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SUMMARY

We routinely accelerate up to micro-amperes of ions at energies ranging from 25 to 95 MeV/A. Already at these levels, space charge (S.C) problems drastically affect the bunching efficiency between the ECR external ion-source and our Co compact injector. Moreover in the "2.5" version of GANIL we expect currents above 50 eμA (Ar+6 for instance) and S.C effects will be of prime importance during acceleration in the injector and even in our first SSC. We present our computer codes and our first results.

INTRODUCTION

The ECR external ion-source was used for the first time at the end of 1985 and almost immediately we noted a strong decrease of the transmission between the source and the CO2 injector outputs when the source intensity was increased. Figure 1 shows the experimental results : without buncher the transmission turns out to be of the order of 3.5% for the whole range of intensities and the gain given by the bunching system decreases very rapidly (from 6 to 1) when the injected intensity increases from 10 eμA to 100 eμA : S.C effects are obviously very important.

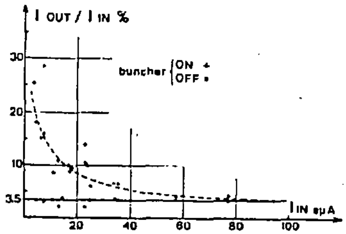

Fig.1

In the "2.5" version of GANIL which is carried on[1] we not only aim to widen the energy and ion ranges of GANIL but also to increase the intensities by a factor 10 or even more if possible, at least for some ions like Ar or Kr where the ECR is not the limiting item. Moreover, we dream of a very high intensity version of GANIL suited to intense exotic beam production ; such an improvement certainly implies a new small separated sector injector.

So, the present, near future and long term of GANIL are obviously related to our capabilities of solving the S.C problems which will occur, if not already the case, either in the beam lines or in the injector and the first SSC.

SPACE CHARGE IN CYCLOTRONS

Multiparticle code developped at GANIL[2] : the three dimensional multiparticle code NAJO was developped in the case of a 4 separated sector cyclotron but in fact, it can accommodate any magnetic field configuration and its main limitation comes from the shape of the accelerating gaps which are presently restricted to radial ones.

Accelerating field effects are expressed as kicks applied at the gap centers and the equations of particle motion in the magnetic field are integrated using the 4th order Runge-Kutta method with a constant integration step of 1° ; the magnetic field itself being introduced point by point in the median plane.

At azimuths chosen at will we can ask for graphical and numerical outputs concerning the 6 coordinates of each particle and the bunch dimensions always defined as two times the RMS value of the related distribution

$$\Delta x = 2\sigma_x \quad \text{with :} \quad \sigma_x^2 = \int_{-\infty}^{+\infty} u^2 p(u)\,du \Big/ \int_{-\infty}^{+\infty} p(u)\,du \qquad (1)$$

In the same way, the two dimensional emittances are defined by :

$$\varepsilon_x = 4\pi\left\{(\overline{\Delta x^2}-\overline{\Delta x}^2)(\overline{\Delta x'^2}-\overline{\Delta x'}^2)-(\overline{\Delta x\,\Delta x'}-\overline{\Delta x}\,\overline{\Delta x'})^2\right\}^{1/2} \qquad (2)$$

S.C effects are taken into account by kicks applied on each particle at given azimuths (n times per turn). The S.C forces are computed using the equivalent distribution[3]

$$X = X_0 \cdot \exp\left\{-\frac{1}{2}\left[\frac{\delta\varphi^2}{\sigma_\varphi^2}+\frac{\delta r^2}{\sigma_r^2}+\frac{\delta z^2}{\sigma_z^2}\right]\right\} \qquad (3)$$

which gives : (x stands for φ, r or z)

$$F_x = \frac{Q^2 e^2}{(2\pi)^{3/2}\varepsilon_0} \cdot \frac{\dot{N}}{F_{HF}} \cdot I_x \cdot \delta x \qquad (4)$$

with

$$I_x = \int_0^{\infty} \frac{\exp\left\{-\frac{1}{2}\left[\frac{\delta\varphi^2}{\sigma_\varphi^2+t}+\frac{\delta r^2}{\sigma_r^2+t}+\frac{\delta z^2}{\sigma_z^2+t}\right]\right\}}{2(\sigma_x^2+t)\left[(\sigma_\varphi^2+t)(\sigma_r^2+t)(\sigma_z^2+t)\right]^{1/2}}\,dt \qquad (5)$$

The three kicks are easily deduced from the Fx, x stands for r or z, δs is the distance travelled between two kicks :

$$\begin{cases}\delta W = F_\varphi \cdot \delta s \\ \delta(p_x/p) = (F_x - F_\varphi \cdot p_x/p)\cdot\delta s/(m_0 c^2 \beta^2 \gamma)\end{cases} \qquad (6)$$

Presently we do not take into account neither image effects nor the influence of the adjacent bunches. On the other hand, the equivalent ellipsoid is always oriented along the φ-r-z axis and centered on the reference particule so that we do not take into account the possible r-φ correlation but this will be done in a near future.

Space charge effects in SSC1 : in the "2.5" version of GANIL, SSC1 will accelerate all ions at energies ranging from 4 to 15 MeV/A. To illustrate the S.C effects we choose the case of Ar+8 accelerated from ≈ 540 KeV/A to 7.5 MeV/A (FHF = 10MHz, h = 5, 64 turns). S.C kicks are applied 8 times per turn, at the valley and sector center lines and the bunch is simulated by 100 particules.

We first compare the results from our code to the ones obtained from theoretical calculations in the case of an isolated bunch at constant energy (no acceleration). Considering a uniformly charged ellipsoid (Ar=Az,Δφ) the S.C forces are[4]:

$$\begin{cases}F_r(0,r) = Qe\rho/2\varepsilon_0 \cdot (1-g(T)) \cdot r = K_r \cdot r \\ F_\varphi(\varphi,0) = Qe\rho/\varepsilon_0 \cdot g(T) = K_\varphi \cdot \varphi\end{cases} \qquad (7)$$

$$0.1 \leq g(T) \leq 0.33 \quad \text{for} \quad 3 \leq T = \Delta\varphi/\Delta r \leq 1$$

In the case of Δs = 15mm (~5°4), Δr = Δz = 5mm and 5.10^{14} pps we find Kr = 16.6 MeV/m² and Ks = 3.7 MeV/m². On fig.2, we compare these result with those given by our code (same Δr, Δz, Δs but different σ for the two distributions !)

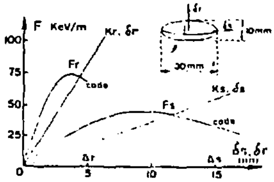

Fig.2 : comparison of S.C forces as given by formulaes (7) and as computed in the code

In the axial phase plane we have :

$$\nu z.\delta\nu z \simeq Kz.R^2/(4.A.W) \qquad (8)$$

Fig.3 shows the axial oscillations for N = 0 and N = 5.10^{14} pps : $\nu z(0) \simeq 0.885$, $\nu z(N) \simeq 0.825$ so that $\delta\nu z$ = -0.060 to be compared to $\delta\nu z \simeq$ -0.064 as given by the formulae (8).

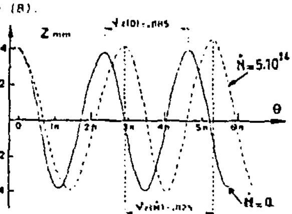

Fig.3

On fig.4 we see the vortex effect due to Fr, the period of the oscillation is 20 turns ; from the formulae used by M.M. GORDON[5]

$$\frac{d\delta\varphi}{dt} = -\frac{h F_r}{A m_0 \omega R} \quad ; \quad \frac{d(\delta W/W)}{dt} = -\frac{\omega R}{A.W} F_\varphi \qquad (9)$$

we can deduce :

$$\Omega \simeq Rc/(A\sqrt{2m_0c^2W})\cdot\sqrt{K_r.K_\varphi}$$

which gives an oscillation period of 10 turns with our parameters.

From these very crude comparisons we can however conclude to a rather good agreement : in the formulaes, forces are always taken as Fr(0.δr) and Fz(δs.0) that means overestimated, moreover the distributions are different and the real ellipsoid does not remain of revolution, its shape changes under S.C forces.

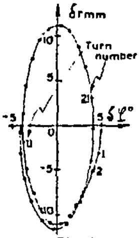

Fig.4

We now simulate the acceleration of an Ar beam into SSC1. In the axial phase space, due to the high value of νz, we do not expect any trouble up to 1 emA (~10^{13}pps) : $\delta\nu z$ remains < 0.2 and νz will never approach critical values ; the axial emittance increase remains quite small at the SSC1 output.

In the median plane, the bunch behaviour is much more complicated due to the strong δW-δr and associated $\delta\varphi$-$\delta r'$ couplings and to the vortices due the radial S.C force.

From the fig.5 which shows the $\Delta W/W$ and $\Delta\varphi$ behaviours of the beam as a function of the turn number for various intensities, we can draw the following comments :

– $\Delta W/W$ increases very quickly during the first turns then it is damped as W increases and the S.C forces decrease but this damping is in fact mainly due to the strong decrease of the phase spread

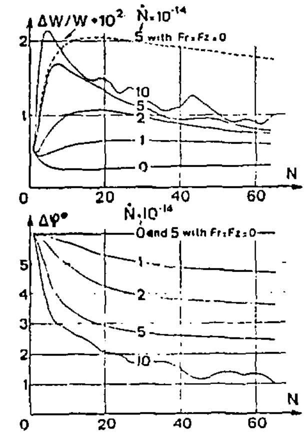

Fig.5

– if we impose Fr = 0, not taking Fs into account, we no more observe the $\Delta\varphi$ and the associated $\Delta W/W$ dampings (vortices are no more present). That is what happens in a machine where the turn separation is low enough so that the local vortices inside the individual bunches are negligeable

– the Δr shown on fig.6 are related to the $\Delta W/W$ and not so much to the radial S.C force.

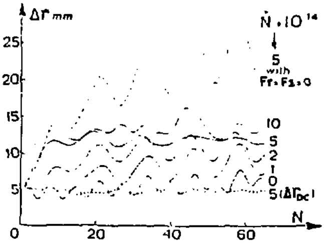

Fig.6

This can be seen looking at the uncorrelated Δr of the bunch (Δr_{DC} =-r/2.$\Delta W/W$). In fact, in our case, the monochromatic radial emittance is not strongly affected but as our νr is very close to 1 (1.07) we will have to check very carefully the case of an imperfect machine where, due to S.C forces, the νr =1 resonance can be crossed near injection.

Another illustration of these behaviours is given on fig.7 which displays, during the first 20 turns, the pattern of two particles in the $\delta\varphi$-δr space for various intensities and on fig.8 which shows the bunch projections at injection and after 1 and 6 turns for a given intensity (5.10^{14}pps).

Fig.9 shows the bunch projections at ejection for 0.2 and 5.10^{14}pps : most of the particles (>90%) remains in a small emittance but of course we observe a filamentation and particles in the tails will be lost in the ejection channel.

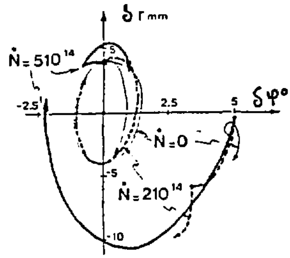

Fig.7

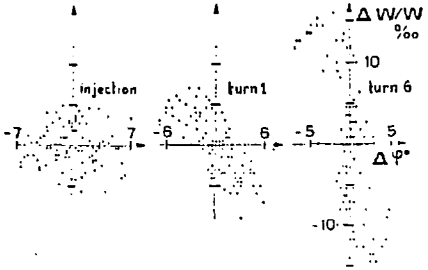

Fig.8

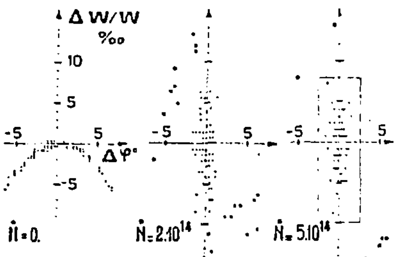

Fig.9

Space charge effect compensation in SSC1 : when the local vortices are strong, the isochronism is destroyed and each particle no longer remains at a given phase versus the central one so that compensation of S.C forces by a flat-topping cavity seems very difficult even if we chose to compensate locally (on the first turns) and not on the mean during the whole acceleration. Moreover, the compensation to be done depends on the intensity, energy and type of ions so that a flat-topping system covering the whole range of our SSC1, even if possible would be a highly sophisticated device and its tuning very difficult. As a matter of fact, in our simulations we were not able to find out a really good compensation !

However, as noted by M.M. GORDON, $d\delta\phi/dt$ given by Fr could be counter balanced by a $\delta B/B$ and we can play very easily with the field pattern and the input central phase. In this case, each particle of the bunch remains at a more or less constant phase versus the central one so that we can obtain a certain amount of compensation which might be improved by a flat-topping cavity. Fig.10 shows the result obtained by a slight $\delta B/B = -7.10^{-5}$ associated with a change of the phase of injection $\delta\phi inj = -7°$.

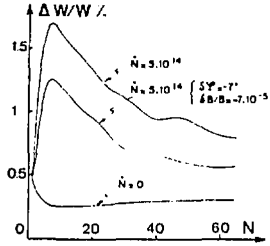

Fig.10

Space charge effects in the compact injector : due to the large phase and energy spreads accepted by our compact injector ($\Delta W/W$ of a few % and $\Delta\phi \simeq 15$-$20°$), the influence of the longitudinal S.C force on the energy spread is hardly seen at least up to some hundreds of eµA. As a consequence, the radial emittance is not much affected and the effect of vortices is of minor importance below 1 emA.

On the contrary, due to the weak vertical restoring forces (νz<0.2) the vertical S.C effect is important.

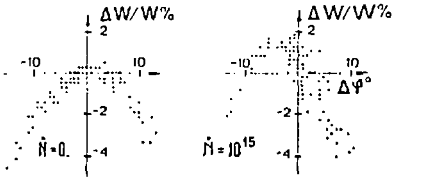

Fig.11

The fig.11 shows the output bunches in the $\Delta\phi$,$\Delta W/W$ plane in the case of Ar+6 accelerated from 28.5 KeV/A to 640 KeV/A at 10 MHz (h = 3) for N = 0 and 10^{15} pps (~ 1 emA). At this current level we begin to see the shift in energy of the front and tail ions and a slight phase spread decrease. If room were available a flat-topping cavity would certainly be efficient in such an injector.

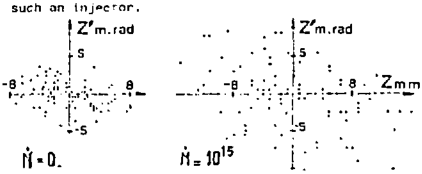

Fig.12

For this same case fig.12 shows the z, z' plane : emittance has been multiplied by a factor ≃ 5.

TRANSFER LINE AND BUNCHING

The main problems concern the longitudinal bunching and the coupling effects introduced by the inflector needed for the axial injection in our compact injector. Two codes have been developped :

Just in order to get very rapidely an idea of what happens in the $\Delta\phi$ - ΔW space, we wrote a very simple code CHADIS using uniformly charged discs of constant radius to simulate the bunches. The results we obtain (after an adjustment of the disc radius) being in rather good agreement with the experimental measurements we think that this code can be used to obtain a first feeling of what has to be done in order to improve the bunching efficiency. As we can see on fig.13 the ECR ion source has to be at as high a potential as possible and we hope to be able to use a 100 kV platform. On the other hand, there is an optimum of the bunching length depending on the beam intensity and on the energy acceptance of the injector as we have to accelerate a wide range of intensities the best choice coincides with the shortest length for I = 0 which still gives an acceptable energy dispersion.

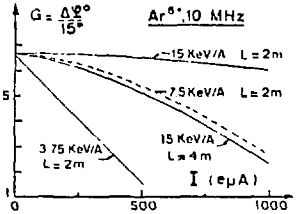

Fig.13 : Buncher gain versus injected intensity for various energies and drift length as given by CHADIS

A more powerful code is necessary to define with precision a transfer line and we have adapted an existing one.[2] This code (GALOPG) using the matrix formalism includes the linear treatment of the S.C forces in the 3 dimensions and allows for an optimization of the transfer line parameters in order to adjust at will the terms of the 6X6 transfer matrix of the line as well as those of the 6X6 covariant matrix of the beam for a maximum of ions. Besides the usual optical element, GALOPG includes bunchers as well as every element of which the transfer matrix including S.C effects is known (for instance the injector inflector). In particular, this code allows very smooth transition from a continuous to a bunched beam. In its original version its results were in good agreement with multiparticle codes.[3,4]

The very first results given by GALOPG concern the transfer line from our ECR ion source to the inflector input of the CO injector. The fig.14 concerns the case of an O^{+2} beam in our present beam line (W=1.4 KeV/A, f = 10 MHz, a single gap buncher and a drift length of 3.3m) and displays the intensity which is accepted in a phase spread of 20° versus the source current :

- results given by the 3 dimensional GALOPG code (curve 4) concerned a beam always maintained matched in the transverse phase space and a resulting uncorrelated ellipse in the $\Delta\phi - \Delta W$ plane. The same results are again obtained with a cylindrical beam of 10mm radius all along the line.

- using this same equivalent radius in CHADIS we find the curve 3.

If the two codes show the same behaviour of the beam in the $\Delta\phi - \Delta W$ plane where they can be compared, the numerical results differ by a factor 2 which comes partly from the various constraints imposed to the beam in GALOPG but mainly to the fact that in CHADIS. The disc radius to be used is not equal to the real equivalent beam radius in the line.

These results are representative of our beam line, the very low accepted and transmitted currents are due to the very bad location of our buncher and to the very low extraction voltage at the ECR : we will as soon as possible move a double-drift harmonic buncher much nearer to the injector and in the "2.5" version of GANIL put the ECR at a high potential.

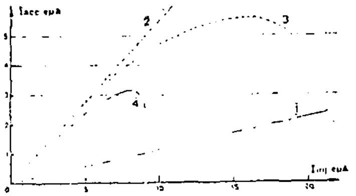

Fig.14 : Bunched current ($\Delta\phi$ = ±40°) versus injected one ($\Delta\phi$ = 360°)

- without space charge : without buncher (curve 1) with buncher (curve 2)

- with space charge and buncher (CHADIS : curve 3, GALOPG : curve 4).

CONCLUSION

Our codes, NAJO for the cyclotrons and GALOPG for the lines, are certainly two good tools for studying space charge problems. Nevertheless we will develop multiparticle codes (particles in cells) in order to confirm from time to time the results given by NAJO and GALOPG.

Concerning the case of GANIL, SSC1 is certainly able to accelerate currents around 1mA, some ions in the tails will be lost but due to the low energy (<15 MeV/A) we do not expect much trouble (power and radiations).

In the case of our compact injector, due to the axial emittance increase, it will be limited to intensities below 100 eµA.

The problems related to the line from the ECR to the injector is much more complicated due to the inflector and to the matching which as to be done. Nevertheless a good position of the buncher together with a higher injection energy will ease these problems.

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