ADIABATIC CAPTURE IN THE CERN PS

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(presented by J. Gareyte)

Abstract

In order to improve accelerated intensity, the main magnet cycling has been modified in the initial phase of acceleration to allow a quasi-adiabatic RF capture. With a low injected current (20 mA), a capture efficiency of 80% was recorded, very near to the computed figure. With an operational injected beam of 160 mA, difficulties appeared in the transverse planes, due to the reduced $\dot{B}$. While the work is still in progress, an increase of 15% in the accelerated intensity has already been obtained.

Introduction

Implementing adiabatic radio frequency capture in a synchrotron involves a compromise between capture efficiency and dilution. As the CPS is going to be an injector itself, the highest possible phase space density must be achieved and the dilution at injection avoided as far as possible. This led us to choose an initial CPS acceptance comparable to the linac emittance. Capture parameters were then optimized to get the highest possible efficiency.

Capture and Acceleration Optimization[1)]

Preliminary Considerations

The linac beam is usually such that, when debunched and circulating in the PS, 95% of its particles lie within $\Delta E = \pm$ 300 keV. With the new debuncher, this could be lowered to $\pm$ 200 keV. Therefore we have centred our study around these values. On the other hand, to make a real adiabatic capture, one must have non-accelerating buckets, therefore a rate of rise of the magnetic field $\dot{B}=0$. This is difficult to realize practically. In fact, we have chosen, for reasons of convenience, a $\dot{B}$ of 0.35 Ts^{-1} to make our experiments.

Capture

A computer program, written by U. Bigliani[2)], has been used to simulate the whole process under different conditions and to find the optimum values. During capture, the RF voltage rises such that

$$\frac{dA}{A} = K \frac{dt}{Ts} \qquad (1)$$

where A is the bucket area, Ts the instantaneous synchrotron period. K is a "coefficient of adiabacity", which must not be much bigger than 1 [3)]. The initial voltage V_{min} is chosen to be 10% of the maximum voltage at the end of the capture, V_{max}. Thus, the height of the bucket at injection is approximately equal to half the linac energy dispersion. The parameters have been varied around a priori chosen mean values, and the capture efficiency CE computed. Some results are displayed in figs. 1 and 2. Fig. 1 shows the influence of the energy spread, fig. 2 of the maximum voltage V_{max}.

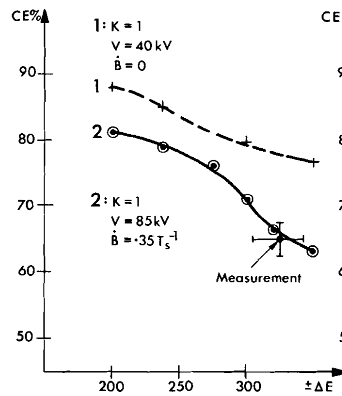


FIG.1 keV

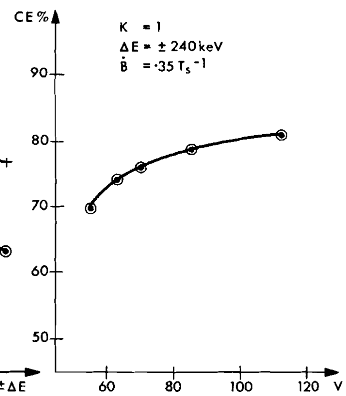


FIG.2 kV

Acceleration

Once captured in the buckets, the beam has to be accelerated as fast as possible, to gain time and to cross rapidly betatron stopbands. On the other hand, the bunching factor BF must not be decreased too rapidly, in order to keep a favourable space charge parameter, and the radial amplitude of the synchrotron motion must not increase in order not to lose particles on the vacuum chamber. All these requirements are satisfied in an optimal manner if the bucket area is kept equal to the bucket area after capture.

A parabolic law of variation of $\dot{B}$ seems suitable at the beginning, with parallel increase of the RF voltage, such that the acceptance is kept constant. When nominal RF voltage is attained, near 200 MeV, the $\dot{B}$ is increased in such a way that the acceptance remains constant, until the nominal $\dot{B}$ is reached. Such an optimized scheme is described in fig. 3, for an initial $\dot{B}$ of 0.35 Ts^{-1} and an initial voltage of 85 kV.

Choice of Experimental Parameters

For a linac energy spread of ± 240 keV, the corresponding PS acceptance (0.16 eVs) is obtained

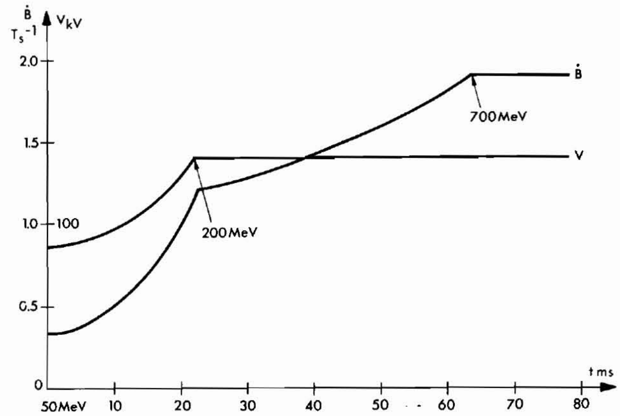


FIG. 3 Parameters of optimized acceleration

with an accelerating voltage of 85 kV. Fig. 2 shows that very little would be gained by increasing the voltage further. For a $\dot{B}$ of $0.35\ Ts^{-1}$, the more favourable value for the coefficient K is around 1, which gives a capture duration of 250 µs. During this time, the beam, being insufficiently accelerated, will drift inwards by 1 cm. After 80 ms of acceleration, the energy has reached 350 MeV and the $\dot{B}$ can be increased to $1.9\ Ts^{-1}$ in 60 ms, with parallel increase of RF voltage to 140 kV.

Experimental Work

Magnet Cycle

Thanks to the flexibility of the CPS magnet supply, the conditions described in the previous paragraph were achieved. 1500 volts is applied to the magnet for 120 ms (starting 40 ms before injection) which gives $\dot{B} = 0.35\ Ts^{-1}$. Then the voltage rises linearly over 60 ms to reach 7600 volts ($\dot{B} = 1.9\ Ts^{-1}$). The voltage program is obtained by varying the firing angle of the rectifiers. The 7600 volts is held until the required machine energy is reached in the operational cycle.

Magnetic Field Changes at Low $\dot{B}$

Studies have been made with a reduced beam of 20 - 40 mA and emittance about 5 π mm mrad. This gave the following results:

a) the dipolar characteristics do not seem to be changed, judging by the closed orbit;

b) no significant quadrupolar change was noted;

c) the sextupolar characteristics, however, were altered; we have noted the following changes

$$\text{for } \frac{\Delta Q_R}{\Delta R} : +0.010\ \text{cm}^{-1}, \text{ for } \frac{\Delta Q_V}{\Delta R} : -0.010\ \text{cm}^{-1}$$

when $\dot{B}$ changes from $1.3\ Ts^{-1}$ to $0.35\ Ts^{-1}$;

d) it seems that an octupolar field component exists in the vertical plane, of the order of

$$\frac{\Delta^2 Q_V}{\Delta R^2} \approx +0.003\ \text{cm}^{-2}$$

which changes to $+0.005\ \text{cm}^{-2}$, but the inaccuracy of the measurements has prevented confirmation of these values.

The above changes have required a modification of the pole-face windings' current at low energy so as to return to the optimum operating conditions of

$$\frac{\Delta Q_R}{\Delta R} \approx -0.022\ \text{cm}^{-1} \quad \text{and} \quad \frac{\Delta Q_V}{\Delta R} \approx -0.030\ \text{cm}^{-1}.$$

Radio-frequency Acceleration

The variations of accelerating voltage were obtained using - the cavity AVC (slow variation at T = 350 MeV) - the dephasing of the cavities in two groups (trapping at 50 MeV, see photo 1). The stable phase is about 10° when $\dot{B}$ is $0.35\ Ts^{-1}$ and goes to 32° for normal acceleration, beam control working around this value. The frequency program approximates to the theoretical curve by a series of straight lines based on the $\dot{B}$ measurement.

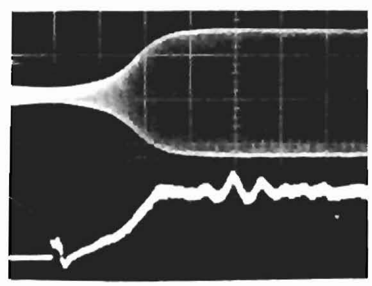


Photo 1 100 µs/cm

RF adiabatic trapping

← Rise of RF voltage (outphasing of 2 groups of cavities)

← Beam bunching (inverse bunch length).

Results

With the reduced beam, RF trapping* figures of 80% were achieved; as the overall trapping was 50% one can see that significant transversal losses occur. In passing to a useful beam, further difficulties arise.

Transverse Beam Evolution at High Intensity

Beam Quantity Effect

It was necessary to increase the focusing to balance the coherent space charge effects. With a uniform distribution[4]), at 50 MeV we could calculate

$$\Delta Q_V \simeq 0.04 \times N \quad (\text{in } 10^{12}\ p^+)$$

and

$$\Delta Q_R \simeq 0.01 \times N \quad (\text{in } 10^{12}\ p^+)$$

for a non-bunched beam. With the bunched beam (BF ∿ 0.66 in our case), at 60 MeV, ΔQ_V became

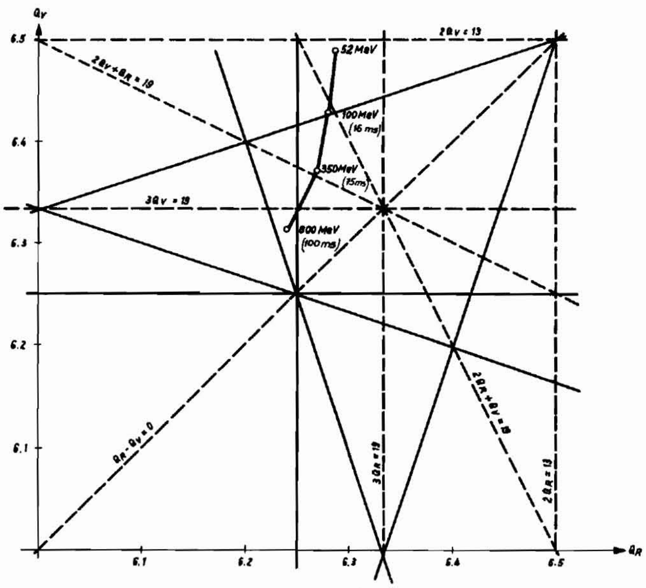
* RF trapping is defined as follows: ratio of protons remaining 2 ms after injection to protons present after the first five turns

$0.05^{-} \times N$ (10^{12} p^+): measured values were in good agreement. The corrections being DC, we have the working point evolution shown in fig. 4.

Resonances - Transverse Losses

We can see from fig. 4 that many stopbands are passed and losses were measured during this journey. Compensation (sometimes rather rudimentary: the machine itself making the filtering) of 2nd and 3rd order stopbands is essential; e.g. acceleration is impossible if one does not compensate the stopband $2Q_V = 13$. Photo 2 shows the losses occurring.

Photo 3 shows that compensation of $2Q_V + Q_R = 19$ allows an increase of approximately 20% in protons accelerated to high energy. Despite this, the overall trapping remains low. One knows from



---- Compensated stop. bands —o—o— Normal operation

FIG. 4 Working point evolution

experience that it is advisable to have as many corrections as possible between injection and, say, 800 MeV. The transverse losses are what might be termed "slow", the space charge effect causing the protons to remain on the stopbands for a long time. As an example, ΔQ_V "single particle" can be calculated as $0.075 \times N$ (N in 10^{12} protons), assuming that PS admittance is uniformly filled at 50 MeV. Unfortunately, factors of 2 or 3 [4] may be introduced to cope with real distributions. To fit photos 2 and 3 with the measurements shown on fig.4, the exact distributions of the beam and their evolution would be needed, as is discussed in [5].

Results

The following results were obtained in operation:

Beam injected (3 turns):	165 mA, i.e. 7	$\times 10^{12}$ p^+/p
Beam at 5th turn	5.25	$\times 10^{12}$ p^+/p (75%)
RF trapping* $\sim$ 65% leaving	3.5	$\times 10^{12}$ p^+/p (50%)
at 60 MeV	2.5	$\times 10^{12}$ p^+/p (36%)
350 MeV (before $\dot{B}$=1.9 Ts^{-1})	2.1	$\times 10^{12}$ p^+/p (30%)
high energy	2	$\times 10^{12}$ p^+/p ($\leq$30%)

These figures refer to a 50 MeV beam with an energy spread of $\pm$ 325 keV and with a 2.7 cm ptp radial and 0.7 cm ptp vertical orbit.

Conclusion, Present and Future Improvements

Working with a front-porch magnetic cycle and adiabatic trapping has brought an overall increase of 15% in the intensity; this procedure also aids the measurements and studies in both longitudinal and transverse planes. Future trials will include:

- better approximation to theoretically optimized curve for $\dot{B}$
- programming of magnetic corrections with $\dot{B}$ (mainly PFW and quadrupoles)
- new (skew quadrupoles) and better non-linear compensations will be used: the philosophy to be adopted is 1 lens ↔ 1 supply, control by computer, and circuit combination being software generated.

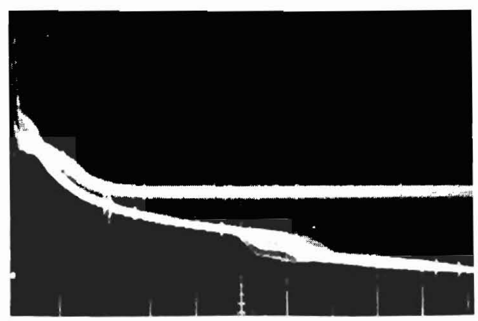


Photo 2 Effect of stopband $2Q_V = 13$

Ip transformer: upper trace with compensation
lower trace without
Injected protons $\sim 6 \times 10^{12}$ (500 μs/cm)

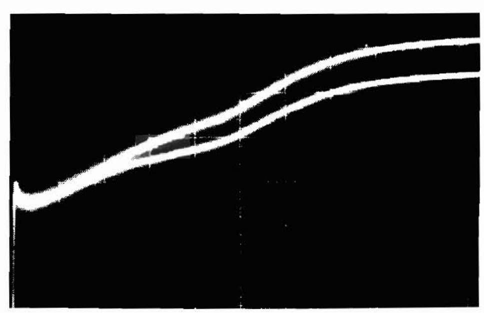


Photo 3 Effect of stopband $2Q_V + Q_R = 19$

Ip transformer: upper trace with compensation
lower trace without
Injected protons $\sim 5 \times 10^{12}$ (20 ms/cm)

References

1) BOUTHEON, M., GAREYTE, J., SCHULTE, E., CERN internal report MPS/CO 70-2

2) BIGLIANI, U., CERN int. report SI/Int.EL/68-2

3) LILLIEQUIST, C.G., SYMON, K.R., MURA 491, July 1959

4) LEFEVRE, P., CERN int. report MPS/DL Note 70-1

5) BACONNIER, Y., GAREYTE, J., LEFEVRE, P., High intensity phenomena observed in the CPS, 1971 Particle Accelerator Conference, Chicago

DISCUSSION

L. TENG : The N.A.L. booster synchrotron magnet is resonant excited. Hence $\dot{B}$ is nearly zero. Adiabatic capture is achieved by turning the 16 RF cavities on one by one. The capture efficiency is estimated to be above 80 %, probably as high as 90 %.

Why don't you reduce the initial $\dot{B}$ to zero ? I believe you will then have more than 90 % capture efficiency.

J. GAREYTE : This would have implied a lot of hardware changes. But as seen in Fig. 1 a gain of $\sim$ 10 % in efficiency would be possible.

K.H. REICH : Single-turn synchronous transfer into the CPS will be used (at 800 MeV) as soon as the PSB becomes operational. At (50 MeV) injection into the booster, $\dot{B} \approx 0$ and programmed adiabatic increase of RF voltage and synchronous phase angle are planned, which give, on paper, multiturn capture efficiencies > 95 %.

R.L. MARTIN : Did you get any idea of incoherent space-charge defocusing forces by investigating the resonances as a function of intensity ?

J. GAREYTE : We made no systematic investigations.