REDUCTION OF Q-LOSS-EFFECTS IN FERRITE-LOADED CAVITIES

H.G. Koenig, S. Schaefer, GSI, Darmstadt, Germany

Abstract

Accelerating cavities loaded with Ni-Zn ferrites have been widely used in synchrotrons for many years. So far their performance is significantly limited by the so-called high-loss-effect (HLE) or quality-loss-effect (QLE) [1] [2]. After some milliseconds, this effect leads to a sudden drop of the resonator's voltage namely under the following conditions: fixed frequencies with RF-power above a specific threshold level and a parallel DC-biasing. The mechanism of this unwanted loss has not been fully understood yet. Now a simple method has been found to work against this effect with the aid of mechanical damping of surface waves. For small samples of ferrites the QLE is fully suppressed by using a rubber belt around the circumference or by covering the surface with a thin layer of hot-melt adhesive. We were able to show that similar methods applied to full size rings lead to a significant increase of the onset voltage of the QLE. Most of the existing ferrite loaded accelerating cavities with QLE-limitations can be increased in their accelerating voltage by the above-mentioned modification.

PHENOMENOLOGICAL EXPLANATION OF THE QLE

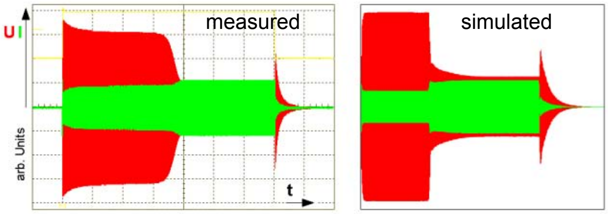


Figure 1: RF-pulse under QLE-conditions

Figure 1 (left) shows a RF-pulse response under a fully developed QLE, measured on FXC4M2. After a short latency or onset time, the voltage of the resonator drops below its half initial value, which means that the corresponding R_p has declined. When the RF-generator is switched off, an after effect occurs. During this follow-up burst [1] the ferrite delivers energy back to the electrical resonant circuit. Looking at the decay times, we noticed that the stored energy is 10 to 1000 times higher than the energy stored in the equivalent parts L_p and C_p of the lumped electrical oscillator. We suppose that only mechanical (acoustical) resonances of the ferrite core with compatible wavelengths could be the reason for these energy traps. The acoustical modes are magnetoelastically coupled to the local magnetisation. The tangential (parallel) biasing is the precondition for the QLE. Under parallel bias DC-currents, the magnetostrictive stress oscillates with the same frequency ($f_{\parallel}$) as the RF-field and an energy transport to the parasitic mechanical modes is possible. Due to the instant transversal contraction, the orthogonal strains oscillate with the same frequency, but a perpendicular coupled magnetisation B_p is only possible at ½f_{RF} ; $f_{\perp}$ see table 1. Figure 3 shows a mechanical model of such an 'orthogonal coupled' parasitic resonator. If the mechanical stimulus meets one of the numerous acoustical modes of the core, the transversal free movements of the spins become locally coherent. This is the effect of a non-linear self-restoring oscillator. Now the RF-field is coupled to the corresponding sound field which is able to store large amounts of energy. The parasitic oscillation of the local magnetisation (think about undulating field lines) are damped by the same mechanisms like eddy currents on microscopic scales or like Bloch wall frictions. These additional core losses are just in parallel to the main LC-parallel-resonance-circuit.

Table 1: Frequency conversion table

Bias	$f_{\parallel}$	$f_{\perp}$
$B_{\parallel}$	1	**1/2**
$B_{\perp}$	2	2
0	2	1

x f_{RF}

magnetostrictive forces ~ F(B²)

Out of the Laboratory

Simulating the behaviour of the QLE is another way to understand the mechanism of this phenomenon. The connection of at least two resonators – in spite of the fact that one of them could be of mechanical nature - leads to the time response of a ferrite loaded cavity under QLE-conditions. The latency time is realised by a simple trick: a time-depending switch (figure 2. right). However, it is more advisable to use a voltage controlled inductive gate (fig. 2. left). As a result, the complete circuit has the effect of a self-restoring oscillator. By choosing the right parameters, most of the QLE's pulse shapes can be generated (see fig. 1. right).

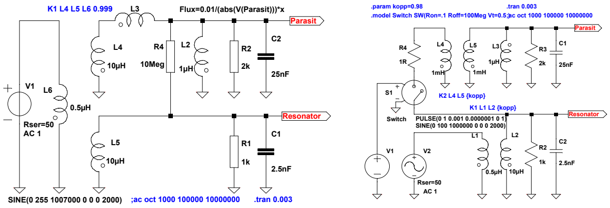


Figure 2: examples of simple SPICE models for the QLE

In the future, the models have to be modified by a frequency dividing sub circuit (see analogon in figure 3) to match the mechanical - with the magnetic oscillation.

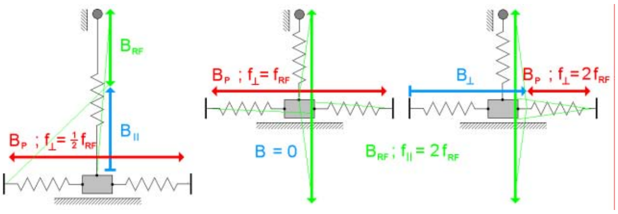


Figure 3: mechanical model of frequency conversion

Modal structure of the QLE

The sound fields within the ferrite core were analysed numerically by 2D-calculations even at frequencies above the circumferential and the bending modes of a circular ring - see Timoshenko [3]. The circumferential modes calculations of a medium-sized ring (100x50x25mm^3) are presented in figure 4. Furthermore shell-like solutions are also possible. At higher frequencies there are mainly pure surface waves which are able to start coupled magnetic oscillations in the core. The mode density is dominated by the largest physical dimension – that means by the outer circumference of the ferrite cores. Modes within the height of the core are also possible, but less significant.

Table 2: Ferrite samples corresponding to fig. 5

Material Ni-Zn Ferrites	MAGNETON 400 N	PHILIPS 8C12 std.	CMI CMD 5005	PHILIPS 8C12 mod.
Size: D x d x h	32x20x5	36x28x6	100x50x25	498x270x25
1st Resonance	57 kHz	54 kHz	26.4 kHz	4.5 kHz
calc. Density	2.4/10kHz	1.6/10kHz	28/10kHz	70/10kHz
meas. Density	3.4/10kHz	1.2/10kHz	28/10kHz	35/10kHz
Q@QLF	~ 500	~ 500	~ 2500	~ 5000

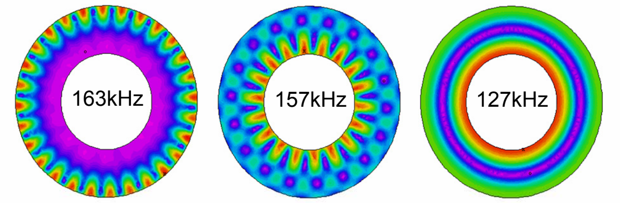


Figure 4: examples of circumferential and shell-modes

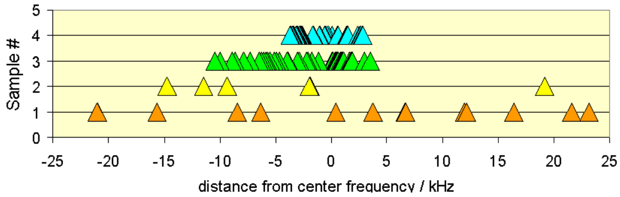


Figure 5: Calculated mode distribution

The calculated mode density in figure 5 is verified with the measurements in figure 7. Our results are summarised in table 2 where the mode density is roughly given in 'number of lines/10kHz'. The geometric influence is evident. The mode density is in fact a good test for the magnetoelastic theory of the QLE. It is also obvious that Timoshenko's frequencies (e.g. multiples of the 1st resonance) describe the problem only partly because the surface waves are not included. In large rings, discrete modes seem to vanish at higher RF-levels as they can hardly be measured because of their overlapping. The exact frequencies are not relevant and may be shifted by about tens of kilohertz.

Surface Stray field probe

In order to find orthogonal components, we used a small stray field probe as shown in figure 6. This probe can either be moved around manually or mounted on a fixed place, close to the ferrite's surface. By turning around the probe in different directions, a clear signal of ½ of the driving RF-frequency and the related Fourier-components can be measured. A spurious RF-line near 84MHz at 32.5MHz driving RF is reported in [1]. This line during the QLE probably derives from the occurrence of a subharmonic oscillation at ½f_{RF}. So all rational broken signal frequencies at 3/2f_{RF}, 5/2f_{RF}, 7/2f_{RF} etc. are Fourier-components of the QLE. Neither 1/3f_{RF} nor 1/4f_{RF} lines were observed in the spectrum. The appearance of the QLE can easily be detected with the aid of the measured subharmonic component. It is advisable to take the measurement on the surface of the ferrite perpendicular to the driving RF-field where its strength will be zero.

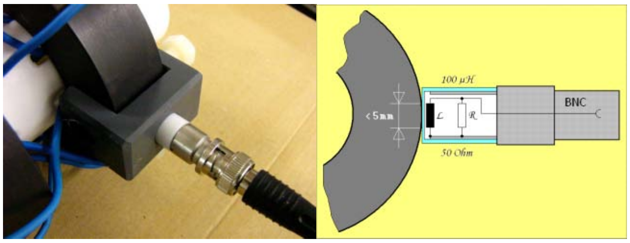


Figure 6: surface stray field probe

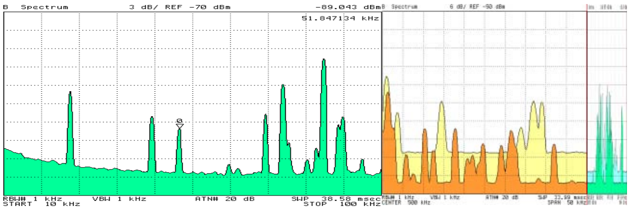


Figure 7: corresponding subharmonic QLE-signals

CURING THE QLE ON DIFFERENT SPECIMENS

Known Methods of QLE-Suppression

There are two approved methods to suppress the QLE in accelerating ferrite cavities: 1) perpendicular biasing and 2) fast frequency ramping [1]. 1) Perpendicular biased ferrites are mechanical stimulated by 2f_{RF} in tangential direction (table 1). Therefore a subharmonic magnetic undulation cannot exist. 2) Due to the QLE's modal structure and its delayed onset time, it is also possible to avoid this effect by sweeping the frequency of the RF-field with a short ramp rate. At fast ramping synchrotrons, ferrite cavities can be driven far beyond the QLE-threshold. The QLE is also negligible on bunch rotating cavities with short pulse durations.

Investigations on different Specimens

The intention of this paper is not to figure out the best ferrite material for accelerating cavities. It should be rather shown how to handle a given type of core material to improve its performance in the case of unwanted QLE. All types of Ni-Zn-ferrites mentioned in this investigation (including FXC4C6 [4] and a Mn-Zn type MN8CX from CMI which are not presented in this paper) are susceptible to QLE and the described mechanical damping methods allow to increase the QLE-threshold considerably. First positive results were achieved with hot-melt adhesive, rubber bands and insulating tapes as shown in fig. 8-10.

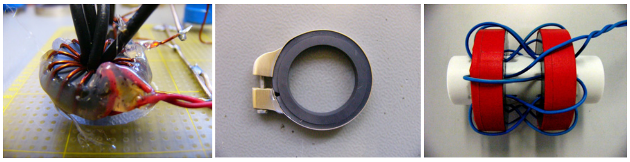
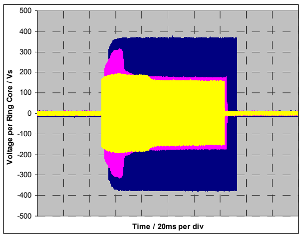


Figure 8-10: damping experiments on small samples

Suppressing the QLE with coatings

In figure 11 three oscilloscope traces are superposed to show the effect of suppressed QLE. The measured ring cores were treated with a thin bitumen coating on two full size (498x270x25mm³) ferrite ring cores at 1MHz - biased with 300A/m. The QLE-threshold is shifted from $180V_p$ to $> 370V_p$ per ring core. The experiment was limited by the available RF-power of the amplifiers (2 x 500W). The duty cycle of the RF-pulse duration was kept lower than 0.1 to avoid an overheating of the air cooled experiment setup. The ferrite rings are made of modified FXC8C12 by FERROXCUBE and they are similar to the SIS18 cavities ferrites which are currently used at GSI. The coating has a thickness of approx. 1mm and consists of two layers of underbody sealant (UBS) for cars.



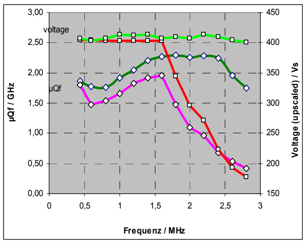


Figure 11 (left): QLE-suppression with bitumen coating

Figure 12 (right): QLE-suppression with insulating tape

A fast and simple test for QLE-suppression can be done by taping the surface of the ferrites with an adequate self-adhesive tape or foil – especially on its inner and outer circumferences. As shown in figure 12, the QLE is banished from the desired frequency and bias range of the planned SIS100 synchrotron (1.1 to 2.8MHz). We examined two CMD5005 ferrite rings (100x50x25mm³) and extrapolated the peak voltage (per single turn) from the sample to a full size ring and kept it constant within the given frequency range. In case of bare surfaces the µQf-value of these rings declined dramatically even under moderate biasing conditions.

Curing the QLE on a full size cavity

In order to verify the effect of mechanical damping, the SIS18 prototype cavity with 64 ring cores FXC8C12mod was treated with ordinary insulation tape on its accessible surface. Although less than 50% of the circumference was covered by this tape, a considerable increase of the final gap voltage was achieved. Under all operating conditions the QLE-threshold voltage raised by 10% (~1kV). – see figure 14. With one SIS18 cavity, we could achieve 34kVp of initial voltage for 0.5ms, but the accelerating voltage is still limited to 16kVp (cw) [2].

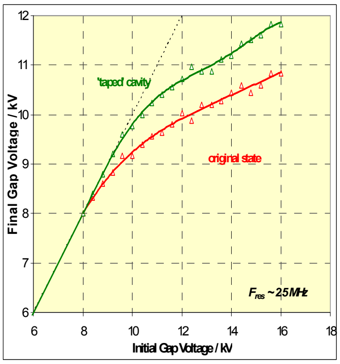


Figure 13 (left): 'taped' full size cavity

Figure 14 (right): increase of the gap voltage

FUTURE PLANS AND CONCLUSION

Currently, the gap voltages reached in the SIS18 cavities are still limited by the QLE. But according to the described experimental results, one can expect a considerable increase just by coating the ferrites' surfaces with bitumen or some similar damping material. Moreover, the simple coating of the ferrite cores seems to be a good possibility to reach higher gap voltages in many other ferrite loaded cavities (limited by the QLE so far). The Budker Institute of Nuclear Physics (BINP) developed a cavity, based on entirely encapsulated ferrite stacks [5]. This cavity contains four blocks. Each of them consists of seventeen ring cores (each ring glued of eight trapezoidal segments) with inserted cooling plates. Each block is completely impregnated and moulded under vacuum with a special silicone resin. On the basis of this assembly, we reckon with a sufficient suppression of the QLE. In this case the gap voltage is only limited by the heat removal and the electric strength of insulation. The observed damping effect can be partly explained by the above-mentioned discussions, but the theory has still to be worked out and verified. Furthermore the magnetostriction of the ferrite cores should also be taken into considerations in future. In case of a reduction of the magnetostriction, we would be able to prevent the QLE.

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