Material Science Underlying High Gradient Performance of NCRF structures and the Theory of RF Breakdown

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SLAC

GARD RF Roadmap Update - NCRF Meeting, 20 January 2026

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Outline

RF Breakdown

- Conditioning
- Reproducibility
- Statistics

Materials

- Properties
- Experimental results

Future needs of material research

Acknowledgment

Here I refer to results obtained by NLC/JLC/CLIC project and US High Gradient Collaboration which included SLAC/KEK/INFN/CERN/ANL/LANL/MIT etc.

For reference, yearly progress in this filed is reported in a series of workshops:

- HG series: with the latest one, 16th Workshop on Breakdown Science and High Gradient Accelerator Technology (HG2025): https://indico.fnal.gov/event/65159/
- MeVArc series: With the latest one, 12th International Workshop on Mechanism of Vacuum Arcs, with latest one, 12th MeVArc 2025: https://indico.cern.ch/event/1424597/
- And a 2025 workshop dedicated to materials:

  Materials for Bright Beams Workshop 2025: https://indico.classe.cornell.edu/event/2526/

Introduction

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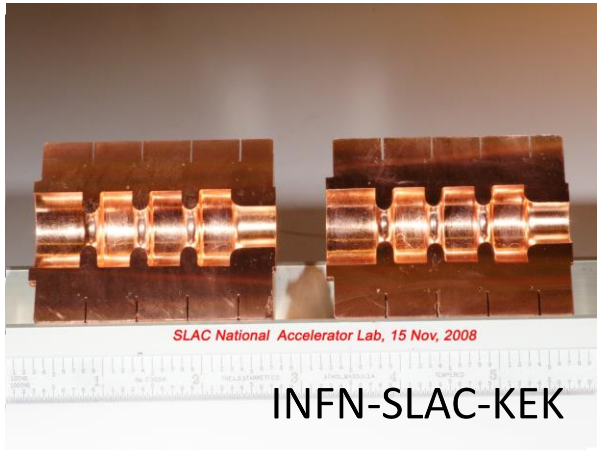
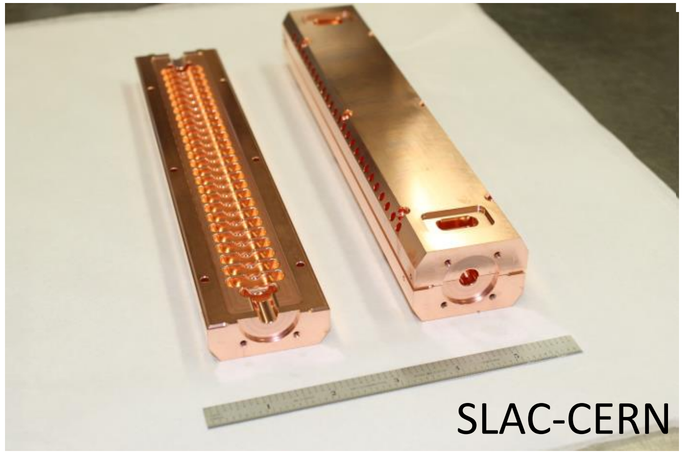
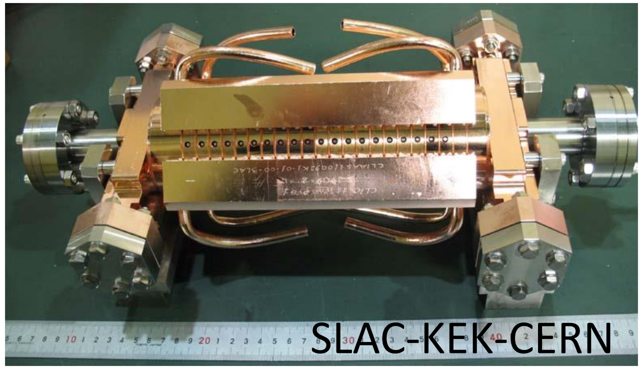
Most of systematic physics data for high gradient materials were obtained for narrow range of parameters, with main target a TeV-scale linear collider:

1. X-band
2. Pulse length 100-1500 ns
3. Standing wave and traveling wave structures of disk–loaded waveguide type supporting TM0 modes
4. Aperture radiuses of 3-6 mm, suitable for acceleration of nanocoulomb beams

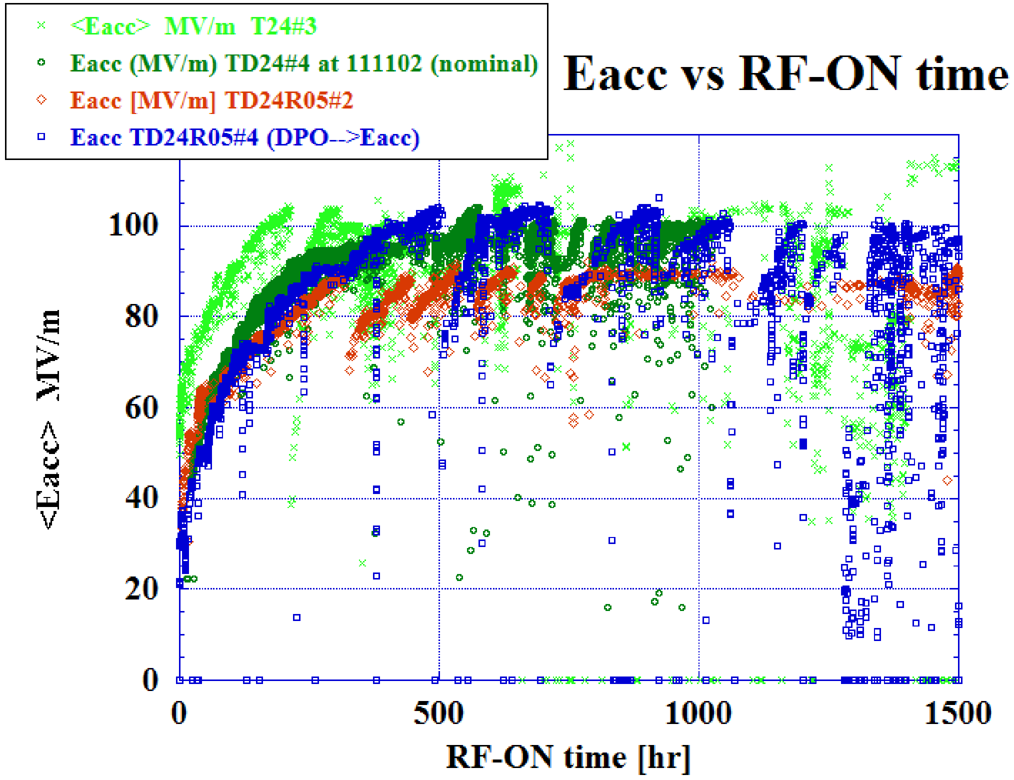






There is enormous parameters space for other frequencies, pulse length, modes, cryo, magnetic fields, etc. which is barely unexplored.

Conditioning



From Toshiyasu Higo, Performance of CLIC prototype accelerator structures tested at Nextef, CLIC2014, 4 February 2014

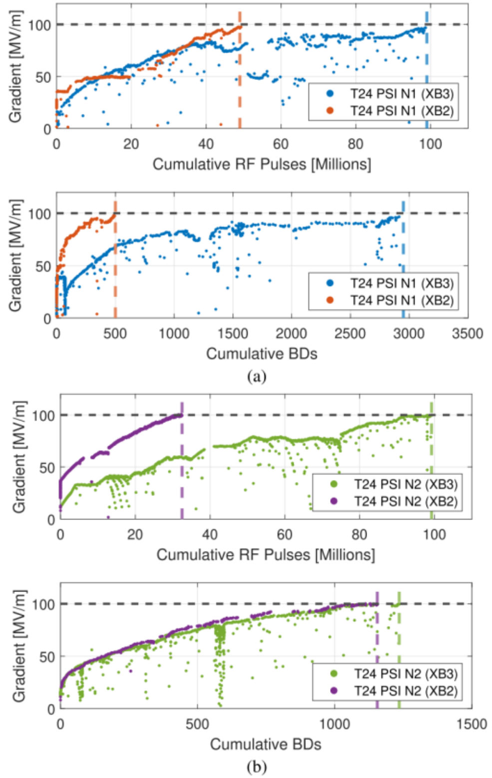
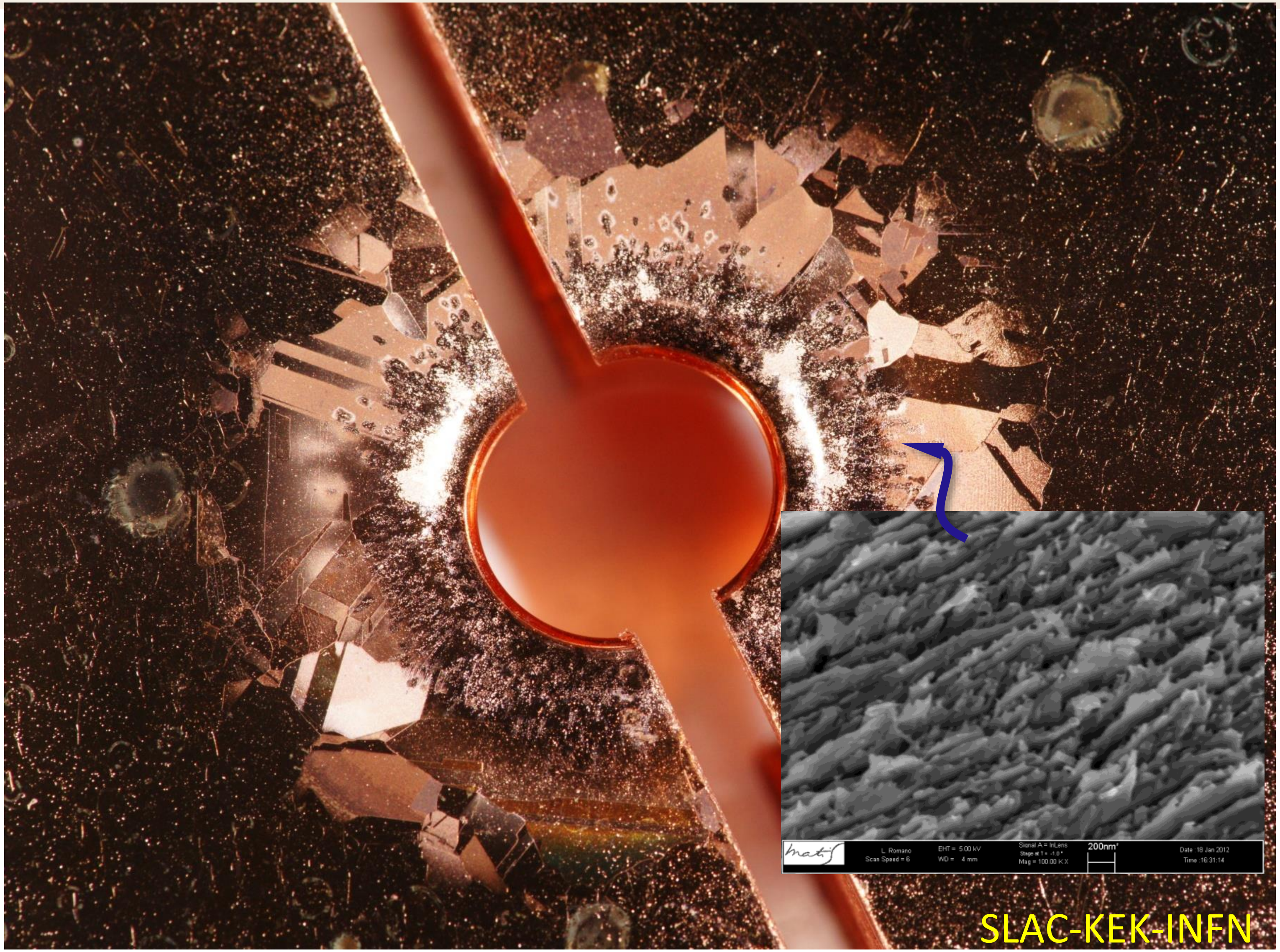


Fig. 18. Conditioning curves of (a) T24 PSI N1 and (b) N2 structures in Xbox-3 and Xbox-2. The numbers of pulses and breakdowns required to reach operation at 100 MV/m are shown by the vertical dashed lines.

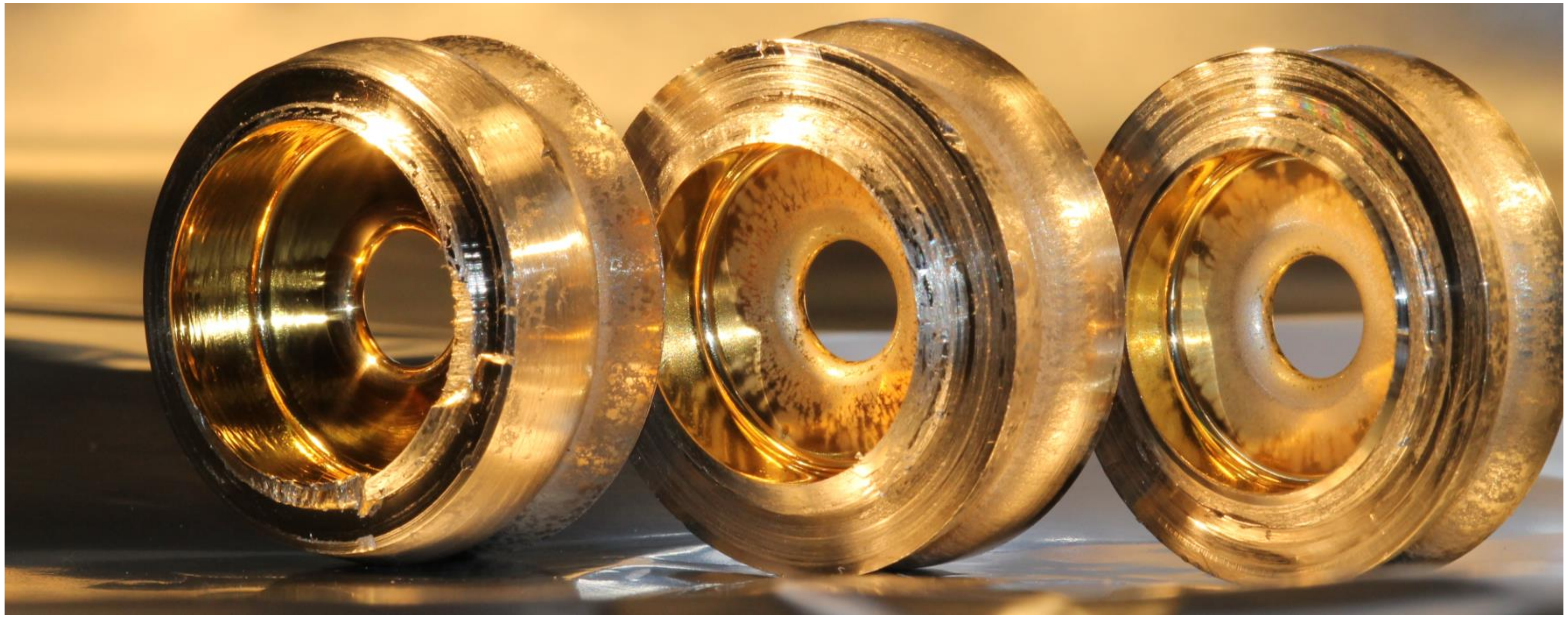
From W. L. Millar et al., "High-Power Test of Two Prototype X-Band Accelerating Structures Based on SwissFEL Fabrication Technology," in IEEE Transactions on Nuclear Science, vol. 70, no. 1, pp. 1-19, Jan. 2023, doi: 10.1109/TNS.2022.3230567.

Conditioning of multi-cell traveling wave structures takes months and millions of pulses

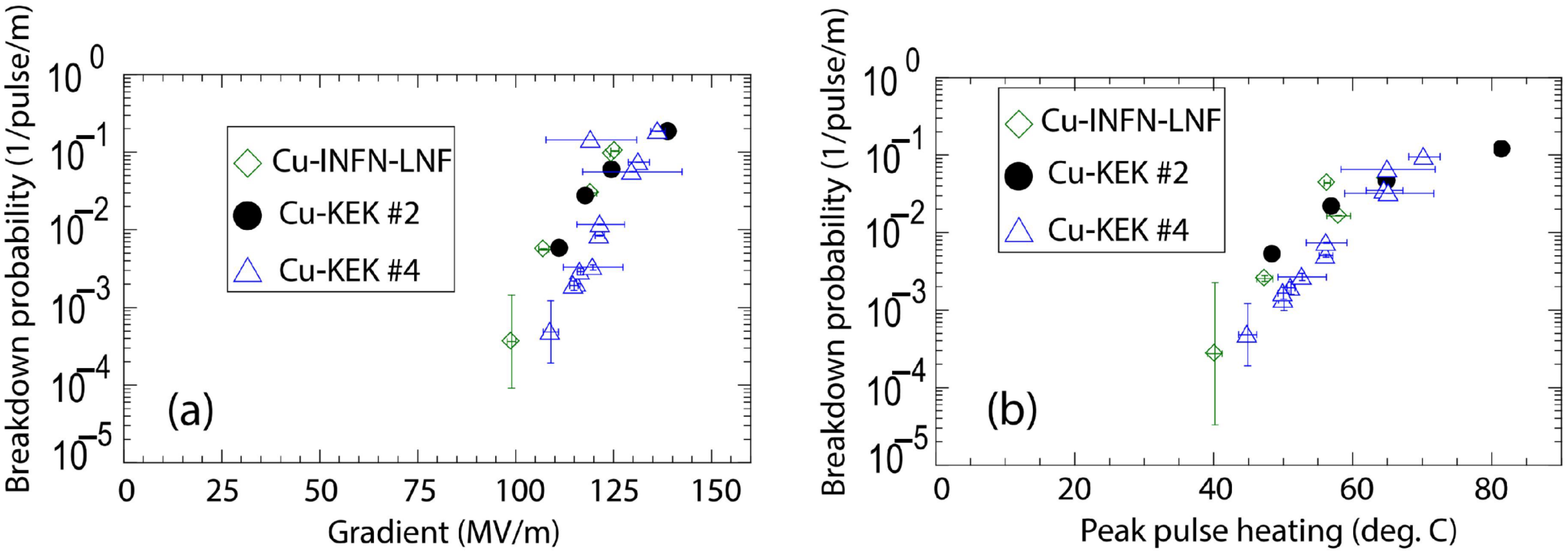
Typical breakdown and pulse heating damage in standing-wave structure cell



Breakdown damage: Electroformed Au
1C-SW-A3.75-T2.6-Electroformed-Frascati-#1



Input side of *Coupler cell*	High gradient side of *End cell*	High gradient side of *Center cell*

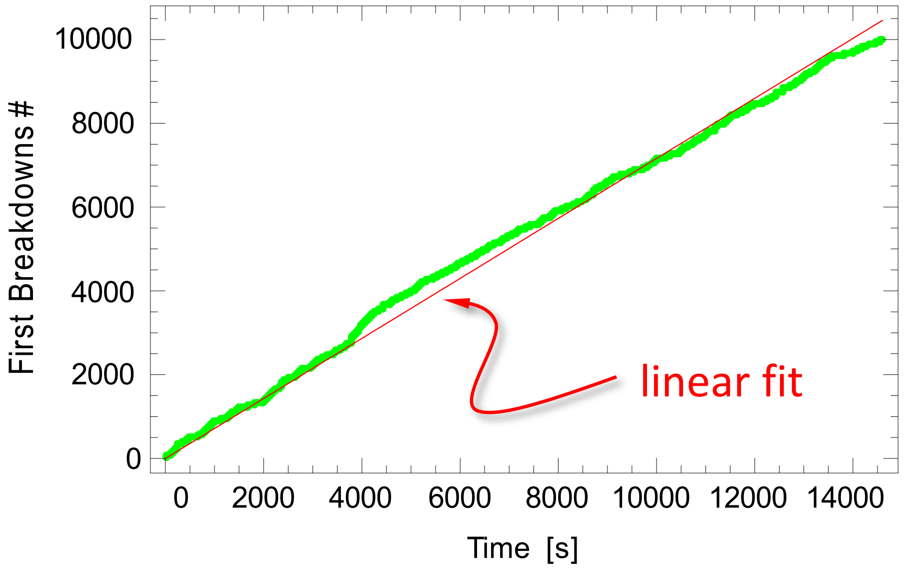


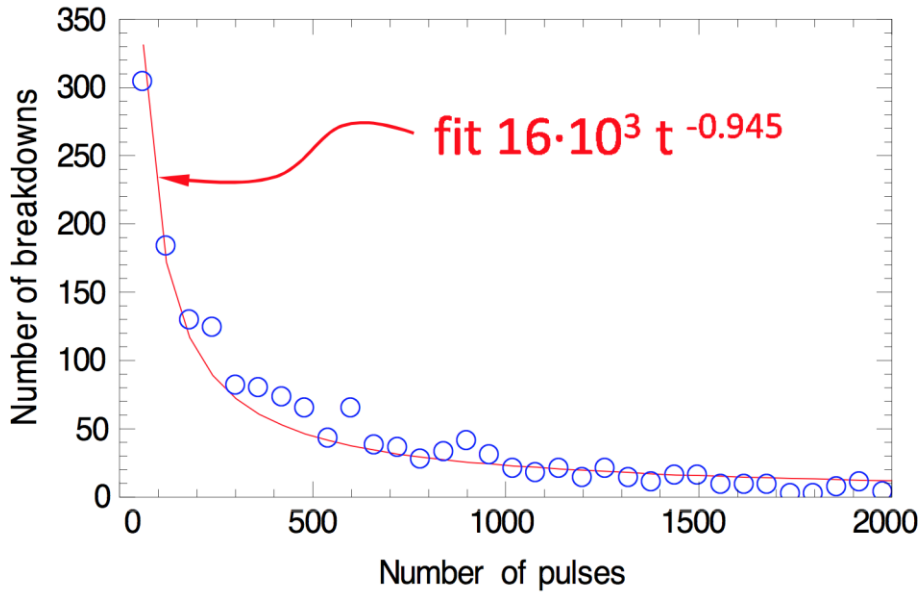
After conditioning the breakdown rates are reproducible for cavities of the same material and geometry. This reproducibility allows us quantitively characterize the materials.

Conditioning

- Perfectly clean materials initially have worse performance than damaged during months of conditioning and thousands of breakdowns, both by arcs and by fatigue
- While final performance is reproducible, the conditioning pace and time are not reproducible from structure to structure and depend on history of the material: cleaning, etching, degassing, oxidation, contamination, etc. The mechanism of conditioning and thus reasons for this variation are not understood.

Statistical behavior: Standing Wave Structures





For conditioned short standing wave structures probability density follows Poisson fit.

Statistical behavior: Traveling Wave Structures

PHYS. REV. ACCEL. BEAMS **20,** 011007 (2017)

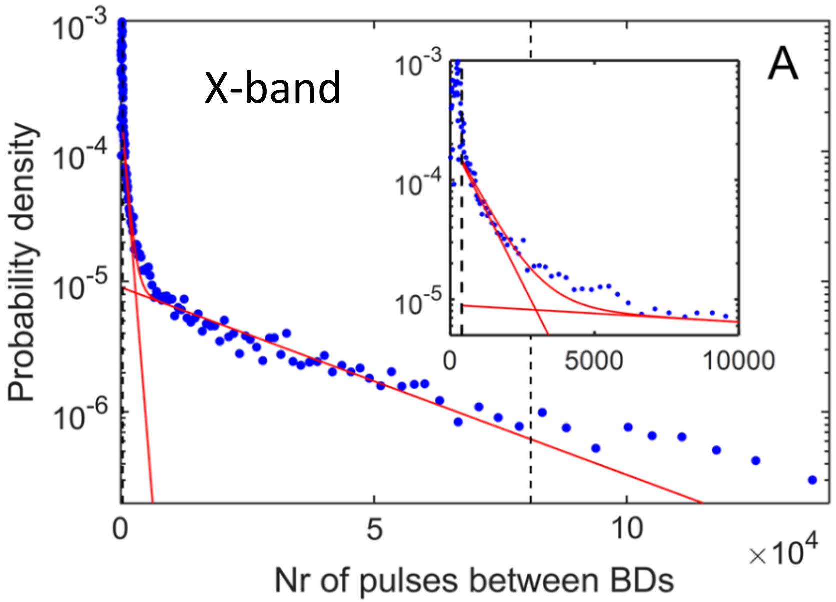


FIG. 5. Distribution of number of pulses between breakdowns and two-exponential fit, data set A. Inset shows a zoom-in of the start of the distribution.

Nuclear Engineering and Technology 57 (2025) 103164

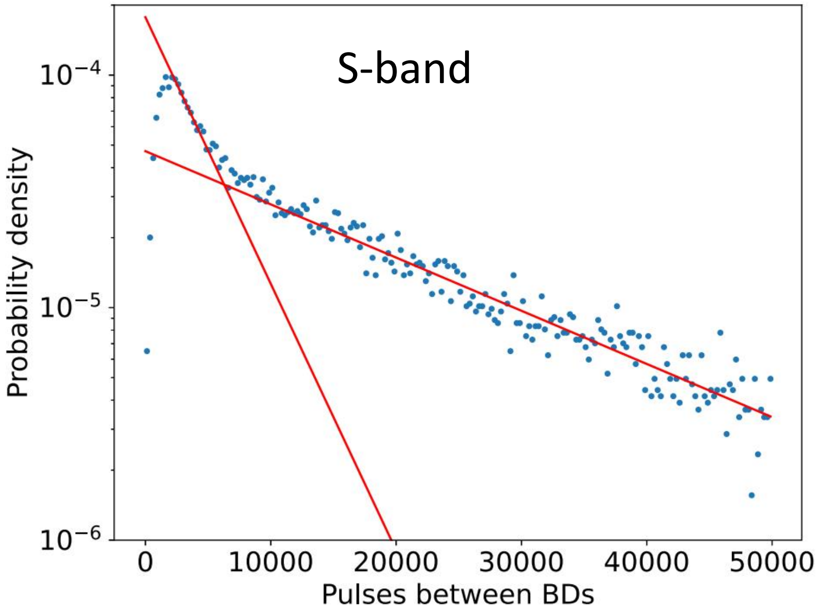


Fig. 7. Probability density of the interval between two consecutive BDs against the number of pulses between consecutive BDs. Blue points: experimental data. Red lines: double-exponential fit.

For traveling wave structures, the probability density is described by a double exponential function, where the steeper curve corresponds to secondary breakdowns, and the flatter curve corresponds to " trigger" breakdowns. Studying the behavior of these two curves allows for a more insight into the properties of the resonator materials.

Material parameters: Physical

- Conductivity ↑
- Thermal conductivity ↑
- Melting temperature ↑
- Expansion coefficient ↓
- Specific heat ↑
- Hardness ↑
- Contamination ↓

After decades of search for better material, OFHC 4N copper remains a preferred option for high gradient applications. Only recently CuAg is considered for practical structures.

Material parameters: Manufacturability

Machining

- Nonpoisonous
- Inert – nonreactive in air and common cleaning chemicals
- Could be machined and polished with high precision
- Could be chemically cleaned
- Could be electroformed or 3D printed

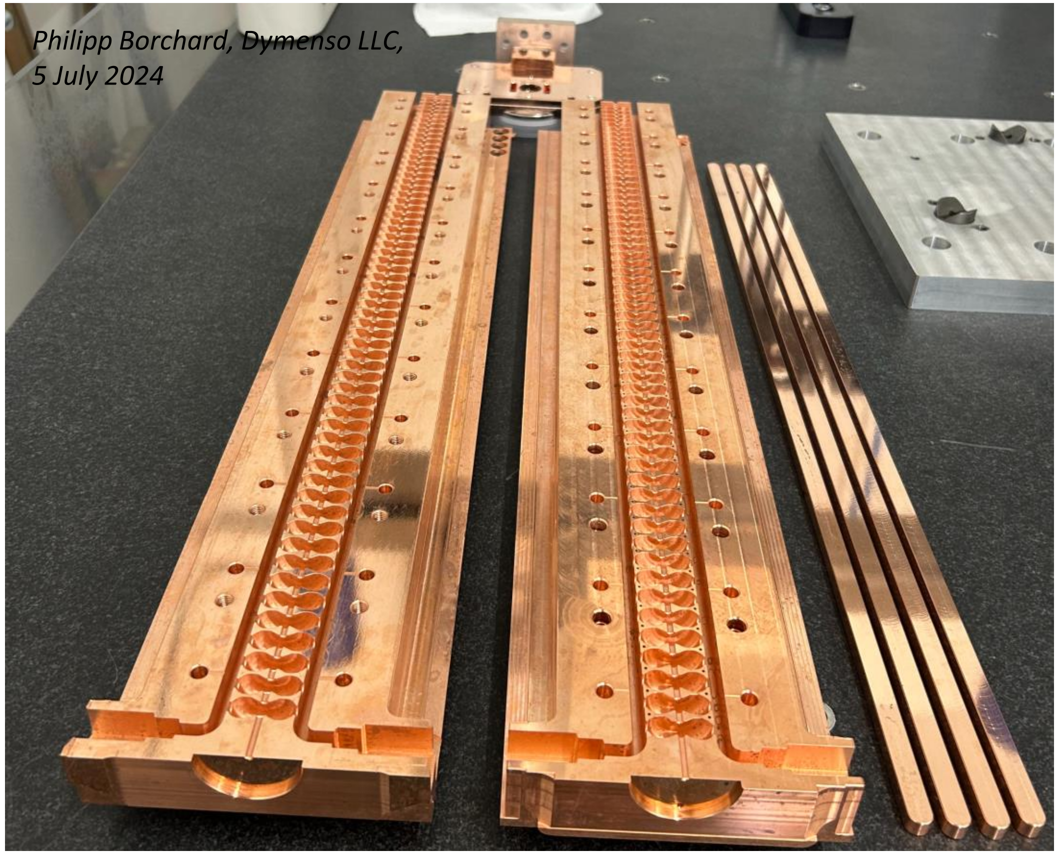
Joining – this is tightly linked to mechanical design of the joints and choice of joining techniques

- Preserve RF and Ultra High Vacuum properties
- Survive high temperature brazing/diffusion bonding
- Could survive welding: electron beam welding, TIG welding, etc.
- Could be joined with common interface materials such as stainless steel
- Could be clamped without high temperature processes
- Could be joined by electroplating

Again, after decades of effort, precision machining and then high temperature brazing or diffusion bonding remain to be preferable methods for building deployable structures. Meanwhile precision milling structures out of halves is gaining momentum.

Accelerating Structure Manufacturing: Structures Made of Two Halves

Open traveling wave CLIC prototype



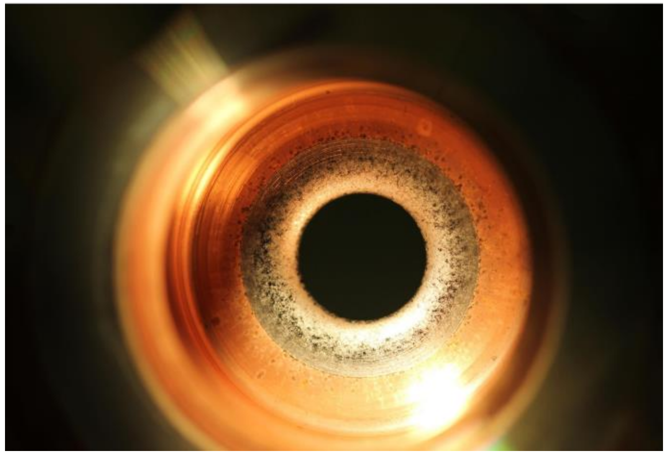
High efficiency tunable traveling wave linac

Material Properties: High Power Operation

- Ultra-high vacuum compatible – low vacuum pressure, low leaks, inert, etc.
- Ability to improve with conditioning
- Slow degradation during long term usage

Material parameters: Designer materials

High gradient side of *central cell* of Cu-Mo clad structure
1C-SW-A3.75-A2.6-Clad-Cu-Mo-KEK-#1

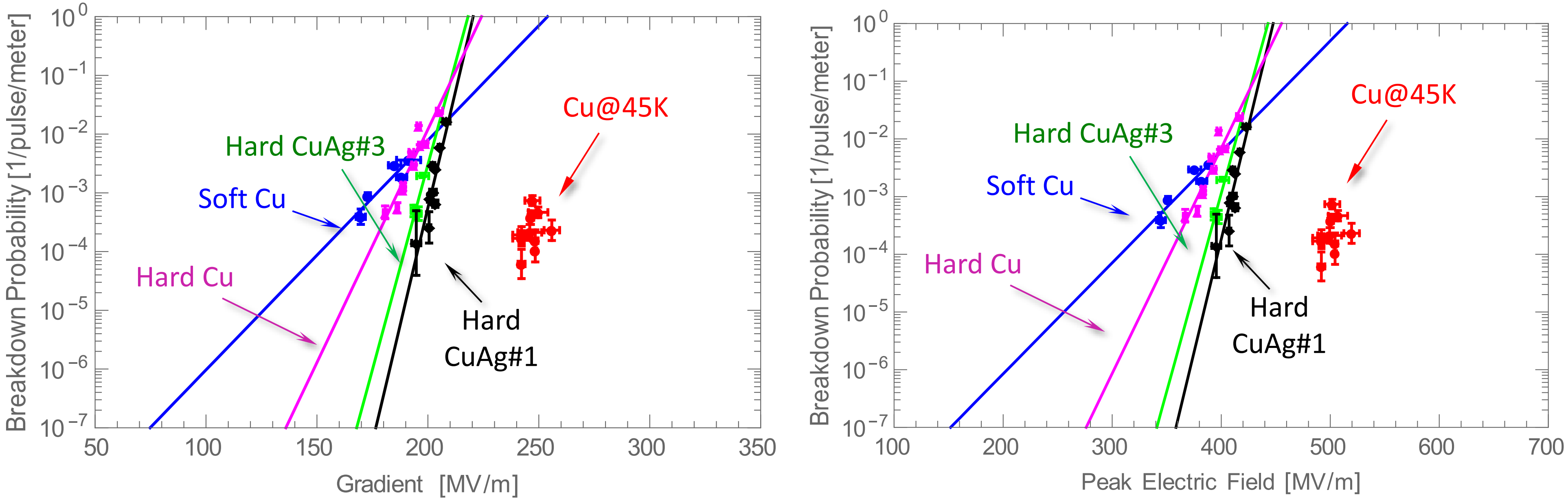


- Alloys ✓
- Multi-layered
- Clad geometries ✓
- Coating and plating ✓
- Novel processes for cavity surface processing such as laser pinning or electropolishing

Experiments: RF

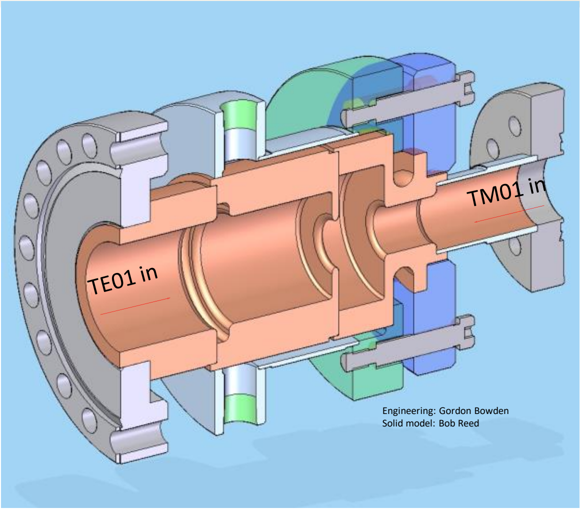
- Standing wave ✓
- Traveling wave ✓
- Dual Mode
  - Dual Mode Cavity ✓
  - Traveling wave structure in resonant ring ✓
- Cryo
  - Standing wave ✓

Summary of Single Cell Structure Results

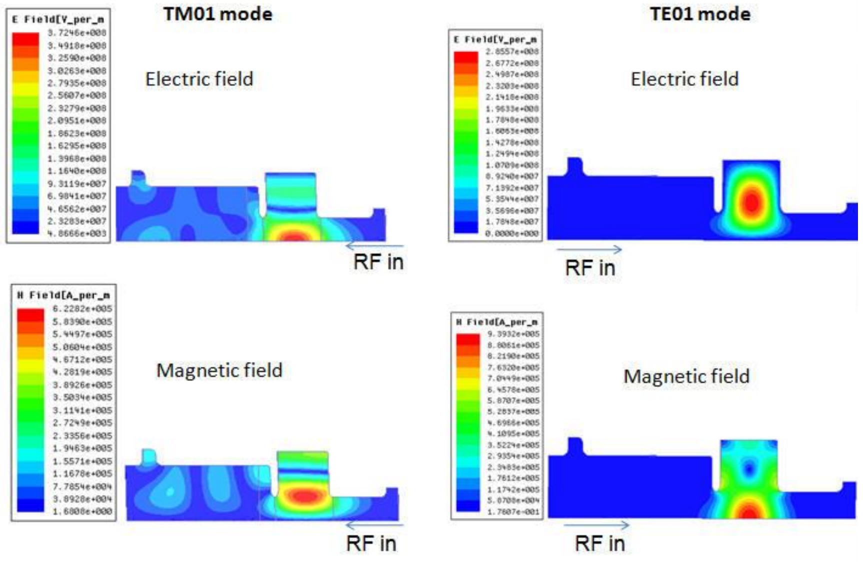


Breakdown rate *vs.* gradient and peak surface electric for first rf breakdowns, 1C-A2.75-T2.0 structures, shaped rf pulse with 150 ns flat part

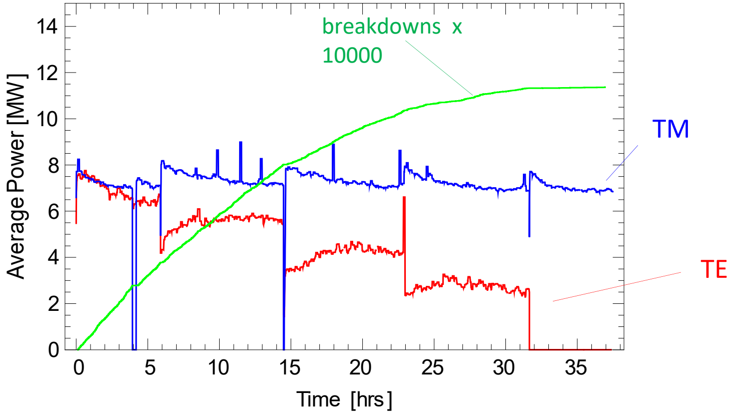
Example of High Power Experiment: Dual Mode Cavity



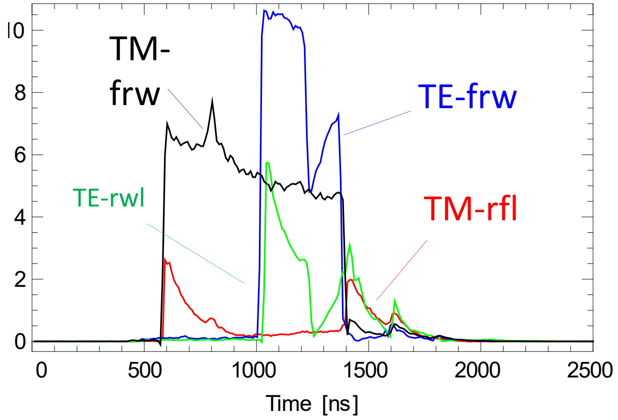
RF Electric and Magnetic Fields for 10MW Input Power (Driven)

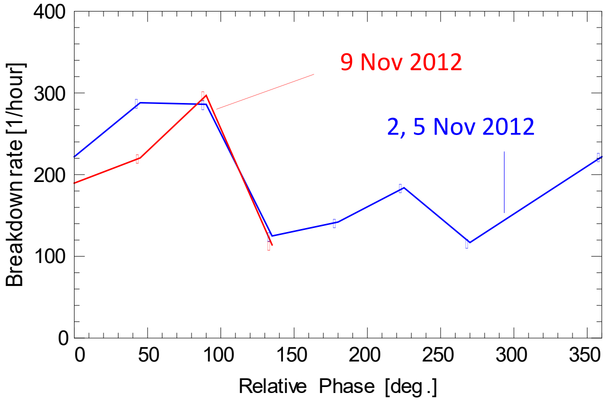


A. D. Yeremian, V. A. Dolgashev, S. G. Tantawi 2011



Breakdowns rate increases with increased magnetic field of TE mode with constant surface RF electric field,





Breakdown rate depends on rf phase between TE and TM mode while holding amplitudes of both modes constant

Experiments: DC

- DC – room temperature
- DC – cryo
- DC with stress

I. Profatilova, X. Stragier, S. Calatroni et al. *Nuclear Inst. and Methods in Physics Research, A 953 (2020) 163079*

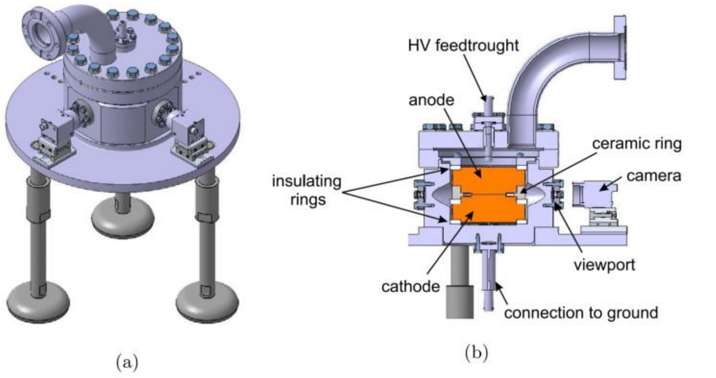
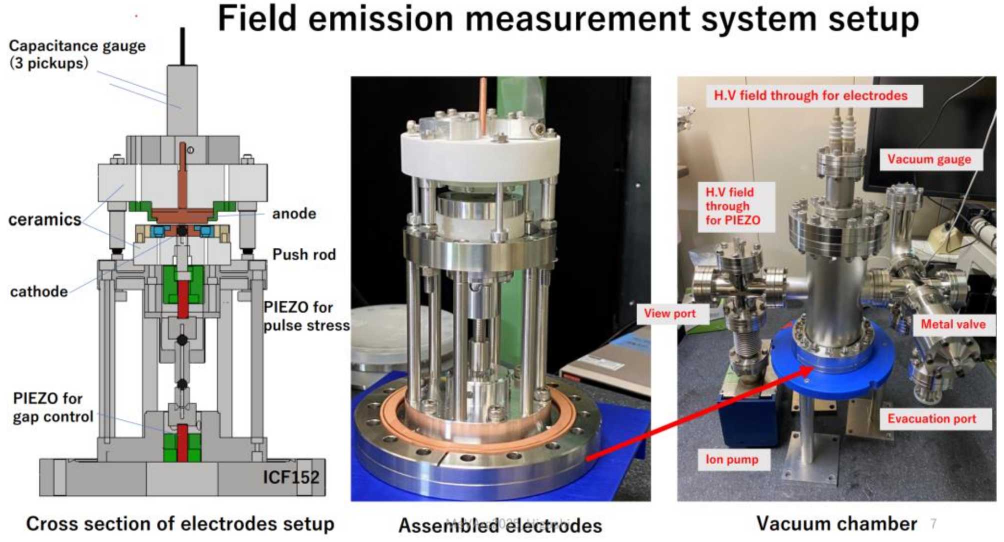


Fig. 1. 3D model of the vacuum chamber for the LES: (a) the view from outside, (b) the cross-section of the chamber.

From Iaroslava Profatilova (CERN) et al., Breakdown localization in a pulsed DC electrode system, Nucl.Instrum.Meth.A 953 (2020), 163079



From Yasuo Higashi at al., DC breakdown test setup with in-situ mechanical pulse stress, prepared for MeVArc2025

DC experiments are less expensive than the RF experiments, which allows for the investigation of a wider range of materials.

What could be next?: Experiments

High throughput (including high repletion rate) high power RF test stands in important frequency bends:
X-band, C-band, S-band, L-band, and UHF

- Standing Wave Structures
  - Single Cell
  - Multi Cell
- Traveling Wave Structures
  - Single Cell
  - Multi Cell
- Dual mode cavities
- RF combined with mechanical stress, say laser, ultrasound, or piezoelectric
- Record and analyze every RF pulse
- Cryo tests for all above

High time and spatial resolution large area in-situ microscopy

- Light
- X-ray
- Electrons?

What could be next?: Theory

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Breakdown trigger – before arc started

Topic:

Evolution of materials under periodic simultaneous influence of RF electric and magnetic fields for

- Materials undamaged by arcs
- Conditioned materials: Materials damaged by arcs – melted and remelted craters.

Methods:

- Dislocation dynamics/statistics
- Optimizing combination of material properties
- Molecular dynamics

Arc induced damage – after the breakdown started

Topic: Dependence of the damage in the material due to geometry and circuit (SW vs TW, magnetic fields, etc.)

Method:

- Multiscale PIC simulations – meter size models with micron resolution

Conclusion

Breakdown material research is very expensive:

- Procurement and maintenance of high-power test stands, in $Ms.
- Conditioning of components takes from hours for small cavities to many months for TW accelerating structures and this needs 24/7 expensive expert support.
- Novel technological activities such as metallurgy or 3D printing, *etc.* require expensive expert support.
- Theoretical effort needs predicable long-term funding to motivate new talents.

Systematic studies bring better quality results with less money and resources, therefore coordinated experimental effort may be beneficial, with standards negotiated and followed for testing protocols and data formats.