C-Mod plasma boundary program

Transport
  Turbulence
  Flow of power in SOL

Plasma-surface interaction
  High-Z compatibility with core
  Impurity transport
  New PSI diagnostic capabilities
  New outer divertor

Summary

Presented by B. Lipschultz
for the C-Mod group
Primary research themes derive from C-Mod’s features as well as research strengths

• **Transport** - central as it controls heat loads, impurity sources...
  - Perpendicular heat and particle flows
  - Parallel heat and particle flows
  - Divertor physics

• **Plasma-surface interaction** - Crucial information for a reactor (high-Z tiles)
  - Fuel retention in a high-Z environment
  - Effects of RF waves on the edge plasma and vice versa
  - Erosion, impurity transport and effects on the core plasma

• The above physics research certainly strongly supports ITER and what is needed for DEMO
At the same time boundary physics research has expanded to other areas

• C-Mod is addressing a range of reactor issues (heat loads, high-Z, heating, current drive) in an integrated way at reactor-like levels of power density & materials
  • At the same time the obvious influence of the boundary plasma on other aspects of the tokamak physics has drawn us into other research areas

**PSI science center** (Whyte)
- investigation of plasma interaction with tile surfaces

**New outer divertor**
- specifying currents, forces and physics requirements

**SOL & divertor transport**
**Plasma Surface Interaction**
LaBombard, Lipschultz, Terry, Whyte, Zweben, students

**Pedestal**
- density limit physics
- turbulence and perp. transport
- L-H threshold

**ICRF**
- impurity sources and B coatings
- Effects of RF waves on SOL and vice versa
- RF-induced sheaths and flows

**LHCD**
- Investigation of the role of SOL in LHCD density limit
- planning for future experiments and diagnostics
Transport: New data & analysis suggest that turbulence at $k \rho_s \sim 0.1$ plays a key role in transport through the edge

Working Hypothesis:

- Energy is being input at a measured size scale, $k \rho_s \sim 0.1$ (both L-mode and EDA H-mode)
  - In L-mode this energy is well-coupled to larger and smaller size scales
  - In EDA H-mode the coupling is reduced and/or the drive is larger

- Gas puff imaging (GPI) turbulence measurements inside the separatrix
  - Need tools to follow the phase coupling and spectral transfer of energy (e.g. GPI spectral analysis)
  - Need tools to probe the spectrum at $k \rho_s \sim 0.1$ (e.g. QCM antenna)
  - Need tools to separate energy vs particle transport (e.g. new T scanning probe head)
Transport: Bi-spectral analysis being used to determine the coupling between different spatial scales/frequencies

- shows the magnitude of coupling of QCM fundamental with itself, producing the 2nd harmonic
- shows the magnitude of coupling of QCM fundamental to 2nd harmonic, producing 3rd harmonic (higher frequencies)
- The strength of QCM bi-coherence correlates with confinement quality ($H_{98}$)
  - some coupling between QCM and lower freq. broadband turbulence observed

**Future plans (2011-2013)**
- Investigate relationship between QCM and H98
- Investigate coupling of QCM to lower frequencies
Transport: Introducing the ‘QCM Antenna’ -- a new tool to explore and exploit boundary layer turbulence

Goal: Inductively couple with and reinforce \( J_\parallel \) filament structures at \( k_\theta \) of QCM -- the most unstable and important \( k_\theta \) in boundary layer turbulence

We desire a ‘knob’ to turn up broad-band boundary layer EM turbulence and/or QCM phenomena, both to study it and to exploit it (control ped., impurities, SOL \( \lambda_q \),…)

‘QCM Antenna’

\[ f = 50 – 300 \text{ kHz} \]

\[ k_\theta = 1.5 \text{ cm}^{-1} \]

Field-aligned windings,

14.5 degrees (\( q_{95} \sim 3 \))

\( B_r \sim B_\theta \sim 1.5 \text{ mT} \)

at LCFS (60 amps)

(Note QCM:

\( B_r \sim B_\theta \sim 0.5 \text{ mT} \))

A simple ‘shoelace’ antenna made from moly wire can satisfy requirements.

\[ J_\parallel \text{ filaments in passing front of an antenna box} \]
Transport: Introducing the ‘QCM Antenna’ -- a new tool to explore and exploit boundary layer turbulence

Physics Experiments (Fall 2011-2012)
- Explore/extend stability boundary of QCM and WCM - excite QCM/WCM? a PhD Thesis topic
- Explore k-space coupling, local perturbation-induced transport
  Excite (at fixed k) and study boundary layer turbulence response via GPI/PCI (spectra) and probes (n, \( \Phi \), \( T_e \) phase and transport)
- Possible probe of edge momentum transport. Antenna may exert toroidal torque of \( \sim 0.03 \) N-m on QCM \( \Rightarrow \Delta V_\phi \sim 2 \) km/s
  May be detected by influence on doppler-shift of modes frequencies.

Targeted time scale
Design of in-vessel components is nearly complete
Key component procurement phase: Feb. - March
Installation during FY 2011 opening

First plasma experiments in FY12
Two recent advancements may facilitate reliable measurements of n, \( E_\theta \) and \( T_e \) fluctuations in scanning probe-accessible discharges.

1. **Advanced probe geometry** ~ avoids perturbation effect [2]
   Quantitative agreement was obtained between \( \langle \vec{n} \vec{E}_\theta \rangle / B \) and parallel return flows that circulate plasma.

2. **Mirror-probe development** [3]
   Fast-switching mirror-probe technique developed to measure n, \( V_f \) and \( T_e \) fluctuations on a single electrode at high bandwidth in a C-Mod [4].

Transport: Te fluctuation capability will allow measurement of particle, heat and momentum transport

Implementing the mirror technique on four midplane scanning probe electrodes, it should be possible to infer k-resolved $n$, $\phi$ and $T_e$ fluctuations and correlations.

### Particle Flux
$$\Gamma_r = \langle \tilde{n} \tilde{E}_\theta \rangle / B$$

### Heat Flux
$$Q_{er} = (5/2) \langle \tilde{P}_e \tilde{E}_\theta \rangle / B$$

### Reynolds Stresses
$$\langle \tilde{v}_r \tilde{v}_r \rangle \quad \langle \tilde{n} \tilde{v}_r \tilde{v}_r \rangle \quad \langle \tilde{v}_r \tilde{v}_\theta \rangle \quad \langle \tilde{n} \tilde{v}_r \tilde{v}_\theta \rangle$$

**Plan**
- Resume deployment of Mirror Langmuir Probe system for midplane scanning probe drive (this has been on hold)
- Target: commission system for experiments in FY2012

**Topics**
- Fluctuation spectra and turbulent particle, heat and momentum transport in:
  - QCM and edge plasma turbulence; active excitation of edge turbulence;
  - blob dynamics; ELMs; interplay of flows and turbulence…
- Comparison with turbulence codes…
Transport: Modeling of EDA H-mode plasmas shows coherent mode in pedestal

- Scrape-off Layer Turbulence (SOLT) code used to model EDA H-mode edge
- Collaboration with Lodestar (Myra, D’Ippolito, Russell) and PPPL
- 3D nonlinear electrostatic fluid and 2D in the plane perp. to B, with parallel closure

Results: 2 different cases modeled (q⊥, magnetic geometry)

- reasonable match between simulation & experiment for SOL Te, ne & q∥ profiles;
- simulation yields a persistent coherent mode (CMSOLT), which dominates the SOLT turbulence and bears qualitative resemblance to QCM in C-Mod’s EDA H-mode;
- although kperp ~1-2 cm⁻¹ for both the mode in SOLT simulation and the QCM, other differences are under investigation.

Plans (2011-2012):

- model L-modes – does the CMSOLT persist?
- compare scaling of L-mode heat flux widths with experiment
- compare simulation results with GPI turbulence data.
Transport: New x-correlation turbulence analysis
advancing the connection between turbulence & transport

raw image from GPI
fast camera

Results:
• measured turbulent-structure phase velocities ($V_{\text{rad}}$, $V_{\text{pol}}$) using x-correlations of time series;
• measured $<V_{\text{rad}} V_{\text{pol}}>$ correlations (Reynolds stress component, related to momentum transport)

Plans:
• search for poloidal zonal flows
• search for fast time dependencies in velocity spectra
• compare zonal flow results and blob tracking results with analytic theory and SOLT (Lodestar collab.)
Transport: Field line mapping of filaments provides new information on $k_{||}$ and the effect of magnetic equilibrium

Successfully cross-correlated “field-aligned” SOL turbulent structures - “blobs” from midplane to divertor region

Results:
• max x-corr. of ~40-75% between GPI fluct. and div. probe $I_{\text{sat}}$ fluct.
• max x-corr. of ~50-75% between GPI and scanning probe just outside divertor

Plans (2011-2013):
• establish time delay (if any) between midplane, div probe, & scanning probe fluctuations;
• determine upper-limit on $k_{||}$
• drive known field-aligned perturbation at div probe – is filament following field?
• test hypotheses of local B perturbations by blobs (Krashenninikov);

C-Mod PAC meeting, March 2-4, 2011
Transport: ICRF appears to be driving flows in the SOL

- Ohmic L-mode
  - Flows outside the separatrix in ion diamagnetic direction

- ICRF is affecting flows in SOL
  - Driving opposing poloidal flows
  - Could be evidence of convective cells which, if they exist, could enhance impurity transport into core

Future plans (2011-2012)
- Explore poloidal extent and connection to specific antennas by varying q
- Vary core resonance location, phasing, and confinement mode
Transport: Lower hybrid density limit correlates with changes in the SOL

• Lower Hybrid current drive results of the last several years point to a density limit
  ■ For $n_e \geq 0.8 \times 10^{20} \text{ m}^{-3}$ the current drive efficiency drops off faster than $1/n_e$
  ■ Concern that waves are traveling through SOL and being absorbed

Results:
• With LH power at high ne $r > r_{\text{antenna}}$
  ■ He ionization source is increased
  ■ Local density is increased
  ■ Evidence for increase in Te as well
  ■ $\Rightarrow$ power to far SOL & heating

• Plans (mix of Boundary and LH groups)
  ■ Mine old data for poloidal variation in pressure increases (2011)
  ■ Expand ionization source measurements to other locations (2011-2012)
  ■ Localized measurements of LH waves in far SOL (2011-2012)
  ■ Systematic experiments as a function of density and LH power (2011-2012)
  ■ Possible use of OSM/EIRENNE to explore the dominant processes
Transport: Lower hybrid density limit correlates with shift of Lyman alpha profile outwards

Results from ‘mining’ of 2007-2008 Lyα data:
- Lyα emissivity profile shifts during LHCD
- Shift increases as a function of density to the LH density limit
  ■ Not dependent on phasing
Transport: Heat Flux Footprint studies started in 2010

In support of the FY2010 Joint Facilities Research Target†, an extensive array of divertor heat flux diagnostics was installed in FY09/10 to diagnose the outer divertor strike point region.

Over the past year, dedicated experiments were performed to investigate heat flux ‘footprints’ for EDA H-modes and L-modes

Physics questions:
1) What is the connection of footprint to ‘upstream’ profiles?
2) What is the relationship, if any, to the pedestal and ‘critical gradients’

B. LaBombard et al., http://dx.doi.org/10.1016/j.jnucmat.2010.07.021
B. LaBombard et al., to be published in Phys. Plasmas.
Transport: EDA H-mode
Heat flux footprint is roughly set by midplane pressure profile

![Diagram of parallel heat flux and electron temperature](image)

- Divertor footprint best explained by $q_{||}$ from pressure mapping
  \[
  q_{||,\text{sheath}} \approx \gamma_{\text{sheath}} \frac{(nT_e)_{\text{mid}}}{2} C_{s,\text{div}}
  \]
as opposed to conduction ($q_{||} \sim T^{7/2}$).
- Peak $q_{||}$ proportional to core plasma energy, $W_{TH}$

Footprint $\leftrightarrow$ Pedestal Pressure Profile $\leftrightarrow$ Confinement

- Caveats/questions:
  - Does near SOL $\lambda_{q||}$ always track variations in pedestal pressure width?
  - Are non-thermal electrons enhancing $\gamma_{sh}$ near strike point
  - How different is $T_i$ from $T_e$ and the effect on $q$ profiles?

### 2011-2013 Plans:
1. Map out $\lambda_{q||}$ versus triangularity -- a known pedestal width control knob
2. Explore pedestal - $\lambda_{q||}$ relationship in I-modes, a regime with H-mode like $T_e$ profiles, but L-mode like $n$ profiles
3. Ion contribution to $q_{||}$? Measure $T_i$ profiles in SOL with ion sensitive probe and RFA
Transport: JFR2010 Results – EDA H-mode
EDA H-mode divertor $\lambda_{q//}$ determined several ways

- Several methods utilized for abstraction of heat load width
- $\lambda_{q//} = \int \frac{q_{//} \delta \rho}{\max q_{//}} = 3$ mm
  $1/e$ length: 1.2 mm
EDA H-mode $\lambda_{q//}$ insensitive to $B_T$, connected to $W_{mhd}, I_p$

- $q_{||}$ e-folding width in near SOL exhibits $1/I_p$ dependence
- No dependence on $P_{DIV}, B_{TOR}$
- Similar dependencies found at DIII-D, NSTX
  - A key commonality
  - All three experiments assembling database for cross-machine dependencies

**Plans**

2011: Participate in joint heat flux footprint database (C-Mod, DIII-D, NSTX) for further study as part of an ITPA DIVSOL initiative.

2012: Plan to participate in ITPA-coordinated experiments
Transport: JFR2010 Heat Flux Footprints -- L-mode

Divertor $\lambda_{q\parallel}$ & $\lambda_{nTe}$ robustly insensitive to $B_T$, depend on $I_p$

\[ n/n_G < 0.2 \text{ L-mode to avoid detachment} \]

\[ \Rightarrow \text{Indicates a commonality of H-mode and L-mode transport physics; L-mode discharges are a good vehicle for basic transport studies.} \]
Transport: JFR2010 Heat Flux Footprints -- L-mode
Midplane $nT_e$ also has an $I_p$ scaling...

$\frac{n}{n_G} < 0.2$ L-mode to avoid detachment

- Same pressure e-folding variation at midplane – consistent with critical gradient transport*

Transport: JFR2010 Heat Flux Footprints -- L-mode

Midplane $nT_e$ also has an $I_p$ scaling...

- SOL exhibits critical-gradient transport behavior† which may explain heat flux footprint observations
  - Plasma profiles ‘adjust’ to satisfy $\alpha_{mhd} \sim \alpha_{crit}$; $\alpha_{crit}$ is a strong function of parallel collisionality, $\alpha_{crit}(V^*_\parallel, ...)$

Plans 2011-2013:
(1) Lodestar collaboration using SOLT to model well-diagnosed L-mode discharges
(2) LLNL BOUT collaboration modelling edge turbulence in same L-mode discharges
Transport: New divertor diagnostics will be used for sheath transmission studies

As the divertor moves from low- to high-recycling (high collisionality) regimes, Langmuir probes begin to disagree with Surface TCs, identifying fundamental issues with LP interpretation (e.g. – divertor ‘death ray’ phenomenon†).  

Plan: We have initiated a collaboration with M. Umansky (LLNL) to simulate the ‘death ray’ artifact on LP using the UEDGE code.

* D. Brunner, APS 2010.
Plasma Surface Interactions: Compatibility of high-Z materials with good core plasmas is a goal

- Current status – High core molybdenum levels reduce performance in ICRF-heated H-mode plasmas
  - Experiments point to enhanced Mo sources and possibly enhanced Mo transport into the core plasma
  - Divertor does not appear to be the primary player
  - Coating many Mo surfaces with thick B has helped
    - B coatings have been contaminated by Mo and W (melting in divertor)
    - B coatings are not ITER or reactor-relevant
Plasma Surface Interactions: path to improved compatibility involves efforts in a number of areas

- We are working in several areas towards reduced boron, if not boron-free, operation

**Seeded plasmas**
- reduce heat loads
- reduce impurity sources
- improve ICRF performance

**New ICRF antenna**
- reduced impurity sources

**Understand ICRF-driven Mo source mechanism**
- use new SOL diagnostics

**Control of transport**
- enhance particle & impurity transport in the pedestal (QCM antenna)

**Optimized operation**
- I-mode
- optimization of plasma wetted area
- improvement of the divertor

**Fully high-Z operation**
- no boronization
- divertor and SOL conditions compatible with core plasma
Plasma Surface Interactions: Current impurity seeding efforts lead to low heat loads and good core confinement

- Current seeding efforts have been very successful with $\text{N}_2$ and Ne
- $H_{98} \sim 1$
- Radiation in the core and divertor varied
- Divertor heat loads low
Plasma Surface Interactions: Current impurity seeding efforts have been successful but more work is needed

- Current seeding technique is not optimal
- $Z_{\text{eff}} \approx 3.5$
- Midplane injection, No feedback control
- 1998 results with divertor injection
- Smaller, divertor injections with feedback
- $Z_{\text{eff}} \approx 1.6$, but $H_{98} \approx 0.7$
Plasma Surface Interaction: Plan for additional gas feeds and feedback development

- Compare the required amount of gas ($\text{N}_2$ and Ne) required for a fiducial discharge from a number of locations (2011-12 run campaign)
  - 5 toroidally-spaced gas injection capillaries in the floor of the divertor (NINJA)
  - Midplane puffing
  - Up vertical port (second port as well?)
  - Design and install new gas tube into divertor from midplane port (Spring 2011)
    - Close off conduction down port to maximize gas concentration in the divertor
    - 2 toroidal locations if possible
- Explore feedback control using
  - X-point bolometer chords (ratio and absolute value)
  - Thermoelectric current
  - Impurity emission lines? Others?
  - Full feedback 2012-2013
Plasma Surface Interactions: Initial foray to address ITER need successful

- ITER concern that an impurity seeding system failure will lead to prolonged divertor high heat loads
  - Burnout of cooling -> water leaks
  - ITPA DSOL-20 collaboration
- As part of the recent seeding of H-modes we inadvertently produced such situations
  - Divertor and core plasma effects fairly immediate
- This work dovetails nicely with improvement of C-Mod impurity seeding work

Plans
- Development of several seeding injection points for comparison of effect (2011-2012)
- Piggyback on Baseline Scenarios work (2011-2012)
- Development of several feedback algorithms (2012-2013)
Plasma Surface Interactions: ICRF sheath rectification strongest on flux tubes connected to antennas

- Surface Science Station ($S^3$) used this campaign for ICRF studies.
- Two independent plasma potential measurements:
  - Ion sensitive probe (ISP) and emissive probe
- Potential highest when probes map along B to antenna
- Potentials appear to have density threshold as predicted*
  - Line-averaged, as opposed to local density

- Plans (2011-2012)
  - Measure local density along with potential for better comparison to model
  - Block out ICRF frequency pickup for Langmuir probe
  - Used in parallel with new scanning probe heads for plasma potential and Ti

Plasma Surface Interaction: Building new probe heads for plasma potential and distribution function measurements

- **Retarding Field Analyzer**
  - Series of grids to reject one charge species and selectively pass the other for measurements of parallel energy distribution
  - Upstream and downstream analyzers necessary for measurements of ion temperature in the presence of flows
  - Measure LH modification to edge electron energy distribution
  - Ready early CY2012

- **Ion Sensitive Probe**
  - Utilizes large difference in ion and electron gyro-radius to scrape off electrons, measure ion temperature perpendicular to B
  - Includes Langmuir probe to measure electron temperature and density
  - Extends work of R. Ochoukov to measure plasma potential through the SOL and ICRF sheath rectification
  - Ready Fall CY2011
Plasma surface interaction: Expand coverage of impurity source locations by factor of 3-4

- Upgrading current F/4 Ebert-Fastie spectrograph with new camera (2011)
  - Can monitor 16 simultaneous views with higher QE and speed
- Two new SLR-lens based spectrographs in development (2011-2012)
  - Design allows each spectrograph to simultaneously monitoring ~ 27 views at F/2.3
- Light collection periscopes upgraded to better optics and fiber bundles (2011)
- New views of rotated ICRF antenna (2012-2013)
Plasma Surface Interactions: Does tungsten/Mo fuzz grow in real tokamak plasmas?

Nano-filaments of tungsten/Mo grow under conditions in linear plasma facilities

- $T_{\text{SURF}} \sim 1100 \text{ K}$, He ion flux $>10^{22} \text{ m}^{-2}\text{s}^{-1}$, $E_{\text{ION}} < 100 \text{ eV}$, $t_{\text{exp}} > 30$ s
  - Concern for ITER/reactors about enhanced erosion and effect on PFC properties

- Fuzz growth has not yet been observed in tokamaks, possibly due to:
  - Surface impurities, implanted D and structural differences e.g. bubbles

- C-Mod tiles, with their tokamak-like surface idiosyncrasies, have been tested in PISCES and fuzz growth was observed for exposure times of 30 s

Plans

- Exposure during a full day of He discharges at end of this run period; Local SEM and ion-beam analysis
Plasma Surface Interactions: Study a controllable divertor
Mo source and effect on core plasma

- Remove a single tile from floor of the divertor
  - Away from strike point on the vertical plate
  - Creates leading edge where surface is perpendicular to B – much higher $q_\perp$
Plasma Surface Interactions: Study a controllable divertor Mo source

Plans (2011)

• For study, move strike point to floor for second half of a high power discharge
  ■ Higher local power loading
  ■ Leading edge melts
  ■ Correlate the changing surface temperature and Mo source with any changes in core Mo concentration
  ■ Repeat to determine if the effect on the core increases over time
  ■ Remove tile after run period for analysis of Mo flow pattern (collaboration w/Jan Coenen of IPP/Juelich)

Status

• No discharges allocated yet, will use data ‘mining’ for now.
Plasma-surface interaction: A deuteron accelerator-based diagnostic for assessing surface compositions \textit{in-situ}

- Radio-Frequency Quadrupole (RFQ) accelerated deuterons induce nuclear reactions in the plasma facing components (PFCs) over a large fraction of the first wall.
- Detection of the reaction products provides PFC surface information.

\textbf{DIAGNOSTIC GOALS (measured between shots)}
- Deuterium bulk retention and depth profiles
- Boronization layer thicknesses
- Erosion rates
- Isotopic analysis of surface composition
- Can diagnose large fraction of poloidal surface + a smaller fraction of the toroidal direction

\textbf{In future D-T burning devices (e.g. ITER), bulk tritium content and retention profiles could be experimentally measured with this technique}

A cartoon depicting the basic principles of \textit{in-situ} ion beam analysis of PFCs surface compositions.
Plasma Surface Interaction: RFQ diagnosis toward deuterium/tritium retention in PFCs

- Injected D+ ions induce energetic neutrons via the $^2\text{H}(d,n)^3\text{He}$ fusion nuclear reaction.

- Energy spectroscopy of the neutrons combined with nuclear kinematics can be used to de-convolve a deuterium retention profile, as well as simple bulk content of deuterium in a PFC.

- A synthetic diagnostic (ACRONYM) is used to model all steps in the measurement process.

**Diagram:**

- Reaction depth used to deconvolve the deuterium retention profile in PFCs (dotted line at right).

- Nuclear kinematics relate neutron energy spectrum to reaction depth in PFCs.
Plasma-surface interaction: RFQ can be used for layer thicknesses and erosion patterns (example for boron)

- Injected D+ ions induce 0.95 and 1.7 MeV gamma rays in boronization layers on the PFCs via the $^{11}\text{B}(d,p+g)^{12}\text{B}$ reaction
- Integration under the 0.95 MeV photopeak in the detector pulse height spectrum determines the boron thickness
- A synthetic diagnostic (ACRONYM) is used to model all steps in the measurement and construct synthetic correlations between boron layer thickness and area under the 0.95 MeV photopeak
- Boron (or other low-Z layer) thickness and erosion patterns can be monitored at any accessible location on C-Mod first wall

**DIAGNOSTIC TIMELINE**

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Tasks</th>
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<tbody>
<tr>
<td>2009 to early-2011 (work complete or nearly complete)</td>
<td>Re-commissioning of RFQ accelerator Development of synthetic diagnostic Assembly of detectors, data acquisition</td>
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<tr>
<td>Early-2011 to mid-2011</td>
<td>Deuterium cross section measurements Engineering beamline, interface to C-Mod</td>
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<tr>
<td>Mid-2011</td>
<td>Installation of RFQ on C-Mod Installation of detectors and DAQ</td>
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<tr>
<td>Mid-2011 to late-2011</td>
<td>Validation of beam steering algorithms Validation of detectors, synthetic diagnostic</td>
</tr>
<tr>
<td>Late-2011</td>
<td>First in-situ PFC composition measurements</td>
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**ACRONYM’s synthetic measurement**

A cartoon depicting the synthetic measurement of boron layer thickness using ACRONYM
Plasma-surface interaction: The new outer divertor design is well underway

Design basis

• Toroidally continuous lower divertor eliminates leading edges and reduces electromagnetic loading from disruptions.
  ■ Required for longer pulses associated with LH
• Long-pulse ops may lead to high divertor temperatures over a runday ~ 500-600 deg. C
• Designing the divertor to allow active heating to 600°C for new fuel retention studies.
• 4 rows of solid tungsten lamellae tiles in high heat flux region.

Plans (2011-2013)

• Installation 2014
• Physics input being supplied in the form of disruption scenarios, forces, current vessel temperature and heater use, and diagnostic access
• Engineering reported in J. Irby’s talk
Halo currents lead to high forces and thus are an important factor in design.

- Data in ITER Physics Basis gives rise to a scaling of Toroidal peaking factor (TPF)
  - TPF ~ $0.75/I_{\text{Halo, max}}/I_0$
- However, the dataset was abstracted only at maximum halo current
Halo currents lead to high forces and thus are an important factor in design.

- Data in ITER Physics Basis argues a scaling of Toroidal peaking factor (TPF)
  - TPF $\sim 0.75[I_{\text{Halo, max}}/I_0]$  
- However, the dataset was abstracted only at maximum halo current
- Revisited available C-Mod shunt data (before 1996) for TPF at all halo current times
  - TPF $\sim 1.5[I_{\text{Halo, tot}}/I_0]$ 
- New measurements are needed
- New TPF scaling leads to same halo current:
  - $I_{\text{Halo, tot}}/I_0 \sim 0.5$, TPF $\sim 3.25 \rightarrow I_{\text{module}} \sim 0.4\text{MA}$
  - $I_{\text{Halo, tot}}/I_0 \sim 0.2$, TPF $\sim 8 \rightarrow I_{\text{module}} \sim 0.4\text{MA}$

C-Mod data only

\[ \text{TPF}[t] = \frac{\text{Peakcur}_{\text{shunt}}[t]}{\left(\frac{I_{\text{TOT shunts}}[t]}{10}\right)} \]

- $0.3 \leq I_{\text{HaloL}}/\max(I_{\text{HaloL}}) < 0.7$
- $0.7 \leq I_{\text{HaloL}}/\max(I_{\text{HaloL}}) < 0.9$
- $0.9 \leq I_{\text{HaloL}}/\max(I_{\text{HaloL}}) \leq 1.0$

New divertor conceptual design review, August 13, 2010
Divertor specifications: The movement of the plasma during a VDE characterized for disruption forces

- Analysis of 10 years of disruptions

**Plans (2011-2013)**

- Transfer a ‘typical’ VDE current movement to ANSYS for induced currents and forces
- Use database to constrain TSC calculations (PPPL)
- Continue working to supply engineering with physics input

C-Mod PAC meeting, March 2-4, 2011
ITER research needs: Divertor and Plasma-Wall Interactions*

- **Key elements - predominantly voluntary R&D:**
  - Analysis of tritium retention/ development of tritium removal techniques
  - Improved definition of requirements for RF conditioning
  - Expansion of operational experience with tungsten divertor - includes operational scenarios, effect of transients (dust), tritium retention …
  - Quantitative characterization of dust production/ distribution
  - Improved characterization of first wall/ divertor heat loads, particularly during ELM/ disruption mitigation
  - Quantitative analysis of erosion/ redeposition phenomena

- **Longer term R&D activities include:**
  - Influence of all-metal walls on plasma-wall interaction phenomena in ITER-relevant regimes
  - Development of improved modelling capability for PWI phenomena

*Items colored in red are where C-Mod obviously contributes*
ITER research needs: Divertor and Plasma-Wall Interactions*

- Extensive R&D required to establish physics basis for ITER reference scenarios with W/ Be PFCs:
  - development of current ramp-up/ ramp-down scenarios (with/ without additional heating and impurity seeding)
  - high performance H-mode scenarios with impurity seeding, ELM control etc
  - core impurity control, particularly in ITB scenarios
  - impurity production with ICRF
  - control of ELM-produced impurities
  - operation with melt-damaged tungsten components

- When are results required?
  - basic elements of operational scenarios should be assessed on 2-3 year timescale
  - more detailed aspects would need answers on 3-5 year timescale to allow time to analyze implications for ITER operation

*Items colored in red are where C-Mod obviously contributes
ITER research needs: Divertor and Plasma-Wall Interactions*

- A range of PWI issues will need to be resolved to build confidence that reliable operation can be sustained:
  - establishment of requirements for carbon/ carbidic compound removal at divertor changeout (eg need to identify distribution of redeposited material)
  - T-retention in W/ Be and their compounds, including role of retention in first wall and neutron irradiation effects
  - tungsten/ beryllium material damage and dust production rates (steady-state, transients)
  - performance of Be-coated tungsten PFCs
  - development of modelling capability for beryllium and tungsten PWI simulation

- When are results required?
  - early quantitative information on key safety-related questions (T-retention, dust production) would be important - ie 2-3 years
  - should aim for a complete picture of W/ Be PWI issues on 5 year timescale

*Items colored in red are where C-Mod obviously contributes
C-Mod plasma boundary program research program

2011-2012 (Continued upgrade of power flow measurements)
- Connect $\lambda q$ scalings and turbulence scalings to edge plasma 'phase space' (critical gradients)
- Initiate additional comparisons of C-Mod data (flows, fluctuations) with BOUT, SOLT
- Feedback control of detachment
- Continued expansion of new RF-sheath diagnostics combined with new tilted antenna
- Investigate role of SOL in LHCD density limit
- Finalize divertor requirements and install RFQ

2012-2013 (finalise outer divertor upgrade and utilize RFQ)
- Connection of turbulence measurements to modelling (e.g. BOUT)
  - T, n and potential fluctuations
  - Role of shear flow in setting SOL profiles and ‘critical gradients’
- Combine new potential and flow diagnostics with source measurements to understand ICRF effects
- Use of RFQ with old divertor to follow local fuel retention and surface changes

2013-2014 (Install outer divertor upgrade)
- Elimination of boron coatings - fully high-Z, high heat flux region all-tungsten (solid lamellae)
- New power flow studies enabled by continuous divertor
- Implement techniques/hardware to reduce impurity influx during ICRF
- Use of RFQ with new divertor to follow local fuel retention and surface changes
- Fuel retention studies with hot outer divertor
Boundary Physics: Summary

Boundary physics program is making progress in a number of areas

• Transport
  ■ Progress in connecting turbulence to transport at the separatrix
  ■ Relating divertor heat load profiles back to critical gradients back at the midplane
  ■ Developing new antenna and diagnostics for probing the edge and SOL

• Plasma-surface interaction
  ■ New results giving rise to an emerging understanding of ICRF-related Mo sources
  ■ Well on the way to the first direct measurements of the surface after a discharge (RFQ)

• Integrated studies
  ■ Strong overlap with pedestal, ICRF and LH studies
  ■ Support the development of the new outer divertor