Deutsches Elektronen-Synchrotron (DESY)
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DESY-Bibliothek

DESY A 2.5

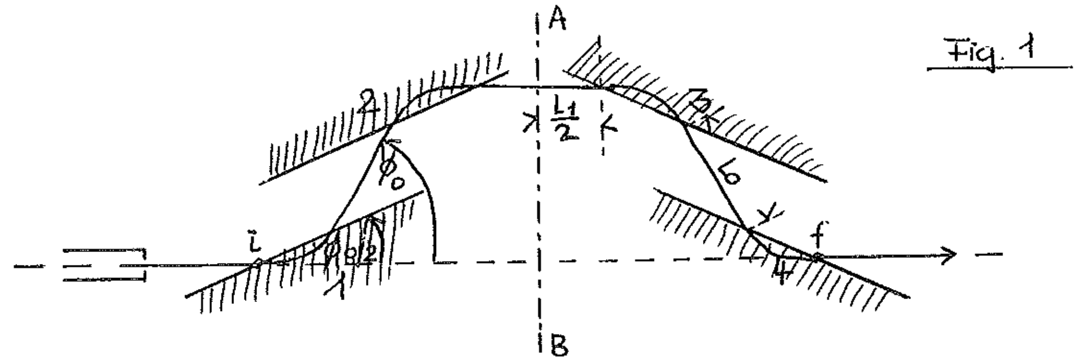
Hamburg, October 19, 1957
M 4 - Dr.Ti.

Description of magnetic debuncher for electron Linacs

Following a proposal of Allan J. Lichtenberg (CEA 13, CEA 22) it is possible to reduce the energy spread at the output of a linear accelerator by introducing an energy dependant phase spread and applying a reverse voltage to the particles. It has been examined in more detail, what exact shape a static magnetic field must have in order to introduce that phase spread (chapter 1). The way in which the reverse voltage may be applied is contained in chapter 2 of this scripture, and possible datas and tolerances of a debuncher are discussed in chapter 3.

1) Shape of static magnetic field

The idea is to bend particles of different energies through different angles by applying a static magnetic field in such a way, that they emerge on their original line of travel. It can be shown that a difference in path length results, which means a phase spred with respect to the linac acceleration frequency. Fig. 1 shows a possible arrangement of fields, indicated by the shaded areas, which is symmetrical with respect to the line AB.



Let the fields be separated by field free lengths L_o, L_1. The figure shows the path of a particle of the principal energy, say "W_p = 40 MeV, which enters the magnetic field under the angle $\phi_o/2$ between particle direction and field limit. This particle is bent by field 1 through the angle ϕ_o, with radius of curvature

$$R = \frac{Wp}{c \circ B} \qquad (1)$$

(Wp in eV, $c = 3 \cdot 10^8$ m/sec, B in Vsec/m^2 = magnetic field). After traversing the field free space of length L_o it is bent another time through the angle $-\phi_o$ and intersects the symmetry line at right angle at a distance $L_1/2$ from field 2. The particle is bent on its original path by the second half of this field arrangement (3, 4). All fields have equal fieldstrength B. We will call this the "principle path" of the particle and introduce coordinates s parallel to that path, and r perpendicular to it, in the plane of movement.

Not it is essential to know how the particle behaves, if it deviates in energy $W \neq W_p$, amplitude $r \neq 0$, and angular divergence $(dr/ds) \neq 0$ from the principal particle at the input point i (see Fig. 1).

If $W-W_p = \Delta W \neq 0$, but $r_i = 0$, $(dr/ds)_i = 0$, the radius of curvature differs from equ. (1) by

$$\Delta R = R \circ \frac{\Delta W}{W_p} \qquad (2)$$

The angle through which the particle is bent remains ϕ_o as before. Therefore, this particle intersects the symmetry line AB at right angle and emerges with $r_f = 0$, $(dr/ds)_f = 0$ as the principal particle. The resulting difference in path length with respect to the principle particle is calculated to be

$$\Delta L = 4 \cdot \Delta R \cdot (\phi_o - \sin \phi_o) \qquad (3)$$

if both particles are injected at the same time. This means, that particles with positive energy deviation have $\Delta L > 0$ and, therefore, slide back with respect to the principal particle, while others with $\Delta W < 0$ are ahead.

An electron with $\Delta W = 0$, which deviates from the principal path by $r_i \neq 0$, while $(dr/ds)_i = 0$, will leave the system with $r_f = r_i$, $(dr/ds)_f = (dr/ds)_i = 0$, as can be seen easily from geometry.

A particle with $\Delta W = 0$, which deviates from the principle direction by $(dr/ds)_i \neq 0$, while $r_i = 0$, will leave the system with

$$(dr/ds)_f = (dr/ds)_i \tag{4}$$

$$r_f = 0, \text{ if } L_1 + 2L_o = 4 R \cdot \sin \phi_o \tag{5}$$

The result (4) is evident from geometry, while (5) involves a more elaborate calculation.

Finally, a particle differing in energy, amplitude, and angular divergence from the principal particle, $\Delta W \neq 0$, $r_i \neq 0$, $(dr/ds)_i \neq 0$, will have the final excursions:

$$(dr/ds)_f = (dr/ds)_i \tag{6}$$

$$r_f = r_i + \left[4 \Delta R \sin \phi_o + 2 r_i \cdot \operatorname{cotg} \frac{\phi_o}{2}\right] \cdot \left(\frac{dr}{ds}\right)_i \tag{7}$$

With ΔR from equ. (2), and with the assumption, that condition (5) is fulfilled. The deviation from the initial values is a second order effect, that can be neglected.

It is thus seen that the above system has the properties desired: it spreads particles with different energies in phase, equ. (3), while it leaves deviations from the principal path in amplitude and angle unaltered within a linear approximation.

2) <u>Application of reverse voltage</u>

As the energy of the electrons leaving the linac is of the order $\pm$ 1 MeV, the application of the reverse voltage by a single cavity of standing wave will be difficult because of the high amplitude in voltage needed. It is easier to use a piece of travelling wave guide, in which the electrons with principal energy enter at zero phase.

Assuming that the electrons have no phase distribution as they enter the debuncher, they will have the following **phase** distribution at the output with respect to the synchrotron frequency:

$$\psi = \Delta L \cdot \frac{2\pi}{\lambda} = \frac{4\omega}{eBc^2} (\phi_o - \sin \phi_o) \cdot \Delta W = K \cdot \Delta W, \tag{8}$$

which is a linear relation with respect to ΔW. If L is the length of the waveguide, and E the axial electric field, which is assumed to be constant over the guide, the final energy spread as a function of Ψ will be:

$$\Delta W_F = \Delta W(\Psi) - e \cdot L \cdot E \cdot \sin\Psi \qquad (9)$$

Here it is assumed, that the reverse voltage guide operates on the same frequency as the main guide, to which Ψ is related. Both guides have to be connected by a phase shifter in order to shift the particles of principal energy to zero phase.

The dependence of ΔW_F from Ψ, which is proportional to ΔW, after equ. (9), is given qualitatively in Fig. 2.

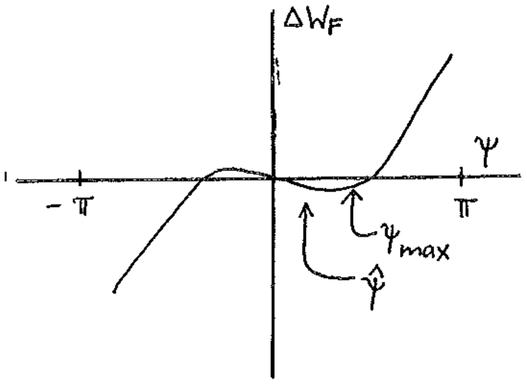


Fig. 2

The maximum final energy deviation may be calculated from equ. (9). By differentiating (9) with respect to Ψ one finds the angle $\hat{\Psi}$ at which the maximum occurs, giving the final maximum deviation

$$\Delta\hat{W}_F = \frac{1}{K}\hat{\Psi} - eLE\sin\hat{\Psi} \qquad (10)$$

3) Dimensions and tolerances

Discussions about practical dimensions have to start from the desired final energy spread $\Delta\hat{W}_F$, which is related to the maximal phase spread Ψ_{max}, obtained by the debuncher, for a specific energy limit ΔW_{max} through equ. (9): if ΔW_{max} be the half intensity point of the energy spread at the exit of the linac, then, by the debuncher, we will obtain a phase spread with the limits

$$\Psi_{max} = K \cdot \Delta W_{max} \qquad (11)$$

This determines the factor of $\sin\Psi$ in equ. (9) if we demand that ΔW_F vanishes at $\Psi = \Psi_{max}$:

$$e \cdot L \cdot E = \frac{\Delta W_{max}}{\sin \psi_{max}} \qquad (12)$$

$$\Delta W_F = \frac{1}{K} \psi_{max} - \frac{\Delta W_{max}}{\sin \psi_{max}} \cdot \sin \psi \qquad (13)$$

If we regard ΔW_{max} as fixed, $\hat{\Delta W}_F$ will be the smaller, the smaller we choose ψ_{max} by suitable choice of K (determined by debuncher). Table I shows the values of $\hat{\Delta W}_F$ for different K with $\Delta W_{max} = \pm 1$ MeV, as computed from equ. (13) for $\psi > 0$ (for $\psi < 0$, all signs are reversed):

Table I

$\psi_{max} = K$ rad	$\hat{\Delta W}_F$ MeV	$\hat{\Delta W}_{F+}$ MeV	$\hat{\Delta W}_{F-}$ MeV
0.90	- 0,060	0,231	- 0,351
0.95	- 0,063	0,213	- 0,339
1.00	- 0,077	0,186	- 0,338
1.05	- 0,082	0,163	- 0,333
1.10	- 0,088	0,151	- 0,326
1.20	- 0,108	0,110	- 0,327
1.30	- 0,131	0,071	- 0,332
1.57	- 0,205	- 0,051	- 0,377

$\Delta W_{max} = 1$ MeV

$\Delta \psi = \pm 15^{\circ}$

On the other hand we have to take into account the phase spread $\Delta \psi$ at the input of the debuncher which for one specific energy deviation ΔW will be the same at the output, giving rise to additional maximal energy spread, derived from equ. (10):

$$\hat{\Delta W}_{F\pm} = \frac{1}{K} (\hat{\psi} \pm \Delta \psi) - eLE \cdot \sin \hat{\psi} \qquad (14)$$

Table I gives these figures under the assumption that $\Delta \psi = \pm 15^{\circ}$. While $\hat{\Delta W}_{F-}$ does not change appreciably with ψ_{max}, $\hat{\Delta W}_{F+}$ approaches zero as ψ_{max} approaches $1,57 = \pi/2$. So if we regard the density of electrons with fail energy $\Delta W > 0$ as constant over the phase interval $\mp \Delta \psi$, an optimum energy-bunching of 33 % can be obtained. In praxi the bunching will be better, because electrons riding ahead of the stable phase,

$\Delta\Psi > 0$, will have less energy, $\Delta W < 0$, so that the density is great for $\Delta\Psi < 0$, small for $\Delta\Psi > 0$. The natural phase-energy relation introduced in the relativistic part of the linac, therefore, favours the debunching effect, and we may choose Ψ_{max} in the vicinity where $\hat{\Delta W_F} = \hat{\Delta W_{F+}}$, i.e.

$$\Psi_{max} = 1{,}20 \text{ rad} \qquad \Delta L \approx 1{,}91 \cdot 10^{-2} \text{ m (equ. (8))} \tag{15}$$

This determines (L · E) after equ. (12). If for inst. we choose E = $5 \cdot 10^6$ V/m = 50 kV/cm, we will have a guide length

$$L = 0{,}215 \text{ m.} \tag{16}$$

The dimensions of the debunching system now, must be regarded from the maximum field realisable. As the field must be exact to a high degree over the whole polefaces, it is not advisable to go above 1 Vsec/m^2 in order to avoid saturation effects:

$$B = 1 \text{ Vsec/m}^2 \tag{17}$$

This, with W_p = 40 MeV determines the radius of curvature after equ. (1):

$$R = 0{,}133 \text{ m} \tag{18}$$

And with ΔW_{max} = 1 MeV we obtain a maximal change in R due to energy deviation, equ. (2):

$$\Delta R = 0{,}00333 \text{ m} \tag{19}$$

Now from equ. (3), with equ. (15), (19), we obtain a value for ϕ_o:

$$\phi_o = 126^o \, 17' \tag{20}$$

The condition for L_o, L_1 is in this case (equ. (5))

$$L_1 + 2 L_o = 3{,}224 R = 0{,}43 \text{ m} \tag{21}$$

Fig. 3 shows a possible field arrangement with these datas and L_o = 1,300 R, L_1 = 0,624 R.

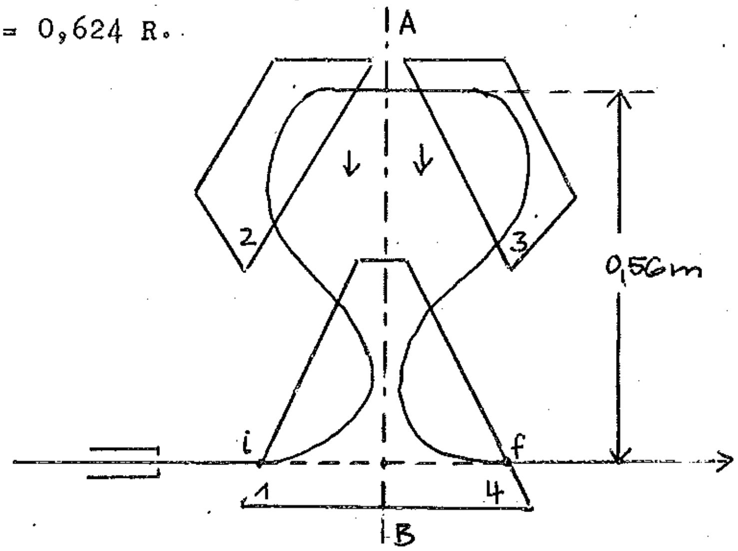


Fig. 3

This set of dimensional datas for the debuncher may, of course, be changed by another choice of B.

As to the tolerances required to retain the focussing properties of this magnetic field arrangement, we have to consider first the stability of the field strength B. A change δB causes an angle deviation $\delta\phi_o$ of the outcoming beam direction: If the maximum divergence of the beam at the exit of the linac is $1 \cdot 10^{-3}$ rad., then we have to demand, that $\delta\phi_o \approx 2 \cdot 10^{-4}$ rad. and consequently a field stable to 10^{-4} results:

$$\frac{\delta B}{B} = \frac{\delta\phi_o}{\phi_o} = \frac{2 \cdot 10^{-4}}{2{,}09} = 10^{-4} \qquad (22)$$

Changes in L_o, L_1 are not critical because one has to adjust the system anyway geometrically, for instance by moving the magnets along AB, fig. 1. This of course implies, that B will be measured absolutely.

More critical is a change in angle between the field limits and the linac axis, because such a deviation enters linearely into the exit beam parameters of the debuncher, see equ. (4). One should demand, that all four field limits are correct in angle to $2 \cdot 10^{-4}$ rad. Fortunately it is possible to correct for relative angle differences simply by joining the two pairs of magnets together (see arrow, fig. 3), so that the required tolerances should be realisable.

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