IMPURITY ION HEATING AND DRIFT VELOCITY IN THE AL'FA EXPERIMENT

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High impurity ion energies (>100 eV) and toroidal drift velocities were reported in the early, ohmically heated experiment, Al'fa (Альфа, ~1960, major radius 1.6 m). These are explained here in terms of charged particle acceleration by the toroidal electric field corresponding to the noisy loop voltage, using data from the experiment, atomic cross section data, and 1-D momentum equations without turbulence, radial fluxes, or microfield anomalies. In general, the impurities are thermally decoupled from the H (bulk) ions and electrons in the transiently runaway discharges.

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1. THE AL'FA EXPERIMENT

The Al'fa experiment, one of the earliest large nuclear fusion experiments, was a diffuse toroidal pinch built at the Physicotechnical Institute (FTI) in St. Petersburg (Leningrad) in the late 1950's. Extensive diagnostic development was done on Al'fa (spectroscopic, microwave, bolometric, charge exchange, electrical, and magnetic field measure-ments). The visible and near-UV measurements, in particular, revealed the existence of high ionization states of impurity ions (O, C, N) and substantial toroidal drift velocities, parallel to the discharge current, along with very high apparent temperatures (far above the nominal electron temperature T_e) of these ions. Al'fa was modelled on and similar to the British ZETA experiment [1-3]. The December 1960 issue of Zhurnal Tekhnicheskoi Fiziki (ЖТФ) was devoted to articles on the construction, system characteristics, and diagnostic results from Al'fa [4]. The high drift velocity and, especially, the high apparent ion temperatures in Al'fa have never received a satisfactory explanation [1,2]. Here the spectroscopic results are interpreted in a model that takes into account the electrical behavior of the discharge, charged particle acceleration in the toroidal electric field E, atomic cross section data, the mechanics of elastic collisions, and diagnostic response to these effects. The observed impurity ion behavior can be explained in terms of the production of high Z impurity ions by runaway electrons generated during spikes in the loop voltage V_L, the average drift of the impurity ions in the average toroidal electric field E of the discharge, and much faster drift in the transient E corresponding to bipolar spikes in the very noisy V_L. This interpretation is consistent with the other data from Al'fa. The best way of remembering that early experiment is to interpret the diagnostic results from it consistently and relate its physical behavior to modern devices, such as reverse field pinches (RFP, of which Al'fa is an ancestor) and tokamaks.

2. DIAGNOSTIC RESULTS

Many pioneering results from newly developed diagnostic techniques, which are now in common use, were reported for Al'fa [1,2,4]. The conclusions from that time are qualitative by today's standards, but clearly demonstrate the existence of collective plasma motions, and fast, nonthermal populations of electrons, and hydrogen and impurity ions.

The diagnostic techniques and results from Al'fa include [4]: (i) Electrical and magnetic characteristics of the discharge: condenser bank voltage, plasma loop (induced) voltage V_L, plasma current I_p, local magnetic field **B**, and current density **j**. The nominal (quiescent, average) current and loop voltage imply an electron temperature T_e=10-20 eV and an electron density $n_e \sim 10^{19}\,\mathrm{m}^{-3}$. (ii) Fast H atoms with energies of several keV were detected by a neutral energy analyzer, i.e., there was a substantial tail in the proton energy distribution. (In ZETA, neutrons from fusion of deuterium were detected. The ions involved were found to be a suprathermal streaming ion population). (iii) Spectroscopy (visible and UV): high drift velocity and high apparent "temperatures" of impurity ions (over 1 keV for OVI). The apparent thermal speeds of the impurity ions (derived from the observed line widths) were roughly 10 times their drift velocities. (iv) Microwave diagnostics revealed the existence of regions of plasma with densities above the critical value for 8 mm ($1.4 \cdot 10^{19}\,\mathrm{cm}^{-3}$) and collective motion of the plasma at frequencies on the order of 10^5 Hz. (v) Bolometry (energy flux from plasma). The basic measurements for Al'fa are summarized in Table 1.

Table 1. Comparison of the parameters of Al'fa [4] and Alcator C-Mod (a currently operating tokamak) [5]. [The velocity ratio (*) refers to spectrum line half-half width/line shift or thermal speed/drift speed]

Parameter	**Al'fa (quiet phase)**	**Alcator-CMod**
major radius R [m]	1.6	0.67
minor radius a [m]	0.50	0.20
toroidal current I	150-350 kA	1.1 MA
*toroidal **B** [T]*	*0.018-0.15*	*to 4.5*
central elec. temp. $T_e(0)$ [eV]	10-20	~1200
central ion temp. $T_i(0)$ [eV]	10-20 (est.)	~1200
central elec. dens. $n_e(0)$ [m^{-3}]	$>10^{19}$	rising to $\sim 2 \times 10^{20}$
impurity ion charge Z_x	2-5 (C, N, O)	17 (Ar)
loop voltage, quiescent V_L [V]	*400-1200*	*~1*
loop voltage, peak [V]	-8000 to +8000	not known
toroidal **E**, quiescent [V/m]	20-500	~0.2
drift velocity v_d [m/s]	$\sim 1 \times 10^4$ (OV)	-6×10^4 to -1×10^4 (early, late discharge)
v_{avg}/v_d *	~8	~1 to 9

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3. ELECTRICAL BEHAVIOR

L. A. Artsimovich, the developer of the tokamak, described ([1], p. 254) traces of the plasma loop voltage and current from the British ZETA experiment as follows: "The first thing that strikes the eye on looking at oscilloscope traces of the discharge is their complete inconsistency with the notion of a 'quasistationary' process. While the variation in I can, in a big stretch, be regarded as comparatively smooth, the trace of V is typical of a highly nonstationary process. The amplitude of the high frequency voltage spikes is comparable to the average voltage applied to the discharge chamber. The characteristic frequency of these spikes is in the range $10^5 \ldots 10^6$ Hz."

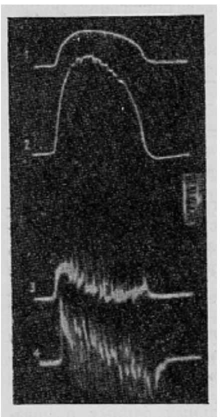

Fig. 1. Oscilloscope traces of a discharge in the ZETA experiment [1]: (1) current on the transformer primary, (2) secondary (discharge) current I, (3) discharge (loop) voltage V_L, (4) dI/dt for the discharge current

The voltage spikes are bipolar relative to the "average," filtered, or nominal value of V_L. The measured parameter for the plasma current I_p trace is actually the (also) very noisy dI_p/dt (Rogowsky loop signal), which is integrated to yield the much smoother $I_p(t)$. We shall assume, as Artsimovich implies, that the amplitudes and frequencies of the spikes in the Al'fa experiment, which was based on ZETA, are similar.

In general, the loop voltage

$$V_L = IR + d(LI)/dt, \qquad (1)$$

but in analyzing the Al'fa data [4], it was assumed that the second term is negligible, i.e. $V_L = IR$. In fact, the observed (smoothed) I and V_L traces and the plasma cross sectional area are consistent [4] with $T_e = 10 \ldots 20$ eV. In the Al'fa discharge, however, $d(LI)/dt = LdI/dt + IdL/dt$ is far larger than IR, based on the time variation in dI/dt and V_L. The inductive terms can be large because of cutoff of all or part of the plasma current (disruptions), whence $\Delta V_L = L\eta I/\Delta t$ for fixed L, a cutoff time Δt and a fraction η of current loss, or because of periodic oscillations in the plasma radius, $a(t) = a_0 + a\sin\omega t$, where the average radius $a_0 >> a$, leaving $dL/dt \sim 4\omega(a/a_0)L_0$, where L_0 is the average L. The first mechanism is equivalent to the well-known inductive kick of electronics [6] and is consistent with the noisy dI/dt curve in Fig. 1, while the second is consistent with the fluctuations in plasma radius observed by microwave reflectometry in Al'fa. The time scales for these fluctuations are on the order of $1 \ldots 10$ μs. Both mechanisms can easily produce bipolar spikes about the average V_L with amplitudes 10 times that of the average voltage.

4. PARTICLE DRIFTS IN AVERAGE E(t)

In order to explain the spectroscopic data, it is necessary to abandon entirely the assumption of thermal populations and evaluate the drifts of all charged particles in the plasma in different phases of the discharge loop voltage. For the nominal T_e and n_e the average toroidal electric field $E = V_L/2\pi R$, where R is the plasma major radius, is close to the Dreicer limit $E_c \sim 0.2\ln\Lambda e/4\pi\varepsilon_0\lambda_D^2$, where $\lambda_D = 7.43\mathrm{x}10^3(T_e/n_e)^{1/2}$ is the Debye length of the plasma. This means that even in the quiescent phase, the electrons are subject to runaway, but the (averge) drift velocity (shift in the line centers) calculated from the momentum equation for the impurity ions is close to the observed values.

The spikes in V_L imply a field far beyond the runaway limit, and this, in turn, leads to two processes that are fundamental to the observed spectroscopic results: (1) production of electrons fast enough ionize the impurity atoms to high degrees of ionization (CV, NV, OVI) and excite the observed lines, and (2) acceleration of these ions in the average and high transient fields to the observed velocities. In this section, we discusss point (2) for the average E(t), assuming the existence of highly charged impurity ions; their origin (ionization by fast electrons) and acceleration in the transient field is discussed in the next section.

We begin with the average ("drift") velocity of these ions in the average (quiescent) electric field.

In general, the 1-D (toroidal direction) equation for the drift of plasma species α contains an electric field term and a collisional drag term [7]

$$m_\alpha \partial \mathbf{u}_\alpha/\partial t = Z_\alpha e\mathbf{E} - \Sigma_{\beta\neq\alpha}\, \mu_{\alpha\beta}\nu_{\alpha\beta}(\mathbf{u}_\alpha - \mathbf{u}_\beta), \qquad (2)$$

where $\nu_{\alpha\beta}$ is the momentum transfer rate in elastic collisions (β is field species) and $\mu_{\alpha\beta}$ is the reduced mass of particles α and β. All gradient and transverse terms are neglected here. In the steady state, for the impurity ions this equation yields

$$\mathbf{u}_X \approx \{Z_X e\mathbf{E} + \mu_{Xe}\nu_{Xe}\mathbf{u}_e\}/(\mu_{XA}\nu_{XA}) + \mathbf{u}_A, \qquad (3)$$

i.e., the sum of an electric field force term and an electron drag term, superimposed on the hydrogenic ion velocity. In Al'fa, the electric field term dominates the drag on the electrons and bulk ions, so that ion X has

$$\mathbf{u}_X \approx Z_X e\mathbf{E}/(\mu_{XA}\nu_{XA}), \qquad (4)$$

parallel to the electric field. Given the current I_p, nominal temperature ($T_e \sim 10 \ldots 20$ eV), n_e, Z_X, average V_L, and plasma dimensions, this roughly yields the observed drift velocities (up to 10^4 m/s parallel to I_p, for high Z) of the various impurity ions in the average field E (cf. Fig. 2).

Table 2 lists the values of the force terms in Eq. (2) for the average toroidal E in Al'fa [4] and L-mode ohmic heating (OH) in Alcator [5] for O^{4+} and Ar^{17+} ions, respectively. In the steady state, they yield u_X parallel to I_p in Al'fa and antiparallel to I_p in Alcator, as observed [4,5], and as expected [8,9].

Table 2. Values of the terms in Eq. (2) for Al'fa and Alcator C-Mod (O^{4+} and Ar^{17+} ions, respectively)

	Al'fa {for range of parameter}	**Alcator-C Mod**
$Z_x e\mathbf{E}$ (N), electric field	$+(2.5\text{-}7.5)\times10^{-17}$ {V_{loop}}	$+6.3\times10^{-19}$
$\mu_{xe}\nu_{xe}$ (kg/s)	$+(0.7\text{-}2)\times10^{-22}$ {T_e}	$+5.6\times10^{-23}$
$\mu_{xe}\nu_{xe}\mathbf{u}_e$ (N), elec. drift	$-(2.0\text{-}5.7)\times10^{-17}$ {T_e, I}	-1.5×10^{-17}
$\mu_{xi}\nu_{xi}$ (kg/s)	$+(0.4\text{-}1.2)\times10^{-20}$ {T_i}	$+3.3\times10^{-21}$
$\mu_{xi}\nu_{xi}\mathbf{u}_i$ (N), ion drift	$+9.2\times10^{-19}$ {T=10,I=.35 MA}	$+2.5\times10^{-19}$
$\mathbf{u}_x$ (m/s, direction relative to Ip)	$\leq 10^4$, positive	$\leq 10^4$, negative

5. IONIZATION AND ACCLERATION IN LOOP VOLTAGE SPIKES

The Dreicer runaway condition implies [7] that electrons gain energy in accordance with the equation (no collisional drag)

$$m_e d\mathbf{v}_e/dt \approx Ze\mathbf{E} = -e\mathbf{E}. \qquad (5)$$

For a spike duration at constant field E (V/m) of Δt (s) (square pulse), this implies a longitudinal velocity (drift) of $-e\mathbf{E}\Delta t/m_e$ (m/s) at the end of the spike. Taking $E=V_L/2\pi R$, with $V_L=8000$ and R=1.6 m, in a spike of duration Δt=1-10 μs, we obtain

$$v_e = 1.76\cdot10^{11} E\Delta t \sim 1.4\cdot10^{8}\ \text{m/s} \rightarrow c. \qquad (6)$$

The corresponding electron kinetic energies can approach *hundreds of keV* (limited by transverse drifts, e.g., curvature drift, inelastic collisions, relativistic effects, and the particular shape of E(t)).

Similar free drift in the electric field takes place among the plasma ions (Z≥1), as they experience little electron drag. For fixed E and Δt, the velocity is proportional to Z and the energy, to Z^2. For O^{4+}, the velocity range for free acceleration in 1…10 μs spikes at 800 V/m ranges from $\pm1.9\cdot10^4$ m/s (as, above, within a factor of ~2 of the observed average drift) to $\pm1.9\cdot10^5$ m/s, close to the nominal thermal speed derived from the line shape of the OV line [4]. Therefore, the OV ions have $v_{OV}=1.9\cdot10^4$ m/s average drift superimposed on up to $\pm1.9\cdot10^5$ m/s during the rise and fall of the bipolar current spikes. This yields symmetric profiles with a peak corresponding to the mean-field drift (up to 10^4 m/s) and a half-half width corresponding to the drift velocity acquired in the spikes (up to 10^5 m/s). In general the line shapes will not be gaussian, but the data are not good enough to confirm that in any case.

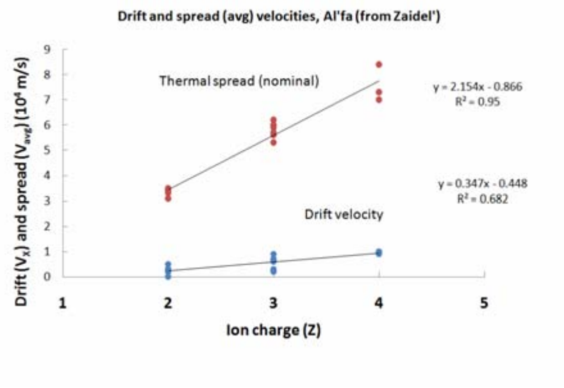

Fig. 2. Averaged drift and spread (nominal Doppler half-half width) of spectrum lines observed in Al'fa as functions of ionic charge (Zaidel', [4])

The actual ion line profiles are determiend by the projections of the velocity along the line of sight, magnetic field curvature, and the time variation of E(t). Deriving the line shape is a complicated problem of plasma particle motions, instrument response, and geometry.

The curves of Fig. 2 illustrate the range of impurity ion drift velocities and nominal impurity temperatures measured on Al'fa [4]. The averages and curve fits are *not definitive*, as the quality of the data do not permit this and the operating conditions at each point varied widely. However, a nearly quadratic fit to the reported $T_X(Z) \propto v_{avg}^2$ and the linear fits to the velocities are consistent with free acceleration in the average and transient toroidal electric fields described here.

How do these highly ionized impurity ions show up in an nominal T_e=10 eV plasma? A transient runaway electron population with energies >100 eV makes multiple ionization of the background gas atoms possible. Fig. 3 illustrates the species content and evolution (accounting for the cumulative time to reach each successive ionization state) of the oxygen ion population for electron (equivalent) temperatures of 10 (mean), 30, and 200 eV (runaway discharge during spikes), with $n_e=10^{19}$ m^{-3} and ion lifetimes of 10 μs (fairly realistic, corresponding to the transit time for neutral hydrogen across the discharge and to the curvature drift motions of the plasma column; also equal to the duration of the longer spikes in V_L) and 100 μs (comparable to the discharge time of 1 ms and inelastic loss times, but much longer than transverse drift times, etc.).

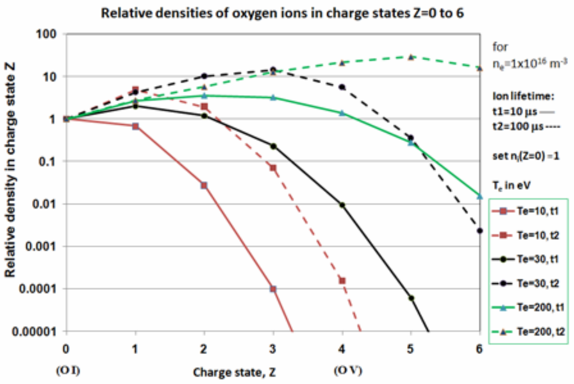

Fig. 3. Illustrating the time evolution of oxygen ionization states in the average and transient phases of an Al'fa discharge

Fig. 3 was obtained as follows: the density of ions in state Z=i+1 is related to that in Z=i by

$$dn_{i+1}/dt = n_e n_i \langle\sigma v\rangle_i - n_{i+1}/\tau_{i+1} - n_e n_{i+1} \langle\sigma v\rangle_{i+1}, \quad (7)$$

where n_e, n_k, and $\langle\sigma v\rangle_k$ are the electron density, density in ion state Z=k, and electron impact ionization rate [10] from state Z=k. τ_k represents the lifetime of ions in state k (loss through transport, other inelastic processes, etc.). In the steady state (long times) this becomes (assuming all electrons locally at T_e)

$$n_{i+1} = n_i \langle\sigma v\rangle_i / (\langle\sigma v\rangle_{i+1} + [n_e \tau_{i+1}]^{-1}). \qquad (8)$$

So, to get the above graph, begin with n_0=1 (neutral atoms) and the conditions T_e, n_e, and τ_k=t1 or t2 (assumed same for all ions) indicated in the figure.

This shows that in the 10 eV discharges, the populations of the OIII and higher ionization states are very low for ion lifetimes of 10 μs. Even for a unrealistically long lifetime of 100 μs, no significant population of the higher states OIV and OV would be detectable. On the other hand, with lifetimes of 10 μs or less (corresponding to the V_L spike durations) electrons with energies (effective temperatures, as the electrons cannot thermalize within 10 μs) of > 100 eV can easily produce all the observed ion species of oxygen within a few microseconds, i.e., within the duration of the voltage spikes.

A more complete picture of the plasma state can be obtained by examining the hierarchy of collision times in the discharge phases ($\tau_{\alpha\beta}\equiv 1/\nu_{\alpha\beta}$). For a $Z_{eff} \geq 1.2$ plasma with a single impurity at Z ~ 3, temperatures ~ 10 eV, and $n_e=10^{19}$ m^{-3}, the major plasma species (hydrogen, electrons, impurity ion) are in equilibrium and all momentum collision times are ≤10 μs, with all energy collision times *shorter than the discharge lifetime of ~1 ms.*

If we assume particle energies (effective temperatures) of ~1 keV, the energy collision times [7] all exceed 10 ms or ten times the discharge duration (except e-e, for which τ_{ee}^E~10 μs). Of the momentum collision times, only the electron field produces a collision time less than 100 μs, so the heavy particle drifts are thoroughly decoupled in the sense described above (in terms of the momentum equation).

6. SUMMARY AND CONCLUSIONS

Extraordinarily high impurity ion temperatures and substantial toroidal drift of these ions, detected by visible and near-UV spectroscopy, were reported for the Al'fa experiment. The reported temperatures have always been something of a mystery, for, at the nominal T_e=10 eV and $n_e=10^{19}$ m^{-3}, these ion states (up to Z=5) cannot form in the plasma during its lifetime (1 ms), much less within the shorter transport, transverse drift, and inelastic collisional loss times.

As in the case of OH tokamaks [8], the observed toroidal drift velocities can be derived from the average (smoothed) loop voltage V_L and discharge current using the momentum equations, but in Al'fa the electric field term dominates, leading to drift in the direction of the plasma current I_p (or toroidal electric field E). The average V_L implies a toroidal electric field close to the Dreicer limit for electron runaway in Al'fa. This is rarely the case in the main discharge phase of modern OH tokamaks, where V_L is low and relatively quiescent, so that the impurity drifts are opposite to the direction of toroidal current (field), i.e., parallel to the electron drift.

The key to the high ion "temperatures" in Al'fa lies in the noisy loop voltage (confirmed by the noisy dI/dt signal), with bipolar excursions to 10 times the average value readily calculable using the measured electrical and plasma parameters. In this case, $I = IR + d(LI)/dt \sim d(LI)/dt >> IR$. The loop voltage spikes could be produced by the term I(dL/dt), i.e., by changes in the plasma configuration, or by L(dI/dt), i.e., by cutoff of all or part of the plasma current (inductive kick). These events occur on time scales of 1…10 μs – the time scales of the observed spikes in V_L, as well as, e.g., for curvature drift out of the plasma column.

These transient voltage spikes imply high electric fields – sufficient to accelerate all ion species as well as electrons in a runaway (no collisional drag) regime; particle losses can occur through transverse drifts, inelastic processes, etc. Electrons may be thermalized, but not the hydrogenic or impurity ions. The resulting electron energies are sufficient to ionize the O, N, and C impurities (within 1…10 μs, in sequence) to the observed ionization states.

These multiply charged ions are then accelerated, in both directions, by the field corresponding to the bipolar spikes in V_L to the velocities observed in the experiments. The velocity is higher for higher ionic charges, roughly consistent with an ion energy $K_Z \propto Z^2$, as in free acceleration in an electric field with little or no collisional drag (other losses limit the ion velocity/energy).

The magnitudes of the velocities of the impurity ions in the average and peak electric fields are sufficient to explain the apparent spectroscopically observed "temperature" of the impurity ions in Al'fa. (The wings of the observed spectral lines correspond to the high field drift when these ions exist during the voltage spikes and the average shift of the line profile corresponds to the drift produced in the average electric field.)

The model used here to interpret the spectroscopic observations involves 3 stages of modelling: (1) electrical characteristics of the discharge (V_L~d(LI)/dt>>IR), (2) acceleration of electrons in the high, transient E field leading to ionization of impurity species, and (3) acceleration of impurity ions in the average and transient electric fields

The spectroscopic and electrical observations on Al'fa are consistent with other data obtained from the device, including charge exchange detectors (fast hydrogen neutrals), microwave reflectometry (fluctuations in plasma position/size and density – as the impurity atoms become multiply ionized there should be a rapid rise in the local n_e), bolometry, and (in ZETA) production of nonthermal neutrons from deuterium (through collisions of fast deuterium ions with walls and in the vessel volume, spallation, etc.). It is noteworthy that a smaller British pinch, Sceptre IV, [11] and, later, ZETA, were operated in a quiescent mode that yielded lower impurity ion (OV) "temperatures," consistent with the present model. Impurity ion drift dominated by the toroidal electric field term (cf. Eq. (3)) may apply to other ohmically heated toroidal devices with high V_L, such as RFPs which are a descendent of Al'fa and ZETA [12], and, possibly, some early tokamak experiments in which the loop voltage was relatively high throughout the discharge.

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НАГРЕВ И ДРЕЙФ ПРИМЕСНЫХ ИОНОВ В УСТАНОВКЕ "АЛЬФА"

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Высокие энергии (>100 эВ) и дрейфы примесных ионов обнаруживались в ранней установке с омическим нагревом "Альфа" (~1960 г., большой радиус 1.6 м). Результаты здесь объясняются ускорением заряженных частиц тороидальным электрическим полем, соответствующим шумному напряжению на оси шнура. Используются измерительные данные, информация об атомных сечениях и одноразмерные уравнения движения, не привлекая турбулентность, радиальные потоки, или аномалии микрополя. Вообще, ионы водорода и примесей (и электроны) термически развязаны в нестационарно убегающих разрядах.

НАГРІВАННЯ І ДРЕЙФ ДОМІШКОВИХ ІОНІВ В УСТАНОВЦІ "АЛЬФА"

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Високі енергії (>100 еВ) і дрейфи домішкових іонів виявлялися в ранній установці з омічним нагріванням "Альфа" (~1960 р., великий радіус 1.6 м). Результати тут порозуміваються прискоренням заряджених часток тороїдальним електричним полем, що відповідає шумовій напрузі на осі шнура. Використовуються вимірювальні дані, інформація про атомні перетини і однорозмірні рівняння руху, не залучаючи турбулентність, радіальні потоки, або аномалії мікрополя. Взагалі, іони водню і домішок (і електрони) термічно розв'язані в нестаціонарно втікаючих розрядах.