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ON CONCEPTS AND LIMITATIONS OF MACROPARTICLE ACCELERATORS USING TRAVELLING MAGNETIC WAVES

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I. INTRODUCTION

The acceleration of macroparticles by travelling magnetic waves and for the purpose of achieving impact fusion was suggested by Winterberg and coworkers.^{1,2} The principle is illustrated in Fig. 1. A suitably magnetized projectile is accelerated by the field gradient of a travelling magnetic wave. Depending on the sign of the magnetization the projectile rides ahead or behind the crest of the wave; diamagnetic projectiles are pushed away from, paramagnetic ones are pulled towards the field maximum of the wave. The force (N/m^3) exerted on the projectile is $M dH/dx$, with M being the magnetization per unit volume (T) and dH/dx the local field gradient (A/m^2). The highest acceleration obtainable is $\frac{M}{\delta} \frac{dH}{dx}$, with δ the density of the projectile material.

Naturally, the speed v of the magnetic wave must be synchronized with the projectile speed v_p . The synchronization is automatic if the projectile rides ahead of the maximum gradient dH/dx where a stable position of the projectile with respect to the magnetic wave is possible: if v_p lags behind v the force increases and vice versa. The projectile can work with an induced moment, $M < 0$ if a superconductor or $M > 0$ if a ferromagnet, or else a permanent magnetic moment can be utilized. In the latter case $M < 0$ is preferable because the projectile position is in a lower field, giving a better margin to the critical field of a superconductor or a lower magnetoresistive effect for a normal conductor.

To my knowledge nobody has yet built such an accelerator. The subject under consideration is at the happy stage where the discussion of ideas is unencumbered by the inertia of heavily vested projects. My presentation may be perceived as being between hand waving and back-of-an-envelope calculations;

I would like to think of it, flattering myself, as closer to the latter, although to some, depending on personal standards, it may seem closer to the former.

The topics to be discussed concern: i. the choice of projectile; should it be superconducting or ferromagnetic ? ii. the driving acceleration, the magnitude of which determines the length of a linear accelerator; iii. the guiding acceleration, specially important for a circular accelerator; iv. some options with regard to the power supply, especially suited to the circular version.

At this stage the mentioning of applications will be peripheral. The eventual use of such accelerators could be for impact fusion; prior to that they will be tools in the study of hypervelocity physics. Emphasis on efficiency and economics can await a future phase of the discussion.

II. PROJECTILE

Superconductors

The accelerating force $Md\mathbf{v}/dx$ is transmitted by the maximum Lorentz force $\mathbf{j} \times \mathbf{B}$ that the superconductor can tolerate and this is equal to the forces pinning the flux line lattice. The highest flux pinning forces reported for various superconductors are presented in Fig. 2. As a rule, the superconductor can be used to its full potential only in the form of filaments in a copper matrix. The pinning force averaged over the composite conductor is therefore lower; it may be as high as 40% of the values displayed in Fig. 2. The possible acceleration then reaches into the range of 10^4 to 10^5 times gravity. Indeed, there have been proposals that envisage accelerations of $3 \times 10^5 \text{ m/s}^2$ for accelerators using superconducting projectiles.³

There is a big snag however: the performances illustrated in Fig. 2 apply for superconductor temperatures close to 4 K. With increasing temperature the pinning force drops rapidly. Table I lists the critical temperatures of the two commercially available materials, together with the highest reported pinning forces and the enthalpy difference between 4 K and T_c for a 4 T field.

A heat input equal to the listed enthalpy difference will bring the pinning force to zero. About 10% of the enthalpy will suffice for a reduction to 75% of the pinning force at 4 K. Considering that expected final speeds are in excess of 50 km/s, corresponding to projectile energies of $>10^7$ J/cm³, the accelerator is required to impart this energy to the superconducting projectile with an efficiency $> 10^9 : 1$. Such an unusually tough requirement would jeopardize the success. As an example: the ac loss of a superconductor for a 1 kG peak field is 10^{-6} to 10^{-5} J per cm² surface - and per cycle; for a 0.8 cm³ projectile with 1.5 cm² surface 500 - 5000 cycles would already produce the tolerable (for Nb₃Sn) 10 mJ/cm³ threshold.

Superconductors cannot be considered as suitable projectile material.

Normal conductors

Normal conductors can be used if the current decay time constant is large enough compared to the acceleration time. For small projectiles this is not the case, as the following example demonstrates. A cylindrical projectile, 1 cm long, 0.5 cm diameter and 0.5 mm wall thickness ($L=25nH$; $R=50\mu\Omega$ at RT) would have an $L/R \approx 50$ ms ; acceleration time to 5×10^4 m/s at 10^5 m/s² would be ten times larger. However, for larger projectiles (diameter > 5 cm) normal conducting materials may possibly be an option.

Ferromagnets

For ferromagnetic projectile material the choice is between ferrous metals (Fe Co Ni and their alloys) or rare earth metals. The higher saturation induction of the latter carries the penalty of a lower Curie temperature, as shown in table II. Choosing Dy as the most likely candidate the above mentioned efficiency of the accelerator has to exceed $10^5 : 1$. While not trivial, this is a good deal less forbidding than the four orders of magnitude higher requirement for superconductors.

III. ACCELERATING FORCES

Basic arrangements

The basic components of the proposed magnetic accelerator are indicated in Fig. 3. The projectile A is in the accelerator tube B. The projectile is guided by superconducting shields C. Parallel to the accelerator tube runs a

drive tube D containing flux displacing coils E; these are single coils spaced at regular intervals along the tube. Both accelerator and drive tubes are surrounded by a superconducting (single layer) winding F producing a longitudinal d.c. field. The windings are shorted by a longitudinal resistive conductor G; the shorts serve to give a good flux linkage to the drive coils E.

The device functions as follows. The d.c. field (order of MA/m) magnetizes the projectile. The drive coils energized in proper sequence by a sine wave current concentrate or dilute the flux in the accelerator tube, thus creating the accelerating wave. In the simplest case, each drive coil is contacted with a charged capacitor and left to ring. More sophisticated switching, such as breaking the contact after one full cycle, is desirable to increase the energy efficiency. It is possible to combine accelerator and drive tube into one. The separation, however, has advantages of design flexibility, besides higher amplitudes of the magnetic wave due to the transformer action.

The principle of levitation and guidance is illustrated in Fig. 4. The field H induces the magnetization of the projectile. The superconducting surface does not allow penetration by any magnetic flux; the approaching projectile induces a current pattern preventing flux penetration. The induced current pattern distorts the flux distribution in the same manner as a mirror image of the projectile would do. The repulsive force between projectile and induced current pattern (mirror image) provides the stable guidance and prevents the attraction of the projectile to the current loops.

It is interesting to reflect on the fact that a superconducting projectile, used as a perfect diamagnet, would not need a guide shield; but for a ferromagnet, or a permanent magnet, there is no stable suspension without a guide shield. Earnshaw's theorem, stating that there is no stable mechanical equilibrium for an unconstrained charge in the static field of other charges, is also valid for permanent magnets instead of charges, and also for ferromagnets and transport current distributions. The theorem does not apply to diamagnetic material; it can also be evaded by combining diamagnetic and ferromagnetic materials as was discussed by M. Bevir.⁴

The superconducting guide sheet is therefore necessary, if a complicated servo guiding system is to be avoided.

Of course, the guide sheet need not necessarily be superconducting: a high conductivity metal will do just as well provided the decay time constant for the induced current pattern is long compared to the passage of the projectile, an easily achievable condition. However, non superconducting sheets cause drag.

The guide sheet has to be open because it forms a barrier to changes in radial flux component, and such changes are essential for the establishment of a travelling magnetic wave. It is suggested that the guide tube is in two, or more, symmetric parts to give a symmetric magnetic field distribution at the projectile position. The longitudinal openings in the guide sheet may be helical to give net guidance in all directions along the flight path. The guide sheet will need careful engineering, also, the calculation of guide forces is a difficult problem.

An approximate estimate of the force between guide sheet and projectile (as used in Fig. 7) is obtained as follows. With the projectile touching the guide sheet one can assume that a magnetic pressure of $\frac{1}{2} B_s^2 / \mu_0$ is acting over half the projectile surface facing the superconductor. (B_s is saturation induction, $\mu_0 = 4\pi \times 10^{-7}$ Vs/Am ; for dysprosium the pressure becomes approx. 4.9 MPa.) This will give the maximum available force. For larger separation the force is proportional to d^2 (see Fig.4).

Driving acceleration

To estimate the highest achievable acceleration the arrangement illustrated in Fig.5 is considered. Each flux displacing coil is connected to a charged capacitor C by a switch operated at the right time. The single wire loop of 10 cm diameter and 2 mm wire diameter has an inductance of $L = 0.27 \mu\text{H}$. A change of average induction of 0.2 T in the drive loop represents a flux change of $\Delta\phi = 1.6 \text{ mVs}$. This needs a drive current $I_p = \phi/L = 6 \text{ kA}$. The magnetic wave length determines the time constant thus: $\pi\sqrt{LC} = \Delta t = d/v$, with $d=2\text{cm}$ and $v = 10^5 \text{ m/s}$, $\Delta t=0.2\mu\text{s}$ and $C = d^2(\pi^2 v^2 L)^{-1} = 0.015 \mu\text{F}$ and the necessary charging voltage becomes $V = LdI/\Delta t = L\pi I_p/\Delta t = 25 \text{ kV}$. It is seen that these are all quite manageable values and not beyond the state-of-the-art. The force obtainable with a Dy projectile ($M=3.5\text{T}$, $dH/dx=1.6\text{GA/m}^2$) is

5.6 GN/m^3 and the acceleration $a = 6.6 \times 10^5 \text{ r/s}^2$ or $\approx 500 \text{ km/s}^2$.

At this acceleration a speed of 50 km/s can be reached in a length of 2.5 km.

Two important effects have not been taken into account in this simple calculation. One is the effect of the mutual inductances between the drive coils, the other the effect of the changing inductance due to the moving projectile. The former can be minimized by disaligning neighboring flux displacing loops as indicated in Fig.5. The latter can be minimized by making the projectile small. Energetic considerations give a simple estimate for the tolerable size of the projectile. With the above values the energy stored in each charged capacitor is close to 5 J, adding up to 5 kJ/m along the accelerator. At the above force the energy needed per units of length of accelerator and projectile volume is 5.6 GJ/m^4 , implying that the projectile has to be much smaller than 10^{-6} m^3 ($\sim 8.5 \text{ g}$). A few percent of this, i.e. a projectile of the order of 100 mg will not substantially reduce the above calculated forces.

The large number of switches can be avoided by making use of two arrangements for the production of magnetic waves as previously used for the acceleration of plasmas. One is a lumped parameter transmission line: the example described by Bieger et al.⁵ has the following approximate dimensions: length 60 cm, coils of 6 cm diameter spaced 2.5 cm. A magnetic step wave is produced with a field rise of 2.5 kG in approx. 4cm, it travels with a speed of $2 \times 10^5 \text{ m/s}$ at the entrance and $8 \times 10^5 \text{ m/s}$ at the exit of the structure, i.e. an acceleration of $5 \times 10^{11} \text{ m/s}^2$ is achieved by decreasing capacities and the inductance of the coils with increasing length position. The other, similar arrangement, is a helical transmission line. The one described by Mayfield et al.⁶ has 13.2 turns/m, a diameter of approx. 10 cm and produces an axial field step of 7 kG travelling at a speed of $1.65 \times 10^5 \text{ m/s}$. Capacitors of 0.5 μF at 25 kV are used.

Both lumped parameter or helical transmission lines can be used with little further development as flux displacing drivers (coils E in Fig.3). The advantage is that a single switch can take care of a length of accelerator of 1 m or longer. The acceleration can be achieved with inductances and capacitors that decrease with increasing position coordinate or else with increasingly smaller spacing of the flux linking coils (F in Fig.3). The

anticipated problems will be dispersion and reflection of the step wave and insufficiently sharp step.⁷ These will probably limit the length of such structures to the order of meters.

Guiding force for circular accelerator

The option of a circular accelerator is available because the guiding force can be used to produce the centripetal acceleration $a_{cp} = \omega^2 R = v^2/R$ necessary to keep the projectile with the speed v , or angular speed ω , on a circle with radius R . The centripetal force $F_{cp} = a_{cp} m$ is produced by a combination of attraction and repulsion. The attraction is obtained by the largest possible gradient dH/dr , with H being at the same time the magnetizing field for the ferromagnetic projectile. Repulsion is produced by a superconducting guideway, necessary for stable suspension.

In Fig. 6 a typical arrangement for the production of a strong guiding force is shown. The projectile A is magnetized and attracted by the field of a current flowing in the conductor B. The diamagnetic guide C repels the projectile. Drive coils D produce the magnetic travelling wave.

Naturally, there is a great deal of scope for investigating and developing such arrangements. Applications not only for accelerators but also for levitated transportation, for high and low speeds, can be contemplated.⁸

Two calculated examples give an estimate for the possibilities of the centripetal driving force. In Fig. 7 a and b the attractive and the repulsive force and the resulting sum of the two versus the radial position of the projectile is given. The right hand ordinate indicates a_{cp} for the projectile of 120 mg mass in Fig. 7a, or 60 mg in 7b. It is reasonable to expect a_{cp} in excess of 10^6 m/s^2 . With $a_{cp} = 2000 \text{ km/s}^2$ the radius of an accelerator for speeds of 50 km/s becomes 1.25 km.*

* The city of Baghdad as originally built between 762 - 766 AD under Al Mansur was perfectly circular and almost exactly this size. Of course, there are several modern particle accelerators of circular shape and similar size, either already built or planned.

IV. SOME OPTIONS

For a circular accelerator the striving for a high driving acceleration is considerably relaxed. There are possibilities to use switchless energy transfer⁹ to the driving coils. As the angular speed of a projectile travelling at 50 km/s around a 2.5 km diameter circle is only 42 s^{-1} , or 6.6 rps, one can use a rotor as a flux displacer (in place of capacitors and single turn coils E as in Fig. 3). For this purpose the coils F (see Fig. 3) are arranged around the periphery of a small circle in a way as to link the flux from the pole tips of a special rotor, as illustrated in Fig. 8. The geometric relationship $d/D = r/R$ has to be fulfilled. Taking $d = 1 \text{ mm}$ as a lowest practical limit gives possible dimensions for r and D as in Table III. Assuming a pole flux of 1 T^* and $h = 5 \text{ m}$ the driving acceleration as stated is obtained.

The rotor in the shape of an arbor produces two accelerating magnetic waves enabling the simultaneous acceleration of two projectiles. The rotor can have more poles for the simultaneous acceleration of more projectiles if desirable.

The connection between flux- and drive loops is made with special low inductance cable, such as copper films on both sides of a 1 mil Kapton film capable of withstanding 7 kV. A 10 cm wide cable has an inductance of $3 \times 10^{-10} \text{ H/m}$, or $0.3 \text{ } \mu\text{H/km}$, which is only a fraction of the inductance of flux- and drive coils of the order of μH .

A further development of the rotor idea leads to a relaxation of the constraining condition $d/D = r/R$. The flux loops can be laid out around the periphery of the rotor on a spiral with two turns as sketched in Fig. 9. The spiral arrangement can be made with more than two turns and correspondingly higher rotor speeds. The results of Table IV apply if the same rotor ($h = 5 \text{ m}$ and $B = 1 \text{ T}$) as in Fig. 8 and flux loops with $d = 3 \text{ mm}$ and $r = 1 \text{ m}$ are used. The case illustrated in Fig. 9 has 4 simultaneous accelerating

* The pole tip consists of two vertical parallel edges very close to each other, each being 1 mm wide. One has a flux density of $+1 \text{ T}$, the other of -1 T . It is assumed that the linkage with the stator flux coils is about 80% so that these would experience a net flux change of 1.6 T as the rotor tip passes over them.

waves going around. More simultaneous waves are possible with $n > 2$.*

The rotor drive concept could, in principle, also be used to energize a linear accelerator, but it will be difficult to obtain the high acceleration desirable.

Using the accelerator for impact fusion it would be of advantage to have four simultaneously accelerated projectiles impacting on each other along the diagonals of a tetrahedron. For this purpose the projectiles are extracted along tangents and then guided along curved paths (twisted S-curves) of equal length and equal, pair-wise mirror symmetric shape as illustrated in Fig. 10. These guide ways have by necessity a radius of curvature $< R/2$ and can therefore not be handled by the same superconducting structure that produces the a_{cp} during acceleration. Normal conducting and correspondingly high currents of a short duration can produce the high attractive forces necessary for this purpose.

V. CONCLUSION

It is possible to accelerate small ferromagnetic particles with linear acceleration of $\sim 500 \text{ km/s}^2$ or more, or centripetal acceleration of $\sim 2000 \text{ km/s}^2$, producing speeds of 50 km/s in linear accelerators of 2.5 km or less length, or circular accelerators of 2.5 km diameter. Higher speeds are possible with larger accelerators. The projectile mass can be approx. 100 mg .

For comparison, the highest velocities, obtained from light gas guns, for projectiles of similar size have been reported¹⁰ to approach 13 km/s which may be a limit.

Projectiles of higher mass are possible with linear accelerators. Circular accelerators have the advantage that a smaller driving acceleration can be employed. This allows the use of switchless and more efficient methods of energizing the accelerating magnetic wave by means of a rotor.

* To have unused magnetic waves circulating may be disadvantageous because of ac losses in the superconductor. If only 4 projectiles are needed the rotor may be programmed that only that part is energized which is needed for the 4 active accelerating waves.

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TABLE I LIMITS OF SUPERCONDUCTING MATERIALS

	T_c	$F_p \text{ max } (4K)$	$T_c (4T)$	$\int_0^{T_c(4T)} T_c dT$
NbTi	9 - 10 K	$1.5 \times 10^{10} \text{ N/m}^3$	7.3 K	10 mJ/cm ³
Nb ₃ Sn	16- 18 K	$4.5 \times 10^{10} \text{ N/m}^3$	14 K	100 mJ/cm ³

TABLE II LIMITS OF FERROMAGNETIC MATERIALS

	ρ [g/cm ³]	M_s [T]	$T_c (4T)$ [K]	$\int_0^{T_c} T_c dT$ (est.) [J/cm ³]
FERROUS	7.8	2.5	1100	2000
Gd	7.9	2.7	280	500
Tb	8.3	3.4	240	
Dy	8.5	3.7	120	100
Ho	8.8	3.6	35	1
Er	9.0	2.8	32	

(Ref: R.S.Tebble and D.J.Craik, Magnetic Materials, John Wiley, London 1969)

TABLE III ACCELERATION DATA FOR ROTOR ENERGIZER (see Fig.8)

r	D	dH/dx	a	(for R=1.2 km)
[m]	[m]	[A/m ²]	[m/s ²]	
1.5	0.8	1.3×10^7	5.6×10^3	
2	0.6	2.3×10^7	10^4	

TABLE IV ACCELERATION DATA FOR SPIRAL STATOR WITH n TURNS (see Fig.9)

(d = 3 mm; R = 1.2 km; r = 1 m)

n	v	D	dH/dx	a
	[rps]	[m]	[A/m ²]	[m/s ²]
2	13.2	1.8	3.7×10^6	1.6×10^3
6	40	0.6	1.1×10^7	4.8×10^3
10	66	0.36	1.85×10^7	8×10^3
14	91	0.26	2.5×10^7	1.1×10^4

Figure 1. PRINCIPLE OF TRAVELLING MAGNETIC WAVE ACCELERATOR

Figure 2 HIGHEST FLUX PINNING FORCES OF VARIOUS SUPERCONDUCTORS
AND CORRESPONDING ACCELERATION OBTAINABLE

- a Nb, irradiated (S. T. Sekula, J. Appl. Phys. 42, 16 (1971))
- b Porous glass, PbBi impregnated (J. H. P. Watson, J. Appl. Phys. 42, 46 (1971))
- c Nb-78%Ti (McInturff et al J. Appl. Phys. 38, 524 (1967))
- d Nb-61%Ti (R. Hampshire et al Proc. Conf. Low Temp. and Electr. Power, 1969)
- e Nb-40%Zr-10%Ti (T. Doi et al Trans. AIME 242, 1793 (1968))
- f Nb₃Sn tape (22 CYO 15, IGC)
- g Nb₃Sn tape (M. G. Benz, IEEE Trans. MAG-2, 760 (1966))
- h Nb₃Sn multifilament (J. E. Crow, M. Suenaga, Proc. Appl. Supercond. Conf, Annapolis, 1972, IEEE Pub. #72CHO682-5-TABSC, p. 472)
- i V₃Ga multifilament (ibid.)
- k V₃Ga tape (Sumitomo Electric Corp. 1970)
- l V₃Ga tape (S. Fukuda, K. Tachikawa, Y. Iwasa, Cryogenics, 13, 153 (1973))
- m V₃Ga+Zr (ibid.)
- n NbGe tape (J. D. Thompson et al, J. Appl. Phys. 50, 977 (1979))
- o NbGe theoretical maximum (ibid.)
- p NbGe (S. Foner et al, Phys. Lett. 47A, 495 (1974))
- q NbN film (J. R. Gavaler et al J. Appl. Phys. 42, 54 (1971))

Figure 3 CROSS SECTION OF CONCEPTUAL ACCELERATOR (see text)

- A Projectile
- B Accelerator tube
- C Superconducting guide shields
- D Drive tube
- E Flux displacing coils
- F Field winding (superconducting)
- G Resistive turn to turn short

Figure 4 PRINCIPLE OF GUIDING FORCE

Figure 5 DRIVING ACCELERATION BY MEANS OF INDIVIDUAL RINGING L-C ELEMENTS

Figure 6 SCHEMATIC OF CIRCULAR GUIDANCE AND ACCELERATION ARMATURE

Figure 7a

EXAMPLE OF GEOMETRY WITH CALCULATED CENTRIPETAL FORCES AND ACCELERATION

Solid curve: sum of attractive and repulsive force versus radial position of projectile. Stable suspension possible in ascending part of curve.

Figure 7b SECOND EXAMPLE (see Fig. 7a)

Figure 8 PRINCIPLE OF OBTAINING DRIVING ACCELERATION FROM ROTOR

Figure 9 FLUX DISPLACER WITH SPIRAL STATOR

Figure 10 LAYOUT OF ACCELERATOR FOR FOUR PROJECTILES
SIMULTANEOUSLY IMPACTING ON EACH OTHER.