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Fixed Frequency Acceleration in the SPS

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1. Introduction

The technique of fixed frequency acceleration of varying speed beams has been proposed [Ref. 1] as the practical solution for the acceleration of lead ions in the SPS. This report describes the principles of the technique and presents results of a demonstration experiment in which protons were accelerated in the SPS at fixed rf frequency.

In the SPS protons can be accelerated from 10 to 450 GeV; in this case, their velocity changes by 0.44%. The RF voltage in the 200 MHz travelling wave cavities is kept in synchronism with the circulating protons by changing the frequency of the drive power to the cavities in exact proportion to the protons' velocity, as in the classical synchrotron. A unique feature of the SPS is that the cavities are not dynamically retuned to the changing drive frequency. Instead, the travelling wave cavities have been designed to have sufficient bandwidth to provide effective acceleration over the full range of frequency variation.

If lead ions, on the other hand, were accelerated from T = 4,23 GeV/nucleon to 177 GeV/c/nucleon using a similar magnetic cycle as that of the protons cited above, their speed would change by 1,66% and the required frequency variation would exceed the bandwidth of the cavities. In fact, the effective voltage of the cavities becomes zero at some frequencies making variable frequency acceleration impossible in this case.

Fortunately, the revolution time in the SPS is much longer than the filling time of the cavities. If a gap were provided in the beam, one could still maintain synchronism between the beam and a fixed frequency cavity voltage by switching off the cavities during the gap and repowering them each turn with a waveform whose phase matches that of the circulating beam.

2. The Principle of Fixed Frequency Acceleration

The basic principle of synchronism of the synchrotron is that the particles accelerated encounter the rf voltage of the accelerating cavities at the same phase on each revolution, even though the period of revolution may change as the particles' energy increases. This condition is normally satisfied by changing the frequency of oscillation in the rf cavities in exact proportion to the particles' revolution frequency.

Large changes in the revolution frequency, therefore, require that the oscillation frequency and usually the resonance frequency of the cavities change by a large amount. When protons or light ions are accelerated in the SPS, however, the change in their revolution frequency is small, less than 1%.

This fact is exploited in the SPS by using travelling-wave cavities, which do not have to be dynamically tuned, providing significant economy in their production and operation. The cavities can be excited at any frequency within their passband which is about 10% of their center frequency, without any reduction of their electric field level. The effective voltage of the cavities is diminished only by the phase slip between the travelling wave and the moving charge. The phase slip determines the practical bandwidth of the cavities. The bandwidth is large enough to cover the full range of frequencies for protons but not large enough for lead ions. For lead, the phase slip would be several π, and the effective voltage would be very small and even zero at some velocities. Fortunately, the large phase slip is not primarily caused by the change in beam velocity, but by the much larger change in phase velocity of the travelling wave when the cavity frequency is changed. Figure 1 shows the transit time factors (the ratio of the actual energy gain per charge to the peak field of the cavity) as a function of beam velocity for two cases. In one case, curve a, the cavity is driven at a frequency proportional to the beam velocity and, in the other case, curve b, the cavity is driven at a fixed frequency that is the optimum value for the structure.

The velocities of protons and lead ions at injection energies are indicated. One can see that the transit time factor at injection for lead with the cavity driven at the optimum frequency is larger than that for protons with the cavity driven at a frequency proportional to the revolution frequency. This opens the possibility of accelerating lead ions with the travelling-wave cavities, if only they are driven at a fixed, or nearly fixed, frequency.

If the cavities are driven continuously at fixed frequency, however, then the phase of the beam with respect to the cavity voltage will be constant only for the special cases when the cavity frequency is an integral multiple of the revolution frequency, a condition that cannot be maintained during acceleration. On the other hand, if the ring is not full, the frequency need not be fixed throughout the whole revolution period. The beam-to-cavity phase on successive revolutions need not be constrained by the cavity frequency and the revolution time.

One might think of each passage of the beam through the cavity as a separate acceleration event, for which the phase of the cavity voltage could be prepared to match the arrival time of the beam. Although this concept is correct, it does not lead in a straightforward way to technical realisation.

Alternatively, one may think of the rf as a continuous waveform that is periodic at the revolution period, with harmonic number equal to one. It need not be periodic on the rf time scale in order to be periodic at the revolution period, which is the requirement for synchronism. The waveform is composed of two regions: one when beam is in the cavity and the other during the gap in the beam. During the beam, the frequency is constant and equal to the cavity frequency, and during the gap the frequency is determined by the revolution frequency. Figure 2 is an illustration of such a waveform. Parts a and c represent the waveform at two different times in the acceleration cycle where the revolution frequencies are different. Parts b and d show the beam pulses. The number of cycles in the actual waveform is very much higher than in this illustration.

This approach is a more natural way to satisfy the synchronism condition rigorously while taking advantage of the affordable tolerance on the frequency at which the cavity can be driven. The condition for synchronism is that the sum of the duration of the two regions equals the revolution period. Let h_1 and h_2 be the number of rf cycles during the two regions of frequencies f_1 and f_2, and if f_{rev} is the revolution frequency, the synchronism condition can be written:

$$\frac{1}{f_{rev}} = \frac{h_1}{f_1} + \frac{h_2}{f_2} \tag{1}$$

The frequency f_2 can be any value that generates the right amount of phase to bring the overall waveform back to the phase it had at the beginning of the time of f_1. However, an important practical simplification comes from imposing the additional constraint that the total number of rf periods during both regions be fixed, and equal to the standard harmonic number of the machine, $h = h_1 + h_2$. This specifies uniquely the value of f_2. For the SPS, $h = 4620$.

One can write equation (1) in a form that easily connects the frequency f_2 to the parameters of the normal rf beam control system. Define $f_{rf} = h \times f_{rev}$. Although f_{rf} does not really exist, it is the average rf frequency, in the sense that h cycles of f_{rf} would occur in a time $1 / f_{rev}$.

The fact that f_{rf} is the average frequency between f_1 and f_2 can also be expressed by the following equation, derived from (1) and schematised on figure 3:

$$(f_{rf} - f_1) \frac{h_1}{f_1} + (f_{rf} - f_2) \frac{h_2}{f_2} = 0 \qquad (2)$$

in which h_1 / f_1 and h_2 / f_2 are the durations of the two frequencies f_1 and f_2. Assume that the frequencies f_1 and f_2 are generated by a voltage controlled oscillator (VCO), which has a response time short compared to the durations h_1 / f_1 and h_2 / f_2. According to equation (2), the control voltage of the VCO can be obtained as the sum of two voltages:

- a DC coupled voltage proportional to f_{rf} (or f_{rev}) (average frequency), derived as usual from magnetic field or radial position;

- an AC coupled voltage (zero average) proportional to the frequency excursion $f_2 - f_1$.

The duration of the modulation pulse h_1 / f_1 at frequency f_1 is constant, as f_1 is to be kept constant and equal to the cavity center frequency f_c. The frequency modulation excursion $(f_2 - f_1)$ is given by:

$$(f_2 - f_1) = \frac{h}{h - h_1} \; \frac{\Delta - \varepsilon}{1 + \dfrac{h_1}{(h - h_1)} \; \dfrac{(\varepsilon - \Delta)}{(f_c + \varepsilon)}} \qquad (3)$$

where $\Delta = f_{rf} - f_c$ and $\varepsilon = f_1 - f_c$.

To achieve $f_1 = f_c$ or $\varepsilon = 0$, we select to first order in ε and Δ:

$$(f_2 - f_1) = \frac{h}{h - h_1} \Delta \qquad (4)$$

This is easy to realize practically: the modulation amplitude is simply proportional to the average frequency deviation. The residual error ($\varepsilon \neq 0$) due to the non linearity of equation (3) is given by:

$$\varepsilon \approx \frac{h_1}{h - h_1} \frac{\Delta^2}{f_c} = \frac{\alpha}{1 - \alpha} \Delta\beta^2 f_c \qquad (5)$$

where $\alpha = h_1 / h$ approximates closely the fraction of the ring filled and $\Delta\beta = \beta - \beta_c$.

For the SPS parameters at injection of lead ions ($\beta = 0{,}983$) one finds $\varepsilon = 0{,}155$ MHz for $\alpha = 3/4$. The cavity drive frequency f_1 will therefore be slightly different from f_c if equation (4) is employed to derive the modulation amplitude. This is of little practical importance: it will only reduce the transit time factor by a very small factor (see figure 1). Similarly, the precision required on the modulation amplitude is not very large.

Figure 4 shows f_2, f_{rf}, and f_c as a function of momentum for lead ions in SPS from 4 GeV/c/u to 30 GeV/c/u for the case $h_1 = 3/4$. Clearly f_2 must be less than f_{rf} when f_{rf} is below f_c, and greater when f_{rf} is above f_c. Varying f_2 in this way guarantees that there is exactly h rf cycles in the changing time, $1 / f_{rev}$, even though the time to accumulate h_1 cycles is constant, independent of f_{rev}.

When f_c differs significantly from f_{rf} and/or h_1 approaches h, then f_2 will be far from f_c. In this case it is necessary to turn off the drive power to the cavities during the time of the frequency f_2. It does not matter to the beam because there is no beam in the cavities at that time anyway, but it may matter greatly to the high power rf equipment which cannot tolerate being driven far from the normal operating frequency. A lower limit will be set on the gap by the filling time of the cavities. Because they are travelling-wave cavities, they attain approximately 100% of their field level in one filling time, as opposed to standing wave cavities which need 3 filling times to reach 95%.

The group velocity of the cavities is 9.5% the speed of light and their length is 20.2 m. Their filling time is, therefore, 0.71 microseconds. The minimum possible h_2 value is then 0.1 h, when the beam gap equals twice the filling time. Practical considerations on the value of f_2 will impose a greater lower limit on the beam gap.

When the drive power is off, the frequency f_2 must still exist in the low-level rf beam control circuitry. Counting h cycles of the composite waveform f_1 and f_2 generated by the VCO defines the f_{rev} clock which is used to modulate the amplitude of the RF power in the cavities and the VCO itself.

3. A Demonstration Experiment with Protons

The viability of the fixed-frequency acceleration technique was demonstrated by accelerating protons in this way in the SPS. The following sections describe the special beam control equipment that was used and give results of the experiment.

a) Beam Control Electronics

Acceleration of lead ions in the SPS must be a regular part of normal operations and, therefore, the equipment used in this mode must be conveniently integrated into the standard circuitry of the low-level beam control system. The equipment used for the demonstration experiment with protons was designed to fulfill this requirement.

b) Frequency-Switching Local Oscillator

The critical component of the fixed-frequency acceleration system is a special Voltage Controlled Oscillator (VCO) which replaces the standard VCO that generates the Local Oscillator (LO) signal used throughout the beam control system. The signal in this special VCO is the continuous waveform that contains the two frequencies, f_1 and f_2 (minus the intermediate frequency, 10.7 MHz). The LO from this VCO is distributed to all the standard systems, such as cavity drive and beam-to-cavity phase measurements. In this way, the measurement of radial error and beam-cavity phase can be done as usual on the fixed intermediate frequency (10.7 MHz).

The inputs to this VCO are the same as the inputs to the other standard VCOs, used for fixed target and p-pbar operation, plus two triggers to switch between f_1 and f_2, and a function input to scale the amplitude of the frequency modulation. One additional output is provided for switching off the power amplifier drive during f_2.

One input to the VCO is the frequency program. This is the signal f_{rf} mentioned above. The VCO has the same response to this signal as the other VCOs. Another input comes from the phase loop amplifier, combining the error signals of the phase and radial loops. A third input is from the injection loop. It anchors the VCO to the injection frequency before the other loops are engaged.

Figure 5 shows a block diagram of the fixed-frequency acceleration VCO. Details of the circuitry are given in (2). In the diagram, "VCO" refers to the actual rf oscillator that is controlled by two inputs, one DC-coupled, for the frequency program and loops, and another AC-coupled for the switching between f_1 and f_2. Separating the inputs is advantageous because the accuracy and speed requirements are different for the two types of inputs. The DC-coupled input should be accurate because an error there is ultimately reflected in a beam radius error. The AC-coupled input must be very fast, so that the transitions between f_1 and f_2 can be fast compared to the duration of the gap in the beam. But the accuracy of the difference between f_1 and f_2 need not be especially high, since an error there will only affect the frequency at which the cavity is driven, f_1. The accuracy required for f_1 is not high because the cavity can be driven over quite a wide frequency range without loss of efficiency.

Switching between f_1 and f_2 is done via a fast analog switch, toggled by the trigger inputs (respecting some delays described below). The switch changes the polarity of a level obtained from the VCO's DC input, f_{rf}, and an adjustable voltage corresponding to the cavity frequency, f_c.

The AC input cannot change the average frequency. The factor, a(t), is a time dependent scaling constant that is used to control the amplitude of the modulation. It is obtained from an external function generator where the rate of rise and fall and the final value are set.

There are two essentially orthogonal parameters, one for the cavity frequency, f_c, and one for the duty factor, a(t). Clearly the setting of f_c (fig. 4) controls the frequency at which there is no modulation, when f_{rf} equals the cavity frequency, The function a(t) can be used to ramp up the modulation slowly, and its final value is given by the switching duty factor. When a(t) equals 1/2 [h / (h - h_1)], f_1 is equal to f_c, for all values of f_{rf}. An especially simple case is when the duty factor is 50%. Then:

$a(t) = 1 \qquad f_1 = f_c \qquad f_2 = 2f_{rf} - f_c$

c) RF Amplitude Control

One important particular case to mention is the stable phase generating circuit. It uses a measurement of dB / dt and the total cavity voltage to obtain an offset for the phase discriminator corresponding to the stable phase angle needed for acceleration. It uses the instantaneous cavity voltage and it obtains the correct stable phase angle.

On the contrary, the slow, amplitude regulating feedback around the cavity power amplifiers uses a circuit which detects the averaged cavity voltage and, hence, senses an error when the cavities are pulsed. The feedback tries to compensate the error by increasing the peak power. This action must be defeated by the circuit that limits the maximum power output of the power amplifiers. The result is a reduction in the quality of regulation of the cavity voltage.

d) Adiabatic Capture

At injection energy in the SPS, after debunching to fill a large fraction of the ring, lead ions must be adiabatically captured.

To establish the precise average capture frequency, it is convenient to close the phase loop before the beam is injected. This provides a reference for the VCO to make sure that its frequency is correct. The reference to which the VCO is locked is the injection frequency synthesizer, which gives f_{rf}. The phase measurement, therefore, cannot be done at f_1, as when the beam is in the machine.

For locking to the injection synthesizer, the phase measurement is done at the revolution frequency by using a fast sample and hold circuit connected to the output of a phase discriminator whose inputs are the synthesizer and the VCO output, (shifted by 10.7 MHz). The sample and hold is triggered by a revolution frequency clock. This phase measurement does assure that the waveform is periodic at the revolution period but it does not guarantee that harmonic number is 4620. If the free-running frequency of the VCO drifts too much, the loop will lock on another harmonic number. This was not a problem in actual operation.

Figure 6 is a block diagram of the special beam control equipment used in the experiment with protons. In fact, bunch-into-bucket transfer was used because the frequency range was small enough and it was considered to provide a more conservative first attempt at fixed-frequency acceleration. The sample and hold phase measurement was used even though the frequency modulation was ramped up slowly after the beam was captured.

The f_{rev} pulses are derived from two trigger E modules driven by the LO signal shifted by 10.7 MHz.

e) Results with a Proton Beam

A single batch of protons at low intensity (2 x 10e12 ppp) was injected into the SPS at 14 GeV/c, filling 5/11 of the ring. The batch was continuously extracted from the PS in five turns, after rebunching at 199.946 MHz. The LO drive to all four SPS travelling-wave cavities was gated on and off with a fast rf switch, triggered by the RF-ON/OFF output of the fixed-frequency acceleration VCO. Figure 7 shows the longitudinal wide band beam pick-up signal and the cavity voltage after the trigger units which control the frequency switching and amplitude modulation were adjusted to match the phase of the beam. The fast rf feedback for the cavities was turned off. It is not necessary for low intensity beam.

There are two types of power amplifiers for the cavities [ref. 3]. One uses eight 125 kW power tetrodes (Siemens) and the other uses 32 Philips power tetrodes (35 kW). The DC supplies of the large power amplifiers (Siemens) were stressed when the output power was modulated 100% at the revolution frequency (43 kHz). One of these cavities was not usable for this reason and the other was used only at reduced power. This limited the total accelerating voltage to about 5.5 MV, compared to about 6.7 MV which is normally used.

Figure 8 shows the cavity voltage at f_1 and after conversion to the intermediate frequency and narrowband filtering. One can see that the filtering is very effective at removing the revolution frequency components from the signal. This is the signal that is applied to the main phase discriminator of the phase loop.

Figure 9 shows the action of the fixed-frequency VCO during an acceleration cycle. Trace a is the beam pick-up, trace b is a fast frequency discriminator measuring the instantaneous frequency of the VCO, and trace c is the gated rf drive signal. The photograph has a four second exposure spanning injection, flat bottom, and acceleration. The frequency discriminator is adjusted to give zero (center scale) when the rf is at the cavity optimum frequency, f_c, (200.22 MHz). The trace stays at zero during the f_1 frequency state for the whole cycle. During the f_2 state the frequency changes from below f_c at the beginning of the cycle to above f_c at the end.

For the actual experiment, a slightly more complicated frequency modulation program was used. The rf system was started at the injection frequency by phase locking to the injection synthesizer, with no frequency modulation. After injection and capture the modulation was ramped up slowly, in 500 ms, to bring the f_1 and beam frequencies to f_c. The modulation continued to hold the beam and the cavities at f_c for the rest of the flat bottom and throughout acceleration to full energy. The frequency discriminator output is shown on a slow time scale in figure 10. The display is a single oscilloscope trace but because the frequency is switching between f_1 and f_2 at a very fast rate, and with short transition times, the appearance is of two curves, one for f_1 and one for f_2. One can see the two frequencies diverge as the modulation is turned on. When the average frequency changes during acceleration the f_2 frequency rises to cross the f_1 frequency, which remains constant.

The beam was successfully accelerated at the fixed frequency. Some beam was lost during acceleration as one can see from figure 11 which shows a beam current transformer in curve b and the frequency modulation amplitude, a(t), in curve a. A loss of about 30% of the beam can be seen. This should be compared to figure 12 where the same beam was accelerated with the standard beam control equipment and a 10% loss is observed. (The modulation amplitude also appears in the photo, but it is irrelevant for the normal beam control system).

The cause of the loss was pursued and eventually traced to an effect that is essentially unrelated to fixed frequency acceleration.

It was found that the same loss occured if the special frequency-switching VCO was used to accelerate the beam with all frequency and amplitude modulations turned off. A large noise component was observed at the phase discriminator output which is most likely caused by inadequate short-term stability of the VCO. Improving this stability is straightforward once it has been shown to be a limiting effect.

4. Conclusions

The fixed-frequency acceleration technique has been shown to be an effective means of accelerating varying velocity particles in a large synchrotron without imposing the conventional constraint of a constant integer ratio between the accelerating and revolution frequencies. This technique can be used to practical advantage for accelerating lead ions in the SPS without any significant modification to the accelerating system.

Acknowledgements

We would like to thank U. Wehrle for assistance in construction of the special hardware used in this work, in particular the most critical component, the voltage controlled oscillator. One of us (JMB) would like to thank CERN and the SPS for their hospitality and support during this work.

References

1. "Planning and Proposals for the CERN Heavy Ion Injector", H. Haseroth, CERN/PS 88-51 (DL), September 28th, 1988.

2. "The Voltage Controlled Oscillator for fixed frequency acceleration", M. Brennan, SPS/ARF Note 89-12.

3. "The RF Power Plant of the SPS", W. Herdrich, H. P. Kindermann, W. Sinclair; CERN SPS/83-20 (ARF) and IEEE Proc. PAC 1983.

4. "The Low Noise Oscillator for ppbar", U. Wehrle, CERN SPS/ARF/UW/gs/Note 83-10.

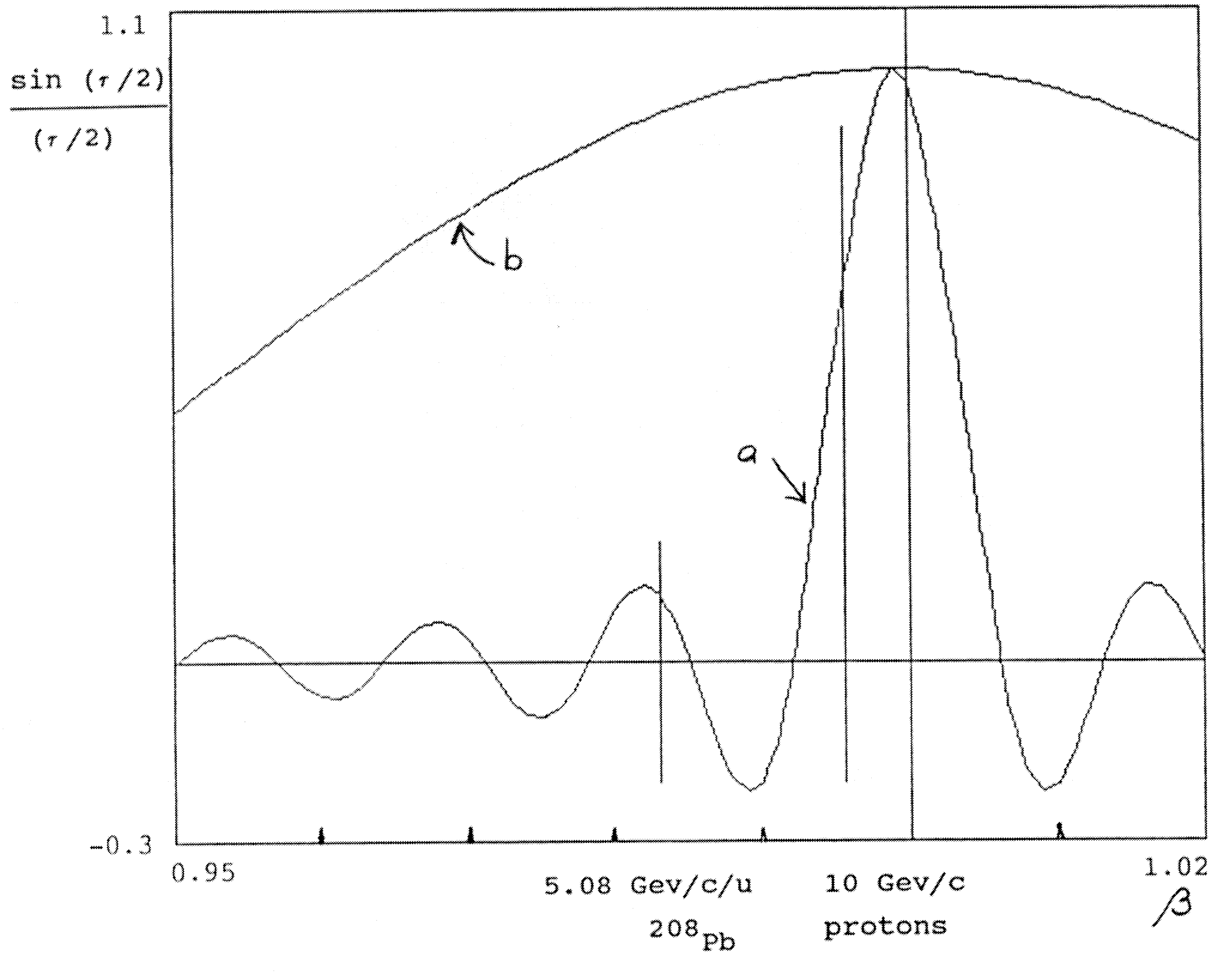


Fig. 1 Transit time factors for the travelling wave cavities;

a) normal operation when $f = h \times f_{rev}$

b) fixed frequency operation

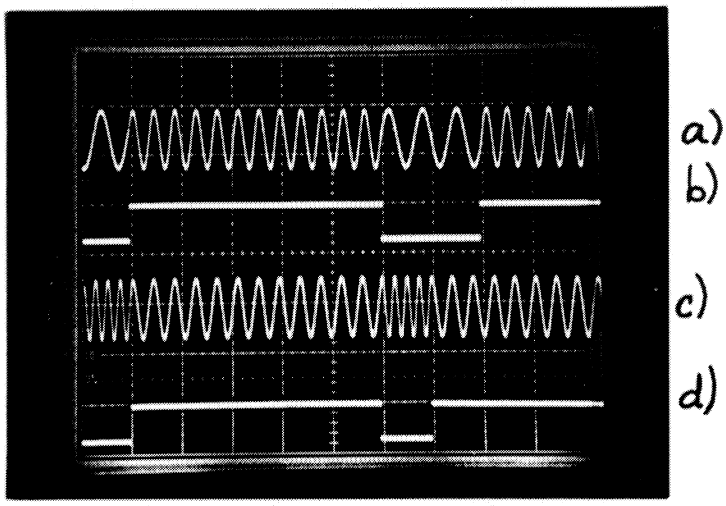


Fig. 2 Illustration of periodic waveform with two frequency regions;
a) waveform when the average frequency is low;
b + d) beam pulse;
c) waveform when average frequency is higher.

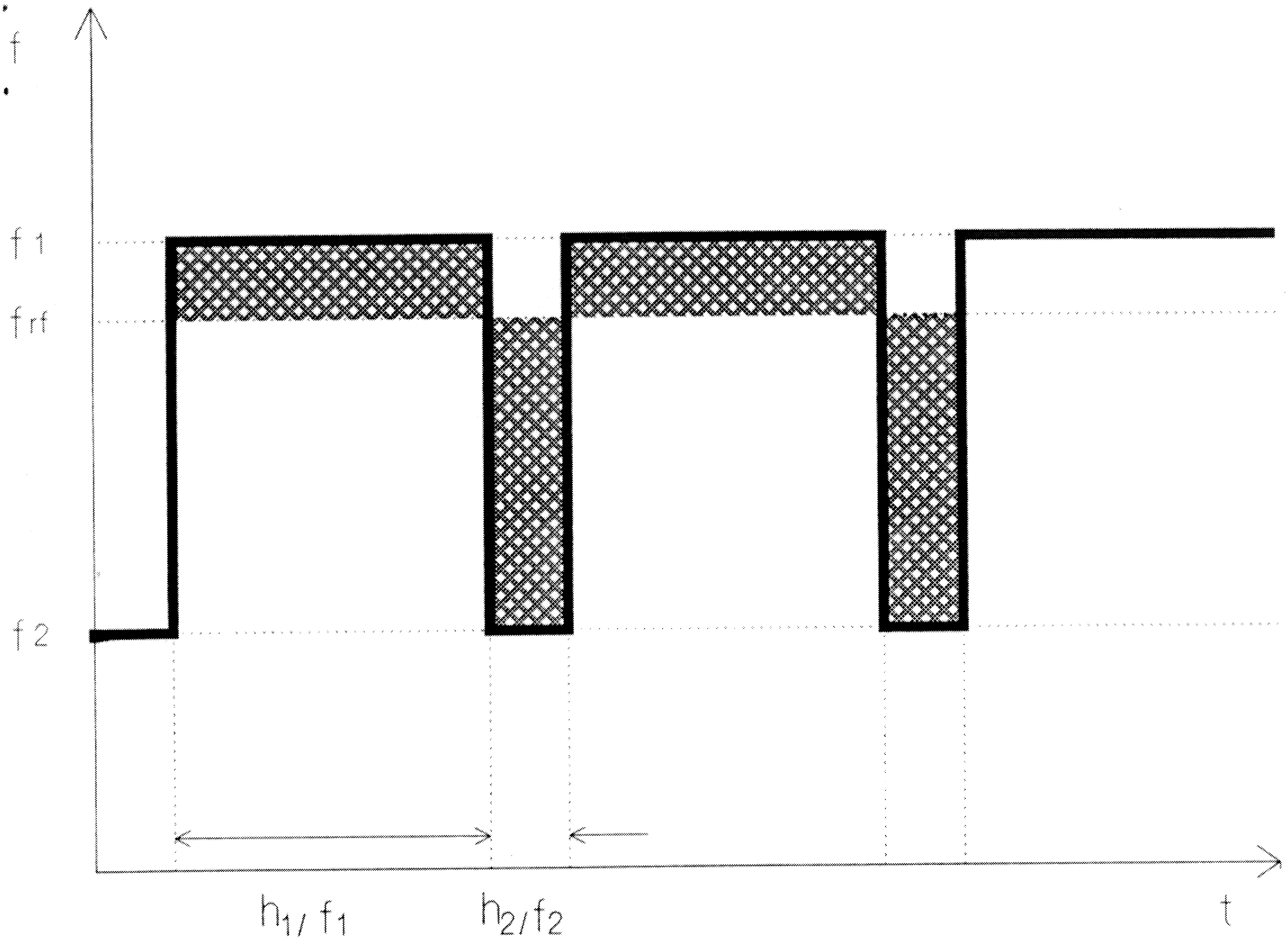


Fig. 3   The time average of f_1 and f_2 is f_{rf}

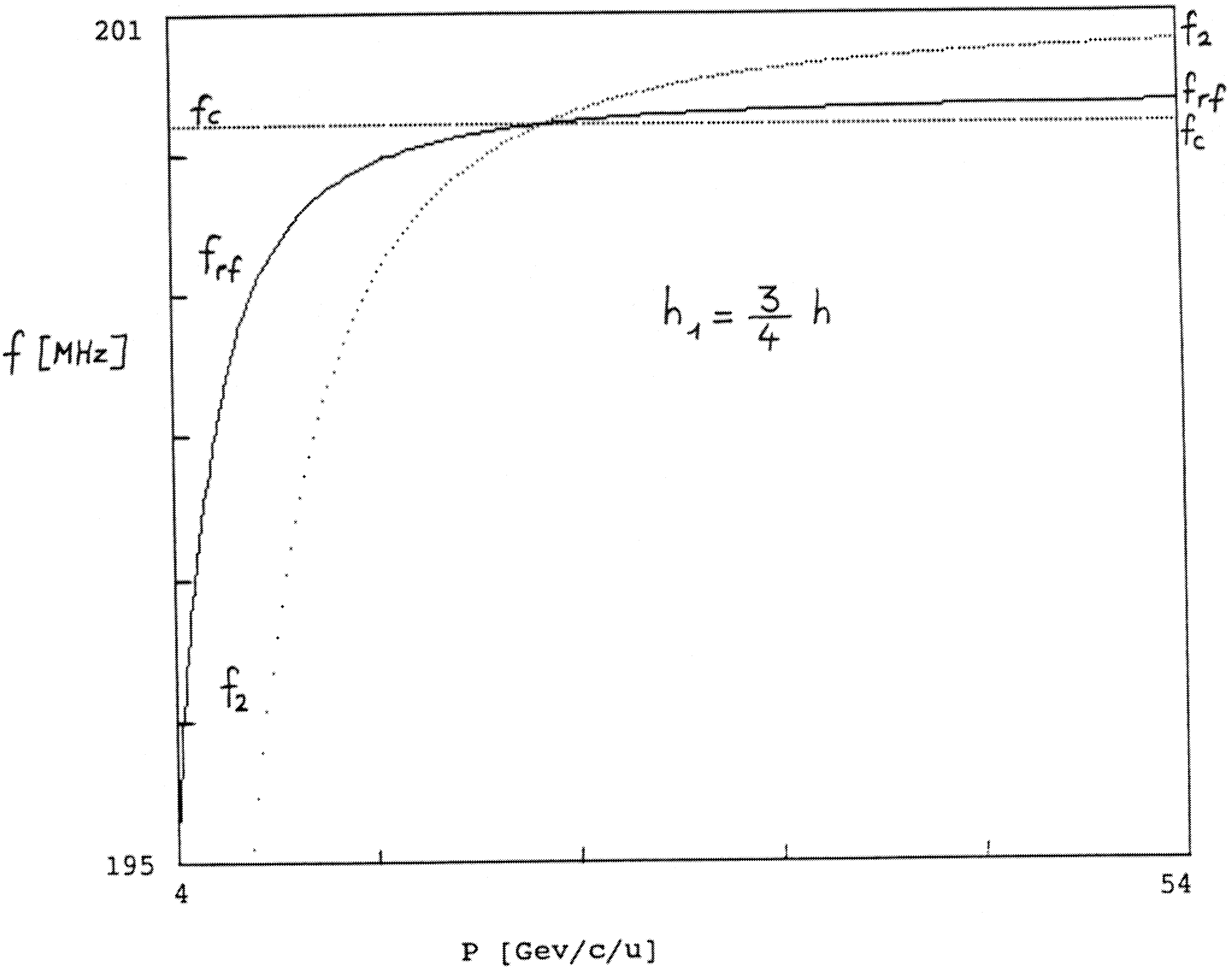
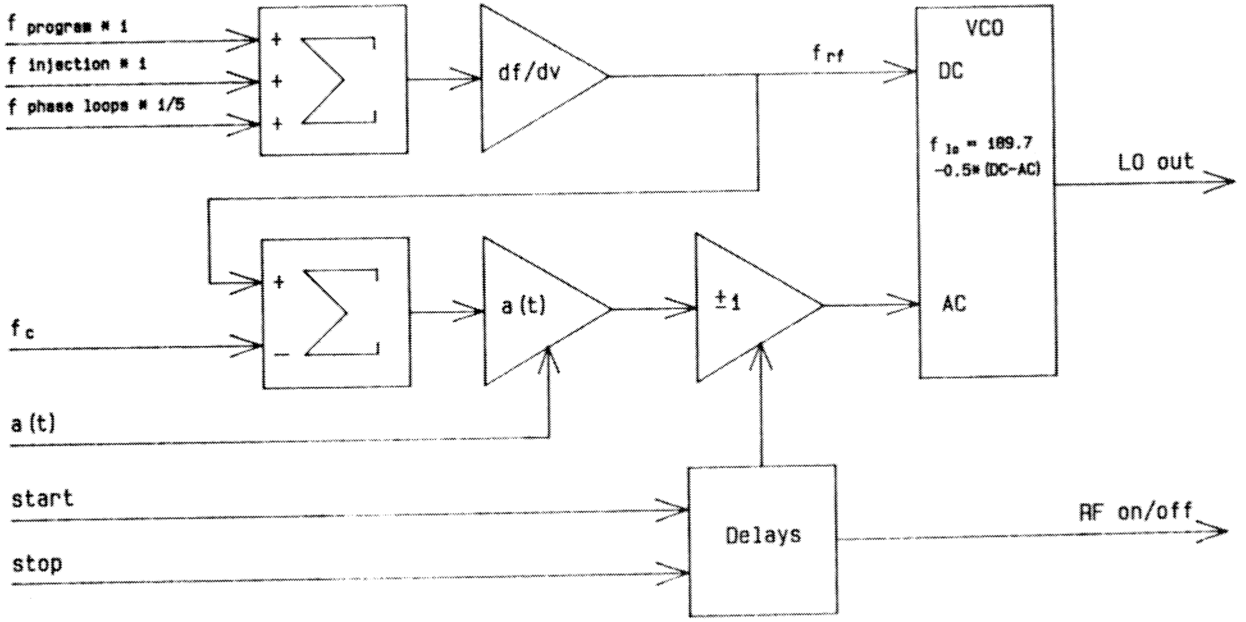


Fig. 4 Frequencies f_c, f_{rf} and f_2 during fixed frequency acceleration.

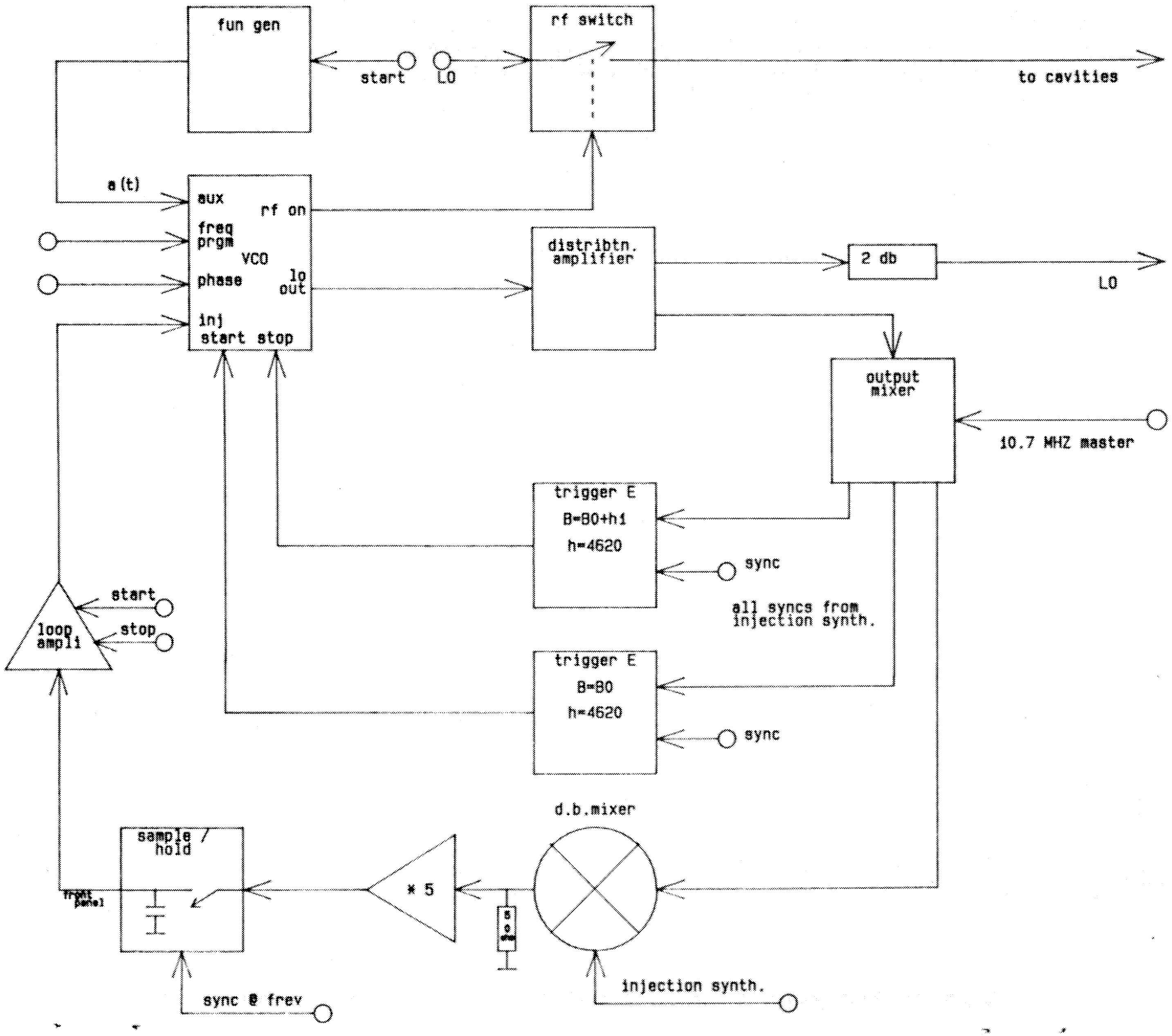
Fixed-Frequency Acceleration LO



h1=(stop-start)
h1+h2=4620

Fig. 5

Fixed Frequency Acceleration.
figure 6



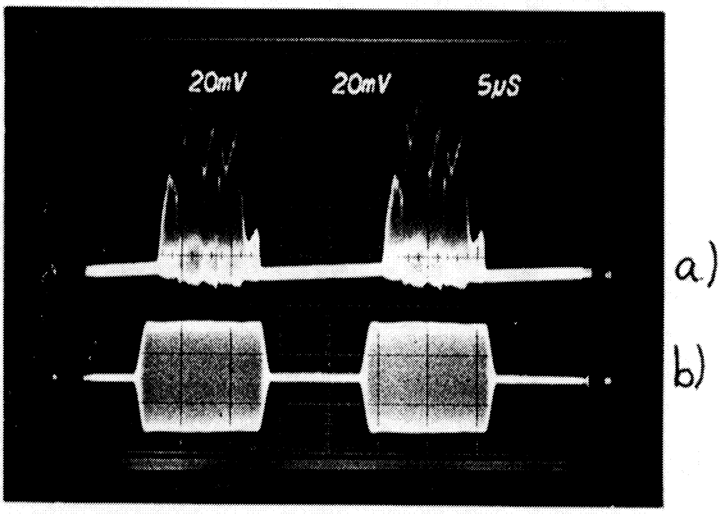


Fig. 7 a) Beam signal
b) cavity voltage
trigger- revolution frequency

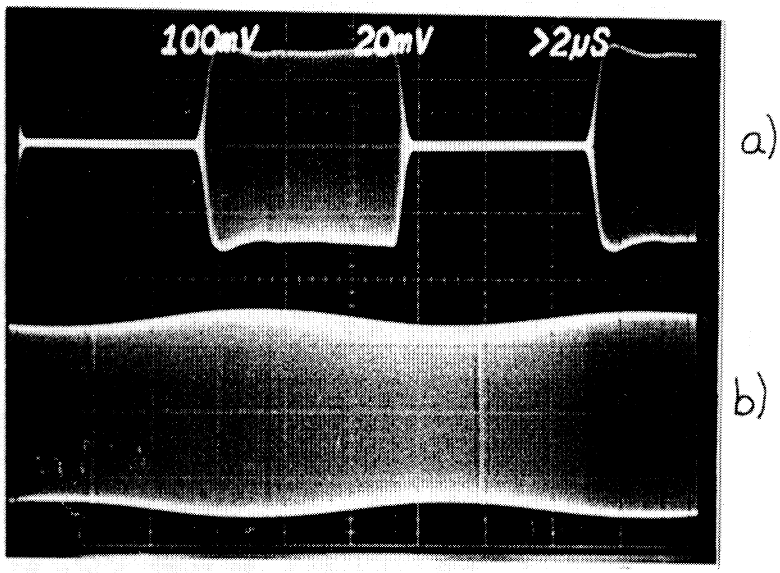


Fig. 8 a) cavity voltage
b) cavity voltage after conversion to 10.7 MHz
and narrowband filtering

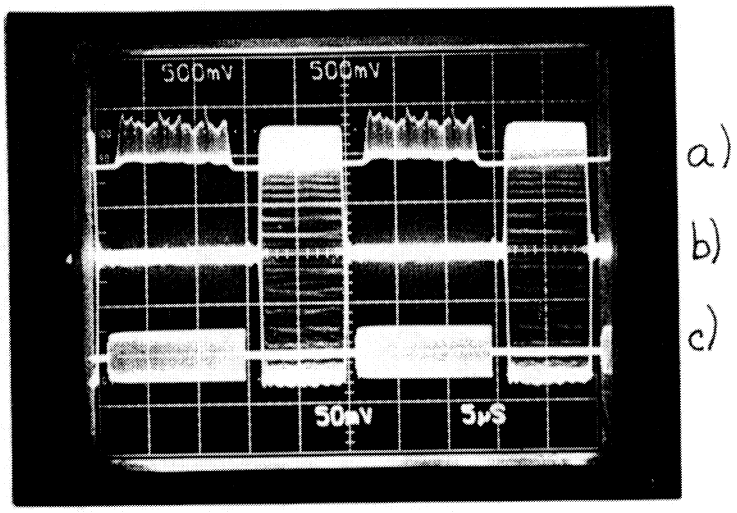


Fig. 9 a) beam pick-up;
b) fast frequency discriminator;
c) cavity drive.

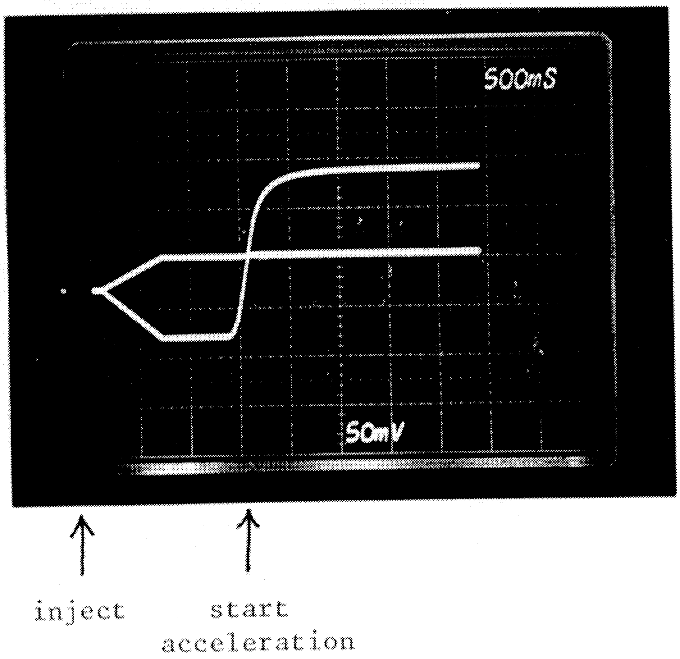


Fig. 10 Fast frequency discriminator.

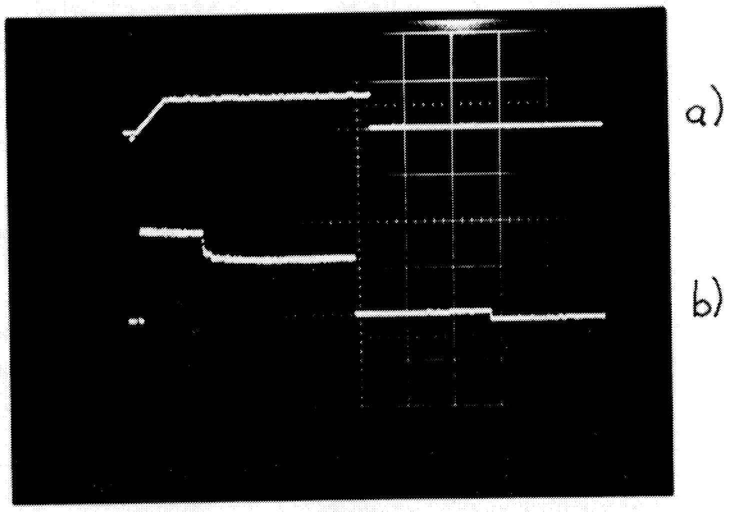


Fig. 11 a) Frequency modulation amplitude function, a(t)
b) beam current transformer during fixed-frequency acceleration

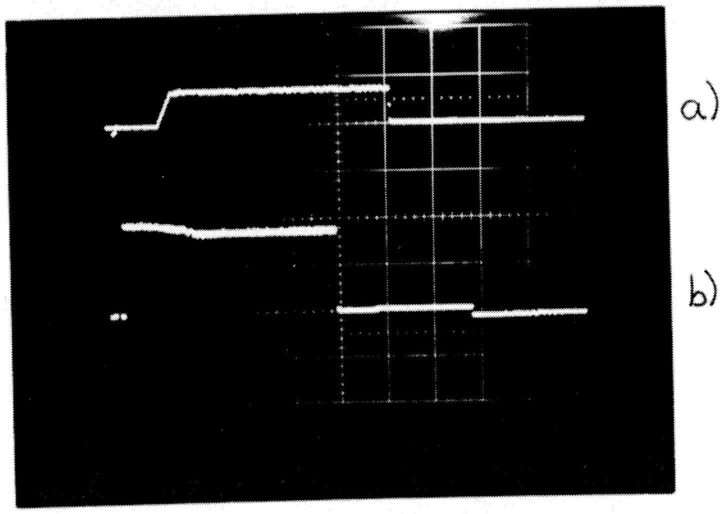


Fig. 12 a) not relevant, see text;
b) beam current transformer with normal beam control electronics