INSTITUTE OF PLASMA PHYSICS

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Interconnected Linear Theta Pinches

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IPPJ-316 December 1977

RESEARCH REPORT

NAGOYA, JAPAN

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ABSTRACT

Several closed configurations consisting of interconnected linear theta pinches are proposed which may considerably reduce their end losses.

Recently there has been renewed interest in linear θ-pinches primarily because of the realization that with the exception of end losses it can realize all other requirements for fusion better than most devices. To date linear θ-pinches have produced hot ($T_i \sim 2$ to 4 keV), dense ($\sim 10^{16}$ cm^{-3}), high β (~.8) and MHD stable plasmas whose life times are limited only by end losses. Therefore efforts are being made to stopper the ends of a linear pinch by mirrors, cusps, cusps with rf. plugging, high-z ion end plugs and tandem mirror concept. These schemes do reduce the particle end loss, but have little effect on energy loss by electron thermal conduction. Instead of going toroidal to eliminate end losses, we propose several closed configurations consisting of interconnected linear θ-pinches. The discussion in this paper is largely conceptual with the intention of provoking plasma physicists to do more thorough and detailed enquiry into some of these alternative schemes of fusion systems to determine their promise, if any.

The first class of devices we propose can be called linear θ-pinches connected by stabilized toroidal sectors. The motivating concept here is that end losses from two linear θ-pinches can be fed into each other. This is accomplished by connecting the ends of two linear pinches by two toroidal sectors so as to form a race track as shown in Fig.1. The toroidal sectors will of-course suffer from the usual lack of toroidal equilibrium and stability unless specific preventive measures are taken. This can be done in a variety of ways by having the sectors in any one of the following forms: periodic

caulked cusp, polytron or tormac. In the case of caulked cusp and tormac the necessary toroidal field can be initially the bias field during the implosion heating phase and later the large magnetic field of the compressed final state of the θ-pinch. θ-pinch plasma in a caulked cusp toroidal field has demonstrated equilibrium and reasonable stability.[1] However the plasma interaction with the ring supports may pose problems. In polytron[2] like sectors the necessity of a toroidal current to produce toroidal acceleration via a poloidal Hall current and radial cusp fields may be an inconvenient complication. Therefore the most attractive possibility may be the use of 'tormac' like toroidal sectors. Toroidal hexapole[3] line cusps superposed on toroidal θ pinch has produced reasonable results. Most promising of this genre is axisymmetric quadrupole[4,5] or dipole[6,7] field superposed on toroidal magnetic field in 'tormacs'. The modest loss along the line cusps in the 'tormac' sectors is made even more tolerable in view of the large volume of plasma in the linear θ-pinch sections which are exempt from these losses.
To avoid the complication of producing a toroidal current for the poloidal field necessary for a bicusp configuration, 'tormac' sectors with quadrupole field superposed on toroidal field is sufficient for our purpose. Because of special attractiveness of this configuration let us briefly consider its $n\tau$ scaling.
The time constant τ of particle loss in tormac[5] is

$$\tau = (r_p/\rho_i)\tau_{ii}$$

where r_p, ρ_i and τ_{ii} are the plasma radius, gyroradius and ion collision time, respectively. In view of the plasma in the two linear pinch sections of length L each this is modified as

$$\tau = (r_p/\rho_i)(1+L/\ell)\tau_{ii} \approx (r_p/\rho_i)(L/\ell)\tau_{ii} .$$

where ℓ is the length of each 'tormac' like sector and $L >> \ell$. Now $n\tau$ can be determined from this loss time constant as

$$n\tau \sim (r_p/\rho_i)(L/\ell)T_i^{3/2} \times 10^6$$
$$= r_p B T_i (L/\ell) \times 10^4 \qquad (1)$$

where all quantities are in CGS units except T_i which is in ev. We can compare this with the corresponding figure for a linear θ-pinch of equivalent length $2(L+\ell)$. Considering the confinement to be the same as the particle end loss time by free streaming ions[8] as

$$\tau \approx \frac{2.4\sqrt{\pi}}{1+\sqrt{1-\beta}} \quad \frac{2(L+\ell)}{2} \quad \left(\frac{m_i}{2kT_i}\right)^{1/2}$$

and using plasma pressure balance with equal electron and ion temperatures we find

$$n\tau \sim \frac{2LB^2}{T_i^{3/2}} \times 2.7 \times 10^4 \quad \frac{\beta}{1+\sqrt{1-\beta}} \quad . \qquad (2)$$

Comparing Eqs.(1) and (2) we can see that for the same values of magnetic field, β and temperature, $n\tau$ for the proposed configuration is larger than that of linear pinch by the following factor

$$(r_p/2\ell)(T_i^{5/2}/2.7B) \sim 2\text{-}5\times10^3$$

for $T_i \sim 10$ keV, $B \sim 30$ to 100 kG, $r_p \sim 10$ cm, $\ell \sim 1$m. Putting it another way, for $n\tau \sim 10^{15}$ the standard linear

θ-pinch requires an enormours length of the order of 33 km (for B ~ 100 kG) whereas the proposed configuration requires a length of 30 m (for each pinch) at a much more reasonable magnetic field of 30 kG.

The second class of proposed devices can be called linear θ-pinch mesh. Here the goal of feeding the end losses of linear pinches into are another is accomplished by converging several pinches into a node. The simplest such node of four identical pinches where $\nabla \cdot \bar{B}=0$ is satisfied and which produces a two-dimensional minimum $|B|$ geometry in the nodal region is shown in Fig.2. The magnetic fields of the pinches in the equilibrium phase are considered to be fields due to long solenoids and the corresponding contours of constant $|B|$ computed with the help of a computer are shown. The constant $|B|$ contours are nearly independent of the parameter L/a so long it is large. It appears that the nodal space of the junction of four linear θ-pinches exhibit excellent min-B properties in the central region where the plasma will be located in the compressed equilibrium state. Therefore a junction like this will considerably reduce both the particle and electron thermal conduction end losses. It is noted that in the plane transverse to the plane of the solenoidal axes there is no minimum $|B|$ characteristics. Therefore there will be some loss in this plane which will be considerably smaller than the corresponding loss at simple cusp ended linear θ-pinch. Furthermore this small loss can be minimized by a spindle cusp with its axis transverse to the plane of Fig.2 through the center of the nodal region with or without R.F. plugging for the cusp leakage.

A problem appears when one considers what to do with the other ends of the linear pinches. One solution is to connect the other ends of these pinches with four more linear pinches so as to form a kite like configuration shown in Fig.3. It is clear that at a typical new vertex where three pinches connect, the magnetic field has minimum $|B|$ characteristics in most of three directions. To supplement this in the fourth direction we include a pancake coil with several turns at each new vertex. The result is roughly a minimum $|B|$ configuration at each new vertex with one leakage point cusp. At each new vertex one may also have a spindle cusp with its axis transverse to the plane of Fig.3 as discussed before for the central node.

The author is indebted to R.A. Gross for pointing out the importance of end stoppering of linear θ-pinches.

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FIGURE CAPTIONS

Fig.1. Two linear pinches connected by stabilized toroidal sectors. The usual theta pinch coil is shown over the entire device. Periodic caulked cusp or tormac like details are not shown in the two semi-circular toroidal sectors.

Fig.2. Min $|B|$ characteristics of a junction of four linear theta pinches. The values of constant $|B|$ shown are normalized by the quantity $.05\mu_0 NI$. The axial field strength at the end of a long solenoid is $.5\mu_0 NI$ where μ_0, N and I are the permability of free space, number of turns per unit axial length and current, respectively.

Fig.3. Interconnected mesh of eight linear theta pinches. The central node has the minimum $|B|$ characteristics shown in Fig.2. Each of the four vertices also has nearly minimum $|B|$ characteristics.

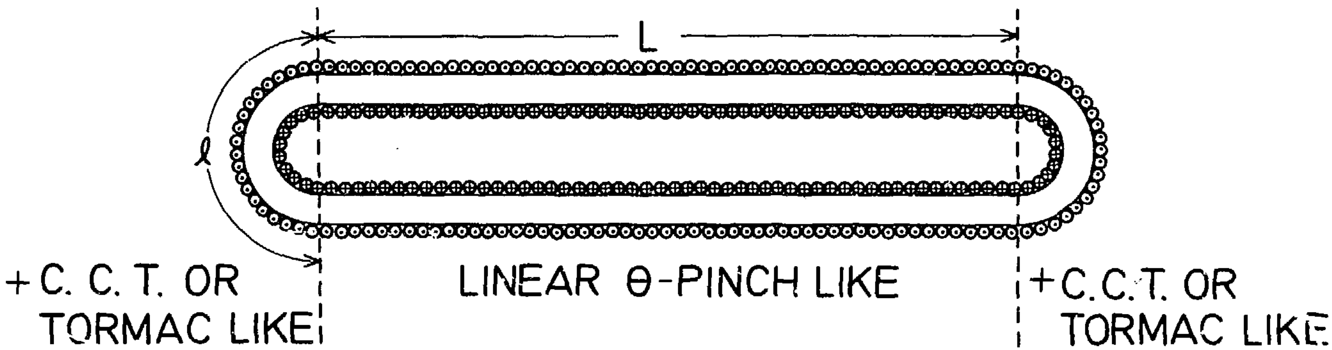

Fig. 1

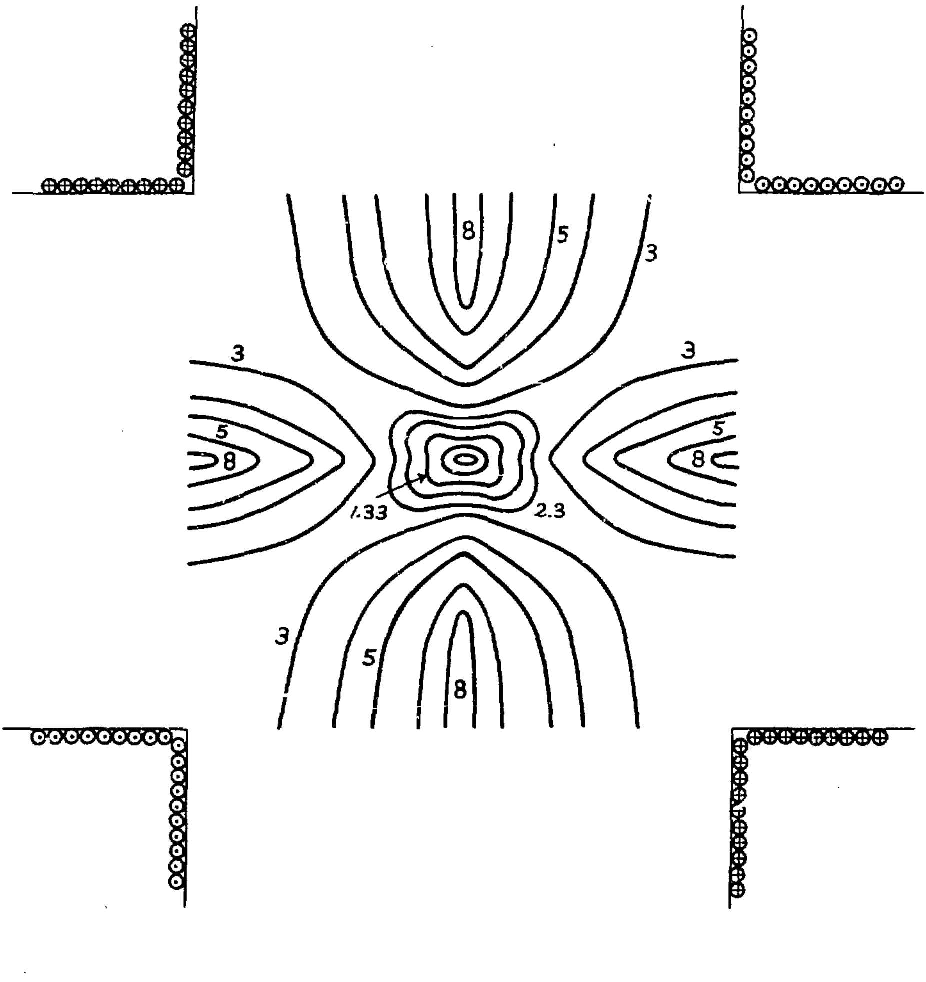

Fig. 2

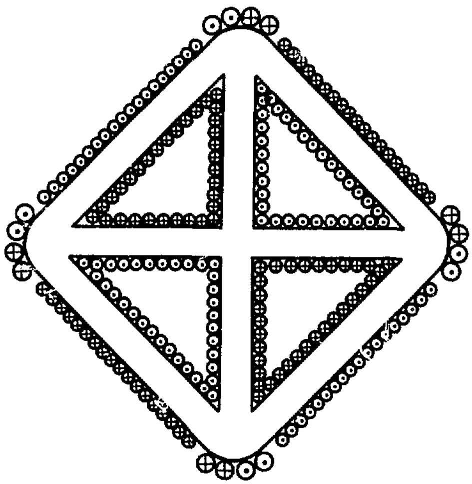

Fig. 3