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Origin of Diffusion in Hamiltonian Dynamics[1]

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Without making any kind of "loss of memory" hypothesis, a diffusion equation is derived for the Hamiltonian dynamics defined by $H = p^2/2 + A\sum_{m=-M}^{M}\cos(q - mt + \varphi_m)$, where the φ_m's are fixed random phases. The key point of the derivation is a property of locality for the waves inducing transport. Using perturbation theory, it is shown that only waves whose phase velocities meet the condition $\mid v_\varphi - p(t) \mid \leq \alpha A^{2/3}$, where α is a constant close to 5, play a relevant role for the statistical properties of the dynamics. This implies that, at each time, a particle can be considered as being acted upon only by these nearby waves. Thus, after a shift of momentum of $2\alpha A^{2/3}$, a particle feels the influence of different waves, with different phases φ_m's, from the ones it initially experienced. Because the phases $\varphi_m^{'}$'s are random, a shift of momentum of $2\alpha A^{2/3}$ then corresponds to the visit of a dynamical system independent from the previous one. This is what is regarded as being the cause of diffusion. Following this idea, one can predict that the force decorrelation, respectively the Gaussianity of the momentum distribution function, is well established after an average change of momentum close to $2\alpha A^{2/3}$, respectively $4\alpha A^{2/3}$. These predictions are in total agreement with the results of the numerical computations. Finally, a careful investigation of the initial behavior of $\langle \Delta p^2(t) \rangle$ enables one to prove the convergence of the diffusion coefficient to its quasilinear value when the amplitude A of the waves goes to infinity.

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Global Resonator in Mode Conversion at the Ion-Ion Hybrid Resonance in Tokamak Plasmas[1] A. BERS, A. K. RAM, Plasma Fusion Center, M.I.T., A. BÉCOULET, B. SAOUTIC, CEA–Association EURATOM, Cadarache, France — Recent analyses of mode conversion at the ion-ion hybrid resonance show that, when it is followed by a right-hand cutoff on the high-field side, it is possible, in principle, to achieve 100% absorption (mode conversion to IBW) of a FAW incident from the low-field side.[2,3] This scenario has been physically described to correspond to a critically coupled *internal* resonator formed by the cutoff-resonance-cutoff triplet layers. In practice, there is always a FAW reflected from the left-hand cutoff in front of the resonance toward the antenna, and one needs to consider the coupling of the antenna to the triplet in the plasma. We present such an analysis and show that the antenna impedance exhibits a *global* (i.e., externally coupled to) resonator. Conditions for 100% absorption (mode conversion) correspond now to critically coupling the antenna to the global resonator. The results are shown to compare with full-wave ALCYON code computations of antenna impedance for Tore Supra mode conversion heating experiments.[4]

[1]Work supported by DoE Contract DE-FG02-91ER-54109 and DoE Contract DE-AC02-78-ET-51013 through TFTR.
[2]V. Fuchs et. al., *Phys. Plasmas*, **2**, 1637 (1995).
[3]A. K. Ram et. al., *Phys. Plasmas*, **3**, 1976 (1996).
[4]B. Saoutic et. al., *Phys. Rev. Lett.*, **76**, 1647 (1996).

Coherent Acceleration of Particles by Perpendicularly Propagating Electrostatic Waves[1] D. BENISTI[2], A. K. RAM, A. BERS, Plasma Fusion Center and Research Laboratory of Electronics, M.I.T. — Acceleration of particles by electrostatic waves in a magnetic field for the case $kr \ll \omega_m/\Omega_c$ is investigated. k is a typical wave number, r is a typical Larmor radius, ω_m is the minimum wave frequency, and Ω_c is the cyclotron frequency. This situation is encountered in the transverse acceleration of ions in the ionosphere.[3] When $kr \ll \omega_m/\Omega_c$, stochastic acceleration does not occur.[4] In the case of one "on-resonance" wave, where the wave frequency is an integer multiple of Ω_c, acceleration is possible through the "web structure". However, we show that the web has a lower bound that lifts up when the wave amplitude is increased, implying that the web is not an effective way to accelerate particles with $kr \ll \omega_m/\Omega_c$. For two waves, we show that particles can be accelerated through a slow and coherent mechanism, regardless of how small their initial Larmor radii are. This concept of coherent acceleration is extended to more general wavepacket electric fields.

[1]Work supported by NSF Contract 94-24282-ATM.
[2]Programme Lavoisier Fellow
[3]See A. K. Ram, D. Benisti, and A. Bers supplemental abstract at this meeting.
[4]C. F. F. Karney and A. Bers, *Phys. Rev. Lett.*, **39**, 550 (1977).

Current Drive by Mode-Converted Ion-Bernstein Waves[1] A. K. RAM, A. BERS, Plasma Fusion Center, M.I.T. — In this paper we discuss theoretical limitations on the use of mode-converted ion-Bernstein waves (IBW) to drive plasma currents in tokamaks. The rapid change in $k_{\parallel}$ of IBW's as they propagate in toroidal plasmas can lead to a loss in the unidirectionality of the initial spectrum and, consequently, reduce the current drive efficiency.[2] Our calculations show that, for maintaining the unidirectional spectrum, the IBW spectrum at mode conversion has to be such that $|k_{\parallel}| < k_c$ where for a Maxwellian plasma $k_c \approx 1.3$. Along the IBW ray, the perpendicular (to the magnetic field) wavelength can become short compared to the Larmor radii of energetic ions. This can lead to a chaotic gain in the energy of the ions if the perpendicular electric field amplitudes are above threshold.[3] We will discuss this possibility along with the conditions for maintaining a unidirectional spectrum.

[1]Work supported by DoE Contract DE-FG02-91ER-54109 and DoE Contract DE-AC02-78-ET-51013 through TFTR.
[2]A. K. Ram and A. Bers, *Phys. Fluids B*, **3**, 1059 (1991).
[3]C. F. F. Karney and A. Bers, *Phys. Rev. Lett.*, **39**, 550 (1977).

Transverse Acceleration of Ions in the Auroral Ionosphere[1] A. K. RAM, D. BENISTI[2], A. BERS, Research Laboratory of Electronics and Plasma Fusion Center, M.I.T. — We show that the recent observations of transverse acceleration of O^+ and H^+ ions in localized regions of the auroral ionosphere,[3] where intense lower-hybrid waves exist, can be understood in terms of the nonlinear interaction of ions with electrostatic wave packets of finite bandwidth in frequency and wavelength. Contrary to previous studies, we find that motion of the ions does not need to become chaotic in order to explain the observed energies needed to escape the ionosphere. The energization process of thermal ions is coherent and occurs over times that are long compared to the ion gyration times. This coherent energization occurs when the ions interact with more than a single plane wave of differing frequencies. The conditions for the energization and an explanation of the observations will be discussed.

[1]Work supported by NSF Contract 94-24282-ATM.
[2]Programme Lavoisier Fellow
[3]J. L. Vago et. al., *J. Geophys. Res.*, **97**, 16935 (1992).

Mode Conversion to Ion-Bernstein Waves of Fast Alfvén Waves With Poloidal Wavenumbers in Sheared Magnetic Fields[1] S. D. SCHULTZ, A. BERS, A. K. RAM, Plasma Fusion Center, M.I.T. — Previous theoretical analysis[2] of mode conversion of fast Alfvén waves (FAW) to ion-Bernstein waves (IBW) neglected poloidal variations of the fields and magnetic shear. Full-wave codes show finite poloidal variations of the incident FAW fields near the ion-ion hybrid resonance (IHR).[3] When poloidal wavenumbers and the poloidal magnetic field are included in the mode conversion model, the equations have singularities not only at the IHR, where coupling to IBW's occurs, but also at a second layer located between the IHR and the left-hand wave cutoff (LHC). Although there is no wave resonance there, this second layer increases the tunneling distance between the IHR and the LHC. When the high-field-side right-hand cutoff is included, nonzero poloidal wavenumbers can change the triplet resonator phase and improve mode conversion at low $k_{\|}$'s. Antenna impedance calculations are compared to full-wave code results from ALCYON.[3]

[1]Work supported by DoE Contract DE-AC02-78-ET-51013 through TFTR and DoE Contract DE-FG02-91ER-54109.
[2]A. K. Ram et. al., *Phys. Plasmas*, **3**, 1976 (1996).
[3]B. Saoutic et. al., *Phys. Rev. Lett.*, **76**, 1647 (1996).

Electron Cyclotron Heating and Current Drive in High-Density, Spherical-Type Tokamaks[1] K. C. WU, A. K. RAM, A. BERS, Plasma Fusion Center, M.I.T. — Heating and current drive by electron cyclotron waves in high magnetic field tokamaks is commonly done by coupling power from the low-field side to the O-mode. However, for tokamaks with central $\omega_{pe}/\Omega_e > 1$, such as the spherical tokamak NSTX, the O-mode is cutoff. Then the only low-field side access to the cyclotron layer is via the fast X-mode and its mode conversion to an electron-Bernstein wave (EBW). Simulations show that substantial mode conversion can be achieved.[2] We show that, for a given plasma density and magnetic field profile, an appropriate choice of the frequency allows one to form a triplet EBW mode-conversion scenario. This is similar to the low-frequency, ion-ion hybrid resonance scenario for which 100% mode conversion was shown to be possible.[3] We extend these theoretical and computational studies to the high-frequency triplet mode conversion from X-mode to EBW. We analyze the conditions for which substantial mode conversion can be achieved.

[1]Work supported by DoE Contract DE-FG02-91ER-54109.
[2]S. Nakajima and H. Abe, *Phys. Rev. A*, **38**, 4373 (1988).
[3]A. K. Ram et. al., *Phys. Plasmas*, **3**, 1976 (1996).

Kinetic Effects in Tokamak Scrape-off Layer Plasmas*

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Transport modeling for the tokamak scrape-off layer is typically done using fluid theory which assumes short Coulomb collisional mean-free paths along the magnetic field, λ, in comparison with the connection length, L. This assumption is often violated for typical discharge parameters, especially above the thermal energy where most of the heat flux is carried; here $\lambda \propto \epsilon^2$ with ϵ being the energy. Thus, the tail of the distribution function can strongly depart from Maxwellian owing to nonlocal effects, modifying plasma transport, impurity radiation, and plasma-neutral gas interactions. These nonlocal effects become particularly pronounced for detached plasma conditions which are characterized by sharp gradients of plasma parameters along the magnetic field. These problems are addressed by developing a 1D-2V fully kinetic collisional time-dependent PIC code, W1, and its parallel-computer version, PW1. Both are used here to study divertor plasma detachment. New developments are presented that include a cross-field spatial dimension to assess the competition between radial and parallel transport in determining the SOL particle distribution functions, as well as impurity radiation and volume recombination. Short time-scale transport effects for ELMs in the tokamak edge are modeled also, and incomplete equilibration of the electron distribution function is observed. A comparison is made with a Fokker-Planck code ALLA and with experimental results. Results on the influence of kinetic effects on probe measurement interpretation, impurity radiation and parallel heat conductivity due to non-Maxwellian features in the SOL plasmas are presented and compared with ad hoc heat flux-limit models. Additional topics discussed are the sheath potential increase caused by hot electrons and plasma flow stagnation in the recycling region due to strong plasma-neutral particle interaction.

†In collaboration with X.Q. Xu, J.A. Byers, T.D. Rognlien, R.H. Cohen, S.I. Krasheninnikov, A.A. Batishcheva, P.J. Catto, M.M. Shoucri, and D.J. Sigmar.

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Kinetic Effects in the C-Mod Scrape-of-layer* O. BATISHCHEV^{A,B}, A. BATISHCHEVA, S. KRASHENINNIKOV^{C}, B. LABOMBARD, B. LIPSCHULTZ, D. SIGMAR, J. TERRY, MIT Plasma Fusion Center, Cambridge, Also: ^{A}Lodestar Research Co., Boulder, ^{B}M.V.Keldysh Inst. for Applied Mathematics, Moscow, RF, ^{C}I.V.Kurchatov Inst. of Atomic Energy, Moscow, RF — We present recent results from a kinetic simulation [1] of parallel electron transport in the scrape-off-layer (SOL) of C-Mod tokamak. We show that non-local effects result in strong deviation of the electron distribution function from equilibrium (elevated or depleted tail) for experimentally observed detached and attached SOL plasma profiles [2]. This leads to a significant change in plasma parallel heat conductivity, and modifies hydrogen excitation and ionization near the divertor plate. We compare our results with data from reciprocating and divertor Langmuir probes. We estimate the effect of the non-Maxwellian electron population on probe and Thompson scattering electron temperature measurements in C-Mod. We also give a comparison between numerical predictions and spectroscopic measurements of impurity line radiation.

[1] A.A.Batishcheva, *et al.*, Bull. APS, **40**, No.11, 1702 (1995).
[2] I.H.Hutchinson, *et al.*, Physics of Plasma **1**, 1511 (1994).
*Supported by U.S. DOE Contracts No. DE-FG02-91-ER-54109 and DE-AC02-78ET51013 at MIT, and DE-FG02-88-ER-53263 at Lodestar.

Kinetic Modeling of Parallel Electron Transport in TdeV Tokamak M. SHOUCRI, I. SHKAROFSKY, B. STANSFIELD, CCFM*, Varennes, QC, Canada J3X 1S1, O. BATISHCHEV^{A,B}, A. BATISHCHEVA, S. KRASHENINNIKOV^{C}, D. SIGMAR, MIT**, Cambridge, MA 02139, Also: ^{A}Lodestar Research Corp., Boulder, CO 80301 , ^{B}M.V.Keldysh Institute for Applied Math., Moscow 125047, RF, ^{C}I.V.Kurchatov Institute of Atomic Energy, Moscow 123098, RF — 1D2V Fokker-Planck code ALLA [1] is used to model parallel electron transport in the scrape-off-layer of TdeV. Our model uses detached and attached experimental data [2] given by Langmuir probes, and lithium and helium ablation. We obtain the electron distribution function on a precise 257x65x60 non-uniform grid. Strong deviations of hydrogen and carbon excitation rates, and heat conduction coefficient from their Maxwellian values is shown. We compare calculated variation of effective temperature at the reciprocating probe position with experimental measurements. We also explain by non-local effects why different experimental techniques show differences in the electron temperature.

[1] A.A.Batishcheva et al., of Plasmas **3** (1996) 1634.
[2] B.L.Stansfield et al., *Proc. 22 Eur.Conf.*, Bornemouth, **19c** pIII-101.
*Supported by Government of Canada, Hydro-Quebec and INRS.
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Fokker-Planck Modelling of PISCES Linear Divertor Simulator* O.V. BATISHCHEV[A,B], S.I. KRASHENINNIKOV[C], MIT Plasma Fusion Center, Cambridge, Also: [A]Lodestar Research Co., Boulder, [B]M.V.Keldysh Inst., Moscow, RF, [C]I.V.Kurchatov Inst., Moscow, RF, L. SCHMITZ, Fusion Energy Research Program, UCSD, San Diego, CA — The gas target operating regime in the PISCES [1] linear divertor simulator is characterized by a relatively high plasma density, $2.5 \times 10^{19} m^{-3}$, and low temperature, $8eV$, in the middle section of an $\approx 1m$ long plasma column. Near the target, the plasma temperature and density as measured by Langmuir probes drop to $2eV$ and $3.5 \times 10^{18} m^{-3}$, respectively, as a result of electron energy loss due to dissociation, ionization, and radiation. Such a sharp gradient in the plasma parameters can enhance non-local effects. To study these, we performed kinetic simulations of the relaxation of the electron energy distribution function on the experimentally measured background plasma using the adaptive finite-volumes code ALLA [2]. We discuss the effects of the observed incompletely equilibrated electron distribution function on key plasma parameter measurements and plasma - neutral particle interactions.

[1] L.Schmitz et al., *Physics of Plasmas* **2** (1995) 3081.
[2] A.A.Batishcheva et al., *Physics of Plasmas* **3** (1996) 1634.
*Under U.S. DoE Contracts No.DE-FG02-91-ER-54109 at MIT, DE-FG02-88-ER-53263 at Lodestar, and DE-FG03-95ER54301 at UCSD.

1D and 2D Kinetic Simulations of Tokamak Scrape off Layers [1,2] J.A. BYERS, X.Q. XU, T.D. ROGNLIEN, University of California, Lawrence Livermore National Lab, O.V. BATISHCHEV, MIT PFC/LODESTAR, (permanent address: Keldysh Institute, Moscow, Russia) — We compare simulations from the kinetic PIC code W1 with 1-D fluid theory to assess kinetic modifications to parallel transport in SOL plasmas. We verify the familiar result that the classical expression breaks down when $\lambda_{mfe} \gtrsim L_{\|}/10$. We find $< 30\%$ deviation from a flux-limited formula for electron heat flux for runs without strong local impurity radiation: $q_e^{Fit} = \frac{5}{2} n u_{\|} T_e - \frac{\kappa_e}{1+|q_e^{SH}/q_f|} \nabla_{\|} T_e$, is plasma parallel velocity and $q_f = c_f n_e v_{Te} T_e$, with $c_f = 0.15$. We find that strong local impurity radiation distorts the electron Maxwellian distribution, and then the above discription of q_e breaks down. 2D kinetic simulations use both W2D, a 2D modification of W1, which runs on a workstation, and PW2D, a 2D modification of PW1, a PVM-parallelized version of W1 that runs on the Cray T3D. The 2D structure is a set of largely independent 1D axial kinetic problems, radially coupled by model turbulent transport. PW2D is simpler than PW1 because of less need for global sums and particle load balancing over processors.

[1]Work for LLNL supported by DoE contract No. W–7405–ENG–48,
[2]MIT/LODESTAR-No.DE-FG02-91-ER-54109/DE-FG02-88-ER-53263

Divertor Scaling Laws for Tokamaks* PETER J. CATTO, MIT, D. A. KNOLL, INEL, S. I. KRASHENINNIKOV, MIT and Kurchatov — The breakdown of two body scaling laws is illustrated by using the two dimensional plasma code UEDGE coupled to an advanced Navier-Stokes neutrals transport package to model attached and detached regimes in rectangular geometry. After checking two body similarity scalings,[1] we systematically investigate non-two body modifications caused by (i) the one body process of spontaneous decay which is included in the multi-step processes that determine the ionization and radiation rates of atomic hydrogen and (ii) three body recombination. Our investigations indicate that two body scaling interpretations[1] of experimental data fail due to (i) multi-step processes when a significant region of the plasma exceeds a plasma density of 10^{19} m^{-3}, and (ii) three body recombination when there is a significant region in which the temperature is $\lesssim 1$ eV and the plasma density is $\gtrsim 10^{20}$ m^{-3}. These studies demonstrate that two body scaling arguments are often inappropriate in the divertor and results for alternate scalings will be presented.
*Supported by US DOE Contract DE-FG02-91ER-54109 at MIT and Contract DE-AC07-94ID13223 at INEL.

[1]P. J. Catto, D. A. Knoll, S. I. Krasheninnikov, Phys. Plasmas **3**, August (1996).

Parallel Ion Transport in Turbulent Edge Plasmas* P. HELANDER, UKAEA-Culham, R. D. HAZELTINE, UT, P. J. CATTO, MIT — Edge plasmas, such as the tokamak scrape-off layer, exist as a consequence of a balance between cross-field diffusion and parallel losses. The cross-field transport in the tokamak SOL is observed to be anomalous, and is generally believed to be caused by electrostatic turbulence. In numerical modeling of the edge plasma, anomalous diffusion coefficients are therefore invoked in the radial direction, usually in such a way as to match experimentally observed density and temperature profiles. On the other hand, the transport is generally taken to be classical along the field. In the present work, it is pointed out that these assumptions are not consistent if the radial diffusion is strong enough to balance a parallel flow of the order of the ion thermal speed. This circumstance is shown to lead to an unconventional form of the parallel ion transport laws by modifying the parallel friction force between different ion species. The resulting anomalous thermal force could be important for impurity retention in a tokamak divertor.
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Effect of Molecular Activated Recombination (MAR) on Plasma Flow in Divertor Simulators* A. YU. PIGAROV, S. I. KRASHENINNIKOV, MIT, T. K. SOBOLEVA, UNAM — We use the CRAMD code[1] to study collisional-radiative (CR) kinetics of atomic and molecular reactions that take place in low-temperature ($T_e = 1 - 5$ eV), hydrogen-helium mixture plasma discharges. The code solves coupled state-to-state rate equations for: (i) atomic $H(n)$, $He(nl)$; (ii) molecular $H_2(v)$; (iii) molecular ion $H_2^+(v)$, $HHe^+(v)$, $HeH^+(v)$; (iv) negative ion H^- systems. Effective CR reaction rates for neutral species ionization and for plasma recombination including MAR process[2] will be presented as a function of plasma parameters. We show that the rate of MAR for helium plasma may be as high as 10^{-10} cm^3/s and study the effect of vibrationally excited molecules on helium plasma flow in linear divertor simulators with the plasma-neutral gas interaction model.[2] Our calculations show that due to MAR the presence of a relatively small fraction of molecular hydrogen in helium discharges may result in anomalously fast helium plasma recombination and in significant decrease of plasma density and plasma flux onto the target in detached regimes.
*Supported by US DOE Contract DE-FG02-91ER-54109.

[1]A. Yu. Pigarov, *et al.* Bull. Am. Phys. Soc., **40** (1995) 1884.
[2]S. I. Krasheninnikov, *et al.* (PSI-96), sub. to J. Nucl. Mat.

Non-linear Monte-Carlo Model for Neutral Gas Transport* A. YU. PIGAROV, S. I. KRASHENINNIKOV, D. J. SIGMAR, MIT — We discuss one possible way of developing the kinetic/Navier-Stokes hybrid code necessary to study neutral gas transport in gas-target divertors. The proposed method is based on the Monte-Carlo approach which has already been well established in kinetic simulations of neutral particle-plasma interaction with plasma. To describe the neutral-neutral scattering collisions we use the reduced collision operator approximation and an appropriate iterative procedure for the calculation of the macroscopic gas parameters. The iterative procedure may also include the solution of the Navier-Stokes equations to determine the lower moments of the distribution function, in order to reduce the number of iterations in the limit of low Knudsen numbers $Kn \to 0$. To test that such a model works properly we have developed a code capable to solve the traditional problems of 1D, stationary rarefied-gas dynamics (heat transfer between parallel plates, Couette flow, etc.). We present results for a wide range of Kn together with the analysis of iteration convergence and required cpu time.
*Supported by US DOE Contract DE-FG02-91ER-54109.

On Impurity Radiation Loss in Tokamak SOL Plasmas*
A. A. BATISHCHEV, S. I. KRASHENINNIKOV, D. J. SIGMAR, MIT — In this paper we continue our investigations of the effects of perpendicular plasma energy transport and plasma convection on impurity radiation loss started in Ref. 1. We investigate analytically and numerically the solutions of the 2D nonlinear heat conduction equation including an energy sink as the simplest model describing plasma temperature distribution and energy loss due to impurity radiation in the SOL plasmas. We confirm the results of Ref. 1 showing that the perpendicular energy transport can result in the strong enlargement of the plasma volume with low temperature and very high density and cause a strongly enhanced energy loss due to impurity radiation from a low temperature region compared to estimates where only parallel plasma heat conduction is retained. Therefore, the magnitude of the perpendicular energy transport coefficient in a low temperature region can be very crucial for accounting of impurity radiation loss from MARFE and radiative divertor regions.
*Supported by US DOE Contract DE-FG02-91ER-54109.
[1]Krasheninnikov, S. I. and Knoll, D. A., Contrib. Plasma Physics **36**, 266 (1996).

Approaches to Development of Neutral Hybrid Code for Tokamak Divertor Modeling* S. I. KRASHENINNIKOV, A. YU. PIGAROV, O. V. BATISHCHEV, P. J. CATTO, D. J. SIGMAR, MIT, G. VAHALA, College of William & Mary, L. VAHALA, Old Dominion University — Currently two main approaches are in use for neutral transport modeling in tokamak edge plasmas: (i) linear (no N-N collisions) Monte-Carlo (MC), and (ii) fluid (short mean free path) Navier-Stokes (NS) model where N-N collisions are retained. However, for the most interesting regimes of divertor operation the neutral transport varies from short (near divertor targets) to long (in the upstream region) mean free path. As a result, none of the present methods of treating neutrals provides an entirely satisfactory description of neutral transport in the entire divertor region. Therefore, the development of the neutral hybrid code for the edge plasma modeling, that will allow all regimes of neutral collisionality to be modeled, has one of the highest priorities. We discuss here different approaches to development of such a code: (i) Non-linear MC method, (ii) Solution of non-linear neutral kinetic equation with reduced collision operator (RCO) using finite difference scheme, and (iii) Combining of RCO and Lattice Boltzmann techniques.
*Supported by US DOE Contract DE-FG02-91ER-54109.

Stability and Confinement in a Comet Cross-section Tokamak * RAMOS J.J., FREIDBERG J.P., KESNER J., MIGLIUOLO S., WALKAUSKAS S., MIT, KOTSCHENREUTHER M., DORLAND W., IFS, GLASSER A., LANL, MARTYNOV A., Keldysh Inst. — It has been suggested that a comet cross-section shaped tokamak ($\kappa < 1,\ \delta < 0$) will improve tokamak transport properties by reducing or reversing the precessional drift direction creating a "maximum-J" configuration ($J = \oint v_{\|} ds$). This would reduce the drive for collisionless trapped particle modes. Previous studies indicate that this approach is particularly effective in reversing the precessional drift in the outer half of the plasma. It has also been suggested that a second stability regime of the virulent toroidal ion-temperature-gradient driven (ITG) instability exists and is more easily accessible in this geometry, even though the ITG mode is not driven by the trapped particle population. Here, we examine the variation of maximum-J properties with shaping and aspect ration. We examine the linear ideal-MHD stability of comet-shaped plasmas using the PEST, KINX and DCON numerical codes. Additionally, we search for profiles that are also stable with respect to ITG and trapped particle modes, using the IFS comprehensive kinetic microinstability code.

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Stability and Confinement in a Levitated Dipole* KESNER J., MIT Plasma Fusion Center, MAUEL M., Columbia University — It has been suggested that a levitated dipole would provide an attractive advanced fuel fusion reactor[1]. Compared with a tokamak such a device is intrinsically steady state, free of disruptions and does not require current drive. Additionally it is free of neo-classical effects and can utilize a large flux expansion to obtain a reduced divertor heat load. We have examined electrostatic modes, including the MHD interchange mode and drift frequency modes under the assumption that the equilibrium distribution functions are Maxwellian. MHD stability requires that the equilibrium pressure gradient does not exceed a critical value and we show that when this restriction is met drift frequency instabilities can also be stable. Therefore the dipole plasma may exhibit classical transport. Experimental observations of instabilities excited in plasmas confined by a non-levitated dipole magnet support the notion of interchange stability when plasmas have sufficiently gentle pressure profiles[2]. Fully self-consistent, nonlinear simulations of these interchange modes show wave saturation as $|\nabla p| \rightarrow |\nabla p_{crit}|$.

*Supported by U.S. DOE.

[1]A. Hasegawa, Comm Pl Phys & Cont Fus, **1**, (1987) 147.
[2]H. P. Warren and M. E. Mauel, Phys. Plasmas. **2**, 4185 (1995).

The Issue of Global Modes in Ignition Regimes* S. MIGLIUOLO, B. COPPI, L. SUGIYAMA, M.I.T., Cambridge, MA, P. DETRAGIACHE, ENEA, Italy — The onset of macroscopic, pressure gradient driven modes in a well confined plasma column is a major issue[1] arising when large plasma currents, corresponding to relatively low safety factors q_ψ have to be produced in order to ensure adequate energy confinement. Then ideal MHD modes become unstable unless ignition can be reached with low values of β-poloidal as in the case of Ignitor. The breakdown conditions of the linearized ideal MHD approximation are analyzed. In regimes of ideal MHD stability, modes involving magnetic reconnection can still be excited. D-T ignition regimes are shown to be characterized by $\nu_e > \omega_e^* \simeq \omega_i^*$ so that these modes cannot be of the benign collisionless type. Approaching ignition with reversed shear configurations and relatively large q_ψ (low ratios of plasma current to magnetic field) raises also the issues of reconnecting modes with $m^o > 1$ that can be excited within the plasma column. "Conventional," low q_ψ regimes explored by the Alcator C-Mod machine are discussed and compared to regimes with relatively low q_ψ and flat $q(\psi)$ profiles produced by D-III-D experiments.
*Sponsored in part by the U.S. Department of Energy.

[1]A.C. Coppi and B. Coppi, Nucl. Fusion 32, 205 (1992).

Recurrent Explosive Events and Singular Non-linear Equations* A.C. COPPI, Yale University, New Haven, CT, B. COPPI, M.I.T., Cambridge, MA 02139 — Relatively brief events (e.g. involving accelerated or heated particles, excitation of fluctuations, radiation emission), related to the onset of explosive instabilities can recur at regular intervals or randomly. A new set of equations[1] is proposed with a characteristic singularity, which can model the realistic circumstance where the physical factor that drives the onset of plasma fluctuations is subject to an explosive instability. The conditions where the growth of these fluctuations can prevent the transition to an explosive state of the driving factor are identified. A parallel set of equations discussed briefly is one in which the fluctuation level itself is subject to an explosive instability. When the considered physical system is in an oscillation that approaches the explosive limit, it is susceptible to small perturbations that can lead it into an explosive state and this occurrence can be a random event. A special case is the existence of a small periodic modulation of the source of the driving factor (or of the threshold for the explosive instability to which fluctuations can be subject) where the period of this modulation is not commesurate with that of the basic fluctuation bursts.
*Supported in part by U.S. Department of Energy.

[1]A. C. Coppi and B. Coppi, Phys. Letters A (29 July 1996) and M.I.T. Report PTP 95/03 (Cambridge, MA, 1995).

Accretion Processes, Momentum Transport and Gravitation* P.S. COPPI, Yale University, New Haven, CT, B. COPPI, M.I.T., Cambridge, MA — Accretion processes are considered to account for the radiation emission by a large variety of objects and the plasma parameters of the accretion disks associated with them are quite different. A common feature is the need to have collective modes that can transport angular momentum at the high rate required to explain the accretion rate [1] inferred from the object luminosity. Referring to a magnetized plasma disk, a simple model is considered where an inhomogeneous flow velocity in the direction of the field exists. The gravitational force is parallel to the velocity gradient, transverse to the field, and in the same direction as that of the density gradient. The combination of these two factors (gravity and velocity gradient) can drive a macroscopic mode unstable provided the frozen-in-law is violated for instance by the presence of a finite electrical resistivity. Contrary to the case of the dissipative electrostatic, velocity gradient driven modes[2] where instead of gravity the mediating factor is the finite electron temperature, the longitudinal ion viscosity does not play an essential role.
*Supported by U.S. Department of Energy.

[1]J.E. Pringle, Ann. Rev. Astron. Astrophys. 19, 137 (1981).
[2]B. Coppi, Plasma Phys. Cont. Fusion 36, B107 (1994).

Instabilities in a Plasma Coupled to a Neutral Population* W. DAUGHTON, B. COPPI, P. CATTO, S. KRASHENINNIKOV, M.I.T. — Low temperature plasmas are often coupled to a neutral population through charge exchange or elastic collisions. The edge and divertor region of a tokamak and the ionosphere are a few well know examples. The linear stability of a coupled plasma - neutral system in plane geometry is examined and several relevant instabilities have been identified. One of these instabilities is an interchange type flute mode driven by the neutral pressure gradient. The second is a dissipative velocity shear instability[1] driven by the perpendicular gradient of a parallel velocity. Previously[1] the neutral population had been treated as a uniform background insensitive to the perturbations in the plasma while in the present work the instability is allowed to perturb the neutrals as well as the plasma. The relevant dispersion relationships and instability conditions are presented.
*Supported in part by the U.S. Department of Energy

[1]B. Basu and B. Coppi, *Journal of Geophysical Research*, Vol. 94 No. A5 p. 5316 (1989)

Reversed Shear Ignition Regimes for High Field Tokamaks* M.H. KUANG, L.E. SUGIYAMA, M.I.T. — The favorable confinement that has been observed to be triggered by non-monotonic current and q profiles in recent neutral beam heated experiments introduces[1] a possible new scenario for deuterium–tritium fusion ignition, at low current and very low fusion power, in high field, magnetically confined plasmas. These parameters may be easier to attain than the high magnetic field and plasma current that had previously been assumed[2] to offer the most efficient path to ignition, by minimizing the need for nonohmic heating and thereby optimizing the plasma confinement. Numerical simulation studies of typical ignition experiments show that it should be possible to attain reversed shear profiles during the initial current ramp phase of the discharge, using proper programming of the ramp without external current drive. The optimal path to ignition assumes that enhanced confinement is triggered during the ramp, but this is not a necessary condition. The minimum value of q necessarily falls below two, but it can easily be kept well above unity to avoid instabilities with mode numbers $m = 1$, $n = 1$ that may threaten full field ignition. Machines with highest magnetic fields are shown to gain the greatest benefit for ignition.
*Sponsored by the U.S. DoE and M.I.T.

[1]L.E. Sugiyama, M.I.T. R.L.E. Report PTP–95/3 (1995).
[2]B. Coppi, M. Nassi, L.E. Sugiyama, *Physica Scripta* **45** 112 (1992).

Composite Transport Coefficient for Electron Thermal Energy* B. COPPI, W. DAUGHTON, M.I.T. — A series of experiments by the Alcator C-Mod machine over a range of heating conditions (ohmic to strongly r.f. heated) has led to the construction of a composite transport coefficient for the electron thermal energy. This is represented by the difference of two terms: one corresponding to an outflow of thermal energy and the other one corresponding to an inflow. There are theoretical arguments[1] in support of a composite transport coefficient involving the elements of a transport matrix with an inflow term related for instance to the features of the current density profile relative to those of the electron temperature. In deriving the transport coefficient D_e^{th} that has been used to simulate the Alcator C-Mod plasmas, we have assumed that the driving factor of the underlying modes is the plasma pressure gradient. Thus $D_e^{th} \propto D_e^o[\beta_{p*} - C]$ where $\beta_{p*} = (8\pi p_*/B_p^2)$, $p_* \equiv -r(dp/dr)$ is evaluated at the point of maximum pressure gradient, $C \approx 3/16$ is a positive numerical coefficient and $D_e^o \propto I_p/(nT)^{5/6}$ is basically the Coppi-Mazzucato-Gruber diffusion coefficient introduced earlier to reproduce the results of experiments with ohmic heating.
*Supported in part by the U.S. Department of Energy

[1]B. Coppi and F. Pegoraro, *Phys. Fluids B* **3** p. 2582 (1991)

Present Context of Fusion Research and the Ignitor Experiment* THE IGNITOR PROJECT GROUP, ENEA, Italy, and, B. COPPI, M.I.T. — The importance of investigating plasmas under ignition conditions has been repeatedly recognized recently. In addition, confinement experiments by high field compact machines, Alcator C-Mod in particular, have confirmed the validity of the machine parameters that have been chosen ($B_T \simeq 13$ T, $R_0 \simeq 1.32$ m, $a \simeq 0.47$ m, $b \simeq 0.87$ m, $\delta_t \simeq 0.4$). The reference discharges for the machine design involve reaching $I_p^T \simeq 12$ MA in 4 sec with an edge safety factor $q_\psi \simeq 3.3$, and then decreasing I_p^T gradually to 10 MA after 1 sec to prevent the q=1 surface from becoming too large. Alternatively, I_p^T is held constant at 11 MA, corresponding to $q_\psi \simeq 3.6$, for 4.5 sec. For low values of β_p, where the configuration is nearly force-free, a high poloidal plasma current is produced ($\lesssim 9$ MA). With a peak density $n_0 \simeq 10^{21}$ m^{-3} and a peak temperature $T_0 \simeq 12$ keV at ignition, the plasma duration time is sufficiently long to cover all the intrinsic time scales as necessary to study the ignited state. The α-particle poisoning that would occur with longer duration times can be simulated by adding helium to the original D-T mixture after ignition. Given the values of q_ψ and of β_p at ignition the onset of large scale, ideal MHD modes driven by the plasma pressure gradient can be avoided.

*Sponsored by ENEA, CNR and ASP, of Italy, and by the US DoE

Assessment of Recent Results on Transport and Expectations for Ignitor* G. CENACCHI, ENEA, Italy, A. AIROLDI, IFP-CNR, Italy, F. BOMBARDA, Associazione Euratom-ENEA sulla Fusione, Italy, B. COPPI, M.I.T, J.A. SNIPES, M.I.T Plasma Fusion Center — One of the features of Ignitor is to approach fusion burn conditions while Ohmic heating is relatively strong. The prevalent heating, due to α-particles, has the same main characteristics as Ohmic heating, i.e., axisymmetry and peaking at the center of the plasma column. Therefore we may expect that the thermal energy confinement will not be as degraded as in the case where nearly all the heating is externally injected at discrete points around the torus and has a different radial distribution. Nevertheless this pessimistic assumption has been included so far in the transport simulations of the plasmas to be produced by Ignitor. The values for the energy confinement time obtained by the Alcator C-Mod machine in the Ohmic L-mode may then be considered as a basis from which to extrapolate for the Ignitor experiment. The possibility of Ignitor accessing the H-mode enhanced confinement regime requires different plasma parameters than those needed for full ignition. These alternative scenarios are analyzed.

*Sponsored by ENEA, CNR, and ASP of Italy, and by the US DoE

Ignition Approach Under L-mode Scaling in Ignitor* A. AIROLDI, IFP, CNR, Italy, G. CENACCHI, ENEA, Italy, B. COPPI, M.I.T. — The scientific objectives of the Ignitor machine ($R_0 \simeq 1.32$ m, $a \times b \simeq 0.47 \times 0.86$ m^2, triangularity $\delta \simeq 0.4$, plasma current $I_p \lesssim 12$ MA, toroidal magnetic field $B_t \lesssim 13$ T) can be achieved thanks to the high plasma currents and current densities that it can produce. This result is confirmed by the detailed simulations, carried out with the 1 1/2 D JETTO code, of the plasma evolution during the current rise and stationary phase considering the most advanced operating scenario envisaged for the machine. The technological constraints of the Ignitor design are respected and bounds on the allowable physical parameters, such as plasma density and pressure, are taken into account. The disruption boundaries in the (l_i, q_{psi}) diagram are avoided during the current rise. Plasma shape and position are checked to assure correspondence with the reference magnetic confinement configurations. The influence of the rate of density and current growth on the overall performance has been analyzed. Full ignition can be obtained even assuming transport diffusion coefficients accounting for energy confinement times close to the ITER89-P scaling. Under such pessimistic conditions that ignition is not achieved, a central ignited core is found in any case.

*Sponsored by ENEA, CNR and ASP, of Italy and by the US DoE

Plasma Engineering in the Ignitor Experiment* M. ROCCELLA, G. CENACCHI, M. GASPAROTTO, C. RITA, A. PIZZUTO, Associazione Euratom-ENEA sulla Fusione, Italy, A. BIANCHI, Ansaldo Ricerche, Italy, B. COPPI, M.I.T., L. LANZAVECCHIA, EMI, Italy — The Poloidal Field Coil (PFC) system and its operation have been optimized: the average plasma current and/or the flat-top duration of the reference operation scenarios at 12, 11 and 10 MA plasma current have been increased. The flux capability of the PFC has been raised up to 37 Vs to match the flux requirements of all the considered scenarios without considering the bootstrap current and the (18 MW) ICRF heating that can decrease the flux requirements by several Vs. The introduction of a radial electromagnetic press, in place of the vertical one, allows operation with a wider range of currents and a better matching of the MHD plasma equilibria with the first wall. The PFC design has been simplified, without loosing in versatility, by a better integration of the system. The relevant structural analyses have been carried out taking into account the (bucking/wedging) interaction with the Toroidal Field Coils. The results show that the magnet temperatures and the mechanical stresses do not exceed the appropriate engineering limits even in the most severe normal and off-normal working conditions.

*Sponsored by ENEA, CNR, and ASP of Italy, and by the US DoE

Radial Electromagnetic Press for Ignitor* A. PIZZUTO, A. CAPRICCIOLI, M. GASPAROTTO, A. PALMIERI, C. RITA, M. ROCCELLA, ENEA-Frascati, Italy, B. COPPPI, M.I.T. — The active vertical press included so far in the Ignitor design can be substituted advantageously (e.g. in terms of the machine maintenance procedure) by a radial electromagnetic press, without involving modification of the main machine components. Only the bracing ring of the radial mechanical preloading system that is permanently applied requires some changes. The radial press has to compensate for the reduced ring load (from 200 MN to 120 MN) and the original vertical press load of 35 MN. To get an equivalent preloading system, the radial press load has to be 140 MN, which is 25 MN higher, to account for the lower efficiency of the radial load. The current needed to originate the 140 MN force is about 3.2 MA. The press is active for 2 s starting from the plasma current rise. The temperature increase is about 20 °C. The stray field at the plasma border is well within the allowable value and can be easily compensated by varying slightly the current of one couple of poloidal coils. The new machine layout is illustrated and the electromagnetic and mechanical analyses carried out for the new configuration are given.

*Sponsored by ENEA, CNR and ASP, of Italy, and by the US DoE

First Wall in the Ignitor Machine* C. FERRO, F. BOMBARDA, Associazione Euratom-ENEA sulla Fusione, Italy — The first wall[1] in the Ignitor machine covers the entire surface of the vacuum vessel, with the exception of the port regions, working as a fully extended limiter which offers the maximum possible area for spreading the plasma heat loads. An average heat load of 0.5 MW/m^2 has been calculated[2] during normal operation, with peak loads of 1.35 MW/m^2 due to possible displacements of the plasma column around the equilibrium position. A common feature of all the existing toroidal machines is the reduction of the plasma contamination with increasing plasma density, suggesting a reduction of impurity production and a corresponding localization of impurities at the plasma edge. The edge parameters expected in Ignitor[3] ($n_a \simeq 2 \times 10^{20} m^{-3}, T_a \simeq 40$ eV) suggest the possibility of operating with a sort of "cold gas blanket"[4]. The rationale for choosing high Z metallic first wall materials (Molybdenum) is given. These issues and the present design of the first wall are discussed.

*Sponsored by ENEA, CNR, and ASP of Italy, and by the US DoE

[1]Consorzio CITIF, Report no.4, Contract 150005,Turin, Italy(1992)
[2]C.Ferro, G.Franzoni, R.Zanino, ENEA Report RT/ERG/FUS/94/14
[3]C. Ferro, R. Zanino, J.Nucl.Mater., 176-177,543 (1990)
[4]B. Lehnert, Nucl. Fusion 8,173 (1968)

ICRF Heating Scenarios for the Ignitor Machine* M. RICCITELLI, B. COPPI, M.I.T., C.K. PHILLIPS, R.P. MAJESKI, J.R. WILSON**, PPPL, D.N. SMITHE, Mission Research Corp., G. VECCHI, Politecnico Torino, Italy — An ICRF system with a large frequency range ($70 < f < 140$ MHz) is proposed for the Ignitor machine, to allow ^{3}He minority heating for all the operational scenarios envisioned, and H minority heating at lower fields. A feasibility study shows the dependence of the power absorbed by the plasma species under various heating scenarios. Alternatives are proposed in order to improve heating performance. The effects of collisions in the redistribution of the absorbed power are considered. The 1-D, FLR, no-magnetic-shear approximation CARDS code has been adopted to evaluate the single pass power absorption rates for every choice of parameters. Additionally, the 2-D, FLR, reduced-order, no-magnetic-shear approximation SHOOT code, which solves the Fokker-Planck-Vlasov equation using Stix's formalism, has been utilized to study the effects of collisional damping during ICRF heating. Single pass absorption by α-particles, including the effects of the magnetic shear as given by the 1-D, full-Bessel-functions code METS95, for the sake of completeness.
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Electrical Design of an ICRF System for Ignitor* R. MAGGIORA, G. VECCHI, M. RICCITELLI, Politecnico Torino, Italy, M.D. CARTER, ORNL — A system of 6 antennae is designed for ion cyclotron resonance heating (ICRH) in Ignitor. The coupling properties of each antenna are calculated by using a two-dimensional slab model to obtain the parameters necessary to model the current strap as a trasmission line then using the calculated current profile in a three-dimensional simulation (the codes have been developed at ORNL). The antenna consists of 4 loop (straps) to form a 2×2 poloidal and toroidal phased array; in our proposal each strap is fed by a coaxial cable, an adapter and a RF power generator. The power spectrum of the radiated parallel index is optimized for out-of-phasing in order to obtain a high heating efficiency and a high loading resistance. The predicted loading and "effective" resistance is sufficient for ICRH experiments with 4.0 MW of power injected in the plasma by each antenna as long as the distance between the Faraday shield and plasma separatrix surface is smaller than 4.0 cm. The maximum RF voltage in the system is 50.0 kV which is limited by generator power and coaxial cable dimensions. The development of a self-consistent integral-equation code is presently under way to analyze geometry effects on the antenna performances.
*Sponsored by ENEA, CNR, and ASP of Italy, and by the US DoE

Electron heating via mode converted ion Bernstein waves in the Alcator C-Mod tokamak*

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Highly localized electron heating (FWHM $\lesssim 0.2$ a) via mode converted ion Bernstein waves (IBW) has been demonstrated in the Alcator C-Mod tokamak. These experiments were carried out using 80 MHz fast wave ICRF power at $P_{rf} \lesssim 2.4$ MW. Electron heating at or near the plasma center ($r/a \lesssim 0.3$) has been observed in H-(^{3}He) plasmas at $B_0 = (6.4 - 7.3)$T. In this case the ion-ion hybrid layer is near the plasma center and the fundamental H and ^{3}He cyclotron resonances are located respectively on the low and high field sides of the tokamak. Off-axis heating ($r/a \gtrsim 0.5$) has also been observed in D-(^{3}He) plasmas at 7.9 T. In this case the ^{3}He cyclotron resonance is on-axis and the fundamental D resonance and mode conversion layer are on the high field side of the tokamak. The concentration of ^{3}He in these experiments was in the range $n_{^3He}/n_e \simeq (0.2 - 0.3)$ and the location of the mode conversion layer was controlled by changing the ^{3}He concentration or the toroidal magnetic field. The rf heating profiles were deduced using an rf power modulation technique in which the local electron heating rate was obtained from a "break in slope" analysis of the measured electron temperature versus time. Detailed comparisons with 1-D and toroidal full-wave ICRF models (FELICE and FISIC codes) have been carried out. The 1-D predictions for the fractional electron power absorption and damping location are found to be in qualitative agreement with the experiment. However discrepancies have been found between the full-wave toroidal code predictions and experiment. This disagreement is thought to be due to a lack of radial and poloidal resolution in the solution of the mode converted ion Bernstein wave in toroidal geometry and will be discussed. A fast wave current drive package has been modified to study the current generated via the mode converted IBW. Based on these numerical results and the experimental results for power absorption, off-axis current of up to 200 kA is predicted for C-Mod with unidirectional wave spectrum, which should be sufficient for studying reversed shear advanced tokamak plasmas.

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†On behalf of the Alcator Group

Impurity Screening in Ohmic and H-Mode Plasmas in the Alcator C-Mod Tokamak*

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The impurity density in the confined plasma is determined not only by the impurity production rate but also by screening, i.e. the balance between the perpendicular and parallel transport in the SOL. The relative importance of screening has been studied by injecting gaseous recycling (Ne, Ar) and non-recycling impurities (N, C) into various poloidal positions of the SOL and divertor in C-Mod. The density of the non-recycling impurities in the core is a function of the poloidal position of injection, while the screening of recycling impurities is not. In both cases screening is significantly worse (~3x) during divertor detachment. For a given injection rate of N_2 gas into H-mode discharges, the number of impurities in the core is typically a factor of 3 greater than for ohmic discharges. Optical imaging of low charge states of the injected non-recycling impurities using a camera and spectral filters shows a directed plume, indicating flow of impurities towards the divertor target at all positions studied, even at the inboard midplane. This implies that the friction force due to plasma flow dominates the parallel ion temperature gradient force. The spatial distribution of low charge states in the divertor has been studied using a multichord visible spectrometer, and the distribution of the nitrogen radiation has been been studied using a 20 chord bolometer array. The results show that for attached discharges the nitrogen radiation is predominantly in the SOL below the X-point. The position of the radiation is not strongly dependent on the position of nitrogen injection. The screening has been compared with calculations using the DIVIMP Monte Carlo code [1] and with an analytical model of the impurity transport.

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†In collaboration with B Lipschultz, B LaBombard, J A Goetz, R Granetz, D Jablonski, H Ohkawa, J Terry, MIT, S Lisgo, P C Stangeby, University of Toronto,

[1]P.C. Stangeby and D. Elder, J. Nucl. Mater., 196-198 (1992) 258.

Observations of Parallel and Perpendicular Impurity Transport from Alcator C-Mod Plasmas*

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Spatially scanning x-ray and VUV spectrometer systems have been used to observe emission from injected argon, scandium and nitrogen from Alcator C-Mod plasmas. Cross-field impurity transport coefficients have been determined by comparison between observed brightness profile time histories following injection of non-recycling scandium (and nitrogen) and predicted profiles from MIST. During L-mode operation, the cross-field impurity diffusion coefficient is anomalously high ($D \sim 0.5$ m^2/s), while in H-mode plasmas, the edge diffusion approaches neo-classical values, and a large (~ -7 m/s) inward convection velocity is seen near the plasma edge, also qualitatively similar to neo-classical predictions. Anomalous processes which ordinarily dominate perpendicular impurity transport are apparently suppressed during H-mode, at least in the outer regions of the plasma. Steady state up-down argon density profiles have been determined from x-ray observations of the forbidden line in Ar^{16+}, out to the last closed flux surface, following argon puffing. Large up-down argon density asymmetries near the plasma edge are seen, in qualitative agreement with the predictions of neo-classical parallel impurity transport. The edge impurity drift is in the direction opposite to the ion $\mathbf{B}\times\nabla\mathbf{B}$ drift direction, and switches direction when the toroidal magnetic field direction is reversed. Central toroidal impurity rotation during ohmic discharges has been measured from the doppler shift of argon and molybdenum x-ray lines. The magnitude of the observed rotation is typically a few $\times 10^4$ m/s, the impurities in the center rotate toroidally in the same direction as the electrons and the rotation direction switches when the plasma current direction is reversed. These observations are also in qualitative agreement with the predictions of neo-classical theory.

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†On behalf of J. Terry, F. Bombarda, E. Marmar and the Alcator Group

ICRF-heated enhanced confinement modes in the Alcator C-Mod tokamak*

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Routine high power operation of the ICRF heating system (up to 3.5 MW at 80 MHz) has enabled study of enhanced confinement modes in Alcator C-Mod up to $B_T = 8\,\mathrm{T}$. L-mode plasmas are well characterized by the ITER89-P scaling, but are observed only at low power levels under typical operating conditions. H-mode is routinely observed at high RF power levels, above a power threshold which is consistent with the scaling $P/S = 0.02\,\overline{n}_e B_T$. In contrast to L-mode plasmas in which the radiated power has little effect on global energy confinement, reduction of the radiated power by boronization has improved the quality of H-mode substantially. Longer ELM-free periods has become possible, and $H = 2.4$ (confinement enhancement factor over the ITER89-P L-mode scaling) has been achieved transiently. However, in this mode of operation gradual impurity accumulation leads to confinement deterioration and eventual termination of H-mode. High quality H-modes which lead to steady-state levels of density ($\overline{n}_e = 4 \times 10^{20}\,\mathrm{m}^{-3}$), stored energy ($H = 2.0$, $\beta_N = 1.5$), and radiated power ($P_{rad}^{main}/P_{in} < 30\%$) have also been achieved. This mode of operation is characterized by high levels of continuous recycling comparable to the L-mode level, sometimes accompanied by small-amplitude ELMs (analogous to grassy ELM H-modes). The recycling behavior can be affected by controlling the particle source rate through wall conditioning and gas puffing. Energy confinement in both types of H-mode exceed the ITER93-H ELMy and ELM-free scaling laws (by factors of 1.5–2), and high H-factors are observed even near the power threshold. Comparison will be made with other H-mode scaling laws and theoretical models. PEP mode is obtained with central ICRF heating combined with pellet (deuterium or lithium) fuelling. PEP mode plasmas have highly peaked density and ion temperature profiles, resulting in central plasma pressures in excess of 0.8 MPa (8 atmospheres). The fusion neutron rate is enhanced over the L-mode level by typically an order of magnitude. Shear reversal is observed in the plasma core and a greatly improved confinement of the core plasma is inferred from transport analysis.

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†On behalf of the Alcator Group

Higher Performance Operation of Alcator C-Mod* I.H. HUTCHINSON, FOR THE ALCATOR C-MOD GROUP, Plasma Fusion Center, MIT — Continued facility development of the Alcator C-Mod tokamak will allow operation at higher plasma currents and toroidal magnetic fields. Confinement times up to 80 ms with H-mode line-average densities up to $4.5 \times 10^{20} \mathrm{m}^{-3}$ at electron and ion temperatures approximately 5 keV have been achieved at 1 MA using ICRF heating launched power up to 3.5 MW. Plasma currents up to 1.5 MA are planned in the August 96 campaign. This operation is expected to give further improvement in confinement time and stored energy. Pellet fueling will also permit high density operation up to $\bar{n}_e = 10^{21} \mathrm{m}^{-3}$ and beyond. Preliminary exploration of different triangularities indicates an effect on confinement by changing the ELM behavior, and a range of triangularity will be further explored. Divertor studies exploit the very high parallel heat-flux characteristic of such high-performance plasmas and a prototype divertor cryopump module will be commissioned. The operational characteristics of Alcator C-Mod in these expanded regimes, near the latest performance limits will be reviewed, and prospects for further development will be discussed.
*Supported by U.S. DOE Contract No. DE-AC02-78ET51013

Recombination in the Alcator C-Mod Divertor* J.L. TERRY, D. LUMMA, B. LIPSCHULTZ, B. LABOMBARD, MIT Plasma Fusion Center — Significant recombination of the majority ion species has been observed in the divertor region of Alcator C-Mod under detached conditions. This determination is made by analysis of the visible spectrum from the divertor, in particular the Balmer series line emission and the observed recombination continuum, including a recombination edge at ~375 nm. The analysis of the continuum emission around the edge shows that the electron temperature in the recombining plasma is 1-1.5 eV. Analysis of the Balmer series Stark-broadened line widths indicate that n_e there is $\sim 9 \times 10^{20}$ m^{-3}. Analysis of the line intensities using the formalism of Ref. 1 shows that the upper levels of these transitions are populated primarily by recombination. Thus the brightnesses of the Lyman series lines (and Balmer series) are related to the recombination rate. The dominant recombination mechanism is 3-body recombination at these densities and temperatures. The measured volume recombination rate is comparable to or exceeds the estimate of the rate of ion collection at the divertor plates. The parallel heat loss due to the recombination is estimated to be ~150 kW, which is comparable to the power conducted to the plates during detachment.
[1]L.C. Johnson, E. Hinnov, JSQRT 11 (1973) p. 333.
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Comparison of Impurity Screening Between Limiter and Divertor Plasmas in Alcator C-Mod*, R.S. GRANETZ, G.M. MCCRACKEN, F. BOMBARDA†, J.A. GOETZ, D. JABLONSKI, B. LABOMBARD, B. LIPSCHULTZ, H. OHKAWA, J.E. RICE, J.L. TERRY, Y. YANG, MIT — A series of experiments has been carried out on Alcator C-Mod to compare impurity penetration between similar limiter and divertor discharges. Known amounts of recycling impurities (Ar and Ne) and non-recycling impurities (N_2 and CH_4) are injected by gas puffing, and the fraction ending up in the plasma is deduced from spectroscopic measurements. The poloidal location of the gas injection is also varied. It is found that during the most recent run campaign, limiter plasmas have 1-3 times higher impurity penetration than divertor plasmas which detach, but 5-20 times higher penetration compared to divertor plasmas which remained attached. During the previous run campaign, limiter plasmas had only 1-3 times higher penetration than attached divertor plasmas. These ratios are the same for both recycling and non-recycling species. There are strong dependencies on gas puff location as well. The reason for the difference in the two run campaigns is not understood, but may be related to gas leakage paths behind the divertor structure, which were plugged up between the two campaigns.

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Thermoelectric Currents as a Mechanism to Support Inside/Outside Divertor Asymmetries in Alcator C-Mod * B. LABOMBARD, I. HUTCHINSON, B. LIPSCHULTZ, M.I.T. Plasma Fusion Center — Asymmetries between the inner and outer divertor legs are inherent in most diverted tokamak plasmas. In Alcator C-Mod, low collisionality SOL plasmas display the largest asymmetry with outside/inside T_e ratios of ~10 (~0.2) for negative (positive) B_T. The asymmetries preserve $nT_e \approx$ constant, suggesting a heat flux asymmetry in the scrape-off layer (SOL) that reverses with B_T reversal. Associated with the T_e asymmetry are "thermoelectric currents", i.e., parallel currents driven by sheath potential differences at the divertor surfaces. Current densities up to ~2 times the ion saturation current are measured by divertor probes, consistent with classical parallel conduction. Parallel heat fluxes due to SOL currents are asymmetric and are estimated to exceed ~1/2 the total heat flux on divertor surfaces. A "thermoelectric instability" mechanism may therefore initiate and/or maintain divertor asymmetries: Asymmetric heat fluxes associated with parallel currents in the SOL can result in asymmetric T_e at the divertor sheaths, which in turn cause larger currents to flow. In principle, the loop voltage could initiate a "seed current", determining the direction of the asymmetry - hotter on the outer divertor when $B \times \nabla B$ is towards the x-point.

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Detached Divertor High $q_{||}$ H-Modes in Alcator C-Mod* J.A. GOETZ, B. LABOMBARD, B. LIPSCHULTZ, G.M. MCCRACKEN, J.L. TERRY, ALCATOR GROUP, MIT Plasma Fusion Center — Detached divertor operation has been achieved in Alcator C-Mod H-mode plasmas with $q_{||}$ comparable to that expected in ITER ($q_{||} \leq 0.5$ GW-m^{-2}). Previous studies have indicated that the electron temperature at the divertor plate (T_e^{plate}) needs to be $\leq$ 5eV for detachment to occur. T_e^{plate} can be lowered by raising the core plasma density, decreasing the power flowing in the scrape-off layer ($q_{||}$), or increasing the radiation in the divertor region. Impurity gases, e.g. nitrogen, neon, and argon, have been puffed into Alcator C-Mod H-mode plasmas. To date, only nitrogen puffing has been successful in producing a detached divertor. This is attributed to the fact that radiation is increased in both the core and divertor plasmas. With neon and argon puffing, an increase in radiation is observed only in the core plasma, while the radiation in the divertor remains constant or decreases slightly. It is also of interest to maintain the performance of these H-mode plasmas while having a detached divertor. The ITER89P H-factor decreases from 1.8 to 1.5 with nitrogen puffing after detachment while it decreases to 1.1 - 1.2 with argon or neon puffing even without detachment. Central Z_{eff} is increased for all impurity puffing cases ($\Delta Z_{eff} \sim 0.5 - 1$).
*Supported by U.S. DOE Contract No. DE-AC02-78ET51013

High Recycling H-modes in Alcator C-Mod* JOSEPH A. SNIPES, J.A. GOETZ, M. GREENWALD, A. HUBBARD, I.H. HUTCHINSON, J. IRBY, B. LABOMBARD, G. MCCRACKEN, J. RICE, P.C. STEK, J.L. TERRY, Y. TAKASE, S.M. WOLFE, MIT Plasma Fusion Center, F. BOMBARDA, Associazione Euratom-ENEA sulla Fusione, Italy — A new steady state H-mode regime has been found in Alcator C-Mod at high density ($\bar{n}_e$ = 2.2 - 4.5 x 10^{20} m^{-3}) and scrape off layer power (P_{SOL}/S > 0.18 MW/m^2) called a High Recycling H-mode (HRH-mode). These H-modes are characterized by a large increase in H_α emission up to or exceeding L-mode levels after the initial drop into H-mode. The H_α emission is strongly peaked on the inboard nose of the divertor and moves up toward the inner wall with increasing P_{SOL}. The emission levels off when the density reaches a steady state, which can be maintained for as long as the ICRF power is on. Small irregular ELMs may accompany the increased H_α emission though in many cases there is no evidence of discrete ELMs. Steady state HRH-modes with τ_E up to 2 x ITER89P were obtained after boronization. Unlike in ELM-free H-modes, no accumulation of impurities is found in HRH-modes due to reduced edge particle confinement and improved impurity screening. Such steady state HRH-modes may be preferable to detached operation in ITER if the divertor heat flux can be tolerated.
*Supported by U.S. DOE Contract No. DE-AC02-78ET51013

Investigation of the Role of Neutrals in H Mode Edge Plasma Dynamics in Alcator C-Mod* R. L. BOIVIN, J. A. GOETZ, M. GREENWALD, A. HUBBARD, M. KOLTONYUK, B. LABOMBARD, B. LIPSCHULTZ, E. MARMAR, J. RICE, J.C. ROST, J. SCHACHTER, J. A. SNIPES, Y. TAKASE, MIT, J. WEAVER, B. WELCH, Johns Hopkins Univ., C.P. MUNSON, LANL — Recent analysis of the edge plasma dynamics indicates that neutrals may play an intricate role in establishing and sustaining H modes. Specifically, neutrals may contribute in the formation of the edge transport barrier itself. With the appearance of an edge density pedestal, the ion density becomes large enough for the plasma to be "optically thick" to neutrals with energies below ~500 eV, which usually carry the bulk in charge-exchange power loss. In this case, not only are the warm neutrals "confined", but the cold (wall) neutrals are unable to penetrate deep in the plasma, hence increasing the local temperature, and modifying ionization rates in the edge. Estimates and indirect measurements of CX losses indicate that this channel may be significant, but this requires a direct confirmation. We use a variety of tools including neutral particle analyzers (neutral flux), a high resolution D_α spectrometer (neutral temperature), a high resolution X-ray spectrometer (neutral density) and bolometers, to help in diagnosing the neutral dynamics.

*Supported by U.S. DOE Contract No. DE-AC02-78ET51013

Local Transport Analysis for Alcator C-Mod* J. SCHACHTER, M. GREENWALD, ALCATOR GROUP, MIT Plasma Fusion Center — Two issues in local transport analysis of Alcator C-Mod plasmas will be presented. The first is a $\rho*$ scaling study of both L- and H-mode plasmas. For L-mode plasmas, with magnetic fields in the range 2.6 T to 8.0 T, the global confinement time τ_E is observed to be independent of the magnetic field. This is in contrast to Bohm ($\tau_E \sim B^{1/3}$) or gyro-Bohm ($\tau_E \sim B$) scaling. The one-fluid effective thermal diffusivity χ_{eff}, calculated by the TRANSP code[1], was also independent of B, though differences in the radiated power profiles complicate the analysis. The results of the H-mode scans are inconclusive to date. The second transport analysis issue to be presented is a study of the plasma resistivity. Given the plasma temperature, density, current, and Zeff, TRANSP solves the poloidal field diffusion equation for the plasma surface voltage using either a neo-classical model or a Spitzer model for the resistivity. By comparing the calculated surface voltage to the measured value, we find that the actual plasma resistivity lies between the neo-classical and Spitzer values. Results from a variety of plasmas, including L- and H-mode, will be presented.

*Supported by U.S. DOE Contract No. DE-AC02-78ET51013

[1]Courtesy PPPL TRANSP Group, D. McCune et al.

Effect of Edge Current on Flux Reconstruction in Alcator C-Mod* S. M. WOLFE, I. H. HUTCHINSON, B. LABOMBARD, A. HUBBARD, P. O'SHEA, M.I.T. Plasma Fusion Center — Substantial edge current density, up to 0.4 times the average toroidal current density, is inferred for H-mode discharges in Alcator C-Mod. This edge current significantly affects the flux reconstructions obtained by EFIT. Accuracy of the order of millimeters in the location of the x-point, strike points, and gaps is desired for divertor studies, and for determination of edge gradients for transport and stability analysis. A systematic study indicates inner and outer gap variation up to 1 cm over a range $0 < j_{edge} < 0.5(I/A)$, for a typical case. Increasing edge current density leads to a drop in the inferred x-point height and strike point locations, and increases in the inner and outer gaps. The magnitude of the effect is roughly consistent with simple analytic estimates based on the addition of toroidal current close to the x-point. The minimum χ^2 based on external magnetic measurements is found to occur for an edge current density slightly higher than that calculated by the standard, between-shots analysis, which employs a weak constraint on the allowed edge current. This higher value of j_{edge} also gives a more consistent mapping to the divertor probe data.
*Supported by U.S. DOE Contract No. DE-AC02-78ET51013

High Power Density ICRF Heating in Alcator C-Mod*
Y. TAKASE, P. T. BONOLI, S. N. GOLOVATO, M. PORKOLAB, ALCATOR GROUP, MIT — Operational improvements implemented during the past year have increased the reliability of high power RF heating of L-mode, H-mode, and PEP mode plasmas. Extremely high power densities of $P/V \leq 5\,\mathrm{MW/m^3}$ and $P/S \leq 0.6\,\mathrm{MW/m^2}$ were achieved with up to 3.5 MW of RF power at 80 MHz. Heating efficiencies of low single-pass absorption scenarios, including D(^{3}He) minority heating at 8 T, have improved substantially by reducing the high-Z impurity influx using boronization. H-mode confinement has also improved substantially after boronization. High power heating of H-mode plasmas has produced a quasi-steady-state plasma with $H_{\mathrm{ITER89-P}} = 2.0$ and $\beta_{\mathrm{N}} = 1.5$ while maintaining $P_{\mathrm{rad}}^{\mathrm{main}}/P_{\mathrm{in}} \leq 0.3$. The combination of increased input power, reduced radiation from the main plasma, and short scrape-off length in H-mode has produced ITER-relevant parallel heat fluxes into the divertor region ($q_{\parallel} \geq 0.5\,\mathrm{GW/m^2}$). Off-axis electron heating by the mode-converted ion Bernstein wave was demonstrated in D-^{3}He plasmas at 8 T. This mode of operation will provide the current profile control capability necessary for future advanced tokamak experiments. Current drive studies are scheduled to start in 1997 using the 40 MHz RF power currently being installed in collaboration with PPPL.
*Supported by U.S. DOE Contract No. DE-AC02-78ET51013

Confinement of H-mode Plasmas in C-Mod* M. GREENWALD, Alcator Group, MIT — A series of experiments, examining the confinement properties of ICRF heated H-mode plasmas, has been carried out on the C-Mod tokamak. For these plasmas, the plasma is essentially thermal with very little contribution to the stored energy from energetic ions and with $T_i \simeq T_e$. The data include those taken both before and after the molybdenum first wall surfaces were coated with boron. H-modes obtained with boronized walls typically had lower impurity content and radiated power and attained higher stored energy than those on bare molybdenum. Confinement enhancement relative to ITER89P for discharges with boronized walls, ranged from 1.6 to 2.4. The unique operating regime of the C-Mod device provided a means for extending the tests of global scaling laws to parameter ranges not previously accessible. For example, the C-Mod ELMfree data was found to be 1.4 times the ITER94 scaling and the ELMy data almost 2 times the ITER92 ELMy scaling law, suggesting that the size scaling in both may be too strong. A clear linear relationship between the edge temperature and the temperature gradient in the core plasma was observed; the discharges with the "best" transport barriers also showing the greatest improvement in core confinement. A summary of the data described in this paper are now available in the ITER H-mode database.
*Supported by U.S. DOE Contract No. DE-AC02-78ET51013

**Negative Central Shear Modes of Operation Near the β-limit in Alcator C-Mod *** P.T. BONOLI, M. PORKOLAB, J.J. RAMOS, MIT, W.M. NEVINS, LLNL, C. KESSEL, PPPL — The ideal MHD stability properties of equilibria with negative central shear and high bootstrap current fraction ($f_{bs} \simeq 0.75$), that may be achieved in Alcator C-Mod have been examined. Without a conducting shell and for relatively broad pressure profiles ($p(0)/p_{avg} \simeq 3.0$), values of normalized beta [$\beta_N = \beta_t/(I_p/aB)$] up to 3.7 were found for highly shaped plasmas with $\kappa_x \simeq 1.8$, $\delta_x \simeq 0.7$, $q_{min} \simeq 2.2$, and $r_{min}/a \simeq 0.75$. For elliptical and circular plasmas with low triangularity ($\delta_x < 0.1$), the stability limits are significantly lower ($\beta_N \simeq 2.2$). The β-limits for more peaked pressure profiles ($p(0)/p_{avg} \simeq 4.5$) were also found to be lower than for the broader pressure profiles. In all these cases the stability limit is determined by the ideal n=1, external kink mode. For the highly shaped plasma cross-section with a broad pressure profile, a maximum $\beta_N \simeq 5.5$ was found with a conducting shell placed at $r_w = 1.3$ a. In this case the β-limit is set by the n=3, external kink mode. In these studies self-consistent current density profiles and MHD equilibria were computed using the ACCOME code and the stability analysis was carried out using the JSOLVER and PEST-II codes. Details of the stability analyses and the current profile control studies will be discussed.
*Supported by U.S. DOE Contract No. DE-AC02-78ET51013

Reversed Shear Mode in Alcator C-Mod with Early ICRF Heating, Current Ramp and Pellet Injection* M. PORKOLAB, P. T. BONOLI, D. GARNIER, M. GREENWALD, I. HUTCHINSON, E. MARMAR, J. SCHACHTER, Y. TAKASE, S. WOLFE, ALCATOR GROUP, MIT — Initial scoping experiments were performed to obtain the enhanced reversed shear (ERS) mode in Alcator C-Mod using current ramp and early ICRF heating in the D(H) minority heating regime. Typical parameters at the end of a 0.23 sec sawtooth free period were $\overline{n}_e = 1 \times 10^{20}\,\mathrm{m}^{-3}$, $B_T = 5.3\,\mathrm{T}$, $P_{rf} = 2\,\mathrm{MW}$, $T_e = 5\,\mathrm{keV}$, $T_i = 2.5\,\mathrm{keV}$, and $I_p = 0.8\,\mathrm{MA}$. The minority concentration was low, typically 2% and therefore we expect mostly electron heating. While good ICRF coupling and excellent heating were observed, there was no evidence of the ERS mode, presumably owing to insufficient power being coupled to ions. In the coming experimental campaign we plan to (a) increase the minority concentration to couple a greater fraction of the power into ions; (b) slow down the current ramp rate to allow more time for the formation of the RS mode; (c) use pellet injection during the initial sawtooth free period with the aim of combining the PEP mode and the RS mode, with the goal of achieving the ERS mode. We have undertaken a modeling effort using TRANSP, FELICE, and ACCOME to predict the optimal operating regimes.
*Supported by U.S. DOE Contract No. DE-AC02-78ET51013

**Studies of ICRF Heating Experiments on Alcator C-Mod Using ECE Temperature Measurements *** P.J. O'SHEA, P. BONOLI, A.E. HUBBARD, M. PORKOLAB, Y. TAKASE, MIT — On Alcator C-Mod, the main heating scenarios are minority ion heating in $D(H)$ and $D(He^3)$ plasmas. The power from the launched fast magnetosonic wave (80 MHz) is absorbed by minority ions at their cyclotron resonance. The energetic minority ion population heats the bulk plasma by slowing down on electrons and majority ions. Another heating regime in which the magnetosonic wave is mode converted to an ion Bernstein wave (IBW) has been explored in both $H - He^3$ and $D - He^3$ plasmas. Because the IBW damps strongly on electrons, this regime can provide localized direct electron heating. Both on axis and off axis heating have been observed, with power profile widths (FWHM) of $\sim 0.2a$. The heating location is observed to follow that of the ion hybrid resonance which is controlled by both magnetic field and ion species ratios. Grating polychromator measurements of electron temperature are used to study the behavior of the heating in both regimes. A minority concentration scan in $D(He^3)$ plasmas allows an examination of the competition between minority heating and mode conversion mechanisms. Experimental measurements are compared with results from the modeling codes FPPRF & FELICE where possible.
*Supported by U.S. DOE Contract No. DE-AC02-78ET51013

Sawteeth and Global Stability in Alcator C-Mod* F. BOMBARDA, Associazione Euratom-ENEA sulla Fusione, Italy, B. COPPI, R. GRANETZ, A. HUBBARD, J. IRBY, S. MIGLIUOLO, P. O'SHEA, Y. TAKASE, S. WOLFE, MIT Plasma Fusion Center — The morphology and the physics of the sawtooth oscillations observed on Alcator C-Mod has been analyzed. Sawteeth are almost always present. They can vary from small, rapid oscillations, to the large sawteeth observed during RF H-modes, where the interval between crashes at the center can exceed 25 msec, several times the ohmic value, and the drop of central temperature at the crash can be 2 keV. The period is observed to be nearly independent of density, to increase with current and with ICRF power. A good correlation is found between the sawtooth period and the plasma stored energy over a range from 20 to 200 kJ. Modes with m=1, n=1 involving magnetic reconnection by finite electrical resistivity are considered to be responsible for the observed sawtooth crashes. The experimental equilibrium configurations have been found to be stable against ideal MHD modes, excluding those with long sawteeth. For these cases, reminiscent of the "monsters" observed at JET, the stabilizing effect of high energy particles [1] is considered.
*Supported by U.S. DOE Contract No. DE-AC02-78ET51013

[1]B.Coppi, et al., Phys. Rev. Lett. 63, 2733 (1989)

Observation of High Energy Hydrogen Tail Ions during ICRF Heating in Alcator C-Mod* M. KOLTONYUK, R. L. BOIVIN, P. BONOLI, C. FIORE, M. GREENWALD, M. PORKOLAB, J. C. ROST, J. SCHACHTER, Y. TAKASE, MIT — In Alcator C-Mod, the main heating scenario is based on the hydrogen minority heating at 80 MHz, with a toroidal field near 5.3 T. The energetic hydrogen population is studied via passive charge-exchange measurements, using two neutral particle analyzers (E||B), one with a fixed tangential view, and one with a scannable poloidal and toroidal view. In low density plasmas ($\leq 1.5\text{x}10^{20}m^{-3}$), and low hydrogen concentration ($\leq$5%), we observe tail ions with energies as high as 150keV (with 2.5 MW of RF power), whereas at higher densities, the hydrogen population is nearly Maxwellian. Preliminary comparisons of the ion velocity distribution with the FPPRF code (Fokker-Planck), indicate a reasonable agreement with the measured neutral particle energy spectrum. However, measurements of the sawtooth reheat rate, made after the RF is turned off, indicate that, compared to code predictions, a smaller amount of energy is stored in the tail, implying that the confinement of fast ions or the tail ion production is lower than anticipated. In addition, we will also explore the stabilizing effects of the tail ions on sawteeth.
*Supported by U.S. DOE Contract No. DE-AC02-78ET51013

Observations of Ion Edge Heating during ICRH in Alcator C-Mod* J. C. ROST, R. BOIVIN, M. PORKOLAB, J. REARDON, Y. TAKASE, MIT Plasma Fusion Center — Observations of edge ion heating during ICRF injection on Alcator C-Mod have been made using a toroidally and poloidally scanning charge-exchange neutral particle analyzer. The phenomenon is characterized by a large flux of charge-exchange neutrals (hydrogen and deuterium), at suprathermal energies, with a short rise time ($\leq$.2ms, the instrumental time resolution), but is not associated with impurity generation or loss of heating efficiency. Previous data showed that the RF power threshold for edge heating is decreased from 500kW to <10kW at certain values of the toroidal field. In this experiment, the energy spectra of escaping energetic neutrals were obtained for several RF power levels and particle pitch angles at three of these fields. It was found that the total energy in these suprathermal edge particles increases faster than linearly with applied RF power. Some conclusions are made about the structure of the damped field that generates the energetic ions.

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Spatial Structure of Pump Wave and Parametric Decay Instabililty during ICRF Injection on Alcator C-Mod* J. REARDON, C. CHRISTENSEN, J. GOETZ, S. GOLOVATO, B. LABOMBARD, E. MARMAR, M. PORKOLAB, C. ROST, Y. TAKASE, J. TERRY, MIT, M. MAY, U. Md — The spatial structure of RF waves in the edge of Alcator C-Mod has been explored. The radial structure of the pump wave and the Parametric Decay Instability (PDI) it generates has been outlined by a shot-to-shot scan of stationary Langmuir probes, and will be measured by a new reciprocating probe during the summer run campaign. The toroidal and poloidal extent of the RF waves has been inferred from stationary probe data from three different toroidal and two different poloidal locations. Preliminary data indicates that the pump wave is not toroidally localized near the antennas. The frequency of the PDI by-product ion quasi-mode detected by the probe appears to vary with the local cyclotron frequency, and the PDI amplitude scales linearly with input RF power for constant plasma conditions. Edge wave fields during different RF heating scenarios are compared. The likelihood that the PDI mediates the oft-observed increase in impurity radiation during ICRF injection is evaluated.

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Ion Mass Spectrometry on Alcator C-Mod: First Results* R. NACHTRIEB, I. JUREIDINI, B. LABOMBARD, B. LIPSCHULTZ, K. SHADMAN, E. THOMAS JR., K. WENZEL, MIT — An Omegatron probe designed for Alcator C-Mod [1] has recently been installed for operation during the summer run campaign. This diagnostic combines an ion mass spectrometer (Omegatron) with a gridded energy analyzer. The Omegatron employs a radiofrequency cavity to selectively collect impurity and background plasma ions with cyclotron frequencies between $0.1 \leq f_c$ (MHz) ≤ 100. In principle, this diagnostic can measure the relative charge state densities of impurity and background ions in the scrape-off layer (SOL) as well their separate temperatures. Knowledge of the impurity concentrations, charge state distributions, and temperatures in the divertor and SOL are critically important both for modelling impurity transport and for optimizing dissipative divertor regimes. We expect ion currents in the range of 1 to 100 nA, and so must carefully consider noise sources in the tokamak environment. We present results from first operation in a tokamak plasma, including signal strength, signal/noise ratio, Z/M resolution, and impurity ion spectra. [1] Thomas, E. Jr., MIT masters thesis, PFC/RR-93-03

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Initial Results from the C-Mod Divertor Thomson Scattering System* B. GREK, D. JOHNSON, R. PALADINO, J. BARTOLICK, Princeton Plasma Physics Laboratory, D. DIMOCK, J. LOWRANCE, Princeton Scientific Instruments, B. LIPSHULTZ, B. LABOMBARD, Plasma Fusion Center, MIT — Thomson scattering system has been installed recently to diagnose the x-point and divertor plasma regions with a resolution of 2-3 mm over a 12 cm field. The light scattered from a 30 HZ Nd:YAG laser is viewed from below through a slot in the outer divertor plate with a reentrant, high throughput collection system. A compact laser dump is located inside the inner divertor plate. Laser alignment is maintained under feedback control to track vessel motion. A filter polychromator spectrally resolves the scattered light from 25 spatial positions onto four 25 element avalanche photodiode arrays. System performance is described in terms of both calibration results and initial measurements of divertor plasma parameters.

*Supported by U.S. DOE Contract No. DE-AC02-78ET51013, DE-AC02-76-CHO-3073 and SBIR Grant No. 20431-92-II.

Phase Contrast Imaging in Alcator C-Mod* . A. MAZURENKO, M. PORKOLAB, Y. TAKASE, ALCATOR GROUP, MIT — A Phase Contrast Imaging (PCI) diagnostic is being set up in the Alcator C-MOD tokamak. It uses 18 cm wide infrared beam generated by a 100 Watt CO_2 laser. The beam passes through the tokamak plasma core vertically. Electron density fluctuations inside the plasma cause the beam wavefront to distort and these distortions can then be observed by PCI. The diagnostic uses a 12-channel photovoltaic detector array optimized for $10.6\mu m$ wavelength. This allows 1-dimensional (along the major radius) measurements of density fluctuations with long wavelength (up to the beam width) and a good frequency response (up to 100 MHz). The expected sensitivity is about $\tilde{n} \geq 10^9 cm^{-3}$. The PCI diagnostic can be used for observation of ICRF wave (80 MHz) propagation and turbulence studies. The diagnostic design and the first measured data will be presented at the session.

*Supported by U.S. DOE Contract No. DE-AC02-78ET51013

Results from a Prototype Second Harmonic Tangential Array Interferometer* N. BRETZ, F. JOBES, Princeton Plasma Physics Laboratory, B. HUMENSK, Carnegie Mellon Univ., J. IRBY, MIT Plasma Fusion Center — A tabletop tangential array interferometer operating at 1.06 and 0.53 mm has been built to test its sensitivity for use on C-Mod. This type of interferometer is insensitive to mechanical vibrations. The prototype uses a pulsed, 35 mJ, 10 Hz multimode, Nd:YAG laser, LiB3O5 non-critically phase matched doublers, a fan beam created by a cylindrical lens, several retro-reflector elements to define the array, and a CCD camera detector. This interferometer has beam diameters of a few millimeters and spatial resolution of a few centimeters as needed for C-Mod. Commercial lasers and CCD arrays are available which can scale this design to ~20kHz. Tokamak applications typically require a limiting sensitivity of 10^{-3} fringes and maximum changes of ~1 fringe. The limiting sensitivity of the prototype system has been investigated along with technical limitations on elements of the optical system relevant to its use on tokamaks. In particular methods of normalizing shot-to-shot and spatial mode variations in the laser intensity are examined. The use of visible and near visible components allows a compact optical design and efficient use of port space.

*Supported by US DoE Contract Nos. DE-AC02-76-CH0-3073 and DE-AC02-78ET51013.

Prototype Tangential Interferometer for Alcator C-Mod* J. IRBY, R. MURRAY, P. STEK, MIT Plasma Fusion Center, P. ACEDO, H. LAMELA, Carlos III University, Madrid, N. BRETZ, Princeton Plasma Physics Laboratory — A prototype single chord tangential interferometer using a frequency doubled, Nd:YAG, CW, diode pumped laser has been installed on Alcator C-Mod. Both the 1.064 and 0.532 μm beams are used in a two color configuration such that vibrational effects can be subtracted. Since the beams are both harmonically related and phase locked, a Bragg cell can be driven at two frequencies to both deflect the beams to the same angle and provide the offset frequencies needed for phase measurements. Electronics designed to provide the plasma phase shift as a direct analog output will be discussed. An in-vessel retro-reflector will reduce the effects of alignment errors caused by vibrations and thermal drifts. Bench tests of the prototype and initial results from C-Mod will be presented.

*Supported by U.S. DOE Contract No. DE-AC02-78ET51013

X-Mode Reflectometry on Alcator C-Mod P. C. STEK, D. GARNIER, J. H. IRBY, MIT — The Alcator C-Mod reflectometer consists of five amplitude modulated, O-mode channels spanning 50 to 110 GHz and provides electron density profiles for densities up to 1.5×10^{20} m^{-3}. However, for most current C-Mod conditions, these densities are limited to the plasma edge. By switching to X-mode launch, we will be able to study electron densities up to 4.5×10^{20} m^{-3} at 8 tesla. We are currently installing equipment to allow operation in the X-mode. Studies of profile and turbulence evolution during H and PEP modes are planned and will be presented.

*Supported by U.S. DOE Contract No. DE-AC02-78ET51013

Measurements of Vacuum Vessel Strain During Disruptions in Alcator C-Mod* J. SORCI, R.S. GRANETZ, MIT — Disruptions in Alcator C-Mod induce large toroidal eddy currents and poloidal halo currents in the highly conducting vacuum vessel and plasma facing components. The halo currents tend to be highly asymmetric, typically having an $n = 1$ toroidal structure, and this structure usually rotates toroidally at a few kHz. In order to quantify the resultant $J \times B$ forces and the dynamic stresses they induce, solid-state strain gauges have been installed on the interior wall of the Alcator C-Mod vacuum vessel, behind the tiles of the inboard divertor nose. Previous measurements of the poloidal distribution of halo currents during disruptions indicate that this is the region of highest current density. Dynamic measurements of vacuum vessel strain during disruptions will be presented. Comparison to engineering calculations and implications for Alcator C-Mod performance limits will be discussed.

*Supported by U.S. DOE Contract No. DE-AC02-78ET51013

Novel Surface Thermocouple Probes for Divertor Heat Flux Measurement* S. GANGADHARA, B. LABOMBARD, B. LIPSCHULTZ, N. PIERCE, MIT — An array of novel surface thermocouple probes have been installed and tested in the outer divertor of Alcator C-Mod. These sensors can, in principle, record divertor surface temperatures with fast time response ($\tau \geq 10\ \mu$ sec), allowing a direct estimate of the plasma heat flux to be inferred. The design is an adaptation of a commercially available device[1], employing a coaxial-like geometry with a single tungsten-rhenium ribbon wire embedded inside a 6.35 mm diameter molybdenum rod. Various prototypes were tested, including probes with flush and 5° angles with respect to the divertor surface, and probes with and without protective surface coatings. Typical surface temperature rises are $\sim$ 300-700 $°C$, corresponding to signals of $\sim$ 3-9 mV. RC filters with 10 ms time constants are used to reduce noise introduced by the plasma environment. The surface temperature corresponding to typical RMS noise levels is $\sim$ 25 $°C$. Using a one-dimensional, semi-infinite slab model, parallel heat fluxes in the range of 50-500 MW/m^2 are estimated. A comparison with heat flux estimates from Langmuir probes located adjacent to the thermocouple array will be presented.
*Supported by U.S. DOE Contract No. DE-AC02-78ET51013

[1] "The Self-Renewing Thermocouple," Nanmac Corp., Framingham, MA

High Resolution Measurements of Zeeman Patterns in Visible/Near Ultraviolet Spectra from the Alcator C-Mod Tokamak* J.L. WEAVER, B.L. WELCH, H.R. GRIEM, J. BRILL, Institute for Plasma Research, University of Maryland, J. TERRY, B. LIPSCHULTZ, D. PAPPAS, S. WOLFE, Plasma Fusion Center, Massachusetts Institute of Technology — Plasmas in Alcator C-Mod have been observed using the University of Maryland high resolution spectrograph in the near ultraviolet and visible range (200-700 nm). Zeeman splittings of emission lines are routinely measured in spectra recorded from light gathered via spatially-resolving fiber optic arrays. With magnetic field reconstructions along selected viewing chords, analysis of the Zeeman patterns of the spectra can aid in localizing the observed emission within the machine. The line shifts and normalized intensities for the lines of interest have been calculated for arbitrary magnetic fields and have been used to create simulated spectra. The distribution of emitters and the ion temperature are adjusted to achieve good agreement with the measured spectra. The analysis from several different chords for several ions will be presented, and the use of these analyses in the determination of Doppler shifts resulting from bulk flow will be discussed.
*DOE Contract No. DE-AC02-78ET51013 and DE-FG02-95ER54307

High-Resolution Visible/Ultraviolet Measurements from the Alcator C-Mod Tokamak* B.L. WELCH, J.U. BRILL, H.R. GRIEM, J.L. WEAVER, Institute for Plasma Research, University of Maryland, J. TERRY, M. GREENWALD, B. LIPSCHULTZ, E. MARMAR, J. RICE, Plasma Fusion Center, Massachusetts Institute of Technology — High-resolution visible and ultraviolet light spectra have been taken of the emission from the edge and divertor regions of the Alcator C-Mod tokamak. These spectra indicate that transitions from the Balmer series of deuterium and transitions from boron I-IV are the predominant lines. The boron is present as a result of the boronization of the vessel walls. The lineshapes of the D_α and boron transitions indicate Zeeman splitting (due to the 3-9 T magnetic field) and Doppler broadening (due to the neutral or ion temperature). Spatially resolved views with chords approximately tangent to the field lines near the last closed flux surface in the main chamber and in the scrape-off layer in the divertor allow measurements of parallel flows. Initial observations from the divertor line of sight indicate a net shift of D_α emission at times during the discharge. These shifts imply a toroidal flow of the neutral deuterium in the divertor. These results, as well as spectra of boron, will be presented.

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Mo XIV to Mo XXIX Quasi-Continuum Emission between 65 - 80 Å as a Plasma Diagnostic* M.J. MAY, K.F. FOURNIER, M. FINKENTHAL, S.P. REGAN, V.A. SOUKHANOVSKII, H.W. MOOS, JHU Plasma Spectroscopy Group, J.L TERRY, J.A. GOETZ, MIT Plasma Fusion Center, W.H. GOLDSTEIN, LLNL — Spectra of low and intermediate charge states of molybdenum (Mo XVI to Mo XXIX) have been measured between 65 and 80Å using a multilayer mirror based polychromator and a grazing incidence spectrometer. The spectral content of the observed 'quasi-continuum' has been analyzed using high resolution spectra from TFR, TEXT and Alcator C-Mod tokamaks and a detailed collisional radiative model for each of the above charge states. The fractional abundance of each ion has been determined using the MIST transport code with updated ionization physics. The analysis focuses on the relative contribution of the low charge states (Mo XVI to Mo XXIII) versus that of the intermediate charge states (Mo XXIV to Mo XXIX) to the observed signal. Theoretical investigation of atomic quantities such as the mean transition wavelength and total array strength of the $\Delta n=0$ transition arrays in this region is presented. The utility and limitations of the 'quasi-continuum' emission as a plasma diagnostic are discussed.

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Measurement of Neutron Production from Alcator C-Mod* C. L. FIORE, R. L. BOIVIN, MIT — Neutron rate measurements in excess of 1×10^{14} neutrons/second lasting for several hundred milliseconds have been obtained routinely from Alcator C-Mod plasmas. These high neutron rate plasmas result from high power (3 MW) ICRF injection, following boronization of the vacuum vessel walls. These data are obtained from a set of 18 neutron detectors of differing sensitivity (12 U^{235} fission chambers, 4 BF_3 and 2 He^3) divided among moderator stations located at four different sites in the experimental cell. Neutron measurements with fast time response are obtained from a bank of 14 He^3 detectors ganged together, which allow study of neutron sawteeth. The addition of a collimated neutron detector array to obtain spatially resolved measurement of the neutron source is planned. Zinc Sulfide detectors will be used to minimize the sensitivity to neutrons below 1 MeV in energy, and thus reduce the collimator size. The design of the collimator has been optimized using three dimensional neutron transport calculations (MCNP). The details of recent measurements from the existing neutron detectors will be presented. The final collimator design and the results obtained from the collimator prototype will be discussed as well.

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The Alcator C-Mod Boronization System* C. REDDY, C. L. FIORE, J. IRBY, J. BOSCO, R. CHILDS, E. MARMAR, G. MC-CRACKEN, MIT, G. ESSER, J. WINTER, Textor, M. HAWTHORNE, R. WATSON, UCLA — A system for boronization of the Alcator C-Mod vacuum vessel and plasma facing components was installed and began routine operation in January of 1996. Significant suppression of impurity levels and record stored energy were achieved during ICRF heating following boronization. Electron cyclotron discharge cleaning in dilute diborane gas (10% D_2B_6, 90% helium) was selected as the simplest and most cost efficient method to achieve boronization in a short period of time. Safety of the diborane storage, delivery, and exhaust systems was the prime consideration in the overall design. In addition, complete remote operation of the system was required in order to minimize personnel exposure to potential gas leaks. The delivery system and its performance will be detailed, as well as discussion of unanticipated post operative clean up problems. Upgrades to the system utilizing multipoint diborane delivery and glow discharge paddles are currently being installed.

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Boronization on Alcator C-Mod* E.S. MARMAR, G. MCCRACKEN, C. FIORE, J. GOETZ, J. IRBY, B. LIPSCHULTZ, C. REDDY, J. RICE, J. TERRY, Alcator Group, MIT Plasma Fusion Center, G. ESSER, KFA Jülich, M. MAY, Johns Hopkins, B. WELCH, U. Md. — Experiments to investigate the effects of boronization on Alcator C-Mod were begun in the winter campaign. The boron layer was deposited onto the Mo plasma facing components using a low temperature electron cyclotron discharge cleaning plasma with deuterated diborane/helium gas (10%/90%). Wall coverage is roughly estimated at about 1000 Å of boron for each 12 hour application. Plasma performance was profoundly impacted. In 0.8MA, 5.3 tesla, ohmic fiducial plasmas, Mo levels were reduced by more than a factor of 10, and C, which had been the dominant low Z impurity (pre-boronization $n_c/n_e \sim .5\%$), was reduced by about a factor of 3; oxygen levels were also reduced by about an order of magnitude; total core radiated power was reduced from $0.2 \times P_{in}$ to $\sim 0.08 \times P_{in}$. Operational limits were extended, allowing access to quasi-steady-state H-modes with high power ICRF heating ($P_{RF} \leq 3.6$ MW). For the highest power H-mode cases, core radiation was reduced by up to a factor of 3, and H-factors were increased up to 2.4. Net power flowing into the divertor was more than doubled, with $q_{||} \leq 500$ MW/m^2 available to challenge the power handling capabilities of the divertor.

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Observations of Parallel and Perpendicular Impurity Transport from Alcator C-Mod Plasmas * J RICE, J TERRY, F BOMBARDA, E MARMAR, PFC MIT — Spatially scanning x-ray and VUV spectrometer systems have been used to observe emission from injected impurities in Alcator C-Mod plasmas. Cross-field impurity transport coefficients have been determined by comparison between observed brightness profile time histories following injection of scandium and predicted profiles from MIST. During L-mode operation, the impurity diffusion coefficient is anomalously high, while in H-mode plasmas it approaches the neo-classical value, and a large inward convection velocity is seen near the plasma edge, also qualitatively similar to neo-classical predictions. Large up-down argon density asymmetries near the plasma edge are infered from x-ray observations of the forbidden line in Ar^{16+}, in qualitative agreement with the predictions of neo-classical parallel impurity transport. The edge impurity drift is in the direction opposite to the ion $\mathbf{B}\times\nabla\mathbf{B}$ drift direction, and switches direction when the toroidal magnetic field direction is reversed. Central toroidal impurity rotation during ohmic discharges has been measured from the doppler shift of argon and molybdenum x-ray lines. The impurities in the center rotate in the same direction as the electrons and these observations are also in qualitative agreement with the predictions of neo-classical theory.

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Kinetic Effects in the Alcator C-Mod Scrape-off-layer*

O. BATISHCHEV^{A,B}, A. BATISHCHEVA, S. KRASHENINNIKOV^{C}, B. LABOMBARD, B. LIPSCHULTZ, D. SIGMAR, J. TERRY, MIT Plasma Fusion Center, Cambridge, MA 02139, ^{A}Lodestar Research Co., Boulder, CO 80301 , ^{B}M.V.Keldysh Inst. for Applied Mathematics, Moscow 125047, R= F, ^{C}I.V.Kurchatov Inst. of Atomic Energy, Moscow 123098, RF — We present recent results from a kinetic simulation [1] of parallel electron transport in the scrape-off-layer (SOL) of Alcator C-Mod. We show that non-local effects result in strong deviation of the electron distribution function from equilibrium (elevated or depleted tail) for experimentally observed detached and attached SOL plasma profiles [2]. This leads to a significant change in plasma parallel heat conductivity, and modifies hydrogen excitation and ionization near the divertor plate. We compare our results with data from reciprocating and divertor Langmuir probes. We estimate, what will be kinetic effect on probe and Thompson scattering electron temperature measurements. We give a comparison between numerical predictions and spectroscopic measurements of impurity line radiation.

[1] A.A.Batishcheva, *et al.*, Bull. APS, **40**, No.11, 1702 (1995).

[2] I.H.Hutchinson, *et al.*, Physics of Plasma **1**, 1511 (1994).

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Simulation of Divertor Detachment in Alcator C-Mod*

F. WISING, A. ÖDBLOM, EM Field Theory, Chalmers Univ. Tech., Sweden, B. LABOMBARD, B. LIPSCHULTZ, S. KRASHENINNIKOV, M.I.T. Plasma Fusion Center — The non-orthogonal 2-D edge plasma fluid code UEDGE has recently been upgraded with a Navier-Stokes fluid model for the neutral particles. Using this model we have successfully simulated detachment in ITER and Alcator C-Mod. Detachment in C-Mod is partial, extending to the divertor nose but not beyond, in agreement with the experimental observations. In this work we extend the C-Mod simulations to other discharge conditions and we investigate the influence of several parameters on partial detachment, such as H-mode and L-mode operation, divertor geometry, and impurity characteristics. The simulated edge plasma conditions are matched to divertor and scrape-off-layer probe measurements and comparisons are made with spatially resolved H-alpha measurements.

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Impurity Screening in Ohmic and H-Mode Plasmas in the Alcator C-Mod Tokamak* G.M. MCCRACKEN, B. LIPSCHULTZ, B. LABOMBARD, J.A. GOETZ, R. GRANETZ, D. JABLONSKI, H. OHKAWA, J. TERRY, MIT, S. LISGO, P.C. STANGEBY, U. of Toronto — The impurity density in a plasma is determined not only by the impurity production rate but also by screening. The relative importance of screening has been studied by puffing recycling (Ne, Ar) and non-recycling (N, C) impurities into various poloidal positions of the SOL and divertor in C-Mod. The density of the non-recycling impurities in the core is a function of the position of injection, while the screening of recycling impurities is not. In both cases screening is significantly worse ($\sim 3\times$) during divertor detachment. Nitrogen penetration into H-mode plasmas is typically a factor of 3 greater than for ohmic discharges. Optical imaging of low charge states of the injected non-recycling impurities shows a directed plume, indicating flow of impurities towards the X-point. This implies that the friction force due to plasma flow dominates the parallel ion temperature gradient force. The spatial distribution of low charge states in the divertor has been studied using a multichord visible spectrometer, and the distribution of the nitrogen radiation has been been studied using a 20 chord bolometer array. Results will be presented.
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