HHU/ab

MPS/SR Note 69-9
4. 7. 1969

BEAM LOADING MODULATING THE ACCELERATING VOLTAGE IN THE PS

by

H. H. Umstätter

Summary

A tuned accelerating cavity at resonance can be considered as a resistive load driven by an RF-current generator. The beam represents a second RF-current generator opposing the first or interfering with it so that the vectorial sum of the currents produces a modulated voltage on the RF cavity. A clear case of this kind has actually been observed confirming calculations that our beam can induce more than 1 kV in every tuned ferrite cavity of the PS if it is outside the range of the AVC.

Formulas for beam and cavity voltage

Each of the 15 cavities can be represented by a parallel resonant circuit with the following data $^{1)}$

$$\left.\begin{aligned} C &= 92\ \text{pF}\\ L &= {}^{1}/_{\omega^2 C} \approx 3\ \mu\text{H at } 9.5\ \text{MHz}\\ \underline{G} &\underline{= {}^{1}/_{10}\ k\Omega + {}^{1}/_{64}\ k\Omega = {}^{1}/_{8.5}\ k\Omega} \end{aligned}\right\} \qquad \begin{aligned} Y &= G + j(\omega L - \frac{1}{\omega C})\\ &= G + jB \end{aligned}$$

where the cavity admittance Y consists of a conductance G and susceptance B. G includes the conductance of the ferrite resonator and the internal conductance of the equivalent RF-current generator which drives the cavity.

PS/7304

At 8 - 9.5 MHz G varies very little with the RF-amplitude 2) and can be considered as a constant in calculations. If we call i_b the fundamental RF-component of a sharply bunched beam

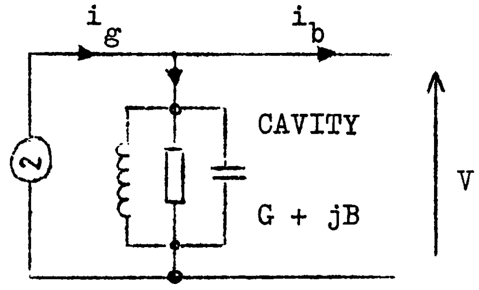
$$i_b = 2 \times 76 \text{ mA} = 0.152 \text{ A for } 10^{12} \text{ protons at } 9.5 \text{ MHz}$$

and if we want to have a generator voltage V = 10 kV on the accelerating gap, then our generator has to supply the current i_g

$$i_g = V \cdot Y + i_b \, e^{j\varphi}$$

$$= (VG + i_b \cos\varphi) + j(VB + i_b \sin\varphi)$$

where $\varphi \approx 60^\circ$ (-60° before transition) is the phase of the fundamental Fourier component of the beam with respect to the RF-voltage. Normally the imaginary part vanishes, because the automatic tuning servo controls B to compensate for the reactive part of the beam current $i_b \sin\varphi$. The generator has to supply only a real current i_g and the AVC controlles i_g in such a way that the voltage V remains constant.



At the end of the debunching process for slow ejection (trigger TB) the generator is suddenly switched from beam controlled frequency f_b to a frequency f_{max} which is 10 - 50 kHz lower. Then the phase changes

$$\varphi = 2\pi(f_b - f_{max})t = \Delta\omega \cdot t$$

so rapidly that neither the AVC nor the tuning servo can follow the beam load variations. They keep average values of i_g and $B \approx 0$ *). Therefore we obtain a modulated gap voltage

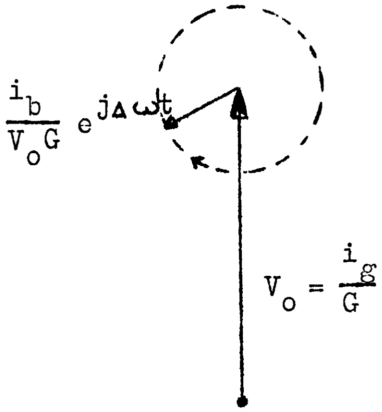
---

*) The frequency difference is small compared with the 180 kHz cavity bandwidth. The tuning servo partly follows, thereby increasing the effective bandwidth.

$$V = (i_g - i_b \cos\Delta\omega t)/G - j\, i_b \sin\Delta\omega t/G$$

$$\underline{V = V_o\left(1 - \frac{i_b}{V_oG}\cos\Delta\omega t - j\frac{i_b}{V_oG}\sin\Delta\omega t\right)}$$

$$= V_o\left(1 - \frac{i_b}{V_oG}\, e^{j\Delta\omega t}\right)$$



The two modulations are 90° out of phase (single side band modulation). The amplitude of the amplitude modulation is

$$m = \frac{i_b}{V_oG} = \frac{0.152\ \text{A}}{10\ \text{kV}/8.5\ \text{k}} = 12.9\ \%$$

and the amplitude of phase modulations

$$\Delta\varphi_{max} \approx \text{arc}\,\frac{i_b}{V_oG} = \pm\ 7.4\ \text{degrees}$$

for 10^{12} protons sharply bunched at 9.5 MHz.

Experimental evidence

Fig. 1 shows the RF voltage at the end of the acceleration cycle in absence of the beam. One can see a constant voltage which is 10 kV. At trigger TB (shown at the bottom) there is a small bump, because the frequency jumps from f_b to f_{max} and the tuning servo needs some time to tune to the new frequency. Finally the RF reduction occurs in 90 μsec.

Fig. 2 shows the same moment in presence of the beam. The indicated beam intensity was around IP = 1.43×10^{12} protons or 1.29×10^{12} on the beam current monitor. Only 80 % were left for slow ejection at the end of the acceleration cycle so that the beam current at this moment was very close to 10^{12} protons. The amplitude modulation is a bit smaller than calculated since the beam is not infinitely sharply bunched. It has a period of 22.4 µs = $^1/45$ kHz. The RF frequency was measured f_{max} = 9497 kHz. $f_{max} + \Delta f$ = <u>9542 kHz</u>.

Fig. 3 shows the same phenomenon with the RF frequency jumping to f_{max} = 9520 kHz. The modulation has a longer period of 44 µs = $^1/23$ kHz. We find again $f_{max} + \Delta f$ = <u>9543 kHz</u> for the beam frequency. Finally we adjusted f_{max} = 9540 kHz and the modulation disappeared. (Small frequency errors resulting in a slow amplitude modulation below 5 kHz should be eliminated by the AVC.)

The whole phenomenon is harmless and short compared with 3000 µs period of a synchrotron oscillation, but it proves that our <u>bunched beam induces more than 1 kV in every tuned cavity</u> if we are out of the range of the AVC.

In fig. 4 one can see that just before the RF voltage is reduced to zero there is a moment where i_g and $i_b e^{j\Delta\omega t}$ cancel. Afterwards remains only the beam-induced voltage

$$|V| = \frac{i_b}{G}$$

which decreases as the beam continues to loose its RF structure and the cavity falls out of tune. The decreasing beam structure (< 30 MHz) is illustrated by the Σ- signal of the compact pick-up station in straight section 50 displayed at the bottom.

We also looked at the phase discriminator signal of the tuning servo. We found that after trigger TB (jump from beam controlled frequency down to f_{max}) the signal first drops and then oscillates with the modulation frequency. After the RF reduction the phase discriminator ceases to work. Although the phase modulation can be expected, the signal is not convincing because the phase discriminator is also sensitive to the amplitude modulation. Since the phase discriminator drives the tuning current amplifier, it tries to compensate the modulation by big current swings in the tuning magnet (fig. 5). This photo is a double exposure. Therefore the trigger for the 2 signals is slightly different due to jitter from one acceleration cycle to the next.

Acknowledgement

I wish to thank Mr. H. Bonnin and Mr. W. Weissflog for their help when searching for the reason of this effect and eliminating other possible causes like hum.

References

1) H.H. Umstätter — Measurements of frequency response, pulse response and beam interaction in the PS-cavities MPS/Int. RF 67-5

2) H.P. Kindermann — Private communication of measurements which are also reprinted in fig. 13 of report SI/Int. EL/68-3 (D. Zanaschi)

Distribution: (open)
Scientific Staff MPS
Scientific Staff SI
Scientific and Technical Staff SR Group

AMPLITUDE MODULATION BY BEAM LOADING

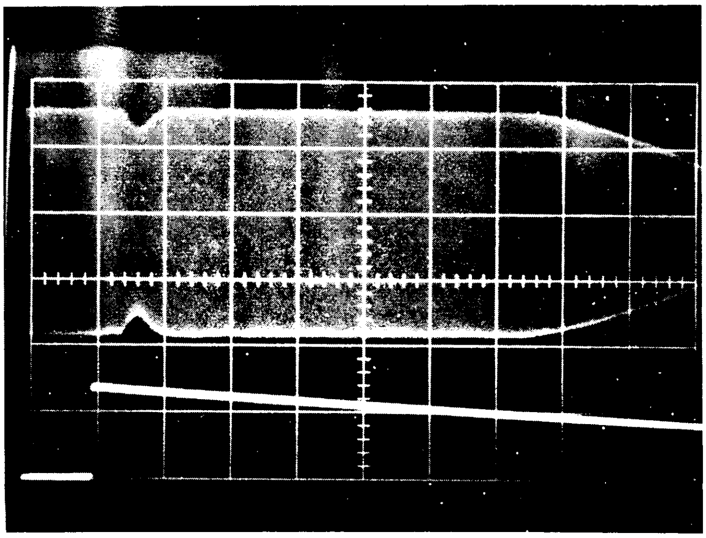
(CAVITY in SS. 41 19. 6. 69)

Fig. 1

NO BEAM

10 kV peak to peak

f_{max} = 9497 kHz



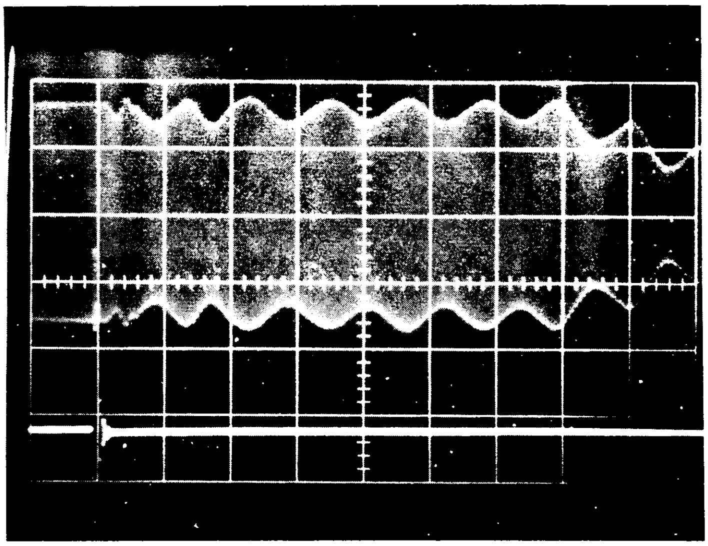
Trigger "TB" ↑ ↓

20 µs/div

Fig. 2

WITH BEAM

f_{max} = 9497 kHz

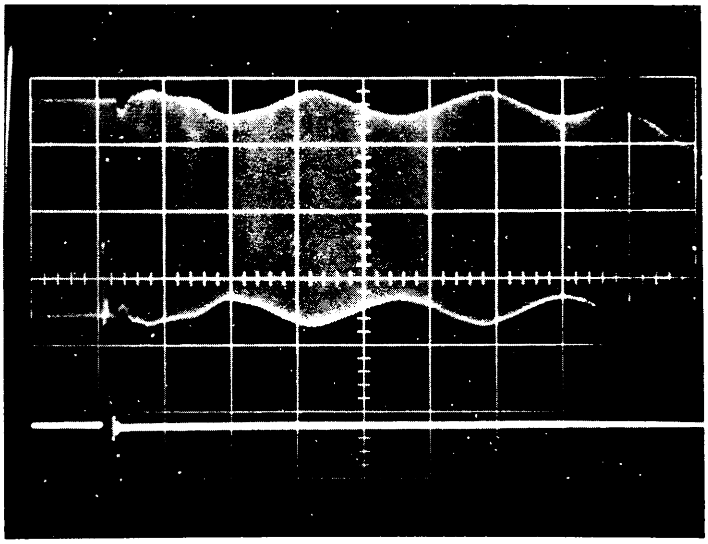


20 µs/div

Fig. 3

WITH BEAM

f_{max} = 9520 kHz

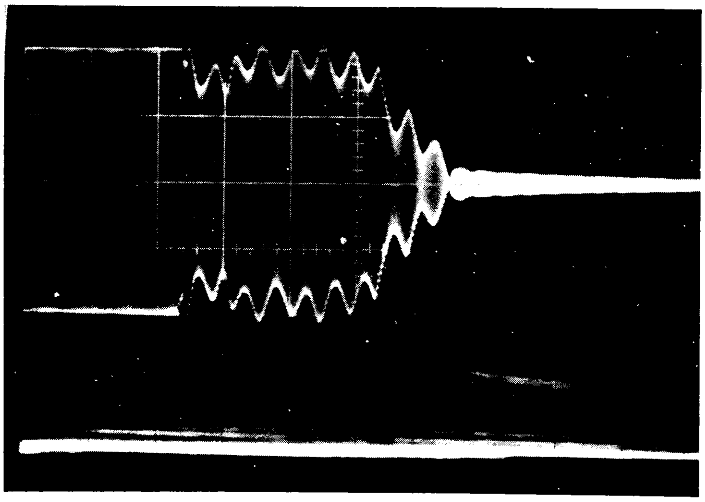


20 µs/div

Fig. 4

Top: amplitude modulation and
beam-induced voltage
(cavity 16, June 20, 1969)

Bottom: Σ-signal of P.U. station 50
0.2 V/div for $1.51 \cdot 10^{12}$ protons

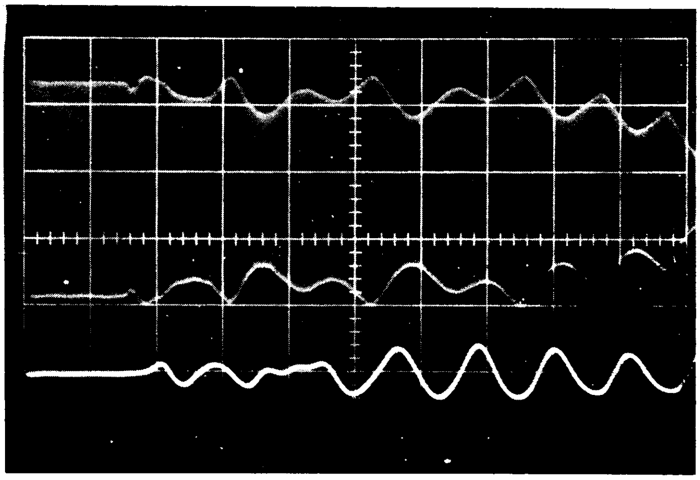


M 288 + 140 µs delay

50 µs/div

Fig. 5

amplitude modulation and
tuning current 2 Amp/div
(cavity 96, June 18, 1969)



20 µs/div