FIRE, An Advanced Burning Plasma Experiment

Mission

The mission of FIRE is to attain, explore, understand and optimize fusion dominated plasmas to provide knowledge for designing attractive MFE systems. FIRE is envisioned as an extension of the existing advanced tokamak program leading to an attractive magnetic fusion reactor (e.g., ARIES-RS). The FIRE [1, 2] design study of a next step burning plasma experiment has the goal of developing a concept for an experimental facility to explore and understand the strong non-linear coupling among confinement, MHD self-heating, stability, edge physics and wave-particle interactions that is fundamental to fusion plasma behavior. This will require plasmas dominated by alpha heating ($Q \approx 10$) that are sustained for a duration comparable to characteristic plasma time scales ($\geq 10\ \tau_E$, $\sim 4\tau_{He}$, $\sim 2\ \tau_{skin}$). The FIRE pre-conceptual design activities, carried out by an U. S. national team, have been undertaken with the objective of finding the minimum size (cost) device to achieve the essential burning plasma science goals.

Machine Description

FIRE activities have focused on the physics and engineering assessment of a compact, high-field tokamak with the capability of achieving $Q \approx 10$ in the Elmy H-mode for a duration of ~ 1.5 plasma current redistribution times (skin times) during an initial burning plasma science phase, and the flexibility to add advanced tokamak hardware (e.g., lower hybrid current drive) later. The configuration chosen for FIRE is similar to that of ARIES-RS, namely a highly shaped plasma, with double-null divertor and aspect ratio ≈ 4. The key "advanced tokamak" features are: strong plasma shaping, double null poloidal divertors, low toroidal field ripple (< 0.3%), internal control coils and space for wall stabilization capabilities.

The reference design point is $R_o = 2.14$ m, $a = 0.595$ m, $B_t(R_o) = 10$T, $I_p = 7.7$ MA with a flat top time of 20 s for 150 MW of fusion power with the cross-section shown in Fig. 1. The baseline magnetic fields and pulse lengths can be provided by a wedged

R (m), a (m)	2.14, 0.595
κ_x , κ_{95}	2.0, 1.77
δ_x , δ_{95}	0.7, ≈ 0.4
q_{95}	> 3
$B_t(R_o)$ (T), I_p (MA)	10, 7.7
$Q = P_{fusion}/(P_{aux} + P_{OH})$	10
H98(y,2)	1.1
β_N	1.81
P_{loss}/P_{LH}	1.3
Z_{eff} (3% Be + He (5 τ_E))	1.4
$R\nabla\beta_\alpha$ (%)	3.8

Table I. FIRE, Q = 10 Parameters

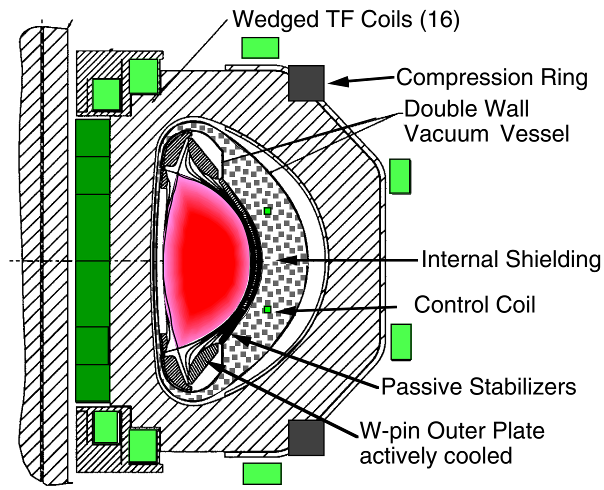


Fig. 1. FIRE Configuration

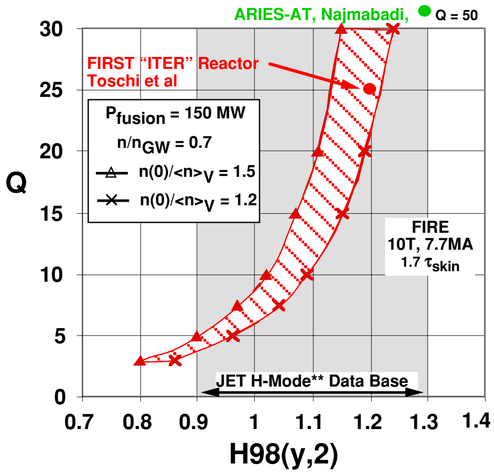
BeCu/OFHC toroidal field (TF) coils and OFHC poloidal field (PF) coils that are pre-cooled to 77 °K prior to the pulse and allowed to warm up to 373 °K at the end of the pulse. 3-D finite-element stress analyses including electromagnetic, and thermal stress due to ohmic and nuclear heating have shown that this design has a margin of 30% beyond the allowable engineering stress. Large (1.3 m by 0.7 m) midplane ports provide access for heating, diagnostics and remote manipulators, while 32 angled ports provide access to the divertor regions for utilities and diagnostics. FIRE, like the previous BPX design, is being designed mechanically to accommodate 3,000 full field, full power pulses and 30,000 pulses at 2/3 field with a total fusion energy production of 5.5 TJ. The repetition time at full field and full pulse length will be < 3 hr, with much shorter times at reduced field or pulse length.

FIRE will provide reactor relevant experience for divertor and first wall power handling since the anticipated thermal power densities on the divertor plates of ~6 MWm^{-2} for detached operation and ~25 MWm^{-2} for attached operation exceed present experiments and approach those anticipated for ARIES-RS. FIRE would use only reactor relevant metallic materials for plasma facing components, and carbon could not allowed in the vessel due to tritium inventory build-up by co-deposition. The divertor plasma-facing components are tungsten “brush” targets mounted on copper backing plates, similar to a concept developed by the ITER R&D activity. The outer divertor plates and baffle are water-cooled and come into steady-state equilibrium during the pulse. The first wall is comprised of Be plasma-sprayed onto copper tiles. The neutron wall loading in FIRE is ~ 2 MWm^{-2} and produces significant nuclear heating of the first wall and vacuum vessel during the 20s pulse. The inner divertor targets and first wall are cooled by mechanical attachment to water-cooled copper plates inside the vacuum vessel. Sixteen cryo-pumps – closely coupled to the divertor chambers, but behind sufficient neutron shielding – provide pumping (≥100 Pa m^3/s) for D-T and He ash during the pulse. Pellet injection scenarios with high-field-side launch capability will reduce tritium throughput, and enhance fusion performance. The in-device tritium inventory will be determined primarily by the cycle time of the divertor cryo-pumps, and can range from < 2 g for regeneration overnight to ~10 g for weekly regeneration. The tritium usage per shot and inventory is comparable to that of TFTR and therefore will not require a large step beyond previous US fusion program experience in tritium shipping and handling.

The construction cost of the tokamak subsystem (magnets, divertor, plasma facing components and mechanical structure) has been estimated to be ≈ \$350M (FY99US) including \$75 M of contingency. Another ≈ \$850 M would be required for auxiliary heating, startup diagnostics, power supplies and buildings to put the project at a new site.

Plasma Performance Projections

The physics issues and physics design guidelines for projecting burning plasma performance in FIRE are similar to those for ITER-FEAT. The operating regime for FIRE is well matched to the existing H-mode database and can access the density range from $0.3 < n/n_{GW} < 1.0$ through a combination of pellet fueling and divertor pumping. This flexibility is important for investigating the onset of alpha-driven modes at the lower densities and to optimize the edge plasma for confinement studies and optimal divertor



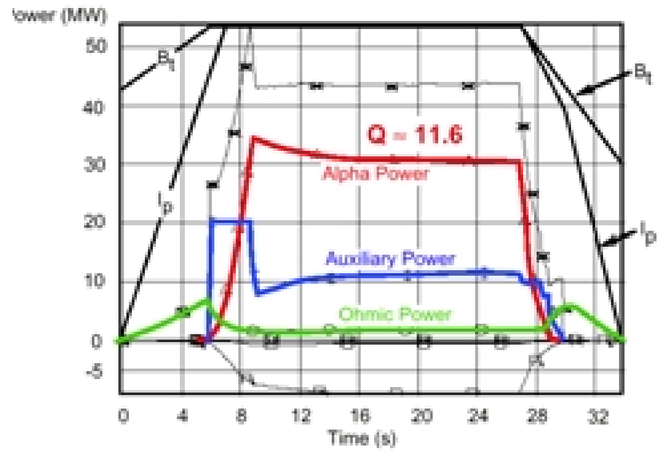


Fig. 2. Fusion Gain for FIRE

Fig. 3. Evolution of a fusion-dominated plasma.

operation. The performance of FIRE was projected by selecting JET data with parameters similar to FIRE, namely $\beta_N \geq 1.7$, $Z_{eff} < 2.0$, $\kappa > 1.7$ and $2.7 < q_{95} < 3.5$. The average H(y, 2) and density profile peaking, $n(0)/\langle n \rangle_V$ for these data was found to be 1.1 and 1.2, respectively. This is consistent with the analysis of JET H-mode data presented by Cordey et al [3]. A 0-D power balance code was used to calculate the Q-value in FIRE as a function of H-factor as shown in Fig. 2. The density profile was assumed to have $n(0)/\langle n \rangle_V = 1.2$ (x points) or 1.5 (Δ points) with 3% Be and self-consistent alpha ash accumulation. On this basis, FIRE would be expected to achieve $Q \geq 10$ for JET-like H-modes. Physics based models using marginal stability transport models such as GLF23 also predict Q values in the range ≈ 10. These models dependent sensitively on the value of the temperature of the H-mode pedestal which is projected to be higher for plasmas with strong shaping (triangularity) and pedestal density low relative to the Greenwald density. A next step experiment, such as FIRE, would provide a strong test of these models and improve their capability for predicting reactor plasma performance. A 1 1/2 -D Tokamak Simulation Code (TSC) simulation of this regime with H(y,2) = 1.1 and $n(0)/\langle n \rangle_V = 1.2$ indicates that FIRE can access the H-Mode and sustain alpha-dominated plasmas for $> 20\ \tau_E$, $> 4\ \tau_{He}$ and $\sim 1.5\ \tau_{skin}$ as shown in Fig. 3. In addition, time is provided for plasma startup and a controlled shutdown to avoid plasma disruptions. The burn phase can study plasma profile evolution, alpha ash accumulation and techniques for burn control and begin studies of plasma current evolution due to alpha heating.

A longer term goal of FIRE is to explore advanced tokamak regimes using pellet injection and current ramps to create reversed shear plasmas (e.g., PEP modes), and then applying lower hybrid current drive to sustain the AT mode at high fusion gain ($Q > 5$) for a duration of 1 to 3 current redistribution times. Simulations using TSC with self-consistent lower hybrid current drive modeling show that 100% non-inductively driven burning plasmas could be sustained at $\beta_N \approx 3$, 64% bootstrap current with $Q \approx 7.5$, fusion powers of 150 MW if confinement enhancements $H(y,2) \approx 1.6$ were attained at B = 8.5T and Ip = 5.5 MA. An important feature of the FIRE cryogenic copper alloy magnets is that the pulse length increases rapidly as the field is reduced with flattops of ~ 40 s at 8 T and ~90 s at 6 T. The primary limitation to exploiting this long pulse capability is the generic problem of handling the plasma exhaust power under reactor relevant conditions.

Assessment of FIRE (Advantages/Disadvantages)

FIRE does not seek to demonstrate that our existing knowledge is correct nor to avoid important physics issues, rather the philosophy of FIRE is to explore the science of burning plasmas as fully as possible within the cost constraints of a $1B class laboratory. FIRE is a natural extension of the existing state of the art tokamaks, and is based on the extensive international H-mode data base for projecting performance to the burning plasma regime. Due to the high magnetic field, the extrapolation required to attain $Q \approx 10$ is a modest factor of 3 in terms of the normalized confinement time ($B\tau_E$). While this reduces the uncertainty in attaining a burning plasma, it does not extend some plasma parameters (e.g., ρ^*) to full reactor values. The MHD stability characteristics of FIRE, with $q_{95} \approx 3.1$ and $\beta_N \approx 1.8$ for initial burning plasma experiments, are similar to the standard MHD regimes in existing tokamaks and will explore the synergistic effects of energetic alphas and MHD modes such as sawteeth and TAE modes. Operation at $\beta_N \approx 3$ or higher in later phases would begin to explore the important areas of neoclassical tearing modes (NTM) and resistive wall modes (RWM). Lower hybrid current drive and feedback stabilization being evaluated as an experimental tools to investigate the control of NTMs and RWMs. Divertor pumping and pellet fueling will allow FIRE to vary the density, hence the TAE driving terms $R\nabla\beta_\alpha$, by a factor of three providing a good test bed for exploring the instability boundary for TAE modes and determining the transport of energetic alpha particles due to multiple overlapping TAE modes.

The double null divertor configuration produces the strongest plasma shaping which is critical for resolving and exploiting a number of physics effects related to confinement and MHD stability. The double null divertor may also significantly reduce the frequency and intensity of vertical displacement disruptions which is a critical issue for the feasibility of a tokamak based reactor. The disadvantage of this approach is the cost associated with the divertor and its impact on space inside the TF coil. The high power density in FIRE poses a significant challenge for the divertor and first wall designs, but this is a generic issue for magnetic fusion. The success of FIRE in this area would provide yield important benefits for technology development for future fusion devices.

A critical issue for all next step experiments is to supply auxiliary heating power to at high power densities to a fusion plasma. FIRE proposes to use ICRF heating which has been demonstrated on existing experiments but the high power densities and neutron wall loading present in FIRE will require significant plasma technology R&D. This R&D will be needed if ICRF is to be used in a fusion application. The toroidal magnet flat top of 20s at 10T is sufficient ($\approx 20\ \tau_E$, $\approx 4\tau_{He}$) for a thorough investigation of burning plasma physics under conditions approaching steady-state, and would allow the initial investigation of advanced modes with significant bootstrap current fractions under quasi-stationary conditions ($1 - 2\ \tau_{skin}$) in a high gain burning plasma.

References

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[3] J. G. Cordey, et al, 28th EPS Conference on Cont. Fus. and Plas. Phy. 2001