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FIRST MEASUREMENT OF PARASITIC MODE LOSSES IN PETRA

by

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FIRST MEASUREMENT OF PARASITIC MODE LOSSES IN PETRA[*]

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Introduction

A bunch of particles moving in an accelerator sets up electromagnetic fields in the various components forming the vacuum envelope and, consequently, the bunch will lose energy. This energy loss is particularly high in electron machines where the bunch, being very short and dense, can excite very high frequencies. This parasitic energy loss adds to the unavoidable synchrotron radiation loss and, therefore, raises the power which has to be supplied to the beam by the RF system. Since the accelerating voltage in the RF cavities must be increased to make up for the enhanced energy loss per turn, the cavity dissipation will augment. This will demand additional power from the RF generator.

Given the importance of this effect for the design of an electron machine, theoretical estimates and measurements of the loss in single components were made. The energy loss experienced by a particle in a real ring was measured in SPEAR(1) and also in DORIS(2). However, the vacuum envelope of SPEAR and DORIS is quite different from the beam environment in the last generation storage rings as PETRA and PEP which were designed as smooth as possible in order to minimize higher mode effects. Thus, it was interesting to measure this effect in PETRA and to compare it with the predictions.

The method used is similar to the method applied in SPEAR and DORIS. In both cases, the phase of the bunch relative to the RF frequency is measured as function of intensity. We use a small prebunch to determine the RF-waveform in the cavities before the arrival of the intense main bunch. The time interval elapsing between prebunch and main bunch is measured and gives the relative phase between the two. Taking into account the known beam loading voltage, one can work out the actual energy supplied by the RF system to the main bunch. Subtracting the synchrotron radiation loss yields the parasitic energy loss. We use the term energy loss or gain for the energy change per turn experienced by a single particle in the bunch.

Measurements

The measurements were performed by the PETRA staff as part of the "High Current Programme". The bunch shapes and the position of the bunches in tune were observed by means of an apparatus designed and built by S. Pätzold; it is similar to the apparatus used in DORIS(3).

Visible synchrotron light is focused on a high speed photodiode F 4014, ITT Tube and Sensor Laboratories, Fort Wayne, with a housing designed to keep the reflections below 5 %. The response time of the diode is 70 ps. The output of the diode is directly coupled to a sampling head (Tectronix S 12/54) which is triggered by a pulse derived from the PETRA 500 MHz master oscillator by digital subdivision.

The RF system was operated such that the average cavity voltage was kept constant by a control loop comparing a signal picked up in the cavity with a reference voltage and acting on the cavity tuning. The average phase of cavity voltage was kept constant with respect to the phase of the 500 MHz master oscillator.

Two of the four five-cell RF cavities were detuned and idling during the experiment. All other installed RF cavities, except these four, were short circuited.

First, three consecutive buckets were filled with the prebunch (0,2 mA), the main bunch (1 to 7 mA) and a trailing bunch (0,2 mA) following the main bunch. It was found that the time elapsing between prebunch and main bunch shrinks by δt = 120 ps when the current of the latter is increased from 1 to 7 mA. Also a change in the delay between prebunch and trailing bunch was detected when increasing the current in the main bunch. However, it is very likely that reflections in the wake of the main bunch disturb the signal from the trailing bunch, so we disregard this information for our analysis.

The coherent synchrotron frequencies were excited by modulating the phase of the RF, and were measured by observing the longitudinal dipole oscillations of the individual bunches. The measurement was made in the presence of many trailing weak bunches. The result is given in Table I (see also Fig. 3).

Table I, Bunch currents and synchrotron frequencies

Bucket Nr.	Bunch current	Synchrotron frequency	
- 4	≤ 0,2 mA	3,117 kHz	Prebunch
0	"	3,117	"
+ 1	7 mA	2,896	Main bunch
9	"	2,888	Trailing bunches
16	"	2,888	"
11	"	2,888	"
48	"	2,888	"
96	"	2,917	"
144	"	2,913	"
240	"	3,117	"
288	"	3,073	"
336	"	3,081	"

The apparent bunch length was measured at 7 mA and turned out to be 310 ps full width at half-height. Unfortunately, the resolution of the photodiode system has not yet been determined. According to S. Pätzold, a rough correction can be worked out by assuming that the system behaves like an RC-circuit with a time constant of 60 ps. Applying this correction and assuming a gaussian bunch shape we get $\sigma_{SFWHH} = 3{,}7$ cm at 7 mA per bunch.

The machine was operating at 6,5 GeV during this experiment and its optical configuration was M15$^{(4)}$. From this one expect

$$(\sigma_E/E) = 4{,}0 \cdot 10^{-4}$$

(momentum compaction $\alpha = 2{,}9 \cdot 10^{-3}$)

For a synchrotron frequency of 3,12 kHz the theoretical bunch length becomes $\sigma_{so} = 1{,}8$ cm. Extrapolating the bunch length measurements to vanishing current yields 2,1 cm, which is responably close to the theoretical value.

Analysis

First we derive the amplitude V_p and relative phase ϕ_p of the RF when the prebunch passes. We assume that the prebunch loses energy only by synchrotron radiation. For negligible beam loading

$$V_p \sin\phi_p = U_o/e$$

U_o being the radiation loss per turn.

The measured synchrotron frequency f_{sp} gives

$$V_p \cos\phi_p = (f_{sp}/2,15)^2$$

where V_p is in MV and f_{sp} in kHz. This yields with U_o = 0,823 MeV and f_{sp} = 3,117 kHz

$$V_p = 2,4 \text{ MV}$$

$$\phi_p = 21^o$$

When the main bunch passes we have to include beam loading. The phasordiagram for the fundamental mode of the cavity is shown in Fig. 1. The main bunch sees $\tilde{V}_m^+$ at its arrival and leaves $\tilde{V}_m^-$ in the cavities after passage. The total beam loading voltage is twice the energy loss into fundamental mode U_{fm} of the RF cavities$^{(5)}$. The centre of the main bunch passes with phase ϕ_m. The net energy gain from the fundamental is $eV_m \sin\phi_m$; it must be equal to the sum of synchrotron radiation loss U_o and the loss into the parasitic modes U_{pm}. Thus by reconstructing this phasordiagram we can calculate U_{pm}.

The time delay δt between prebunch and main bunch (module $2\pi/\omega_{RF}$) is

$$\delta t = (\phi_p - \phi_m)/\omega_{RF}$$

With δt = 120 ps and $\omega_{RF} = 2\pi \cdot 5.10^8 \text{ s}^{-1}$

$$\phi_m = 43^o$$

The voltage V_m^+ must be equal to the voltage seen by the prebunch

$$V_m^+ = 2{,}4 \text{ MV}$$

and the total beam loading voltage is

$$V_b = 2U_{fm}/e = 2I_m R_s \, T_o/T_{fu} = 0{,}37 \text{ MV}$$

where

I_m = 7 mA d.c. component of current in main bunch

R_s = 72 MΩ shunt impedance of <u>4</u> cavities at the fundamental$^{(6)}$

T_o = 7,68 μs revolution time

T_{fu} = 21 μs unloaded filling time of the cavities

Knowing ϕ_m, V_m^+ and V_b we can calculate the total loss per particle in the main bunch

$$U_o + U_{pm} = eV_m \sin\phi_m = 1{,}5 \text{ MeV}$$

and the parasitic loss

$$U_{pm} = 0{,}65 \text{ MeV}$$

The coordinates of the individual vectors are summarized below

$$V_m^+ = 2{,}4 \text{ MV} \qquad \phi_m^+ = 47{,}^o$$

$$V_m = 2{,}2 \text{ MV} \qquad \phi_m = 43{,}^o$$

$$V_m^- = 2{,}0 \text{ MV} \qquad \phi_m^- = 40^o$$

$$V_b = 0{,}37 \text{ MV} \qquad \phi_b = 180^o$$

Inspection of table I shows that the synchrotron frequency f_{st} of the first trailing bunches is fairly constant, indicating that the higher modes excited by the strong main bunch do not perturb them. Hence, the effective RF voltage

V_t is equal to V_m^-. From this we can calculate the energy loss U_t experienced by these bunches

$$U_t = \sqrt{(V_m^-)^2 - (f_{st}/2,15)^4} = 0,863 \text{ MeV}$$

which is equal to the synchrotron radiation loss U_o = 0,823 MeV within our accuracy. Thus the procedure seems to be consistent.

The increase of synchrotron frequency of the bunches passing much later is due to the RF-generator refilling of the cavities.

The calculated synchrotron frequency of the main bunch

$$f_{sm} = \sqrt{V_m \cos\phi_m} = 2,69 \text{ kHz}$$

is in disagreement with the measured value of f_{sm} = 2,896 kHz (of table I). This is the only fly in the otherwise consistent ointment; at present, we cannot offer an explanation for this discrepancy.

Fig. 2 shows the superimposed phasordiagram for prebunch, main bunch and trailing bunch on a correct scale in the frame of the undisturbed RF rotating clockwise. The accelerating voltage is the projection of the voltage phasor onto the real axis of this rotating frame; the projection onto the imaginary axis is proportional to the square of the synchrotron frequency.

Results

The measured parasitic mode loss U_{pm} = 0,65 MeV can be split into two parts

$$U_{pm} = U_{hm}(RF) + U_{pm}(Vac),$$

the higher mode losses in RF cavities and the parasitic loss in the rest of the machine. Since the first term can be derived from bench measurements, one can calculate the second one which is hardly known for these new, big machines.

In order to find the higher mode loss in the RF we must first work out the total loss in the RF system

$$U_{tot}(RF) = e \cdot 4 \cdot Z_{tot} \cdot I_m = 0{,}32\ \text{MeV}$$

where Z_{tot} = 11,3 MΩ/cavity* is taken from the bench measurement of a 5 cell PETRA cavity for σ_s = 1,4 cm (7). This value of Z_{tot} is within 20 % of the value calculated for the EPIC cavities(8). Subtracting the loss due to the fundamental mode $U_{fm}^{(RF)}$ = 0,19 MV, which we have calculated before, from $U_{tot}^{(RF)}$ yields and in turn

$$U_{hm}\ (RF) = 0{,}13\ \text{MeV}$$

$$U_{pm}\ (Vac) = 0{,}51\ \text{MeV}$$

Normalizing to a bunch with unit charge gives

$$k_{pm}\ (Vac) = U/(I_m T_o) = 5{,}4 \cdot 10^{12}\ \text{eV/C}$$

The result can also be cast into the popular form

$$R_{pm}\ (Vac) = U/I_m \cdot e = 72\ \text{M}\Omega$$

This value is compatible with an estimate of the upper limit of these losses in the vacuum chamber (9)

$$R_{pm}\ (Vac) \leq 400\ \text{M}\Omega$$

for σ_s = 1,4 cm.

One may argue that bench measurements of $U_{hm}^{(RF)}$ and the estimate $R_{pm}^{(Vac)}$ refer to σ_s = 1,4 cm and not to σ_s = 3,7 cm as we had during the measurements. Though the measurement of bunch length can not yet be interpretated reliably, some simple scaling will be attempted. To try more exotic scaling laws is left as an exercise for the interested reader.

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* Note: This Z_{tot} should be compared with $Z_{fm}(RF) = R_s\ (T_o/T_{fu})$ and not with R_s.

In order to scale $U_{hm}(RF)$ with bunch length we consider the function $k = k(\sigma_s)$ calculated for an EPIC cavity cell$^{(8)}$. Taking into account

$$k_{hm}\ (\sigma_s = 1{,}4\ \text{cm})/k_{hm}(\sigma_s = 3{,}7\ \text{cm}) = 4{,}5$$

Applying this factor to our estimate of $U_{hm}(RF) = 0{,}13$ MeV yields

$$U_{hm}(RF) = 0{,}03\ \text{MeV}$$

and we get

$$U_{pm}(Vac) = 0{,}61\ \text{MeV}$$

This value is 20 % higher than the value given before where scaling was neglected. Obviously, scaling errors will have little influence on our result. In analogy we get

$$k_{pm}(Vac) = 11 \cdot 10^{12}\ \text{eV/C}$$

$$R_{pm}(Vac) = 87\ \text{M}\Omega$$

To scale the estimate of $R_{pm}(Vac)$ we may use $R_{pm} \sim \sigma_s^{-2}$ (10) which is appropriate for loss in many narrow gaps. This brings the estimate down to $R_{pm}(Vac) = 57$ MΩ. If we use a linear scaling law. $R_{pm} \sim \sigma_s$ the estimate becomes $R_{pm}(Vac) = 150$ MΩ, bracketing nicely the measured value of $R_{pm}(Vac)$ which seems to be between 70 and 80 MΩ.

Summary

From the measurement of synchrotron frequencies and time lag between a weak prebunch and a strong main bunch a total parasitic loss parameter

$$k = 1{,}2 \cdot 10^{13}\ \text{eV/C}$$

is derived for PETRA at 6,5 GeV for a bunch length $\sigma_s \simeq 3{,}7$ cm. We attribute at least 80 % of these losses to losses occuring outside the RF system, which consisted of four 5-cell cavities durint this experiment. Since the measurements are very preliminary, the result must be considered with caution.

Acknowledgements

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References

(1) M.A. Allen, J.M. Paterson, J.R. Rees and P.B. Wilson, IEEE Trans. Nucl. Sci., 22 (1975) 1838
(2) H. Gerke, J. Kouptsidis, H.P. Scholz, A. Zolfaghari, Int. Bericht DESY H3-75/2 (1975)
(3) S. Pätzold, Int. Bericht DESY H2-77/02 (1977)
(4) K. Steffen, Int. Bericht DESY PET-78/07 (1978)
(5) P.B. Wilson, IX Int. Conf. on High En. Acc., Stanford (1974) 57
P.B. Wilson, PEP-100 (1974)
P.B. Wilson, CERN-ISR-TH/78-23 (1978)
(6) H. Gerke, H.A. Scholz, M. Sommerfeld, A. Zolfaghari, Int. Bericht DESY PET-77/08 (1977)
(7) J. Peters, Int. Bericht DESY PET-77/14 (1974)
(8) M.H.R. Donald, IEEE Trans. Nucl. Sci. 22 (1975) 1843
(9) J. Peters, Int. Bericht DESY PET-76/02 (1976)
(10) A.W. Chao, PEP-118 (1975)

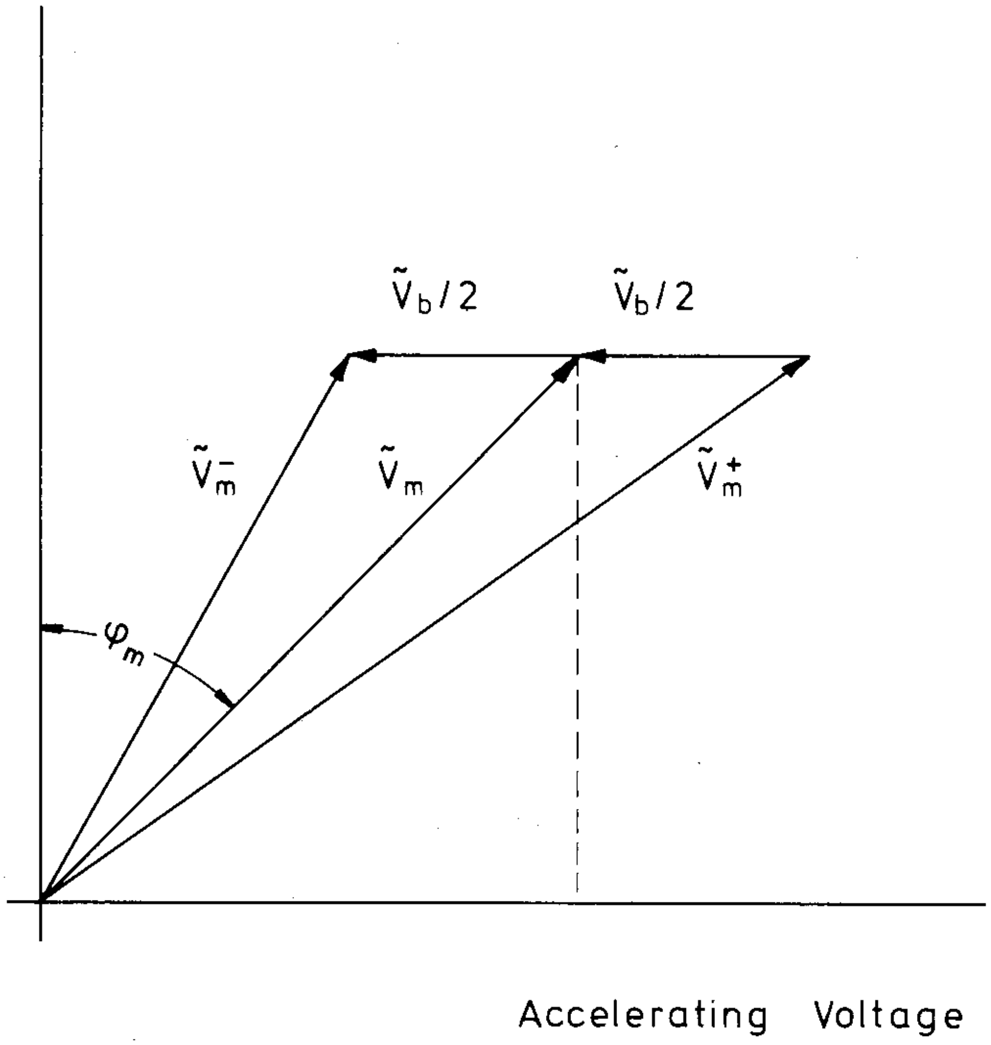

Fig. 1 Phasordiagram for the beam loading of the main bunch

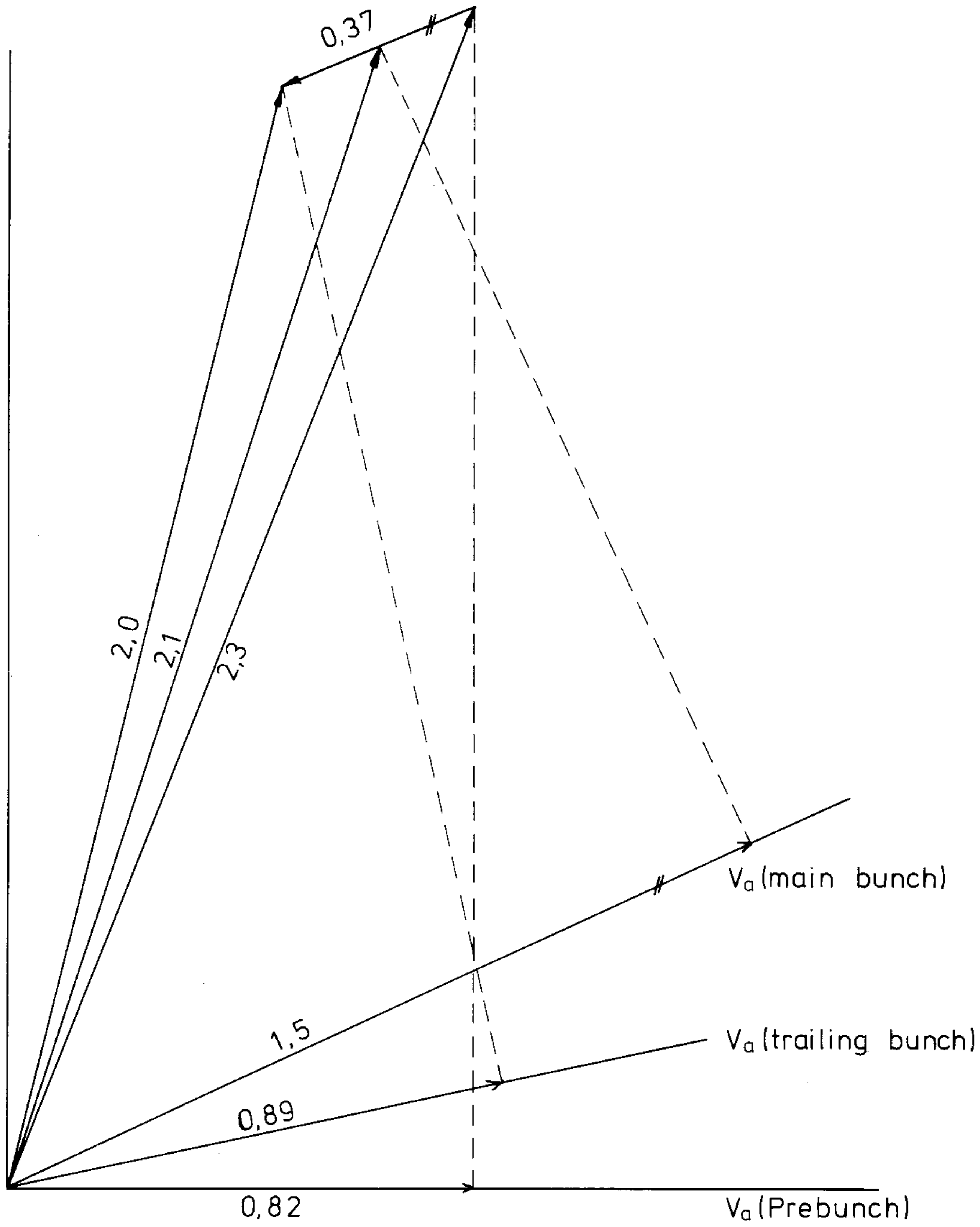

Fig. 2 Phasordiagram in the frame of undisturbed RF. All voltages in MV.

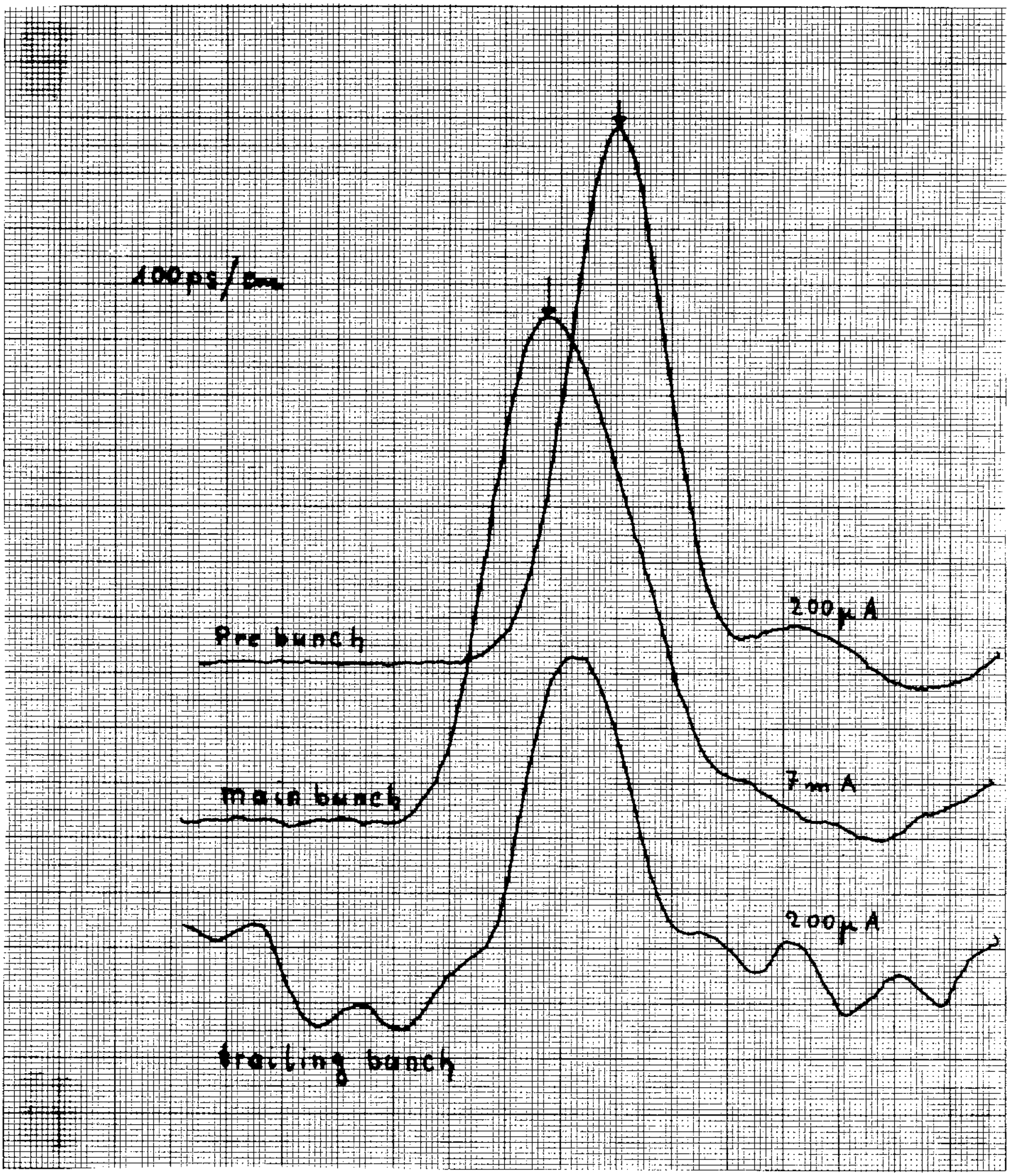

Fig. 3 Measured bunch shapes and positions