High-Gradient Copper:
State of the Art

Objective

The objective of this presentation:

Survey key ideas about the fundamental high-field limitations of copper, as used in accelerating structures, through reference to published papers.

The state-of-the-art for this presentation is our best knowledge of limits.

This presentation is subjective and incomplete!!! The selection of material is influenced by my personal experience and opinion. But the ideas contained do form a reasonably coherent story backed up by experimental results. Maybe a broader review of this subject can be made one day.

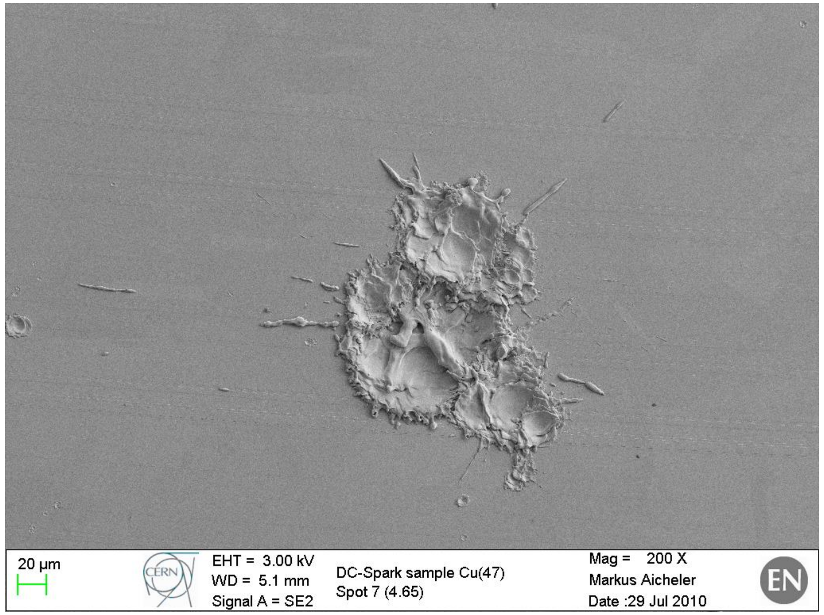
The main high-gradient limitations

Fundamental limitations of achievable field:

- Breakdowns – Aka vacuum arcs. Expressed as a rate, computed as number breakdown divided by the number of pulses. Very strong function of applied field. Occur mainly in areas of high surface electric field.
- Field emission current – Part of breakdown process, but annoyance in its own right. Potential loss of power, radiation source, can affect beam instrumentation, and even deflection of beam.
- Pulsed surface heating – Ohmic loss driven fatigue, leading to irreversible degradation of cavity surface.

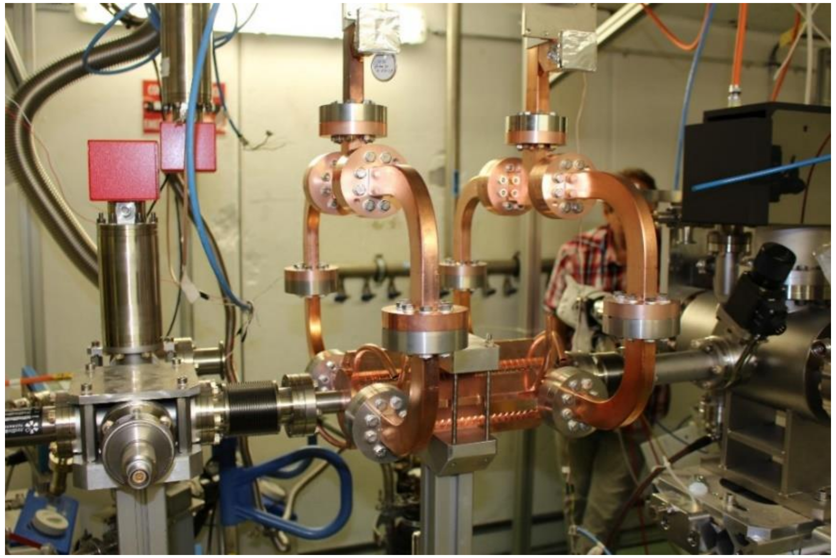
Then there are the practical limitations:

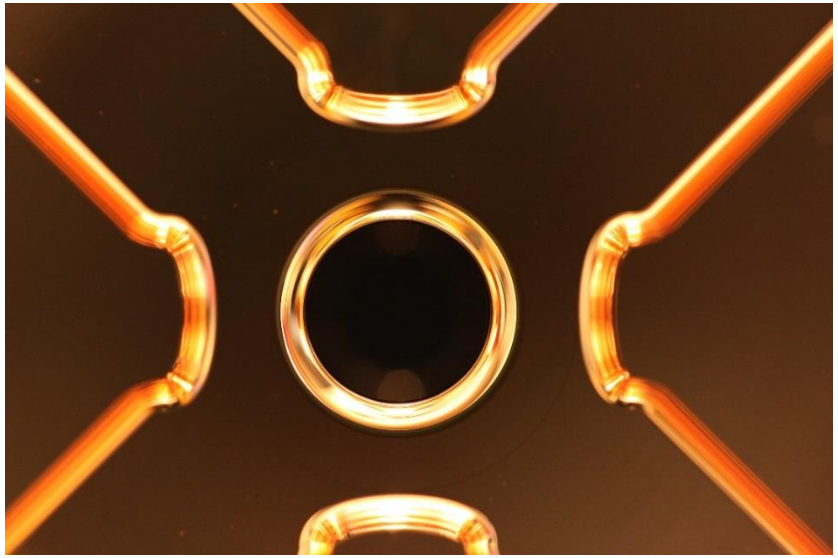
- Conditioning time
- RF power requirements
- Efficiency
- Cooling capacity

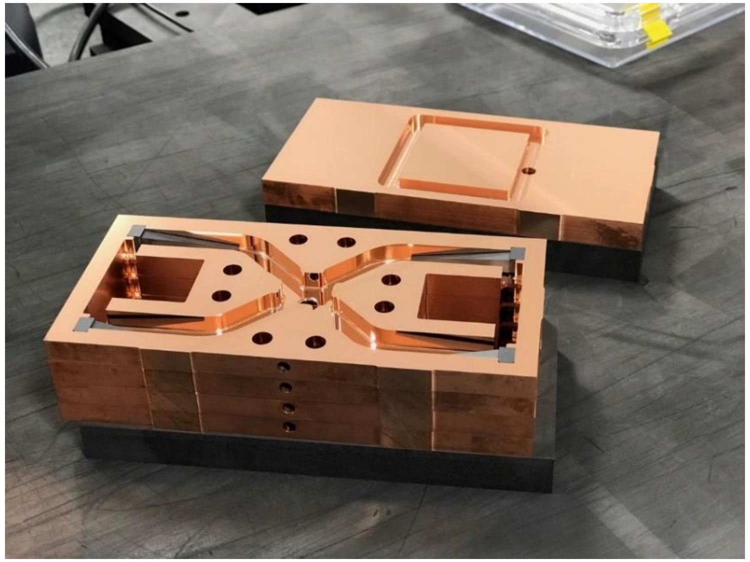


Structure implementation driven constraints

- Minimum aperture requirements – High-gradient better with small apertures, but most applications require large apertures for
  - maximizing transmission
  - minimizing short range wakefields
- Power feeds
- Higher order mode (long-range wakefields) suppression features







Early days – frequency dependence

SLAC – PUB – 4647
May 1988
(A)

RF BREAKDOWN STUDIES IN ROOM TEMPERATURE ELECTRON LINAC STRUCTURES*

GREGORY A. LOEW AND J. W. WANG

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309

Fig. 3. S-band (two-cavity, π-mode) structure, complete with water cooling system.

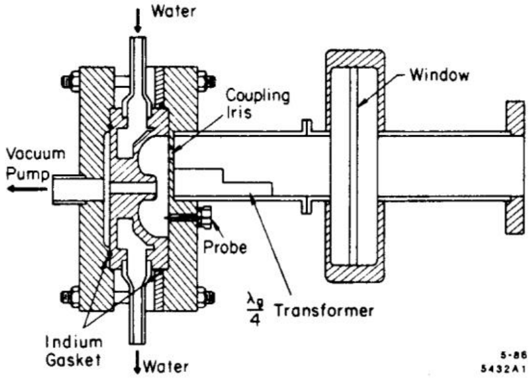


Fig. 4. Cross-sectional view of demountable C-band cavity.

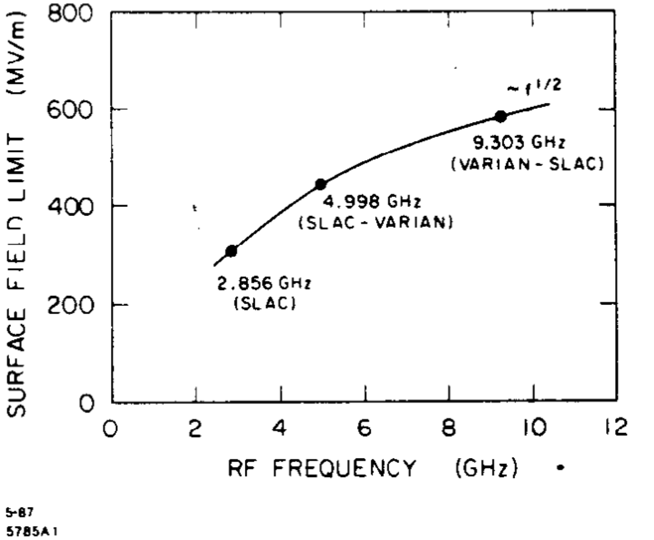


Fig. 5. Peak breakdown surface fields measured as a function of frequency.

$$E_s \sim 195\ [f\ (\mathrm{GHz})]^{1/2}\ .$$

Trying to be more systematic

Frequency and Temperature Dependence of Electrical Breakdown at 21, 30, and 39 GHz

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(Received 1 July 2002; published 5 June 2003)

A TeV-range e^+e^- linear collider has emerged as one of the most promising candidates to extend the high energy frontier of experimental elementary particle physics. A high accelerating gradient for such a collider is desirable to limit its overall length. Accelerating gradient is mainly limited by electrical breakdown, and it has been generally assumed that this limit increases with increasing frequency for normal-conducting accelerating structures. Since the choice of frequency has a profound influence on the design of a linear collider, the frequency dependence of breakdown has been measured using six exactly scaled single-cell cavities at 21, 30, and 39 GHz. The influence of temperature on breakdown behavior was also investigated. The maximum obtainable surface fields were found to be in the range of 300 to 400 MV/m for copper, with no significant dependence on either frequency or temperature.

https://doi.org/10.1103/PhysRevLett.90.224801

- Breakdown limited field measured – not breakdown rate
- No field emission measurement (although no field-dependent Q variation)
- No field enhancement due to power coupler (just small diagnostic coupling)
- Short pulse
- Super low stored energy
- Nothing like a prototype
- No acceleration of beam
- Etc.

VOLUME 90, NUMBER 22 PHYSICAL REVIEW LETTERS week ending 6 JUNE 2003

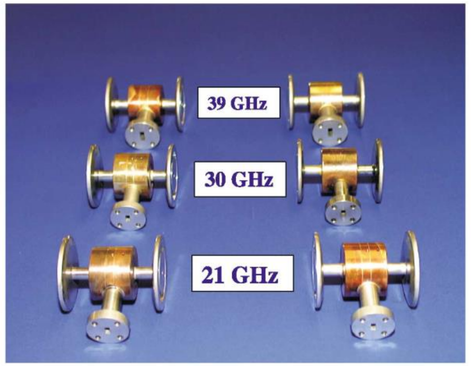


FIG. 2 (color online). Photograph of the six single cell cavities tested.

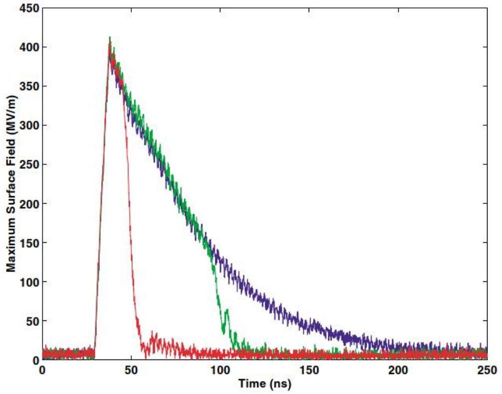


FIG. 3 (color online). Envelope of typical rf pulses with and without pulse shortening from a 30 GHz cavity.

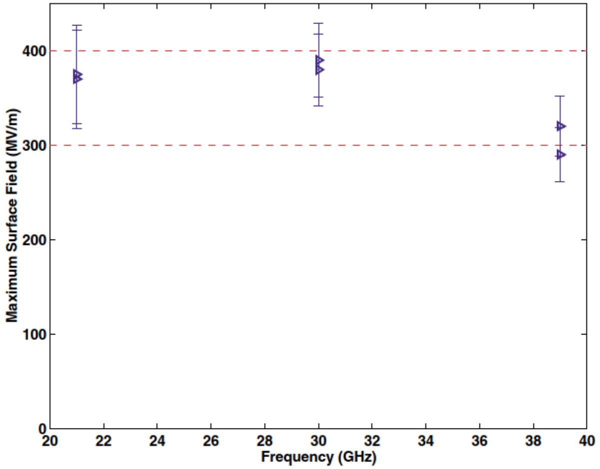


FIG. 4 (color online). Frequency dependence of the maximum surface field.

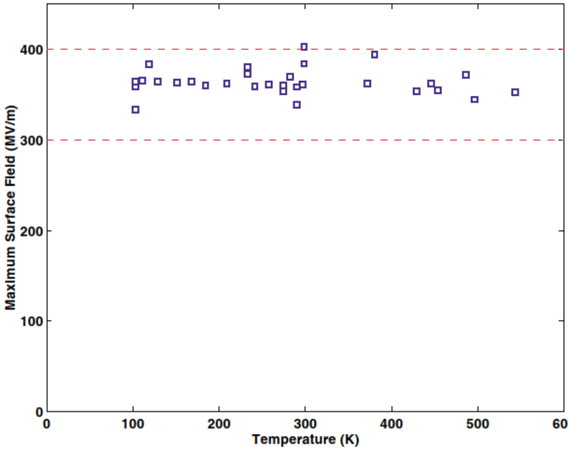
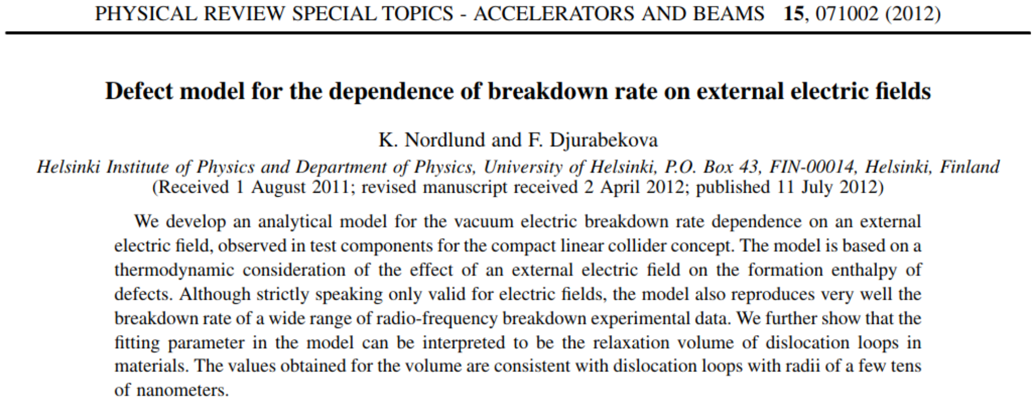


FIG. 6 (color online). Temperature dependence of maximum surface field.

Breakdown rate – Vacancy model



PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **15**, 071002 (2012)

Defect model for the dependence of breakdown rate on external electric fields

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(Received 1 August 2011; revised manuscript received 2 April 2012; published 11 July 2012)

We develop an analytical model for the vacuum electric breakdown rate dependence on an external electric field, observed in test components for the compact linear collider concept. The model is based on a thermodynamic consideration of the effect of an external electric field on the formation enthalpy of defects. Although strictly speaking only valid for electric fields, the model also reproduces very well the breakdown rate of a wide range of radio-frequency breakdown experimental data. We further show that the fitting parameter in the model can be interpreted to be the relaxation volume of dislocation loops in materials. The values obtained for the volume are consistent with dislocation loops with radii of a few tens of nanometers.

https://doi.org/10.1103/PhysRevSTAB.15.071002

$$BDR \propto e^{\frac{-E^f+\varepsilon_0 E^2 \Delta V}{k_b T}}$$

$$E^f = 0.8\ eV$$

$$\Delta V = 0.8 \times 10^{-24} m^3$$

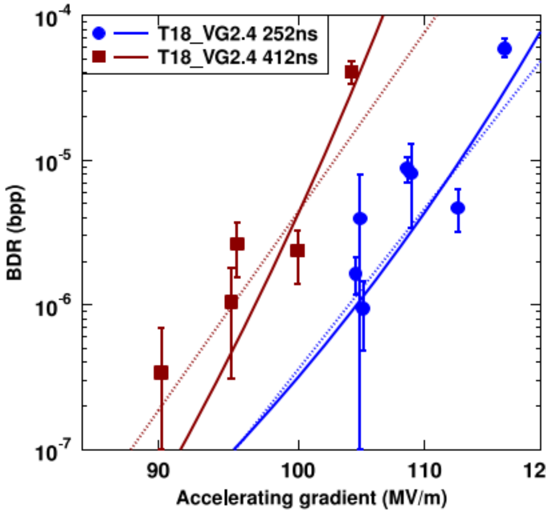

FIG. 4. Measured dependences of R_{BD} (in units of breakdown per pulse, bpp) versus electric field for the T18 accelerating structure [33,43] and fits of our model (solid lines) as well as power laws (dashed lines) to the data.

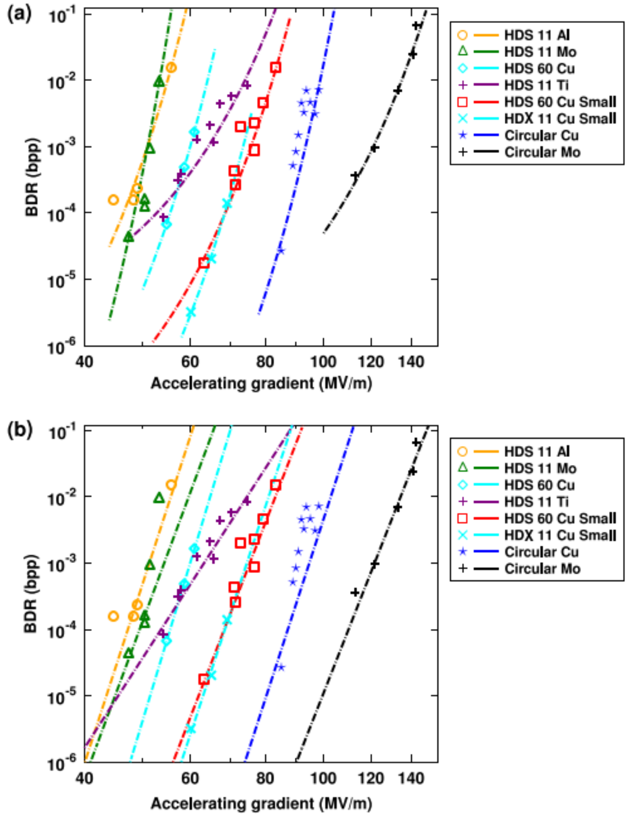

FIG. 3. (a) Measured dependences of R_{BD} (in units of breakdown per pulse, bpp) versus electric field for different accelerating structures and fits of the model to the data. For clarity, the results of the functional fit are not shown for all E values for all data sets. (b) Fits of power law functions to the same data. The experimental data and their labels are from [42].

Breakdown rate – Dislocation dynamics model

PHYSICAL REVIEW LETTERS **120,** 124801 (2018)

Stochastic Model of Breakdown Nucleation under Intense Electric Fields

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(Received 31 August 2017; published 20 March 2018)

A plastic response due to dislocation activity under intense electric fields is proposed as a source of breakdown. A model is formulated based on stochastic multiplication and arrest under the stress generated by the field. A critical transition in the dislocation population is suggested as the cause of protrusion formation leading to subsequent arcing. The model is studied using Monte Carlo simulations and theoretical analysis, yielding a simplified dependence of the breakdown rates on the electric field. These agree with experimental observations of field and temperature breakdown dependencies.

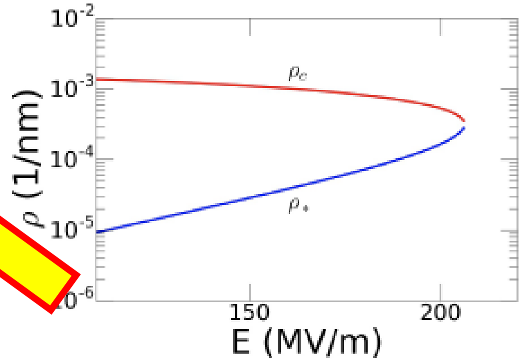
https://doi.org/10.1103/PhysRevLett.120.124801

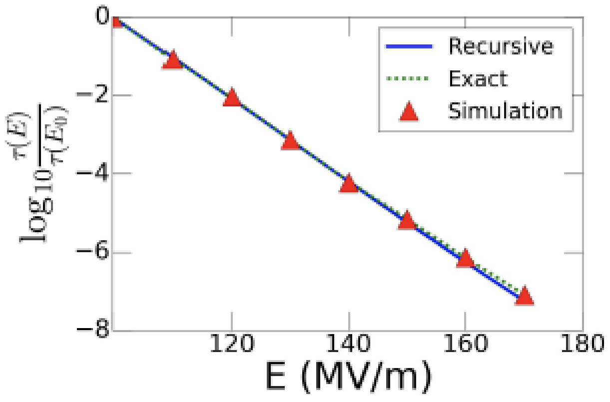
Describing mobile dislocation population evolution:

$$\dot{\rho}^{+} = \frac{25\kappa C_t}{G^2 b}(\rho + c)\sigma^2 e^{-\frac{E_a - \Omega\sigma}{k_B T}}$$

$$\dot{\rho}^{-} = \frac{50\xi C_t}{G}\sigma\rho(c + \rho)$$

$$\sigma = \beta\epsilon_0 E^2/2 + ZGb\rho$$





$$\tau \sim e^{-\gamma\frac{E}{E_0}}$$

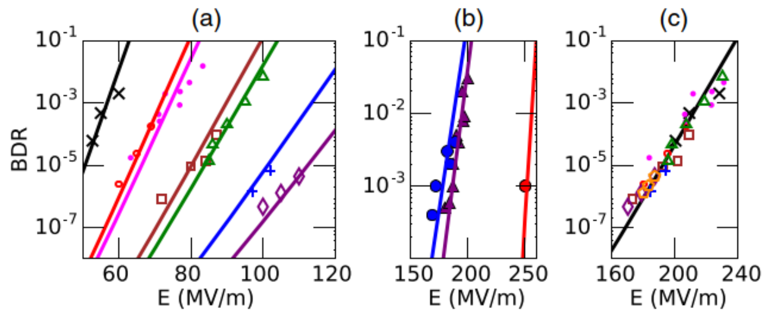
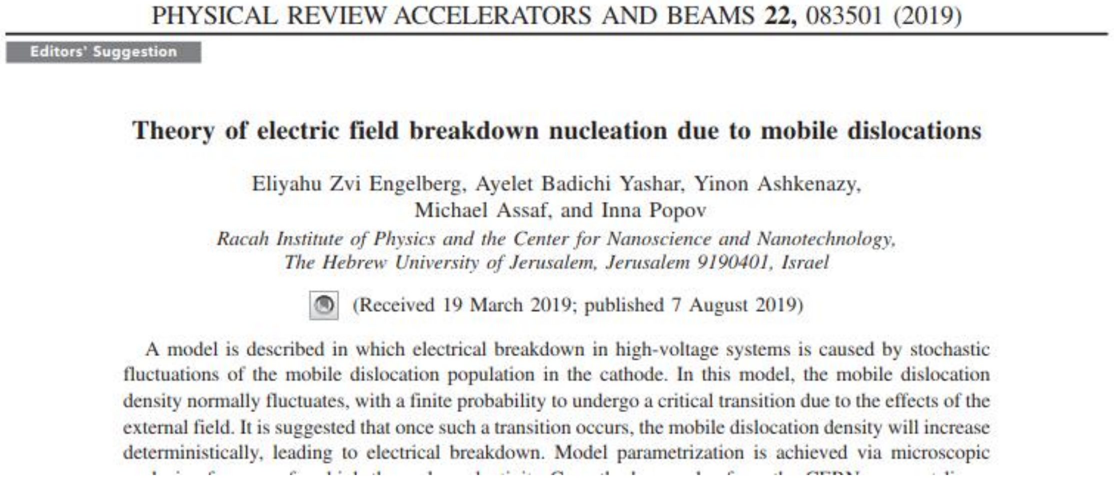


FIG. 3. Experimental BDRs with fitted theoretical lines using Eq. (7): (a) BDR versus E for various Cu accelerating structures [11]. (b) BDR variation with E at room temperature (two lines on the left) and at 45 K (line on the right) [51]. (c) BDR versus E for various Cu accelerating structures [11,52], with E rescaled so that all measurements are fitted with $\beta = 4.8$.

Breakdown rate – Dislocation dynamics model 2



PHYSICAL REVIEW ACCELERATORS AND BEAMS **22,** 083501 (2019)

Editors' Suggestion

Theory of electric field breakdown nucleation due to mobile dislocations

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(Received 19 March 2019; published 7 August 2019)

A model is described in which electrical breakdown in high-voltage systems is caused by stochastic fluctuations of the mobile dislocation population in the cathode. In this model, the mobile dislocation density normally fluctuates, with a finite probability to undergo a critical transition due to the effects of the external field. It is suggested that once such a transition occurs, the mobile dislocation density will increase deterministically, leading to electrical breakdown. Model parametrization is achieved via microscopic

https://doi.org/10.1103/PhysRevAccelBeams.22.083501

$$\dot{\rho}^{+} = \frac{25\kappa C_t c}{G^2 b}\sigma^2 \exp\left(-\frac{E_a - \Omega\sigma}{k_B T}\right), \qquad (1)$$

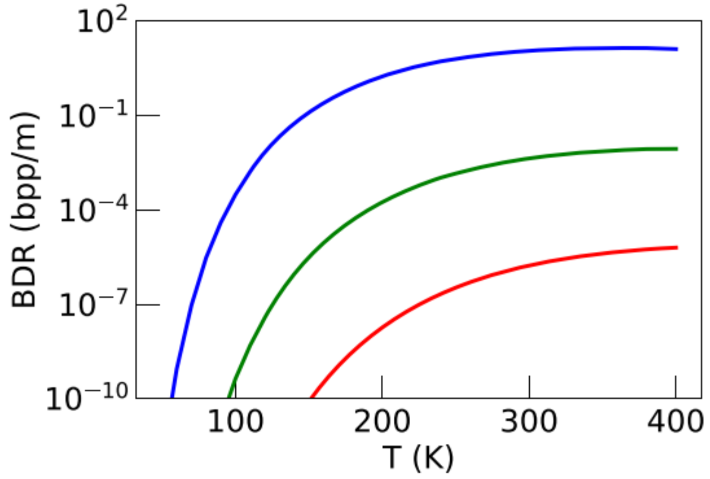
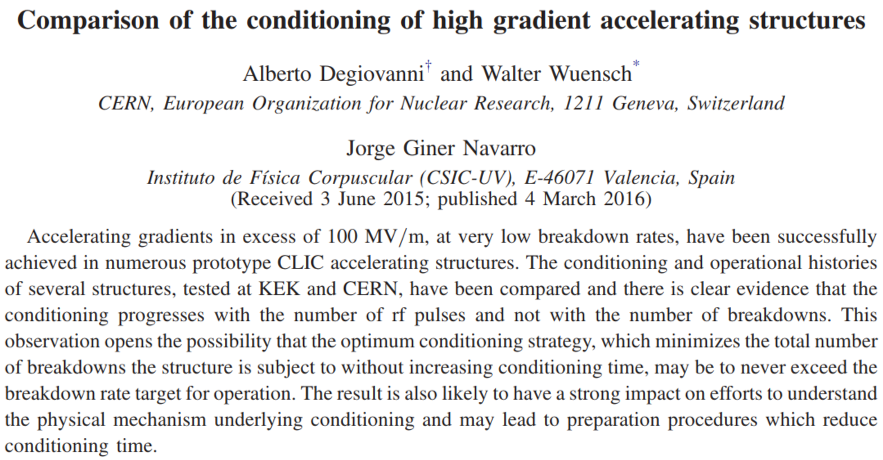


FIG. 11. BDR as a function of the temperature for the nominal parameter set, calculated using the metastable approximation [Eq. (18)]. The lines, from bottom to top, are for fields of 180, 220, and 260 MV/m.

Conditioning



Comparison of the conditioning of high gradient accelerating structures

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(Received 3 June 2015; published 4 March 2016)

Accelerating gradients in excess of 100 MV/m, at very low breakdown rates, have been successfully achieved in numerous prototype CLIC accelerating structures. The conditioning and operational histories of several structures, tested at KEK and CERN, have been compared and there is clear evidence that the conditioning progresses with the number of rf pulses and not with the number of breakdowns. This observation opens the possibility that the optimum conditioning strategy, which minimizes the total number of breakdowns the structure is subject to without increasing conditioning time, may be to never exceed the breakdown rate target for operation. The result is also likely to have a strong impact on efforts to understand the physical mechanism underlying conditioning and may lead to preparation procedures which reduce conditioning time.

https://doi.org/10.1103/PhysRevAccelBeams.19.032001

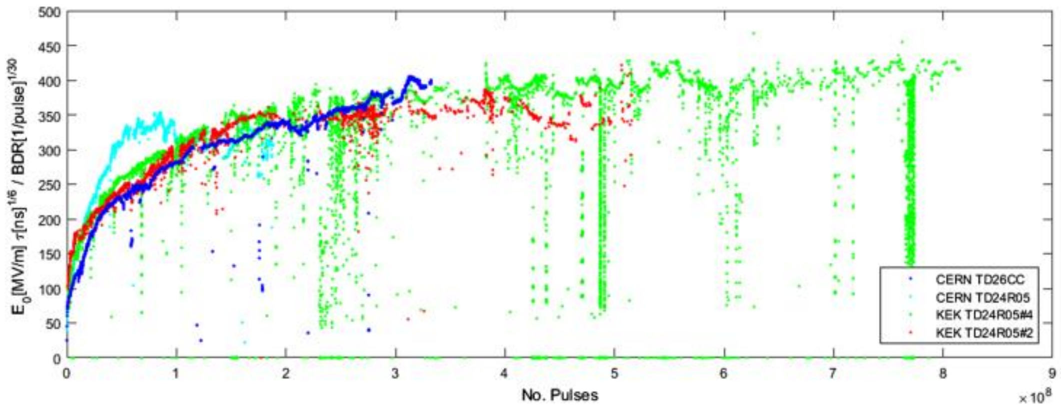


FIG. 3. Comparison of the scaled gradient vs number of accumulated pulses for several structures. Despite the different conditioning approaches, the curves for the scaled gradient are similar.

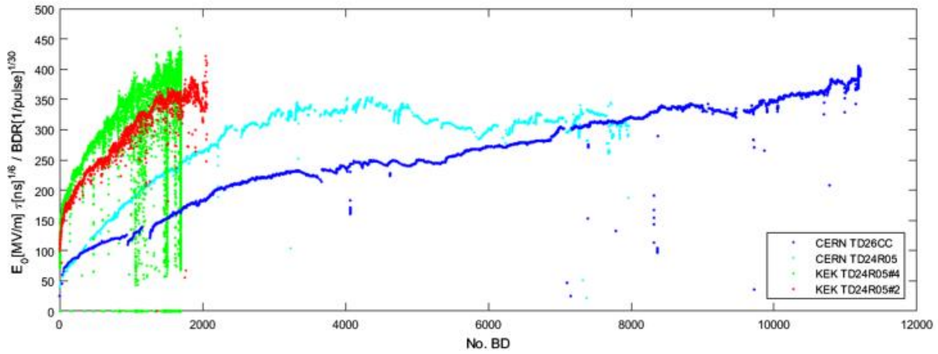


FIG. 4. Comparison of the scaled gradient vs number of accumulated breakdowns for several structures. When plotted with respect to the total accumulated number of breakdowns, the curves of the scaled gradient diverge significantly.

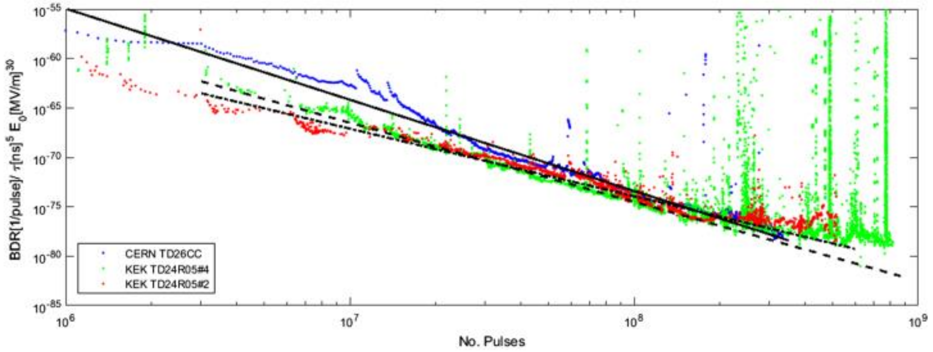
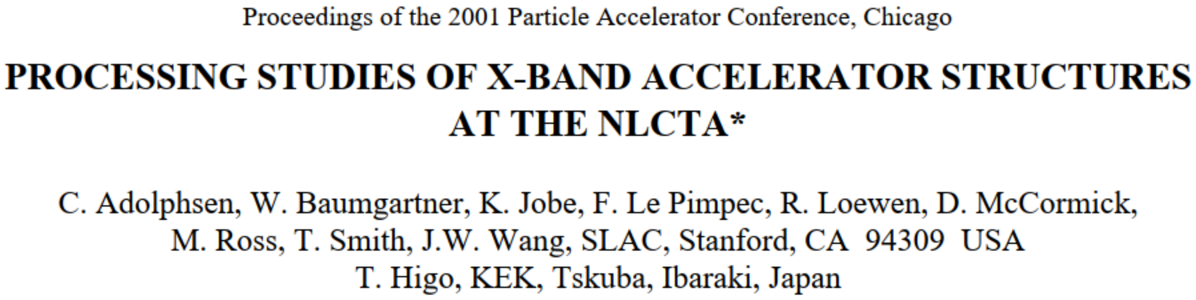


FIG. 5. Comparison of scaled BDR for different structures. The data are plotted in a log-log scale. The scaled BDR is decreasing monotonically with respect to the number of pulses. The curves are fitted with a power law.

Starting to understand the role of power flow



Proceedings of the 2001 Particle Accelerator Conference, Chicago

PROCESSING STUDIES OF X-BAND ACCELERATOR STRUCTURES AT THE NLCTA*

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M. Ross, T. Smith, J.W. Wang, SLAC, Stanford, CA 94309 USA
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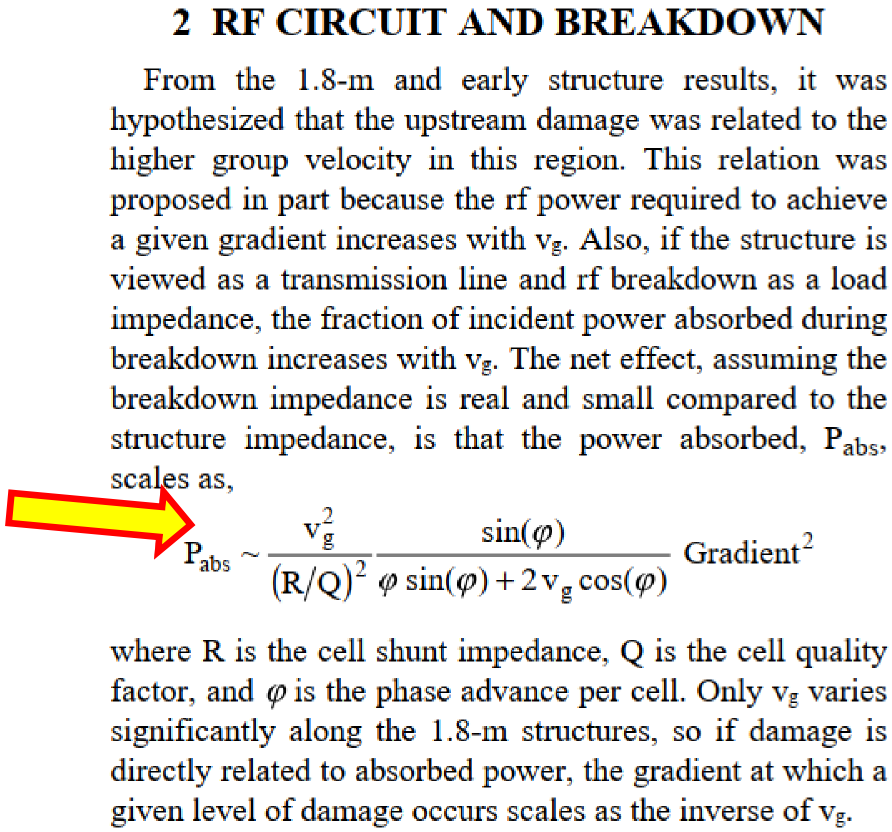

2 RF CIRCUIT AND BREAKDOWN

From the 1.8-m and early structure results, it was hypothesized that the upstream damage was related to the higher group velocity in this region. This relation was proposed in part because the rf power required to achieve a given gradient increases with v_g. Also, if the structure is viewed as a transmission line and rf breakdown as a load impedance, the fraction of incident power absorbed during breakdown increases with v_g. The net effect, assuming the breakdown impedance is real and small compared to the structure impedance, is that the power absorbed, P_{abs}, scales as,

$$P_{abs} \sim \frac{v_g^2}{(R/Q)^2} \frac{\sin(\varphi)}{\varphi \sin(\varphi) + 2 v_g \cos(\varphi)} \text{Gradient}^2$$

where R is the cell shunt impedance, Q is the cell quality factor, and φ is the phase advance per cell. Only v_g varies significantly along the 1.8-m structures, so if damage is directly related to absorbed power, the gradient at which a given level of damage occurs scales as the inverse of v_g.

The role of power flow

New local field quantity describing the high gradient limit of accelerating structures

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(Received 28 January 2009; published 26 October 2009)

A new local field quantity is presented which gives the high gradient performance limit of accelerating structures due to vacuum rf breakdown. The new field quantity, a modified Poynting vector S_c, is derived from a model of the breakdown trigger in which field emission currents from potential breakdown sites cause local pulsed heating. The field quantity S_c takes into account both active and reactive power flow on the structure surface. This new quantity has been evaluated for many X-band and 30 GHz rf tests, both traveling wave and standing wave, and the value of S_c achieved in the experiments agrees well with analytical estimates.

https://doi.org/10.1103/PhysRevSTAB.12.102001

Thus the modified Poynting vector,

$$S_c = \mathrm{Re}\{\bar{S}\} + g_c \cdot \mathrm{Im}\{\bar{S}\}, \qquad (16)$$

is proposed as a new local field quantity which gives the high gradient performance limit of accelerating structures in the presence of vacuum rf breakdown.

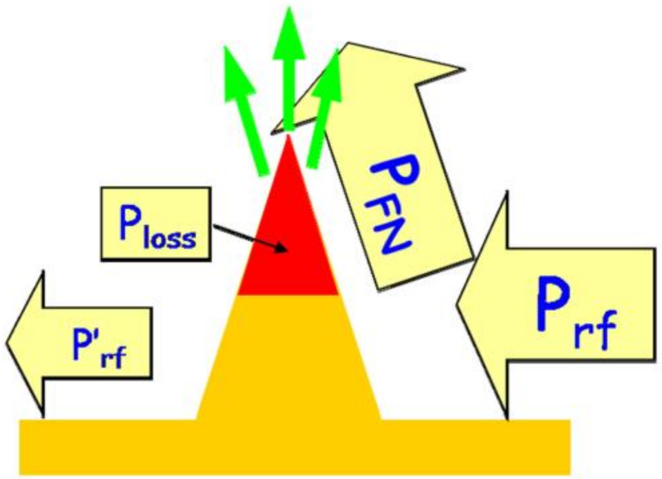


FIG. 9. (Color) Schematic view of the power flow balance near the tip.

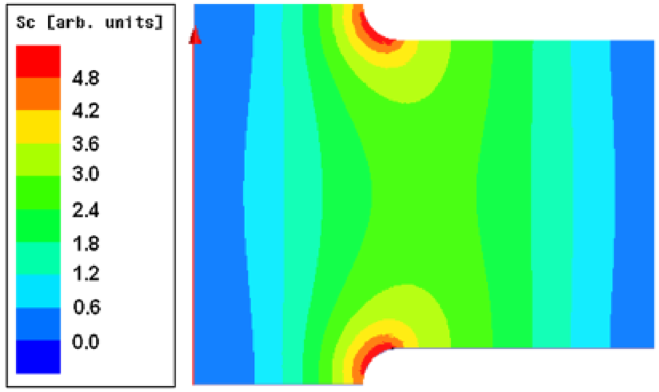


FIG. 13. (Color) Distribution of S_c in a TWS cell. The first cell of the structure number 3 from Table I is taken as an example.

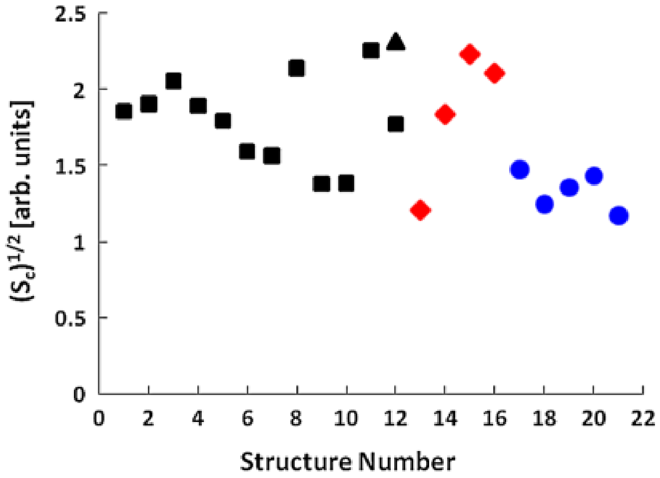
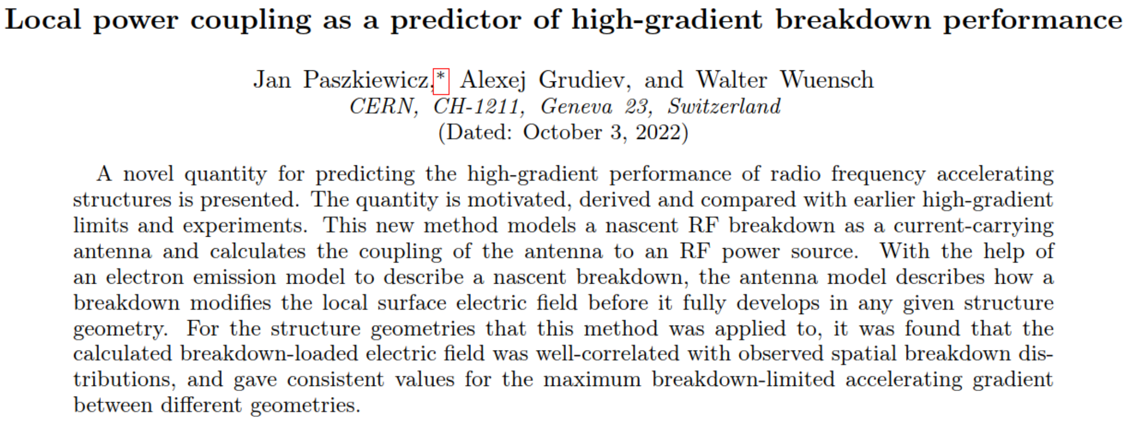


FIG. 12. (Color) Square root of S_c is plotted for the data presented in Fig. 3.

Refinement of power flow theory



Local power coupling as a predictor of high-gradient breakdown performance

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(Dated: October 3, 2022)

A novel quantity for predicting the high-gradient performance of radio frequency accelerating structures is presented. The quantity is motivated, derived and compared with earlier high-gradient limits and experiments. This new method models a nascent RF breakdown as a current-carrying antenna and calculates the coupling of the antenna to an RF power source. With the help of an electron emission model to describe a nascent breakdown, the antenna model describes how a breakdown modifies the local surface electric field before it fully develops in any given structure geometry. For the structure geometries that this method was applied to, it was found that the calculated breakdown-loaded electric field was well-correlated with observed spatial breakdown distributions, and gave consistent values for the maximum breakdown-limited accelerating gradient between different geometries.

https://arxiv.org/abs/2209.15291

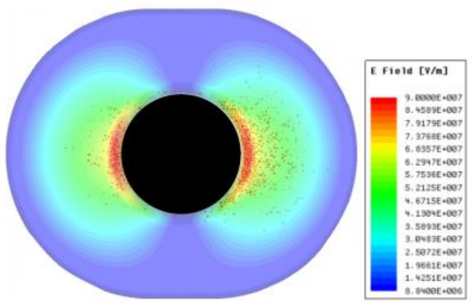


FIG. 1. Breakdown locations, represented by black dots, vs. position transverse to the beam in the second cell of the CLIC Crab Cavity, obtained from *post-mortem* analysis [7]. Colours represent the surface electric field vs. position transverse to the beam. The magnetic field has a similar distribution, but rotated by 90° compared to the electric field.

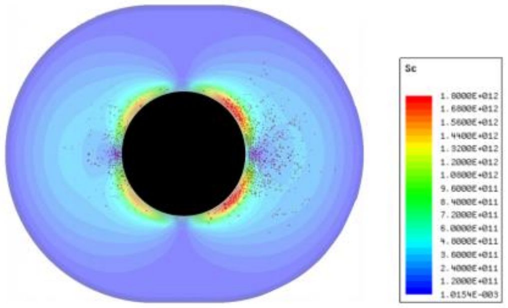


FIG. 2. Breakdown locations, represented by black dots, vs. position transverse to the beam in the second cell of the CLIC Crab Cavity, obtained from *post-mortem* analysis [7]. Colours represent S_c value vs. position transverse to the beam.

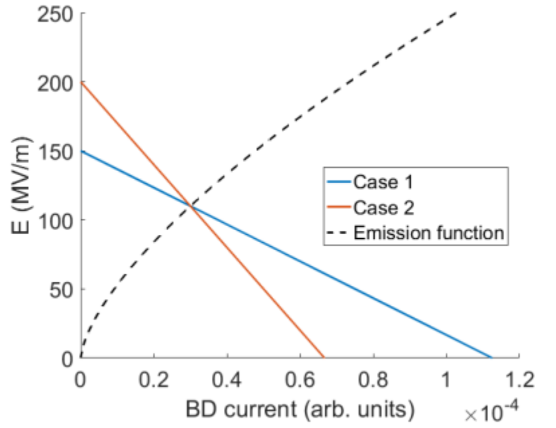


FIG. 3. Calculation of E^* on a plot of surface electric field in MV/m vs. current emitted by a breakdown. Black: emission function as given by Eq. (6). Blue: a breakdown site with an unloaded field of 150 MV/m and a low breakdown resistance. Red: a breakdown site with an unloaded field of 200 MV/m and a larger breakdown resistance.

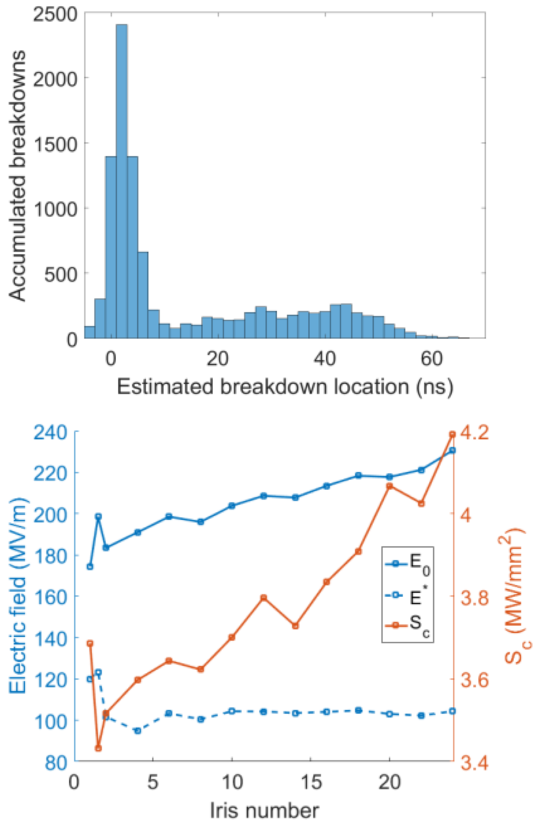
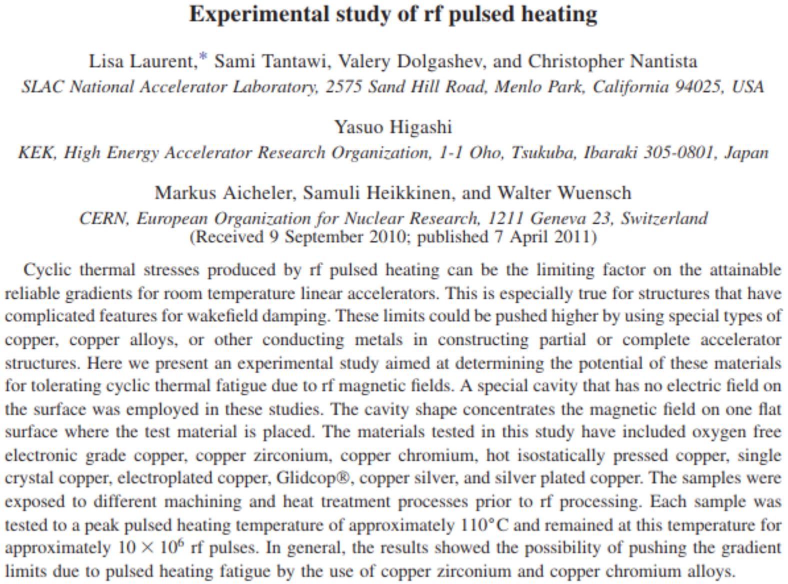


FIG. 18. Top: Accumulated breakdowns vs. longitudinal position in the T24PSIN1 over its entire test run in XBox 2, in units of RF signal propagation time in ns. 0 ns represents the structure input and 65 ns represents the structure output [17]. Bottom: unloaded surface electric field (solid blue) and E^* (dashed blue) in MV/m and S_c (red) in MW/mm^2 vs. iris number, at an input power of 42.4 MW.

Pulsed surface heating fatigue damage



Experimental study of rf pulsed heating

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(Received 9 September 2010; published 7 April 2011)

Cyclic thermal stresses produced by rf pulsed heating can be the limiting factor on the attainable reliable gradients for room temperature linear accelerators. This is especially true for structures that have complicated features for wakefield damping. These limits could be pushed higher by using special types of copper, copper alloys, or other conducting metals in constructing partial or complete accelerator structures. Here we present an experimental study aimed at determining the potential of these materials for tolerating cyclic thermal fatigue due to rf magnetic fields. A special cavity that has no electric field on the surface was employed in these studies. The cavity shape concentrates the magnetic field on one flat surface where the test material is placed. The materials tested in this study have included oxygen free electronic grade copper, copper zirconium, copper chromium, hot isostatically pressed copper, single crystal copper, electroplated copper, Glidcop®, copper silver, and silver plated copper. The samples were exposed to different machining and heat treatment processes prior to rf processing. Each sample was tested to a peak pulsed heating temperature of approximately 110°C and remained at this temperature for approximately 10×10^6 rf pulses. In general, the results showed the possibility of pushing the gradient limits due to pulsed heating fatigue by the use of copper zirconium and copper chromium alloys.

https://doi.org/10.1103/PhysRevSTAB.14.041001

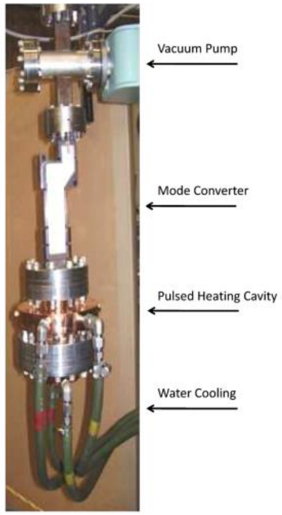


FIG. 5. The cavity has water cooling and is connected to the power source through a TE_{01} (WR90) to TE_{01} mode converter.

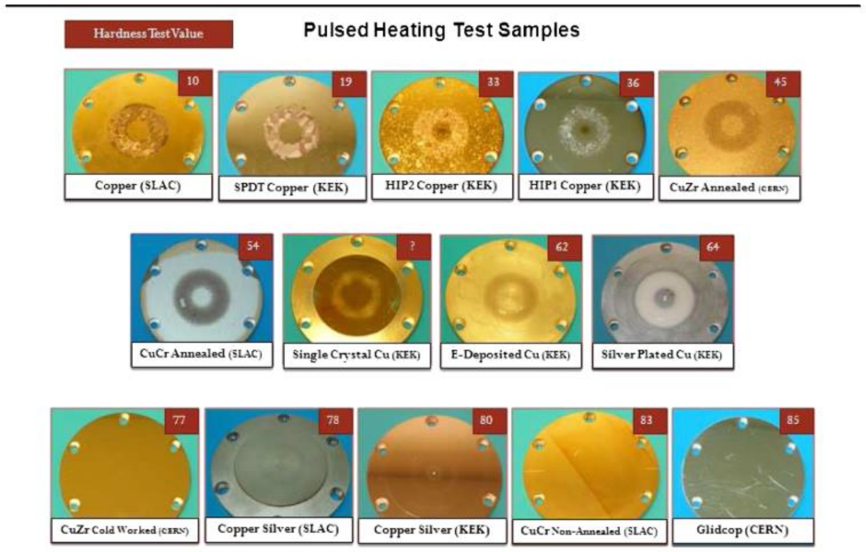


FIG. 54. Pulsed heating samples that have been tested to 110°C. They are listed in order of material hardness values with the softest materials in the top row and the harder materials in the bottom row (hardness values are located in the top right corner of each photograph).

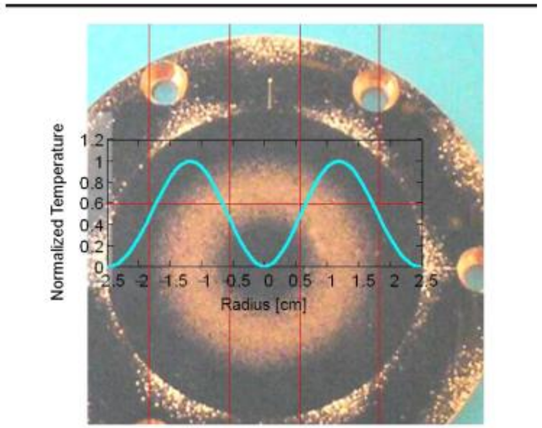


FIG. 6. Normalized pulsed heating temperature calculations superimposed on a copper pulsed heating sample.

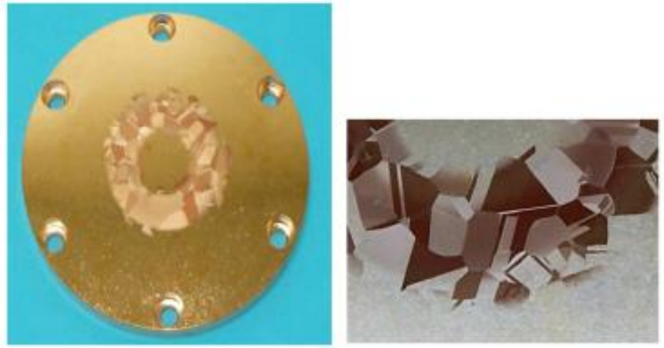
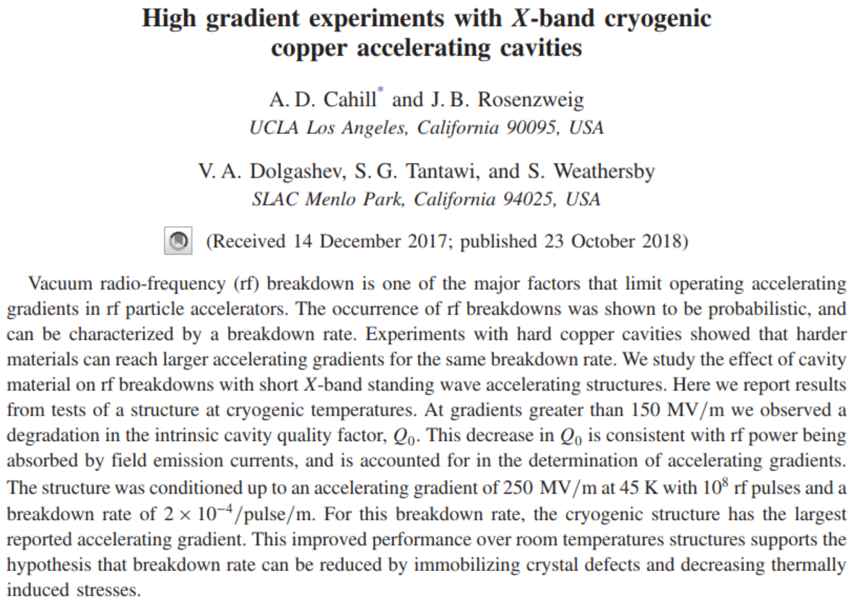


FIG. 20. Diamond-turned OFE copper with larger grains due to hydrogen firing at 1000°C. Testing to 110°C showed pulsed heating surface damage to be dependent on crystallographic orientation.

Cryogenic copper - RF



High gradient experiments with *X*-band cryogenic copper accelerating cavities

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Vacuum radio-frequency (rf) breakdown is one of the major factors that limit operating accelerating gradients in rf particle accelerators. The occurrence of rf breakdowns was shown to be probabilistic, and can be characterized by a breakdown rate. Experiments with hard copper cavities showed that harder materials can reach larger accelerating gradients for the same breakdown rate. We study the effect of cavity material on rf breakdowns with short *X*-band standing wave accelerating structures. Here we report results from tests of a structure at cryogenic temperatures. At gradients greater than 150 MV/m we observed a degradation in the intrinsic cavity quality factor, Q_0. This decrease in Q_0 is consistent with rf power being absorbed by field emission currents, and is accounted for in the determination of accelerating gradients. The structure was conditioned up to an accelerating gradient of 250 MV/m at 45 K with 10^8 rf pulses and a breakdown rate of 2×10^{-4}/pulse/m. For this breakdown rate, the cryogenic structure has the largest reported accelerating gradient. This improved performance over room temperatures structures supports the hypothesis that breakdown rate can be reduced by immobilizing crystal defects and decreasing thermally induced stresses.

https://doi.org/10.1103/PhysRevAccelBeams.21.102002

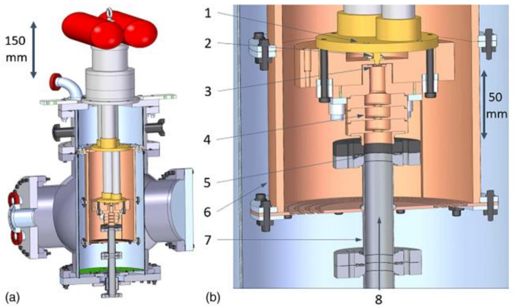

FIG. 3. (a) Solid model of the cryostat and (b) zoom in on Cryo-Cu-SLAC-#2 in same model. (1) Cold head of cryocooler; (2) current monitor; (3) brazed metal foil; (4) Cryo-Cu-SLAC-#2; (5) rf flange; (6) thermal shield; (7) Cu-plated stainless steel waveguide; (8) rf input.

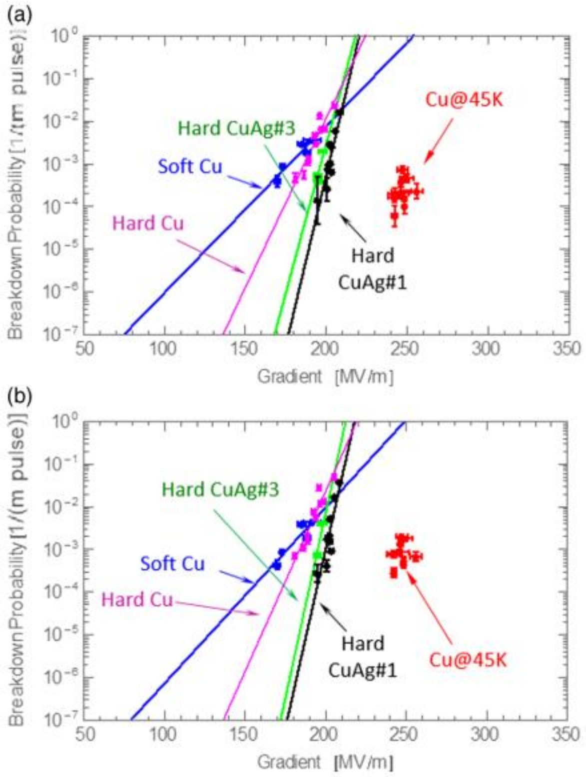

FIG. 11. Breakdown rate vs gradient:(a): first, trigger rf breakdowns; (b): all rf breakdowns. For the breakdown probability ~10^{-4}/pulse/m cryogenic structure clearly outperforms record data from hard CuAg [36].

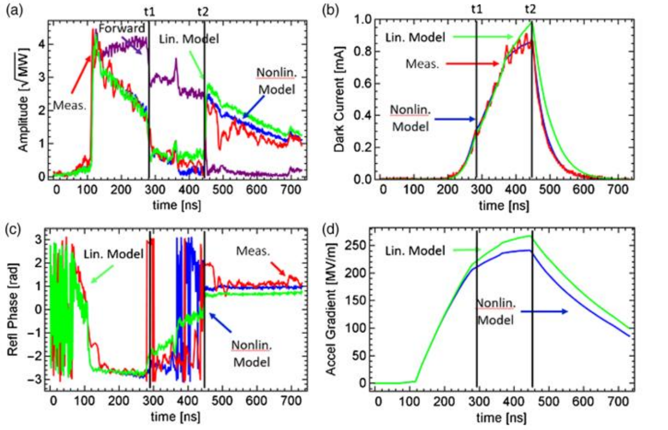

FIG. 6. Measured and reconstructed rf and current monitor signals for an example rf pulse. The measured current will be a small percentage of the field emitted current inside the cavity, which we estimated to be on the order of .1–1% [70]. Measured signals are in purple and red. Results of the nonlinear model are in blue and results from a linear model are in green. t_1 and t_2 are defined as the section where the input rf power is decreased to a lower power level and the gradient is flat, which for this pulse is 150 ns long.

Cryogenic copper – Pulsed dc

Temperature-Dependent Field Emission and Breakdown Measurements Using a Pulsed High-Voltage Cryosystem

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A variable-temperature pulsed high-voltage system has been constructed and a series of high-field measurements on copper electrodes have been carried out. The measurements are made at ambient to cryogenic temperatures and include conditioning, breakdown threshold, and field emission. A significant, up to 50%, increase in the breakdown threshold and remarkable stability of field emission are observed when cooled to cryogenic temperatures compared to room temperature. These results provide important experimental input for the development of quantitative theories and models of high-field processes as well as practical input for cryogenic radio-frequency systems.

https://doi.org/10.1103/PhysRevApplied.14.061002

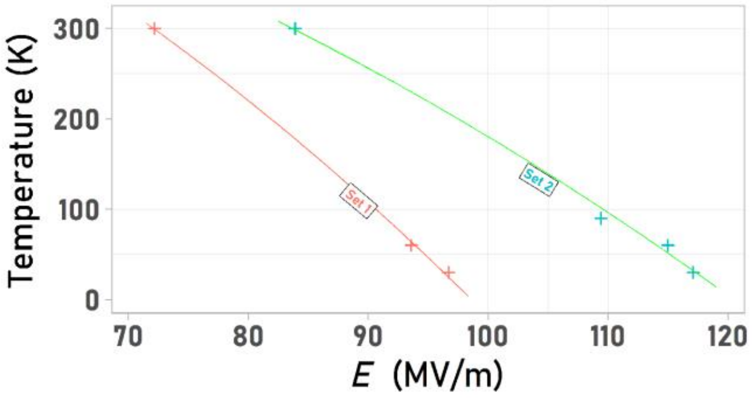


FIG. 2. Measured values of the maximum surface field at different temperatures for both sets of electrodes. The lines are the fits from the crystal defect model [Eq. (2)].

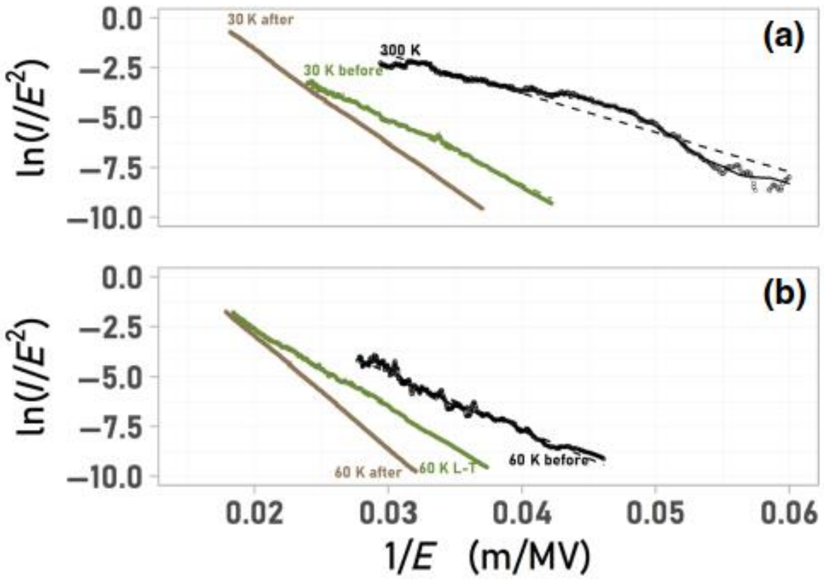
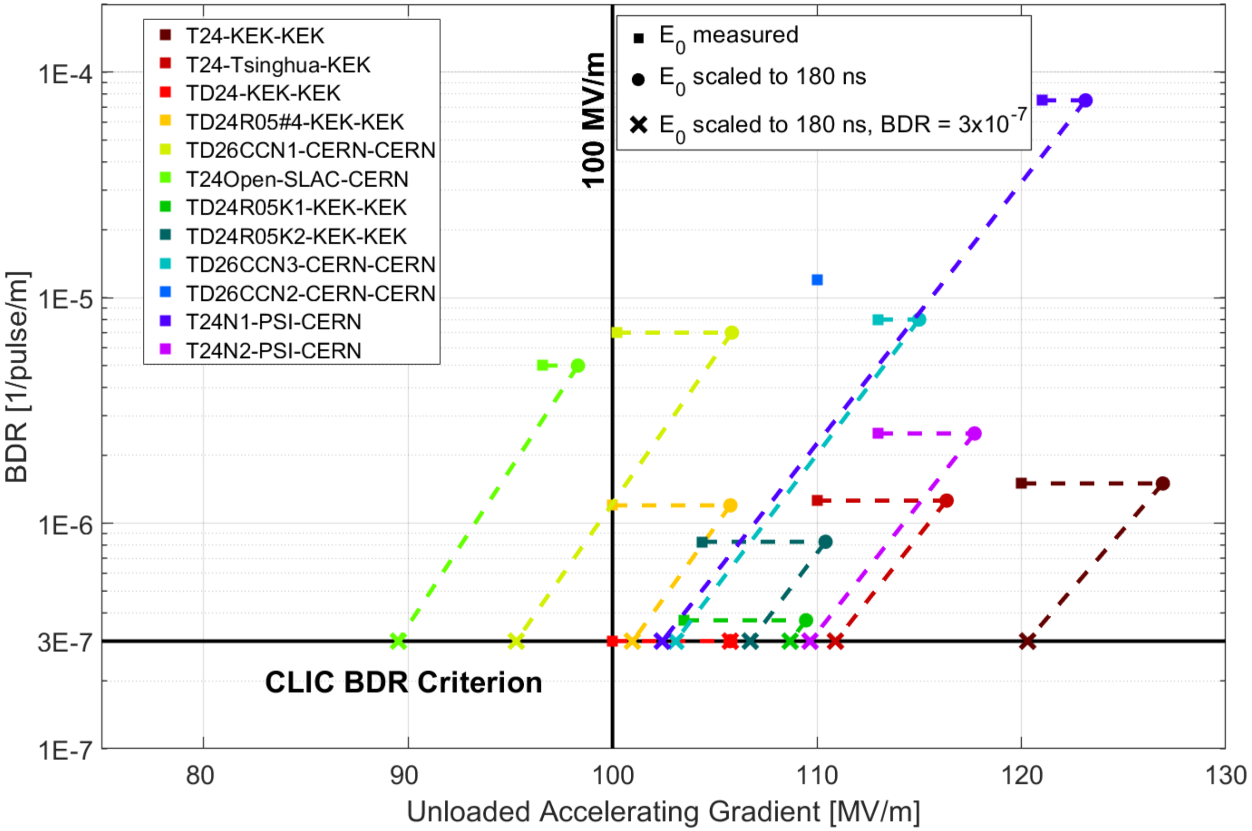
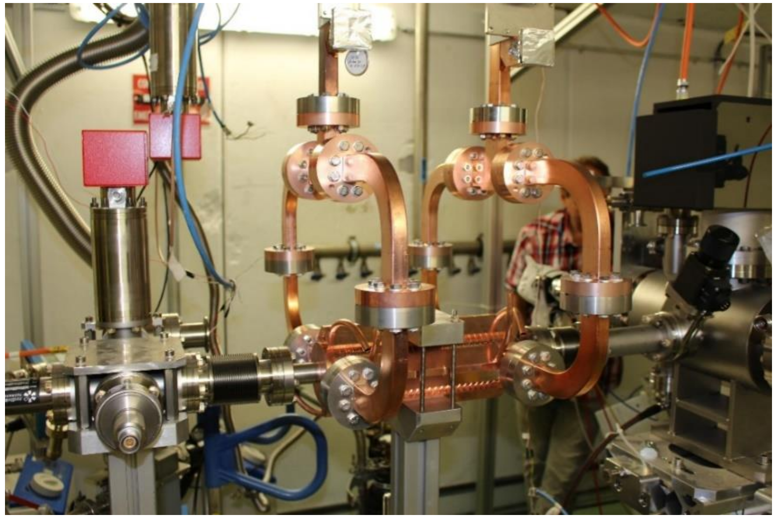
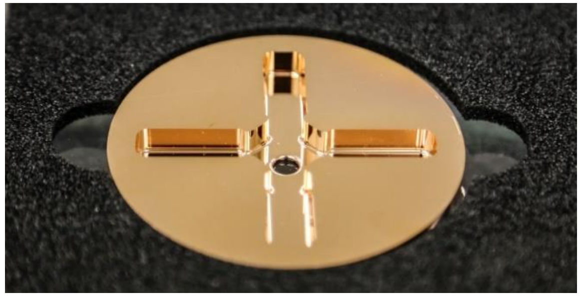


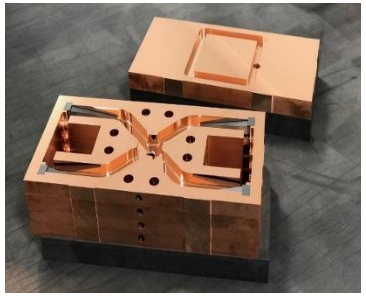
FIG. 3. (a) Field emission after conditioning at 300 K (black), cool-down to 30 K (green), and after re-conditioning at 30 K (brown). (b) FE for surface cooled down to 60 K after conditioning at 300 K (black), after re-conditioning at 60 K (brown), and compared with FE at 60 K after 9 days (green).

Something like statistics





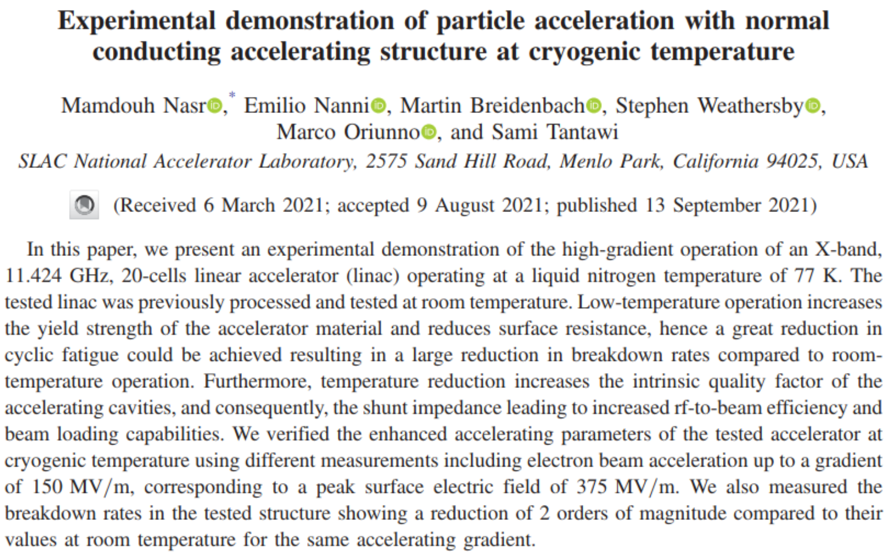




Peak surface electric fields about x 2.5 higher

https://doi.org/10.1103/PhysRevAccelBeams.21.061001,
https://doi.org/10.1103/PhysRevAccelBeams.20.052001 etc.

Recent cryo-copper



Experimental demonstration of particle acceleration with normal conducting accelerating structure at cryogenic temperature

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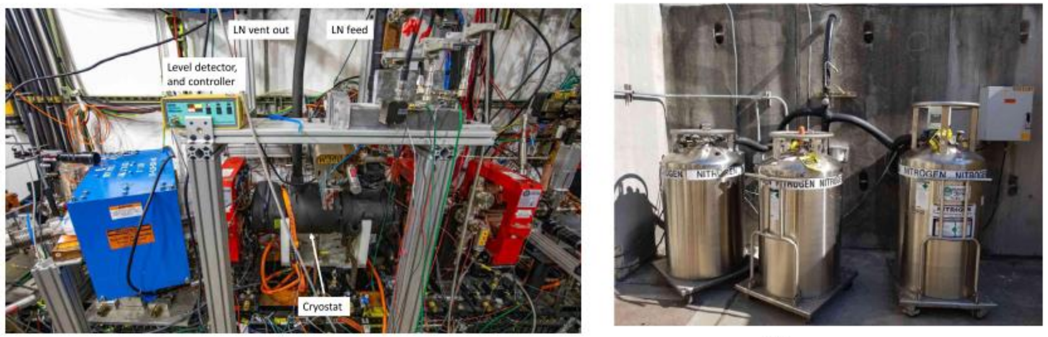
In this paper, we present an experimental demonstration of the high-gradient operation of an X-band, 11.424 GHz, 20-cells linear accelerator (linac) operating at a liquid nitrogen temperature of 77 K. The tested linac was previously processed and tested at room temperature. Low-temperature operation increases the yield strength of the accelerator material and reduces surface resistance, hence a great reduction in cyclic fatigue could be achieved resulting in a large reduction in breakdown rates compared to room-temperature operation. Furthermore, temperature reduction increases the intrinsic quality factor of the accelerating cavities, and consequently, the shunt impedance leading to increased rf-to-beam efficiency and beam loading capabilities. We verified the enhanced accelerating parameters of the tested accelerator at cryogenic temperature using different measurements including electron beam acceleration up to a gradient of 150 MV/m, corresponding to a peak surface electric field of 375 MV/m. We also measured the breakdown rates in the tested structure showing a reduction of 2 orders of magnitude compared to their values at room temperature for the same accelerating gradient.

https://doi.org/10.1103/PhysRevAccelBeams.24.093201



(a)   (b)

FIG. 5. (a) A picture of the installed cryostat in the XTA beam line and (b) the LN feeding system outside the tunnel.

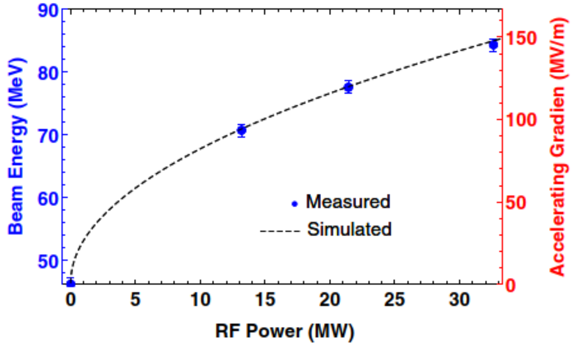


FIG. 6. The measured energy gain of an electron beam moving down the axis of the distributed-coupling linac for a compressed 200 ns square rf pulse with an input power of 13–33 MW, achieving an accelerating gradient of 100–150 MV/m and a peak surface electric field of 250–375 MV/m. Blue dots and the dashed line are measured and simulated values, respectively. Simulations used the measured input rf pulse and the cavity model at 77 K.

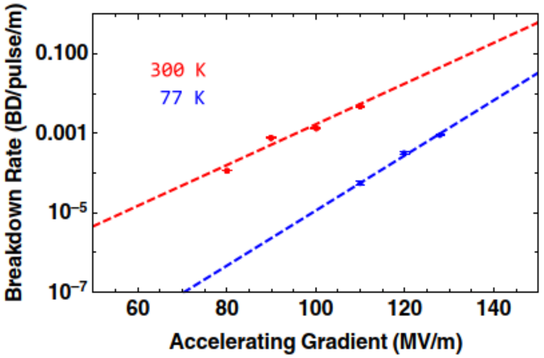
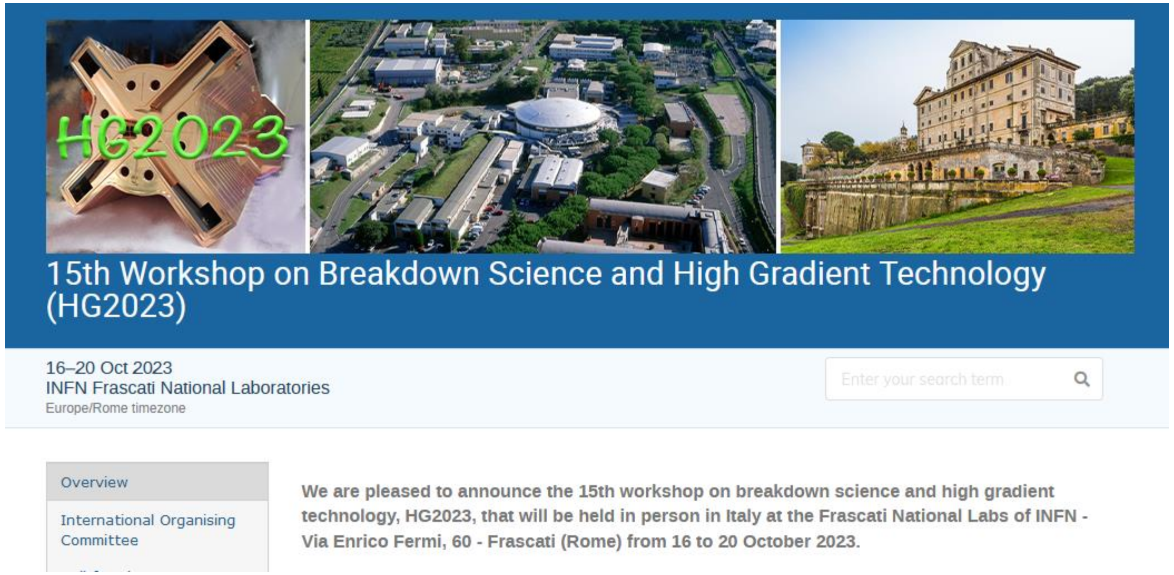


FIG. 9. The collected breakdown rates with the fitted slope of the distributed-coupling accelerator structure at 300 and 77 K. The breakdown rates at 300 K are obtained from our previous testing of the same accelerator structure at room temperature. For both operating temperatures, the data were collected for a 400 ns

Community



15th Workshop on Breakdown Science and High Gradient Technology (HG2023)

16–20 Oct 2023
INFN Frascati National Laboratories
Europe/Rome timezone

We are pleased to announce the 15th workshop on breakdown science and high gradient technology, HG2023, that will be held in person in Italy at the Frascati National Labs of INFN - Via Enrico Fermi, 60 - Frascati (Rome) from 16 to 20 October 2023.

10th International Workshop on the Mechanisms of Vacuum Arcs (Hybrid MeVArc 2022)

18–22 Sept 2022
Chania, Crete
Europe/Zurich timezone

MeVArc 2022

https://agenda.infn.it/event/34253/

https://indico.cern.ch/event/1099613/

Registration is open!

Next edition early March 2024, probably Lake Tahoe.
Hosted by Sandia Lab. Information soon.

Conclusions

- We now have a significant body of experiments that show how copper structures can perform and what the main dependencies are.
- Care must be used in interpreting these results!
- We have a reasonably good explanations/theories for most of the observed gradient dependencies.
- The dependencies can be used to successfully optimize structures for particular applications.

Thank you for your attention!