BEAM DYNAMICS IN SEPARATE SECTOR CYCLOTRONS

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Abstract

Two main topics are discussed.We first present beam behavior with flat-topping and problems related to the double gap nature of our cavities.Results concerning flat-topping parameters and tolerances are given . It is also shown how the gap angle of the cavities influences the choice of harmonic numbers. Then space charge effects are analysed with special attention to space charge compensation by flat-topping phase shift and vortex phenomena.

1. FLAT-TOPPING AND DOUBLE GAP CAVITY EFFECTS

1. 1. Flat-topping

It has been shown (1) that it is necessary to use flat-topping technique to obtain the beam characteristics wanted for GANIL (2). To minimize the frequency range associated with the large energy range we choose the fundamental harmonic h = 2 ,4, 8 and 16 with flat-topping harmonics K = 3 or 5.

Such flat-topping harmonic numbers provide still large usable phase extensions (3) :29° for K = 3 and 22° for K = 5 with $\Delta W/W<4.10^{-4}$, which are to be compared with the 15° injected beam. They require moderate power, flat-topping amplitudes being respectively 12% and 4% of the fundamental one and less stringent tolerances than for K = 2.

Tolerances required on flat-topping set up and regulation have been determined with the multi-particle GOUPIL code (1). It has been found that tolerances need not to be maintained locally everywhere along accelerating gaps, but only in a global manner. In computer runs flat-topping was set to get the minimum energy spread at extraction. Figure 1 shows how the energy spread deteriorates as flat-topping amplitude and phase depart from their optimum values.

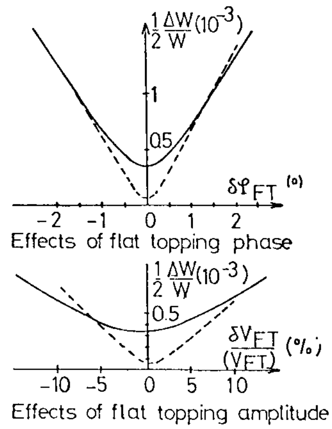

Fig1: Flat topping tolerances
— C_{12}^{+2} dans CSS1 h=8 k=4
---- C_{12}^{+6} dans CSS2 h=8 k=4

In the C_{12}^{+2} case, the beam is injected with a ±0.5% relative energy spread which is theoretically damped to $\pm 3.10^{-4}$ at extraction.

As expected we need rather tight tolerance on phase which has to be kept within ± 0.3°.

Preceding results were obtained for h = 2 , 4, 8 either in SSC1 or SSC2 for various ions and energies. Flat-topping acceleration in double gap cavities performs quite well : relative energy dispersion, radial and vertical emittances behave normally. The study of acceleration with h = 16 in the same double gap cavities (28° gap angle)has also been done ; we were still able to obtain the required energy spread at extraction ; but the evolution of relative energy bunch length and width during the acceleration (fig.2) were quite different from the other cases; radial emittance was increased at least by a factor 2. Such a behavior cannot be entirely explained by either a worst local set up of flat-topping parameters, or a greater difficulty to get isochronism, or coupling between radial and longitudinal extension of the bunch. The reason for such a behavior has been suggested by Dr Lapostolle; it lays in the double-gap nature of our cavities which may introduce a strong coupling between the $\Delta W/W$, $\Delta\phi$ and $\Delta r,\Delta r'$ phase planes.

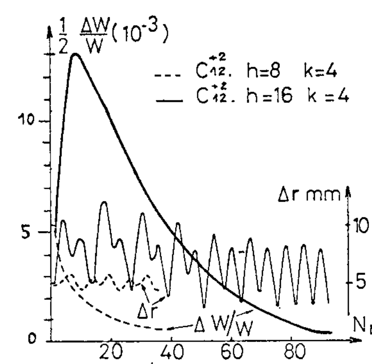

fig 2 = ΔW/W and Δr behaviour during the acceleration with 8th and 16th harmonics

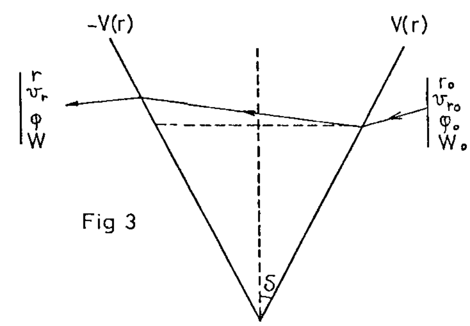

Fig 3

Proc. 7th Int. Conf. on Cyclotrons and their Applications (Birkhäuser, Basel, 1975), p. 245-248

1.2. Double gap cavity effect :

Let us consider a double gap cavity (fig.3). A reference particle chosen inside a bunch enters the cavity with initial coordinates r_o, v_{ro}, ϕ_o, W_o ; final coordinates will be r, v_r, ϕ, W. Other particles initial coordinates can be written as $r_o+\Delta r_o$, $v_{ro}+\Delta v_{ro}$ ... anf final coordinates $r + \Delta r$, $v_r+\Delta v_r$ ...

Now the final variations can be related to the initial variations :

$\Delta r = \Delta r_o + A\Delta r_o/r_o + B\Delta W_o/W_o + C\Delta v_{ro}/v_o$ and same expressions for Δv_r, ΔW, $\Delta\phi$.

One can define for this cavity transit time factors similar to those defined for proton linear accelerators (4). Coefficients A, B, C... are functions of the phase angle ϕ and also functions of transit time factors and their derivative with respect to r. This means that A,B,C ... are functions of the gap angle 2δ and the harmonic number h.

Clearly terms like A may directly produce emittance growth, while terms like C may also produce emittance growth by envelope effect. In addition to that, the magnetic structure of the cyclotron has to be taken into account, and some effects may be either canceled or enhanced depending of the wave number ν_r.

Effects proportional to cos (hδ) disappear in a single gap cavity, or if $\delta=\pi(n+\frac{1}{2})/h$. This is illustrated in figure 4 which shows for h = 16 and K=5 the results obtained with 3 different cavities; single gap cavity and double gap cavity with $\delta = 7°$ produce no emittance growth while double gap cavity with $\delta = 14°$ clearly induces an emittance growth.

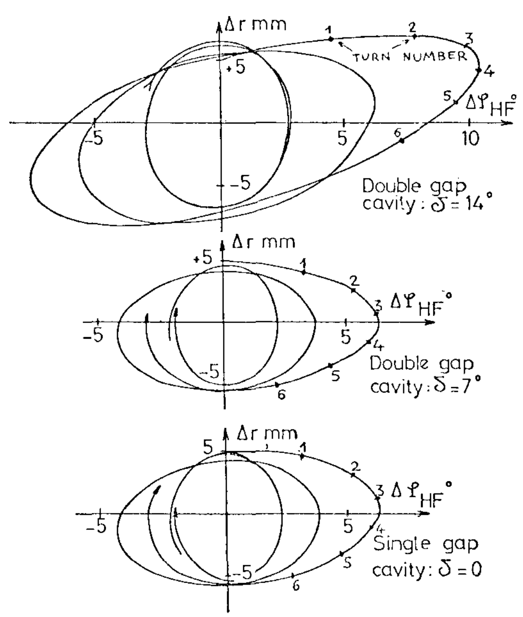

Fig 4 : C^{+2}_{12} accelerated with h=16 k=5
initial conditions: $\Delta\varphi_o = \Delta W_o = \Delta Vr_o = 0$
$\Delta r_o = 5$mm
(TRAJECTORIES SAMPLED ONCE PER TURN)

Theoretical studies and investigations on computer are still in a preliminary step, but it might be possible to treat in a synthetic manner the most general problems of particle dynamics in hard edge separate sector cyclotrons.

Although acceleration on 16th harmonic with 28° double gap cavities produces beams of rather bad quality, it is good enough for our purpose since this mode of acceleration will be restricted to SSC1 in the case of heavy ions (A>40) and low energies (W<16 MeV/A) where the GANIL beam requirements are less stringent.

2. SPACE CHARGE

2.1. It has been shown previously (1) that the most conspicuous space charge effect is to be seen on the energy spread. Due to the longitudinal component of the space charge forces the leading particles of a bunch are accelerated by the rest of the bunch, while the lagging particles are decelerated. The isochronism is not affected by this process, so the bunch is only tilted in the energy-phase plane (see fig.5) Of course the radial dimension of the beam is accordingly increased.

It is rather easy to compensate for that effect particularly in a flat topped cyclotron. One only has to give to the RF flat top a slope opposite to the slope produced by the space charge forces. Leading particles are less accelerated by the RF system than the lagging particles. This is achieved by phase shifting the flat-topping cavities. Figure 6 shows how the energy spread of the body of the bunch is reduced by a 4 degrees phase shift. Figure 7 shows the r.m.s. energy spread of the whole bunch as a function of the RF phase shift. It can be seen in figure 6 that the compensation works only where space charge forces are linear. If the few particles in the non linear region were discarded, the energy spread computed on the body of the bunch would be much less than shown in figure 7.

2.2. Under heavy space charge condition one can also observe the typical effect of radial space charge forces. These forces add to the Laplace force of the main magnetic field and destroy the isochronism. Outer particles of the bunch move toward the tail of the bunch, inner particles toward the head. In other words vortices are formed, as was predicted by Dr Gordon (5). Figure 8 shows how the bunch spins in the horizontal plane. As the bunch spins, longitudinal and radial dimensions ($\Delta\phi$ and ΔR) are periodically swapped, producing alternate phase expansion and compression. Fig. 9 et 10 show the beginning of such a mechanism. With a suitable ratio of the radial over longidudinal dimension, the bunch would turn on itself and appear as being stationary. As pointed out by Dr Lapostolle a spherical bunch would be stationary while the angular velocity around the vortex center is proportional to the beam intensity. This can be simply derived from the gyroscopic equations of the motion (assuming ν_r=1) and from the linearized expression of the space charge forces :

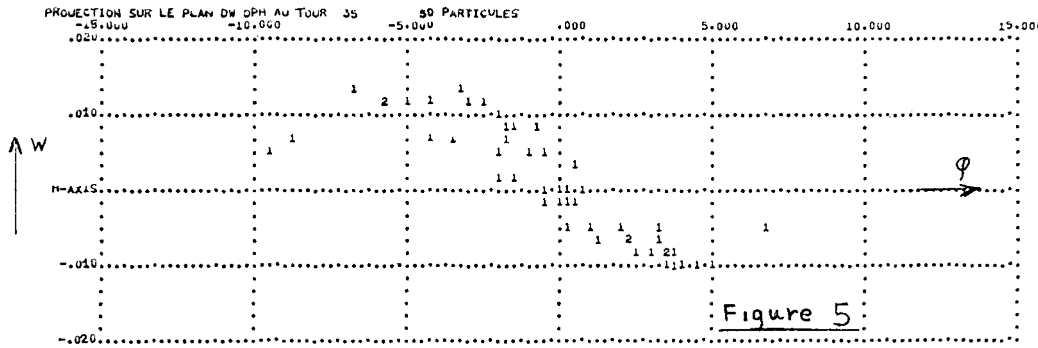

Figure 5

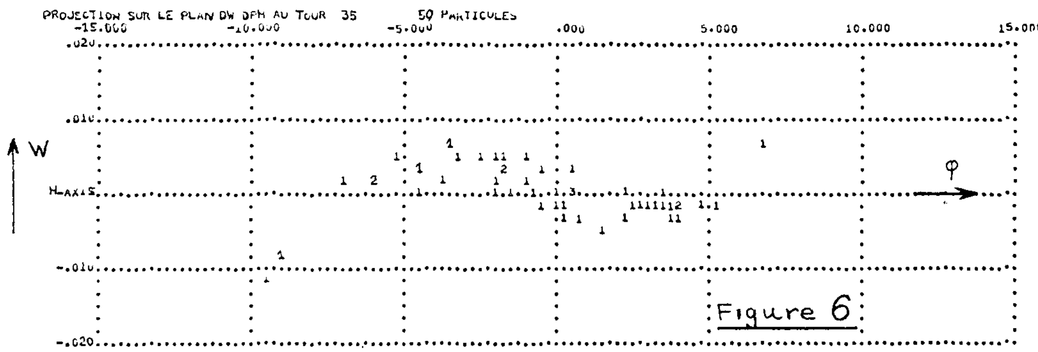

Figure 6

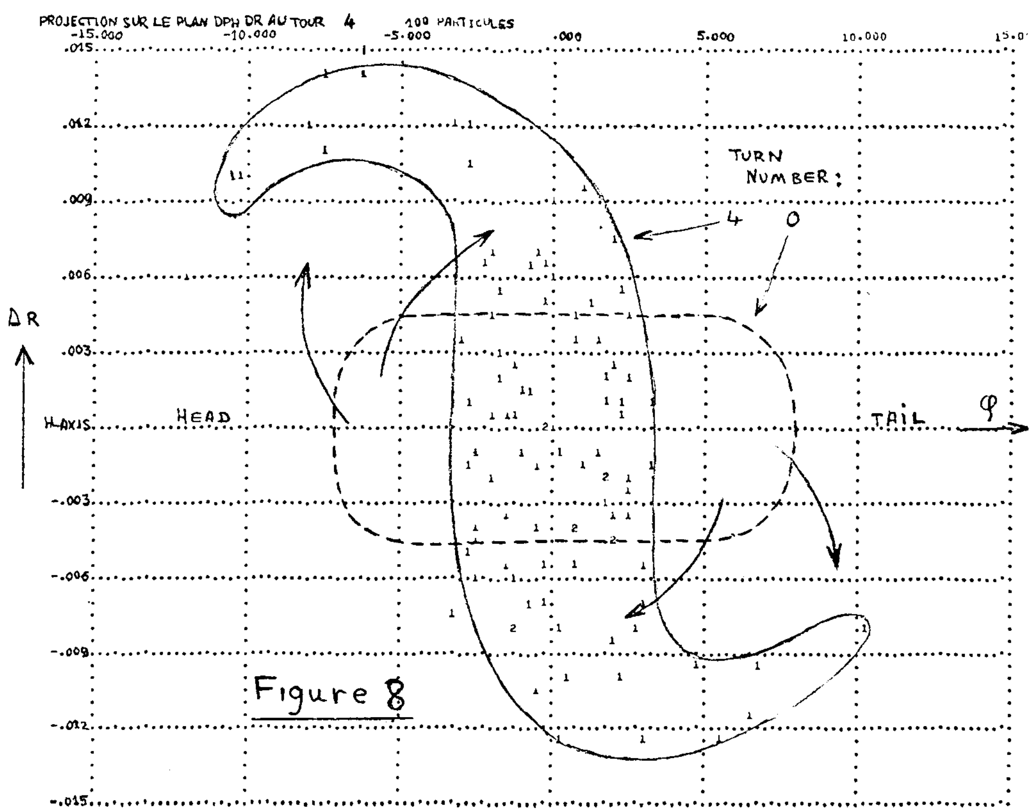

Figure 8

$$\begin{cases} \dfrac{d(\Delta s)}{dt} = \dfrac{r F_r}{m v_s} \\ \dfrac{d(\Delta r)}{dt} = \dfrac{r F_s}{m v_s} \end{cases} \qquad \begin{cases} F_r = K_r I \Delta r \\ F_s = K_s I \Delta s \end{cases}$$

where r and s are the radial and longitudinal coordinates.

2.3. Figures 5,6,7 are related to the behavior of a 200µA beam of C^{+2} in the first separate sector cyclotron SSC1. Such a beam would produce 5.10^{13} ions/s at the output of SSC2 at 85 MeV/A. That is 10 times the required intensity. Figures 8,9,10 are related to a 200 µA beam of U^{+6} in SSC1 that would produce 5.10^{12} ions/s at the output of SSC2 at 4 MeV/A, 50 times more than the required intensity.

The numbers of ions per second are calculated assuming a 0.25 source duty factor and a 0.6 efficiency per SSC.

ACKNOWLEDGEMENTS

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