Divertor and Edge Physics program

Relationship to other programs
General program description
Past 5 year highlights
Transport
Neutrals
Impurities
High heat flux & particle handling

Presented by B. Lipschultz
C-Mod in relation to other tokamaks

- C-Mod operation overlaps that of other tokamaks in edge/divertor dimensionless parameters w/different dimensional parameters
- Some of the differences in edge & divertor dimensional parameters are
  - Higher density (similar to ITER in divertor)
  - Higher parallel heat flux (300-500 MW/m², 3-5x other tokamaks, similar to ITER)
  - Higher divertor opacity to Ly_α (similar to ITER)
  - Higher SOL plasma pressures (similar than ITER)
- The range in dimensionless parameters can be different too
  - High collisionality (~ 1-4 x ν* for other tokamaks and ITER)
  - Short λ_{0,mfp}/λ_{SOL} & λ_{0,mfp}/λ_{Div} (~ 2-4x less than other tokamaks, similar to ITER)
- Different scalings for neutral penetration may help unfold the roles of atomic and plasma physics
- Operation with Mo first wall makes an important contribution
  - ASDEX-U is gradually converting to W
C-Mod in relation to other tokamaks

- The C-Mod boundary research program complements work being done around the world

<table>
<thead>
<tr>
<th>Research area</th>
<th>C-Mod</th>
<th>Other tokamaks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma transport</td>
<td>Turbulence visualization Probes, D_α, Thomson from particle balance</td>
<td>NSTX, DIII-D (core) DIII-D, JET DIII-D, JET (by C-Mod)</td>
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<tr>
<td>Turbulence imaging</td>
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<td>Turbulence statistics</td>
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<tr>
<td>Radial flux analysis</td>
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<tr>
<td>Impurities (through ‘lifecycle’)</td>
<td>Mo sources, transport, screening, redeposition Mo physical sputtering</td>
<td>C sources, transport, screening, redeposition C chemical erosion</td>
</tr>
<tr>
<td>Neutral transport</td>
<td>main chamber recycling Compare w/div leakage Hydrogen and metals n-n collisions important</td>
<td>Emphasis on divertor effects, cryopump, T codeposition w/C Kinetic neutrals</td>
</tr>
<tr>
<td>ELM effect on SOL and divertor</td>
<td>Concentrating on small or no ELM regimes</td>
<td>Major program on DIII-D, JET</td>
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Relation to IPPA goals

The C-Mod boundary physics program addresses a number of issues listed in the IPPA document.

- **3.1.1 Turbulence and transport (3.1.1.1, 3.1.1.2, 3.1.1.3)**
  - Advance the scientific understanding of turbulent transport, forming the basis for a reliable predictive capability in externally controlled systems.

- **3.1.4 Plasma boundary physics (3.1.4.1, 3.1.4.2, 3.1.4.3)**
  - Advance the capability to predict detailed multi-phase plasma-wall interfaces at very high power- and particle-fluxes.

- **3.3.1 Profile control (3.3.1.4, 3.3.1.5 - low \( n_e \) divertor operation)**
  - Assess profile control methods for efficient current sustainment and confinement enhancement in the advanced tokamak, consistent with efficient divertor operation, for pulse lengths much greater than energy confinement times.

- **3.4.1 Plasma technologies (3.4.1.3 - Plasma facing components)**
  - Develop enabling technologies to support the goals of the scientific program, including methods for plasma measurements, ….; develop plasma facing components….
C-Mod Boundary physics program

- Optimize the performance of fusion devices through
  - minimal core impurities (radiation, fuel dilution),
  - maximal first-wall lifetime, power handling
  - divertor design for optimal impurity/neutral compression and pumping

- To those ends we concentrate our research on
  - Edge plasma transport
    - Our primary emphasis because it is the determining factor for heat and particle loadings, impurity sources and transport
  - Neutral dynamics and fueling
  - Impurities

- Develop predictive capability scaleable to reactor

- We also identify and develop hardware and techniques for
  - Heat flux handling & density control
Highlights of the previous 5 year period

- A technique was developed to derive $\Gamma_\perp$ based on particle balance
  - $v_{\text{eff}} (\equiv \Gamma_\perp/n)$ and $D_{\text{eff}} (\equiv \Gamma_\perp/\nabla n)$ increase with distance into the SOL
  - Radial transport can compete w/parallel transport,
  - ‘main chamber recycling’ shown to affect fueling, impurities,…
- ‘Bursty’, turbulent cross-field transport has been identified
  - Linked to the strong radial transport, potential link to density limit,
  - Development of 2-D visualization technique (w/Zweben).
- Divertor detachment studies provided important contributions
  - Determination of the effect of geometry (vertical vs horizontal plate)
  - Achievement of detachment under high heat flux H-mode conditions.
  - Demonstration and measurement of recombination and opacity effects,
- Development of high-Z PFC operation compatible with high-power plasmas
- Impurity screening shown to be dependent on source location, impurity mass
- Demonstration of low (e.g. N, C) and high-Z (Mo) screening similarities
- Showed close coupling between divertor neutral compression and transport
- Divertor leakage is a minor contributor to main chamber neutrals.
## Edge Transport

- Determines heat/particle loads on surrounding structures
- Sets boundary conditions affecting core transport quality
- May play a role in setting density limit
- A controlling factor in impurity transport

### Status

<table>
<thead>
<tr>
<th>Item</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time-averaged profiles</td>
<td>Used to extract $\Gamma_\perp$ transport fluxes</td>
</tr>
<tr>
<td></td>
<td>Imply non-diffusive transport</td>
</tr>
<tr>
<td>Turbulence studies</td>
<td>Initial turbulence visualization</td>
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<tr>
<td></td>
<td>Initial turbulence statistics</td>
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<tr>
<td>Numerical simulation</td>
<td>Matching some experimental measurements</td>
</tr>
<tr>
<td></td>
<td>Time-averaged profiles specified, not predicted</td>
</tr>
<tr>
<td>Control - exploring ideas</td>
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</table>

### Goals/Program

<table>
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<tbody>
<tr>
<td>Explore transport scalings and role of plasma vs neutral physics</td>
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<tr>
<td>Fully identify/characterize turbulence responsible for transport</td>
<td></td>
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<tr>
<td>1st principle simulations reproduce</td>
<td>Turbulence characteristics</td>
</tr>
<tr>
<td></td>
<td>Time-averaged profiles</td>
</tr>
<tr>
<td>Develop capability to modify radial transport</td>
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</tbody>
</table>
**Edge transport: time-averaged profiles**

**Status**
- Non-exponential SOL profiles
  - radial transport large
  - \(\Rightarrow\) wall recycling & impurity sources
  - Radial transport very non-diffusive
  - cross-machine comparisons started
- 2D fluid models
  - transport coeff. are fitting parameters
  - turbulent transport not included
- Strong parallel flows measured
  - Relationship to transport still unknown

**Goals**
- Extract relationships between time-averaged profiles &
  - Radial particle and heat fluxes,
  - poloidal variations in transport,
  - role of atomic vs plasma physics
  - scalings including the density limit
Edge transport: time-averaged profiles

Program

- Expand profile studies
  - More poloidal points & discharge types
  - across-machines (DIII-D, JET, NSTX, ASDEX Upgrade)

- Diagnostics
  - SOL Thomson (‘05 - )
  - Inner wall probe, D\(\alpha\) (‘04 - )
  - D\(\alpha\) profile measurements

- Correlations among
  - Transport changes,
  - Turbulence changes, and
  - Neutrals changes

- Parallel flows
  - Doppler spectroscopy (‘04 - )
  - Probe (‘04 - )
Edge transport - turbulence studies

**Status**
- Visualization technique (GPI)
  - Follows ‘striations’ moving radially
  - Gives k-spectrum (size distribution)
- Statistics of fluctuations
  - probe and Dα statistics consistent
  - Bursty, non-Gaussian
  - Non-diffusive transport
  - Probe transport fluxes suspect
  - Diagnostics show radial velocity of ‘bursts’ or ‘striations’ ≤ 500 m/s
- Turbulence moves inside separatrix near density limit
  - Large convective heat losses depress Te
  - Potential cause of thermal instability

**Goal** - understand turbulence mechanisms
- Characterize turbulence
  - Poloidal variation
  - Statistics, k-spectra
  - Transport fluxes
  - scalings
- Compare with numerical simulation

C-Mod 5-yr program review May 13-14, 2003
Edge transport- turbulence studies

Program
- Expand turbulence visualization through gas puff imaging (GPI)
  - Inner SOL (‘03 - )
  - Better resolution, < 1 mm (‘03 - )
- Develop direct \( \tilde{n}, \tilde{T} \) measurements
  - Line ratio technique
  - 1-D prototype (‘03 - )
  - 2-D implementation (‘05 - )
- Expand time series measurements
  - Better statistics (‘04 - ‘07)
  - More probes, \( D_{\alpha}, \) SOL Thomson (‘03 - )
  - More poloidal locations (‘04 - )
- Density limit physics
  - changes in turbulence

\[ \begin{array}{c|c|c|c|c|c|c|c|c|c} \hline \text{density (m}^{-3}\text{)} & 10^{18} & 10^{19} & 10^{20} \\ \hline \text{\( I_{(728\text{ nm})}/I_{(706\text{ nm})} \)} & 10 & 0.1 & 1.0 & 10.0 & 0.1 & 1.0 & 10.0 & 0.1 & 1.0 & 10.0 \\ \hline \text{\( I_{(668\text{ nm})}/I_{(728\text{ nm})} \)} & 237.4 & 95.4 & 38.3 & 15.4 & 6.2 & 2.5 & 1.0 & 1.0 & 1.0 & 1.0 \\ \hline \text{T\( \text{e (eV)} \)} & 192 & 92.4 & 44.6 & 21.5 & 10.4 & 5.0 \\ \hline \text{n\( \text{e (10^{18} m}^{-3}\text{)} \)} & 10 & 10 & 10 & 10 & 10 & 10 & 10 & 10 & 10 & 10 \\ \hline \end{array} \]
**Status** of collaborative work

- Turbulence simulations
  - Show similar striation movement
  - Similar perp. & poloidal size scale
  - Roughly reproduces k-spectrum
  - Predicts in-out asymmetry
  - Time-averaged profiles are specified

**Goals**

- 1st principle models reproduce
  - Turbulence characteristics for a range in plasma operation
  - Time-averaged profiles based only on input of particle and heat fluxes
Edge transport- numerical simulation

**Program** (collaborative)

- Close coupling to turbulence simulations/theory
  - Hallatschek (IPP-Garching)
    - Non-local turbulence
    - Move towards relying on more physical inputs
  - BOUT simulations (Xu, Nevins, Umansky, LLNL)
    - X-pt, plasma effects
    - Impurity effects (are there impurity ‘blobs’ and ‘holes’?)
  - Stotler (PPPL)
    - atomic physics of gas-puff imaging diagnostic
Edge transport- control turbulence/profiles

**Status**
- Ideas are being proposed
- Some techniques have been demonstrated elsewhere
  - ergodic limiter
  - Electric H-mode thru biasing and RF
  - we will need different tools

**Goal**
- Identify/develop turbulence and transport modification techniques

**Program**
- Test ICRF edge-heating to modify edge $E_r$
- Utilize slow/small Li-pellet injection to produce sharp density gradient
Neutral Dynamics

- Determines fueling
- Determines capability to pump the divertor (specifically He)
- Can affect core performance (edge cooling)
- May play a role in edge plasma transport

<table>
<thead>
<tr>
<th>Status</th>
<th>Goals/Program</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutral distribution inherently 3D</td>
<td>More detailed measurements</td>
</tr>
<tr>
<td>Models unsuccessful in simultaneously matching plasma and neutral distribution all around the plasma</td>
<td>1st principle models reproduce observations</td>
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<tr>
<td></td>
<td>Optimize cryopump</td>
</tr>
<tr>
<td></td>
<td>Understand the role of wall &amp; geometry</td>
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</tbody>
</table>
Neutral dynamics - experiment

Status
- Main chamber pressure primarily due to radial transport, not divertor leakage
- DEGAS & B2/EIRENE neutral models predict divertor pressures 2-10 x too low
- low neutral sources, too low wall interaction
- Upper ’open’ divertor pressures similar to closed divertor for USN appears to be good location for cryopump
- Evidence of wall pumping direct implantation? codeposition?

Goals
- Constrain modeling with multiple toroidal & poloidal measurements
- Clarify the relative roles of fueling sources (wall vs divertor), wall pumping/release & magnetic geometry
- Optimize cryopump performance

Proposed cryopump Operating point
Neutral dynamics - experiment

Program

- Measure
  - Poloidal pressure distribution
  - Conductances with/without plasma
  - D co-deposition studies (w/ U. Wisc.)

- Explore the effect of magnetic geometry on fueling & recycling

- Understand cryopump performance dependence on
  - magnetic geometry
  - plasma conditions

- Diagnostics
  - Localized gas puff delivery (‘03 - )
  - Penning gauges (‘02 - )
  - Surface analysis stations (‘04 - )
  - Wall flux measurements (transport topic)
Neutral dynamics - modelling

Goals
- Constrain models with poloidal distribution of
  - Neutral pressures
  - Core fueling
  - Wall sources
- Clarify the role of
  - Wall interaction
  - Wall pumping/release
- Correctly predict measured pressures

Program
- Utilize additional measurements to benchmark
  - B2/EIRENE (U. Toronto - Lisgo/Stangeby)
  - DEGAS2 (PPPL-Stotler)

• 2D grid shown, 3D also used
## Impurity transport

- Determines the core dilution/radiation
- Determines divertor power dissipation
- Determines pumping of He
- Plays a role in tritium codeposition

<table>
<thead>
<tr>
<th>Status</th>
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</tr>
</thead>
<tbody>
<tr>
<td>- Modelling predictions uncertain</td>
<td>- Improve characterization of underlying transport</td>
</tr>
<tr>
<td>- Significant high-Z PFC experience (C-Mod)</td>
<td>- Models reproduce experiment</td>
</tr>
<tr>
<td>- Wall sources are important because penetration is efficient</td>
<td>- Measure/characterize impurities at all points in their ‘lifecycle’</td>
</tr>
<tr>
<td>- RF effects can be important</td>
<td>- Clarify important sources/sinks</td>
</tr>
</tbody>
</table>
Impurity sources & transport

**Status**

- Low-field side impurity screening is poor
  - True for low-Z and molybdenum
  - Screening improves at high density
- C-Mod divertor sources fairly well in hand
  - Physical sputtering in divertor
  - B chemical sputtering exists but low
- Divertor impurity compression
  - Improves with $n_e$ and impurity mass
  - Modelling reproduces trends
- RF sheath-rectification -> impurity sources
- Modelling of core levels uncertain because of poor plasma transport understanding

**Goals**

- Integrate impurity and edge transport studies
- Better diagnostic coverage
- Benchmark against simulations
Impurity sources & transport

Program

- Additional spectrometers and views
  - Poloidal source measurements (‘03 - )
  - LH launcher sources (‘03 - )

- Impurity density measurements
  - low charge state CXRS in SOL (‘05 - )
  - CXRS in core - U. Texas (‘05 - )

- In situ deposition measurements
  - Quartz Microbalance (Julich collab.)
    - Overall deposition rate (‘04 - )
  - Surface analysis (Whyte/UW, Robertson/UM)
    - Mo, B deposition rate (RBS)

- DIVIMP modelling of fluxes/densities
  - Lisgo/Stangeby - U. Toronto

JET Quartz Microbalance (QMB)

- Reference crystal (RC)
- ASIC application specific integrated circuit
- Deposition crystal (DC)
- Temperature crystal (TC)

1 cm
## Divertor and Edge Physics Research Goals

### Transport/Turbulence

<table>
<thead>
<tr>
<th>Calendar Year</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \bar{n}, \bar{T} ) SOL/EDGE Turbulence Measurements</td>
<td>✔</td>
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<td>✔</td>
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<tr>
<td>Multipoint 2-D measurement of ( \bar{n}, \bar{T} )</td>
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<tr>
<td>Inner-wall scanning probe</td>
<td>✔</td>
<td>✔</td>
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<tr>
<td>Measurements of Turbulence/Transport in Inner SOL</td>
<td>✔</td>
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<tr>
<td>Development of Inner-wall ( D_\alpha ) profile &amp; fluctuation Diag.</td>
<td>✔</td>
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<tr>
<td>Studies of Edge Turbulence/Transport in AT Plasmas</td>
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<tr>
<td>Gas-Puff-Imaging with 28 fr, 1 MHz camera</td>
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<tr>
<td>Gas-Puff-Imaging with 312 fr, 1 MHz camera</td>
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<tr>
<td>Gas-Puff-Imaging of Inner SOL</td>
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<tr>
<td>SOL profiles, turbulence structure &amp; dynamics</td>
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<tr>
<td>Transport scaling/density limit physics</td>
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</table>

### Neutral Dynamics/Fueling

<table>
<thead>
<tr>
<th>Density control scoping</th>
<th>Cryopump operation/optimization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double-null configurations</td>
<td>✔</td>
</tr>
<tr>
<td>Poloidal pressure distribution, gas conductances</td>
<td>✔</td>
</tr>
<tr>
<td>Wall pumping and release</td>
<td>✔</td>
</tr>
<tr>
<td>Inner wall recycling</td>
<td>✔</td>
</tr>
<tr>
<td>Divertor and main-chamber neutral pressures, gas leakage, pumping</td>
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</tbody>
</table>

### Impurity Sources/Transport

<table>
<thead>
<tr>
<th>Impurity sources: ICRF</th>
<th>Impurity sources/sinks: LH</th>
<th>SOL profile optimization for LHCD</th>
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</thead>
<tbody>
<tr>
<td>Source Meas.: Upper chamber, LH launcher; deposition measurements (QMB, RBS)</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Impurity densities in Core, SOL (CXRS) and Divertor</td>
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<td>✔</td>
</tr>
<tr>
<td>Measurement: Inward ‘blob’ convection of impurities</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Main-chamber impurity sources, sinks and transport</td>
<td>✔</td>
<td>✔</td>
</tr>
</tbody>
</table>

**Key:**
- Red: Research Topic
- Green: Diagnostic Develop
- Blue: Theory/Simulation
# High heat flux handling & density control

- Important for the success of the C-Mod program
- Also supports advancement of ITER/BPX

## Status

- Presently, 5 - 1.0 s pulse, 4 MW RF
  - melting at some divertor leading edges (shielded from the core)
- Energy deposited will increase
  - Power increase by $\sim x2$, 5 seconds
  - $\Delta T^o = q_\perp (W/m^2) \times \gamma_{Mo} \times (t/sec)^{0.5}$
  - $\Delta T$ increases by $\sim x4$
  - extrapolation $\Rightarrow$ melting at strike points if nothing is done
- No pumping, but H-mode densities might be too high for AT

## Goals/Program

- Develop improved surface temperature monitoring
- Extend divertor heat-handling capability ($\sim x2$).
- Extend power dissipation techniques (efficacy, low-$n_e$)
- Cryopump operation forces gas-puffing to maintain $n_e$. 

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C-Mod 5-yr program review May 13-14, 2003
High heat flux handling & density control: development

- Implement measurements/techniques (‘03–’05)
  - surface temperature measurement
  - strike point sweeping
  - dissipative divertor
  - divertor impurity puffing
- Test advanced divertor materials (‘03–’05)
  - single tungsten-brush tiles (w/Sandia National Lab)
  - W-brush modules (ITER/BPX prototype)
  - decision on liquid-metal test (collab. w/SNL)
- New outer divertor (‘05 -)
- Evaluate divertor target performance (‘03–’08) with
  - increasing pulse length
  - increasing power
  - above dissipation techniques/materials
- Optimize cryopump
  - neutral pressure & conductance studies during design
  - magnetic geometry optimization after installation

Sandia W brush tile

~ 1.2 cm
High Heat Flux Handling: new hardware

- New upper divertor (‘04-’05)
  - necessary for cryopump
  - necessary for ~ double-null
  - optimized for pumping

- New outer divertor (‘05-’06)
  - no toroidal gaps/leading edges
  - better alignment
  - simplified geometry
  - W-brush tile section (1/10th)

- ‘Advanced’ divertor (‘06 - ‘07)
  - full outer divertor coverage with W-brush
  - potential for other improvements
## High heat flux handling & density control

### Calendar Year

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### Solutions

- Strike point sweeping
- Dissipative divertor development
- New inner div.
- W brush tile test
- New outer divertor
- Full toroidal advanced divertor
- Cryopump/Upper divertor
- Heat flux upper divertor (if double null)
- W brush tile module
- Possible liq. metal test module

### Diagnostics

- Expand impurity source & deposition measurements
- Diagnose effect of LH on SOL and energy fluxes
- Core/SOL impurity densities (CXRS)
- Outer/Inner div. IR surface T

### Power loading

- ICRF: 5 MW, 6 MW
- LHCD: 2 MW, 3 MW

### Pulse length

- 1.5 sec, 3 sec, 5 sec
Our intent is to continue to make fundamental contributions:

- Steady state profile transport analysis to understand
  - Poloidal variations, machine scalings -> uncover underlying physics
- Turbulence studies
  - Direct measurement of $\tilde{n}$, $\tilde{T}$,
  - improved images/analysis,
  - Control if possible
- Measure and model the 3D aspects of neutral dynamics
- Develop separable divertor particle and heat control functions
- Characterize impurities at every step in ‘lifecycle’ - develop ‘predictive codes’.
- Optimize high-Z first-wall for long-pulse AT operation

Providing vital support for overall physics program

- Advanced Tokamak
- Burning Plasma