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A POSSIBLE DESIGN OF AN AXIAL INJECTION SYSTEM INTO THE PROPOSED SUPERCONDUCTING CYCLOTRON AT ORSAY

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Abstract.- The Orsay proposal of a superconducting cyclotron (K_B = 600, K_F = 220, R_e = 0.87 m) is based on two types of injection : a radial injection at a few MeV per nucleon from the M.P. Tandem and an axial injection from ion sources like duoplasmatron and EBIS-type, the later one being developed at Orsay.Three harmonic modes h = 2,3 and 4 will be used with R.F frequencies ranging from 24 to 62 MHz.The axial injection system is based on an electrostatic mirror centered on the cyclotron axis,which bends the beam at 90° into the median plane with electrical field less than 30 kV/cm in the vertical direction. A buncher placed between 13 and 20 cm on the axis before the mirror will deliver beam pulses with a phase extension down to ± 1.5° and with an efficiency of 50%. At each harmonic mode there is a constant geometrical set-up for the buncher and the inflector associated with a fixed value of the injection radius. The two first accelerating gaps have been designed in such a way that the 3 constant trajectories corresponding to each of the harmonic mode have the right electrical phase after a few turns for further acceleration. With these characteristics, space charge effects will limit extracted intensities to values ranging from few 10^{12} p.p.s (in the case of Neon beam) to few 10^{11} p.p.s.(in the case of Uranium beam). Further studies are in progress.

1. Introduction.- With the recent developments on ion sources capable of delivering highly stripped ions together with good emittance, axial injection systems into a superconducting cyclotron appear as a very attractive possibility. In the case of the Orsay proposal (K_B=600, K_F=220 and R_e= 0.87 m), ions ranging from protons (up to 200 MeV) to Uranium (up to 25 MeV/A) will be accelerated using a R.F frequency range from 24 to 62 MHz covering the three harmonic modes h = 2,3 and 4 of the orbital frequency. Moreover it will be highly desirable to bunch the injected beam on a very short time of the order of ± 1.5° of electrical phase for light and medium ions, and of ± 3° for ions heavier than Krypton, so that good quality beams in intensity and in time and energy resolution will be produced.

The various aspects of the axial injection are the following :

a - Beam transport from an external ion source along the cyclotron axis down to the entrance of the inflector.

b - Inflector design which bends the beam at 90° into the median plane.

c - Central geometry of the accelerating gaps in order to match the injected trajectories with the "centered equilibrium orbits".

d - Buncher design for phase grouping.

e - Space charge effects.

f - Emittance and beam stability.

The present paper deals with topics a - e for which a first theoretical and simplified approach has been undertaken in order to establish some technical options. These are based on two criteria :

- the central geometry of the accelerating electrodes must be compatible with each harmonic mode.
- there is a constant geometry for the buncher, the inflector and for the trajectories, depending only on the harmonic mode.

The basic parameter which determines this geometrical set-up and the trajectories characteristics, is (see fig.1) :

$$p = \frac{Z_i}{A} B^2(0) \qquad (1)$$

where Z_i and A are the usual charge and mass numbers of the ion, B(0) the magnetic field supposed uniform in the central region. For each harmonic mode, the geometry is calculated with the maximum value of p, the maximum voltage of the 1 cm wide accelerating gaps being chosen at V_{max} = 100 kV. For a certain ion (Z_i , A) at a certain energy, one has only to change the buncher, inflector and accelerating gap voltages. In the case of a superconducting cyclotron, difficulties with axial injection arise because of lack of space and high magnetic field.Nevertheless in our case, the need to accelerate protons make things easier and one is able to define dimensions higher than 1cm, especially for the radius of the injection trajectories (which are circles).

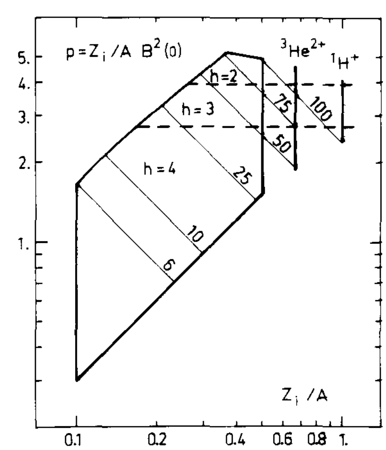

Fig.1 : Diagram of the possible values of $p = \frac{Z_i}{A}B^2$ (0) and the regions of utilization of the 3 harmonic modes h = 2,3,4.One shows also the constant energy lines indicated in MeV per nucleon.

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2. Beam transport to the inflector.- First order calculations have been performed on the beam transport along the axis. This beam has been supposed to be of revolution with a normalized emittance $\epsilon_N = 1.5\pi \times 10^{-7}$ m x rad . Because of the good focusing properties of the cyclotron magnetic field along its axis, and making use of two solenoidal coils placed outside the machine, one produces any ellipse of emittance at the entrance of the inflector. So beam spot less than 1 mm can be obtained.

3. Inflector and central geometry.- In order to have the smallest inflector, well shielded against the radiofrequency, an electrostatic mirror has been considered. It is centered on the axis of the machine and inclined at around 45° with respect to the median plane. For each harmonic mode, the maximum value of the z-component of the electrical field is set at 30 kV/cm. The trajectories make an angle less than 52° at the exit of the inflector, corresponding to a transit angle $\alpha_s = \omega t$ of 105° ($\omega = \frac{Zie}{Am_o}$. B(0). In these conditions, trajectory calculations using a 2-dimensional model for the gap with a uniform electrical field V_{max} sin(h $\omega t + \phi$), lead to a central geometry compatible with the 3 harmonic modes. So, injection for each harmonic mode is possible on the same electrode, provided that the two first accelerating gaps are twisted in such a way that after a few turns each of the three trajectories has the right phase for further acceleration (matching to a "centered accelerated orbits").

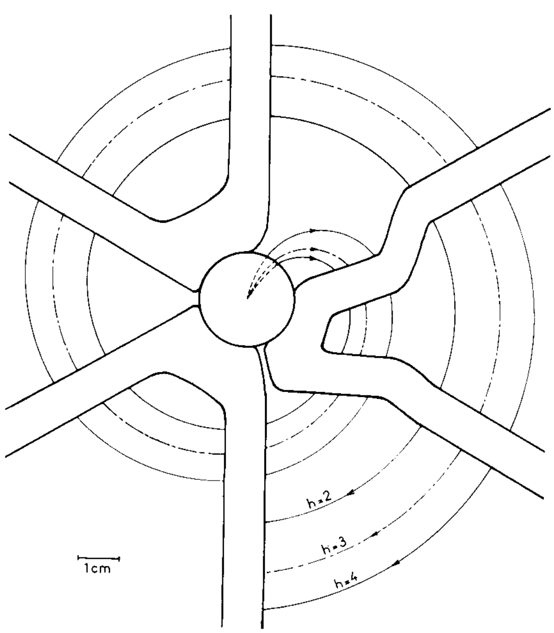

Fig.2 : Constant trajectories in the median plane corresponding to each harmonic mode, and shapes of the first accelerating gaps.
The inflector is centered inside a circle of radius ≅ 1 cm.

h	$\frac{Zi}{A}B^2(0)$ (max)	a) α_s (deg)	b) ρ_{inj} (cm)	c) ϕ_E (deg)	d) gain (1st gap)	d) gain (2nd gap)
2	5.168	104.	1.15	-91.74	75	90
3	3.930	92.	1.34	-121.95	86	95
4	2.693	77.	1.65	-144.60	89	92

a) α_s/ω = t = transit time in the inflector

b) ρ_{inj} = injection radius ; the source voltage is V(kV) = 4.824 $p\rho^2_{inj}$.

c) ϕ_E = electrical phase at the entrance of the first accelerating gap (V = V_{max} sin ϕ_E).

d) gain in percent of the maximum voltage V_{max}=100 kV.

Table 1 : Main characteristics of the centered axial injection (see fig.2)

3. Bunching and charge space limitations.- The characteristics (geometry and voltage) of an electrostatic buncher using a linear velocity modulation are determined by the following considerations :

- The maximum velocity modulation $\delta v/v_o$ must be compatible with the beam energy resolution required at the extraction. Calculations show that one can accept $\delta v/v_o = \pm 5\%$ and that the limiting factors are within the inflector itself. For a certain bunching efficiency R , this 5% limit determines the minimum distance D between the buncher and the edge of the first accelerating gap, through the relation :

$$\frac{\delta v}{v_o} \simeq \pi R \frac{\rho_{inj}}{hD} \qquad (2)$$

- The intrinsic noise ΔV_o on the voltage V_o of the ion source, limits the ultimate bunching phase $\Delta\phi_f$ to :

$$\Delta\phi_f = -\frac{1}{2}\frac{h\,D}{\rho_{inj}}\frac{\Delta V_o}{V_o} \qquad (3)$$

In order to minimize this last effect, the buncher should be the nearest possible to the inflector. For $\Delta\phi_f = \pm 1.5°$, R = 50% , ΔV_o = 50 eV , V_o = 30 kV and $\frac{\delta v_o}{v_o}$ = 5% , the compromise will be D = 19 cm, 15 cm and 13 cm between the buncher and the entrance of the inflector for h = 2, 3 and 4 respectively. These figures take into account the transit time in the inflector. Moreover the size of the buncher is fixed for each harmonic mode, especially if one used two bunchers in cascades working on the fundamental and second harmonic of the R.F. frequency (this design allows to obtain R = 50% and $\Delta\phi_f$ = 1.5°).

Because the bunching of the beam in so small a bunch is considered, charge space effects come into play. Because the tranverse and axial dimensions of these bunches are of the same order of magnitude $\ell \cong 2\pi R \frac{\rho_{inj}}{h}$ (before bunching), one has used a simplified but pessimistic model to calculate the maximum number N of particles per second (p.p.s) available in the extracted beam. This model considers the bunches as spheres of initial radius $r_o \cong 0.2$ cm compressed to a certain value r_1 due to the velocity modulation acting against the electrostatic repulsion. The limiting factor $\frac{r_1}{r_o}$ depends on a parameter $\lambda = \tilde{\lambda}$. N.A where

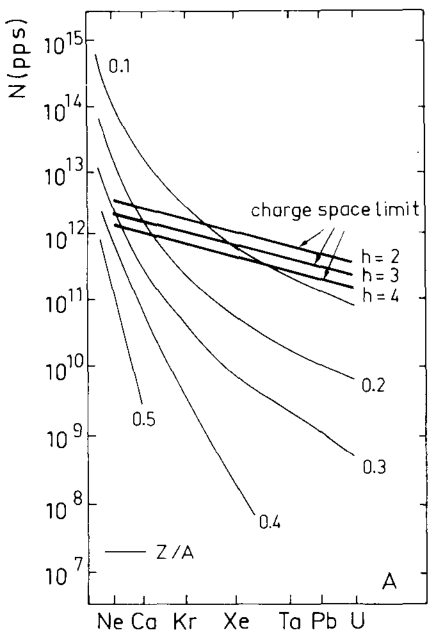

Fig.3 : EBIS-type of an ion source : inferior limits of the intensities N (p.p.s) at the cyclotron exit for electronic beam density of $J_c = 10^4$ A/cm². One supposes an overall 10% efficiency. The charge space limit related to a ± 1.5° bunching has been estimated within the frame of the "spherical bunch" model. (eq. 4,5,6).

A is the mass number and :

$$\tilde{\lambda} = 9.72 \times 10^{-25} \frac{p^{-3/2}}{h\ \rho^2_{inj}} \left(\frac{Z_i}{A}\right)^{1/2} \text{(meter)} \qquad (4)$$

It turns out that the quantity $\tilde{\lambda}$ is nearly independent from $\frac{Z_i}{A}$ within the $(p, \frac{Z_i}{A})$ diagram of fig.1. In order to bunch the beam from $\Delta\phi_i$ to $\Delta\phi_f$,one easily shows that the following condition has to be fulfilled:

$$\lambda < \frac{r_o}{2} \frac{\Delta\phi_f}{\Delta\phi_i} \left(\frac{\delta v}{v_o}\right)^2 \qquad (5)$$

Taking into account a possible efficiency of 10% between source and extraction, relation (5) leads to the following limit for N :

$$N < 0.1 \times \frac{2\pi}{\Delta\phi_i} \frac{1}{\tilde{\lambda}} \frac{1}{A} \frac{r_o}{2} \frac{\Delta\phi_f}{\Delta\phi_i} \left(\frac{\delta v}{v_o}\right)^2 \qquad (6)$$

which shows a simple 1/A dependance. With the above parameters, there is a limit set at few x 10^{12} p.p.s for a Neon beam and few 10^{11} p.p.s for a Uranium beam. These limits are compatible with the expected performance for an EBIS-type source (excepted for moderatly stripped light ions), as can be seen on fig.3.

4. Conclusion.- These preliminary calculations show the feasibility of an axial injection system into the proposed Orsay cryogenic cyclotron. Crucial points, like the possibility of having 30 kV/cm electrical fields in the inflector will have to be investigated. More sophisticated calculations on the central geometry and 3-dimensionnal electrolytic tank measurements of electric fields are now underway.