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# WILD CABLES IN TOKAMAK PLASMAS (THEORETICAL VIEW)

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**1. Introduction.** Our previous studies of long-living filaments (LLFs) in various laboratory plasmas [1], namely gaseous Z-pinches, plasma foci, laser-produced plasmas, tokamaks, and cosmic space, has lead us to the conclusion [1(b)] that only the quantum long-range bonds inside LLFs may be responsible for their observed unbelievably high mechanical stability and survivability, rather than the mechanisms of a classical particles plasma. Specifically, the carbon nanotubes, or similar nanostructures from other relevant chemical elements, have been proposed [1(b)] to be the major microscopic building blocks of a hypothetical microsolid skeleton of the LLFs (recall that nanotubes are known to be produced in various *low-temperature* electric discharges). In the present paper, we give very short description of ***(i)*** formulated hypotheses suggested for interpreting the observations [1(b),2(a)] of the tubular rigid-body LLFs of macroscopic size in tokamak and Z-pinch plasmas (see also papers P2.029 and P2.051 of this conference) and ***(ii)*** a qualitative model for the survivability of skeletons in *high-temperature* plasmas.

**2. Microsolid skeletons of long-living filaments in plasmas: hypothetical life story.** The qualitative picture of electrical breakdown [1(b)], with allowing for the possibility of transporting the EM energy along/inside the LLFs [1(c)], may be extended to give the following picture of LLF's formation and survivability for particular case of tokamak plasmas.

(i) A deposit of carbon nanotubes, of relevant quantity, is produced at the inner surface of the chamber during discharge training, from either graphite-containing construction elements (like, e.g. limiters or walls) or carbon films produced by the deposition of the organic oils normally used in the vacuum pumping systems (the nanotubes may be formed due to rolling up of monolayers ablated from solid surfaces or thin films).

(ii) Electrical breakdown occurs along chamber's surface (or its part, namely, the inner side of the torus) and is based on the substantially enhanced rate of (cold) autoemission and thermoelectric emission of electrons by the nanotube (as compared to macroscopic needles).

(iii) The microsolid skeletons are assembled from individual nanotubes which are attracted and welded to each other by the passing electric current to produce self-similar tubules [1(b)] of macroscopic size, of centimeter length scale and larger (this electric current is produced by the poloidal magnetic field $B_{pol}$ pumped from the external electric circuit into the chamber).

(iv) Once the skeleton (or its relevant portion) is assembled, the substantial part of the incoming $B_{pol}$ brakes at it and produces a cold heterogeneous electric current sheath which is made of conventional plasma. A part of $B_{pol}$ near the skeleton is bouncing along its every rectilinear section (i.e. between the closest points of the deviation, even small enough, from rectilinearity). This produces a high-frequency EM wave which, in turn, produces, by the force of the high-frequency (HF) pressure [3] (sometimes called in literature the Miller force), the cylindrical cavities of a depleted electron density (primary channels) around the skeletons.

(v) At the plasma column's edge the bouncing boundary of the cavity from the scrape-off layer side produces a HF valve for the incoming $B_{pol}$ , because of the node of the standing wave at the edge. This works as a HF convertor of a part of the incoming $B_{pol}$ which is transported then along the skeleton in the form of EM waves. (Besides, a part of $B_{pol}$ which reaches the cavity in the conventional regime of the diffusion of $B_{pol}$ , is transformed into a HF field by the oscillating boundary of the cavity). These waves sustain the cavity and protect the skeletons from direct access of thermal plasma particles. Therefore the skeleton appears to be an inner wire of the cable network (a ***wild cable*** network) in which the role of a screening conductor is played by the ambient plasma.

In what follows we restrict ourselves to quantifying the above picture in its quasi-stationary stage of energy inflow through the wild cable network.

**3. A mechanism of survivability of microsolid skeletons in hot plasmas.** The individual wild cable is formed by a microsolid tubule, of length $L_c$, which plays the role of an inner wire of radius $r_w$. Significantly, the channel for transporting the EM energy is formed by the EM waves themselves so that each inner wire is embedded into its own cylindrical almost-vacuum cavity of the effective radius $r_c$ in a plasma of electron and ion temperatures $T_e$ and $T_i$, respectively. We consider the frequency of the EM wave, which propagates in the individual cable, to be determined by the geometry of the cavity rather than by the eigenmodes of the ambient plasma. The latter requires large enough internal reflection of the EM wave inside the cavity (as in a resonator) so that substantial part of the EM energy is trapped in the individual cavity and possesses, in its major harmonic $\omega_C$, a narrow spectral distribution ($\omega_{pe}$ is plasma frequency, *c*, the speed of light):

$$\omega_c \approx (\pi\, c / L_c) < \omega_{pe} . \qquad (1)$$

For tokamak geometry, one has the following chain of transformations of EM waves. The cavities at plasma edge (they normally possess some declination with respect to the boundary magnetic surface) allow the field lines of $B_{pol}$ to move directly inside the cavity and, thus, to produce a magnetic (H) wave. For the strongest EM wave among H waves, the $H_{11}$ wave, one has: $\lambda \approx 2L_c > \lambda_{crit} \sim \alpha\, r_c$, where $\lambda_{crit}$ is the critical wavelength for free propagation of the respective EM wave in the cable; for $H_{11}$ wave one has $\alpha_{H_{11}} \sim \pi$. The trapping of $H_{11}$ wave in the edge cavity results in the wiring of magnetic field lines round the inner rod to produce TEM and electric (E) waves propagating in both directions. The strongest wave among E-waves, the $E_{01}$ wave, will also be trapped in the cavity (because of $\alpha_{E_{01}} \approx 2.6$), in contrast to TEM wave (because of $\lambda_{crit}^{TEM}$ is infinite). Also, the H and E-waves, in contrast to TEM wave, are detached from the wall (in radial direction, these waves are the standing ones) so that only the TEM wave can actually maintain the boundary of the cavity. Thus, the edge cable (cf. e.g. Fig. 2 in P2.029) may convert a part of $B_{pol}$ into HF TEM wave propagating inward. The signs of this HF field may be found in the measurements of EM fields outside plasma column because a small part of this field is reflected outward, into the gap between the plasma and the chamber (see below).

It is assumed also that the presence of a strong static external magnetic field doesn't influence substantially the form of the cavity (even when $\omega_C \ll \omega_{Be}$ , $\omega_{Be}$ is electron gyrofrequency): the latter requires the amplitude $\mathbf{E}_0$ of the HF electric field to have a non-zero component parallel to external magnetic field.

The distribution of plasma density around the inner wire can be described by a set of equations for the two-temperature quasi-hydrodynamics of a plasma in a HF EM field [3]. Under condition $l_E \gg r_D$, where $l_E$ is the characteristic length of spatial profile of $\mathbf{E}_0(\mathbf{r})$ and $r_D$ is Debye radius, one can neglect the deviation from the quasi-neutrality and arrive at quasi-Boltzmann distribution (see e.g. [3(b)]; $n_{e0}$ is background density of plasma electrons):

$$n_e = n_{e0} \exp(-\frac{\Psi}{T_e + T_i}), \quad \Psi = \frac{e^2 E_0^2}{4 m_e \omega_c^2}, \qquad (2)$$

Equation (2) gives the following condition for the detachment of electrons:

$$e U_0 > 2\pi\, (r_c / L_c) \sqrt{A m_e c^2 (T_e + T_i)}, \quad A \sim (r_w^2 / r_c^2) \ln(n_{e0} / n_{e\min}), \qquad (3)$$

where $U_0$ is the effective voltage bias of the TEM wave in the cable ($E_0(r) \sim U_0/r$, where r is the radial coordinate in a circular cylindrical cable), $n_{emin}$ is the minimal density permitted, at a temperature $T_e$, for the inner wire to be not destroyed by the plasma impact. For tokamak case ($n_{e0} \sim 10^{13}$ cm$^{-3}$), we take A ~ 5.

Equation (3) is to be coupled to the condition of applicability of the concept of the «gradient Ψ» force (Miller force), $\rho \ll l_E$ (ρ is the amplitude of electron's oscillations in the HF electric field), which limits the eigenfrequency $\omega_C$ from the side of low values. For our estimates, this limitation may be weakened to take the form:

$$eU_0 < \pi^2 m_e c^2 r_c (r_c - r_w) / L_c^2, \qquad (4)$$

Also, the HF electric field in the cables may be related to the observable turbulent electric fields. Indeed, the wild cables are the strong sources of electrostatic oscillations in plasma, first of all, along strong external magnetic field. For wild cables to be compatible with a strong turbulence, one may consider the cable's cavity as a soliton with such a strong reduction of the eigenfrequency (a redshift) that the soliton's velocity becomes independent from dispersion. For $W / nT < 1$, where $W = E_0^2 / 16\pi$, this gives the following rough estimate

$$(W / nT) \sim \{1 - (\omega_c / \omega_{pe})\}. \qquad (5)$$

Moreover, at the quasi-stationary stage of discharge, one may evaluate the spatial distribution of the amplitude $E_{turb}$ of the turbulent electric field, regardless of its spectral distribution, as described by the scaling of the TEM wave. For the contribution of a single cable to electric field directed radially with respect to the cable's axis, one has:

$$E_{turb}(r) \sim (U_0 / r). \qquad (6)$$

Equations (1), (3), (4), along with rough estimates of Eqs.(5), (6), establish a set of equations that enable one to evaluate the plausibility of the presence of wild cables in tokamak plasmas, using available data on measuring the values of $\omega_C$ [4] (and/or $L_C$) and $E_{turb}$ [5].

Now we can test the problem for typical data from the periphery of the T-10 tokamak, keeping in mind the closeness of T-10 regimes analyzed in [4,5] and those for experimental data analyzed in [2]. First, the spectra of the HF EM field in the GHz frequency range in the gap between the plasma column and the chamber were measured in [4]. They revealed a distinct bump at $\nu_C \sim$ (4-5) $10^9$ Hz, of the width ~ 2 $10^9$ Hz, which always exists in ohmic heating regimes and increases with electron cyclotron heating (this bump is a stable formation and it moves to the lower frequencies and turns into a strong peak only under condition of strong instabilities, especially disruption instability). This gives $L_C \approx 3$ cm (note that this is in reasonable agreement with the visible light data from T-10, see e.g. Fig. 5 in paper P2.029, where $L_C \sim$ 4-5 cm). For $L_C$ = 3 cm, $T_e$ = 100 eV, Eqs. (3) and (4) give a constraint $S = (r_c - r_w) / L_c > 0.03$. For $(r_C - r_W) \sim r_C$, one can find, from Eq. (3), absolute minimum of voltage bias: $(U_0)_{min} \approx 5$ kV. For S = 0.03, Eqs. (3) and (4) give $U_0 \approx 5$ kV, while for S = 0.1 one has $15 < U_0(\text{kV}) < 50$.

Second, the analysis of observations of Stark broadening of deuterium spectral lines (and their polarization state) at the periphery of the T-10 tokamak in the region of $T_e \sim 100$ eV, allowed [5] to estimate the spectral range of HF electric fields ($\omega \approx \omega_{pe} \sim 10^{11}$ Hz), their amplitude (E ~ 10-20 kV/cm) and angular distribution. Here, Eq. (5) gives $E_0(r_C) > 50$ kV/cm, while Eq. (6) gives, for $r_C \sim$ 1-2 mm and $\langle r \rangle \sim$ 1-3 cm ($\langle r \rangle$ is the average distance between individual cables in the region of observation), the estimate $E_0(r_C) > 10^2$ kV/cm, or $U_0 > 10$ kV.

The above estimates are confirmed by the results [2(a)] of solving numerically the Poisson equation [3] for arbitrary values of ratio ($l_E/r_D$): e.g., for $U_0 \sim 30$ kV the effective electron density falls down at r ~ 2 mm by seven orders of magnitude, with respect to its background value, and practically disappears at slightly smaller radii.

The above high values of $E_0$ on the surface of the inner rod (for $r_{wire} \sim 1$ mm) require simultaneously (i) anomalously low consumption of EM energy by the rod and (ii) ability of the rod to transport the EM waves along its surface. Both these assumptions [2] are supported by the recent observations [6] of the magnetic field behavior in the fragments of *non-processed* (i.e. *wild* !) cathode deposits which contain the multiwall carbon nanotubes. Regarding the very plausibility of the nanotube production in tokamak discharges and assembling of hypothetical microsolid skeletons from such nanostructures, we are to refer to the evidences for tubular structures in the range from few nanometers to few micrometers in diameter, which were very recently found [7] in various dust deposits in tokamak T-10.

**4. Conclusions.** The above concept of wild cables suggests strong coupling of the probable mechanisms of **(*)** nonlocal (non-diffusion) component of energy transport and **(**)** survivability of hypothetical microsolid skeletons in high-temperature plasmas. Besides observed anomalous mechanical stability of LLFs, a skeleton is needed to form the TEM waves which only may transport the EM energy through the cable network. On the other hand, only TEM waves may sustain the vacuum cavity around the skeleton and thus protect it from thermal plasma particles.

Among particular implications of the concept, we suggest that wild cables could be responsible for

***(i)*** observed phenomena of fast nonlocal responses in tokamaks,

***(ii)*** a powerful source of non-linear waves (and strong turbulence) throughout plasma volume,

***(iii)*** a low-dissipation radial «transfer» of the poloidal magnetic field $B_{pol}$ in tokamaks (the «in-cable» transport may significantly influence radial profile of $B_{pol}$ and have simultaneously a small impact upon total electrical resistance of plasma, in agreement with the well-known applicability of Spitzer, or close, resistivity to describing the ohmic heat release in tokamaks).

The wild cables seem to be a universal phenomenon in well-done laboratory plasmas and space (see paper P2.051 for a gaseous Z-pinch and plasma focus). In general, we suggest plasmas with *long-living* filaments to be such a form of the fourth state of matter, which is an intricate mixture of three other states: namely, gaseous (plasma particles), liquid (magnetic field which is frozen, as a rule, at least in plasma electrons) and solid (microsolid skeletons).

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