THE COMPUTER AIDED TEST SYSTEM FOR RF SUPERCONDUCTING CAVITY HIGH-Q MEASUREMENT

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Abctract

A Computer Aided Test System was developed for the High-Q measurement of RF superconducting cavities. This CAT system is based on the combination of IBM PC/AT and RF instruments through the GPIB bus. A smart program is capable of controlling all the instruments to finish both Pulsed and Continuous Wave mode measurements. The results, such as β, Q, Eacc and Eacc-Q curve are carried out automatically with digital and/or graphic forms. More than one year's application shows that it is reliable and easy to use. In this paper, the system structure, the mathematic formula used in the program and some data processing methods are described. Also some examples of measurement results are shown at the end of paper.

1. Introduction

In order to upgrad the electron beam energy, 16 superconducting cavities have been designed and manufactured, and are being installed in HERA storage ring. For these cavities, many routine experiments must be done to study their behavior, and to measure their performance under different conditions. A Computer Aided Test (CAT) system based on IBM PC/AT was developed for above requirements. Most measurements and calculations can be carried out automatically. And the results are given digitally and graphically. Moreover, the original measurement data can be saved as the disk files and reanalysed at any time later.

With the help of this CAT system, not only the measurement process becomes much shorter, but also the results are more accurate, stable and objective than manual operation.

2. Genearl Description on Superconducting Cavity Measurement

(1) Pulsed RF Mode Measurement

The main index of the superconducting cavity is its quality factor Q and the electric field intensity Eacc inside the cavity. Because the

Q value of the superconducting cavity is too high, i.e. about 10^9 order, so the Pulsed RF method is used to measure the Q value of superconducting cavity.

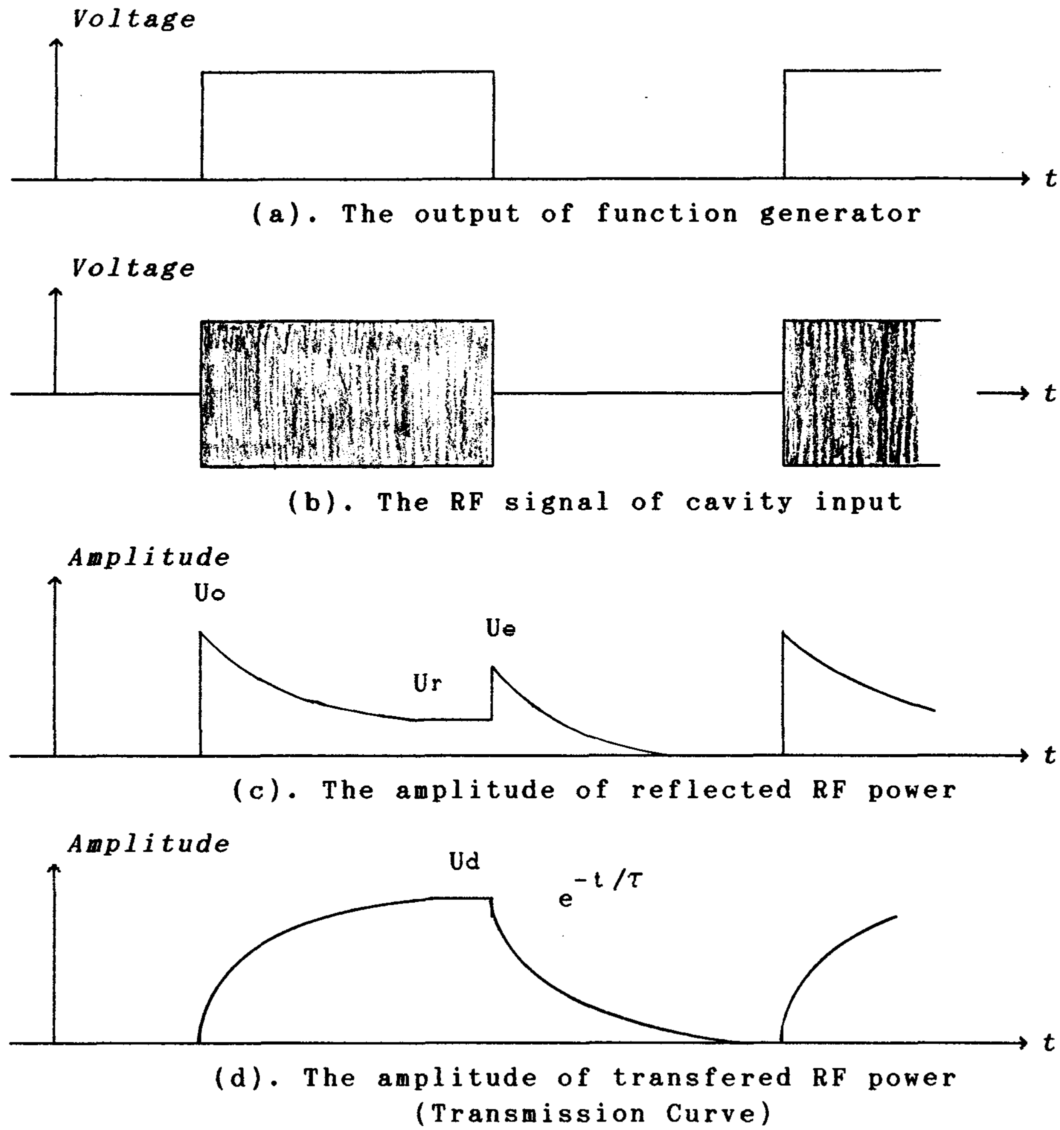


Fig.1. The diagram of Pulse RF Mode measurement

For the Pulsed RF Mode measurement, the input RF signal (sent to the cavity) is switched on and off by a PIN diode switch, which is controlled by a function generator. By using the Spectrum Analyzers, which are set in Time Scan working state, we can get the curves (vs.time) of reflected power at input end of the cavity and transfered power from a pickup antenna. We named these two curves Reflection Curve and Transmission Curve respectively. Several important signals are shown in Fig.1.

The formula to calculate the Q and Eacc by Pulsed RF Mode are following:

$$Q = \pi \cdot F \cdot \tau \cdot (1+\beta) \qquad (1)$$

F — the RF frequency in unit of Hz
τ — the decay time constant of the RF power inside the cavity, in unit of Second
β — the input coupling factor

$$E_{acc} = \frac{2}{L} \cdot \sqrt{P \cdot \frac{R}{Q} \cdot \pi \cdot F \cdot \tau \cdot \frac{\beta}{1+\beta}} \qquad (2)$$

P — The input power in unit of watt.
L — The length of efficative length of the cavity.

$\frac{R}{Q}$ is a constant for a certain cavity

If we get the values of U_o, U_r, U_e, U_d and τ, see the Fig.1., then we can can do following calcultions:

$$\beta_1 = \frac{1}{2\frac{U_o}{U_e} - 1} \qquad (3)$$

$$\beta_2 = \frac{U_e^2}{U_o^2 - U_r^2} \quad \text{or} \quad \beta_2 = \frac{U_e}{\pm 2U_r + U_e} \qquad \begin{matrix} + \text{ under coupling} \\ - \text{ over coupling} \end{matrix} \qquad (4)$$

$$\beta_3 = \begin{cases} \dfrac{1 - \frac{U_r}{U_o}}{1 + \frac{U_r}{U_o}} & \text{if } \beta_1<1 \text{ or } \beta_2<1 \\ \dfrac{1 + \frac{U_r}{U_o}}{1 - \frac{U_r}{U_o}} & \text{if } \beta_1>1 \text{ and } \beta_2>1 \end{cases} \qquad (5)$$

$$\bar{\beta} = (\beta_1+\beta_2+\beta_3)/3 \qquad (6)$$

$$Q_i = \pi \cdot F \cdot \tau \cdot (1+\beta_i) \qquad i = 1,2,3 \qquad (7)$$

$$\bar{Q} = (Q_1+Q_2+Q_3)/3 \qquad (8)$$

$$E_{acc\,i} = \frac{2}{L} \cdot \sqrt{P \cdot \frac{R}{Q} \cdot \pi \cdot F \cdot \tau \cdot \frac{\beta_i}{1+\beta_i}} \qquad i = 1, 2, 3 \qquad (9)$$

$L = Nc \cdot 0.3$ m, Nc is the cell number of the cavity.

$$\frac{R}{Q} \cong 114.4 \cdot Nc$$

The unit of E_{acci} is Voltage/Meter

$$\overline{E_{acc}} = (E_{acc1} + E_{acc2} + E_{acc3})/3 \qquad (10)$$

Above are the main formulas for Pulsed RF Mode measurement. By the results of Q and E_{acc}, we can evaluate the characteristics of the cavity under testing.

(2) Continuous RF (CW) Mode Measurement

The purpose of Continuous RF Wave measurement is to get the Q of cavity versus the electric field. In order to carry out the Continuous Mode measurement, it is necessary to do Pulse Mode measurement at least one time as the calibration. From Pulse Mode measurement, we can get two parameters:

$$Q_{ext} \equiv \frac{Q_o}{\beta} \qquad (11)$$

$$\alpha \equiv \frac{U_d}{E_{acc}} \qquad (12)$$

In Continuous Mode, we adjust the input power, and measure the input power P_{in} and the amplitude of transmission signal U_d. Then we get following results:

$\{P(i), U_d(i)\}$, $i = 1, 2, \ldots N$.

Then we do following calculations:

The electrical field strength

$$E_{acc}(i) = \frac{U_d(i)}{\alpha} \qquad (13)$$

The voltage inside of the cavity

$$V(i) = E_{acc}(i) \cdot LM \qquad (14)$$

where LM is the length of the cavity (1.2 meter for four cell cavity).

The Qo and Qoeffect

$$Qo(i) = Qext \cdot \frac{\sqrt{\dfrac{V^2(i)}{4 \cdot \dfrac{R}{Q} \cdot Qext \cdot P(i)}}}{1 - \sqrt{\dfrac{V^2(i)}{4 \cdot \dfrac{R}{Q} \cdot Qext \cdot P(i)}}} \tag{15}$$

By the equation

$$\frac{1}{Qo} = \frac{1}{Qext\,HOM} + \frac{1}{Qoeffect} \tag{16}$$

we can get the Qoeffect from following equation

$$Qoeffect(i) = \frac{Qo(i) \cdot Qext\,HOM}{Qext\,HOM - Qo(i)} \tag{17}$$

After above calculation, we can get the Qoeffect — Eacc curve. This is the result of Continuous Mode measurement.

3. Hardware System

The block diagram of measurement system is shown in Fig.2. We use two Spectrum Analyzers to measure the reflected power curve and transfered power curve, and one Power Meter, which has two input channels, to measure the absolute power value of input power and reflected power. The Function Generator is used for controlling the PIN switch for different working mode. If the PIN switch is at on and off state, it is the Pulsed RF Mode. If the PIN switch is always on, it is in Continuous RF Mode.

One GPIB card is installed in the IBM PC/AT as the interface between the microcomputer and the instruments. Every instrument must has one address on GBIB, which is predefined in program. But it is changable if necessary. The Phase-Lock subsystem is a standalone circuit, which has no relation to the CAT system, thus it needs adjusting by the operator manually.

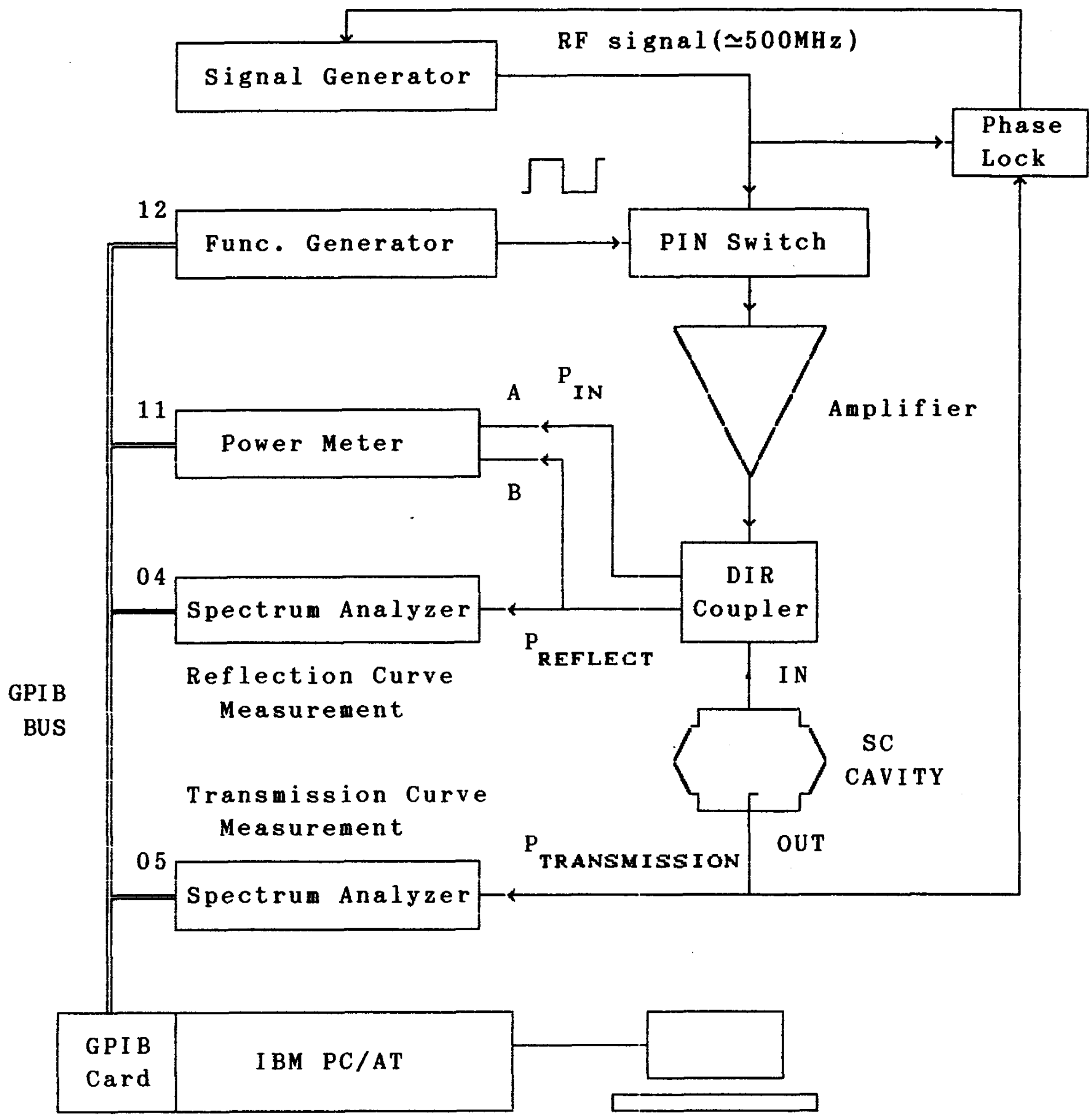


Fig.2. The block diagram of measurement system

4 Software structure

The software include two parts: the supporting environment and the program. Supporting environment software includes Operating System (DOS V2.0 or later), screen copy program, IEEE488 driver, etc. The program, named KCATHQ, was written in Turbo BASIC, is a full friendly menu driven program. Fig.3. gives a simple overview of the structure of whole program.

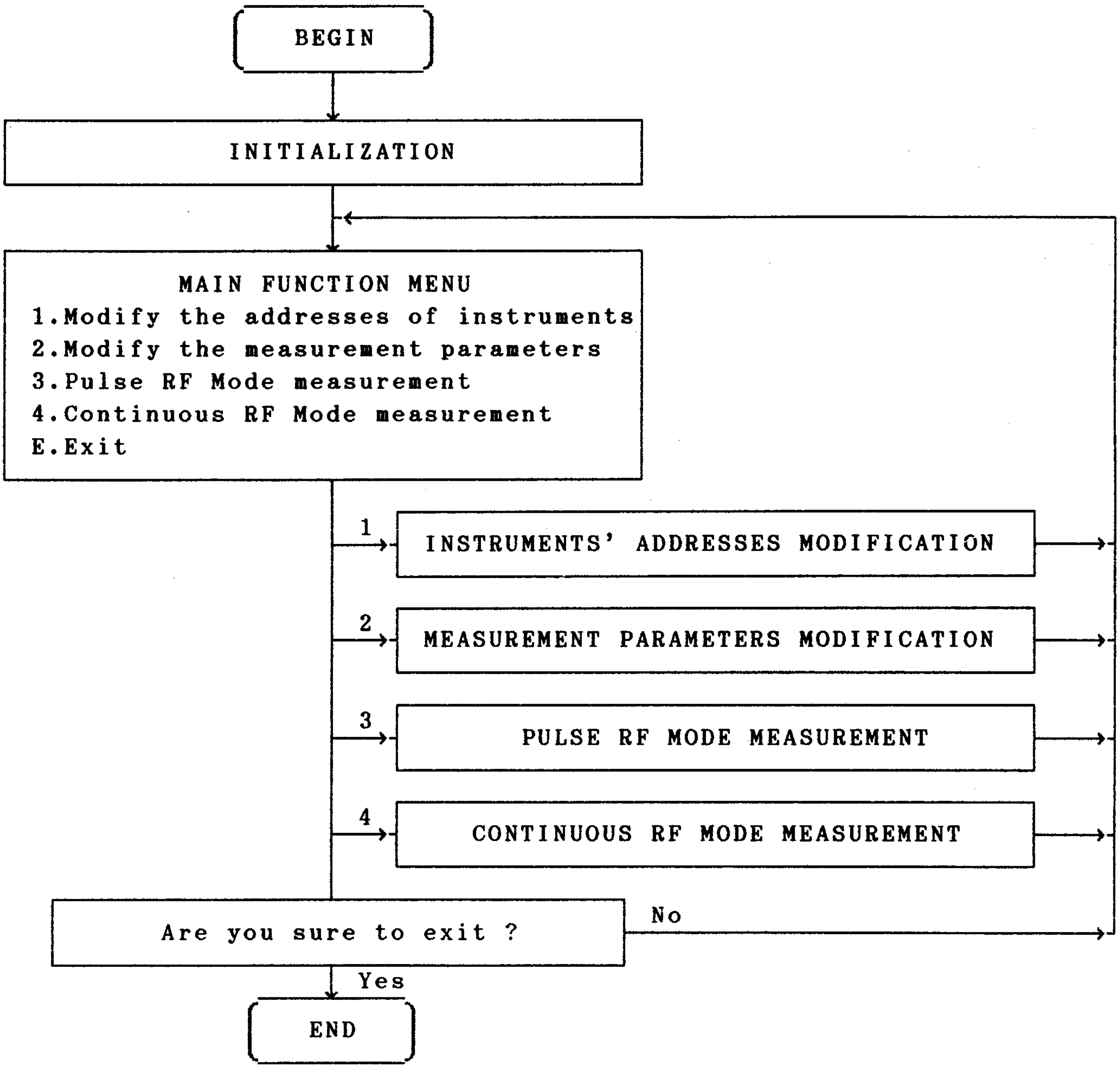


Fig.3. The basic structure of KCATRF program

5. Some methods for data processing

From the formula of part 2, it is clear that the reliability of the results depends on the correctness of U_o, U_r, U_e, U_d, and τ. In this section we will discuss how to find these values on Reflection and Transmission Curves.

(1) Searching U_o, U_r and U_e on the Reflection Curve

There are three basic forms of the Reflection Curve shown in Fig.4.

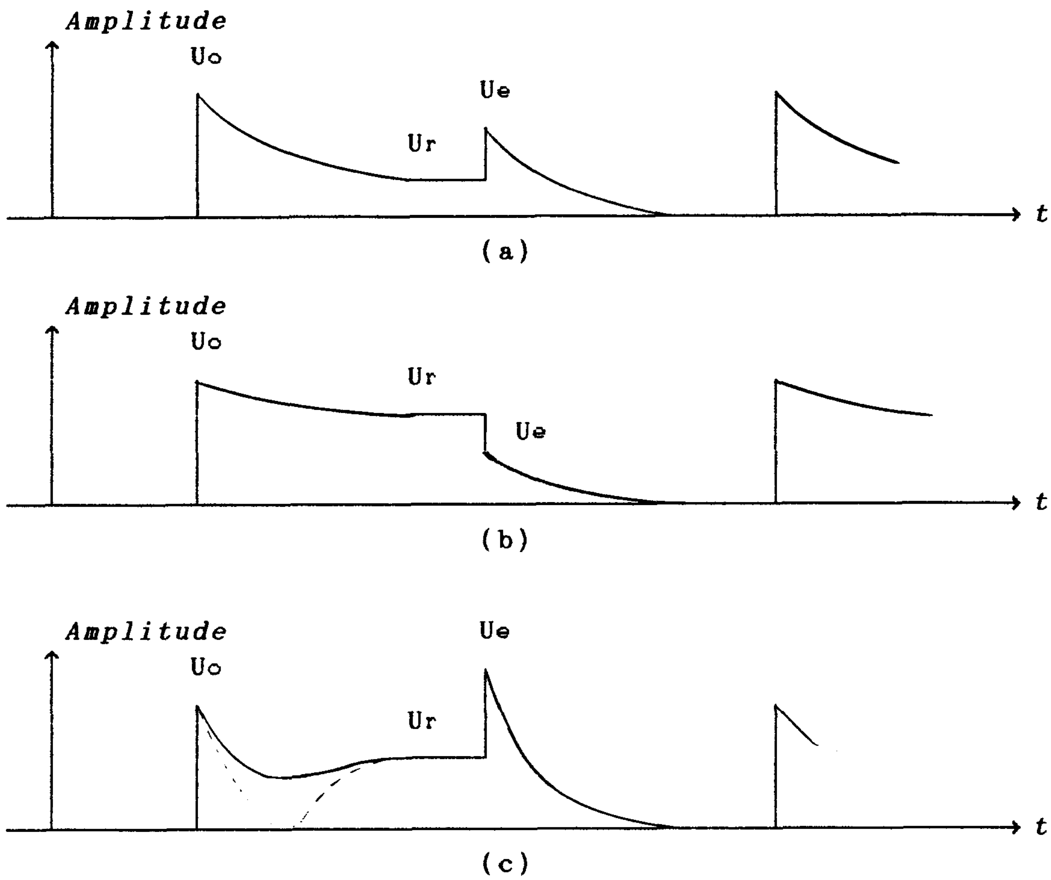


Fig.4. Three basic forms of Reflection Curves

After evaluating these curves, we filter the Reflection Curve by a predefined special filter kernal $\mathbb{L}r$:

$$\mathbb{D}r = \mathbb{R}ef * \mathbb{L}r \qquad (18)$$

$$\mathbb{L}r \equiv [-1,-1,4,-1,-1] \qquad (19)$$

where $\mathbb{R}ef$ is the Reflection Curve, $\mathbb{D}r$ is the filtered curve.

In case (a) and (c), The two peek positions of $\mathbb{D}r$ should be Uo and Ue. By comapring the values just before the peek positions, we can ditinguish them easily.

For case (b) the very sharp drop before Ue is detected rather than the real position of Ue. In this case, we need to move the detected position several points right. The number of moving points is depended on the drop rate of the curve at this region.

(2). Searching Ud on the Transmission Curve

The Transmission Curve is shown in Fig.5. The Ud is the Maximum value of the curve, and after Ud, the curve is decreasing sharply.

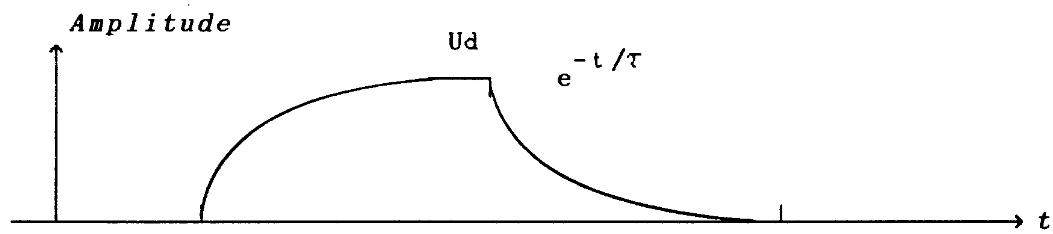


Fig.5. The amplitude of transfered RF power

We use another filter to process the Transmission Curve:

$$\mathbb{D}t = \mathbb{T}ra * \mathbb{L}t \tag{20}$$

$$\mathbb{L}t \equiv [\ 0,\ 0,\ 0,\ 0,\ 0,\ 5,-1,-1,-1,-1,-1] \tag{21}$$

where $\mathbb{T}ra$ is the Transmission Curve, $\mathbb{D}t$ is the filtered curve.

The position Pd is the right point, if following two conditions are satisfied:

- Dt(Pd) is maximum of the curve;
- Tra(Pd) is great than 0.95*maximum of Transmission curve.

Then U(Pd) is the Ud.

(3). Calculating the τ value

As we know that τ is important to carry out the Q value, so it is necessary to evaluate the τ value as precise as possible. In KCATHQ program we use the Least-square-fitting method to estimate the τ value. The Transmission Curve, after the point Ud, is varying according to function:

$$y = Ae^{-t/\tau} \tag{22}$$

We transform the function by taking logarithm:

$$\begin{aligned} \ln(y) &= \ln(Ae^{-t/\tau}) \\ &= \frac{-1}{\tau}\cdot t + \ln A \end{aligned} \tag{23}$$

Equition (23) is a linear function and it is easy to apply the Least-square-fitting method to get the parameter $-1/\tau$. We need to fulfill following steps:

- Take 25 points in Transmission Curve from Ud point (including Ud point) to form a new data pair array:

$$(x_i, y_i) \qquad i = 0,1,\ldots 24 \tag{24}$$

where $x_i = i\cdot\Delta t$, Δt is the time interval between two adjacent points in Transmission Curve. y_i is the value of the Transmission Curve from the point Ud (y_0=Ud).

- Take logarithm to y_i to get a new data pair array:

$$(X_i, Y_i) \qquad i = 0,1,\ldots 24$$

where

$$X_i = x_i$$

$$Y_i = \ln(y_i) \tag{25}$$

- Calculate following values:

$$\bar{X} = \frac{1}{25}\sum_{i=0}^{24} X_i \tag{26}$$

$$\bar{Y} = \frac{1}{25}\sum_{i=0}^{24} Y_i \tag{27}$$

$$Lxx = \frac{1}{25}\sum_{i=0}^{24} (X_i - \bar{X})^2 \tag{28}$$

$$Lxy = \frac{1}{25}\sum_{i=0}^{24} (X_i - \bar{X})(Y_i - \bar{Y}) \tag{29}$$

- Calculate τ. By the linear least-square-fitting method, there is:

$$-\frac{1}{\tau} = \frac{Lxy}{Lxx} \tag{30}$$

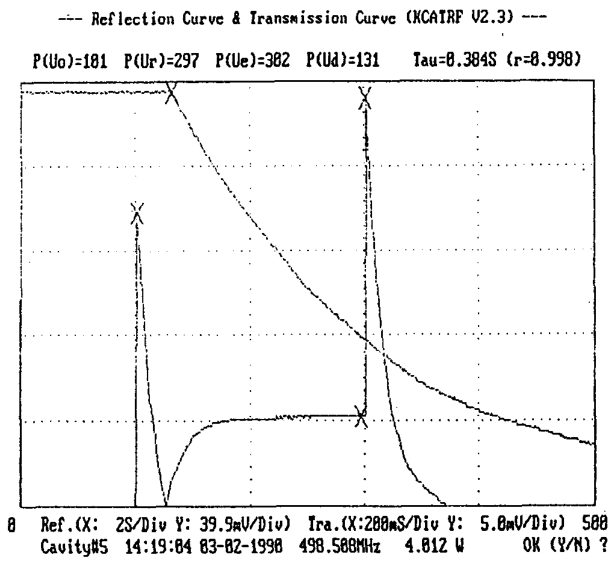
Then we get

$$\tau = -\frac{Lxx}{Lxy} \tag{31}$$

6. Acknoledgment

The authors are grateful to Dr. D. Proch, Mr. J. Sekutowicz and Mr. D. Renken for their support and helpful discussions.

7. Examples of superconducting cavity's measurement results



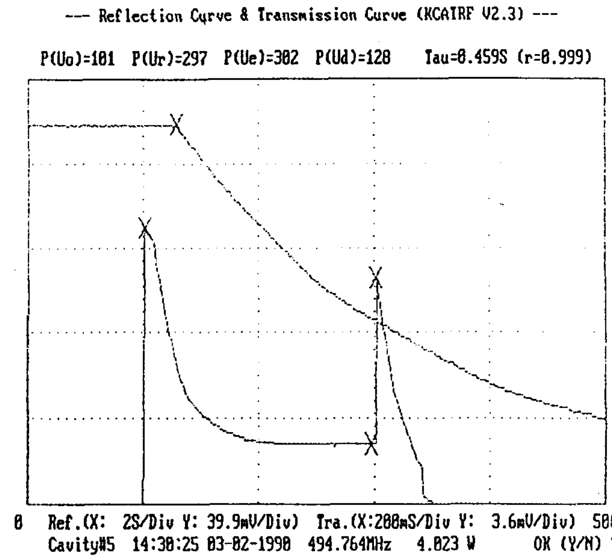
The Pulse Mode Measurement Results of HQ Cavity

Cavity No: 5, Measurement Serial No: 3, 14:19:04 03-02-1990

Freq = 498.508 MHz Power = 4.012 W Tau = 384.248 mS
Uo = 137.510 mV Ur = 41.851 mV Ue = 191.318 mV
Ud = 24.512 mV Ud/Eacc = 17.191 mV/(MV/m)

B1 = 2.286	Qo1 = 1.977*E9	Eacc1 = 1.461 MV/m
B2 = 1.778	Qo2 = 1.672*E9	Eacc2 = 1.402 MV/m
B3 = 1.875	Qo3 = 1.730*E9	Eacc3 = 1.415 MV/m
B = 1.979	Qo = 1.793*E9	Eacc = 1.426 MV/m

KCATRF (V2.3 Kang Jan.1990.) Data File = a:c05_2_2.p03



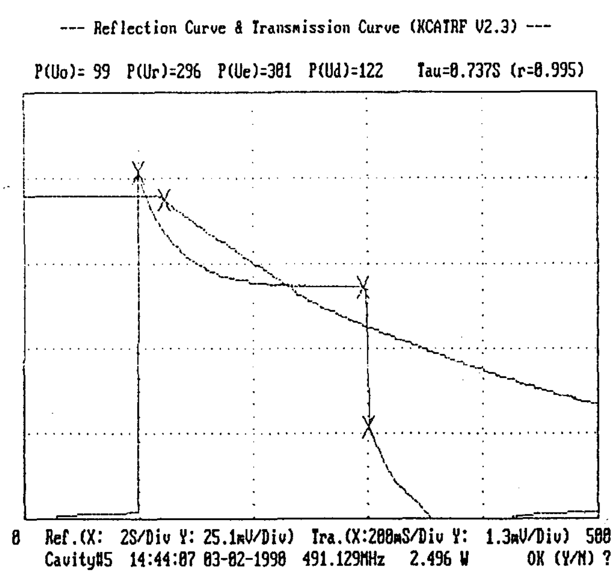
The Pulse Mode Measurement Results of HQ Cavity

Cavity No: 5, Measurement Serial No: 4, 14:30:25 03-02-1990

Freq = 494.764 MHz Power = 4.023 W Tau = 458.962 mS
Uo = 129.538 mV Ur = 27.901 mV Ue = 105.624 mV
Ud = 15.861 mV Ud/Eacc = 13.155 mV/(MV/m)

B1 = 0.688	Qo1 = 1.204*E9	Eacc1 = 1.220 MV/m
B2 = 0.654	Qo2 = 1.180*E9	Eacc2 = 1.201 MV/m
B3 = 0.646	Qo3 = 1.174*E9	Eacc3 = 1.196 MV/m
B = 0.663	Qo = 1.186*E9	Eacc = 1.206 MV/m

KCATRF (V2.3 Kang Jan.1990.) Data File = a:c05_2_2.p04



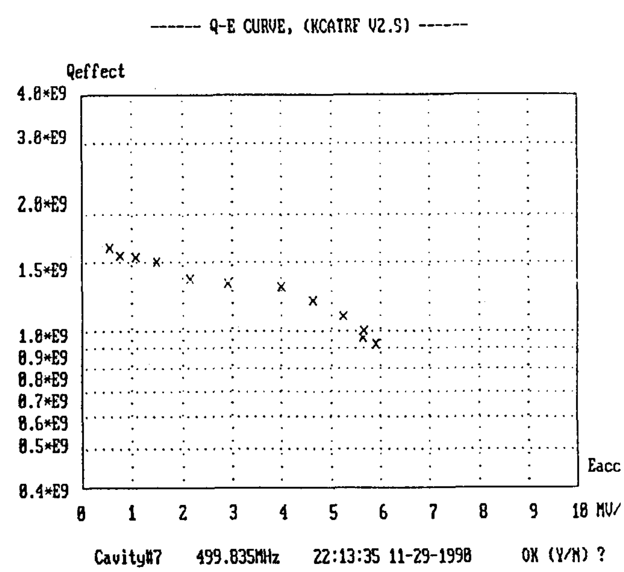
The Pulse Mode Measurement Results of HQ Cavity

Cavity No: 5, Measurement Serial No: 5, 14:44:07 03-02-1990

Freq = 491.129 MHz Power = 2.496 W Tau = 736.667 mS
Uo = 102.481 mV Ur = 68.530 mV Ue = 27.035 mV
Ud = 4.761 mV Ud/Eacc = 6.562 mV/(MV/m)

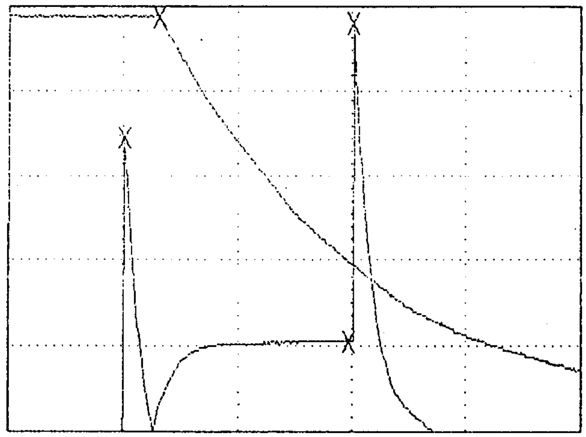
B1 = 0.152	Qo1 = 1.309*E9	Eacc1 = 0.690 MV/m
B2 = 0.165	Qo2 = 1.324*E9	Eacc2 = 0.714 MV/m
B3 = 0.199	Qo3 = 1.362*E9	Eacc3 = 0.773 MV/m
B = 0.172	Qo = 1.332*E9	Eacc = 0.726 MV/m

KCATRF (V2.3 Kang Jan.1990.) Data File = a:c05_2_2.p05



--- Reflection Curve & Transmission Curve (KCATRF V2.3) ---

P(Uo)=101 P(Ur)=297 P(Ue)=302 P(Ud)=131   Tau=0.384S (r=0.998)



0 Ref.(X: 2S/Div Y: 39.9mV/Div) Tra.(X:200mS/Div Y: 5.0mV/Div) 500
Cavity#5 14:19:04 03-02-1990 498.508MHz 4.012 W OK (Y/N) ?

The Pulse Mode Measurement Results of HQ Cavity

Cavity No: 5, Measurement Serial No: 3, 14:19:04 03-02-1990

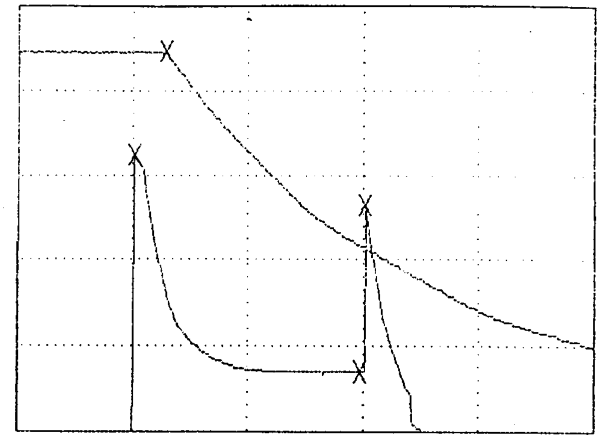
Freq = 498.508 MHz	Power = 4.012 W	Tau = 384.248 mS
Uo = 137.510 mV	Ur = 41.851 mV	Ue = 191.318 mV
Ud = 24.512 mV	Ud/Eacc = 17.191 mV/(MV/m)	

B1 = 2.286	Qo1 = 1.977*E9	Eacc1 = 1.461 MV/m
B2 = 1.778	Qo2 = 1.672*E9	Eacc2 = 1.402 MV/m
B3 = 1.875	Qo3 = 1.730*E9	Eacc3 = 1.415 MV/m
B = 1.979	Qo = 1.793*E9	Eacc = 1.426 MV/m

KCATRF (V2.3 Kang Jan.1990.) Data File = a:c05_2_2.p03

--- Reflection Curve & Transmission Curve (KCATRF V2.3) ---

P(Uo)=101 P(Ur)=297 P(Ue)=302 P(Ud)=120   Tau=0.459S (r=0.999)



0 Ref.(X: 2S/Div Y: 39.9mV/Div) Tra.(X:200mS/Div Y: 3.6mV/Div) 500
Cavity#5 14:30:25 03-02-1990 494.764MHz 4.023 W OK (Y/N) ?

The Pulse Mode Measurement Results of HQ Cavity

Cavity No: 5, Measurement Serial No: 4, 14:30:25 03-02-1990

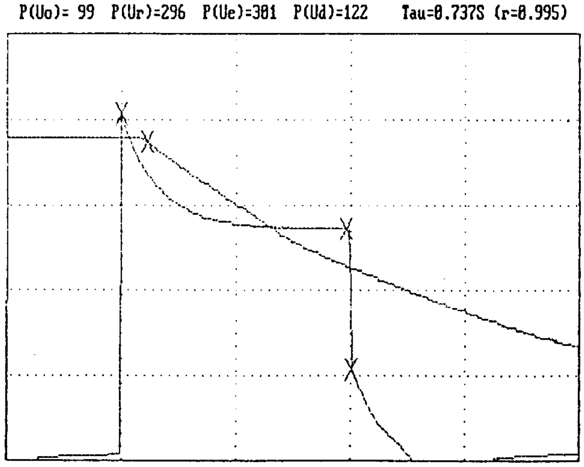
Freq = 494.764 MHz	Power = 4.023 W	Tau = 458.962 mS
Uo = 129.538 mV	Ur = 27.901 mV	Ue = 105.624 mV
Ud = 15.861 mV	Ud/Eacc = 13.155 mV/(MV/m)	

B1 = 0.688	Qo1 = 1.204*E9	Eacc1 = 1.220 MV/m
B2 = 0.654	Qo2 = 1.180*E9	Eacc2 = 1.201 MV/m
B3 = 0.646	Qo3 = 1.174*E9	Eacc3 = 1.196 MV/m
B = 0.663	Qo = 1.186*E9	Eacc = 1.206 MV/m

KCATRF (V2.3 Kang Jan.1990.) Data File = a:c05_2_2.p04

--- Reflection Curve & Transmission Curve (KCATRF V2.3) ---

P(Uo)= 99 P(Ur)=296 P(Ue)=301 P(Ud)=122   Tau=0.737S (r=0.995)



0 Ref.(X: 2S/Div Y: 25.1mV/Div) Tra.(X:200mS/Div Y: 1.3mV/Div) 500
Cavity#5 14:44:07 03-02-1990 491.129MHz 2.496 W OK (Y/N) ?

The Pulse Mode Measurement Results of HQ Cavity

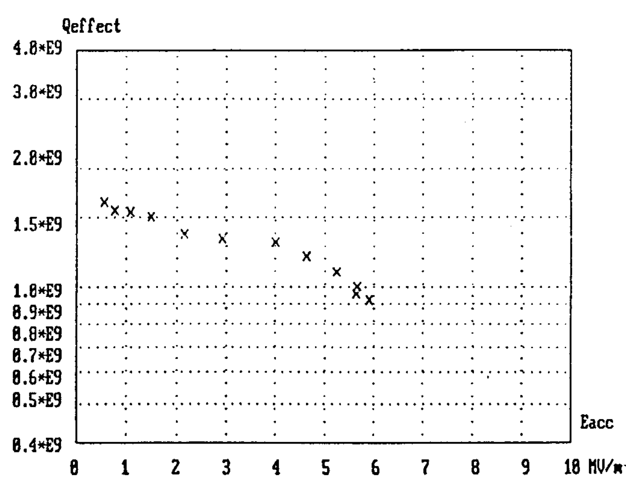
Cavity No: 5, Measurement Serial No: 5, 14:44:07 03-02-1990

Freq = 491.129 MHz	Power = 2.496 W	Tau = 736.667 mS
Uo = 102.481 mV	Ur = 68.530 mV	Ue = 27.035 mV
Ud = 4.761 mV	Ud/Eacc = 6.562 mV/(MV/m)	

B1 = 0.152	Qo1 = 1.309*E9	Eacc1 = 0.690 MV/m
B2 = 0.165	Qo2 = 1.324*E9	Eacc2 = 0.714 MV/m
B3 = 0.199	Qo3 = 1.362*E9	Eacc3 = 0.773 MV/m
B = 0.172	Qo = 1.332*E9	Eacc = 0.726 MV/m

KCATRF (V2.3 Kang Jan.1990.) Data File = a:c05_2_2.p05

------ Q-E CURVE, (KCATRF V2.9) ------



Cavity#7 499.835MHz 22:13:35 11-29-1990 OK (Y/N) ?

SRF91E16