Magnetically Induced Plasma Rotation and the Dense Plasma Focus

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Fusion for fission fuel breeding and other incentives for unconventional magnetic fusion research are introductorily mentioned. The design, operation and peculiar characteristics of dense plasma foci are briefly described with attention to their remarkable ion acceleration and plasma heating capabilities. Attempts for interpretations are reviewed, and a brief account is given for an explanation based on the concept of magnetically induced plasma rotation, recently derived in detail in this journal. Basically an ion acceleration mechanism of betraton character it describes in combination with a dynamic, generalized Bennett relation focus plasma characteristics like the polarity dependence, the current channel disruption, the axial ion beam formation and the pre-requisites for the ensuing turbulent plasma dissipative stage. Fundamental differences with respect to mainline fusion research are emphasized, and some conjectures and proposals are presented as to the further development of plasma focus nuclear fusion or fission energy production.

1. Introduction

Crucial questions about reactor potential, safety and economic viability of the presently dominating Tokamak fusion reactor concepts are now subject to critical discussions also in non-specialized journals [1]. In conjunction, there is an increasing interest in unconventional approaches [2] to thermonuclear fusion energy from magnetically confined plasmas as well as fission-fusion hybrid schemes [2, 3] ("fissile fuel factories"). In short, the reason is that fission fuel can be seen as energy rich but scarce and neutron poor, rather the reverse holds for fusion. A combination appears technically and economically so attractive that there are reasons for the belief [4] that fusion for purely heat production can hardly be expected before the development and operation of the fusion breeder, also denoted the hybrid reactor.

The dense plasma focus [5–11], to be described in more detail in the next section, is a plasma compression device producing a highly energetic plasma of a small size and a short lifetime. Whether the focus assembly is of the wide Filippov [5] type or the slim Mather [6–9] type its geometry is hardly compatible with presently envisaged thermonuclear fusion reactor concepts [1], however, its capability as a remarkably intense fusion neutron source is well-established and recognized for materials testing [8] and, potentially, as the fusion neutron source in a hybrid reactor [12]. The focus plasma neutron yield exceeds that expected from calculations based on data from a thermal plasma by two or more orders of magnitude [8–10], however, only when operated with a proper matching of the external power source to the focus electrodes, and if a number of experimental parameters have been identified and adjusted for high neutron yield. Another and more intriguing focus characteristic is that its center electrode must necessarily be positive, and this sign dependence has long defied plasma theory in the usual MHD approximation. For negative polarity the plasma column compression and discharge electrical characteristics are normally well described by fast z-pinch MHD theory and successfully modelled numerically [13] or even analytically [14]. In contrast, the positive case leads to one or several plasma current disruptions and channel instabilities followed by the comparatively steady and neutron-producing diffuse or dissipative phase [6–11].

There are apparent similarities between features in the disrupting plasma focus channel (magnetized whirl structures, current filaments, accelerating electric fields) and solar flare characteristics [10, 14, 15],

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in particular, the plasma particle acceleration has been associated with the interruption of the channel current and the accompanied release as kinetic energy of exceedingly strong [15, 16] magnetic field energy densities.

The first conference entirely devoted to plasma foci took place in Brussels in 1980. Its proceedings [17] provide an excellent review of presently dominating theories, areas of uncertainty, past and present research efforts as well as conflicting views.

2. Design and properties of the plasma focus

A plasma focus device [5–11] consists basically of two coaxial electrodes separated by an insulator at the bottom end where the ignition of a gas discharge at an initial density of about $10^{17}\,\mathrm{cm}^{-3}$ takes place. The discharge is usually driven by a condenser bank in the 1 to 1000 kJ and 10 to 100 kV range. During the so-called run-down phase the discharge is driven by the $\boldsymbol{j} \times \boldsymbol{B}$ force like an umbrella-shaped current layer in the annular space between the electrodes, sweeping parts of the ambient neutral gas ahead. When reaching the front end of the center electrode the discharge turns into a horn shape and the compression phase begins. The horn compresses into a high density plasma channel protuding from center electrode tip. At this stage the channel current and the magnetic pinching force reach peak values yielding plasma densities of the order $10^{20}\,\mathrm{cm}^{-3}$, still, few fusion reactions take place. With the center electrode positive fast disruptive instabilities normally and suddenly occur, best seen as deformations to the previously cylindrical current channel and accompanied by one or a few transient variations in the discharge current. After this short instability period, ≈ 10 ns, the comparatively long, ≈ 100 ns, and steady, diffuse, also called dissipative, phase begins with its strong neutron emission, $\approx 10^{11}$, from the expanded plasma channel, density $\approx 10^{18}\,\mathrm{cm}^{-3}$.

Compared to other approaches in obtaining magnetically confined and fusion reacting deuterium plasmas a peculiar property of plasma foci is the strong localization both as to the short emission time, ≈ 100 ns, and to the small reaction volume, $\approx 100\,\mathrm{mm}^3$. Another characteristic is its non-thermal fusion reaction capability. There has to exist an efficient conversion process whereby the supplied electromagnetic energy is transferred as directed kinetic energy to the plasma ions, i.e. an ion acceleration mechanism capable of bringing the ions up to energies of several Mega electron volts, to be compared with the kilo electron volts obtainable by a direct acceleration between the electrodes.

3. Particle acceleration mechanisms

Many attempts have been made to clarify the kinetic energy transfer mechanism. Those simplest processes rely on electric fields associated with constrictions of the plasma column because of magnetohydrodynamic instabilities [18, 19]. More advanced theories invoke plasma turbulence [19–24], collective acceleration of ions [25], wave-particle interactions [26] and other processes [27, 28]. "Selfconsistent anomalous phenomena" have been suggested by [11]. Numerical modeling results [13, 14] including an "artificial viscosity" [29] hardly reproduce more than the early plasma channel compression phase [17].

A candid "explanation" was recently suggested in the concluding remarks about the neutron production mechanisms given in [30]: An unknown fundamental physical phenomenon is probably developing during the dissipative phase. This proposal, in effect a rejection of most previous theoretical models, was proved [30] to be strongly supported experimentally, in particular by the existence of a universal scaling law for the neutron yield in experiments which show substantial differences in the details of their phenomenology. The often conflicting views accounted in [17] tend to verify this bold proposal.

Experimental investigations, in particular a recently published paper [31], "Experimental studies of fast deutrons, impurity- and admixture-ions emitted from a plasma focus" lend support to the proposal about an "unknown but fundamental physical phenomenon" [30]. It was concluded in [31] that the impurity ions and possibly parts of the deutrons are accelerated in common processes. At least for the high-energy ions mechanisms leading to a uniform velocity of different ion species, as for instance wave-particle interactions, were claimed to appear very unlikely. The maximum energy E_m of the emitted ions was found to be proportional to their charge, clearly pointing to an acceleration in electric fields which were estimated to reach up to such an immense field strength as 50 MV/cm.

4. Magnetically induced plasma rotation

The magnetically induced plasma rotation is driven by the preferential action of a rotational electric field upon the ionic species in a quasi-neutral plasma. This rotation is, paradoxically, both contained in and also denied by generally accepted fluid plasma formulations and reasonings. As the resolution [32] was recently discussed in detail it will not be repeated here, except for a mentioning that it brings to attention the normally overlooked fact that the quasi-neutrality in a plasma with magnetically gyrating charge carriers is sustained by internal forces of non-central character, thus invalidating the common mechanical theorem that states that the time rate of change of mechanical angular momentum of a system equals the sum of the external torques acting on it.

Consider the Generalized Ohm's law in standard SI notations and with the usual neglect of electron inertia

$$\frac{\boldsymbol{j}}{\sigma}+\frac{1}{e\,n_e}\,\boldsymbol{j}\times\boldsymbol{B}=\boldsymbol{E}+\boldsymbol{V}\times\boldsymbol{B}+\frac{1}{e\,n_e}\,\mathrm{grad}\,p_e\,. \quad (1)$$

For a highly ionized plasma the mass velocity $\boldsymbol{V}$ equals the average ionic velocity. The scalar conductivity σ in (1) can then be expressed as the product $e\,n_e\mu_e$ of the plasma charge density $e\,n_e$ and the electronic mobility $\mu_e = e\,\tau_{ei}/m_e$ where τ_{ei} and m_e are the electron collision time and mass, respectively. The magnetic Reynolds number $R_m = \mu_0\sigma L V_0$ involves, in addition to the permeability μ_0 of free space, characteristic values L and V_0 for length and velocity, respectively. When R_m is introduced in (1) it is found

$$\frac{\boldsymbol{j}}{R_m}+\frac{\mu_e B}{R_m}\,(\boldsymbol{j}\times\boldsymbol{B}/B) = (\boldsymbol{E}+\boldsymbol{V}\times\boldsymbol{B})/\mu_0 L V_0+\frac{\mu_e}{R_m}\,\mathrm{grad}\,p_e\,. \quad (2)$$

Obviously, and trivially, just a high conductivity will make R_m large and resistive electric field negligible, however, $R_m \gg 1$ is not a sufficient argument to neglect the second so-called Hall term. It contains as a factor the Hall parameter

$$\mu_e B = \omega_{ge}\tau_{ei}\,, \quad \omega_{ge} = eB/m_e \quad (3)$$

which, like R_m, takes large values whenever the electrons have sufficient mobility to make many magnetic gyrations during the collision time τ_{ei}. This is a characteristic property for magnetically confined fusions plasmas, in contrast to metals for which $R_m \gg 1$ but $\mu_e B \ll 1$. Thus, there is a duality in the concept of high conductivity, and only the "metal case" leads directly to classical concepts like magnetic flux conservation, "frozen" fields lines, etc.

Under reasonably dynamic plasma condition the full criterion for neglecting the Hall term can be derived in various ways [32], yielding a necessarily small value of the *ion* collisionless skin depth λ_i

$$\lambda_i^2/L^2 = m_i/\mu_0\,n_e\,e^2 L^2 \ll 1\,. \quad (4)$$

For a fully ionized deuterium plasma of density range $10^{15}-10^{17}\,\mathrm{cm}^{-3}$ λ_i will range between 1 cm and 1 mm. Evidently, the inequality (4) can be readily satisfied only by high-density plasmas with comparatively large dimensions like high-current electric arcs, imploding cylindrical shells or exploding wires and, of importance here, the dense focus plasma channel before its diffuse or dissipative phase. The inequality (4) does not seem reasonably well satisfied by any of the mainline magnetic compression or confinement schemes [32].

The Generalized Ohm's law (1) is actually a rewritten form of the equation of motion for the plasma electrons with their inertia neglected. With the same simplification and negligible plasma viscous effects the plasma mass transport equation is given by

$$\varrho_m\,(\mathrm{d}\boldsymbol{V}/\mathrm{d}t) = \varrho_e\boldsymbol{E}+\boldsymbol{j}\times\boldsymbol{B}-\mathrm{grad}\,p\,, \quad (5)$$

where the plasma excess charge force $\varrho_e\boldsymbol{E}$ is usually taken negligible. In case of complete, $\varrho_m = n_i m_i$, or spatially uniform ionization degree (1) and (5) have together with the Maxwell equations

$$\mathrm{div}\,\boldsymbol{B} = 0\,, \quad (6)$$

$$\mathrm{curl}\,\boldsymbol{E} = -\,\partial\boldsymbol{B}/\partial t \quad (7)$$

as a mathematical consequence an expression that primarily relates magnetic flux changes, in time or space, with plasma rotation

$$\frac{\mathrm{d}}{\mathrm{d}t}\int\boldsymbol{B}\cdot\mathrm{d}\boldsymbol{S} = -\frac{\mathrm{d}}{\mathrm{d}t}\oint\frac{\varrho_m}{e\,n_e}\,\boldsymbol{V}\cdot\mathrm{d}\boldsymbol{s} + \oint\left[\frac{\varrho_e}{e\,n_e}\boldsymbol{E}-\frac{1}{e\,n_e}\,\mathrm{grad}\,(p-p_e)-\frac{\boldsymbol{j}}{\sigma}\right]\cdot\mathrm{d}\boldsymbol{s}\,. \quad (8)$$

The integrals refer to a closed loop, length element $\mathrm{d}\boldsymbol{s}$ which defines the boundary of a simple closed

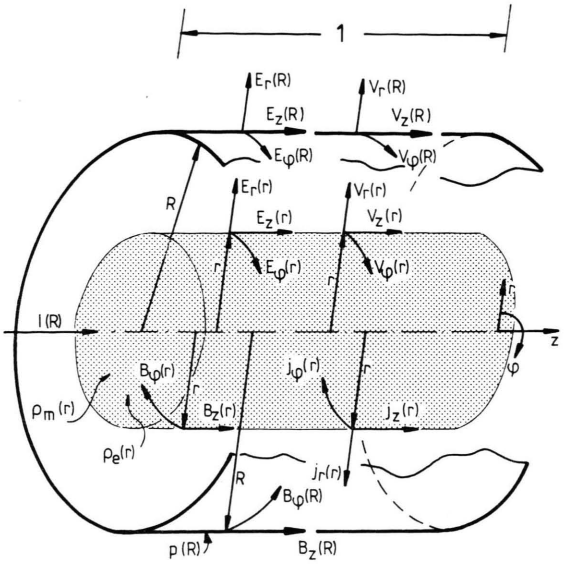

Fig. 1. Cylindrical plasma whirl structure, or homogeneous current channel portion of unit length described by the Generalized Bennett Relation.

surface, surface element $\mathrm{d}\boldsymbol{S}$. The loop is "frozen" into the plasma so that it follows its motion. The integrand terms of the last integral mean, in order, rotation driven by a rotational field acting on plasma excess charge, effects by the ionic baroclinic vector and resistive retardation of plasma rotation. These effects have been discussed and proved small or negligible under focus plasma conditions [32].

5. The current channel

The assumed geometry of the high density plasma channel is shown in Figure 1. The channel is located coaxially within a hypothetical cylinder surface of fixed radius R and unit length. This length is assumed to be short enough to make axial variations in any fluid plasma parameter negligible. Additionally, general rotational symmetry is assumed with respect to the symmetry axis. The plasma is not taken to electrically quasi-neutral. The channel cylinder boundary is diffuse and axial as well as radial and azimuthal mass transports may take place within the plasma. The plasma density ϱ_{m} obeys the equation of continuity

$$\partial \varrho_{\mathrm{m}} / \partial t + \operatorname{div}(\varrho_{\mathrm{m}} \boldsymbol{V}) = 0 . \tag{9}$$

From (5), (6), (7), (9) and the additional two Maxwell equations, in standard SI notations and plasma-dynamic approximation,

$$\operatorname{curl} \boldsymbol{B} = \mu_0 \boldsymbol{j} , \tag{10}$$

$$\varepsilon_0 \operatorname{div} \boldsymbol{E} = \varrho_{\mathrm{e}} , \tag{11}$$

a generalized Bennett relation has been derived [33] for the described current channel by extending the Chandrasekhar-Fermi-Schmidt virial theorem. In full this generalized Bennett relation reads

$$\begin{aligned} &\frac{1}{4} \frac{\partial^2}{\partial t^2} [J_0 - M(R) R^2] + \pi R^2 \varrho_{\mathrm{m}}(R) V_r^2(R) \\ &\quad = W_{\mathrm{kin}\perp} + W_{\mathrm{e}z} + W_{\mathrm{m}z} + \frac{2}{3} W_{\mathrm{p}} - W_{\mathrm{R}} - W_0 \\ &\quad - \frac{\pi}{2} R^2 \varepsilon_0 E^2(R) + \pi R^2 \varepsilon_0 E_r^2(R) . \end{aligned} \tag{12}$$

$M(R)$ and J_0 are the plasma cylinder mass and moment of inertia, respectively

$$M(R) = \int_0^R \varrho_{\mathrm{m}}(\xi)\, 2\pi \xi \,\mathrm{d}\xi , \tag{13}$$

$$J_0 = \int_0^R \varrho_{\mathrm{m}}(\xi)\, 2\pi \xi^3 \,\mathrm{d}\xi . \tag{14}$$

With the cylinder surface R sufficiently distant from the current channel it can be assumed $\varrho_{\mathrm{m}}(R) = 0$ or, less restrictively, $V_r(R) = 0$. Then, only the second derivative of the moment of inertia will be retained of the LHS of (12). Although a positive value of this derivative is also obtained upon a retarded channel compression positive RHS terms will be denoted as expansional. These terms are given by

$$W_{\mathrm{kin}\perp} = \int_0^R \varrho_{\mathrm{m}}(\xi) [V_\varphi^2(\xi) + V_r^2(\xi)] \pi \xi \,\mathrm{d}\xi ,$$

$$W_{\mathrm{e}z} = \int_0^R \varepsilon_0 E_z^2(\xi) \pi \xi \,\mathrm{d}\xi ,$$

$$W_{\mathrm{m}z} = \mu_0^{-1} \int_0^R B_z^2(\xi) \pi \xi \,\mathrm{d}\xi ,$$

$$W_{\mathrm{p}} = \int_0^R 3 p(\xi) \pi \xi \,\mathrm{d}\xi , \quad p = n k_{\mathrm{B}} T ,$$

$$E^2(R) = E_r^2(R) + E_\varphi^2(R) + E_z^2(R) , \tag{15}$$

all with obvious interpretations. The term W_{R} accounts for possible channel compression by an axial field $B_z(R)$, or a gas pressure acting at R

$$W_{\mathrm{R}} = \pi R^2 [B_z^2(R)/2\mu_0 + p(R)] . \tag{16}$$

This term, important to "magnetic bottles" and "gas-embedded pinches" is small or irrelevant here. W_0, however, is always dominant, related to B_φ and the channel current I by the Biot-Savart law

$$W_0 = \pi R^2 B_\varphi^2(R)/2\mu_0 = \mu_0 I^2(R)/8\pi\,,$$
$$r B_\varphi(r) = \mu_0 \int_0^r j_z(\xi)\,\xi\,\mathrm{d}\xi = \mu_0 I(r)/2\pi\,. \qquad (17)$$

The static balance between W_0 and 2/3 W_p in (12) gives the usual Bennett relation. In [33] the electric terms in (12) were discussed. In the present context there might arise only a slight or negligible expansional effect given by $\pi R^2 \varepsilon_0 E_r^2(R)/2$ by electrostatic charge build-up.

With all the discussed simplifications the generalized Bennett relation (12) now reduces to

$$\frac{1}{4}\frac{\partial^2 J_0}{\partial t^2} = W_{\mathrm{kin}\perp} + W_{\mathrm{m}z} + \frac{2}{3} W_\mathrm{p} - W_0 + \pi R^2 \varepsilon_0 E_r^2(R)/2\,. \qquad (18)$$

Note that the three expansional W-terms form a crude energy conservation balance within the current channel. It has long been recognized that only some kind of disruption of magnetic structures with very or extremely high magnetic energy density, peak field strengths $\approx 10^4$T [16], can provide that intense primary energy release which gives rise to localized fusion reaction regions [17]. Hardly can the mentioned estimated accelerating electric field strengths, ≈ 50 MV/cm, be explained differently. Equation (18) not only supports the belief that released magnetic energy is the primary source of kinetic ion energy, it even states that the energy conversions magnetic energy → directed gas-kinetic plasma energy → quasi-thermal plasma energy can taken place within the channel without imparting strong effects on its gross dynamic behaviour. Another result from (18) is that there is no limit to the equilibrium current carried by a helical current system wound so as to generate an axial magnetic field $B_z(r)$ balancing the pinch field $B_\varphi(r)$. Such a discharge relaxation into a helical force-free configuration has often been suggested, and there are even experimental observations [34].

6. The polarity effect

Plasma foci are always operated with the inner electrode as the anode. A reversed polarity reduces the neutron yield by one or several orders of magnitude, and related features like the current disruption, voltage transients and particle and X-rays emissions will also be missing or much reduced. The polarity effect has long been the test, actually the stumbling-block, for plasma focus theories. It may also be noted that the current disruption occurs much faster than the magnetic diffusion time $\mu_0 \sigma L^2$, even faster or equal to the Alfvén wave propagation time L/V_A.

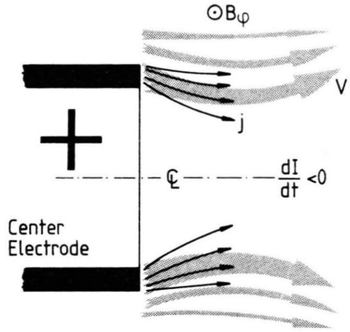

Fig. 2. The polarity effect. Plasma flow directed from the anode and driven by magnetically induced plasma rotation for a decreasing positive electrode current.

(8) states that the inductive electric field associated with magnetic flux variations drives plasma mass motion. Combined with the fact that the current disruption occurs immediately after the instant of maximum discharge current (8) gives a straight-forward explanation: An essentially axially directed magnetically induced plasma motion starts to sweep away the ambient plasma in front of the anode, necessary for the electrode current passage. Once started, this mechanism *driven by* the decrease in current *acts to* decrease the current, i.e. there will be a positive feed-back current choking mechanism. Vacuum replaces conducting plasma! Figure 2 depicts qualitatively the current and plasma flow pattern outside an anode of the usual tubular form *emitting* a *decreasing* current. Note that the plasma flow pattern will be roughly the same for a cathode receiving an *increasing* current which may then be impeded, in principle up to $\mathrm{d}I/\mathrm{d}t = 0$, but not further.

In spite of no direct polarity dependence and the slow growth rate for $m = 0$ ("sausage") instabilities the focus plasma channel constriction and current disruption is often interpreted, or at least referred to in this way. To this it may be noted that it does not seem possible to give any obvious physical meaning to the concept of m-number instabilities when the Hall term of (1) or (2) is non-negligible. Another interpretation, but hardly with better physical relevance for the current channel necking-off is that of the hydrodynamic Rayleigh-Taylor instabilities.

7. The axial ion acceleration

Although most fusion reactions seem to take place under a kind of dynamic but still magnetic confinement during the comparatively late dissipative phase, experiments at usually lower initial gas density exhibit an earlier and axially directed ion acceleration [8–10, 17], intense enough to suggest plasma foci assemblies as ion beam sources [8]. This capability will be estimated semi-quantitatively.

Consider the total electromagnetic power input P_{in} into the plasma channel section shown by Figure 1. It is given by the Poynting vector $\boldsymbol{E}\times\boldsymbol{B}/\mu_0$, only taken over the cylinder surface as the symmetry makes the circular surface contributions cancel.

$$P_{in} = 2\pi R[E_z(R)\,B_\varphi(R) - E_\varphi(R)\,B_z(R)]/\mu_0\,. \tag{19}$$

From

$$\mu_0 I(R) = 2\pi R B_\varphi(R) \tag{20}$$

the first term of (19) is recognized as the usual $I(R)E_z(R)$ expression for the power input into a unit length straight z-pinch. The two sources of the total electric field $E_z(R)$ are found as

$$E_z(R) = E_z(0) + \partial\Phi_\varphi(R)/\partial t\,, \qquad \Phi_\varphi(R) = \int_0^R B_\varphi(\xi)\,\mathrm{d}\xi\,. \tag{21}$$

The radial distribution of $I(R)$ is not known. It is certainly not uniform, rather will $I(R)$ because of skin-effect probably be restricted to a cylindrical shell of thickness $\delta r(t)$ which, however, not necessarily must be small compared to the actual channel radius r. Thus

$$\mu_0\, I(r) = 2\pi\, B_\varphi(r)\,, \quad I(r) = 2\pi\, r\, \delta r\, e\, n_e\, V_{ez} \tag{22}$$

and the shell contains the azimuthal magnetic flux

$$\Phi_\varphi(r) \approx \tfrac{1}{2}\, B_\varphi(r)\, \delta r = \mu_0\, I(r)\, \delta r/4\pi r\,. \tag{23}$$

The time rise in $\Phi_\varphi(r,t)$ will lead to an axial velocity shear ΔV_z, given by (8) as

$$\Delta V_z = e\, n_e\, \Phi_\varphi(r)/\varrho_m \approx e\, \delta r\, B_\varphi/2m_i\,. \tag{24}$$

The magnitude of this velocity is compared with the average conduction current electron velocity $V_{ez} = B_\varphi(r)/\mu_0\, r\, \delta r\, e\, n_e$. It is found

$$\Delta V_z/V_{ez} = \tfrac{1}{2}\,(\delta r/\lambda_i)^2 \tag{25}$$

which also substantiates the polarity effect description in the previous section. Before the peak plasma compression the ambient plasma density is low enough to make $\lambda_i = (m_i/\mu_0\, e^2\, n_e)^{1/2}$ larger than an electronic current layer thickness δr. However, as λ_i equals or falls below pertinent plasma channel dimensions, like δr, (25) predicts not only a break-down for the assumed plasma channel conduction process but also the features of this break-down: There will be an axially directed ion acceleration, and as nothing but vacuum has time to replace the conducting plasma, there will be an electronic current disruption also seen as the necking-off of the plasma channel.

In early years the "axial beam-target" school-of-thought fought that of the "moving boiler". It seems here that the former was right, but only to the extent of the early fusion processes, before the dissipative phase when the large neutron emission is obtained for "neutron optimized" focus assembly conditions.

8. The Dissipative Stage Neutron Production

At the Moscow plasma focus workshop agreement was reached on a description of the focus neutron production origin, as follows [35]: "Most neutrons are due to the interaction with low density ($10^{17}-10^{18}$) plasma structures of medium energy (≈ 100 keV) ions confined for a long period of time in a self-sustained magnetic configuration."

This interpretation, stressing a two-component particle energy distribution, implicitely asssumes effects from a preceding, and also experimentally observed [31], highly efficient ion acceleration. From considerations as to its localization in time, space and origin of power, it is found to occur during the preceding current channel partial disruption with the accompanying, rapid current and magnetic field variations.

Particle acceleration associated with fluctuating electromagnetic self-fields is also a characteristic of unstable straight discharges [17], so-called z-pinches, as well as toroidally bent discharges with or without an externally applied stabilizing magnetic field in the discharge direction. A most well-established but still remarkable observations is the total optimum neutron yield proportionality with a strong power, $I^{3.5}-I^4$, [6−11] of the plasma channel current I in deuterium discharges. As discussed by, e.g., [11] the fraction two of this large exponent, usually taken to be near or equal to four, can be satisfactorily explained by the particle accumulation from the $\boldsymbol{j}\times\boldsymbol{B}$-force acting on neutral deuterium atoms or molecules to serve as targets for the accelerated deuterium ions in the ensuing fusion reaction collisions. An analysis accounting for the remaining part, about two, in the exponent, however, necessarily involves exceedingly intricate multiple integrations over time, reaction volume and particle velocity distributions. Clearly, any proper set of simplifying but reasonable assumptions may lead to the desired power of about four, yet, as stressed by [30] the *general nature* of this relation would then still not be explained.

Consider (8). With the last line integral negligible, as discussed, it expresses conservation of canonical, i.e. matter-plus-field, angular momentum for the plasma heavy species, in practice the ions in a highly ionized plasma focus discharge. (8) thus describes the transfer of the field angular momentum part into the purely matter part, and, of course, the reverse. Consider a cross section of the plasma column in Figure 1. Approximately, such a *momentum* transfer from field to matter can be indicated as

$$\Phi_z(r) \approx \pi r^2 B_z(r) \to \frac{\varrho_m(r)}{e\, n_e(r)}\, 2\pi r V_\varphi(r)\,,$$
$$\varrho_m = n_i m_i \qquad (26)$$

and squared, this can be expressed as the *energy* transfer

$$\frac{B_z^2(r)}{2\mu_0} \to 4\left(\frac{\lambda_i}{r}\right)^2 \frac{1}{2}\varrho_m V_\varphi^2,$$
$$\lambda_i^2 = m_i/\mu_0 e^2 n_i\,. \qquad (27)$$

The factor 4 here is just the square of the figure two in the classical betatron 2 : 1 field rule. For a uniform field B_z the ions will move towards the symmetry axis. The remarkable single particle trajectories occurring then have been derived analytically in [36].

The collisionless skin depth λ_i in (27), typically about 0.2 mm for the usual deuterium-impurities mixture in a "conditioned" focus plasma at its peak density, $\approx 10^{19}\,\mathrm{cm}^{-3}$, is found experimentally to be smaller or, at most, approximately equal to the compressed current channel radius r. Focus discharges often exhibit a filamentary structure [37−39]. Then, the individual filament is a magnetized whirl structure, and it is not only described by (8, 27) but is also closely related, as seen experimentally [40] and derived theoretically [41], to the filamentary current whirl structures exhibited by Type II superconductors. This relationship, i.e. magnetized plasma described by the Meissner effect London equations, was brought up in [42].

(27) scales the magnetically induced ion acceleration energy as the selfgenerated magnetic energy density which, in turn, approximately scales as the square of the discharge current. Hence, with both beam particle energy and target particle number scaling as the current squared it would seem that something like the desired approximate fourth power is obtained. This, however, is probably just a part of a full explanation. It is more likely that the observed universal I^4 relation, in addition, also expresses the ability of the discharge current magnetic field to retain the magnetically accelerated particles confined, a property that also scales more or less as the current squared. This brings agreement with the empirically obtained description cited at the beginning of this section. More important, any apparent conflict is removed about the view and observations that also turbulence is a common or even characteristic feature of the neutron-emitting focus plasma during the dissipative stage. Actually, the magnetically induced plasma rotation just creates the necessary proverbial early big whirl which in turn becomes smaller whirls becoming turbulence! The analysis of such processes requires turbulence theory and, preferably, also powerful computer techniques like those applied in [23, 24].

Thermonuclear fusion research is generally taken to originate from the fact that a net fusion output can not be obtained by having accelerated deuterium or tritium ions impinging upon cold fusion fuel, see e.g. [43]. Clearly, this situation has no or little relevance for the turbulent and dynamic, yet magnetically confined plasma, as observed and described in the dissipative stage of the focus discharge.

9. The Plasma Focus and the Mainline Fusion

The plasma focus is often regarded as a kind of the dynamic z-pinch because of its radially contracting current channel. Historically, however, it has developed from the coaxial Marshall plasma gun [44] and the Filippov non-cylindrical plasma sheath compression device [5]. Further, its key feature, the strong ion acceleration, is caused by the same mechanism as that which drives the intense plasma rotation and preferential ion acceleration, leading to $T_i \gg T_e$ and other features typical of fast theta-pinches [32].

Progress in focus research has been achieved rather by experimental skill and brilliant intuition than by theoretical deliberations by, in particular, pioneers like Mather, Bostick, and the Filippov couple. In contrast, those nuclear fusion conditions which magnetic and inertial fusion are aiming at were reasonably well known at the very start of controlled fusion research decades ago and, ever since, increasingly more knowledge has been gained about them. For instance, laser fusion with its origin in H-bomb technology has plasma compression as the imperative requirement. The ensuing chains of nuclear reactions to occur in the compressed pellet have been numerically modelled in detail. The acceptable and low impurity contents in the magnetically confined plasma is well known as also the necessity and properties of various external heating mechanisms. In contrast, the focus plasma emits most neutrons *after*, not during, its peak compression. It can be *very dirty* with little effect on its fusion output, and it apparently carries a powerful *built-in* heating mechanism released during the dissipative phase. As discussed in the recent [32] these experimentally seen discrepancies between the desired properties of the mainline magnetic confinement fusion plasmas and the properties actually exhibited by the focus plasma have as their physical origin some simplifications, far more restrictive than usually realized, inherent in the "ideal" MHD plasma fluid description.

10. Some Conjectures, Summary and Conclusions

Experiments have been carried out with small DT-filled microballoons placed in the focus discharge with the aim of increasing the fusion neutron production [45]. The negative outcome of these attempts indicates, as many focus scientists would suspect, [17], that the early discharge run-down and subsequent current channel formation stage are crucial for the later focus performance, probably by involving a delicate sweeping-up and accumulation in the contracting channel of a proper amount of ambient gas. If the added fusion fuel had been fed beforehand into the discharge region as a vapour stream or cloud, e.g. ejected from a nozzle at the center electrode tip, the results might, perhaps, have turned out better.

During the run-down and/or the compression phase the electrode current through the plasma usually distributes into filaments. This general tendency of plasma volume currents to turn into separate structures ("line currents", "flux ropes", "ray constrictions") is one of the most pronounced and, seemingly, least understood *fundamental* property of magnetized plasmas [46]. By its transition into a discrete helical current distribution the individual current filament relaxes into a more force-free configuration, i.e. a self-generated axial magnetic field partly balances the magnetic pinch effect, see the Generalized Bennett relation (18). The energy associated with this axial magnetic field, strenghts of the order many Megagauss [16], is the primary source for the kinetic energy transfer to the whirl ions upon an electrode current disruption, in accordance with the ion canonical angular momentum conservation relation (8), and also the crude energy balance $W_m \rightarrow W_{kinz}$ expressed by (18).

The ion collisionless skin depth λ_i (4), is seen both in experiments and from theory [32, 40–42] to be the characteristic whirl radius. The striking similarity [40] between magnetized whirl formation in focus discharges and type II superconductors should be noted, also, that with λ_i scaling as $(n_i)^{-1/2}$, the fuel injection conjecture above might lead to an increased number of thinner whirls.

Upon the total or partial disruption of the electrode current carried by the whirls their axial magnetic field energy is transferred inductively into ion kinetic energy, see (18) and (27). This suggests, of course, current switching by external means instead of that by the polarity effect described in Section 6. According to the interpretation there that switching process starts operating at the very instant when the total current starts to decrease. Another conjecture would then be to make use of a suitable alternating component superimposed upon a comparatively steady and larger electrode current so as to obtain periodically repeated dissipative stages with, hopefully, the possibility of regulating the degree of current disruption which, in turn, may determine the transfer ratio between axially and tangentially directed kinetic ion energy.

A proposal rather than a conjecture is achieving neutron-free nuclear energy by the reactions of isotopes of lithium, beryllium or boron in energetic collisions with protons or deutrons under the described energetic and turbulent dissipative phase of the focus plasma. Several fission, not fusion(!), reactions by such processes are conceivable, normally resulting in helium as the final product element.

The present work has attempted to interpret the dense plasma focus operation as a series of physically different but closely interrelated consecutive steps, each of which is a pre-requisite for the ensuing one. Those initial are well-known from observations and early theory, i.e. the sheath run-down and the channel compression including a proper amount of swept-up fusion fuel. The next phase starts at the instant of the electrode current decrease by the polarity effect which is a partial, sudden electrode current choking mechanism caused by an axial plasma flow driven by magnetically induced plasma rotation. It leads to an axial ion beam emission and usually also to fusion reactions mainly of beam-target character. More important, the electrode current decrease causes the self-generated magnetic field energies in one or several magnetized plasma channel whirl structures, described by the Generalized Bennett Relation, to be released by *magnetically induced plasma rotation* as electrically field-gained ion kinetic energies. In our view, *this is the key process which fundamentally distinguishes the plasma focus, both as to this unique physical principle and as to orders of magnitude more intense performance, from other magnetic fusion research concepts.* Under empirically obtained neutron-optimized conditions turbulence mechanisms are most likely very efficient in converting these ion kinetic energies into that energetic yet quasi-thermal plasma particle distribution responsible for the remarkably anisotropic, copious and steady neutron emission during the dissipative phase.

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