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FOM-INSTITUUT VOOR PLASMAFYSICA

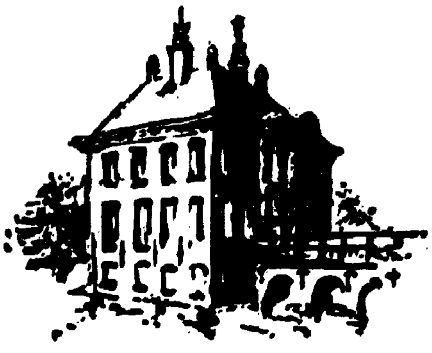
RIJNHUIZEN — NIEUWEGEIN — NEDERLAND

HEATING OF PLASMAS IN TOKAMAKS BY CURRENT-DRIVEN TURBULENCE

by

H. de Kluiver

Rijnhuizen Report 85-159



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1. Introduction

In the beginning of the decade 1960-1970, experiments on turbulence in magnetized plasmas aroused considerable general interest because, in these experiments, it was shown possible to produce extremely high temperature plasmas (in the keV-region) with relatively simple methods. However, the confinement of these hot plasmas was not the first priority and was indeed poor in the open-ended magnetic systems usually employed.

For a major part, the experimental investigations in those days were concentrated in several institutes in the USSR particularly those in Moscow, Leningrad and Kharkov. Well-known devices were OGRA, NPR, GROM, etc. (See references). A few years later, investigations in closed systems followed in the USSR and also elsewhere in all types of magnetic confinement systems. Without attempting to be complete, closed systems in the USSR, such as the SIRIUS and URAGAN stellarators, the VIKhR' bumpy torus and the TM3 tokamak can be mentioned [20,21, 22,24,25,43]. In the United Kingdom the stellarators TWIST and TORSO were introduced [26,27], in Canada a betatron device and later the STOR tokamaks [28,40,41]. In Japan, various open-ended devices were used, such as OCU, BSG and MACH [17,18]. Later, various generations of a high field tokamak type appeared such as the TRIAM devices [35a,b,42]. In The Netherlands, current-driven turbulence was initially studied in the linear TURHE device, later followed by the TORTUR tokamaks [19,36,37,38]. In the USA, plasmas were both studied in open-ended systems and in the tokamak TTT [14,15,16,34].

A comprehensive survey of the results and analysis of the various turbulent-heating efforts of the different countries can be found in monographs and a review paper as listed in references 44 and

45. At densities up to 10^{21} m^{-3} temperatures, T_e and T_i up to several keV have been attained. Corresponding maximum energy densities reached far into the 10^{24} eV/m^3. Important parameters of experimental investigations on turbulent heating in open and closed magnetic devices have been assembled in Table I, together with the relevant references. In Section 2, a general discussion on anomalous resistivity and turbulent heating is presented. In Section 3, results on turbulent heating specialized to tokamaks are given.

2. Anomalous resistivity and turbulent heating. A classification of current-driven turbulence

Though the efforts of study of plasma turbulence are by no means limited to those investigations qualified as turbulent heating experiments, a discussion of the present status is limited to the later cases. It is devoted in particular to those experiments and theoretical results in which plasma turbulence is provoked by increase of the electron-drift velocity, v_d, by increasing the electric field-strength, E, parallel with the confining magnetic field to sufficiently high values. A turbulent plasma state may macroscopically be characterized by a considerable decrease of the electrical conductivity, σ. The decrease can be as high as five orders of magnitude. As long as a reduction of σ can be maintained under changing plasma conditions, intensified dissipation by a factor σ_{cl}/σ_t, can lead to strong plasma heating. (σ_{cl} denotes a classical expression for the electrical conductivity, whereas σ_t is the turbulent case).

As a result of the experimental and theoretical investigations, a classification of the turbulent plasma state can be presented conveniently in a table (see Table II) using the following parameters: E, the electric field-strength; the runaway or critical (Dreicer-) field-strength: $E_{cr} \sim n/T_e$; the plasma density, n; the magnetic field-strength, B; the electron drift velocity, $v_d = j/ne$; the current density, j; the electron and ion temperatures, T_e, T_i; and the ion mass, m_i. The following typifying ratios appear: E/E_{cr}; σ_{cl}/σ_t; T_e/T_i; ω_{ce}/ω_{pe}; $v_d/v_{Te} \equiv \alpha$.

The various investigations on plasma turbulence of the last two decades have been covering and identifying a major part of the different cases as cryptically indicated by the elements of the table. To assess the status of turbulent heating in tokamaks, first a brief discussion of the main results in the various (E/E_{cr})-domains will be given.

A. $E/E_{cr} < 0.02 \; (= (\frac{m_e}{m_i})^{\frac{1}{2}})$.

Plasmas for all values of $(\omega_{ce}/\omega_{pe})$ and T_e/T_i behave "classical" for the larger parts of the energy-distribution function. That is, changes in $f_{i,e}(v)$ can be found by solving Boltzmann's equation, using classical collision terms, together with Maxwell's equations. The only non-collisional deformation in $f_e(v)$ results from a minor fraction of "true"-runaway electrons in the tail.

A clear-cut example of a classical tokamak conductive state are the very high-density discharges in ALCATOR [46,47]. In these cases, $\sigma_{cl}/\sigma_{exp} = 1$ (Z_{eff}(impurity) $= 1$): $\alpha \equiv v_d/v_{Te} = 0.02$.

B. $0.02 \leq E/E_{cr} < 1$.

This region could be called "the accelerative turbulence region" [22]. The magnitude of the electric field enables considerable acceleration of the electrons to drift velocities such that, depending on the ratios $(\omega_{ce}/\omega_{pe})$ and (T_e/T_i), weak turbulent waves of the electrostatic ion-cyclotron, or ion-acoustic types can exist, together with weak beam plasma interactions for the tail parts.

In many tokamaks, especially at the lower density range, with relatively high values of α, the presence of weak quasi-stationary turbulence of the ion-cyclotron type should be present. In TFR and TORTUR evidence of this weak turbulence is obtained from 4-mm scattering measurements and from deformation of the gaussian shape of Thomson-scattering spectra [38,48]. In many tokamak experiments as, e.g. TFR, ALCATOR, TORTUR, the stagnation of tail-electron acceleration by anomalous or normal Doppler-type interactions have been concluded from soft X-ray and electron-cyclotron emission spectroscopy [47,49,50]. The simultaneous excitation of marginally stable current-driven ion-cyclotron modes ($f = 50$-100 MHz) modulated by low-frequency drift waves, and the magnetosonic branches (f: 100 kHz up to 2 MHz) leads to effective pitch-angle scattering of the tail electrons [49]. Typical truncation energies of 50 to 100 keV have been deduced from ECE spectra.

Macroscopic evidence for a slightly turbulent state is the decreased σ and the saturation of v_d, such that an approximately constant drift parameter, α, is found. This indicates a condition of marginal stability of - presumably - weak ion-cyclotron modes for the bulk of the electrons.

As a result, reduction factors for the anomaly in the conductivity above the trivial reduction by Z_{eff} due to impurities can be concluded from the assembled data of a great many smaller and larger tokamaks [46]. Anomalous values averaged over the profile can amount from 2-4 and even much higher near the axis. For the TORTUR tokamak, the anomalous factor at the axis could be as high as 10 [49,51] In Fig. 1a, this effect is shown for a number of tokamaks and a stellarator. There the reduced conductivities $\sigma_{c\ell}/\sigma_t$ have been plotted vs E/E_{cr} in the range 0.02 (classical) up to 0.6. A natural grouping along straight lines corresponding to the pertaining value of the drift parameter α can be observed. At lower densities - or perhaps higher values of $(\omega_{ce}/\omega_{pe})$ - higher values of α are found.

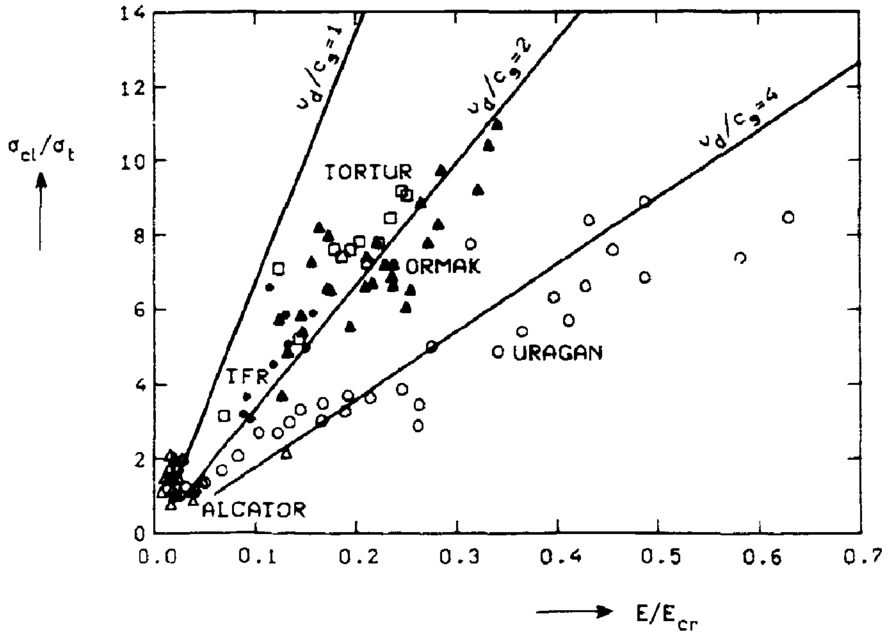

Fig. 1a.

In TORTUR, both classically conductive and weakly turbulent regimes can be realized. Which state is realized depends on the initial plasma production and heating, and the following maintenance of the plateau state. Classical conductive states are characterized by relatively strongly peaked density and temperature profiles, whereas the weakly turbulent states have much flatter profiles. No influence on the impurity generation is observed. In the turbulent discharge state appreciably higher central temperatures could be obtained, be it at higher loop voltages and - consequently - at the cost of voltseconds of the transformer [51].

It has been found in TORTUR that the maximum density scales as $n \sim I_p$, near the Murakami limit. This finding is virtually the same as the statement that $v_d \approx c_s = (kT_e/m_i)^{1/2}$. Also the temperatures in the quasi-stationary turbulent state increase as $T_e \sim I_p$. Both proportionalities and the unaltered energy confinement time, τ_E, as compared with usual scaling predictions ($\tau_E \sim n\sqrt{q}$) are consistent with an electric conductivity which behaves in a turbulent way ($\sigma_t \sim n^{1/2}$). The radial energy transport is obviously not changed by a weakly turbulent state.

C $1 < E/E_{cr}$. Turbulent heating in the high-electric field-region:

The interest in turbulent heating initially started in this region of electric fields. It was the purpose to obtain the highest possible temperatures starting from a completely ionized but cold plasma state. Indeed surprisingly high temperatures and plasma pressures could be obtained as shown in Table I for the different devices.

This is the consequence of the strongly decreased plasma conductivity. The decreases are shown for a large interval of E/E_{cr} for various devices in Fig. 1b.

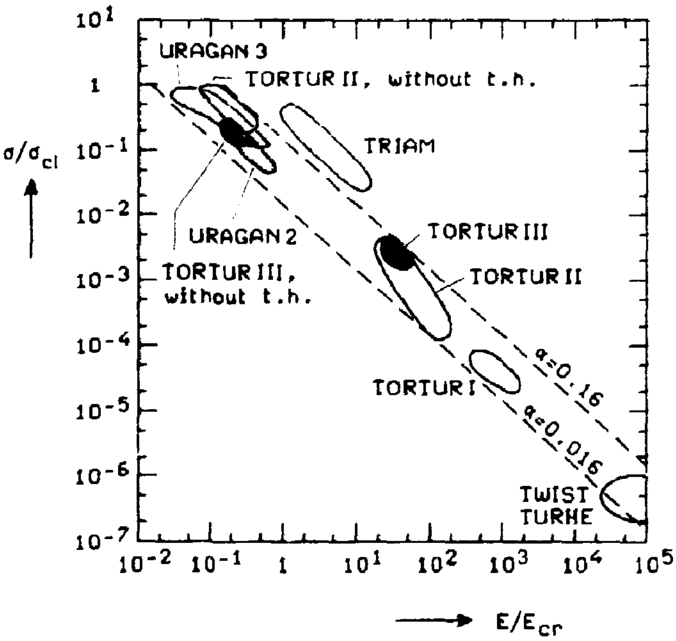

Fig. 1b.

Several disadvantages are attached to the use of turbulent heating high electric fields. When the rapidly increasing high electric fields are used, the plasma current increases such, that the current density, $j = env_d$, after an initial free acceleration period, levels off. An approximately constant drift parameter is maintained. (For marginally stable ion-acoustic turbulence, the ratio v_d/c_s = 2 is found [36b,51].) Consequently, during the increase the current and the high dissipational rate are concentrated in a narrow skin layer, δ, near the plasma surface. Typically, δ amounts to 1-4 cm for different types of turbulence as has been measured in various experiments of Table I. Relatively high electrical fields have to be applied to keep the necessary acceleration of the electrons so as to keep the increasingly hotter plasma in a turbulent state. A very effective heating occurs in the skin layer with $\beta_{pol} = 1$. This is a consequence of the constant ratio of α. A disadvantage is that the heating process takes place in a relatively tenuous area of the plasma, which generally also contains a high level of impurities. The bombardment of the wall by lost energetic ions may result in extra impurity influx.

It can be shown in a general way that to provoke a certain type of turbulence during the rising phase of a current pulse the necessary maximum electric field, E_{max}, and the pulse rise time are related as follows:

$$E_{max}t_p = I_p \left(3\mu_0 m_i \gamma(\gamma-1)(1-f)n_{ps}\right)^{\frac{1}{2}}/2\pi a\cdot q \ ,$$

where $\gamma = v_d/c_s$; $(1-f)$ denotes the fraction of energy dissipated in the skin; a is the plasma radius; q the electron charge; n_{ps} the plasma density in the skin.

This condition for pulsed turbulence holds as long as $t_p \lesssim (m_e/m_i)^{\frac{1}{2}}\, t_{e,i}$, with $t_{e,i}$ the electron-ion collision time. The necessary electric field, E_{max}, can therefore be taken at more convenient levels by choosing the largest allowable value for t_p. For JET, as an example, pulses with E_{max} = 10 V/m and pulse duration t_p = 2.5 ms can be adapted [52]. Because the maximum attainable value for betapoloidal is limited to about 1 in the skin region, a scheme of pulsed heating requires a repetition of the addition of pulses to increase the entire plasma cross-section to a uniform temperature approximately equal to the skin temperature. Clearly, a number of about (a/δ) pulses should be given within the energy confinement time, τ_E. This procedure has been tested in TORTUR and TRIAM as will be shown below.

Fortunately - as found in several experiments - the energy deposition in one pulse is somewhat better than described before, due to several factors. In many open as well as closed devices a rapid radial energy transport towards the centre has been measured [40,53, 54,49]. Typical velocities are close to the ion-acoustic velocity. Another, perhaps independent, favourable effect is a convective energy transport later during the pulse, as evidenced from magnetic probe measurements as well as from Thomson scattering and ECE spectroscopy [36b,49]. This skin implosion can be the result of the - unstable - two-valuedness of the outer q-profile in combination with resistive tearing modes.

Furthermore, a much more effective heating can be expected when the current is kept constant after the pulse ramp has reached its maximum. In that case the skin can broaden by resistive turbulent diffusion and deposit its magnetic energy until the decreasing drift ratio $\alpha = v_d/v_{Te}$ becomes so low that the turbulent state is finished [55]. The initial fast heating in TORTUR can be explained following this idea.

3. Pulsed turbulent heating results and energy confinement in tokamak experiments

The principal achievements from turbulent heating in tokamak experiments are assembled in Table 1. In most cases both electron and ion heating have been found. Very characteristic, however, for the ion heating is the presence of a two-temperature Maxwellian energy distribution (as a fair approximation). This feature can be understood from theoretical arguments [56,57].

As discussed, during the current pulse already the heating occurred throughout the entire plasma cross-section, indicating a rapid energy transport, reaching a maximum shortly after the pulse. Also an implosion-like distortion of the current skin has been observed.

In some cases, the efficiency of the conversion of the input energy at the plasma, $\int_0^t I_p \cdot V_\ell \, dt$, with V_ℓ the loop voltage, into thermal energy was determined. For the TRIAM tokamak, a fraction of 0.25 has been given [35a,b]. In TORTUR III, a fraction of 0.6 is found. In all cases reported here, the dissipation was ascribed to ion-acoustic turbulence. Typical values of the effective collision frequency were all in the range $\nu_{eff} = (0.01-0.1) \times \omega_{pi}$. Saturation mechanisms considered, differed between various experiments and depended on the relevant parameters and the author's taste. However, the predictions on anomalous resistivity and the drift parameters do not depend strongly on the particular type of saturation processes. Studies have been performed on saturation due to mechanisms as linear electron-ion Landau damping, non-linear Landau damping, resonant trapping in waves, ion resonant broadening, etc.

In all experiments, severe external MHD-instability modes of the column were absent for q(a) at safe values. In several cases the feared impurity generation was small or even ignorable.

The effect on the confinement after the sudden plasma heating could not be studied in most cases because the experiments were usually designed with emphasis on the study of the heating only.

The confinement in a tokamak was studied in greater detail in TRIAM I and TORTUR III [35,49,38]. In TRIAM it was found that after heating the energy transport was not increased and corresponded with neo-classical heat-conduction of the ions. Ion temperatures reached a maximum after the turbulent pulse at a time corresponding with the thermalization of a tail heated ion distribution (τ_{ii}).

The evolution of the dissipated energy after the pulse was also studied in the TORTUR III tokamak. The behaviour showed to be very complicated. As in other tokamaks, very effective heating of the electrons was found during and after the pulse. After the short duration pulse ($t_p \approx 5$ μs; $\Delta I_p = 30\text{-}60$ kA; $E_{max} < 1$ kV/m), the temperature rise disappeared extremely rapidly. The temperature profile became almost unperturbed. Surprisingly, it is found that electron and ion temperatures rise on a slow timescale, reaching a maximum about 2 ms after the pulse. The increases ΔT were proportional with $(\Delta I_p)^2$ (as also is found in most of the other turbulent heating experiments). The explanation offered for this complicated behaviour is as follows. Initially the plasma is heated due to thermalization of the compressive turbulent shock-like structure of the unstable skin. Indeed a slight density increase is found near the plasma centre and some decrease near the edge.

Meanwhile, the extra current of the pulse is removed, the retraction occurring again in a skin-like region near the periphery. A much more peaked current profile remains. The overheated plasma undergoes a fast adiabatic expansion with cooling on a microsecond timescale. However, the current profile is still considerably peaked. The initial energy of the turbulent layer now resides predominantly as increased magnetic energy of the narrowed current profile. Also the magnetic turbulence is increased proportional with $(\Delta I_p)^2$ [58].

Evidently, this current distribution is not an equilibrium one and relaxes towards the initial shape by decay of the magnetic energy into thermal energy of the plasma through resistive dissipation. The time evolution of temperatures and energies follows a simple model. The final efficiency of the heating amounts to 40% of the capacitor energy delivered at the plasma during the pulse. Heat losses are normal or even diminished during the energy evolution.

Relying on pulsed heating, a scheme of pulse repetition is needed to heat larger radius tokamaks. In the TRIAM and TORTUR tokamaks the heating to multiple pulses has been studied [35,38,49]. In TRIAM I it has been shown that two additional current pulses within the energy-confinement time resulted in plasma heating equal to the sum of the heating of the separate pulses. However, this result could be achieved only when an opposite polarity of the two pulses was chosen. Application of the same polarity was far less effective.

In TORTUR, the polarity of following pulses could not be altered for technical reasons. The addition of two pulses within τ_E resulted even in a diminuation of the heating as due to one pulse only. In view of the proposed explanation for the heating due to one pulse, it is reasonable to expect that the thermalization has first to be completed before a new pulse should be administered. However, the addition of pulses separated by $t \approx \tau_E$ has been shown to be successful. The heating due to one pulse can be prolonged for all following pulses. Up to four pulses have been used leading to overlapping and repetitive heating. Impurity generation is small.

Conclusions

Investigations of current-driven turbulence have shown the potential to heat plasmas to elevated temperatures in relatively small cross-section devices (a/δ relatively small). The fundamental processes are rather well understood theoretically.

Even as it is shown to be possible to relax the technical requirements on the necessary electric field and the pulse length to acceptable values, the effect of energy generation near the plasma edge, the energy transport, the impurity influx and the variation of the current profile are still unknown for present-day large-radius tokamaks.

Heating of plasmas by quasi-stationary weakly turbulent states caused by moderate increases of the resistivity due to higher loop voltages could be envisaged. Power supplies able to furnish power levels 5-10 times higher than the usual values could be used for a demonstration of those regimes.

At several institutes and university laboratories the study of turbulent heating in larger tokamaks and stellarators is pursued [41,42].

TABLE I

OPEN DEVICES	cm/cm R,a L,a	B (tesla)	$n_{pl}(m^{-3})$	I_{pl} (kA)	V_0(kV)	ΔI_{turb} (kA)	ΔT_e(keV)	ΔT_i(keV)	E(V/m)	$\sigma(mh_o/m)$	$\frac{\sigma}{\sqrt{n}}\times10^7$	nT (eV/m^3)	nT/E^2 $(m.V^{-1})$	Refs.
GROM1 a	50,9	0.03	1×10^{20}		1.5	99			3×10^{3}	5×10^{3}	2.7	4×10^{22}	4×10^{15}	1
GROM3 a	24,4	1.5	10^{21}		28	200	3	1-2	1.5×10^{4}	1.2×10^{4}	4.6	3×10^{24}	8×10^{15}	2
GROM4 a	30,1.5	5.0	7×10^{20}		28	200	2	1	3×10^{4}			2×10^{24}	3×10^{15}	3
MIRROR h	-,1.8	0.3	2×10^{19}							10^{3}	3.2			4
PR-I b	100,4	0.18	5×10^{18}		10	3	0.2	3						5
TN-4 b	200,3	0.35	1×10^{19}		140		5	2				5×10^{22}		6
TN-5 h	300,12	1.2	1.4×10^{19}		140		3	3				6×10^{22}		7
NPR-2 h	90,4	2.5	10^{20}				1		2×10^{4}	7×10^{2}	3.8	4×10^{22}	10^{14}	8
r'PR-2M b	10,1	9.0	10^{22}		45							2×10^{24}		9
OGRA-2T b	106,6	1.5	10^{19}		40	20		3-10				6×10^{22}		10
SRIEPA c	100,2	0.3	10^{20}		25		0.1	0.7				5×10^{22}		11
MIRROR d	100,3	0.16	5×10^{19}		40		2.5	0.8				2.5×10^{21}		12
MIRROR e	180,6	0.16	2×10^{20}		76	5		0.5				2×10^{21}		13
ORNL f	30,0.5	0	3×10^{16}		9		0.1							14
MIRROR g	180,4	0.3	8×10^{19}		40			1.5				7.5×10^{23}		15
NRL h	3.5,0.1	0	10^{25}		600	1200		0.2						16
BSGII i	120,3	0.2	5×10^{19}		36	3	0.1		8.3×10^{3}	2.9×10^{2}	0.4	5×10^{21}	7×10^{13}	17
MACHII i	135,2	3.0	10^{20}		36		8	2	2.2×10^{4}	30	0.03	8×10^{23}	1.4×10^{15}	18
OCUII j	30,3.5	1.7	5×10^{20}		25		10	1						18
TURHE k	80,6	2.0	5×10^{19}		40	20	6	2	3×10^{4}	600	1	5×10^{23}	2×10^{14}	19
TOROIDAL DISCHARGES														
Stellarators & other closed devices														
SIRIUS a	600,2.5	2.0	1×10^{19}				1-9	0.08-0.4	2×10^{3}	1.2×10^{3}	4.6	10^{21}		20
URAGAN2 a	110,10	2.2		20				0.7						21,22
BETATRON b	20,2	0.3	5×10^{16}	1.2			tens of keV		2.5×10^{4}					23
VIKhR'-1 b	15,1.5	0.1	10^{19}	2			2		1.5×10^{4}					24
VIKhR'-2 b	25,2	0.3	10^{19}	1			0.1	0.01	2.5×10^{4}	3.3×10^{2}	3.3	7×10^{22}	2.5×10^{13}	25
TWIST 1	32,5	0.5	10^{19}	6				0.7	5.0×10^{4}	3.2×10^{2}	3.3	2×10^{23}	8×10^{13}	26
TORSO 1	40,5.5	2.0	10^{19}				10		5×10^{3}			10^{22}		27
BETATRON q	19,2.5	0.2	10^{19}	1			0.3	0.01	10^{4}			10^{22}		28
JIPP-1b i			5×10^{17}			0,7	20	0.5	5×10^{2}					29
Tokamaks														
TOR. disch. b	18.5,4.5	0.6	4×10^{19}	5	25(1 MHz)	5			2.5×10^{4}			3×10^{22}	4.8×10^{13}	30
TOR-IV b	18,2	2.0	3×10^{19}	5					2.5×10^{4}			3×10^{22}		31
TOK.LPI m	18,5	1.0	7×10^{19}				0.3		1.5×10^{4}			4×10^{22}		32
TTF n	30,4	0.6	5×10^{19}	5					2.5×10^{3}			10^{21}		33
TTT o	60,10	2.0	10^{19}				1.0	0.5	5×10^{4}			3×10^{22}		34
TRIAM-1 p	30,7	4.0	5×10^{19}	10				0.5	10^{4}					35a,b
TORTUR I k	46,9	1.7	$(4-20)\times10^{19}$	40		140	2.0	0.6	5×10^{3}			2×10^{23}		36a,b
TORTUR II k	46,9	3.0	$(4-20)\times10^{19}$	55		100	0.4	0.4	3×10^{3}			2×10^{22}		37
TORTUR III k	46,9	3.0	10^{20}	60		60	0.4	0.4	10^{3}	3.7×10^{3}	6.7	10^{22}	10^{16}	38
r.f. TORUS q	19,3	0.3	5×10^{17}			0.1 f~1.8 MHz			10^{2}					39
STOR I q	22,3.5	1.7	5×10^{19}	10		50	2.0	0.13	10^{4}					40
STOR IM q	30,7	1.7	5×10^{19}	10		50			10^{4}					40
STOR II q (in constr.)	75,15	1.0	10^{20}	65		100			10^{4}					41
TRIAM-1M p (in constr.)	ell.,a×b 12×18 R=84 cm	8.0												42

Explanation of abbreviations in Table I

a) KhPTI : Kharkov Physico-Technical Institute, Kharkov.
b) IAE : Kurchatov Institute of Atomic Energy, Moscow.
c) SRIEPA: Scientific Research Institute for Electrophysical Equipment, Leningrad.
d) INP : Institute of Nuclear Physics, Novosibirsk.
e) SGAI : SGAI Laboratory, San Diego.
f) ORNL : Oak Ridge National Laboratory, Oak Ridge.
g) : Cornell University, Ithaca.
h) NRL : Naval Research Laboratory, Washington.
i) : Nagoya University, Nagoya.
j) : Osaka University, Osaka.
k) FOM : FOM-Institute for Plasma Physics, Nieuwegein.
l) Culham: Culham Laboratory, Abingdon.
m) LPI : Lebedev Institute of Physics, Moscow.
n) : Associazione Euratom-ENEA Fusione, Frascati.
o) : University of Texas, Austin.
p) : Kyushu University, Fukuoka.
q) : University of Saskatchewan, Saskatoon.

Table II

		$E/E_D \leq 0.02$ classical regime classical collision theory collision-dominated "true runaways"	$0.02 < E/E_D \leq 1$ weak turbulence accelerative regime	$1 < E/E_D \leq 1000$ 'bulk' turbulence minority tail effects	$E/E_D > 1000$ strong turbulence non-linear theories
			quasi-linear theories beam-plasma interaction by anomalous Doppler effect and Cerenkov resonance		
$\frac{\omega_{ce}}{\omega_{pe}} < 1$	$\frac{T_e}{T_i} \gtrsim 3$	$\sigma = \sigma_{cl}$ (Spitzer resistivity)	$\sigma/\sigma_{cl} \sim E_D/E \quad \gamma \approx 1$ T-P interaction: Cerenkov resonance plasma modes: IA, LM	$\sigma/\sigma_{cl} \sim E_D/E \quad \gamma \geq 1$ bulk: IA turbulence T-P interaction: Cerenkov plasma modes: IA, LM	two-stream instability ion-acoustic instability stop runaway production
	$\frac{T_e}{T_i} \lesssim 3$		$\sigma/\sigma_{cl} \sim E_D/E \quad \gamma \gtrsim 1$ T-P interaction: Cerenkov plasma modes: IC, DW, MS	$\sigma/\sigma_{cl} \sim E_D/E \quad \gamma \geq 1$ bulk: IC turbulence T-P interaction: Cerenkov plasma modes: IC, DW, MS	
$\frac{\omega_{ce}}{\omega_{pe}} > 1$	$\frac{T_e}{T_i} \gtrsim 3$		$\sigma/\sigma_{cl} \sim E_D/E \quad \gamma \gtrsim 1$ T-P interaction: A.D. res. plasma modes: IA, DW, MS	$\sigma/\sigma_{cl} \sim E_D/E \quad \gamma \geq 1$ bulk: IA turbulence T-P interaction: A.D. res. plasma modes: IA, DW, MS	
	$\frac{T_e}{T_i} \lesssim 3$		$\sigma/\sigma_{cl} \sim E_D/E \quad \gamma \geq 1$ T-P interaction: A.D. res plasma modes: IC, DW, MS	$\sigma/\sigma_{cl} \sim E_D/E \quad \gamma \geq 1$ bulk: IC turbulence T-P interaction: A.D. res. plasma modes: IC, DW, MS	

A systematic survey of turbulent plasma states.

Abbreviations:

T-P interaction	tail-plasma interaction	DW	Drift waves
A.D. resonance	Anomalous Doppler resonance	MS	Magnetic sound waves
IA	Ion-acoustic waves	LM	Langmuir oscillations.
IC	Ion-cyclotron waves		

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