RF Waves in Magnetically Confined Plasmas for Heating and Current Drive: A Historical Perspective.

MIKLOS PORKOLAB, MIT Plasma Science and Fusion Center, Cambridge, MA 02139,USA.

The history of high power RF waves injected into magnetically confined plasmas for the purposes of heating to fusion relevant temperatures spans nearly five decades. The road to success demanded the development of the theory of plasma wave propagation, development of antenna structures and transmission lines capable of handling high RF powers reliably, and the development of high power RF sources. In the early days, progress was hindered by the lack of good confinement of energetic particles in the relatively small and low current tokamaks and poorly designed stellarators, especially in the ICRF regime where minority heating resulted in ions with energies in the multi-100keV range. In this talk I will summarize the historical evolution of results since the 1960s in 3 frequency regimes, namely ICRF, ECRH and LHRF. Beside the fundamental theoretical concepts, I will give examples of the major experimental developments and results. Naturally, only examples will be given rather than an exhaustive summary of all the important results. For example, in the ICRF regime heating results in the early 1970s were limited by poor confinement of energetic minority species ions before thermalizing. This was followed by spectacular heating results in the 1980s at the multi-MW power levels in machines with good confinement, such as PLT, TFTR and JET. In the late 1970s and early to mid 1980s the theory of LHCD, ECCD and ICCD (Fast Wave) current drive was developed by Fisch, Karney, Boozer and others, and by the mid-1980s lower hybrid current drive was firmly established by experiments on Versator-II, PLT and Alcator –C in the USA, as well as in Europe (WEGA and Petula, ASDEX and JET) and in Japan (JT-60). Experimental verification of the theoretical predictions is now available in all three frequency regimes. State of the art Fokker Planck codes (CQL3-D, etc) are now in use to model current drive, and the recent development of full wave codes on parallellized computers are revolutionizing our understanding and visualization of wave propagation in tokamak geometry. Moreover, multi MW level long pulse LHCD experiments are being carried out on Tore-Supra, JET and most recently Alcator C-Mod. ECRH was progressing rapidly in the 1980s with the development of gyrotron tubes at 28-56 GHz at the 200 kW level, while in the late 1990s MW level tubes were developed at frequencies up to 110 (140)GHz. Multi-MW experiments followed in T-3, DIII-D, ASDEX-U, TCV and JT-60 very recently. Recent tube development at the MW level has been achieved at frequencies up to 170 GHz, and development of 1.5-2 MW long pulse tubes is underway for ITER applications. While RF wave propagation in the plasma core is now an established branch of plasma science, the coupling around metallic antennas in the ICRF and LH regimes is still an area of active research, including nonlinear effects, sheath rectifications and impurity generation. However, steady progress is being made to identify these interactions, including development of antenna codes and we can expect that these RF wave techniques should be available for implementation in ITER in the next decade. Reliability of antenna operations at high RF voltages and long pulses will need further attention, and further novel antenna design techniques should be developed and tested on ongoing experiments. Finally, we should mention that recently RF current drive techniques have been used successfully to stabilize MHD modes (sawteeth, NTM, etc) and development of new diagnostics (PCI, or Phase Contrast Imaging) offer ways to measure the injected RF waves and mode converted waves inside the hot plasma. In the future, a quantitative determination of power flow inside hot fusion plasmas should be feasible.

*Work supported by the US DOE.