Magnetohydrodynamics (MHD) II

Yong-Su Na
National Fusion Research Center

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1. What is confinement? Why is single particle motion approach required?

2. Fluid description of plasma – Fluid equations

3. Single fluid equation – 7 MHD equations

4. MHD equilibrium
   - Concept of beta
   - Equilibrium in the z-Pinch
   - Equilibrium in the tokamak – GS equation
• The single particle approach gets to be complicated.

• A more statistical approach can be used because we cannot follow each particle separately.

• Now introduce the concept of an electrically charged current-carrying fluid.

→ Magnetohydrodynamic (magnetic fluid dynamic) equations
The set of MHD Equations

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \]

\[ \frac{\partial \sigma}{\partial t} + \nabla \cdot j = 0 \]

\[ \rho \left( \frac{\partial u}{\partial t} + u \cdot \nabla u \right) = \sigma E + j \times B - \nabla p \]

\[ E + u \times B = \eta j \]  \text{Simple Ohm's law}

\[ \nabla \times B = \mu_0 j \]

\[ \nabla \times E = -\frac{\partial B}{\partial t} \]

\[ \nabla \cdot B = 0 \]
Plasma Equilibrium and Concept of Beta

\[ \nabla p = \vec{j} \times \vec{B} \]
\[ \nabla \times \vec{B} = \mu_0 \vec{j} \]
\[ \nabla \cdot \vec{B} = 0 \]

→ Force balance
→ Ampere’s law
→ Closed magnetic field lines

\[ \beta = 2\mu_0 p / B^2 \]

- The ratio of the plasma pressure to the magnetic field pressure
- A measure of the degree to which the magnetic field is holding a non-uniform plasma in equilibrium
Equilibrium in a Tokamak

- \( \nabla p = \vec{j} \times \vec{B} \Rightarrow \nabla p \cdot \vec{j} = \nabla p \cdot \vec{B} = 0 \):

  \( j \) and \( B \) lie in the surfaces \( p=\text{const.} \).

\[ -\Delta^* \psi = R \frac{\partial}{\partial R} \left( \frac{1}{R} \frac{\partial \psi}{\partial R} \right) + \frac{\partial^2 \psi}{\partial Z^2} = \mu_0 (2\pi R)^2 p' + \mu_0^2 I_{pol} I'_{pol} \]

Grad-Shafranov equation (GS-eqn)
Equilibrium in a Tokamak

Visible light image of START plasma

Magnetic reconstruction

Strike point
X-point
Closed flux surfaces
‘Core Plasma’
Separatrix
Scrape-off layer
Divertor region

Magnetic reconstruction
Shape Control in KSTAR

- All iso-flux points are outward-shifted by 3cm through iso-flux shape control.
1. What is Stability?

2. MHD Instability
   - Interchange Mode
   - Flux Tube Instabilities

3. Formulation of MHD Instabilities

4. Classification of MHD Instabilities

5. MHD Instabilities in a Tokamak

6. Microinstability
1. What is Stability?

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Stability

Equilibrium...

Is it stable??
Stability
Stability

http://blog.naver.com/wafercalla

가벼워서 흔히는 눈물보다 돌파서 흔히는 눈물이 더 많이칠 때.
Concept of instability

The fact that one can find an equilibrium does not guarantee that it is stable. Ball on hill analogies:

- Stable
- Linear unstable
- Metastable
- Non-linear unstable

Generation of instability is the general way of redistributing energy which was accumulated in a non-equilibrium state.
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A static MHD equilibrium (plasma fluid velocity \( u=0 \), hence electric field \( E=0 \)) occurs when the plasma pressure gradients are balanced by magnetic \( (j \times B) \) forces.

However, even if a MHD equilibrium exists in some particular case, the lack of plasma stability can lead to the spontaneous generation of \( E \) fields and associated plasma velocities \( u \).

For if the plasma is disturbed slightly, its motion can deform the magnetic field in such a way as to produce magnetic forces that tend to amplify the original disturbance.

→ MHD instability
It is the instability of a plasma boundary under the influence of a gravitational field. It is called Rayleigh-Taylor or gravitational instability. If the attractive gravitation is replaced by the centrifugal force, the instability is called flute instability.

• Consider a heavy plasma supported against gravity, \( \mathbf{g} = -g \mathbf{e}_z \), by a magnetic field, \( \mathbf{B}_0 = B_0 \mathbf{e}_x \), while the density gradient with scale \( L_n \) points upward, \( \nabla n_0 = \partial n_0(z)/\partial z \mathbf{e}_z \), and \( \mathbf{g} \cdot \nabla n_0 < 0 \).
Consider a distortion of the boundary so the plasma density makes a sinusoidal excursion.

The gravitational field causes an ion drift and current in the negative y direction, \( v_{iy} = -\frac{mg}{eB_0} \), in which electrons do not participate.

Charge separation electric field \( \delta E_y \) evolves. Opposing drifts amplify the original distortions. The bubbles develop similar distortions on even smaller scales.
Flux Tube Instabilities

- Stability against small perturbation in z-Pinch?
Flux Tube Instabilities

• Stability against small perturbation in z-Pinch?

Pinch -(`Sausage`-) Instability

- A small perturbation induces a force tending to increase itself.
- Can be stabilised by addition of $B_z$

\[ F = -\mu \nabla B \]
Then how to analyse the stability?
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• Solve time-dependent MHD equations for a linearised eigenmode ansatz. All quantities (densities, pressure, fields and so on) would have the form,

\[ f = f_0(y) + f_1(y)\exp(iky-iwt) : \text{wave-like perturbations} \]

\[ \exp(-iwt) = \exp(-iw_r t)\exp(w_it), \quad w = w_r + iw_i \]

• Find dispersion relation \((w = w(k))\),

\(w_i < 0\): stable
- oscillative damping \((w_r \neq 0)\)
- aperiodic damping \((w_r = 0)\)
\(w_i > 0\): unstable
- overstability \((w_r \neq 0)\)
- aperiodic growing \((w_r = 0)\)
\(w_i = 0\): marginally (neutrally) stable
The Energy Principle

• Calculate total energy of configuration as functional of $\xi$

$$W(\{\xi\}) = W_0 + \delta W_1 + \delta W_2 + \ldots$$

• Equilibrium condition: $\delta W_1 = 0$; stability requires $\delta W_2 > 0$
  for arbitrary $\xi$.

• If a $\xi$ with $\delta W_2 < 0$ is found, system is unstable.

  Instability easier to prove than stability!

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Classification of Instabilities

✓ With respect to drive.....

• Two sources of free energy available:
  - Magnetic energy associated with poloidal field
  - Kinetic energy of hot plasma

current driven instabilities
  (kink mode)

pressure driven instabilities
  (interchange mode)
Classification of Instabilities

- ....and with respect to topology

- Perturbed magnetic field $B_{1r}$ grows according to Ohm’s law:

\[
\frac{\partial B_{1r}}{\partial t} \begin{array}{c}
= \frac{1}{r} \frac{\partial}{\partial \theta} \frac{\partial E_{1z}}{\partial r} = \frac{1}{r} \frac{\partial}{\partial \theta} (\eta j_{1z} + (\vec{v}_1 \times \vec{B}_0)_z)
\end{array}
\]
Classification of Instabilities

✓ ....and with respect to topology

• Perturbed magnetic field $B_{1r}$ grows according to Ohm‘s law:

- Ideal MHD: $\eta = 0$
  - flux conservation
  - deformation of flux surfaces
  - topology unchanged
  - „kink“, „ballooning“

- Resistive MHD: $\eta \neq 0$
  - reconnection of field lines
  - change of magnetic topology
  - Islands
  - „tearing (resistive kink) modes“
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Our aim is to maximise the fusion power at given magnetic field:

\[ P_{\text{fus}} \propto (nT)^2 \propto \beta^2 B^4 \],

where \( \beta = \frac{p}{(B^2/(2\mu_0))} \)

Macro-instabilities - pose upper limits to pressure/current gradients
- can deform or destroy magnetic surfaces
- transport, (non-) disruptive
• Pressure flattening across magnetic islands due to large transport coefficients along magnetic field lines
Description of a Tokamak

• Proper quantities to describe the tokamak:

  poloidal quantities
  $B_\theta, j_\theta \rightarrow B_p, j_p$
  $B_z, j_z \rightarrow B_\phi, j_\phi$

  toroidal quantities

  tokamak axisymmetric, (independent of toroidal co-ordinate)
Safety Factor

- Tokamak characterised by aspect ratio $A = R / a$ and safety factor $q$ of a fieldline on the torus.

\[
q = \frac{\text{number of toroidal windings}}{\text{number of poloidal windings}}
\]

- In cylindrical approximation (screw-pincho): $q = \frac{r B_t}{R B_p}$
MHD Instabilities in a Tokamak
• Solve time dependent MHD equations for a linearised eigenmode ansatz, e.g. 
\[ \xi = \xi_0 e^{i(m\theta+n\phi)} e^{\gamma t} \]
(poloidal and toroidal modenumbers \(m\) and \(n\), growth rate \(\gamma\))

• For rational \(q_{res} = m/n\), flux surfaces especially susceptible for instabilities \(\Rightarrow\) standing waves on `resonant surfaces`
MHD Instabilities impact tokamak discharges

- $I_p$ (MA)
- $P_{NBI}$ (MW)
- $\beta_N$
- $H_{98}(\gamma,2)$
- $<n_e>in_{GW}$

Time (s): $0$ to $8$
MHD Instabilities impact tokamak discharges

- Desaster
- $\beta$-limit, disruption
MHD Instabilities impact tokamak discharges

- Desaster
- $\beta$-limit, disruption

- Self-organisation
- Stationarity of profiles $j(r), p(r)$
ELMs (Edge Localised Modes)
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Micro Instabilities

- Free energy source: plasma inhomogeneity (pressure gradient) in B
NTM Stabilisation by ECCD
NTM Stabilisation by ECCD
The end

...of the talk
• From stability considerations (pinch): $q > 1$ required.

$q$ varies from $q(0)=1$ on axis to $q(a) = 3-5$ at boundary:
• From stability considerations (pinch): $q > 1$ required!

$q$ varies from $q(0) = 1$ on axis to $q(a) = 3-5$ at boundary:

\[
B_\phi > 3 - 5 \frac{R}{r} B_p \approx 10 B_p
\]
• From stability considerations (pinch): $q > 1$ required.

$q$ varies from $q(0)=1$ on axis to $q(a) = 3-5$ at boundary:

$$B_\phi > 3 - 5 \frac{R}{r} B_p \approx 10 B_p$$

• This requirement on $B_\phi$ has severe impact on economy:
• From stability considerations (pinch): \( q > 1 \) required!

\( q \) varies from \( q(0)=1 \) on axis to \( q(a) = 3-5 \) at boundary:

\[
B_\phi > 3 - 5 \frac{R}{r} B_p \approx 10 B_p
\]

• This requirement on \( B_\phi \) has severe impact on economy:

\[
\beta = \frac{2\mu_0 < p >}{B_{tot}^2} \approx \frac{2\mu_0 < p >}{B_t^2} \approx \frac{1}{100} \beta_p
\]
• From stability considerations (pinch): $q > 1$ required!

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• This requirement on $B_\phi$ has severe impact on economy:

$$\beta = \frac{2 \mu_0 < p >}{B_{tot}^2} \approx \frac{2 \mu_0 < p >}{B_t^2} \approx \frac{1}{100} \beta_p$$

The total $\beta$ is of the order of 1-10 %!
The Role of Plasma Instabilities in Tokamak Physics

- Theoretical approaches to plasma instabilities

- How do micro-instabilities and turbulence determine temperature and density profiles?

- Upper limits set by macro-instabilities

- Towards an “advanced” tokamak by turbulence suppression
Theoretical description of plasma instabilities

Relevant time scales:

$10^{-8}s$ $<<$ $10^{-5}s$ $<<$ $10^{-3}s$ $<<$ $0.1\ s$

Ion gyration            transit time            Collision time (ions)            Confinement time

(for a middle-sized tokamak) (for ASDEX upgrade)
Theoretical description of plasma instabilities

Start from kinetic equation:

\[
\frac{\partial f_\alpha}{\partial t} + v \cdot \nabla_r f_\alpha + \frac{q_\alpha}{m_\alpha} (E + v \times B) \nabla_v f_\alpha = \left( \frac{\partial f_\alpha}{\partial t} \right)_{\text{coll.}}
\]

distribution function \quad Electric field Lorentz force \quad Influence of collisions

**together with Maxwell’s equations**

- Assume charge neutrality: spatial scales large compared to Debye length

- Average over fast gyro-motion
Theoretical description of plasma instabilities

For: micro-instabilities in the plasma centre

- kinetic equations solved in phase space or by PIC codes
- Restricted geometry (flux tubes) as small scales to be resolved
Theoretical description of plasma instabilities

For: micro-instabilities at the edge and many Macro-instabilities

(two)- Fluid description possible (only lowest moments of kinetic equation)

\[
10^{-5}s \ll 10^{-3}s \ll 0.1s
\]

Ion transit time \hspace{1cm} Collision time (ions) \hspace{1cm} Confinement time

Although we deal with high temperature plasmas, on flux surfaces everything is close to thermodynamic equilibrium due to strong magnetic field!
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Anomalous transport due to turbulence

PLOT

⊥B within magn. surface

radial direction
To lowest order (homogeneous field):

- free motion along magnetic field lines
- gyration around magnetic field lines

Corrections (inhomogeneous field or forces $\perp$ to magnetic field):

$$v_D = \frac{\vec{F} \times \vec{B}}{q B^2}$$

$$v_D \approx 10^{-3} v_{th}$$
Particle Motion in Magnetic Field:

- Drift perpendicular to the field lines

Magnetic field in toroidal devices is inhomogeneous.
An example for a mode leading to turbulence:

**Toroidal ITG (Ion Temperature Gradient) Mode**

Drift due to inhomogeneous magnetic field is temperature dependent

\[
\vec{V}_d = \frac{v_{\parallel}^2 + v_{\perp}^2}{2} \frac{2}{\omega_c B} \vec{b} \times \nabla \vec{B}
\]

Initial temperature perturbation causes density perturbation

(90° phase shift)
An example for a mode leading to turbulence:

Toroidal ITG (Ion Temperature Gradient) Mode

\[ \vec{E} = -\frac{\nabla n_e}{e n_e} \]

Density perturbation causes potential perturbation

\[ \nabla B \]

Resulting \( E \times B \)-Drift enhances initial perturbation on LFS

\[ \vec{v}_E = -\frac{c}{\mathcal{B}^2} \mathcal{B} \times \vec{E} \]
Critical temperature gradient above which mode is strongly growing ($\sim e^{\gamma t}$)

$$\frac{1}{L_T} = \left| \frac{\nabla T}{T} \right| > \frac{1}{L_{T,cr}}$$

determines temperature profiles

$$\frac{d \ln T}{dr} = \frac{\nabla T}{T} = -\frac{1}{L_{T,cr}}$$

$$T(a) = T(b) \exp \left( \frac{b - a}{L_{T,cr}} \right)$$
“Stiff” temperature profile found in experiment: temperature at half radius proportional to edge temperature.

Simulation results reproduce measured temperatures.
Turbulence suppression at the plasma edge

One reason:

Losses of fast ions at the plasma edge
- sheared radial electric field
- sheared ExB rotation
- eddies get tilted and ripped apart
cause turbulence suppression
Turbulence suppression at the plasma edge leads to transport barrier
Central temperature determined by temperature just inside the transport barrier

Stiffness: $\nabla T / T = \text{const.}$

Pressure gradients inside the transport barrier
- limited by one fluid (MHD) instabilities
- can be influenced by plasma shaping
What about the density profile?

Experiment: peaked density profiles for low densities in spite of sources only at the edge

Theory explains how density peaking varies with collisionality
The Role of Plasma Instabilities in Tokamak Physics

- Theoretical approaches to plasma instabilities

- How do micro-instabilities and turbulence determine temperature and density profiles?

- Upper limits set by macro-instabilities

- Towards an “advanced” tokamak by turbulence suppression
Macro-instabilities pose upper limits on pressure/current gradients in the centre.

Finite resistivity allows magnetic reconnection.

An example: magnetic islands

Magnetic islands driven by helical perturbation current.
Magnetic islands influence temperature profile

- Preferentially on "resonant" surfaces: closed magnetic field lines
- Pressure flattening across magnetic islands due to large transport coefficients along magnetic field lines
Pressure gradient drives plasma current by thermo-electric effects (Bootstrap current):

\[ j_{BS} \propto \nabla p \]

Inside islands \( \nabla p \) and thus \( j_{BS} \) vanish

Loss of BS current inside magnetic islands acts as helical perturbation current driving the islands
Bootstrap driven islands pose $\beta$ limit in tokamaks

Experiments for very short times

Normalized plasma pressure limited to values well below ideal MHD limit
Active stabilisation of magnetic islands

Missing bootstrap current inside island can be replaced by localised external current drive.

Complete stabilisation in quantitative agreement with theory!
The Role of Plasma Instabilities in Tokamak Physics

• Theoretical approaches to plasma instabilities

• How do micro-instabilities and turbulence determine temperature and density profiles?

• Upper limits set by macro-instabilities

• Towards an “advanced” tokamak by turbulence suppression
Turbulence itself generates sheared plasma rotation which partly suppresses the turbulence.

Gyrokinetic Simulations of Plasma Microinstabilities

simulation by

Zhihong Lin et al.

Science 281, 1835 (1998)
Turbulence suppression most effective for non-monotonic current profiles.

Current profile corresponding to conductivity

Non-monotonic or flat current profile
Transport barriers due to suppressed turbulence

Conventional Tokamak

"Advanced Tokamak"

Internal Transport-Barrier (ITB)
Transport barriers due to suppressed turbulence

Conventional Tokamak

„Advanced Tokamak“

For non-monotonic or flat current profiles non-stiff profiles
ignition Temperature on ASDEX Upgrade!
Ignition temperatures in ASDEX Upgrade due to ITBs

 Tokamaks
 Stellarators

 T in Mio. Grad

 Ignition
 Break-even

 JT 60-U
 JT 60
 JET (DT)
 TFTR
 TFTR
 Alcator C-mod
 Tore Supra
 LHD
 ASDEX

 n·T·τ [m⁻³·keV·s]

 T 10
 W 7-AS
 Pulsator
 W 7-A
 T 3
 ASDEX

 Tokamaks
 Stellarators

 1                        10                      100            1000
Advanced Tokamaks: Steady state operation possible.

- Non-monotonic current profile
- Turbulence suppression
- High pressure gradients
- Large bootstrap current
Transition to turbulence suppressed state often needs some “help“:

- at the edge:
  e.g., sheared rotation due to fast ion losses

- in the centre:
  trigger due to sheared rotation provided by macroscopic instabilities

Shown instability:
- driven by resonance with fast (trapped) particles
- frequency slowing down due to expulsion of fast particles (resonance with most energetic particles)

Exp: temperature increases during frequency slowing down
Turbulence suppression triggered by macroscopic instabilities

Hypothesis:
• Expulsion of fast particles causes radial current in background plasma
• $\mathbf{j} \times \mathbf{B}$ force causes sheared plasma rotation
Radial current of fast particles across mode resonant surface leads to sheared plasma rotation sufficient to suppress turbulence
Conclusions:
Plasma instabilities determine energy and particle confinement

ITG turbulence leads to stiff temperature profile
\((\nabla T/T)\)

Turbulence suppression at the plasma edge, upper limit by MHD instability

For turbulence at the plasma edge see B.D. Scott, PIV

- Density peaking depends on collisionality (in agreement with theory)
Conclusions:
Plasma instabilities determine energy and particle confinement.

Conventional tokamak:
Magnetic islands can additionally limit confinement.

but active stabilisation possible.
Conclusions:
Plasma instabilities determine energy and particle confinement

**Advanced tokamak:**

- Internal transport barrier due to turbulence suppression for flat or non-monotonic current profiles

- Still basic research (only transient, low density)

**Aim:** Smaller and/or stationary tokamaks
Conclusions

Turbulence determines radial dependence of temperature (and thus heat insulation)

- most important ITG: leads to stiff temperature profile ($\nabla T/T$)

Turbulence can be suppressed

- at the edge (e.g., loss of fast ions)

- in the centre by non-monotonic current profiles, suppression can be supported by MHD instabilities
Conclusions

MHD instabilities pose upper limits to pressure (or current) gradients

• always if turbulence is suppressed by shear flow (edge, ITBs)

• most important pressure limit even with turbulent transport: magnetic islands, driven by pressure flattening across the islands

• active control of MHD instabilities possible
Outlook

Turbulence simulations still far away from global simulation of complete turbulence spectrum:

this is a challenge as:

- spatial scales: from \( \rho_e \) (close to \( \lambda_{\text{Debye}} = 10^{-5}...10^{-4}\text{m} \)) to minor radius (m)

Not shown here:
- drift waves
- ballooning modes
- adiabatic ITG modes
- adiabatic ETG modes
- trapped electron modes
Outlook

Turbulence simulations still far away from global simulation of complete turbulence spectrum:

this is a challenge as:
• spatial scales (from $\rho_e$ (close to $\lambda_{\text{Debye}}$) to minor radius)
• time scales from electron transition time ($10^{-6}$s) to confinement time (5s)

\[
\mu = \frac{m_e}{m_i} \left(\frac{L_\parallel}{2 \pi L_\perp}\right)^2
\]

see B.D. Scott, PIV
Large scale instabilities cannot always be described within a simple MHD picture:

- Fast particle driven modes (alpha particles!) require gyrokinetic description
- Physics of bootstrap driven tearing modes (for small islands)

and finally:

coupling between small- and large-scale modes
Simulation of the mode activity
Radial Current Causes Poloidal Plasma Rotation

Poloidal Plasma Rotation due to mode activity:

sufficient to suppress turbulence

S. Pinches, S. Günter, A. Peeters
Introduction: Why is anomalous transport so important?

3D fluid: conservation of energy

\[ E = \frac{1}{2} \int v^2 \, d^3x = \int_{0}^{\infty} E(k) \, dk \]

ensures cascading of perturbations to smaller scales (dissipation)
Magnetised plasma behaves very similar to a 2D fluid. For a 2D-fluid, the simultaneous conservation of energy and enstrophy is given by:

\[ H = \frac{1}{2} \int_0^\infty \omega^2 \, d^2x = \int k^2 \, E(k) \, dk \]

\[ \omega = \nabla \times \mathbf{v} \]

Where \( H \) represents the Helmholtz free energy. The energy spectrum \( E(k) \) has two cascades:
- **Direct cascade**: Drives large eddies.
- **Indirect cascade**: Drives small scale structures.

The diagram shows the energy spectrum \( E(k) \) with regions for large eddies, direct cascade, indirect cascade, drive, inertial range, and dissipation. The 2D fluid is characterized by cascading to large scales.
Pressure gradient at the edge determined by MHD instabilities

\[q = \frac{\Delta \Phi}{\Delta \theta}\]

\(q'\): shear of magnetic field lines

Low triangularity \((\delta = 0.25)\)

High triangularity \((\delta = 0.5)\)
Joint European Undertaking

\[ R = 2.95 \text{ m} \quad a = 1.25 \text{ m} \quad \kappa = 1.6 \]

\[ B_t \leq 3.5 \text{ T} \quad I_p \leq 7.0 \text{ MA} \quad P_H \leq 30 \text{ MW} \]

Start of operation in 1983

1997, Mark IIA Divertor
JET DT-Experiments

DT-Experiments only in
- JET
- TFTR, Princeton

with world records in JET:

\[ P_{\text{fusion}} = 16 \text{ MW} \]

\[ Q = 0.65 \]
Status of Fusion Research

- Todays tokamak plasmas are close to breakeven,
- The next step (ITER) will ignite or at least operate at high Q (∼10),
- and thereby prove the scientific and technological feasibility of fusion energy.
• International project: Europe, Japan, Russia, and the USA (before 1998).


- $R [m] = 6.2$
- $a [m] = 2.0$
- $k = 1.7$
- $d = 0.35$
- $I_p [MA] = 15.1$
- $B [T] = 5.3$
- $T_{puls} [s] = 400$
- $P_{fusion} [MW] = 400$
International collaborations are ongoing through ITPA.

ITPA SSO group is working on development and modelling of ITER advanced scenarios.
  ✓ Joining experiments
  ✓ Code benchmarking for heating & CD systems
  ✓ Code benchmarking for ITER scenarios

Exchange of manpower is under discussion between experiments to build a real-time profile control system.

Participation of the Korean party is encouraged.