Multi-machine Modelling of Divertor Geometry Effects

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Outline of the talk

1. Introduction

2. Divertor Geometry and Detachment  
   (Power Losses + Density Limits)

3. Divertor Geometry and Pumping  
   (Hydrogen + Impurities)

4. Divertor Geometry and Plasma Flows  
   (Hydrogen + Impurities)

5. Conclusions
1. Introduction

- Divertor Geometry affects Recycling Sources
  - Divertor Density and Temperature
    - Flow Patterns in Divertor
      - Divertor Radiative Losses

2-D Plasma Edge Simulation Codes used to analyse Effects of Divertor Geometry
- Divertor Geometry affects Transport in the Divertor itself

DIII-D X-point Scans (D. Hill APS 92)
Can account for ~ 2 Power Flux Reduction near Separatrix ASDEX-U Div I → Div II

(ASDEX-U, R. Schneider, B2-Eirene, IAEA 98)

Divertor energy balance:
For each flux bundle

Integrals between target plate and divertor entrance
Energy losses from neutrals
Contribution of the divergence of radial energy fluxes

Decrease depends on anomalous Transport

(ASDEX-U, D. Coster, B2-Eirene, EPS 98)
2. Divertor Geometry and Detachment (Power Losses + Density Limits)

- Effects of Divertor Geometry on Detachment seen in Alcator C-mod, JET, ASDEX-U, JT-60U, TCV

- Modelling (B2-Eirene, EDGE2D-NIMBUS & UEDGE) reproduces Features in Experiment

- Vertical Divertor promotes Detachment close to Separatrix (Alcator C-mod, F. Wising, UEDGE, PSI 96)
Easier Separatrix Detachment does not lead to Lower Density Limit \((\rightarrow \text{total Detachment})\)

\((\text{ASDEX-U, R. Schneider, B2-Eirene, PSI 98})\)

**ASDEX-U Div I & Div II Divertor \(T_e\)**

**ASDEX-U Div I & Div II calculated Ion Flux**

separatrix particle flux density (2MW)

integrated particle flux (2MW)
Most pronounced Geometry Effects seen in JET-Mk IIA Horizontal \(\leftrightarrow\) Vertical Discharges

(JET, K. Borrass, B2-Eirene, EPTSW 98)

JET-Mk IIA Vertical Modelling

Experiment

Modelling

Plasma Recombination Sink
Divertor Geometry promotes Recombination away from Separatrix for JET-Mk IIA horizontal Discharges

(JET, K. Borrass, B2-Eirene, EPS 97)

“Corner Effect”

JET- Mk IIA Horizontal Plasma Recombination Sink

JET- Mk IIA Vertical Plasma Recombination Sink
Detachment characterised by DOD or “Degree of Detachment” (A. Loarte, Nucl. Fusion 98)

High recycling Scaling: \( I_{d}^{\text{scal}} = C \left( n_e \right)^2 \)

\[
\text{D.O.D.} = \frac{I_{d}^{\text{scal}}}{I_{d}^{\text{measured}}}
\]

DOD >> 1 \( \rightarrow \) Detachment

(JET, R. Monk, EPS 97)

JET Pulses Nos. 36862, 37154

![Graph showing the relationship between D.O.D. and distance from separatrix for different plasma states.](image)
ASDEX-U Divertor Geometry promotes Recombination for Div II with respect to Div I at lower Densities

(ASDEX-U, R. Schneider, B2-Eirene, PSI 98)
Septum in JET-Gas Box isolates in/out Divertor

Gas Puffing changes Detachment Symmetry

(JET, C. Maggi, EPS 99)
Modelling is consistent with “Septum Effect”
(JET, C. Maggi, EDGE2D-NIMBUS, EPS 99)
Large Difference in Divertor Power Deposition between Div I and Div II in ASDEX-U

(ASDEX-U, Kaufmann, IAEA 98)

Change Div I → Div II in Agreement with Modelling

(ASDEX-U, R. Schneider, B2-Eirene, PSI 98)
ASDEX-U Divertor Geometry creates optimum Conditions for extended Region of Radiation
(ASDEX-U, R. Schneider, B2-Eirene, PSI 98)
Exact Change in Radiation Div I $\rightarrow$ Div II

due mainly to access to Low Divertor $T_e$ regimes

(ASDEX-U, D. Coster, B2-Eirene, EPS 99)
Radiation Fraction in ASDEX-U Div II

(ASDEX-U, D. Coster, B2-Eirene, EPS 99)
Carbon Flow Pattern induced by Geometry increases Radiation Efficiency

(ASDEX-U, R. Schneider, B2-Eirene, IAEA 98)

Carbon mass flow:
flow reversal close to separatrix
forward flow in the outer SOL
3. Divertor Geometry and Pumping (Hydrogen + Impurities)

- DIII-D Experiments → Strong Dependence of Hydrogen Pumping on Divertor Geometry

(DIII-D, R. Maingi, PSI 94)
- Strong dependence not seen in other Experiments (JET-Mk I, JET-Mk IIA, C-mod, ASDEX-U)
Physics Basis for Difference found with 2-D Codes (Ballistic Flux \leftrightarrow Diffusive Flux)

(A. Loarte, EPS 97)

(DIII-D, R. Maingi, Nucl. Fusion 99)
Diffusive Flux leads to weak Strike Point Position Pumping Dependence

(A. Loarte, EDGE2D-NIMBUS, EPS 97)
- He, Ne do not Charge-Exchange so Pumping Subject to stronger Effects of Divertor Geometry
  (ASDEX-U, D. Coster, B2-Eirene, PSI 96)

![Diagram showing additional pumping baffle and parallel particle flux](image)

In ASDEX-U Div I Ne is more compressed than He

![Graph showing compression factor vs. neutral gas flux density](image)
Change from Div I to Div II expected from ballistic Transport of He and Ne to the Pump

(ASDEX-U, R. Schneider, B2-Eirene, IAEA 98)

Improved helium exhaust, worse compression of neon

(ASDEX-U, H. - S. Bosch, B2-Eirene, He Workshop 99)

Deuterium Compression

He & Ne Pumping
Ballistic Effects for He also seen in JET – Mk II
(JET MK II, M. Groth, He Workshop 99)

Enrichment decreases with increasing $n_e$ + Detachment
(JET Mk II Gas Box, H. Guo, EDGE2D-NIMBUS, Nucl. Fusion 2000)
For ITER He enrichment increase with Detachment

Helium Concentration
Separatrix De-enrichment due to Thermal Forces

Going to Partial Detachment helps He Pumping
(Increased Neutral He Penetration to PFR)
Detachment helps for He Pumping in ITER-FEAT

Detachment increases D Pressure & He Enrichment
Experiments + Modelling for DIII-D show different D and He Behaviour

(DIII-D, A. Loarte, B2-Eirene, PET99)

For D standard Detachment Picture

Electron Temperature

Electron Density

Strong Recombination but Neutrals don't reach Main Plasma

Ionisation/Recombination

Neutral Density
For He Main Bulk Plasma collapses before Recombination can be achieved (He penetration through X-point)

Electron Temperature

Helium Atomic Density

Ionisation/Recombination

Momentum Losses

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4. Divertor Geometry and Plasma Flows
(Hydrogen + Impurities)

- Divertor Particle Flows are determined by Sources (Divertor Geometry) but also by Drifts

- High Density Operation can lead to Flow Reversal in the Divertor

- Vertical Divertors are more prone to Flow Reversal due to Recycling Pattern

(Alcator C-mod, A. Loarte, B2-Eirene, PSI 98)
Momentum Transport across the SOL between normal and reversed Flow Regions leads to Separatrix overpressure at Divertor "Death Ray" in Alcator C-mod

(A. Loarte, EDGE2D-NIMBUS, PSI 96, Stotler, B2-Eirene, PSI 98)
Flow reversal occurs also in Horizontal Divertors
(DIII-D, J. Boedo, G. Porter, UEDGE, APS 99)
Flow reversal disappears at Detachment in Horizontal Divertors

(DIII-D, J. Boedo, G. Porter, UEDGE, APS 99)
Impurity Flow Reversal can occur without Deuterium Flow reversal

Thermal Force wins over Friction

(DIII-D, G. Porter, UEDGE, APS 98)
In ASDEX-U Div II Impurity Flow Reversal occurs @ Detachment in Agreement with Predictions

(ASDEX-U, J. Gafert, D. Coster, R. Schneider, B2-Eirene, PSI 98)

Carbon mass flow:
flow reversal close to separatrix
forward flow in the outer SOL

<table>
<thead>
<tr>
<th>Measured PU004</th>
<th>Modelled PU004</th>
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<tbody>
<tr>
<td>+ 21 Km/s</td>
<td>+ 15 Km/s</td>
</tr>
<tr>
<td>- 24 Km/s</td>
<td>-17 Km/s</td>
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● Detachment after ionisation Front in Divertor M

(ASDEX-U, D. Coster, B2-Eirene, EPTSW 98)

Mach number

Plasma particle source (m$^{-3}$s$^{-1}$)

Well documented in JT-60U

(JT-60U, N. Asakura, Nucl. Fusion 99)
5. Conclusions

- Predicted Effects of Divertor Geometry on Detachment seen in most Experiments

- Strong Dependence of Separatrix Detachment on Geometry but weak Geometry Effect on L-mode Density Limit ("Total Detachment")

- Divertor Geometry can enhance Radiation Losses for Carbon (ASDEX-U Div I → Div II)

- Divertor Geometry Effect on Hydrogen and Impurity Pumping understood in Terms of ballistic and diffusive Fluxes to pumping Plenum

- Divertor Geometry Effect on Hydrogen and Impurity Flows from 2-D Codes seen in Experiment: Hydrogen and Impurity Flow Reversal and ⊥ Momentum Transport ("Death Rays")

Modelling with Drifts needed for better understanding

- Divertor Geometry Effect on Midplane $n_e$ Profiles unclear ↔ SOL Flows+Main Chamber Recycling