Summary of Reports
presented to Section
Magnetic Confinement Theory and Modelling (TH)
(Main ideas and achievements)

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Distribution of Reports

- Total numbers of TH Reports 128

- The distribution of Reports between different areas:
  - 1. Transport, Gyrokinetics, Turbulence 54
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Transport, Gyrokinetics, Turbulence

- Quasi-linear fluid models;
- Plasma heating;
- Momentum transport;
- Transport Barriers;
- Non-local transport;
- Transport based on variation problems.
- Impurity transport;
- Turbulence;
- Fresh ideas.
Quasi-linear fluid models
Verification of Quasi-linear models.

Testing the Trapped Gyro-Landau Fluid Transport Model with Data from Tokamaks and Spherical Tori (1087,10)
G.M. Staebler, G. Colyer, S. Kaye, J.E. Kinsey, and R.E. Waltz

A new quasilinear transport code TGLF (Trapped Gyro-Landau Fluid) is created. This is a development of very known code GLF23.

Effective energy diffusivities predicted by TGLF for an L-mode (a) and H-mode (b) discharges in the DIII-D tokamak.

Verification of code.

The unresolved problem so far is the description of plasma periphery at $\rho>0.8$. 
Verification of Quasi-linear models.

Validity of Quasilinear Transport Model.
C. Bourdelle, A. Casati, X. Garbet, F. Imbeaux, J. Candy, F. Clairet, G. Dif-Pradalier, G. Falchetto, T. Gerbaud, V. Gfandgirard, P. Hennequin, R. Sabot, Y. Sarazin, L. Vermjare, R. Waltz (869)

Verification of a new quasilinear code QuaLiKiz by nonlinear Gyrokinetic code GYRO using ITG and TEM turbulence.

Quasi-Linear fluxes are compared with fluxes calculated by GYRO code.

Quasi-linear fluxes
red: ion heat flux,
blue: electron heat flux,
green: particle flux,
normalized to one single nonlinear ion heat flux versus Ti/Te.
Foundation of quasi-linear models.

Gyrokinetic turbulence simulation of physics basis for transport modeling

(1077)

Gyrokinetic turbulence simulations with GTC code were provided to verify the validity of quasilinear theory (QLT)

Conclusions:

• For ETG turbulence.
The quasilinear calculation of the electron heat conductivity using measured spectra agrees well with the simulation value.

• For ITG turbulence.
Both the particle transport and the electron thermal transport are much smaller than the ion thermal transport.

• For CTEM turbulence.
The applicability of quasilinear methods is somewhat problematic.
Combination of Gyrokinetic and quasi-linear codes.

Validation of Gyrokinetic Transport Simulations Using DIII-D Core Turbulence Measurements (1065)

Using the new **TGYRO transport** code, which adjusts local plasma scale lengths **within a GYRO** simulation at each time step the **temperature** profiles is possible to compare.

\[ T_i(\rho) \quad T_e(\rho) \]

Plasma radius

![Graphs showing temperature profiles](image)
Long time gyrokinetic calculations.

Conservative Global Gyrokinetic Toroidal Full-$f$ 5D Vlasov Simulation (933.6)
Y. Idomura, S. Tokuda, N. Aiba, and H. Urano

ITG driven turbulence simulations are performed using a global gyrokinetic full-$f$ Vlasov code GT5D.

- The profile evolutions are traced over an ion collision time.
- The turbulent transport due to quasi-periodic avalanches is dominant.
- The profiles show stiffness with increasing input power.

For JT-60U $\tau_{ii} \sim 20$ ms, so the avalanches period is 0.2 ms
Turbulence

Multi-Scale, Multi-Mode Gyrokinetic Simulations and Implications for Transport Modelling of Tokamaks and Optimized Stellarators

F. Jenko, S. Brunner, T. Dannert, T. Goerler, M. Kammerer, X. Lapillonne, F. Merz, M.J. Pueschel, D. Told, P. Xanthopoulos

- Authors developed gyrokinetic GENE-code.
- Nonlinear gyrokinetic simulations of microturbulence simultaneously driven by ETG, TEM and ITG modes are presented.

There is better agreement between simulations and experiments in this case.
Momentum transport
Physics of Non-Diffusive Turbulent Transport of Momentum and the Origins of Spontaneous Rotation in Tokamaks (1053,15)

It is shown that the flux of toroidal momentum $U_\varphi$ takes the generic form

\[ \pi_{r,\varphi} = -\chi_\varphi \frac{dU_\varphi}{dr} + V_{\text{pinch}} U_\varphi + \pi_{\text{resid}} \]

$\pi_{\text{resid}}$ is driven by $\nabla P_i$ and saturates at increasing $\nabla P_i$. 
Momentum Transport. The origin of spontaneous momentum.

**An Intrinsic Angular Momentum Source in Tokamaks.** (1039,16)
A.Y. Aydemir.

The intrinsic angular momentum source arises when the up-down symmetry is removed.
Calculations with code CTD show very good qualitative agreement with “transport-driven” flows measured on tokamak C-Mod.

**Toroidal Rotation in Tokamak Plasma.** (1043,17)
J.D. Callen, A.J. Cole, C.C. Hegna

The influence of toroidal non-axisymmetry effects on plasma rotation is researched.
Such an effect can excite the intrinsic rotation also.
The origin of spontaneous momentum.

Self-consistent Simulation of Torque Generation by Radial Current due to Fast Particles
M. Honda, T. Takizuka, *A. Fukuyama, M. Yoshida and T. Ozeki

- Toroidal rotation induced by charge separation at the NBI.
Momentum pinch

**Gyro-Kinetic Study of Toroidal Momentum Transport** (1035)
A.G. Peeters, C. Angioni, D. Strintzi, Y. Camenen, F. Casson, W. Hornsby, A. Snodin

The calculations are performed with the *gyro kinetic code GKW* and used flux tube geometry.

The diffusive part of momentum transport $\chi_\theta$ is investigated. **It is found that the Prandtl number Pr is limited**

\[
\text{Pr} = \frac{\chi_\theta}{\chi_i} = 0.7 - 1.2
\]

Here $v_\theta$ is the momentum pinch velocity. It is negative i.e. directed inward.
Momentum Transport (modelling).

**Integrated Modelling Simulations of Toroidal Momentum Transport in Tokamaks.** (1041,18)

G. BATEMAN, F.D. HALPERN, A.H. KRITZ, A.Y. PANKIN, T. RAFIQ
R.V. BUDNY, D.C. McCUNE, J. KINSEY, I. VOITSEKHOVITCH, J. WEILAND

The **quasilinear transport code GLF23 together with code PEDESTAL** are used for simulation including momentum transport.

Electron temperature and toroidal rotational frequency profiles from GLF23 simulation of JET discharge 52014 compared with experimental data.
Other transport problems
Transport due to Electromagnetic Turbulence in Externally Heated Plasma (937).
A. Ishizawa and N. Nakajima

Turbulent transport is investigated by a reduced set of two-fluid 3D equations.

The fast turbulent thermal diffusion by a strong external heating is found.

- (a) The steepening of ion temperature profile $T_i$ by an additional heating.
- (b) The thermal diffusivity coefficient increases.
The dynamic evolution of the plasma edge region is found by self-consistent simulations with XGC0 code.

Simulation of DIII-D discharge 113317. Radial profiles

The shear of toroidal velocity leads to the appearance of temperature pedestal
Non-local transport (fresh idea)
Non-local Models of Perturbative Transport: Numerical Results and Application to JET Experiments (1051,32).
D.del-Castillo-Negrete 1, P.Mantica 2, V.Naulin 3, J.J. Rasmussen 3 and JET EFDA contributors #

The heat flux here is defined by the fractional-diffusion operator:
\[ q_{ai} = -\chi n [ l_a \overset{\alpha}{D}^{a-1} - r_x \overset{\alpha}{D}^{b-1} ] T \]

where \( l_a \overset{\alpha}{D}^{a-1} \) and \( r_x \overset{\alpha}{D}^{b-1} \) are integro-differential operators defined as
\[ l_a \overset{\alpha}{D}^{a-1} T = \frac{\partial}{\partial y} \int_x^y T(y,t) \frac{(x-y)^{\alpha-1}}{(x-y)^{\alpha-1}} dy \]
\[ r_x \overset{\alpha}{D}^{b-1} T = -\frac{\partial}{\partial y} \int_x^y T(y,t) \frac{(y-x)^{\alpha-1}}{(y-x)^{\alpha-1}} dy \]

At \( \alpha \to 1 \) this operator is close to convection, at \( \alpha \to 2 \) it is close to diffusion.

This is an example of cold pulse propagation with \( x=0.75 \) denoting the initial location of the cold pulse and \( \alpha = 1.25, 1.75, 1.99 \)

But several new parameters are amended

Plasma core

Periphery

Time-scale = 5 ms
Transport based on variation principles

**Canonical Profiles Transport Model for H-mode Shots in Tokamaks**


The Canonical Profiles Transport Model (CPTM), which includes both the heat and particle transport equations, is used to simulate core and pedestal plasma for JET, and MAST ELMy and ELM-free H-mode shots.

![Graph showing RMS deviations of calculated profiles from experimental ones for 10 JET ELMy H-mode shots.](image)

RMS deviations of calculated profiles from experimental ones for 10 JET ELMy H-mode shots.

There is no equation so far for momentum transport
Impurity diffusion.

Gyrokinetic simulations of impurity, He ash and alfa-particle transport and consequences on ITER transport modeling (881).
C. Angioni, A.G. Peeters, G.V. Pereverzev, J. Candy, R. Dux, E. Fable, T. Hein, R.E.Waltz

The gyrokinetic simulations of the impurity diffusion and convection is carried out.
It is shown that the peaking of Helium density profile increases at low concentration.

(a) He profiles ;
(b) peaking of the He profile as a function of the total He concentration.

Very interesting result !!!
Comparison with experiment.

Full f Gyrokinetic Simulation of Tokamak Plasma Turbulence Using ELMFIRE (865)

- A global gyrokinetic full f particle-in-cell code ELMFIRE is used for transport simulation in tokamaks.

Comparison of calculated poloidal velocity with FT2 experiment (St. Petersburg)

Fig 1. The simulated $E_r \times B$ velocity and total poloidal velocity of fluctuations in FT-2.

Red line is the poloidal velocity measured by reflectometry, blue line is the result of calculations.
In contrast to typical gyrokinetic treatments, **canonical angular momentum** is taken as the **gyrokinetic radial variable** rather than the radial guiding center location.

Such an approach allows strong radial plasma gradients to be treated.
Waves and Instabilities

- Magnetic islands;
- ELMs and RMP;
- Sawteeth;
- RWM;
- Plasma heating by EC waves.
Magnetic Islands.

The Interaction between Transport and Reconnection Processes
(1037,14)
H.R. Wilson(1), D.J. Applegate(2), J.W. Connor(2) and M. James(2,3)

The main point is the impact of transport on the island evolution.

The distribution function in the vicinity of the island separatrix was evaluated. It allows to find the impact of the cross-field transport on the polarization current (right part in the P. Rutherford equation)

2-D colour contour plots of the density (a) and electrostatic potential (b) in the vicinity of the separatrix ($\chi=1$).
ELMs mitigation by RMP
Physics of Penetration of Resonant Magnetic Perturbations Used for Type I Edge Localized Modes Suppression in Tokamaks.\textsuperscript{(867,26)}.
M. Becoulet, G. Huysmans, X. Garbet, E. Nardon, M. Schaffer, A. Garofalo, T. Evans, A. Cole, P. Cahyna

The non-linear cylindrical reduced MHD code is used to describe the penetration of Resonant Magnetic Perturbations (RMP).
The influence of plasma rotation is taken into account.

Conclusions:
- The shielding of the RMP is larger for stronger rotation.
- But the plasma rotation is braking by the RMP and even can be stopped.
- Periphery density transport rises with the RMP.
ELMs mitigation by RMP
MHD Simulation of Resonant Magnetic Perturbations and ELMs
(1089,27).

The calculations were provided with the M3D code.

Plasma isoterms

DIII-D plasma with and without applied RMP and toroidal rotation.
(a) Temperature in the non-rotating RMP case.
(b) Temperature in the rotating case with RMP.
ELMs
Integrated Simulation of ELM Energy Loss and Cycle in Improved H-mode Plasmas

N. Hayashi, T. Takizuka, N. Aiba, N. Oyama, T. Ozeki, V. Parail and S. Wiesen

- Stability code MARG2D for peeling-ballooning modes.
- Transport model of SOL and divertor plasma.

Energy storage

![Diagram of profiles](image)

**Fig 1.** Profiles of
(a) electron temperature just before and after an ELM and
(b) heat diffusivity during ELM.

**Fig. 2.** Time evolution of stored energy $W_s$ for net input powers of $P_{in} = 9, 12, 15$ MW for JT-60U parameters.
Sawtooth Control
The Physics of Sawtooth Stabilisation in Tokamak Plasmas


- Sawtooth period can be shortened by applying off-axis NBI

- Explained by destabilising contribution from passing fast ions born outside $q=1$
Resistive Wall Modes (RWM)

Modelling Resistive Wall Modes with Self-consistent Inclusion of Drift Kinetic Resonances
Yueqiang Liu, M.S. Chu, I.T. Chapman, T.C. Hender

- The kinetic terms are included self-consistently in the MHD equations.

\( \delta W \) (potential energy variation)

\( r_w/a \) (\( r_w \) is the wall radius)

Red (solid) – no wall;
Red (dashed) – ideal wall;
Blue (solid) – kinetically modified RWM

If the wall approaches plasma the instability can appear.
The 3D code STELEC for waves is developed. This is the example for FT-2 tokamak modelling: O-mode, the fundamental EC wave. In toroidal plasma the O- and X-modes are coupled.

The waves are absorbed before they come to cyclotron resonance!!!
SOL and divertor

1. Impurity and Helium transport.
2. Upper and lower x-points.
Impurity transport in SOL

Kinetic Modelling of Impurity Transport in Detached Plasma for Integrated Divertor Simulation with SONIC (SOLDOR/NEUT2D/IMPMC/EDDY) (953.30).

The Monte-Carlo impurity code IMPMC connected with divertor code SOLDOR/NEUT2D were used for modeling. The kinetic effects improve the helium compression by a factor of 2 - 6, compared with the conventional (fluid) evaluation.

He\textsuperscript{2+} density profile in the flux tube close to the separatrix surface.
Two-dimensional Full Particle Simulation of the Flow Patterns in the Scrape-off-layer Plasma for Upper- and Lower- Null Point Divertor Configurations in Tokamaks (957)
T. Takizuka, K. Shimizu, N. Hayashi, M. Hosokawa and M. Yagi

• A two-dimensional full particle simulation code PARASOL is applied to study the SOL.

• Fig. 2. Radial profiles of parallel velocity $V//\text{ in the SOL for Upper Null (UN) configuration (dashed green line) and Lower Null (LN) configuration (solid red line).}$
The direction of toroidal drift is fixed.
ITER and reactors
ITER, operation window.

Operation Window with Mutually Consistent Core-SOL-Divertor Conditions in ELMy H-Mode: Prospects for Long Pulse Operation in ITER and DEMO (851,25)

G.W. Pacher1, H.D. Pacher2, G. Janeschitz3, A.S. Kukushkin4

Operating space for ITER in ELMy H-mode at 15 MA plotted in the Q-P-alpha plane.
Stellarators and other helical configurations

- Role of neoclassical transport.
- Turbulent transport.
- Self-consistency of pressure profiles.
The goal.
- The goal is to provide a comprehensive description of neoclassical transport processes in stellarator experiments.

The methods:
- Benchmarking of various numerical methods used to calculate mono-energetic neoclassical transport coefficients in 3D magnetic field topology with multiple classes of trapped particles.

The results:
- All devices exhibit radial transport in the long-meanfree-path ($l_{mfp}$) regime which scales $1/\nu$ with the collision frequency.
- This $1/\nu$ transport can be partially suppressed by the radial electric field $E_r$.
- For the radial transport of particles and heat the effects of momentum conservation are entirely negligible.
Turbulent transport.

Regulation of Turbulent Transport in Neoclassically Optimized Helical Configurations with Radial Electric Fields (967,23).
T.-H.Watanabe, H.Sugama, and S. Ferrando-Margalet

- **Gyrokinetic Vlasov** simulations are performed by using the GKV code.
- The simulation result obtained for the inward-shifted configuration of the LHD manifests generation of large-amplitude stationary zonal-flow structures leading to significant turbulent-transport reduction.
- This provides a **possible explanation** to the confinement improvement observed in the LHD experiments of inward plasma shift.

- **Fig.1. Time history of the ion heat conductivity** $\chi_i$ for the inward shifted (solid) and standard (dashed) LHD configurations.
Self-consistency of pressure profiles.

Approach to Canonical Pressure Profiles in Stellarators (987,24)
Yu.N. Dnестровский, A.V. Melnikov, L.G. Eliseev, S.E. Lysenko, V.D. Pustovitov,
A.Fujisawa, T. Minami and J.H. Harris

- The plasma pressure $P_e$, presents strong profile resilience in the confinement zone of the plasma column in TJ-II (Figure 1).

Fig. 1

To describe the pressure self-consistency the authors use the variation problem to minimize the energy functional $W$ under the constraint the total plasma current $J$ is a constant.

- In the cylinder low $\beta$ approximation the canonical pressure profile is:

$$p_c(\xi) = p_0 \exp\left\{-2\left[\ln\left(\frac{p_0}{p_b}\right)/(1 + \frac{\mu_b}{\mu_0})\right]\xi^2 [1 + (\frac{\mu_b}{\mu_0} - 1)\xi^2 / 2]\right\}$$

- Here $\xi = \rho/a$, $\mu$ is the rotational transform, $p$ is the pressure.
Fast particles
Gyrokinetic simulation of energetic particle turbulence using GTC and GYRO is carried out.

- It is shown that the energetic particle transport induced by the microturbulence decreases rapidly with the energy rise.

- Fig. 1. Diffusivity driven by the microturbulence as a function of the energy for isotropic, monoenergetic particles.
Conclusions (1)

• 1. In this Conference the most attention was attracted to the research of transport processes. The characteristic point is the higher interest to the toroidal momentum transport.

• 2. The gyro-kinetic codes are extended over the world. The number of codes reaches several tenth. Both the development of computers and elaboration of the improved difference schemes are going simultaneously. The achieved time interval for plasma simulations reaches now the times comparable with ion-ion collision time. But the real perspective to describe transport in ITER is the combining of gyro-kinetic and fluid codes.

• 3. Theoretical analysis and calculations show that the Resonant Magnetic Perturbations (RMPs) can brake the plasma rotation increasing the danger of disruption.
Conclusions (2)

• 4. The problems of SOL and divertor attract the larger number of theoreticians. The unsolved problem of energy extraction from reactor plasma forced the scientists both to improve the understanding of periphery plasma processes and to suggest new ideas.

• 5. ITER and reactor problems are in the centre of attention as before. To-day calculations confirm that ITER can have $Q = 10$ or larger.

• 6. Some Reports confirm that the neoclassical transport dominates in the stellarator. But the influence of turbulent transport can define such important effects as improved confinement regimes and the resilience of pressure profiles.

• 7. It is shown that the alfa-particles diffusion will be small in ITER.
8. International collaboration in plasma theory and modelling is high.

- Formal distribution of TH Section Reports between countries.
  - USA 30
  - Japan 25
  - Germany 10
  - Russian Federation 10
  - France 7
  - Italy 6
  - UK 5
  - China 4
  - Republic of Korea 4
  - Others 37
  - Total numbers of Reports 128

- Total number of countries: 26

- But really 70 Reports were presented by international teams which include peoples from different countries.

- So the international collaboration coefficient equals to
  \[ C_{ic} = \frac{70}{128} = 0.55 \] (!!!!) that is larger than one half.
Thank you for attention