Ultimate Field Gradient in Metal Structures
Ultimate Field Gradient Limitation in Metal Structures
In order to reach multi-TeV $e^+e^-$ collision energies the CLIC collaboration has invested significant effort to develop 100 MV/m gradient accelerating structures.
CLIC accelerating structures

- 11.994 GHz, X-band
- OFE copper, hydrogen bonded 1040 °C
- 100 MV/m accelerating gradient
- Input power ≈50 MW
- Pulse length ≈200 ns
- Repetition rate 50-400 Hz
Vacuum arcing

One of the main limitations we have is vacuum arcing, aka breakdown,

- Supresses power flow reducing acceleration
- Gives beam transverse kick

Transverse effect on beam measured in CTF3, A. Palaia
Very high-field vacuum arcs

Vacuum arcs – the formation of plasma accompanied by large electron currents - occur in many devices and applications.

What’s so special about us?

• Very high surface electric fields, over 200 MV/m
• Opportunity to test over 20 rf structures and over 40 pulsed dc electrodes combined with significant theoretical and simulation effort.

We believe that we see processes which give fundamental field limits for copper.

Onset of a vacuum arc simulated by ArcPIC, K. Sjobaek
Where we do our experiments

Klystron-based test stands at CERN:
- XBox1 to 3
- NEXTEF at KEK
- Two pulsed-dc systems.
CLIC accelerating structures - performance summary

Currently under test:
- XBox1 – TD26CC N2
- XBox2 – TD26CC N3
- XBox3 – TD24CC SiC
- T24 PSI
- SBox - 3 GHz BTW
- NEXTEF (KEK) – TD24 R05
Consider the vacuum arc trigger.

Need a site which produces enhanced electron field emission and neutral atom emission.

What is the nature of such a site?

For most applications these are contaminants: dust, particles, oxides etc.

But at high fields, > 100 MV/m surface electric field, we see clear evidence of field-generated features – that give the ultimate field limit.

These features seem to form below the surface and are generated by dislocation dynamics.
Conditioning

Accelerating structures do not run right away at full specification – pulse length and gradient need to be gradually increased while pulsing. Typical behaviour looks like this:

4 million pulses per day at 50 Hz

Pulse length steps

50 ns  250 ns

BDR falls during flat E run

Number of BPs

0  2000  4000  6000  8000  10000

10^{-7}  10^{-6}  10^{-5}  10^{-4}

Gradient [MV/m]

0  20  40  60  80  100  120

Number of Pulses (millions)

0  50  100  150  200  250  300  350

10^{-3}
BDR dependence

Regularly observed dependence:

\[ BDR \propto E^{3.0} \tau^{5} \]

Data taken in XBox-2 with TD26CC structure, T. Lucas

Physical model based on defect formation

\[ BDR \propto e \frac{-E_f + \varepsilon_0 E^2 \Delta V}{k_B T} \]

\[ E_f = 0.8 \text{ eV} \]

\[ \Delta V = 0.8 \times 10^{-24} \text{ m}^3 \]

Comparison of three similar structures

We normalize by:

\[ BDR \propto E^{30} \tau^{5} \]

And get

Interpretation: Conditioning is a reproducible process which implies a well defined physical mechanism.
Comparing conditioning

Interpretation – conditioning proceeds as the number of pulses not the number of breakdowns. This implies a steady modification of the structure for each pulse.

Comparison of mechanical and rf samples

Experiment:
1. Build rf structure, standard procedure with 1040 °C bonding, and mechanical sample with same heat treatment.
2. Condition rf structure and fatigue mechanical sample.
3. Compare material state before/after/between using advanced microscopy techniques: FIB cutting lamella and image using STEM and TEM.
Mechanical fatigue – STEM images

After heat treatment

Formation of dislocation patterns characteristic of hardening.

After mechanical fatigue

200 nm

E. Rodriguez Castro
Comparison of mechanical and rf samples

After rf conditioning, high E field region – TEM image

from a TD24

A. Yashar, I. Popov
Interpretation

RF operation at high fields produces dislocation patterns similar to fatigue implying:

• A hardening process occurs during conditioning,

• Dislocation dynamics, formation and movement, are central to high-gradient behaviour.

Some numbers:

• Electric field stress is $\sigma = \frac{1}{2} \varepsilon_0 E^2$ so for 250 MV/m surface field, 270 kPa – for perfect flat surface.

• The onset of plastic behaviour in Cu is of the order of kPa, so well above already at 100 MV/m surface field.

• Speed of sound in copper is .38 mm/100 ns, so bulk phenomenon.
Tensile stress induces plastic behaviour, i.e. creates dislocations.
Dislocations move to surface to reduce energy.
Projection of dislocation on surface in nucleation point for continuation of breakdown process (too little time today for rest of story)

(Pulsed surface heating – not subject for today)
Exact Solution: Master Equation

\[
\frac{dP(n, t)}{dt} = \lambda(n-1)P(n-1, t) + \mu(n+1)P(n+1, t) - [\lambda(n) + \mu(n)]P(n, t)
\]

BDR dependence - II

Experiment: Dependence on Field

A. Grudiev, S. Calatroni, and W. Wuensch, PRST-AB 12, 102001 (2009)
K. Nordlund and F. Djurabekova, PRST \& AB 15, 071002 (2012)

Good fits, consistent with the previously proposed power law:

\[\tau \sim E^\nu, \quad 25 < \nu < 30\]
Copper in its annealed state always has some, but very mobile, dislocations.

Stresses from rf pulses create and move dislocations, which migrate towards surface creating surface features which nucleate breakdown sites.

This dynamic gives us breakdown rate.

Movement of dislocations also form interlocking “sessile” patterns, which reduce movement of later-formed dislocations.

This interplay is what lies behind field dependence, conditioning and gives ultimate gradient.

*BD nucleation as a critical transition in dislocation population*, Y. Ashkenazy

*Stochastic Model of Breakdown Nucleation under Intense Electric Fields*, E. Engelberg

both at MeVArc2017 [https://indico.cern.ch/event/521667/](https://indico.cern.ch/event/521667/)
Hard vs. soft copper in pulsed dc system

Data consistent with idea of conditioning as hardening process

As-machined

1040 °C treated electrodes

Gradient vs N. Pulses

N. Pulses [Millions]

Gradient [MV/m]

Hard Cu Electrodes 2

Soft Cu Electrodes 3

Hard Cu Electrodes 4

Soft Cu Electrodes 5
Hard vs. soft copper in pulsed dc system

RF structure in milled halves:
Heat-treated reference successful (presented at LINAC)
Hard-copper version under preparation
Summary

• Breakdown rate vs gradient,
• Conditioning vs number of pulses,
• Material state before and after conditioning,

All point to the importance of dislocation dynamics in determining behaviour and Ultimate Gradient in high-gradient normal conducting rf structures.

A crucial stage of the action is below the surface!
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Much more at Mechanisms of Vacuum Arcs, MeVArc2017
https://indico.cern.ch/event/521667/overview