Development and application of LPD model based on BOUT++

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Outline

1. Background & Research Significance
2. Mesh & Physical Model
3. Numerical Results
4. Conclusions and Future Plans
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The introduction of LPD (linear plasma device)

- Long experiment period
- High cost and time-consuming
- Parameters and rules are complex

- Easy to upgrade
- Short experimental period and low cost
- Single parameter, suitable for principle experiments
- Simplified environment

The LPDs have been applied to investigate the high particle/heat flux irradiation [1], erosion of the materials [2], fuel retention [3] and PMI[4].

Basic information of MPS-LD linear plasma device

The device is about 3m long and consists of 11 coils

<table>
<thead>
<tr>
<th>parameters</th>
<th>Desired Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic field (axis)</td>
<td>3000 G</td>
</tr>
<tr>
<td>Ion temperature</td>
<td>1-20 eV</td>
</tr>
<tr>
<td>Electron temperature</td>
<td>1-20 eV</td>
</tr>
<tr>
<td>Electron density</td>
<td>$10^{18}-10^{19}/m^3$</td>
</tr>
<tr>
<td>Ion flux</td>
<td>$10^{21}-10^{23}/m^2s$</td>
</tr>
<tr>
<td>Ion fluence</td>
<td>up to $10^{26}$ m^{-2} per exposure</td>
</tr>
<tr>
<td>Target bias voltage</td>
<td>&lt; 300 V</td>
</tr>
<tr>
<td>Target (sample) temperature</td>
<td>300-1000K</td>
</tr>
<tr>
<td>Diameter of plasma column</td>
<td>&lt; 10 cm</td>
</tr>
<tr>
<td>Operational pressure</td>
<td>down to $10^{-2}$ Pa</td>
</tr>
<tr>
<td>Vacuum pressure</td>
<td>$10^{-4}$ Pa</td>
</tr>
</tbody>
</table>

- PMIs, e.g. irradiation damage, fuel retention
- Edge plasma transport
- High density plasma source
- Plasma heating
Simulation of Plasma Transport in Linear Device

- The plasma will be transported along magnetic lines in the magnetic field, undergo complex atomic and molecular processes, and eventually reach the divertor target;
- The plasma is similar to the plasma behavior of the scraping layer in tokamak, and the scraping layer and divertor are simulated in the laboratory.
- In order to understand the plasma transport in MPS-LD device and accurately predict the energy flow and particle flow deposited on the divertor target, it is urgent to carry out relevant numerical simulation research.

<table>
<thead>
<tr>
<th>Code</th>
<th>Device</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOLPS</td>
<td>MPEX, MPS-LDMagnum-PSI, MAGPIE, Proto-MPEX, GyM</td>
</tr>
<tr>
<td>EMC3-Eirene</td>
<td>MPEX</td>
</tr>
<tr>
<td>B2.5-Eunomia</td>
<td>Pilot-PSI, Magnum-PSI</td>
</tr>
<tr>
<td>SolEdge2D-Eirene</td>
<td>Pilot-PSI</td>
</tr>
<tr>
<td>BOUT++ Hermes</td>
<td>Magnum-PSI</td>
</tr>
<tr>
<td>LINDA</td>
<td>NAGDIS-II</td>
</tr>
</tbody>
</table>
BOUT++ for Tokamak Simulation

EAST

C-Mod

KSTAR

Nucl. Fusion 55 (2015) 113030

AIP Adv., 10 (2020) 015222

DIII-D

Nucl. Fusion 58 (2018) 026026

Nucl. Fusion 54 (2014) 09300
Necessity of Simulating Linear Device Based on BOUT++

- efficient parallel code, which allows obtaining the numerical solution faster
- Separation of source code from user application code
- Modularization of physical algorithms
- Support open source

- A steady-state plasma beam can be formed by constructing a steady-state magnetic field to construct a divertor-like plasma environment
- low cost, short cycle, easy diagnosis and single and controllable experimental variables
- Existing device

LPD module simulating Linear device based on BOUT++

- Plasma parameters near the target can be obtained
- We know the dependence of plasma parameters near the target on the plasma source,
- A New Numerical Tool for Linear Device Modeling
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LPD module simulates MPS-LD device

LD-MCC magnetic field calculation code
- Calculate the magnetic field configuration
- Magnetic field information is stored as standard magnetic field data file

Mesh generator code
- Standard data storage interface program
- Generate mesh files readable by BOUT++

2D Transport model
- Reduce Braginskii equation

The simulation of the plasma transport in MPS-LD device is modeled by the LPD module of BOUT++
The magnetic vector potential $\vec{A}(r, \varphi, z)$ in the cylindrical coordinate system can be calculated by circular current loop:

$$\vec{A}(r, \varphi, \theta) = \frac{\mu I_0 a}{\pi K_c [r_c a \sin \theta]^2} \left[ \left( 1 - \frac{K_c}{2} \right) K(K_c) - E(K_c) \right] \hat{\phi}$$

$$k_c^2 = \frac{4r_c a \sin \theta}{r_c^2 + a^2 + 2r_c a \sin \theta}$$

where $K(k_c), E(k_c)$ are complete elliptic integral functions of the first and second types

The components of the magnetic field are expressed as:

$$B_R = -\frac{1}{R} \frac{\partial \psi}{\partial z}, \quad B_z = -\frac{1}{R} \frac{\partial \psi}{\partial R}$$

The total magnetic field $B$ in the LPD is

$$B_n = \sqrt{B_{n,r}^2 + B_{n,z}^2} \quad B = \sum_{n=1}^{11} B_n$$

By using the location and current of each coil in MPS-LD, see table 2 in [1], LPD-MCC (Linear Plasma Devices-Magnetic field Configuration Calculation) can be verified by benchmarking against the COMSOL calculation.

2D Transport model

Continuity equations
\[
\frac{\partial N_i}{\partial t} + \nabla \cdot (V_i N_i) = S_i^p - S_i^{rec}
\]
\[
\frac{\partial N_{He^+}}{\partial t} + \nabla \cdot (V_{He^+} N_{He^+}) = S_{He}^i - S_{rec}^He
\]

Momentum equations
\[
\frac{\partial V_{||}}{\partial t} + V_{||} \nabla V_{||} - \frac{4}{3N_i M_i} \nabla \left( \eta_i \nabla V_{||} \right) = - \frac{\nabla P_i}{N_i M_i} + \frac{D_i}{N_i} \nabla N_i \cdot \nabla V_{||} - \frac{N_i + N_{He^+}}{N_i} v_i V_{||} - F_i
\]

Energy equations
\[
\frac{\partial T_e}{\partial t} - \frac{2}{3N_e} \nabla (\kappa_e \nabla T_e) = \frac{2}{3} \chi_e \nabla^2 T_e - v_i \left( T_e + \frac{2}{3} W_L \right) - v_{He^+} \left( T_e + \frac{2}{3} W_{He^+} \right) - \frac{2m_e T_e - T_i}{M_i \tau_e} - \frac{2m_e T_e - T_{He^+}}{M_{He} \tau_{He^+}^e}
\]

Neutral equations
\[
\frac{\partial V_a}{\partial t} = -V_a \nabla V_a - \frac{\nabla P_a}{N_a M_a} - \frac{v_{He} V_{He} N_{He}}{N_{He} M_{He}} - v_{He} \nabla V_a - \frac{v_{He} V_{He} N_{He}}{N_{He} M_{He}}
\]

Boundary conditions applicable to linear devices

**Continuity equations**

\[
N_i |_{Z=0} = N_0 e^{-\frac{(R-\rho)^2}{2b^2}}, \quad \nabla_n N_{He^+} |_{Z=0} = 0
\]

**Momentum equations**

\[
V_{\parallel} |_{Z=0} = V_0 e^{-\frac{(R-\rho)^2}{2f^2}}, \quad \nabla_n V_{He^+} |_{Z=0} = 0
\]

**Energy equations**

\[
\nabla_n T_e |_{Z=0} = \nabla_n T_i |_{Z=0} = T_0 e^{-\frac{(R-c)^2}{2d^2}}, \quad \nabla_n T_{He^+} |_{Z=0} = 0
\]

**Neutral equations**

\[
\nabla_n N_a |_{Z=0} = 0, \quad N_{He} |_{Z=0} = N_{He0} e^{-\frac{(R-\rho)^2}{h^2}}, \quad \nabla_n V_{He} |_{Z=0} = V_{He0}
\]

### Plasma source boundary

- **Continuity equations**: \( \nabla_n N_i |_{Z=-1} = 0, \quad \nabla_n N_{He^+} |_{Z=-1} = 0 \)
- **Momentum equations**: \( \nabla_n V_i |_{Z=-1} = C_s |_{Z=-1}, \quad \nabla_n V_{He^+} |_{Z=-1} = C_s |_{Z=-1} \)
- **Energy equations**: 
  \[
  \nabla_n T_i |_{Z=-1} = \nabla_n T_{He^+} |_{Z=-1} = -q_{sh,i} / (k \kappa_{ii}) |_{Z=-1}
  \]
  \[
  \nabla_n T_e |_{Z=-1} = -q_{sh,e} / (k \kappa_{ee}) |_{Z=-1}
  \]
- **Neutral equations**: 
  \[
  \nabla_n N_a |_{Z=-1} = - \frac{\Gamma_a^d}{D_{\parallel a}}, \quad \nabla_n N_{He} |_{Z=-1} = - \frac{\Gamma_{He}^d}{D_{\parallel He}}, \quad \nabla_n V_{He} |_{Z=-1} = 0
  \]

### Target boundary

- **Continuity equations**: \( \nabla_n N_i |_{Z=-1} = 0, \quad \nabla_n N_{He^+} |_{Z=-1} = 0 \)
- **Momentum equations**: \( \nabla_n V_i |_{Z=-1} = C_s |_{Z=-1}, \quad \nabla_n V_{He^+} |_{Z=-1} = C_s |_{Z=-1} \)
- **Energy equations**: 
  \[
  \nabla_n T_i |_{Z=-1} = \nabla_n T_{He^+} |_{Z=-1} = -q_{sh,i} / (k \kappa_{ii}) |_{Z=-1}
  \]
  \[
  \nabla_n T_e |_{Z=-1} = -q_{sh,e} / (k \kappa_{ee}) |_{Z=-1}
  \]
- **Neutral equations**: 
  \[
  \nabla_n N_a |_{Z=-1} = - \frac{\Gamma_a^d}{D_{\parallel a}}, \quad \nabla_n N_{He} |_{Z=-1} = - \frac{\Gamma_{He}^d}{D_{\parallel He}}, \quad \nabla_n V_{He} |_{Z=-1} = 0
  \]

### Chamber wall boundary

- **Neutral equations**: 
  \[
  \nabla_n N_a |_{R=-1} = - \frac{\Gamma_a^w}{D_{\perp a}}, \quad \nabla_n N_{He} |_{R=-1} = - \frac{\Gamma_{He}^w}{D_{\perp He}}, \quad \nabla_n V_{He} |_{R=-1} = 0
  \]

### Axis boundary

Neumann boundary conditions are used for density, velocity and temperature equations

Gaussian distribution radially

Sheath boundary conditions

Yue Wang | 2023 BOUT++ Workshop | Development and application of LPD model based on BOUT++
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A two-point model is applied to analyze the results

The simulated main plasma parameters are shown

Continuity equations: \[ \Gamma_t - \Gamma_u = \int_u^t S^R_t \, dz + \int_u^t S^N_t \, dz \]

Momentum equations: \[ \Pi_t - \Pi_u = \int_u^t M_i S^R_i \, dz + \int_u^t M_i S^N_i \, dz \]

Energy equations: \[ Q_{t,\alpha} - Q_{u,\alpha} = \int_u^t S^R_{Q,\alpha} \, dz + \int_u^t S^N_{Q,\alpha} \, dz \pm \int_u^t q_{\alpha} \, dz \]

The differences of particle, momentum and energy fluxes between the upstream and target are almost identical to the integration of each term

Wang Yue et al., Plasma Phys. Control. Fusion 64 (2022) 115010
Simulation Results verification

The results of BOUT++ were qualitatively compared with those of a simulated Pilot-PSI device using SOLE2D-Eirene.

In the radial direction, $N_e$ gradually decreases toward the wall, and the distribution is similar to that of the Magnum-PSI experiment.

Quantitative comparison between BOUT++ and SOLPS-ITER modeling are shown.

The consistency of the trend of the main parameters

Y. J Zhang, Nuclear Materials and Energy 33 (2022) 101280
The increase of $D_\perp$ will lead to a significant decrease in $N_e$ at the target, resulting in a decrease $\Gamma_{t,\text{peak}}$, but has little effect on $T_{et,\text{peak}}$, so $Q_{\text{wall}}$ is enhanced, resulting in a decrease in $q_{t,\text{peak}}$ and a corresponding decrease in $Q_r$.

$\chi_{\perp i,e}$ only affects $q$. $Q_{\text{wall}}$ increases with the increase of $\chi_{\perp i,e}$, while $Q_t$ decreases with the increase of $\chi_{\perp i,e}$.

The variation of the main plasma parameters at the target with $D_\perp$ and $\chi_{\perp i,e}$

- Smaller $D_\perp$ and $\chi_{\perp i,e}$ are beneficial to suppress the radial transport, reduce the beam spot width, and increase the particle flux and heat flux reaching the target. This requires enhance magnetic field strength to obtain stronger particle flux and plasma energy flux density.
Evolution of helium ions

- At $t = 0.02$ ms the helium atom is ionized and reaches $1.628 \times 10^{18} m^{-3}$ near the gas inlet.
- At $t = 0.135$ ms, He$^+$ reaches the target for the first time.
- It reaches a maximum of about $2.5 \times 10^{18} m^{-3}$ at about $t = 0.09$ ms, and then $N_{He^+}$ begins to decrease over time.
- At $t = 0.27$ ms, the $N_{He^+}$ near the gas charging port decreases obviously, but there is obvious He$^+$ accumulation in the whole device due to the recycle target.

$$D_\perp = 0.5 \text{ m}^2\text{s}^{-1}, \quad \chi_{\perp,e} = 1.0 \text{ m}^2\text{s}^{-1}, \quad R = 0.75,$$

$$R_{\text{source}}^{D^+} = 1.5 \times 10^{21} \text{ D}^+ \text{s}^{-1}, \quad R_{\text{source}}^{He} = 4.0 \times 10^{20} \text{ He s}^{-1}.$$
Helium injection can control target thermal load

- $q_t$ is inversely proportional to the number of He atoms in the simulation region $\Sigma_{He}$. With the increase of injection time, the $Q_t$ and $q$ of the whole target plate continue to decrease, and begin to stabilize after reaching a dynamic balance.

$$Q_{ion} = VE_{ion}S_{ion} = VE_{ion}N_e\nu_{He}$$

$E_{ion}$ is ionization energy loss,

$$\nu_{He} = N_{He} < \sigma_{He}V_{th,e}$$

$V$ is the simulation area,

$N_{he}$ is impurity density,

$$\Sigma_{He} = VN_{He}$$
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Conclusions

◆ Based on BOUT++, a new LPD module is developed to simulate linear devices.
◆ For the first time, the LPD module is used to simulate the plasma transport in MPS-LD, and the main plasma parameters are obtained. And the corresponding verification was carried out.
◆ The smaller $D_{\perp}$ is beneficial to reduce the particle beam width, so the particle flux and the corresponding energy flux are significantly enhanced, while $\chi_{\perp i,e}$ only affects the energy flux.

Future plan:

✓ The neutral transport model need to be optimized to simulate plasma-neutral collisions more accurately.
✓ The impact of drifts on edge plasma transport in the LPD will be studied, especially on the plasma beam size.

Thank you for your attention