Tungsten impurity transport experiments in Alcator C-Mod to address high priority R&D for ITER

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Background

- ITER will employ a full tungsten divertor from day one
- the negative impact of excessive high-Z (Mo, W, etc.) impurities has been well demonstrated over decades of MCF research
  - perturbation through radiation, not through dilution \( (Z^*n_Z) \) or \( Z_{\text{eff}} \)
  - we seek to manage this through control of impurity source and transport (boundary + core)
- research on AUG/JET shows the tendency to accumulate in the plasma center in H-mode [C. Angioni - NI1.00003 (Wed. AM)]
  - high-Z neoclassical transport enhanced by centrifugal force, core fueling
  - ICRH can mitigate effect, minority/impurity interactions can be important
- motivated ITER W transport modelling and experiments on Alcator C-Mod to study W transport in plasmas without sources of core momentum and particles
  - C-Mod experiments proposed in March 2014 Ideas Forum
GLF23/NCLASS modelling of ITER tungsten transport
- on-axis ICRH/ECRH will modify core profiles to drop on-axis \(n_w\)
- introduce Alcator C-Mod, diagnostics used to track high-Z imp.
- H-mode plasmas used to investigate effects of core RF heating
  - D(H) ICRH leads to kinetic profile changes (\(a/L_{ne}\), \(a/L_{Ti}\)) that would modify neoclassical transport from inward to outward
- tungsten transport investigated using laser-blow off
  - mid-radius W profile is nominally flat, with intra-sawtooth peaking
  - increase in on-axis peaking with increased minority concentration

**GOAL: use C-Mod to provide insight into ITER modelling**
- similarities/differences between C-Mod and ITER response to \(P_{RF}\)
- empirically determine what could be missing from the ITER modelling
- (eventually) try and validate modelling codes against C-Mod data
ITER Modelling Using GLF23/NCLASS

- simulations of W transport carried out with ASTRA and JINTRAC using GLF23 model for anomalous transport
  - pedestal plasma conditions from EPED model used as “boundary” conditions
  - core energy and particle + W transport GLF23 + neoclassical (NCLASS)
    ✓ \( \chi_e = \chi_{e\text{-neo}} + \chi_{e\text{-GLF}} \)
    ✓ \( \chi_i = \chi_{i\text{-neo}} + \chi_{i\text{-GLF}} \)
    ✓ \( \chi_{\text{torque}} = \chi_{i\text{-neo}} + P_r \times \chi_{i\text{-GLF}} \)
    ✓ \( D = D_{i\text{-neo}} + D_{\text{GLF}} ; V = V_{i\text{-neo}} + V_{\text{GLF}} \)
    ✓ \( D_W = D_{W\text{-neo}} + D_{W\text{-GLF}} ; V_W = V_{W\text{-neo}} + V_{W\text{-GLF}} \)
- simulations carried out for 15MA/5.3T with \( Q \sim 10 \)
  - 33 MW NBI + 20 MW RF (ICRH and ECRH) with on-axis and off-axis RF
  - \( P_r \) adjusted to get target confinement
- for all cases relatively small W core peaking is found in ITER due to low \( n_i \) peaking in the core (low NBI source)
- ECRH and ICRH have power densities similar to alpha heating, allowing and affect core profiles and the tungsten transport
W-Peaking Reduced Using 20 MW of Core Heating

- main ion thermal transport and W transport is anomalous in wide plasma region except very center \((r/a \leq 0.2-0.3)\) where it is neoclassical
- absolute level and ability for peaking to impact core depends on source level, tungsten transport in the edge transport barrier region
- modelling shows auxiliary heating (on-axis ECRH/ICRH) can reduce the peaking

![Graph showing normalized \(n_W\) and \(D_W\) with different heating scenarios](image)
Auxiliary Heating Power Densities Compete with Alpha Heating

IONS - $\alpha$

IONS - AUX

ELEC - $\alpha$

ELEC - AUX

$P_{\alpha}$ (ions (MWm$^{-3}$))

$P_{\alpha}$ (electrons (MWm$^{-3}$))

$P_{\text{aux}}$ (ions (MWm$^{-3}$))

$P_{\text{aux}}$ (electrons (MWm$^{-3}$))

Graphs showing the comparison of auxiliary heating power densities with alpha heating for ions and electrons under different heating conditions.
Power is Sufficient to Modify Profile Gradients

- replacing off-axis ECRH with central ICRH increases temperature scale length at fixed $a/L_{ni}$
- moving ECRH on-axis increases $a/L_{Ti}$ and drops $a/L_{ni}$

Power is Sufficient to Modify Profile Gradients
Alcator C-Mod is a compact ($R_0=0.68$), high field ($B_T<8$ T) tokamak featuring wave-based heating & current drive tools

- Lower Hybrid Current Drive: 4.6 GHz [Mumgaard - Y11.00002 (Fri AM)]
- Ion Cyclotron Res. Heating: 78/80 MHz, D(H) [Lin - Y11.00003 (Fri AM)]

**kinetic profile diagnostics**

- Thomson scattering: $n_e, T_e$
- electron cyclotron emission: $T_e$
- x-ray imaging crystal spec: Ti, $\omega$

**multi-pulse Laser Blow-Off (LBO) used to inject W**
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Multi-pulse Laser Blow-Off (LBO) used to inject W

- Radially and vertically viewing SXR tomography x2 38-channel arrays (50 $\mu$m Be)
- Horizontally viewing midplane AXUV diode arrays and resistive bolometry
- Radially viewing, flat-field VUV spectroscopy (1-7 nm, 10-30 nm)
ionization and recombination rates are large making it hard to for transport to disturb coronal equilibrium

- diffusive STRAHL simulations for C-Mod EDA H-mode

- little change in mid-radius charge states emitting in UTA

- stronger drop possible for core production of higher ion. states

  - replaced by lower charge state, so net radiation, SXR emission more weakly perturbed

**motivation to bring our best diagnostic to future W transport experiments - XI CS**
Tungsten Transport Probed in Low-Collisionality EDA H-modes

- low-Ip, high $P_{RF}$ allows access to low $0.3 < \nu_{\text{EFF}} < 1.0$, peaked density regimes [Greenwald NF 2007, Chilenski PO3.00006 Wed PM]

- new experiments scanned $I_p$ & $P_{RF}$ operating space with LBO
  - $6 < q_{95} < 8$
  - LOW POWER: LBO causing H/L back transition (W-persists!)
  - HIGH POWER: operational limit due to fast-ion orbit loss

- scanned minority/impurity coupling $H_2$ puffing (< 10%)
  - motivated by initial result from JET [Casson PPCF 2014]
Peaked Density and Decoupling of Ion and Electron Temperatures Observed

- Density peaking achieved
- Found significant difference between $T_e$ and $T_i$ profiles
- Important for analysis of neoclassical transport to distinguish $a/LT_e$ and $a/LT_i$
- Most of the dataset shows poloidally symmetric impurities
  - $|n_{z,\cos}| < 0.05$ for $r/a < 0.4$
  - Weak centrifugal effect (hollow rotation profiles) balanced by minority anisotropy
  - H$_2$ puffing cases have stronger LFS localization
- Shafranov shift led to slightly high-field side heating

**Graph:**
- $P_{RF}=1.5 \, [MW]$  
- $P_{RF}=3.0 \, [MW]$  
- Cross-calibration w/ high $\nu_*$ (flat $n_e$, $T_e=T_i$) plasmas used to reduce TS/XICS diagnostic uncertainties
RF Power Modifies $a/L_{ne}$, $a/L_{Ti}$

- pre-LBO profiles in each plasma (x16) examined, looking at cases modifying direction of neo. imp. transport ($a/L_{ni} - 0.5a/L_{Ti} > 0$)

\[
\frac{\alpha}{L_X} = -\frac{1}{X} \frac{\partial X}{\partial \rho} \quad \rho = \frac{R_{LFS} - R_0}{\alpha_{LFS}}
\]

- core ($r/a = 0.25, 0.15$) sits just above, straddles boundary and does not change with ICRF power
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- $r/a=0.55$: increased $P_{RF}$ modifies profiles from outward to inward neo. imp. transport
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\[ \gamma \equiv -\frac{1}{\Lambda_{x}} \frac{\partial X}{\partial \rho} \]
\[ \rho = \frac{R_{\text{LFS}} - R_{o}}{a_{\text{LFS}}} \]

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ICRH Leads to Different $a/L_Ti$ & $a/L_Te$

- **$r/a=0.35$**: increasing ICRF power (marginal) increase of $a/L_Ti$
  - brings it closer to $a/L_te$
  - Gradient limited $T_e$ and $T_i$
- **$r/a=0.55$**: increasing ICRF power decreases $a/L_Ti$
  - $a/L_Ti <$ half of $a/L_Te$
  - outside the RF heating volume

**Different than ITER simulations**

- *which found* $a/L_Te \sim a/L_Ti$ for on-axis ICRH for all $r/a$
  - $C$-Mod ICRF power balance $IONS/ELEC < 0.6$
  - *ITER has strong equipartition*
ITER Kinetic Profile Shapes Similar To Those Achieved in Alcator C-Mod

- addition of both on-axis ECRH and ICRH result in profiles similar to those achieved with ICRF scan of present C-Mod experiments
  - shows a better agreement at the lower power C-Mod shots
- input power densities on C-Mod well in excess of expectations for ITER
  - ITER ICRH: peak 0.7 (elec), 0.7 (ion) [MW/m³] @ 1.0x10²⁰ [m⁻³]
  - C-Mod ICRH: peak ~20 (elec), 7-9 (ion) [MW/m³] @ 2.5x10²⁰ [m⁻³]
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Are changes in kinetic profiles impacting impurity transport?
examine ST-averaged resistive bolometer and SXR tomography before injection and at peak change in radiation attributed to tungsten can be used to estimate density and rough profile shape

$$n_z = \frac{\Delta \varepsilon}{n_e L_z (T_e)}$$

absolute density within x2 from SXR and bolometry, $f_W < 10^{-4}$

no significant peaking in inner half of the plasma found

peaking in the outer 1/3 needs to be examined further

pedestal high-Z transport open topic!
Mid-Radius Transport Appears Anomalous Despite Profile Changes

- AXUV diode arrays show prompt inward radiation front
  - no change between \( r/a = 0.55 \) and \( r/a = 0.35 \) where neo. impurity flux changes sign
- spectroscopy (W UTA) shows fast (< 10 ms) rise time

**GOOD NEWS:** \( n_i \) peaking in regions with anomalous impurity transport avoid W accumulation and improve ITER fusion performance
*(not too surprising if density peaking is turbulent driven)*
Approaching Core Transport Slows, Sawteeth Impact Observed

- AXUV show for r/a < 0.3, front slows, becomes modulated by sawtooth instability
- Core localized spectroscopy (W XLIII/XLIV and XLV) show slower (~20 ms) rise time and sawtooth perturbations

**CHALLENGE:** investigate if core, intra-sawtooth changes represent tungsten peaking and if ICRF power is having an impact on imp. transport
Estimate $a/LnW$ from SXR Emissivity Gradient Scale Length, $a/Lem$

$$n_W = \frac{\varepsilon_{SXR}(r)}{n_eL_W(T_e)}$$

$$\frac{\nabla n_W}{n_W} = \frac{\nabla \varepsilon_{SXR}}{\varepsilon_{SXR}} - \frac{T_e}{L_W} \left( \frac{\partial L_w}{\partial T_e} \right) \frac{\nabla T_e}{T_e} - \frac{\nabla n_e}{n_e}$$

- can have $a/LnW < 0$ with $a/Lem > 0$!
- ranges relevant for these experiments
  - $0 < a/Ln_e < 0.5$
  - $0.5 < a/LT_e < 1.5$
  - $0.5 < \text{atomic physics} < 3$
    - at $T_e=3.2$, both models agree!
- $a/Lem$ taken from experiment
- $a/LnW = a/Lem - (0.25 \text{ to } 5)$
LBO increases SXR emission well above background

results in varying impact on $T_{e,0}$
EXAMPLE: Intra-Sawtooth SXR Analysis

- LBO increases SXR emission well above background
- results in varying impact on $T_{e,0}$
- background subtracted emissivity used to compute emission gradient scale length $a/L_{em}$
- intra-sawtooth behavior shows repeatable cycle, reaching stationary scale length at $r/a=0.15$

$r/\ a=0.15$
ICRF Power Scan Shows Weak Change in Impurity Peaking at $r/a \sim 0.15$

- intra-sawtooth trajectories of $a/L_{em}$ show slight drop in peak as ICRF power is increased
  - $a/L_{em} \sim 5 \rightarrow 3$
  - could simply be atomic physics
- absolute level consistent with flat to weakly peaked ($a/LnW \sim 2$) profiles
Increasing Minority Concentration Increases Core Impurity Peaking

- limited scan of $\text{H}_2$ puff and ICRF power level shows strongest change in $a/L_{\text{Em}}$ within dataset
- increasing minority fraction at fixed ICRF power leads to x3 increase of $a/L_{\text{Em}}$ at nominally fixed $T_e$
- increasing ICRF power at fixed minority fraction drops $a/L_{\text{Em}}$
- trend shows peaking decreases as power/minority density increases
  - i.e. high energy tail decouples minority and impurity ions
Increasing Minority Concentration Increases Core Impurity Peaking

consistent with JET findings [Casson PPCF 2014] that highlight minority-impurity friction as an important component of high-Z neoclassical transport

potential implications for ITER simulations which only account interactions between high-Z impurities and thermal ions
Open Issues For Continued Alcator C-Mod/ITER Comparison Experiments

- GLF23 w/o rotation effects and pedestal boundary conditions produces $Q \sim 6$ for ITER, rotation effects are used to tune transport for $Q \sim 10$
  - anomalous transport, key for flat $n_W$ needs to be check by other models
- choice of electron temperature stiffness, formulation of momentum transport ($\chi_{\text{torque}} = \chi_{i-neo} + P_r \times \chi_{i-GLF}$) a range of main-ion Mach # obtained
  - in general low $M_{DT} \sim 0.1$ but can be as large as 0.4 depending on choices for $Q \sim 10$ in ITER from the NBI torque alone
  - Alcator C-Mod experiments shown here have $M_i < 0.05$ but can reach up to 0.2 with intrinsic rotation
- NCLASS used for impurity transport, which does not include centrifugal effects (NEO) which will may be present in ITER if $v_{z}/v_{th,z} \sim 8.5M_{DT} \sim 1$
- no effect of fast particles ($\alpha$’s, NBI ions, ICRH minority ions) on W neoclassical transport is considered (NEO)
- effect of sawteeth shows no peaking between ST for ITER, further work required
- FUTURE: expand ITER/C-Mod simulations to NEO/GKW model demonstrated on JET/AUG [C. Angioni - Wed. AM] work w/ CCFE & IPP-Garching
GLF23/NCLASS simulations of ITER demonstrated on-axis auxiliary heating can modify W transport by modifying kinetic profiles
- on-axis ECH reduced a/LTi and a/Lni, on-axis ICRH increased a/LTi
- experiments conducted on Alcator C-Mod examined W impurity transport H-mode plasmas for the ITER-relevant case of wave-heated plasmas without core particle and momentum sources
- EDA H-mode w/o H₂ puffing exhibited flat or weakly peaked n_W
  - changes in a/Lne and a/LTi that favored inward neo. flux for r/a > 0.3 did not lead to qualitative change in the bulk W transport
- EDA H-modes with H₂ puffing showed decreasing that power/particle led to an increased peaking of core W
- continued experiments and modelling will help C-Mod benchmark core tungsten transport physics critical for the success of ITER