Progress in MFE Science — Tokamak Research
by R.D. Stambaugh

Full text narrative of the review talk at the American Physical Society Division of Plasma Physics Meeting, Quebec City, Quebec, Canada.

A portion of the title of each viewgraph appears above the text used to explain that viewgraph.

0. Progress in MFE Science — Tokamak Research

1. Research Results From …

Covering all the progress that MFE science has made using the tokamak configuration means covering an enormous ground. My intent is for a necessarily broad but shallow coverage to convey a perspective of the tokamak MFE research field as a whole. I found it impossible to take a historical type approach to this talk, tracing the origins of ideas and seminal contributions. Instead, I have adopted a tutorial style with research highlights, hoping to convey to those not directly involved in MFE research a feeling for the concepts of interest and the progress that has been made and to those who do work in MFE a sense of pride in the magnitude of your accomplishment and excitement for what lies ahead. I have listed here those who have directly given me material and/or helped me understand the material.

2. Main Points

The Main Points of this talk are:

We have learned a tremendous amount about magnetically confined plasmas. Advances in measurements and theory have led to a situation in which we can calculate most processes of interest, the exception being cross-field transport, but we are getting close on that.

Exciting new directions are opening. That package of issues is now known as Advanced Tokamak Research.

We are technically ready for next steps.

3. Outline

We will discuss in order, the tokamak equilibrium, heating and current drive, stability, confinement, power and particle control, burning plasma physics, next steps, and a conclusion.

4. **What is a Tokamak?**

What is a tokamak? It is an axisymmetric toroidal confinement configuration with a strong toroidal plasma current and an applied toroidal magnetic field strong enough to make the edge field line winding factor greater than 2. The winding factor q of the helical field is how many times the field line goes around toroidally for once around poloidally in the combined helical magnetic field. In this inset, I show a field line that goes around 4 times toroidally for once poloidally, or a winding factor q of 4.

Not part of the basic definition but certainly part of the opportunity for variation and innovation within the concept are: plasma shape, aspect ratio, choice of limiting boundary surface, toroidal field strength, and the optimization of this last set of issues, the radial profiles of current, pressure, rotation, electric field, and the use of a conducting wall to stabilize the plasma, are the substance of Advanced Tokamak Research.

For example, in most tokamaks the current has been driven by induction from a transformer, in which case the radial profile of the current follows in proportion to the local conductivity which goes as temperature to the 3/2 and results in this typical peaked current profile. But if the configuration is freed from the inductive constraint, then many different current profiles (very peaked to very hollow) are possible and have profound stability and confinement implications.

5. **Tokamaks Have Made Excellent Progress in Fusion Power.**

One reason to take a keen interest in this research is that the tokamak can make copious fusion power. Here we show the history of actual fusion power achieved in tokamaks, culminating in fusion power of 11 MW in TFTR and 16 MW in JET in deuterium-tritium mixtures. How did that happen. Let's find out.

6. **Plasma Equilibrium Theory is Well Understood and Extensively Used.**

It all starts with the basic tokamak magnetic equilibrium which is well understood. Ampere's Law and the equation that balances the plasma pressure gradient against the JxB forces leads to the Grad-Shafranov equation for the equilibrium poloidal magnetic flux function. Equilibrium codes solve this equation for the closed flux contours that give the tokamak its good confinement. Here you see in a poloidal cut such closed flux contours. Heat and particles have to leak out across the magnetic field. At some minor radius in modern divertor tokamaks, the closed contours give way to open field lines at a separatrix (in green). The open field lines guide particle and heat effluent to a divertor region where pumps can be placed. The plasma shape is determined by a set of poloidal field coils. The current is driven in the plasma by an Ohmic heating transformer coil. The strong toroidal field comes from this large coil.

7. **Plasma Equilibrium Shape Control is a Highly Developed Science.**
Plasma Equilibrium Shape control is a highly developed science. Here I have shown the more exotic shapes that have been made in various machines: various divertor shapes, square shapes, bean shapes, and small divertors in DIII-D; extreme vertical elongation and inverse dee shapes in TCV; extreme bean shapes in PBX-M; two radically different divertor arrangements in JT-60 and its successor JT-60U; and perhaps the more standard, modern divertor shape in ASDEX Upgrade.

8. **Successful Methods of Heating and Current Drive for Steady-State Have Been Developed.**
We need to heat these plasmas to fusion conditions and for steady-state find ways to drive the plasma current without induction. Successful methods of heating and current drive have been developed.

In the 70s we just began to explore heating methods. In the 80s, we deployed multi-MW heating systems, began to look at current drive, produced our first enhanced confinement regime (the H or high-mode) by heating, measured the plasma's self driven bootstrap current, and had ray tracing and Fokker-Planck codes for rf methods. In the 90s we moved on to control of the current profile and MHD activity, achieved high bootstrap fraction, and brought to bear full wave codes for rf heating.

9. **The Plasma's Self-generated Bootstrap Current is the Basis for Modern Approaches to Steady-state Operation.**
The plasma's self-generated bootstrap current is the basis for modern approaches to steady-state operation. The reason is that the efficiency of the various beam and rf techniques we will discuss is not high enough to support more than about 50% of the plasma current in a fusion reactor. The bootstrap current is a basic element of neoclassical transport theory (known in the 70s) and derivable just from the orbit properties of the electrons. Looking down on the torus, we see the projection of trapped electron orbits in a common test volume. Because there are more electrons on the inside of the torus, there will be more trapped particles passing through the test volume along the plasma current than against it. This net current appears as a distortion in the trapped particle population in the distribution function which couples into the passing particles, which amplify the effect. The net bootstrap current is proportional to the local pressure gradient.

The existence of the bootstrap current was not confirmed in tokamaks until 1988 in TFTR because we had to develop sufficient heating to make enough pressure gradient to create a detectable bootstrap current and high quality diagnostics were required to extract the bootstrap current from this loop voltage signal by taking out the Ohmic heating and neutral beam current drive contributions.

10. **A High Performance Plasma with Full Non-inductive Current Drive and 80% Bootstrap Current in JT-60U.**
The record in bootstrap current as a fraction of the total current is 80%, achieved in both the JT-60U and its predecessor JT-60 tokamak in Japan. Here we show a high performance plasma with full non-inductive current drive and with 80% of that current as bootstrap current. You can see the current profile is unusually hollow and mainly bootstrap current. In the standard inductively driven tokamak, the radial profile of the winding transform normally decreases monotonically to a stability limited value of 1.0 at the plasma center. Here you can see this turn-up in the plasma interior because of the hollow current profile reverses the shear or radial variation of the twist in the field lines, a key Advanced Tokamak feature.

11. **Neutral Beam Heating and Current Drive.**
Neutral beam heating and current drive were the first methods developed and have been the work horse for studies of plasmas at high temperatures and betas. Beta is the ratio of plasma pressure to confining magnetic field pressure; one wants beta as high as possible for reactor economics. Neutral atom streams of H, D, or T are shot in across the magnetic field. The plasma ionizes the atom and the resulting energetic ion orbits and thermalizes in the plasma. Codes calculate these processes. Injecting momentum in the toroidal direction can drive current. Beams derived from positive ion sources can be used up to 150 keV and from negative ion sources up to 1 MeV.

Beam heating works. Here we show 45 keV plasma temperatures produced in TFTR.

12. **Neutral Beam Current Drive in Accord with Theory.**
Neutral beam current drive is in accord with theory. Here we show a full non-inductive current drive case from JT-60U. O.6 MA of current came from their negative ion beams, 0.3 MA from the positive ion beams, and 0.8 MA from the bootstrap current. In this figure, we see the upper bound to the measured current drive efficiency for both positive and negative ion beams is good agreement with code calculations.

13. **Electron Cyclotron Heating and Current Drive.**
The simplest rf heating method is application of rf waves at the electron cyclotron resonance frequency (or harmonics), typically 100 GHz. These waves propagate in vacuum. Quasi-optical waveguide techniques are used to carry the power to the torus. Launching into the torus just requires reflection off a copper mirror. As shown by these ray tracing calculations, the waves propagate mainly straight into the plasma (there is some refraction), and are strongly absorbed very locally at the electron cyclotron resonance field. Damping of the EC waves causes diffusion of the electrons in the perpendicular direction in velocity space. Collisional relaxation on the ions generates plasma current through generation of an asymmetric v parallel distribution as shown in this Fokker-Planck code calculation.

14. **Microwave Electron Cyclotron Heating Provides Localized Current Drive.**
The main strength of EC waves is that the strong absorption allows very localized heating and current drive for precision control of plasmas. Here we show two aiming points from the launching mirror that result in absorption at different minor radii in the plasma and the radial profile of the driven current as measured by a Motional Stark Effect diagnostic agrees rather precisely with what was intended.

15. **Fully Non-Inductive Discharges.**
Here we show a case of a total plasma current of 210 kilo Amperes being entirely sustained by 2.7 MW of ECCD power in the TCV tokamak. Electron temperatures over 5 keV were produced.

16. **Lower Hybrid Heating and Current Drive.**
Between the electron and ion cyclotron frequencies (in the few GHz range) we find the Lower Hybrid Heating and Current Drive regime. These slow waves propagate at the speed of light divided by the parallel index of refraction which is greater than one (in fact has been up to 76, very slow waves). Such waves do not propagate in vacuum and so coupling requires a phased array of waveguides and solution of a wave tunneling problem that is well calculated. Ray tracing codes follow these waves many times around the torus before they are damped. The damping is by electron Landau damping (like a traveling wave accelerator). A high energy tail is pulled out of the electron distribution function as seen in this Fokker-Planck code calculation. That tail constitutes the driven current. Lower hybrid has produced strong electron heating as in this case in PLT, which in retrospect we would now see as having formed an electron transport barrier.

17. **LHCD Successful in Many Applications.**
The strength of lower hybrid is that it is the most efficient current drive scheme. In PLT many years ago the plasma current was initiated and ramped up entirely by LHCD showing the possibility of complete transformerless operation of the tokamak. In a spectacular demonstration of the steady-state potential of the tokamak, the TRIAM-1M tokamak in Japan has sustained a small current for 2 hours. In the large, high current superconducting tokamak Tore-Supra in France, 0.8 MA was sustained by LH waves for two minutes, with the machine handling a total injected energy of 290 MJ.

18. **ICRF Heating and Current Drive Involves Wave Excitation, Propagation, Absorption, and Mode Conversion.**
Ion cyclotron range of frequencies heating and current drive takes place at harmonics of the ion cyclotron frequency, about 30–100 MHz and its strength is direct manipulation of the ion distribution function. With wavelengths comparable to the minor radius of the plasma, these waves are launched from extended structures, and propagate to either the ion cyclotron resonance or a mode conversion layer. Coupling is from vertical current straps behind these Faraday screens. Codes calculate the coupling of these waves, which also do not propagate in vacuum. These codes follow the waves as they converge into the plasma center. Massively parallel codes can now solve hard problems like the conversion of this launched long wavelength fast magnetosonic wave to the short wavelength ion Bernstein wave in the plasma. The ion Bernstein wave has been directly detected in Alcator C-Mod with a phase contrast imaging diagnostic.

19. **Basic ICRF Schemes For a DT Reactor Have Been Verified.**
There is a rich variety of ICRF schemes. Here we highlight that the basic schemes for a DT reactor have been verified. In TFTR, mode conversion with minority Helium 3 ions produced the highest electron heating efficiency of any heating method. In the JET tokamak, we show 6 MW of fast wave power at the tritium second harmonic producing 1.66 MW of actual DT fusion power for a gain of 0.25 in nearly steady-state.

20. **Heating and Current Drive Challenges for the Next Decade.**
The heating and current drive challenges for the next decade are current profile control, transport barrier control, coupling of the, wave coupling and propagation, Fokker-Planck, transport, and stability codes, and actual strong heating by alpha particles! Remember alpha heating is what fusion is all about, but we need a new facility for that.

21. MHD Stability Physics Matured in the 80s and Moved to Profile Optimization in the 90s.

With heating, we challenged plasma stability limits. Stability physics matured in the 80s and moved to profile optimization in the 90s. In the 70s we had no auxiliary heating power and so could not test plasma pressure limits. In the 80s, multi-megawatt neutral beam heating enabled us to push beta into the reactor relevant 5%–10% range. We found agreement between both experimental and theoretical beta limit scalings. The pressure profile was measured, enabling detailed comparison to kink and ballooning mode codes. In the 90s, beta was pushed to the conventional aspect ratio record of 13%. The current profile was measured by the Motional Stark Effect enabling precision tests of theory. Theory optimization of profiles led to their variation and control in experiments and with wall stabilization, neoclassical tearing modes, and second stability, defined the Advanced Tokamak research direction.

22. The Effects of Plasma Instabilities Range …

The effects of plasma instabilities range from loss of the configuration to local transport, depending on their spatial scale. At the minor radius scale, we find global kink modes calculated by ideal MHD, in which plasma resistivity is taken zero. These fastest growing modes delineate the stable operational space by disruptions, fast losses of thermal energy and then current, which put large thermal and structural loads on near plasma components. At 1/5 minor radius scale are the tearing modes and other forms of resistive instabilities which give rise to macroscopic transport and profile modification. At the edge of the plasma, in the H-mode, periodic bursts appear, called edge localized modes (ELMs). These energy bursts may be too large in future machines. At smaller spatial scales, the ion and electron gyroradii, we encounter a rich non-linearly saturated spectrum of waves which are the subject of confinement research. In this section, we concentrate on the macroscopic stability elements in red.

23. Ideal MHD Instabilities Limit the Maximum β.

Ideal MHD instabilities are calculated from an energy principle. The perturbed energy arising from a candidate displacement ξ, has stabilizing and destabilizing terms, especially the pressure gradient and the parallel current. A spectral language is used in which the periodicity of the mode in the poloidal direction is m and in the toroidal direction is n. Modes with m/n equal to the local winding factor are especially unstable. Codes exist to calculate the low order global kink distortions of the plasma column as shown in this artist's conception of a 2/1 mode. Codes also exist in the opposite limit, n goes to infinity, called ballooning codes, in which for such fine scale modes, the stability criterion becomes local to each flux surface. Here is an artist's attempt at such a higher order mode, but this is still far from n=infinity.

24. Beta Limit Scalings Were Derived That Fit Well Experimental Results.

Beta limit scalings were derived that fit well experimental results. In the early 80s we were plotting our newly heated plasmas in beta toroidal — beta poloidal space (beta poloidal is the pressure normed to the poloidal field pressure) trying to find structures without much luck. Troyon's calculations of kink mode stability suggested a simple unifying scaling, (beta toroidal in percent less than a constant, 2.8, times the plasma current over the minor radius and toroidal field), which defined the quantity beta normalized as the coefficient of the scaling. Sykes also derived such a scaling from ballooning mode theory. The same data replotted in β_T versus I/aB showed a clear limiting line. By 1993, it was possible to show the stable envelope of all tokamaks obeyed Troyon scaling for the beta limit. The varied right hand limit is the current limit given by q = 2. The importance of this simple picture lies in this equilibrium relation. Beta poloidal is essentially the bootstrap current fraction. Beta toroidal is fusion power through β^2 x B^4. Hence to simultaneously have both steady-state and high fusion power output, it is necessary to elongate the plasma, and more importantly to raise β_N, the focus of advanced tokamak research in the stability area. Hints of how to raise β_N were apparent in these data from 1993.

25. Wall Stabilization, Plasma Shaping, and Optimal …

Theory work suggests that wall stabilization, plasma shaping, and optimal pressure and current profiles may double the stable operating space of the tokamak. When a conducting wall is far from the plasma surface, kink calculations give Troyon's limit β_N = 2.8. But if a conducting wall is moved closer to the plasma surface, and the current profile is made hollow as shown in the inset, then β_N in the range 5–6 is predicted. This requires optimal plasma shaping as shown here. As the plasma shaping is increased, with broad pressure profiles, the kink stable β_N increases to over 5.

26. Ideal Kink Mode Growth is Slowed …

Struggling against essentially ideal modes with wall stabilization is a challenge, faced also by the reversed field pinch, spheromak, and field reversed configuration. So far, we have shown that the ideal kink mode growth is slowed by a resistive wall and responds to feedback stabilization. This is done with picture frame coils like this fed from a feedback amplifier sensing the growing non-axisymmetric distortion of the plasma surface. Increasingly sophisticated feedback has delayed the mode growth. Calculations indicate that with optimized realizable feedback sensors and coils, 80% of the possible gain above the no-wall β_N limit might be obtained.

27. Low Aspect Ratio Raises β_N and β_T.
Lowering the aspect ratio into the spherical torus regime (A around 1.3) can raise the β_N limit and dramatically raise the accessible beta toroidal values. The small START device in the UK produced this diagram of beta toroidal up to 40% and β_N up to 6. Note that the entire operating space of tokamaks circa 1993 that I showed you two viewgraphs ago is just this yellow shaded area here. Two larger spherical tori, MAST in the UK and NSTX in the US have just begun operation.

28. Tearing Modes.
When resistivity is taken into account, one finds tearing modes in which the current can diffuse and form clumps — magnetic islands — on rational q surfaces. Here we show a 2/1 tearing mode and you can see the isolated helical flux tubes formed when a surface tears. These regions are like heat flow short circuits and flatten the pressure gradient across the island. The new element in this theory is the neoclassical effects. In a seed island the flattened pressure profile removes the equilibrium bootstrap current on that surface. The resulting helical current perturbation amplifies the seed island. Theory shows with a width above the seed island the mode will grow to a saturated level. Then if rf current drive is applied to replace the missing bootstrap current, the island will shrink to this point and become abruptly stable. This is exactly what happens in the experiment.

29. Stabilization of NTMs by ECCD.
Here we show in the ASDEX tokamak, localized electron cyclotron current drive is beamed to locations near the island by aiming up and down the resonance line. When the aiming resonance lies right at the island location, the 3/2 tearing mode is completely suppressed. In this example from DIII-D, when the EC waves are aimed just right, the island shrinks slowly and then becomes abruptly stabilized, just as the theory suggests. One is rewarded with a 25% increase in β_N.

30. Precise Control Near the β-Limit is the Key to Avoiding Disruptions.
The kink modes for sure and the tearing modes if allowed to grow too large lead to disruptions. The key for the future is to have precise control to operate near the β-limit. That requires good control and good knowledge of the stability limits. Here we show a high performance discharge from DIII-D in which β_N is held rock steady for 6.3 seconds (35 energy confinement times) about 5% below the threshold for the 2/1

tearing mode. Even with good control, disruptions will occasionally occur owing to the odd piece of material falling into the plasma so it is necessary to have ready means to mitigate their consequences. It appears that massive gas puffs or pellet injection can prevent runaway electrons, reduce structural forces, and heat pulses to the divertor surfaces.

31. Edge Localized Modes (ELMs) Are Now Understood …

Finally, the periodic bursting edge localized modes are an illuminating physics story. They arose in the first enhanced confinement mode discovered in the tokamak, the H-mode in 1982. Diagnostics with high spatial (mm scale) and temporal precision (100s microseconds) had to be deployed to study the strong edge pressure gradients that built up in a region of about 2 cm just inside the separatrix. These pressure gradients were first found to be about at the ballooning limit, but increased measurement precision and more detailed evaluation of the ballooning limit showed the pressure gradient could range up to 2–3 times the infinite n ballooning limit. The answer to this puzzle lay in the strong spike in the bootstrap current that is caused by the large pressure gradient. Without that bootstrap current, infinite n ballooning theory predicts this constant limit versus radius at the edge. With the bootstrap current, the stability limit tears open like this and the pressure gradient is allowed to move up into the so-called second stable regime. Still the mystery remained why such second stable edges still eventually had ELM instabilities. That answer came by improving the numerics of the low n kink codes so that intermediate n modes could be calculated. Kink calculations with n=5 are able to reproduce the rise in stable edge pressure gradient with plasma triangularity that is not predicted by the infinite n ballooning approximation. The displacement vector pattern calculated by GATO shows these n=5 modes just riffle the plasma surface.

32. Both Alcator C-Mod and DIII-D Have Found ELM-Free Regimes Without Density or Impurity Accumulation.

As usual, however, just when we thought we understood the edge stability, new discoveries are made. Both Alcator C-Mod and DIII-D have found regimes that puncture a universally accepted 18 year old theorem that the ELM-free plasmas unavoidably accumulated density and impurities. Here in Alcator C-Mod you see some continuous, not bursting, instability detected as a density fluctuation by reflectometry in the plasma edge which has the effect of arresting the density rise in ELM-free H-mode. These regimes are of great promise; they are the best plasma edge I can imagine.

33. **The Future.**
Theory work in the ARIES reactor studies at both normal and low aspect ratio have found stable states with very high β_N values, 6 in this case and 8.2 in this case. Astonishingly, these cases share an almost identical extremely hollow current profile. Look how far we have come from the inductive Ohmic current profile in which the current is in the plasma center. Here the current is in a sheet out near the outboard side. The pressure profiles are very broad. The interior magnetic shear does depend on aspect ratio. Can we make these astonishing plasmas? We must try.

34. **Stability Challenges for the Next Decade.**
The stability challenges for the next decade are to seek the wall stabilized β limit, push the bootstrap fraction up, control very hollow current profiles and very broad pressure profiles, optimize edge stability, deal with the neoclassical tearing modes, mitigate disruptions, and perhaps as a frontier area in theory understand stability in plasmas already seeded with 3-D perturbations.

35. **The 90s Have Seen Exciting Advances in Confinement Science.**
The 90s have seen exciting advances in confinement science. In the 70s we basically could only measure the global energy confinement time; results appeared to vary wildly across tokamaks; and we only had linear theory scaling. In the 80s tokamak results became reproducible leading to the empirical scaling rules. 1-D transport codes confronted 1-D measurements. And we discovered our first enhanced confinement regime, the H-mode edge barrier. In the 90s scaling moved to a dimensionless parameter wind tunnel approach. 3-D non-linear turbulence simulations fed comprehensive theory based models. Detailed, space and time resolved measurements of turbulence became available and the transport was shown to arise from the turbulence. A consensus that the ion transport mainly arose from the ion temperature gradient mode emerged. We discovered internal transport barriers and turbulence suppression by sheared ExB flows which resulted in actually attaining the theoretical minimum ion transport arising from collisions, after nearly a three decade quest to beat turbulent transport.

36. **Tokamak Confinement Proved (Empirically) Predictable.**
In the 80s consistent scaling behavior was seen across many tokamaks implying that a common underlying transport was discoverable. Multi-machine scaling rules were constructed which actually predicted JET operation before it began.. The dimensionless wind tunnel scaling approach is providing a more fundamental physics basis for projection to the burning plasma regime.

37. **Strategy to Calculate Transport.**
We have a current strategy to calculate transport. Theory based 3-D nonlinear simulations are being used to benchmark theoretical transport models which are then compared to experiment. Linear gyrokinetic codes describe local fine scale ballooning mode instabilities. Long wavelength modes are driven by the ion temperature gradient and trapped electrons. Short wavelength modes are driven by the electron temperature gradient. But we need nonlinear codes, and flux tube and approximate gyrofluid codes exist in the limit of vanishing ion gyroradius. Some much more computationally intensive nonlinear codes spanning several hundred gyroradii with finite ρ_* are available. The status is that the ITG/trapped electron flux tube simulations have been used to benchmark gyrofluid local transport models which then have predicted the stored energy for the experimentally measured discharges in the ITER database with a 26% RMS scatter, about as good as the empirical scaling dispersion.

38. **Recent Excitement: Transport Barriers Formed By Sheared ExB Flow.**
The biggest recent excitement in the field revolves around transport barriers formed by sheared ExB flows. A transport barrier manifests itself as in this figure in regions with high gradients of the temperatures and densities, which imply locally reduced transport coefficients. Here in JT-60U we see an internal transport barrier and at the edge the H-mode transport barrier. In both regions the measured transport coefficients are strongly reduced. The basic idea underlying transport barrier formation is that sheared ExB flows tear apart turbulent eddies reducing their radial correlation lengths. If we put two turbulent eddies in a sheared fluid flow field, they get torn in the poloidal direction and compressed in the radial direction.

39. **Sheared ExB Flow Suppression of Turbulence Underlies …**
We have found that sheared ExB flow suppression of turbulence underlies both the edge and internal transport barriers. Here we show the early work from DIII-D in which high spatial resolution charge exchange recombination spectroscopy allowed the discovery of this signature electric field well at the edge of H-mode plasmas where the pressure gradient became steep. Later the same radial electric field well was found in the internal transport barriers in TFTR. The equilibrium radial electric field arises from the pressure gradient and the toroidal and poloidal rotation, so that a rich number of feedback loop possibilities are available to the plasma and to the experimenter to work with transport barriers.

40. Equilibrium Scale Sheared ExB Flows Can Quench ITG …

Turbulence simulations have shown that the equilibrium sheared ExB flows can quench the ITG transport if the shearing rate exceeds the maximum linear growth rate of the turbulence. Here you see the diffusion coefficient going steadily downward to zero as the ratio of the ExB shearing rate exceeds the maximum linear growth rate in the spectrum of turbulence. The picture on the right shows the radial structure of the turbulence with no ExB flow. I have not shown the picture when the turbulence shearing rate exceeds the maximum growth rate because that picture is just black, there is no turbulence left.

41. Plasma Turbulence Simulation Codes Use Full Toroidal Geometry to Calculate Transport Rates.

To show the sophistication of these non-linear gyrokinetic simulations, Here is an example of a full toroidal geometry non-linear turbulence simulation that exhibits another recent theoretical advance, namely that small scale poloidal flows self-generated by the turbulence, so-called zonal flows, act also to shear apart turbulent eddies and suppress transport by an order of magnitude. With the development of the zonal flows, which circulate in the poloidal direction in this figure, turned off in the calculation, you see the development of long radial streamers. When the zonal flows are allowed to develop, the radial streamers are broken up and the transport is reduced.

42. Ion-Neoclassical Transport Without Turbulence Across Entire Plasma Radius.

The experimental implications of this physics have been spectacular. After three decades of struggle against turbulent transport, here is a discharge from DIII-D in which the internal and H-mode transport barriers merged together. This turbulence frequency spectrum maps across the entire radius of the plasma and you can see that during this period when the neutron rate increases the turbulence at all radii in the ion gyroradius wavelength range is almost completely gone. The reward is an ion transport rate near the theoretical minimum neoclassical rate arising from Coulomb collisions across the whole plasma.

43. Confinement Challenges for the Next Decade.

The confinement challenges for the next decade are really exciting. We should complete a theory based understanding of transport barrier formation which will allow us to control the ITB radius and gradient toward those astonishing stability profiles I showed you earlier. Although we have a good handle on ion transport, electron transport must be better understood. We need first principles diffusion coefficient calculations and to move our understanding to momentum and particle transport with nonlinear simulations of both electrons and ions.

44. The Science of Power and Particle Exhaust Leaped Forward in the 90s.

In all plasmas, especially burning plasmas, the heating power and the helium ash have to come out and be exhausted. The science of power and particle exhaust leaped forward in the 90s. In the 70s we just put sacrificial material, limiters, near the plasma and the plasmas were full of impurities. With the advent of divertors and wall conditioning techniques in the 80s clean plasmas were obtained but the emphasis was on the result, not the physics of the divertors. Sparked by the ITER study, which identified the problem of power and particle exhaust as its most unresolved problem and called for radically innovative solutions like recombining plasmas, the science took off in the 90s. Helium ash and fuel exhaust were demonstrated. Divertor plasmas that radiated most of the power were developed. Recombining divertor plasmas were actually achieved. 2-D measurements and 2-D fluid codes were developed.

45 The JET Divertor is Typical of Tokamaks Today.

The JET divertor is typical of tokamaks today. In the bottom of JET you see these two troughs which receive the two legs of the divertor plasma. Pumps are accessed through openings in these surfaces.

46. The Physics Elements That Are Dominant …

The physics elements that are dominant in the divertor problem are now incorporated in 2-D codes. Here I show a tomographic reconstruction of the radiation patterns in an actual open field line plasma outside the separatrix and in the divertor region. Parallel transport is dominant. Fluid drifts are important. The codes use this actual flux surface geometry. In the divertor, non-equilibrium radiation rates must be used. Complex 2-D flow patterns, circulations, occur in this region. Neutral recycling from surfaces is treated. Recombination is occurring where this light emission comes from. The detailed divertor structures are modeled. Just at the material surfaces, special codes treat the important problems of erosion during both normal operation and during intense heat pulses as occur in disruptions.

47. An Example of Excellent Agreement …

Here is an example of excellent agreement between tomographic measurements of the radiation patterns in the divertor and the B2-Eirene code widely used in Europe. The agreement is excellent. These code runs, because of the neutrals, can take up to a week on a fast computer.

48. Recombining Divertor Plasmas Discovered.

Perhaps the biggest physics discovery in this area was recombining divertor plasmas. We often describe magnetic confinement as using magnetic fields to keep hot plasma from material walls, but that is literally true only if the plasma recombines into neutrals before it reaches the walls. The ionization rate drops dramatically as the temperature falls and crosses the recombination curves about 1 eV. The 2-D codes actually predicted recombining plasma solutions before Alcator C-Mod measured 1 eV temperatures at their divertor plates and even lower temperatures in the plasma. These 2-D maps of temperature measured by Thomson scattering show an extended region in purple of about 1 eV plasma in the divertor region of DIII-D. Fluid code simulations are able to reproduce this 2-D distribution. Direct experimental evidence for recombination was obtained in spectroscopic data on Alcator C-Mod and elsewhere. Recently it was discovered that these recombining plasmas have the property that the divertor surfaces do not erode; they are regions of net deposition, a remarkable discovery after two decades of worry about the divertor surfaces eroding away.

49. Divertor Detachment in Alcator C-Mod.

Cameras capture 2-D patterns of light from recombining regions. They show the recombining region starts at the divertor surface and moves up the separatrix field line to the X-point as the density is increased.

50. Exhaust of Fuel and Helium Ash Demonstrated.

Exhaust of fuel and helium ash has been demonstrated. Pumps in the divertor region with gas puffing can regulate the plasma density constant as shown in this 6.3 second steady discharge. In JT-60U, helium beams were injected to simulate eventual energetic alpha ash from fusion reactions. Without pumping, the helium builds up. Pumping arrests the buildup. The pumpout rate of helium, normed to the energy confinement time is as low as 3, well below the reactor feasibility requirement of 15.

51. Codes to Calculate the Erosion of Divertor Surfaces …

Special codes to calculate the erosion of divertor surfaces are being tested against experimental data. For normal operation, these codes treat physical and chemical sputtering and transport in 2-D. Good agreement with experiment is being obtained. For the more difficult problem of ablative heat pulses as in disruptions in today's machines or ELMs in future machines like ITER, vaporization, melting, vapor shield formation, and radiation transport are treated in 2-D. Here you seen in these density contours at the end of a divertor slot the formation of a vapor shield, the green line, from material boiled off the divertor plate. This strongly radiating vapor shield then protects the divertor surface. Radiation transport strongly affects the geometry of the vapor shield.

52. Power and Particle Exhaust Challenges for the Next Decade.
The power and particle exhaust challenges for the next decade are to decide the optimal edge plasma shape, to fully understand 2-D flow patterns, helium and fuel exhaust in Advanced Tokamak regimes, the use of copious core radiation, and understanding erosion and redeposition.

53. Scientific Basis — Deep, Extensive, Full of Promise.
The scientific basis I have shown you is deep, extensive, and full of promise. In heating, the physics is understood and the technology developed. The advanced tokamak challenge is pressure profile control and alpha heating leading to burning plasmas. In current drive, the physics is understood. The challenges are high bootstrap perhaps toward 100% and local profile control. In stability, the operating space is understood. We can rely on the predictions of MHD stability theory. Wall stabilization is the challenge and could double the stable operating space. We are closing in on the ability to calculate transport. The challenge is transport barrier control. The promise is near neoclassical ion transport. In power and particle control, the main physics elements are calculable. The challenge is low density divertors compatible with current drive in order to have steady-state with low surface erosion.

54. We are Ready to Take Up Burning Plasma and Steady-State Issues.
We are now ready to take up burning plasma and steady-state issues. What are these issues? Here is a rough time sequence chart. Burning plasma issues revolve around power gain, extending from DT plasma properties, through alpha confinement, alpha driven instabilities, self-heated profiles to high gain burn control. Steady-state issues revolve around fluence, both neutron and plasma fluence, and need to move from high bootstrap fraction physics, through steady-state current drive, tritium inventory, hour long pulses (which are how I think the disruption issue will get settled), blanket development, tritium breeding, month long operation, and finally to first electric output. There is a lot to do, but we have made a start on burning plasma physics in the DT experiments in TFTR and JET.

55. Alpha Heating Observed.
Alpha heating was observed. A statistically significant electron temperature increase from alpha heating was measured in TFTR. In JET, the electron temperature rises linearly with alpha power with the highest values of both temperature and stored energy coming as they should at a 50:50 DT mixture.

56. Classical Alpha Confinement Verified (TFTR).
Classical alpha confinement was observed in TFTR. Escaping alpha detectors showed classical first orbit losses. The radial transport of

alphas was consistent with classical transport. The slowing down spectrum of the alphas as measured by a pellet charge exchange diagnostic was classical.

57. **Theoretically Predicted Alfvén Eigenmodes Were Observed.**
The Alfvén eigenmode instabilities predicted by theory to be driven by energetic ion populations, and alpha particles are the worry here, were observed. Here superthermal minority ion populations in JET produced this spectrum of Alfvén eigenmodes. Substantial fast ion losses from Alfvén eigenmodes driven by neutral beam or ICRF tail ions were seen in TFTR. The good news is the Alfvén eigenmodes were not seen in the highest fusion power cases.

58. **Observed Alpha-Driven TAEs Consistent With Full Linear Theory.**
TFTR was able to see alpha driven Alfvén eigenmodes in special plasmas in which the instability threshold was lowered by lowering the magnetic shear. The observed thresholds were well in accord with theory.

59. **Copious Fusion Power Has Been Produced.**
Finally, copious fusion power was produced. TFTR produced 10 MW of fusion power and a gain of 0.27. Integrated over the course of their whole DT campaign, 1.55 GJ of fusion energy was produced. JET produced 16 MW of fusion power with a gain of 0.6 and 0.68 GJ of fusion energy. These remarkable achievements have brought fusion to the threshold of the burning plasma era. But new devices are needed for burning plasma and steady-state studies. Here are some of the devices being designed or built.

60. **The ITER-FEAT Machine.**
ITER-FEAT is an all superconducting coil 6.2 meter major radius, 5 T, 15 MA machine for burning plasma and steady-state research being pursued by the European Union, Japan, and Russia.

61. **Fusion Ignition Research Experiment (FIRE).**
Preceded by designs such as Ignitor and CIT, the FIRE study in the US exemplifies the high field approach to a burning plasma experiment. The radius is 2 meters, field 10 Tesla, and current 6.5 MA.

62. **A Proposal of JT-60 Modification.**
The Japan Atomic Energy Research Institute is proposing to modify its JT-60U device by replacing the copper coil interior of the machine with an all superconducting coil machine, JT-60SC, for steady-state and advanced tokamak research. Parameters are 3.4 meters, 4 Tesla, and 5 MA.

63. Extending the Advanced Tokamak: KSTAR.
Korea is building the KSTAR, an all superconducting machine to extend Advanced Tokamak physics to 300 second pulses. The radius is 1.8 meters, field 3.5 T, and current 2 MA.

64. HT-7U Advanced Tokamak — Hefei China.
China is building the superconducting machine HT-7U. India plans a similar machine.

65. The Advanced Tokamak Leads to an Attractive Fusion Power Plant.
The Advanced Tokamak leads to an attractive fusion power plant as found in the US ARIES studies and the Japanese SSTR study. The cost of electricity is in a competitive range.

66. Summary
In summary, research in the tokamak has greatly advanced fusion energy science.

Tokamak research has shown that fusion energy is feasible in the laboratory.

The tokamak is scientifically and technically ready to proceed to burning plasma and/or steady-state next steps

Advanced tokamak research seeks to find the ultimate potential of the tokamak as a magnetic confinement configuration. Anticipated results point to practical and attractive fusion energy.

Thank you for your attention and your work.