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FAST CAPTURE OF HEAVY IONS IN THE CERN PS BOOSTER

F. Pedersen, N. Rasmussen, H. Schönauer

Abstract

In the context of the CERN Lead Ion Facility now near to completion, the PS Booster will accelerate Pb^{53+} ions from 4.2 to 95.4 MeV/u. For these ions the cross-sections of charge exchange with the residual gas are very large and give rise to substantial loss with the vacuum conditions achievable. An effort to accelerate as quickly as possible, in particular at low energies, pays off in overall transmission. However the rapidly shrinking area of the bucket at the very fast rising magnetic field tends to reduce capture efficiency at early acceleration.

The paper describes computer and machine studies performed to optimise the capture efficiency at the beginning of the magnetic cycle (dB/dt = 0) as well as for injection and capture later, at higher values of dB/dt. A novel method of evaluating the capture efficiency is employed.

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In the context of the CERN Lead Ion Facility now near to completion, the PS Booster will accelerate Pb^{53+} ions from 4.2 to 95.4 MeV/u. For these ions the cross-sections of charge exchange with the residual gas are very large and give rise to substantial loss with the vacuum conditions achievable. An effort to accelerate as quickly as possible, in particular at low energies, pays off in overall transmission. However the rapidly shrinking area of the bucket at the very fast rising magnetic field tends to reduce capture efficiency at early acceleration. The paper describes computer and machine studies performed to optimise the capture efficiency at the beginning of the magnetic cycle (dB/dt = 0) as well as for injection and capture later, at higher values of dB/dt. A novel method of evaluating the capture efficiency is employed.

1 INTRODUCTION

Although the PS Booster has accelerated light ions, accelerating highly but not completely ionised heavy ions is impossible without substantial modifications. The most significant effects are due to the large cross-sections of charge exchange processes between circulating ions and the residual gas at low energies [1]. The obvious cure is to improve the vacuum but achieving a low pressure such as to guarantee negligible transmission losses is out of reach with the existing machine. One remedy is to accelerate as fast as possible, at least during the low energy phase. Figure 1 showing the computed lifetime of the nominal Pb ions versus of their energy, illustrates the importance of the low energy phase.

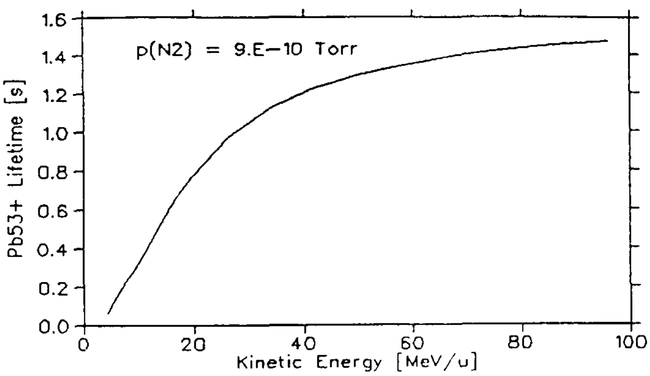

Figure 1. Life-time of Pb^{53+} versus kinetic energy in the PS Booster.

If the pressure of N_2 or equivalent gases is 10^{-9} torr or higher the losses are such that it is worthwhile to capture and accelerate the beam very rapidly and accept some longitudinal and transverse losses which arise, and we have prepared ourselves for this eventuality.

The longitudinal losses arise because of the very fast rising bending field; the particles which are captured at a stable phase angle of zero for maximum bucket area, spiralise very fast, and in order to reduce the ensuing transverse losses, the duration of the capture process must be short. Hence the capture is less adiabatic and less efficient.

2 GENERAL PROCEDURE

The usual rate of rise of the magnet supply voltage for the capture of protons in the PSB is about 43V/ms for the generation of the field parabola in the beginning of the cycle.

For the ions we increase the rate of voltage rise to 100 V/ms, which is the maximum value for a proper functioning of the main quadrupole supplies, and the voltage is allowed to rise with this slope, up to its maximum value. In addition we inject the beam at a value of the slope of the field which is about 5 to 6 times higher than the value for protons. This optimum value of the slope at injection is the object of this investigation.

3 CALCULATIONS

3.1 General

Below is given a set of calculated values for parameters which represents a near optimum and is listed in table 1. The constant of adiabaticity k_a is defined as the relative increase of the bucket area divided by the time in terms of the synchrotron period.

Table 1
Parameter values for ions

T MeV/u	Q	A_r a.m.u.	h	k_a	dB/dt]i T/s	dV_m/dt V/ms
4.2	53	207.948	17	2.4	2	100

In order that the particles are accelerated quickly out of the low energy regime, they are captured at a high value of dB/dt and accelerated with a high value of d^2B/dt^2 up to the maximum value of the magnet supply voltage. The value of d^2B/dt^2 is proportional to the rate of rise of the magnet voltage (dV_m/dt), which in turn is limited to 100 V/ms.

The calculations are made with a combination of Mathcad and QuickBasic [2].

3.1 Capture of Ions

The best capture efficiency [3] is obtained with a stationary bucket, that is, when the stable phase angle is zero. If, on the contrary, the beam is accelerated during capture, the gain of time obtained does not outweigh the low capture efficiency then experienced.

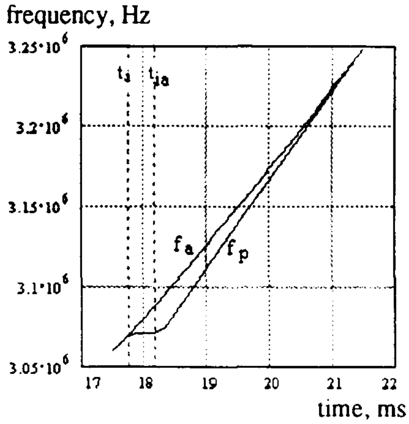

Fig.2. Acceleration frequency (f_a) for $\Delta R = 0$ and programmed frequency (f_p) versus time. Capture takes place in the interval t_i to t_{ia}.

Due to the increasing bending field, the above mentioned constraint means that the trajectories of the particles are spirals approaching the centre of the accelerator and hence, their revolution frequencies increase, but very slightly. To return to a correct orbit again the acceleration frequency subsequently has to increase more rapidly in order to join the field derived frequency i.e., the one for which $\Delta R = 0$. This is illustrated in fig. 2 where f_p is the programmed frequency and f_a is the field derived frequency. Since the phase loop, by nature, reacts very slowly to a frequency input but rapidly to a phase program, it is advantageous to program the stable phase angle as well as the frequency input to the phase loop. The stable phase (ϕ_s) calculated [4] for the frequency f_p, is shown in fig. 3 together with the stable phase angle (ϕ_{sa}) corresponding to a correct orbit.

The evolution of the radial error which appears during capture is shown in figure 4. In the time interval (t_i to t_{ia}) where capture takes place, the mean radius of the beam decreases approximately linearly and thereafter increases due to the programmed frequency until the error becomes zero.

The optimum value of the slope dB/dt is determined by a compromise between the longitudinal and transversal losses. The first mentioned is a function of the duration and adiabaticity of the capture process and of the longitudinal acceptance at $t = t_k$, the second is a function of the maximum radial excursion and the transversal acceptance. The radial excursion is influenced as well by the duration of capture.

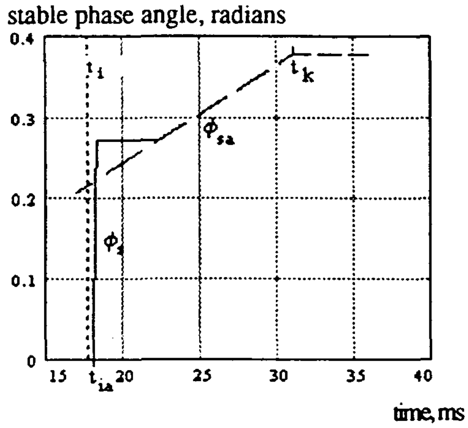

Figure 3. Stable phase angle versus time. Note that the time scale is different from that in fig. 2.

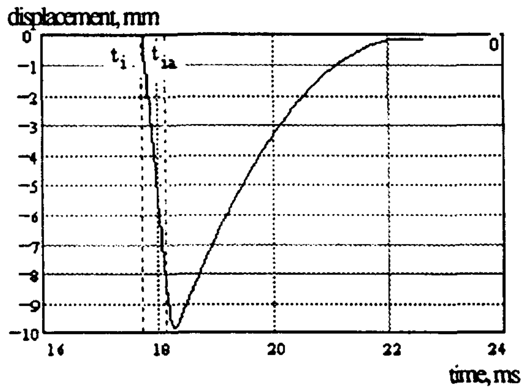

Figure 4. Radial excursion during capture into a stationary bucket.

3.3 Capture Efficiency

The energy spread (2σ) of the injected beam is small, approximately ±5 keV so the gap voltage needed for capture is only a fraction of the voltage needed later on, when the bucket shrinks due to the fast acceleration. During capture the gap voltage rises adiabatically up to a value (3 kV) which is necessary

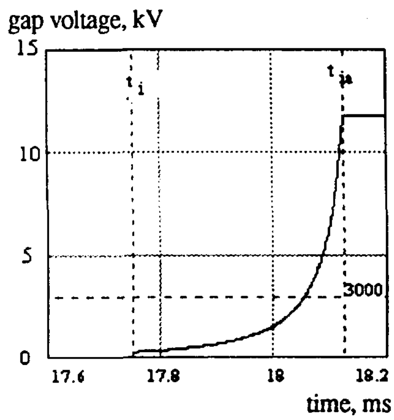

Figure 5. The Iso-adiabatic gap voltage function i.e., the function which ensures constant adiabaticity during capture.

for a good efficiency, and afterwards we let it continue adiabatically up to the maximum possible value (12 kV). This is illustrated in fig. 5.

For calculation of the longitudinal capture efficiency a program has been developed [5]. By this, the particle trajectories are tracked backwards from the separatrix of the final moving bucket at $t = t_k$ to the very beginning of the capture. The locus of the ends of the trajectories encloses an area (see fig. 6) which includes all the particles of the injected beam which are captured in the bucket at $t = t_k$. This area is in the following called a capture region. Particles lying outside the capture regions are lost.

The injected ion beam lies in a ribbon of the width 10 keV symmetrically around zero energy deviation so the captured parts have shapes of parallellograms and the capture efficiency can easily be calculated.

To facilitate the search for an optimum, the capture efficiency and the maximum radial excursion have been plotted versus the adiabaticity coefficient in the figures 7 and 8 respectively.

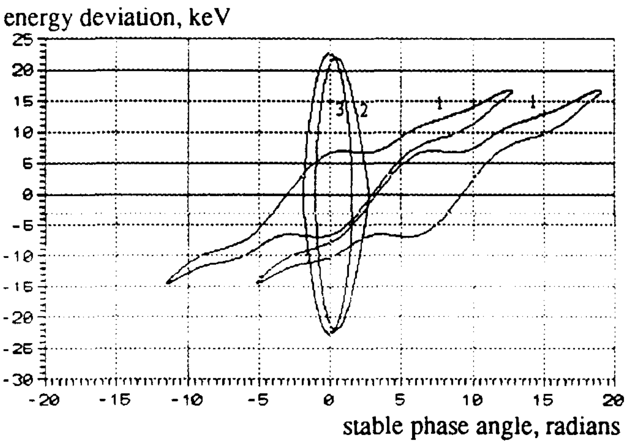

Figure 6. Capture regions (1) for two adjacent buckets. Additionally one final bunch at $t = t_k$ (2), and one bunch at the end of capture (3) at $t = t_{ia}$ are shown.

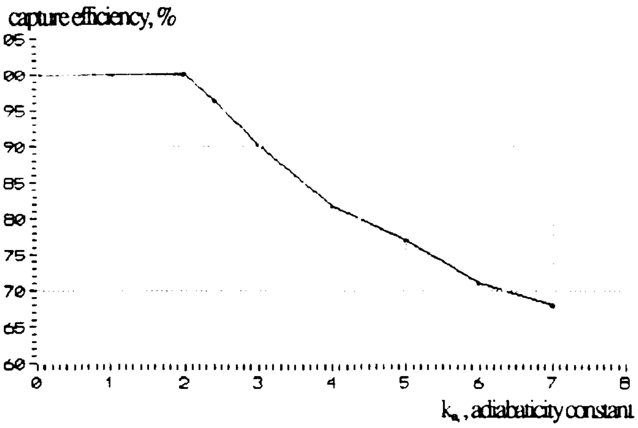

Figure 7. Longitudinal capture efficiency versus adiabaticity constant (k_a).

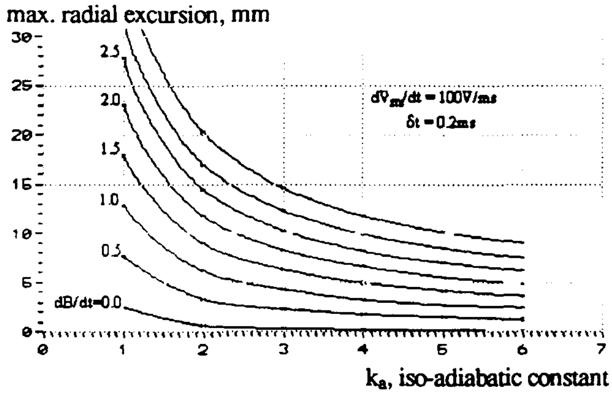

Figure 8. Family of curves for the maximum radial excursion versus adiabaticity constant. The time δt is the interval during which the stable phase rises linearly (see figure 3).

4 MACHINE STUDIES

In order to check the calculations an analogical case to the one just described has been calculated for protons so that it may be tested without the charge exchange losses. The efficiency for this case was found to be about 70%. A capture efficiency for protons of 63% has been measured but this is not yet the maximum. We have also had a coasting beam of Pb ions at injection energy in one ring. The intensity is decaying with a time constant of 20ms so it looks as if fast acceleration will be advisable. Indeed the vacuum must be improved to have a lifetime of at least 60 ms.

5 CONCLUSIONS

To minimise losses due to charge exchanges, parameter values of the capture process of lead ions have been calculated for the optimisation of the transmission through the PS Booster. The result is a compromise betweeen charge exchange, and longitudinal and transversal losses.

6 REFERENCES

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[3] N. Rasmussen, "The Influence of Voltage Function on Capture Efficiency. Low Intensity Studies", CERN, PS/HI Note 92-09, 1992.

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[5] N. Rasmussen, "Tracking Particle Trajectories in the Phase Plane", CERN, PS/HI Note 94-07, 1994.