Elements of a US R&D Plan to Solve Plasma-Material Interaction Challenges for Magnetic Fusion Energy

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Divertor and main chamber wall components in a DT fusion reactor must be capable of handling extreme levels of plasma heat exhaust and plasma-material interactions (PMI). A central question for magnetic fusion energy development is: does there exist a combination of plasma physics scenarios and material technologies that can make this happen? US fusion researchers are pioneering world-leading approaches to solve PMI challenges, as highlighted in the 2015 FES Workshop on PMI [1]. Elements of this research were presented at the Madison and Austin Strategic Planning Workshops. A consensus view was: *"PMI/divertor problems [are] very important, compelling options need to be evaluated"* [2]. This paper discusses 6 PMI program sub-elements that received considerable discussion at the workshops [3-5]: (1) Advanced Divertors, (2) Advanced Solid PFC Materials and Manufacturing, (3) Liquid Metal PFCs, (4) Linear Plasma Test Stand for long-pulse PMI, (5) High Field Side RF systems, and (6) Divertor Test Tokamak. These sub-elements are not competing proposals. Integrated closely together, they would form the underpinnings of a compelling, world-leading, PMI R&D program.

1. <u>Advanced Divertors</u> [6]: Present experiments indicate an unavoidable tradeoff between good core confinement and protecting conventional divertor targets. This prohibits the use of conventional divertor solutions for DEMO since power handling must be increased by an order-of-magnitude while nearly complete suppression of target plate erosion must also be attained.

Benefits: New physics ideas embodied in advanced divertor concepts could meet this challenge, including: passive or active control mechanisms to keep the "divertor detachment front" from degrading the core; operating highly dissipative attached divertor regimes; using a liquid or vapor as the divertor target. The US has been the primary innovator in this area, proposing a number of options: snowflake, X, super-X, active liquid Li replenishment, Li vapor box, long-leg X-pt target, small angle slot (SAS); as well as from QST, the v-shaped deep slot [7-12].

Current Status: Exploratory, proof-of-concept experiments have been performed at low and moderate power on ~half these concepts in US tokamaks and tokamaks overseas, some accessing DEMO-relevant PMI conditions at their target plates ($T_{et} <\sim 5$ eV, $n_{et} \sim 10^{21}$m^{-3}) [13].

International context: TCV, MAST-U, AUG plan to continue proof-of-concept experiments.

Possible 15-year U.S. research agenda: From 2015 FES Workshop Report on PMI [1]: (1) exploit and upgrade existing divertor experiments for enhanced runtime, diagnostics and personnel; explore power handling limits of existing divertor configurations; upgrade divertor configurations and materials (solid and liquid) and explore power handling limits; (2) complement with targeted collaborations on overseas experiments; maximize U.S. benefits from ITER; (3) establish national working group to examine design options for DTT; implement DTT.

Research directions beyond the 15-year horizon: US DTT; further overseas collaborations.

Critics' objections: No existing experiment can produce reactor-level plasma conditions throughout its divertor and so cannot provide experimental access to the integrated, dissipative physics regimes that will likely exist in a reactor.

Advocates' responses: Well diagnosed existing divertor experiments can improve our understanding and validate codes for more reliable predictions for reactor conditions.

2. Advanced Solid PFC Materials and Manufacturing [14]: New materials are potential game changers for fusion. Large impacts on concepts and performance are possible for plasma-facing components (PFCs), structural and blanket materials. In many cases, conventional materials technology cannot meet the requirements. Incident plasma heat fluxes of 100's of MWm^{-2} and particle fluxes of $\sim 10^{24}$ $m^{-2}s^{-1}$ are anticipated. The fusion reactor wall and PFCs must withstand incident particle energies varying from a few eV ions to MeV neutrons [15, 16] and some reactor designs call for operation at temperatures up to ~1000 C to obtain high thermal efficiencies. Expected rates of net erosion and deposition of solid PFC material in reactors are projected to be 10^2-10^5 kg/yr for all elements and compounds. Heavy deposits (slag) can interfere with operation (e.g. UFO-induced disruptions) making PFC slag management critical.

Benefits: Robust Advanced Manufacturing (AM) including additive manufacturing processes build parts layer by layer using lasers or other techniques that fuse powders or fibers. AM is expected to transform the world's industrial output and enable new materials and products [17]. Desired microstructure, PMI properties, self-healing and radiation resistant properties, can be *designed* into complex geometries and hierarchical structures addressing surface/bulk functions in a single graded system [18-20]. AM is potentially transformative for PFCs by enabling low-Z material integration with complex high-Z substrates that provide PMI protection for high-Z components. Flow-through solid PFCs could provide in-situ replenishable clad-like designs using weakly bonded ceramic-based material at the plasma material interface.

Current status: PMI research is being performed on tungsten-based materials: advanced W-based composites, ductile W metal-matrix, W particulate, W laminate, and continuous W fiber. Work on non-W composites: SiC/UTHC, SiC/MAX, mostly in bulk with some PMI efforts. Recent efforts in innovative PMI materials include: nanostructured and mesoporous refractory-based materials; carbon nanostructures and 2D materials; ultra-high temperature ceramics (UHTC), B_4C, SiC, ZrB2, ZrC, and high-entropy alloys (HEAs) [21].

Programmatic context: AM has a strong technology pull in the aerospace structure and automotive sectors but very little synergy with DOE FES programs. DOE FES has some effort in PMI technology development and leverages international collaboration (DIFFER, FZ Julich).

Possible 15-year U.S. research agenda: A panel is needed to examine the wide range of options and to set short-term and long-term priorities for AM PFC R&D. Early-stage research in high-risk materials could include self-healing and adaptive PFCs, amorphous metals, advanced ceramic composites, such as MAX-phase (layered, hexagonal carbides and nitrides) composites. Determining linkages between AM and PMI properties through process/structure/function relationships could expedite development, along with a robust testing program on several platforms, including: linear plasma test stands, current tokamaks, DTT.

Research directions beyond the 15-year horizon: This area will require a growing level of R&D effort to fully exploit the coupling of advanced manufacturing techniques with enhanced component function – ultimately delivering PMI tolerant PFCs, integrated into bulk radiation-resistant heat sink materials and incorporated into complex blanket geometries.

3. Liquid Metal (LM) PFCs [22]: Liquid metal plasma-facing components (PFCs) have the potential to solve PMI challenges for fusion – self-healing, renewable surfaces that accommodate high heat loads (including transients) while potentially enhancing plasma energy confinement.

Benefits: Lithium-plasma interactions are found favorable: reduction in SOL recycling, plasma impurities and ELMs (by modifying pedestal); increase in edge plasma temperature. Lithium has a self-shielding response to plasma heat fluxes (divertor vapor target concept). Tin is a higher temperature alternative liquid metal. Both may be combined in an alloy.

Current status: Research is focused on controlling LM MHD effects [23, 24] and self-shielding [25] response to lithium PFCs (recycling, edge temperatures, pedestal, confinement) [26, 27]. Techniques include *slow-flow* and *fast-flow. Slow-flow* – liquid metal wets a cooled substrate and is slowly replenished [28]. Near term issues include: vapor shielding, substrate and flow control, lithium vs. tin or tin-lithium alloys, and integrated closed-loop testing on confinement devices. *Fast-flow* – liquid metal flow provides heat and particle removal [29]. Issues include MHD effects in magnetic fields, and material ejection from plasma-induced transients. MHD flows in narrow channels have been investigated in test stands [30], but not for toroidal flows. Efficient tritium separation is required for lithium PFCs, but few techniques have been studied [31, 32]. Effects of lithium on confinement and equilibrium have been noted, but technical solutions to slow and fast flow have undergone little testing. Test stands are needed to develop control approaches, and test/optimize ideas for deployment in a confinement facility [33, 34]. EUROfusion and China [35] are developing LM PFCs, although it is clear that the US is the world leader in this area.

Possible 15-year U.S. research agenda: Technological development of flowing LM PFCs, and vapor shielded systems. Fuel recovery/control demonstrated at large scales; assessment of tritium removal systems, material corrosion and embrittlement issues. Recycling of eroded materials (e.g., Sn, Li) demonstrated, performance limits of lithium vapor shielding [36] defined. Integrated performance and response/recovery from transients assessed experimentally.

Research directions beyond the 15-year horizon: Evaluate added complexity of LM PFCs against gains in erosion resilience, power handling, and confinement. Impacts on thermal-to-electricity conversion efficiency for reactors, safety, and economics studied. Inform reactor designs based on parallel development of advanced divertors and in-situ renewal of solid PFCs. Liquid metal concepts tested under the stress (PMI, heat fluxes) of a high-power, linear plasma test stand. Most promising ideas tested on a DTT, at reactor levels in an integrated tokamak environment.

Critics' objections: LM PFCs add complexity and may restrict operating temperatures of first wall components.

Advocates' responses: Liquid lithium PFCs may increase confinement significantly over solid high-Z walls; SOL modifications may be favorable for power handling. Technology development and scoping studies are certainly needed for all LM PFC implementations.

4. <u>Linear Plasma Test Stand (LPTS) for long-pulse PMI</u> [37]: Candidate PFCs must be tested for ability to withstand PMI under steady-state and transient heat loads, including thermo-mechanical properties (thermal conductivity, creep strength, He and H embrittlement), plasma-induced effects (erosion, redeposition, surface modification, dust formation) and hydrogen retention. Neutron damage effects (dpa, He production, transmutation) must also be considered.

Benefits: A high power density LPTS can expose small samples and mock-up modules to plasma conditions anticipated at reactor divertor targets. Operating in steady state, they can extend the PMI knowledge gained from short pulse exposure, e.g., tokamaks, to very long pulse and high plasma fluence, as needed for reactors. The performance of a wide range of materials now available – advanced PFCs, AM materials, liquid metals – can be rapidly tested, including samples previously exposed to neutron irradiation. Testing of prototype mockup modules at performance parameters, including liquid metal technologies, is necessary before deployment on tokamaks. A dedicated, high power LPTS facility with excellent diagnostic access would work synergistically with a solid/liquid PFC R&D program and DTT, to expedite PFC development.

Current status: Existing LPTSs have proven successful in providing basic data on PMI, e.g., PISCES (US) at low power density and Magnum (EU) at low target T_{et} and T_{it}. FZ-Juelich is proceeding with JULE-PSI [38], based on their PSI-2 with plans to include radioactive hot cells. China is also formulating plans for a high power LPTS.

Possible 15-year U.S. research agenda: The Material Plasma Exposure eXperiment (MPEX) [39] is proposed to perform this function. ORNL has built a prototype device, proto-MPEX, with the aim of assembling three key components for MPEX: (1) high power helicon source, (2) the means to heat electrons in an overdense plasma (EBW and/or whistler waves), (3) ICRH ion heating. Tests of (1-3) have shown necessary performance albeit not simultaneously.

Critics' objections: It's not certain MPEX can achieve its performance objectives. Other facilities in the world will be similarly capable to MPEX.

Advocates' responses: Capabilities are distributed over several devices in the world. MPEX aims for integrating all those capabilities in one device. Materials testing is often the rate-limiting step. The possibilities for advanced materials are exploding; intellectual property will likely extend far beyond fusion applications. These considerations, in addition to practicalities of shipping and handling neutron-activated materials, call for a dedicated US LPTS facility as part of an integrated PMI R&D plan.

5. <u>High field side RF systems</u> [40]: High Field Side RF launch (HFS RF) is identified as a potentially transformative approach to solve PMI challenges for RF launch structures, and also to enable efficient non-inductive current drive, which is essential for a steady state tokamak reactor.

Benefits: PMI on RF launchers – regarded as a potential show-stopper for application in a reactor – may be mitigated by placing RF structures on the HFS [41]. A quiescent scrape-off layer naturally forms there, producing steep SOL density gradients in near double-null configurations. Plasma density, and RF coupling, at the launcher may be *actively controlled* via external control knobs of magnetic flux balance and wall gap. Fluxes of energetic particles from various origins (e.g. runaway electrons, trapped ions, ELMs) are largely absent at the HFS. In addition, the RF wave physics for HFS launch is projected to be highly favorable. For lower hybrid current drive (LHCD), high magnetic field allows waves with low $n_{//}$ to penetrate deep into the plasma before damping, driving current where it is needed (0.6 < r/a < 0.9). CD efficiency, which scales as $1/n_{//}$, may be increased ~40% or more compared to LFS launch. RF waveguides are relatively small and may be embedded in the neutron shield blanket of a reactor. Locating HFS launchers off mid-plane may reduce neutron fluxes relative to the LFS. HFS launch is also favorable for mode conversion current drive in the ion cyclotron range of frequencies (ICRF) [42], with similar PMI advantages.

Current status: To date, no HFS LHCD experiments and virtually no HFS ICRF experiments have ever been performed. The technical means exist today to perform proof of concept experiments on existing tokamaks.

International context: The US is the innovator and leader in the world program.

Possible 15-year U.S. research agenda: Proof-of-concept HFS LHCD experiments are proposed for DIII-D in a 2 to 5 year time frame. CD efficiencies are projected to be 2 to 10 times higher than NBI, vertical ECCD or Helicon wave. WEST, operating at long pulse and with high-Z walls, could test HFS RF efficacy at higher fields (3.7 T) as well as coupler technologies with active cooling. A purpose-built DTT could serve as a platform to test HFS RF at reactor-level magnetic fields, plasma densities, PMI fluxes and surface power loadings. Additional R&D is required to improve RF source and antenna efficiencies for reactor application. RF and material testing/R&D programs are also required to investigate/develop manufacturing techniques for couplers, waveguides, and antennas using reactor relevant materials.

Critics' objections: HFS location and antenna feeds are difficult to access and service.

Advocates' responses: Radial build of couplers is modest, HFS couplers can be installed even on smaller present-day tokamaks, performance must be demonstrated in tests.

6. <u>Divertor Test Tokamak (DTT)</u> [43]: Exciting new advanced divertor ideas have potential to increase power exhaust handling to reactor levels ($q_{//}$ > 10 GW m^{-2}) while suppressing material erosion and damage. These include magnetic geometries with optimized target plate geometries, embedded x-points, extended legs, tight gas baffling, and various combinations of the above [7-11]. Liquid metal divertor schemes have also been proposed [36]. Present experiments cannot achieve upstream parameters of plasma pressure or heat flux approaching those of fusion power systems. In addition, present devices lack the flexibility to provide high power-density tests of advanced divertor options, and cannot readily vary solid and liquid plasma-facing materials.

Benefits: From 2015 FES Workshop Report on PMI[1]: "*We recommend establishing within the FES strategic plan a national working group to examine design options for a DTT facility. This facility should be capable of producing reactor-level plasma parameters in its divertor – while at the same time having the divertor volume and flexibility to explore a variety of advanced divertor concepts: magnetic geometries, topologies, mechanical shapes, gas dynamic options, and different target materials including liquid metals. In our judgment, the development of this science and technology is the most critical issue for advancement to DEMO, and the country that leads here will be in a leading scientific and technological position for the future.*" The consensus position of the Madison NAS Workshop is in resonance with the 2015 FES PMI Workshop. Both Workshops also noted that a new high-power-density DTT facility has been analyzed recently, featuring long divertor legs and a flexible poloidal field configuration, along with flexibility in gas dynamics and the use of solid and liquid plasma-facing materials [44].

Current status: No community-wide activity to date on examining design options for a DTT.

Possible 15-year U.S. research agenda: Establish within the FES strategic plan a national working group to examine design options for a DTT facility; implement a US DTT.

Research directions beyond the 15-year horizon: Taken together as part of a coordinated strategic plan, a DTT would work synergistically with solid/liquid PFC R&D programs and a high power linear plasma test stand – identifying and developing new concepts, testing them first in a high power linear plasma test stand and then deploying the most promising ideas for testing in an integrated tokamak reactor environment at the required performance levels on a DTT.

Critics' objections: Need for a DTT vs divertor studies in existing devices. The cost, which is estimated to be ~ $70M for an ADX-DTT and ~500M€ for the DTT recently proposed by Italy. Next step studies should also include neutrons. The challenge of power exhaust might not be as severe as the PB/R scaling suggests, possibly mitigated by cross field transport in the divertor region under high density detached divertor conditions.

Advocates' responses: Divertor physics involves interplay among plasma turbulence, neutral dynamics and atomic physics, which is impossible to model reliably. A U.S. DTT would address divertor designs specific to the more compact reactor concepts favored here. The strategic advantage of a DTT is that many concepts can be tested quickly, at relevant scale and at the plasma physics parameters required; rapid test cycles are precluded by neutron activation.

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[5] Austin discussion groups summary slides and comments on 6 PMI sub-elements

[6] **Advanced Divertors**

Presentations made at MFRSD Workshop -- Madison, July 24-28, 2017

Menard Increase emphasis on physics and technology innovations for compact tokamak fusion
Hill U.S. Tokamak Facilities: Powerful Tools for Developing a Faster Path to Fusion Energy

White papers submitted to MFRSD Workshop -- Madison, July 24-28, 2017

Guo Developing and Validating Heat Flux Solutions for Steady-State Fusion
Meade The Need for Innovation in Fusion and Strategy for PFC Development
Menard Increase emphasis on physics and technology innovations for compact tokamak fusion
Navratil Perspectives for a strategic plan for a reinvigorated US fusion energy program

White papers submitted to Fusion Energy Sciences Advisory Committee on Transformative Enabling Capabilities

Guo Development of Advanced Divertor Concepts for Steady-State Fusion

Presentations at FESAC TEC Meeting June 20-22, 2017

Guo Development of Advanced Divertor Concepts for Steady-State Fusion
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[14] **Advanced Solid PFC Materials and Manufacturing**

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Stangeby Developing refractory low-Z ceramic-clad Plasma Facing Components (PFCs) for robust burning plasma device operation
Henager Enhanced Fusion Energy Materials Program to Explore Potential Game-Changing Materials

White papers submitted to MFRSD Workshop -- Madison, July 24-28, 2017

Dehoff Advancing Fusion with Advanced Manufacturing
Henager Enhanced Fusion Energy Materials Program to Explore Potential Game-Changing Materials

Lumsdaine	Topology optimization for enabling innovative, high performance designs for additively manufactured first wall and divertor components
Nygren	High Impact on Fusion - Multiple Transformative Enabling Capabilities
Stangeby	Developing refractory low-Z ceramic-clad plasma facing components for robust burning plasma device operation

White papers submitted to Fusion Energy Sciences Advisory Committee on Transformative Enabling Capabilities
El-Atwani	Advanced Material Design for Fusion Applications
Henager	Plasma-Facing Materials by Design and Rapid Prototyping via Additive Manufacturing
Katoh	Advanced Manufacturing for Fusion PFC and Blanket Materials
Katoh	Emerging High Temperature Materials for Potential Application to Fusion
Nygren	Advancing Fusion Power -- Smart Tiles and Fast Data
Nygren	Development of Fusion Sub-components with Additive Manufacturing
Nygren	High Impact on Fusion - Multiple Transformative Enabling Capabilities
Tillack	Accelerated Deployment of Silicon Carbide Composites for an Attractive Fusion Energy Source
Wang	Laser powder-bed-fusion additive manufacturing as a transformative technology for plasma-facing materials and components
Youchison	Advanced Cooling Technologies through Additive Manufacturing

Presentations at FESAC TEC Meeting May 30 - June 1, 2017
Tillack	Accelerated Deployment of Silicon Carbide Composites for an Attractive Fusion Energy Source

Presentations at FESAC TEC Meeting June 20-22, 2017
Dehoff	Additive Manufacturing: Manufacturing Demonstration Facility
Henager	Plasma-Facing Materials-by-Design and Rapid Prototyping via Additive Manufacturing
Katoh	Advanced Manufacturing for Fusion PFC and Blanket Materials
Katoh	Emerging High Temperature Materials for Potential Application to Fusion
Martinez	Advanced Material Design for Fusion Applications
Nygren	Development of Fusion Subcomponents with Additive Manufacturing
Wang	Additive manufacturing for fusion energy sciences
Youchison	Additive Manufacturing for Advanced Cooling Technologies

Presentations at FESAC TEC Meeting July 19-21, 2017
Nygren	High Impact on Fusion - Multiple Transformative Enabling Capabilities
Rochau	Advanced Energy Conversion Cycles
Sarrao	Materials by Design; Materials for Harsh Environments

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Andruczyk The Case for Liquid Lithium as a Surface Material in Fusion Devices
Smolentsev Integrated approach to the development of liquid metal systems for FNSF and next fusion machines

White papers submitted to MFRSD Workshop -- Madison, July 24-28, 2017

Andruczyk The Case for Liquid Lithium as a Surface Material in Fusion Devices
Jaworski Breaking through to Reactor Solutions with a Focused, Liquid Metal Program
Majeski Magnetic confinement without anomalous transport

White papers submitted to Fusion Energy Sciences Advisory Committee on Transformative Enabling Capabilities

Jaworski Slowly flowing and high temperature liquid metals as plasma-facing materials
Kolemen Fast Liquid Metal Program for Fusion Reactor Divertor
Majeski Mitigation of scrape-off layer power flow with lithium plasma-facing surfaces
Majeski Recycling reduction for control of anomalous transport
Ruzic Liquid - Lithium as a Plasma Facing Material for Fusion Reactors
Williams Self-Healing Liquid Metal Protection System for Plasma-Facing Components

Presentations at FESAC TEC Meeting May 30 - June 1, 2017

Majeski Recycling reduction for control of anomalous transport

Presentations at FESAC TEC Meeting June 20-22, 2017

Ghoniem Self-Healing Liquid Metal Protection System for Plasma-Facing Components
Jaworski Slowly flowing and high temperature liquid metals as plasma-facing materials
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[37] **Linear Plasma Test Stand**

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Rapp — Development of the PMI science and PFC technology for fusion reactors with steady-state linear plasma devices

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Rapp — Development of the PMI science and PFC technology for fusion reactors with steady-state linear plasma devices

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Bonoli — PMI Challenges and Path towards RF Sustainment of Steady State Fusion Reactor Plasmas

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Caughman — Reliable Long-Pulse Plasma Heating and Current Drive using ICRF

Bonoli — PMI Challenges and Path towards RF Sustainment of Steady State Fusion Reactor Plasmas

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[43] **Divertor Test Tokamak**

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Brunner — A strategy to solve divertor heat flux and plasma-material interaction challenges for fusion

White papers submitted to MFRSD Workshop -- Madison, July 24-28, 2017

LaBombard — A strategy to solve divertor heat flux and plasma-material interaction challenges for fusion - aided by the development of demountable superconducting magnets

LaBombard — ADX: A compact, high-field, high power density Divertor Test Tokamak (DTT) and RF Sustainment Test Tokamak (STT) for fusion energy development

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Brunner — Developing a reactor power exhaust solution by testing advanced divertors in a compact, divertor test tokamak

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Abbreviations and Symbols

PMI	Plasma-Materials Interactions
DEMO	Demonstration power reactor or pilot plant
DTT	Divertor Test Tokamak
PFCs	Plasma Facing Components
AM	Advanced Manufacturing
UHTC	Ultra high temperature ceramics
MAX	Layered, hexagonal carbides and nitrides that have the general formula: $M_{n+1}AX_n$ where n = 1 to 3, M is an early transition metal, A is an A-group (mostly IIIA and IVA, or groups 13 and 14) element and X is either carbon and/or nitrogen.
HEA	High entropy alloys
LM	Liquid metal
MHD	Magnetohydrodynamic
Pedestal	Region of steep plasma pressure gradients at the edge of confined plasma
SOL	Scrape-off layer – plasma region on open magnetic field lines
Recycling	Plasma ions (hydrogen, deuterium, tritium) that impact wall surfaces are ‘recycled’ as neutrals at a rate that depends on the wall material and its level of hydrogenic saturation
ELMs	Edge localized modes – quasi-periodic bursts of hot, dense plasma into the SOL arising from instabilities in the Pedestal
LPTS	Linear Plasma Test Stand
HFS RF	High field side radio frequency
NBI	Neutral beam injection
ECCD	Electron cyclotron current drive
T_{et}	Divertor plate target electron temperature
T_{it}	Divertor plate target ion temperature
n_{et}	Divertor plate target electron density
$n_{//}$	Parallel index of refraction, $n_{//} = ck_{//}/\omega$. $k_{//}$ is component of parallel wavenumber along magnetic field.
$q_{//}$	“Upstream” parallel heat flux entering into the divertor region