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VTT

13/03/2024

DEEPlasma GENE Surrogate Model for Tokamak Pedestal Plasma

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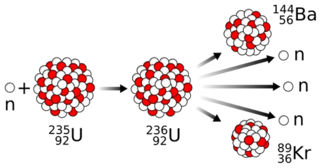
Introduction to Nuclear Fusion

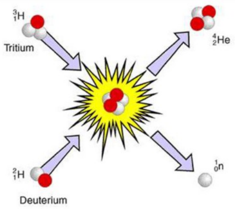
Overview

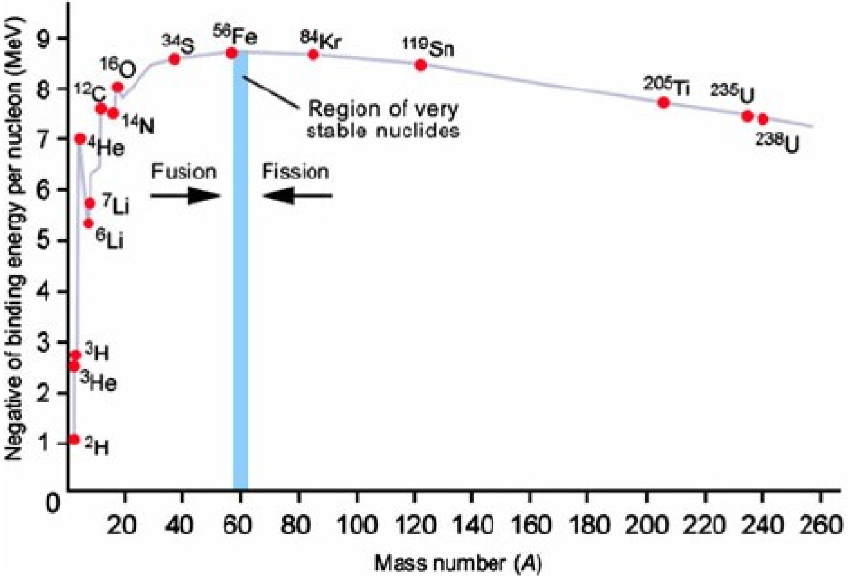
- Fusion Vs Fission
- Why DT Reaction?
- What is the Q factor and Lawson’s Criterion for Ignition?
- External Heating
- What is a Plasma?
- Plasma Confinement
- Flux Surfaces and Divertor
- Safety Factor
- Banana Orbits
- H-Mode, Pedestal and ELMS
- Link to DEEPlasma

Fusion vs Fission

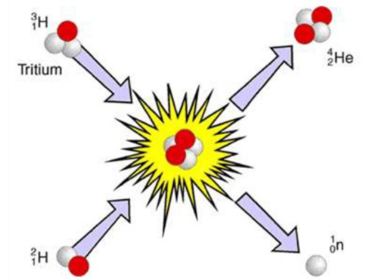
- Each fusion reaction produces more energy than a fission reaction
- Fission fuel is finite and limited, 230 years Uranium supply at current consumption, Fusion fuel is abundant
- Fusion has no long lived radioactive waist, tritium has a half life of 12 years activated materials around 100 years as opposed to thousands of years for fission waste.





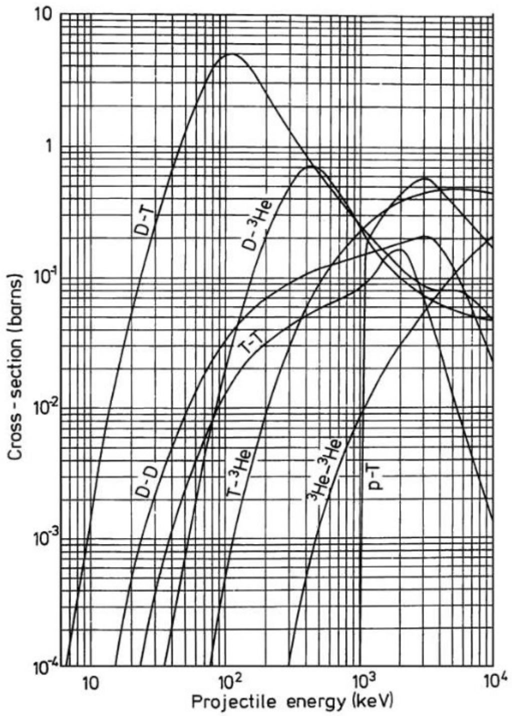


Lepine-Szily et al, International Journal of Astrobiology. 11, 243-250 (2012)



Why Deturium Tritium Reaction?

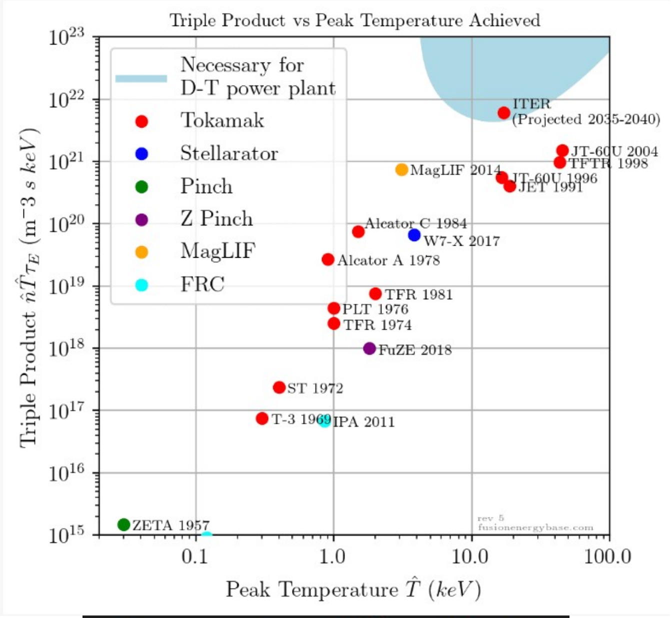
Simply because these reactions have the highest chance of occurrence at “low” temperatures



What is the Q factor and Triple Product for Ignition?

$$Q = \frac{P_n}{P_H}$$

- Q is the ratio of neutron energy released and heating energy inserted.
- Q does not incorporate converting neutron energy into electricity or heating inefficiencies. JET = 0.67, ITER Q=10
- Q=5 is said to allow for the energy extracted to match the heating demands
- The triple product must be above a threshold to achieve ignition; when fusion alphas sufficiently heat the plasma for further fusion
- Both of these metrics are used to measure fusion performance and guide the design of future reactors



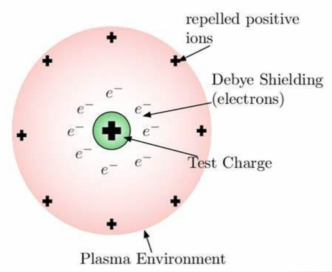
$$P_\alpha > P_L$$

$$nT\tau_E > 3 \times 10^{21} m^{-3} keV\, s$$

$$\vec{B}^2 \beta \tau_E \propto nT\tau_E$$

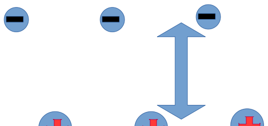
What is a Plasma?

- A plasma is an ionised gas that exhibits collective effects:
  - Deby Shielding
  - Plasma Waves
  - Drifts
  - Instabilities
  - Glowing
- If the dominating interaction is collisions then the ionised gas behaves like a normal gas and is thus not a plasma
  - Highly Collisional
  - Low Ionisation



Deby Shielding is the plasmas tennancy to cancel an electric field by rearranging its charged constituents. If the Deby length is larger than the gas then it is not a plasma.

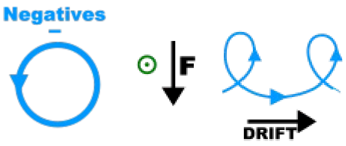
$$\phi = \phi_0 \exp\left(-\frac{r}{\lambda_D}\right),\ \lambda_D = \left(\frac{\epsilon_0 k_B T}{n_e e^2}\right)$$



If the electrons and Ions are seperated, the resulting **wave** would oscillate at the plasma frequency. It is the natural frequency of the plasma, or resonant frequency.

$$\omega_p = \left(\frac{n_e e^2}{\epsilon_0 m_e}\right)$$

EM waves faster than the plasma frequency can penetrate the plasma, anything slower is reflected.



Gyrating particles when exposed to an external force will **drift** perpendicular to both the force and magnetic field.

The force can come from many sources, electric field, variable magnetic field, gravity, centrifugal forces.

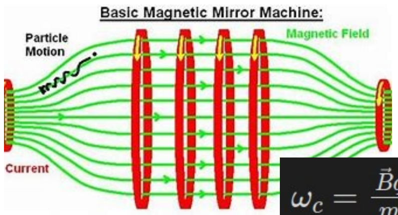

Normal gases are also thrown out of equilibrium by external forces but there are many more driving mechanisms and possible features of turbulence and instabilities for plasma.



The thermal radiation of plasma is often in the visible spectrum.

Plasma Confinement

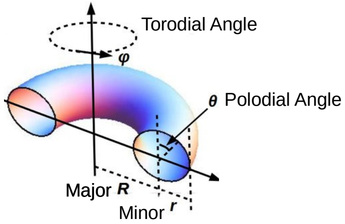
- Magnetic Mirror
- Torus
- Tokamak and Stellerator

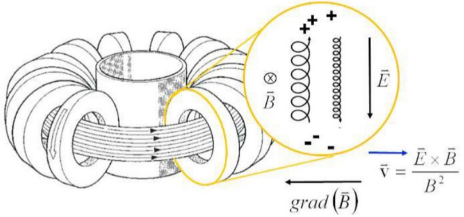


$$\omega_c = \frac{\vec{B}q}{m}$$

As the particles reach the high field their gyrofrequency increases. This requires energy and the systems mechanics allows this energy to come from the translational motion of the particles until they are stationary and cannot go gurther to the high field region so are **reflected**.

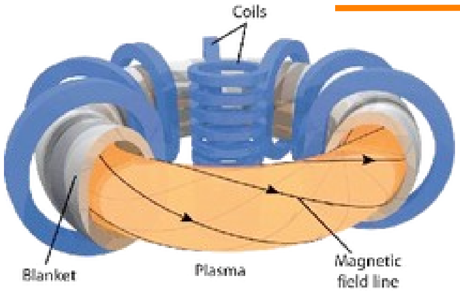
Particles with enough translational velocity will escape. Since at thermodynamic equilibrium there are always some fast particles, eventually almost all particles escape.



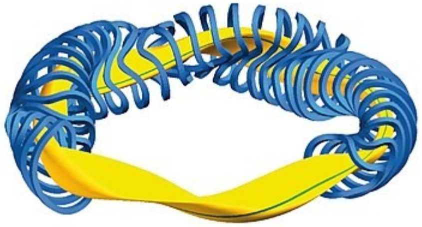


The obvious solution is to make a **torus** so there are no ends to plug.

The problem here is that drifts cause all the particles to leave almost instantly.

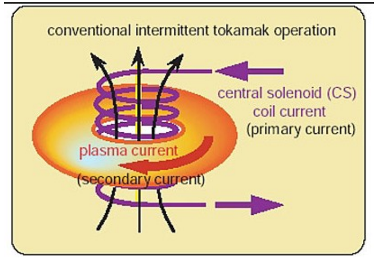


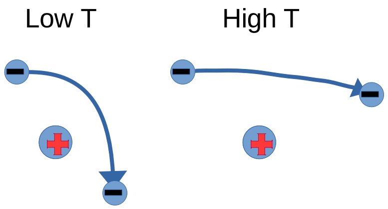
The **tokamak** uses a central solenoid to drive a changing magnetic field which induces a current in the plasma which creates a polodial magnetic field. The resulting **magnetic field is a helix** around the torus. Since the dominating drifts point major radially outwards the particles drift away from the core when outside the torus and towards the core when inside the torus. Effectively the **drifts cancel** and we have confinement.



To achieve the same effect the **stellerator** tries to curve the magnetic field lines with a **complex torodial field coil design**. There is **no plasma current**. Since there is no central solenoid to charge it can operate in **steady state**. The coils can also be **optimised to reduce turbulence** and instabilities. Although due to less symmetry **modeling a stellerator is much more difficult.**

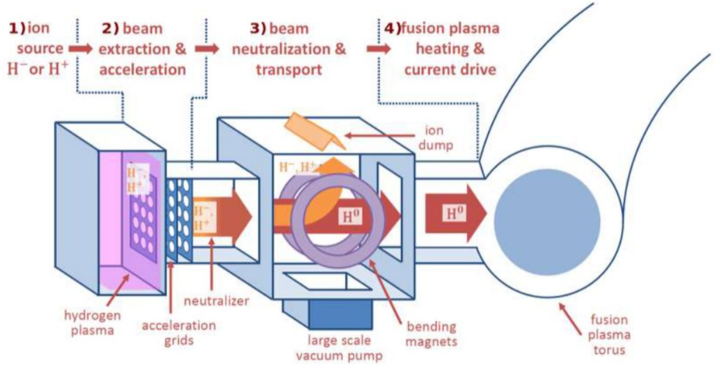
External Heating





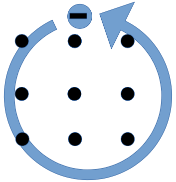
Inducing a current in the plasma can heat the plasma. Although as temperature increases the coulomb collisions become less severe in disrupting trajectories and resistivity decreases. This reduces the effectiveness of ohmic heating at high temperatures required for fusion and other heating methods are needed

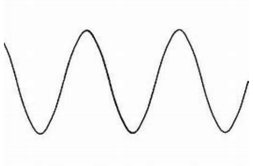
- Ohmic heating
- Neutral Beam Injection
- Cyclotron Resonance Heating ECRH, ICRH



1) First a radio frequency EM wave ionises some fuel
2) Then charged grids accelerate the ions to high energies
3)
   i) It is passed through a neutral gas where the beam steals electrons to become neutral
   ii) Any remaining ions are directed away using a magnetic field and the Lorenz force
4) The high energy neutral beam passes though any magnetic confinement and reaches the plasma; effectively heating it.

$$\omega_c = \frac{\vec{B}q}{m}$$

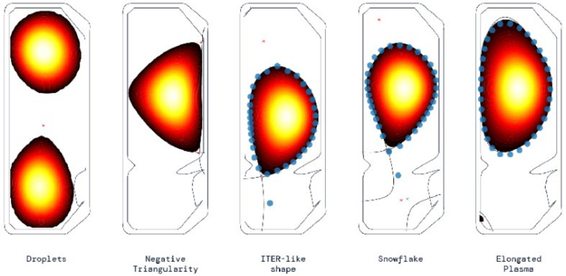




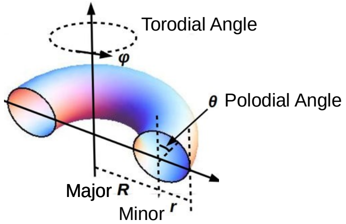
EM waves can be fired into the plasma that have the same frequency as the cyclotron frequency of the electrons or ions. This allows them to resonantly interact and the particles can absorb the energy

Flux Surfaces and Divertor

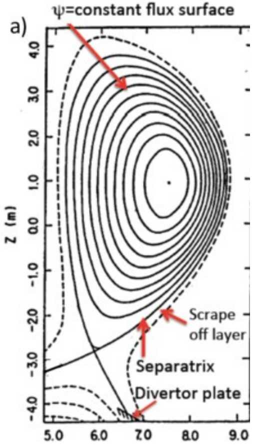
- Flux Surfaces represent the **equilibrium** that is being aimed for, constructing them from magnetic diagnostics is often called equilibrium reconstruction
- Assuming particles follow magnetic field lines the flux surfaces are **contours of constant** density, temperature, pressure, safety factor q, beta thus allow a tokamak plasma to be described by 1D profiles
- The **flux surface shape mostly affects** β and the D shape maximises beta. There is still debate on left/right D and degree of triangularity.
- The **diverter** is a component close to the X-point of the seperatrix that is designed to receive a **high particle flux** as majority of particles that leave the plasma or wall will arrive there.



https://www.newscientist.com/article/2308243-deepmind-uses-ai-to-control-plasma-inside-tokamak-fusion-reactor/

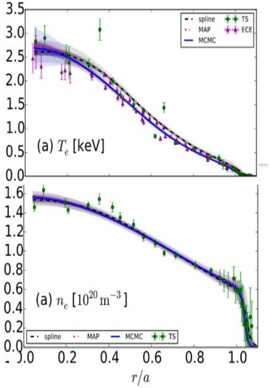


Solving the Grad Shafranov Equation with magnetic diagnostics



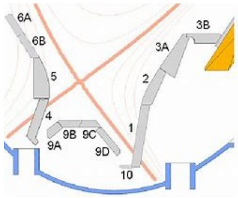
$$R\frac{\partial}{\partial R}\frac{1}{R}\frac{\partial\psi}{\partial R}+\frac{\partial^2\psi}{\partial z^2}=-\mu_0 R^2 p'(\psi)-\mu_0^2 f(\psi)f'(\psi). \qquad 3.3.9$$

Wesson Tokamaks



Electron denstiy and temperature profiles fit to Thompson scattering points with Gaussian process regression. Chilenski et al, Nuclear Fusion 55, 2015.

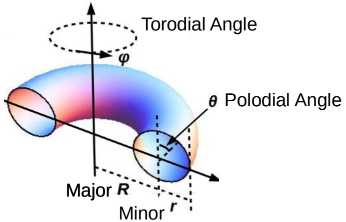
Asdex Upgrade Garching Germany



A high impact angle spreads the load and sprinkler motion gives time for plate to cool

Safety Factor, q

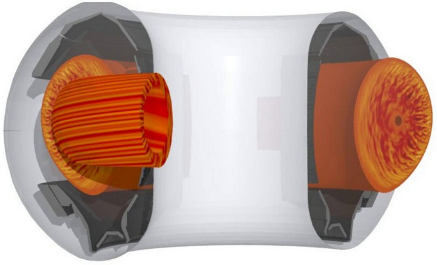
- The safety factor physically **represents how coiled the helix** of the magnetic field lines are. A high safety factor means the field line is less coiled.
- The magnetic field line **bites its on tail** after m toroidal turns and n polodial turns where m and n are integers.
- The safety factor is highly linked to **instabilities,** hence its name.
- Micro turbulence structures have a high length-scale along the magnetic field lines and low perpindicular, if the field lines **bites it's own tail then the turbulence can easily circulate and resonate.**
- Tuning the safety factor profile is greatly important for avoiding macro instabilities. Example: q=1 at core stabilises kink instability.



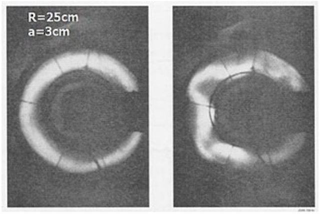
$$q = \frac{\Delta\phi}{2\pi}.$$

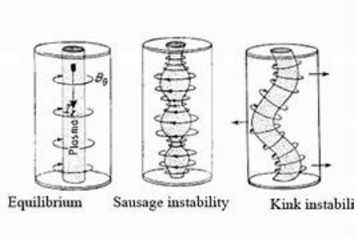
Δϕ is the toroidal angle required to return to the same polodial angle, θ.

$q = m/n$, where m and n are integers,

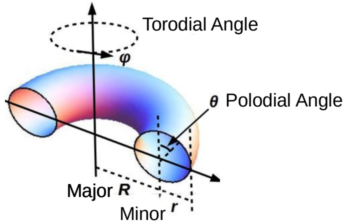


gene.org

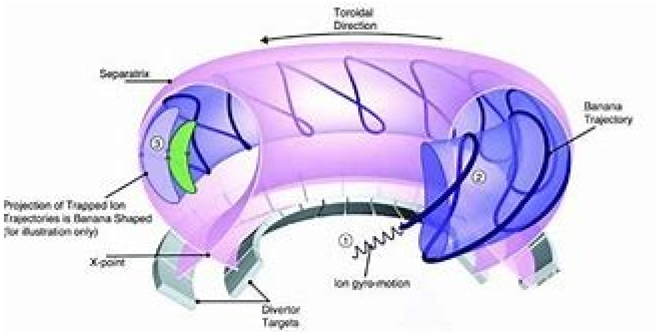


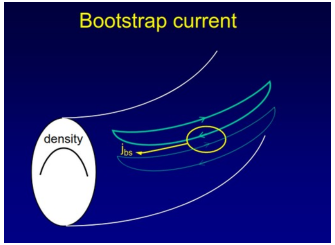


Banana Orbits and Bootstrap Current



- The tokamak has a **stronger toroidal magnetic field in the core** due to the geometry of the torodial coils.
- Particles with low energy are **reflected when they get to the high field side**, just like in the magnetic mirror.
- This leads them to follow **banana orbits** that are confined closer to the high field side of the tokamak.
- This is important for various **turbulence and transport** processes.
- It is also important in the explanation of **bootstrap current**.
- Bootstrap current is a toroidal current that results **purely from the geometrical orbits** of particles.
- It is a **sizeable** current that lowers the reliance on the central solenoid and thus the cost of a reactor



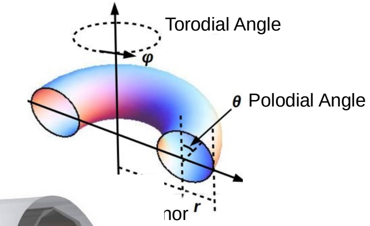


$$j_b \sim -\varepsilon^{1/2}\frac{1}{B_p}\frac{dp}{dr}$$

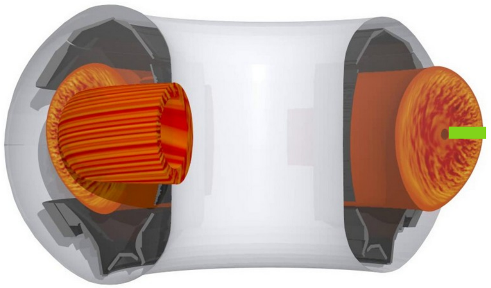
Fusion Wiki

Here, ε is the inverse aspect ratio a/R, B_p the poloidal magnetic field, and p the pressure. More precise estimates can be made by simulating particle orbits.

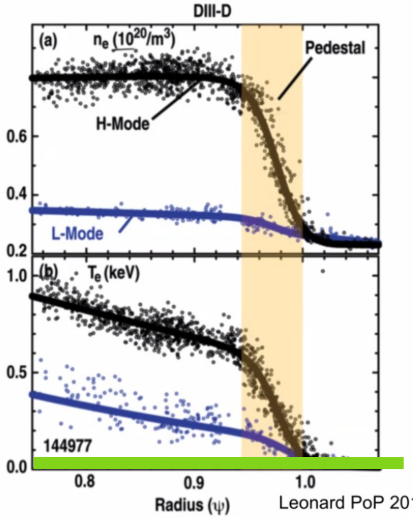
H-mode, Pedestal and ELM’s



- If the **external heating** is increased and a divertor is used then H-mode appears.
- The core profiles appear to be lifted up by a pedestal.
- A **sharp gradient** in the profiles appears at the edge and the plasma is well confined, thus high confinement mode. The **time delay** part of the triple product largely increases.
- A large flow of plasma known as shear flow cuts through instabilities
- A new instability is introduced known as Electron Localised Modes, **ELM’s**.
- ELM free scnearios??
- There are three types of ELM’s but type I are the destructive ELM’s and thus what most people mean when they say ELM.
- ELM’s are short lived sudden bursts of energy with **high heat and particle fluxes that immediately damage** the plasma facing components and trigger other instabilities which leads to a **full disruption**; complete loss of confinement, large damage to the tokamak.



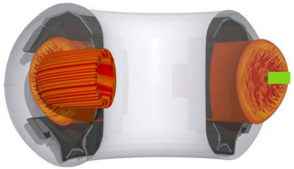
https://www.genecode.org

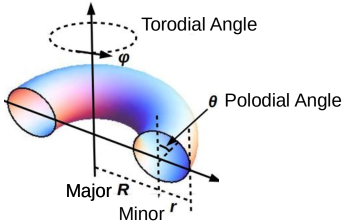


Leonard PoP 2014

Link to DEEPlasma

- DEEPlasma is trying to surrogate the GENE code for the pedestal region of H-mode tokamak plasmas.
- GENE simulates the distribution of plasma particles and can find the growth rate of instabilities.
- Micro-instabilities are driven by temperature and density gradients and drifts (among other things).
- The pedestal is a region of steep gradients and thus high micro-instability drive (although flow shear should remove some of this).
- Micro-instabilities resonate at rational safety factor values
- The instabilities cause outward heat and particle flux, which are the engineering parameters of interest
- DEEPlasma focuses on linear GENE which cannot output an accurate heat flux but it can provide an input for a quasi-linear analysis.





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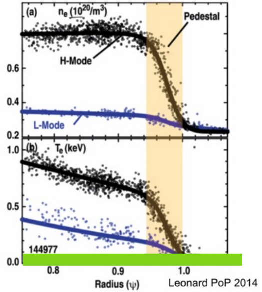

$$q = \frac{\Delta\phi}{2\pi}.$$

Δϕ is the toroidal angle required to return to the same polodial angle, θ.

$q = m/n$, where m and n are integers,

$$Q = n\Delta T\chi$$

$$\chi = \frac{\gamma c}{< k_{\perp} >^2}$$

γ is the growth-rate of the instability, $< k_{\perp} >$ is the average micro instability wave vector perpendicular to the magnetic field, c is the saturation rule; it is a fudge factor that is tuned to match non linear simulations or experiment.