Interim Report from the

Waves and Energetic Particles Working Group

of the FESAC Priorities Panel

July 26, 2004, Gaithersburg, MD

<u>Topical Questions</u>:

- **T10**: How can heavy ion beams be compressed to the high intensities required for high energy density matter and fusion ignition conditions?
- **T11**: How do electromagnetic waves interact with plasma?
- **T12**: How do high energy particles interact with plasma?

For each topical question, the following will be discussed:

- Organization and methodology
- Issues
- Research approach
- Thrust areas

T10 Workgroup Organization and Methodology

- Participants:
  - John Barnard (T10 chair)
  - Grant Logan (principal author)
  - Ron Davidson, Christine Celata, Alex Friedman, and other HIF community members
- Methodology:
  - Town meetings, some via the Virtual National Laboratory.
  - Fortunately this community recently drafted a closely related document for the Interagency Panel on heavy-ion research plans. The FESAC and Interagency plans are consistent, with the FESAC version including discussion of the relevance of the research approach as a response to the “Overarching Themes”.

T10 Issues

The primary scientific challenge is to compress intense ion beams in time and space sufficiently to heat targets to the desired conditions of temperature and density.

- Understanding the physics limits of longitudinal beam compression and radial compression to small focal spots is essential for heavy-ion-beam-driven high energy density physics as well as for inertial fusion energy.
  - For HEDP physics: Study warm dense matter by isochorically depositing 10^{11} J m^{-3} to heat solid density material to 1 – 10 eV.
  - For IFE: Deliver 5 TW in a focal spot < few mm radius.
- The final pulse duration must be of order of, or less than, the target hydrodynamic expansion time.

T10 Research Approach

- Minimum pulse length and focal spot radius depend on beam $T_{\perp}$ and $T_{||}$ accumulated from source to target

- Accelerators for HEDP and IFE must:
  - Inject sufficiently bright beams
  - Accelerate ions to the desired energy range, then
  - Longitudinally compress and radially focus the beams onto target
  - Sustain minimal growth in temperatures

- Two research thrusts have been identified:
  - T10.1—Understand limits on pulse length and focusing
  - T10.2—Develop a predictive capability for high brightness beam transport, including gas and electron cloud effects

T10.1—Understand the limits on minimum pulse length and focal spot size for the compression and focusing of intense beams within neutralizing background plasma, and subsequent target interactions.

- Particle simulations predict that propagation through neutralizing plasma after modest acceleration can greatly shorten the achievable minimum pulse length and that thick magnetic or plasma-based lenses can focus the resulting short ion bunches to small focal spots.

- Experiments are planned to understand:
  - The dependence of minimum pulse length and focal spot radii on initial beam longitudinal and transverse temperatures, respectively.
  - The potential constraints associated with the avoidance of deleterious beam-plasma interactions.

- Relevance and importance:
  - Understanding beam-plasma instabilities (O1).
  - Learning the physics that predicts the minimum pulse and focal spot size is central to evaluating the potential of heavy ions to test time-dependent symmetry effects in high-gain hohlraum ignition targets (O2, O3).
  - Neutralized longitudinal compression and better focusing would enable shorter accelerators (O3).

T10.2—Develop a predictive capability for high brightness beam transport, including gas and electron cloud effects.

- Anharmonic forces can adversely impact beam quality during transport, leading to beam heating and decreased focusability.
- Theory and 3-D beam simulation tools must be improved and validated, so that they can quantitatively predict beam behavior in future experiments with fractional ion loss rates of $< 10^{-4}$ per meter and beam temperature increases of < 1% per meter, and must be fully exercised on the range of problems of interest.
- Improved diagnostics are required to measure sources and sinks of gas and electrons within focusing magnets and the subsequent impact on beam loss and temperature growth.
- Development and benchmarking of diagnostics and simulations initially in short (< 3m long) transport experiments and eventually in longer (30 m to 100 m) experiments will be essential.
- Relevance and importance:
  - This thrust will provide increased understanding of transport in high intensity ion accelerators (O1, O2), and is a prerequisite to the application of heavy-ion accelerators to HEDP studies and the development of future HI drivers for IFE (O2,O3).

T11 Workgroup Organization and Methodology

- Participants:
  - Donald Batchelor (T11 chair)
  - Thrust #1: Robert Pinsker, Randy Wilson
  - Thrust #2: Paul Bonoli, Ronald Prater
  - Thrust #3: Vincent Chan, Amanda Hubbard
  - Also: Joseph Snipes (mail, web), Lee Berry, Daniel D'Ippolito, Cynthia Phillips (and PPPL RF working group).
- Methodology:
  - Initial draft by DB.
  - An initial conference call assigning writers to each thrust, followed by extensive email exchanges and web site postings. Additional conference calls to finalize drafts.
- Web site:
  - lists.psfc.mit.edu/mailman/listinfo/waves

T11 Issues

- High power electromagnetic waves can heat plasmas, can drive localized currents and plasma flow, and can modify the velocity distribution of particles.
- These effects are observed to influence plasma equilibrium, stability and transport.
- Understanding these interactions can provide a basis to control fusion plasmas for optimum performance, to extend their duration towards steady state, and to probe the plasma, yielding understanding of other, non-wave processes.
- Improved understanding will also benefit other plasma research, including plasma processing and space physics applications.

T11 Research Approach

- Externally launched high-power EM waves in the ion-cyclotron to electron-cyclotron frequency range can initiate wave-particle interactions with electrons and ions
- These interactions can be localized in space and velocity, resulting in precise sources of heating, current drive, and mass flow profiles, which enable control of macroscopic plasma profiles [N, T, $f(r, v)$] and, consequently, of stability and transport properties.
- The principles are experimentally demonstrated, but the full potential is yet to be realized.
- Three thrusts have been put forward, to better understand:
  - Wave coupling
  - Physics of wave propagation, absorption and plasma modification
  - Full integration into fusion system dynamics

T11.1—What are the most important processes that determine the electromagnetic wave spectra and constrain the maximum power that can be coupled into magnetically confined plasmas?

- Basic understanding of many of the physical processes has been achieved.
- However, direct application to real world experiments is more complicated. Three-dimensional computations, including realistic plasma and neutral models, with experimental verification via in-situ diagnostics are needed to develop confidence in predicting performance in future situations.
- In addition to spectral content and polarization, an understanding of the processes responsible for the limiting power is particularly important for ITER or any energy-producing device.
- Relevance: O1, O2, and particularly O3.

T11.2—Understand the physics of wave propagation and absorption in magnetized plasmas and understand the plasma response to high power injected waves.

- Many interacting physical effects:
  - Propagation in inhomogeneous (2 and 3 D), anisotropic, hot plasma, with the complications of mode conversion, and linear and nonlinear wave-particle interaction
  - Absorption via collisional, Landau, and cyclotron damping as well as through stochastic particle interactions.
  - Nonlinear modification of the plasma medium which affects both propagation and macroscopic plasma properties such as transport.
- Theory: Correct formulation of multi-dimensional hot plasma response and computational advances (3D full-wave + Fokker Planck solvers on vector/parallel computers) require continuing development.
- Experiment: Widespread employment of advanced diagnostics for wave field and distribution function measurement are required.
- Relevance: O1 (WP interactions), O2 (heating, current drive, profile control), O3 (discharge control techniques).

T11.3—Integration: Understand the interaction in fusion plasmas between wave processes and other critical processes such as MHD stability and transport and use this to control profiles and develop attractive integrated burning plasma scenarios.

- To realize the potential of waves for heating and plasma control, it is necessary to have a predictive understanding of the effects that the localized heat deposition, driven currents, driven plasma flows, and distribution function modifications induced by waves have on equilibrium, stability, and transport.
- Requirement:
  - Coupled package of simulation codes that evolve self-consistently the magnetic equilibrium and wave-driven fluxes (current, heat, mass flow), as well as modifications to profiles and transport properties.
  - Experimental facilities with pulse length >> current diffusion time, which can simulate aspects of a burning plasma.
  - Tools: Flexible, localized current-drive and heating capabilities, and diagnostics for current, pressure, fluctuations, and flows.
- Relevance: O2 (most strongly) and O3. Code development and benchmarking contribute to O1.

T12 Workgroup Organization and Methodology

- Participants:
  - Boris Breizman (T12 chair) and Joseph Snipes
  - Also: Douglass Darrow, Nikolai Gorelenkov, William Heidbrink, James Van Dam, and King Lap Wong.
- Methodology:
  - Discussions between BB and community members at Sherwood.
  - Initial draft by BB, modified in response to feedback.
  - Thrusts evolved and scientific issues were regrouped.
  - Communication via email, individual phone conversation,s and web site postings.
- Web site:
  - lists.psfc.mit.edu/mailman/listinfo/energetic_particles

T12 Issues

- The fusion of deuterium and tritium nuclei produces 3.5 MeV alpha particles, whose energy deposition into the confined plasma is required for sustained burn.
  - Recent advances in diagnostics and theory/simulations of fast ions in a magnetized plasma indicate the need and opportunity to assess the potential role of energetic particles, including alpha particles, on bulk plasma confinement as well as the confinement of the alphas themselves.
- An important concern is that alpha particles provide free energy to drive plasma modes, which may degrade alpha-particle confinement.
  - The alpha particles and other populations of energetic ions may also affect MHD-stability of the bulk plasma.
  - High-energy runaway electrons, produced occasionally, may damage the facility.
- Understanding the interaction of the alpha particle population with the background plasma is critical to practical applications of fusion.

T12 Research Approach

- Understanding:
  - Much has been learned about the generation and effects of energetic particle-driven instabilities. However, understanding in novel regimes (high pressure, inverted shear, strong flow), which have the potential for performance enhancement, is incomplete. Models, codes, and wave and particle diagnostics for these new regimes need to be developed. (Thrust T12.1)
- Performance:
  - The existence of a sufficiently broad alpha confinement parameter regime in fusion plasma needs to be demonstrated. Also, ideas for performance enhancement require further exploration, and innovative diagnostics need to be developed. (Thrust T12.2)

T12.1—Explore the internal features of energetic particle excited instabilities in new plasma regimes.

- Model the radial structure of energetic particle-driven waves and the contributions to the mode damping rates from various physics mechanisms predicted by theory, including mode conversion physics in realistic magnetic geometries, with measured plasma profiles.
- Model nonlinear properties of the excited modes, including wave-particle nonlinearities.
- Use ICRF heating and NBI to create energetic ion populations to drive stable candidate modes unstable. (Also external antennas.)
- Develop techniques to resolve internal radial mode structure.
- Relevance:
  - Contributes to O1 through improved understanding of the stability properties of energetic particle-driven modes.
  - Contributes to O2 through the development of improved stability conditions for burning plasmas.
  - Contributes to O3 through improved understanding of burning plasma stability, the safety factor behavior for "advanced tokamak" scenarios, and the time-evolved energetic particle content.

T12.2—Understand the synergistic behavior of alpha particle-dominated burning plasmas.

- This understanding is needed to answer urgent questions such as:
  - Is there a sufficiently broad operating space for stable confinement of alpha particles in a burning plasma?
  - How much fast-ion transport can result from instabilities once they occur and to what extent can the instabilities be controlled?
  - Is it feasible to use waves to enhance alpha particle energy transfer to plasma ions and/or to remove helium ash?
- Required capabilities:
  - Self-consistent nonlinear predictions for the wave fields and the fast-ion transport treating both fluid and wave-particle nonlinearities simultaneously.
  - Employ ICRF and NBI and trace tritium to create fast ion populations to model alpha particle confinement.
- Relevance:
  - The interplay between energetic particles and turbulence is important in astrophysical, space, and laboratory plasmas (O1-Understanding Plasmas).
  - The transport of alpha particles is a critical issue for burning plasmas (O2), and transport control is needed to make fusion power practical (O3).

Conclusions

- Waves and energetic particles are critical elements of all Fusion Energy Sciences endeavors, including both magnetic and inertial confinement approaches, as well as fundamental science topics in astrophysics and near-space physics.
  - Waves and energetic particle physics are especially relevant to burning plasmas.
  - The material presented here identifies the key issues associated with these topics, and describes the approach being taken to develop the required understanding.
- There has been good community input and agreement with the top-level research thrust descriptions in all three topical areas.
- Some discussion of details in T11 and T12 will be continued, for the final report.
- The working group efforts requested by FESAC have fostered valuable discussion and awareness of research needs in the community.