STUDIES ON MAXIMUM RF VOLTAGES IN FERRITE-TUNED ACCELERATING CAVITIES

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Abstract

The GSI SIS100 project requires very high accelerating voltages. With ferrite-tuned cavities the gap voltage is often strongly limited by the Q-Loss Effect at medium dc bias fields, whereas with lower bias fields, much higher voltages can be reached. The maximum usable amplitudes over the bias region have been studied. At zero bias, the ferrites could be driven to more than a factor 3 above the Q-Loss limit. With increasing bias, the usable amplitudes decrease continuously to the lowest Q-Loss level. In this fall-off region there is still a tuning factor up to 2 available, with rf flux densities by at least a factor 1.5 above the Q-Loss level. Measurements on small samples of the ferrite material used in the GSI cavities could be verified very well in the GSI SIS and ESR full-size cavities. The tests were mainly limited by the available anode voltage. It seems possible to generalize the main results for other ferrite materials, also. Based on the results, an improved scenario for the SIS100 rf system is discussed.

GENERAL

GSI is developing the new accelerator facility FAIR. For the main synchrotron SIS100 accelerating voltages up to 450 kV for H=10 are required. Short rf pulses with up to 1 MV for H=2 are needed for bunch compression [1,2].

Intense studies for generating such high accelerating voltages in ferrite-tuned cavities have been carried out (see also P. Hülsmann, GSI, this Conference).

Most part of this paper refers to studies with the GSI SIS18 and ESR synchrotron cavities. Fig.1 and Table 1 give an overview of the design and the characteristic data of the these cavities.

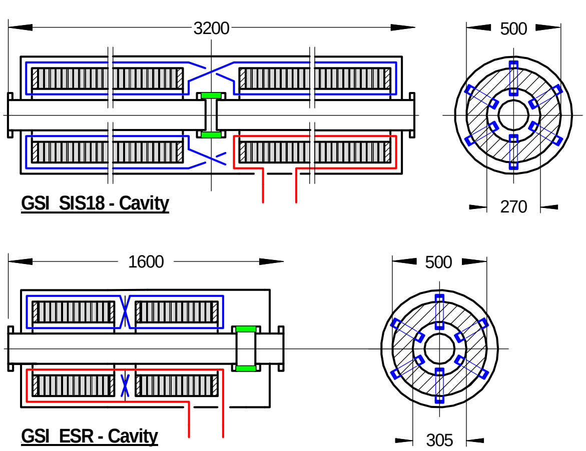


Fig.1: Cross-sections of the SIS18 and ESR cavities.

Table 1: Data of the present GSI SIS18 and ESR cavities

GSI Accelerator		SIS18	ESR
Total acc. voltage	kVp	32	10
Frequency range	MHz	0.8-5.4	0.8-5.4
No of Cavities		2	2
Gap Voltage/cavity	kVp	16	5
Ferrite Material	Philips	FXC 8C12m	FXC 8C12m
No of ferrite rings		2 x 32	2 x 12
Bias windgs x currents	A	6 x 5-600	6 x 5-600

Q-LOSS EFFECT LIMITATIONS

In ferrite-tuned cavities, the maximum usable accelerating voltage is often strongly restricted by the so-called Q-Loss-Effect [3, et al.]. In the GSI SIS18 cavities the lowest Q-Loss threshold (QLT) is about 16 kV, and about 5 kV in the ESR cavities. The maximum allowed operating voltages over the whole frequency range have been limited to these values accordingly.

Fig. 2 illustrates the QLE in a GSI ESR cavity. When a square pulse of rf power with constant frequency is applied to the ferrite cavities, above a certain level, the rf voltage follows the pulse shape only for about 5-10 ms and then drops to a lower level. Any further increase of the voltage requires disproportionately more input power.

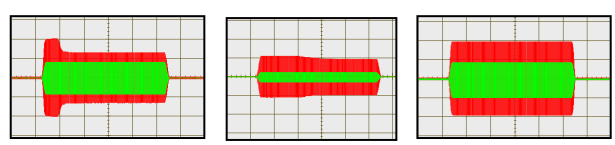


Fig.2: Example of the Q-Loss-Effect in an ESR cavity.
Outer signal: Cavity gap voltage, 4 kV/div, 10 ms/div
Inner signal: Power amplifier grid 1 drive voltage
Left: Strong QLE at medium dc bias field and 2 MHz,
Middle: Same as left, QL-threshold with beginning QLE,
Right: Very low dc bias, 0.8 MHz: regular response to input power, no QLE, much higher gap voltages possible

The QLE usually appears at moderate dc bias levels. With very low dc bias fields, much higher rf voltages and rf flux densities in the ferrites can realized, however.

MEASUREMENTS AND RESULTS

Measurements have been carried out on small sample rings of the materials Philips FXC 4L2, 4M2, and 8C12m, all with do=36, di=28, th=6mm. The measured 8C12m sample rings have been cut out of a large, original SIS18 ring. This material proved to be the most interesting also for SIS100 and has been investigated in more detail.

Two sample rings with opposite-sense rf windings were connected in parallel with a resonance capacity to form a parallel resonant circuit. The dc bias windings were passed through both rings. For a bias variation of 0-1200 A/m the resulting resonant frequencies and the connected QLT values have been measured. Different frequency ranges were studied by changing the capacity. The resonant voltages were measured on an oscilloscope with a 200:1 divider. To reduce heating of the samples, air cooling was used and the rf power was switched on only for very short times. In some cases, at zero bias, the resonant voltages exceeded the sparking limit. Possible QLT values at higher levels could not be measured then.

Fig.3 summarizes the results. The x-axis shows the relative frequency variation corresponding to a dc bias range of about 0-550 A/m. The real frequencies and some further details are given in the caption. The ordinate shows the QLT gap voltages calculated for a SIS18 cavity under the assumption that the small sample ring results may be scaled up to the ferrite dimensions of the large cavity just by the ratio of the ferrite cross-sections.

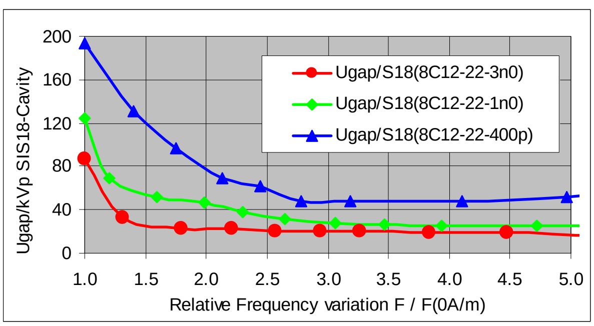


Fig. 3: Q-Loss thresholds scaled up to a full-size SIS18 cavity from measurements on small ferrite sample rings of the material Philips FXC 8C12m. Measuring conditions:
8C12-22-3n0: 22 rf wdgs/ring, C=3.0 nF, 0.33-1.7 MHz
8C12-22-1n0: 22 rf wdgs/ring, C=1.0 nF, 0.64-3.2 MHz
8C12-22-400p:22 rf wdgs/ring, C=0.4 nF, 0.94-4.7 MHz

Curve 8C12-22-1n0 corresponds best to the conditions of the SIS18 cavities. The lowest QLT of this curve is still about a factor of 1.5 above the real SIS18 cavity value. Probably, the scaling assumptions are too rough. Also, larger errors can be due to temperature variations.

What seems to be more important is the relative variation of the curves. At zero and very low bias fields, the ferrites can be driven up to a factor of 4-5 above the lowest QLT value at higher bias fields. Here it is possible to drive ferrite cavities beyond the voltage levels and rf flux densities where other technical limitations in the cavities become predominant, like maximum available rf power, ferrite cooling, high voltage problems, etc., but not the QLE. The observed very high voltage capabilities of ferrites can be useful for applications with very short pulses and/or very low tuning ranges. For acceleration purposes with longer duty cycles, in this low bias region, an operating window with a tuning factor of about 2 and accelerating voltages by a factor of 1.5 above the lowest QLT seems available without any major problems.

Interpretation

Fig.4 shows the rf flux densities as calculated for the measured QLT values and, in addition, part of the static hysteresis curve of FXC 8C12 from the data book. The measured Brf peak values and their variations with dc bias are in the same order as the limitations ΔBdc (marked with arrows) which have to be expected from the static hysteresis curve; one has roughly Brfp ≈ ΔBdc / 2.

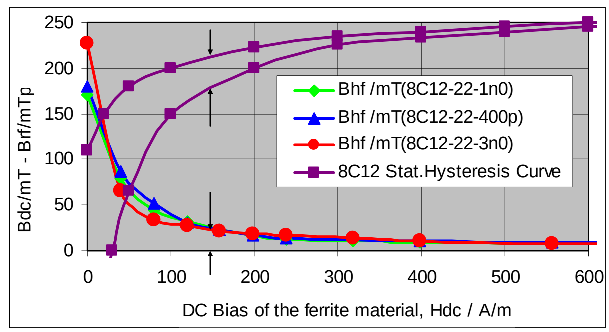


Fig. 4: Measured QLT peak rf flux densities compared with the static hysteresis curve given by the manufacturer.

On one hand, the result simply expresses the well-known hysteresis properties of ferromagnetic materials and may be called trivial. However, it is surprising that the large amplitude capabilities of ferrites in the low bias area have neither been discussed nor applied for practice.

Limits of generalization for other materials

Samples of FXC 4M2 and FXC 4L2 did not show the same close correlation between rf flux densities and the static dc hysteresis curves. At low bias, and below about 1 MHz, already for relatively low voltages, these materials seem to need a delay of many ms before reaching the final amplitude (cf. Fig.5 left). With the operating range shifted higher than about 1.3 MHz, these materials exhibit a behaviour more similar to Fig.3, and even much higher QLTs can be reached then (cf. Fig.5, right, 1V/div here).

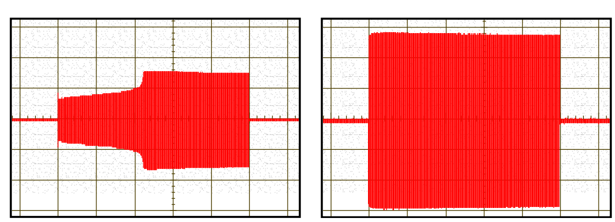


Fig.5: Resonator voltages measured on sample rings of Philips FXC 4M2.
Both cases with 44 windings per ring and dc bias 40 A/m
Left: C=1nF, Fres=0.63 MHz, 10ms/div, 0.5V/div,
Right: C=100pF, Fres=1.35 MHz, 10ms/div, 1.0V/div

Low-bias Studies in the full-size GSI Cavities

In both the SIS and the ESR cavities, at low bias conditions, the gap voltages could be raised by at least 1.5 above the design voltages used up to now. A further increase of the voltages seemed to be limited only by the available anode voltages and the driver amplifier power.

To overcome these limitations, an ESR cavity has been shifted by capacity to about half of the usual frequency. The QLTs decrease then about linearly with frequency. In this case, the maximum gap voltage at near zero bias could be raised to about 2.2 times the lowest QLT at medium bias.

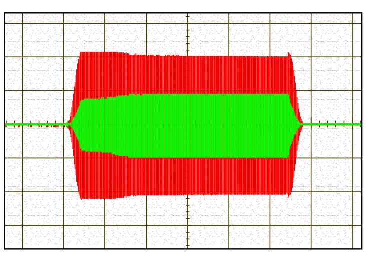
Studies with dynamic tuning of the cavities

The QLE limitations of ferrites show up primarily at constant operating frequencies. When the frequency is varied, as during the usual synchrotron acceleration, the QLTs usually move to considerably higher levels [4] .

This fact could be verified also in a SIS18 cavity. With a tuning rate df/dt>1 MHz/s, and closed loop amplitude and frequency control, this cavity could be run up to 24 kV over the full SIS18 tuning range of 0.85-5.4 MHz.

In SIS100 the total frequency range of 1.1-2.8 MHz is required only for maximum intensities with U28+. The minimum df/dt for U28+ is about 0.5 MHz/s here.

Nearly all other ions with a higher charge/mass ratio need only a small fraction of the upper tuning range and the tuning rates decrease until 0.01 MHz/sec at the end of the cycles. The advantages of dynamic tuning can no longer be expected then.



Outer signal:
Gap voltage
(4 kV/div, 100ms/div)

Inner signal:
Grid voltage power tube

Fig.6: Simulation of SIS100 proton accelerating cycle in an ESR cavity. Factor 1.6 above QLT reached.

To simulate these operating conditions, an ESR cavity was shifted up by about a factor 1.4 to the SIS100 frequency range and run with the original accelerating cycles. For U28+ with df/dt≥0.5 MHz, up to 10 kV could be reached in stable operation. The proton cycle is shown in Fig.6. With df/dt<0.1 MHz/s, the QLE appears soon after the beginning of the cycle. However, the amplitude control system automatically raises the rf power so that a gap voltage by a factor 1.6 above the QLT (value at normal ESR-operation) was reached over the whole cycle. Again, the studies were limited by the available anode voltage and driver power. Serious limitations from the power tube or from ferrite cooling have not been seen.

Excursion: Cavities with external ferrite tuners

The results in Fig.3 initiated the idea of a new cavity design, as also found in [5]: A ferrite cavity without any dc bias and practically no QLE limitations installed in the synchrotron beam pipe and one or more external ferrite tuners with dc bias in parallel. In the external tuners, much larger ferrite cross-sections can be realized without affecting the length of the accelerating cavity itself. The larger amount and costs of ferrite material and the reduced frequency tuning range seemed worth the expected gain of accelerating voltage per cavity length.

Model measurements and refined calculations revealed that the advantages are less significant than expected, however. Further studies have been postponed.

APPLICATIONS FOR SIS18 AND SIS100

As a first result, it seems possible to increase the gap voltages of the existing SIS18 cavities, without further changes, to at least 20 kV per cavity. To overcome the QLT of about 16 kV at frequencies above 2 MHz, the side condition df/dt>1 MHz has to be fulfilled. This is the case for all accelerating modes used in SIS18 up to now.

As a second result, the existing SIS18 accelerating stations can be proposed, practically without any essential technical changes, as a base for the future SIS100 accelerating system, and under SIS100 operating conditions, 25 kV per cavity can be expected. With adequate precautions and measures against high voltage problems, this voltage level can be reached with a high degree of reliability in the final system.

According to Fig.3, at the low bias / low frequency end, with the same SIS18 ferrite system, voltages up to at least 2.0 times the actual 16 kV seem within reach. With an optimum high voltage design and sufficiently high anode voltages, 30-32 of these SIS100 cavities should be able to deliver short high voltage pulses up to 1 MV. This seems at least realistic for the lowest frequency around 1 MHz.

Future studies will have to show, if by capacitive tuning down to about 0.5 MHz, the SIS100 cavities can be used to realize these voltages also in the planned frequency range for bunch compression.

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