Plasma Science of Wave-Particle Interactions

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Introduction

The goal for the Wave/Particle Interaction (WGI) subgroup was to answer three questions which followed directly from the stated goals of the Snowmass meeting:

1) What are the most critical wave physics issues/opportunities impacting the chances for realizing attractive fusion reactors – this included theoretical, experimental, and technological issues.

2) What could be done to address these issues – What is an optimal research program for addressing the issues over the next decade? What theories or codes are needed? What experiments need to be done? What technology needs to be developed? Where do we want to be in 5 yr. or 10 yr.?

3) How should existing facilities be employed and what new facilities are needed to carry out the research program described in item 2?

We divided into a three broad topical areas, or breakout groups, 2 topics for MFE consideration and 1 for IFE

1) Use of injected waves for plasma heating and control – plasma production, heating, current drive, flow drive, plasma stabilization, including the basic plasma physics needed for these applications;

2) Plasma generated waves and interaction of energetic particles with waves – Alfven eigenmodes and energetic particle instabilities, fishbones, phase space engineering of α particles (alpha channeling), including the needed basic plasma physics;

3) IFE – Because the number of participants in the WPI subgroup from IFE was small it made sense for them to combine discussion with colleagues in the Turbulence and Transport subgroup for many of the sessions.

There was a joint session between the WPI subgroup and the Turbulence and Transport subgroup which served as the IFE session on issues and opportunities for both. In addition a joint session was held with the subgroup on Steady State to discuss overlapping issues of current drive and steady-state maintenance of advanced confinement modes.

In the area of injected waves we saw the key issues and opportunities as being in plasma control. We saw the 5 to 10 year goal as: **To develop reliable RF plasma control techniques for successful experiments, leading to attractive reactors**. The success of any magnetic fusion concept will likely depend on controlling a number of tightly and non-linearly coupled processes: transport, turbulence, MHD stability, alpha heating. These processes are determined by and coupled through the plasma parameters and profiles: pressure profiles, current or rotational transform profile, flow profiles, radial electric field. There are RF techniques which can be used to control these parameters: localized heating, localized current drive, driven plasma flows, driven radial fluxes, modification of the distribution functions. Some of these RF techniques are well developed and used routinely in tokamaks, but we have only scratched the surface for other techniques and for other devices. The key to realizing the potential of RF to effect such control is to understand the RF physics and develop accurate predictive capability. We identified 4 areas of priority for the research program:

- Support for ongoing research in application of advanced RF techniques to tokamaks and to address the special needs of non-tokamak devices
- Improving the reliability, compatibility and flexibility of RF couplers by understanding the physics of antenna/plasma interactions, and by supporting innovative launcher development
- Understanding the coupling problems of Ion Bernstein Waves (IBW) and developing the science and technology necessary to make it work reliably
- Support for development of innovative wave physics approaches such as high harmonic fast wave, fast wave/IBW mode conversion, IBW flow drive, electron Bernstein wave (EBW) applications, low phase velocity current drive, alpha channeling. This must include experiment theory, modeling, launcher development, and advanced wave diagnostics.

In the area of plasma generated waves and wave interaction with energetic particles we saw the key issues as being: **to develop predictive understanding of the linear stability and non-linear dynamics of kinetic-MHD phenomena, and to develop techniques for phase space "engineering" of alpha/energetic particles in an MFE reactor**. Energetic particles, such as alpha particles, provide a universal drive for possible instabilities if the drift frequency is larger than the wave frequency. Otherwise stable plasma waves can be destabilized as in the various Alfven eigenmodes and new modes, associated explicitly with the energetic particles have been identified. While there has been considerable analytic and numerical progress in describing these phenomena there is a need to develop comprehensive predictive understanding using fully non-linear, non-perturbative, general geometry, kinetic-MHD codes coupled to experimental data and analytic interpretation. One example of an outstanding issue concerns the anomalous stability of FRC plasmas which may be due to finite ion orbit width effects. Non-linear 3-D kinetic MHD codes with arbitrary geometry are currently being developed, and this effort should be strengthened in order to achieve a comprehensive understanding of kinetic-MHD phenomena in the next 10 years. New theoretical methods applied to the non-linear growth of kinetic instabilities have revealed universal (generic) dynamics such as limit cycle behavior, mode bursting and chirping which have now been confirmed on a number of facilities. The validation of analytic models of non-linear saturation and growth suggests that a comprehensive predictive understanding of energetic particle driven modes is an accessible goal. Along with this thrust is the need to develop in parallel viable methods for the manipulation of energetic particles in a reactor for the purpose of plasma control and discharge optimization. As a case in point, the observed strong interaction of energetic particles with externally injected waves (e.g., D beam ion heating with mode converted IBW on TFTR) suggest possibilities for current drive, pressure and momentum profile control, or increase of fusion power density through alpha channeling. The development of such techniques require that we demonstrate in experiments the possibility of externally injected wave amplification with the properties required for efficient ion heating or current drive. Priorities for the program include:

- Laboratory experiments with detailed measurement of RF waves, energetic particles and plasma instabilities which can address generic wave-particle issues.
- Development of credible, experimentally validated models with the most advanced computational and analytical techniques.

In IFE issues and opportunities were identified in 2 areas. (1) Fast ignition – the goal being to obtain experimentally-tested theory and computational models for this very strongly driven relativistic plasma regime. And (2) conventional laser-driven approaches to IFE, where an improved understanding and control of the non-linear levels of plasma instabilities driven by intense electromagnetic waves would allow more confident design of higher gain targets and guide the choice of future IFE drivers. Wave plasma interactions represent an ideal area for mutually beneficial collaborations between the inertial and magnetic fusion communities. The non-linear behavior of intense electromagnetic waves, the saturation mechanisms for unstable plasma waves, linear and non-linear wave-particle interactions, and relativistic plasma phenomena are clearly issues of common interest.

1 Use of injected waves for heating and profile control

1.1 Current sustainment and profile control

Many MFE concepts require electrical currents in the plasma in order to obtain the desired equilibrium. The tokamak, for example, needs a large plasma current to generate rotational transform, without which there is no equilibrium. Such plasma currents may be created inductively, as in present-day tokamaks, but the pulse length of this approach is inherently limited. For steady state operation, the plasma currents which are required for equilibrium must be sustained non-inductively.

There are several possible approaches to sustaining plasma current non-inductively. One approach, successful in many experiments, is the application of waves with a phase velocity along the direction of the plasma current to accelerate electrons in that direction. The interaction may be parallel, in that the wave accelerates electrons parallel to **B**. An example is lower hybrid current drive (LHCD), which has very high current drive efficiency due to the strong damping of the wave by parallel-moving electrons (Landau damping) on the tail of the electron distribution function where collisions are rare. LHCD experiments which demonstrate the capability for current maintenance have been successfully performed in many tokamaks worldwide. Alfven waves, which interact with very low energy electrons, are also predicted to be effective, but there have been few experiments. Alfvén wave CD will be tested on CDX-U to test the effects of trapping of the current carriers in the magnetic well. Fast wave current drive (FWCD) and high harmonic fast wave current drive (HHFWCD) apply a combination of Landau damping and transit time magnetic pumping to accelerate electrons toroidally. FWCD is well established for central current drive, with ongoing programs in the US on DIII-D and C-Mod. HHFWCD experiments in plasmas with high dielectric constant and closely spaced ion cyclotron resonances are planned for NSTX. The competitive absorption of wave power by energetic ions or alpha particles, which would act to reduce the current drive efficiency, is a key issue needing resolution for FWCD and HHFWCD.

Toroidally directional waves which accelerate electrons perpendicular to **B** can also be used for current drive. Electron cyclotron current drive (ECCD) has provided current drive near the axis in many tokamaks and stellarators, with a magnitude in good agreement with theory. A major ECCD experiment is being developed on the DIII-D tokamak. A related approach is to use the conversion of electron cyclotron waves to electron Bernstein waves (EBW) at the plasma edge to gain access for the waves to plasmas with a high dielectric constant like the spherical torus (ST). Such experiments are planned for the NSTX and Pegasus ST devices.

Other approaches to non-inductive current sustainment include the bootstrap current, a neoclassical effect which is expected to provide most of the current for a high beta plasma, and neutral beam current drive, in which the energetic neutrals injected with a toroidal velocity component generate current following ionization. Both bootstrap current and NBCD have been verified on many toroidal devices. More speculatively, coaxial helicity injection (CHI) using currents drawn to electrodes at the plasma boundary may provide very efficient current drive, but magnetic turbulence is needed to transport the current density from the edge to the center, and the heat confinement may be compromised by the turbulence. CHI will be used on NSTX and on the SSPX spheromak. Oscillating flux current drive (OFCD), in which low frequency oscillating toroidal and poloidal electric fields are applied in phase quadrature at the plasma boundary to produce a net edge current which may diffuse inwards as the plasma relaxes, will be tested on the MST reversed field pinch. Finally, some positive results on current drive have been reported from the Rotomak device, using externally applied rotating magnetic fields. This approach, which is predicted to have efficiency near that of ohmic drive, will be further tested on CDX-U

In addition to sustainment of the plasma current, most MFE concepts benefit from control of the shape of the current profile as well in order to access regimes of improved performance (high confinement and stability at high beta). Specifically, Advanced Tokamak (AT) scenarios can be extrapolated from tokamak experiments in which improved confinement and stability were achieved when the current profile was optimized. For a given level of performance, the AT needs less plasma current, so the beta poloidal is larger and therefore the bootstrap fraction can be larger and the requirements on the non-inductive current drive smaller than for a conventional tokamak. A key issue is the alignment of the bootstrap current with the desired current profile, an issue which links the heating and transport properties with the current profile. Control of the diffusivity, leading to an appropriate profile of the plasma pressure, may be needed. A second key issue is development of efficient non-inductive current techniques which can be localized in a controlled and predictable way. ECCD is a promising candidate for this purpose since the deposition location can be robustly controlled and the localization is high. The first off-axis ECCD experiments have recently been completed on DIII-D with encouraging results. LHCD with controlled deposition location is being developed, and the experiments planned for C-Mod will explore this. LHCD will also be used in the MST device for generation of edge current drive as required for stability. FWCD is very useful for central CD, but, for off-axis current drive, mode conversion current drive (MCCD) using conversion of the fast wave to the ion Bernstein wave (IBW) at the two-ion hybrid resonance looks more promising and will be further explored in the C-Mod program. For the ST, HHFWCD will be tested on the NSTX device in the regime of very strong single pass damping, which is expected to provide off-axis CD. Mode conversion of EC waves to EBW waves with a toroidal directivity will also be tried for CD in NSTX and CDX-U.

Some stellarator concepts, such as the quasi-axisymmetric stellarator (QAS), can make use of bootstrap current to generate a large fraction of the rotational transform needed for the equilibrium. The proposed QAS device NCSX will explore the use of HHFWCD for central CD to supplement the externally generated transform before the bootstrap current profile is fully formed.

1.2 Plasma Heating

Injection of RF waves over a wide range of frequencies has proven to be an efficient and reliable method of plasma heating. ICRF, ECH or LH systems are present on many plasma experiments. While LH and ECH are basically used to heat electrons, ICRF has been used to heat both electrons and ions. In addition to increasing the plasma temperature, RF heating has been observed to have an effect on plasma energy confinement, particle confinement, rotation and stability.

Plasmas with high dielectric constant, such as in ST's or FRC's, cannot utilize conventional ECH or LH. EBW heating via mode conversion has been proposed as a solution to this problem and one such scheme has been demonstrated on a stellarator (W-VIIAS). Significant theoretical work has already taken place and experiments are being planned for NSTX. Issues of high dielectric constant and large values of $k\ \rho_i$ are important for ICRF in ST's. NSTX will test HHFW in regimes that will involve large $k\ \rho_i$, $k\ L_s$, and close spacing of cyclotron harmonics. Ion absorption at high harmonics (already observed for fast ions in conventional tokamaks) is an area of particular concern as a competing mechanism for the expected strong electron heating.

Off axis heating is important for possible transport control leading to profile modifications for improved stability and confinement as well as steady state bootstrap alignment. Both ECH and IBW (direct launch and mode converted) have been proposed for this advanced tokamak application. DIII-D will test intense off axis ECH and C-MOD will explore mode converted IBW. Direct launch IBW is being investigated on FTU and LHD but is not planned at present within the US program. However, direct IBW is theoretically the most attractive candidate for this role due to its large energy content in ion kinetic motion. A significant theoretical and experimental development to understand and improve on the wave-launching problem found in previous experiments should be put in place within the US program in the future.

Electron cyclotron resonant (ECR) has proved to be very reliable heating method for stellarator plasmas. Moreover, strong ECR heating has enabled access to the "electron root" configuration in which the radial electric field associated with the loss of high energy electrons leads to a significant improvement of neoclassical confinement in stellarator plasmas. To date, ICRF heating has not been as well explored in stellarators as in tokamaks, primarily because of the greater loss rate of high energy ions in conventional stellarators. Nonetheless, minority ion heating experiments have demonstrated that energetic ion tails are produced and bulk ion heating is also observed. Furthermore, direct electron heating is obtained by two-ion hybrid heating. There exist a number of opportunities for further developing these initial ICRF studies on stellarators, and in particular on the new breed of symmetric and omnigeneous stellarators in which neoclassical confinement of energetic particles is predicted to be comparable to or even better than that in an equivalent tokamak.

For all applications discussed, the physics of coupling (antenna-plasma edge interaction and wave launching efficiency) and wave propagation can be as important as the deposition physics. Much progress in these areas has been made over the years but further understanding of the basic physics involved (particularly where non-linearity's occur) is required, especially to optimize coupling to the desired wave spectrum while minimizing antenna-plasma interaction, to extrapolate to new regimes and devices. Integrated theory, modeling and experiment should continue to be performed, especially for mode conversion, direct IBW, Alfven wave and device specific applications.

1.3 Pressure Profile Control, Flow and Rotation Control

Plasma rotation has been the subject of intense study in recent years because of its many beneficial effects on tokamak operation. Toroidal rotation in tokamaks has been demonstrated to be necessary for stabilization of magnetohydrodynamic (MHD) modes in order to sustain high beta equilibria. Radial electric field shear generated by sheared rotation, either toroidally or poloidally, has been shown to suppress turbulence and allow improvement in energy confinement. In present-day tokamaks, rotation is mostly driven by unbalanced neutral beam injection (NBI), which may not scale favorably to the reactor regime. Encouraging preliminary experimental and theoretical results have emerged showing that radio frequency (RF)- induced plasma rotation can potentially be a very important tool for improving the performance of tokamaks. Unlike NBI, RF waves carry little momentum, hence the mechanism(s) by which waves influence plasma rotation is a subject of considerable scientific debate and interest.

A variety of RF effects on toroidal rotation have been reported from tokamak experiments worldwide. (a) In dominantly NBI-heated discharges, addition of RF heating usually reduces toroidal rotation in the direction parallel to the plasma current (co-current rotation), and this has been observed on TFTR, JET and DIII-D with both ion heating (ICRH) and electron heating (FW and ECH). Although RF acts as a viscous force in slowing down (rather than accelerating) plasma rotation in these experiments, studying this effect will contribute to our understanding of momentum transport in tokamaks. With 6MW of ICRF, 6MW of ECH (planned) and 20MW of NBI, DIII-D is well suited to address this subject. (b) In the case of purely ICRF-heated plasmas, counter-current rotation consistent with RF-induced ion orbit loss was reported in an early TFTR experiment. Recently, co-current rotation was observed in H-mode discharges with ICRH alone on JET and Alcator C-Mod. While the co-current rotation observed in JET appears to be correlated with L-H transition, significant core rotation observed on C-mod cannot be accounted for by this explanation. The co-current acceleration result is encouraging for reactor applications. Both C-Mod (with 8 MW of ICRF power) and DIII-D have plans to continue studying this subject. (c) Localized sheared poloidal flow generation was reported with ion Bernstein wave (IBW)-heating on PBX-M and TFTR. Poloidal flow driven by IBW was also suggested as an explanation for confinement improvement in FT-U at the recent EPS. To efficiently couple IBW to the plasma, high magnetic field may be required to avoid parametric instabilities. C-Mod should be able to revisit this subject in the future

Theoretical explanations of RF-induced rotation can be categorized under different ways of breaking the toroidal symmetry in particle and wave momentum space. Nonlinear ponderomotive force and the consequence of asymmetric energetic particle loss cones are examples. Another promising physical mechanism is RF induced non-ambipolar radial transport of minority or beam ions, which gives rise to a radial current and J x B torque for toroidal and poloidal plasma acceleration. Large drift-orbits and momentum dissipation mechanisms play significant roles in these theoretical models. To quantify the proposed mechanisms requires going beyond standard theories such as thin-banana approximations. Orbit codes taking into account RF scattering effects and improved Coulomb collision operators are being developed and will need to run on parallel computers for realistic simulations.

Besides tokamaks, many magnetic confinement concepts will benefit from plasma rotation. The spherical torus will require high confinement to achieve high beta and strong rotational shear can help establish an internal transport barrier for high confinement. For NSTX, if the pressure gradient does not provide sufficient diamagnetic rotation, external rotation control may be required. For immediate purpose, NBI may be the most reliable method, but RF induced rotation (perhaps with Alfven waves which carry larger momentum or IBW) should be investigated further down the road. Symmetric stellarators such as HSX and the planned NCSX should exhibit reduced neoclassical viscosity in comparison to conventional stellarators, and may be able to more efficiently access improved confinement regimes through driven plasma rotation. Experiments to test the reduced neoclassical viscosity are explicitly planned for the quasi-helically symmetric HSX device, and IBW is under consideration for NCSX as well as other major stellarators in the world program. Both spheromaks and RFPs rely on wall stabilization which again depends on plasma rotation to be effective. At present, there are no plans for rotation drive for these devices. MST is proposing LHCD for current profile control. It would be interesting to see if LH waves can also modify plasma rotation.

1.4 Energetic particles/RF plasma stabilization

Critical to the success of many magnetic fusion energy concepts is the ability to suppress or control various instabilities which threaten to degrade plasma performance. Two possible approaches have been identified which may lead to viable methods of instability suppression: fast particle stabilization due to kinetic modifications of MHD stability criteria and localized rf modifications of pressure and current profiles which influence stability limits.

A population of fast particles may lead, depending on specific details to either new instability mechanisms or to suppression of MHD instability by essentially providing a degree of stiffness to the plasma. Experimental evidence for this has already been observed with fast particle stabilization of the sawtooth instability in tokamaks. Such stabilization needs to be subsequently controlled. An example is the case of the giant sawtooth, where fast particle stabilization allows the plasma to reach unstable parameters that have more deleterious relaxation effects than the original unstable case. Continued study of these effects may be particularly important near marginal stability where the stability limits of tokamaks can be altered to allow improved operating regimes and at small ratios of a/ρ_i in FRC’s. It may also provide a means of stabilizing the n=1 tilt instability that has been of concern for a number of the emerging concepts in the past, such as spheromaks and FRC's.

While some success has been achieved in understanding fast particle stabilization, existing models are incomplete and detailed experimental measurements and comparisons with theory are lacking. Furthermore, the interplay between regimes in which fast particles provide stabilization rather than causing kinetically driven instabilities needs to be better understood. On DIII-D, accurate measurements of the q profile together with active shape and current profile control will be employed in detailed studies of sawtooth stability in the presence of an energetic ion population.

Suppression of instabilities may also be achieved by using RF techniques to modify the local pressure and current profiles, which provide sources of free energy for instabilities, or by driving localized sheared plasma flows as discussed in the previous section. Though off-axis heating with waves in either the ion cyclotron or electron cyclotron range of frequencies (ICRF or ECRF heating, respectively) has been studied extensively on tokamaks, the effect of this heating on local pressure profiles and ultimately on the plasma stability has not been quantified. Ultimately, given the small ratio of externally applied power to alpha heating power, profile modification will require the RF to modify the local transport properties. Out of the various methods for providing RF-driven current, LHCD is the most developed. Efficient off-axis current drive via lower hybrid waves (LHCD) has been demonstrated experimentally on a number of tokamaks and is reasonably well-supported by theory and modeling. Electron cyclotron current drive has been demonstrated on a number of tokamaks at modest power levels, but some disagreements remain between theoretical predictions and experimental measurements of the effects of trapped particles on efficiency. Off-axis mode conversion current drive (MCCD) has also been observed but the questions remain about the current drive efficiency, driven current localization and applicable operating regimes. The viability of utilizing localized current profile control for feedback stabilization of plasma instabilities remains to be established. Common to all three possibilities are issues of process efficiency and deposition localization, as well as possible interactions with energetic fusion alpha particles. Of the three, ECCD is predicted to provide the most localized deposition, while LHCD is predicted to deliver the highest gross efficiency. Recently, some evidence for partial suppression of neoclassical islands with localized ECCD has been obtained on the ASDEX-U device in Germany. Within the US domestic tokamak program, the capability to investigate the physics basis for stabilization of neoclassical tearing modes and other MHD modes in tokamaks with ECCD and with MCCD is in place, while a program for using LHCD is under consideration. The main issue for rf stabilization in RFP's is whether or not a stable driven Taylor state can be established with localized current drive. A proposal has been made to investigate this possibility with LHCD.

1.5 Discharge initiation

Virtually all present-day concepts for an MFE reactor are steady-state. Non-inductive techniques would be utilized to maintain the discharge once initiated. If these same systems could also be used for plasma startup, a considerable simplification of the reactor concept is possible. In fact, in some MFE concepts (the spherical torus, and stellarators for example) ohmic initiation of the discharge is impractical or undesirable. Discharge initiation using radio frequency techniques has been demonstrated in experiments dating back to the Princeton Large Torus. Many U.S. programs have plans to investigate RF startup.

A potentially attractive approach to ramp the current non-inductively in a tokamak is bootstrap overdrive. If the poloidal beta of the plasma can be raised sufficiently high then the fraction of the plasma current due to the neoclassical bootstrap effect can be larger than unity, causing the total current to increase. Experiments are planned for DIII-D to test this concept. High power electron heating is required, and MHD stability at the high beta poloidal is a key issue. Successful development of the concept has a high payoff, since tokamaks, particularly low aspect ratio tokamaks, could be constructed without an ohmic heating coil.

Since the success of the spherical torus as a reactor concept is critically dependent on the viability of non-inductive startup, several approaches will also be investigated in NSTX. An electron cyclotron resonant (ECR) system capable of 30 kW at any pulse length up to 1 sec is being installed on NSTX primarily to provide plasma pre-ionization. This system will also be used for preliminary experiments in the excitation and propagation of electron Bernstein waves (EBW). The advantage of EBW heating or current drive in the ST is that, unlike conventional electron cyclotron excitation, the EBW can propagate through the high density plasmas typical of high beta plasmas to the cyclotron resonance layer.

A high power 28 GHz ECH/EBW system has been proposed which will consist of 2-4 300 kW gyrotrons and associated hardware. This system will be designed to provide highly directional launch beams with adjustable launch angle and polarization for optimum coupling to the EBW mode as well as flexibility with startup assist and non-inductive current drive experiments. This system will be used in conjunction with the 6 MW high harmonic fast wave (HHFW) system in an attempt to provide non-inductive ramp-up to full current operation of NSTX.

Similar approaches to non-inductive startup will also be investigated in the Pegasus ultra-low aspect ratio ST. Pegasus will employ HHFW with adjustable phasing to provide an extra assist to the startup plasma formation. HHFW heating and current drive in Pegasus will be coupled with inductive startup and/or an alternative (non RF) plasma startup technique which uses a toroidal array of plasma current injection guns to provide a poloidal current source. Plans have been made to install a second HHFW antenna so one can be used for startup assist and one for central heating. An EBW program is also under way at Pegasus, with plans to install a 200 kW 3 GHz system to test wave propagation and demonstrate power absorption.

Non-inductive startup using various techniques has been demonstrated in the CDX-U ST. Future plans for such studies center on very low frequency techniques, in particular the rotamak – ST approach to discharge formation recently demonstrated at Flinders University in Australia. The CDX-U experiments will attempt to extend the Flinders work to higher density and higher toroidal fields in order to test the relevance of the rotamak technique to NSTX-scale experiments.

RF plasma production is an important issue in stellarators because the discharges are seldom initiated by ohmic current, as in tokamaks. ECR breakdown and heating is reliable and very effective, and is commonly used in high performance stellarators. However, the resonant nature of the ECR breakdown process limits operation to specific values of the magnetic field. As is the case in the ST, there is interest in the excitation of the mode-converted EBW to extend ECR techniques to higher plasma densities. The use of EBW should allow relatively high density ECR plasma production, and may well be the explanation for the observed over-dense plasma production in Heliotron DR.

Plasma generation in the ion cyclotron range of frequencies (ICRF) has also been demonstrated in stellarators, and there exist numerous opportunities for improved understanding and improvement of the various techniques in this frequency range. The basic advantage of ICRF plasma production is that the magnetic field can be varied over a relatively wide range for a given RF excitation frequency. In CHS for example, target plasmas of density $n \leq 5 \times 10^{18}\ \mathrm{m}^{-3}$ for NBI heating are generated over the magnetic field range B = 0.5 – 1.5 T. In this case, the plasma production scheme is associated with slow wave excitation (shear Alfven wave at $\omega < \omega_{ci}$ and likely ion Bernstein wave at $\omega > \omega_{ci}$). Whistler/helicon waves have also been used to generate plasmas in helical devices, and other non-resonant ICRF techniques have also been explored.

1.6 Innovative Wave Physics and Wave Diagnostics

Essentially all of the magnetic fusion experimental facilities are equipped with various forms of high power wave injection systems used to support the "mainline" experimental programs in what might be termed "standard" heating and current drive. However, many of these facilities have sufficient flexibility to also explore new regimes of wave physics. The motivation for this kind of innovative research is both to challenge the theoretical models in new parameter regimes and to explore techniques to substantially improve the reactor prospects of the MFE concepts. One example of the range of possibilities is the so-called "alpha channeling" discussed by Fisch, et al., which could provide entirely new operating scenarios for D-T reactors. Another is the use of ion Bernstein waves (IBW) to produce localized velocity shear in the ion fluid and thereby possibly creating controllable local transport barriers.

Detailed investigation of these novel wave regimes often requires development of special-purpose diagnostics to fully characterize wave propagation and absorption. Examples of such diagnostics are laser scattering systems and imaging systems sensitive to wave-induced density fluctuations. After the wave physics is understood, these diagnostics can often be used to measure the plasma parameters, as in case of the simple O-mode mm-wave interferometer - the physics of O-mode propagation is well known, and this interferometer has become the best-known technique for measuring the line-averaged electron density. The development of new wave diagnostics can likewise result in new techniques for measuring plasma parameters.

The development of an innovative high frequency heating technique using Electron Bernstein Waves (EBW) illustrates the interplay between innovative wave physics and diagnostic development. In this case, the wave absorptivity is closely related to the emissivity - so the first stage in the investigation of this heating scheme is an experimental study of the emissivity of a plasma in the appropriate wave mode. This work is being carried out on the CDX-U device at Princeton. The emission measurements also can be used to determine the local electron temperature, in a regime in which conventional electron cyclotron emission diagnostics are not possible. The first stage in the development of an efficient EBW launcher can be to use the proposed design as a receiving antenna for the electron temperature diagnostic. Hence, the research on EBW is expected to result in a new electron temperature diagnostic with high time resolution as well as an electron heating scheme applicable to situations in which conventional ECH is not possible. Both of these applications of EBW are planned for the NSTX experiment, and are possible for other STs, such as Pegasus.

Other innovative wave physics research in the electron cyclotron range of frequencies (ECRF) is being carried out on the DIII-D tokamak, where the phenomenon of the electron "heat pinch" documented in high power ECH experiments is under study to understand the implications for electron energy transport. More generally, high power ECH, particularly in amplitude modulated experiments, is being used as a well-characterized, highly localizable source of electron heat to quantitatively test theories of energy transport. In addition, various fast electron diagnostics are being developed to measure the non-Maxwellian effects of high power ECH, in both position and velocity space.

Somewhat similar fast electron diagnostics are planned for the Alcator C Mod lower hybrid current drive experiments. The substantial fast electron population produced by this lower hybrid system will provide an excellent opportunity to study electron energy transport in quite a different range of plasma parameters than the DIII-D ECH experiments.

A major area for innovative wave physics research is the effect of magnetically trapped particles on the efficiency of wave current drive, both in the ECRF and at lower wave frequencies. Off-axis ECCD experiments in DIII-D, undertaken in connection with the Advanced Tokamak concept, have also yielded a fascinating confrontation of theory and experiment, with the theory predicting a strong degradation of the current drive efficiency due to trapped electrons, which is not seen in the experiment. These results would appear to justify a re-examination of current drive techniques that had been largely abandoned due to theoretical expectations of trapped particle problems, such as those schemes with low wave phase velocities compared with the electron thermal speed. Opportunities exist to study this on CDX-U (Alfven wave or Rotomak current drive), Alcator C Mod and DIII-D (low phase velocity fast wave current drive), and possibly in NSTX, if sufficiently high electron temperature can be achieved (relative to the minimum practical high harmonic fast wave phase velocity). In all cases, adequate current drive diagnostics are necessary for detailed comparison of theory and experiment.

Several relatively unexplored wave physics regimes involve interaction with the ions and affecting their fluid flows and transport, such as the previously mentioned alpha channeling and IBW areas. To damp power on the ions, waves in the ion cyclotron range of frequencies are used. An advantage of the IBW over the fast Alfvén wave (used in most ICRF experiments to date) for some of these advanced applications is its very strong ion cyclotron harmonic damping at higher harmonics. The strong damping results in strong wave field gradients and the accompanying Reynolds stress at the harmonic layers. The same property that leads to these desirable features (essentially, very short wavelength) also is probably responsible for the observed difficulties in coupling high power to the IBW. Therefore, an important area of research is developing efficient methods of coupling high power to the IBW in large, hot devices. An essential aspect of these investigations is the capability of measuring the IBW electric fields in the plasma interior in a non-perturbative manner, such as by laser scattering or phase contrast interferometry (PCI). Experimental programs on various aspects of ICRF wave physics and diagnostics are underway on Alcator C Mod (PCI, IBW excitation through mode conversion of the fast wave, RF effects on plasma rotation), DIII-D (fast wave/fast ion interaction at high harmonics, RF effects on plasma rotation, PCI), NSTX (fast wave-on interaction at very high harmonics and high ion beta) and on smaller devices in which detailed wave field measurements are practical, like LAPD and CDX-U.

1.7 Theory, modeling and validation

As can be seen from the discussion above, the kinds of jobs which need to be done with RF go far beyond bulk heating and current drive to much more precise and localized plasma control. RF is being applied to a number of devices with different or more complicated magnetic geometry than the conventional tokamak, such as stellarators or RFP. Also we are now encountering very different wave physics regimes with which we have relatively little experience, as with Spherical Torus with its very high dielectric constant. In addition a number of new, or relatively little developed, wave techniques are being considered which could have considerable impact if successful, such as mode converted IBW or EBW. To achieve this promise clearly we must understand the physics involved. And we must develop models which can calculate these processes with the quantitative accuracy and self-consistency as to definitively identify the phenomena active in experiments, and to reliably project to new applications and devices. The theory of RF interaction with plasmas is conveniently separated into pieces, which interact, but to a large extent can be studied independently: wave launching, wave propagation and absorption, the response of the plasma distribution function to the waves. To be useful the pieces must be integrated together and must be integrated with models of transport and stability and with experimental data.

Wave Launching The first step in any application of RF power is to launch the correct spectrum of waves into the desired plasma mode. For lower frequency waves such as lower hybrid, ICRF or IBW, which propagate only above a certain plasma cutoff density, a complicated 3D launching structure must be located quite near to the plasma. Although some three dimensional aspects are included in the numerical , the present models do involve certain limitations. The plasma is assumed to be one dimensional, the plasma response is linear, and the antenna geometry is approximated as rectilinear. In cases for which these approximations are valid the models give reliable results which have been benchmarked against experiments. However in other cases when the antenna shape does not conform well to the plasma surface, as in devices employing a range of plasma shapes, or when non-linear effects are important, as in direct launch IBW, the models are of doubtful applicability.

An even more serious issue for the technology of antennas and a more difficult issue for theory and modeling is the interaction of the antenna with the edge plasma. High amplitude RF fields near the antenna non-linearly modify the edge plasma parameters, which in turn affect coupling to the desired modes. Eliminating or reducing these effects is certainly one of the most critical challenges in making RF attractive and reliable at frequencies below the electron cyclotron range. Most of the work to date is more in the nature of identifying candidate effects to explain observations than the production of quantitative, predictive models. To really get a comprehensive solution probably requires a fully 3D, electromagnetic PIC code solution in the entire antenna/edge domain, with complete geometry.

Wave Propagation and Absorption Once launched the wave propagation can be approximated by one of two methods: geometrical optics or solution of a wave equation, usually highly approximated. For short wavelength modes, such as ECH and lower hybrid, geometrical optics is usually valid except at isolated surfaces such as mode conversion layers. These must be treated by full solution of the wave equation, usually approximating the geometry as one-dimensional. Another issue for ray tracing is the lack of an unambiguous way to initialize a set of rays to represent the field excited by a real antenna.

In situations requiring solution of the wave equation, such as at lower frequency where the wavelength is of order the plasma size or near mode conversion regions, there are a number of challenges for theory and modeling. In 2D or 3D a great deal of compromising, approximating and analyzing of specific cases is required to obtain a computationally feasible formulation. These compromises are typically: restriction to low cyclotron harmonics $\ell \leq 2$, restriction to small Larmor radius, $\rho / a << 1, k \ \rho << 1$, assumption that orbits don't deviate much from flux surface (banana width → 0), neglect variation of k , $v_{||}$ along field line, zero-order distribution function is approximate Maxwellian. The physics retained after these approximations is essentially the expanded slab conductivity operator applied locally in 2 or 3D. Within these compromises we do get useful results, for example in minority heating where mode conversion is not dominant, or for fast wave current drive. However it is necessary to consider cyclotron harmonics much greater than $\ell = 2$ for many of the IBW applications such as the IBW experiments on TFTR and FTU and also for HHFW. The approximation $k \rho << 1$ is often violated for energetic tail populations, in low field devices such as ST, and in many mode conversion situations. To treat large reactor scale devices, high dielectric constant devices or stellarators, a significant increase in available resolution is needed, necessitating a large scale-up in computing power.

Response of the Plasma Distribution Function In many cases the RF power does not cause a significant distortion of f_0 away from Maxwellian, rather it can be thought of as providing macroscopic sources to transport or stability – heat deposition, driven current, or driven plasma flow. Given the RF fields there are fairly well developed formalisms for local power deposition or driven current. However in the important area of flow drive we have only scratched the surface. To date the flow velocity has been estimated by calculating an RF poloidal force in 0D then balancing this force against a rather *ad hoc* "viscous drag" based on the neoclassical viscosity. What is required is a complete neoclassical formulation including toroidal geometry, plasma flow and proper treatment of the RF driven radial particle fluxes and ambipolar electric field. Of course a rigorous theory must include the effect of turbulent fluctuations on the driven flow.

In other cases, particularly with high power, there may be significant deviation of f_0 away from Maxwellian making it necessary to directly solve the Fokker Planck equation. There is considerable experience in solving the Fokker Planck by finite difference or finite element methods in the zero banana thickness limit such that heating is balanced by collisional relaxation within a single flux surface. In principle radial transport effects can also be included to get a true 3D solution for f_0 but no rigorous form for the transport coefficients is available. Another approach is to solve the Fokker Planck equation by Monte Carlo techniques. An ensemble of individual particles is followed in time and statistical velocity increments are added to model the effects of RF and collisions. The guiding center orbit can be followed, making it comparatively straightforward to treat very complicated geometries such as stellarators and to include radial transport, although this is a computationally intensive process.

Validation, integration with transport and stability and experiment All of the theories and models require idealizations and approximations to remain computationally feasible. It is a real challenge to convincingly demonstrate or determine range of the validity of RF models. This is because of the long chain of detailed experimental data, and integration with transport and stability codes needed to obtain the required input and interpret the model results. The most powerful of the RF models are not well coupled to the transport/stability codes or other interpretive tools used to understand experiments. A particular need is for tighter connection to experiments. It is very time consuming to get the experimental data needed as input for the RF models, even if the data exists. This is especially the case if one attempts to compare results from several devices, each having a different format and retrieval process. For similar reasons of lack of standardization information flow from modeling back to the experiments is not what it should be either. Many of the limitations to what we can achieve with present models stems from our failure to put together all of the pieces. In many cases some of the pieces have been combined: antenna + 2D full wave + equilibrium, Fokker Planck + ray tracing + 2D

equilibrium (e.g. CQL3D), interpretive transport + RF. But it has not all been put together anywhere.
Heating and non-inductive current drive of plasmas is supported by several different technologies.

1.8 RF Technology

Heating and non-inductive current drive of plasmas is supported by several different technologies.

<u>ECH:</u> Significant progress has been made in developing and deploying high-power gyrotrons at the ~1-MW level at 110 GHz, and the development of 170-GHz prototype units for electron cyclotron heating/current drive (ECH/ECCD. Sources and systems of the required power and pulse length are beginning to come on line. The physics of EC heating (ECH) and current drive (ECCD) is well developed in both experiment and theory. Experiments have demonstrated effective plasma heating, current drive, off-axis current drive, control of sawteeth, ELMs, locked modes and plasma startup.

<u>ICRF:</u> Fast-wave (FW) antenna arrays in the >1-MW unit size for Ion Cyclotron Heating (ICH) and current drive (via direct electron heating) have been developed and tested The long-term goal of the ion cyclotron program R&D is to develop reliable, advanced ion cyclotron heating and current drive systems. The emphasis is on improving RF system reliability, robustness and performance; increasing power density (higher voltage limits for ICRF launchers), tuning and matching systems that are tolerant to rapid load changes, and actively cooled ICRF launchers for long-pulse/burning-plasma. One of the promising avenues for ITB control and modification is the use of IBW to control shear flow, thereby affecting ITB formation. Antenna and matching system development will be required as part of a broader effort to demonstrate reliable IBW heating and shear flow control.

<u>LHCD:</u> LHCD has an important role in providing off-axis current density, especially in the presence of an internal transport barrier (ITB). The scientific basis of LH current profile control is well established. Further technological development is needed in this area for long pulse cooling, quasi-optical or hyperguide grill designs and CW source development (5.5 GHz and the 1 MW).

2 Plasma generated waves

In the area of plasma generated waves and wave interaction with energetic particles, the key issues were: (1) the development of predictive understanding of linear stability and non-linear dynamics of kinetic-MHD phenomena, and (2) the development of techniques for phase space “engineering” of alpha/energetic particles in an MFE reactor.

Energetic particles in thermal plasmas supply a means of heating and also free energy for instability generation. Energetic particles arise naturally during RF plasma heating, electron runaway in ohmic and laser-fusion compression (basis for fast ignitor concept), fusion processes during ignition and burn. Plasmas are heated and instabilities can be generated, sometimes by destabilizing the basic waves supported by the background plasma and sometimes by generating waves intrinsic to the presence of the energetic particles. While there has been considerable analytic and numerical progress in describing these phenomena there is a need to develop comprehensive predictive understanding using fully non-linear, non-perturbative, general geometry, kinetic-MHD codes coupled to experimental data and analytic interpretation. Along with this thrust is the need to develop, in parallel, viable methods for manipulating energetic particles in a reactor for the purpose of plasma control and discharge optimization.

2.1 Energetic particle driven instabilities:

Several areas of energetic particle physics have had a rich development these last few years, but further work needs to be continued. One area is the Alfven waves excited by energetic particles, a crucial area for understanding the stability of burning plasmas. In this case the numerical codes, though quite sophisticated, are often deficient in treating continuum damping properly and for describing new modes, such as energetic particle modes (EPM). This is because proper treatment requires solving integral, rather than partial differential equations, and as result the codes with the most sophisticated geometry often lacked key physics information.

In the past, perturbative codes such as NOVA-K have been successfully used to model and predict the stability of fast ion-driven Alfven Eigenmodes in tokamaks. A recent example is the prediction of alpha-driven TAE modes in the TFTR DT experiments. The NOVA-K code incorporates key physics of fast ion drive with full orbit width and various damping mechanisms, including the non-perturbative radiative damping. The code assumes that the kinetic effects of both fast ions and thermal species are small so that they can be treated perturbatively. However, in an ignited tokamak reactor, both the alpha particle drive and background damping is expected to be large so that a non-perturbative model is needed to calculate the linear stability.

Non-perturbative global stability codes exist, which include full orbit width of fast ions as well as various thermal particle kinetic effects, such as diamagnetic drift, finite ion Larmor radius, and electron-ion collision. However, these codes tend to be deficient in not having realistic plasma geometry. Improvement of this situation has begun. The spherical tokamak clearly needs to examine the effect of energetic particles in its conventional heating modes of neutral beam and ICRF heating. This development will also help the assessment of energetic particle effects in burning plasmas.

The goal in this area is understanding and predictive modeling of energetic particle-driven MHD modes in toroidal magnetic confinement devices, such as advanced tokamaks, spherical torus (ST) and stellarators. Key questions for a fusion reactor are whether Alfven Eigenmodes can be destabilized by alpha particles and whether these modes can affect the confinement of alpha particles. To answer these two questions, we need a comprehensive non-perturbative linear stability code and a fully nonlinear code for energetic particle-driven MHD modes. In the following, we briefly describe motivations and future plan to address these key issues.

Nonlinear saturation and associated particle transport

One of the recent surprises in wave-particle interactions is that wave chirping phenomena can spontaneously arise for waves excited near marginal stability. Chirping occurs because spontaneous phase space structures form holes and clumps and these phase space structures force side-band oscillations to evolve with increasing frequency shifts as the holes and clumps move in phase space away from the original resonant position. Thus the nonlinear motion of the particles force a change of the linear character of the wave. Fast spontaneous chirping phenomena are frequently observed in experiment and this phase space mechanism (coupled with dissipation from the background plasma) is a prime candidate to explain the data. However, more additional theory needs development, including the development of nonlinear codes with realistic geometrical effects, and perhaps additional nonlinear wave coupling, to obtain a quantitative description of experimental phenomena. Significantly, for the case where particle collisionality is strong enough, phase space structures do not form, but bifurcation of the saturation level to side-band excitations can still arise. Extensive analysis of JET data seems compatible with this theory and this method offers a possible means of inferring energetic particle and plasma parameters. However, more systematic correlation of this theory with experiment is needed to establish the unique self-consistency of the explanation and the usefulness of the experimental interpretation for inferring energetic particle and plasma parameters.

Recently there has been considerable theoretical progress in understanding new aspects of the nonlinear wave-particle resonance phenomena in plasmas. The new feature of this work is that it describes the self-consistent dynamics of isolated nonlinear resonances over a long time-scale reflecting the role of the energetic particle source and classical relaxation processes. It has also addressed the transition from a set of isolated resonances to global quasilinear diffusion produced by resonance overlap. This work has started from investigating weak instabilities, where the wave-particle resonances can be treated as a perturbation to linear collective modes that exist in the absence of the resonant particles. The theory has also been generalized to so-called non-perturbative modes, such as fishbones, whose basic structure depends on the presence of energetic particles.

It was shown that for sufficiently weak instability drive, the mathematical structure of the theory is nearly independent of the specific mode. Thus very diverse problems, from the electrostatic bump-on-tail instability to the TAE instability in a tokamak, can be treated with similar analysis. This analysis covers a broad range of experimentally relevant nonlinear effects. Examples include the steady state and intermittent nonlinear regimes of mode saturation, explosive growth of the weakly unstable modes and the nonlinear frequency sweeping phenomena.

Such quasilinear models are successful in predicting the saturation level of a single TAE mode driven by fast ions such as in the successful interpretation of the pitchfork splitting of TAE frequency in JET. The quasilinear model assumes fixed mode structure for a single mode. Particles interacting with multiple modes, where the wave-particle nonlinear islands overlap, presents a new set of challenges. Also, quasi-linear models need to be revised if the mode structures change significantly during the nonlinear evolution of the mode, as is expected for some EPMs. In a fusion tokamak reactor, many high-n modes are expected to be excited by alpha particles due to large size, which suggests that a fully nonlinear numerical model is required to treat multiple modes self-consistently.

Kinetic-MHD hybrid codes are being developed for this purpose. In the short term, unstructured mesh will be added to some of these codes in order to treat more general toroidal geometry such as STs and stellarators. In the long term, these codes will need to be upgraded to include more complete kinetic effects of thermal species such as FLR and collisions. These improved codes can then be applied to make quantitative predictions/simulations of NBI-driven AE in STs, NBI-driven AE in stellarators, and alpha particle-driven AE in advanced tokamaks.

2.2 Issues in classical orbit physics and collisional processes in symmetric and more complex 3-D systems

There have been extensive studies of classical orbit effects of energetic particles in tokamaks, including the effect of field ripple. In recent years analytic formulas have been refined to describe quantitatively the effect of field coupled with collisions. In more advanced symmetric devices such as in the spherical tokamak and the Electric Tokamak these studies need to be pursued. Usually electric fields are ignored for the effect on energetic particles, but this effect should be more important in the electric tokamak or in advanced tokamaks, where large shear profiles imply regions where the electric field may be relatively large. Studies of energetic particle orbits in RFP’s and FRC’s are fairly limited and should be developed. In stellarators, with three dimensional magnetic fields, the energetic particle issue can be quite crucial, as intrinsic loss regions can exist for a reasonably large fraction of the energetic particles, and the losses might be concentrated on spots of the wall (leading to sputtering). The issue of containment may be crucial for the burning plasma feasibility of many stellarator designs.

2.3 Opportunity for Dedicated Development of Advanced and Fast Computer codes that combine MHD and kinetic aspects of the problem.

The need is found for kinetic MHD codes also in the area of burn physics and even thermal long mean-free path MHD effects in conventional high toroidal field devices like tokamaks as well as high poloidal field devices like FRC. Close correlation with theory, numerical work and experimental data has had only limited success in kinetic problems in the past and there is an opportunity for much more progress in the future.

It is clear from experimental data that energetic particle instabilities cause nonlinear MHD response of the background plasma. This is seen in Alfven wave activity, and probably in fishbone phenomena, where there are changing stability conditions (for both inducing and ameliorating the instability) with energetic particles present and various means of relaxation when energetic particles are affected by instability such as the giant sawtooth. The understanding of these phenomena is a challenge for joint MHD and energetic particle development. The richness of the phenomena will allow for many interesting studies in this area and the opportunity to explain experimental phenomena. It will also offer the opportunity to investigate rather naturally kinetic phenomena in the bulk plasma. A significant case is the simulation of neoclassical tearing modes, which in principle can be described by a comprehensive kinetic-MHD code. Further extensions of the calculations can be made to kinetic phenomena in concepts other than tokamaks. A particular case in point is the investigation of FRC stability theory, which is still not resolved, but is almost certainly based on the kinetic aspect of the FRC configuration.

Energetic ions in Field Reversed Configurations and Ion Rings

As MFE approaches burning plasma conditions the need to integrate kinetic effects of large-orbit energetic ions into the standard MHD paradigm becomes pressing. One MFE configuration has been confronted with this necessity from its beginning: the FRC. The reason is that prolate FRC's are ideal-MHD unstable, particularly to the internal l=1 tilt mode. Nevertheless, experimental prolate FRC's have been studied for many years, and are generally robustly stable: they have been formed, translated and compressed rapidly and violently without disruption. Kinetic effects have generally been invoked to understand this stability. It was long ago established theoretically that Field-reversed Ion Rings, in which the current is carried by large-orbit axis-encircling ions, should be tilt-stable, and FRC's in which s (the number of ion gyroradii from the field null to the separatrix) is below 3-4 should also be stable. Almost all experimental FRC's fall in this range, because the theta-pinch formation method results in $T_i > T_e$, and the ~keV ion temperature leads to such orbits.

An FRC plasma with reactor-scale confinement must have s>20. A primary physics issue for FRC is therefore: will such a plasma be stable to MHD modes, and if not, can a large-orbit ion component, created either by injection or internal heating, or by fusion alphas, stabilize the plasma. This question is being addressed presently primarily with simulation codes. Barnes and Milroy used a 3D MHD code (MOQUI) with added large-orbit ions to show that certain classes of orbits were most effective in stabilizing the tilt. They concluded that the total kinetic energy in this ring-like ion component needed to be of the same order as the total plasma thermal energy for stability. These calculations, though very valuable for the insight developed into the physical mechanism of stabilization, almost certainly overstated the ring energy requirement, because the FRC was treated as ideal-MHD, leaving out the kinetics that stabilize present experimental FRC's without an added ring. Presently, a simulation initiative (Jardin et al) is using new codes (Belova, Omelchenko) to further study this issue with more complete FRC physics.

Experimental investigation of large-s FRC's and large-orbit stabilization is at an early stage. Experiments at LANL in the 1980's gave indication of tilt-like perturbations in FRC's that were unstable under conditions that should have produced larger s. LSX in the late 1980's was designed to probe FRC stability up to s~10, but was shut down shortly after beginning experiments. In any case, the theta-pinch formation method is limited in its ability to reach high s, and present experiments are investigating new rotating magnetic field formation techniques to overcome this limitation. Meanwhile, ion ring formation experiments are presently working toward preoducing strongly diamagnetic ion rings which can either form the FRC configuration by themselves (field-reversed ring) or be injected into and merge with an FRC to introduce a large-orbit component to study its physics. Here, Alfven interactions of the energetic ion ring with the background plasma are of critical importance. Theory and simulations have identified a regime in which an ion ring formed by axial cusp injection of a rotating beam into a solenoid is slowed down and compressed axially to the point where it can form a field-reversed ring or be trapped in an FRC. Demonstration of this strong coupling of axial ring momentum to Alfven waves in the background is the necessary physics milestone for the Cornell FIREX field-reversed ion ring program, before it can reach its goal of study of large-orbit physics in FRC's. At the same time, coupling of ring azimuthal energy to Alfven modes must be avoided. Growing perturbations of ion ring azimuthal structure are observed under some conditions in FIREX which may be associated with fast ion excitation of Alfven modes. This is an active area of present study, and might provide an opportunity to investigate physics relevant to energetic ion-Alfven interactions in other MFE configurations. If FRC's at reactor scale require a substantial population of large-orbit ions for stability, wave-particle interactions of this population would play a substantial role in FRC physics.

2.4 Opportunity to develop feasibility of novel ideas that improve conventional plasma characteristics: e.g. feedback to suppress neoclassical islands, demonstrate phenomena in alpha channeling from either quasilinear or a phase-space bucket process.

<u>Alpha channeling</u>

An idea that has generated some excitement in recent years is the possibility of using high frequency and low frequency waves (IBW + TAE) to transfer directly the energy of charged fusion products to the background ions. This could improve the power production of a relatively small size fusing tokamak by allowing the background ions to be hot, without the necessity of "wasting" energy to heat electrons. This idea is still speculative, and the controlled release of energetic particle energy has not as yet been demonstrated (although the control of the inverse heating process has been shown).

Continued study of this problem will make for interesting experiments, and with new data, a better appreciation of the feasibility of the channeling process will be obtained.

Advanced tokamak scenarios, where there is small magnetic shear, are expected to have low instability thresholds for Alfven waves and perhaps even ion cyclotron waves. In this case the classical slowing down distribution should give energetic particle pressure profiles substantially above threshold, with the likelihood that a rather rich spectrum of noise would be observed. However, if through externally controlled excitations, selected waves can be excited that will allow controlled chirping of well defined modes with energy release of the kinetic particles, the goals of energetic particle channeling might be achieved. What is important in this conception, is that the wave spectrum remain controlled while the energetic particle distribution remains close to a linear marginal stability profile. These and other ideas need to be tested in detail on facilities where the wave field(s) and energetic particle distributions can be measured.

Alpha ICRCD

In the case of FWCD, a significant fraction of the fast wave power can be absorbed by the alpha particles due to their unavoidable Doppler-shifted resonance layers in the plasma. This can reduce the electron FWCD efficiency significantly. However, recent theoretical and numerical investigations find that the directional fast wave absorption by alpha particles can result in additional plasma current (Alpha-ICRCD) at similar efficiency as FWCD. The radial profile of the alpha-ICRCD can be different from that of FWCD. Alpha-ICRCD can be off-axis, as opposed to the strong on-axis nature of FWCD. It has been found that the degree of off-axis profile is adjustable with the parallel wave number. Further numerical and experimental study of the minority Alpha-ICRCD may yield an interesting result with the novel possibility of a significant improvement of the FWCD and current profile control with Fast Waves alone. Experimental set up will need directional FWCD capability in a plasma where stationary warm minority ion species (possibly by balanced beam injection) is resonant with the fast wave.

Bucket Transport

It should also be noted that the spontaneous wave chirping phenomena discussed in sec. 2.1 is probably due to self generated phase space buckets and that these have been observed in JET, JT-60U and other facilities. Bucket transport (also called "frequency sweeping", or "frequency chirping") is a mechanism which non-stochastically transports fast ions (both radially and in energy). This has been invoked both as a technique for the control and manipulation of fast ion distributions in toroidal magnetically-confined plasmas, as well as an explanation for fast-ion loss from naturally-occurring chirping perturbations. Used intentionally, some of its potential applications in a fusion reactor are enhancing neutral beam penetration, ash removal, profile control, current production, and enhancing alpha-channeling by providing a non-stochastic mechanism in addition to the stochastic mechanisms usually envisioned in constructing alpha-channeling scenarios.

The basic idea of the mechanism is simple. A perturbation applied to a tokamak with given mode numbers m and n and frequency w will induce an island, or `bucket', in the drift surfaces of ions, whose radial position depends upon w and on the velocity of the ions, so that by sweeping the frequency, one can non-stochastically move the position of that island from any one flux surface to any other in the plasma. And provided the frequency is swept slowly enough that ions initially contained within the bucket experience 1 or 2 trapping oscillations in the time the bucket moves radially through a bucket width, these ions will remain with the bucket as it moves. This provides a mechanism which can be tuned to selectively transport ions in a given region of phase space, while hardly affecting ions in other regions at all. This energy--selectivity has been demonstrated in non-optimized simulations for the original application, ash-removal. Other applications noted above, which may be of comparable importance, are actually less demanding of energy selectivity than ash-removal. By suitably choosing the parameters of the swept perturbation, one can have it do positive, negative, or negligible work on the swept particles. The perturbations studied thus far have been of the same long-wavelength and relatively low frequency (0 through 100s of kHz) characterizing the Alfven-eigenmodes, which are envisioned to be used stochastically in alpha-channeling scenarios. Perturbations inducing the bucket may be of the same `magnetic braiding' type as those inducing magnetic islands, but may also be just in mod-B, or even electrostatic, which do not disrupt flux surfaces, and have energy scaling more advantageous for some purposes.

Probably the principal challenge which must be addressed in making the potential of bucket transport a reality lies in how chirped perturbations with the desired characteristics can be produced and controlled. There are 3 general methods which have been advanced, and a workable technique might employ them individually or in some combination:

(a)’Direct’ method: Applying the needed long-wavelength, low-frequency perturbations from an antenna array constructed with those characteristics, similar to the saddle-coil array presently on JET.

(b)’Beat-wave’ method: Producing the swept perturbation as the beat-wave of 2 or more perturbations from the higher-frequency ICRF range (10s of MHz).

(c) using naturally--occurring `chirping modes', which since the original introduction of the bucket transport technique have been seen on most major tokamaks.

For the direct and beat-wave methods, an important question needing better understanding is the power requirements to create a perturbation of adequate amplitude. To be able to sweep alpha ash out in a time less than a slowing-down time, a perturbation B_r/B_0 of order 10^{-4} is needed. Smaller perturbations might be adequate for testing the basic concept. A rough estimate based on amplitudes induced by the saddle-coils and ICRF in TAE studies on JET along with rough scaling arguments indicates that an adequate magnetic fluctuation level could be produced in an ITER-sized reactor with 12 MW with the beat-wave method, and 0.25 MW for the direct method.

Use of the chirping-mode method will require a much deeper understanding of the dynamics of these modes than now exists, which will provide information on the constraints on plasma conditions needed to generate a spectrum of chirping modes with the specifications required to perform a given task. Some theoretical work in this area has been done - a great deal of further theoretical and experimental study remains. Several major tokamaks already have much of the equipment needed to carry out studies of this technique, as well as of the related alpha-channeling technique. The JET tokamak is particularly well suited.

Helium Ash removal by RF waves

Thermalized helium ash ions are known to follow the background ion transport rate, which can lead to a slow ash removal and severe restriction on the operation regime of a steady state burning plasma. Since ICRH provides an additional dissipation to the particle motion, particle transport control by ICRH has been known to be possible but the ICRH control of thermal helium ions is not efficient due to degeneracy of the gyro-frequency with the background deutrium ions. However, the helium ions spend a significant amount of slowing-down time (of order the particle confinement time, at least) at energies above the thermal energy of the background ions, where preferential coupling of higher-harmonic ICRH to the warm helium ions is possible.

Theoretical ideas and limited experimental verifications in TEXTOR exist to verify the radial warm (of order 100 keV) ion transport control by fast waves. Further experimental verifications can be an interesting subject. Since the radial helium flow by RF waves can be non-ambipolar this problem may have an intrinsic relationship with the radial electric field and rotation generation. In other words, the RF-control of helium ash transport can lead to plasma rotation and/or L-H transition control. This is a important subject for further investigation in existing facilities and in a future burning plasma experiment.

2.5 Opportunities for fundamental tests of fast ion processes in fusion plasmas.

Both the development of alpha channeling and bucket transport require deeper fundamental understanding of wave particle interactions. Such understanding may be facilitated by use of a device dedicated to the investigation of wave-particle interactions. Such a device must generate reproducible and quiescent plasmas in which it is possible to perform experiments over periods of a month in which delicate, small signals can be detected. The device should have sufficient flexibility to accommodate methods for the phase space modification of the energetic particles in perturbing fields, and allow for detailed diagnostic measurements of the fast particle distribution. The LAPD device is one such facility which has been proposed as a national center for basic plasma studies. Other user facilities along these lines should also be considered in order to provide a means for testing basic science of fast ions relevant to fusion plasmas.

As an example, consider the problem of fast ion transport in Tokamaks. Naively, one might expect larger transport for energetic ions than for thermal ions but, in tokamaks, energetic ions are often much better confined than thermal species. A likely explanation for this phenomenon is that the small-scale turbulence responsible for anomalous thermal transport has little effect on fast ions, whose large orbits effectively average over the fluctuation spectrum. This orbit-averaging mechanism is of generic importance, with applications from ion rings in the FRC and runaway electrons in tokamaks to space plasmas. To date, there have been no quantitative comparisons between theory and experiment, however. Detailed comparisons require thorough measurements of both the fluctuations and the fast-ion transport, quantities that are difficult to measure accurately in the fusion environment. A laboratory-scale experiment is well suited to investigation of this important issue.

Under other conditions, large-scale perturbing magnetic fields cause rapid fast-ion transport with little effect on thermal ions. Theoretically, the coupling of fast-ion motion and field perturbations is thought to generate island overlap in the phase space that describes the fast-ion trajectories, resulting in rapid radial transport. This explanation is closely related to the proposals for alpha ash control by chirping the frequency of externally controlled perturbation fields. This is another area where detailed measurements on a fusion facility are difficult, but the basic physics could be elucidated in smaller, laboratory-scale experiments. For example, one could establish a mirror geometry, then perturb the field to measure quantitatively the threshold for island overlap. In addition to its other applications, the stochasticity threshold is an important (and highly uncertain) parameter used to predict damage to the first wall of a tokamak reactor caused by ripple-induced losses of alpha particles.

3 Wave particle interactions in IFE

3.1 IFE wave particle issues and opportunities

In IFE, significant plasma wave and wave particle interaction issues arise in connection with the coupling of laser energy to targets and with the transport of ion beams through the target chamber. Since the ion beam transport is discussed in another section of this report, the focus here will be on laser plasma interaction issues. The IFE sessions for the Wave Particle Interaction subgroup were held jointly with the Turbulence and Transport subgroup, since there was a considerable overlap in subject matter and there were relatively few inertial fusion scientists attending the Snowmass meeting. Hence only a brief discussion of the status and issues for laser plasma interactions will be given in this section.

A great deal of progress has been made in understanding laser plasma interactions. Interaction processes ranging from collisional absorption to many nonlinear optical processes have been identified, studied and controlled in experiments with current lasers. Diagnostics have become impressively detailed, including simultaneous measurements in space and time of the amplitudes of both electron plasma waves and ion sound waves. This progress provides a solid base on which to develop an improved understanding of nonlinear regimes of the interaction physics, which will enable more timely success with the National Ignition Facility, design of higher gain targets for IFE, and assessment of advanced IFE options, such as Fast Ignition.

Issues and opportunities were identified in several areas. The first area involves fast ignition, an exploratory but potentially revolutionary approach to IFE. In fast ignition, Mev electrons generated by a short, ultra-intense laser pulse are used as a match to ignite cold, pre-compressed DT fuel. Recent experiments show efficient absorption of such laser pulses into relativistic electrons. However, the angular divergence and energy spectrum of the electrons and their transport require improved understanding. The goal is to obtain experimentally-tested theory and computational models for this very strongly driven relativistic plasma regime. Tools and facilities needed include access to terascale computing and to a petawatt-class laser.

Conventional laser-driven approaches to IFE are another area with significant issues and opportunities. Here an improved understanding and control of the nonlinear levels of plasma instabilities driven by intense electromagnetic waves would both allow more confident design of higher gain targets and guide the choice of future IFE drivers. The goal is an integrated coupling physics code incorporating nonlinear models of the various laser-driven plasma instabilities for interface with radiation-hydrodynamic target design codes. A combination of theory, terascale computing, and experiments with both small lasers (such as the Trident laser at LANL) and large lasers (such as the Omega-Upgrade at the University of Rochester) would be needed.

3.2 Potential for IFE/MFE collaborations

Wave plasma interactions represent an ideal area for mutually beneficial collaborations between the inertial and magnetic fusion communities. The nonlinear behavior of intense electromagnetic waves, the saturation mechanisms for unstable plasma waves, linear and nonlinear wave particle interactions, and relativistic plasma phenomena are clearly issues of common interest. There are also many computational tools ranging from 3D particle simulation codes to various reduced models as well as many plasma diagnostic techniques, which are of use to both communities. Finally, there is the common grand challenge to model plasma behavior on very disparate time and space scales and to exploit terascale computing.

Two examples well illustrate the potential for fruitful collaboration. The first involves the excitation of ion Bernstein waves for profile control in advanced tokamaks. In one scheme, the antenna fields very strongly perturb the plasma, requiring the inclusion of nonlinear effects to understand and optimize the coupling to the waves. Similar issues are encountered in inertial fusion, where the ponderomotive force due to intense laser light is often important. Recent experiments and calculations show that a steepening of the density profile by the ponderomotive force in a flowing plasma leads to a nonlinear bending of the laser beam, which can impact implosion symmetry in hohlraums. For a second example, in inertial fusion there's a growing appreciation for the potential influence of self-generated magnetic fields on the laser coupling and energy transport in hohlraums. Recent experiments and calculations emphasize that self-generated magnetic fields must be included to correctly model the measured gradients in electron temperature in laser-irradiated hohlraums. Here expertize in the magnetic fusion program would help to develop an improved understanding of the generation of these magnetic fields and their effect on the interaction physics. Clearly a few collaborative projects in the wave plasma interaction area would enable a very productive cross-fertilization.

4 Conclusions

We were able to identify many opportunities for increased scientific understanding and for improving the possibility for attractive fusion reactors. We were able to agree on a few broad goals for research on wave particle interactions over the next 5 to 10 year period. We discussed the relevant ongoing and proposed research programs for the various US experimental devices, and to a lesser extent the theory and technology programs. We found that the programs address the key issues at some level. But we did not evaluate the extent to which the key issues would actually be resolved or to which the broad goals would actually be achieved by the present program. Nor did we evaluate what level research program would be required to achieve the goals with confidence. There simply was not time for broad ranging technical discussions which might have brought out new ideas, issues and opportunities which are not being addressed at all within the present and proposed program.

It should be noted that several physics and technology working groups emphasized the need for improved control of pressure and current profiles and internal transport barriers in order to access long-pulse, advanced-tokamak scenarios. Improvements in system reliability and flexibility, and a transition from the present “blunt tool” capability to a more refined ability to tailor profiles to access the high-beta, high-bootstrap-fraction plasmas were seen as needed for future research. The table below shows specific needs for operation of next-generation experiments identified by different Snowmass working groups .

Needs for improved profile control identified by various Working Groups

Group	**Needs**
MFE Transport Physics	Control turbulence and transport/optimize confinement – Sharpen up current drive, heating, flow drive, and fueling tools – Tokamak, ST, RFP, Spheromak
MHD Physics	Avoid/mitigate disruptions and control tearing modes – Profile control, current drive, RF stabilization
Steady-state Physics	Continuously sustainable high performance fusion plasma – Equilibrium, MHD, profile control, using IBW/ EBW(ITB), HHFW/OFCD/LH/EC(CD), SC magnets
Burning Plasma Physics	Fueling (for burn control), current drive, disruption mitigation
Wave Particle Physics	Develop reliable rf plasma control techniques for j(r) control P(r) control by localized heating and fueling IBW for shear flow (has great potential for ITB if developed)