Waves and Energetic Particle Research are Integral Component of US Fusion Program

- High power, externally launched radio-frequency waves (30 MHz to 110 GHz) heat plasmas and drive non-inductive toroidal current.
  - Only method for heating core of large burning plasma
  - Precision methods to control heating, current, and possibly plasma flow; crucial to innovations of “advanced tokamak” scenarios for ITER and beyond.

- Non-thermal particle distributions, e.g., fusion-produced $\alpha$-particles in ITER, may destabilize Alfven wave modes of the plasma.
  - Possibility of reduced confinement and enhanced macroscopic instability in burning plasmas.
Variety of Wave Heating Schemes in Distinct Plasma Conditions in 3 US facilities

Missions: plasma heating, local current drive, instability control

- **DIII-D:** Moderate field, moderate density advanced tokamak
  - Electron cyclotron waves for current drive (broader current profile, control of tearing instabilities); selected for ITER
  - Fast wave (ion cyclotron frequency range) for current replacement in core

- **NSTX:** Spherical tori address non-inductive current profile control in “overdense” plasmas for long-pulse operation.
  - Novel electron Bernstein wave current drive to be initiated for current drive.
  - Fast wave for core current drive.
  - Coaxial Helicity Injection for non-inductive start-up.

- **C-Mod:** Entirely radio-frequency wave-heated, high-density, high-field plasmas.
  - Ion cyclotron minority heating delivers flexible, controlled heating profile; selected for ITER.
  - Ion cyclotron mode conversion to supply local current drive and plasma flow
  - Lower hybrid current drive was recently implemented to access advanced tokamak schemes; this is a reserve option for ITER.
Wave heating research has long development path in US fusion program.

Accurate comparisons of wave propagation and absorption measurements with comprehensive modeling of radio-frequency heating are hallmark of US program.

- Example: State-of-the-art full-wave calculation of ion cyclotron wave mode conversion is consistent with measurements of wave by versatile phase contrast imaging on C-Mod.
- Similar capability for full-wave lower hybrid propagation and absorption on self-consistent fast electron population.
- Ray tracing and absorption of electron cyclotron wave (DIII-D); electron Bernstein waves (NSTX).
Energetic Particle Studies on the Three Major US Facilities

Energetic particle modes studied in all 3 US facilities for understanding of $\alpha$ particle-driven instabilities in ITER.
- Neutral beam ions in NSTX, DIII-D
- RF-driven ions in C-Mod

In parameters relevant to energetic particle-driven modes, operating range of US facilities exceeds that for ITER.
- $V_{\text{fast}} / V_{\text{Alfvén}}$ range extensive in DIII-D, NSTX
- $\beta_{\text{fast}}$ drive of fast particle instability high in all
- $\rho_{\text{fast}} / a >$ ITER value in all; best approached in C-Mod
U.S. Facilities Contribute Significantly to Energetic Particle Physics Research

Since the shutdown of TFTR, experimental leadership in this area has belonged to the world’s largest tokamaks, JET and JT-60U.

U.S. facilities now provide key capabilities and strong physics program for world effort.

- Plasma shaping and aspect ratio flexibility (DIII-D, NSTX)
- Advanced diagnostics
- Control of strength and anisotropy of fast particle distribution.
- External antennae to excite Alfven eigenmodes to separate drive from damping (C-Mod)
- Close interaction between experiment and modeling.
Assessment of Wave and Energetic Particle Physics

- U.S. facilities pursue non-duplicative methods of wave heating and current drive appropriate to diverse missions of
  - MHD instability suppression
  - Control of the radial profile of plasma current
  - Localized plasma heating

in significantly different parameter ranges of the experiments.

- Studies performed in next five years will be important for ITER, and crucial for advanced tokamak/innovative concept development.

- U.S. facilities contribute significantly to vitally important understanding of threat of Alfven eigenmodes to burning plasma confinement.