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Two-dimensional transport modeling in tokamak plasmas

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Outline

- Background and Motivation
- Modeling of Two-dimensional Transport
- Present status of 2D Transport Code TASK/T2
- Summary

Background and motivation (1/2)

- **The core and peripheral plasmas are strongly coupled with each other in tokamaks**. The particle and heat fluxes from the core determine the behavior of the peripheral plasma, while the latter determines the edge density and temperature, boundary conditions of the core plasma.
- **The transport in the core and the peripheral regions have been analyzed separately until recently owing to the difference of modeling configurations**.
  - **In the core region of tokamaks**
    - By the use of flux-surface averaging, transport is **1D problem**.
    - A standard transport modeling is based on the **neoclassical transport theory** and **turbulent transport theory**
  - **In the peripheral region of tokamaks**
    - By the use of simplified transport models, transport is **2D problem**.
    - A standard transport modeling is based on the **Braginskii's equations** and **turbulent transport theory**

Background and motivation (2/2)

- **Integrated core-peripheral transport simulations by 1.5D core transport code and 2D peripheral transport code**
  - Quantities obtained by a core transport simulation lack poloidal dependence in the edge region.
  - In the case of H-mode plasmas, Braginskii's equations are not suitable in the edge region, since the plasma temperature becomes a few keV and the plasma becomes weakly collisional.
- **For more consistent core-peripheral transport simulation**
  - Two-dimensional transport modeling based on the neoclassical transport theory and turbulent transport theory applicable to both core and peripheral region are desirable.

We have formulated an axisymmetric two-dimensional transport model applicable to both the core and peripheral regions and are developing a two-dimensional transport code **TASK/T2.**

Assumptions and Coordinates

- **Assumptions**
  - **Two-dimensional MHD equilibrium**
    - Spacial variation of quantities are two-dimensional
  - **Relaxation processes much slower than the Alfvén time scale**
    - Time dependence of basis vector is negligible in the transport time scale
  - **Radial force balance in the transport time scale**
- **Coordinates**
  - **Magnetic surface coordinate (MSC)**: (ρ, χ, ζ)
    - **Axisymmetric magnetic field in MSC**: $\boldsymbol{B} = \boldsymbol{\nabla}\zeta \times \boldsymbol{\nabla}\psi + I\boldsymbol{\nabla}\zeta$
  - **Transport oriented coordinate (TOC)**: $(\rho, \|, \zeta)$

We employ **MSC** to express **spatial variations of quantities**
and **TOC** to express **components of vector quantities**
for compatibility with neoclassical (NC) transport and peripheral transport theory

- **Multi-fluid equations**

$$\begin{aligned}
\left.\frac{\partial n_a}{\partial t}\right|_{\boldsymbol{x}} &+ \boldsymbol{\nabla}\cdot\boldsymbol{\Gamma}_a = && && S_{na} \\
\left.\frac{\partial}{\partial t}(m_a n_a \boldsymbol{u}_a)\right|_{\boldsymbol{x}} &+ \boldsymbol{\nabla}\cdot\overleftrightarrow{P}_a = e_a n_a(\boldsymbol{E}+\boldsymbol{u}_a\times\boldsymbol{B}) + \boldsymbol{F}_a && && + \boldsymbol{S}_{ma} \\
\left.\frac{\partial}{\partial t}\left(\frac{3}{2}p_a + \frac{1}{2}m_a n_a u_a^2\right)\right|_{\boldsymbol{x}} &+ \boldsymbol{\nabla}\cdot\boldsymbol{Q}_a = e_a n_a \boldsymbol{E}\cdot\boldsymbol{u}_a && + (\boldsymbol{F}_a\cdot\boldsymbol{u}_a + Q_{\Delta a}) && + S_{pa} \\
\left.\frac{\partial \boldsymbol{Q}_a}{\partial t}\right|_{\boldsymbol{x}} &+ \boldsymbol{\nabla}\cdot\overleftrightarrow{R}_a = \boldsymbol{F}_{qa}^{\mathsf{Lor}} && + \boldsymbol{G}_a && + \boldsymbol{S}_{qa}
\end{aligned}$$

where $\boldsymbol{F}_{qa}^{\mathsf{Lor}}$ is the Energy weighted (EW) Lorentz force defined as

$$\boldsymbol{F}_{qa}^{\mathsf{Lor}} \equiv \frac{e_a}{m_a}\left[\left(\frac{5}{2}p_a\overleftrightarrow{I} + \overleftrightarrow{\pi}_a\right)\cdot\boldsymbol{E} + \boldsymbol{Q}_a\times\boldsymbol{B}\right]$$

- **Definition of higher moment quantities in each equation**
  - **Particle flux**: $\boldsymbol{\Gamma}_a \equiv n_a\boldsymbol{u}_a$
  - **Total stress tensor**: $\overleftrightarrow{P}_a \equiv m_a n_a \boldsymbol{u}_a\boldsymbol{u}_a + p_a\overleftrightarrow{I} + \overleftrightarrow{\pi}_a$
  - **Total heat flux**: $\boldsymbol{Q}_a \equiv \boldsymbol{q}_a + \frac{5}{2}p_a\boldsymbol{u}_a + \overleftrightarrow{\pi}_a\cdot\boldsymbol{u}_a + \frac{1}{2}m_a n_a u_a^2\boldsymbol{u}_a$
  - **EW total stress tensor**: $\overleftrightarrow{R}_a \equiv \frac{5}{2}\frac{T_a}{m_a}p_a\overleftrightarrow{I} + \overleftrightarrow{r}_a + \boldsymbol{Q}_a\boldsymbol{u}_a + \boldsymbol{u}_a\boldsymbol{Q}_a - \frac{3}{2}p_a\boldsymbol{u}_a\boldsymbol{u}_a$

- **Collision terms**
  - **Friction and Heat friction force**: $\begin{bmatrix} \boldsymbol{F}_a \\ \boldsymbol{H}_a \end{bmatrix} \equiv \sum_b \begin{bmatrix} l_{11}^{ab} & -l_{12}^{ab} \\ -l_{21}^{ab} & l_{22}^{ab} \end{bmatrix} \begin{bmatrix} \boldsymbol{u}_b \\ \dfrac{2\boldsymbol{q}_b}{5p_b} \end{bmatrix}$
  - **Energy equipartition**: $Q_{\Delta a} = \sum_b \frac{3}{2} n_a \frac{T_b - T_a}{\tau_{ab}}$
  - **EW friction force**: $\boldsymbol{G}_a \equiv \frac{T_a}{m_a}\left(\frac{5}{2}\boldsymbol{F}_a + \boldsymbol{H}_a\right)$
- **Viscosity tensors**: Only parallel viscosity tensors are taken into account
  - **Parallel viscosity and heat viscosity tensor**

$$\begin{bmatrix} \overleftrightarrow{\pi}_{\parallel a} \\ \overleftrightarrow{\theta}_{\parallel a} \end{bmatrix} \equiv -\frac{3}{2} \begin{bmatrix} \mu_{1a} \, \mu_{2a} \\ \mu_{2a} \, \mu_{3a} \end{bmatrix} \begin{bmatrix} w_{ua} \\ w_{qa} \end{bmatrix} \left(\boldsymbol{e}_\parallel \boldsymbol{e}_\parallel - \frac{1}{3} \overleftrightarrow{I} \right)$$

    - $w_{ua} \equiv 2\left(\nabla_\parallel u_{a\parallel} - \boldsymbol{u}_a \cdot \boldsymbol{\kappa}\right)$ and $w_{qa} \equiv 2\left[\nabla_\parallel \left(\frac{2q_{a\parallel}}{5p_a}\right) - \frac{2\boldsymbol{q}_a}{5p_a} \cdot \boldsymbol{\kappa}\right]$ are quantities related to rate-of-strain tensor, where $\boldsymbol{\kappa} \equiv \boldsymbol{e}_\parallel \cdot \boldsymbol{\nabla} \boldsymbol{e}_\parallel$ is magnetic curvature
  - **EW parallel viscosity tensor**: $\overleftrightarrow{r}_{a\parallel} \equiv \frac{T_a}{m_a}\left(\frac{5}{2}\overleftrightarrow{\pi}_{\parallel a} + \overleftrightarrow{\theta}_{\parallel a}\right)$
  - **These expressions are equivalent to that of the Hirshman's moment approach in the limit of equilibrium return flows**

2D transport equations in tokamak (1/3)

- **Equation for particle transport**

$$\left.\frac{\partial n_a}{\partial t}\right|_{\boldsymbol{x}} + \boldsymbol{\nabla}\cdot(n_a \boldsymbol{u}_a) = S_{na}$$

- **Equation for Force balance in radial direction**

$$\boldsymbol{\nabla}\rho\cdot\boldsymbol{\nabla}p_a = e_a n_a E^\rho + e_a \frac{IB}{\psi'} n_a u_{a\parallel} - e_a \frac{B^2}{\psi'} n_a u_{a\zeta}$$

  - Since the time derivative of radial momentum is $\mathcal{O}(\delta^3)$, the lowest order radial force balance $\mathcal{O}(\delta^0)$ is assumed for simplicity as previously indicated.

- **Equation for parallel momentum transport**

$$\left.\frac{\partial}{\partial t}\left(m_a n_a u_{a\parallel} B\right)\right|_{\boldsymbol{x}} + F_{ua\parallel}^{\mathrm{ine}} B + B\nabla_\parallel p_a + F_{ua\parallel}^{\mathrm{vis}} B = e_a n_a E_\parallel B + F_{a\parallel} B + S_{ma\parallel} B$$

  - **Inertial force in parallel direction**

$$F_{ua\parallel}^{\mathrm{ine}} B = \boldsymbol{B}\cdot\boldsymbol{\nabla}\cdot\left(m_a n_a \boldsymbol{u}_{a\parallel}\boldsymbol{u}_{a\parallel}\right) = B\nabla_\parallel\left(m_a n_a u_{a\parallel} u_{a\parallel}\right) - m_a n_a u_{a\parallel} u_{a\parallel}\nabla_\parallel B$$

  - **Viscous force in parallel direction**:

$$F_{ua\parallel}^{\mathrm{vis}} B = \boldsymbol{B}\cdot\boldsymbol{\nabla}\cdot\overset{\leftrightarrow}{\pi}_{a\parallel} = \frac{2}{3} B\nabla_\parallel \pi_{a\parallel} - \pi_{a\parallel}\nabla_\parallel B$$

2D transport equations in tokamak (2/3)

- **Equation for toroidal momentum transport**

$$\frac{\partial}{\partial t}(m_a n_a u_{a\zeta})\bigg|_{\boldsymbol{x}} + F^{\mathrm{ine}}_{ua\zeta} + F^{\mathrm{vis}}_{ua\zeta} = e_a n_a E_\zeta + e_a n_a \psi' u^\rho_a + F_{a\zeta} + S_{ma\zeta}$$

  - **Inertial force in the toroidal direction**

$$F^{\mathrm{ine}}_{ua\zeta} = \boldsymbol{\nabla}\cdot(m_a n_a u_{a\zeta}\boldsymbol{u}_a)$$

  - **Viscous force in the toroidal direction**

$$F^{\mathrm{vis}}_{ua\zeta} = \boldsymbol{\nabla}\cdot\left(R^2\boldsymbol{\nabla}\zeta\cdot\overleftrightarrow{\pi}_{a\parallel}\right) = \boldsymbol{\nabla}\cdot\left[\frac{I\pi_{a\parallel}}{B^2}B^\chi\boldsymbol{e}_\chi + \pi_{\parallel a}\left(\frac{I^2}{B^2R^2}-\frac{1}{3}\right)R^2\boldsymbol{\nabla}\zeta\right]$$

$$= B\nabla_\parallel\left(\frac{I\pi_{a\parallel}}{B^2}\right)$$

- **Equation for internal energy transport**

$$\frac{3}{2}\frac{\partial p_a}{\partial t}\bigg|_{\boldsymbol{x}} + \boldsymbol{\nabla}\cdot\left(\boldsymbol{Q}_a - \frac{1}{2}m_a n_a u_a^2\boldsymbol{u}_a\right) = \boldsymbol{u}_a\cdot\boldsymbol{\nabla}p_a + Q^{\mathrm{vis}}_a + Q_{\Delta a} + S_{pa}$$

where $S_{pa} \equiv S_{Ea} - \boldsymbol{S}_{ma}\cdot\boldsymbol{u}_a + \frac{1}{2}m_a u_a^2 S_{na}$ is internal energy source

  - **Viscous heating due to parallel viscosity**

$$Q^{\mathrm{vis}}_a \equiv \boldsymbol{u}_a\cdot\boldsymbol{\nabla}\cdot\overleftrightarrow{\pi}_{a\parallel} = B\nabla_\parallel\left(\frac{u_{a\parallel}\pi_{\parallel a}}{B}\right) - \frac{1}{2}w_{ua}\pi_{\parallel a} - \frac{1}{3}\boldsymbol{u}_a\cdot\boldsymbol{\nabla}\pi_{\parallel a}$$

2D transport equations in tokamak (3/3)

- **Equation for EW force balance in radial direction**

$$\boldsymbol{\nabla}\rho\cdot\boldsymbol{\nabla}\left(\frac{5T_a}{2m_a}p_a\right)=\frac{e_a}{m_a}\left(\frac{5}{2}p_aE^\rho+\frac{IB}{\psi'}Q_{a\parallel}+\frac{B^2}{\psi'}Q_{a\zeta}\right)$$

- **Equation for parallel total heat flux transport**

$$\frac{\partial}{\partial t}(Q_{a\parallel}B)\bigg|_{\boldsymbol{x}}+F^{\rm ine}_{qa\parallel}B+B\nabla_\parallel\left(\frac{5}{2}\frac{T_ap_a}{m_a}\right)+F^{\rm vis}_{qa\parallel}B=\frac{e_a}{m_a}\left(\frac{5}{2}p_a+\frac{2}{3}\pi_{\parallel a}\right)E_\parallel B+G_{a\parallel}B+S_{qa\parallel}B$$

where the EW inertial and viscous force in parallel direction are defined as

$$F^{\rm ine}_{qa\parallel}B\equiv B\nabla_\parallel\left(Q_{a\parallel}u_{a\parallel}+u_{a\parallel}Q_{a\parallel}-\frac{3}{2}p_au_{a\parallel}u_{a\parallel}\right)-\left(Q_{a\parallel}u_{a\parallel}+u_{a\parallel}Q_{a\parallel}-\frac{3}{2}p_au_{a\parallel}u_{a\parallel}\right)\nabla_\parallel B$$

$$F^{\rm vis}_{qa\parallel}B\equiv r_{\parallel a}\nabla_\parallel B+\frac{2}{3}B\nabla_\parallel r_{\parallel a}$$

- **Equation for toroidal total heat flux transport**

$$\frac{\partial Q_{a\zeta}}{\partial t}\bigg|_{\boldsymbol{x}}+F^{\rm ine}_{qa\zeta}+F^{\rm vis}_{qa\zeta}=\frac{e_a}{m_a}\left[\left(\frac{5}{2}p_a-\frac{1}{3}\pi_{\parallel a}\right)E_\zeta+\frac{I\pi_{\parallel a}}{B}E_\parallel+\psi'Q^\rho_a\right]+G_{a\zeta}+S_{qa\zeta}$$

where the EW inertial and viscous force in toroidal direction are defined as

$$F^{\rm ine}_{qa\zeta}\equiv\boldsymbol{\nabla}\cdot\left(Q_{a\zeta}\boldsymbol{u}_a+u_{a\zeta}\boldsymbol{Q}_a-\frac{3}{2}p_au_{a\zeta}\boldsymbol{u}_a\right)$$

$$F^{\rm vis}_{qa\zeta}\equiv B\nabla_\parallel\left(\frac{Ir_{\parallel a}}{B^2}\right)$$

- **Flux averaged parallel force and EW force balance up to $\mathcal{O}(\delta)$**

$$\left\langle \boldsymbol{B}\cdot\boldsymbol{\nabla}\cdot\overset{\leftrightarrow}{\pi}_{\parallel a}\right\rangle = e_a n_a \left\langle E_\parallel B\right\rangle + \left\langle F_{a\parallel}B\right\rangle$$

$$\left\langle \boldsymbol{B}\cdot\boldsymbol{\nabla}\cdot\overset{\leftrightarrow}{r}_{\parallel a}\right\rangle = \frac{5T_a}{2m_a} e_a n_a \left\langle E_\parallel B\right\rangle + \left\langle G_{a\parallel}B\right\rangle$$

- **Equilibrium return flows inside the last closed flux surface**

$$\bar{\boldsymbol{u}}_a = \omega_{ua}R^2\boldsymbol{\nabla}\zeta + L_{ua}\boldsymbol{B} \quad \text{and} \quad \bar{\boldsymbol{q}}_a = \omega_{qa}R^2\boldsymbol{\nabla}\zeta + L_{qa}\boldsymbol{B},$$

  - ω_{ua} and ω_{qa} are the toroidal angular frequencies
  - L_{ua} and L_{qa} are the quantities related to poloidal flows.

- **w_{ua} and w_{qa} with equilibrium return flows**

$$\bar{w}_{ua} = 2(\nabla_\parallel B)L_{ua} \quad \text{and} \quad \bar{w}_{qa} = 2(\nabla_\parallel B)\frac{2L_{qa}}{5p_a}$$

- **Parallel viscosity tensors with equilibrium return flows**

$$\begin{bmatrix} \overset{\leftrightarrow}{\pi}_{\parallel a} \\ \overset{\leftrightarrow}{\theta}_{\parallel a} \end{bmatrix} \equiv -3\left(\nabla_\parallel B\right)\begin{bmatrix} \mu_{1a} & \mu_{2a} \\ \mu_{2a} & \mu_{3a} \end{bmatrix}\begin{bmatrix} L_{ua} \\ \dfrac{2L_{qa}}{5p_a} \end{bmatrix}\left(\boldsymbol{e}_\parallel\boldsymbol{e}_\parallel - \frac{1}{3}\overset{\leftrightarrow}{I}\right)$$

- **Flux averaged parallel flow in equilibrium return flow limit**

$$\left\langle u_{a\|}B\right\rangle = V_{1a} + L_{ua}\left\langle B^2\right\rangle, \qquad V_{1a} = \frac{I}{B}\omega_{ua}$$

$$\left\langle q_{a\|}B\right\rangle = \frac{5}{2}p_a V_{2a} + L_{qa}\left\langle B^2\right\rangle, \qquad V_{2a} = \frac{I}{B}\omega_{qa}$$

- **Matrix equation for poloidal rotations in our transport model**

$$\left\langle 3(\nabla_\| B)^2\right\rangle \begin{bmatrix} \mu_{1a} & \mu_{2a} \\ \mu_{2a} & \mu_{3a} \end{bmatrix} \begin{bmatrix} L_{ua} \\ \dfrac{2L_{qa}}{5p_a} \end{bmatrix} = \sum_b \begin{bmatrix} l_{11}^{ab} & -l_{12}^{ab} \\ -l_{21}^{ab} & l_{22}^{ab} \end{bmatrix} \begin{bmatrix} V_{1b}B + L_{ub}\left\langle B^2\right\rangle \\ V_{2b}B + \dfrac{2L_{qb}}{5p_b}\left\langle B^2\right\rangle \end{bmatrix} + \begin{bmatrix} e_a n_a \left\langle E_\| B\right\rangle \\ 0 \end{bmatrix}$$

  - This expression is equivalent to matrix equation for poloidal rotations in the conventional neoclassical transport theory

Electromagnetic equations

- **Evolution equatoin for B^χ**: $(B^\chi = \sqrt{g}d\psi/d\rho)$

$$\left.\frac{\partial B^\chi}{\partial t}\right|_{\boldsymbol{x}} - \frac{1}{\sqrt{g}}\frac{\partial E_\rho}{\partial \rho} = 0$$

- **Evolution equation for B_ζ**: $(B_\zeta = I)$

$$\left.\frac{\partial B_\zeta}{\partial t}\right|_{\boldsymbol{x}} + \frac{R^2}{\sqrt{g}}\left(\frac{\partial E_\chi}{\partial \rho} - \frac{\partial E_\rho}{\partial \xi_\chi}\right) = 0$$

- **Gauss's law**

$$\boldsymbol{\nabla}\cdot\boldsymbol{E} = \sum_a \frac{e_a}{\varepsilon_0}$$

- **Evolution equation for E_χ**

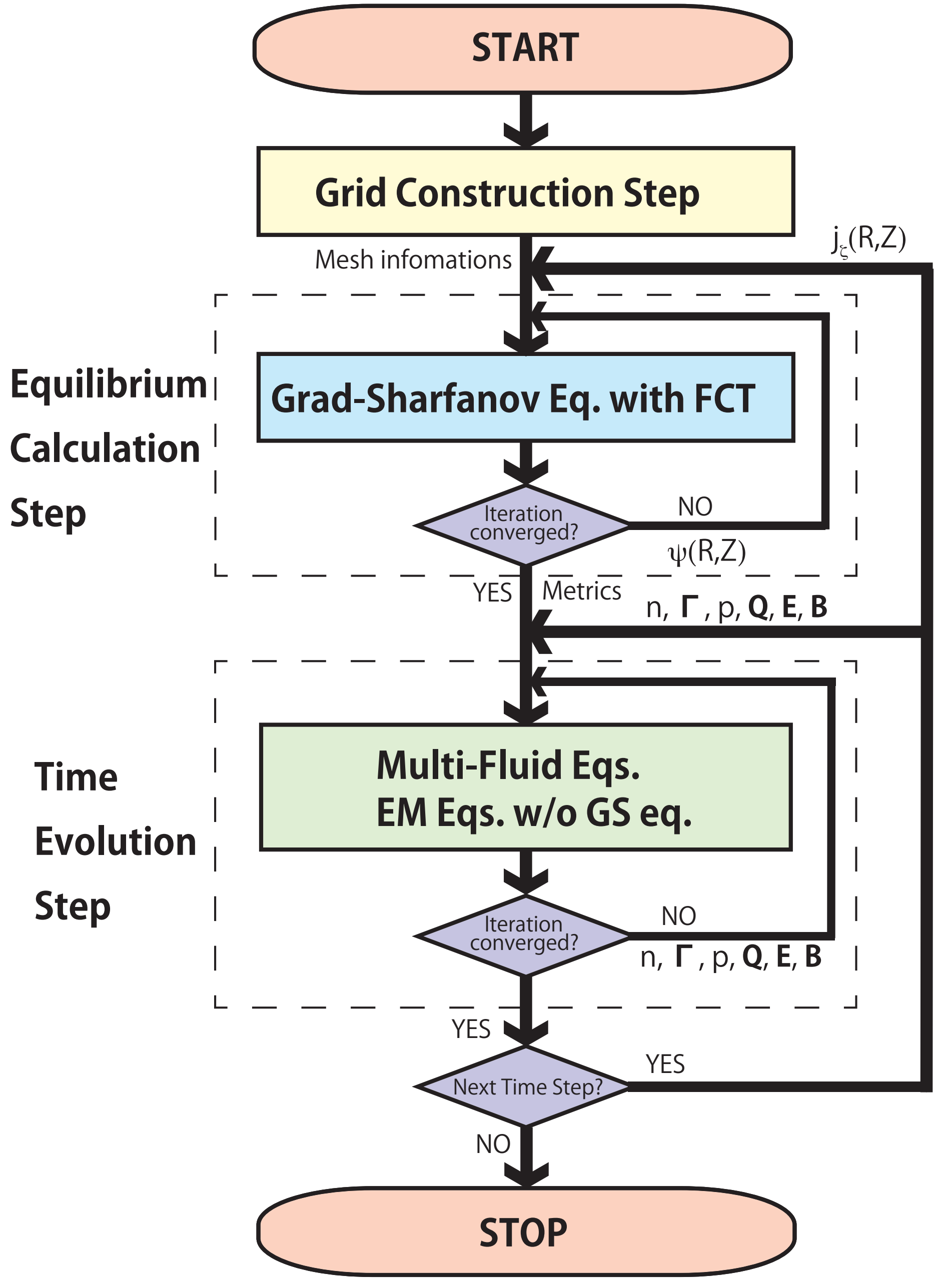
$$\frac{1}{c^2}\left.\frac{\partial E_\chi}{\partial t}\right|_{\boldsymbol{x}} + \frac{g_{\chi\chi}}{\sqrt{g}}\frac{\partial B_\zeta}{\partial \rho} + \mu_0\sum_a \frac{e_a n_a u_{a\parallel}B - e_a n_a u_a^\zeta B_\zeta}{B^\chi} = 0$$

- **Evolution equation for E_ζ**

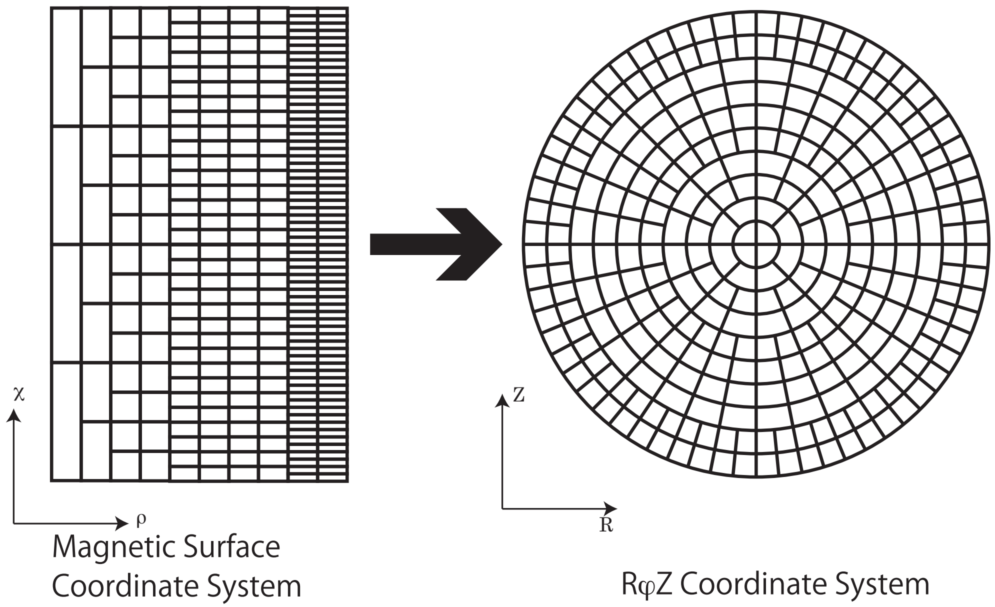
$$\frac{1}{c^2}\left.\frac{\partial E_\zeta}{\partial t}\right|_{\boldsymbol{x}} + R^2\boldsymbol{\nabla}\cdot\left(\frac{B^\chi}{\sqrt{g}R^2}\boldsymbol{\nabla}\rho\right) + \mu_0\sum_a e_a n_a u_{a\zeta} = 0$$

Code design of TASK/T2

- **Time evolution algorithm**
  1. **Grid construction step**
     - TASK/T2
     - Grid generation in MSC
  2. **Equilibrium calculation step**
     - TASK/EQU
     - Grad-Shafranov Eq.
     - Metrics calculation
  3. **Time evolution step**
     - TASK/T2, TASK/MTXP
     - Multi-fluid Eqs., EM Eqs.
     - Calculation of time evolution of plasma



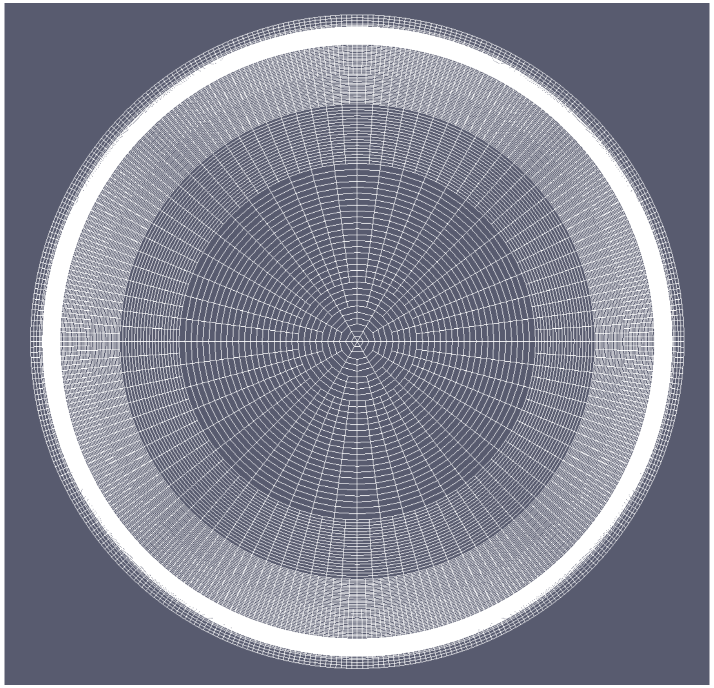
Concept of Grid construction

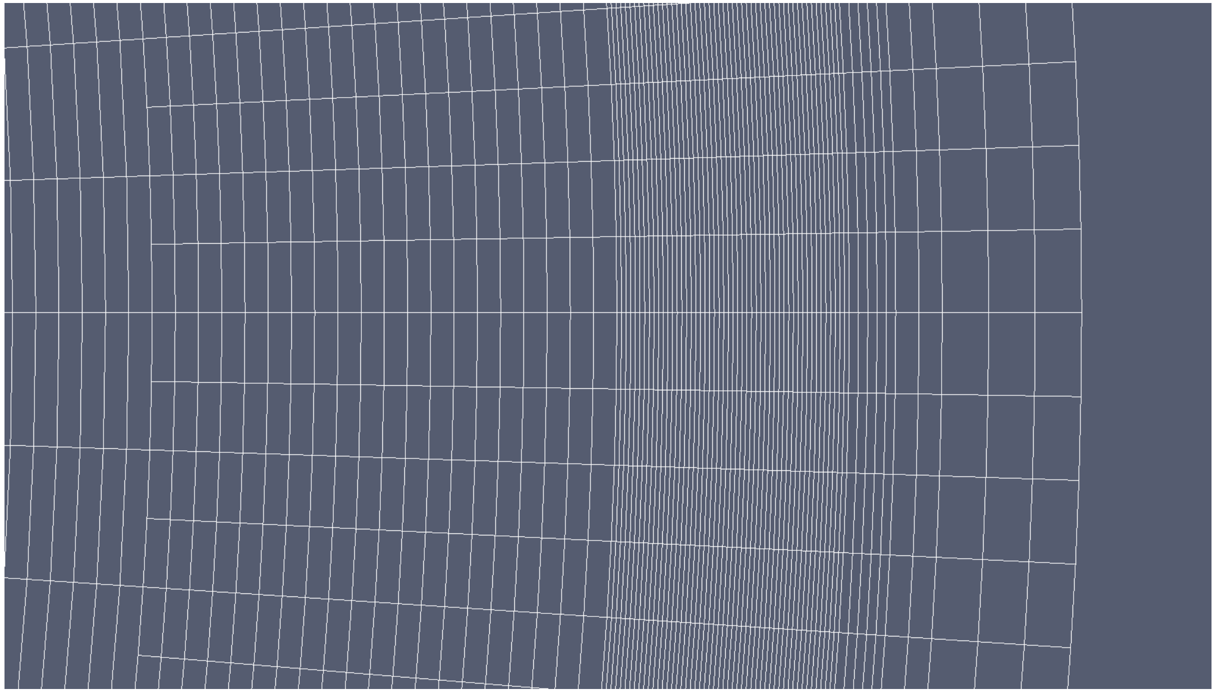


- **Desirable grid property for two-dimensional transport analysis**
  - **Good separation of the parallel and perpendicular fluxes**
    - Rectangular grid whose sides are parallel or perpendicular to axes of MSC
  - **Uniform poloidal resolution in real space**
    - Hierarchical structure that becomes gradually finer at greater ρ region
  - **High flexibility of radial grid width**
    - Radial grid width can be easily changed if grid is structural

Hierarchical rectangular grid in MSC is employed in TASK/T2

Example of Grid construction

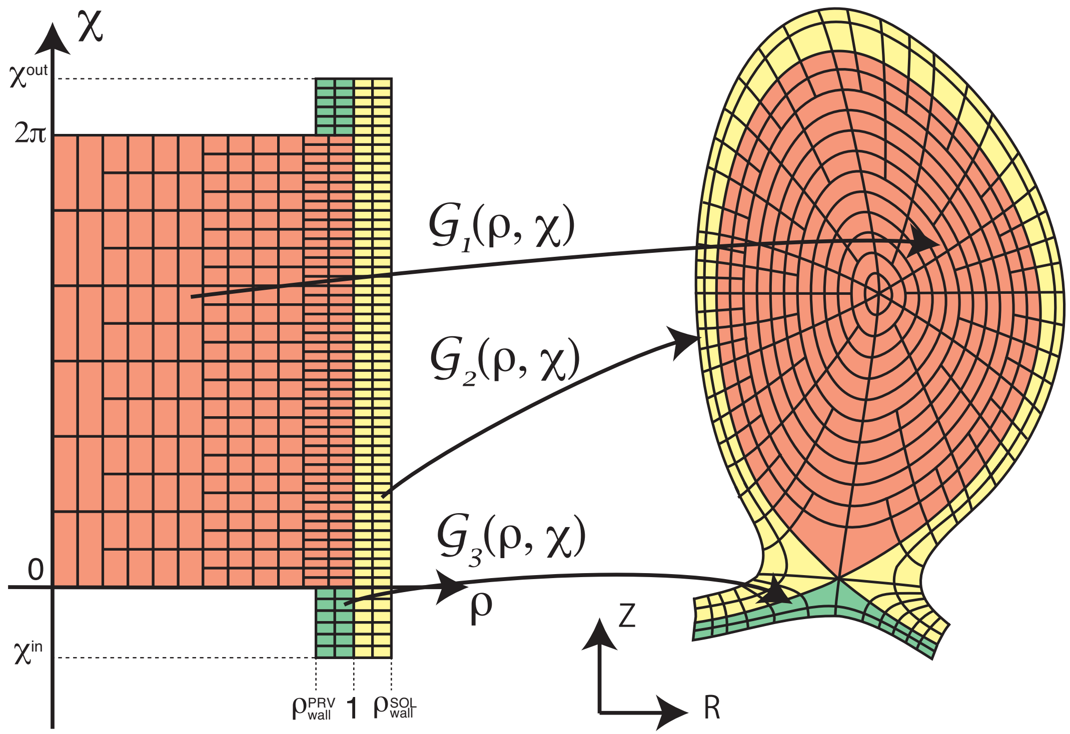




- **Example of grid construction for limiter configuration**
  - **Hierarchical grid generation in cylindrical coordinate**
  - **Number of elements**: 37590
    - **Core region** $(0.0 \leq r \leq 1.0)$:
      Number of radial partitions: 100, Number of poloidal partitions: 6-384
    - **Peripheral region** $(1.0 \leq r \leq 1.1)$:
      Number of radial partitions: 50, Number of poloidal partitions: 384

Concept of Grid for Single-Null Divertor

- **Sub-domains of Single-null grid**
  - **Core domain**:
    $\rho \in [0,\ 1],\ \chi \in [0,\ 2\pi]$
  - **SOL domain**:
    $\rho \in [1,\ \rho_{\rm wall}^{\rm SOL}],\ \chi \in [\chi^{\rm in},\ \chi^{\rm out}]$
  - **Private domain**:
    $\rho \in [\rho_{\rm wall}^{\rm PRV},\ 1],\ \chi \in [\chi^{\rm in},\ 0]$
    $\rho \in [\rho_{\rm wall}^{\rm PRV},\ 1],\ \chi \in [2\pi,\ \chi^{\rm out}]$



- **Each sub-domain has different mapping function from MSC to RφZ system**
- **Continuity between sub-domains at separatrix ($\rho = 1,\ \chi^{\rm in} \le \chi \le \chi^{\rm out}$)**
  - $0 \le \chi \le 2\pi$: core and SOL domain
  - $\chi^{\rm in} \le \chi \le 0$ and $2\pi \le \chi \le \chi^{\rm out}$: SOL and private domain
- **Periodic conditions ($0 \le \rho \le 1,\ \chi = 0, 2\pi$)**
  - $0 \le \rho \le 1,\ \chi = +0, 2\pi - 0$: for core domain
  - $\rho_{\rm wall}^{\rm PRV} \le \rho \le 1,\ \chi = -0, 2\pi + 0$: for private domain

Specification of transport equation solver

- **Governing equation**: Simultaneous Advection-Diffusion equation
- **Discretization scheme**: Finite Element Method
  - **Stabilization scheme**: SUPG-FEM
  - **Element type**: Structured bi-linear rectangular element
- **Time-advancing scheme**: Full implicit
- **Nonlinear calculation scheme**: Picard iteration
- **Matrix solver**: TASK/MTXP
  - **Parallel solver**: PETSc (Iterative method), MUMPS (direct method)
  - **Serial solver**: Gauss elimination for band matrix
- **Visualization**: Paraview

Summary and Future work

- **Summary**
  - A set of equations required for 2D transport modeling of tokamak plasmas has been derived.
    - 2D transport equations have been derived from multi-fluid equations with neoclassical viscosity in MSC.
    - The neoclassical parallel viscosity and heat viscosity have been extended in order to be applicable in the open field region outside the last closed flux surface.
- **Future works**
  - Developing the two-dimensional transport code TASK/T2
  - Modeling of 2D momentum and heat flux transport due to the turbulent electric field based on quasi-linear transport theory
  - 2D core and peripheral transport analysis of tokamaks with limiter configurations as a preliminary step to divertor configurations