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ORIGINAL PAPER

On tuning mechanisms of DPF devices

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Abstract A global instability theory of pinching plasmas allows us to justify the well-known empirical facts of the use of a mismatched dense plasma focus (DPF) and heavy inert gas admixtures. We assume that an instability of tangential discontinuity is responsible for the instability of a current-carrying plasma column. To inhibit development of a tangential discontinuity in a plasma focus, an array of insulator fibers or metallic wires placed on the anode near the axis of a discharge camera can be used.

Key words instability • nonlinear dynamics • plasma focus

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Introduction

A successive theoretical description of DPF discharge dynamics, including generation of the energetic deuterons and directed electron beam, demands a detailed information about nonlinear processes of plasma-current interaction.

Here, some experimental findings have received further support through certain results of the analytical theory of tangential discontinuity instability. At the beginning of the relation between the agreed parameters of DPF and electric circuit is demonstrated. Then the theory of tangential discontinuity is used to reveal the properties of pinching plasmas. Analyzing them, one can conclude that the employment of the heavy inert admixtures and mismatch of DPF lead to better pinching.

Finally, we offer to place an array of parallel isolator fibers on the anode near the discharge camera axis that can reduce an azimuthal pinching plasma motion and, therefore, an influence of tangential discontinuity on current-plasma dynamics.

Matched DPF

Recall [1] that DPF is a matched load in an electric circuit if a current sheath of discharge reaches the axis in a quarter of a current pulse period. Let us assume that the current sheath velocity V is proportional to the Alfven plasma velocity V_A. Then the condition under which DPF and an electrical circuit are matched can be written as:

(1) $$\frac{1}{4}(R_0 + r_0)^2 + z_0(R_0 + r_0) = \frac{2K}{\sqrt{\pi}}\frac{I_0}{c\omega\sqrt{\rho_0}}$$

Here R_0 is the radius of a cathode, r_0 and z_0 are the radius and height of a anode, I_0 is the amplitude of a discharge current, ρ_0 is the gas density in a focus camera, ω is the electric circuit frequency, and $K = V/V_A$. In formula (1) all the values are given in the Gaussian units. Deriving the above relation, we employ a snowplow model for plane and cylindrical current sheaths.

According to formula (1), at $I = I_0$ a column of pinching plasma has the smallest diameter and a derivative of current with respect to time is equal to zero: $dI/dt = 0$. In practice, the tightest pinch was detected at the moment when the discharge current began to decrease after a maximum value (see, e.g., the experiments in a wide range of pinching plasmas, including DPF [2], vacuum spark [3] and array Z-pinch [5]. In Fig. 1 the arrow indicates the favourable regime. It turns out that dI/dt is an important parameter of the theory of instability of tangential discontinuities in pinching plasmas [4, 6].

Main relations

In a tangential discontinuity, plasma velocity **v** and magnetic field **H** are tangent to surfaces of discontinuity and experience an arbitrary jump in value and direction. In hydrodynamics (HD) and magnetohydrodynamics (MHD) tangential discontinuities are unstable, and these instabilities give a birth to the turbulence in HD and MHD. We assume that the instability of pinching plasmas could be due to the tangential discontinuity whose increment strongly depends on current density. The tangential discontinuity is an interface joining two plasma columns revolving on an axis at different frequencies (one column on top of another). These rotations could arise from the initial azimuthal and axial inhomogeneities of a discharge, when a plasma has an angular momentum due to the ponderomotive forces. During plasma pinching, the laminar dynamics of a discharge can be disrupted by the above instability. In Fig. 2 the axis of discharge and direction of current is denoted by an arrow. The bold-faced curve indicates a tangential discontinuity.

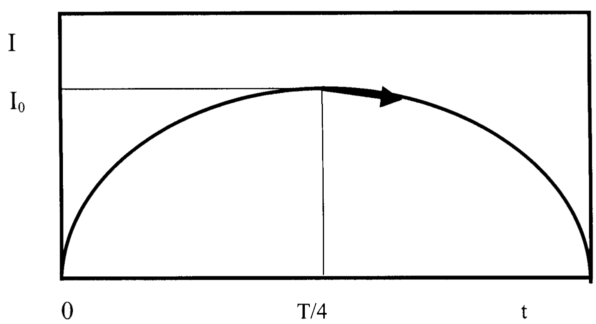

Fig. 1. Mismatched DPF.

To examine the instability of tangential discontinuities we linearize the equations taking into account the electron vorticity effect on the plasma motion and magnetic field behaviour [4, 6]. From the linearized system the dispersion relation between the frequency ω and the wave vector **k** of discontinuity disturbances is derived:

(2) $$\left\{ \frac{\rho^2(\omega - \vec{k}\vec{v})^4}{\dfrac{(\omega - \vec{k}\vec{v})^2}{\dfrac{4\pi j^2}{\rho\omega_p^2} - v_s^2} + \vec{k}} \right\} = 0,$$

where j is the component of current density normal to the surfaces of discontinuity. In (2) the braces denote the difference of two values of the internal parameter, $0 < |\mathbf{k}| \le k_{max}$ and k_{max} is determined by the dispersion length c/ω_p.

Let us examine the plasma dynamics limit, when the electromagnetic terms in (2) are dominant on both sides of the discontinuity. Then, the solution of (2) can be written as

(3) $$\omega = \frac{1}{2}\vec{k}(\vec{v}_2 - \vec{v}_1) \pm i\Im\,\omega,$$

where $$\Im\,\omega = 2\sqrt{2}kj/\omega_p\sqrt{\rho}.$$

Let us evaluate the scale $T = 1/\Im\omega$ of temporal evolution of the discontinuity in response to the above instability. Take that the discharge current I is of the order of 1 MA, the pinch radius r is of the order of 1 cm, the deuterium concentration N is of the order of 10^{18} cm^{-3}, $k \ge \omega_p/c$. We obtain that $T \ge 10$ ns.

Here, the time variation of current – increase or decrease – must be much slower than the temporal evolution of discontinuity, that is

(4) $$\frac{dj}{dt} << \Im\,\omega_{max}\,j,$$

where $\Im\omega_{max} = \Im\omega(k_{max})$. The total derivative dj/dt takes into account a term corresponding to the current drift effect.

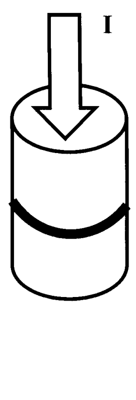

Fig. 2. Current-carrying plasma column divided by tangential discontinuity.

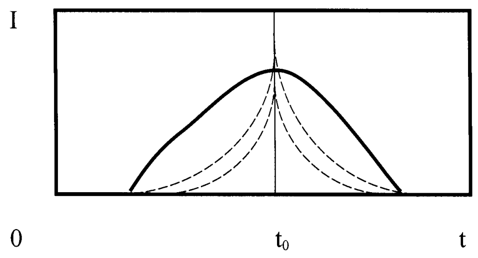

Fig. 3. A family of the solutions of the balance equation.

According to the asymptotic analysis widely used in theoretical studies (for example, in a kinetic description, plasmas are classified as collisional or collisionless if the collision frequency justified in quasi-static contexts is accounted for), the above instability should not develop when there is a rapid current variation, that is, at

(5) $$\left|\frac{dj}{dt}\right| >> \Im\, \omega_{\max}\, j.$$

For separation of the stable modes from the unstable ones it is convenient to employ the solution j_{cr} of the balance equation

(6) $$\left|\frac{dj_{cr}}{dt}\right| = \Im\, \omega_{cr}\, j_{cr},$$

where $\Im\omega_{cr} \propto j_{cr}$. Then, for a stable mode

(7) $$\left|\frac{dj}{dt}\right| > \left|\frac{dj_{cr}}{dt}\right|$$

at each current pulse time on the surface of the discontinuity.

The current drift velocity is an intrinsic parameter of the complex plasma-current flow and, therefore, cannot be controlled. On the contrary, a partial derivative of current with respect to time is determined by the discharge current pulse. Thus, modulation of the current pulse can be a technique for stabilization of a tangential discontinuity.

Let us demonstrate the possibility in an idealized case. Instead of complex dynamical structures of current in pinching plasmas (for example, shock waves, filaments) we consider a cylindrical column of homogeneous plasma (with a constant plasma density equal to an averaged density) through which a uniform current (a current density is equal to an averaged current density) flows. Then the solution of (6) has the form

(8) $$I_{cr} = I_0(1 - \Im\, \omega_{cr} |t - t_0|),$$

where I_0 and t_0 are the arbitrary constants. This solution monotonically increases for $t < t_0$ and monotonically decreases for $t > t_0$. Thus, when t_0 corresponds to the maximum current I_0, the tangential discontinuity is stabilized if $dI/dt > dI_{cr}/dt$ for the first half-period of the current pulse and if $dI/dt < dI_{cr}/dt$ for the second half-period. In Fig. 3 the dash curves denote the solutions of the balance equation and a current discharge pulse is the bold curve.

Conclusion

One may conclude that the tangential discontinuity is unstable in the vicinity of t_0. And we achieve a more stable DPF regime when the current pulse singularity occurs at the moment after or before the first quarter of the current pulse period.

A different method of stabilizing the tangential discontinuity is the use of Argon and Xenon admixtures. Indeed, the scale of temporal evolution of tangential discontinuity $T \propto \sqrt{m}$, where m is an effective mass of plasma ion. When an admixture molecule mass increases, T increases, too.

Another opportunity to suppress the above instability in the early stages is to create a small scale plasma azimuthal inhomogeneity by means of a large number of straight parallel wires [5]. Because DPF has a power much less than the power of current pulse generator, we offer to change metallic wires by isolator fibers on an anode surface near the discharge axis. These fibers (wires) may be an obstacle and may inhibit an azimuthal plasma motion near a central part of the DPF anode.

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