THE PROGRAMMING AND TIMING OF BETATRON ACCELERATION CYCLES OF THE STORAGE RING FOR 2 MeV ELECTRONS.

1. Introduction

In the following report we shall describe the operational possibilities of the R.F. and betatron acceleration systems which are available on the Storage Ring.

We have developed function and timing generators for both systems, making available a rather wide variety of single and combined modes of operation.

The inherent possibilities of the R.F. system alone have already been explained by A. Susini\(^1\), who has based himself on data provided by D. A. Swenson\(^2\). We therefore restrict ourselves to the operation of the betatron core and its combined use with R.F. acceleration.

2. Time dependence of betatron voltage

The theory of operation of the betatron core and its design are given in detail in 3) and 4).

There is, however, not yet any estimate on how quickly one is allowed to turn on the betatron voltage. It seems to be a reasonable assumption to foresee at the start of betatron acceleration an adiabatic variation of the betatron voltage\(^5\). The maximum length of the acceleration cycle must be smaller than 20 ms, and the shortest acceleration cycle has been set.
arbitrarily to 5 ms. It will be possible to vary the adiabatic voltage change independently of the pulse length, and the voltage form is shown in Fig. 1.

The maximum energy that can be transferred into the beam is $\sim 300$ KeV and corresponds to a radial displacement of 8 cm. By decreasing the amplitude of the betatron voltage (i.e. swinging the core from its rest position $- B_{\text{max}}$ to a certain $B$ yielding the desired voltage variation) the beam can be moved to any position within the vacuum chamber. The duration of the return of the betatron voltage will have to be made of the same order of magnitude as the adiabatic rise of the start, in order to avoid overvoltages to appear across the driver tubes of the core.

2.1. The function generator for the betatron core

As shown in Fig. 1, the betatron voltage has a certain time dependence which must be rather flexible. This is to say that slope, duration and amplitude of the pulse must be variable independent of each other. There is, however, a certain limit to this, particularly since the total duration of a period must not exceed 20 ms. The voltage on the core can be expressed in terms of its inductance $L$ and the current swing $\Delta i$ in the time interval $\Delta t$, we write

$$U_{\beta} = \frac{d}{dt} (L \cdot i) = L \frac{di}{dt} + i \frac{dL}{dt} \cdot \frac{di}{dt}$$

We have to take into account that $L = L(\mu)$ where $\mu$ is the permeability of the iron out of which the core is made. Therefore it is possible to write $L = L[\mu(i)]$ and

$$U_{\beta} = \frac{di}{dt} \left[ L + i \frac{dL}{d\mu} \cdot \frac{d\mu}{di} \right]$$

$\propto \mu$, we have to find how $\mu$ depends upon $i$, or rather on the magnetic field strength $H \propto i$ (Fig. 2). Assuming that $\mu$ depends linearly on $i$
(which is justified by the fact that we make use of \( \mu \) only between \( \mu_A \) and \( \mu_{\text{max}} \)) we expect little distortion due to \( \mu = \mu(i) \).

This then means that \( \mu_B \propto \frac{di}{dt} \). Using a current source to drive the core, we have to provide a current, the time dependence of which is given by \( i = \int \mu_B \, dt \). (Fig. 3).

The driver stage of the core is made of two power tetrodes that behave as current sources. Therefore the grid voltage has to follow the same law as shown in Fig. 3.

It is necessary to design a function generator that obeys the requirements pointed out in section 2, and has the final slope shown in Fig. 3. A block diagram explains the operations needed to drive the amplifier of the betatron core.

### 2.2. The betatron core timing cycle

The following modes of operation are foreseen with the betatron core:

a. Single beam acceleration

b. Stacked beam acceleration
   i) repetitive stack acceleration
   ii) non repetitive stack acceleration

c. Stacking
   i) stacking with the betatron core
   ii) constant frequency stacking

### a. Single beam acceleration

By single beam acceleration we understand that each injected beam is accelerated with the betatron core over part or the whole width of the vacuum chamber.
Two possibilities exist for betatron core acceleration of single beams: the first is to accelerate the injected beam from the injection orbit radially outwards until it hits the external targets. The second is to accelerate the injected beam with R.F. to any position in the vacuum chamber, turn off the R.F. voltage adiabatically or non-adiabatically, then accelerate the beam against the external targets with the betatron core voltage. The possibility also exists to have R.F. voltage and betatron core voltage on simultaneously.

b. Stacked beam acceleration

Stacked beam acceleration means betatron core acceleration only taking place after having injected a previously set number of pulses which form the stack. The stack is then swept against the external target by the betatron voltage. Two types of operation are foreseen in this mode of acceleration:

i) repetitive stack acceleration,

ii) non repetitive stack acceleration.

i) In order to carry out repetitive stack acceleration a repetitive "big cycle" is foreseen. A big cycle stands for the following process: a certain number of pulses is injected, and accelerated by R.F. to form a stack. The stack is then accelerated by the betatron core voltage against an external target. This cycle repeats itself without any interruption in the "small" machine cycle.

ii) In the non repetitive stack acceleration, the process is the same as under i) except that only one "big cycle" takes place before the machine stops. A manual button has then to be operated before another stacking cycle plus betatron core acceleration can take place. The push button system can also be replaced by a signal from an outside clock.
c. Stacking

1) Stacking with the betatron core

An interesting characteristic of betatron acceleration is that all particles circulating on an orbit enclosing the magnetic flux are effected by the voltage \( U = \frac{d\Phi}{dt} = \oint B \cdot \hat{n} \, ds \). If we suppose the vacuum chamber to be infinitely well conducting and allowing for one insulated gap around its circumference, then the voltage \( U \) will appear entirely across this gap in the circumference. Furthermore, a beam exposed to such a voltage will have no R.F. structure and all the particles will receive an energy gain \( \Delta U \cdot e \) each time they pass across the gap. This implies that 2 beams circulating on different orbits in the vacuum chamber will be accelerated (or decelerated depending on polarity) simultaneously. In other words, it is impossible to affect only one specific beam in the presence of several others, which is a feature different from R.F. acceleration.

We can, however, find a possibility to get around this. We shall define that for \( U = \frac{d\Phi}{dt} = \frac{\Phi_{\text{max}} - \Phi_1}{\Delta t} \) (assuming \( \Phi \) a linear function of time) we have the right polarity to accelerate electrons. This means we drive the betatron core from \( \Phi_1 \) to \( \Phi_{\text{max}} \), \( \Phi_{\text{max}} > \Phi_1 \). Driving the core back from \( \Phi_{\text{max}} \) to \( \Phi_1 \) will deliver the same \( U \) as before, however, of opposite polarity. This voltage decelerates the electrons and the electrons find themselves on the orbit of departure. We change this situation by driving the core on its return from \( \Phi_{\text{max}} \) to \( \Phi_2 \), where \( \Phi_2 > \Phi_1 \), and \( \Phi_{\text{max}} > \Phi_2 \), \( \Phi_1 \). The electrons are then left with a net energy gain of

\[
\Delta u = e \left[ \frac{\Phi_2 - \Phi_1}{\Delta t} \right]
\]

and find themselves on an orbit which is different from that of departure (the deflecting field \( B \) being constant).

The injection orbit is free again to accept a new beam. The next cycle will drive the core from \( \Phi_2 \) to \( \Phi_{\text{max}} \), and the return will only be to \( \Phi_3 \), \( \Phi_3 > \Phi_2 \).

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The problem how to stack several beams as close as possible to each other is reduced to making \( \Delta u \) well defined over several cycles. The main difficulty lies in the fact of \( \Phi \) being actually a non-linear function of the biasing current of the core. This feature has the tendency to influence \( \Delta u \) as one moves from \( \Phi_1 \) over \( \Phi_2 \ldots \Phi_n \) to \( \Phi_{\text{max}} \).

ii) Constant frequency stacking

It has already been pointed out the possibility of stacking with a combined operation of the R.F. system and the betatron core. The process would be the following: a beam circulating on the injection orbit would be picked up by the R.F. voltage at constant frequency thus forming stationary buckets. We then turn on the betatron core with a polarity as to decelerate the beam. This will transform the stationary buckets into moving buckets, and the R.F. voltage has to make up for the betatron voltage so as to keep the beam on its original orbit.

The radio frequency is on as long as the betatron is driven from \(- \Phi_{\text{max}} \) to \( + \Phi_{\text{max}} \). The R.F. is turned off upon reaching \( + \Phi_{\text{max}} \).

The bias of the betatron core is then swung back to \(- \Phi_{\text{max}} \), thereby accelerating the beam until the betatron core reaches \(- \Phi_{\text{max}} \).

Now the beam finds itself moved away from the injection orbit. A newly injected beam will again be trapped by the R.F. voltage, the stacked beam will be driven through or up to the injected beam by the betatron voltage, and both beams will be taken to the stack by the return swing of the betatron. This method needs adiabatic turn-on and turn-off of the R.F. voltage at fixed frequency and accurate timing and driving of the betatron core.

3. Operational limits

The betatron core operation system has been designed as flexible as possible. It will allow to carry out the variety of practical experiments that could be foreseen at the time when the circuits were designed.
In position 1, the betatron voltage can be switched on with various delays after the injected pulse is on orbit. The betatron voltage can be switched on at any time from 4 μs to 20 ms after the injected beam is on orbit.

The shortest accelerating time is 5 ms. The longest accelerating time is 16 ms. The acceleration time can be varied in steps of 1 ms from min. 5 ms to max. 16 ms.

Coordination has of course to be foreseen to make sure that the betatron voltage is off, before the next beam is injected, in the case where injection takes place every 20 ms.

In position 2, the maximum number of pulses injected and put into the stack is 100, before betatron acceleration takes place. This can be made in repetitive mode and non-repetitive mode. The betatron voltage can be switched on from 4 μs to 20 ms after the last injected pulse. The acceleration time is the same as under 1.

The betatron voltage can be switched on at any predetermined time after the last stacking process, limited only by the small cycle of the machine, which is 20 ms. In non-repetitive mode, it is of course possible to delay the betatron acceleration start with an outside delay so that the stack can circulate a much longer time than 20 ms.

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BETATRON-CORE, TIMING-UNIT

Block diagram

from timer

Pulse-shaper

Counter
0-99

Reset

non-repetativ
repetativ

manual-reset
ext. - reset

F/F 1

F/F 2

to function generator

Gate

Delay

single beam

stacked beam