Comparison between tokamaks and stellarators based on MHD stability and equilibrium

Ananya Pulgam

Master of Science in Nuclear Fusion and engineering physics

I. Introduction

This report is a comparative study between tokamaks and stellarators from the point of view of magnetohydrodynamic stability and equilibrium. Magnetohydrodynamic theory is a reduction of the two-fluid model, which is derived by focusing only on macroscopic scales. Thus, under MHD framework, relevant length scales are the ones comparable to plasma radius ($L \sim a$) and relevant time scales are the ones comparable to the ion thermal transit through plasma ($\tau \sim a/v_{Ti}$) [1].

MHD equilibrium refers to the balance between internal forces in plasma, namely: external magnetic field force and plasma pressure gradient force. For a toroidal geometry this equilibrium can qualitatively be described as balance between radial pressure of plasma and toroidal magnetic field force. Mathematically, this is given by the MHD force balance equation: $\vec{J} \times \vec{B} = \nabla p$. It is important to study this as it is important to design magnetic field geometries in order to hold plasma in stable macroscopic equilibrium, therefore allowing steady state operation our fusion device..

The problem of MHD stability is gauging whether plasma in equilibrium state will return to its original state after it is perturbed. In other words, we try to look at how stable our equilibrium is under the MHD framework. The reason MHD stability, ideal MHD stability in particular, is necessary to be studied carefully is because ideal MHD instability is known to cause catastrophic disruptions and eventually loss of plasma.

This report will first discuss some general inherent differences between tokamaks and stellarators that are relevant for studying MHD equilibrium/stability. Then, we have a look at some concepts specific to both these devices. Proceeding by discussing briefly the instability mitigation and control in both devices. Finally ending with some concluding remarks and my opinion on advantages and disadvantages of both machines from MHD stability point of view.

II. Some general remarks on equilibrium and stability in both devices

In order to maintain equilibrium between plasma pressure and magnetic field, it is important for the toroidal magnetic field to have a rotational transform, for a toroidal confinement device. This is mainly to stop the guiding center of plasma particles to drift towards the wall. There are 3 ways of achieving this twisting of magnetic field lines as proposed by Spitzer and Mercier [2, 3]:

- creating a poloidal field using toroidal current within the device.
- rotating the poloidal cross-section of stretched flux surfaces around the torus (altering shape of the machine itself)
- making the magnetic axis non-planar. (having a 3D shape as opposed to a planar geometry such as a circular loop)

Tokamaks use the first method of using toroidal currents; which it generates with the help of a transformer. Whereas, stellarators go with the other 2 ways generally. Basically, in tokamaks the twisting of magnetic field lines is done by the toroidal plasma current and in stellarators, it's done by the external non-axisymmetric coils.

Both methods have their advantages and disadvantages. while tokamaks are axisymmetric, structurally simple, offer good plasma confinement etc. but due to use of a transformer (who's primary winding uses time varying current), tokamaks can only operate in pulsed mode and not in steady-state. Thus making the plasma prone to current-driven instabilities. Continuous operation would require systems like non-inductive current drive mechanisms, which are complex and not very efficient.

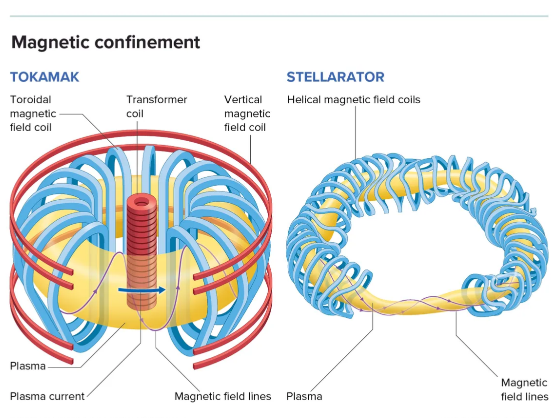

Fig. 1. Schematics of tokamaks and stellarators

On the other hand, a stellarator can operate in steady-state, which to begin with is a big advantage, but stellarators are, generally speaking, much more difficult to build. From a confinement perspective, stellarators are prone to high

neoclassical transport of unconfined thermal and fast particles. Neoclassical transport is a classical transport but with added effects of a toroidal geometry. Gibson and Taylor observed [4], there usually are unconfined particle orbits regardless of the magnetic field strength. This is also problematic for the confinement of alpha particles, whose orbits are practically collision-less.
This could be a problem in many ways such as energy losses due to enhanced radial transport and reduced efficiency of external heating systems. Ongoing efforts being made to improve stellarator confinement to avoid transport losses include proposing optimized magnetic configurations. For example Quasi-isodynamic (QI) designs, Quasi-symmetric (QS) configurations, etc [5, 6].

There are various classes of MHD instabilities that occur in fusion devices, such as sawtooth oscillations, kink instabilities, ballooning instabilities, neoclassical tearing modes to name a few. These generally arise from current and pressure gradients in presence of magnetic field curvatures. Thus there are two classes of MHD instabilities: **current-driven** instabilities and **pressure-driven** instabilities. These said ideal-MHD instabilities eventually cause plasma disruption and that is critical in defining operational lifetime of our machine.
Some other concepts important in this concept are beta limit and density limit. Plasma beta ($\beta = p/\frac{B^2}{2\mu_0}$) is the ratio between plasma pressure and magnetic pressure. There is a limit imposed on this quantity based on MHD instabilities that arise from pressure gradients. In tokamaks this limit is governed by the Troyon scaling [7] and in stellarators by the neoclassical transport and other 3D MHD effects.
The critical density a tokamak can achieve before plasma disruption is given by the Greenwald limit ($n_G = I_P/\pi a^2$; where I_p is plasma current and a is minor radius) [8]. Stellarators do not have a Greenwald limit but instead the limit is determined by absorbed power along with magnetic field and plasma volume [9, 10].

To end this section, I would like to discuss briefly the geometrical parameters of both the devices. The aspect ratio of a fusion device is R/a (R and a being the major and minor radii, respectively). Tokamaks generally tend to have a aspect ratio of 2.5-4 (could be lesser for spherical tokamaks). Considering attaining equilibrium, high aspect ratio could simplify the geometry and make it easier to achieve equilibrium but at the same time increase the cost of operation substantially. From a stability point-of-view, lower aspect ratio offers higher beta values which offer better confinement.
Stellarators usually have an aspect ratio of 5-12. It can be observed directly that plasma volume in stellarators is much lower than tokamaks generally. The equilibrium concept remains same for both devices, that higher aspect ratio makes it easy to achieve equilibrium. Higher aspect ratio in stellarators offer better stability. Present day stellarators tend to have higher R/a to avoid resonances between the field lines and harmonics of the symmetry of the configuration, which needs small rotational transform and thus large R/a.
As it can be observed in fig. 1, tokamaks cross section are toroidally symmetric but stellarators are highly 3D devices.
Further difference could be seen in magnetic shear ($s = r\partial q/q\partial r$) which are different between the two systems. Tokamaks normally have positive magnetic shear throughout the plasmas whereas in stellarators the shear is negative (except for non-planar types, which may have a zero magnetic shear).

III. MHD Equilibrium and Stability in Tokamaks

Tokamak MHD equilibrium is given by an equation called Grad-Shafranov equation [11]:

$$\Delta^*\psi = -\mu_0 R^2 \frac{d\psi}{dp} - F(\psi)\frac{d\psi}{dF}$$

where ψ is the poloidal flux function, p is the plasma pressure, $F(\psi)$ relates to the toroidal magnetic field, R is the major radius, and μ_0 is the permeability of free space. Thanks to the axisymmetric geometry of tokamaks, by solving this equation we get the magnetic flux surfaces that define the plasma's equilibrium state.

As discussed in the previous section, presence of a toroidal current makes tokamaks vulnerable to some current-driven MHD instabilities. This section will be describing some of those instabilities that I find interesting, namely, ballooning modes, Neoclassical tearing modes (NTMs) and toroidal Alfvén eigenmodes (TAEs).

A. Neoclassical tearing modes

Neoclassical tearing modes are concerning global current-driven instability. Tearing modes are a class of instability that occur due to tearing and reconnection of magnetic field lines. Classical tearing modes are result of presence of resistivity whereas neoclassical tearing modes follow a different mechanism. In a tokamak, plasma pressure is not uniform—it is higher in the center and lower at the edges. This difference creates a bootstrap current, which helps maintain the plasma's magnetic field, who's strength depends on the pressure gradient.

Sometimes, a small "magnetic island" can appear due to minor disturbances in the plasma such as an ELMy H-mode. A magnetic island or in this case a seed island is a localized region where magnetic field lines form closed loops, trapping plasma inside. Within the magnetic island, plasma moves around freely along field lines, reducing the pressure gradient inside the island. Since the bootstrap current depends on the pressure gradient, a lower pressure gradient means a weaker bootstrap current in that region.

The decrease in bootstrap current inside the island disturbs the balance of currents in the tokamak. This disturbance worsens the instability, making the island grow bigger. As the island grows, it further weakens the pressure gradient, which weakens the bootstrap current even more, thus generating a cycle. It can be seen in fig.2 how the mode contributes to flattening of pressure gradient, which is not desired.

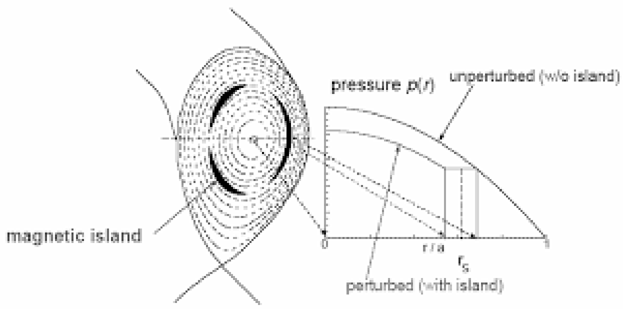

Fig. 2. An example of NTM and the graph depicts the effect it has on the pressure profile [12]

More catastrophic NTMs are observed at higher β_N values. NTMs are a major concern because they degrade confinement significantly and sometimes end up in disruption.

B. Ballooning modes

Ballooning modes are pressure-driven ideal MHD instability that occur due to steep pressure gradients (particularly in the low field side region with). These edge-localized instabilities are seen when the plasma pressure stabilizing effect from the magnetic field is not strong enough and leads to plasma bulging outwards like a balloon.

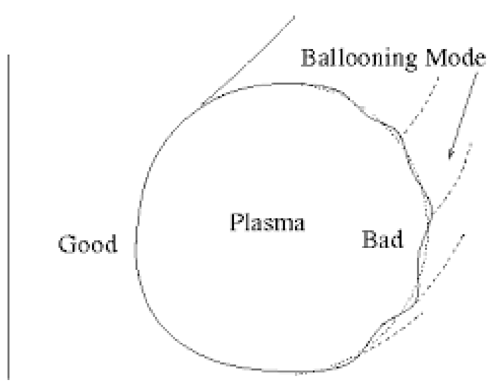

Fig. 3. Ballooning mode [13]

There are a few reason ballooning modes are a crucial instability to study. To begin, they are primarily what set the limit on maximum achievable plasma beta value. Increase in β causes steeper pressure gradients and when the stabilizing forces are no longer sufficient, causing these instabilities grow more and more unstable. This ultimately may lead to disruption and loss of plasma.

Ballooning modes can be observed alongside a current-driven instability called peeling modes and together form a hybrid MHD instability called **Peeling-Ballooning modes**. Peeling modes occur and become unstable when the plasma edge current (bootstrap and Pfirsch-Schlüter current) density is too high. Ballooning-Peeling modes can lead to onset of another type of instability called ELMs or Edge localized modes in high confinement (H-mode) regime. ELMs occur in the edge transport barrier of H-mode. They appear as bursts of energy and particles expelled from the plasma edge, leading to periodic losses of confinement. The frequency and size of ELMs depend on the balance between plasma edge pressure, bootstrap current, and magnetic shear. ELMs are a major concern ans thus, it is important to understand their creation mechanism and their mitigation [14].

Lastly, ballooning modes are also a potential threat to the plasma-facing material. Thus understanding and controlling ballooning modes is important from the perspective of machine's operating lifetime.

C. Toroidal Alfvén eigenmodes

Toroidal Alfvén eigenmodes or TAEs are a type of MHD instability that arise from interaction between Alfvén waves and energetic particles in plasma [15].
Alfvén waves are a type of fundamental MHD waves that exists in plasma as a consequence of the restoring force in magnetic field lines. They are characterized by Alfvén frequency, given by:

$$\omega_A = \frac{k_{||} v_A}{2\pi}$$

Where $k_{||}$ is parallel wave number, $v_A = \frac{B}{\sqrt{\mu_0 \rho}}$ is the Alfvén speed; B is magnetic field strength and ρ is mass density of plasma.
TAEs become unstable when they resonate with the fast ions (e.g., alpha particles from fusion reactions or neutral beam injection fast ions). To give an idea of these resonances, in a circular tokamak with large aspect ratio the main TAE resonances occur at $v_{||}$ = v_A and $v_{||}$ = v_A, where v_A is the Alfvén speed. The energy transfer from the energetic particles to the waves can drive the exponential growth of the wave amplitude, leading to instability. TAEs emerge within gaps in continuum spectrum of Alfvén waves (due to plasma pressure or density profile), allowing them to oscillate without immediate damping from continuous interactions. These eigenmodes cause enhanced transport of energy, thus degrading overall plasma confinement and also affecting the efficiency of heating.

IV. MHD Equilibrium and Stability in Stellarators

Since there is no axisymmetry present in stellarator geometry, the equilibrium state is described by the three-dimensional MHD equilibrium equations which are far more complex than the Grad-Shafranov equation and need to be solved numerically.

Stellarators also avoid the need for a toroidal current making them resistant to most MHD instabilities. To be precise the net plasma current in stellarators is not zero. In stellarators two small plasma current components also exist. One is the bootstrap current driven by pressure gradients in the banana regime at low collisionality (similar to tokamaks).

The other is the parallel Pfirsch-Schlüter current used to compensate the non-zero poloidal plasma current, which appears to force balance the radial pressure gradient, so that the total plasma current is divergence-free.[16] Nonetheless, both these sorts of current are substantially small to cause disruptions from big MHD modes.

A. Neoclassical tearing modes

Neoclassical tearing modes can also occur in stellarators but not due to the ohmic current profile like in tokamaks. Rather they occur due to non-zero bootstrap current. Unlike tokamaks, magnetic islands don't reduce this current by flattening the pressure profile. Because Stellarators have a opposite/ negative global magnetic shear, these island tend to be 'healed' rather than grown by the magnetic shear. Which means that if an island were to form, cause flattening of pressure profile and thus reduction of bootstrap current, this reduction would rather lead to the island shrinking than growing.

One can say that NTMs in stellarators are stable non linearly when bootstrap current is non-negative (It is taken to be negative if decreases the rotational transform) [17]. To avoid the risk of NTM caused plasma disruptions is a major advantage of the inherent magnetic field geometry of stellarators.

B. Ballooning modes

In theory ballooning modes can be observed in stellarators but it is not necessarily crucial in determining the beta or maximum achievable pressure limit. The beta limit for stellarators is often termed to be 'soft' or not very heavily dependent on the pressure-driven MHD instability. It is evident from the the example of LHD which routinely operates much above the ideal-MHD ballooning limit.

Speaking of LHD, at very high densities, a region of peaked pressure pressure profile called Internal Diffusion Barrier (IDB) forms in plasma. However, this also causes a large shift in the plasma position (Shafranov shift), which can be over half of minor radius. However, what is not entirely clear is the exact limit on how high the plasma pressure (β) can go in a stellarators. The finite Larmor radius effect seems to influence this limit, but more research is needed to fully understand its role. Furthermore, it has been observed that a significant amount of plasma pressure comes from supra-thermal ions from neutral-beam injection. This reduces steepness of the pressure profile and thus, stabilizes ballooning modes [18].

Mathematical intricacies arise in the theory of ballooning modes for non-axisymmetric plasmas. The ballooning equation, which helps predict plasma stability, shows that different field lines on the same flux surface can have different stability properties. This makes it difficult to describe the instability in a simple way and construct global modes. Additionally, when solving the equations that describe how these instabilities evolve, the solutions tend to be chaotic, meaning small changes can lead to unpredictable results. This chaotic behavior is similar to semi-classical or quantum systems with chaos, where certain properties of particles become unpredictable due to complex interactions [19].

C. Toroidal Alfvén eigenmodes

Fast ion-driven modes like the TAEs are commonly observed in stellarators. As discussed in previous section, these arise because of wave-particle resonance in gaps of the continuous Alfvén spectrum which occur due when we bend the plasma column into a torus. Since stellarators break axisymmetry, there are more such gaps and discrete modes in stellarators then in tokamaks. There is more scope for wave-particle resonance and thus, more instability. Some examples of possible Alfvénic eigenmodes in stellarators are helicity- and mirror-induced Alfvén eigenmodes.

We saw previously that main TAE resonances in tokamaks but in stellarators, additional resonances can appear at speeds higher than v_A, leading to more possible interactions between waves and particles.
Alpha particles, produced in fusion reactions, contribute to plasma pressure (p_α), which depends on how long they remain in the plasma before slowing down. This slowing-down time (τ_S) follows the relation:

$$\mathrm{p}_\alpha \sim \tau_S \sim \frac{T_e^{3/2}}{n_e}$$

meaning that higher electron density (n_e) decreases p_α . Stellarators can operate at higher densities than tokamaks, thanks to their ability to exceed the Greenwald density limit. The fast-particle drive for Alfvénic modes can thus be smaller in the stellarator, if an operating point with high density can be chosen. The relation $p_\alpha \sim n_e^{-5/2}$ gives that increasing the plasma density by a factor of 2.5 can lower alpha-particle pressure by a factor of 10. Therefore, indirectly making stellarators potentially more stable against fast-particle-driven instabilities TAEs compared to tokamaks, although the magnetic geometry higher number and types of TAEs [16].

V. Control of instabilities in tokamaks

I would now like to speak briefly about some of the known and under-research methods of control of the instabilities discussed above.

Effective control of NTMs is crucial for achieving sustained plasma performance. One common method involves using Electron Cyclotron Resonance Heating (ECRH) or Electron Cyclotron Current Drive (ECCD) to deliver localized heating or current to the magnetic island associated with the NTM. This localized intervention can modify the current density profile, thereby stabilizing the mode.
Another approach is using Lower Hybrid Current Drive (LHCD). Recent studies suggest that LHCD can be sufficiently localized to stabilize NTMs, especially when considering the RF current condensation effect, where

localized heating within the island enhances current drive efficiency [19].

Feedback control systems have been developed to detect and respond to NTMs in real-time. For instance, the HL-2A tokamak has implemented a system that monitors magnetic fluctuations indicative of NTMs and adjusts control parameters accordingly to suppress the modes [20].

In theory, controlling of ballooning modes requires adjustment in plasma shape and aspect ratio. For example, elongating the plasma profile/ modifying the triangularity, will alter the magnetic shear and plasma pressure. This in turn will help stabilize the ballooning modes. Experimental results from the K-STAR (Korean Superconducting Tokamak Advanced Research) and NSTX-U (National Spherical Torus Experiment Upgrade) have shown that magnetic shear can be adjusted to mitigate ballooning modes.

Another method of indirect ballooning mode mitigation is RMP or Resonant Magnetic Perturbations. These external perturbations are introduced to mitigate or suppress ELMs, which is closely related to suppression of ballooning modes. RMPs apply a small magnetic field to the plasma edge, which disrupts the conditions under which ballooning modes can grow.The DIII-D and JET tokamaks have shown that RMPs can be effective in suppressing ballooning modes and reducing ELM events [21].

In many tokamaks the locally reversed negative shear has also been observed accompanied with better confinement and a strong local pressure gradient. Because this strong pressure gradient may induce a large bootstrap current (which is desired) that forms the reversed q profile and negative magnetic shear, this in turn has shown to have a stabilizing effect on ballooning modes. This method of reversed magnetic shear with a large bootstrap current has been proposed as a key approach to stabilize ballooning modes for advanced tokamak operation case [22].

Energetic electron could possibly have a stabilizing effect on an energetic-ion driven toroidal Alfvén eigenmodes (TAE). It is found that the TAE can be effectively stabilized by off-axis peaked energetic electrons which are located near the mode center, while the centrally peaked energetic electrons fail to stabilize the mode. It was observed that the power transfer to a resonant barely trapped energetic electron, which taps energy from the wave, can be comparable to the power transfer from a resonant energetic ion. This suggests that if a sufficient number of resonant barely trapped electrons are present, they might stabilize energetic-ion driven TAE through the wave-particle interaction.

Prediction of possible occurrence of fast-ion-driven instabilities could be of huge advantage in process of its mitigation. One study showed that a large safety factor in the core $q_0 = 2.5$ in deeply shear reversed configurations and a relatively large bulk ion Larmor radius in a low magnetic field, can trigger global drift-kinetic Alfvén eigenmodes. These are unstable in high performance JET, NSTX and ITER plasmas. It was also observed that the eigenmodes are stabilized when the global wavefield reaches the divertor region and the kinetic Alfvén wave gets heavily Landau damped [22].

VI. Control of instabilities in stellarators

It has been seen in above sections how inherent geometry of stellarators provides it with stabilizing mechanisms towards several idea-MHD instabilities. However, they are not absent entirely in stellarators and demand active mitigation ans suppression of instabilities.

Speaking firstly of Neoclassical tearing modes. Stellarators naturally have an optimized rotational transform profile, which reduces the likelihood of rational surfaces aligning in a way that favors NTM formation.

A commonly used scheme for NTM stabilization consists of driving a helical current at the resonance surface of interest with electron-cyclotron-current drive. Depending on the ratio between the magnetic island size and the RF beam width, complete stabilization of the NTM will only be achieved with deep RF power modulation in phase with the mode.

Stellarators benefit from their large local magnetic shear as well as the negative global magnetic shear, which tends to stabilize curvature-driven modes.However, ballooning modes are possible in stellarators. Scientists have found that ballooning modes can be stabilized in QA stellarators by appropriate axisymmetric shaping.

Electron cyclotron heating should be considered as a destabilizing mechanism for fast-ion-driven instabilities like TAEs; because the related decrease in plasma collisionality would result in a longer slowing down time of the energetic ions and a concomitant increase of their pressure. However, under some conditions, ECH can also play a stabilizing role. Scientists have proposed two step mechanism for stabilization of TAEs by ECH. In first step, the continuous character of the unstable AEs changes to a chirping character of the marginally unstable AEs when moderate values of ECH power are applied to the NBI-only-heated plasma. In a second step, a significant reduction of the AE amplitude is observed when the ECH power is doubled. The observed stabilizing effect was observed to be stronger with on-axis ECH than with off-axis ECH power injection. These mechanisms were experimentally confirmed [23].

VII. Conclusions

This report provides a brief overview of key aspects of MHD equilibrium and stability in tokamaks and stellarators, focusing on neoclassical tearing modes (NTMs), ballooning instability, and toroidal Alfvén eigenmodes (TAEs).

While both devices have unique advantages and limitations, stellarators generally offer improved ideal-MHD stability due to their intrinsic steady-state operation and reduced susceptibility to major disruptions. Unlike tokamaks, which rely on a toroidal plasma current (prone to instabilities like NTMs and sawtooth oscillations), stellarators are primarily magnetic-field-driven, minimizing current-driven instabilities. Stellarators still experience challenges such as bootstrap currents, complex magnetic geometry, and neoclassical transport losses, which require optimization for better confinement and performance. In my opinion, ideal-MHD stability is a far more critical issue for tokamaks than it is for stellarators. Continued advancement in this area is crucial to ensure improvement in stellarators and more importantly, the successful operation of future tokamak-based fusion reactors

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