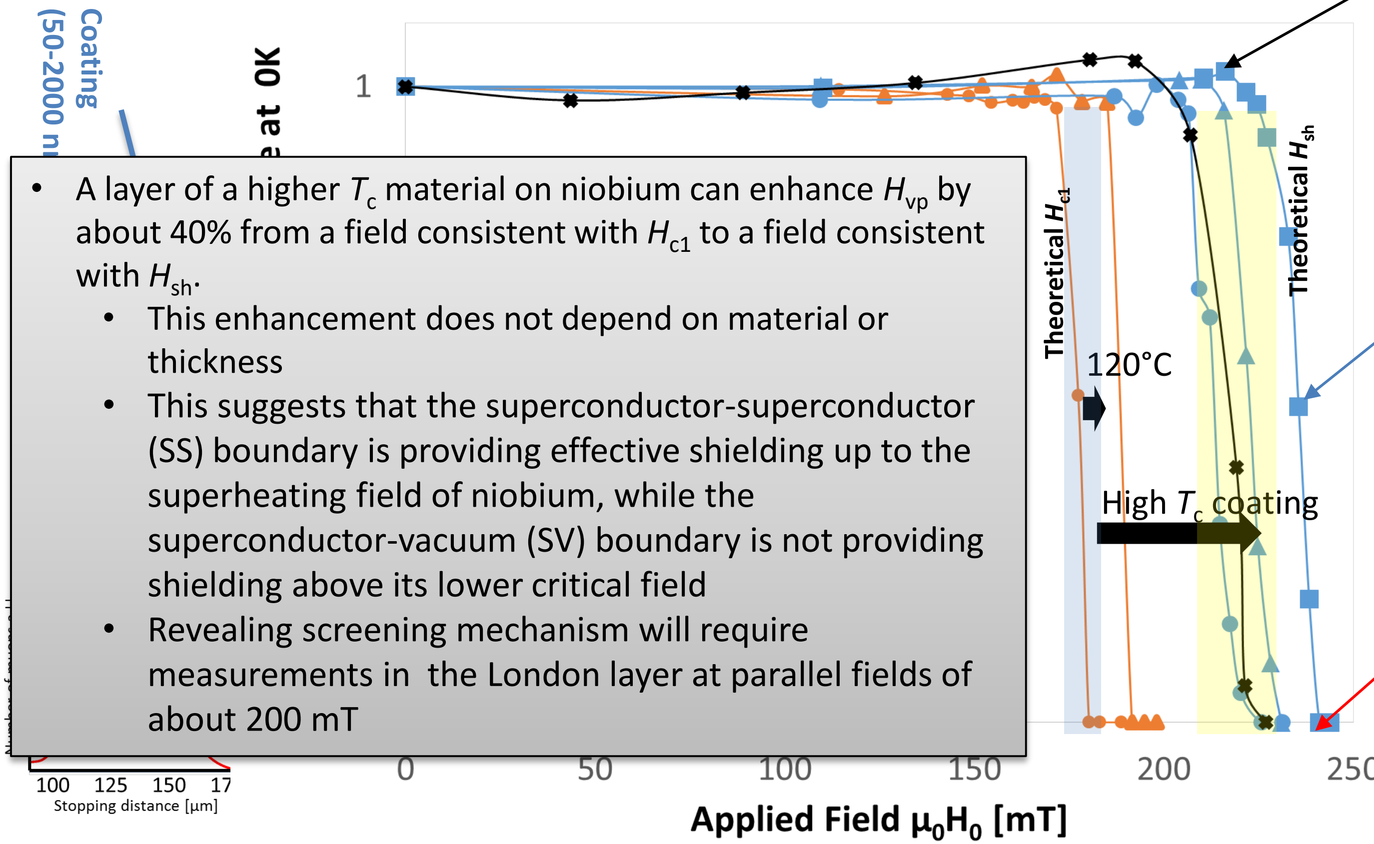
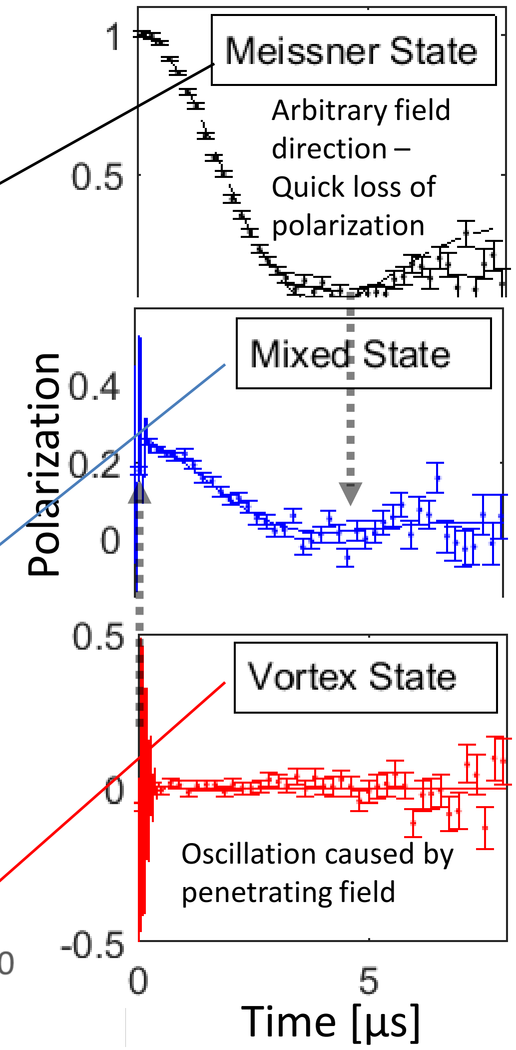


- A layer of a higher T_c material on niobium can enhance H_{vp} by about 40% from a field consistent with H_{c1} to a field consistent with H_{sh}.
  - This enhancement does not depend on material or thickness
  - This suggests that the superconductor-superconductor (SS) boundary is providing effective shielding up to the superheating field of niobium, while the superconductor-vacuum (SV) boundary is not providing shielding above its lower critical field
  - Revealing screening mechanism will require measurements in the London layer at parallel fields of about 200 mT



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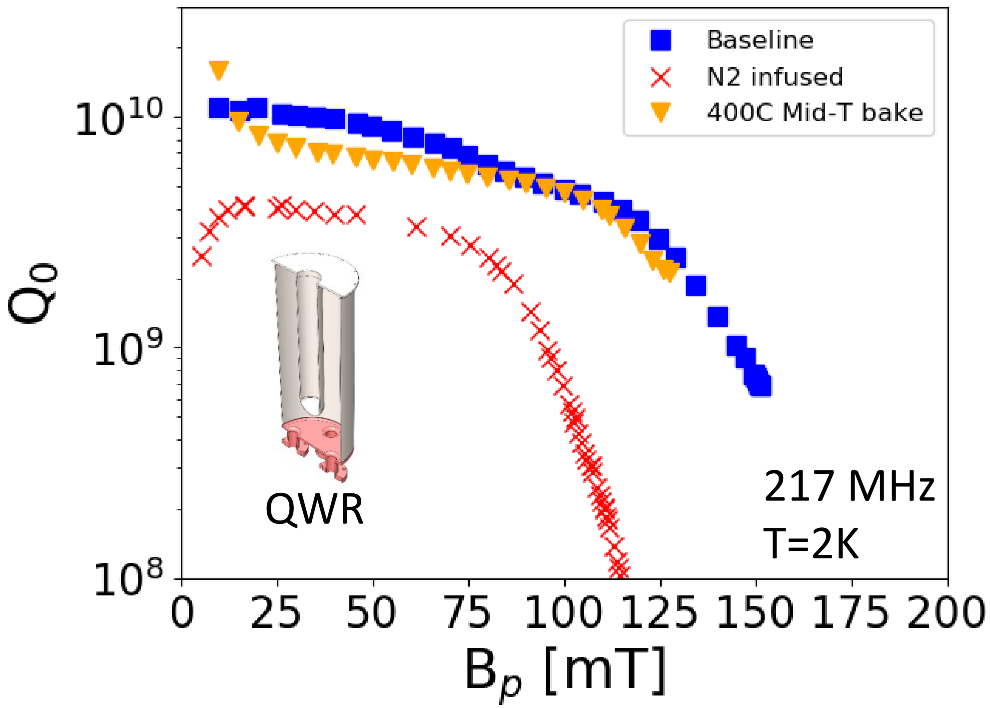
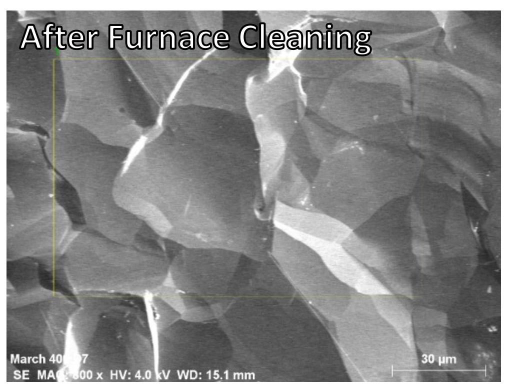
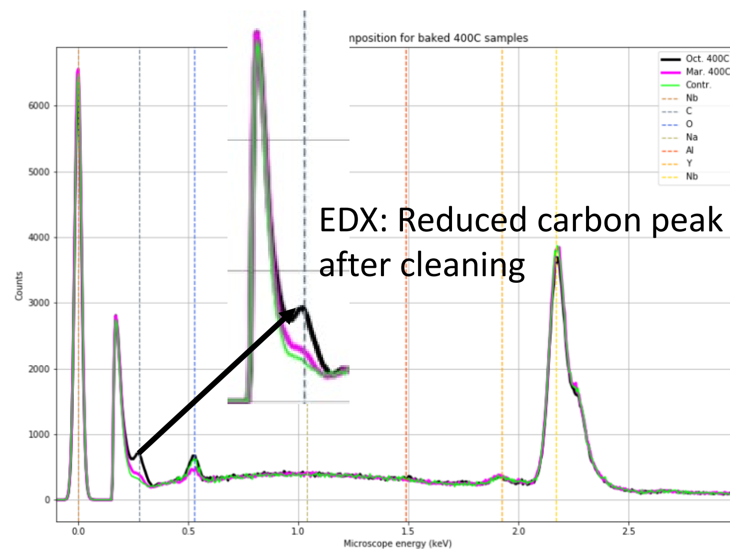
Coaxial Research Cavities at TRIUMF



Two new baking procedures tried for the first time on coaxial cavities

- Performance got weaker in both cases
- 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
- Furnace cleaning: Wiping down surfaces with methanol, cleaning burn-off at 100°C reduced CO2 content in RGA spectrum and EDX analysis
- **Next cavity has been treated and to be tested soon**

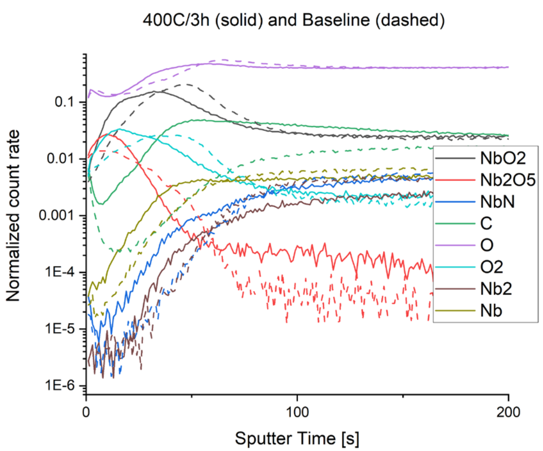




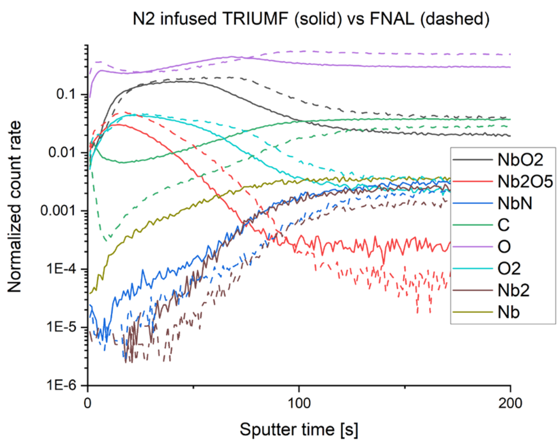
SEM: scanning electron microscopy, EDX: energy dispersive X-Ray spectroscopy, RGA: residual gas analyzer

SIMS + SEM sample study

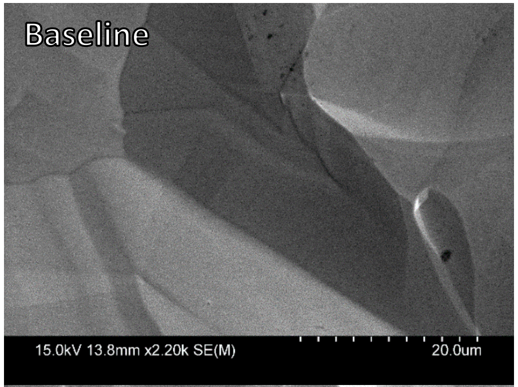
- EDX generally only gives the elemental composition for a fixed depth
- Secondary ion mass spectroscopy (SIMS) can provide depth can provide depth resolved elemental composition
- Most SIMS traces are very similar, except Carbon.

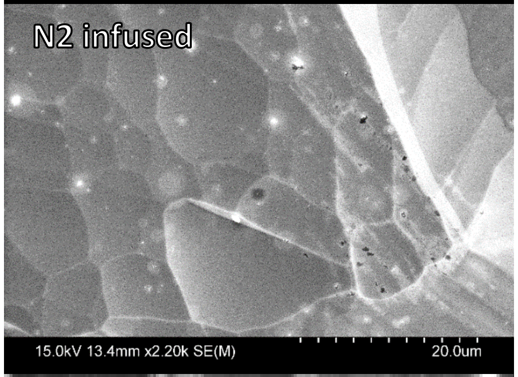


Witness samples for baseline test and 400°C treatment



Witness samples for N2 Infusion compared with a sample from Fermilab (High performing)





SIMS analysis performed at U Western Ontario

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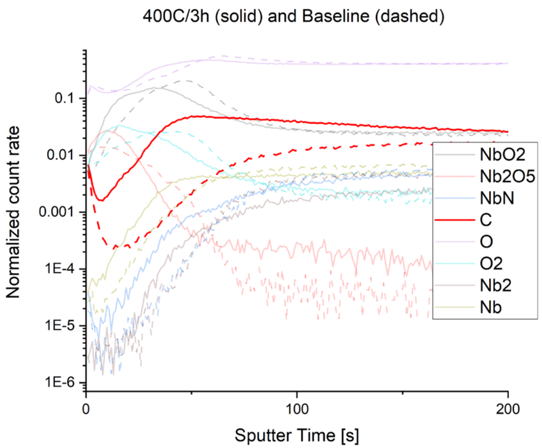

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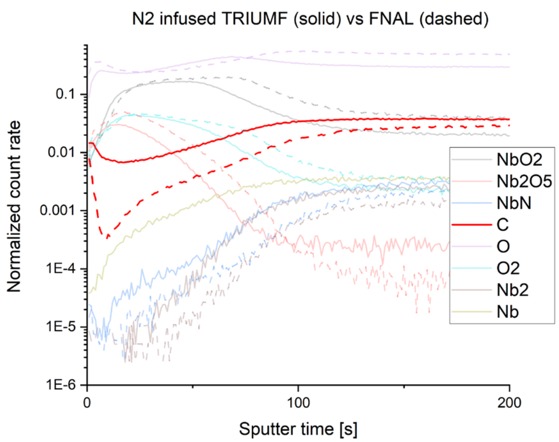

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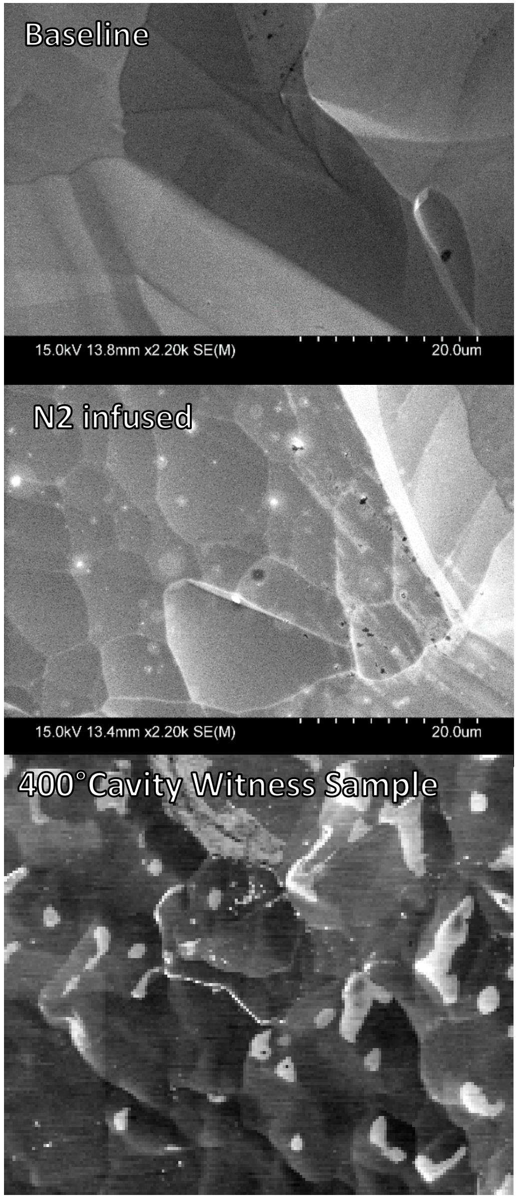

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