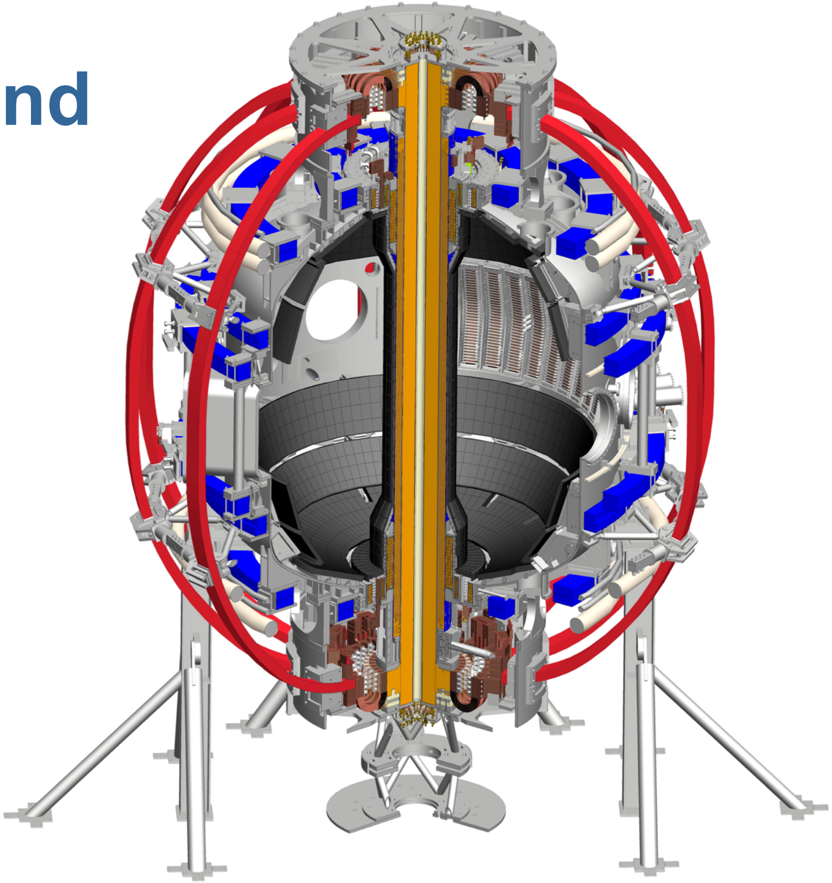
NSTX-U is sponsored by the
U.S. Department of Energy Office of Science
Fusion Energy Sciences

Introduction to Tokamaks and Spherical Tokamaks

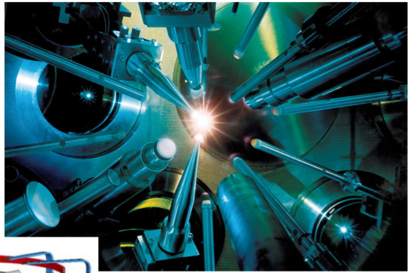
2020 SULI Introduction to Fusion Energy and Plasma Physics Course

Devon Battaglia

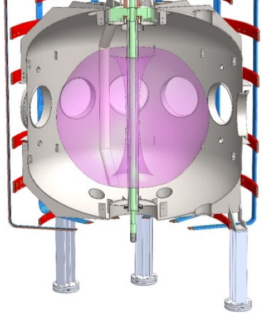
June 18, 2020



Who am I?



- Introduced to fusion energy research in a high school summer program at the Laboratory for Laser Energetics (University of Rochester)
  - I became enamored with the atmosphere within the Control Room of a big, collaborative experiment
  - Construction of a fusion reactor is a grand project that could be a “giant leap” toward a sustainable future for humans on Earth



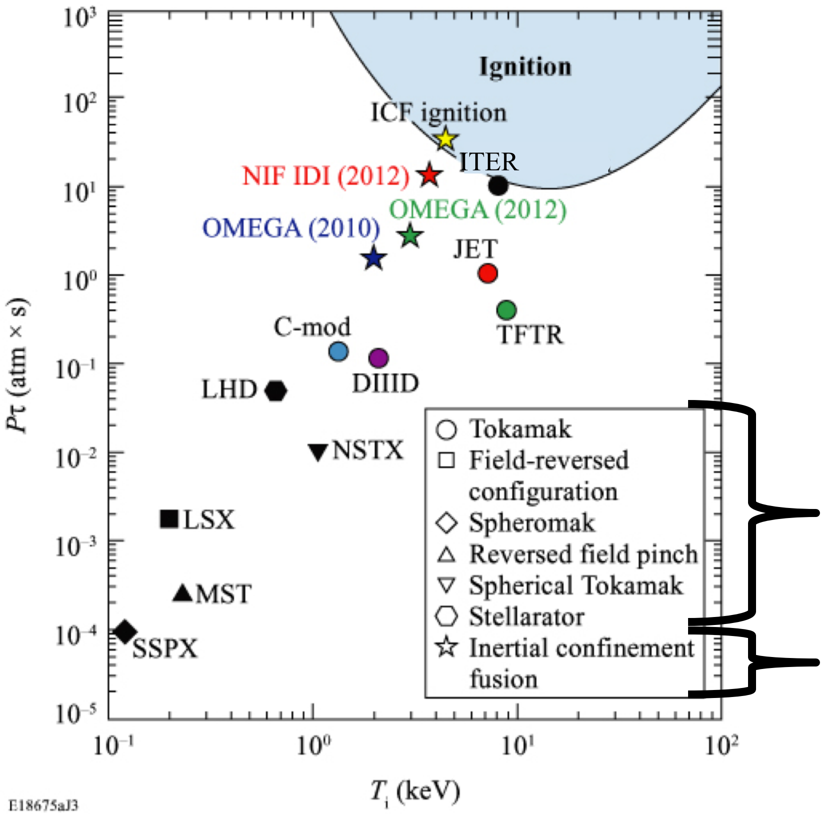
- B.S. Engineering Physics, B.A. in Music at Lehigh University
  - Five year Arts-Engineering program
- PhD in Nuclear Engineering – Engineering Physics (NEEP) University of Wisconsin - Madison
  - Thesis research on Pegasus, a spherical tokamak experiment
- Post-doctorial appointments at US tokamaks: NSTX and DIII-D
- Research Scientist and Lead Physics Operator at NSTX-U
  - I am living my “Gene Krantz” dream

Gene Krantz, NASA

NSTX-U Control room

Fusion experiments are approaching ignition conditions

- Ignition: fusion reactions completely sustain plasma temperature



MCF

(Magnetic confinement fusion)

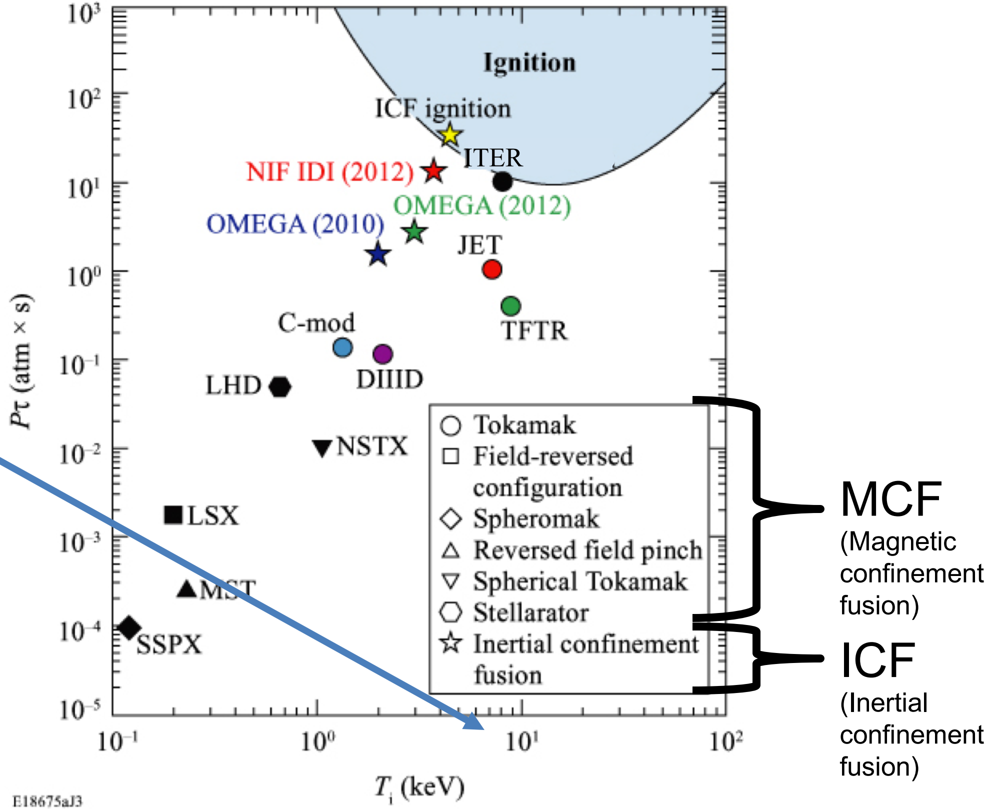
ICF

(Inertial confinement fusion)

Fusion experiments are approaching ignition conditions

- Ignition: fusion reactions completely sustain plasma temperature

- Plasma temperature ~ 10 keV
  - Dictated by fusion cross-section of deuterium-tritium

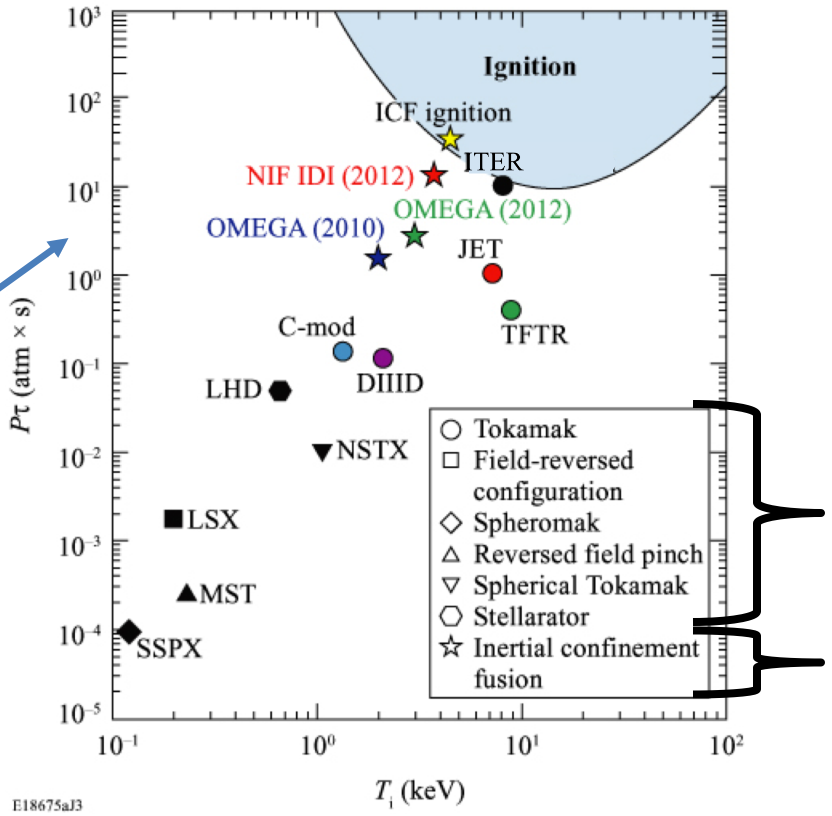


Fusion experiments are approaching ignition conditions

- Ignition: fusion reactions completely sustain plasma temperature

- Plasma temperature ~ 10 keV
  - Dictated by fusion cross-section of deuterium-tritium

- Must achieve critical pτ
  - Pressure = density x temperature
    - Increase pressure with density
  - Energy confinement time (τ) is the exponential decay time constant of the stored energy
    - Larger τ → energy leaks slower



MCF
(Magnetic confinement fusion)

ICF
(Inertial confinement fusion)

There are many ways to make a “star in a jar”

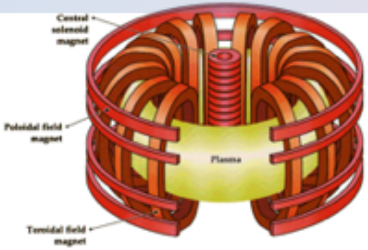
Continuous

Pulsed

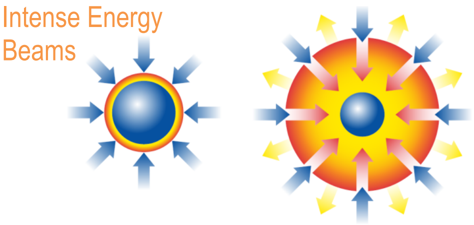
Magnetic Confinement (MCF)

Magnetized target fusion (MTF)

Inertial Confinement (ICF)



Hold on to a super hot plasma for hours, days, weeks …



Implode many new fuel pellets every second

Density: 10^{20} m^{-3}
Confinement time (τ): seconds

Density: 10^{31} m^{-3} (10^{3} x solid)
Confinement time (τ): 10^{-10} seconds

There are many ways to make a “star in a jar”

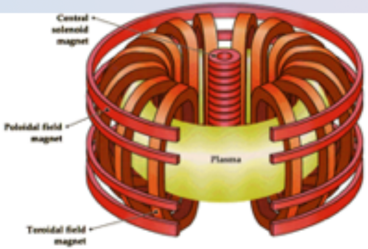
Continuous

Pulsed

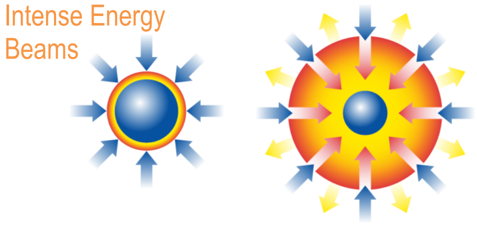
Magnetic Confinement (MCF)

Magnetized target fusion (MTF)

Inertial Confinement (ICF)



Day 5
Sefkow



Implode many new fuel pellets every second

Hold on to a super hot plasma for hours, days, weeks …

Day 10
Ma

Tokamaks

Stellarators — Day 4 Bader

Reversed-field pinch

Spheromaks

Field-reversed configurations

…

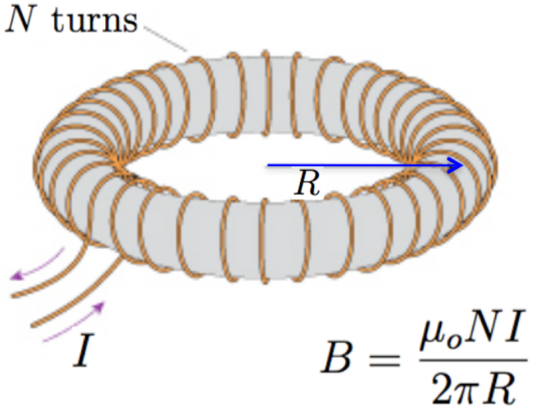
Day 4
Sutherland

Outline

- Introduction to tokamaks
- Tokamak design considerations
- Present-day tokamak research

Flashback to Tuesday

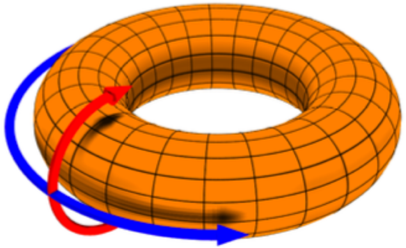
- What if we make a magnetic bottle that looks like a donut?
  - With only a toroidal field, the charged particles drift outward



$$B = \frac{\mu_o N I}{2\pi R}$$

- Solution: twist the magnetic field by adding a poloidal magnetic field
  - Creates magnetic surfaces

Torodial direction
Poloidal direction

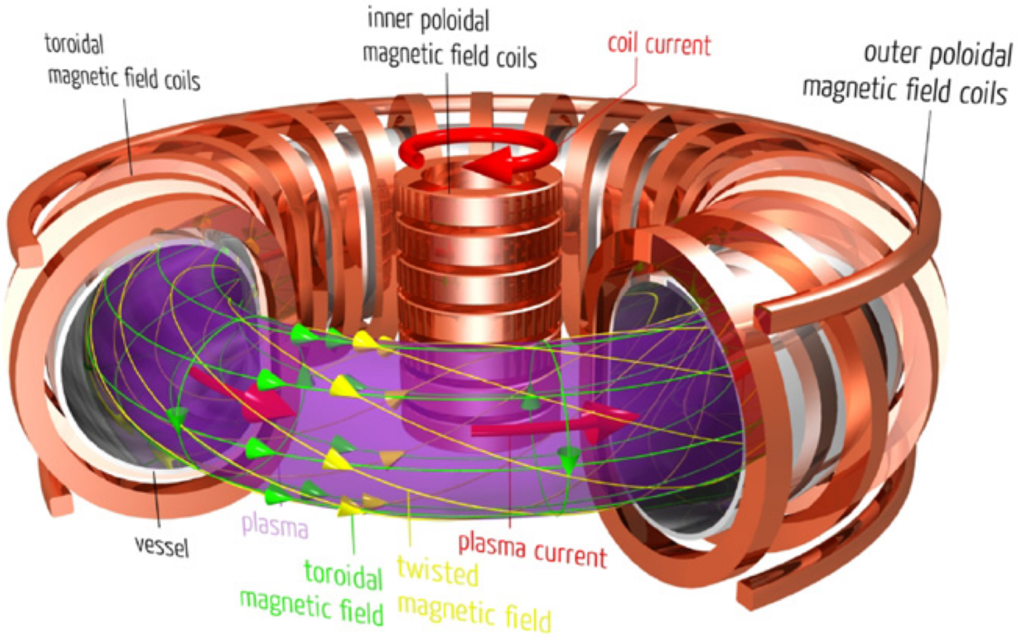


Day 2
Fox

Two leading schemes for making helical magnetic fields to confine a hot plasma for seconds, minutes, days …

1) Tokamak

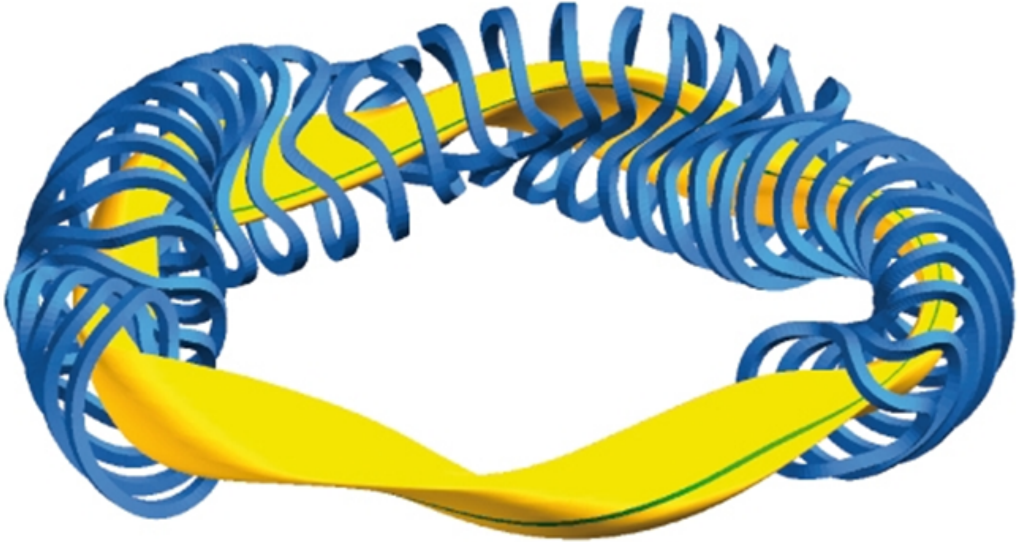
- External coils produce toroidal field
- Drive a toroidal current through the plasma (I_p) to produce a poloidal field
- Demonstrated largest pτ of all MCF concepts



Two leading schemes for making helical magnetic fields to confine a hot plasma for seconds, minutes, days …

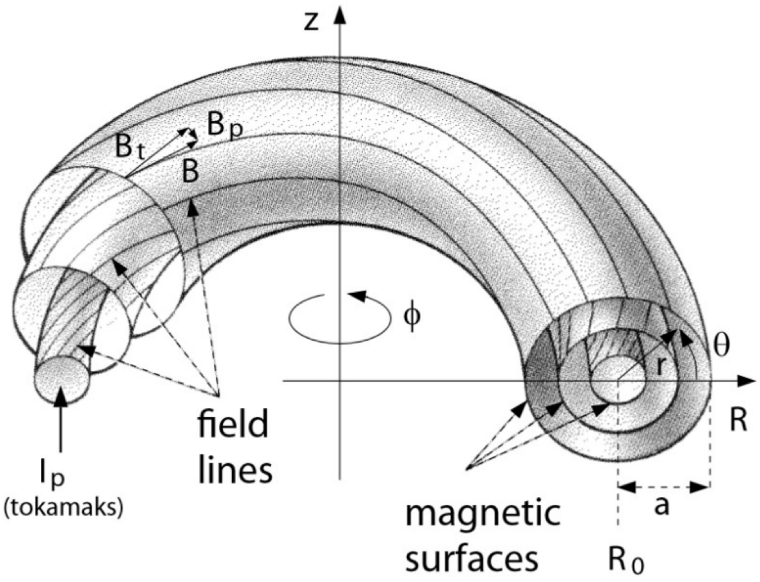
2) Stellarator

- External coils produce twisted magnetic field
- Easier to operate for long periods of time since no plasma current is needed
- Recent innovations have enabled the design and construction of optimized stellarators



Day 4 Bader

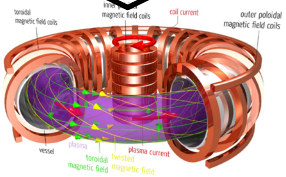
Each magnetic surface has field lines of a given helicity

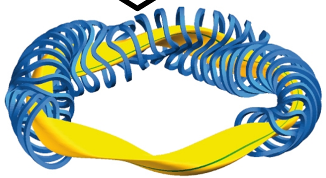


q = 2π/ί = toroidal transits / poloidal transit

"q" !!
Safety factor!!

"iota" !!
Rotational transform!!





Let's call the whole thing off …

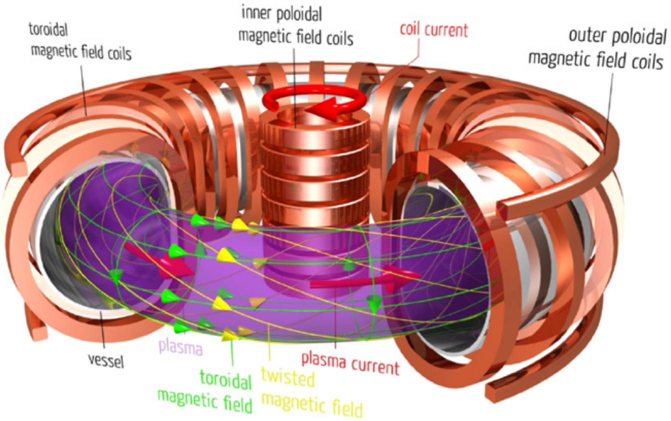
Convenient to reduce 3D toroidal coordinates (ϕ,θ,R) to 1D magnetic surface coordinates (ψ) when possible

Toroidal current must be sustained in a tokamak

- Induce current using a central solenoid
  - Cannot sustain current indefinitely
  - Could be used to start up the plasma current

$$I_p \propto V_\phi = -\frac{d\Phi_{CS}}{dt} \propto \frac{dI_{CS}}{dt}$$

- Tokamaks have a self-driven *bootstrap current*
  - Accounts for about 60% ± 20% of the needed current
- Must sustain current using external sources
  - Described in next slide
- Rapid loss of plasma current leads to the rapid loss of the plasma confinement
  - This is called a *disruption*
  - Really important to avoid in a reactor
  - Stellarators do not have this issue (we think)



Radio Frequency (RF) and Neutral Beam Injection (NBI) are the primary methods for current drive on tokamaks

- RF and NBI can heat the plasma and drive current
  - Tokamak reactors need efficient current drive
  - RF will be discussed tomorrow

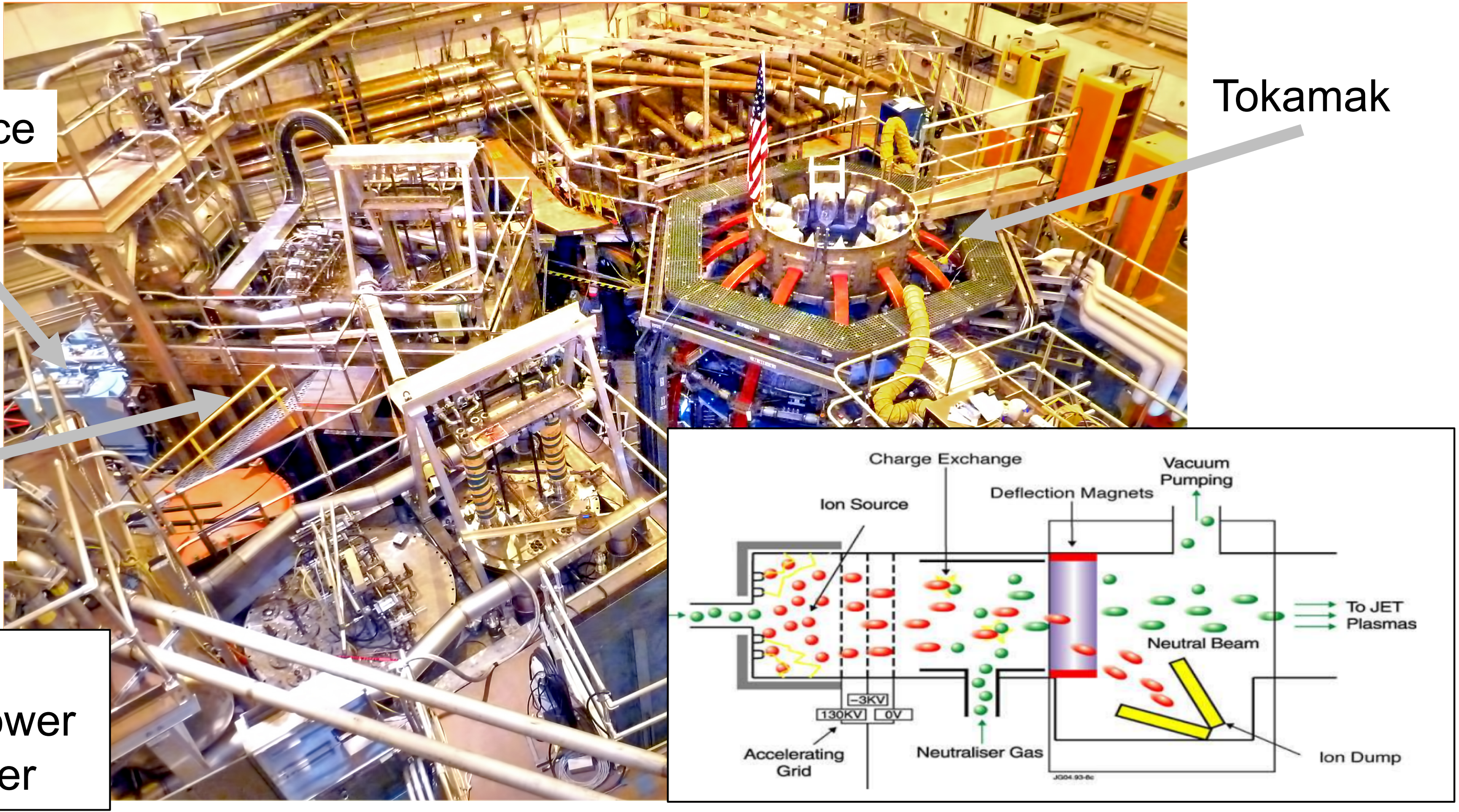
Day 5 Pinsker

- NBI: powerful beams of neutral particles
  - Neutral particles can cross the magnetic fields
  - Once inside the plasma, fast neutral particles may lose their electron to become a fast ion trapped in the magnetic field
  - Fast ions collide with colder ions and raise the plasma temperature
  - Will also fuel the plasma, drive current and induce plasma rotation

- Other current drive methods may be possible
  - Helicity injection will be discussed later today

Day 4 Sutherland

NBI systems can be as big as the tokamak



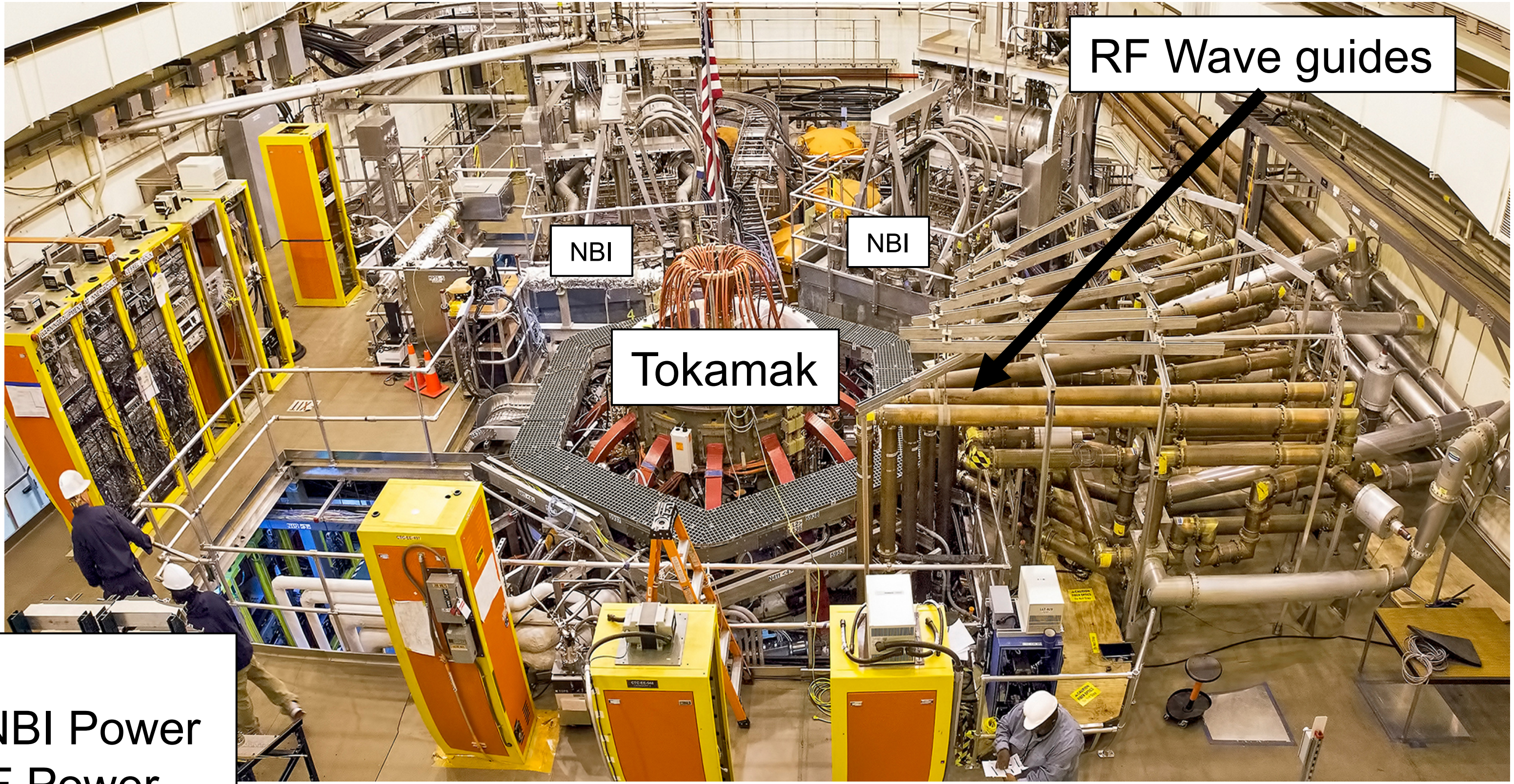
NBI ion source

Tokamak

NBI beam box

NSTX-U
12 MW NBI Power
6 MW RF Power

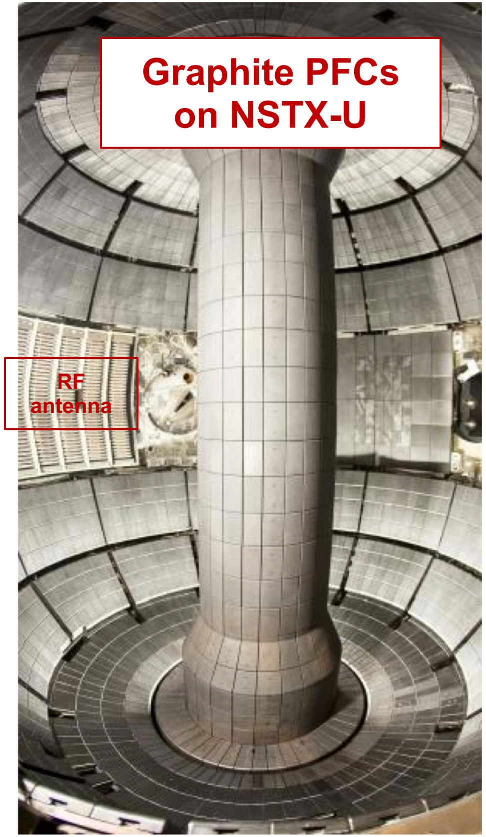
RF sources can be far away from the tokamak and connected to an antenna using wave guides



NSTX-U
12 MW NBI Power
6 MW RF Power

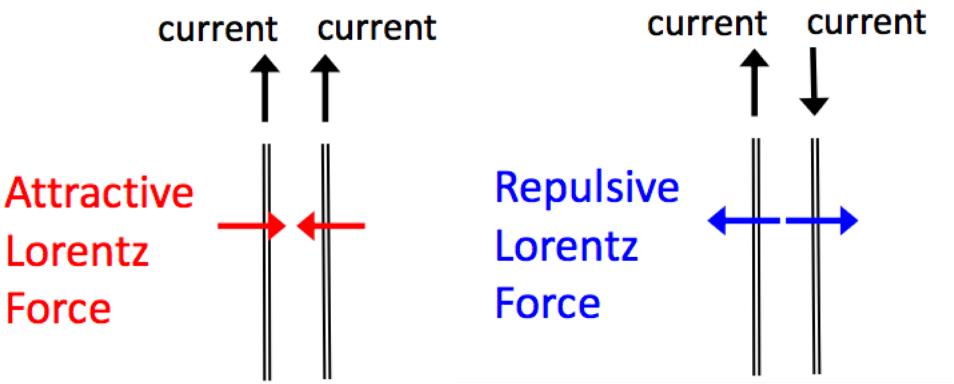
It is best to keep the hot plasma from touching the wall of the container

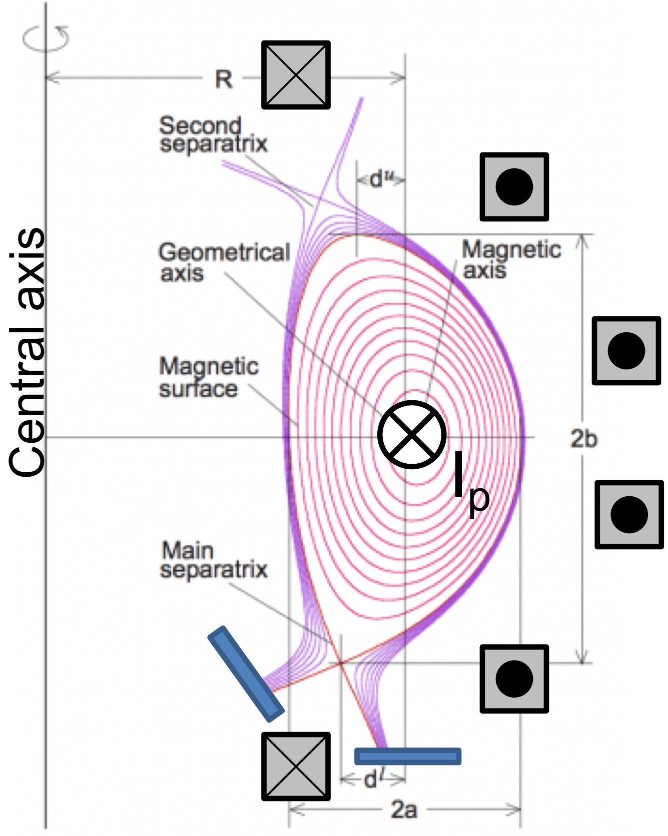
- Plasmas are created in a vacuum vessel
  - Vessel is pumped down to ultra-high vacuum
- Anything in the plasma that is not deuterium or tritium is an impurity
  - Impurities dilute the fuel and can bleed away energy from the plasma via radiation
- The plasma facing components (PFCs) are a source of impurities into the plasma
  - Best to ”levitate” the plasma inside the vessel to avoid direct contact



External poloidal magnetic fields shape the plasma

- Plasma wants to expand like a tire tube due to pressure and toroidal current
  - Use external poloidal magnetic fields to maintain a stable (i.e. equilibrium) position inside the vessel



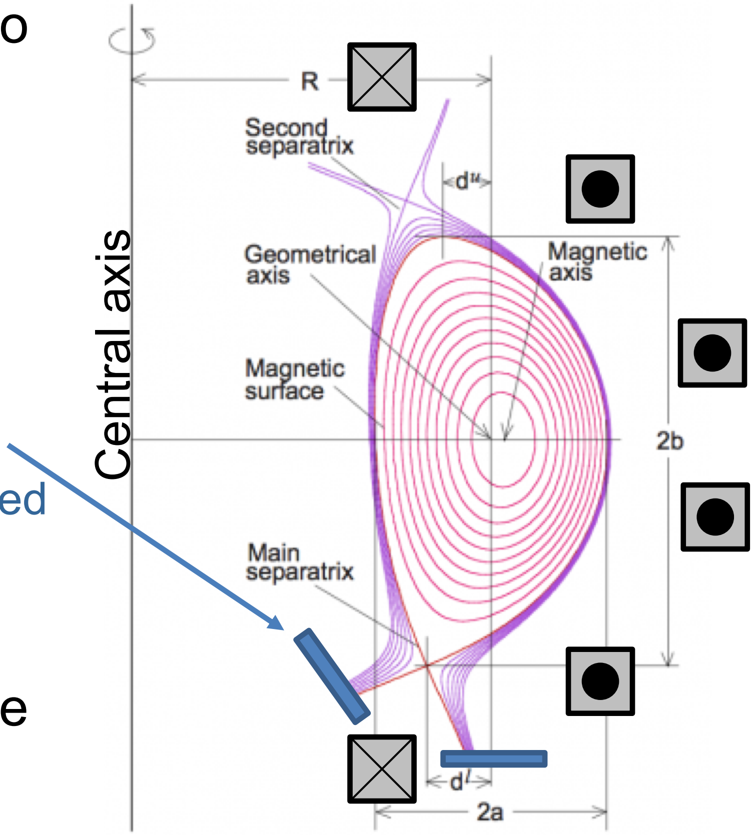


External poloidal magnetic fields shape the plasma

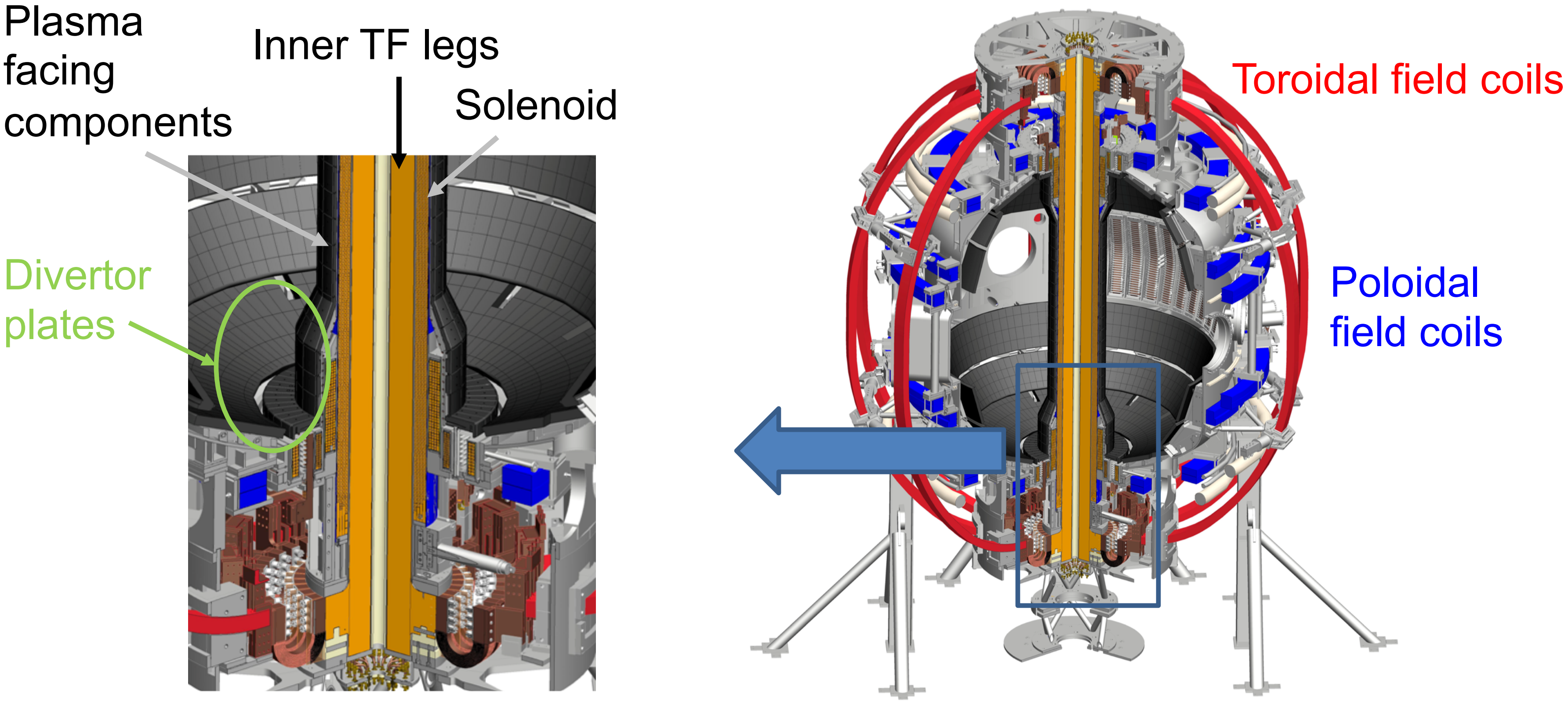
- Plasma wants to expand like a tire tube due to pressure and toroidal current
  - Use external poloidal magnetic fields to maintain a stable (i.e. equilibrium) position inside the vessel

- Coils with current in the same direction as I_p will create magnetic X-points
  - Produces a *scrape-off layer (SOL)* with *open* field lines that intersect divertor plates
  - Last magnetic surface with *closed* field lines is called the *separatrix*

- It is good to socially distance where most impurities are created (divertor plates) and the edge of the confined plasma (separatrix)



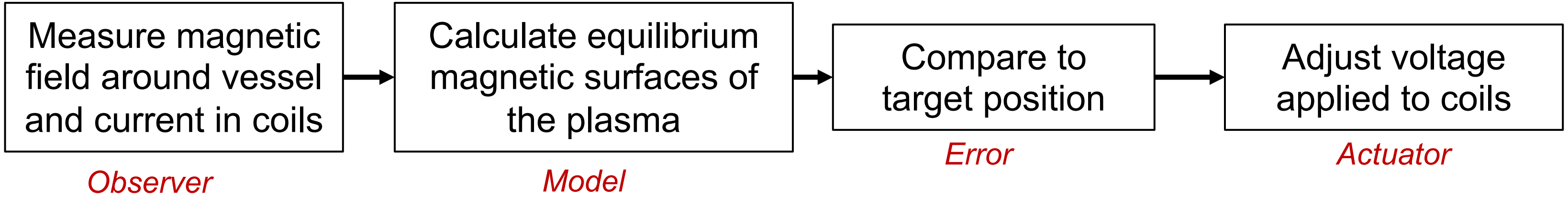
NSTX-U: National Spherical Torus Experiment



Real-time feedback is used to maintain the plasma position inside the vessel

- Movie of plasma discharge on the MAST experiment: https://www.youtube.com/watch?v=Yu9C5TEhAdQ

Example of real-time (sub-millisecond) control scheme



Measure magnetic field around vessel and current in coils → Calculate equilibrium magnetic surfaces of the plasma → Compare to target position → Adjust voltage applied to coils

Observer *Model* *Error* *Actuator*

One of the many cool things about working in this field:

Scientists and engineers come from all sorts of backgrounds to contribute to the realization of fusion energy. Real-time control of non-linear, multi-scale systems is a research field in and of itself and fusion energy is just one application.

Outline

- Introduction to tokamaks

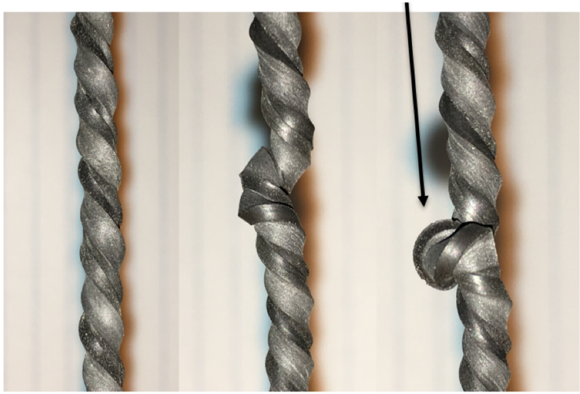
- Tokamak design considerations

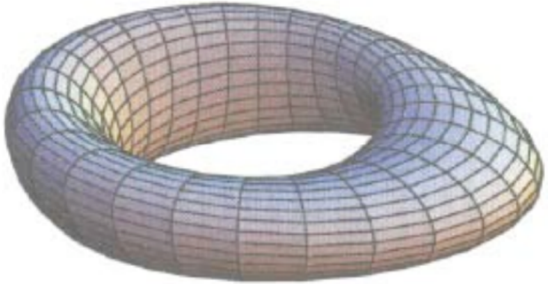
- Present-day tokamak research

There is a limit to I_p in a tokamak

- Energy confinement (τ) improves with larger I_p
  - As I_p increases, the magnetic field lines make fewer toroidal transits for each poloidal transit
  - Lower q

$$q_* = \frac{2\pi}{\mu_0}\frac{B_\phi}{I_P}\frac{a^2}{R}$$

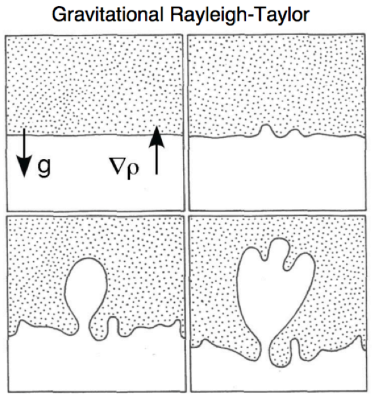




- If q is too small, the magnetic field can kink
  - Thus q is the “safety factor”

There is a limit to the achievable plasma pressure for all magnetic confinement schemes

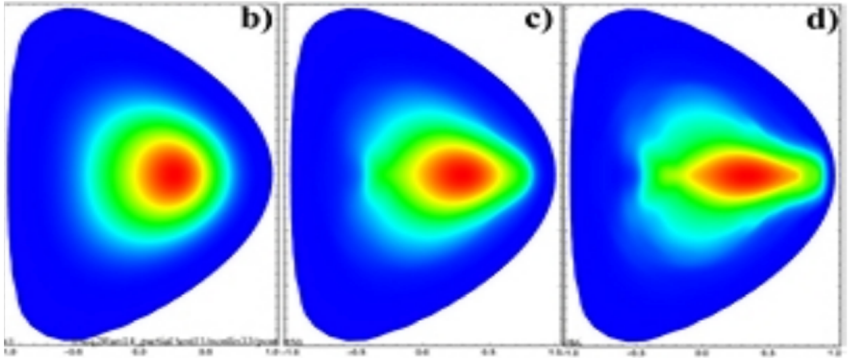
- An (imperfect) analogy: restoring force of the magnetic field is gravity in the familiar Rayleigh-Taylor instability
  - Plasma can *balloon* and degrade confinement (τ)


Gravitational Rayleigh-Taylor

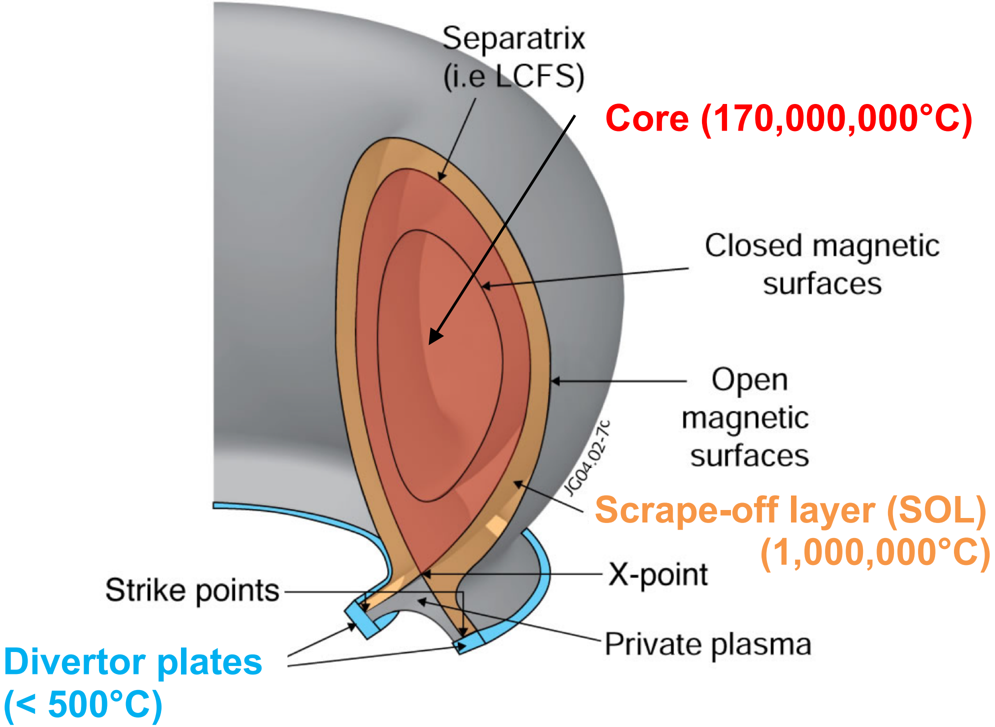
- Pressure limits are expressed in terms of a normalized pressure called beta:

$$\beta = \frac{\text{plasma pressure}}{\text{magnetic pressure}}$$

$$\beta = \frac{2\mu_0 <p>}{B^2}$$



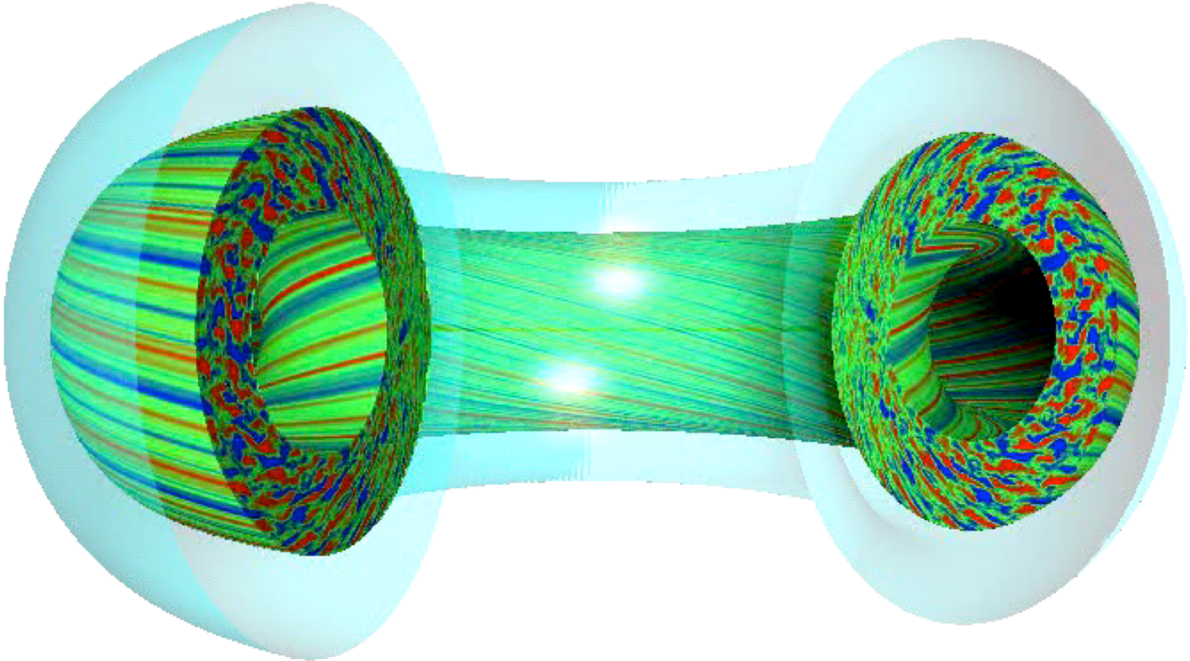
Insulating the hot core from the “cold” wall impacts the size of the reactor



- Core temperature dictated by ideal temp for D-T fusion
- Physical distance between core and separatrix related to the achievable temperature gradient (∇T)
  - Larger ∇T → more compact
- Energy confinement time (τ) describes how energy diffuses (leaks) across the gradient
  - Larger τ → slower leak

Day 1
Cowley

Plasma turbulence is typically what leaks the most energy from the core



Day 2
Mordijick

Calculations enabled by recent advances in supercomputing

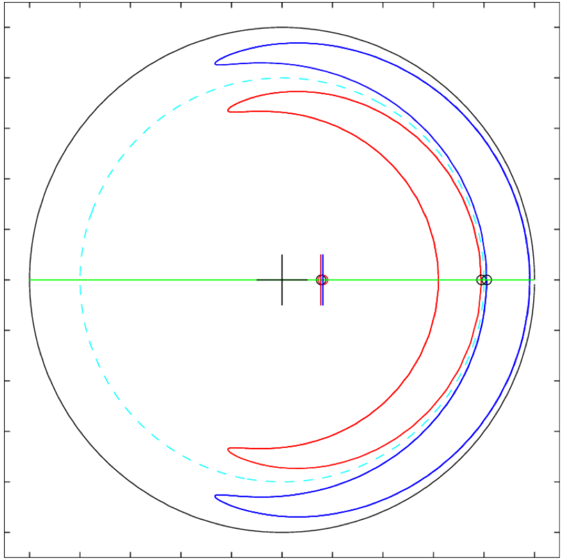
Energy also leaks from the plasma by radiation and conduction (collisions)

- Just like the sun, laboratory plasmas emit radiation across the electromagnetic spectrum
  - Really useful for diagnosing the plasma

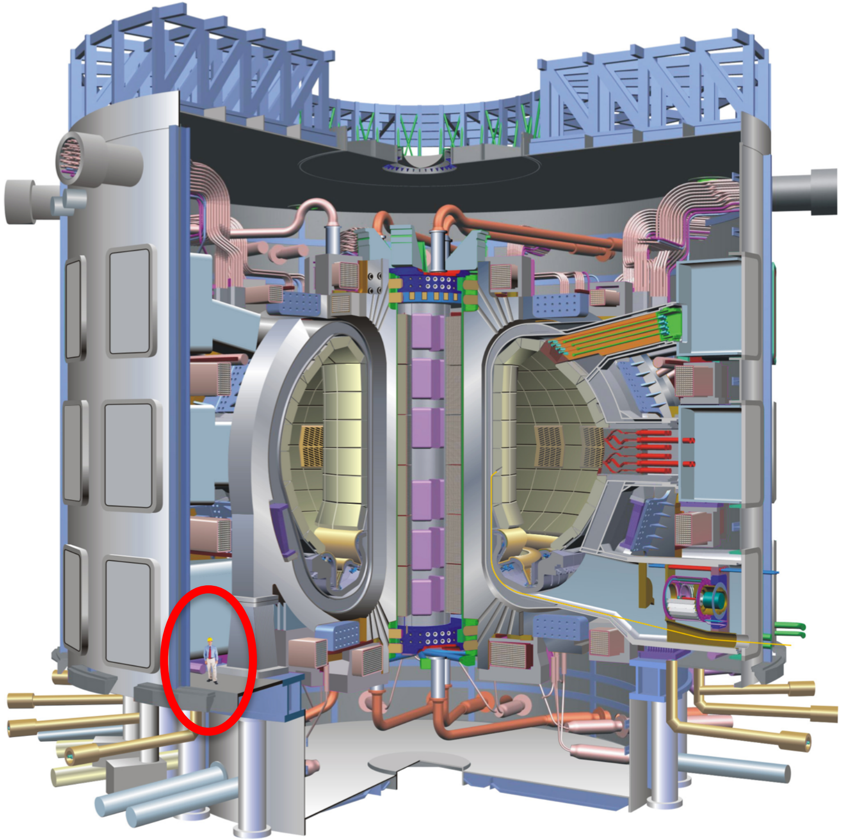
Day 5
Reinke

- In toroidal systems, collisions between particles on *banana* orbits set the energy diffusion step size
  - Mathematics describing diffusion in a toroidal system is called *neo-classical theory*
  - Existence of banana orbits leads to the bootstrap current

Day 2 Fox



Present magnet technology and tokamak physics understanding leads to big fusion reactors



- ITER designed to produce a DT plasma with fusion energy ten times greater than the heating energy
  - Majority of plasma heating comes from fusion reactions
  - Will not put energy on the grid
- It is a grand engineering and science challenge
  - EU, Japan, US, China, Russia, South Korea and India all contributing

Day 4
Laggner

Outline

- Introduction to tokamaks

- Tokamak design considerations

- Present-day tokamak research

After ITER, what comes next?

- One option is to take technology proven on ITER to build the first demonstration fusion reactor (pilot plant)
  - Building an "ITER-like" pilot plant will require a lot of capital
  - Studies suggest this design choice can be economically competitive in markets with a cap placed on carbon emissions

Day 1
Umstattd

- World-wide magnetic confinement fusion research is focused on two main goals:
  - Make the first study of burning plasmas in ITER a success
  - Develop innovations that reduce the capital needed to construct a pilot plant and make it attractive for the energy sector

US tokamak research community is pursuing compact fusion reactors

- Compact tokamak concepts could reduce the capital cost of a fusion energy reactor

Day 7 Guttenfelder

- Requires innovations in
  - Magnetic field coils
  - First wall materials
  - Construction and maintenance
  - Heating and current drive
  - Blanket design and tritium breading

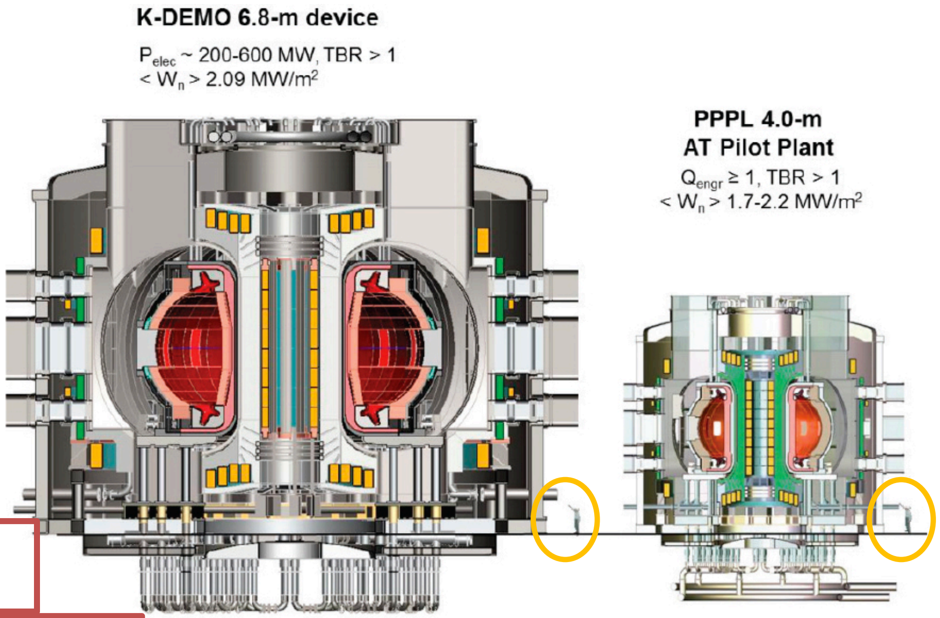
Day 5 Sorbom

Day 6 Donovan, Lasa, Allain

Day 7 Humrickhouse, Garrison

Day 5 Pinsker

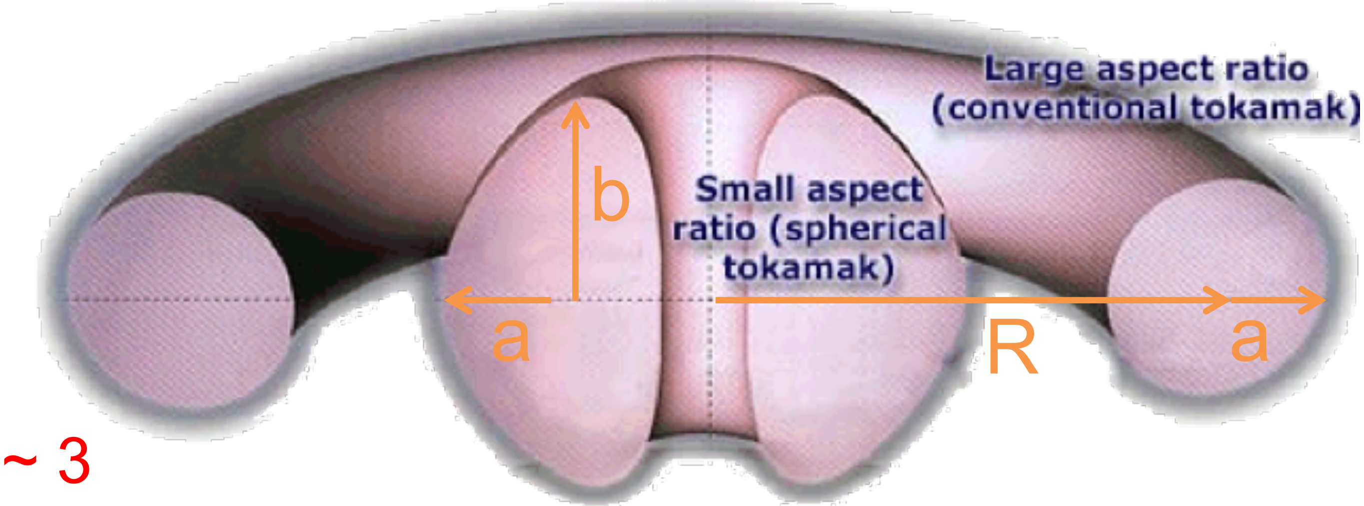
Day 6 Kessel
Day 7 Xiao



Aspect ratio and elongation are free parameters in the design of a tokamak

Aspect ratio A = R / a, Elongation κ = b / a

R = major radius, a = minor radius, b = vertical ½ height



A ~ 3

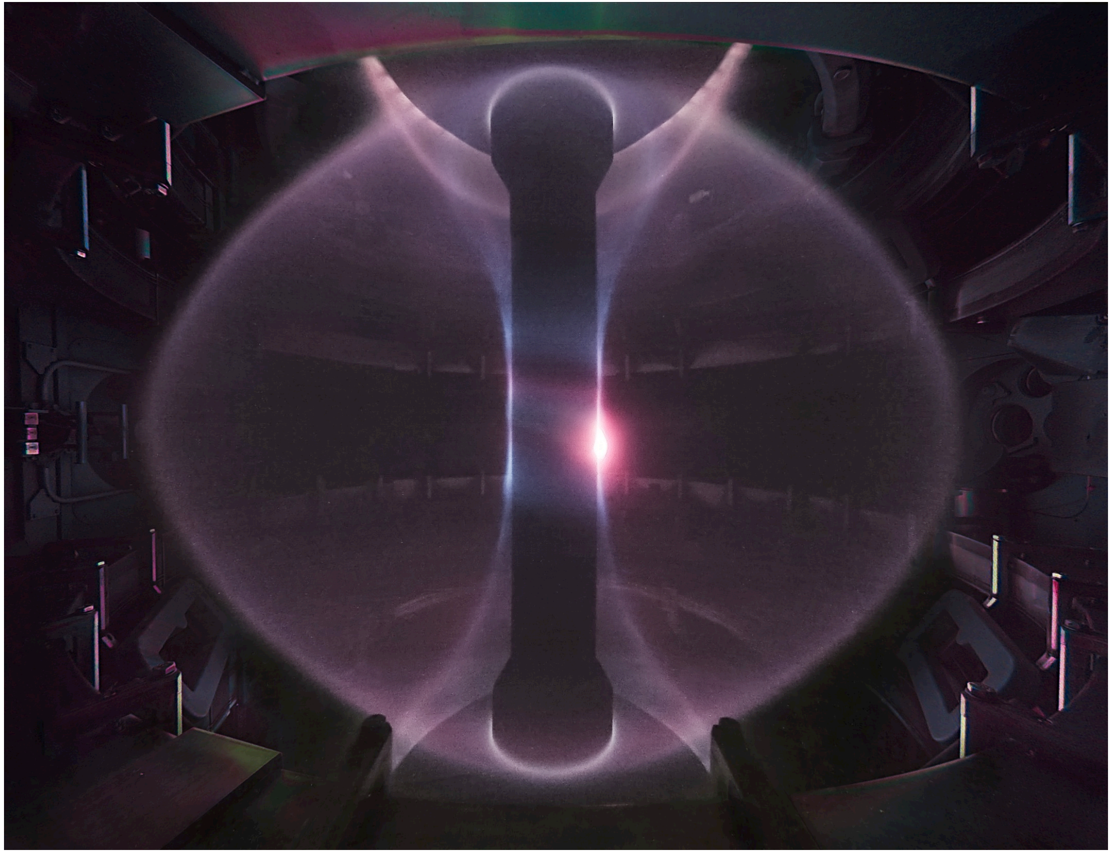
κ = 1.5 - 2

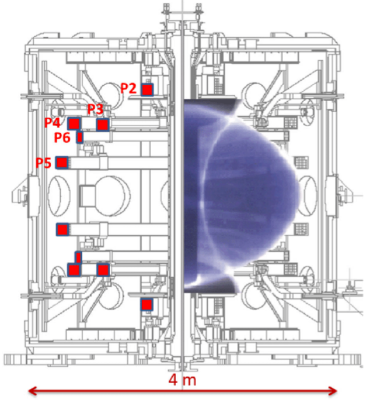
A ~ 1.5

κ = 2 - 3

Inside the DIII-D tokamak: it looks like a donut

Spherical tokamaks look more like a cored apple



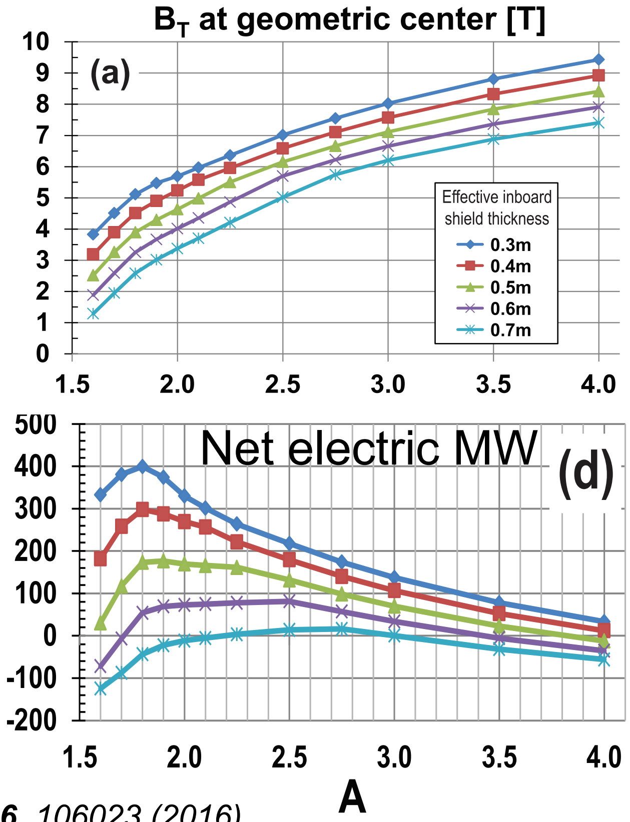


MAST experiment in the U.K.

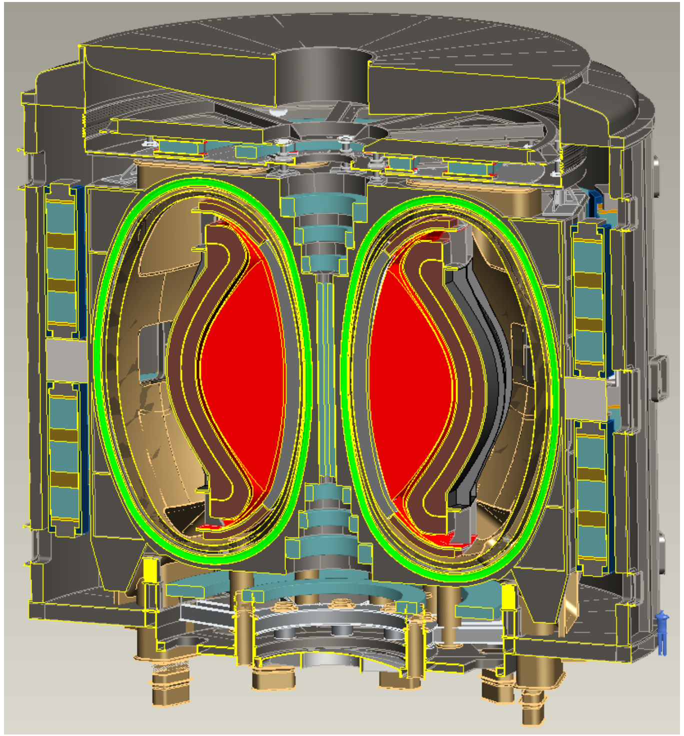
Compact tokamak design studies show impact of aspect ratio on performance

- Design study fixed size of cryostat and 50 MW of heating power
  - Assumes high-temperature superconducting magnets are available

- Optimization in design studies depends on validated models
  - Both in plasma physics and engineering



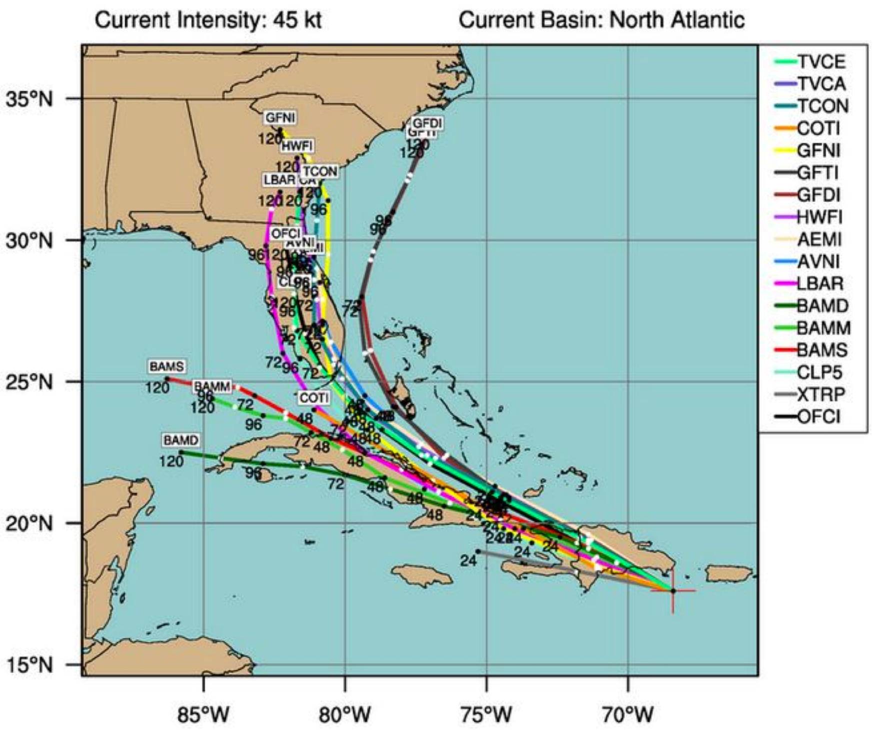
J. E. Menard, et al., Nucl. Fusion ***56****, 106023 (2016).*



Cryostat volume ~ 1/3 of ITER

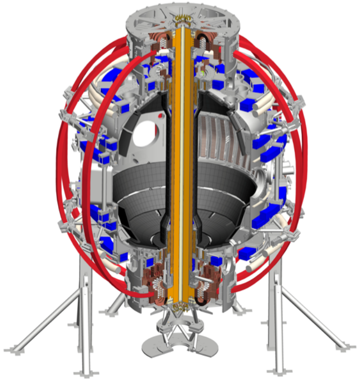
Confident projections require validated models

- Will probably need to be confident that a fusion reactor concept will work before it gets an investor
  - Like hurricanes, non-linear multi-scale plasma physics is complicated
- Build experiments to challenge and validate models
  - Present day experiments are ”wind tunnels”
    - For example, only deuterium fuel is used
  - Models, design and analysis all aided by advances in computational power

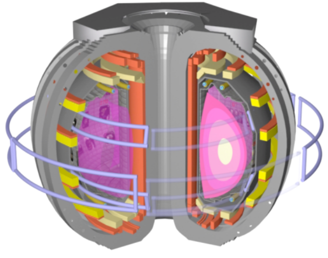


Is there a "sweet spot" in the aspect ratio for compact tokamak reactors?

- Fusion power density: P_{fusion}/volume $\propto \beta_T^2 B_T^4$
  - β_T is limited by the pressure limits
  - B_T set by magnet engineering and shielding constraints
- Spherical tokamaks (lower A) have larger β_T, but lower B_T
- Characteristics of turbulence, stability and current drive vary with β_T and aspect ratio
  - Two US tokamaks provide bookends in aspect ratio for developing and testing models



NSTX-U, A = 1.8
Princeton, NJ



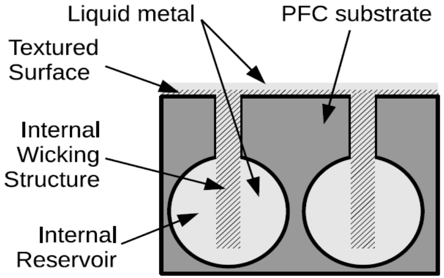
DIII-D, A = 3
San Diego, CA

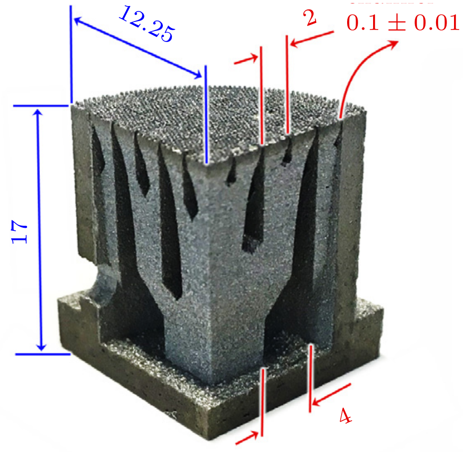
Tokamaks are used as a test-bed for technology development needed for fusion reactors

- Fusion reactors require plasma facing surfaces that are resilient to the large neutron and energy flux
  - Challenge becomes more critical in a compact design

- Liquid metal walls are a solution with the ability to self-heal, replenish and dissipate energy (evaporation and flow)

- NSTX-U is preparing for large-scale test of liquid lithium PFCs in a magnetic confinement device
  - This is just one example of the fusion R&D being pursued on tokamak devices that benefits all MCF schemes





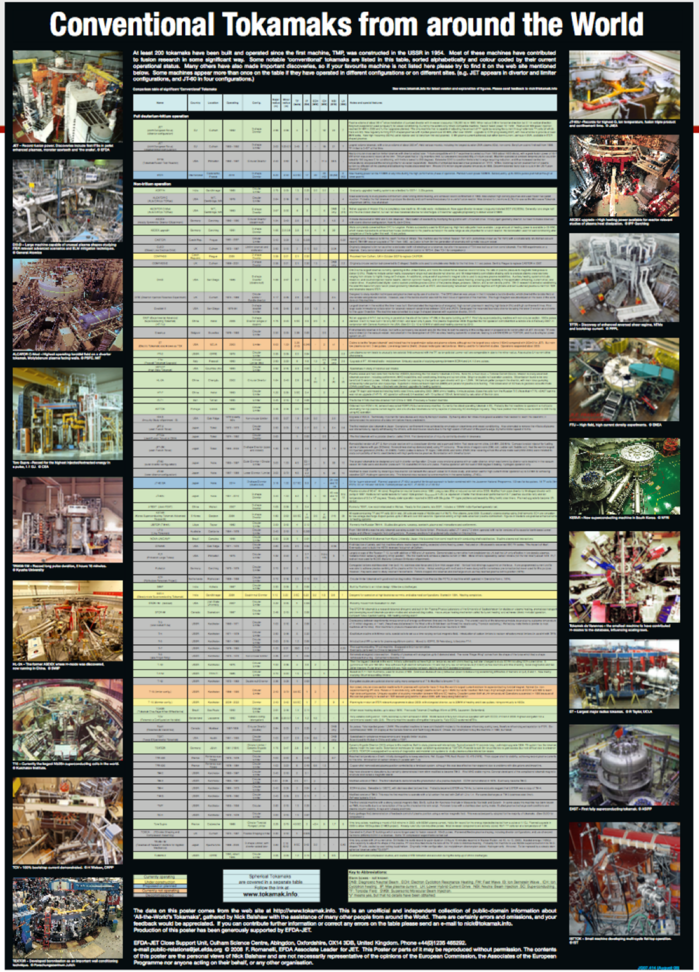
Tokamak research is conducted collaboratively world-wide

- JET: largest operating tokamak (UK/EU)
  - Holds world-record for D-T fusion power
- Tokamaks with superconducting coils
  - EAST(China), KSTAR (Korea)
  - JT60-SA (Japan) … brand new!
- Tokamaks with copper coils
  - A = 3: DIII-D (USA), ASDEX-U (Germany)
  - A < 2: NSTX-U (USA), MAST-U (UK)
- Private companies developing tokamaks with HTS magnets
  - A = 3: Commonwealth Fusion Systems (USA)
  - A < 2: Tokamak Energy (UK)

Day 8 Mumgaard

(Not an exhaustive list)

www.alltheworldstokamaks.com



Conventional Tokamaks from around the World

At least 200 tokamaks have been built and operated since the first machine, TMP, was constructed in the USSR in 1954. Most of these machines have contributed to fusion research in some significant way. Some notable 'conventional' tokamaks are listed in this table, sorted alphabetically and colour coded by their current operational status. Many others have also made important discoveries, so if your favourite machine is not listed here please try to find it on the web site mentioned below. Some machines appear more than once on the table if they have operated in different configurations or on different sites. (e.g. JET appears in divertor and limiter configurations, and JT-60 in four configurations.)

Spherical Tokamaks
are covered in a separate table
Follow the link at
www.tokamak.info

The data on this poster comes from the web site at http://www.tokamak.info. This is an unofficial and independent collection of public-domain information about 'All-the-World's Tokamaks', gathered by Nick Balshaw with the assistance of many other people from around the World. There are certainly errors and omissions, and your feedback would be appreciated. If you can contribute further information or correct any errors on the table please send an e-mail to nick@tokamak.info.
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In summary …

- Tokamaks create a helical magnetic field by driving a toroidal current in the plasma
  - Demonstrated the highest $p\tau$ (pressure x energy confinement time) of any magnetic confinement concept (to date)
  - Useful devices for producing high temperature plasmas for sec. to minutes
    - ITER will produce plasmas that last minutes
    - Next frontier is demonstrating longer pulse tokamaks at high $p\tau$

- Two operating tokamaks in the US: DIII-D (San Diego) and NSTX-U (Princeton)
  - Experiments support preparations for ITER operation
  - Span aspect ratio to validate science and engineering models needed to optimize the design of a compact tokamak pilot plant
  - Serve as a test-bed for R&D innovations that reduce the cost of a reactor

Welcome to the NSTX-U control room!

- 20 – 40 scientists and engineers at any given time
  - Experiment is locked up for the day
  - All aspects controlled and monitored remotely

- One plasma discharge about every 20 minutes (25 – 30 per day)
  - Copper magnets need to cool down
  - Countdown clock keeps the pace of the day

- Each discharge lasts a few seconds
  - Longest discharges limited by component heating
  - Each discharge generates GBs of data

- Operate for 15 – 20 weeks per year
  - Down time spent on maintenance, upgrades, planning and analysis

Chief Operating Engineer

Physics Operator

Session leader