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AN ACHROMATIC BEAM TRANSFER SYSTEM WITH A STRONGLY NEGATIVE EQUIVALENT LENGTH

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Abstract.- An achromatic beam transfer system using six identical magnetic dipoles is presented. Its strongly negative equivalent length enables the system to compensate the time spreading effect of a 65 metres long drift space. This value can easily be adjusted between 40 and 90 m. with the use of tuning quadrupoles making possible an isochronous transfer between the tandem terminal and the cyclotron injection.

1. Coupling of a tandem with a cyclotron.- In the Orsay project which couples a tandem with a cyclotron, the time structure of the tandem beam (continuous) has to be matched to the phase admittance of the cyclotron i.e. a few degrees of phase at a radius of 20 cm and for H.F. frequencies of 24 to 62 MHz used on harmonic 2 to 4. Such a matching is usually accomplished with two bunchers. A first one is associated with a chopper and works at a few hundreds keV at the injection in the tandem. The second buncher is a high energy one and is placed between the two machines. Such a system is well known but is associated with the inconveniences of the second buncher, namely those of a high-powered apparatus working at a variable H.F.

The first buncher could in principle produce a sharp time pulse at the injection in the cyclotron by introducing a time-energy correlation at the entrance of the tandem. It is the uncorrelated energy spread introduced by the stripper at the tandem terminal which broadens the particle bunch further down at the injection in the cyclotron. This broadening is calculated here for unrelativistic particles.

Along a drift space of length ℓ, a narrow bunch of particles with a velocity $\upsilon \pm \Delta\upsilon$ (energy $E \pm \Delta E$) will get a width $\Delta\ell$ given by

$$\frac{\Delta\ell}{\ell} = \frac{\Delta\upsilon}{\upsilon} = \frac{1}{2}\frac{\Delta E}{E} \qquad (1)$$

At the injection radius R in the cyclotron, $\Delta\ell$ corresponds to a phase angle $\theta = \frac{\Delta\ell}{R} \cdot h$ for the harmonic h. For $R = 0.2$ metre and ℓ given in metres

$$\theta_{\text{degrees}} = \frac{1}{2}\,\frac{\ell h}{R}\,\frac{180}{\pi}\,\frac{\Delta E}{E} = \frac{h\ell}{70}\,10^4\,\frac{\Delta E}{E} \qquad (2)$$

$\Delta E/E$ being given at the energy corresponding at the entrance of the cyclotron, $\ell = L + L'$ where L is the equivalent length of the second half of the tandem and L the physical length of the transfer line.

Table I gives these quantities for a sampling of ions and charge states.

The broadening width given in the last column of Table I is to be compared with the phase width (1.5 to 3°) compatible with the final energy spread (2 to 4 10^{-4}) at the exit of the cyclotron. For the light and medium ions it would be possible to reduce the energy spread by a convenient setting on the tandem beam energy analysis and to accept the relatively small corresponding beam-intensity lost. But for the →

ion	Terminal Voltage (MV)	Charge State	Energy Straggling $\frac{\Delta E}{E} \times 10^{+4}$	Tandem equ. length L(metres)	Total * equ. length ℓ(metres)	Number of harmonic h	Phase width θ degrees
^{16}O	12.	2	.72	30.	80.	2	1.7
^{32}S	13.	4	.77	44.	94.	2	2.1
^{58}Ni	13.	5	.83	55.	105.	2	2.5
^{80}Br	14.	6	.82	61	111.	2	2.7
^{124}I	15.	6	1.2	61.	111.	2	4.0
^{124}I	15.	9	2.9	85.	135.	2	11.3
^{197}Au	15.	12	2.5	110.	160.	3	17.0
^{197}Au	15.	13	2.4	120.	170.	3	17.4

* a L'=50 m. long transfer line has been assumed

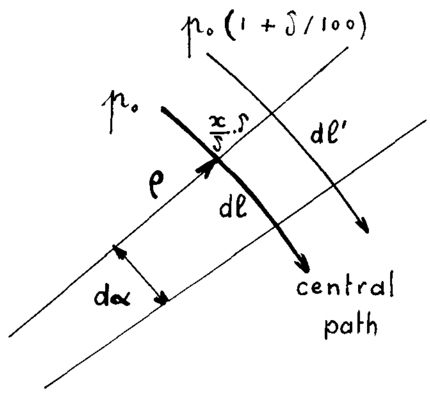
Table I. Final relative energy spread, tandem and total equivalent length and phase width at the entrance of the cyclotron for different ions and charge states. L and ΔE/E are from [1]. The first part of the table is for a gas stripper(.1 to .3μg/cm²). The second part is for a carbon foil stripper (3μg/cm²).

→heavier ions and for the foil stripper (the thickness inhomogeneity has not even been taken into account) this intensity lost would become prohibitive and either the use of a second buncher must be introduced or else a system has to be designed with a strongly negative equivalent length in order to compensate for the (positive !) 30 to 120 m. equivalent length of the second half of the tandem. In such a system, a dispersive point must also be present to allow for the driving of the tandem terminal voltage.

2. Generation of a negative equivalent length by a magnetic dipole : the $R_{56} = \ell/\delta$ matrix element of "TRANSPORT".- In order to obtain a negative equivalent length i.e. a system after which the fast particles will be late, one has to lengthen the paths of the fast (high-energy) particles and to shorten those of the slow ones. One or several magnetic dipoles can generate this difference of paths.

We shall use first order approximation and notations of "TRANSPORT" [2].

For the central trajectory (radius of curvature ρ the elementary path length is $d\ell = \rho d\alpha$



For a relative increase δ of magnetic rigidity, the trajectory is displaced by

$$\frac{x}{\delta} \cdot \delta = R_{16}\delta$$

where $R_{16} = x/\delta$ is the local linear dispersion of the system.The corresponding elementary path length is then

$$d\ell' = (\rho + R_{16}\ \delta) d\alpha$$

leading to a path length difference

$$\Delta\ell = d\ell' - d\ell = R_{16}\ \delta d\alpha$$

Hence $$R_{56} = \frac{\Delta\ell}{\delta} = \int R_{16}\ d\alpha = \int \frac{x}{\delta}\ d\alpha \qquad (4)$$

Where $d\alpha$ is the element of angle of the central trajectory. The integral being then limited to the dipoles.

Comparison between (4) and (1) shows that R_{56} is just the measure of the negative (if $\Delta\ell/\delta > 0$) equivalent length of the system : the ability the system possesses to cancel the effect of a drift space of length R_{56} .

Taking account of the fact that it is $-\Delta\ell/\delta$ which is printed out for R_{56} in "Transport" (if a value zero has been given to the particle mass - see further down), there won't be any effect on the width of the particle bunch if :

$-R_{56}$	$= \ell = L + L'$	$= \int R_{16}$	$d\alpha$
cm/% or metre	metre	cm/% or metre	radian

where L is the drift space to be compensated R_{56} the ℓ/δ term of the compensating system and L' its physical length.

The question then arises how to generate a strong R_{56} . A single dipole is not efficient since R_{16} starts from zero , and $R_{56} = \int R_{16}\ d\alpha$ will increase very slowly with α . Indeed for a uniform field magnet of radius ρ , $-R_{56} = \rho\ (\alpha - \sin\alpha)$. The compensating power $-R_{56} - L' = -R_{56} - \rho\alpha = -\rho \sin\alpha$ peaks, for $\alpha = 3\pi/2$, at ρ , far away from the value $L \sim 100$ m. which is looked for. The use of a non uniform field (index n as large as possible) increases R_{56} but not enough if the index is limited to a reasonable value.

An attempt is then made to separate two functions : i) generation of the dispersion R_{16} ii) compensation i.e. generation of $R_{56} = \int R_{16}\ d\alpha = \overline{R_{16}}\ \alpha$. If one neglects the R_{56} of the first part of the system and the change of R_{16} in the second part, $\overline{R_{16}}$ is the dispersion which has to be produced by the dispersive part if α is the total deflection angle of the compensative one. For $\alpha \sim 2$ to 3 radians, R_{16} must be $\sim$ 30-50 cm/% or metres so that $R_{56} \sim 100$ m.

Again, for a dipole, $R_{16} = \rho\ (1 - \cos\alpha)$ is found ten times smaller than expected. This factor could be regained by a magnifying set of quadrupoles but with the specific difficulties of alignment and tuning and it is preferable to utilize the "natural" magnification of the linear dispersion by the working of the angular dispersion along a simple drift space. With a single dipole the angular dispersion $R_{26} = \sin\alpha$ would require too long a drift space. But if two dipoles are coupled with inverse rotations, the resulting R_{26} is strongly enhanced since, with two dipoles of 80°, R_{26} is found a value 60 mr/% = 6 metres (instead of 1.) leading to $R_{16} = 50$ in less than 10 metres.

3. Description of the system.- The proposed compensating system is based on the use of six identical magnets which are set as indicated on fig. 1. The two first dipoles are coupled to generate the angular dispersion (the linear dispersion found at the focal point D can be used for the tandem energy control). After a long enough drift space, a third magnet is inserted to generate the compensation. In order to optimize the use of this magnet, a zero angular dispersion is imposed in the middle of it. The trajectories are then refocused towards a zero linear-dispersion point I . The system is made achromatic by adding to it the symetrical system of again three identical magnets (linear and angular achromatisms are necessary to insure that the path lengths are independant of the initial angle and abscissa). Note that the initial object distance can then be changed and adjusted in order to fit a further condition without disturbing the total achromatism or changing the value of R_{56}. For the design of the system, the common deviation angle of the magnets is chosen so that the vertical envelope of the beam does not lead to a too large magnetic air-gap; DR_3 can be increased if a larger value of $-R_{56}$ is needed while the pole face angle ϕ is then also slightly increased to keep the condition on R_{26} ($R_{26} = 0$).Note that one pole face angle is fixed at zero.

4. Tuning of the system.- Note that so far, nothing but dipoles have been used, in order to reduce the problems of alignment. But if R_{56} is to be tuned while keeping the achromatism, quadrupoles are inserted (just after the control point D) in order to change the local angular dispersion hence the linear dispersion at the place of the compensation. Two quadrupoles are needed in A and B so that the condition $R_{16} = 0$ is preserved at point I . The symmetrical quadrupoles B' and A' are needed for the total achromatism. The used quadrupoles are 25 cm long and separated by 25cm. Their diameter is 10 cm.

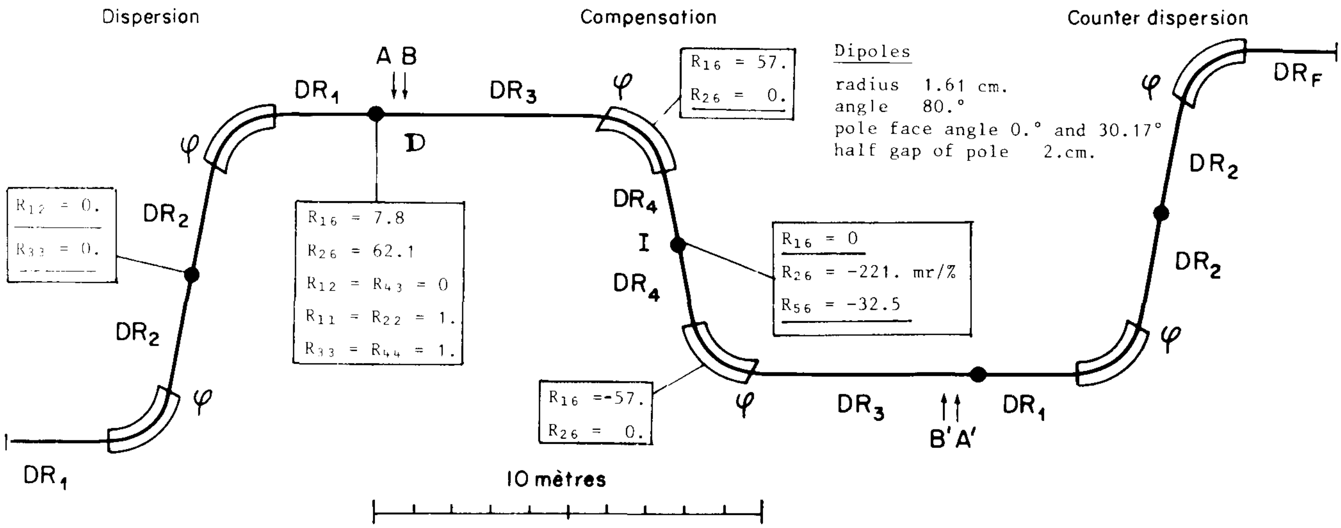


Fig.1 : Scheme of the compensating system. When an identical label is used at different places (Dr_1, ϕ...) the corresponding elements are kept equal during the fitting procedure. Among the different (R) matrix elements which are given, the constraint ones have been underlined. (* R_{56} = − 32.5 at point I corresponds to $-\ell/\delta$ = 65 + L' altogether).

5. Results of the calculation.- Several results have already been given in fig.1, they will be completed here in the table II with the value of R_{56} for three different setting of the field in the tuning quadrupoles and by the final R matrix in two cases. There is some confusion concerning the value of R_{56} because it can be simply $-\ell/\delta$ (if a mass equal zero is entered in TRANSPORT) or it can include the spreading effect of the physical length L' of the compensating system (if a non-zero mass is entered). Both have been indicated in the table while the value shown in the R matrix is the compensated length L for slow heavy ions (no relativistic effects)

Table II.- Value of $-R_{56}$ and the compensated length for two setting of the tuning quadrupoles and with no quadrupoles.

	$Q_A = Q_{A'}$ field at the tip kG	$Q_B = Q_{B'}$ field at the tip kG	$-R_{56}$ * $\ell = -\ell/\delta$ metres	$L = -\frac{\ell}{\delta} - L'$ metres
a)	− 0.411	0.127	143.	92.
b)	0.0	0.0	116.	65.
c)	+ 0.411	−0.147	90.	39.

* L' length of the compensating system
L=ℓ−L'= compensated length for heavy ions at tandem energies

R matrix at the end point symetrical of the initial point : DRF = DR_1 = 2.617 metres with no tuning quadrupoles (case b)

1.99421	.05614	.00000	.00000	.00000	.00000
53.02508	1.99421	-.00000	.00000	.00000	.00002
.00000	.00000	.94628	-.03591	.00000	.00000
.00000	.00000	2.91203	.94628	.00000	-.00000
.00000	.00000	.00000	.00000	1.00000	-65.00001
.00000	.00000	.00000	.00000	.00000	1.00000

R matrix at the last horizontal focal point (DRF=2.329 m) for the larger compensated length (case a)

.45694	.00000	.00000	.00000	.00000	.00000
50.03311	2.18849	-.00000	.00000	.00000	.00000
.00000	.00000	1.42795	.36426	.00000	.00000
.00000	.00000	3.21622	1.52073	.00000	.00001
.00000	.00000	.00000	.00000	1.00000	-91.94407
.00000	.00000	.00000	.00000	.00000	1.00000

6. Conclusion.- The compensating system with a strongly negative equivalent length which has been presented is well adapted to the compensation of the tandem for charge states from 2 to 9. To go further if needed, a small change in the geometry of the magnet and/or in that of their coupling could be done to increase the central value of R_{56} . The span of the values obtained by tuning could also be easily enlarged. The symetries encountered in the designing of the system should minimize some elements of the second order transfer matrices. Preliminary calculations have been done indicating that the effect of these terms should not destroy the time structure of the particle bunch for a standard emittance of a tandem. Sextupoles could otherwise be introduced.

The presence of two points with a strong dispersion (D and its symmetric) can be used to separate the two functions of driving the tandem terminal and to analyse the beam energy if necessary.

As regard as building and running prices, the use of six fully identical magnets, hence possibly the use of a single power supply, could made this system competitive with the use of a high energy buncher associated with the necessary achromatic beam transport with its also necessary analyzing part.

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References

1. A.CABRESPINE, GEPL, 07/81/22 et 23, I.P.N. ORSAY (1981)
2. K.L. BROWN, SLAC, Report n°75, revision 3
K.L.BROWN, F.ROTHACHER, D.C.CAREY, Ch.ISELIN, SLAC 91, Rev.2, or CERN 73-16 or NAL 91.