Physics Letters A 165 (1992) 1–13
North-Holland

PHYSICS LETTERS A

# The role of Ampère forces in nuclear fusion

Peter Graneau
*Centre for Electromagnetic Research, Northeastern University, Boston, MA 02115, USA*

and

Neal Graneau
*Department of Engineering Science, University of Oxford, Oxford, OX1 3PJ, UK*

Received 14 October 1991; revised manuscript received 27 January 1992; accepted for publication 3 March 1992
Communicated by J.P. Vigier

Three different non-tokamak fusion mechanisms are examined, involving plasma filaments formed from gaseous, liquid or solid deuterium. Results from previous experiments, in which up to $10^{12}$ neutrons were produced, point to non-thermal fusion mechanisms. The role of electrodynamic forces, including those predicted by Ampère's force law, are investigated as the possible mechanism of ion acceleration.

## 1. Introduction

Thermonuclear fusion has now been researched for nearly forty years. Almost all efforts have been devoted to magnetically confined toroidal tokamak plasmas. This type of machine requires complex and very costly external electromagnets. It is generally believed that two or more generations of experimental tokamaks are needed before the process could become commercially viable. In 1991 the European Community, the US, USSR, and Japan have agreed to design an international thermonuclear experimental reactor (ITER). It is estimated that the machine will cost $ 5 billion, and the design and research budget will require at least another $ 1 billion [1]. The performance of ITER will not be evaluated until the next century.

Against this background, it is surprising to find that far simpler alternative fusion schemes, not depending on plasma confinement by magnets, are being discouraged by government funding agencies, and in a number of cases have been terminated.

This paper considers three alternative fusion processes which are closely related to each other and could be collectively called *filament fusion*. In each method, large current pulses have been passed through short ($\simeq 10$ cm) and thin ($\simeq 1$ mm) gaseous, liquid or solid filaments containing deuterium. The neutron yield from deuterium fusion reactions has been reported to be as high as $10^{12}$ per current pulse.

Gaseous filament fusion has been achieved with *plasma focus* devices. Liquid filaments were used in *capillary fusion*, and *dense Z-pinch* experiments have been performed with solid filaments. Today researchers face the challenge of designing further small scale filament fusion experiments in which the reaction rate, measured by neutron emission, is increased by several orders of magnitude to achieve energy break-even and ultimately a net gain in useful energy.

The search for such new small scale devices must inevitably be guided by the understanding of what makes filament fusion work. There is no agreement on this issue. Some investigators continue to believe that MHD instabilities can create highly local plasma regions in which the temperature rises to levels at which thermonuclear fusion can occur while others think that the Coulomb barrier between two deuterons can be lowered by electron screening [2,3]. It is also argued that conventional electromagnetic forces are able to accelerate nuclei to fusion velocities. To this list of mechanisms, we now wish to add the unconventional longitudinal Ampère forces as a necessary ingredient to explain the phenomena during the short transit of a high current, and how this can contribute to nuclear acceleration.

Ampère [4] established by experiment the existence of electrodynamic forces which acted, simultaneously, in both directions along the current streamlines in metallic conductors. His electrodynamics was based on an empirical force law which has never failed when applied to metallic conductors for the 170 years of its existence. Recently, we have pointed out that this law seems to apply equally to dense plasmas [5]. It is not yet known at how low a plasma density the Ampère law will fail, for it certainly does not hold for individual charges drifting in vacuum, as in a particle accelerator.

## 2. MHD instabilities in a cylindrical plasma column

Amongst the earliest ideal MHD instabilities to be studied were those pertaining to cylindrical plasma columns. This was due to their inherently simple geometry, which was useful both for theoretical calculations as well as ease of construction in the laboratory. These instabilities are usually viewed as a hindrance for designers of plasma machines such as tokamaks, where they cause disruption in the plasma. To combat this, techniques have been developed to minimize their role. At the same time, Anderson et al. [6] have found that the disruption of a linear plasma coincides with a burst of neutrons, indicating that fusion is occurring. As a result, these common MHD instabilities, particularly the $m=0$ *sausage* and $m=1$ *kink* instabilities, will be investigated.

In fig. 1, we employ cylindrical coordinates $(r, \theta, z)$ where $z$ is the axis of the cylinder. In the simplest case, the radial pressure gradient $\nabla p$ is balanced by the $\boldsymbol{J}\times\boldsymbol{B}$ Lorentz force due to the axial current and the poloidal magnetic field,

$$\nabla\cdot \boldsymbol{p}+J_z B_\theta=0\ . \qquad (1)$$

However this is an unstable condition. Recalling that the poloidal field that is produced at the surface

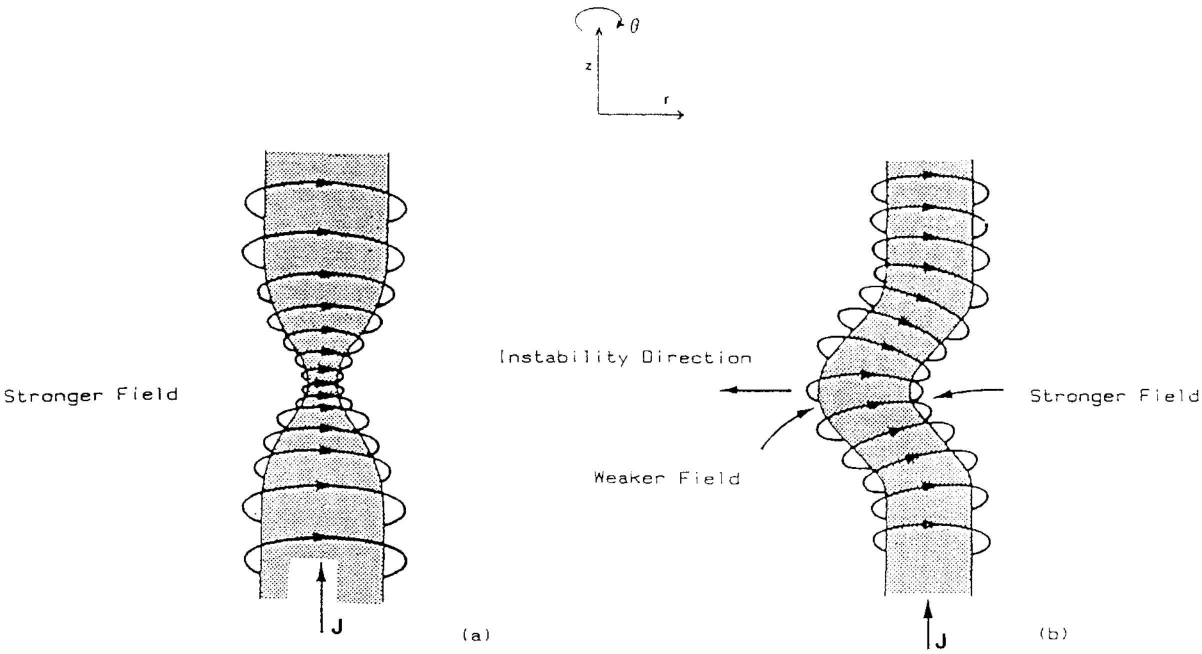


Fig. 1. Two linear MHD instabilities; (a) "sausage", $m=0$, (b) "kink", $m=1$.

of the plasma column of radius $r$ and passing current $I$ is given by

$$B_\theta(r)=\frac{\mu_0 I}{2\pi r}, \quad (2)$$

we can see that an axisymmetric perturbation which causes a contraction will create a consequent increase in magnetic field. The radially inward Lorentz force is thus increased, which further contracts the radius of the column. This unstable behaviour leads to a rapid decrease in plasma radius and eventually can disrupt the plasma column. This behaviour, often called the *sausage* instability, and shown in fig. 1a, can be reduced by the addition of an axial magnetic field $B_z$. This creates a magnetic pressure $B_z^2/2\mu_0$ inside the plasma which opposes contraction. Theoretically the plasma becomes stable to this type of behaviour when

$$B_z^2>\tfrac{1}{2}B_\theta^2 \quad (3)$$

and the growth rate is approximately $a/r$, where $a$ is the sonic speed [7].

The *kink* instability is a result of a perturbation that bends the plasma column as shown in fig. 1b. Such a perturbation causes an increased poloidal field strength at the inside of the bend, where the resulting increased magnetic pressure will enhance the column deformation. This mode is driven by the torque $\nabla\times(-\nabla\cdot\boldsymbol{p}+\boldsymbol{J}\times\boldsymbol{B})$. As with the *sausage* instability, the result can be rendered less severe by the addition of an axial magnetic field $B_z$. The criterion for *kink* stabilization involves the factor $q(r)$,

$$q(r)=\frac{krB_z(r)}{B_\theta(r)}. \quad (4)$$

The Kruskal–Shefranov criterion for stability is $q(r)>1$ [8], where $r$ is the radius at the edge of the plasma column, and $k$ is the wavenumber $(2\pi/\lambda)$ of the disturbance.

It can be shown that solutions to the general equation for MHD instabilities vary as $\exp[i(m\theta+kz)]$. The *sausage* instability is cylindrically symmetric, and thus is independent of $\theta$, so that in this case $m=0$. The simplest *kink* instabilities have $m=1$.

The stability condition for a standard linear pinch can be shown to be [9]

$$\frac{r^2}{B_\theta}\frac{d}{dr}\frac{B_\theta}{r}<\tfrac{1}{2}(m^2-4). \quad (5)$$

Since $B_\theta/r$ decreases with radius as a result of eq. (2), $(d/dr)(B_\theta/r)<0$. In general, this predicts stability for modes of $m\geqslant 2$. These higher modes, which involve twisting, do however occur in tokamaks and other non-linear geometries.

The $m=0$ instability is the one most often shown in papers relating to the break-up of linear plasma columns. In these models, there is not only a tendency for decreasing the column radius in places, but also for a radius expansion in between the regions of contraction. This behaviour is explained [9] by assuming that the curvature of the surface after the initial perturbation leads to a charge separation as shown in fig. 2. It is claimed that the resulting $\boldsymbol{E}\times\boldsymbol{B}$ plasma drift accentuates the instability and explains the observed behaviour.

However the $\boldsymbol{E}\times\boldsymbol{B}$ vector must be in the same direction as the Poynting vector $\boldsymbol{E}\times\boldsymbol{H}$. Fig. 2 thus shows some of the conductor surface with an outward Poynting vector, implying that at these places the conductor is not receiving any energy to support current flow. This should stop the current which is contrary to experimental observations and suggests a logical flaw in the model. This model also claims that the column breaks up as the result of the gradual

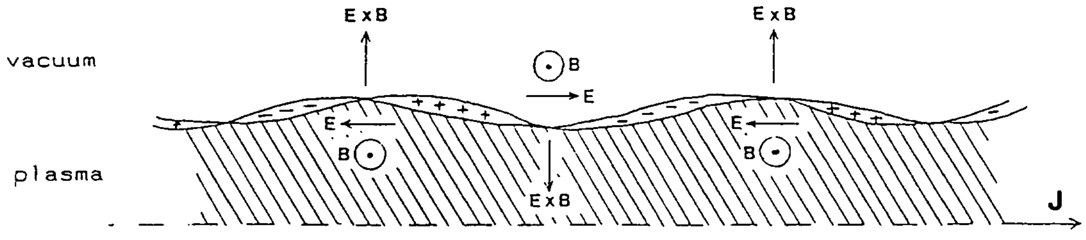


Fig. 2. Charge separation in a $m=0$ instability, leading to destabilizing $\boldsymbol{E}\times\boldsymbol{B}$ drifts.

necking down process, whereas in fact there is evidence that the column does rupture before any significant reduction in radius is observed [10].

Anderson et al. [6] argued that the $m=0$ *sausage* instability was the event related to the production of neutrons in a deuterium plasma. In the next section, it is shown that the Ampère force law can not only predict the macroscopic observations of the breaking up of the plasma column, but also the microscopic deuteron acceleration that can explain the observed neutrons as a result of fusion reactions.

## 3. Longitudinal Ampère forces

Ampère's force law will not be found in modern textbooks, however it has been the subject of many recent research papers which are discussed in ref. [5], together with the technological consequences. The law takes the form

$$\Delta F_{m,n} = -\frac{\mu_0}{4\pi} i_m i_n \frac{\mathrm{d}m\,\mathrm{d}n}{r_{m,n}^2} \times (2\cos\epsilon - 3\cos\alpha\cos\beta) . \qquad (6)$$

$\Delta F_{m,n}$ is a Newtonian force of repulsion (if positive) or attraction (if negative) between two current elements of length d$m$ and d$n$, and passing currents $i_m$ and $i_n$ respectively. The angle of inclination between the elements is $\epsilon$, and $\alpha$ and $\beta$ are the inclinations of the elements to the distance vector $r_{m,n}$. Eq. (6) is an inverse square law like Newton's law of gravitation and Coulomb's law. The physical reality of the Ampère force has recently been justified by Vigier and Rambaut [11,12], on the basis of an integration of Lorentz interactions between charged particles. This shows that the Ampère force is a collective effect resulting from the mixing ions and electrons in the conductor.

When computing the interaction forces between two circuits, the calculations with eq. (6) agree with Lorentz force calculations. However, a pronounced difference arises when determining internal electrodynamic stress in a conductor due to its own current. Regarding a current carrying plasma filament, both laws agree on the pinch forces, but the Ampère law predicts axial forces which the Lorentz law does not.

To illustrate these axial forces, we consider two current elements lying on the same straight streamline. For these two elements $\epsilon=\alpha=\beta=0$, and eq. (6) reduces to

$$\Delta F_{m,n} = \frac{\mu_0}{4\pi} i_m i_n \frac{\mathrm{d}m\,\mathrm{d}n}{r_{m,n}^2} . \qquad (7)$$

As this is always a positive quantity, Ampère's law predicts that collinear current elements repel each other. In a straight wire, this leads to tension which is capable of breaking the wire if sufficient current is flowing [13]. Photographs of wires broken in this manner are shown in fig. 3. The wire fracture forces of eq. (7) must be exerted on the lattice ions, because no current discontinuity is observed, thus implying that the electrons are not affected.

It is conjectured that longitudinal Ampère forces also rupture plasma current filaments. The positive ions may then be the nuclei of hydrogen and its isotopes. In this way Ampère forces may not only disrupt plasma columns but also accelerate nuclei and cause fusion reactions by the resulting collisions. It is probable that other mechanisms of accelerating nuclei will also be present.

## 4. Plasma focus devises

A typical plasma focus device is shown in fig. 4. It has to be operated in a vessel which contains deuterium gas at the pressure of a few Torr. When discharging the high-voltage capacitor bank, flashover occurs across the surface of the insulator which separates the central anode from the cathode tube. Electrodynamic forces sweep the resulting arc upward. As the discharge passes the tip of the anode, the plasma filament starts to form as shown in fig. 4. Depending on the voltage and capacitance of the current source, the filament may be one or more centimeters long. Its diameter varies during the course of the discharge, but is usually not less than one millimetre.

A large number of neutrons are released from the filament as a result of fusion reactions. The neutrons are only emitted during a brief period within the current pulse, just when the filament is known to rupture. The neutron yield in some experiments has approached $10^{12}$ per shot. It has never been claimed that the entire filament reaches thermonuclear re-

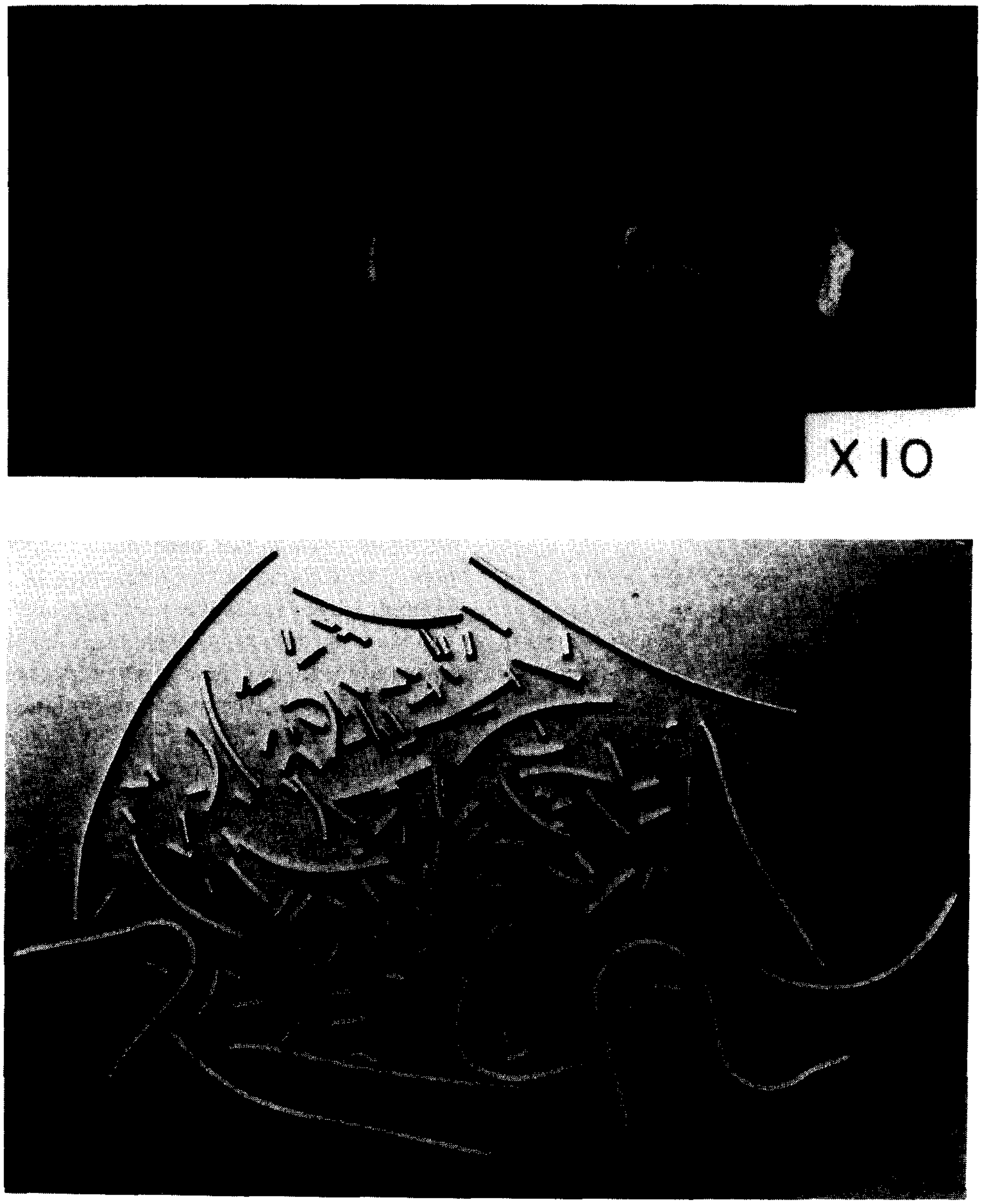


Fig. 3. Photographs of aluminum wire fragments.

action temperatures, thus much attention has been paid to local effects in the column such as the region where the rupture occurs.

The neutron output does not appear to be a function of the voltage applied between the ends of the filament, however it depends strongly on the pulse current amplitude. These two facts suggest that the deuterium acceleration forces are of electrodynamic rather than electrostatic origin. In a 1981 review, Haines [14] points out that in four different plasma focus experiments, carried out in two separate laboratories, the neutron yield was proportional to the fourth power of the maximum current, which ranged from 0.3 to 1.1 MA.

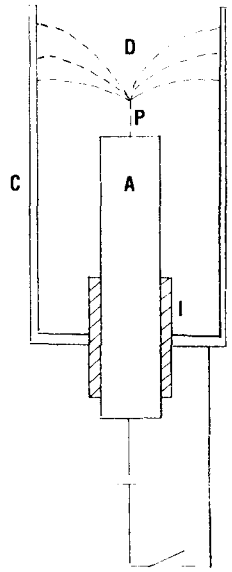


Fig. 4. Coaxial plasma focus device. A: anode; C: cathode; D: deuterium (3–4 Torr); I: insulator; P: plasma filament.

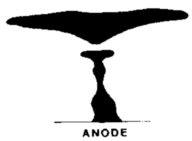


Fig. 5. Sketch of a plasma focus filament disruption [10].

With optical framing photographs of 5 ns exposure, and time resolved neutron detection, Decker and Wienecke [15] have proved that the neutron emission always coincides with filament rupture. The appearance of this event is sketched in fig. 5. There is no doubt that pinch forces are responsible for the formation of the plasma filament, but we are faced with two possible rupture mechanisms. Without knowledge of longitudinal Ampère forces, investigators had no choice but to attribute filament rupture to an $m=0$ MHD instability. This phenomenon forms a neck in the filament, and the consequent radial current components on both sides of the neck repel each other and fracture the plasma column. Using the Ampère electrodynamics, we expect the longitudinal repulsion of current elements (deuterons) to be the cause of the fracture, with no requirement for the formation of a neck. In both cases the electron current continues to flow across the gap without producing a visible plasma.

The opening of the gap must be due to axial ion motion in opposite directions on both ends of the gap. Haines [14] mentions that there is also a centre-of-mass ion motion, away from the central electrode (anode). The simplest explanation of this motion is longitudinal Ampère repulsion forces between the current elements in the anode and others in the plasma filament. Very high axial ion velocities, of the order of 100 km/s, have been mentioned in the literature.

The neutrons are almost certainly not produced by thermonuclear reactions, because their flux is anisotropic, with most flowing along the axis of the filament. Thus the fusion reactions appear to be the consequence of the axially accelerated deuterons. The mechanism which has been put forward most frequently to account for this ion acceleration is a high induced voltage across the $m=0$ instability neck [6].

In such an induction mechanism, let the longitudinal induced e.m.f. be $e$. Then for a conductor of self-inductance $L$, carrying an instantaneous current $i$, Faraday's law, or more precisely Neumann's [5] law of induction, requires that

$$e=-\frac{\mathrm{d}(Li)}{\mathrm{d}t}=-\left(L\frac{\mathrm{d}i}{\mathrm{d}t}+i\frac{\mathrm{d}L}{\mathrm{d}t}\right). \tag{8}$$

When $L$ is constant and $i$ increases with time, the induced voltage is negative, which is a back-e.m.f., opposing current flow. In the case of the $m=0$ instability, when $i$ is constant and $L$ increases due to radius reduction, the induced e.m.f. is again negative and opposes current flow. Hence induction effects at the instability actually reduce the voltage across the constriction. If the back-e.m.f. were greater than the applied e.m.f., resulting in current reversal and possibly an increased but reversed voltage cross the gap, then extra ion acceleration could occur as a result of induced voltages. No current reversal has ever been observed at the moment of filament rupture, and the current remained essentially constant during the period of neutron emission.

Very large current pulses, in the mega-ampere range, decrease the effectiveness of plasma focus devices. Investigators at the University of Stuttgart and Imperial College in London are responsible for the following pessimistic outlook [16], based on their experience with the most powerful plasma focus devices: "Particularly in the large PF (plasma focus) devices, however, it was found that the neutron yield stagnates or even decreases when the energy input and the current are increased above a certain critical value, despite extensive efforts to optimize the electrode dimension. This effect seemed to limit the future of the PF as a fusion device."

It appear to be an indication that longitudinal Ampère forces become too powerful, and disperse the plasma by radial expansion. This expansion is the result of hydrostatic conversion of the axial pressure created by the longitudinal forces. To overcome the fusion stagnation effect it may be advantageous to enclose the filament in a strong containment tube, specifically to prevent the plasma expansion. This approach is supported by the following arguments.

The particle density in plasma focus filaments is often quoted as being $10^{25}$ $m^{-3}$. It is therefore equivalent to the density of high-pressure electric arcs. Hence the knowledge gained in arc physics should apply to plasma focus experiments. In this respect, the arc jets described by Sheer [17] are of interest. They have been produced with coaxial electrodes and various gas fillings. The coaxial electrode arrangement also works with arcs in liquids. An example is the water-arc gun shown in fig. 6. This device was developed by the authors in their MIT electrodynamics laboratory. The operation of this water-arc accelerator is described in ref. [18]. It resembles the plasma focus device of fig. 4, except that the insulator reaches up to the end of the centre electrode, and the tubular electrode is a strong steel barrel of 10 cm in length. When the 1.2 cm diameter barrel was filled up to a height of 7 cm with salt water, and an 8 μF, 75 kV, capacitor bank was discharged through the water, the plasma column in the barrel ruptured, and about half of the water was ejected as a coherent cylindrical projectile, at the velocity of 1 km/s. After travelling 10 cm through ambient air, the water hit a 0.6 cm thick aluminium plate, and punched a 1.2 cm diameter hole through it, without evaporating. Pinch forces and the axial thrust, created as the result of hydrostatic pressure, are orders of magnitude too small to generate the momentum of the ionized water projectile. There was no evidence that the water had been substantially heated, and it was recovered with its original salt content. This suggests that the acceleration could only have been produced by Ampère forces.

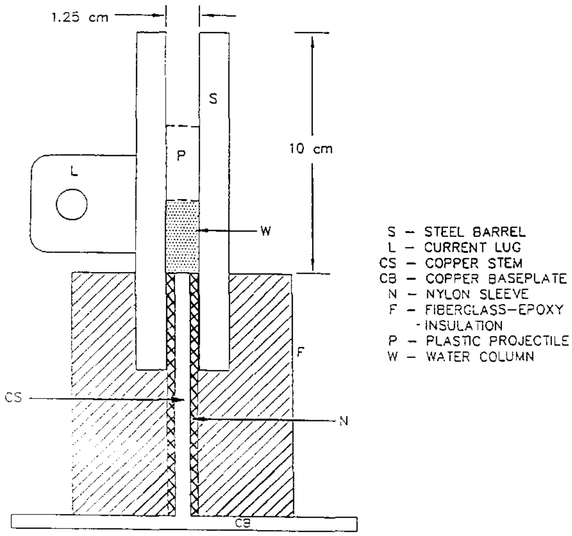


Fig. 6. Diagram of a water-arc gun.

The energy dumped into the water arc was too small to boil all of the water. Thermal acceleration arguments based on very thin super-heated steam filaments are disproved by the fact that the plasma is observed to fill the gun barrel [18] and no breakdown mechanism is known which could constrain the current to a very thin filament.

In principle a water-arc gun can accelerate small volumes of heavy water to velocities far in excess of 1 km/s. It might be possible to increase this velocity by two orders of magnitude if the plasma column break-up can be delayed by inertial or mechanical means. The invention of the water-arc gun has become the basis of two French patents [19], one of which exploits longitudinal Ampère forces for nuclear fusion in deuterium containing liquids.

## 5. Wire explosions and capillary fusion

In 1960, Nasilowski [20] discovered that a current pulse would shatter a copper wire into many solid fragments provided that the current did not flow long enough to melt the metal. He performed other experiments in which the wire was buried in sand and the current pulse lasted long enough to vapourize the metal. He then X-rayed the sand and found the metal vapour pattern shown in fig. 7. He called this wire *striations*. Apparently the wire was fragmented into solid pieces about the length of the wire diameter. As inductive energy was stored by the circuit, arcs bridged the gaps between the solid pieces. Later these pieces melted and evaporated. The vapour expanded to three times the wire diameter without closing the gaps between striations. Once the current pulse was over, the metal vapour condensed on nearby sand particles, freezing the striation pattern of fig. 7.

Exploding wire research in air with capacitor discharges revealed a *current pause* early in the explosion which coincided in time with the break-up of the wire and the formation of many bridging arcs [13]. The multi-arc impedance actually stopped the current flow, leaving the capacitors partially charged. As the arc ions dispersed, a single overall arc of low impedance would suddenly strike. This completed the capacitor discharge without further interruption. By performing the experiment with increasingly higher voltages, the current pause could be shortened until it degenerated into a mere dip in the current oscillogram. Not knowing Ampère's force law at the time, Nasilowski [20] was unable to explain the wire fragmentation phenomenon.

Lochte-Holtgreven and his collaborators at the University of Kiel were familiar with the nature of wire explosions and applied this knowledge to a process they called *capillary fusion*. Their most important paper on this project was published in 1976 [21]. It reported experiments with a solution of lithium in heavy ammonia $Li(ND_3)_4$ consisting of 70 atomic percent of deuterium. The capillary filaments were 7 to 8 cm long, and from 0.5 to 1.5 mm in diameter, set in a block of glass which was compressed with dry nitrogen at 10 to 20 atm.

Current was forced through the conducting liquid filament by capacitor discharge from a 5 μF bank charged to voltages between 100 and 200 kV (100 kJ maximum). The discharge circuit was underdamped which resulted in current oscillations of about 200 kHz. Bursts of $10^4$ to $10^5$ neutrons were detected in every shot with voltages between 150 and 200 kV. When light ammonia (no deuterium) was substituted for heavy ammonia, the discharge produced no neutrons. This was taken to be positive proof of fu-

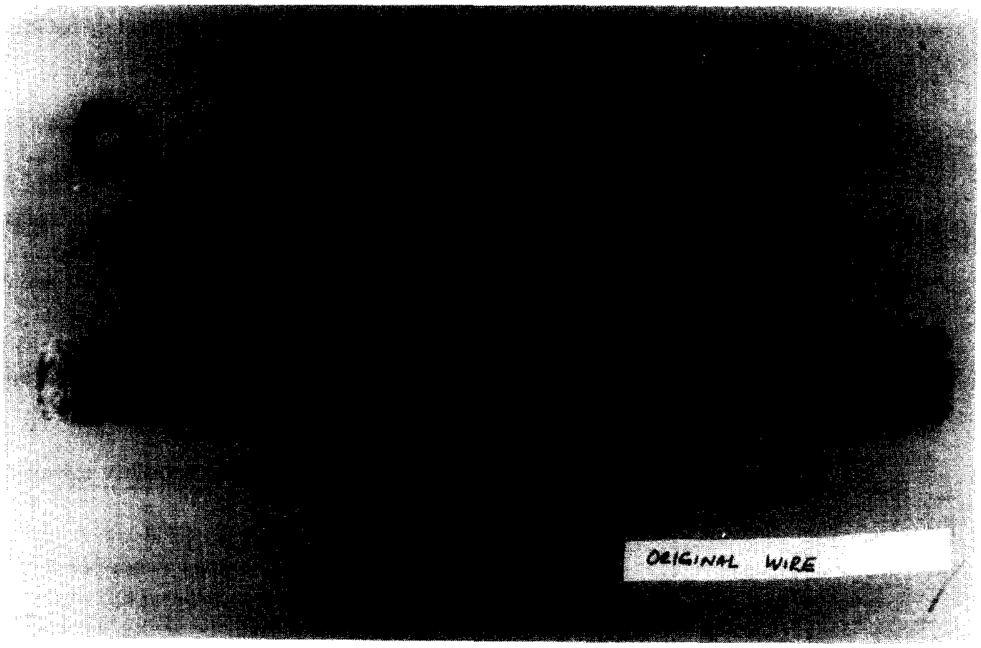


Fig. 7. Nasilowski's copper vapour striations in sand [16].

sion reactions in the heavy ammonia solutions.

The neutron bursts lasted for 30 to 50 ns. They were much shorter than the ringing capacitor discharges of 20 μs duration. Each neutron burst occurred at the same time as a dip in the current oscillogram. This dip was almost certainly caused by the disruption and observed striation of the liquid-plasma filament. At the time of the neutron burst, the current had reached a relative peak of only about 10 percent of the current maximum of 10 kA (see fig. 8).

An important observation made by the Kiel group was the fracture of the glass block which followed each neutron burst with a delay of 100 to 300 ns. It seems unlikely that the glass was broken by thermal forces, because information in the paper can be used to show that most of the electrical energy is converted directly to mechanical energy, without passing through heat. In 1976, the significance of this observation was not appreciated, and thus it is very important that these results receive further confirmation, for they contain far-reaching implications which should not be ignored.

The information used to analyze the energy conversion comes partly from the oscillogram shown in fig. 8. The 5 μF capacitor bank was discharged from 100 kV. Dividing the applied voltage by the first current maximum indicates a plasma filament impedance of the order of $Z=10\ \Omega$. This is unusually large for an experiment of this nature. Normally it would be assumed that the total impedance, $Z$, is the sum

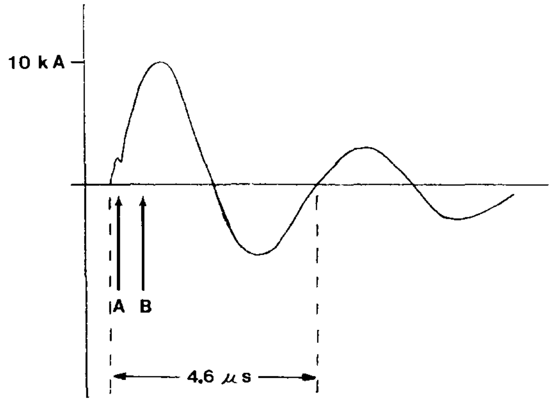


Fig. 8. Discharge current oscillogram of capillary fusion [17]. A: neutron burst; B: fracture of the glass block.

of the surge impedance, $Z_0$, and the resistance, $R$, of the circuit, represented by

$$Z=Z_0+R\,. \tag{9}$$

With $L$ and $C$ being the circuit self-inductance and the capacitance respectively, we can write

$$Z_0=\sqrt{L/C}\,. \tag{10}$$

The oscillating frequency, $f$, of the series circuit is given by

$$f=\frac{1}{2\pi\sqrt{LC}}\,. \tag{11}$$

This frequency was measured to be $f=217$ kHz. Using eq. (11) indicates that $L=0.1$ μH. Lochte-Holtgreven correctly described this as a low-inductance circuit.

The lithium–ammonia solution in the capillary tube was said to have had a similar resistivity to liquid mercury. For a filament of 8 cm length and 0.5 mm diameter, this results in a resistance of $R=0.4\ \Omega$. After the liquid has been ionized, it will be a better conductor, and thus 0.4 Ω is an upper bound of the filament resistance.

With a 0.1 μH self-inductance, the surge impedance comes to $Z_0=0.14\ \Omega$, and together with the resistance, it gives a total filament impedance of $Z=0.54\ \Omega$, which is much less than the observed 10 Ω. Analysis of this discrepancy provides important information.

$Z_0$ in eq. (9) allows for the storage of magnetic energy during the first current rise in fig. 8. $R$ accounts for the generation of Joule heat. Eq. (9) ignores the kinetic energy gained by the deuterons as well as the energy used to break the glass block before the first current peak in fig. 8 is reached. The last two items can be regarded as mechanical work. Whenever electrical energy is converted directly to mechanical work (without passing through heat), as in an electric motor, a back-e.m.f., $e_b$ is induced in the circuit. This back-e.m.f. opposes the instantaneous current, $i$. If $e$ is the instantaneous driving e.m.f. applied between the ends of the capillary filament, then the instantaneous electric power supplied becomes

$$ei=i^2Z+e_b i \tag{12}$$

or

$$e/i = Z + e_b/i\,. \tag{13}$$

Since $e/i = 10\ \Omega$ (observed) and $Z = 0.54\ \Omega$ (deduced), we have $e_b/i = 9.46\ \Omega$, indicating that nearly 95% of the electric energy consumed is converted to mechanical energy. This suggests that capillary fusion could be an extraordinarily efficient method of accelerating nuclei, unless much of the mechanical work is wasted in breaking the glass tube. A further review of the Kiel experiments has been published by Handel and Jonnson [22].

If the high total measured impedance can be confirmed, and Ampère forces were responsible for the acceleration of nuclei and glass breakage, one way to improve the energy utilization for fusion would be to use much stronger capillary tubes, leaving more of the mechanical energy for particle acceleration. On the other hand, if capillary fusion is mainly due to pinch forces, stronger capillaries will make little difference to the neutron yield. Hence the issue of the nature of the forces can be resolved by experiment.

## 6. Solid-fibre fusion

Of all of the filament fusion concepts, the solid-fibre experiments come the closest to wire explosions. Tensile wire breaking is the strongest evidence to support the existence of longitudinal Ampère forces. However, the deuterated polyethylene and solid deuterium filaments, used in fibre fusion research, are insulators and not conducting wires. The initial current surge therefore will probably flow through the surrounding plasma of gas atoms which had been adsorbed on the fibre surface.

Lindemuth [23] has suggested that the fibres may not completely evaporate during the current pulses. The temperature of high-current arcs has been consistently overestimated. Only recently has it been shown by one of us [24] that thermal expansion is not the cause of an arc generated shockwave, but that it is created by electrodynamic forces. Streak photographs [25] unambiguously prove the continuous radial expansion of the fibre plasma against the concurrent pinch forces during the fast current surge. This expansion is generally believed to be caused by thermal forces, but it could equally be the result of radial pressure generated by longitudinal Ampère forces.

The most important discovery made by Sethian et al. [25] was that the neutron and X-ray emissions from the fibre plasma occurred at the moment of the longitudinal breaking of the plasma column into a number (8–10) of beads, as revealed by the X-ray pinhole photograph of fig. 9. This refers to a current of 350 kA, and the neutron yield was of the order of $10^7$ per shot. For an 80 μm diameter fibre, and currents ranging from 350 to 640 kA, the neutron production from D–D reactions scaled with the tenth power of current up to approximately $5\times10^9$ per shot at 640 kA.

From neutron time-of-flight measurements, Sethian et al. deduced that the average deuteron was moving toward the cathode with an energy of 18 keV, or a velocity of 1300 km/s. Ion motion toward the cathode represents a positive current, and thus cannot be generated by the pinch induced e.m.f. $-i\,dL/dt$ of eq. (8). Thus the only explanation of this high ion velocity appears to be longitudinal Ampère forces, and these ions are most probably responsible for at least some of the observed fusion reactions.

From their various measurements, and particularly from the stability of the plasma column, the re-

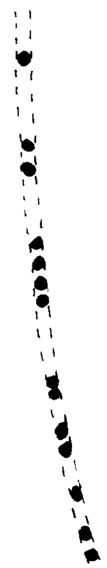

Fig. 9. Sketch of an X-ray photograph of deuterium fibre fragmentation [21].

searchers in the Naval Research Laboratory [25] concluded: "Clearly the neutrons do not come from a uniformly heated plasma. (...) These observations are obviously inconsistent with the predictions of MHD theory and we need to look for features of the experiment that are not included in the assumptions upon which the theory is based."

In subsequent experiments, Sethian et al. [26] raised the peak current to 920 kA, extended the pulse rise time from 130 to 840 ns, and increased the deuterium fibre diameter from 80 to 125 μm. These changes generally lowered the neutron yield, which at the highest current, was still only $4\times10^9$ per shot. Furthermore, the neutron count was no longer proportional to the tenth, but to the fifth power of maximum current. During the longer current pulses, neutrons were emitted in several bursts occurring over a period of several hundred nanoseconds. The neutron generation again coincided with the rupture of the plasma column in several places, as indicated by time correlated optical and X-ray photography.

As in the case of more conventional plasma fusion devices as well as filamentary experiments, megaampere currents did not achieve the expected results. Apparently, the plasma is always rapidly dispersed in the radial direction. As explained in conjunction with capillary fusion, this radial plasma dispersal, due to the hydrostatic conversion of axial to radial pressure, which is probably driven by Ampère forces, can be controlled by enclosing the plasma filament in a strong capillary tube. If this were done, the fibre might as well be replaced by a deuterium containing liquid. Keeping the fusible material away from the wall is not so important if the fusion is not thermonuclear.

## 7. Ampère forces in tokamaks?

In tokamak reactors, a circular plasma current is pinched away from the walls of the toroidal enclosure. When $10^6$ A flows in the plasma, the resulting Ampère tension, trying to disrupt the plasma ring, could be as high as $2\times10^5$ N. If this tension does exist, it is not surprising that enormous electromagnets are required to keep the plasma away from the walls. However, we have no proof that the dilute tokamak plasma obeys Ampère's force law in the same way as a metallic conductor or high density plasma.

The remarkable stability of electron, positron and proton beams in vacuum clearly demonstrates that Ampère's law does not apply to charges drifting in vacuum. Experimental facts however, clearly demonstrate the existence of Ampère forces in metals and dense plasmas. This discrepancy highlights the ambiguity of the notion of the *current element*. The current element used in the Lorentz force law is represented by a charge, $q$, multiplied by a velocity, $v$. Thus the Lorentz law is easily applied to charged particle beams. In metals, for which the Ampère force law was derived, the Ampèrian current element is a volume. The interaction of the high density particles in a metal lead to a different type of behaviour to the free charges. This issue is more closely analyzed by one of us in ref. [27]. Other theoretical considerations show that the current element is an ion–electron combination [12]. It is however not yet known whether the tokamak plasma behaves more like free charges or like a metal.

There is no doubt that the tokamak ring-shaped plasmas, carrying large currents, break out in many instabilities which propel ions to the metal walls. This can be prevented with magnets which impose an axial field through the current. The instabilities may also be caused by Nasilowski's plasma striation process [20].

We can also investigate whether Ampère forces could explain these phenomena, assuming that the Ampère force is effective in the low density tokamak plasma. Ampère's force law predicts the pinch forces between parallel current filaments. This force, usually attributed to the Lorentz force, is central to the MHD picture of the tokamak plasma. However, the Ampère force also predicts repulsive longitudinal forces between collinear current elements. The attraction of the filaments could generate the sausage instability, because the forces of attraction increase as the filaments move closer together. The longitudinal repulsion of current elements could give rise to the kink instability, which is usually thought to resemble the buckling of a solid bar. However there are no atomic bonds between plasma ions, and thus there is no reason for buckling in just one radial direction, as shown in fig. 1b. A more likely result of longitudinal Ampère forces is that each filament will buckle radially outward. This would give rise to the *fan in-*

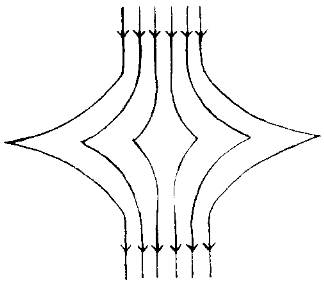

Fig. 10. Ampère fan-instability.

*stability* shown in fig. 10. It may not be coincidental that photographs of filament plasma instabilities (see fig. 5) look more like the fan picture of fig. 10 than either the sausage or kink pictures of fig. 1.

It is more complicated to assess to what extent Ampère forces caused by interaction with the containment magnets can explain the observed stabilizing effect. These calculations have not yet been carried out.

## 8. Discussion

The most important outcome of comparing different filament fusion experiments with each other is the growing consensus that they are not thermonuclear events. They must therefore be the result of a collective ion acceleration mechanism which operates along the current streamlines in the plasma. It could be due to electromotive (unidirectional) forces resulting from electromagnetic induction, or the bidirectional ponderomotive forces governed by Ampère's electrodynamic law. The magnetic component of the Lorentz force is always transverse to the current and cannot cause longitudinal ion acceleration.

The induced e.m.f.'s in the circuit would have to be back-e.m.f.'s. They oppose current flow, and thus reduce the ion velocity rather than increase it. Significant ion movement in the direction of induced back-e.m.f.'s would imply a reversal of current which has never been observed. This rules out electromagnetic induction as being the cause of filament fusion reactions. They must therefore either be thermonuclear or bidirectionally driven by longitudinal Ampère forces.

Work on *cluster impact fusion* [28] has shown that a deuteron energy as low as 300 eV may be sufficient to cause a fusion reaction. This is much lower than the customary 10 keV assumed to be required for thermonuclear reactions. Rabinowitz and Worledge [29] called the cluster impact result "luke-warm fusion". It is likely that the unexpected high neutron yield in some filament fusion experiments is a consequence of 300 eV deuteron collisions. It has been shown [2,3] that pairs of low energy deuterons can overcome the Coulomb repulsion barrier as the result of electrostatic screening due to a local high density electron cloud in the region of the colliding nuclei.

The probability of achieving fusion energy breakeven is the most important aspect when considering the prospects of non-thermonuclear fusion techniques. However, the best results to date reveal the ratio of energy out to energy in to be no better than $10^{-4}$. However, there has been no attempt to mechanically constrain the plasma. If Ampère forces are dominant in these situations, the best way to proceed is to mechanically encapsulate the high velocity nuclei, and thus greatly prolong the period of time during which fusion reactions may occur. Since this process does not require extremely high temperatures, plasma contact with the containment vessel is no longer a critical problem. In this way, filament fusion could eliminate the costly magnets of tokamak systems and greatly improve the prospect of commercial fusion reactors.

## References

[1] P. Rodgers, Phys. World (August 1991) p. 8.
[2] M. Rambaut, Phys. Lett. A 163 (1992) 335.
[3] M. Rambaut, Phys. Lett. A 164 (1992) 155.
[4] A.M. Ampère, Théorie mathématique des phenomènes electrodynamiques uniquement déduit de l'expérience (Blanchard, Paris, 1958).
[5] P. Graneau, Ampère–Neumann electrodynamics of metals (Hadronic Press, Nonantum, MA, 1985).
[6] O.A. Anderson, W.R. Baker, S.A. Colgate, J. Ise and R.V. Pyle, Phys. Rev. 110 (1958) 1375.
[7] F.F. Cap, Handbook on plasma instabilities, Vol. 1 (Academic Press, New York, 1978).
[8] D.B. Melrose, Instabilities in space and laboratory plasmas (Cambridge Univ. Press, Cambridge, 1986).
[9] J.F. Friedberg, Ideal magnetohydrodynamics (Plenum, New York, 1987).

[10] Y.V. Sopkin, L.A. Dorokhin, K.N. Koshelev and Y.V. Sidelnikov, Phys. Lett. A 152 (1991) 215.
[11] M. Rambaut and J.P. Vigier, Phys. Lett. A 142 (1989) 442.
[12] M. Rambaut, Phys. Lett. A 154 (1991) 210.
[13] P. Graneau, Phys. Lett. A 97 (1983) 253.
[14] M.G. Haines, Philos. Trans. R. Soc. A 300 (1981) 649.
[15] G. Decker and R. Wienecke, Physica C 82 (1976) 155.
[16] H. Herold, H.J. Keppeler, H. Schmidt, M. Shakhatre, C.S. Wong, C. Deeney and P. Choi, in: Plasma physics and controlled nuclear fusion research, Conf. Proc., Nice, France, October 1988 (International Atomic Energy Agency, Vienna, 1989).
[17] C. Sheer, in: Vistas in science, ed. D.L. Arm (Univ. of New Mexico Press, Albuquerque, NM, 1968) p. 135.
[18] P. Graneau, Galileian Electrodyn. 2 (1991) 3.
[19] M. Rambaut and J.P. Vigier, French patent nos. 9003660 (March 22, 1990) and 9004886 (April 17, 1990).
[20] J. Nasilowski, in: Exploding wires, Vol. 3, eds. W.G. Chase and H.K. Moore (Plenum, New York, 1964) p. 295.
[21] W. Lochte-Holtgreven, Atomenkernenergie 28 (1976) 150.
[22] S.K. Handel and O. Jonnson, Atomkernenerg. Kerntech. 36 (1980) 170.
[23] I.R. Lindemuth, Phys. Rev. Lett. 65 (1990) 179.
[24] P. Graneau, J. Phys. D 22 (1989) 1083.
[25] J.D. Sethian, A.E. Robson, K.A. Gerber and A.W. DeSilva, Phys. Rev. Lett. 59 (1987) 892.
[26] J.D. Sethian, A.E. Robson, K.A. Gerber and A.W. DeSilva, Workshop on Alternative magnetic confinement systems, Varenna, Italy, October 1990.
[27] N. Graneau, Phys. Lett. A 147 (1990) 92.
[28] R.J. Beuhler, Y.Y. Chu, G. Friedlander, L. Friedman and W. Kunnmann, J. Phys. Chem. 94 (1990) 7665.
[29] M. Rabinowitz and D.H. Worledge, Fusion Technol. 17 (1990) 344.