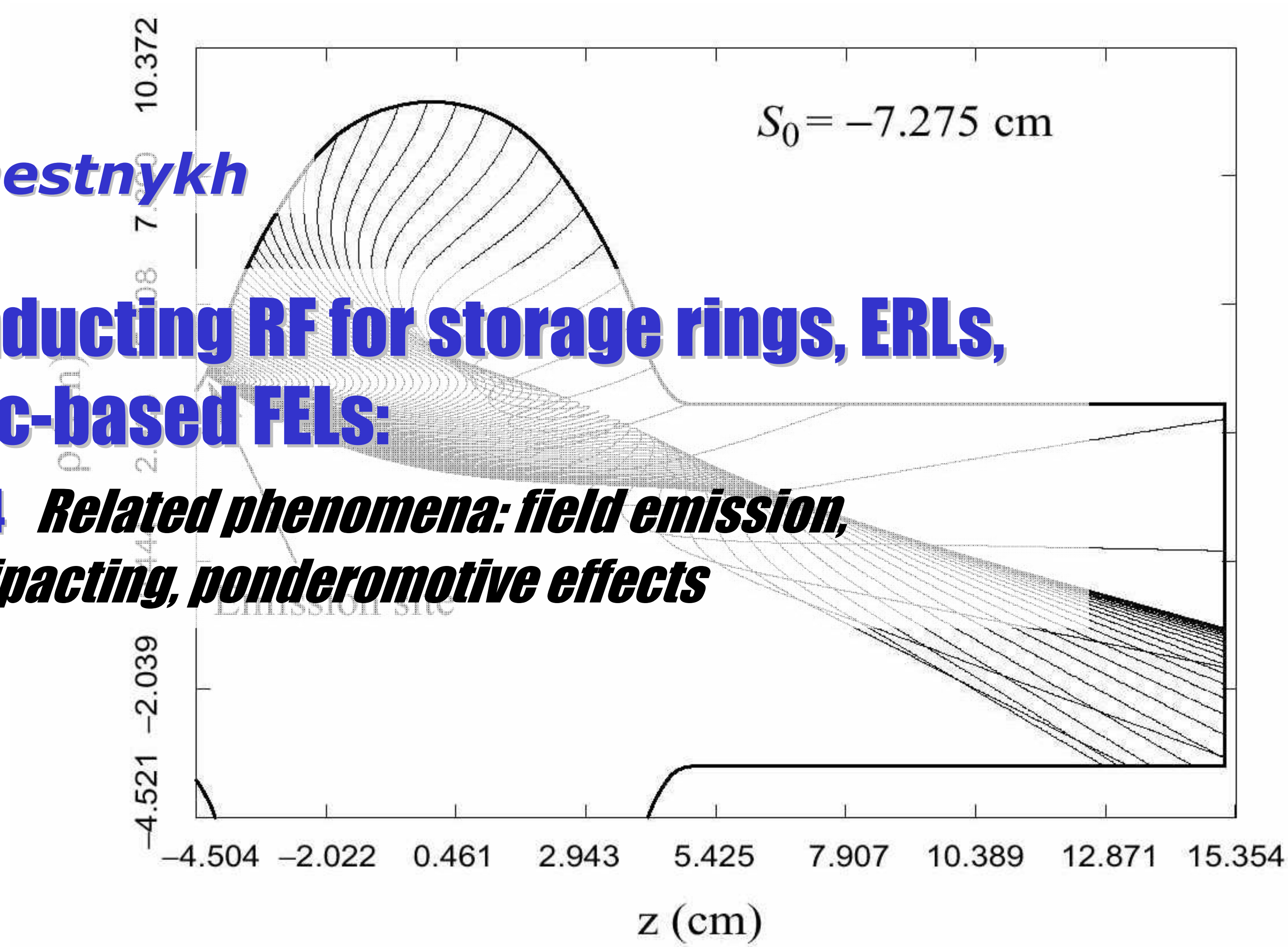
S. Belomestnykh

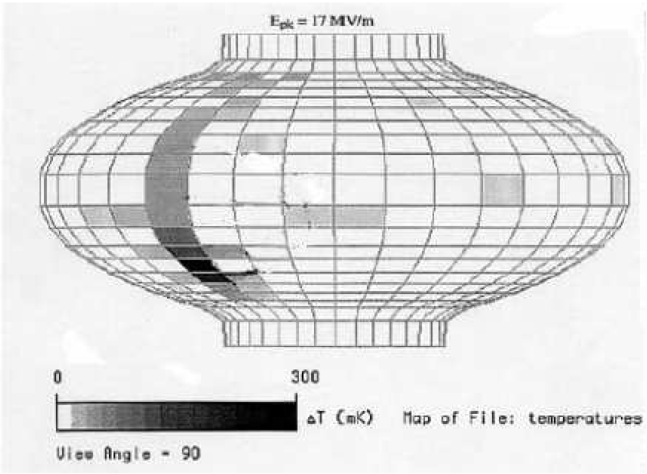
Superconducting RF for storage rings, ERLs, and linac-based FELs:

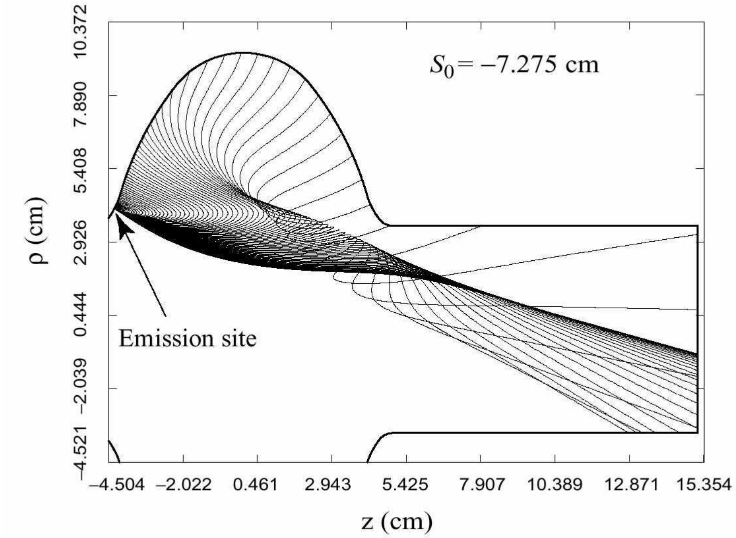
- **Lecture 4** ***Related phenomena: field emission, multipacting, ponderomotive effects***



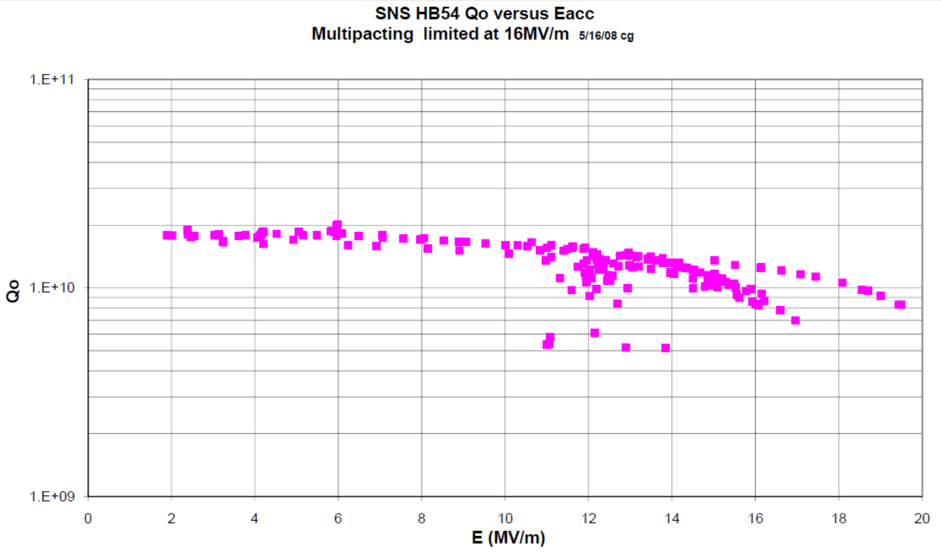
Field emission

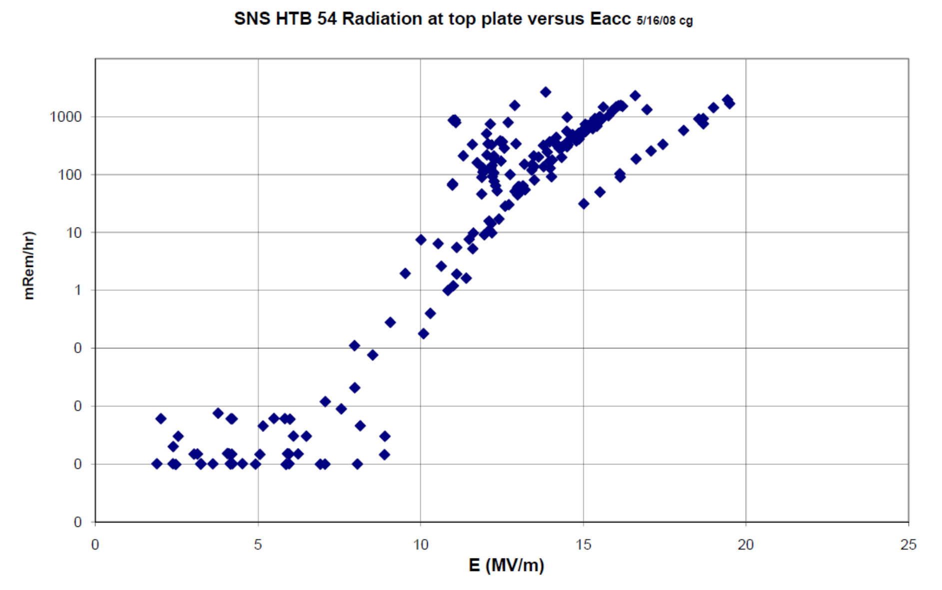
- Exponential increase of losses due to acceleration of FE electrons.
- Associated with production of X-rays and dark current.
- It is a general difficulty in accelerating structures, but does not present an ultimate fundamental limit to the maximum surface electric field. Surface fields above 100 MV/m over many cm^2 have been maintained CW in superconducting cavities.
- A detailed temperature map shows line heating along the longitude at the location of the emitter (due to the cylindrical symmetry of the fields in the accelerating mode.)
- The main cause of FE is particulate contamination.





Field emission example





Field emission theory

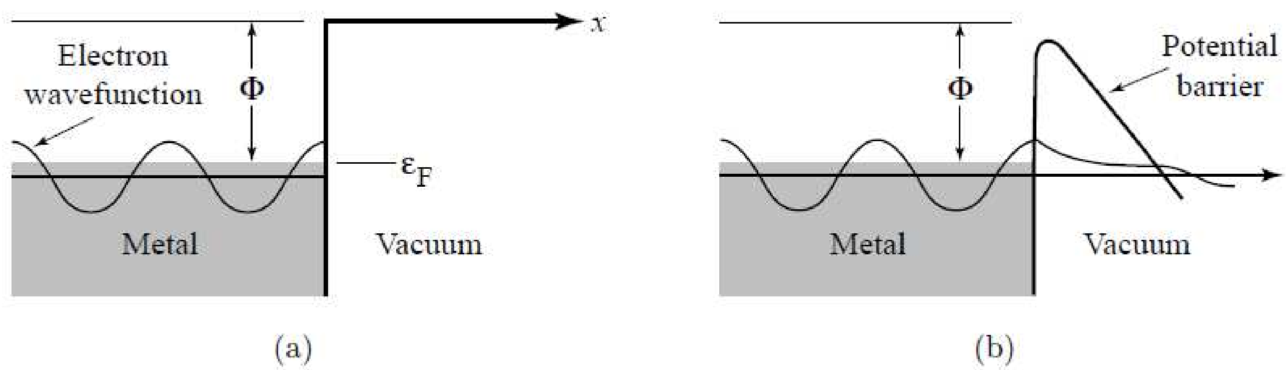


Figure 3.2: Electrostatic potential of the metal–vacuum interface. (a) No electric field applied, (b) with an electric field applied.

- **Fowler and Nordheim (FN) showed that when the work function barrier at the metal surface is lowered by an applied surface electric field, electrons can tunnel through.**
- **The tunneling current density is:**

$$J = \frac{1.54\times10^{-6}E^2}{\Phi}\exp\left(-\frac{6.83\times10^{9}\Phi^{3/2}}{E}\right)$$

J: Current density (A/m^2)

E: Electric field (MV/m)

Φ: Work function (eV)

- **The theory has been experimentally confirmed for DC electric field.**

RF field emission

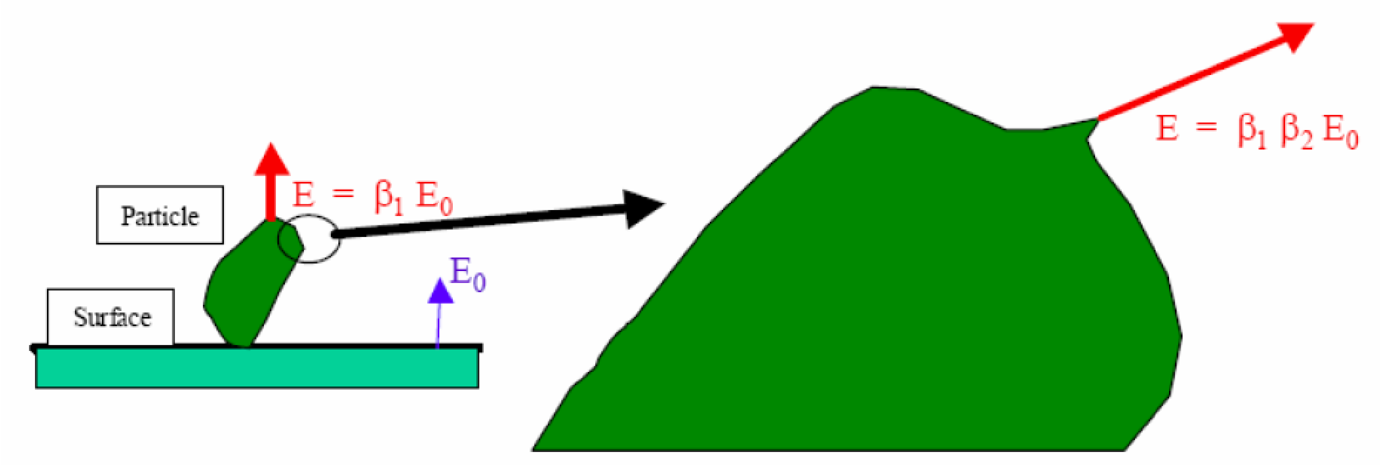
- For RF fields, however, the FN law has to be modified:

$$J = k\frac{1.54\times10^{-6}(\beta E)^{5/2}}{\Phi}\exp\left(-\frac{6.83\times10^{9}\Phi^{3/2}}{\beta E}\right)$$

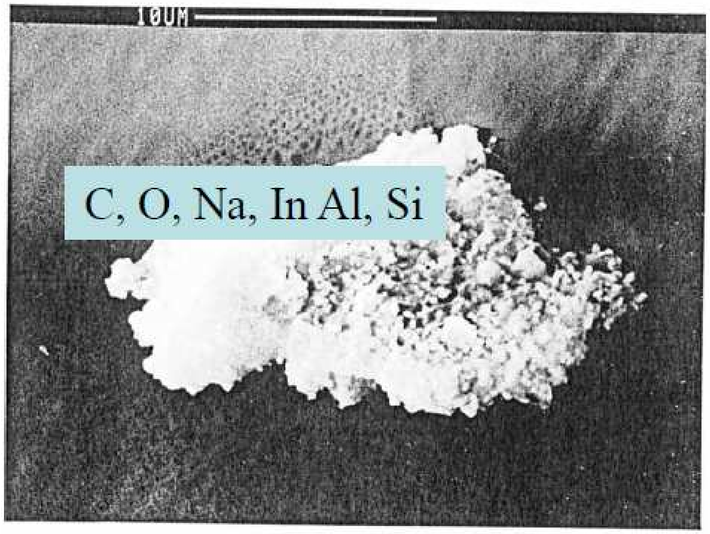
β : Enhancement factor (10s to 100s)

k : Effective emitting surface

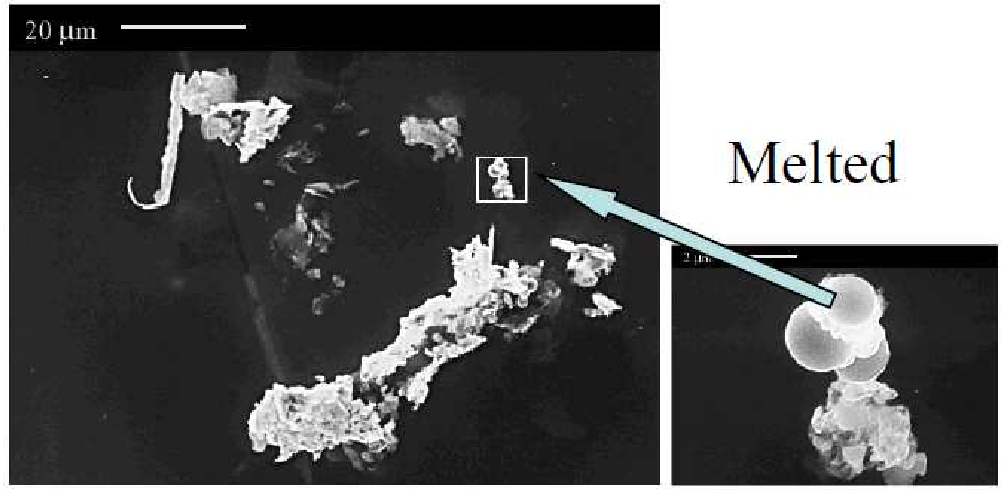
- Smooth particles show little field emission → simple protrusions are not sufficient to explain the measured enhancement factors.
- Possible explanation: tip on tip (compounded enhancement).

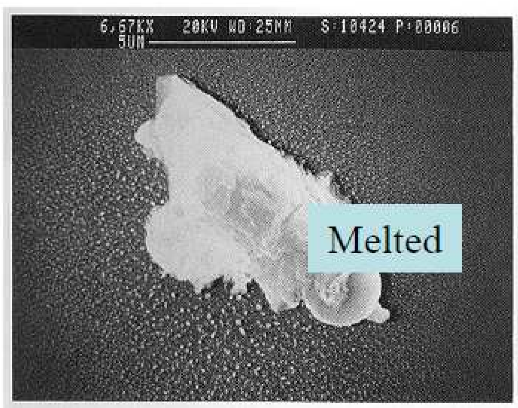


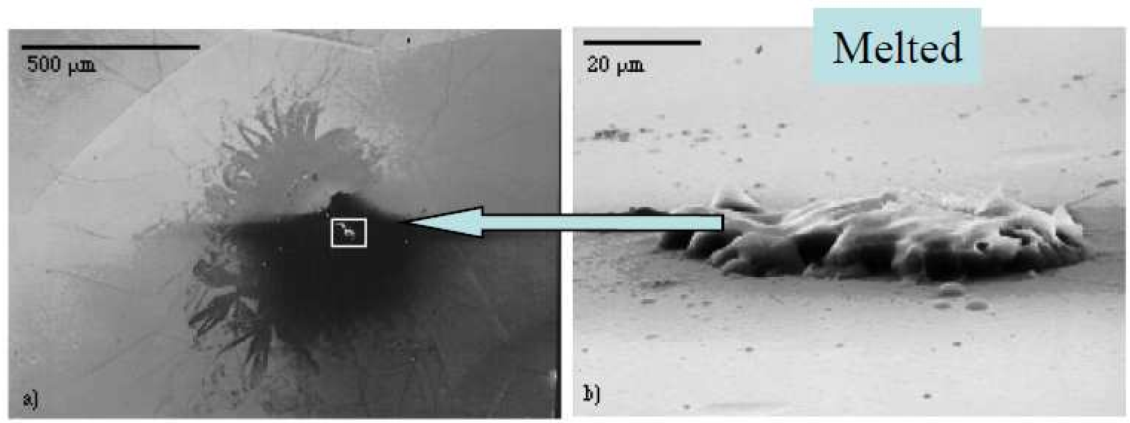
Examples of field emitters



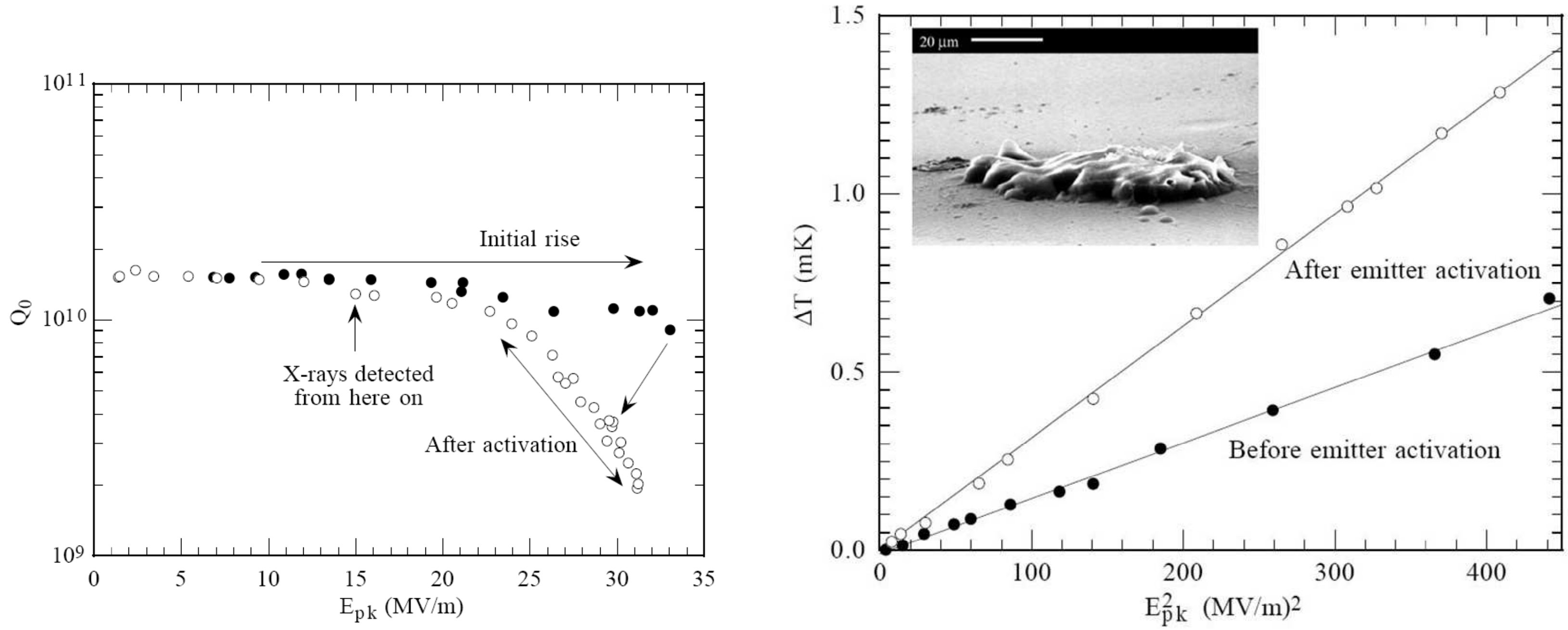
Stainless steel







FE activation



(a) Q_0 versus E_{pk} for a 1.5 GHz single cell cavity before and after activation of field emission.

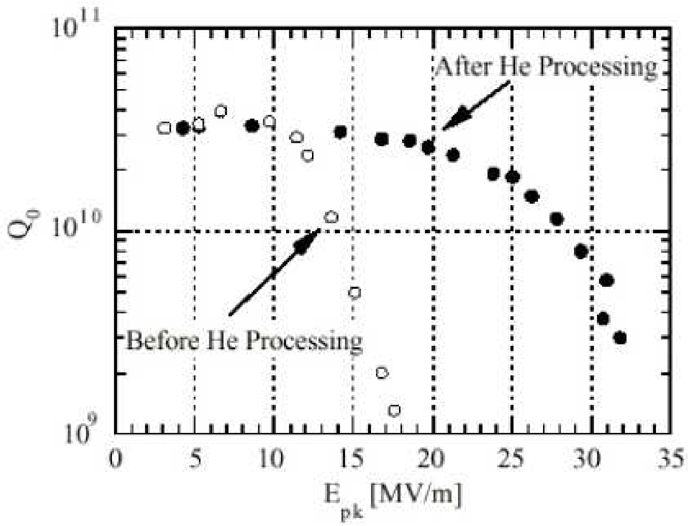
(b) Temperature rise vs. E_{pk}^2 before and after activation showing Ohmic heating.

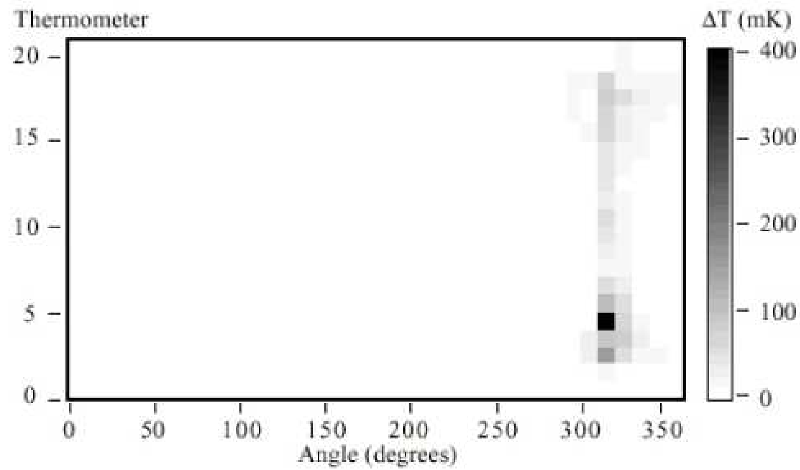
Inset : SEM micrograph of the particle found after cavity dissection at the emitter location determined from temperature map analysis below.

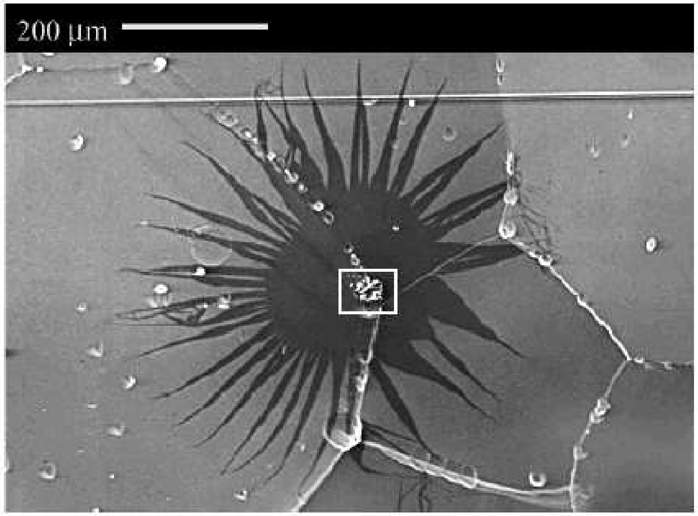
FE processing

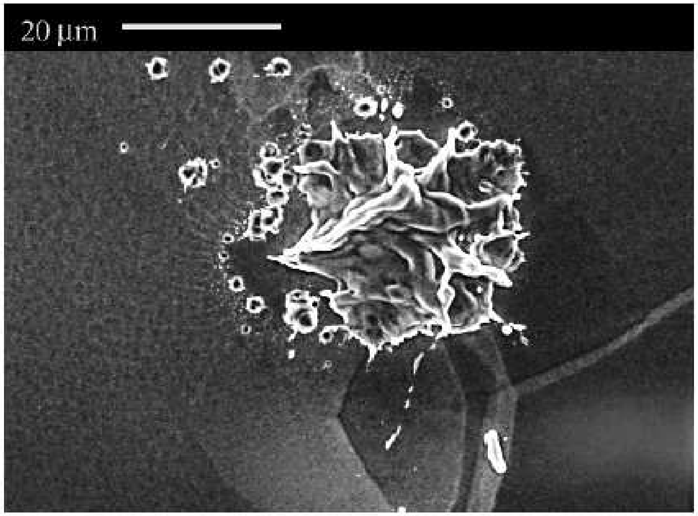
- FE can be prevented by proper surface preparation and contamination control.
- However, contamination can occur during string and cryomodule assembly; accelerator beam lines are not clean and particulate can migrate from beam line to cavities; vacuum accidents happen.
- Field emission can occur or increase during operation.
- It is possible to reduce if not completely eliminate FE using CW RF processing, High-power Pulsed Processing (HPP) and/or Helium processing.
- When FE dominates a high gradient cavity, there frequently occurs a "conditioning event" or "processing event" as the surface electric field rises. After such an event the field emission current drops substantially, as indicated by a sharp drop in RF losses and X-ray intensity. After the event it is possible to raise the surface field further.
- To reach the high electric field conditions needed for continued processing it is necessary to use very high power. But to minimize the power dissipation into liquid helium, the cavity fill time and RF pulse length have to be short.
- Helium processing: gas is introduced in the cavity at a pressure just below breakdown (~10^{-5} Torr); cavity is operating at the highest field possible (in heavy field emission regime); duty cycle is adjusted to remain thermally stable.
- Field emitted electrons ionize helium gas, helium ions stream back to emitting site and clean surface contamination by sputtering sharp protrusions.

FE processing example



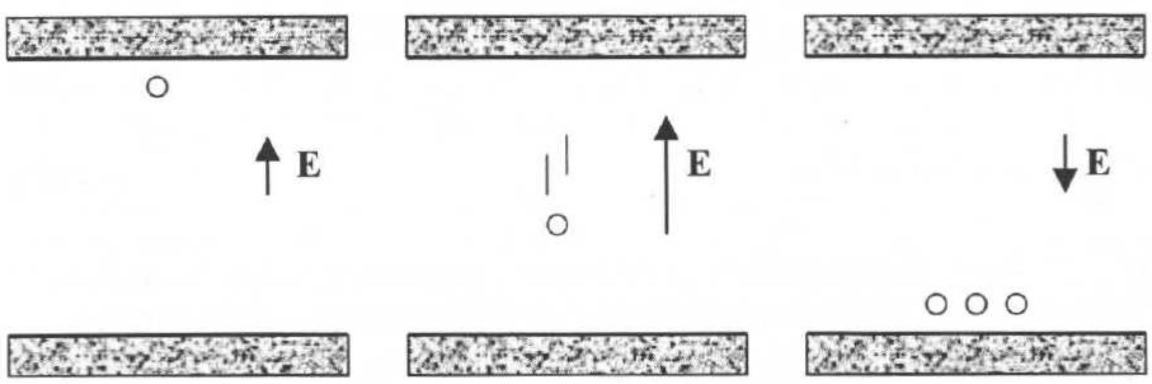


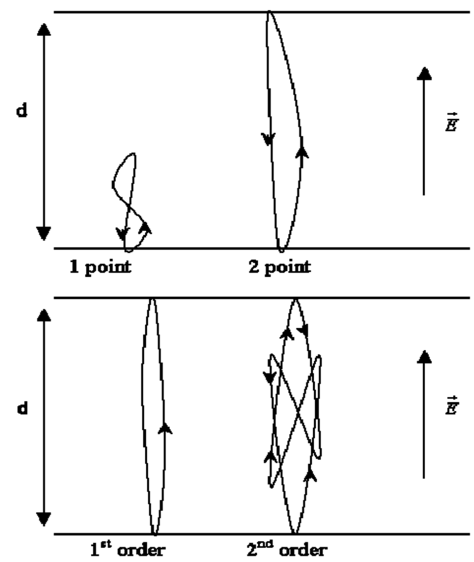




Multipacting basics: parallel plates

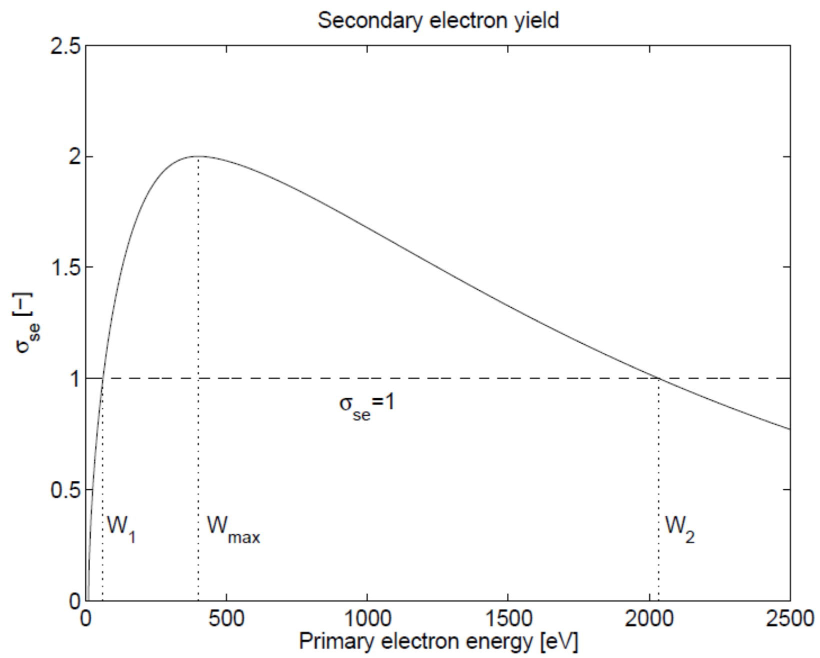
- Multipacting is a resonant process, when a large number of electrons build up under influence of RF field in evacuated equipment (input couplers, cavities, etc.)
- A multipactor discharge starts when a free electron inside a microwave device is accelerated by an electric field. In a strong field the electron will quickly reach a high velocity and upon impact with one of the device walls, secondary electrons may be emitted from the wall. If the field direction reverses at this moment, the newly emitted electrons will start accelerating towards the opposite wall and, when colliding with this wall, knock out additional electrons. As this procedure is repeated, the electron density grows quickly and within fractions of a microsecond a fully developed multipactor discharge is obtained.
- When the trajectory is such that the electrons returns to their initial position, it can be called one-point multipactor. Should the trajectory of the electrons loop between two impact points, it becomes two-point (two-surface) multipactor and so on. The order of the multipactor is defined as the number of RF periods taken for the electron to transit from its creation to its impact with a wall (in the case of two point multipactor, the electron takes 2n-1 half periods to reach the other wall, where n is the order).

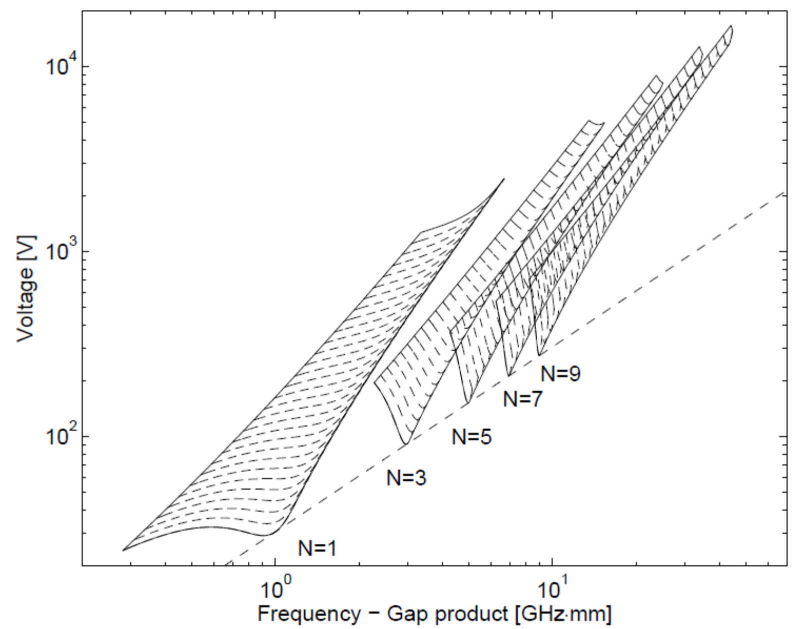




SEY and Hatch diagram

- Multipacting requires following conditions: electron motion is periodic and the impact energy is such that secondary emission coefficient is greater than 1. Unfortunately, most materials have maximum values of their secondary electron yield that are greater than unity.
- In a two-plate geometry, there are well-defined multipacting bands for which electrons in transit impact on a wall at phases such that their energy is sufficient to release multiple secondary electrons, and that the secondary electrons can escape the surface. A representation of this is the diagram commonly referred to as a Hatch diagram. It shows the existence zones for multipacting bands for various gap field strengths as a function of frequency multiplied by gap distance.





SEY of Nb

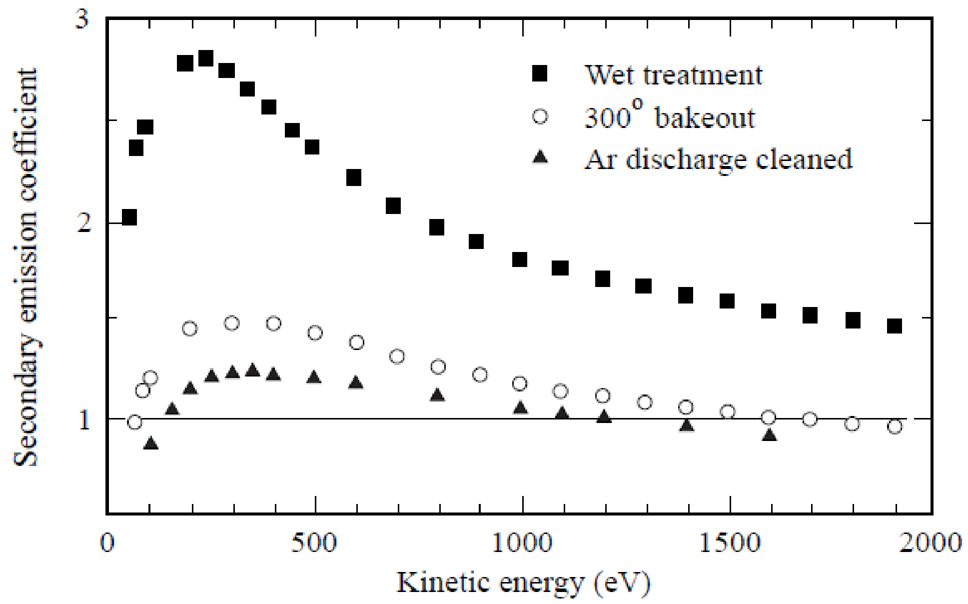
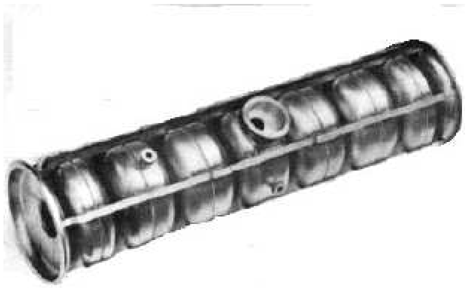
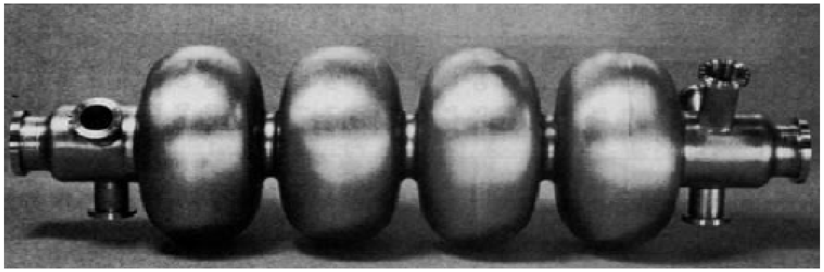


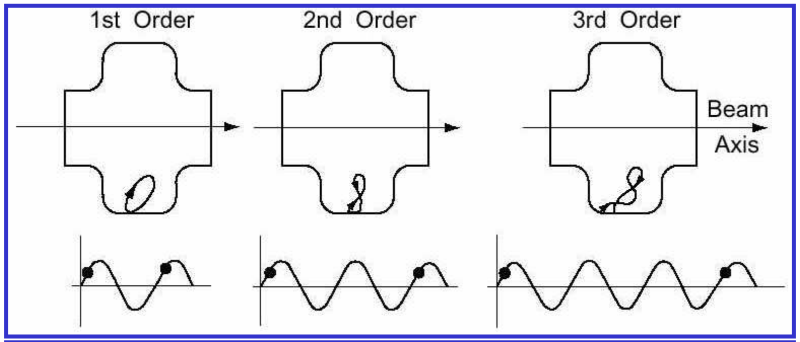
Figure 3.14: Secondary emission coefficient of niobium following various treatments. [8] Accurate measurements at very low impact energies have not been performed to our knowledge.

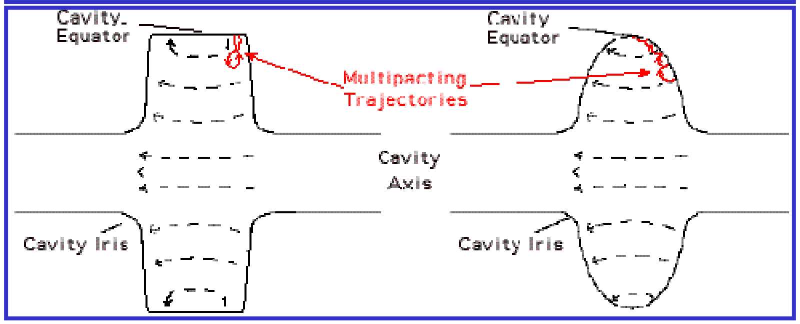
Multipacting in cavities

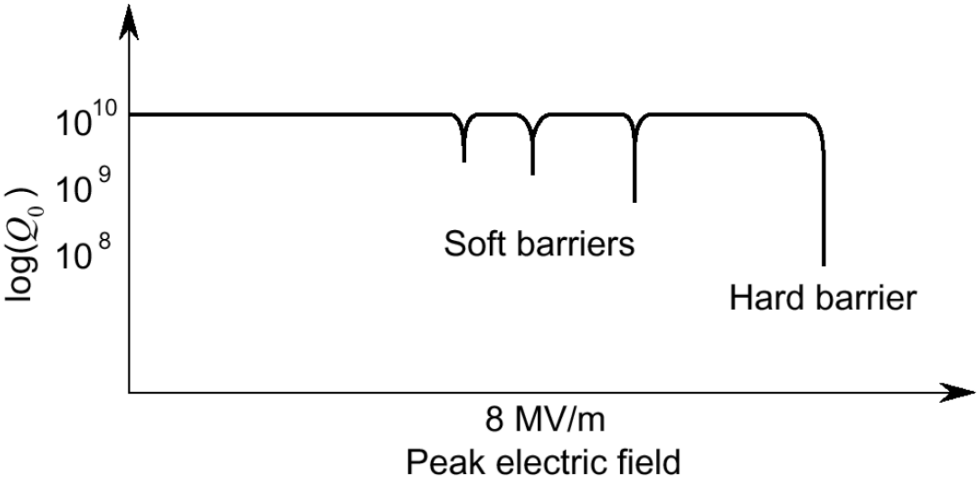
- MP was an early limitation of SRF cavities' performance.
- It was overcome by adopting spherical/elliptical cell shapes.
- In severe cases MP may cause quench and limit the cavity field.





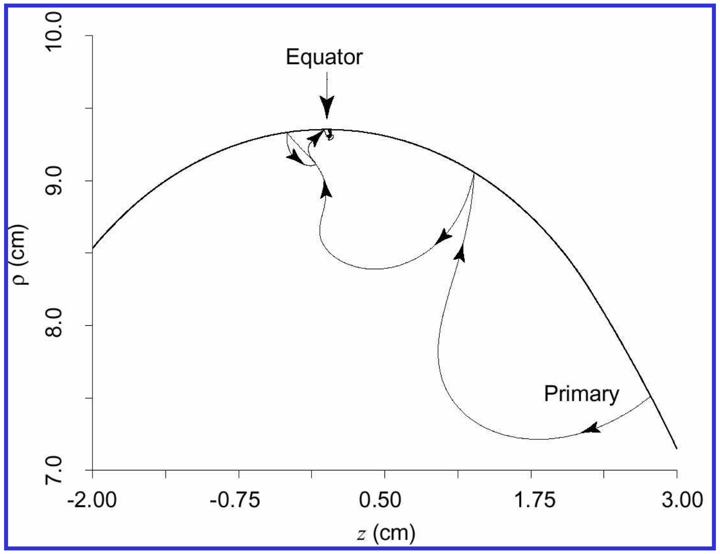


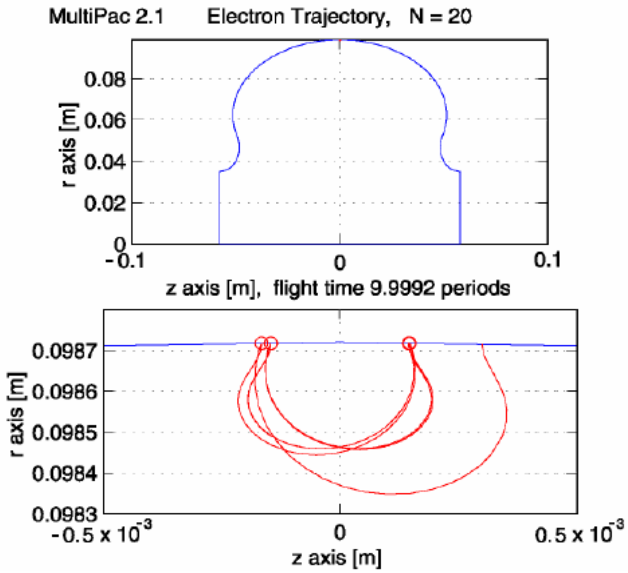




Multipacting in cavities

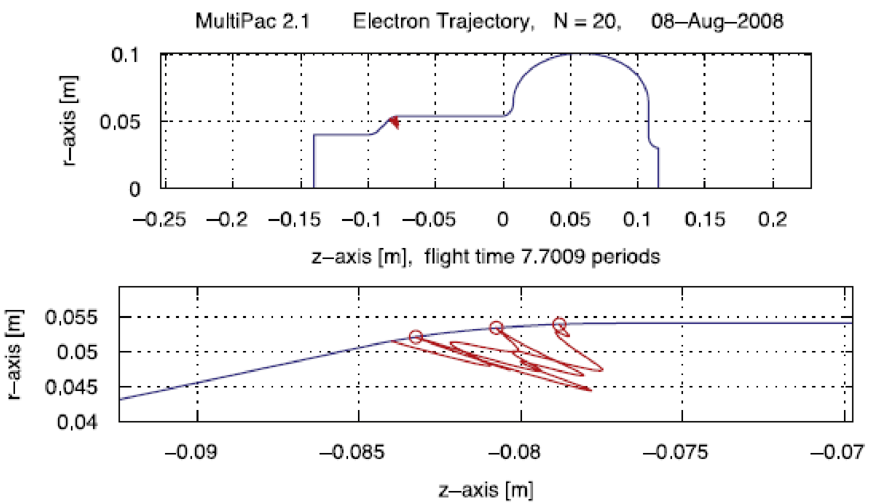
- In a spherical/elliptical geometry electrons drift to equator region, where electric field is near zero. As a result MP electrons gain very little energy and MP stops.
- However, at high gradients conditions exist for stable MP though it is usually very weak and easily processed.

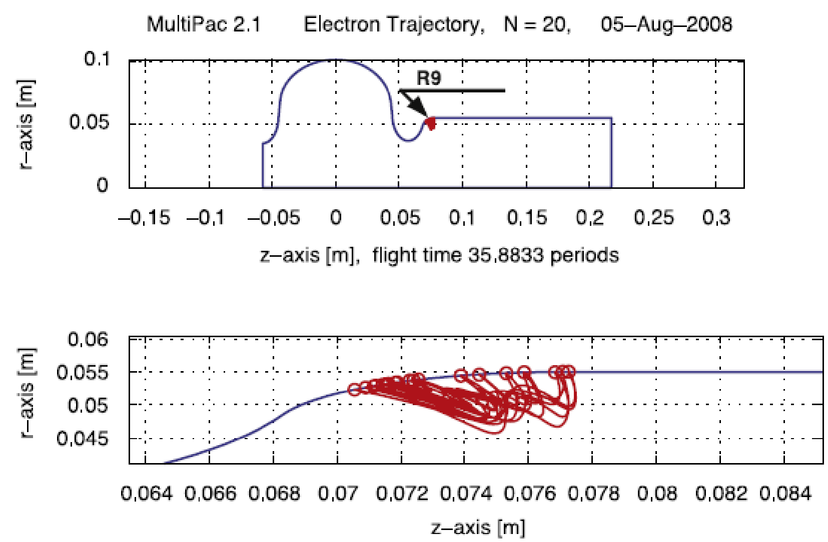




Multipacting in beam pipes

- **Recently relatively strong MP was found in two elliptical cavities (9-cell ICHIRO cavity at KEK and 2-cell Cornell ERL injector cavity) to the surprise of experimenters.**
- **It turned out that a minimum of the electric field at the beam line corners, associated with the RF potential well, attracts electrons and thus creates conditions favorable for multipactor.**
- **Increasing the transition radius eliminates this MP.**



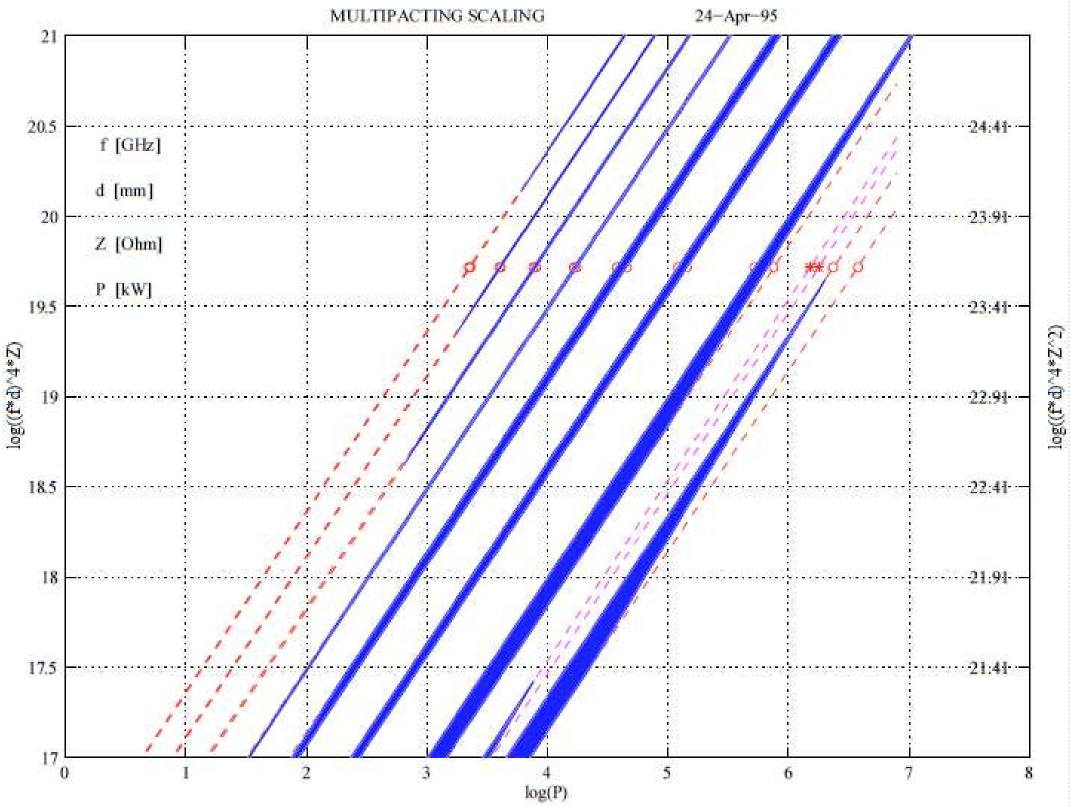


Multipacting in couplers

- MP can be a limiting factors in RF input and HOM couplers.
- In input couplers it causes vacuum degradation and limits power delivered to cavities. If RF is not interlocked properly, MP can damage RF windows.
- It is very important to carefully simulate MP during the design stage.
- In HOM coupler excess heating can cause severe stress at weld junctions and fracture in the cold.
- In rectangular waveguides MP zones can be predicted relatively well using parallel-plate model.
- In coaxial lines both one- and two-surface MP can exist. One-surface MP is stronger and more difficult to condition.
- One important general outcome from the MP codes is that the RF power at which a resonance occurs scales with the 4th power of the coax outer conductor dimension. Simple rules give the scaling of levels for one-point MP and two point MP, as these vary with frequency f, gap-size d and coaxial line impedance Z:

  $Power \sim (fd)^4 Z$ (one point MP)

  $Power \sim (fd)^4 Z^2$ (two-point MP)



Suppression of multipacting

1. Choosing geometry less susceptible to MP (elliptical cavity shape, large radius of beam line transitions, larger dimensions of transmission lines…)
2. Selecting materials with lower SEY.
3. Coating RF windows with thin layer (~10 nm) of anti-multipacting material like TiN.
4. Applying DC bias (electric or magnetic) to disturb the trajectories of electrons.
5. RF conditioning → cleaning surfaces → reducing SEY.

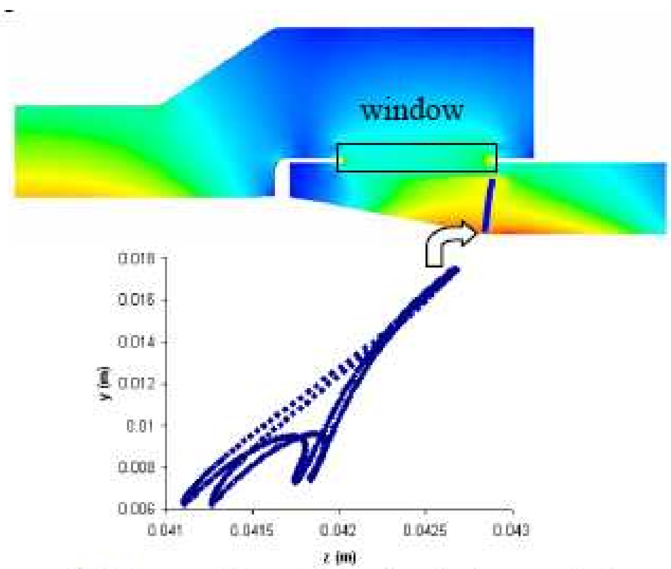


Figure 7: A two-point multipacting trajectory between the ceramic window and the inner conductor of the coax.

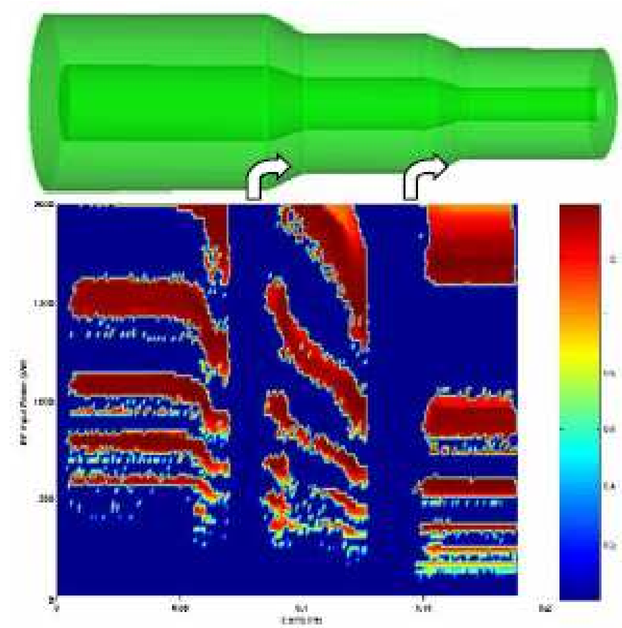


Figure 9: Multipacting activities in the taper region. The bottom picture shows the multipacting map as a function of the longitudinal position along the taper region.

Ponderomotive effects

- Ponderomotive effects: changes in frequency caused by the electromagnetic field (radiation pressure)
  – Static Lorentz detuning (CW operation)
  – Dynamic Lorentz detuning (pulsed operation)

- Microphonics: changes in frequency caused by connections to the external world
  – Vibrations
  – Pressure fluctuations

Note: The two are not completely independent. When phase and amplitude feedbacks are active, the ponderomotive effects can change the response to external disturbances.

- The electromagnetic fields in a cavity exert Lorentz forces on the cavity wall. The force per unit area (radiation pressure) is given by

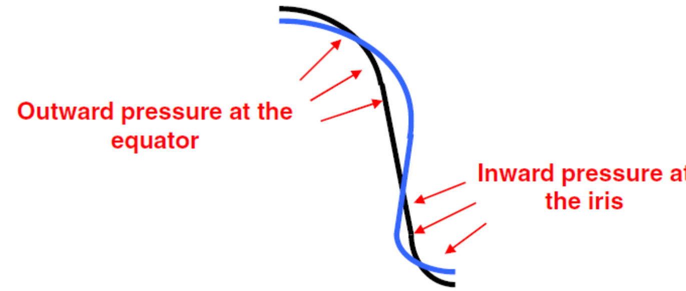
$$P_R = \frac{1}{4}\left(\mu_0 H^2 - \varepsilon_0 E^2\right)$$

Lorentz-force detuning

- The Lorentz forces near the irises try to contract the cells, while forces near the equators try to expand the cells.
- The residual deformation of the cavity shape shifts the resonant frequency of the accelerating mode from its original value by

$$\frac{\Delta f_L}{f} \approx \frac{1}{4U}\int_{\Delta V}\left(\mu_0 H^2 - \varepsilon_0 E^2\right)dv$$

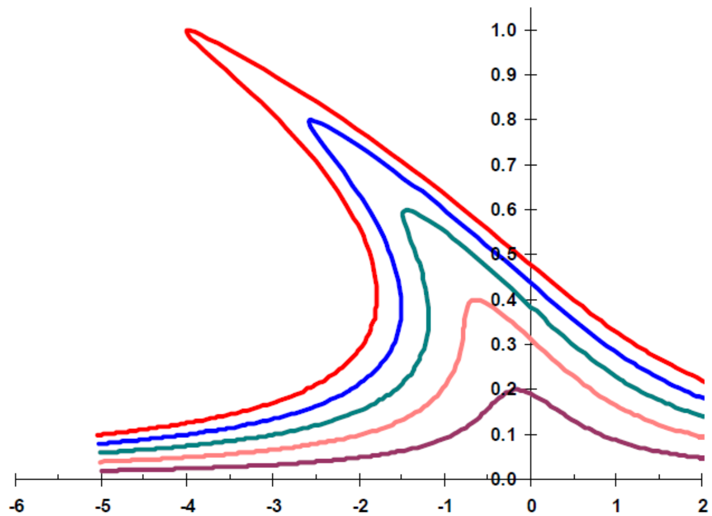
where ΔV is the small change in the cavity volume.



- In the linear approximation, the steady-state Lorentz-force frequency shift at a constant accelerating gradient is

$$\Delta f_{L,stat} = -K_L \cdot E_{acc}^2$$

- The quantity K_L is called the Lorentz-force detuning constant.
- The 9-cell TESLA cavities have K_L = 1 Hz/(MV/m)^2.



What have we learned so far?

- Field emission causes exponential growth of RF losses.
- The main cause of FE is particulate contamination.
- It can be prevented by proper surface preparation and contamination control
- There are several techniques of processing FE.
- Multipacting was early limitation of superconducting cavities, but was “cured” by adopting spherical/elliptical cell shapes.
- MP simulations and preventive measures are still very important for input and HOM couplers.
- There are several methods of suppressing MP.
- Radiation pressure causes cavity resonant frequency shift, which scales quadratically with the accelerating gradient .

✪ In the next lecture we will discuss requirements and challenges to superconducting RF systems of different accelerators.