Electrical Insulation in Vacuum

Yoshio SAITO (KEK)

1. Vacuum as an insulator

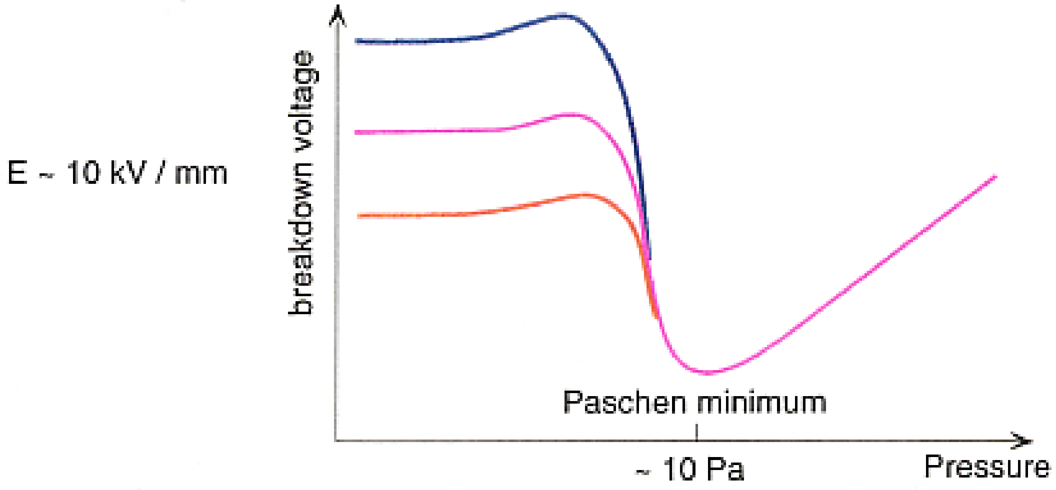
* Paschen minimum in electrodes gap

among the most effective insulating methods

- **electron mean-free-path** $\lambda_e = \dfrac{4}{n\pi\sigma^2} = 4\sqrt{2}\lambda$

($\lambda = \dfrac{1}{\sqrt{2}n\pi\sigma^2}$ **: mean-free-path of a residual gas molecule**)

- **less probability of volumetric collision**



* $\lambda_e >> d$; surface-depending breakdown voltage

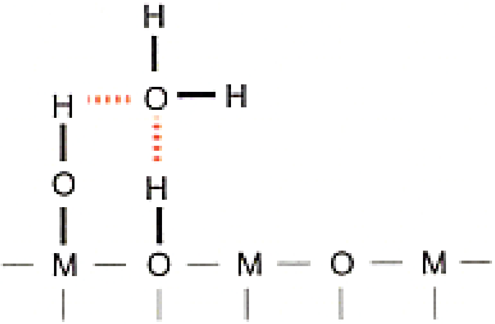
- **electron emission from the surface**
- **secondary emission of charged particles from/adjact to it**

* surface condition and vacuum pressure

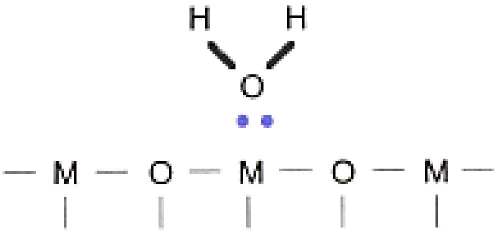
- as surface becomes clean, vacuum pressure decreases
- adsorption of H_2O on metal surfaces is dominant

- physisorption; 0.44 – 0.5 eV, $\tau = 7\times10^{-6} - 9\times10^{-5}$ s

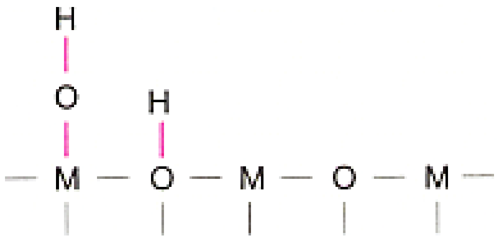
- hydrogen-bonded adsorprion; 0.5 – 0.7 eV, $\tau = 9\times10^{-5} - 3\times10^{-1}$ s



- coordinative adsorprion; 0.7 – 1.2 eV, $\tau = 3\times10^{-1} - 2\times10^{8}$ s



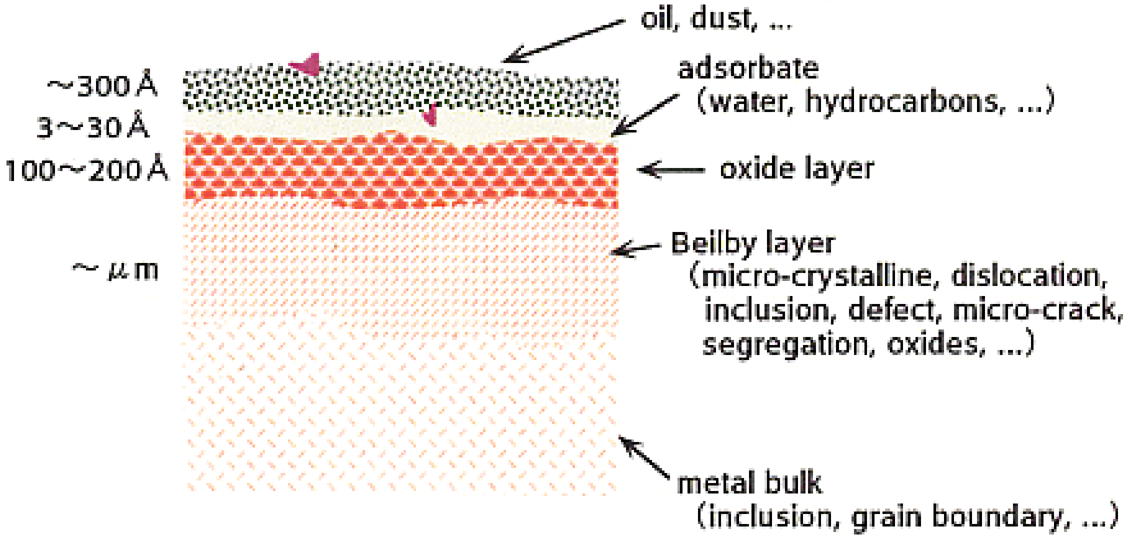
- dissociative adsorprion; 1.2 – 1.5 eV



2. Breakdown phenomena on metallic electrodes

* surface condition inducing breakdown

- surface contamination and oxide layer
- residual stress in Beilby layer
- ad/absorbed gas molecules

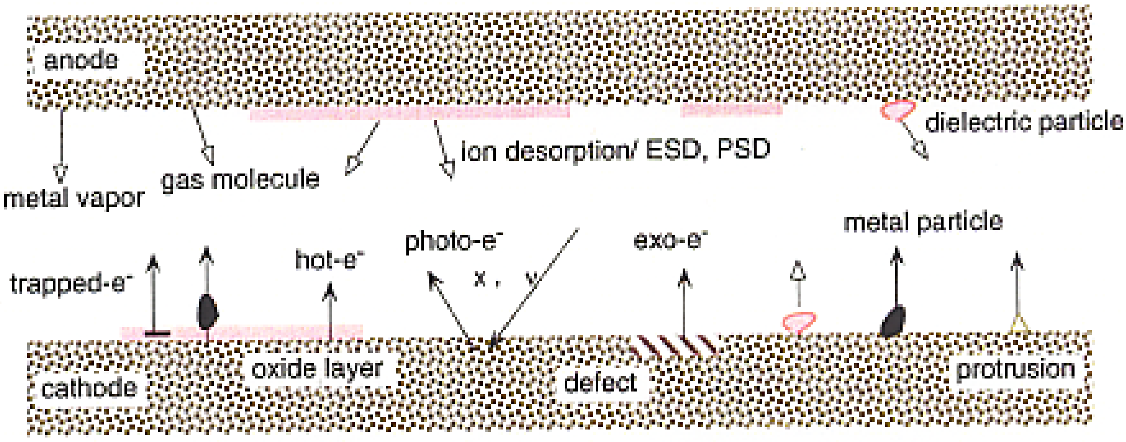


* surface finishing - technical surface

- mechanical
    - diamond turning
    - polishing with abrasives (blast, buffing, lapping...)
- chemical (chemical and mechano-chemical polishing...)
- optical (laser polishing)
- electrical
    - chemical (electrolytic polishing, electro-chemical buffing)
    - thermal (plasma polishing, ion polishing)

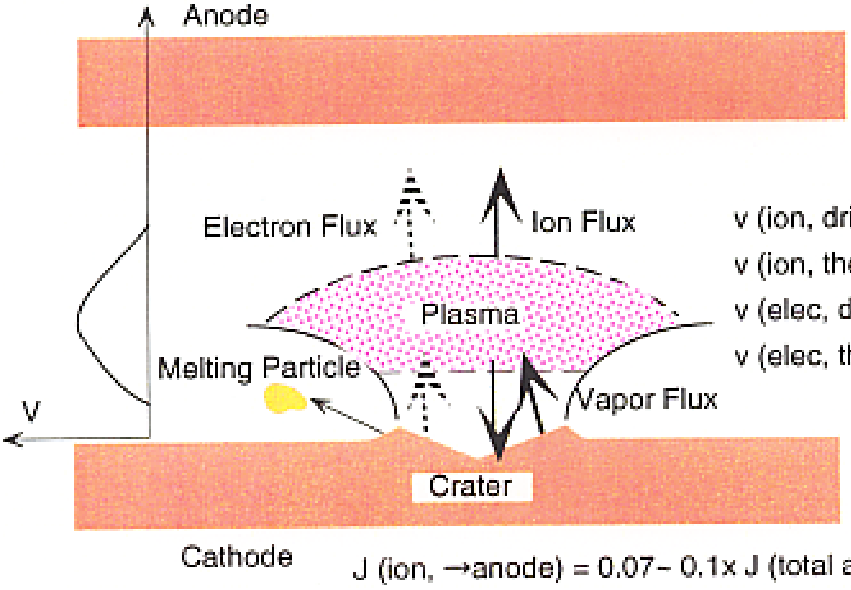
* electron emission followed by breakdown

- not only field emission but also other excitation mechanism
- electron stimulated desorption



* final stage of breakdown; detrimental arcing

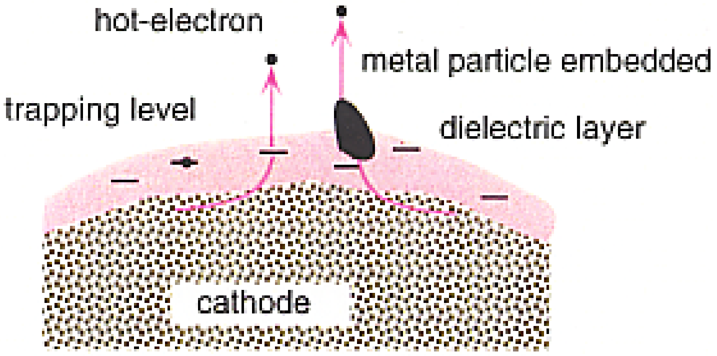
- localized charged-particle density (cathode spot)
- damage depends on energy dose amount/pulse duration

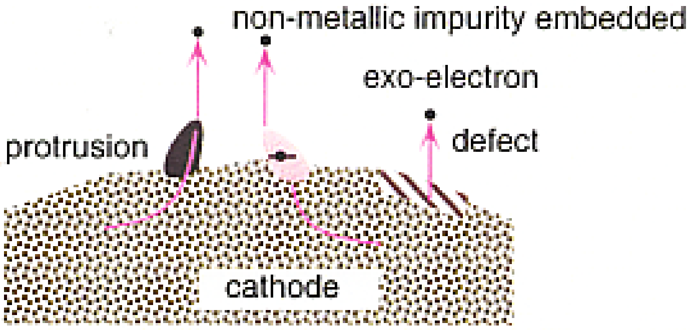


v (ion, drift) = 1~ 2 x 10^4 m/s
v (ion, therm) ~ 2 x 10^3 m/s
v (elec, drift) = 1~ 3 x 10^5 m/s
v (elec, therm) ~ 10^6 m/s

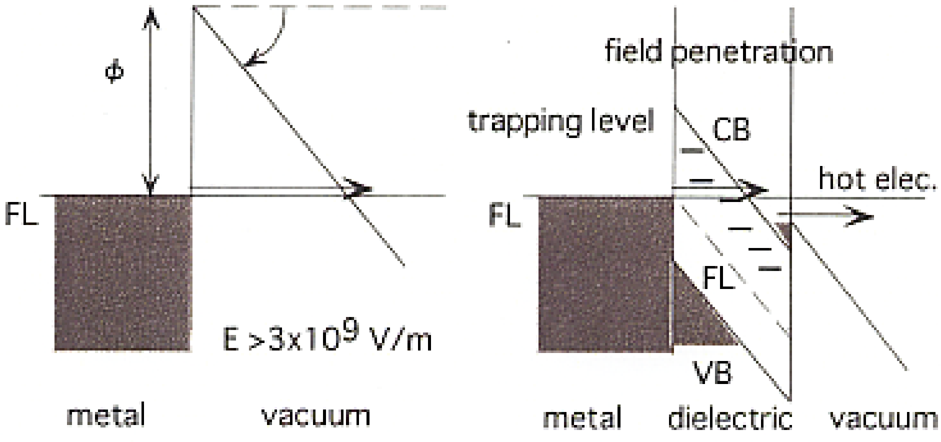
J (ion, →anode) = 0.07~ 0.1x J (total arc current)
J (ion, →cathode) = 0.1~ 0.2 x J (total arc current)
J (elec, →anode) = 1.07~ 1.1 x J (total arc current)

* electron emission site



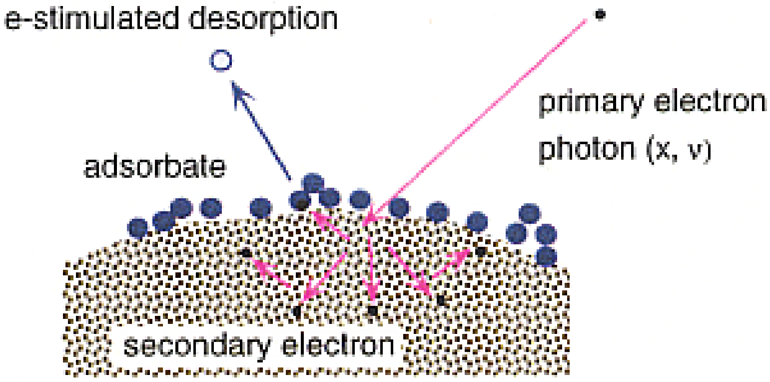


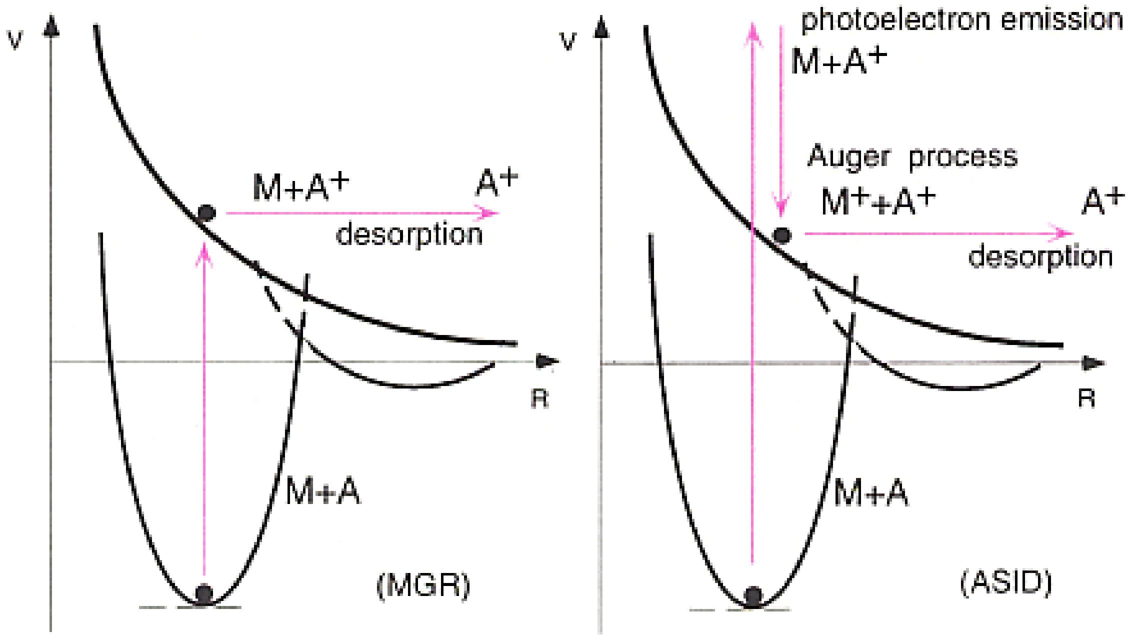
- hot-electron emission from dielectric layer



* electron stimulated desorption (ESD)

- secondary electrons generated in the outermost layer
- ionization of the adsorbed molecules





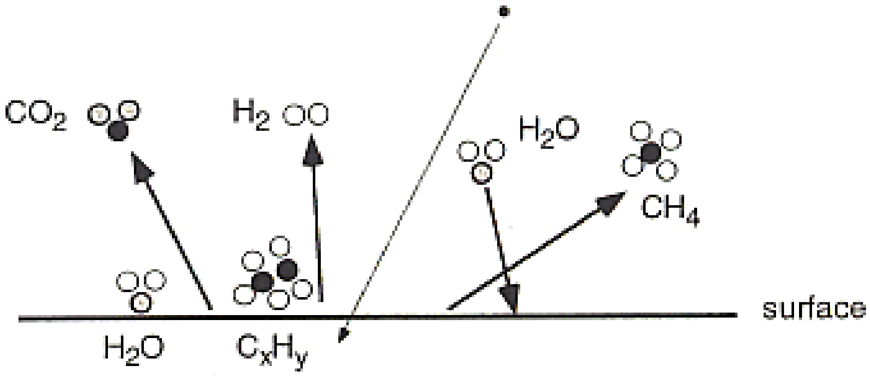
Menzel-Gomer-Redhead model / Auger stimulated ion desorption

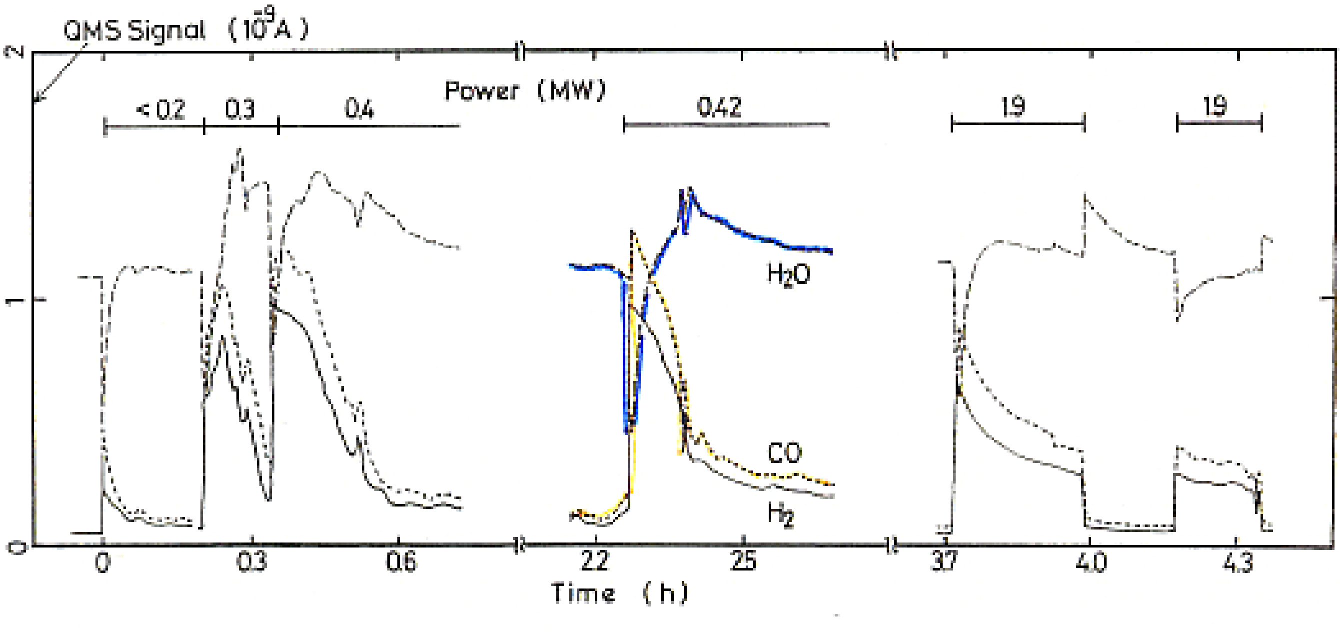
3. Experimentally and empirically obtained results, concerning gap breakdown

- adsorbed water molecules and contamination
  - gas evolution during conditioning
- absorbed hydrogen molecules in bulk
  - hydrogen content in oxygen-free-copper
- surface residual stresses and roughness
  - diamond turning and electro-chemical buffing
- non-metallic inclusion in bulk
  - inorganic inclusion in electroformed copper
- surface oxide layer
  - field emission current from copper electrode
- total voltage effect
  - breakdown voltage in narrow and long gap
- pulse duration and frequency
  - millisecond and microsecond pulse duration
- RF structure effect; emitted electron behavior
  - multipactor mapping

* adsorbed water molecules and contamination

- gas evolution during conditioning / S-band waveguide system
- dissociative release of water and hydrocarbon adsorbates
- ESD outgassing process is necessary, even after bake-out,
  surface cleaning of hydrocarbon removal before installation
- for shortening conditioning process, bake-out is effective



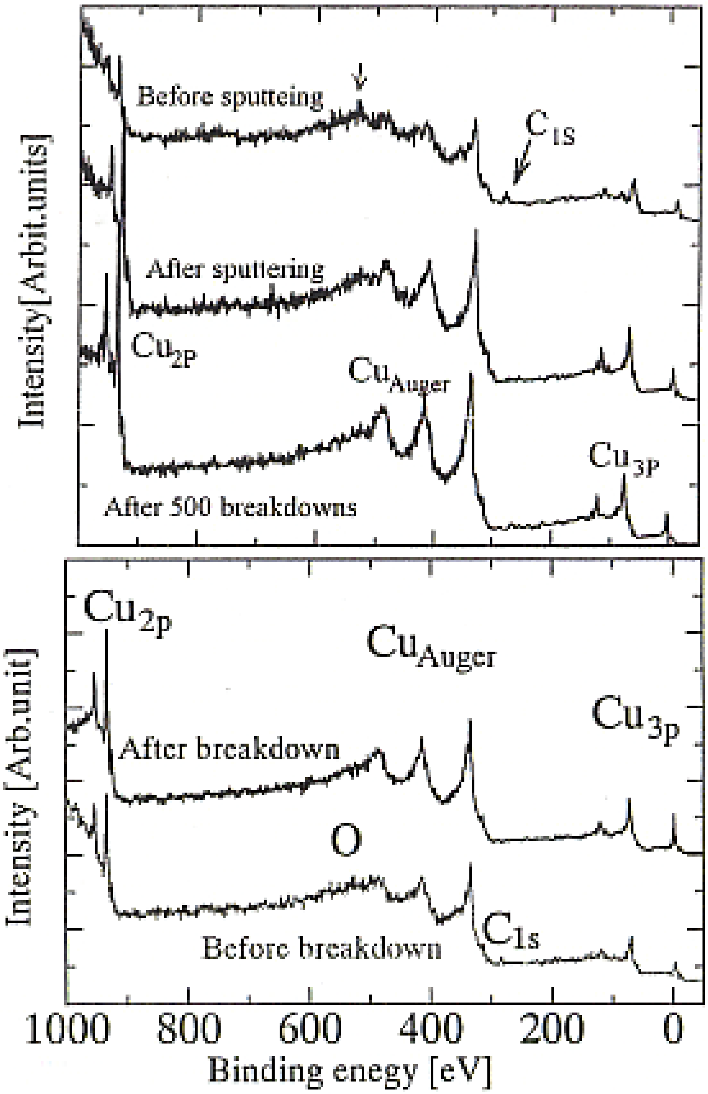


* oxide layer and contamination

- surface cleaning treatment for oxygen-free-copper electrode
  - He ion sputter <$5\ 10^{-4}$ Pa, 4 keV, 0.37 μA, 4 mm in dia., 5min.>
  - hydrogen firing <1050C, 1 atm, 5 min.>
  - HV-applying conditioning <0-100 kV, 150 shots, 1 mm gap>

- removal of carbon contamination after HV conditioning
- reducing effect of oxygen by He ion sputter cleaning
- reducing effect of carbon and oxygen by hydrogen firing

XPS spectra observed for Cu electrode

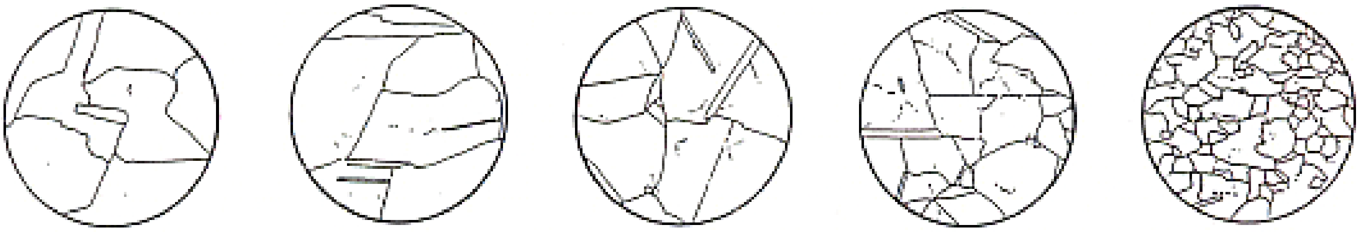


hydrogen fired

* absorbed hydrogen molecules in bulk

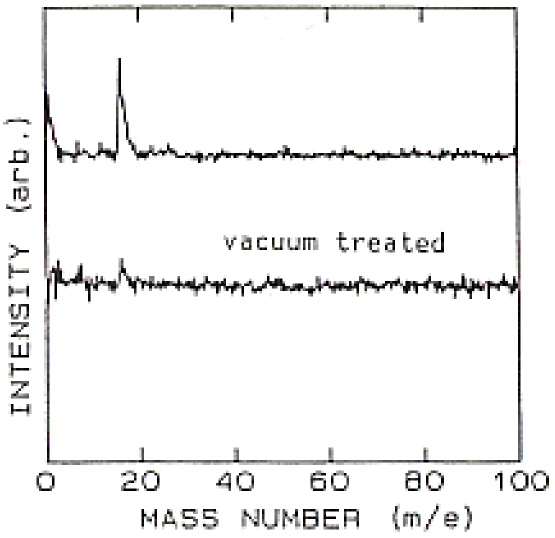
- hydrogen content in oxygen-free-copper
- higher performance for vacuum-degassed copper (<0.3 ppm)

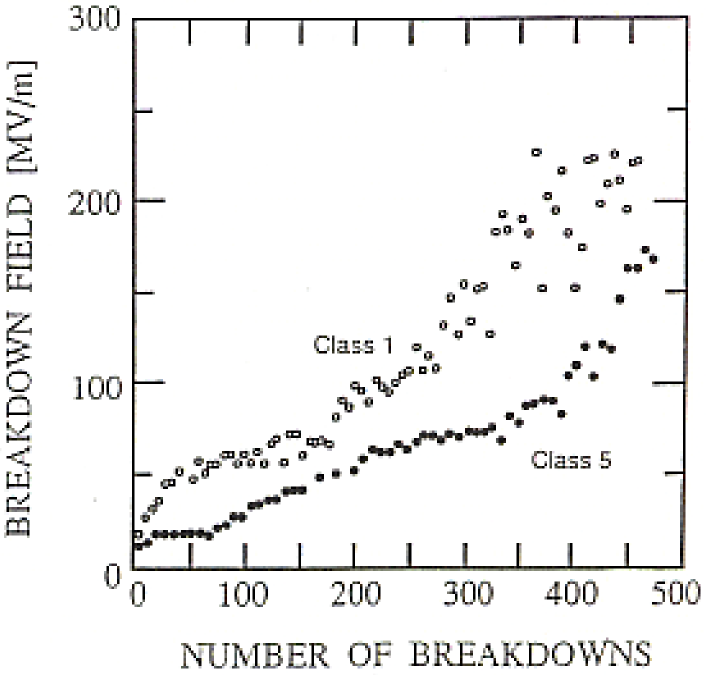
Comparison chart for estimating a degree of porosities in oxygen free copper (OFC).



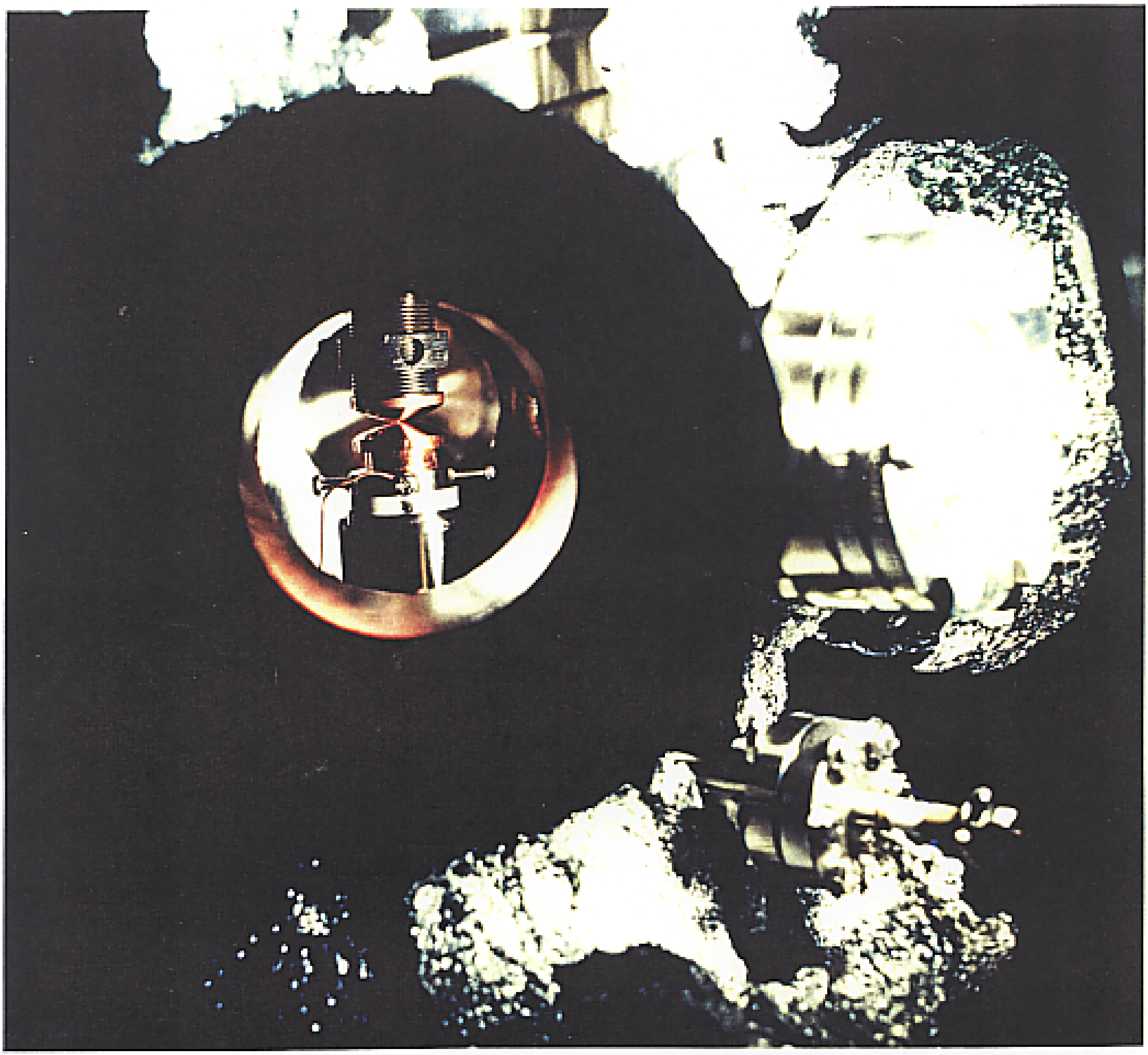
Class 1 Class 2 Class 3 Class 4 Class 5

Negative-SIMS (secondary ion mass spectrometry) signals observed for a vacuum treated and a normally manufacured OFC.





Dependence of breakdown field strengths on the number of breakdowns observed for OFC Class "1" and "5" electrodes.



OFC electrodes for impulse breakdown experiments.

The electrodes are of spherical shape 18 mm in radius and having a 3.5 mm initial gap spacing.

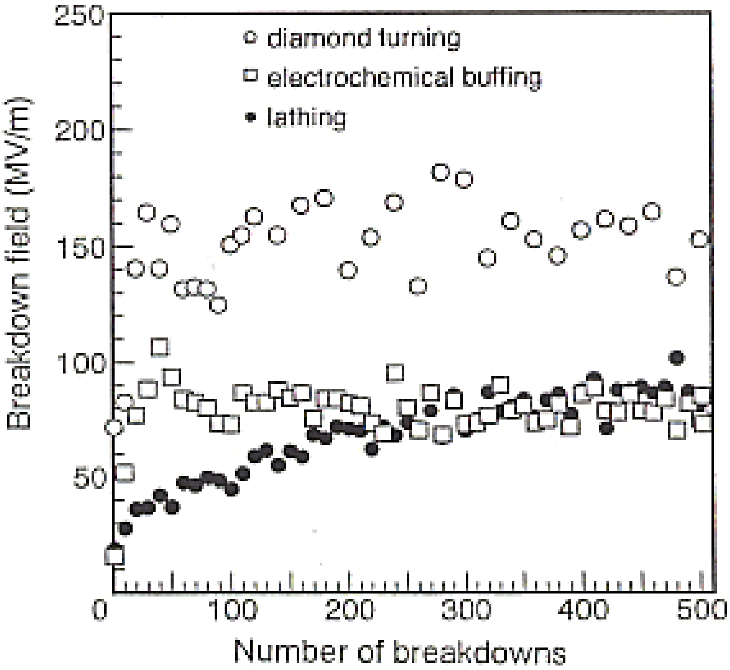
An impulse(60 x 700 ~~m~~μs) is applied to the gap. Breakdown field strength increase as a number of breakdowns (HV conditioning by repetitive breakdown).

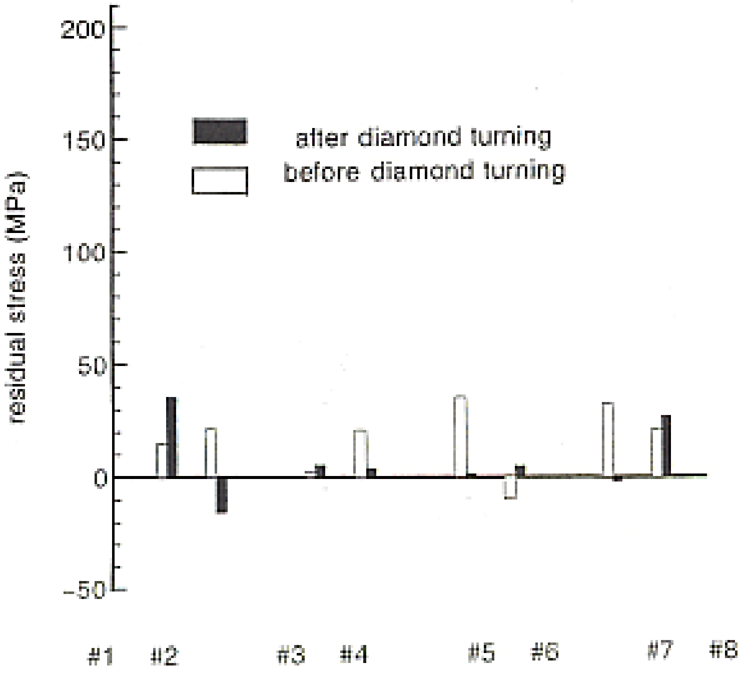
In order to increase the applied field the gap-spacing shortening is carried out; the applied voltage is in the region of 60 ~ 100 kV.

Vacuum pressure is ~ 10^{-10} Torr.

* surface residual stresses and roughness

- mirror finish by
  - diamond turning (Rmax = 0.06 μm)
  - electro-chemical buffing (Rav = 0.03 μm)
    - effective for reducing conditioning period
- diamond turned surface, having less residual-stress, shows higher Vb.

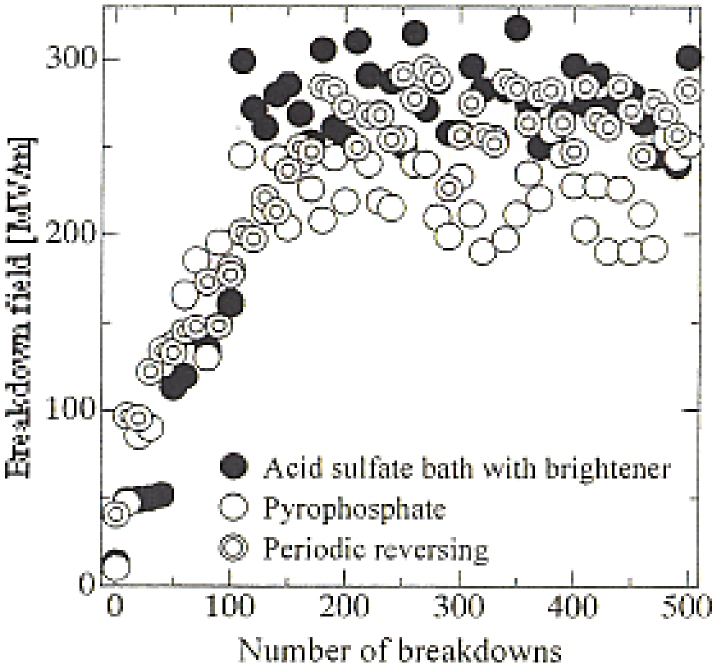




* non-metallic inclusion in bulk

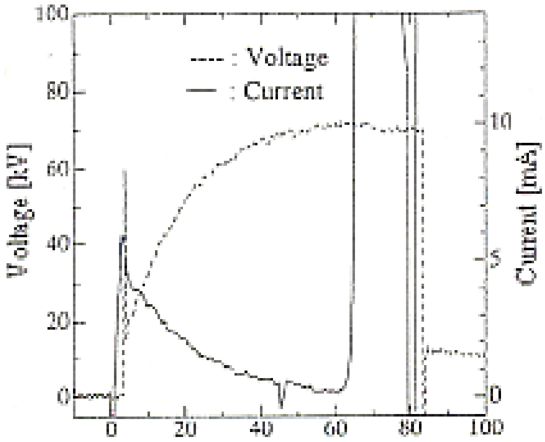
- inorganic inclusion in electroformed copper

		electr.. cond. IACS	impurity [ppm]	E/1st [MV/m]
casted oxygen-free-copper		102	< 40	71
electro-	periodic reversing	102	< 35	55
formed	sulfate + brightener	77	220 – 1500	30
copper	pyrophosphate	80	....	18



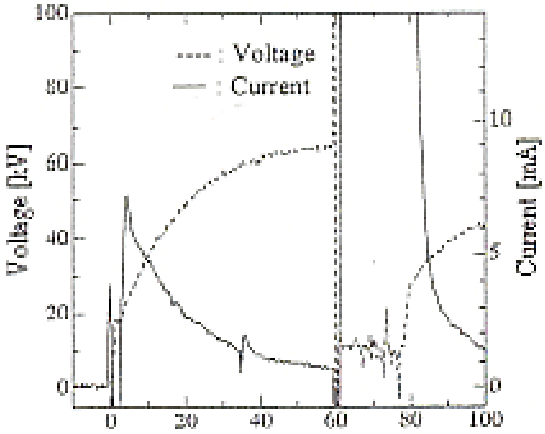
* non-metallic inclusion in bulk and surface

- I-V characteristics during conditioning



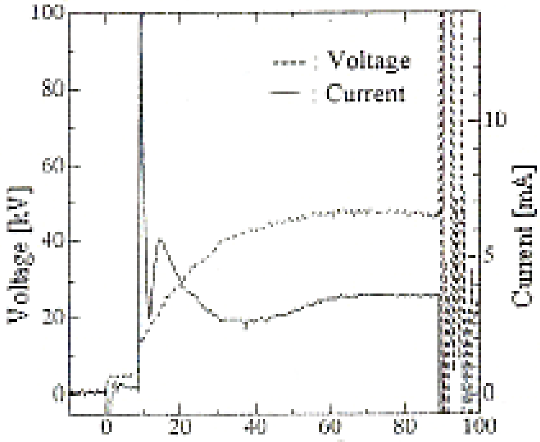
(a) 10th voltage application

- current increase w/o V change
- emission from non-metallic inclusion
- initial stage of conditioning process



(b) 80th voltage application

- breakdown w/o pre-breakdown current
- micro-particle, non-metallic inclusion (clump)

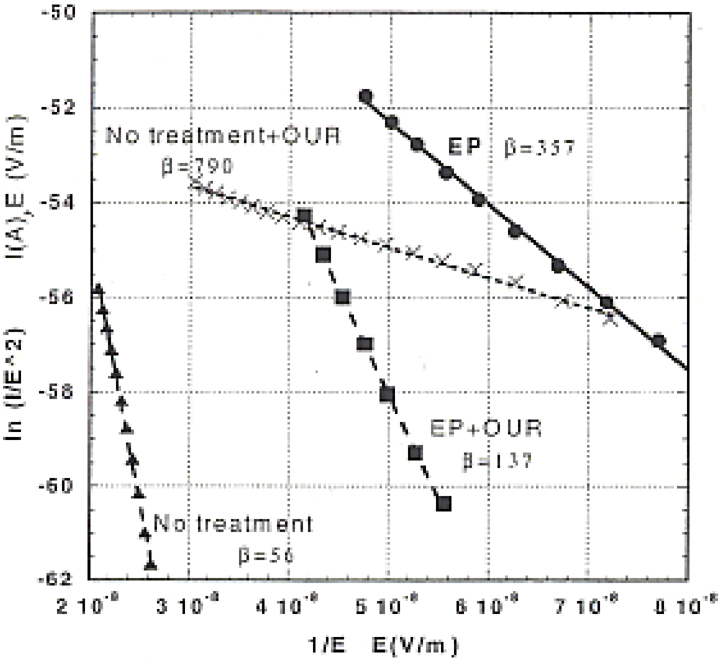


(c) 240th voltage application

- pre-breakdown current
- field emission current as a pre-breakdown
- final stage of conditioning process

* surface oxide layer

- field emission current from copper electrode
- depending on oxide-copper composition
- passivated surface not showing Total-Voltage Effect



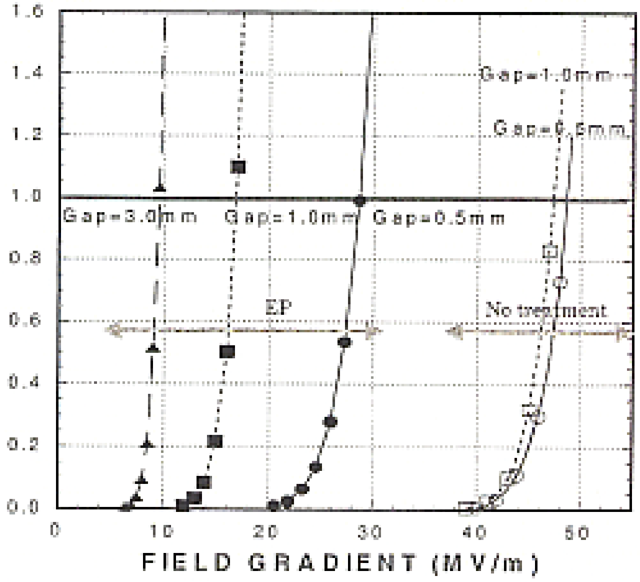


Table 8
Difference in composition of surface oxidant

Surface treatment	Rinsing	Oxidized layer	Existence of $Cu(OH)_2$
EP	UWR	$Cu(OH)_2$	Many
EP	OUR + UWR	$Cu(OH)_2 + CuO$	A little
None	UWR	Cu_2O	Few
None	OUR	CuO	Few

* pulse duration and frequency

Kp (Vb_{pulse} / Vb_{DC}) = 1.7 max (pulse width of $10^{-4} - 10^{-7}$ sec)

- **breakdown proceeds with a delay time t_d and a commutation time t_c**
- **longer delay time for lower electric field**
- **longer commutation time for larger gap length**

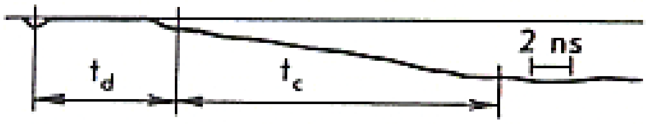


Fig.4.1. A current waveform recorded at vacuum breakdown with the use of a capacitive voltage divider with d = 0.5, V_0 = 50 kV

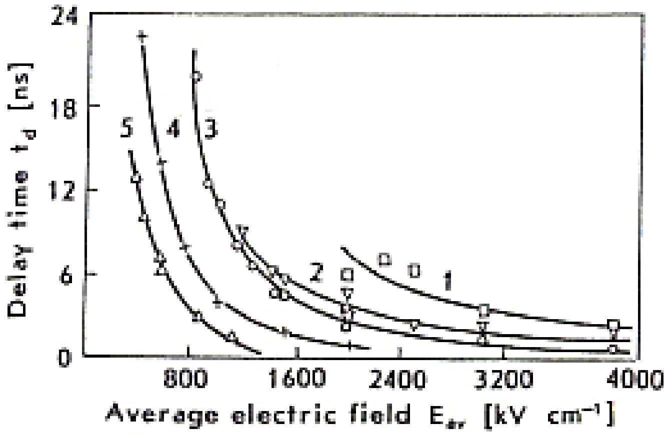


Fig.4.2. Breakdown delay time as a function of the average electric field for electrodes made of molybdenum (*1*), copper (*2*), aluminum (*3*), lead (*4*), and graphite (*5*)

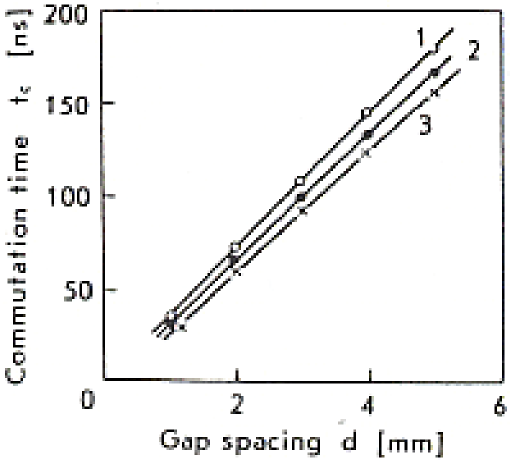


Fig.4.3. Commutation time as a function of the gap spacing for electrodes made of aluminum (*1*), copper (*2*), and molybdenum (*3*)

* total voltage effect

- breakdown voltage in narrow and long gap
- not only depending on cathode field-strength,
  but also on accelerated electron energy
- electron incidence to anode induces breakdown
- gap length dependence of the incident energy

$$V_b \propto K d^{\alpha}$$

empirical (DC application)

$d \leq 0.5mm$ **(short gap)**

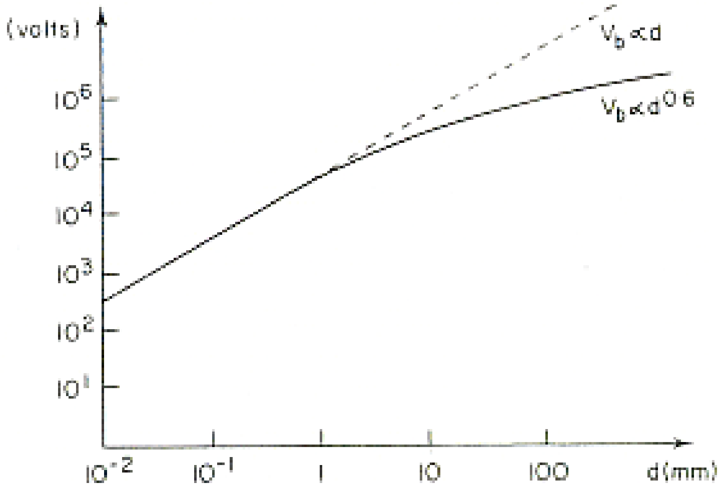
$\alpha = 1$ **depending on cathode field-strength**

$V_b[kV] = 60 - 80 \times d[mm]$

$d > 2mm$ **(long gap)**

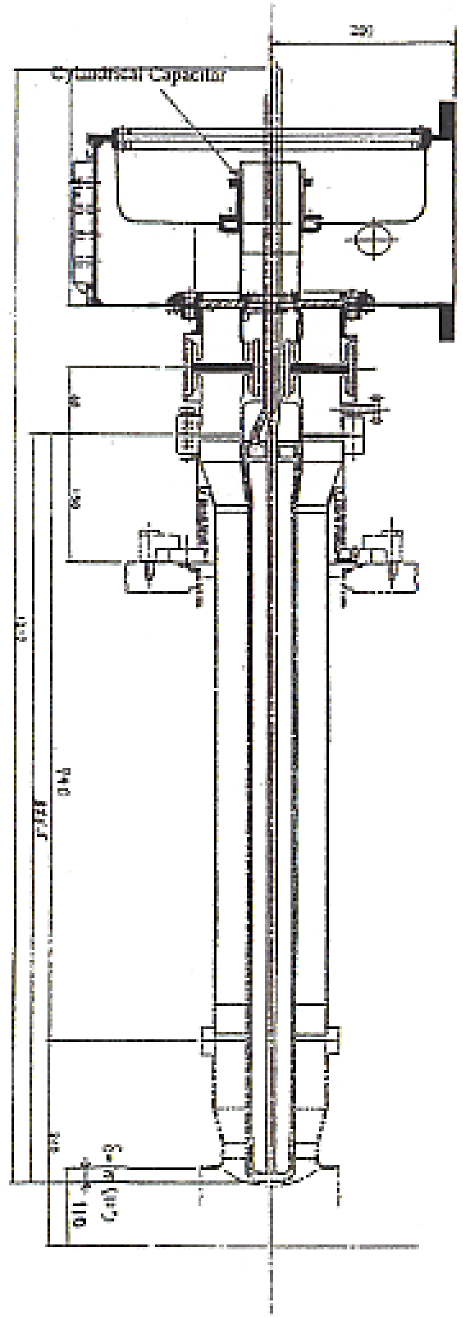
$\alpha = 0.4 - 0.6$ **showing total voltage effect**

$V_b = 40 - 45 \times d^{\alpha}[mm]$

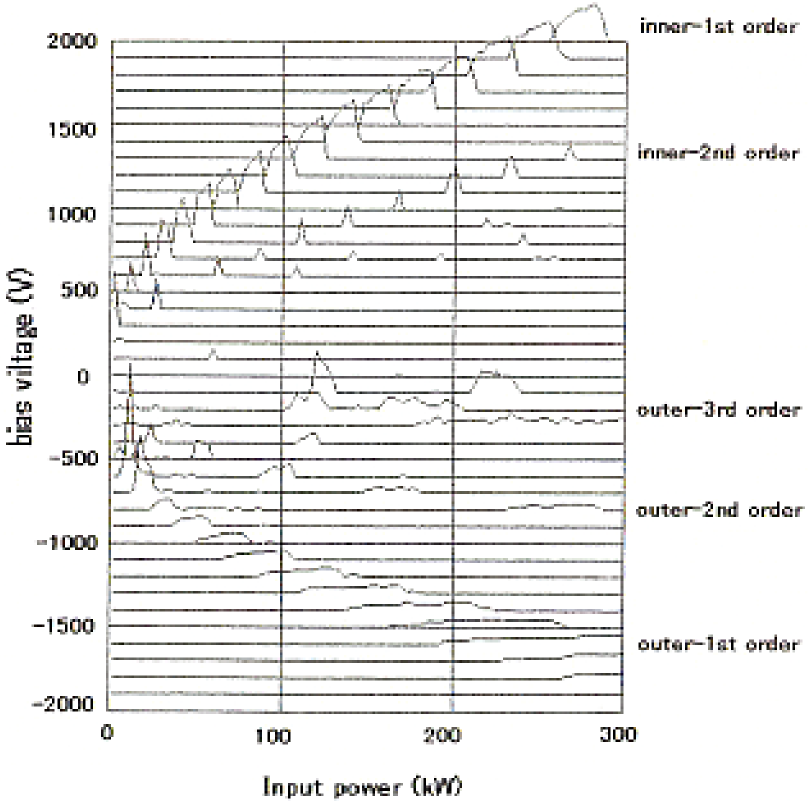


* RF structure effect; emitted electron behavior

- multipactor mapping in an input coupler of 500 MHz SC cavity
- according to traveling or standing wave
- bias voltage application to the inner conductor



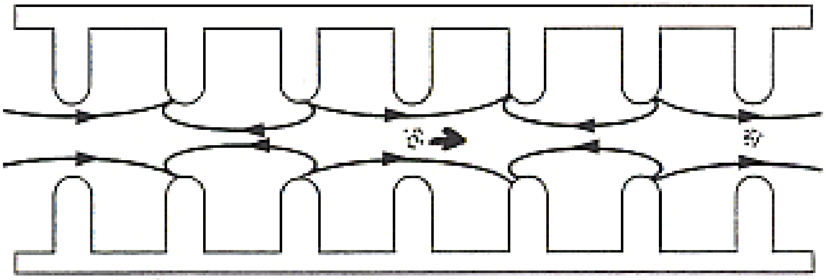
High Power Input Coupler for KEKB SC Cavity



* $\delta = 12^{mm}$ $Q_L = 7 \times 10^4$
$\delta = 15^{mm}$ $Q_L = 5 \times 10^4$

* RF structure effect; emitted electron behavior

- dark current evaluation in an S-band accelerator guides
- electron behavior in the accelerator guides was simulated
  electrons are supposed to be emitted from discs,
  at every 10 deg of rf phase and to be accelerated



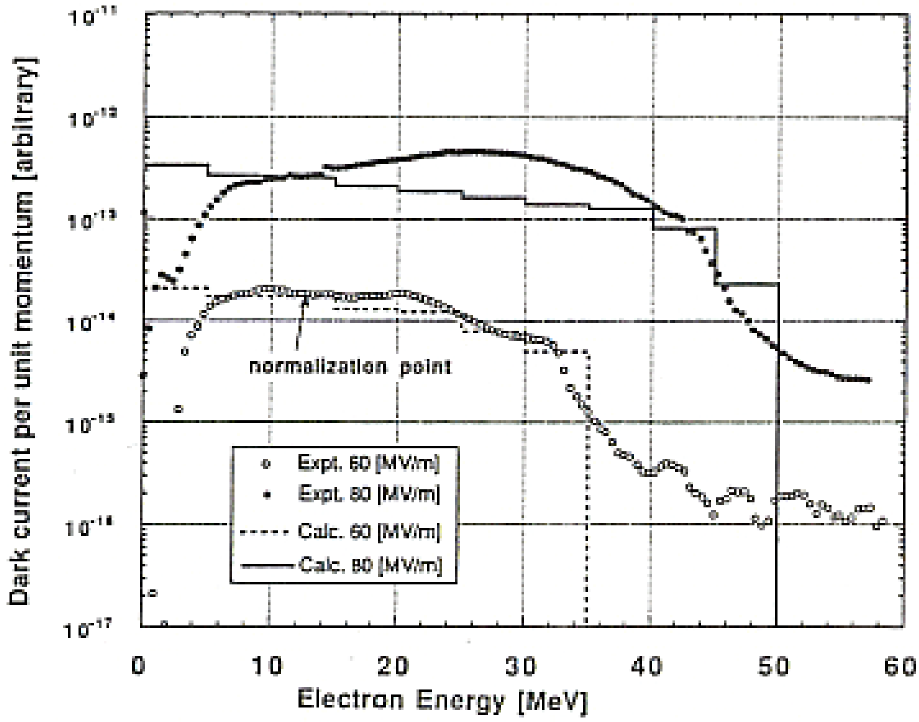


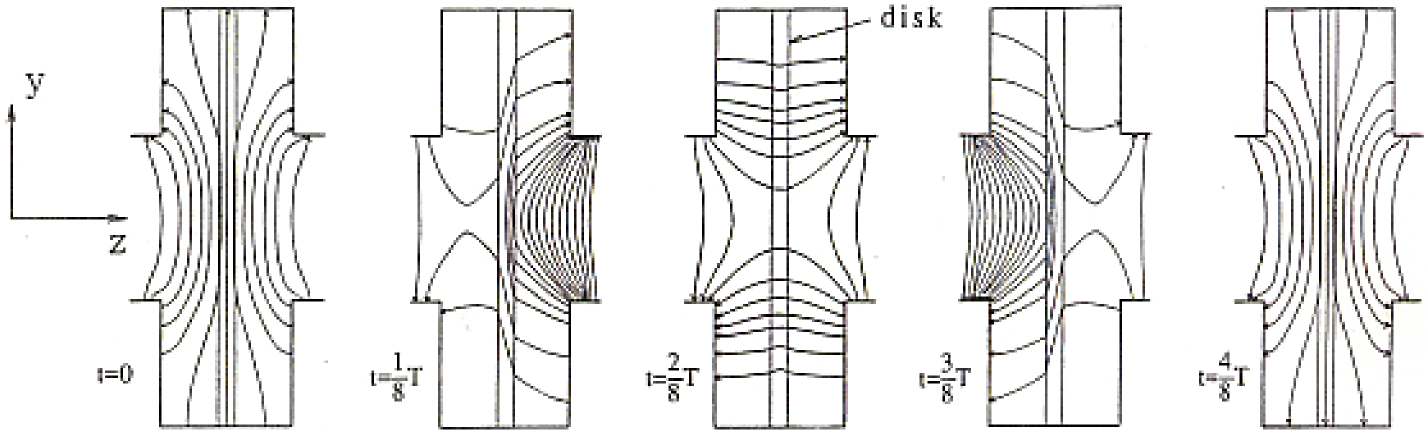
Fig. 10. Calculated and experimental energy spectra of field-emitted electrons in a 0.6 m long *S*-band accelerating structure.

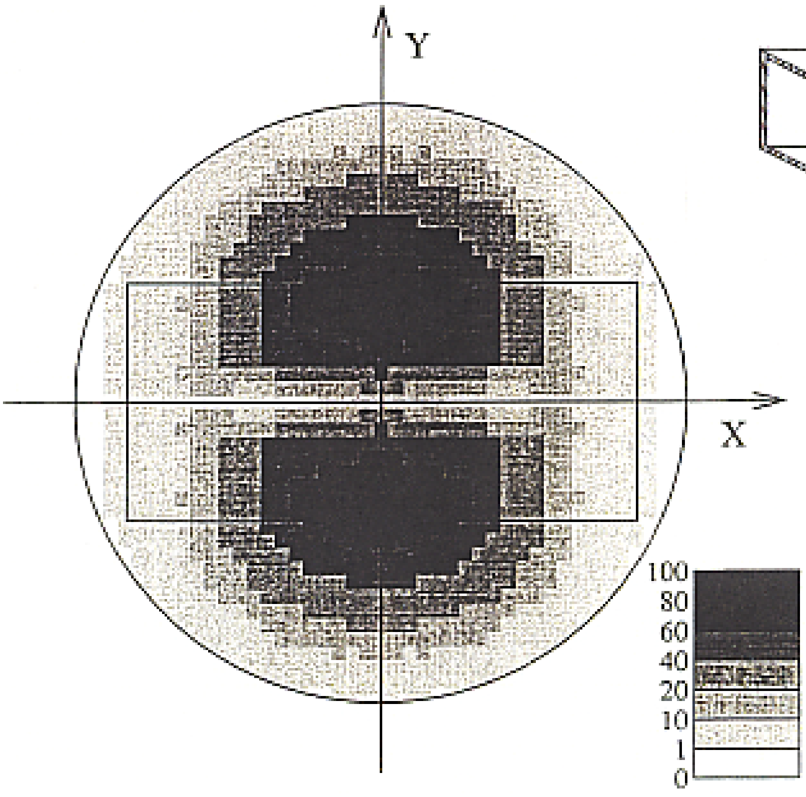
* RF structure effect; emitted electron behavior

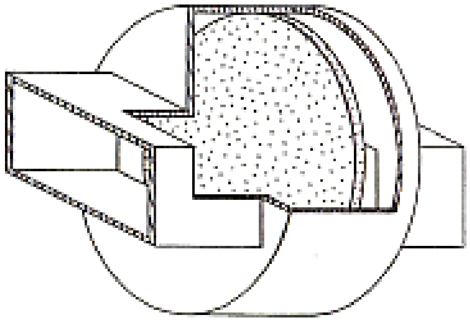
- multipactor in an S-band pill-box window
- electron behavior in the window was simulated

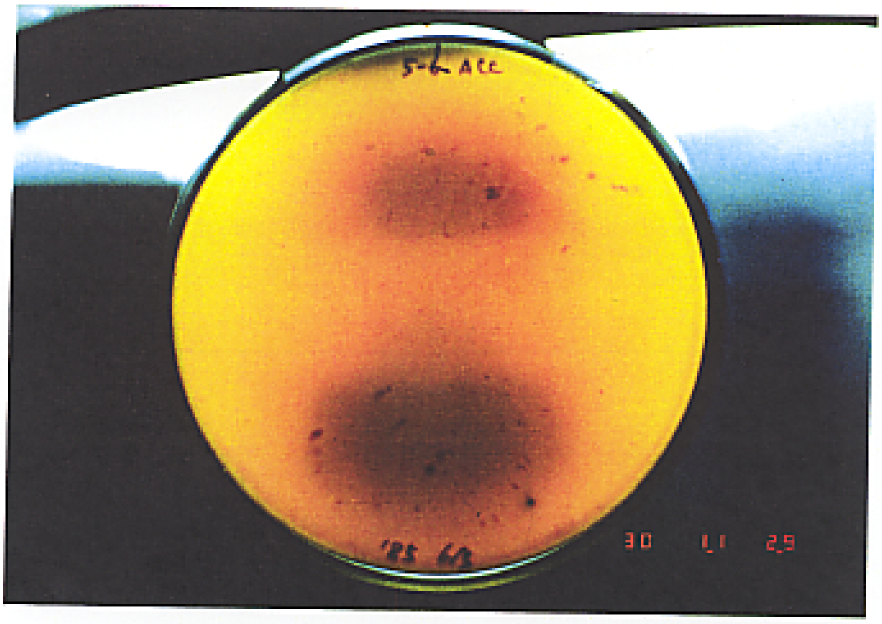
  electrons are supposed to be emitted from alumina discs,

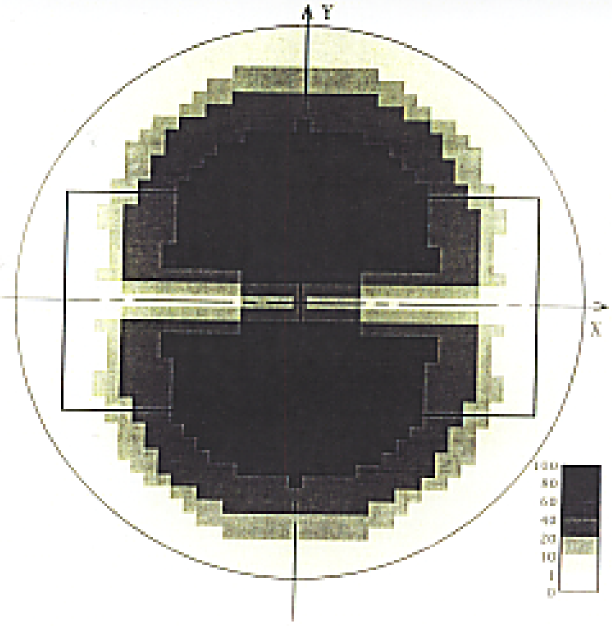
  secondary electron emission coefficient (alumina) >1











The incident energy distribution of multipactor electrons, simulated by a Monte-Carlo method.

Trajectory Simulation of Secondary-Emitted-Electrons in the RF Window Field ;

...Random emission-sites on the alumina surface
(Monte Carlo method)

...Solving "equation of motion" for primary- and secondary-emitted electrons
(Runge-Kutta-Gill method)

...Emission timing at every 10 degrees of RF phase

* Conclusion

for shortening conditioning period

for suppressing breakdown

Ultra-High Vacuum

- reducing adsorbed H_2O and C_xH_y contamination

High Purity Metal Material

- reducing hydrogen content and non-metallic inclusion

Passivated Surface

- making surface stress-free and hydro-oxide-free
- controlling oxide layer not to have trap sites

Electron Behavior

- simulating trajectory and energy
- checking gap length, pulse duration, accelerating phase