

## CONTENTS

	FOREWORD TO THE RUSSIAN EDITION .. .. .	v
	FOREWORD TO THE ENGLISH EDITION .. .. .	vii
	EDITORS' NOTE .. .. .	ix
I	INTRODUCTION .. .. .	1
	1.1. Thermonuclear reactions and energy balance with radiation	1
	1.2. Magnetic confinement of plasma—reactor efficiency— minimum confinement time—optimal temperature—trans- formation of fusion energy to electrical energy—fuels— tritium breeding	9
	1.3. Classification of confinement and heating schemes	18
II	THE MOTION OF PARTICLES IN PLASMAS .. .. .	22
	2.1. Single particle motion: adiabatic invariance—motion parallel to the magnetic field	22
	2.2. Motion in non-uniform fields: drift—motion perpendicular to the magnetic field—adiabatic trapping—experiments	26
	2.3. Drift in combined electric and magnetic fields—quasi- periodic motion in time-varying non-uniform fields	33
	2.4. Collisions between charged particles: cross-sections— mean-free-paths—collision times	38
	2.5. Collisional relaxation—ions and electrons—slowing down rates—scattering	42
	2.6. Collisions with neutral atoms — ionisation — impurity radiation	49
	2.7. Charge-exchange processes	56
III	TRANSPORT PHENOMENA IN PLASMAS .. .. .	61
	3.1. Electrical transport coefficients: conductivity—dielectric constant—polarisation	61
	3.2. Runaway electrons and thermal conductivity	64
	3.3. Transport phenomena in magnetic fields: electrical conduc- tivity—dielectric constant—anisotropy of conductivity	67
	3.4. Diffusion across a magnetic field: collisions between like particles and between unlike particles—heat conduction— Bohm diffusion and relation to experiment	71

IV	MAGNETOHYDRODYNAMIC THEORY OF PLASMA ..	77
	4.1. Magnetohydrodynamic equations: two-fluid equations— equations of motion—Ohm's law—validity of MHD ap- proximation	77
	4.2. Magnetostatics: pressure balance—pinch effect—Joule heating	82
	4.3. Toroidal configurations: toroidal drift—toroidal pinch— effect of conducting walls—stabilised toroidal pinch	87
	4.4. Collisional diffusion of plasma boundary	94
	4.5. The collisionless plasma boundary	96
	4.6. Motion of plasma with the lines of force	100
	4.7. Oscillations and waves: electron plasma oscillations—sound waves—Alfvén waves—magnetosonic waves	102
V	FAST HIGH-POWER DISCHARGES .. .. .	109
	5.1. Pinch effect: historical comments—experimental apparatus —diagnostic techniques	109
	5.2. Experimental studies of plasma motion in the dynamic pinch	113
	5.3. The dynamic pinch—measurements of plasma density and temperature—instabilities—impurities—the theory of Leon- tovich and Osovets (snow-plow model)—MHD calculations —microscopic processes	117
	5.4. Neutron and X-ray emission from linear pinches—accelera- tion process—thermonuclear prospects of the dynamic pinch	132
	5.5. The Triax hard core pinch	144
	5.6. Theta-pinches: experimental	146
	5.7. Theta-pinches: theoretical interpretation—inertial heating —effect of particle loss—trapped magnetic field—origin of nuclear reactions	154
	5.8. Plasma loop in a transverse field	162
	5.9. Plasma accelerators (injectors)—rail sources—coaxial guns	165
VI	HEATING AND CONFINEMENT OF A PLASMA BY SUSTAINED ELECTRICAL DISCHARGES .. .. .	172
	6.1. General theory: 'slow' and 'fast' discharges—kink and sausage instabilities—the stabilised pinch—Kruskal-Sha- franov stability condition—normal modes—the Suydam criterion—theoretical uncertainties	172
	6.2. Experimental apparatus: insulated versus conducting dis- charge chambers—transformer design consideration—Zeta —pre-ionisation	182
	6.3. Experimental techniques: discharge resistance and electron	

	temperature—electron density from microwave transmission —spectroscopy—infra-red measurements—energy loss mea- surements	189
	6.4. Stabilised toroidal pinch, experimental results: typical parameters—plasma pressure—electron and ion tempera- tures—mass motion—emission of neutrals—X-ray emission —neutron radiation—energy balance	197
	6.5. Stabilised toroidal pinch, general conclusions: instability— particle energies—acceleration processes—energy exchange —anomalous resistance—magnetohydrodynamic instabili- ties—runaway electrons—thermonuclear prospects	205
	6.6. Toroidal discharges in strong longitudinal fields: the use of limiters—equilibrium position—Tokamak installations and experimental results: properties of the discharges—in- stability—influence of stray fields on equilibrium—electron density and 'pump-out'—hard X-ray emission and runaway electrons—new Tokamak installations and experimental results	208
	6.7. Conclusions from studies of Tokamak systems: stability— ion temperature—force-free field configurations—pressure balance considerations—anisotropic conductivity and tur- bulent diffusion—future experiments—Joule heating ex- pectations	223
	6.8. Other varieties of sustained pinches: compressional heating —stabilisation by internal conductors—the Levitron	231
VII	MAGNETIC TRAPS: GENERAL PRINCIPLES .. .. .	236
	7.1. Definition of magnetic trap—general approach to the problem—initial work in the Soviet Union	236
	7.2. Single particle motion, qualitative ideas:—drift motions— the current-carrying ring—practical magnetic systems: Levitron, Astron, Stellarator, bumpy-torus	238
	7.3. Single particle motion: general theory in axially symmetric magnetic fields—adiabatic motion—trapping of particles with large Larmor radii	242
	7.4. Stability of plasmas in magnetic traps: magnetohydro- dynamic and kinetic-type instabilities—flute and inter- change instabilities—stability criteria—stability theory based on the motion of individual particles—mirror traps with anisotropic plasma pressure	249
	7.5. Magnetohydrodynamic instabilities: growth rates—in- fluence of a diffuse boundary—finite Larmor radius effects —influence of conducting walls and end-plates in mirror traps—Kadomtsev theory of turbulent diffusion	258
	7.6. Other MHD-type instabilities: centrifugal instability— connection with anomalous diffusion and Rayleigh-Taylor	

instability—theory of instability, of the positive column— waves generated by temperature gradients	262
7.7. Kinetic instabilities: beam instability—velocity space in- stabilities—Landau damping—growth rates—excitation of plasma oscillations—excitation of ion-sound waves—wave excitation and confinement time—anomalous diffusion coefficient—instabilities due to anisotropic velocity distribu- tion—some unsolved theoretical problems	269
7.8. Betatron radiation: its origin—relativistic effects—absorp- tion in the plasma—implications for thermonuclear reactors	281
VIII SPECIFIC TYPES OF MAGNETIC TRAP . . . . .	286
THE STELLARATOR: 8.1—8.6	
8.1. Single particle motion—rotational transform and magnetic surfaces—figure-eight configuration—helical windings— shear stabilisation—construction tolerances—particle tra- jectories—mirror effects	286
8.2. Magnetohydrodynamics: equilibrium plasma configuration —influence of plasma diamagnetism—maximum plasma pressure—stability against flute perturbations—stability during ohmic heating	292
8.3. Construction and plasma heating: the race-track Stellarator —the divertor and impurities—ohmic heating—magnetic pumping at the collision frequency—magneto-sonic reso- nance—transit-time heating	297
8.4. Ion cyclotron resonance heating: single particle theory—in rarefied and high-density plasma—cyclotron waves and the magnetic beach	301
8.5. Experimental results: ohmic heating phase—Kruskal- Shafranov limit—spectroscopic observations—anomalous diffusion	304
8.6. Anomalous diffusion mechanisms: runaway electrons and plasma oscillations—ion oscillations—Kadomtsev mechan- ism—universal instabilities—trend of future research	308
MAGNETIC MIRROR TRAPS: 8.7—8.14	
8.7. Axially symmetric adiabatic traps: particle distributions— influence of electrostatic fields—the high- $\beta$ limit—mirror losses by collisions—confinement time—ratio of diffusion losses and scattering losses—production of net fusion power	311
8.8. Injection of high-energy particles: molecular ion dissocia- tion—trapping in a rising field—injection across a rising magnetic field—non-adiabatic trapping in spatially varying fields—fast neutral injection—ionisation on background gas or other beams—vacuum requirements—Lorentz ionisation of neutral atoms	318

8.9. Heating methods: ion magnetron—plasma injection— magnetic compression	323
8.10. Experiments with compressional mirror traps: hot electron plasmas—X-rays—electron temperature—plasma volume— confinement time—interchange instabilities—'line-tying'— an interpretation of Pyrotron experiments—ion tempera- ture—multi-stage compression experiments	325
8.11. Ion magnetron experiments: charge-exchange losses and containment time—losses due to instability—loss of energetic ions—influence of geometry on losses	329
8.12. Rotating plasma experiments: plasma currents—enhanced mirror ratio—plasma capacitance and electrical character- istics—future possibilities	336
8.13. Experiments with Ogra: molecular ion dissociation on residual gas—'burn-out'—vacuum conditions—critical cur- rent—Ogra design features—status of Ogra experiments— non-stationary effects—space charge—ion cyclotron radia- tion	340
8.14. The DCX experiments: molecular ion dissociation with an arc—ion beam characteristics—charge exchange losses in the arc—special nature of plasma	347
8.15. Astron: relativistic electron current ('E-layer')	349
HIGH-FREQUENCY CONFINEMENT: 8.16—8.18	
8.16. Theory: the skin effect—motion of single particles in HF fields—HF fields combined with static magnetic fields (high-frequency plugs)—compensation of toroidal drift	351
8.17. Confinement of plasmas: equilibrium conditions—boundary between plasma and confining fields—particle losses	356
8.18. Experimental: travelling waves in a toroidal chamber— an experiment with two waves travelling in opposite direc- tions—high-frequency magnetic 'plugs' for axial confine- ment—confinement in resonant cavities—HF stabilisation	358
CUSP-SHAPED FIELDS: 8.19—8.20	
8.19. Cusp-shaped fields—field distribution near field-zero— non-adiabatic particle motion—loss rates—influence of boundary layer structure—diffusion broadening of boun- dary layer—thermonuclear prospects—confinement at low $\beta$	361
8.20. Experimental investigation of cusp-shaped fields: plasma injection and penetration into a strong field—finite con- ductivity effects—trapping mechanisms—heating by com- pression—experimental apparatus—life-time of the plasma —the search for non-adiabatic losses	367

	8.21. Hybrid magnetic field traps: defects of, simple geometries— general requirements—examples of hybrid geometries— Ioffe's apparatus—Ioffe's experimental results	375
IX	CONCLUSION .. .. .	380
	BIBLIOGRAPHY .. .. .	383
	LIST OF SYMBOLS .. .. .	397
	INDEX .. .. .	399