Burning Plasma Science Workshop II
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Summary of the Working Group-2 Presentations on Heating and Current Drive.

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The questions posed to the Breakout Group-2 were as follows:

What types of heating and current drive are planned and what are the prospects for investigating "steady–state" plasma operation on the relevant plasma time scales ? Specific scenarios for FIRE, ITER-FEAT and IGNITOR were to be addressed.

The presentations and discussions were focused around four topics, namely Neutral Beam Injection (NBI), Ion Cyclotron Range of Frequencies (ICRF Heating and Fast Wave and/or Mode Conversion Current Drive), Lower Hybrid Current Drive (LHCD) and Electron Cyclotron Heating and Current Drive (ECH and ECCD). To forecast what the requirements may be beyond the above three BP concepts, we have included two presentations on the requirements for potential future reactor concepts such as Aries-RS and ATBX (Advanced Tokamak Burning Plasma Experiment). This turned out to be informative since the three reference designs listed above, namely ITER-FEAT, FIRE and IGNITOR did not really address in depth the charge: *what are the prospects for investigating "steady–state" plasma operation on the relevant plasma time scale**s.*** In addition, we heard presentations on NTM stabilization by ECCD and/or LHCD, and possible RF heating scenarios with Electrostatic Waves (EW) in high beta (i.e., high dielectric constant) innovative BP concepts such as STs. For the record, the Breakout Group-2 Agenda and the list of presentations is included at the end of this Summary.

A logical way to summarize heating and current drive options in different machines may be as follows:

Heating:

- ITER: ICRH, NBI, ECRH
- FIRE: ICRH, NBI
- IGNITOR: ICRH
- ARIES-RS/AT and ATBX: ICRH, (NBI,ECRH)

Current Drive for AT operation:

- ITER: NBCD, FWCD, ECCD, (LHCD)
- FIRE: (FWCD, LHCD)
- IGNITOR: (LHCD)
- ARIES-RS/AT and ATBX: FWCD, NBCD, LHCD

Other applications

- NTM stabilization: ECCD in ITER and ARIES/AT, LHCD in FIRE, ATBX and ARIES-RS
- RF startup with ECH and LHCD (ST, ARIES -RS/AT)

The presentations were often given by experts in different RF frequency regimes (since the technologies vary widely with RF frequency). Therefore, first we shall give a brief summary of the status of the physics and the technology of NBI technology and different RF frequency regimes. We shall then follow up by giving a summary of the proposed heating and current drive scenarios in the above listed BP experiments.

Neutral Beam Technology.

Neutral beam heating, based on positive ion sources, is the “workhorse” for heating in most of the presently operating major tokamak experiments. Owing to the reduced neutralizing efficiencies at high energies, the maximum positive ion beam energies are restricted to about 140kV, not sufficient to penetrate to the core of “Next Step” burning plasma experiments of the ITER class. To alleviate this problem, negative ion beams have been under development for the past 10 years at the 0.5 MeV level, in particular in Japan, which are suitable for penetrating ITER class devices. For reactor size devices, development of negative ion beams with energies at the 1-2 MeV level will be be necessary. It should be noted that while in present day experiments neutral beams at the 100 keV energy heat mostly ions, MeV beams and alpha particles in reactor scale devices will heat primarily electrons. Hence, in future BP experiments $T_e \approx T_i$, while in many present beam heated experiments $T_i >> T_e$. In addition, tangentially injected beams may be used to drive currents in the plasma core with efficiencies up to σ=nIR/P≈0.5x10^{20} A-m^{-2}/W at energies of *E* > 0.5 MeV.

Ion Cyclotron Range of Frequencies.

Plasma heating in the ion cyclotron range of frequencies is the most mature of all RF heating methods, and the sources are the least expensive. In particular, cw high power tetrodes at power levels in excess of 2.0 MW (depending on frequency) are commercially available at frequencies up to 120 MHz at a cost of ~120 k$. In typical applications the so-called Fast (Magnetosonic) Wave is launched in D-D or D-T plasmas , and absorption is achieved by adding a small amount (typically 2-5 %) of “minority ion “ species (H, ^{3}He) which then absorbs the power at its fundamental cyclotron frequency in the plasma core at a frequency of 15.2B(T) MHz with protons or 10.1B(T) MHz with ^{3}He. Alternatively, absorption at the 2nd harmonic of the majority species may be used once the beta of the majority ions exceeds a few percent. Thus, in a DT plasma the most attractive heating scenario would be to initially add a few percent of ^{3}He minority species, and inject RF power at the appropriate frequency (say 50 MHz at 5 Tesla). Once the beta of the plasma tritons exceeds the ^{3}He minority concentration, second harmonic triton absorption takes over, removing the need for the ^{3}He minority species. The energetic minority tail is well confined and transfers its energy to the background electrons (and ions at high densities) by Coulomb collisions, thus heating the bulk plasma. The physics of the minority heating has been well demonstrated experimentally and is being used in many ongoing tokamak and stellarator experiments. The main difficulty of this technique lies with the design of appropriate antenna structures and tuning elements in the transmission line, owing to the large mismatch between the characteristic impedance of transmission lines and the loading of the antenna that faces (and is in direct contact with) the plasma. Further development work is desirable to improve on the power handling capability of typical present day antenna designs which often break down at voltages above 20-30kV, while 50kV would be desirable for an attractive reactor application (assuming that the antenna must be removable by remote control techniques from accessible ports). Nevertheless, in ITER size devices injecting 50-75 MW of ICRF power appears feasible using present day technology. Other potential applications of ICRF waves are on-axis (seed) current drive by the fast wave and off-axis localized flow-drive using mode converted IBW. The physics of fast-wave current drive has been well established, with an efficiency of σ=nIR/P$\approx$0.1x10^{20} T_e where T_e is given in units of 10 keV and the other parameters are in units of A-m^{-2}/W.

Lower Hybrid Current Drive.

Lower hybrid waves (slow-waves, partially electrostatic waves) propagate in the 5-8 GHz frequency range in the proposed burning plasma experiments. Here klystrons (or gyro-amplifiers at the higher frequency end) are the power sources of choice. CW klystron sources that are being used in present day experiments include the 3.7GHz, 0.5MW klystrons developed by Thompson for JET and Tore-Supra, and the 4.6GHz sources developed by Varian (now CPI) for Alcator-C nearly 20 years ago. More recently an 8 GHz gyrotron was developed by Thomson for FT-U. The waves must be launched at the plasma edge by slow-wave structures, typically a phased array of waveguides (grill). The grill must be in contact with the plasma so that at its edge $\omega=\omega_{pe}$ for good coupling. For wave accessibility, the typical parallel index of refraction will be in the range $N_{||}$ = 1.5-2.0 in a plasma with $\omega_{pe}\approx\omega_{ce}$. Since the wave is strongly Landau damped at v_{ph}/v_{th} = 2.4, the power is absorbed at local temperatures $T_e = 44/ N_{||}^2$, or about 15-20 keV. In an ITER size device, with T_e = 30 keV, wave absorption will be off-axis, and the LH wave is suitable for off-axis current drive and NTM stabilization. Furthermore, off-axis absorption of LH waves on electrons is essential in a burning plasma to avoid strong alpha-particle absorption in the plasma core. For optimizing applications, detailed modeling with ray-tracing codes, such as ACCOME, is essential. On the plus side, the LH wave is the most efficient among all possible current drive techniques for off-axis current drive and for developing a RS equilibrium, (ie., see Aries-RS or AT or ATBX scenario modeling). Regarding technology, further development of high power microwave sources at 5-6 GHz would be desirable. Power transmission is “in hand” and is relatively straight-forward. On the minus side, reactor relevant launcher design and development work needs to be carried out and tested.

Electron Cyclotron Heating and Current Drive

Electron cyclotron heating (ECH) and current drive (ECCD) are methods of heating or driving current in a toroidal plasma by applying high frequency electromagnetic waves near the electron cyclotron resonance frequency or its low harmonics. EC waves have important advantages that are especially relevant for burning plasmas. First, the EC wave propagates in vacuum, which means that the wave launchers may be far from the plasma surface and still have excellent coupling properties. Second, the power density can be very high compared with other heating methods, which provides favorable engineering aspects: the waveguides can be quite small, which makes neutron shielding and tritium containment easier, along with structural support. And third, the physics of ECH/ECCD is rather well understood, so that the heating properties can be predicted with confidence. Applications of EC power include startup (breakdown and burnthrough), bulk plasma heating, current drive, current profile control for AT scenarios, development and control of internal transport barriers, and stabilization of neoclassical tearing modes. It should be noted, however, that the off-axis current drive efficiency may not be sufficently high to establish steady state RS scenarios such as required for an ARIES-RS design. The basic technical approach is low-field side launch of the fundamental ordinary mode for heating and current profile control. For control applications or to accommodate a range of toroidal field, toroidal and/or poloidal steering capability is needed. Means to carry out the steering without using any moving parts near the tokamak are being developed, as well as gyrotrons with step-tunable frequency. Power transmission techniques are mature and robust.

The electron cyclotron frequency is given by f_{ce}=28B(GHz), where B is the magnetic field in Tesla. The implication for burning plasma experiments is that the frequency is higher for higher field devices. For ITER-like tokamaks, the EC frequency lies in the range 160-180 GHz. For high field devices like FIRE, the EC frequency is in the neighborhood of 280 GHz. Very high field devices like IGNITOR require 360 GHz sources. For low field devices like low aspect ratio spherical tokamaks, the frequency is lower, but the physics of heating is much more complicated due to the high density compared to the cutoff density for electromagnetic waves. In particular, EC fundamental O-mode propagation is restricted to densities such that the electron plasma frequency is less than the electron cyclotron frequency, or in practical terms $n_{20} \leq 0.1\ B_T^2\,(T)$ where n_{20} is in units of $10^{20} m^{-3}$.

Second harmonic heating would allow twice as high density, but presently sources are not available. Development of suitable sources for EC waves has made great progress in the last few years. In particular, the development of commercially viable diamond windows now ensures the availability of long pulse (10 sec) gyrotrons at the 1 MW level in the 110 to 170 GHz range. A second major improvement in gyrotrons has come from the development of the “depressed collector”, a retarding voltage applied to the collector which improves the gyrotron electrical efficiency from 30% to 50% while at the same time reducing the heat load on the gyrotron collector and water cooling system. Gyrotrons using these innovations have operated for 10 sec pulses at 1 MW with 47% efficiency. Operation for 10 sec pulses is nearly steady-state for the active components of gyrotrons, so this result implies that the gyrotron source suitable for ITER-like devices and spherical tokamaks is already developed. Current research on high frequency gyrotrons at MIT has shown operation for short pulses at frequencies of 202, 229, 280, and 292 GHz, all at power approaching 1 MW, covering the range needed for FIRE. Lower power operation (0.3 MW) at 303 GHz was also obtained. This research is continuing, and it seems highly likely that gyrotrons suitable for FIRE can be constucted, although a considerably larger research program would be needed to develop CW gyrotrons at 280 GHz.

Machine Specific Heating Scenarios

In the tables below we list the proposed heating and current drive scenarios for ITER-FEAT, FIRE, IGNITOR, ARIES-RS/AT, and ATBX.

Table I.

ITER FEAT Heating and Current Drive System

EC	170 GHz, 20 MW (+20 MW) Horizontal port: 20 MW/port, toroidally steerable mirror Upper port: 7 MW/port x 3, stabilize NTM, poloidally steerable mirror
ICRF	40 – 55 MHz, 20 MW (+20 MW) [8 MW/m^2]
LH	5 GHz, 0 MW (+40 MW)
NB	1 MeV, 33 MW/2 ports (+17 MW)

Table II.

ITER FEAT ICRF Options

Resonance	**(MHz)**	**Comments**
$2\Omega_1 = \Omega_{3He}$	53	Second harmonic + minority heating
Ω_D	40	Minority heating. Strong competition of Be and α-particles
FWCD	56	On axis current drive
Ω_{3He}	45	Minority ion current drive at sawtooth inversion radius (outboard)

Table III.

External Current Drive and Heating for FIRE

30 MW ICRF
minority heating
- 4 ports, 100-150 MHz

<10 MW ICRF / FW
(electron heating / CD)
for AT mode;
- 1 (or 2) ports, 90-110 MHz??, phasable antenna
- Use the above ICRF transmitter

20-30 MW LHCD
- 2-3 ports, 5.6 GHz, $n_{||}$ = 2.0-2.5
- For NTM control

??MW ECH / ECCD
(electron heating / CD)
for startup and NTM
control (issue is high
B_T and high density)

Table IV.

IGNITOR RF Heating

	Frequency	**Method**	**Advantages**	**Disadvantages**
ICRF	130-140 MHz--20 MW coupled	3He minority in DT & $2\Omega_T$	Established technique; efficient heating; help stabilize sawteeth	Cannot be easily used during TF ramp; bulky antennas; disruptive forces
		Future Upgrade Options		
HHFW	400-800 MHz	ELD of high harmonic fast waves	Can be used during TF ramp;	Untested launcher
Lower Hybrid	8-12 GHz	ELD of LH Waves	Can be used during TF ramp and in AT scenarios	Improve source and launcher development
ECH	300-400Ghz			Needs source development;

Table V.

Current Drive Scenarios for ARIES-RS/AT 1 Gwe Power Plants

ARIES-AT has better bootstrap alignment than ARIES-RS

Device	**ARIES-RS**	**ARIES-AT**
R (m)	5.5	5.2
A	4.0	4.0
κ	1.89	2.18
δ	0.77	0.84
I_p (MA)	11.3	12.8
β (%)	5.0	9.2
I_{bs}/I_p	0.88	0.915
On-axis CD*	ICRF/FW	ICRF/FW
Off-axis CD*	HHFW, LHW	LHW
Power (MW)	82.0	41.6

Table VI.

Advanced Tokamak Burning Plasma Experiment (ATBX)

Steady State Reversed Shear Scenario [ACCOME Simulation]

R=5.60 m, a=1.75 m, κ =1.85, δ_{95}=0.44, B_o=6.25 T

q_o=4.0, q_{min}=2.5, q_{95}=4.5

P_{NBI}=20 MW, 0.5 MeV [or 20 MW fast wave]

P_{LH}=60 MW, 5.5 GHz, $N_{\|}$ =1.90

Ip=12.0 MA, I_{BS}=8.5 MA, I_{NI}=1.0 MA, I_{LH}=2.5 MA

Q=10

Table VII.
Breakout Group-2 Agenda

Organizers: Miklos Porkolab and Ron Prater

ICRH	
2.00-2.30:	D.A. Rasmussen Ion Cyclotron Systems for ITER and FIRE
2.30-2.50:	Y. Shimomura Technology of Heating and Current Drive in ITER
2.50-3.15:	T.K. Mau Heating and Current Drive in Aries-RS / AT and FIRE
3.15-3.25:	M. Porkolab AT Results in C-Mod with ICRF : New Options in a BPX
3.25-3.35;	M. Ono Review of ICRF Results in TFTR DT Plasmas
3.35-3.45:	C. Petty FWCD results from DIII-D and Projections to BPX
3.45-4.00:	Coffee Break
LHCD	
4.00-4.30:	M. Porkolab LHCD Profile Control and AT Options in a BPX
4.30-4.40:	P.H. Rutherford Prospects for Suppression of NTMs in FIRE by LHCD
ECRH	
4.40-5.10:	M. Makowski ECH in ITER and ITER-like BPX
5.10-5.40:	R.Temkin ECH Technology for BPX
5.40-6.00:	R. Pinsker Applications of Electrostatic Waves in BPX