Overall Motivation for Fusion Integrated Simulations: Developing Improved Fusion Power Plants

G.W. Hammett, hammett@pppl.gov (PPPL)

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The exponential growth of computer power (a factor of a million in the past 30 years, with more to come), combined with major advances in our ability to simulate plasmas in fusion devices, has led many to conclude that the time is ripe for an initiative to develop integrated computer simulations of fusion devices. There are now detailed 5D gyrokinetic simulations in the main core region of tokamaks (r/a < ~0.9) that can predict fluctuation spectra and turbulent transport fairly well in many regimes. A major computational initiative could develop a comprehensive whole-device simulation capability that would have several important uses:

* It would drive an extensive validation campaign to compare simulations with measurements on existing experiments in various parameter regimes.

* Every shot on ITER will first be planned with such a "flight simulator" to predict the evolution of the plasma, from startup through burn and shutdown, to ensure that operational limits are not exceeded and the plasma pressure and current profiles stay far enough away from MHD stability boundaries to avoid or minimize disruptions that could damage the machine.

But the most important applications would be to:

* Use this comprehensive integrated simulation capability to explore various ways of improving fusion reactor performance, bring down their cost, and improve our confidence in extrapolation to future fusion devices.

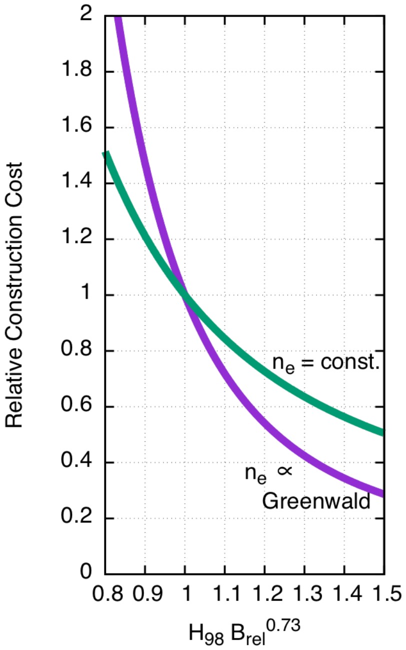

Fig. 1. Assuming construction cost scales roughly as the size R squared, and that confinement can be improved by a factor of H_{98} over standard empirical scaling, this shows how the estimated cost of a fusion reactor (at fixed gain Q) can be significantly reduced with modest improvements in the confinement time and magnetic field B.

There are a number of interesting ideas that are currently being explored in the fusion program to improve fusion reactor designs, and some of these could potentially lead to quite significant cost reductions. It is well known that improvements in the confinement time and/or pressure stability limits can significantly lower the cost of electricity per kWh at a fixed total output power [Galambos95]. But there is an even stronger effect of confinement time on the construction cost of a fusion device if we instead consider devices with smaller output power. (This does not necessarily optimize the cost of electricity per kWh because of economies of scale, but smaller devices with reduced construction costs are attractive for part of the market and can help reduce power loads on the wall in some cases.) Improving the confinement allows one to build a smaller reactor while maintaining the same desired fusion gain Q. The reduction in cost can be quite significant, as illustrated in Fig. 1.

While $H_{98}=1$ is the average performance in standard H-modes on tokamaks, experiments have in fact achieved levels of improved confinement of $H_{98}\sim 1.5$ through a variety of methods, but we are not as confident in these improved methods so the standard inductive scenario for ITER assumes only $H_{98}=1$. A comprehensive Integrated Simulation capability using powerful modern supercomputers that was well tested against experiments would help improve our confidence in extrapolating these improved regimes to reactor scales, and help us bring down the size and cost of future designs. Indeed, the ITER steady-state scenarios assume $H_{98} \sim 1.5$ to reduce the needed current drive, and the ARIES-AT design assumes $H_{98} \sim 1.5$ (and higher beta) to help produce 3.5 times the power despite a 35% smaller minor radius.

The MIT ARC design [Sorbom14] assumes a similar moderate confinement improvement, and also makes use of recent advances in practical high-field, high-temperature superconductors that allow them to almost double the magnetic field. This leads to a design with a major radius of just 3.2 m, comparable to JET, that has $Q_{\mathrm{plasma}} > 10$ and a net engineering $Q_{\mathrm{electric}} \sim 4$. (There are limits on the minimum device size, but the ARC study demonstrates that significantly smaller sizes might be possible.) One can see the major advantages of higher field by noting that increasing the field by a factor of 2 is a factor of 4 increase in the magnetic pressure, which at fixed beta is a factor of 16 increase in the fusion reaction rate ($\sim n^2 \langle \sigma v \rangle \sim n^2 T^2 \sim B^4$). This allows one to reduce the size of the tokamak and/or move to lower beta, further from instability limits.

There are various interesting ideas for improving fusion reactor designs that are being studied in the fusion program, including high-field superconductors, lithium or other liquid metals as thin films or flows to reduce recycling of cold neutrals back into the plasma, reversed or reduced central magnetic shear to reduce turbulence, spontaneous rotation that reduces turbulence and MHD instabilities, divertor boxes with lithium continuous vapor shielding to handle high power loads, methods to control ELMs, low aspect-ratio spherical tokamaks with improved confinement, quasi-symmetric stellarator concepts that can significantly reduce the aspect ratio and size of a stellarator reactor, and 3D printing and other robotic manufacturing techniques that may bring down the cost of high-precision, complex components. Lithium is particularly interesting because multiple experiments have seen large improvements with lithium, and we don't yet know what might set limits on it. All of these ideas will benefit from a major computational initiative that will help us understand how they work and will quantify their extrapolation to reactor scales.

Appendix: **Assumptions in Cost vs. Confinement Scaling.** Fig. 1 explores the effects of improving the confinement time τ_E by a factor of H_{98} over the standard IPB98(y,2) H-mode empirical scaling [Doyle07] that was fit to an international database of experiments, $\tau_E = H_{98}\ 0.0562\, I_p^{0.93}\, B_t^{0.15}\, P^{-0.69}\, n_e^{0.41}\, R^{1.97} M^{0.19}\, \varepsilon^{0.58} \kappa^{0.78}$. Fixing the average mass M and the geometry (aspect ratio $\varepsilon = a/R$ and elongation κ), we eliminate heating power P in terms of τ_E using $P = 3\,(n_e\, T\, V)/\,\tau_E \propto B^2 R^3/\,\tau_E$ at fixed β, take a fixed q to scale the plasma current $I_p \propto R\, B_t$, assume the density $n_e \propto I_p/a^2$ at fixed Greenwald fraction, and set the device size R by the requirement that it achieve a specified fusion gain $Q \sim n_e^2\, T^2\, V/P \sim nT\tau_E \propto B^2\, \tau_E$. The result is $R \sim 1/(B_t^{1.74} H^{2.38})$. Assuming the cost scales roughly as $\$ \propto R^2$ (motivated by fixed coil thickness at a fixed superconducting current density, and fixed blanket/shield thickness), then the construction cost $\$ \sim 1/(B_t^{3.5} H^{4.8})$. Fig. 1 accounts for the blanket/field constraint $B_t = B_{mag}\,(R-a-a_{BS})/R$, where B_{mag} is the limit on the field at the magnet, using the ARIES-AT blanket and shield thickness $a_{BS} = 1.16\ m$ and aspect ratio $a/R=0.25$, and scaling from a reactor with $R=6.2m$ at $H_{98}=1$. (Among many other things, this scaling neglects current drive requirements, though that would not be an issue in stellarators.) Clearly one needs more detailed calculations for more reliable estimates, but this analytic estimate illustrates the overall usefulness of improved confinement and stronger magnetic field.

References

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