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17 Years Plasma Physics in Innsbruck
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ABSTRACT AND CONTENTS

In this report the results of 17 years (1957 - 1973) of research in Magnetohydrodynamics and Plasma Physics are summarized and reviewed. It also covers a summary lecture held by F. Cap in Jülich, Germany, Plasma Physics Institute of the Kernforschungsanlage Jülich on 14 September 1973. It covers

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PREFACE

The publication of a Scientific Report Nr. 1oo within the frame of a research project might be an appropriate time to review and summarize the past activity. Furthermore, many participants of the International Congress on Waves and Instabilities in Plasmas, Innsbruck, April 2 - 7, 1973 expressed their wish to be informed on the history of plasma physics research in Innsbruck and the Directors of the Plasma Physics Institute in Jülich, Germany, invited the author to give in Jülich a Summary Lecture on Plasma Physics in Innsbruck on 14 September 1973.

During World War II the author was engaged in gasdynamic research [1] - [7] and when the war was over he worked in the fields of elementary particle and nuclear physics [8] - [34], in general relativity [35] - [38], and in mathematical methods of theortical physics etc. [39] - [49]. In summer 1956 the author had the privilege to meet W. B. Thompson, at this time in Harwell, (the Culham Laboratory was not yet in existence)who attracted the author's interest to magnetohydrodynamics.

At this time it was quite a venture to start [6o] a new field

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at Innsbruck University. The Institute of theoretical Physics had a staff of 2 and the yearly total budget was approximately US $ 15o.- so that only 3 periodicals could be subscribed (Nuovo Cimento, Physical Review, Progress theor. Phys.) and some 15 - 2o books could be bought per year. No plasma physics periodicals were in existence and the publication in e.g. Acta Physica Austriaca needed more than one year [5o] [6o].

Optimistic by nature and charged in 1957 to take the professorship for theoretical physics at the University of Innsbruck, the author started and what resulted is reported here.

It was only with the support of a US - Government Research Contract (1963), later with the support of the Austrian Scientific Research Council (1968), the Austrian Ministry of Technology (1967), the Austrian Technological Research Council (1968) and the Austrian Academy of Sciences (1971), that the necessary funds were received to carry through the research described herein. The support given by the Garching, Jülich, Culham Centers and by other scientists will be mentioned in th eappropriate chapters.

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1. MHD - Theory of Ideal Plasmas.

After a certain time of learbing we started to investigate the question, in how far the gasdynamical methods using characteristics could be used to solve magnetohydrodynamic problems. Since many gasdynamic problems are investigated under the assumption that the flow is a potential flow it was of interest to understand under what condition potential flow in magnetogasdynamics can occur [5o], [52], [57], [6o]. It was shown that an analog to Crocco's theorem in gasdynamics exists in magnetogasdynamics and that certain thermodynamic and mechanic relations must be satisfied in order that a potential flow may occur [51], [53], [61]. It was shown that only twodimensional flow problems could be a potential flow and several practical examples using characteristics methods were solved, [54], [55], [56]. Also non-stationary onedimensional problems where the flow may always be considered to be a potential flow were investigated [58], [59], [62]. Also varaitional principles have been used to solve stationary [63] and non-stationary potential flows of MGD [64] [62]. According to a suggestion by W. B. Thompson, the equivalence between a special form

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of a rigid wall, a boundary value problem, and a special exterior magnetic field simulating the form of the wall, was investigated with low success [65], [66], [68].
Since real plasmas do not have infinite electrical conductivity, research started on plasmas with finite conductivity.

2. MHD - Theory of a Finite Conductive Plasma.

First of all, we tried to understand the physical and mathematical differences between ideal and real plasmas. When a physical parameter which was assumed to be infinite now has to be assumed to be big, but finite it is custom to start theories with series developments with respect to powers of the inverse of the big parameter. So we first tried to solve the MGD equations of a real plasma by series expansions with respect to powers of resistivity [59]. Having obtained some useful equations we started numerical investiagtions [67], [68], [7o], [71], [72], [73].

In another attempt we tried to find an analytical solution for twodimensional flows of a conductive compressible medium. We arrived at the Tricomi equation, [74]. Flows of finite conductive plasmas as e.g.in an accelerator were also treated, see chapter 3 [75].

In all flow problems, boundary layer problems are of importance. So also in plasma physics, where two, even three different boundary layers -viscous, magnetic, thermal - exist. So it was important for us to investigate plasma boundary layer problems. In [76] a viscous channel flow in boundary layer approximation with heat conduction was investigated using similarity transformations, see also chapter 6. Quite another approach - by solving analytically complicated nonlinear partial differential equations describing the boundary layer may be found in [77], [78].

Simple waves and shocks are basci phenomena. If one understands them, one can learn for more complicated problems. So the influence of finite electrical conductivity on the classical MGD shocks was investigated. A relation between shock thickness and electrical conductivity was found [79], [67], [8o] see also [72]. Going deeper into this problem it was recognized that finite conductivity plays a special part in the manner with which discontinuities develop in a plasma. This is the basic reason for the different behavior of ideal and real plasmas - a paper in Journal of Mathematical Physics gives a deeper insight [81], [82], see also chapter 4.

3. MHD - Channel Flow and Accelerators.

The various methods worked out by our group for MHD flows of a plasma exhibiting a finite electrical conductivity were tested on practical examples. So first the twodimensional stationary and then the onedimensional non-stationary flow at small magnetic Reynoldsnumbers was calculated on a computer [70], [69], [72], [73]. Then the methods were applied to the calculation of different types of plasma accelerator, including travelling wave accelerators [83], [84], [85], [86], [75], [87].

Later on a quite extensive programme on numerical studies on MHD power generating channels was started. First, two-dimensional investigations for single electrode pairs and for periodic electrode pairs were made on the Hall effect and the ion slip. Several papers were published: [88], [89], [9o], [91]. Then, a more broad programme to investigate theoretical problems in the technological realisation of MHD power production was started.Preliminary results can be found [92]; analytical solutions of channel flow problems may be found in [93], [94], [76], [95], [96]. Later, attempts were made to understand and calculate the degree of efficiency and of energy conversion in a MHD channel: [97]. We then concentrated on the question of plasma - wall heat transfer in MGD generators, published in [98]. On the basis of this work a collaboration with M. Lengyel, Brederlow, K. Witter and Witkowsky from the Garching Plasma Physics Center developped. The support given to us in th eform of the availability of the Garching IBM 36o/91 computer is gratefully acknowledged. P. Fritzer calculated numerically the current and density distribution in a twodimensional MGD flow of a working gas with variable properties including heat transfer, Hall effect and segmented electrodes [99], [1oo], [1o1], [105] and F. Woerndle made numerical computations on the influence of ionization and excitation mechanisms including atom - atom collisions upon a non equilibrium MGD entrance flow. This work was supported not only by Garching, but also by R. Bohn, ARGUS project, Jülich, Germany [1o2], [1o3]. Finally, starting from the old idea of electrodes with stepwise varying electric conductivity (segmented electrodes) investigations were made how a given continously varying electric conductivity in extended twodimensional electrodes influences the current density field line pattern and therefore influences the electrode heating and corrosion problems. After some preliminary but interesting results [1o6], [107] we now hope to be able to predict optimum distributions of the electric conductivity along and across thick electrodes so that the corrosion due to Joule heating is a minimum. We are happy to have the - just starting - collaboration of Prof. Haines, London, Prof. laing and Prof. J. C.Tayler both from Glasgow.

In the frame of our work on practical applications of mathematical methods for the solution of MGD problems for a real plasma also some work on plasma explosions in an inhomogeneous magnetic field was done [1o8], [1o9], [11o].

4. MHD - Waves, Shocks, Characteristics.

In order to understand the difference in the behavior of ideal and real plasmas we quite early started to investigate small waves and characteristics in real plasmas [111]

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and shock waves [8o], [112]. Then the characteristic curves of the system of partial differential equations describing real plasma flow were derived and found to be complexe due to the magnetic diffusion [113], [114], [115], [81], [8o]. The paper by Friedl [81] gave a break through in understanding and helped to develop a new mathematical characteristics method to solve such problems [72]. Some first remarks on all these problems are given in Volume 3 of my book on plasma physics [116].

5. MHD - Instabilities.

Having been interested some time in plasma instabilities we later took up the suggestion made by Dr. Georges Samaras from the US Government Research Office to investigate instabilities. To learn we started in 1965 Literature surveys on plasma instabilities which were continued up to 1973: [117]. We have produced more than 55oo abstracts on more than 15o instabilities.

Later on we started own research on plasmainstabilities. First we were mainly concerned with MHD instabilities, with macrosocopic instabilities. Herrnegger investigated the

Helmholtz instability in a discontinuous magnetic field [118], [119] and reported in Stockholm on his results. The influence of finite electrical resistivity alone and combined with viscosity on stationary magnetostatic equilibria was investigated by H. Friedel and P. Unteregger. Reports were given at the Novosibirsk Conference 1968 [12o] [121] [122]. A general algorithm to investigate plasma MHD instabilities using Lie series was worked out by Floriani and published in Nuclear Fusion [123][124]. The effects of gradients of electric resistivity and the generation of overstable modes by this effect were investigated by Herrnegger [125][126]. Also instabilities of flowing plasmas have been investigated in innsbruck.So. E. Jager wrote some papers on dissipative instabilities of an MHD sheet flow [127][128]. Furthermore the magnetohydrodynamic Poiseuille flow and its stability was investigated by Jager [129], who reported als on his findings at the occasion of the Innsbruck Congress on Waves and instabilities in plasmas in April this year [13o}. Resistive drift waves for adaibatic plasmas - all other authors had investigated isothermal plasmas - were the subject of research of Gerhard Auer who reported on the results at the Paris Quiescent Plasma

Conference [131], [132], [133].

The concept of local potential was also used in Innsbruck to carry through nonlinear stability investigations [134], [135]. The theory of nonlinear waves and the question if added nonlinear terms might destabilize stable linear systems was investigated in a series of papers, [136], [137]. A special problem, namely amplitude dispersion for dissipative waves, i. e.the dependence of the dispersionrelation on the amplitude for strongly nonlinear weakly dissipative waves will be treated in a special seminar on 14 September 1973 at the Jülich Plasma Physics Theory Seminar [138]. The main ideas are published in J. Mathematical Physics [139].

It is well known that finite Larmor radius effects have a stabilizing action. Also in Innsbruck this action was investigated: Herrnegger tested the effects of collision and gyroviscosity on th egravitational instability in a two component plasma [14o} [141] [142]. Due to th esupport given to our group by Prof. Fünfer, Garching. Mr. Herrnegger was able to work in Garching for two years. He there produced several papers mainly on the equilibrium and the stability of the belt pinch [143].

Parametric effects may destabilize or stabilize a plasma. Such parametric effects are therefore of interest. The Langevin Equation of an electron in a collisional plasma under the influence of an electromagnetic wave has the same form as the equation of a weakly damped inverted pendulum whose support is oscillated. To understand the mechanism of nonlinear parametric stabilization the equations of the inverted and parametrically excited pendulum was solved by Mr. Sellmeier [144]. It was shown that for big amplitudes new equilibria are possible. Nonlinear effects play also an important role in stabilization. If the amplitude grows, nonlinear terms in the differential equations might stabilize, possibly but not necessarily by damping but also by other effects.

So a collaboration between Prof. Herbert Lashinsky, University of Maryland, College Park, and author showed that convection phenomena of the Benard problem could be stabilized by nonlinear terms [145] [146]. Then it was investigeated if the same non linear terms could stabilize also the oscillatory solution of the Lashinsky-Cap equation

[147] and then a more systematic investigation on the effects of nonlinear damping terms of 3 rd degree and with a first derivative and its powers and restoring forces up to the third power were investigated.
More details on plasma instabilities might also be found in the books on plasma instabilities [149].

We also should mention the International Congress on Waves and Instabilities in Plasmas organized by the Innsbruck group in April 1973. Here the support of Professors Lehnert and Vandenplaas should be acknowledged [15o]. In concluding this chapter we should mention our collarboration with Prof. Boyd and Dr. Gardner from Bangor University, Wales. Dr. gardner will stay in Innsbruck in October - November 1973 to investigate Tokamak and belt pinch instabilities. We are also negociating with Prof. Allis from MIT to stay with us in the academic year 1974/75.

6. Mathematical Methods.

When a group of theoreticians is working on new problems then inevitably problems of new mathematical status arise.

Four topics might be worthwile to mention.

In order to find analytical solutions of channel flow problems of real plasmas the so called similarity transformations which transform a particla differential equation into an ordinary differential equation were investigated [151] and applied [76][96].

Another topic was to find a new method to solve strongly nonlinear ordinary differentialequations which possess nearly periodic solutions. On the lines of the Kryolov - Bogoljubow method an averaging method to solve such strongly nonlinear weakly dissipative equations using Jacobi elliptic functions with slowly time varying modulus was devised and applied [153].

Another idea was to transform dissipative terms into time dependent coefficients. A quite general transformation was found which is able to transform nonlinear damping terms into linear time dependent terms [154].

The paper using Jacobi elliptic functions to solve the equation of the parametrically excited pendulum with big amplitudes has been mentioned before [144].

7. Vlasov Plasmas and Echoes.

Turning now to Microinstabilities we first investigated possibilities to solve analytically the Vlasov equation. The results were quite meager, though we were able to find some closed analytical solutions for very special cases [155][156]. The solutions of the Langevin equation of motion of an electron in a collisional plasma under the influence of an electromagnetic wave gives the solution of the characteristic equation of a certain class of collisional kinetic equations and is then connected with nonlinear collisional Landau damping [157][158]. P. Koch, now Paris, investigated in Innsbruck turbulent plasmas [159] and L. Lerch started, in collaboration with the Berlin group (Baumgärtel,Sauer etc) to investigate collisional plasma echoes in bounded plasmas [16o]. Other plans for international collaboration with a theoretician from Culham are under way. P. Shukla produced several papers on test particles in Innsbruck [161], [162].

8. Microinstabilities.

In this field our results are very scarce and concentrate around the name of S. Kuhn. Extendings a paper by Hastie and Taylor he was able to give a method to find plasma equilibria in arbitrary geometries and to give stability criteria for high frequency oscillations in a collisionless plasma of arbitrary geometric configuration [163][164][149]. A collaboration was initiated with C. Oberman, Princeton who visited Innsbruck and who invited G. Auer for a year (Sept. 73 - Aug 74) to Princeton.

9. Experimental plasma physics.

Having been 1967 half year guest Professor for plasma physics at the City University in New York, Prof. Jen from City gave us the privilege to come in exchange to Innsbruck in 1969 This guest - professorship was the starting point for our experimental programme [165]. We built a Q-machine and started to understand and to handle the machine. Many basic parameters of the machine and their interdependence were measured [166]. Details of the Innsbruck Q-machine are described in [167]. During all this time the advice of Professors Varney and Kunkel who stayed both as guest professors in Innsbruck (1971/72 resp. 1972/73) were very useful. From this month, September 1973 we appreciate the collaboration of P. Sugai from Japan, who worked there on a Q-machine. Our programme at present comprises the heating of plasmas by kHz modulated carrierwaves of MHz to produce harmonically varying temperature in the plasma and to test linear and nonlinear parametric temperature effects. The experiments are in due course.

Other experiments were made on a hollow cathode which exhibited strange oscillations [168][169].

1o. Space Plasmas.

In 1971, the author had the privilege to be senior research associate at the Goddard Space FlightCenter of NASA in Greenbelt, Maryland. He was there for 1o months associated with the theory division under Dr. Ted Northrop.
At the end of 1971 the Austrian Academy of Sciences decided to create an Institute for Space Research. This Institutes received also a department for Space Plasma Physics which was situated in Innsbruck.

The first space plasma contribtion from Innsbruck was a plasma theory of lunar magnetic fields [17o][171]. Then a series of papers by P. Shukla, guest from India for half a year on plasma waves in natural plasmas followed [172][173]. Also the instability of longitudinal waves in a collisional natural magneto plasma was investigated by him [174][175].

In this year E. Märk started a research on the increase of th eprecipitation of radiation belt particles by increa-sing the density of the cold plasma. It is well known that O. Brien and Brice had suggested such experiments and it is known that the Williamson proton in nature actually do, but the Barium release experiments do not increase the particle precitipation. It was shown the precitipation condition is very sensitive from the ion mass of the plasma released [176]. According to Dr. Pease, Culham this work is of interest for mirror machines since this effect might allow to control the ion cyclotron instability - and the mirror instability.

The last problem under consideration just how is a new mo-del for the magnetosphere. If one assumes a certain direc-tional distribution of the particles coming from the Sun in the solar wind, then the magnetospheric boundary is

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distorted. It seems that some observations are in better agreement with the new theory than the theory by Beard, Mead and others [177].

11. Present staff.
(October 1973)

a. MHD - channel problems and power generation:

Kuhn, Ramberger, J. C. Taylor (Glasgow) [2 months].
Collaboration with Garching, Jülich (Bohn), Glasgow (Laing, Taylor), London (Haines, Imperial College), Blankenhorn (Jülich), (on leave).

b. Similarity transformations:

Floriani, Rosenau (?), Cap.

c. Instabilities:

Auer (on leave in Princeton), Herrnegger (on leave in Garching), Kuhn, Cap, Sellmeier, Holzmann, Gardner (Bangor), Mrs. Gardner.
(Collaboration with Bangor - Boyd); possibly collaboration Culham.

d. Q Machine:

E. Maerk, Mravlag, Sugai (Collaboration Japan). Possibly Collaboration with Culham (Hamberger).

e. Echoes:

Lerch, S. Kuhn, Collaboration with Berlin and possibly Prague.

f. Space Plasma Physics:

M. Leubner, Stoessel, Cap, Collaboration Goddard Space Flight Center (T. Northrop hopefully 1974 here).

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3	Pressure Hill	July 1963
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7	Twodimensional potential flow	Feb. 1964
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9	Unsteady MGD flow	April 1964
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16	Conference Report Berlin, Paris MHD	Nov.	1964
17	see [65] Interaction	Oct.	1964
18	see [114] Numerical formulation	Dec.	1964
19	Variational method (steady)	Sept.	1964
20	Conference Report Karlsruhe	Oct.	1964
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22	see [113] Finite conductivity	Dec.	1964
23	see [115] Dispersion relation	March	1965
24	see [79] Finite conductivity	March	1965
25	see [7o] Small Reynolds	Feb.	1965
26	Conference Report Plasma USA	May	1965
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32	Variational method (unsteady)	March	1966
33	see [68] Numerical treatment	June	1966
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35	Conference Report Plasma Kiel	May	1966
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61	see [163] Equilibria arbitrary geometries	Feb. 1969
62	see [123] General algorithm	Jan. 1969
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64	see [134] Local potential	April 197o
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