PPPL PRINCETON PLASMA PHYSICS LABORATORY

NSTX-U National Spherical Torus Experiment - Upgrade

Magnetic Confinement Fusion: The Path to the Spherical Tokamak and NSTX-U

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University of Michigan – Ann Arbor

I am a Michigander/Wolverine like many of you!

2009-2013

Undergraduate
- Physics and Math major
- UROP participant
- HED/ICF related research
+ honors thesis

2013-2019

Grad School
- Started research in MCF
- Focus on energetic particles

2019-2021

PostDoc
- Still in MCF
- Participated in DT-experiments on JET

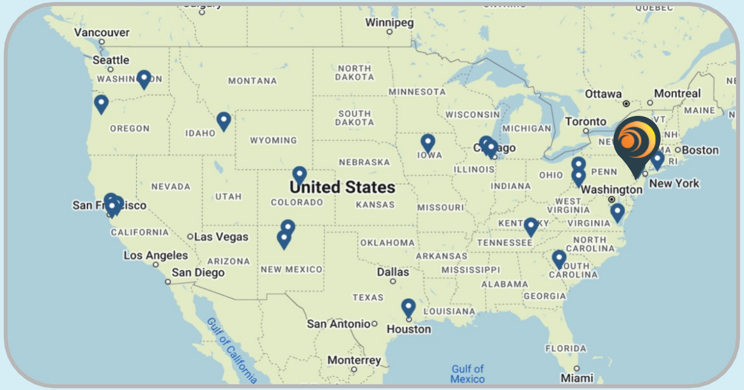
2021-Present

Scientist
- Still in MCF
- Worked on almost every type of MCF device
- Experimental and computational research

Princeton Plasma Physics Laboratory

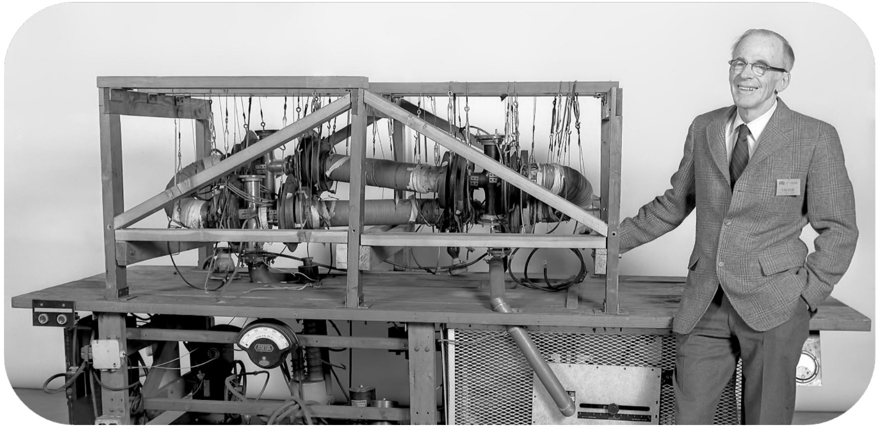
U.S. DEPARTMENT OF ENERGY

One of 17 Dept. of Energy **National Labs**



Managed by PRINCETON UNIVERSITY

- Magnetic fusion research at Princeton began as a classified government project in 1951 under renowned physicist Lyman Spitzer Jr., using the code name “Project Matterhorn”
- PPPL Today: 700+ employees, \$150 Million+ government funding, 300+ annual publications



What will we learn today?

- Why do we need fusion?
- What is fusion?
- Why do we need confinement?
- How do we confine a plasma?
    - Magnetic confinement: pinches, magnetic mirror, stellarator, tokamak, spherical tokamak
    - Pros and cons of each design
    - Potential positives of the spherical tokamak and NSTX-U
- What are the biggest obstacles and problems?
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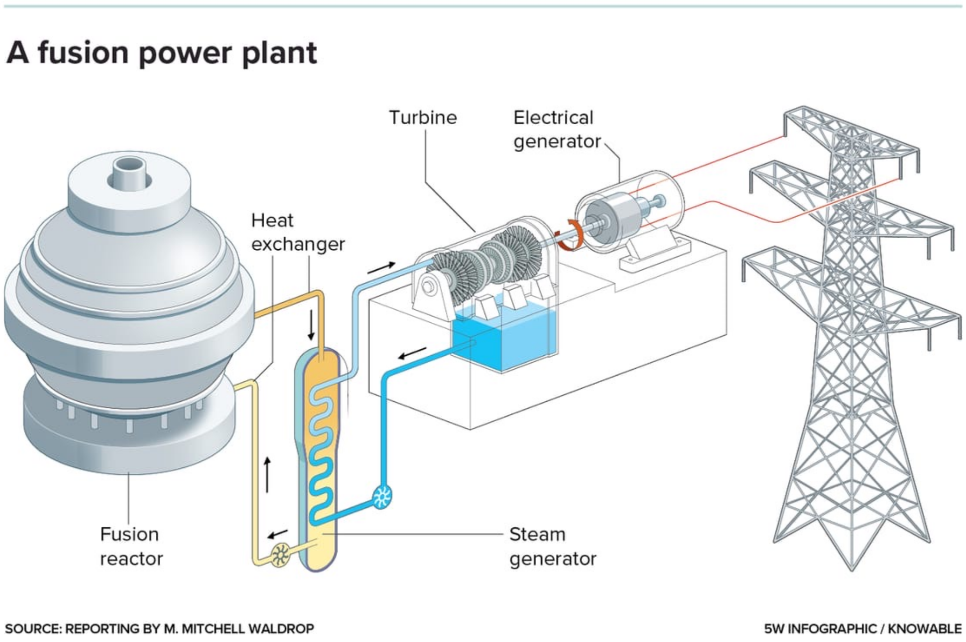
Fusion Power: Safe, Abundant, Energy Dense, Clean, & Sustainable

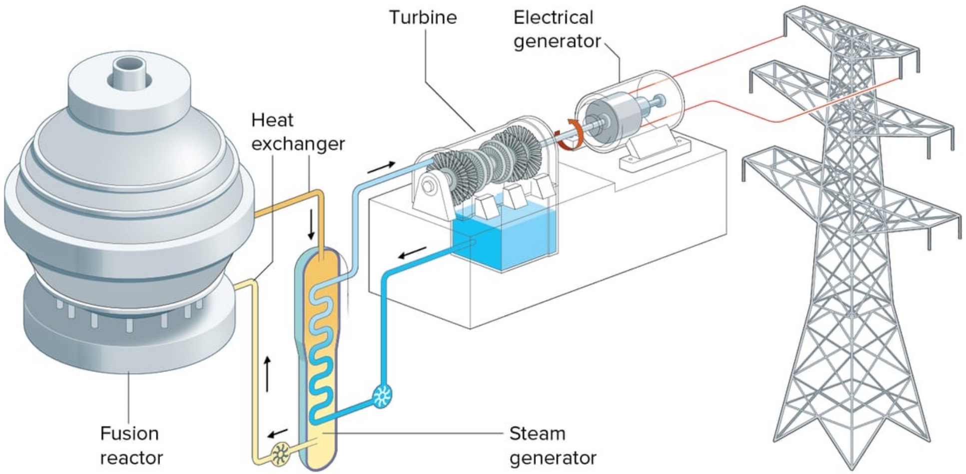


- Cannot have runaway reactions
  - Only small amount of fuel present
  - If particles cool, fusion stops
- Abundant fuel supply
  - D from seawater
  - T bred from Li in earth's crust
- Very high energy density
  - Most efficient process per mass
- Minimal radioactive waste: short-lived, low-level
  - Trace T, neutron activated material
- No CO_2 production

A Fusion Power Plant will Function just like a Fission Plant

- Use neutrons to heat water, to produce steam, to drive a turbine

A fusion power plant



SOURCE: REPORTING BY M. MITCHELL WALDROP

5W INFOGRAPHIC / KNOWABLE

- Surround machine in water blanket to capture neutrons for energy production
- Surround machine in Li or FLiBe blanket for T production (tritium breeding)

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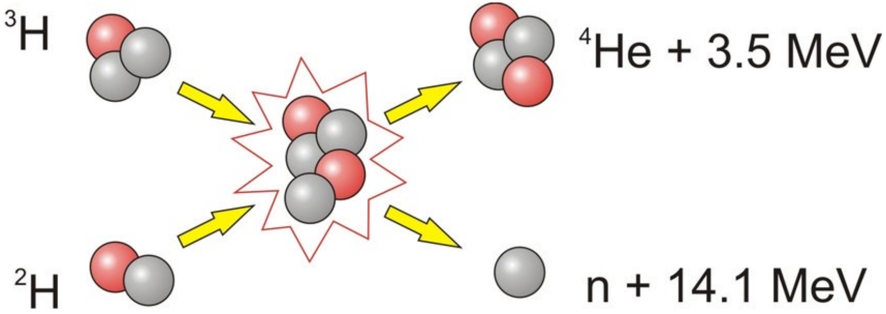
Fusion Combines Smaller Nuclei to Larger Nuclei

- Converting binding energy (mass) to energy: $\Delta E = mc^2$

$$D + T \rightarrow He^4\,(3.5MeV) + n\,(14.1MeV)$$



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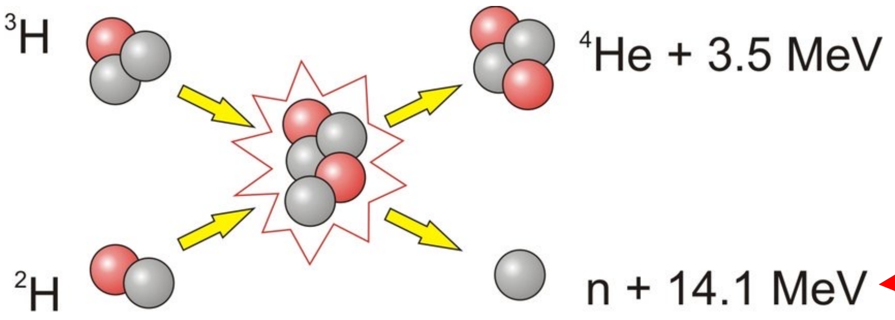

Produces neutrons
1. Use for power production
2. Breed tritium

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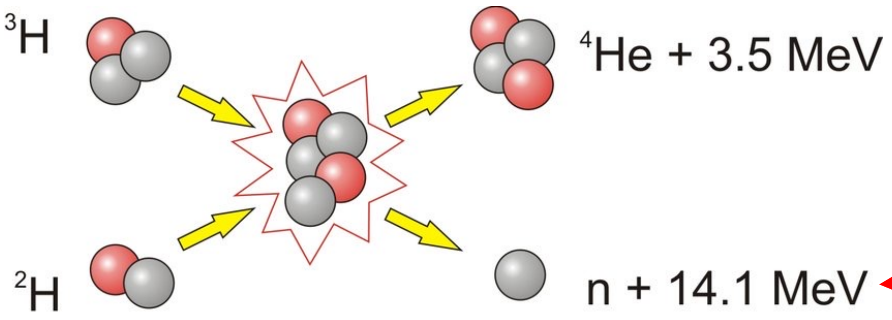
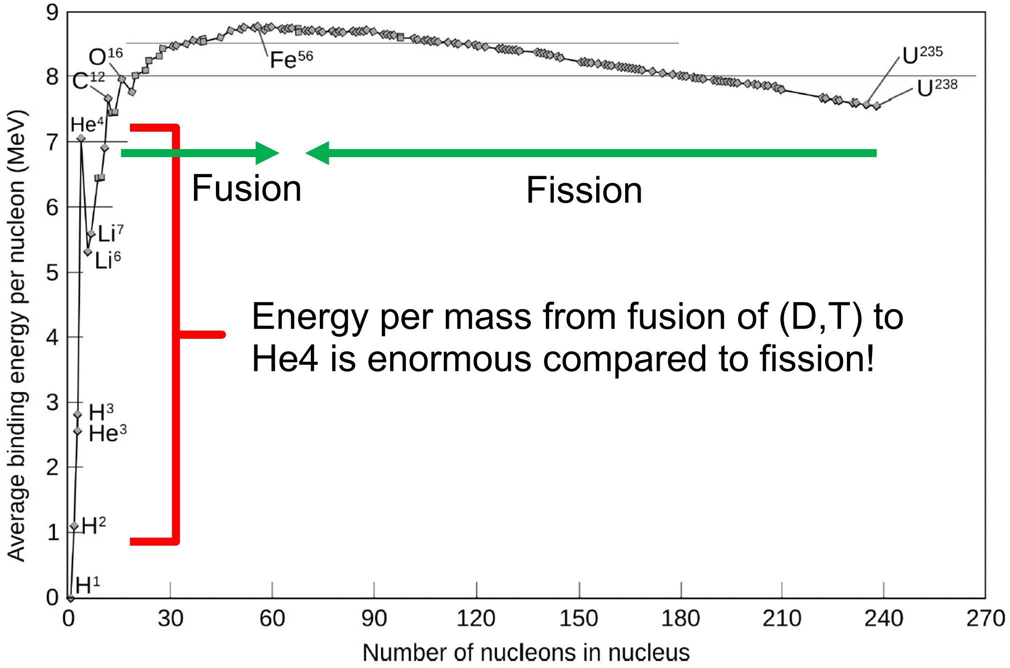


Stable alpha particle
Use to self-heat the plasma

Produces neutrons
1. Use for power production
2. Breed tritium

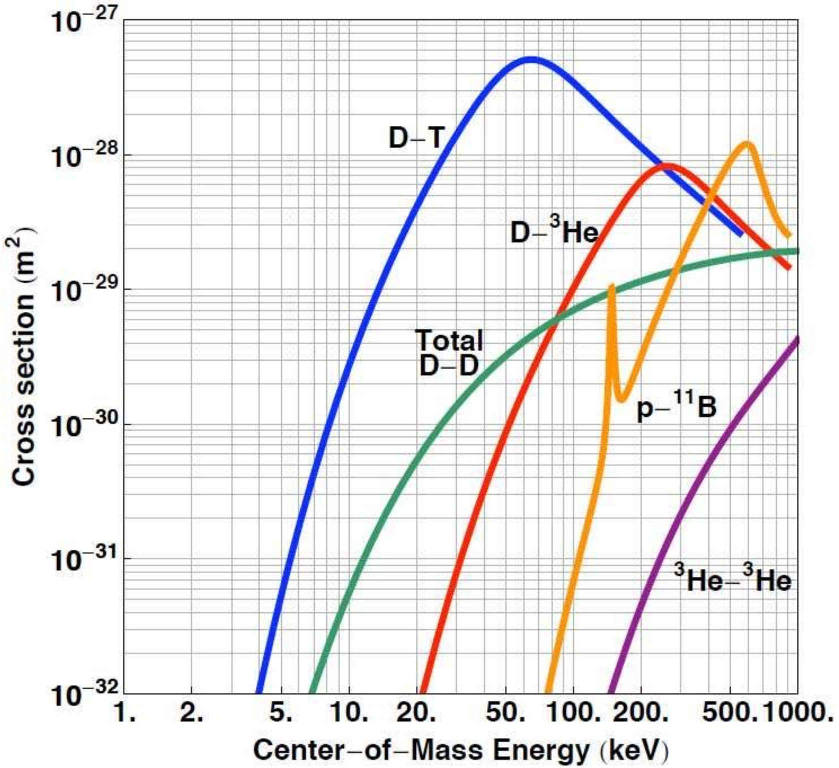
Fusion is more Energetically Advantageous than Fission

- Converting binding energy (mass) to energy: $\Delta E = mc^2$



DT-Fusion has the Largest Cross-section (Easiest!)

- Requires temps. 10-20 keV (radiative and transport losses prevent higher temps.)
- Maintain a high temperature and dense plasma to induce fusion reactions



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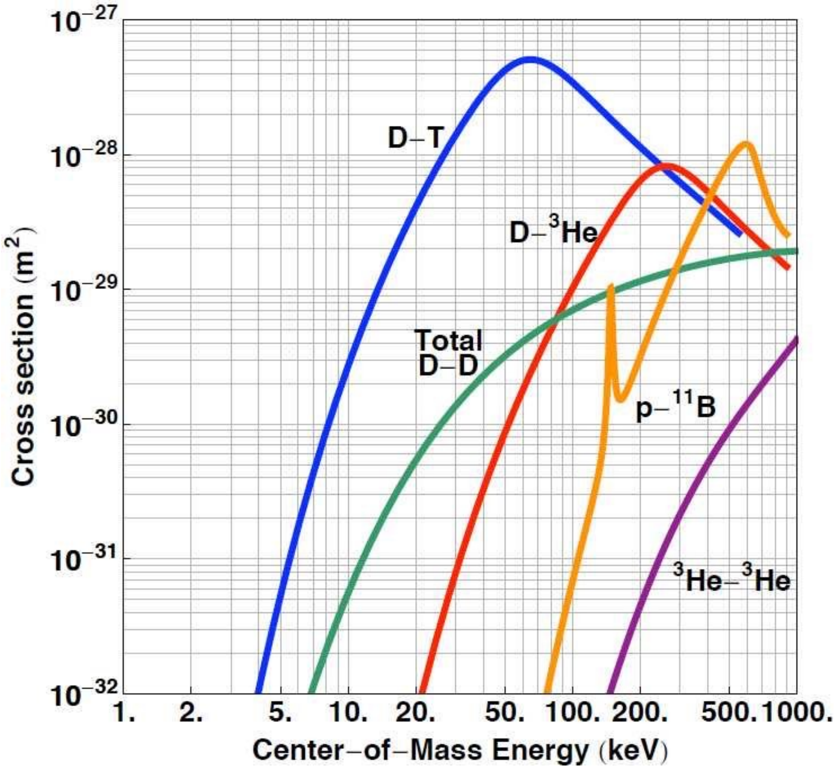
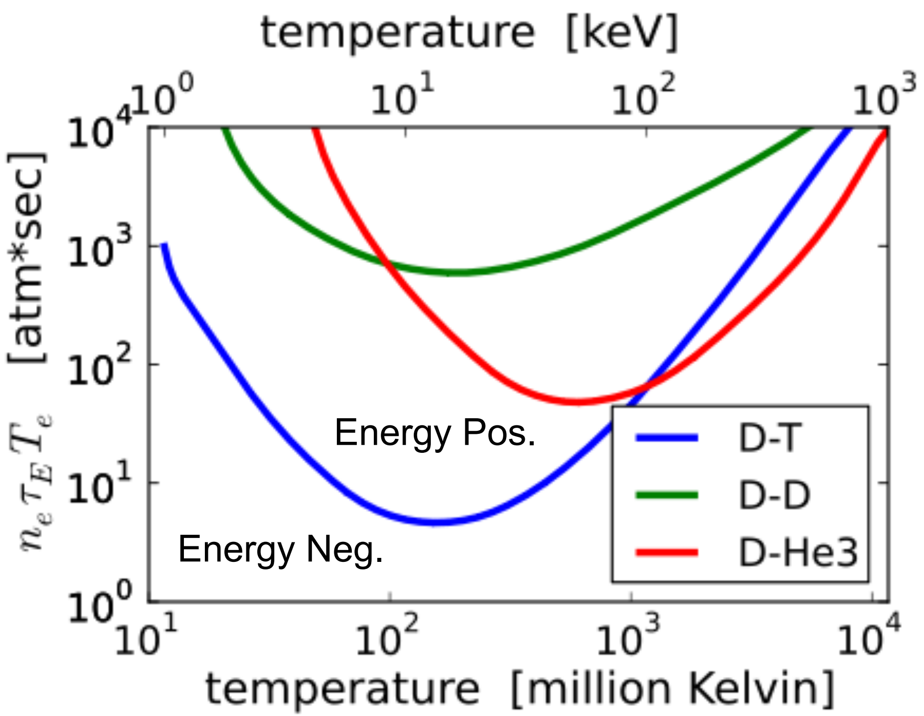


<u>Notes</u>

- Some groups are investigating non DT-concepts, such as PB^{11} or DHe^3 (aneutronic, but harder…)
- DT-experiments are rare… JET in 2022-23, JET in 1997, TFTR in 1995
- DD-plasmas are the most common for basic fusion research

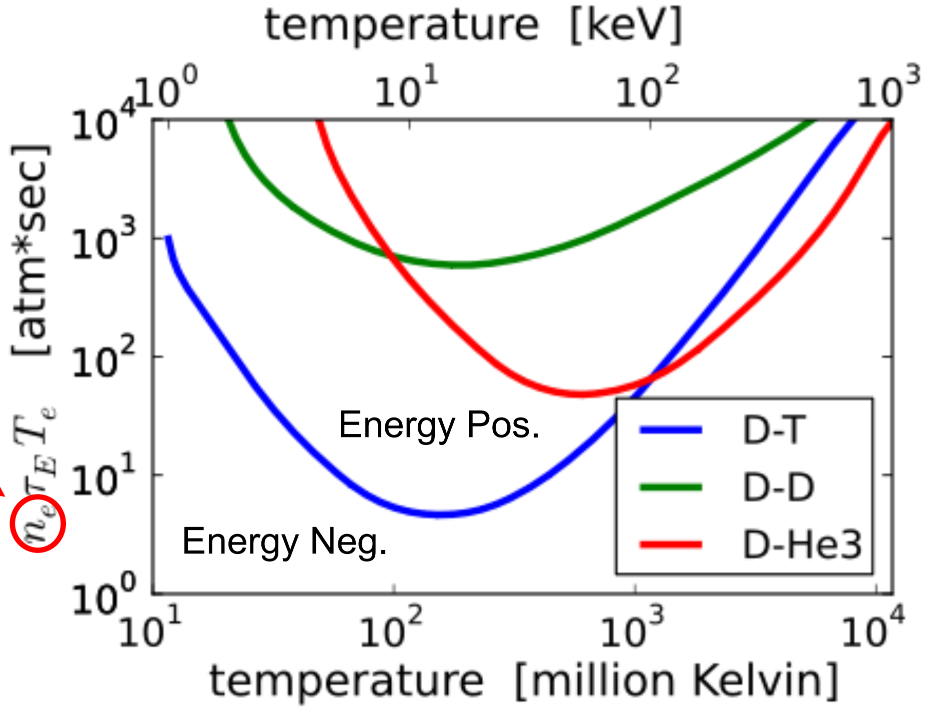
Lawson Criterion - Parameters needed for Fusion

- Create a plasma of DT-ions to overcome Coulomb repulsion and fuse



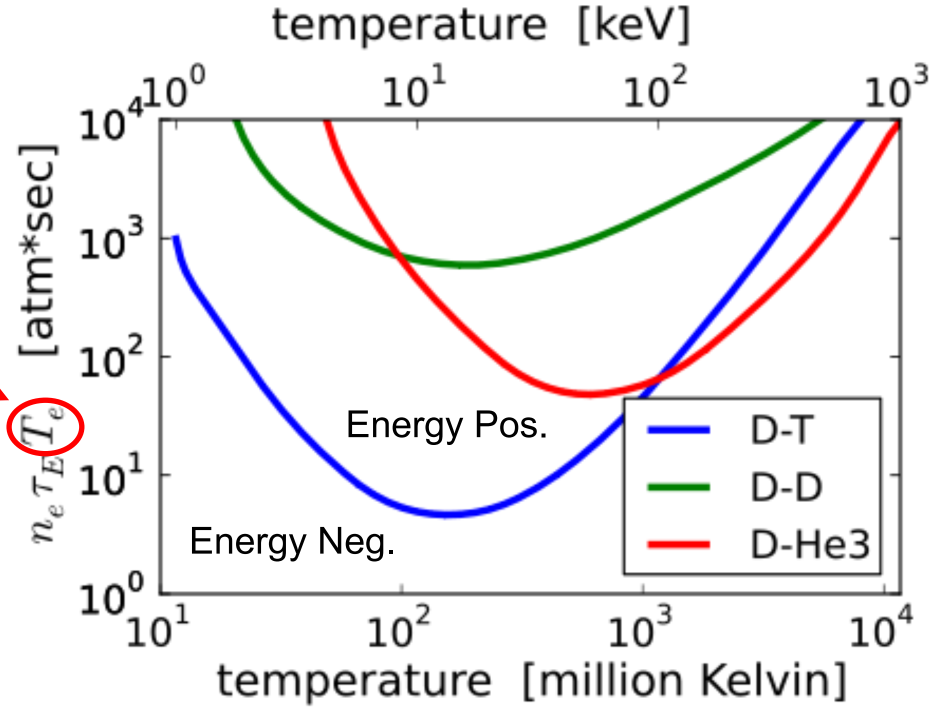
Lawson Criterion - Parameters needed for Fusion

- Create a plasma of DT-ions to overcome Coulomb repulsion and fuse
    - High density



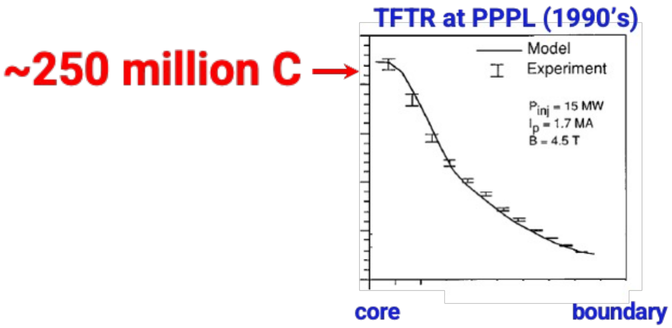
Lawson Criterion - Parameters needed for Fusion

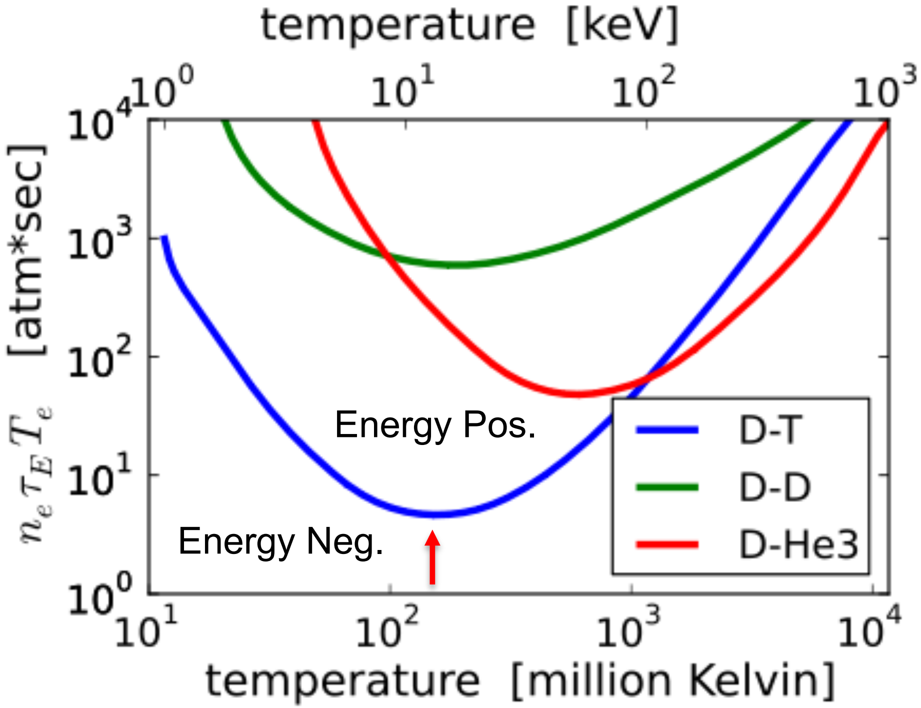
- Create a plasma of DT-ions to overcome Coulomb repulsion and fuse
  - High density
  - High temperature



Lawson Criterion - Parameters needed for Fusion

- Create a plasma of DT-ions to overcome Coulomb repulsion and fuse
  - High density
  - High temperature
    - We have already achieved the necessary temperature in magnetic confinement fusion

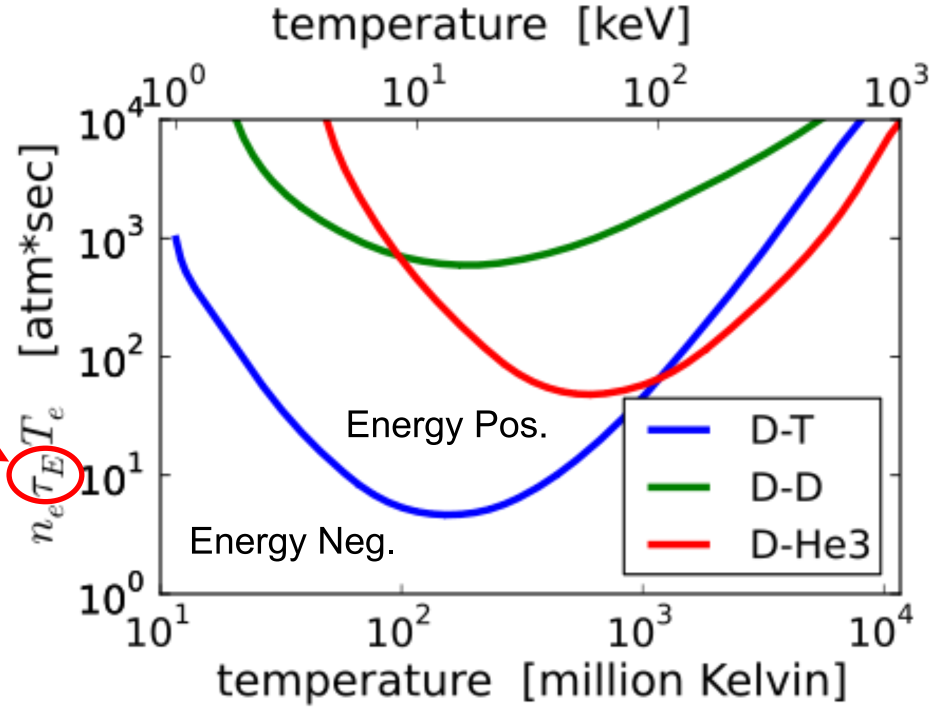




Lawson Criterion - Parameters needed for Fusion

- Create a plasma of DT-ions to overcome Coulomb repulsion and fuse
  - High density
  - High temperature
  - High confinement time

Why confinement?



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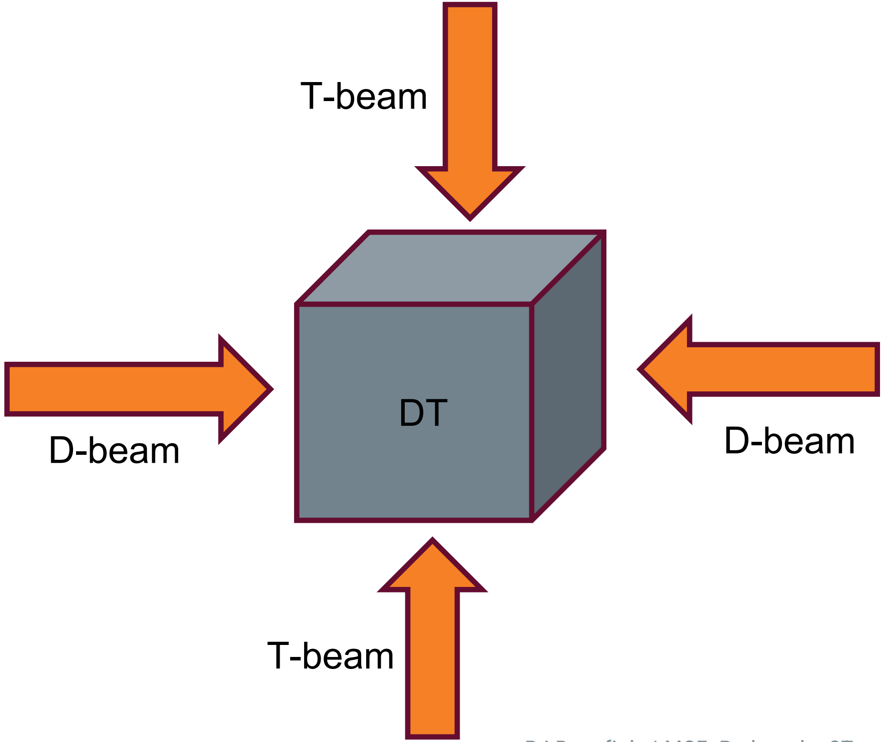
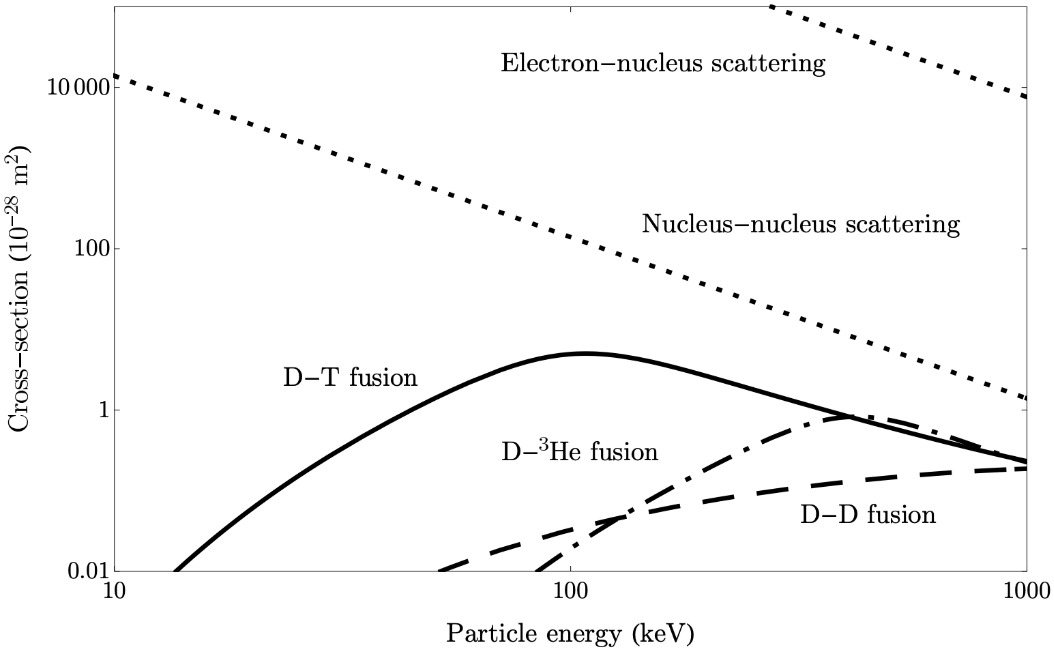
Why do we need confinement? We can get to high energies and densities with beams

- Can't we take a high energy beam and blast some high-density fuel? Or beam-beam?



Collisional scattering dominates over fusion reactions!

- Need long time periods for fusion reactions to occur
- Must have sustained confinement of ions -> many scattering events before fusion



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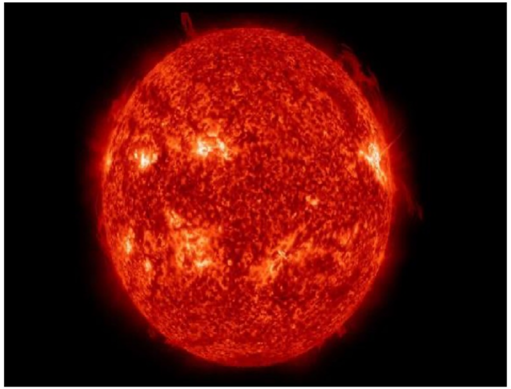
How can we confine a plasma?

Gravity



How can we confine a plasma?

Gravity

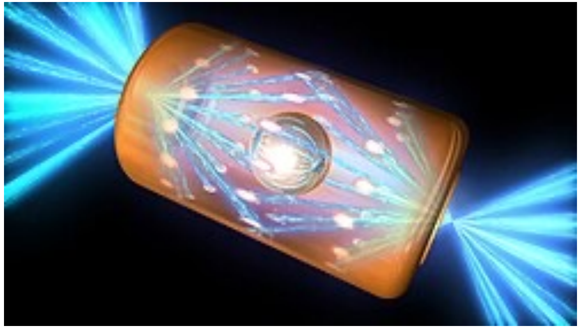
Too slow

How can we confine a plasma?

<u>Gravity</u>

Too slow

<u>Inertial Confinement Fusion (ICF)</u>



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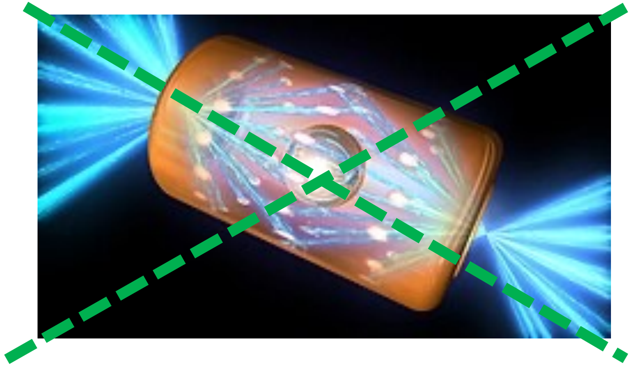


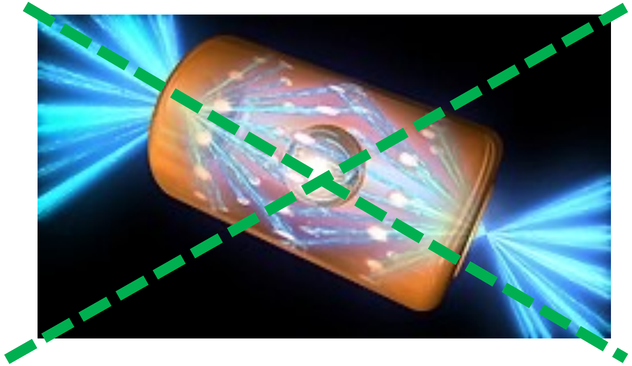
Radiative compression

How can we confine a plasma?

Gravity

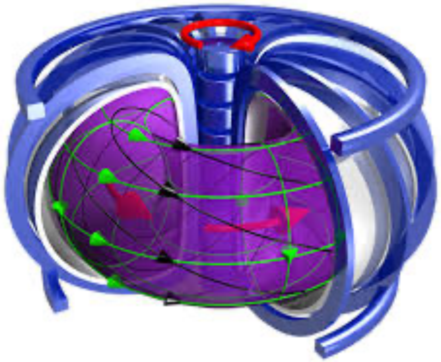
Too slow

Inertial Confinement Fusion (ICF)



Radiative compression

Magentic Confinement Fusion (MCF)



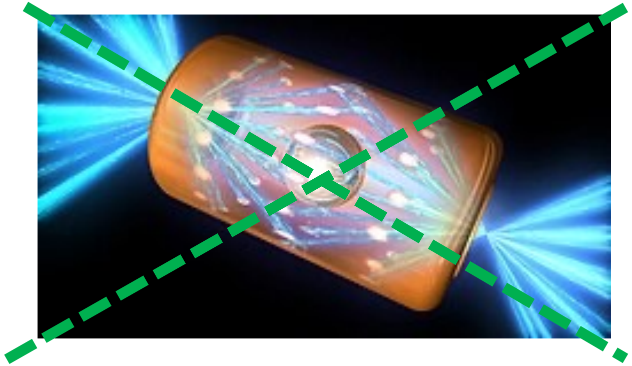
“Magnetic Bottle”

How can we confine a plasma?

Gravity

Too slow

Inertial Confinement Fusion (ICF)



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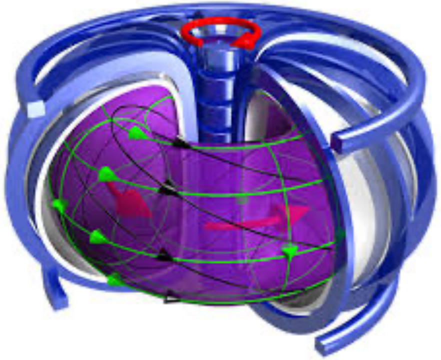
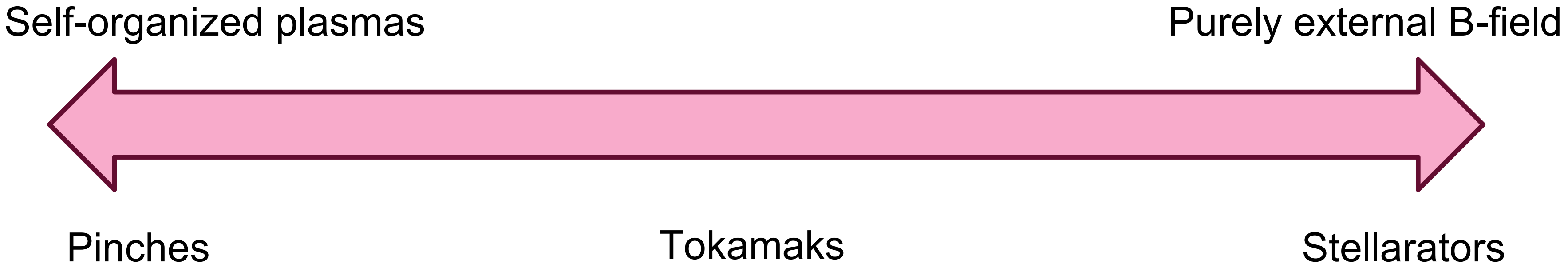


"Magnetic Bottle"

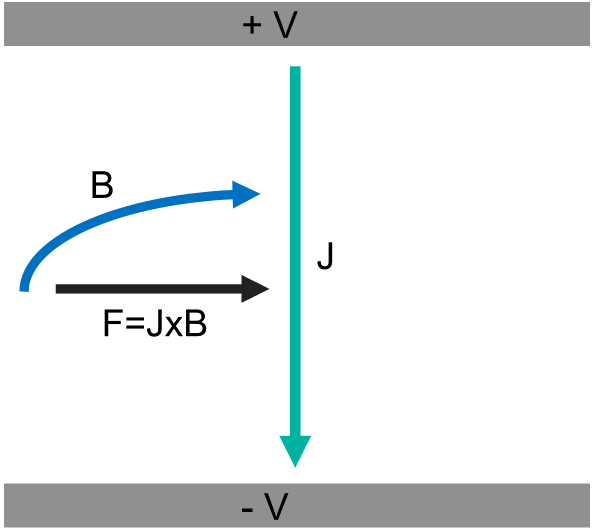
Create a Magnetic Field Structure to Hold the Plasma

- Goal: Heat gas to high temperature to make plasma and confine with B-field
- Plasmas are a soupy mixture of electrons and ions susceptible to EM-fields, but they can also generate their own EM-fields
- B-field: external magnets ans/or internal currents in the plasma



Z-pinch: Easy but Unstable

- Drive an axial current to induce an azimuthal B-field
- JxB force compresses plasma radially inward



Pros

- Very simple (no magnets!)

Cons

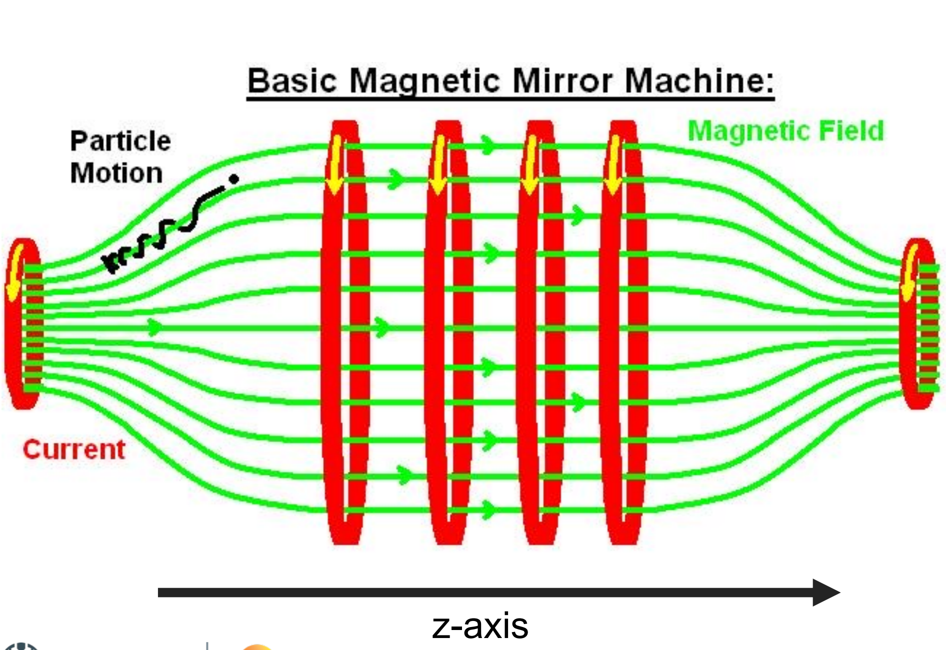
- MHD stability
- Engineering and scaling issues

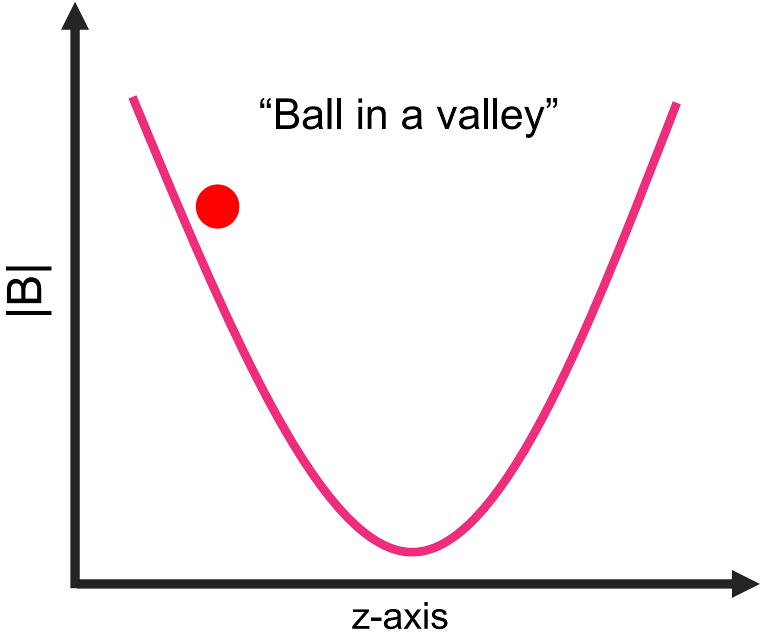
Active Solutions

- Shear-flow stabilization

Magnetic Mirror: Traps Particles in Magnetic Well

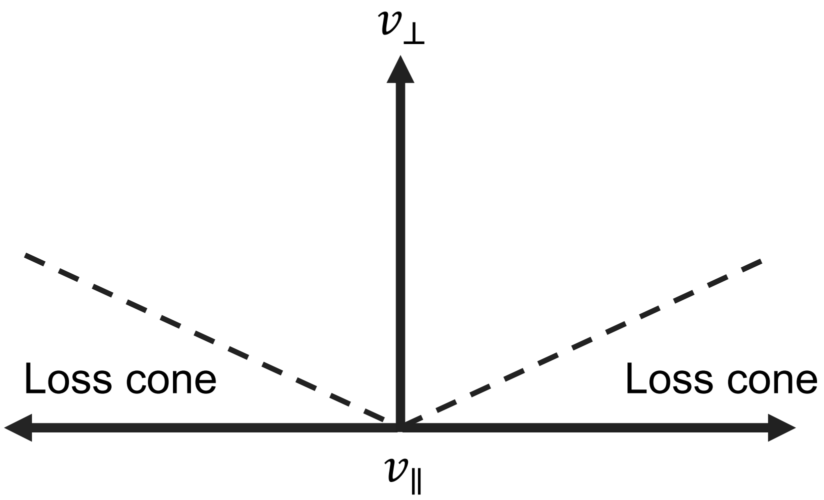
- Axial field capped by high magnetic field
- Particles transit back and forth and reflect at choke points





Magnetic Mirror: Simple but Lossy and Unstable

- Particles with sufficient energy will escape the magnetic well and escape
- Loss cone is produced in velocity-space (parallel defined w.r.t. to the magnetic field)



Pros

- Very simple

Cons

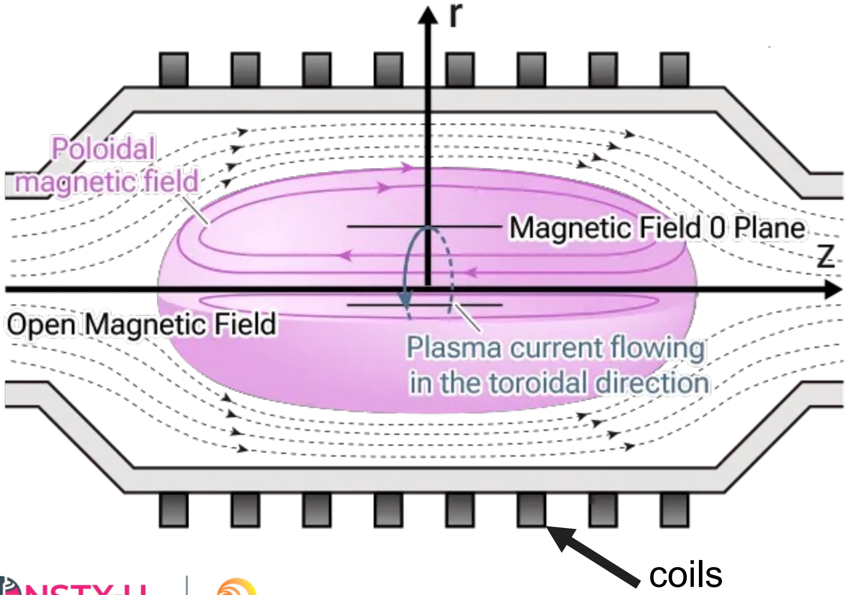
- Inherent losses
- MHD stability
- Traditionally very long (1-2 km)

Active Solutions

- Stronger magnets for higher B-field
- Kinetic stabilization with beam and ECH ions
- Create good field curvature in end cells

Field Reversed Configuration: Exploits Self-Organization

- Use coils to set a B-field axially, then quickly reverse the magnetic field; Magnetic reconnection occurs at the ends producing closed field lines
- Other formation methods: collisional merging, beam injection, etc.



Pros

- Most of the magnetic field is self-organized
- Weak B-field relative to pressure

Cons

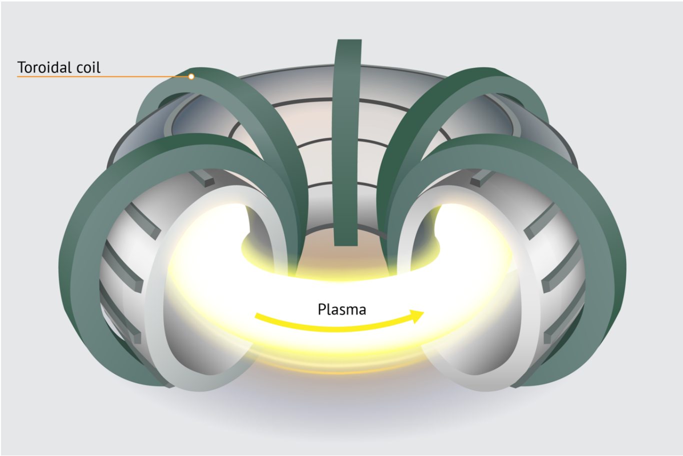
- MHD stability
- Need for active control
- Current sustainment
- Large orbits due to low field

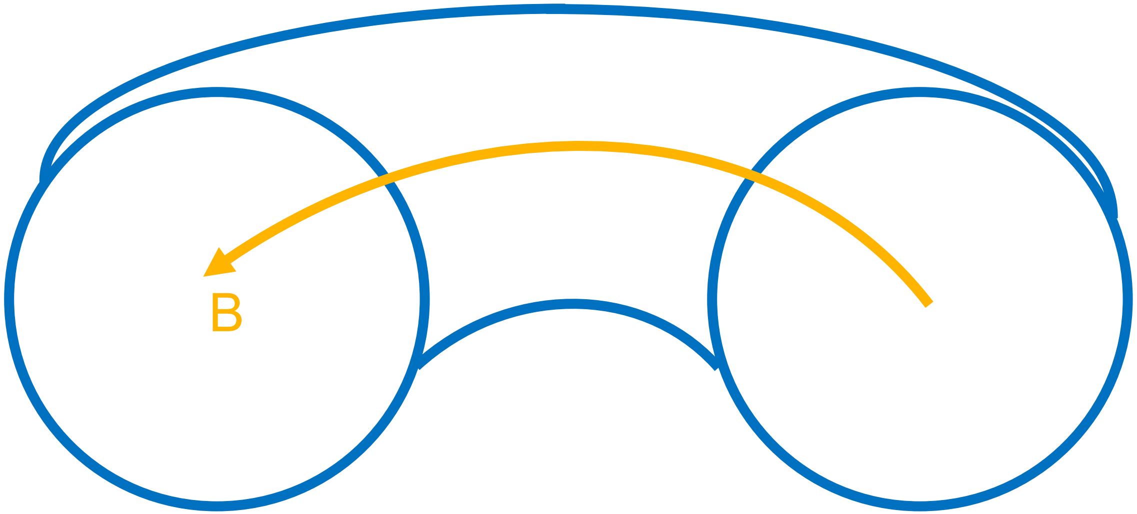
Active Solutions

- Shaping coils and beams
- Coils and active feedback mechanisms
- Neutral beams

Let's Wrap the Magnetic Field on Itself to Make a Donut

- Natural to make closed magnetic field lines by wrapping them on themself



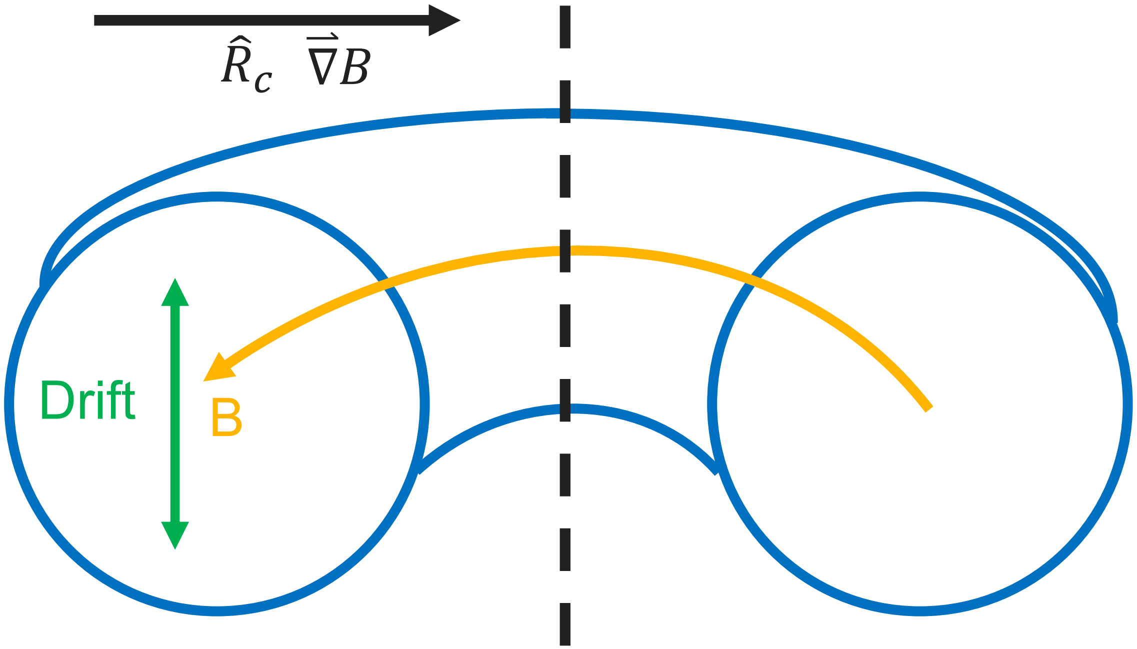


Forces Perpendicular to a Magnetic Field Create Velocity Drifts

- Natural gradients in the magnetic field from coils and curvature will produce vertical drifts

$$\vec{v} = \frac{2E_{\parallel}}{qB}\left[\frac{\hat{B} \times \hat{R}_c}{R_c}\right]$$

$$\vec{v} = \frac{E_{\perp}}{qB}\left[\frac{\hat{B} \times \vec{\nabla} B}{B}\right]$$



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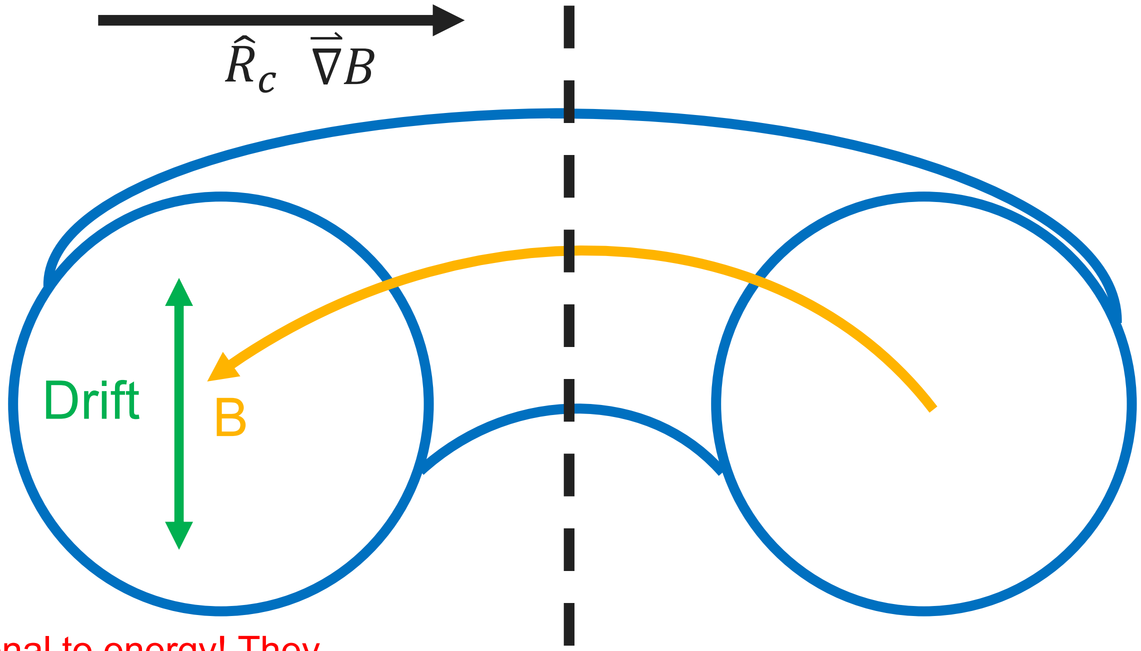
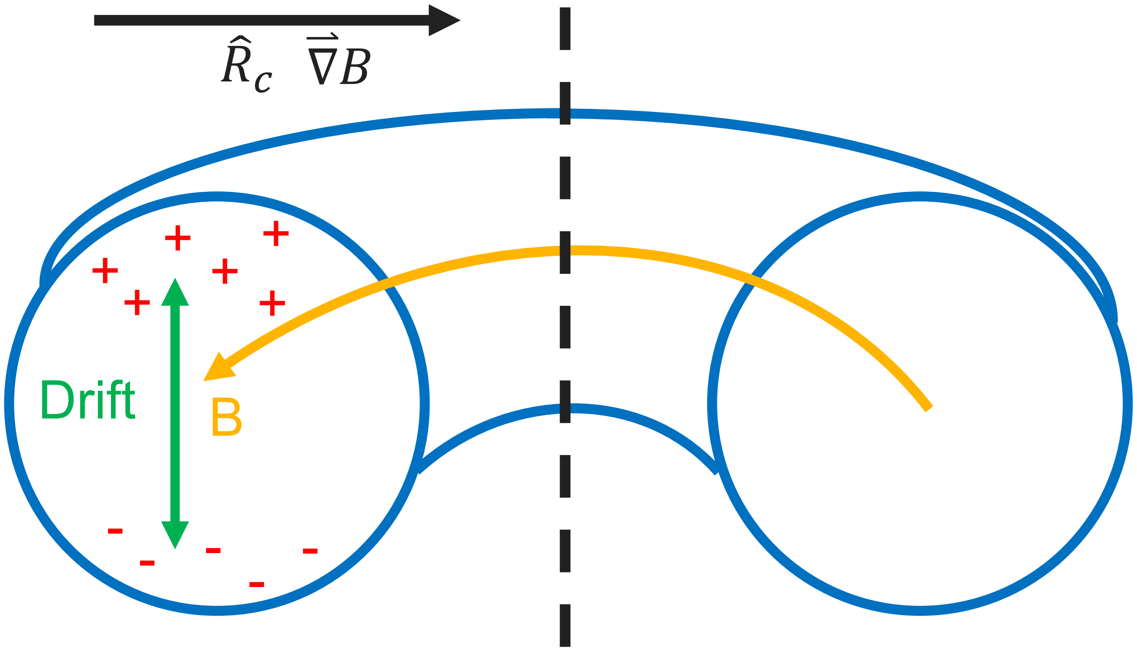


Drifts are proportional to energy! They are stronger for more energetic particles such as DT-alphas!

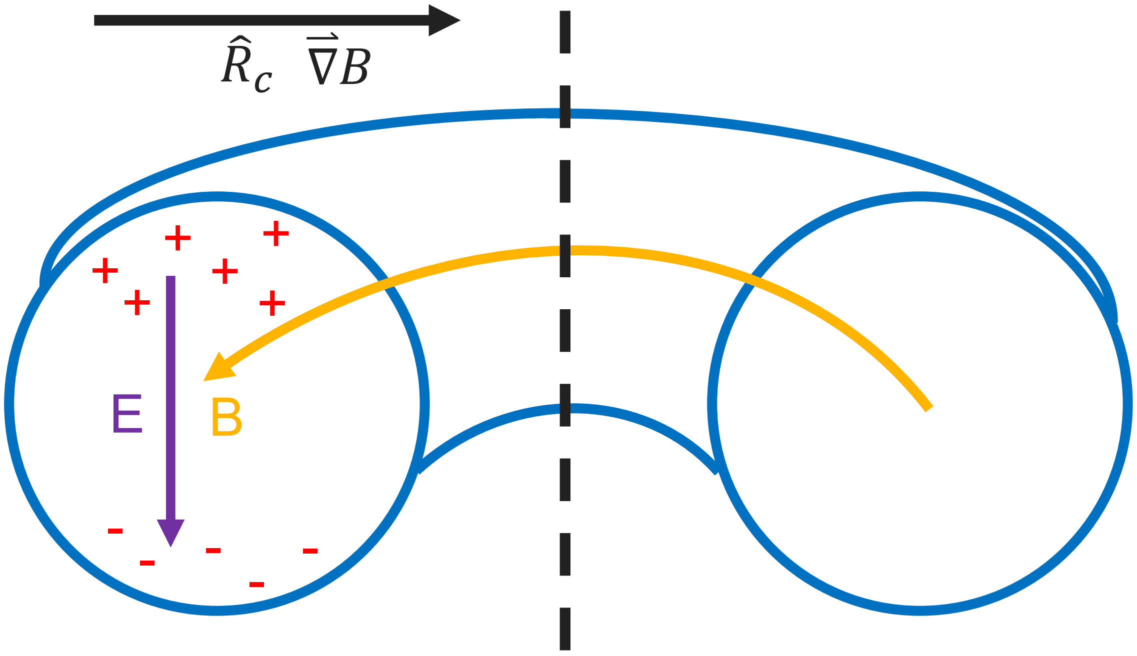
Forces Perpendicular to a Magnetic Field Create Velocity Drifts

- ions go up, electrons go down
- Charge separation will occur



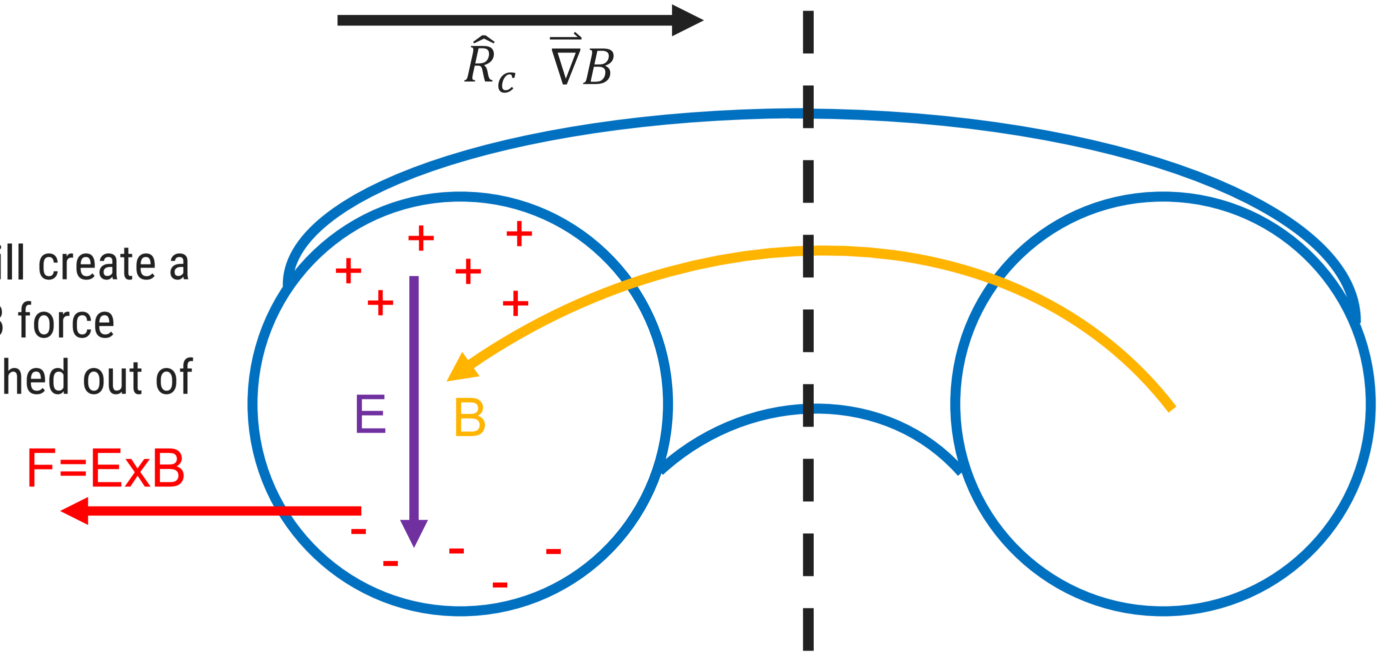
Forces Perpendicular to a Magnetic Field Create Velocity Drifts

- Charge separation induces a downward electric field



Solenoidal Magnetic Field will not Confine Particles

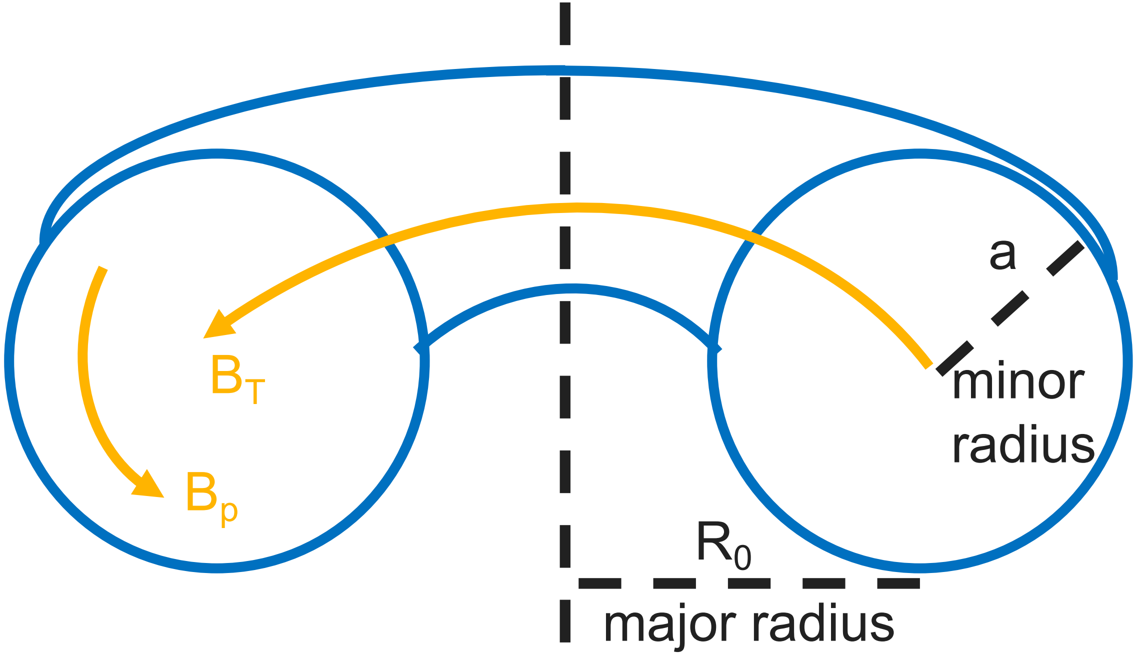
- New electric field will create a radially outward ExB force
- Particles will be pushed out of the plasma!



We Solve this by Adding a Helical Twist

- As particles go around toroidally, they will experience different drifts as they move poloidally incurring a net radial drift close to 0

- Toroidal = long way around the donut
- Poloidal = short way around the donut



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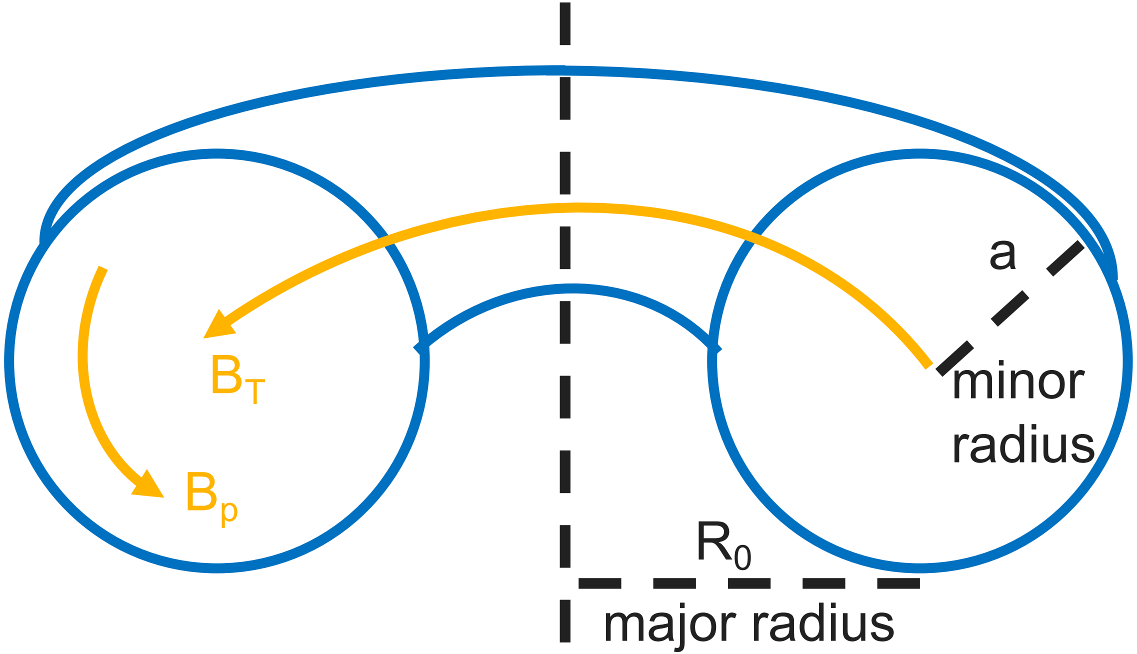


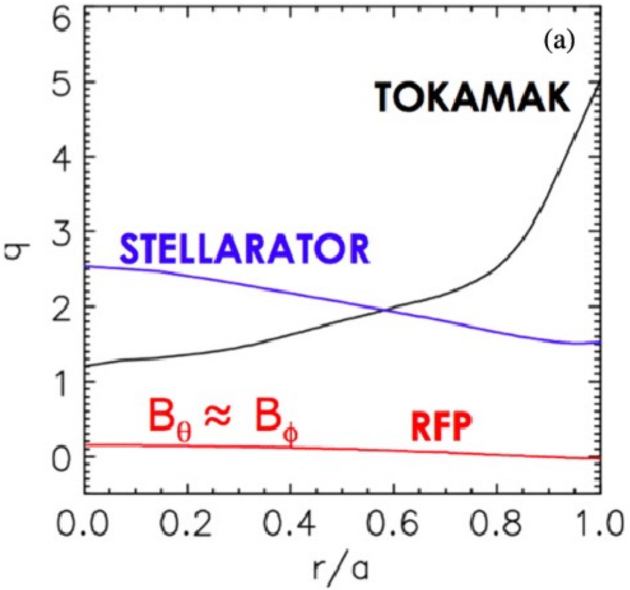
Safety Factor or q-profile

$$q = \frac{rB_T}{RB_p}$$

ratio of the number of times a field line travels toroidally per poloidal transit

The q-profile (Safety Factor) is Profoundly Important

- q-profile defines your magnetic topology and equilibrium
- Iota-profile is used in stellarators: $\iota \sim 1/q$
- Name “safety factor” is historical. At low q-values, plasmas become strongly unstable
- Defines many stability properties as well: q < 1.0, q = m/n, dq/dr ~ shear, edge value (q_{95}), etc.



Safety Factor or q-profile

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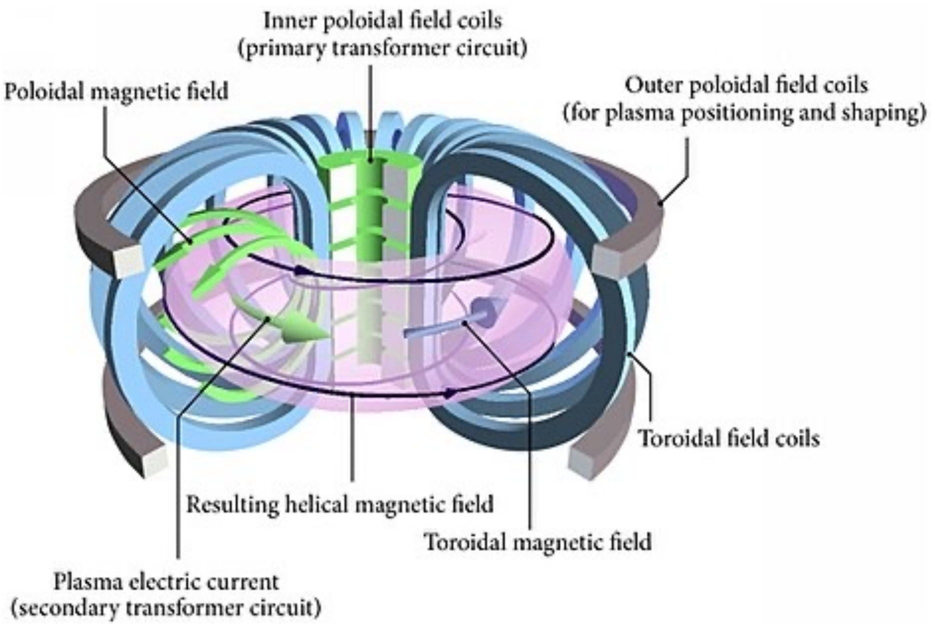
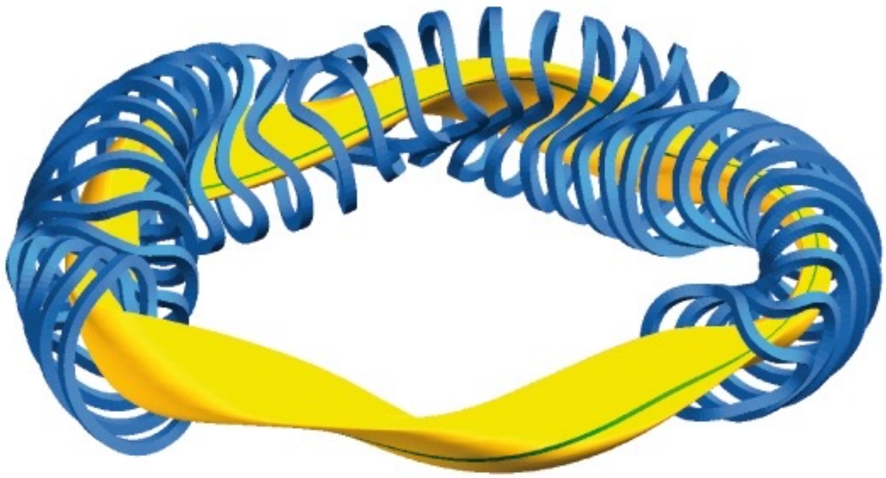
How do we add the helical twist?

Tokamak



Stellarator



Stellarator adds Twist via Non-Planar Coils

- Literal shaping of the magnetic coils creates the magnetic field

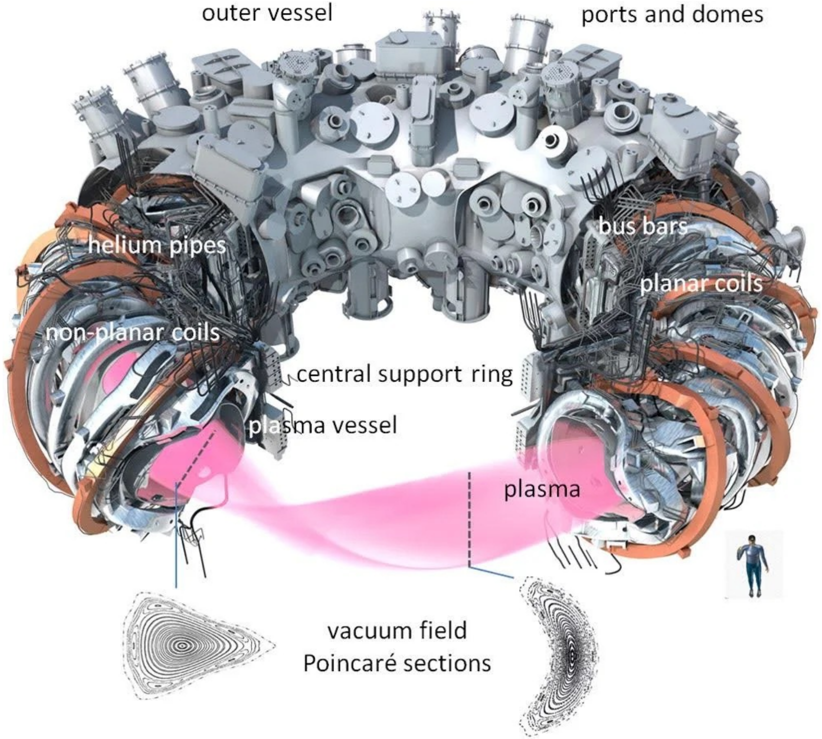
<u>Pros</u>

- No current drive
- Better MHD stability
- Inherently steady-state

<u>Cons</u>

- Symmetry breaking (3D problem)
- Engineering complexity
- Must solve for B-field numerically
- Traditionally poor particle confinement

<u>Wendelstein 7-X (Germany)</u>



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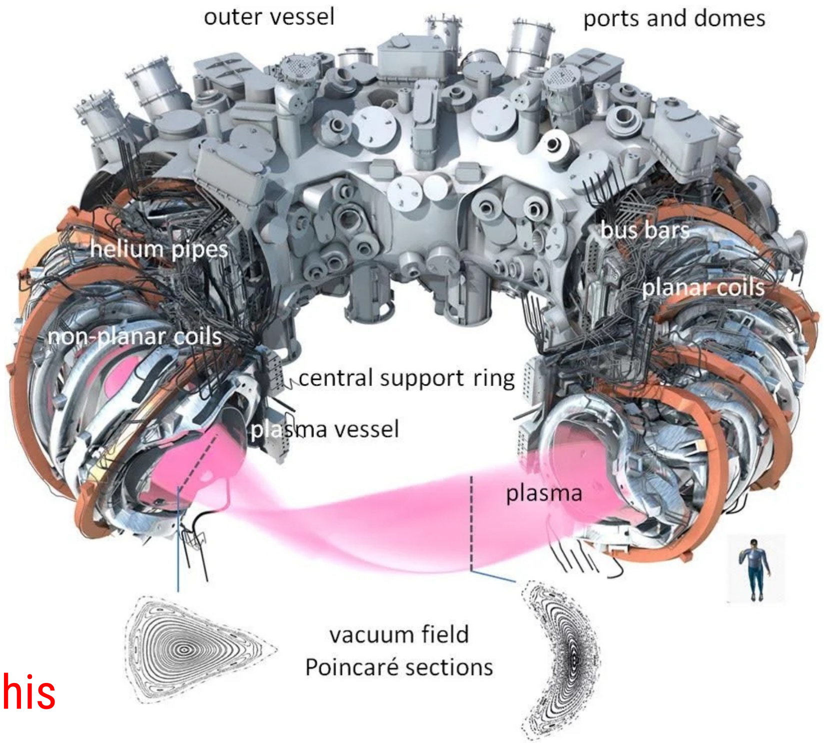
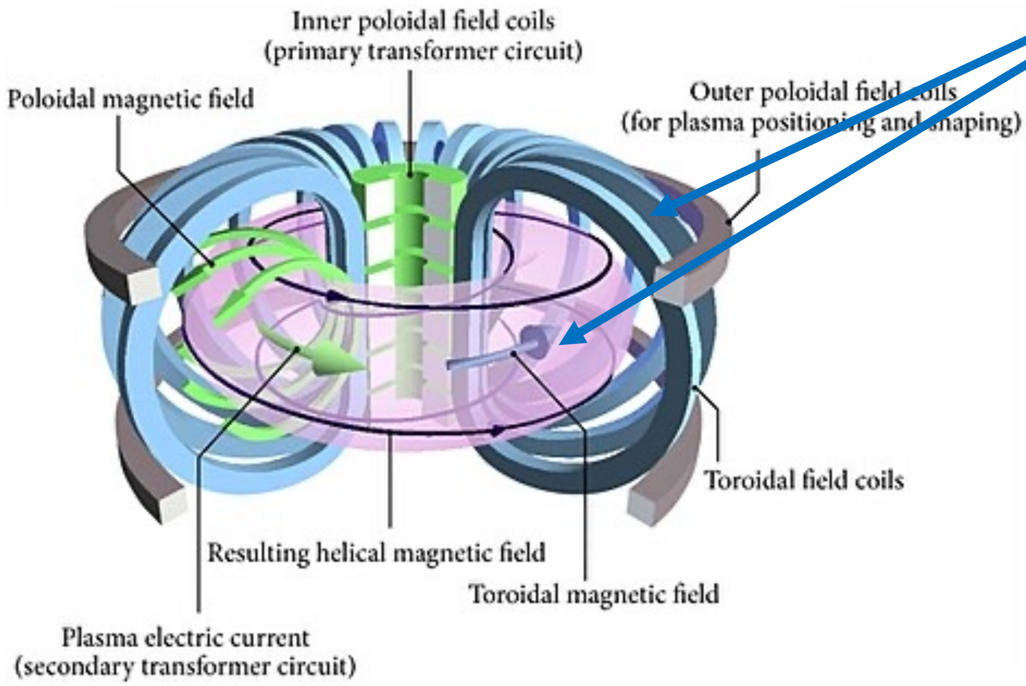
*Computational optimization has largely solved this

Wendelstein 7-X (Germany)

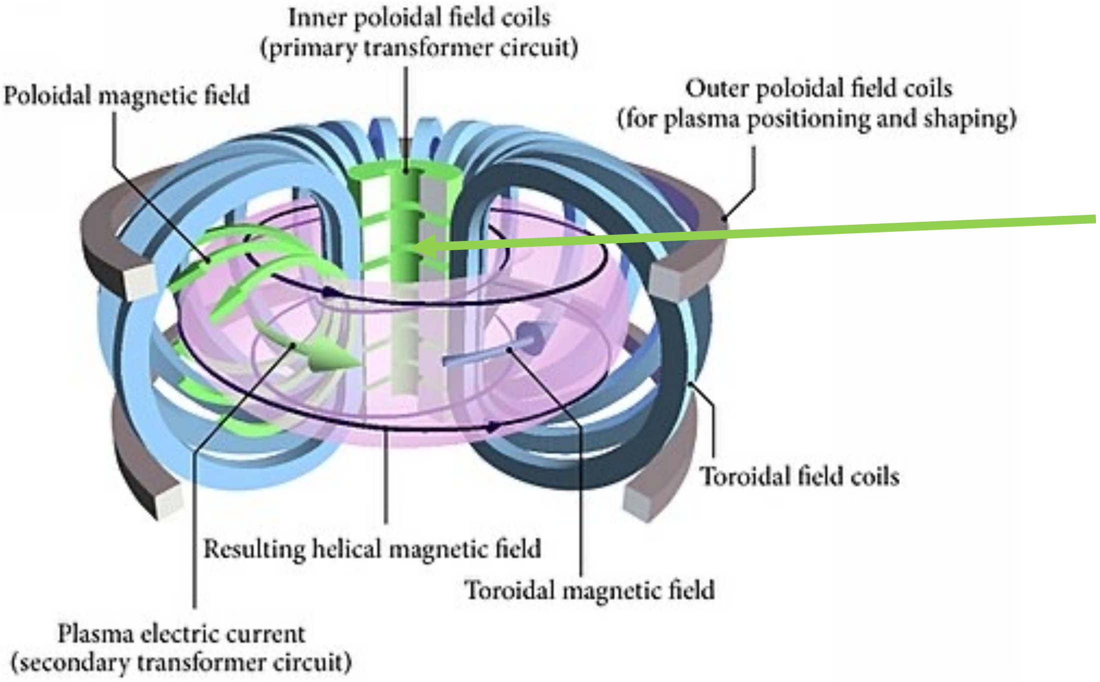


Tokamak adds Twist via a Plasma Current



1. Drive current in your TF-coils to create toroidal field component

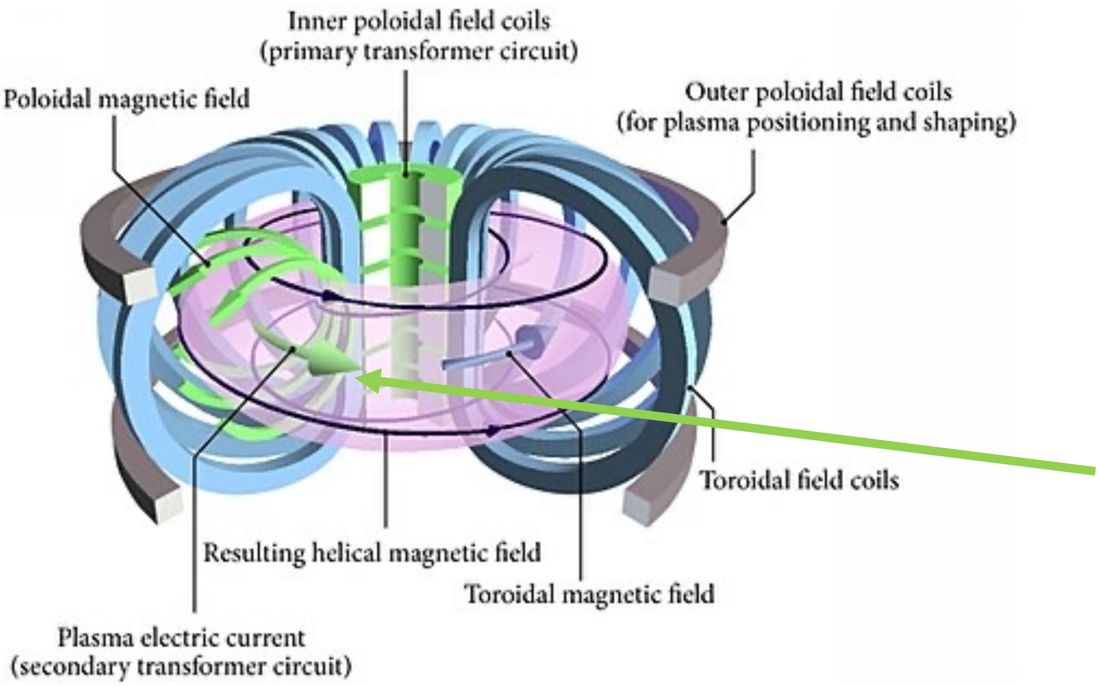
Tokamak adds Twist via a Plasma Current



1.Drive current in your TF-coils to create toroidal field component

2. Use a transformer to drive an electric field – central solenoid = primary coil, plasma = secondary coil

Tokamak adds Twist via a Plasma Current



1.Drive current in your TF-coils to create toroidal field component

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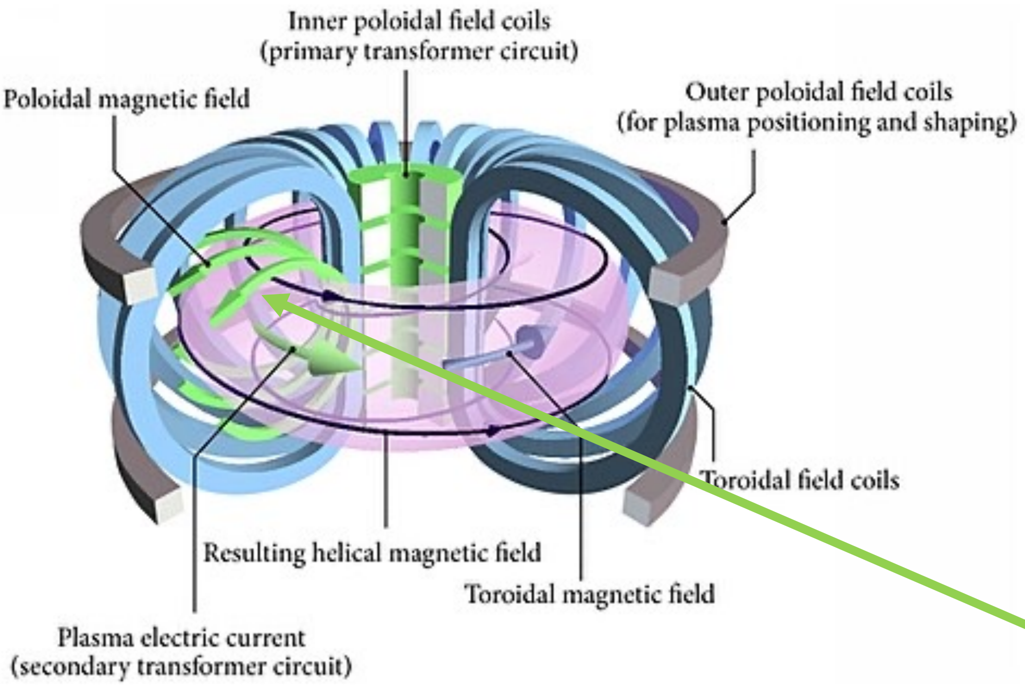
3. Electric field induces plasma current

Tokamak adds Twist via a Plasma Current



1. Drive current in your TF-coils to create toroidal field component

2. Use a transformer to drive an electric field – central solenoid = primary coil, plasma = secondary coil

3. Electric field induces plasma current

4. Plasma current creates poloidal magnetic field component

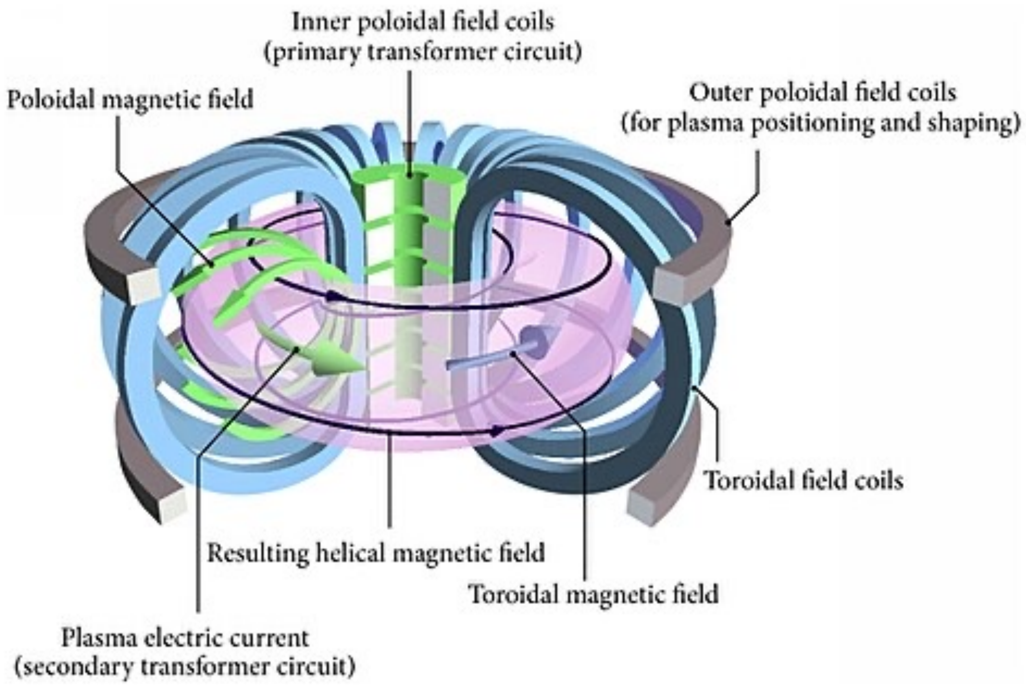
Tokamak adds Twist via a Plasma Current

Pros

- Better particle confinement
- Simpler planar coil design
- Simpler power exhaust
- Equilibrium can be solved analytically (Grad-Shafranov eqn.)

Cons

- Must drive MA plasma current
- Plasma current is source of instabilities
- Prone to disruptions (rapid loss of confinement)



A Spherical Tokamak is a Tokamak with a Smaller Aspect Ratio

- More of a cored-apple than a donut

<u>Spherical Tokamak</u>

$A \sim 1\text{-}2$

$\kappa \sim 2\text{-}3$

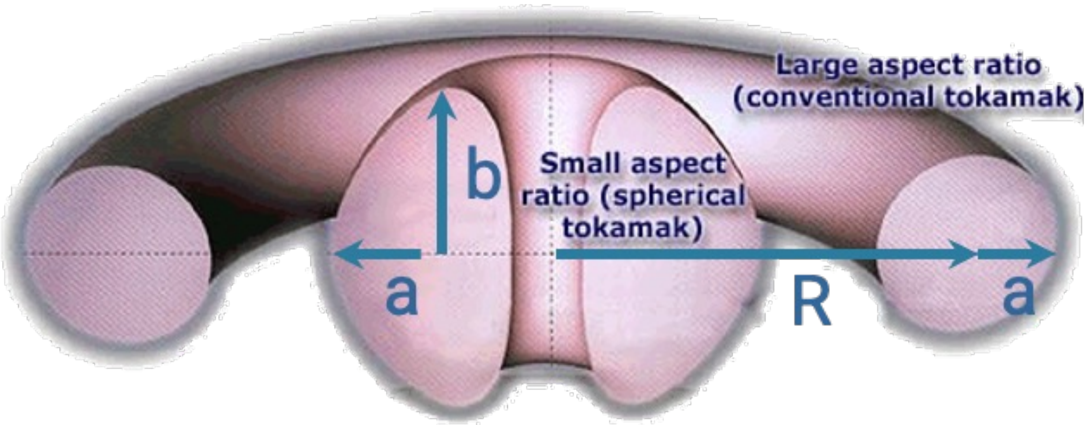
$\beta \gtrsim 0.1$

<u>Conventional Tokamak</u>

$A \sim 2\text{-}4$

$\kappa \sim 1.5\text{-}2$

$\beta \lesssim 0.1$



Aspect Ratio A = R /a

Elongation κ = b/a

Beta β = nT/B^2

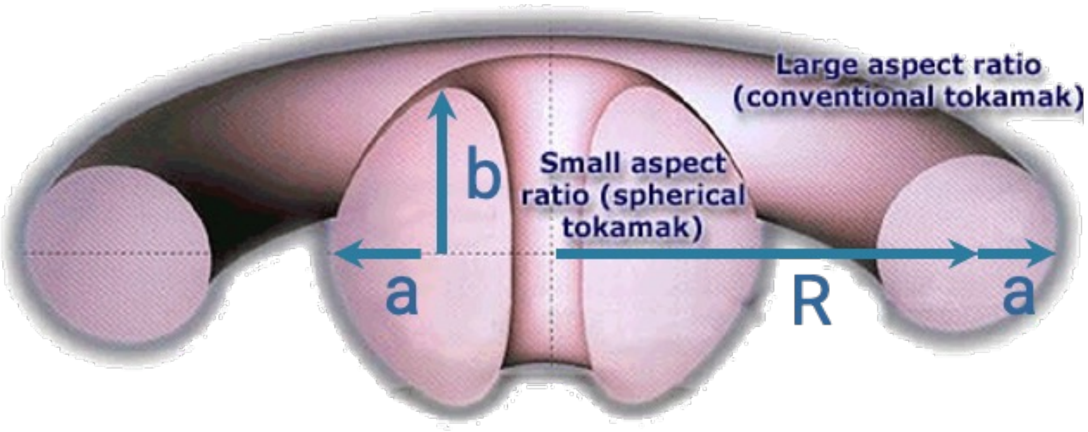
A Spherical Tokamak is a Tokamak with a Smaller Aspect Ratio

Pros

- Smaller = lower cost to build
- High beta = more fusion power per magnetic field
- Favorable curvature for MHD stability and confinement

Cons

- Not much room for central solenoid = inductive current drive is harder
- Higher heat loads
- Too high of beta leads to instabilities

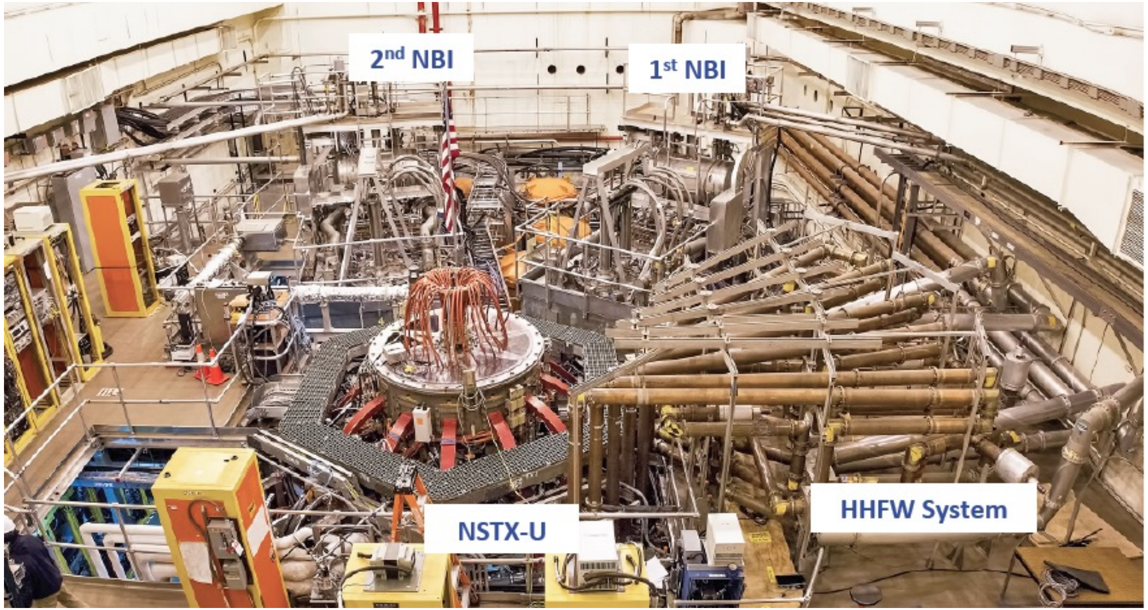


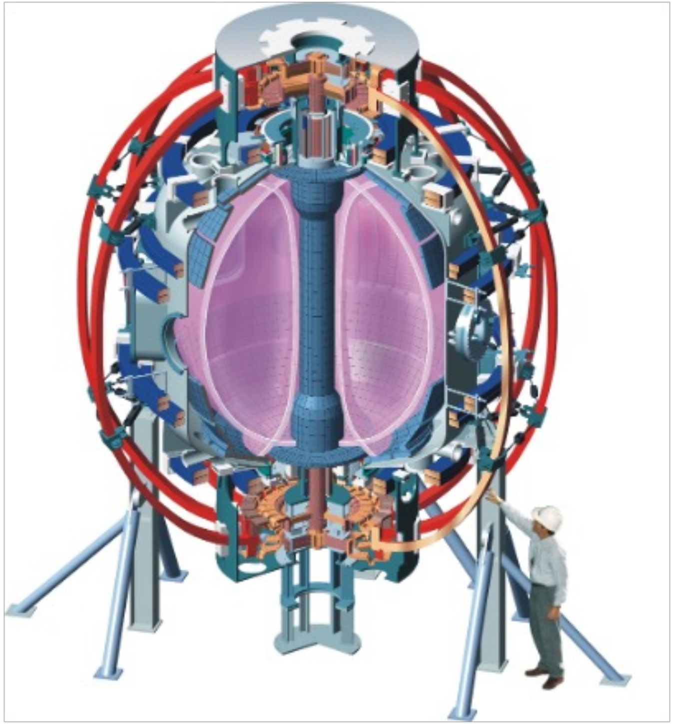
Aspect Ratio A = R /a

Elongation κ = b/a

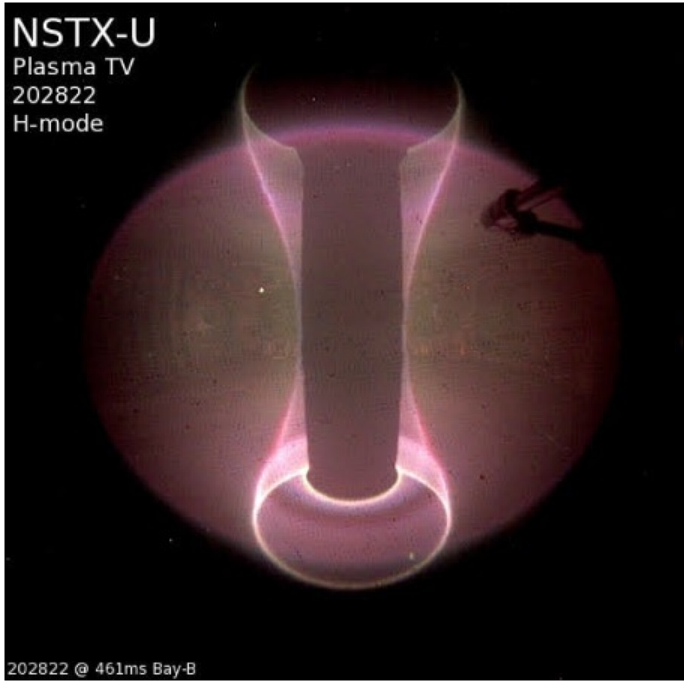
Beta β = nT/B^2

NSTX-U Operations will Resume at the End of the Year



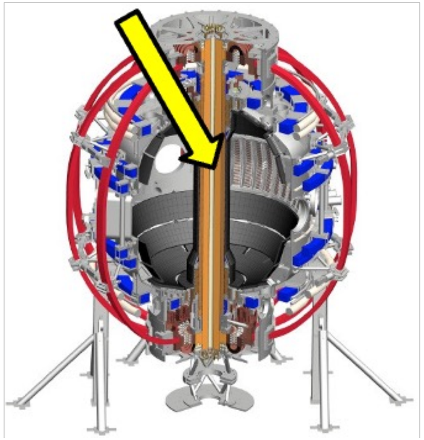


NSTX-U Operations will Resume at the End of the Year



NSTX-U Will Have Increased Performance

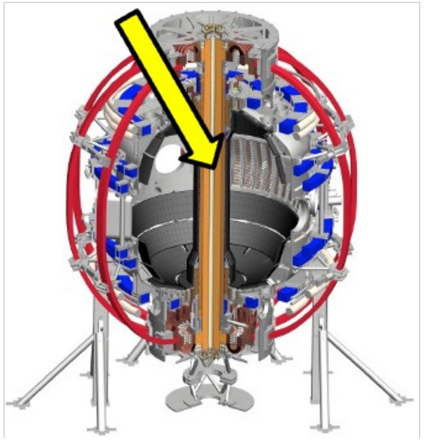
New Central Magnet

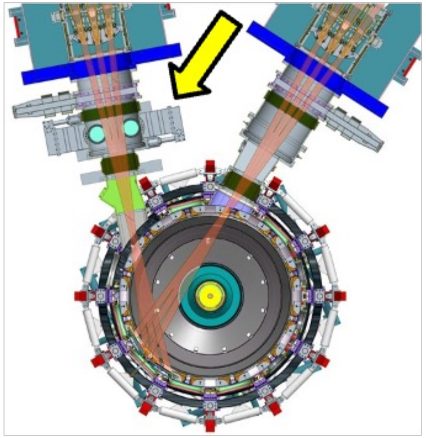


2x toroidal field (0.5 -> 1 T)
2x plasma current (1 -> 2 MA)
5x pulse length (1 -> 5s)

NSTX-U Will Have Increased Performance

New Central Magnet | **Tangential 2nd Neutral Beam**

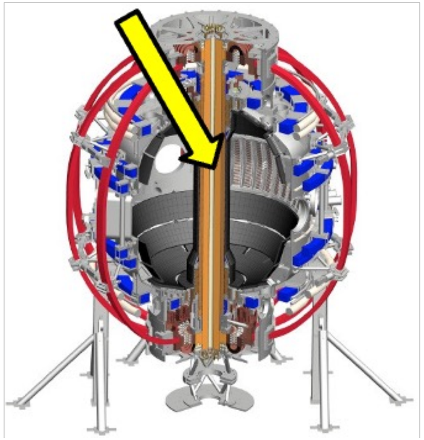


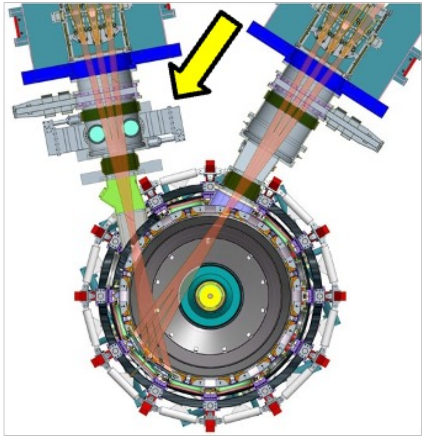


2x heating power (5 -> 10 MW)
2x current drive (tangential NBI)

NSTX-U Will Have Increased Performance

New Central Magnet	Tangential 2nd Neutral Beam





- NSTX-U will access unexplored plasma regimes
- Up to 10x $nT\tau_E$
- 4x heat flux to surfaces
- Higher T -> lower particle collisionality
- Fully non-inductive current drive (via beams)
  - Never been demonstrated in high β ST
  - Essential for steady-state

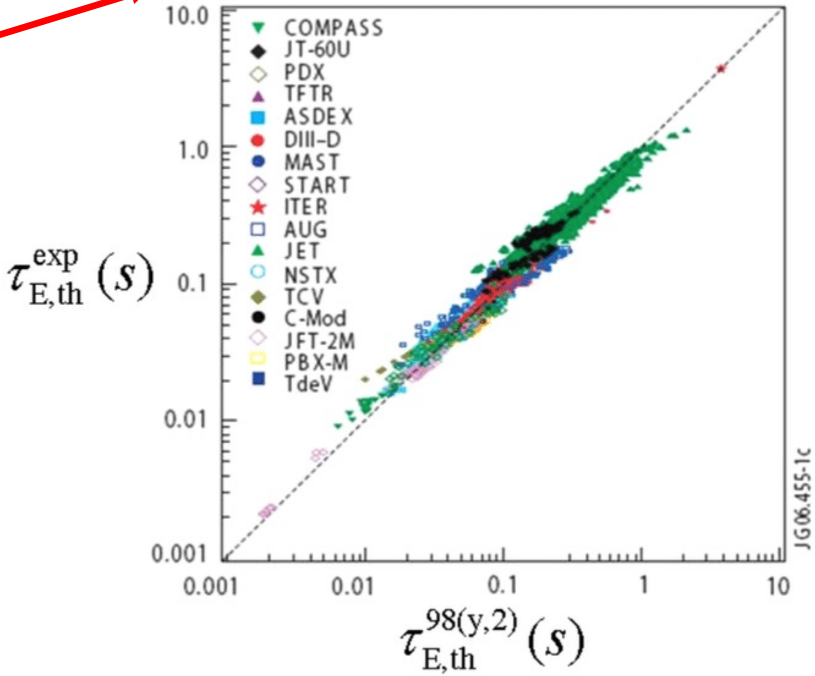
What will we learn today?

- Why do we need fusion?
- What is fusion?
- Why do we need confinement?
- How do we confine a plasma?
    - Magnetic confinement: pinches, magnetic mirror, stellarator, tokamak, spherical tokamak
    - Pros and cons of each design
    - Potential positives of the spherical tokamak and NSTX-U
- What are the biggest obstacles and problems?
- Where are we now?

How Does Confinement Time Vary with Aspect Ratio?

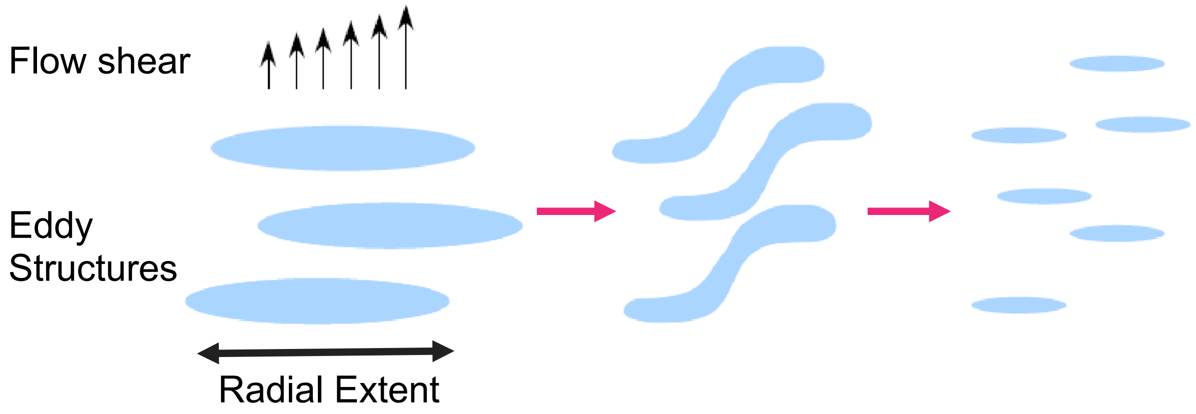
$$\tau_E = 0.0562\, I_p^{0.93}\, B_T^{0.15}\, P^{-0.69}\, n^{0.41}\, R^{1.97}\, A^{-0.58}\, \kappa^{0.78}$$

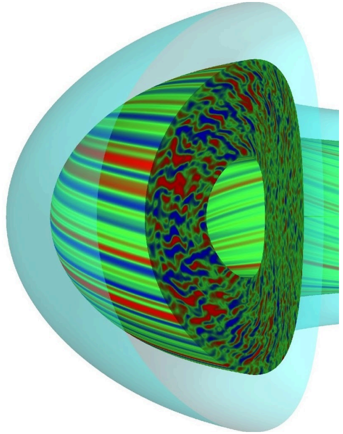
- Power scaling law is found empirically
- Favorable to low aspect ratios
- Can we isolate the effect of aspect ratio on confinement time?
- How can we really compare a low aspect ratio plasma to conventional aspect ratio plasma?
- NSTX-U aims to do self-similarity studies
    - Find subspaces of similar dimensionless variables: $\upsilon^*, \rho^*, \beta, q, A$



Tokamaks are Prone to Small-Scale Microinstabilities (Turbulence)

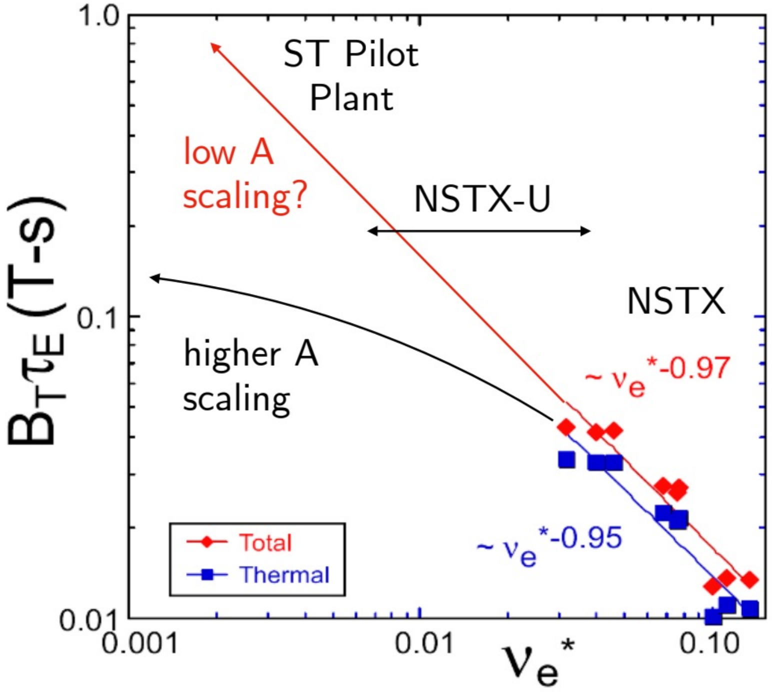
- Plasma turbulence produces eddies which can lead to enhanced outward diffusion of particles and energy
- Plasma flows can reduce turbulent transport by shearing radial structure of turbulent eddies/modes
- STs and conventional tokamaks have different turbulence due magnetic curvature, shear, and β





Confinement Time May be Better in STs at Low Collisionality

- NSTX-U will probe new collisionality regimes
- Low collisionality needs:
    - Higher plasma current
    - Higher toroidal field
    - Higher heating power
    - Density control
- Will low A or high A scaling hold?
    - Smaller STs may be more favorable for a power plant

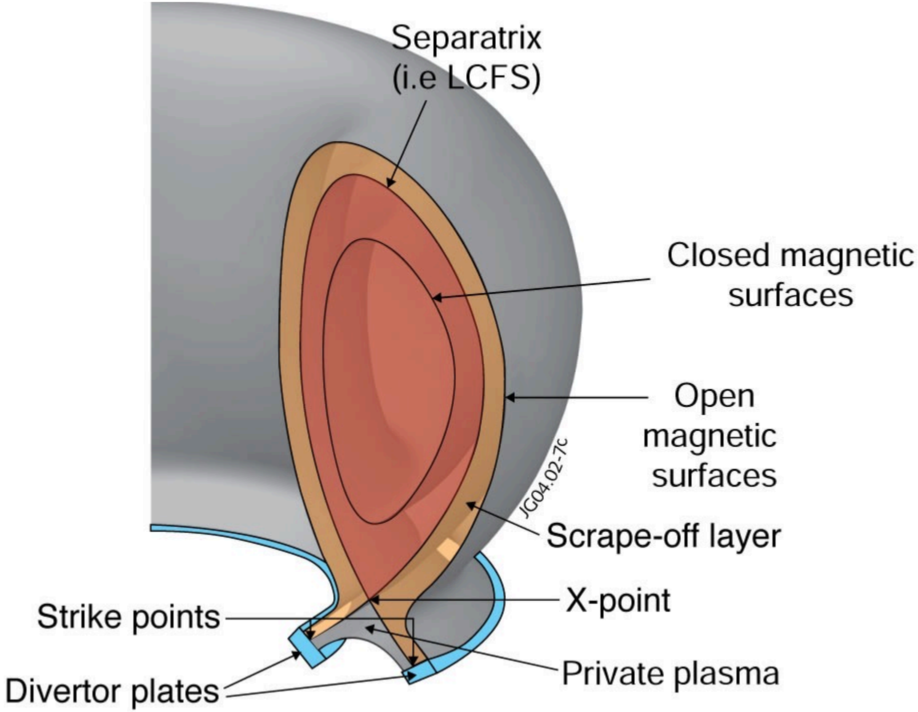


Wall and Divertor will Experience High Heat Loads

- Plasma flows along separatrix to divertor region
- Wall subject to heat fluxes from edge-localized modes (ELMs)
- Wall materials: C[Z=6], Be[Z=4], W[Z=74]
- May damage wall or lead to radiative power losses from impurities

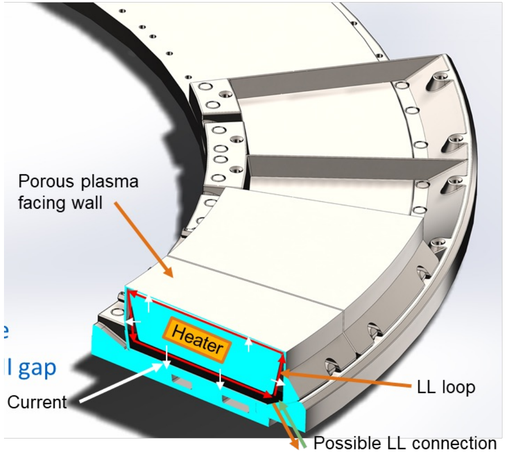
$$P_{Brem} \sim Z^2$$

- If plasma cools too much too quick, it will disrupt!

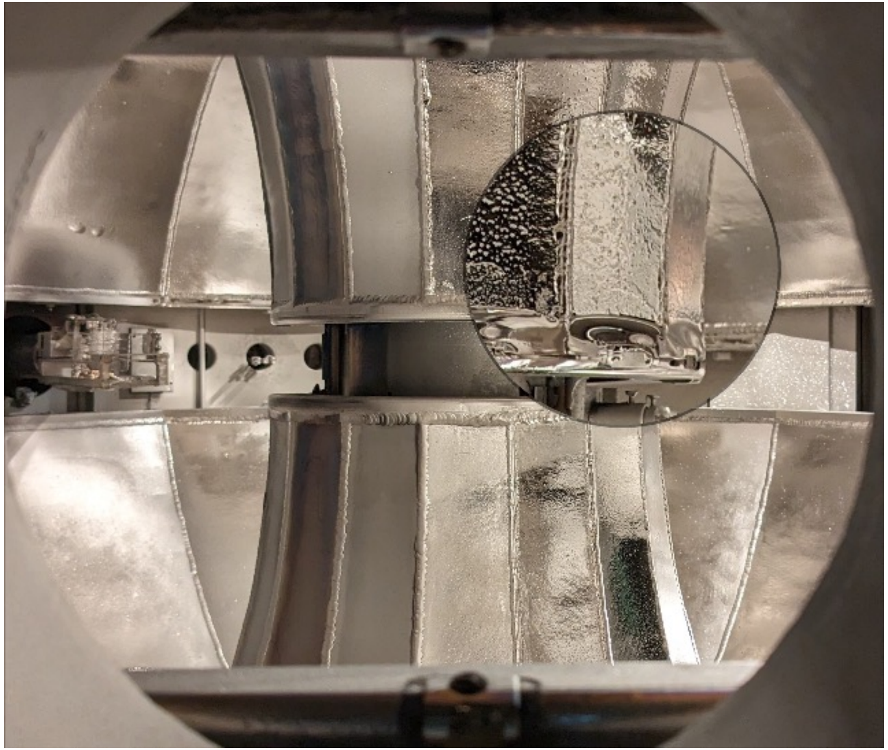


NSTX-U Will Use Liquid Li to Handle Heat Loads

- Li captures hot ions leaving the plasma
  - Reduces heat load to walls and divertor
  - Reduces impurities
  - Improved τ_E
  - Reduce ELMs
- Explored in NSTX by coating divertor tiles in Li

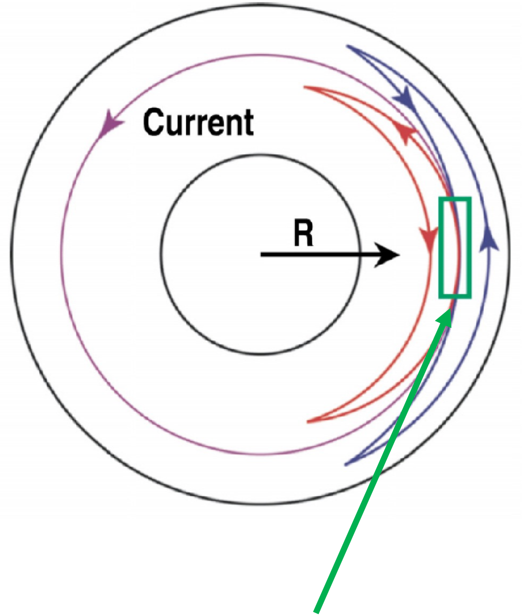


LTX-β (Smaller ST at PPPL)



STs Need Non-Inductive Current Drive for Long Pulses

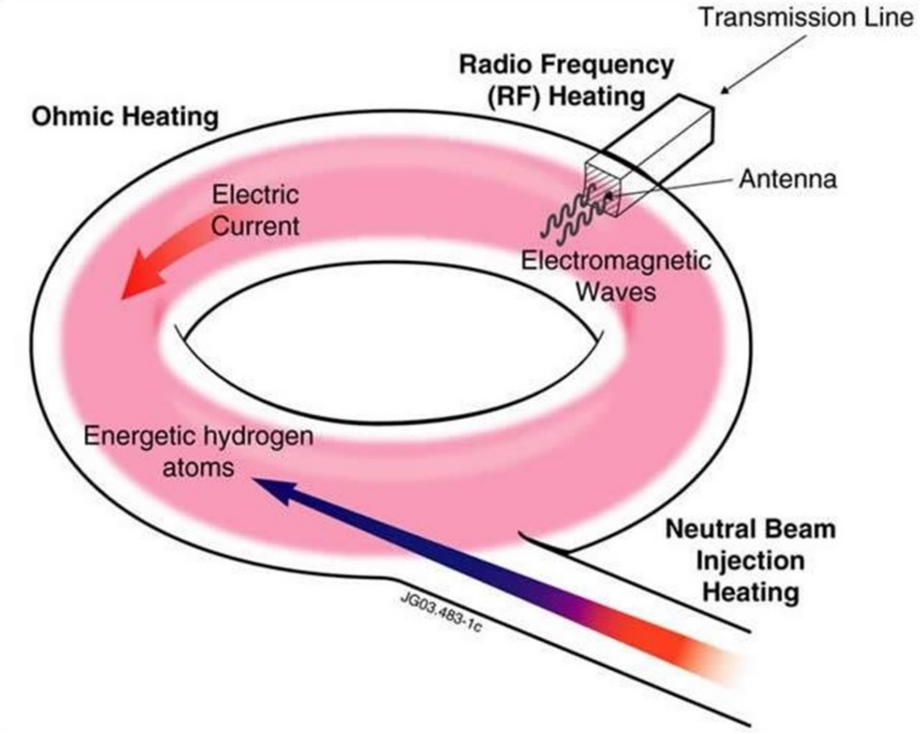
- STs have higher bootstrap current
  - “Free” or “extra” current in the toroidal direction to add more poloidal field
  - Trapped, “banana,” orbits have more particles go one way along a field line than the other
  - Pressure gradient creates a net current that is transferred to non-trapped particles via collisions
  - Higher bootstrap current -> less ohmic current needed
- Stronger in STs due to high beta



Additional “bootstrap” current in toroidal direction

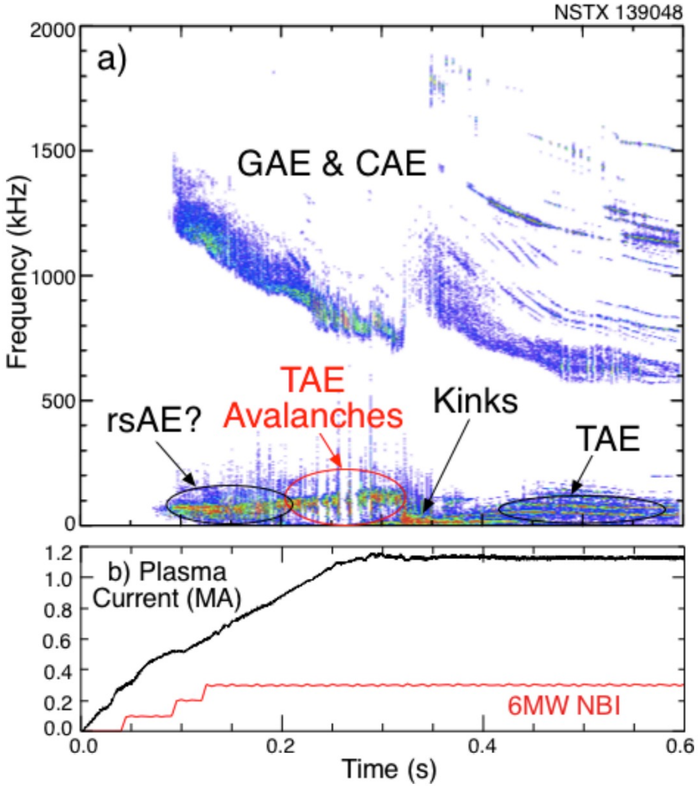
NSTX-U Will Utilize NBI for Non-Inductive Current Drive

- Neutral particle beams can inject particles tangentially to drive additional plasma current
- With 2nd NBI, NSTX-U plans to do 100% non-inductive current drive



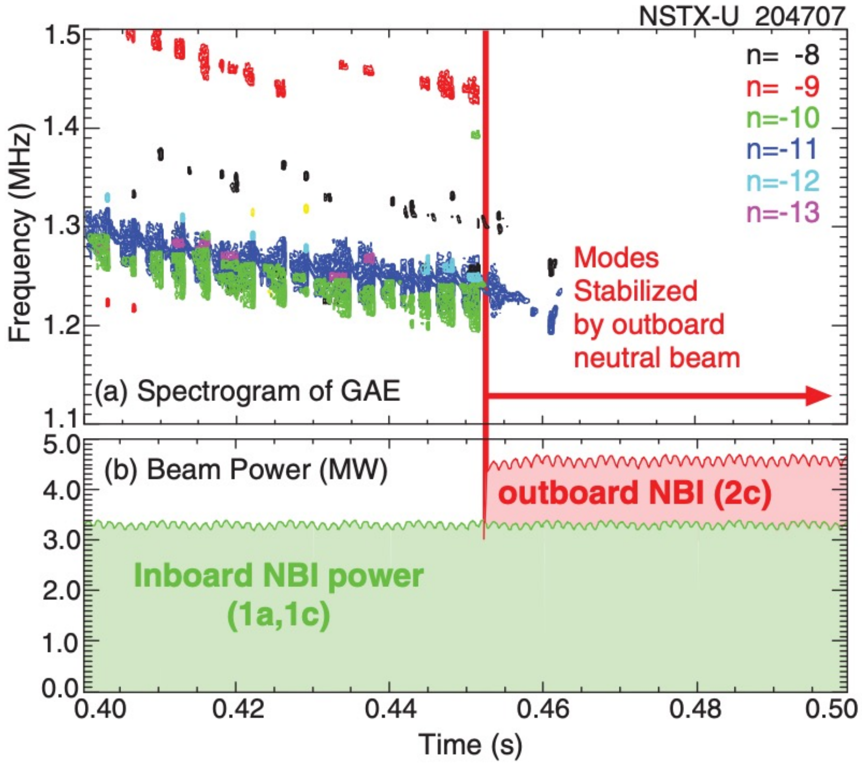
Fast Ions Can Drive Deleterious Instabilities

- STs experience more fast ion driven instabilities
  - High β_{fi} -> Free energy source for drive
  - $^{v_{fi}}/_{v_A} > 1$, where $v_A = {}^{B}/_{\sqrt{\mu_o n_i m_i}}$ -> wave-particle resonance $\omega = k_{\parallel} v_A$
- Whole “zoo” of possible instabilities: TAEs, RSAEs, BAEs, BAAEs, CAEs, GAEs, etc.
- Instabilities in turn induce fast ion transport and losses
- Weaken current drive, reduce heating, increase wall heat flux



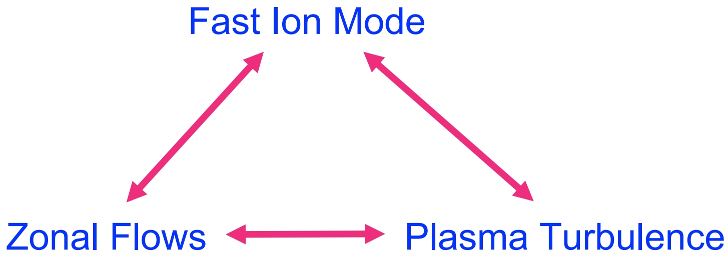
NSTX-U Will Try to Control Fast Ion Activity via “Phase-Space Engineering”

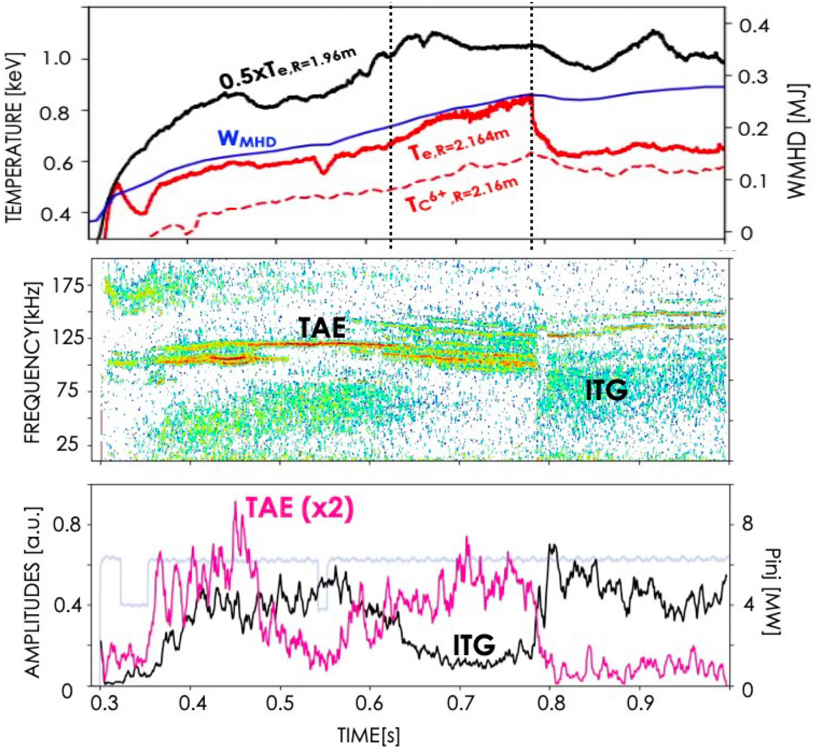
- Can we reliably and predictably control the fast ion driven modes?
- Can use NBI and RF-antenna to control the fast ion population to preferentially control fast ion instabilities
- Want to maintain current drive and plasma heating while minimizing wave-particle induced transport



The Interplay of Fast Ions and Thermal Confinement has yet to be Explored in STs

- Conventional tokamaks have observed regimes where fast ion instabilities *improve* plasma performance
- Never been reported or tested in STs
    - First experiments in MAST-U 2 weeks ago!
    - Will be explored in NSTX-U as well





More Obstacles Exist, but We Have Active Solutions

- MHD instabilities: kinks, tearing modes
  - Tailoring of q-profile and current profile
- Disruptions
  - Advanced detections algorithms with various actuators in real-time
- Runaway electrons
  - Detection and mitigation coils
- Edge-localized modes
  - Resonant-magnetic perturbations, pellet injection
- Tritium breeding
  - Rely on past DT-experiments; never been demonstrated at scale

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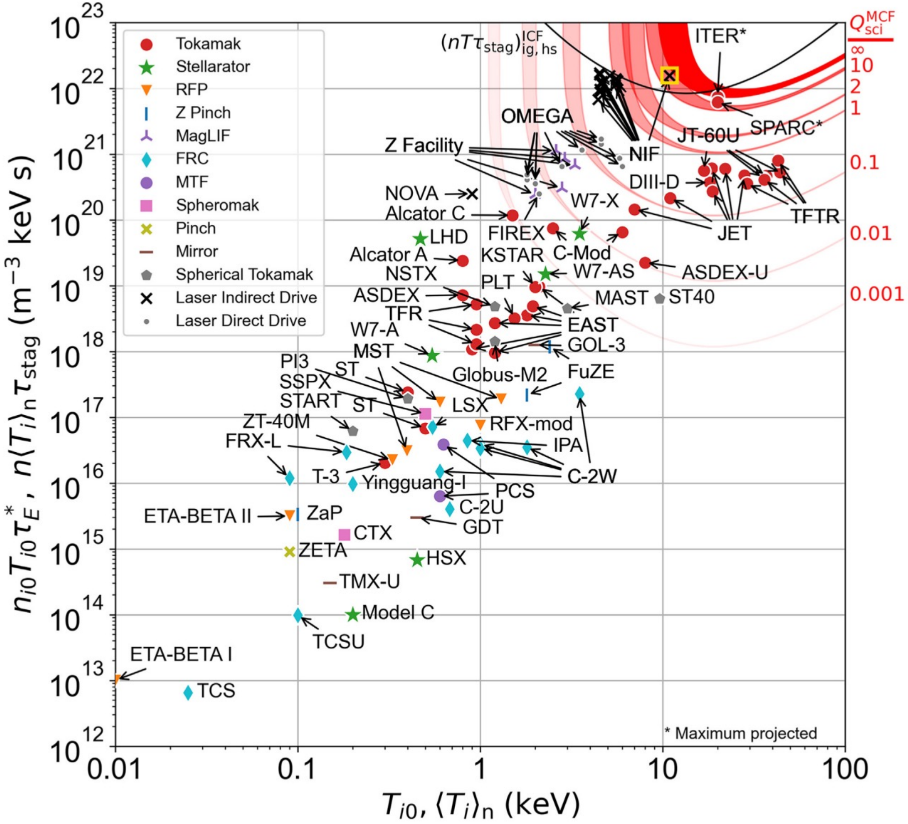
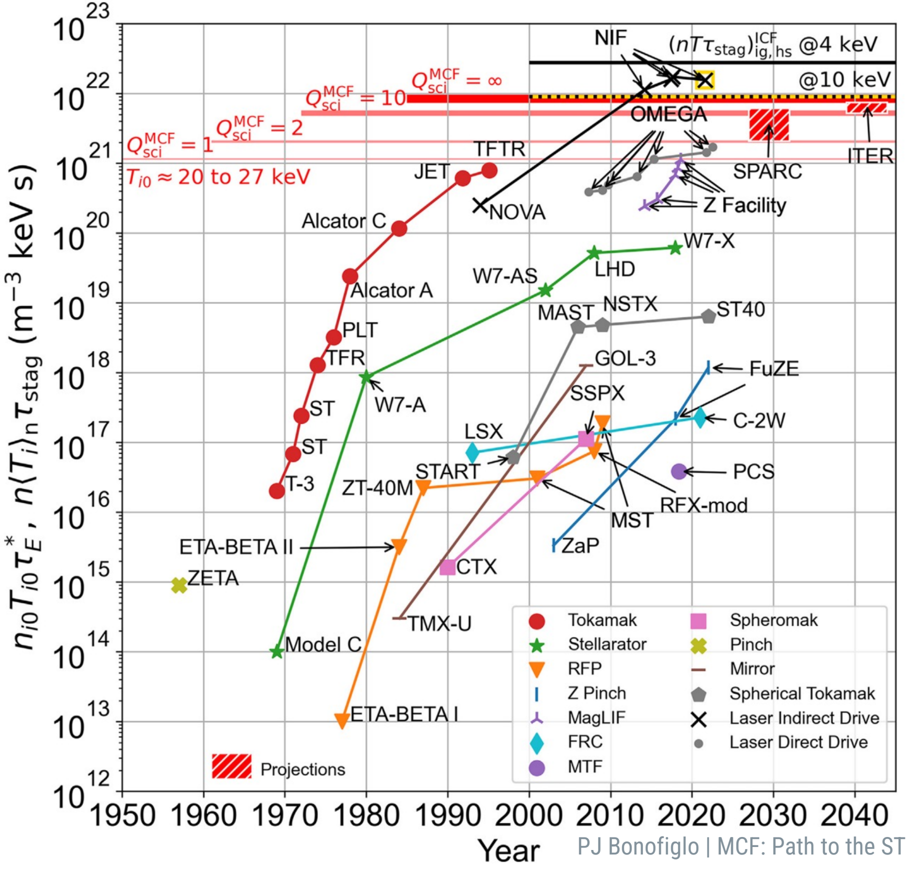
MCF has Achieved Very High Fusion Gain Factors

$$Q = \frac{P_{fus}}{P_{ext}}$$

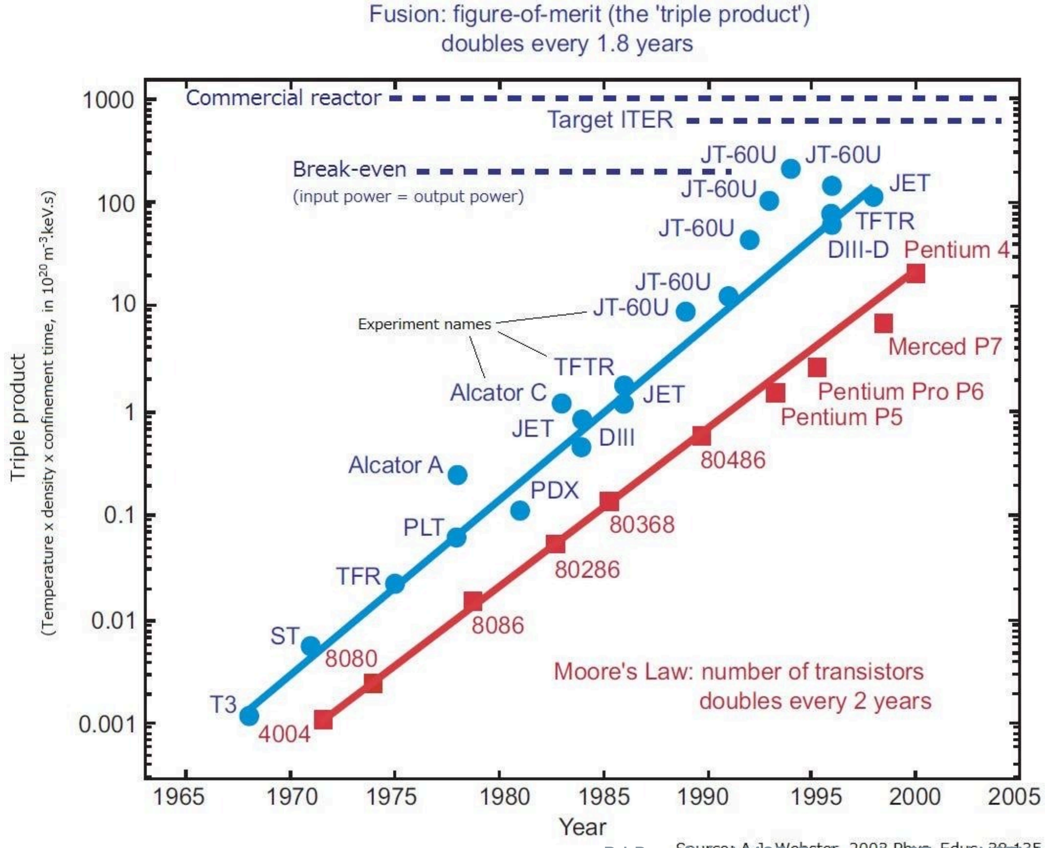
- Q = 0.67 is MCF record
- Q = 1 breakeven
- Q > 5 burning plasma with majority self-heating
- Q > 15 power plant



Experiments are Continually Getting Closer and Closer



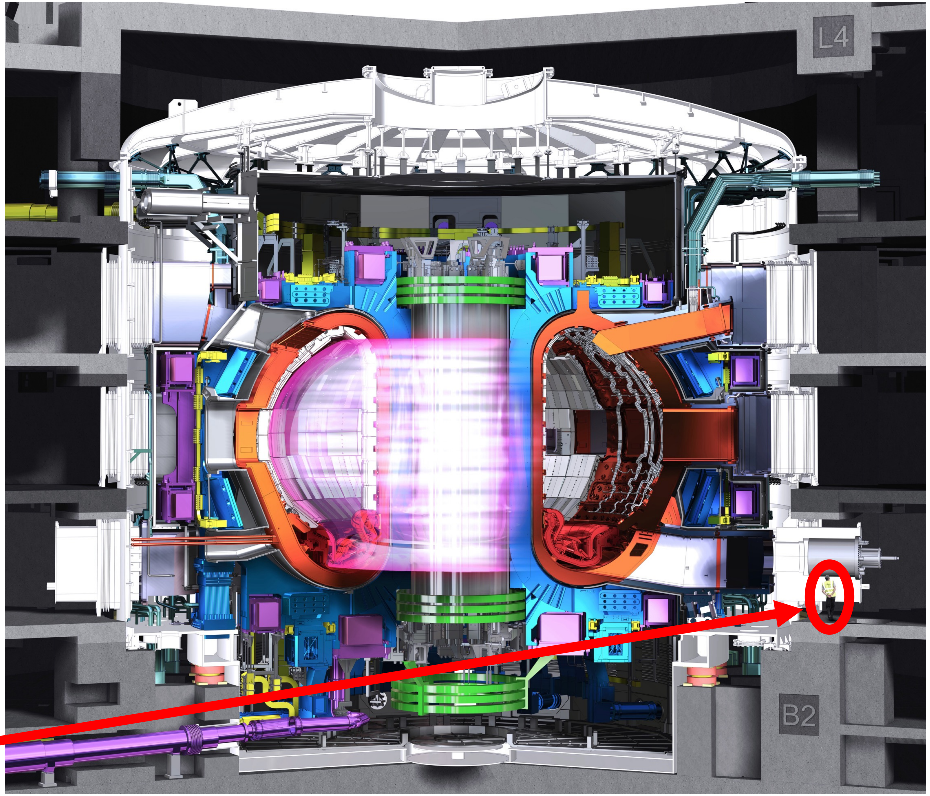
Analogous to Moore's Law for Transistors



Source: A.J. Webster, 2003 Phys. Educ. 38 135

ITER: The World’s Tokamak

- Members: USA, China, Japan, EU, Korea, Russia, India
- Demonstrate burning plasmas and investigate route towards a fusion power plant
- Construction begin in southern France in 2010; expect first plasma ~2034
- Q ~ 10, P_{fus}=500 MW



Explosive Growth of Private Fusion Enterprises

- Public-private partnerships are numerous and growing
- PPPL has working relationships/projects with many private fusion companies

Tokamaks

Commonwealth Fusion Systems

Stellarators

THEA ENERGY

TYPE ONE ENERGY

Spherical Tokamaks

Tokamak Energy

Mirror

REALTA FUSION

Z-Pinches/MagLif

ZAP ENERGY

fuse

Field Reverse Configurations

HELION

tae TECHNOLOGIES

How can you get involved?

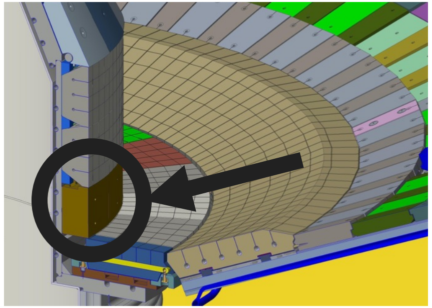
Science Undergraduate Laboratory Internship (SULI)

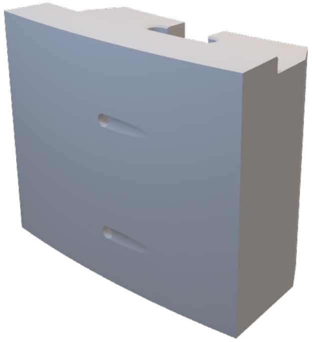
Princeton Plasma Physics Laboratory

The Science Undergraduate Laboratory Internship (SULI) program at PPPL is for undergraduates interested in performing plasma physics and fusion energy research. Students perform research, under the guidance of laboratory staff scientists or engineers, on projects supporting PPPL's research and participate in the Intro to Plasma and Fusion course hosted at PPPL.

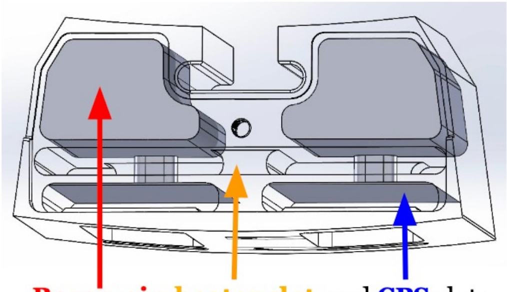
SULI intern David Wenger (UMich Nuclear Engineering ‘26): Designed, modeled & prototyped Li Capillary Porous System tile for fusion reactor

Existing Tile

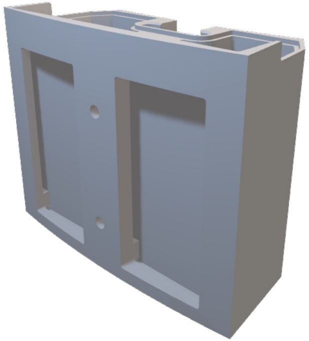




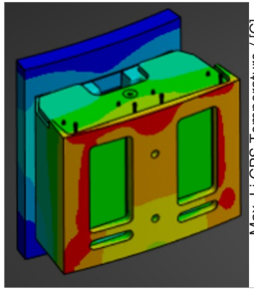
New Lithium-Filled Tile Design

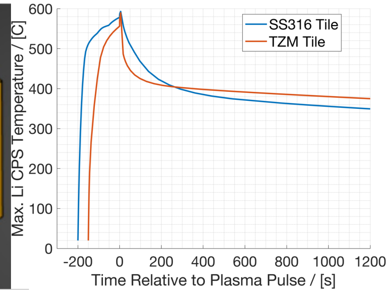


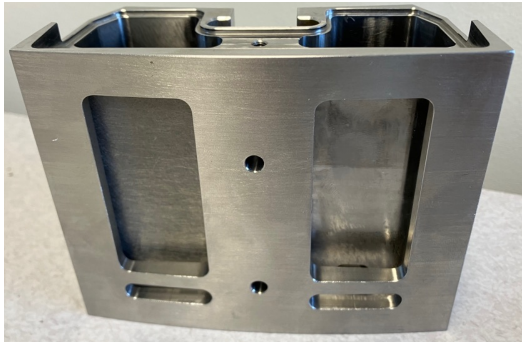
Reservoir, heater slot, and CPS slots carved out from the top of the tile



Modeling + Prototyping







Graduate Studies

The U.S. Department of Energy's

Princeton Plasma Physics Laboratory

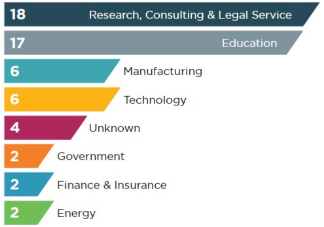
300+ alumni over a **60+** year program

Program in Plasma Physics, a graduate program in the Dept. of Astrophysical Sciences at Princeton University, based at PPPL.

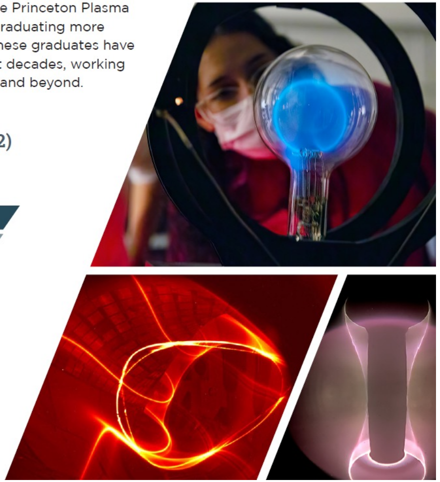
The Program in Plasma Physics, based at the Princeton Plasma Physics Laboratory, is 60+ years strong — graduating more than 300 students since it began in 1959. These graduates have shaped the field of plasma physics in recent decades, working in academia, national laboratories, industry and beyond.

Where Our Alumni Work (2012-2022)

FIRST-YEAR DESTINATIONS



Total: 57



Strategic Science Initiative Fellowship

Calling all postdoctoral researchers

The **Princeton Plasma Physics Laboratory (PPPL)** seeks exceptional postdoctoral researchers with demonstrated leadership potential to play a major role in exploring new research directions at our national laboratory, which is tackling some of the world's toughest science and technical challenges using plasma, the fourth state of matter. This opportunity offers early-career science, technology, engineering, computation and applied mathematics professionals the opportunity to conduct impactful research at a world-leading research institution.

Scan the QR Code for more info and to apply!

www.pppl.gov/SSI-associate-research-scientist

For questions: careers@pppl.gov

PPPL | U.S. DEPARTMENT OF ENERGY | PRINCETON UNIVERSITY

Dr. Robert A. Ellis Fellowship

Calling all doctoral thesis students and postdoctoral researchers

The **Princeton Plasma Physics Laboratory (PPPL)** seeks doctoral thesis students and postdoctoral researchers who are enthusiastic, passionate and have a deep interest and a strong desire to pursue a career in plasma physics or fusion science, computational engineering or a related field. This prestigious fellowship, which advances the values of scientific excellence and leadership, provides funding for a two-year appointment with the possibility of extension to a third year.

Dr. Ellis, pioneer in modern, experimental plasma physics.

Scan the QR Code for more info and to apply!

www.pppl.gov/robert-ellis-fellowship

For questions: careers@pppl.gov

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Conclusions

- Why do we need fusion? – Clean, abundant, efficient, energy
- What is fusion? – Combine (D,T) -> He4+n in a hot plasma state
- Why do we need confinement? – Fusion is slow relative to collisions
- How do we confine a plasma? – “Magnetic Bottles”
    - Many confinement schemes: stellarator, tokamak, and spherical tokamak are most popular
    - Spherical tokamak advantages: smaller, lower cost, high beta, improved confinement
- What are the biggest obstacles and problems? – NSTX-U will test these
    - High heat flux – Liquid lithium walls and divertor
    - Non-inductive current drive – Utilize high ST bootstrap current and NBIs
    - Fast ion instabilities – Phase-space engineering; possible improved thermal confinement
- Where are we now? – Very close! Rapid progress in public and private sectors
- We welcome you to get involved!

Thank You!

Contact

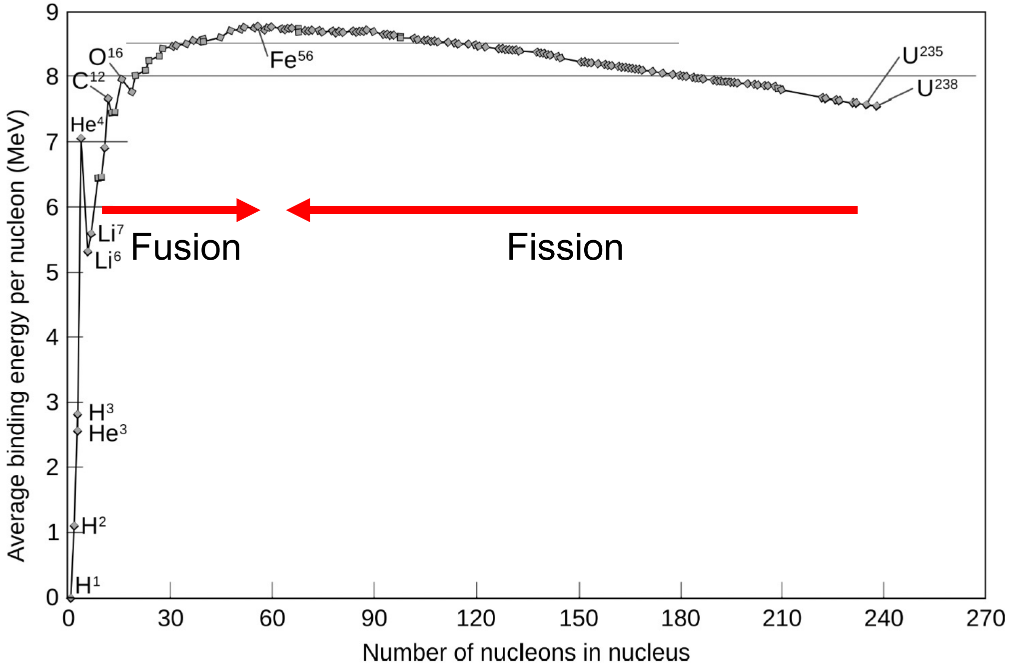
Phillip Bonofiglo

pbonofig@pppl.gov

Extra

Fusion is the Same Process that Occurs in Stars

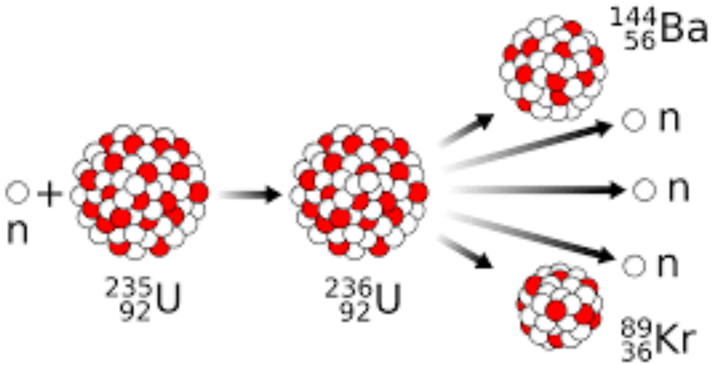
- Converting binding energy (mass) to energy: $\Delta E = \Delta mc^2$



Fission Splits Larger Nuclei to Smaller Nuclei

- Converting binding energy (mass) to energy: $\Delta E = \Delta m c^2$

$$n + U^{235} \rightarrow Ba^{144} + Kr^{89} + 3n$$



Fission Splits Larger Nuclei to Smaller Nuclei

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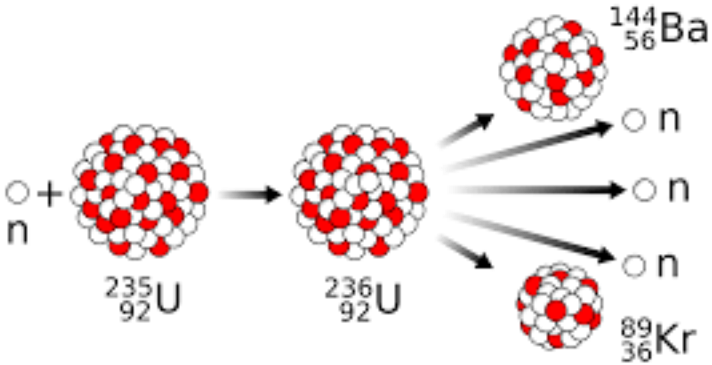

Produces neutrons
1. Use for power production
2. Drive more reactions…

Fission Splits Larger Nuclei to Smaller Nuclei

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$$n + U^{235} \rightarrow Ba^{144} + Kr^{89} + 3n$$