Dust migration into (S)RF cavities

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Outline

1. Superconducting RF at TRIUMF
2. Dust and Field Emission
3. Historical Studies
4. Proposed Mitigation Technique

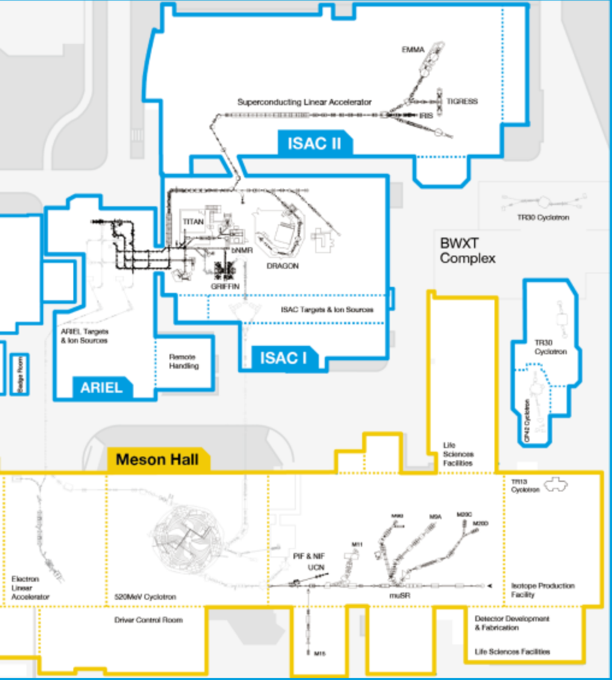
TRIUMF: Canada's particle accelerator centre

Founded in 1968 by 3 universities, TRIUMF has evolved into a multidisciplinary facility owned and operated by a consortium of Canadian universities from coast to coast.

TRIUMF is home to ~600 staff members and students.

Member Universities

University of Alberta
University of British Columbia
Carleton University
University of Calgary
University of Guelph
University of Manitoba
McMaster University
Université de Montréal
Queen's University
University of Regina
Simon Fraser University
University of Toronto
University of Victoria
York University



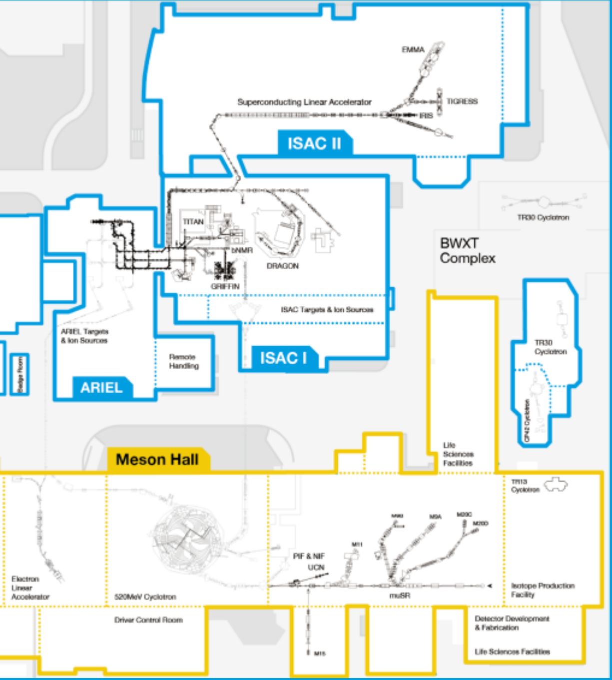
TRIUMF accelerator complex

A diversity of particle accelerators from:

- High-power to rare isotope beams
- Cyclotrons to Linacs
- Normal-conducting to superconducting
- Over 1 km of beamlines

Supporting:

- Flexible RIB delivery for physics
- Medical isotope research and production
- Neutron & muon science
- Accelerator R&D



Key Areas

520 MeV Cyclotron:

- Accelerates H^- ions for isotope production

ISAC I & II

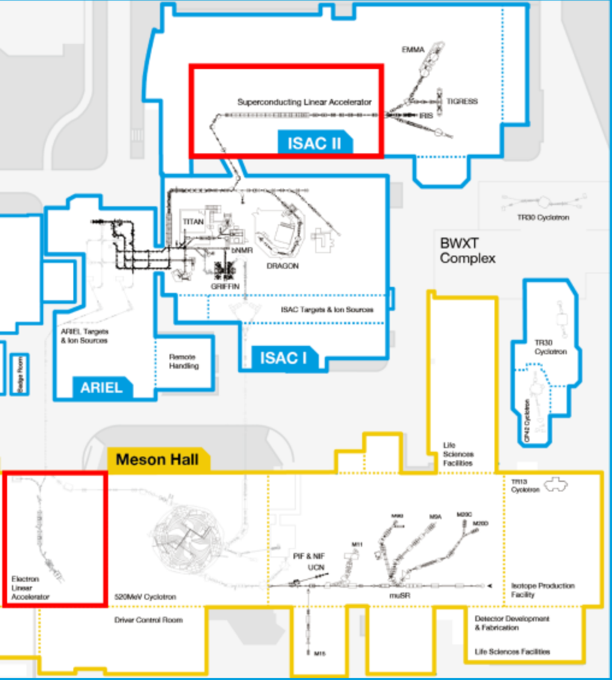
- Isotope separator and accelerator facility

ARIEL

- Advanced rare isotope laboratory

30 MeV Electron Linac (e-Linac)

- Second driver beam for ARIEL facility



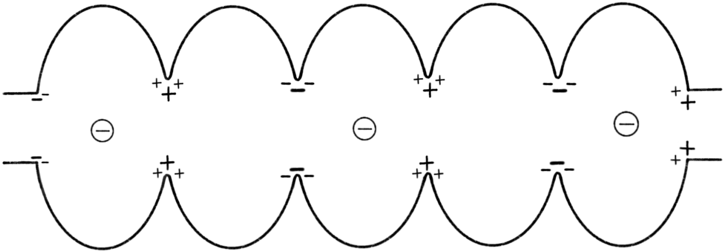
Main SRF lines

ISAC II

e-Linac

Radio frequency acceleration (RF)

- Technique of applying time varying electromagnetic (EM) fields to particles.
- Cavities designed to resonate at a specific frequency in synch with passage of particles to supply them with energy and accelerate them.



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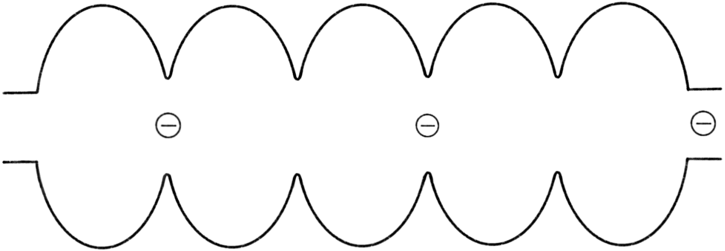

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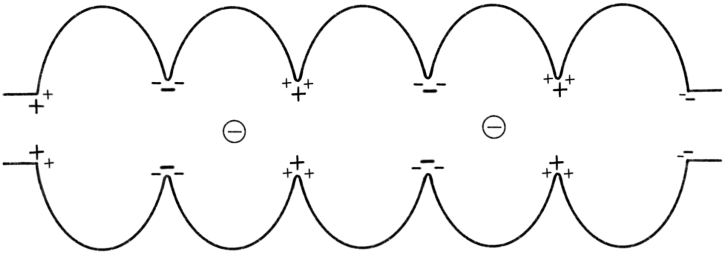
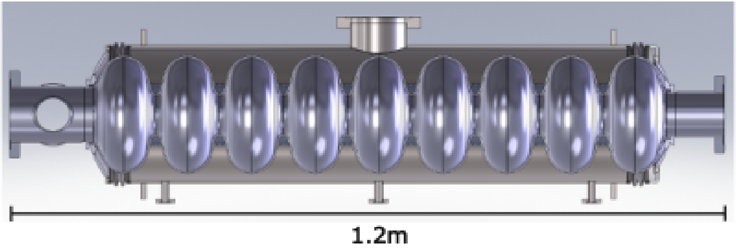


Superconducting RF (SRF)

- Use of superconducting materials (eg. Niobium) to build cavities.
- Kept at 2-4 degrees Kelvin $\rightarrow$ requires significant cryogenic infrastructure



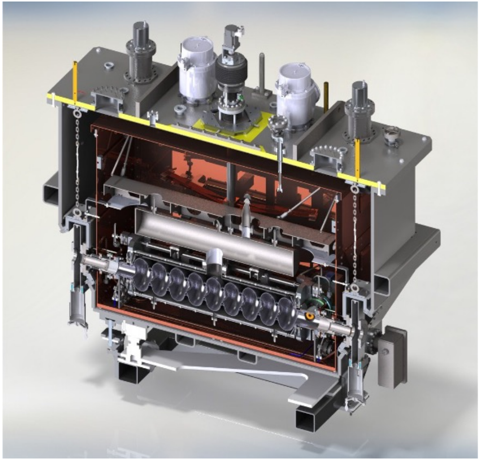
TRIUMF e-Linac superconducting niobium cavity

Superconducting RF (SRF)

Advantages of SRF cavities:

- More efficient power consumption:
  - $\approx$ 100x less AC wall power required vs normal conducting.
- Continuous wave (CW) and long-pulse operation achievable at high accelerating gradients (Ea)
- High **Quality Factor (Q)**:

$$Q = \frac{\text{Energy Stored}}{\text{Energy Dissipated}}$$



TRIUMF e-Linac injector cryomodule

Dust in SRF cavities $\rightarrow$ Field Emission (FE)

FE $\rightarrow$ emission of e^- from regions of high surface electric field.

Prevalent in SRF cavities due to high gradient.

Can cause:

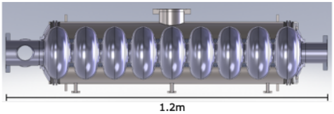
- Localized heating $\rightarrow$ extra load on RF power;
- Quench of superconducting state;
- X-rays $\rightarrow$ long term damage to equipment.

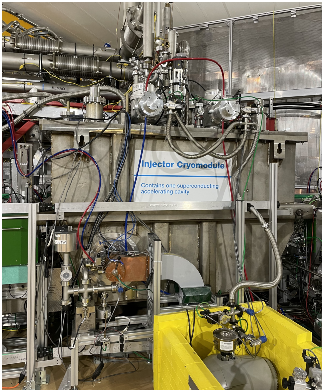
Emitters are commonly μm to sub μm sized contaminants $\rightarrow$ dust.

Field Emission at TRIUMF: e-Linac

RF parameters:

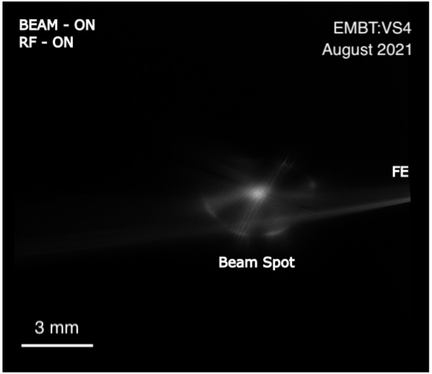
- $\beta \approx 1$
- 2 degrees Kelvin
- RF frequency 1.3 GHz
- Elliptical 9-cell cavities

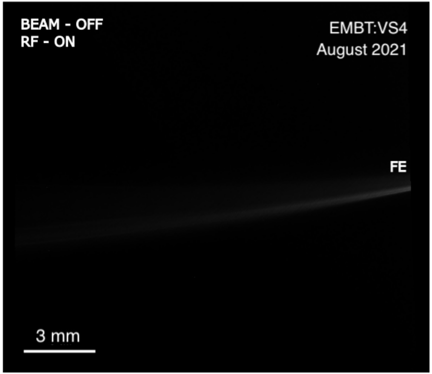




Field Emission at TRIUMF: e-Linac

Most easily observed on viewscreen diagnostics:

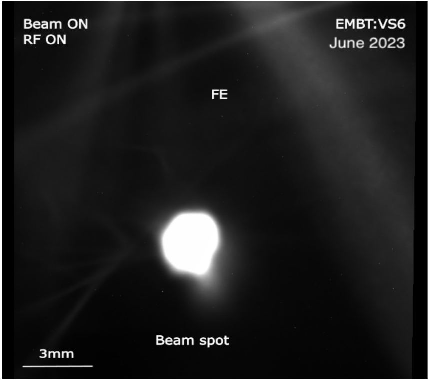


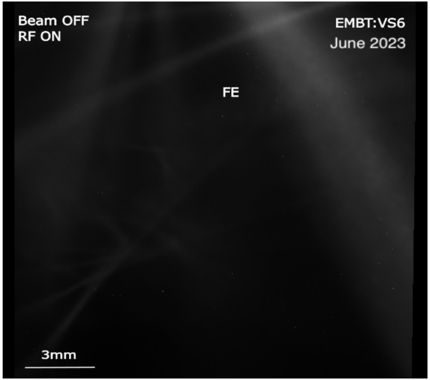


Field Emission REMAINS

Field Emission at TRIUMF: e-Linac

Most easily observed on viewscreen diagnostics:

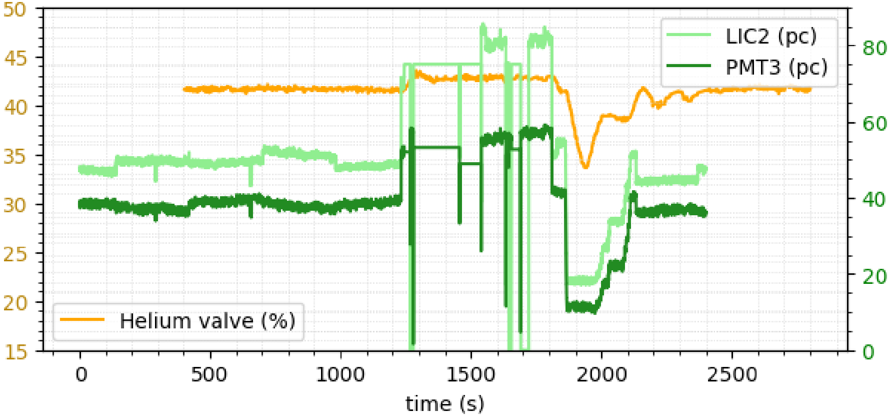




Field Emission REMAINS

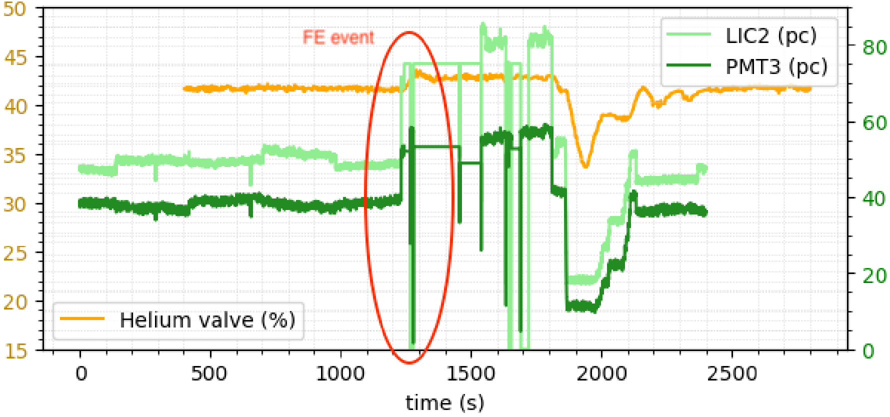
Field Emission at TRIUMF: e-Linac

Recent field emitter events as registered by RF and cryogenics readback:



Field Emission at TRIUMF: e-Linac

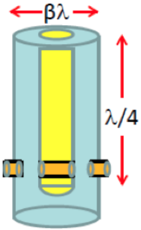
Simultaneous response from X-ray monitors and cryogenics system.



Field Emission at TRIUMF - ISAC II

RF parameters:

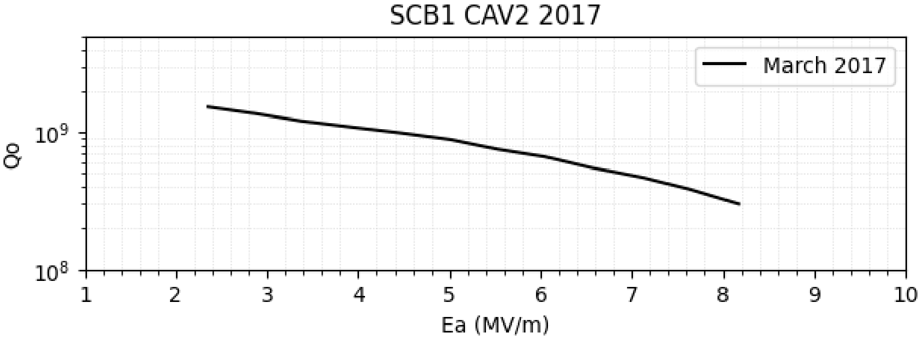
- Low β ($\approx$ 0.05-0.15)
- 4 degrees Kelvin
- RF frequency 106.08 MHz
- Quarter wave resonator cavities interspersed with SC solenoids



Quarter Wave - QWR

Q curve

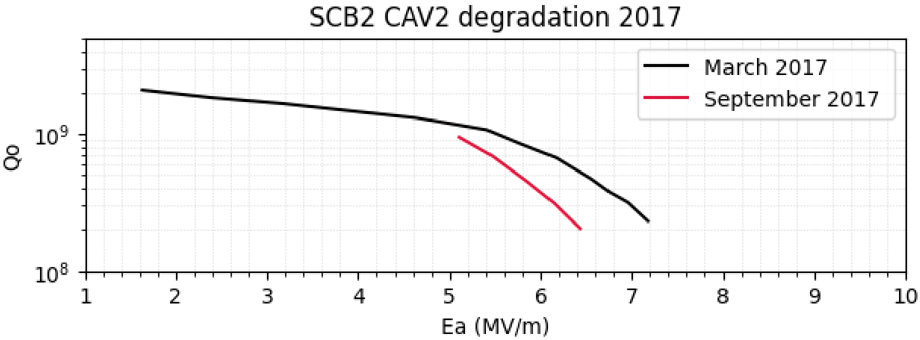
Cavity quality factor (Q) as a function of accelerating gradient (Ea).



Natural downward slope as Ea increases due to thermal effects.

Q degradation

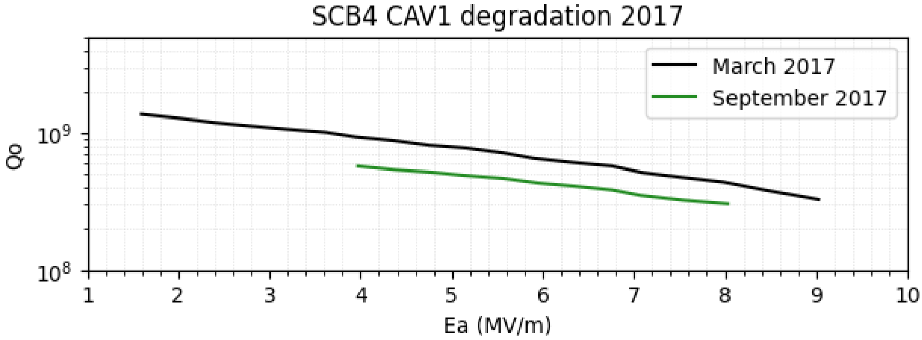
Direct load on RF power likely due to emission of FE electrons.



Q degradation

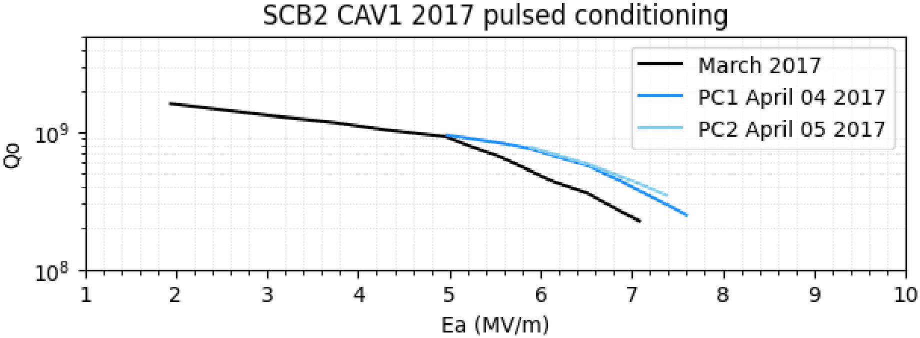
Particular case: quench of SC state due to heating of cavity walls from FE:

- Restoring SC state while exposed to solenoid fields → trapped fields



Current mitigation techniques

Pulsed conditioning → process emitters with short bursts of high field.



Other in situ techniques in development at TRIUMF:

- Helium conditioning: requires partial warmup of cavities.
- Plasma conditioning: requires room temperature conditions.

Z. Yao

Consequences of Q degradation

Higher RF power consumption needed to maintain same gradient.

Only so much cryo power available → forced to operate at lower gradient if enough cavities affected.

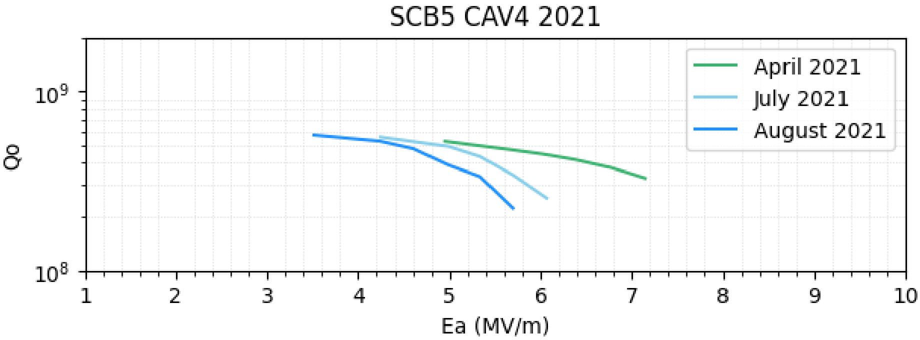
Limits the **energy output** of the facility.

Only way to fully restore the gradient is to remove cavity for reprocessing → considerable downtime

Recent Evidence Supporting Dust Migration - 2021

Progressive degradation of cavity quality factor over short period:

- Suggests progressive increase in field emission.

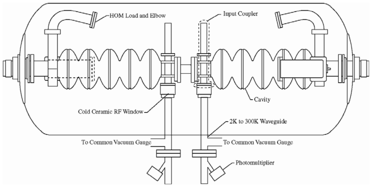


What is the cause of this degradation? → More fundamental issue...

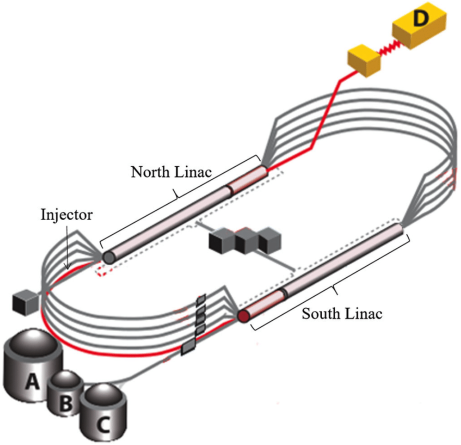
Historical Dust Studies - Jefferson Lab (JLab)

CEBAF - Continuous Electron Beam Accelerator Facility:

- Leading SRF based accelerator
- 5-cell/7-cell cavities



(Benesch, 2006)



(Tennant et al., 2020)

Historical Dust Studies - Jefferson Lab (JLab)

Series of studies on CEBAF beamline elements seeking to identify and characterize contaminating particulates. (2015-2019)

CEBAF FEL2 5-cell cavity dissection. (Geng et al.,2015)

Detailed collection and characterization process using scanning electron microscopy (SEM) to analyse collected samples.

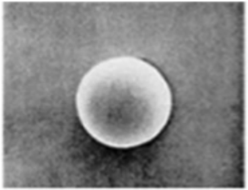
Particulate Characterization via SEM

Particulates are the principal cause of field emission, BUT not all particles emit.

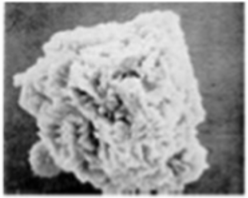
Influenced by:

- Geometry
- Conductivity

Where β = field enhancement factor.
(C.Z. Antoine, 2015)

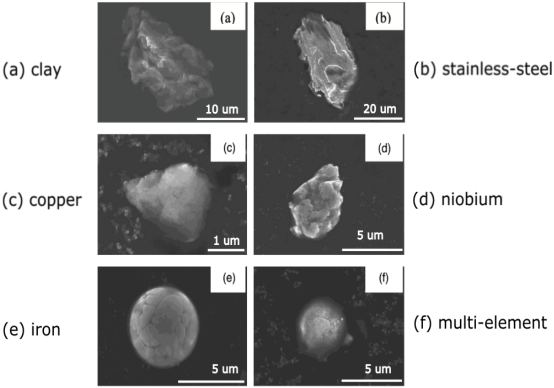


$\beta \sim 3$



$\beta \sim 100\text{-}500$

JLab Studies - Key Takeaways



(Geng et al.,2015)

Dust analysis defied expectations:

- Abundance
- Size
- Location

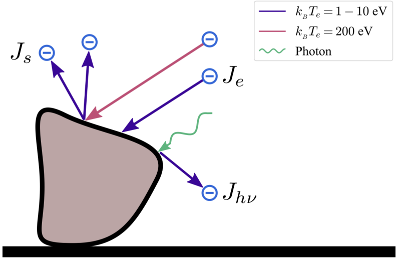
⇒ Migrate via unknown mechanism

Historical Dust Studies - LHC

Injection kicker beam losses investigated Goddard et al.,2012

- Time scale of UFO events too short to be gravity
- particles must be **charged**

Significant contribution on charging mechanisms of dust in accelerator systems Bélanger et al., 2022



Hypothesis: Migration of dust into SRF cavities is linked to charge

RIKEN, Japan

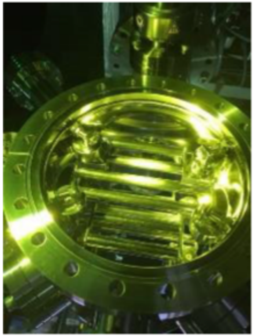
19th Int. Conf. on RF Superconductivity SRF2019, Dresden, Germany JACoW Publishing
ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-TUP013

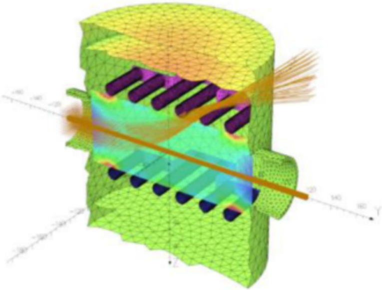
NON-EVAPORABLE GETTER-BASED DIFFERENTIAL PUMPING SYSTEM FOR SRILAC AT RIBF

H. Imao, K. Yamada, N. Sakamoto, T. Watanabe, Y. Watanabe, O. Kamigaito
RIKEN Nishina Center for Accelerator-based Science, Saitama, Japan
K. Oyamada
Sumitomo Heavy Industries Accelerator Science Ltd., Tokyo, Japan

Dipole field

- Deflect dust particulates circulating beam

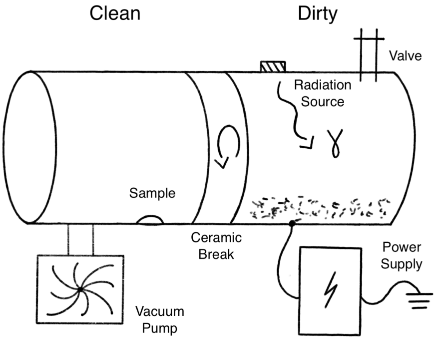


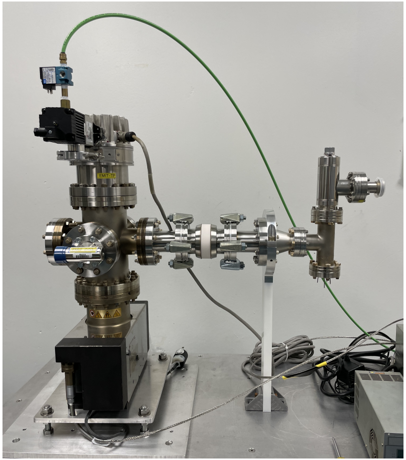


TRIUMF Study

Goal: Investigate dust migration mechanism and test mitigation technique

- Potential Barrier → Block particulates

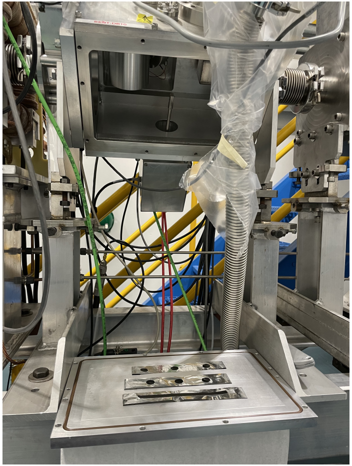




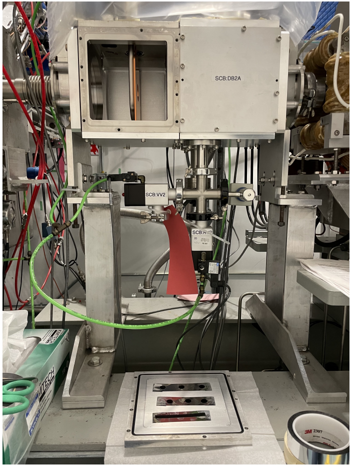
Sample Installation ISAC II SC Linac

Long term sample installation:

- Quantify particulate migration.



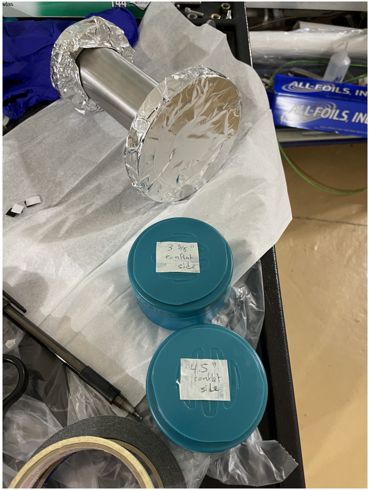
DB10



DB2B

Preliminary Analysis of e-Linac Particulates

- Installation of new diagnostics element.
- Breaking of vacuum and extraction of section of beampipe.
- Opportunity for sample collection.



Summary

- Evidence in TRIUMF SRF cavities of Q degradation due to particulate migration
- Hypothesis that migration is driven by charging of particulates
- Assembly of test setup to investigate mechanism and mitigation method
  $\rightarrow$ awaiting final components
- Analysis of existing contaminants in progress to better inform study

TRIUMF

Thank you
Merci

References I

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Jay Benesch. Field emission in cebaf's superconducting rf cavities and implications for future accelerators. *arXiv preprint physics/0606141*, 2006.

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CE Reece, J Spradlin, O Trofimova, AM Valente-Feliciano, et al. Standardized Beamline Particulate Characterization Analysis: Initial Application to CEBAF and LCLS-II Cryomodule Components. In *Proc. 18th Int. Conf. on RF Superconductivity (SRF'17)*, pages 647–650, 2017.

References II

CE Reece, JK Spradlin, Olga Trofimova, and Anne-Marie Valente-Feliciano. Identifying specific cryomodule and cleanroom particulate contamination: understanding legacy issues and providing new feedback standards. Technical report, Thomas Jefferson National Accelerator Facility (TJNAF), Newport News, VA ..., 2019.

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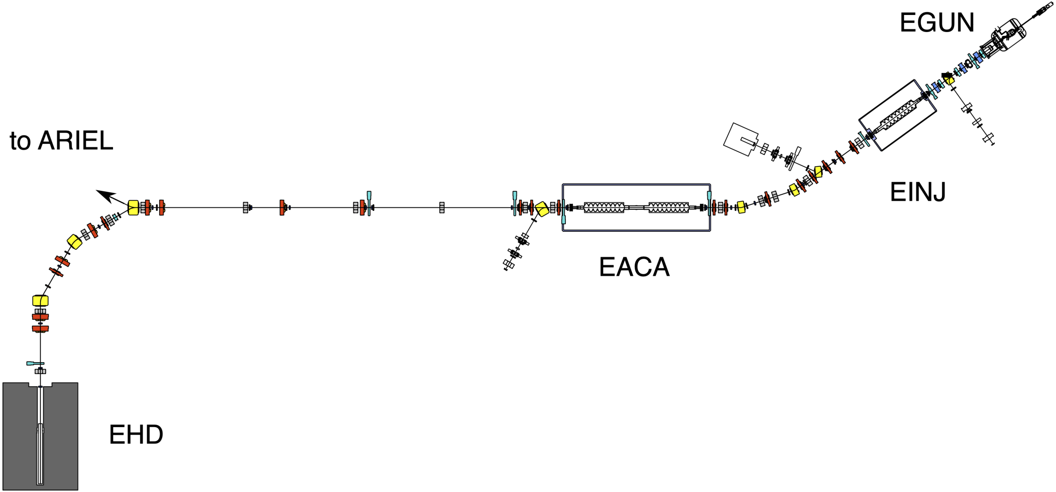
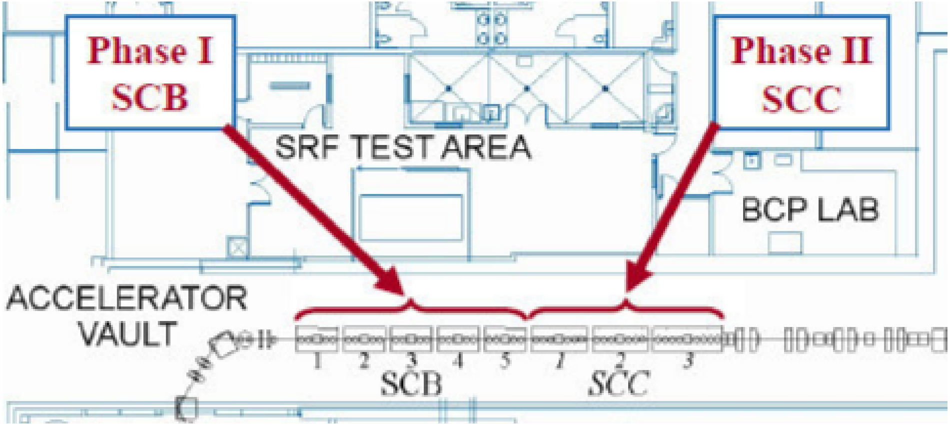
TRIUMF e-Linac



ISAC II


Phase I
SCB
Phase II
SCC
SRF TEST AREA
BCP LAB
ACCELERATOR
VAULT
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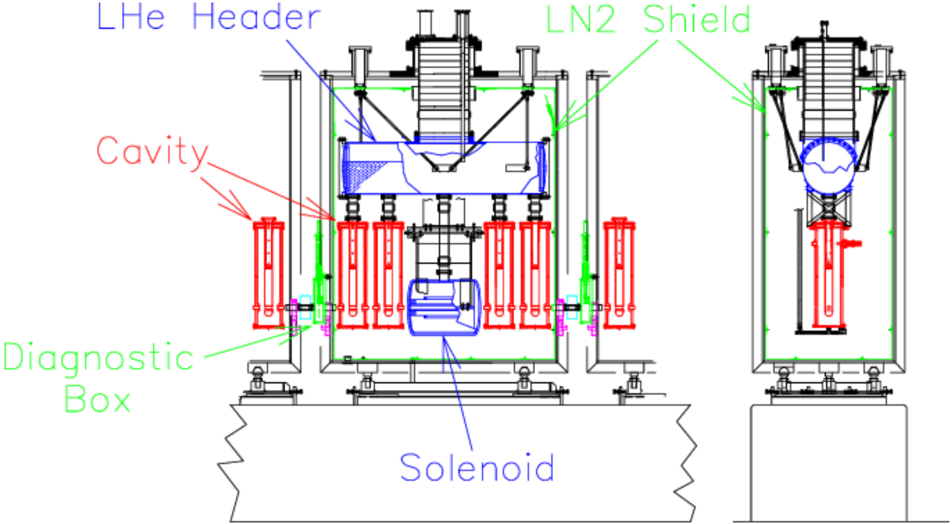
2
3
4
5
1
2
3
SCB
SCC

ISAC II



SEM principles