Fundamentally Fastest Method Measuring $Q_0(E_{acc})$-Performance of S.C. Cavities

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Abstract

In pulsed operation of a cavity resonator the stored energy W and thus any radiated power P_{rad} decrease exponentially with a time constant $\tau(E_{acc})$. While τ represents the momentary loaded quality factor $Q_L = \omega\tau$, $P_{rad}(t)$ is a measure of the momentary field amplitude E_{acc}. Therefore, any single $P_{rad}(t)$-measurement is sufficient to evaluate a complete $Q_0(E_{acc})$-curve. Obviously, this is the fundamentally fastest way to determine the $Q_0(E_{acc})$ performance. Measuring and analyzing $P_{rad}(t)$ with an automatized computer system allows - for instance - a quick check whether the $Q_0(E_{acc})$-curve is changing during high field operation or fieldemission processing. In addition, it presents an useful tool to study non-quadratic losses (NQL [1]) with high resolution and accuracy. In this paper, the principle of operation, programming structure, and typical experimental results of such an automatic measurement are discussed.

PRINCIPLE OF OPERATION

Operating superconducting accelerator cavities at high field strengths often changes their $Q_0(E_{acc})$-behaviour. Especially RF- and He-processing may influence the onset of field emission loading as well as the amplitude and the field dependence of the residual surface resistance. Usually these effects are studied by a stepwise increase of the incident rf power [2]. However, this procedure is neither suited to catch momentary states of short lifetime nor to characterize non quadratic losses (NQL) with a conveniently high resolution.

Fortunately, the whole information about the momentary $Q_0(E_{acc})$-performance is contained in the time decay of the stored energy W and thus any radiated power P_{rad}. As soon as the incident power is switched off, W and P_{rad} decrease proportional to $\exp(-t/\tau)$, where τ is given by the momentary loaded $Q_L = \omega\cdot\tau$. While the amplitude of the transmitted power is a direct measure of the acceleration gradient

$$E_{acc} = \sqrt{\frac{1}{l^2}\left(\frac{r}{Q}\right) Q_{ext}} \cdot \sqrt{P_{rad}} \tag{1}$$

its time derivative can be used to evaluate the loaded quality factor Q_L

$$\frac{dP_{rad}}{dt}(t) = \frac{-1}{\tau(t)}\cdot P_{rad}(t)\cdot\left(1-\frac{t}{\tau}\frac{d\tau}{dt}\right) \approx \frac{-1}{\tau(t)}\cdot P_{rad}(t) \tag{2}$$

Finally the unloaded Q_0 can be calculated from Q_L using the external quality factors of the coupling probes

$$\frac{1}{Q_0} = \frac{1}{Q_L} - \frac{1}{Q_{ext,1}} - \frac{1}{Q_{ext,2}} \qquad (3)$$

Since $Q_{ext,1}$ and $Q_{ext,2}$ have to be determined from a previous calibration we consider the "single shot" measurement as an useful additional tool for both manual and computer aided [2] characterisation of SRF cavities. Once the decay of the P_{rad} signal has been stored, it is easy to analyze the data set with respect to field emission loading (Fowler-Nordheim-plot: E_{acc}^{onset}, β) or non-quadratic losses ($R_s(H)$-plot).

TECHNICAL AND PROGRAMMING DETAILS

In our present installation we run our online measurement on a HP VECTRA 386 PC with HPIB bus. The RF data are taken digitally by a Network Analyzer (HP 8753 C). Switching the PIN diode for the incident power and triggering are still operated manually. For simplicity, the software was developed in HP IBASIC under Windows. It consists of two main parts:

a) Online readout and saving of the $P_d(t)$-data (max. 1601 points due to the digital time scale of the Network Analyzer; time resolution $\geq$ 0.5 ms/point).

b) Offline analysis: Evaluation of $E_{acc}(t_i)$ out of $P_d(t_i)$. Calculation of the momentary $\tau(t_i)$ from the slope of a least square fit to $\log(P_d(t_i))$. Calculation of $Q_0(t_i)$ from $\tau(t_i)$, using the previously entered calibration parameters ($Q_{ext,1}$, $Q_{ext,2}$, attenuation of cables etc.). Graphical output of $Q_0(E_{acc})$- and $R_s(H)$-plots.

While part a) needs only five to seven time constants of the loaded cavity plus about 10 seconds, the offline analysis runs for up to 2 minutes, depending on the number of points for the individual least-square fits and the hardware performance of our comparably slow computer. Significant acceleration is obtained with a faster computer, if desired.

Due to the dynamic range of the phase-locked-loop, necessary to stabilize the local oscillator of our Network Analyzer, any radiated signal can be followed for about −30 dB ($E_{acc}^{min} \approx 0.032 \cdot E_{acc}^{max}$). Even when the stored decay trace (e.g. Fig. 1a) fits only about 40 % of the Network Analyzer screen the individual measurements are taken at a distance of less than 0.05 dB ($\Delta E_{acc} \leq 0.01 \cdot E_{acc}$). Thus, at low signal levels averaging over many points is allowed to eliminate noise contributions. At high fields, where Q_L may change comparably fast due to fieldemission, the least-square fit must not be extended over many points. In our system a good match to the results of measurements in cw operation is obtained with values between five points (near max. E_{acc}) and fifty points (very small P_{rad}). A further improved noise reduction can be obtained by digital filtering $P_{rad}(t)$ instead of the simple least-square fit method.

EXAMPLES

The program was successfully tested and optimized during several experiments on superconducting single- and nine-cell cavities. Figs.1-4 show typical results, obtained in a test on a 3 GHz single-cell cavity during He-processing of fieldemission loading. The development of the $Q_0(E_{acc})$-behaviour can be seen clearly.In the final state the results were successfully confirmed in cw operation.

In Fig.5 an example for the postprocessing of the stored data in another test with respect to the residual surface resistance is shown. The maximum $H_s{}^2 = 1.5 \cdot 10^9 (A/m)^2$ corresponds to a gradient of E_{acc}=11.7MV/m, where fieldemission loading was already present during this experiment. Therefore, the steep increase of R_s above $H_s{}^2 = 1.3 \cdot 10^9 (A/m)^2 \hat{=} E_{acc} = 10.8$MV/m is due to fieldemission loading. Below the fieldemission threshold a straight line fits the data well, which is in agreement with the often observed increase of the residual surface resistance $R_s \sim H_s{}^2$ [3]. At low fields a minimum of R_s appears, which has no physical interpretation up to now, but was confirmed by careful cw calibration measurements as well as the other parts of the curve. The surface resistance R_s uis determined with a typical scatteringof less than 0.2nΩ. Even in the worst case of very low signal levels, ΔR_s stays below 0.5nΩ.

CONCLUSION

The presented method allows the fundamentally fastest determination of the $Q_0(E_{acc})$-performance of a s.c. cavity. Only one $P_{rad}(t)$-measurement is sufficent to evaluate the $Q_0(E_{acc})$-curve with dynamic range of at least a factor of 30 ($E_{acc}^{min} \approx 0.032 \cdot E_{acc}^{max}$). The computer based analysis of the data gives a useful and fast tool to check on-line the momentary state of a s.c. cavity within a few time constants, e.g. during the processing of fieldemission. Furthermore, the high resolution and accuracy is adequate for a detailed characterization of non-quadratic losses.

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[2] Ke-Jun Kang et al., 5th Workshop on RF Superconductivity, p.527, 1991, Hamburg
[3] R.W.Röth et al., ibid. [2], p.599

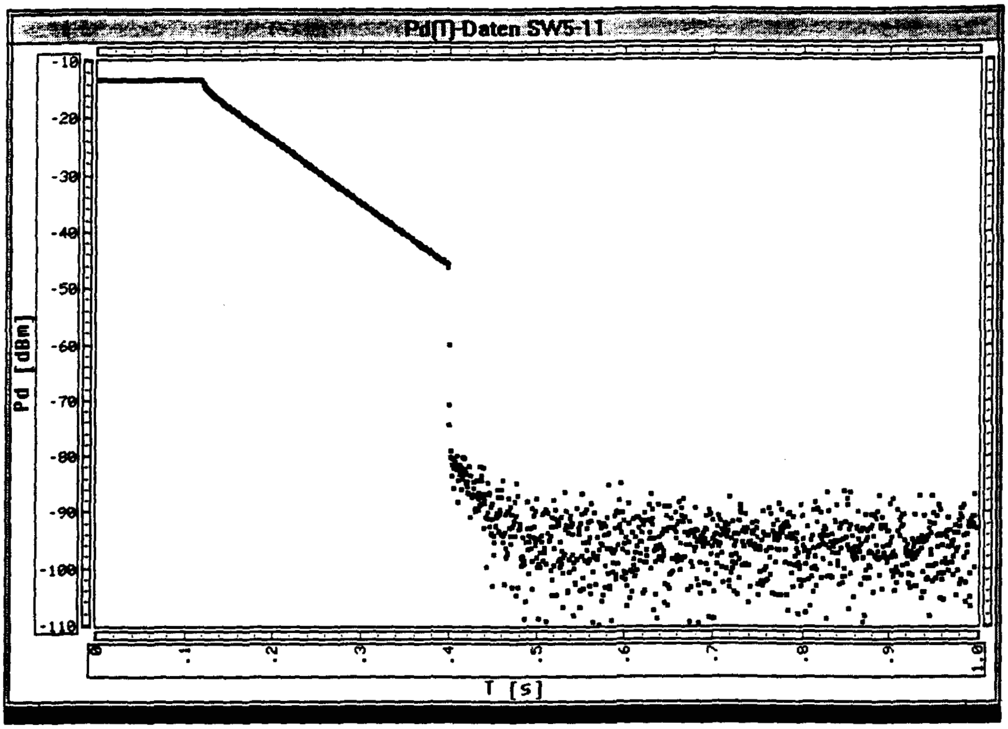

Fig.1a: Stored data trace $P_d(t)$ as measured by the Networkanalyzer

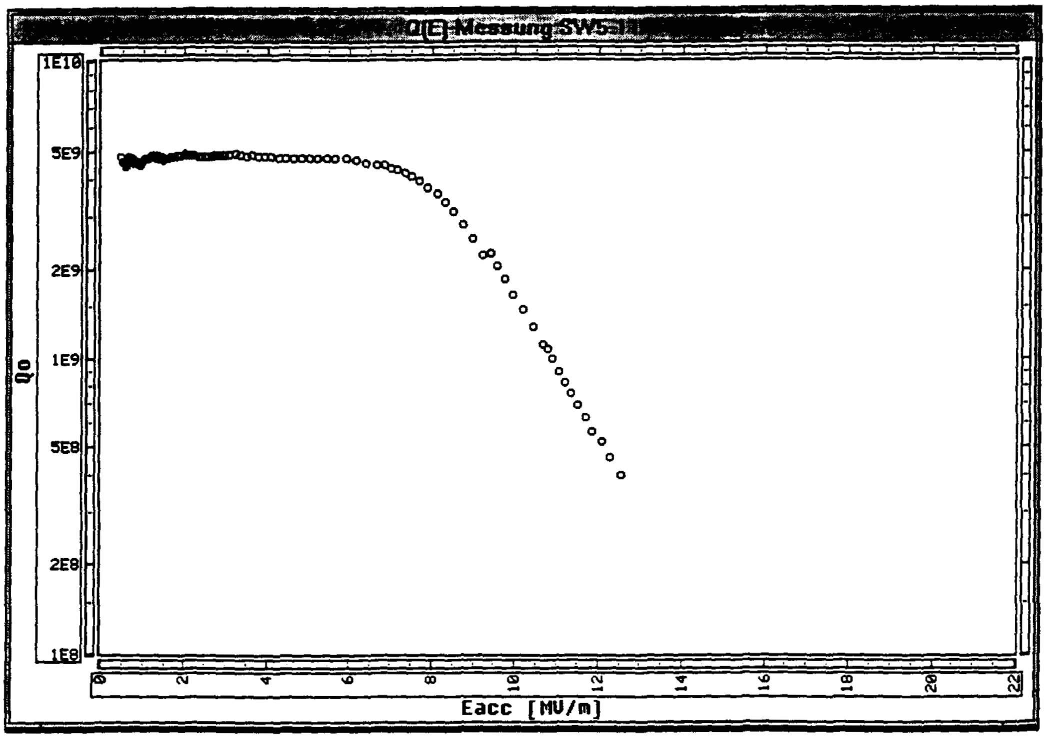

Fig.1b: Corresponding $Q_0(E_{acc})$-curve at the beginning of He-processing ($E_{acc} = 12.5$MV/m)

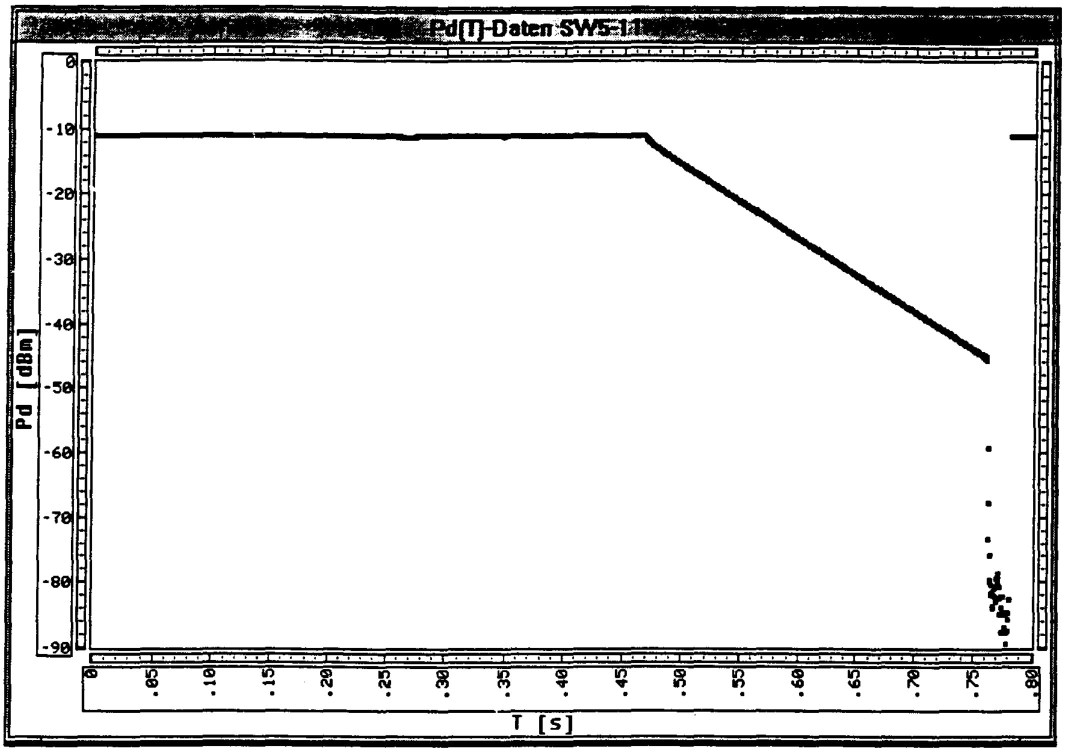

Fig.2a: Stored data trace $P_d(t)$

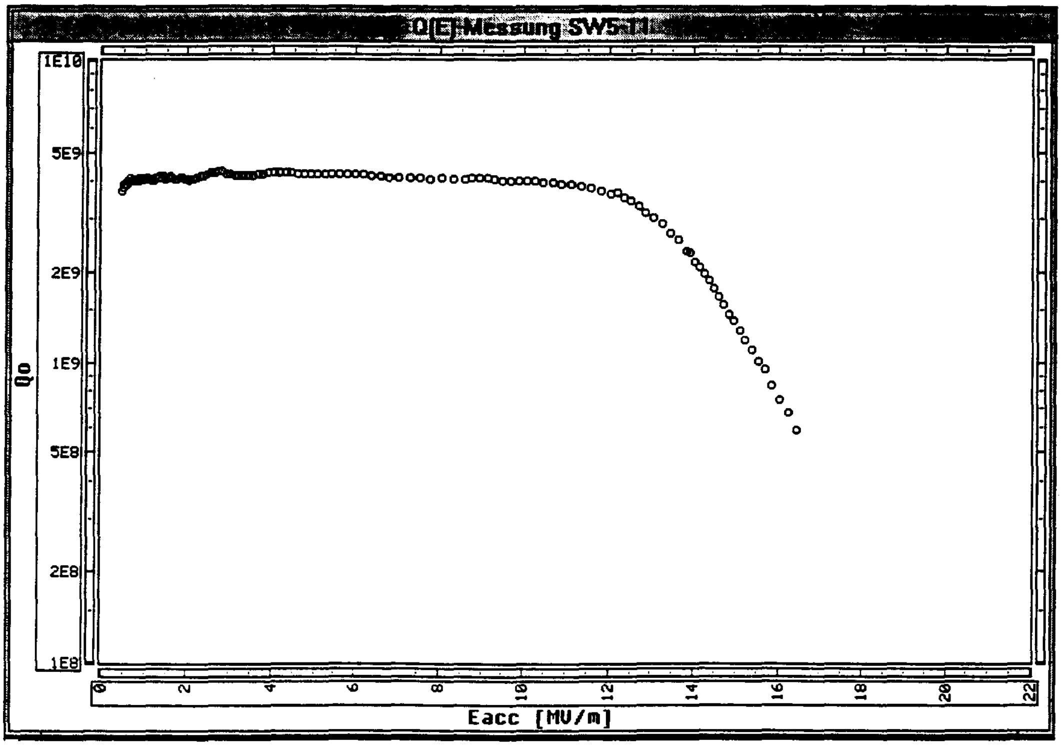

Fig.2b: Corresponding $Q_0(E_{acc})$-curve during He-processing ($E_{acc} = 16.5$MV/m)

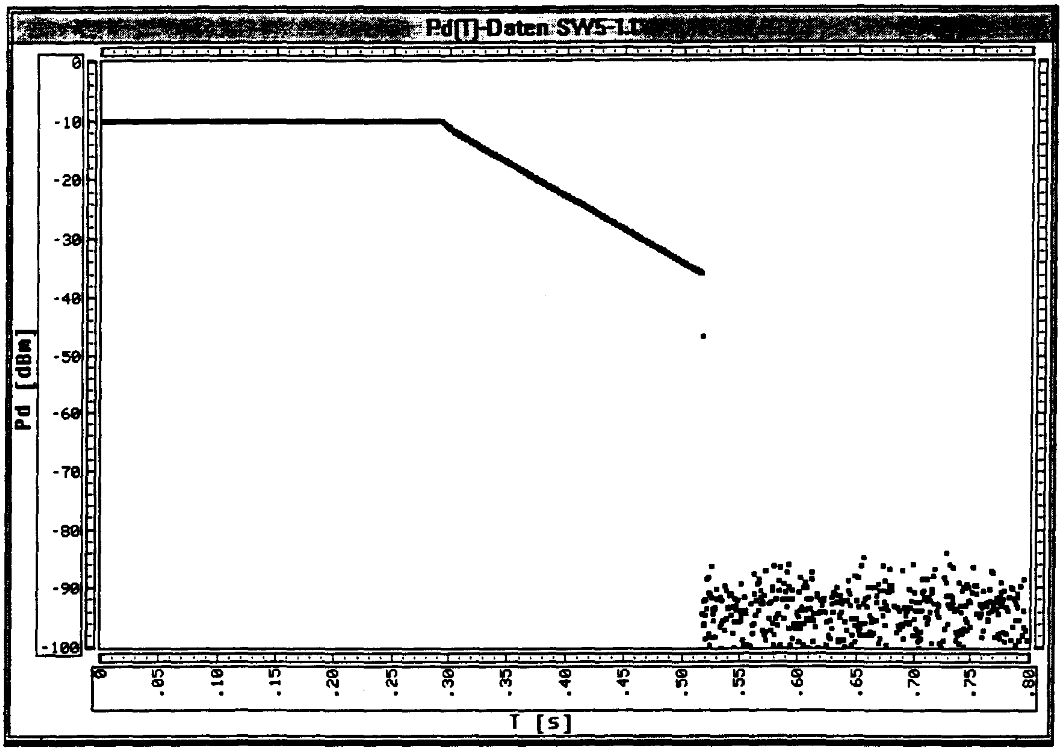

Fig.3a: Stored data trace $P_d(t)$

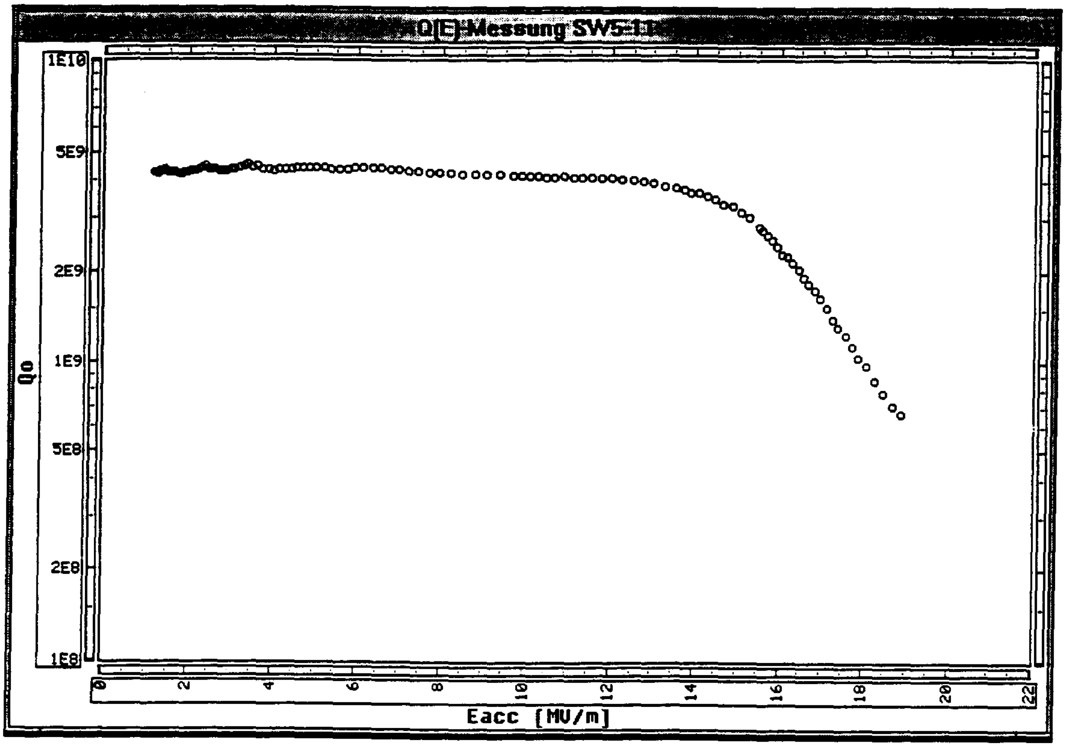

Fig.3b: Corresponding $Q_0(E_{acc})$-curve during He-processing (E_{acc} = 19.0MV/m)

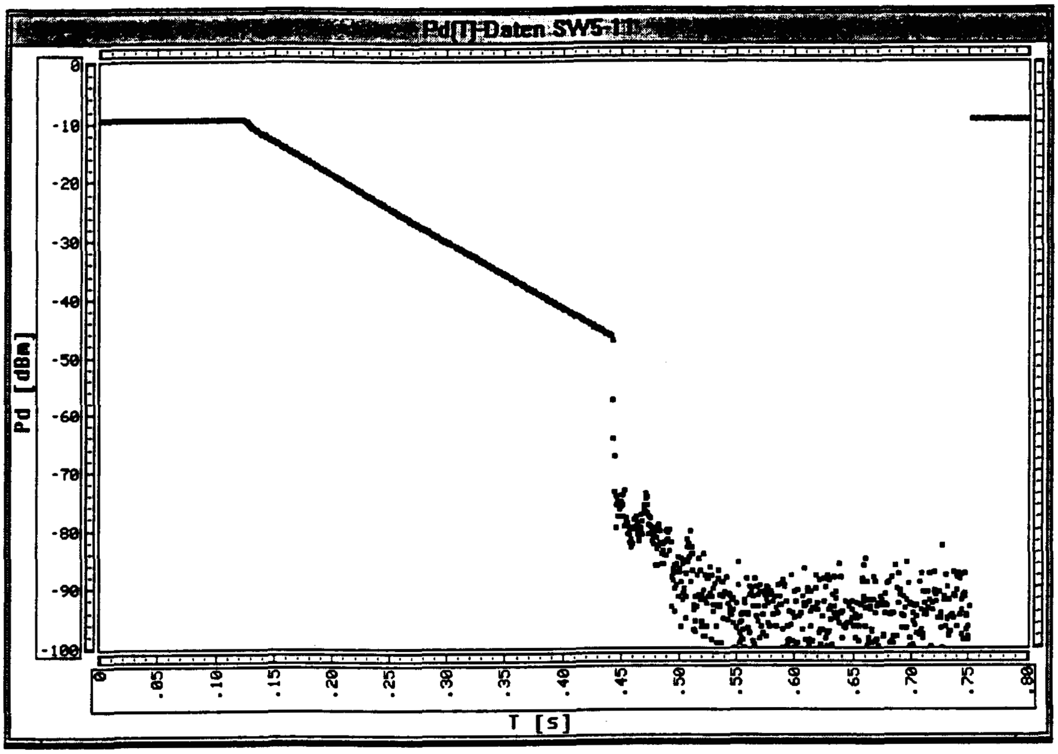

Fig.4a: Stored data trace $P_d(t)$

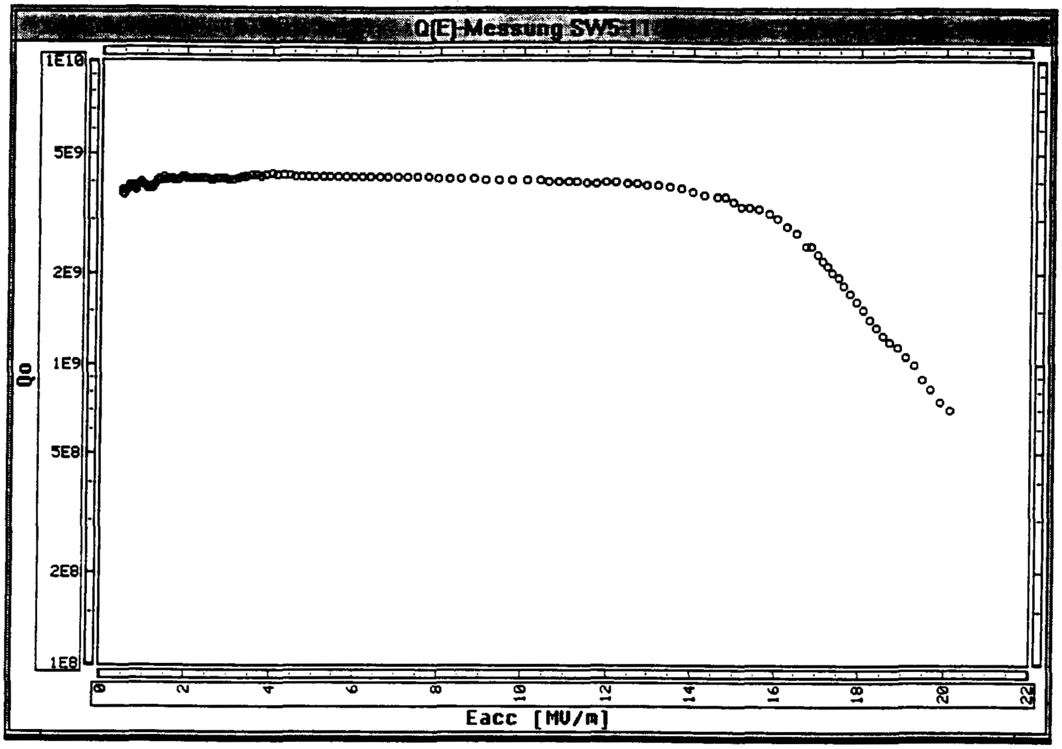

Fig.4b: Corresponding $Q_0(E_{acc})$-curve in the final state (E_{acc} = 20.1MV/m)

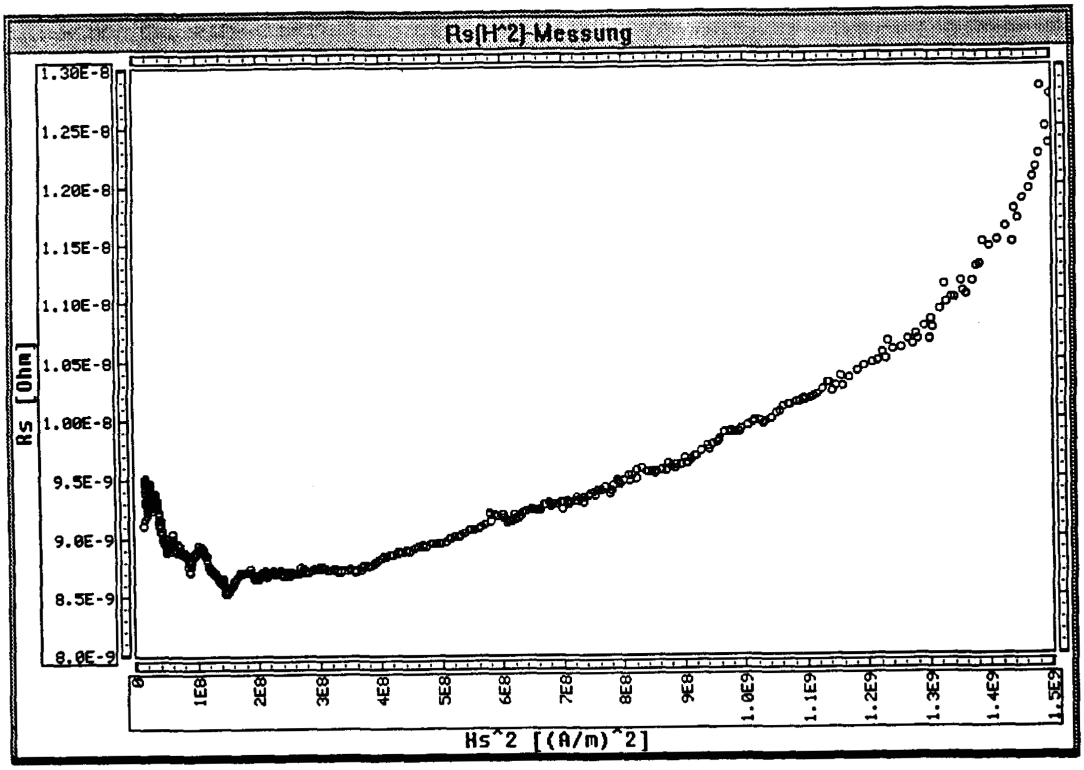

Fig.5: Analysis with respect to the field dependence of the residual surface resistance $R_s \sim H_s^2$ in a different experiment