First-time analysis of detached divertor conditions in RMP ELM suppressed H-mode plasma in ITER

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Third IAEA Technical Meeting on Divertor Concepts, 4-7 November, 2019, Vienna, Austria

Acknowledgements: This work was supported by the U.S. Department of Energy under grants DE-SC0012315, DE-SC0013911 and DE-SC0020357, by the College of Engineering at the University of Wisconsin - Madison, and by the ITER Scientist Fellow Network. The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.
Motivation: compatibility of detached divertor plasmas with RMPs for ELM control

Control of divertor loads is required for next step magnetic fusion devices → detached plasma operation

Resonant magnetic perturbations (RMPs) will be used for ELM control in ITER

A 3D plasma edge model (EMC3-EIRENE) is required to analyze the impact on divertor performance

Staged Approach: Pre-Fusion Power Operation (PFPO): $P_{\text{SOL}} = 30 \, \text{MW}$, $B_t/I_p = 1.8 \, \text{T}/5 \, \text{MA}$, $q_{95} = 3$

Focus on $n = 3$ RMP field with coil phasing optimized for ELM control
Outline

1. EMC3-EIRENE: 3D model for the (steady state) plasma boundary
2. Plasma response effects on the magnetic topology
3. Divertor performance with RMP application
4. Sensitivity on assumptions within the plasma response model
EMC3-EIRENE extends the traditional (axisymmetric) framework for divertor performance analysis to 3 dimensions

- Magnetic geometry is input for plasma boundary modeling

- Boundary plasma is determined by particle, momentum, and energy balances

**Diagram:**
- Geometry
  - Magnetic field (equilibrium)
  - Divertor design
- Model parameters
  - 2D Plasma boundary model
  - SOLPS-4.3 / SOLPS-ITER
    - Plasma 🔄 Neutral gas
- Simulation data
  - Density
  - Temperature
  - Divertor loads

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Detached divertor conditions in RMP H-mode plasmas in ITER 3
EMC3-EIRENE extends the traditional (axisymmetric) framework for divertor performance analysis to 3 dimensions.

- Magnetic geometry is input for plasma boundary modeling and can include plasma response effects (MARS-F, ...)

- Boundary plasma is determined by particle, momentum, and energy balances.

H. Frerichs (hfrerichs@wisc.edu) [Detached divertor conditions in RMP H-mode plasmas in ITER]
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Resistive single fluid calculations (MARS-F) show strong screening of resonant field components

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- Ideal magneto-hydrodynamics (MHD) suggests screening of resonant fields

- Strong **screening** response is recovered in resistive single fluid (MARS-F) calculations

- But plasma response includes field **amplification** near separatrix
  \[\rightarrow\] important for divertor operation
Plasma response affects size and radial connection of magnetic footprint

Unperturbed configuration

Reference

H. Frerichs (hfrerichs@wisc.edu)  Detached divertor conditions in RMP H-mode plasmas in ITER
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Perturbed separatrix guides field lines from the bulk plasma to divertor targets

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- Screening: reduced radial extent of perturbed SOL

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Detached divertor conditions in RMP H-mode plasmas in ITER
Plasma response affects size and radial connection of magnetic footprint

- Perturbed separatrix guides field lines from the bulk plasma to divertor targets
- **Screening**: reduced radial extent of perturbed SOL
- But large non-axisymmetric footprint from field amplification in competition with screening

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1. EMC3-EIRENE: 3D model for the (steady state) plasma boundary
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EMC3-EIRENE simulations show heat flux peaking correlated with radial connection of perturbed field lines

- Model parameters: $\Gamma_{\text{gas}} = 3 \cdot 10^{22} \text{ s}^{-1}$, $P_{\text{SOL}} = 30 \text{ MW}$, $D_\perp = 0.3 \text{ m}^2 \text{ s}^{-1}$, $\chi_\perp = 1 \text{ m}^2 \text{ s}^{-1}$

- Reference (unperturbed) configuration still attached
EMC3-EIRENE simulations show heat flux peaking correlated with radial connection of perturbed field lines

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H. Frerichs (hfrerichs@wisc.edu) Detached divertor conditions in RMP H-mode plasmas in ITER
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- RMPs: earlier onset of detachment in original strike zone (OSZ)
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- RMPs: earlier onset of detachment in original strike zone (OSZ)

- Far SOL remains attached with heat flux peaking away from OSZ

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- RMPs: earlier onset of detachment in original strike zone (OSZ)
- Far SOL remains attached with heat flux peaking away from OSZ

next: evaluate OSZ and compare to far SOL
RMPs: significantly different exhaust characteristics at primary and secondary strike locations

- Divertor performance is evaluated with gas puff (density) scan

- Particle flux roll-over found in reference (unperturbed) configuration

![Graph showing particle load vs. upstream density](image)

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RMPs: significantly different exhaust characteristics at primary and secondary strike locations

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- Early detachment of primary perturbed strike location

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RMPs: significantly different exhaust characteristics at primary and secondary strike locations

- Divertor performance is evaluated with gas puff (density) scan
- Particle flux roll-over found in reference (unperturbed) configuration
- Early detachment of primary perturbed strike location
- Secondary perturbed strike location remains attached

Detected divertor conditions in RMP H-mode plasmas in ITER
Leading role of $T_t$ facilitates parametrization of characteristic curves for divertor operation

Boundary condition sets link between particle and heat loads:

$$\Gamma_t = \frac{q_t}{\gamma T_t}, \quad Q_t = q_t + \varepsilon \Gamma_t$$

thermal load

from surface recombination

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- Power losses in the divertor provide link to heat flux from bulk plasma:

  $$q_t = (1 - f_{\text{cool}}) \cdot \underbrace{q_{\parallel} \cdot B_t / B_u \cdot \sin \vartheta}_{= \hat{q}}$$
Leading role of $T_t$ facilitates parametrization of characteristic curves for divertor operation

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  \]

- Parametrization of $f_{\text{cool}}$:
  \[
  1 - f_{\text{cool}}(T_t) = A \left( 1 - e^{-T_t/T^*} \right)^\alpha
  \]

\[\begin{align*}
A & = 0.9 - 1.1, \quad T^* = 2.4 - 6, \quad \alpha = 1.6 - 1.9
\end{align*}\]

P.C. Stangeby PPCF 60 (2018) 044022

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Qualitative explanation by splitting of upstream heat flux and different radial field line connections

Toy model captures roll-over of unperturbed SP

- Splitting of perturbed heat flux consistent with reduction of peak particle load by factor 2
- Primary SP is on low T branch ahead of secondary SP on same (type of) curve
- Higher T consistent with deeper radial connection from secondary SP to higher T
Qualitative explanation by splitting of upstream heat flux and different radial field line connections

Toy model captures roll-over of unperturbed SP

Primary Channel
Secondary Channel

Splitting of perturbed heat flux consistent with reduction of peak particle load by factor 2

Primary SP is on low \( T \) branch ahead of secondary SP on same (type of) curve

Higher \( T \) consistent with deeper radial connection from secondary SP to higher \( T \)

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- Higher $T_t$ consistent with deeper radial connection from secondary SP to higher $T_u$
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Footprint size is sensitive to rotation profile in MARS-F

- **Amplification** competes with **screening**, and depends on assumed rotation profile

![Graph showing Omega vs. s for different Pr and tau/tau_E values.](image)

L. Li *et al.*, Nucl. Fusion 59 (2019) 096038
**Footprint size is sensitive to rotation profile in MARS-F**

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L. Li et al., Nucl. Fusion 59 (2019) 096038

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H. Frerichs (hfrerichs@wisc.edu) | Detached divertor conditions in RMP H-mode plasmas in ITER
Footprint size is sensitive to rotation profile in MARS-F

- **Amplification** competes with screening, and depends on assumed rotation profile.
- Significant extension of footprint possible from strong amplification near separatrix.

(L.Li et al., Nucl. Fusion 59 (2019) 096038)

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Heat loads may occur far outside of dedicated high heat flux region.
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Heat loads may occur far outside of **dedicated high heat flux region**

Optimal coil phasing for ELM control may not be optimal for divertor operation at full power → rotate RMPs

L. Li et al., Nucl. Fusion 59 (2019) 096038
Optimal ELM control phasings imply large footprint size

- ELM control optimized based on displacement near X-point
- Footprint size $s$: max. distance from original strike point with connection to $\Psi_N < 1$

![Diagram showing footprint size and ELM control phasings](image)

- Reduced divertor closure at $s \gtrsim 70 \text{ cm}$ (soft limit), and extension beyond dedicated high heat flux region (hard limit at full power?) → **reliable prediction of plasma response required!**

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Detached divertor conditions in RMP H-mode plasmas in ITER
Conclusions

1. An earlier transition to detachment is found at the OSZ with RMPs while the far SOL non-axisymmetric SP remains attached
   → high $T_t$ at secondary SP is problematic for extrinsic impurities required for dissipation at full power

2. Non-axisymmetric particle and heat loads during RMP application are sensitive to the plasma response (in particular the toroidal rotation used in MARS-F)
   → Optimal coil phasing for ELM control not optimal for divertor operation?
     (rotation of RMPs possible but should be avoided)
   → Reliable predictions for plasma response models required!

H. Frerichs (hfrerichs@wisc.edu)
Detached divertor conditions in RMP H-mode plasmas in ITER
Plasma response determines radial extent of perturbed SOL

- Screening response: smaller, non-overlapping island chains
  → reduced radial extent of perturbed SOL

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Detached divertor conditions in RMP H-mode plasmas in ITER
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Perturbed SOL: field lines connect to divertor targets

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Detached divertor conditions in RMP H-mode plasmas in ITER
Plasma response determines radial extent of perturbed SOL

- Screening response: smaller, non-overlapping island chains
  $\rightarrow$ reduced radial extent of perturbed SOL

- Perturbed SOL: field lines connect to divertor targets
  $\rightarrow$ higher edge temperature can be sustained with RMP screening

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Detached divertor conditions in RMP H-mode plasmas in ITER
Heat loads may occur far from original strike zone depending on plasma response

- Model parameters: $\Gamma_{\text{gas}} = 3 \cdot 10^{22} \text{s}^{-1}$, $P_{\text{edge}} = 30 \text{MW}$, $D_\perp = 0.3 \text{m}^2\text{s}^{-1}$, $\chi_\perp = 1 \text{m}^2\text{s}^{-1}$

Reference  Vacuum approximation  MARS–F (slow rotation)  MARS–F (fast rotation)

Optimal coil phasing for ELM control may not be optimal for divertor operation
MARS-F plasma response includes both **screening** of resonances within the bulk plasma and **amplification** near the separatrix.
Absence of power and momentum losses confirm: secondary SP (RMPs) remains attached

Evaluate power and momentum losses with respect to divertor entrance:

\[ 1 - f_{\text{cool}} = \frac{q_t}{q_u^{(\text{tot.})}} \]

\[ 1 - f_{\text{mom}} = \frac{p_t^{(\text{tot.})}}{p_u^{(\text{tot.})}} \]

Power losses

Momentum losses

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Detached divertor conditions in RMP H-mode plasmas in ITER
What are the implications of 2ndary SP for divertor operation?

- Initially even weaker $T_t$ scaling than traditional attached conditions ($T_t \sim \Gamma_t^{-1}$) because of increasing $\dot{q}$
  \[ T_t = \Gamma_t^{-0.58} \]
  \[ T_t = \Gamma_t^{-1.04} \]
  \[ \rightarrow \] increasing $q_t$ observed at EAST (J. Li, Nature Physics 9 817 (2013))

- High $T_t$ increases sputtering on tungsten plates

- Field lines connect deeper into the plasma
  \[ \rightarrow \] even higher $T_u$ at full power

- From divertor entrance (X-point) to targets: shorter connection length
  \[ \rightarrow \] less dissipation possible (even if $T_t$ can be brought down)
Linearization of $S_{ee}$ provides stabilization at low divertor temperatures

First order Taylor expansion allows more accurate treatment of $T_e$ dependence:

$$S_{ee}^{(j)} \approx S_{ee}(T_e^{(j-1)}) + \left( T_e^{(j)} - T_e^{(j-1)} \right) \left. \frac{dS_{ee}}{dT_e} \right|_{T_e^{(j-1)}}$$
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- Source decomposition (linearization) can be stabilizing if $S_{ee1} \leq 0$:

$$S_{ee} \approx S_{ee0} + T_e \cdot S_{ee1}$$

explicit method

implicit method

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Detached divertor conditions in RMP H-mode plasmas in ITER
Linearization of $S_{ee}$ provides stabilization at low divertor temperatures

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  S_{ee}^{(j)} \approx S_{ee}(T_e^{(j-1)}) + \left( T_e^{(j)} - T_e^{(j-1)} \right) \frac{dS_{ee}}{dT_e} \bigg|_{T_e^{(j-1)}}
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- Source decomposition (linearization) can be stabilizing if $S_{ee1} \leq 0$:

  \[
  S_{ee} \approx S_{ee0} + T_e \cdot S_{ee1}
  \]

  - **explicit method**
  - **implicit method**

**Graph:***

Averaged Temperature at inner target

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Detached divertor conditions in RMP H-mode plasmas in ITER
EMC3: A 3D fluid model for the (steady state) edge plasma

Particle balance ($n$: plasma density)

\[ \nabla \cdot \left[ n u_{||} - D_{\perp} e_{\perp} \cdot \nabla n \right] = S_p \]

$D_{\perp}$: anomalous cross-field diffusion, $S_p$: ionization of neutral particles
EMC3: A 3D fluid model for the (steady state) edge plasma

Particle balance ($n$: plasma density)

$$\nabla \cdot \left[ n u \| e \| - D_\perp e_\perp e_\perp \cdot \nabla n \right] = S_p$$

Momentum balance ($u\|$: fluid velocity parallel to magnetic field lines)

$$\nabla \cdot \left[ m_i n u^2 \| e \| - \eta_\| e \| \cdot \nabla u \| - D_\perp e_\perp e_\perp \cdot \nabla (m_i n u \|) \right] = -e \| \cdot \nabla (T_e + T_i) + S_m$$

$$\eta_\perp = m_i n D_\perp$$: anomalous cross-field viscosity,

$$S_m$$: interaction (CX) with neutral particles
EMC3: A 3D fluid model for the (steady state) edge plasma

Particle balance ($n$: plasma density)

$$\nabla \cdot \left[ nu_{\parallel} e_{\parallel} - D_{\perp} e_{\perp} \cdot \nabla n \right] = S_p$$

Momentum balance ($u_{\parallel}$: fluid velocity parallel to magnetic field lines)

$$\nabla \cdot \left[ m_i n u_{\parallel}^2 e_{\parallel} - \eta_{\parallel} e_{\parallel} \cdot \nabla u_{\parallel} - D_{\perp} e_{\perp} \cdot \nabla (m_i n u_{\parallel}) \right] = -e_{\parallel} \cdot \nabla n (T_e + T_i) + S_m$$

Energy balance ($T_e, T_i$: electron and ion temperature)

$$\nabla \cdot \left[ \frac{5}{2} T_e (nu_{\parallel} e_{\parallel} - D_{\perp} e_{\perp} \cdot \nabla n) - (\kappa_e e_{\parallel} + \chi_e n e_{\perp}) \cdot \nabla T_e \right] = +K (T_i - T_e) + S_{ee} + S_{e,imp}$$

$$\nabla \cdot \left[ \frac{5}{2} T_i (nu_{\parallel} e_{\parallel} - D_{\perp} e_{\perp} \cdot \nabla n) - (\kappa_i e_{\parallel} + \chi_i n e_{\perp}) \cdot \nabla T_i \right] = -K (T_i - T_e) + S_{ei}$$

$\chi_e, \chi_i$: anomalous cross-field transport

$S_{e...}$: interaction with neutral particles and impurities
EMC3: A 3D fluid model for the (steady state) edge plasma

Particle balance ($n$: plasma density)

$$\nabla \cdot \left[ n u_\parallel e_\parallel - D_\perp e_\perp \cdot \nabla n \right] = S_p$$

Momentum balance ($u_\parallel$: fluid velocity parallel to magnetic field lines)

$$\nabla \cdot \left[ m_i n u_\parallel^2 e_\parallel - \eta_\parallel e_\parallel \cdot \nabla u_\parallel - D_\perp e_\perp \cdot \nabla (m_i n u_\parallel) \right] = -e_\parallel \cdot \nabla n (T_e + T_i) + S_m$$

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$\chi_e, \chi_i$: anomalous cross-field transport  $S_{e...}$: interaction with neutral particles and impurities

Y. Feng et al. PPCF 59 (2017) 034006
Energy losses are very sensitive at low temperature

- EIRENE: kinetic transport of neutral particles
  \[ \rightarrow n_H, n_{H_2}, n_{H_2^+} \]

convolution of atomic and molecular processes

Energy loss rate coefficients

![Graph showing energy loss rate coefficients versus electron temperature]

- Rate coefficient [eV cm$^3$ s$^{-1}$]

- Detached divertor conditions in RMP H-mode plasmas in ITER
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Energy losses are very sensitive at low temperature

- EIRENE: kinetic transport of neutral particles
  \[ \rightarrow n_H, n_{H_2}, n_{H_2^+} \]
  convolution of atomic and molecular processes

- Energy losses from electron impact processes:
  \[ S_{ee} = - \sum_{\chi} n_e \cdot n_{\ldots} \cdot R_{\chi}(T_e, n_e) \]


\begin{align*}
  e + H & \rightarrow 2e + H^+ \\
  e + H_2 & \rightarrow e + H + H \\
  2e + H + H^+ & \rightarrow 2e + H^+ + H^+ \\
  e + H_2^+ & \rightarrow 2e + H^+ + H^+ \\
  H + H^+ & \rightarrow H^+ + H
\end{align*}

AMJUEL / HYDHEL
Rate coefficient [eV cm$^3$ s$^{-1}$]
Electron Temperature [eV]
Energy losses are very sensitive at low temperature

- **EIRENE**: kinetic transport of neutral particles
  
  $\rightarrow n_H, n_{H_2}, n_{H^+_2}$

  convolution of atomic and molecular processes

- Energy losses from electron impact processes:
  
  $S_{ee} = - \sum_X n_e \cdot n_{\ldots} \cdot R_X(T_e, n_e)$

- Iterative approximation of energy balance:
  
  $S_{ee}^{(j)} \approx S_{ee}(T_e^{(j-1)})$

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Linearization of $S_{ee}$ provides stabilization at detachment relevant low divertor temperatures

attached conditions:

$S_{ee}^{(j)} \approx S_{ee}(T_e^{(j-1)})$
Linearization of $S_{ee}$ provides stabilization at detachment relevant low divertor temperatures

- Temperature dependence of $S_{ee}$ is not treated accurately enough at low $T_e$ relevant for detachment

\[
S_{ee}^{(j)} \approx S_{ee}\left(T_{e}^{(j-1)}\right)
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Linearization of $S_{ee}$ provides stabilization at detachment relevant low divertor temperatures

- Temperature dependence of $S_{ee}$ is not treated accurately enough at low $T_e$ relevant for detachment

- More accurate treatment of $T_e$ dependence based on first order Taylor expansion:

$$S_{ee}^{(j)} \approx S_{ee}(T_e^{(j-1)}) + \left( T_e^{(j)} - T_e^{(j-1)} \right) \left. \frac{dS_{ee}}{dT_e} \right|_{T_e^{(j-1)}}$$

H. Frerichs (hfrerichs@wisc.edu)
Extended operation range of EMC3-EIRENE is verified by comparison to SOLPS-ITER

- H-plasma (PFPO, no seeded impurities), model parameters:
  \[ D_\perp = 0.3 \, \text{m}^2\text{s}^{-1}, \chi_\perp = 1 \, \text{m}^2\text{s}^{-1} \]

- Self-consistent particle balance \( \Gamma_{\text{pump}} = \Gamma_{\text{gas}} + \Gamma_{\text{core}} \) including recirculation below the dome
  \[ \rightarrow \text{Semi-transparent dome support (50\%)} \]
  \[ \text{Pumping (0.72\%)} \]

- Include N-N collisions (BGK), molecular assisted recombination (MAR)

- Fueling scan (\( \Gamma_{\text{gas}} \)) \( \rightarrow \) evaluate neutral pressure & divertor loads
Extended operation range of EMC3-EIRENE is verified by comparison to SOLPS-ITER

- Continuous reduction of peak heat flux during gas puff scan

Heat load profiles (Outer target)

Gas puff \([10^{22} \text{ s}^{-1}] = 0.15\)

EMC3-EIRENE (solid)
SOLPS-ITER (dashed)

Divertor Neutral Pressure [Pa]

Peak particle load (Outer target)

SOLPS-ITER
EMC3-EIRENE

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Detached divertor conditions in RMP H-mode plasmas in ITER
Extended operation range of EMC3-EIRENE is verified by comparison to SOLPS-ITER

- Continuous reduction of peak heat flux during gas puff scan

![Heat load profiles (Outer target)](image)

Gas puff $[10^{22} \text{s}^{-1}] = 0.15, 0.38, 0.89, 1.13$

- EMC3-EIRENE (solid)
- SOLPS-ITER (dashed)
Extended operation range of EMC3-EIRENE is verified by comparison to SOLPS-ITER

- Continuous reduction of peak heat flux during gas puff scan

Heat load profiles (Outer target)

Gas puff \([10^{22} \text{ s}^{-1}]\) = 0.15

0.38

0.89

1.13

3.31

6.80

Heat load \([\text{MW m}^{-2}]\)

Distance from Separatrix \([\text{cm}]\)

- Detached divertor conditions in RMP H-mode plasmas in ITER

H. Frerichs (hfrerichs@wisc.edu)
Extended operation range of EMC3-EIRENE is verified by comparison to SOLPS-ITER

- Continuous reduction of peak heat flux during gas puff scan
- A clear roll-over of peak particle flux is found by both codes in good agreement

**Heat load profiles (Outer target)**

Gas puff \(10^{22} \text{s}^{-1}\) = 0.15, 0.38, 0.89, 1.13, 3.31, 6.80

EMC3-EIRENE (solid) SOLPS-ITER (dashed)

**Peak particle load (Outer target)**

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Detached divertor conditions in RMP H-mode plasmas in ITER