Physical Processes Controlling Dark Current Emission and Resulting Breakdown in linacs

Presented by

I.Konkashbaev (ANL)

Workshop on High Gradient RF

ANL, Argonne, IL, USA 7-9 October 2003

- **Higher accelerating gradient are required for future demands like μ-μ and e¯-e+ collider.
Rf dark current and the resulting electrical breakdown impose a limit in the E_{max}**

- **Two critical questions needed to be answered:
What causes the high dark current and breakdown?
Can the breakdown threshold be increased?**

- **The focal point of this paper is to shed some light on the possible mechanisms that limit field gradient in linacs with and without guiding magnetic fields B_z.**

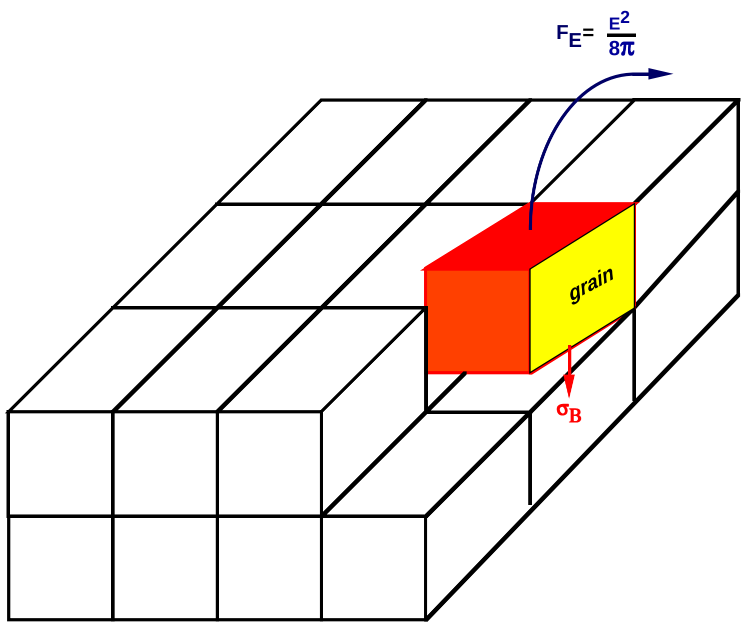
- **Enhancement of the dark current and breakdown is a single surface phenomenon due to existing of small-size protrusions. Surface processing decreases the field enhancement factor, but there are limits of surface improvement following treatment.**

- **In an extreme case of perfect treatment grains (grain boundaries) play role of such protrusions because used metals are polycrystalline consisting of micron-size grains.**

- **Three processes having an important bearing e are discussed:**

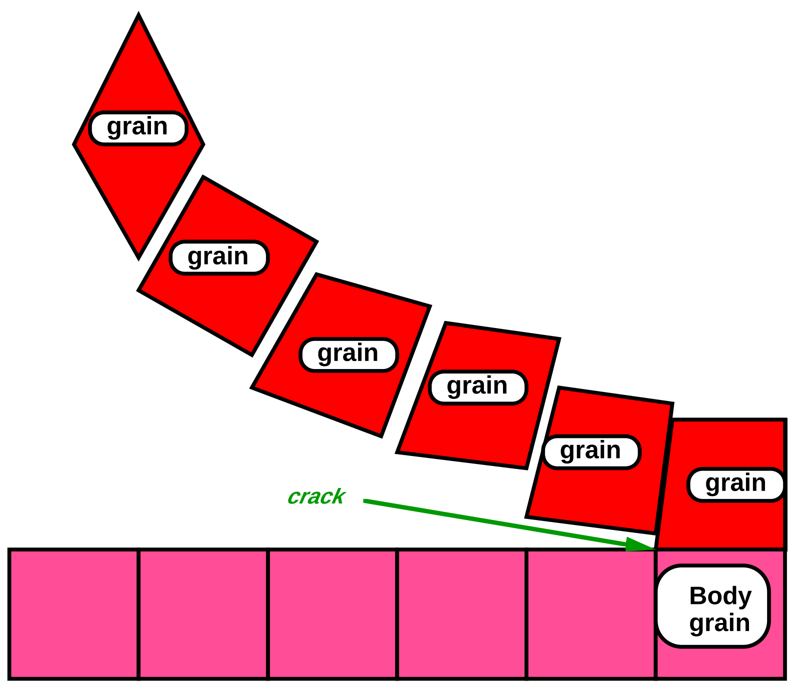
  a) the grain separation,
  b) the of secondary electron emission increasing ,
  c) the field evaporation of ions

Grain separation
from body by the electric field tension



- **Separation of one grain results in crack formation that provokes separation of the next grain, then another, and so on.**
  The enhanced electric field results from a displaced linear protrusion

Schematic of grain-by-grain separation



- **The kind of brittle destruction takes place by the stripping of grains one by one. The binding force can be estimated by the threshold force, i.e. yield of strength σ_B. ($\sigma_B(Be)=(1.4\text{-}4.5)\ katm$)**

- **The electric field at which the grain can separate is**

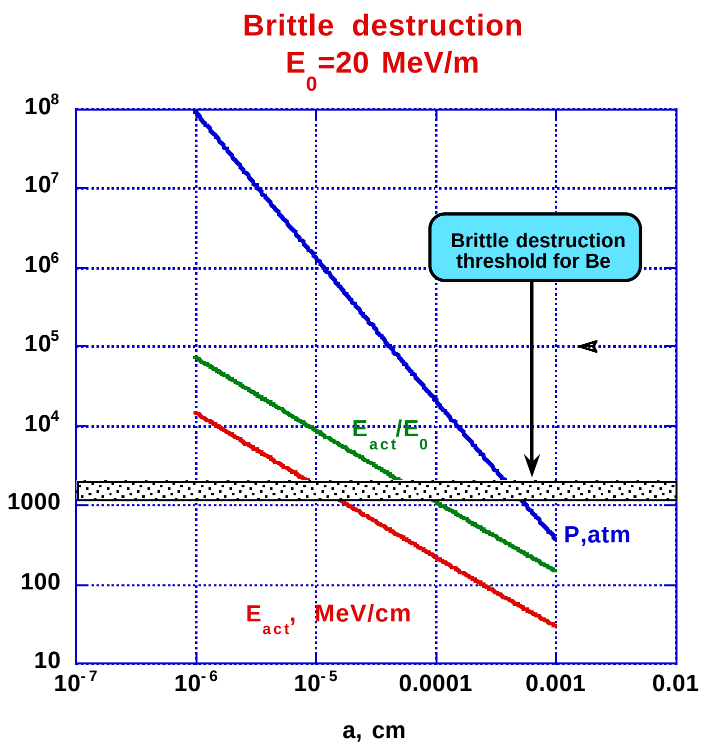
$$\frac{E_{\max}^2}{8\pi} = \sigma_B, \quad E_{\max} = \sqrt{8\pi\sigma_B},$$

$$E_{\max}(\sigma_B = 4\,katm) = 10\ \frac{GeV}{m}$$

- **The electric field, E_a, of hemicylinder with radius a, between electrodes displaced on distance, L, is**

$$U = E_0 L, \quad E_0 \approx 10\ \frac{MeV}{m},\ L \approx 10\,cm,\ a \approx 10\,\mu m$$

$$E_a \approx E_0 \frac{L}{a}\frac{1}{\ln a} \approx 10^3 E_0 = 10\ \frac{GeV}{m} >> E_0$$


Brittle destruction
E_0=20 MeV/m
Brittle destruction threshold for Be
E_{act}/E_0
P,atm
E_{act}, MeV/cm
10^8
10^7
10^6
10^5
10^4
1000
100
10
10^{-7}
10^{-6}
10^{-5}
0.0001
0.001
0.01
a, cm

Current during breakdown

- **The current is determined by the number of spots, N_{spot}, (i.e., points in which grains are separated), and electric field , E_{max}, which is determined by size of the grains, a, detached by the brittle destruction:**

$$E_{\max} = E_{act} = E_0 \frac{L}{a} \frac{1}{|\ln a|},$$

$$a \approx \left(L \frac{E_0}{E_{\max}} \right)^{\frac{4}{5}}$$

- **Maximal number of spots N_{spot} is determined by conservation of the total charge, Q_0 , on electrode surface:**

$$Q_0 = \pi R^2 \sigma_0, \ \sigma_0 = \frac{E_0}{4\pi}$$

$$Q_0 = Q_{spot} = \sum_{j=1,N_{spot}} q_{j,spot} = \pi a^2 N_{spot} \sigma_{spot}$$

- **In the ultimate case, all charge displaces on the grains surfaces with density σ_{spot} with zero surface charge density between grains.**

$$\sigma_{spot} = \frac{E_{\max}}{4\pi}, \ q_{spot} = \pi a^2 \sigma_{spot}$$

$$N_{spot} = \frac{Q_0}{q_{spot}} = \frac{R^2}{a^2} \frac{E_0}{E_{\max}}$$

$$S_{spot} = \pi a^2 N_{spot} = \pi R^2 \frac{E_0}{E_{\max}} << \pi R^2$$

- **The total number of spots, N_{spot}, can be very high, but density of spots, n_{spot}, is not large**

- **Nevertheless, the total current, I_{max}, ejected from these spots can be very high due to exponential character of field emission dependence on E_{act}.**

- **These spots eject current due to the field emission according to $E_{act}=E_{max}$. The time for spot discharging according to the Fowler-Nordheim formula is very small**

$$q_{spot} = \sigma_{spot} \pi a^2 = \frac{E}{4\pi} \pi a^2 = \frac{1}{4} 10^{-9} coulomb$$

$$\tau_d = \frac{q_{spot}}{i_{spot}^{FN}} = 1.2 \cdot 10^{-14}\ s,\ \ \lambda_d = c\tau_d = 3.6 \cdot 10^{-4}\ cm$$

resulting in space charge near the spot surface at a distance close to the spot radius, therefore current is determined by the Child-Langmuir current

- **The spot temperature is determined by the equilibrium between a joule heating and cooling by heat conduction**

$$c_v \frac{dT}{dt} = \rho j^2 - \frac{\kappa T}{a^2}, \; T = \frac{\rho j^2 a^2}{\kappa} = \frac{\rho i^2}{\kappa a^2}$$

$$Be: a = 30\,\mu m, \; T = 0.75 \cdot 10^3 i_{kA}^2 \,, K$$

Table2. **Spot parameters according to the Child-Langmuir current**

$$E_{\max} = 10\frac{GeV}{m}, \; E_0 = 10\frac{MeV}{m}, \; TM_{010} - \mathrm{mode}, R = 2.405\,L$$

f GHz	L cm	R cm	$a, \mu m$	i_{spot}^{FN}, kA	i_{spot}^{CL}, kA	T, eV
0.5	30	72	60	84	9.6	1.75
1.0	15	36	30	21	4.8	0.43

- **One can obtain the breakdown condition as a function of frequency *f*, and material properties as electric resistance, *ρ*, heat conductivity, *κ*, and σ_B:**

$$E_0(Be) > (10-25)\, f \sigma_B^{-0.36} \left(\frac{\kappa T_{ion}}{\rho} \right)^{0.57}$$

$$E\left[\frac{MeV}{m}\right], \quad f\,[GHz]$$

Secondary electrons emission

- **One of the main reasons, from our point of view, is the transition of the ejected electrons accelerated in the linacs to relativistic and ultra-relativistic energies.**

- **The stopping power of relativistic and ultra-relativistic electrons, $E >> mc^2$, became similar to stopping power of ions with the same energy that results in more production of the secondary electrons. A significant amount of experimental data and calculations have been made at low energy, $E < 1$ *MeV*, but interaction at higher energies , $E > 10$ *MeV*, have been studied much less**

- **Relatively increasing of the stopping power results in increasing of a secondary electron emission, ζ.**

- **ζ is determined by the range of primary electrons, λ_e, and energy losses of the secondary electrons.**

- **It is well known that *ζ* in insulators is very large: *ζ>>1 (up to 100)*) – low energy losses of the secondary electrons**
- **In metals at low energy of primary electrons *ζ<1* – high energy losses of the secondary electrons**
- **fission reactions fragments interaction can reach *ζ=10-100* – secondary electrons are borne at low distance from the surface**
- **Ultrarelativistic electron *ζ* can be more 1 – secondary electrons are borne at low distance from the surface (should be prove!)**

FIELD EVAPORATION

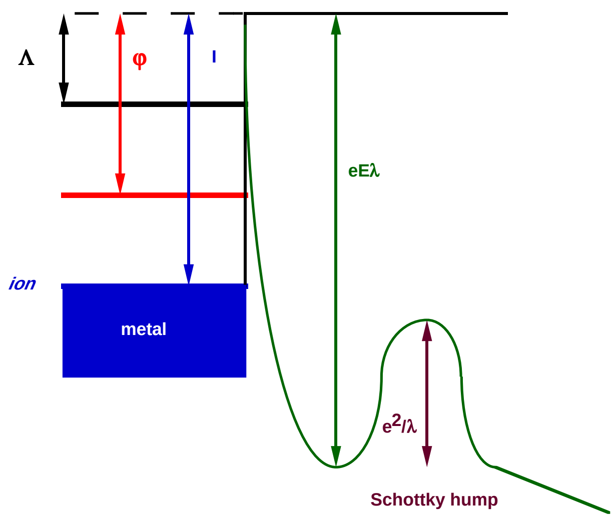
as possible mechanism of enhancement dark current and breakdown

- **Under high electric field near the electrode surface due to existing protrusions of grain size of microns ions can also leave surface at E>0, i.e., so-called "field evaporization" take place**

Mechanism of field evaporation

$$\Delta E = \Lambda + I - \varphi - eEx + e^2/x$$

$$S = \nu\exp(-\Delta E/T)$$



Field evaporation

$$\frac{x_{\max}}{a_0} = \sqrt{\frac{I_H}{4}\frac{1}{E_{eV}a_0}} = \frac{2.535}{\sqrt{E}}$$

$$\Delta Q_{Schottky} = \max\left(U_{Schottky}\right) = \sqrt{2E_{\frac{MeV}{cm}}}$$

$Q_0 = \Lambda + I - \varphi$

A	Λ	I	φ	Q_0	E	E
	eV	eV	eV	eV	eV/A°	GeV/m
W	8.78	7.98	5	11.76	5.7	57
Be	3.27	9.32	3.92	8.67	-	-
Au	3.23	9.22	4.82	7.63	3.5	35
Fe	4.11	7.90	4.5	7.63	3.4	34
Cu	3.17	7.72	4.55	6.34	2.4	24

♦ Evaporation flux for Cu

Field enhancement factor

$$\xi = \frac{E_{act}}{E_0} = \frac{2L}{a}$$

Ions flux

$$S = \nu e^{\frac{-Q_0 + Q_E}{T}},$$

$$Q_E(Cu) = \sqrt{0.02 \cdot E_{act}},\ \text{E in } \frac{\text{MeV}}{\text{m}}$$

with ν the mean vibration frequency of the surface atoms

$$\nu(Cu) = 0.67 \cdot 10^{13},\ s^{-1}$$

Maximal ions flux

$$Q = -Q_0 + Q_E = 0$$

$$S_{\max} = \nu = 0.67 \cdot 10^{13},\ \frac{ions}{cm^2 s}$$

Evaporated ion motion

- **Solution of equation of motion for evaporated ion coming out at $t=t_0$ is**

$$\frac{V}{V_\omega} = \cos(\omega t_0) - \cos(\omega t)$$
$$\frac{Z}{Z_\omega} = (\omega t - \omega t_0) + [\sin(\omega t_0) - \sin(\omega t)]$$

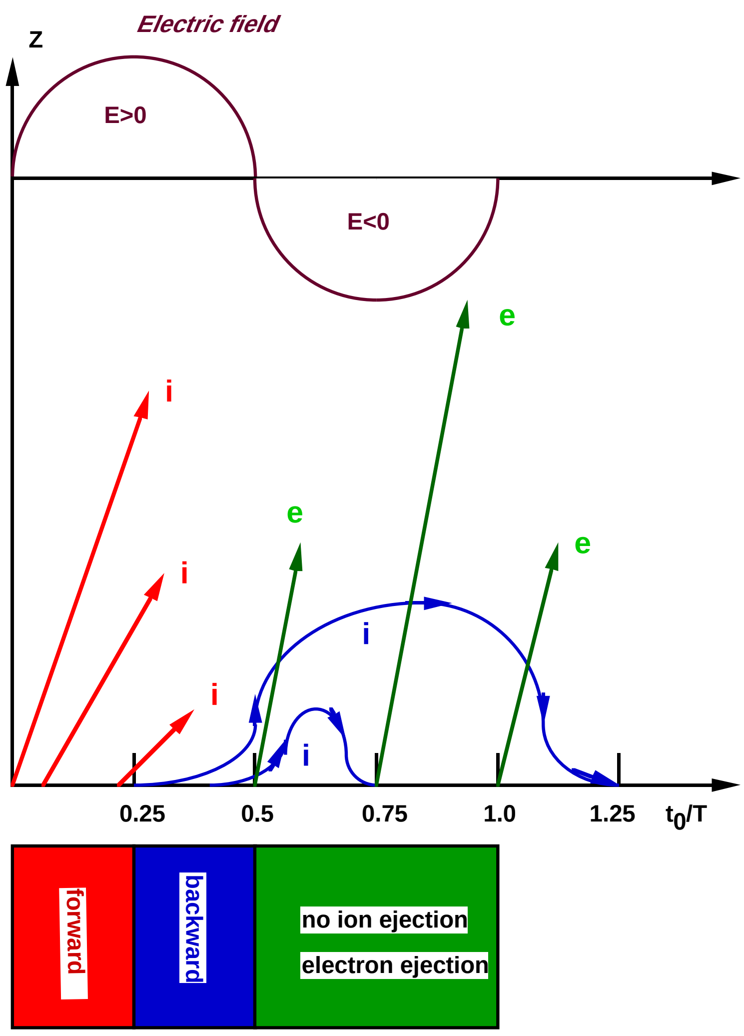
- **Characteristic velocity and magnitude of ions and electrons are**

$$f = 1GHz, \;\; E\; in \frac{MeV}{m},$$

Electron   *ion*

$$V_{\omega e} = \frac{eE_0}{m_e \omega} = 3 \cdot 10^{10} E, \qquad V_{\omega i} = 2.5 \cdot 10^{6} E, \;\; \frac{cm}{s},$$
$$Z_{\omega e} = \frac{eE_0}{m_e \omega^2} = 4.7 \cdot 10^{2} E, \quad Z_{\omega i} = 4 \cdot 10^{-4} E, \;\; cm$$

- **Dynamics of ions and electrons coming out at different phase of the electric field**



- **During time $\pi<\omega t< 2\pi$ ions cloud is runned through by electrons with energy ΔE_e**

$$\Delta E_e(eV) \approx eE\Delta z = (10-10^2)\ E_{MeV/m},$$
$$\Delta E_e \approx (10^2-10^3),\ eV$$

that enough for ionization of ion to more high Z

- **Ion cloud has density about**

$$n_i = \frac{S\tau}{\Delta z} \approx 6\cdot 10^8\ cm^{-3}$$

and part of ions ionized by ejected electron beam to Z>1 can come back with more large energy gained during negative electric field phase

- **These ions coming back with energy, $\Delta E_i \leq \Delta E$ can produce secondary ions (sputtering) and some secondary electrons**

- **Possibility of chain process resulting in the dark current enhancement and even breakdown needs in investigation**

SUMMARY

- **The extreme case of perfect treatment when grains play role of small protrusions with enhanced electric field near the electrodes surface is discussed**

- **Three processes having an important bearing e are discussed:**

  a) the grain separation,
  b) the of secondary electron emission increasing ,
  d) the field evaporation of ions

- **All these processes can result in increasing of the dark current and breakdown and need in more detail investigation**