Excitation of passband modes in superconducting RF cavities

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Technical note

Contents

1 Introduction

Superconducting RF cavities are a key component of the modern particle accelerator. This is an eletromagnetic cavity resonating at microwave frequency which operates at liquid helium temperature. It is used for imparting energy to the charged particles. An important figure of merit for accelerating cavitites is the quaity factor (Q_0), which is related to the power dissipation and is defined as

$$Q_0 = \frac{\omega_0 U}{P_c}, \tag{1}$$

where U is the stored energy and P_c is the power dissipated in the cavity walls. Another important quantity used to characterize the losses in a cavity is the shunt impedance (R_a), which is defined as

$$R_a = \frac{V_c^2}{P_c} \tag{2}$$

where V_c is the accelerating voltage. The ratio of R_a/Q_0 is given by

$$\frac{R_a}{Q_0} = \frac{V_c^2}{\omega_0 U}, \tag{3}$$

which is independent of the surface resistance and cavity size. This quantity is frequently quoted as a figure of merit and is also used for determining the level of mode excitation by charges passing through the cavity.

2 Passband mode excitation

Spontaneous excitation of modes with resonance frequencies close to the main mode (so-called passband) has been frequently (almost in 50% of tests) observed during vertical cold tests of 9-cell cavities in DESY [1] and in Fermilab. When this occurs generally the $7/9\pi$ mode is excited, along with that little bremsstrahlung is observed outside the cryostat and the radiation energy is low, of order 100-200 keV. Measured bremsstrahlung on axis yields energies up to 50 keV. what makes big errors of E_{acc} and Q_0 measurements of π mode. Understanding the nature of modes generation will help improve quality of cavity tests.

One of the possible excitation mechanism is due to field emitted electrons. The spontaneous excitation of the $7/9\pi$ passband mode suggests that electrons in cavity are at first accelerated to high energy, and then are again decelerated to low impact energy, thus transfering their energy to the $7/9\pi$ mode. Experimental data [1] show that excitation of $7/9\pi$ mode starts in $E_{acc} = 20 \div 30$ MV/m. Also the mode excitation depends strongly on the Q_{load}.

To understand whether or not can field emission explain phenomena of passband mode excitation we study this mechanism by means of simulation.

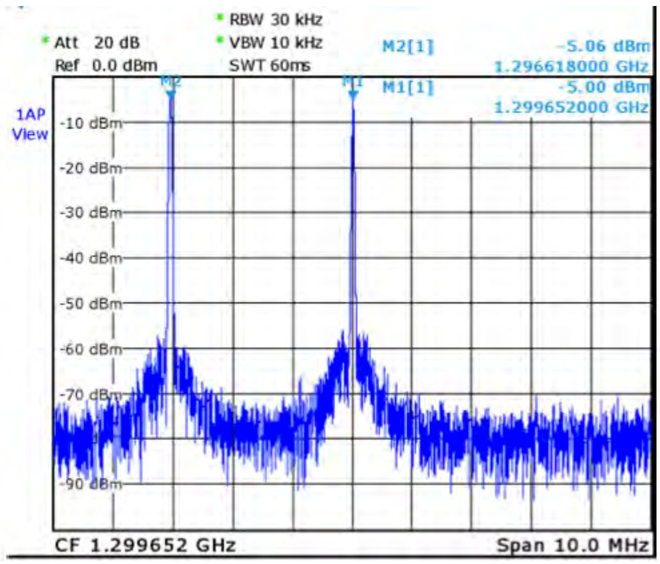

Figure 1: π mode and passband 7/9 π are separated by the spectrum analyzer connected to the pickup antenna

3 Simulations

Trajectories of electrons moving in cavity in field of 2 modes - main π mode and passband 7/9 π - were simulated. The electric field patterns of π and 7/9 π modes are shown in Fig.2. The simulation was carried out through the whole range of parameters like maximum on-axis field and phase for π and 7/9 π modes. Maximum on-axis field for π mode E_1 changed in the range $10-60$ MV/m with step 5 MV/m, phase ϕ_1 was the phase of maximum electric field (for some cells it is 0° and for other - 180°). Maximum on-axis field for 7/9 π mode was fixed and equal to 2 MV/m, the phase ϕ_2 changed in range $0-360°$ with step 10°. Besides this different potential field emission sites on cavity surface were considered. The electric field peaks in the cavity iris regions - this makes irises the most probable source of field emission. Due to cavity symmetry, the simulation was carried out for emission points located in the left part of the cavity (first 4 cells and the half of 5th cell). So in simulations emitters were located symmetricly about each iris (20 emitters per iris) starting with the first in 0.5 mm from iris and then going 10 emitters in one direction from iris and 10 in the other with distance between them 1 mm - altogether 80 emission sites. In simulation program emmiter location is set by the length of the cavity boundary. Output files of the program contain every electron trajectory: coordinates z and x in metres and time stamp in seconds.

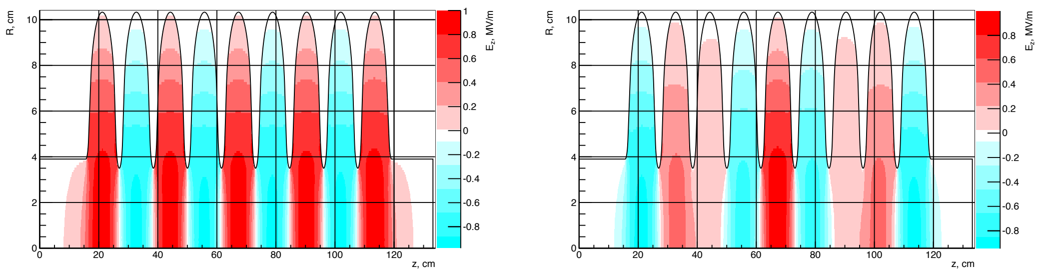

Figure 2: Electric field pattern of the 1300 MHz accelerating mode and of the 1297 MHz 7/9 π mode

4 Simulation analysis

The excitation of $7/9\ \pi$ mode occurs if the field emitted electron transfers the energy to passband mode - so it looses energy comparing with the case when there is only one π mode in cavity. Ehergy gained by the passband mode is the energy lost by the electron and it is calculated simply as the difference of two values - final electron energies in field of one main mode and in field of two modes. Electron energy gained because of the interaction with the second mode can be due to the changing of the bunch trajectory by the passband field or due to the modulation of the current by the passband field. The current density is described by the Fowler-Nordheim (FN) formula,

$$j(E) = \frac{A_{FN}(\beta_{FN}E)^2}{\phi} exp(\frac{-B_{FN}\phi^{3/2}}{\beta_{FN}E}), \tag{4}$$

where $A_{FN} = 1.54 \times 10^6$, $B_{FN} = 6.83 \times 10^3$, E is the surface electric field in MV/m, $\phi = 4\ eV$ is the work function of niobium, $\beta_{FN} = 50 - 2000$ is the field enhancement factor, and j is the current density in A/m^2. The β parameter is used to fit experimentally obtained dependence of the emitted current on the field in niobium cavities.

So, we considered both effects in calculation of energy gained by $7/9\ \pi$ mode. In order to take into account changing of electron trajectory in the passband field energy gain was averaged over all phases of the second mode. To include second effect averaging was performed with diffirent trajectory weights for each phase according to formula (4). If the energy gain, V, is larger than the mode's energy loss in the cavity wall, the field will grow exponentially until it is limited by some other nonlinear mechanisms. The threshold current thus is

$$I_{th} = \omega U/QV, \tag{5}$$

where ω is frequency of $7/9\ \pi$ mode, U is stored field energy, Q is the quality factor. Threshold current was estimated and in our case is about $1\ \mu A$.

5 Results

Examples of simulated electron trajectories for various parameters are shown in Fig. 3. Different curves correspond to different phases of the passband field. Also there are given values of energy gain for each trajectory. These are the cases when passband mode excitation occurs.

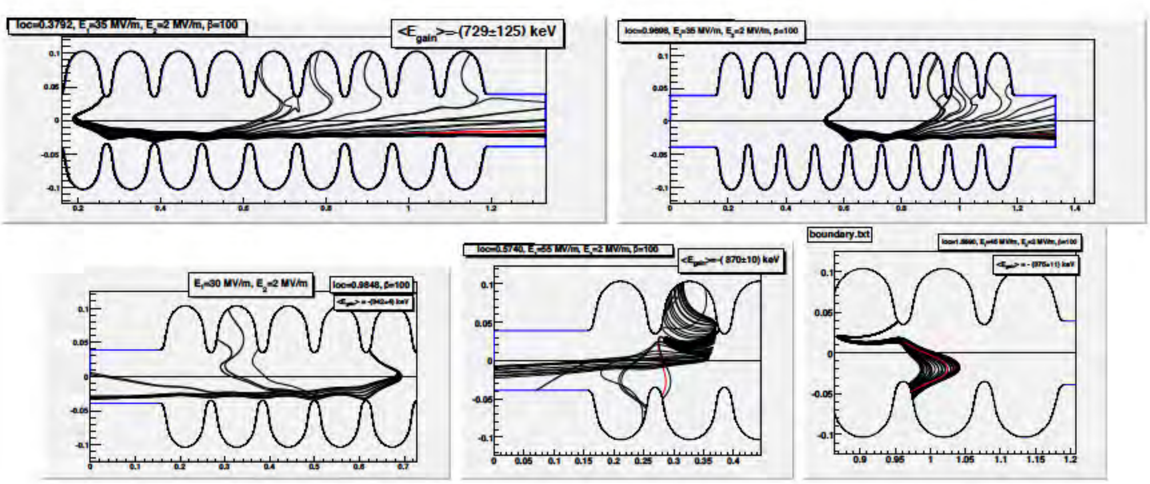

Figure 3: Examples of electron trajectories in cavity in field of 2 modes

For the emitter location from first picture in Fig. 3 dependence of energy gained by the electron E_{gain} in passband field on maximum on-axis field of the main mode E_1 is shown in Fig.4. For this particular emitter location from this plot it is evident that spontaneous excitation occurs in fields $E_1 = 25 \div 35$ MV/m (meanwhile gradient $E_{acc} = E_1/2$). Two curves on tne plot correspond to two cases when we take into account effect of current modulation and when we don't. It is clear that current modulation doesn't play any significant role in passband mode excitation - the main part of energy gain is due to changing of electron trajectory by the passband field.

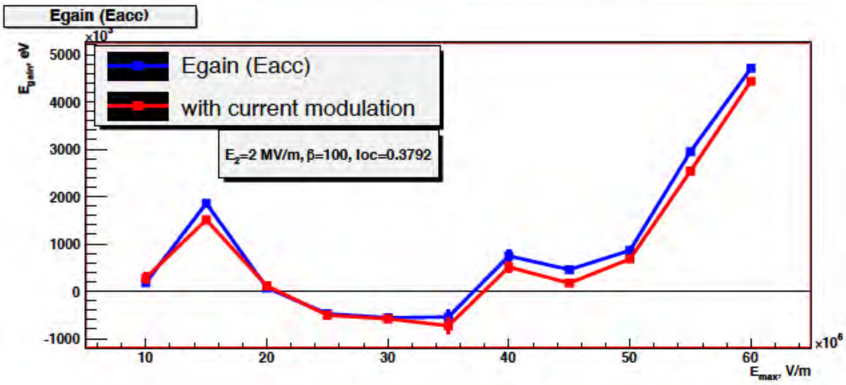

Figure 4: Electron energy gain E_{gain} in passband field for different values of maximum on-axis field of π mode

In Fig.5 same curves for diffirent emitter locations through all cavity boundary are shown. The distance between emitters is 1 mm, however curves vary greatly - so passband excitation is very sensitive to emitter location. And it occurs only when emitter is close to the spot with maximun surface electric field. The electron trajectories in cases of strong interaction with the second mode are shown in Fig.6

Analogous simulation has been done also in [2], but results don't agree with experimental data. And moreover strong disagreement with our simulation was found. In Fig.7 contradiction in results is shown.

6 Summary

The simulation of field emitted electron trajectories for 1.3 GHz TESLA cavity at different gradients of accelerating field has been performed. However more precise analysis of electron trajectories - like calculation of energy gain by means of integral along trajectory - needs to be carried out.

References

[1] G. Kreps, et al, *Proceedings of SRF2009* (HZB, Berlin, Germany, 2009).

[2] V. Volkov, J. Knobloch, A. Matveenko *Monopole passband excitation by field emitters in 9-cell TESLA-type cavities* Phys. Rev. ST 13, 084201 (2010).

[3] E. Kako, S. Noguchi, KEK *Passband mode excitation* TTC meeting 2009.6.17

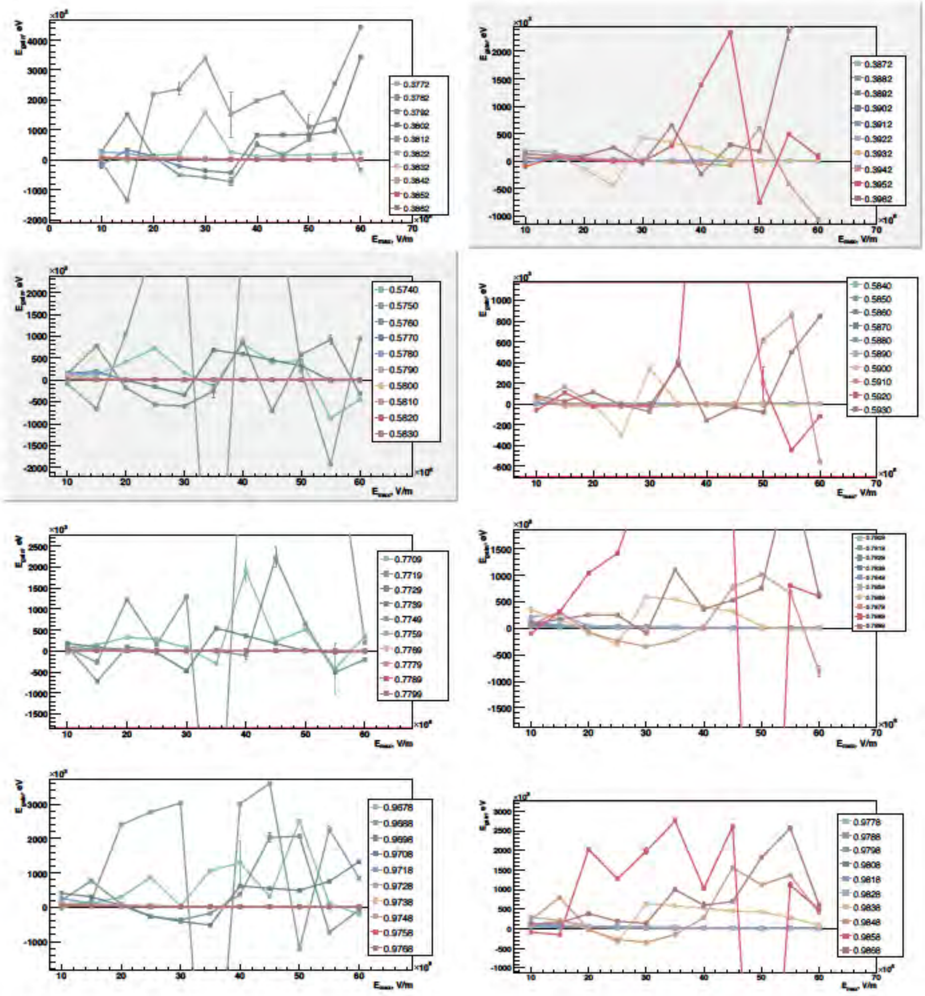

Figure 5: Energy gain curves for different emission sites

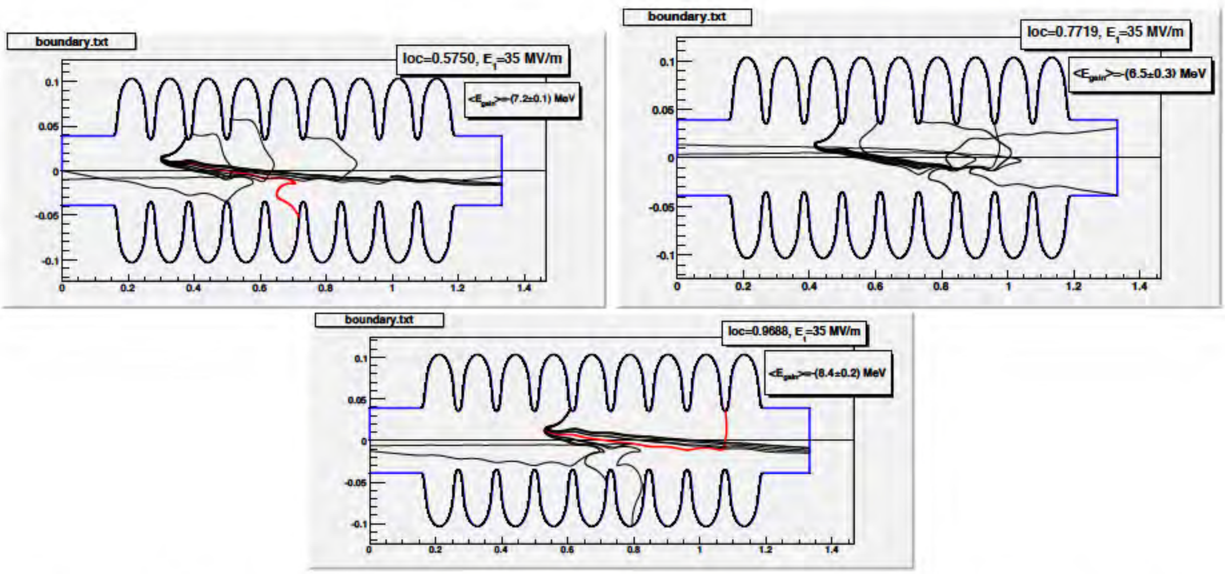

Figure 6: Electron trajectories in cases of strong interaction with the second mode

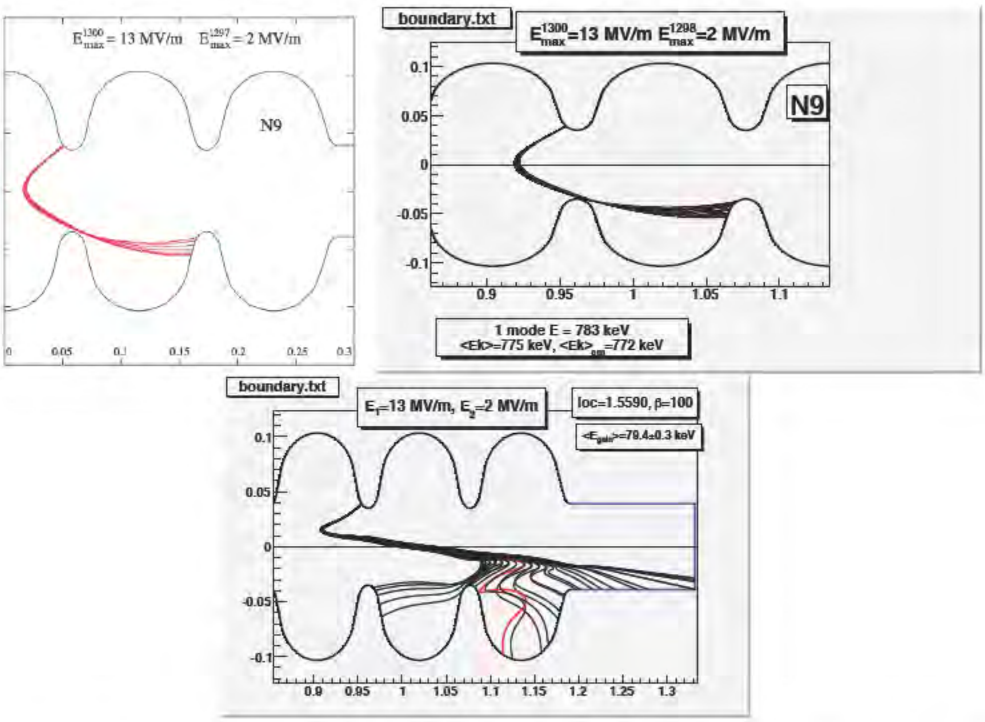

Figure 7: Disagreement with [2] was found - (a) electron trajectory from [2] (b) our simulation with wrong sign of magnetic field (c) our simulation with right sign of magnetic field