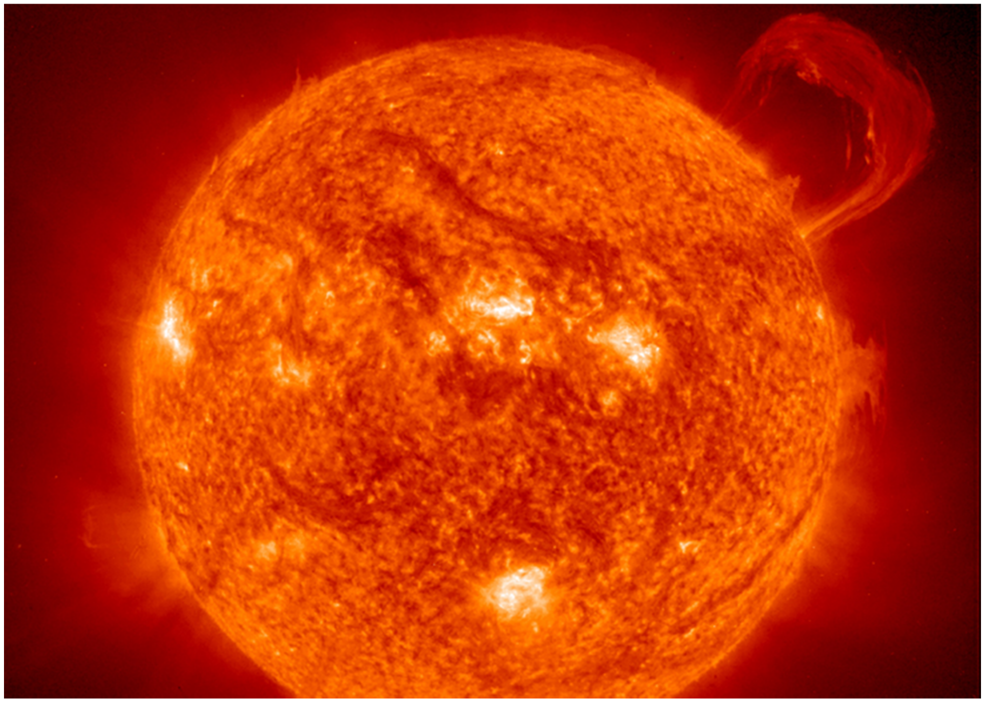
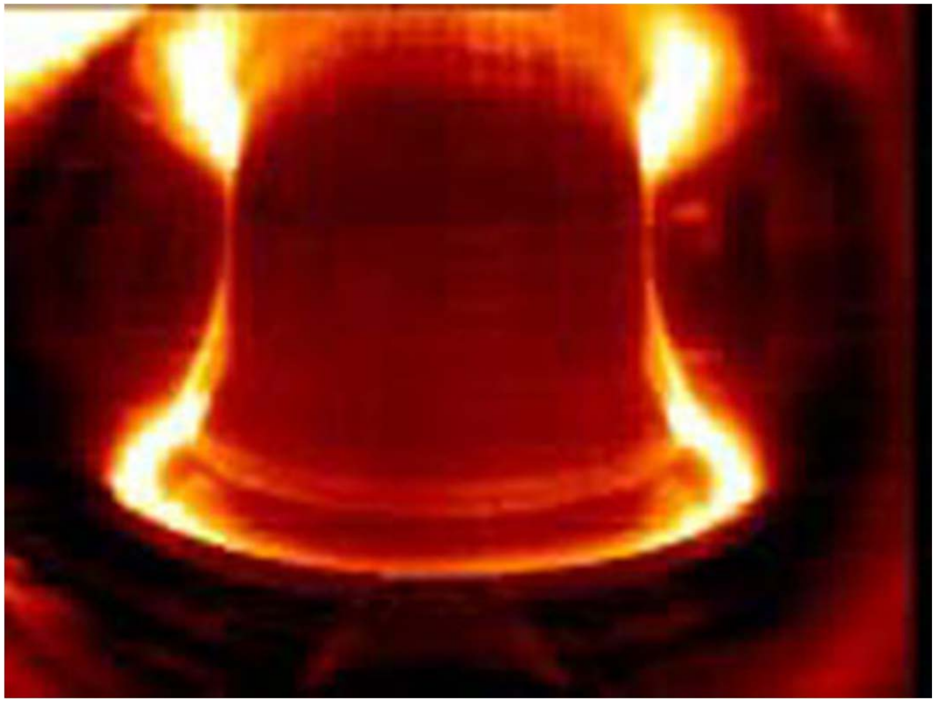
# Fusion energy, tokamaks & NSTX-U





**Walter Guttenfelder**

PPPL undergrad seminar
July 24, 2014

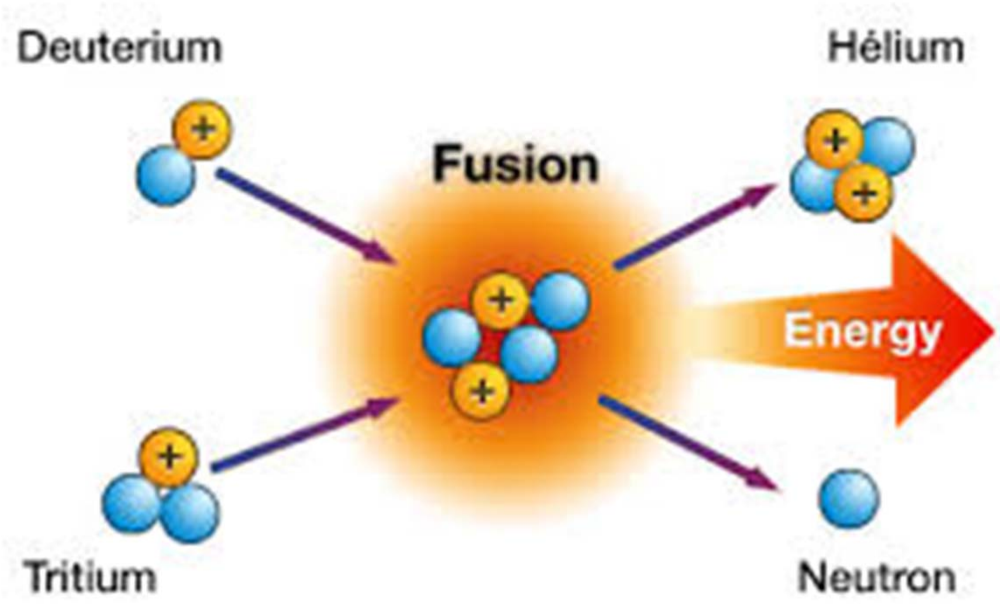
w3.pppl.gov/~wgutten/talks/Guttenfelder_undergrad_seminar_2014_07_24.pdf

# Questions I hope to address

- Why study fusion?
- How do we make fusion plasmas/what is a tokamak?
- What's the best performance accomplished to date?
- What is needed to make sufficient fusion energy?
- What issues remain for developing fusion reactors & electricity generation?
- What are we doing with NSTX-U here at PPPL?

- *Biased by my personal knowledge & experience (e.g. some turbulence examples)*

# The promise of fusion energy



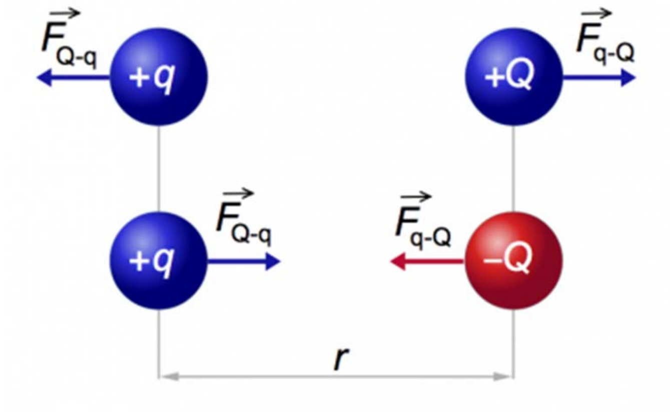
# The tremendous potential of fusion energy has motivated 65 years of research

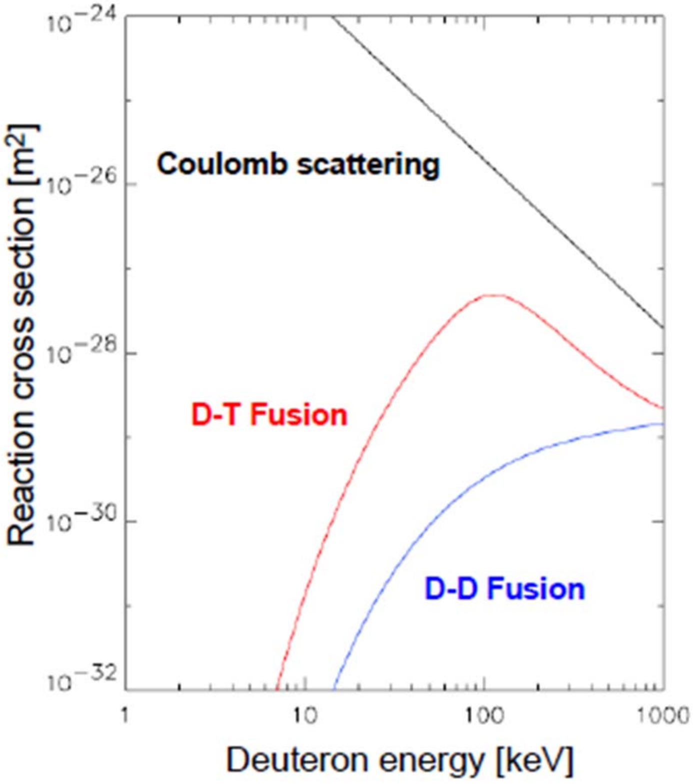
- **Fusion energy advantages over nuclear fission:**
  - No high-level radioactive waste
  - No nuclear waste as a fuel cycle by- product
  - No fissile (weapons-related) material
  - No physical possibility of a “meltdown” event or runaway nuclear reaction
- **Fusion energy advantages over most renewables:**
  - *Dispatchable* - independent of geography and weather conditions
  - *Efficient land use* - High energy output per unit area of physical plant
  - *Base-load* electricity production
- **Fusion energy advantages over fossil fuels:**
  - Does not emit green house gases, $SO_x$, $NO_x$, particulate emissions
  - Inexhaustible fuel supply:
    - Present technology using lithium and deuterium : **~30,000 years**
    - Advanced technology using only deuterium : **~1,000,000,000 years**
  - Geographic accessibility of fuels, especially deuterium (ocean water)
- **Disadvantages of fusion energy**
  - Structural materials become radioactive (low-level waste classification, acceptable for recycling/shallow-burial)
  - Cost
  - It doesn’t work...yet!

*Courtesy Zach Hartwig, MIT (http://www.psfc.mit.edu/~hartwig/)*

# Must overcome repulsive electrostatic force to fuse atomic nuclei

$$\boxed{F_E = \frac{q_1 q_2}{4\pi\varepsilon_0 \cdot r^2}}$$





- Temperatures must be ~150 million C ~15 keV → no longer gas, but a <u>plasma</u>

  (Core of the sun ~15 million C)

# How do we create and contain a hot plasma on earth?

Recipe:

- Establish an appropriate magnetic field
- Inject appropriate gases (in a container at vacuum pressure)
- Heat the gases

# Magnetic field confines particles away from boundaries

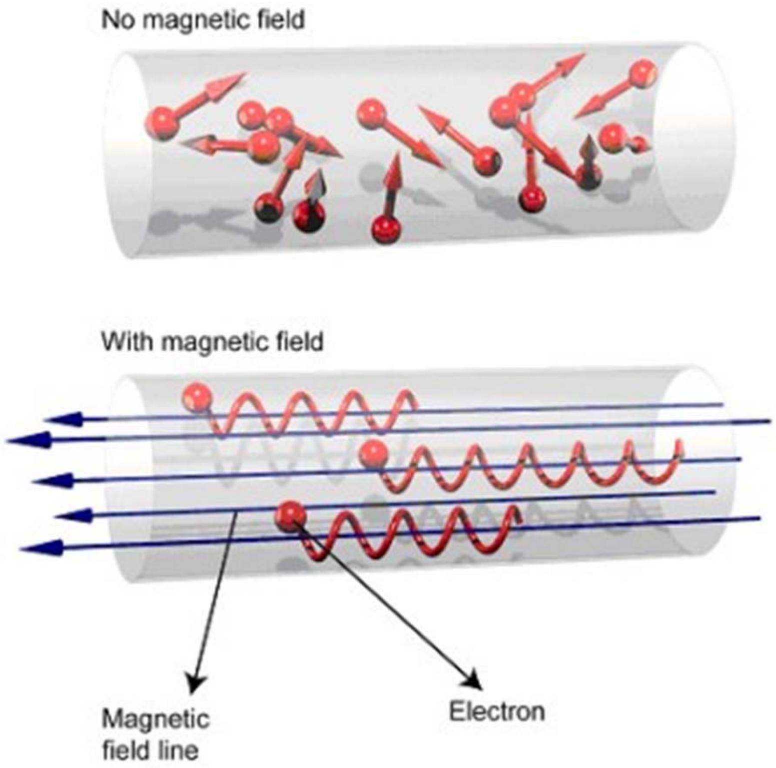
$$\boxed{\vec{F} = q\vec{v} \times \vec{B}}$$

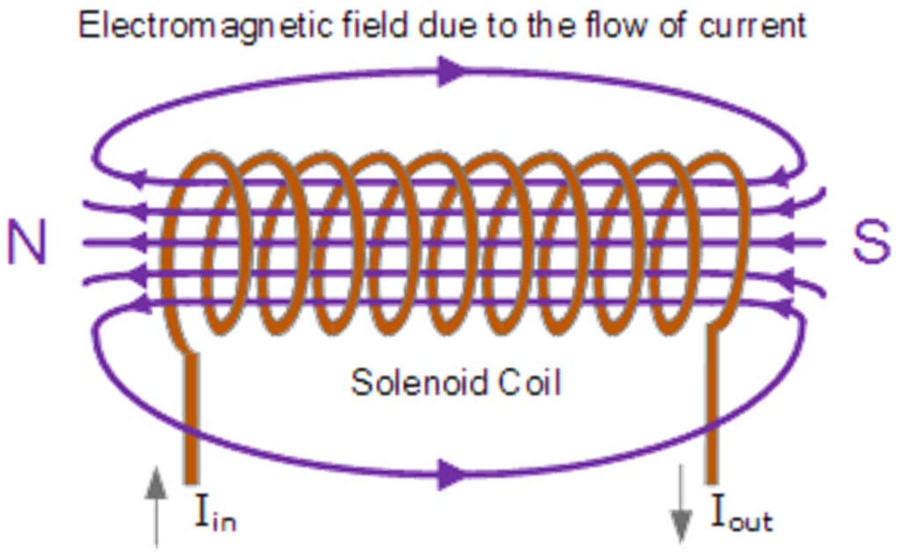
For a 5 Tesla magnetic field,
100 million C plasma

ion radius ~ 3 mm
electron radius ~ 0.05 mm << 1-2 meter device size

For comparison

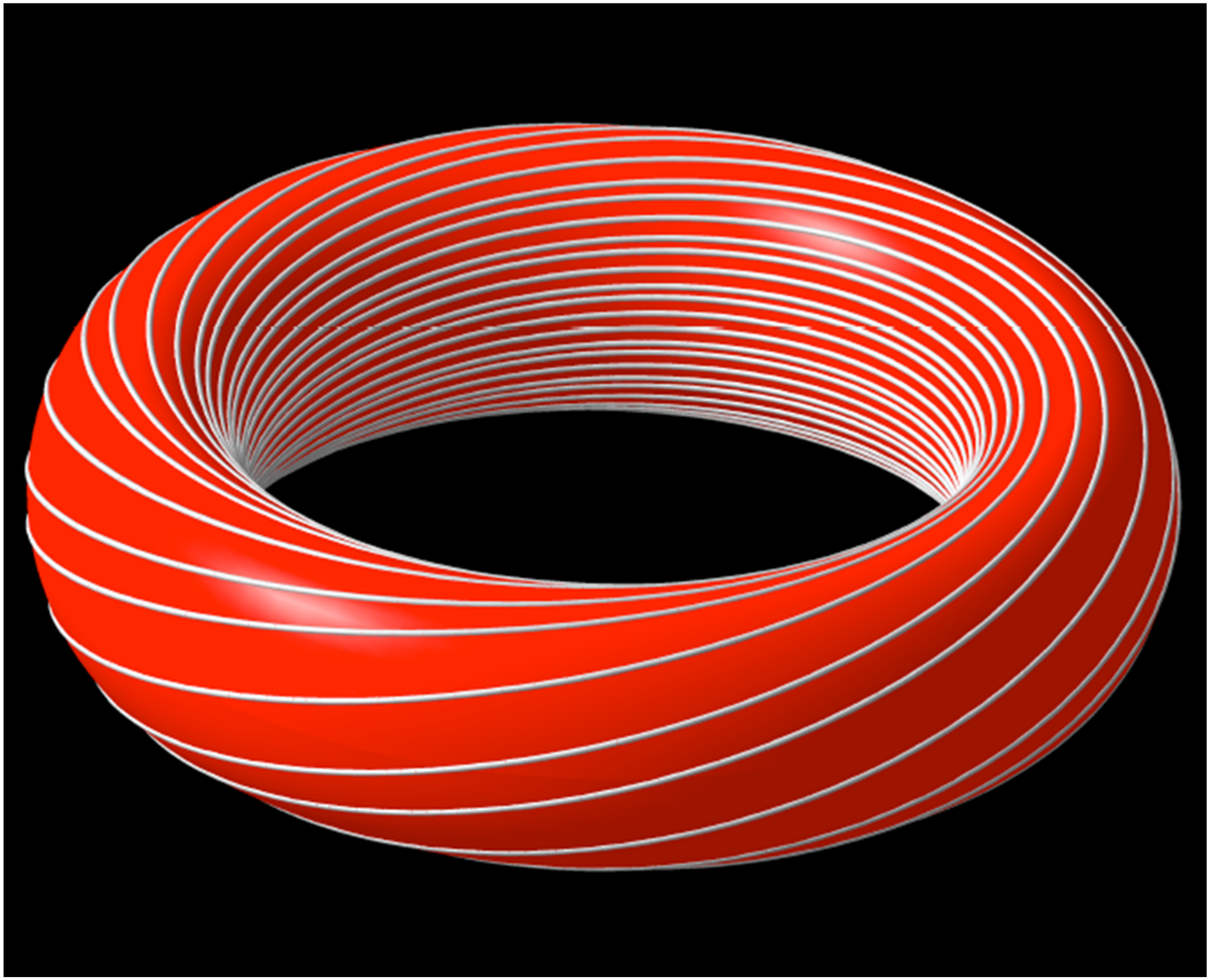
- Earth's magnetic field – 50 μT
- MRI – 1-3 T
- Junkyard magnet – 1-2 T





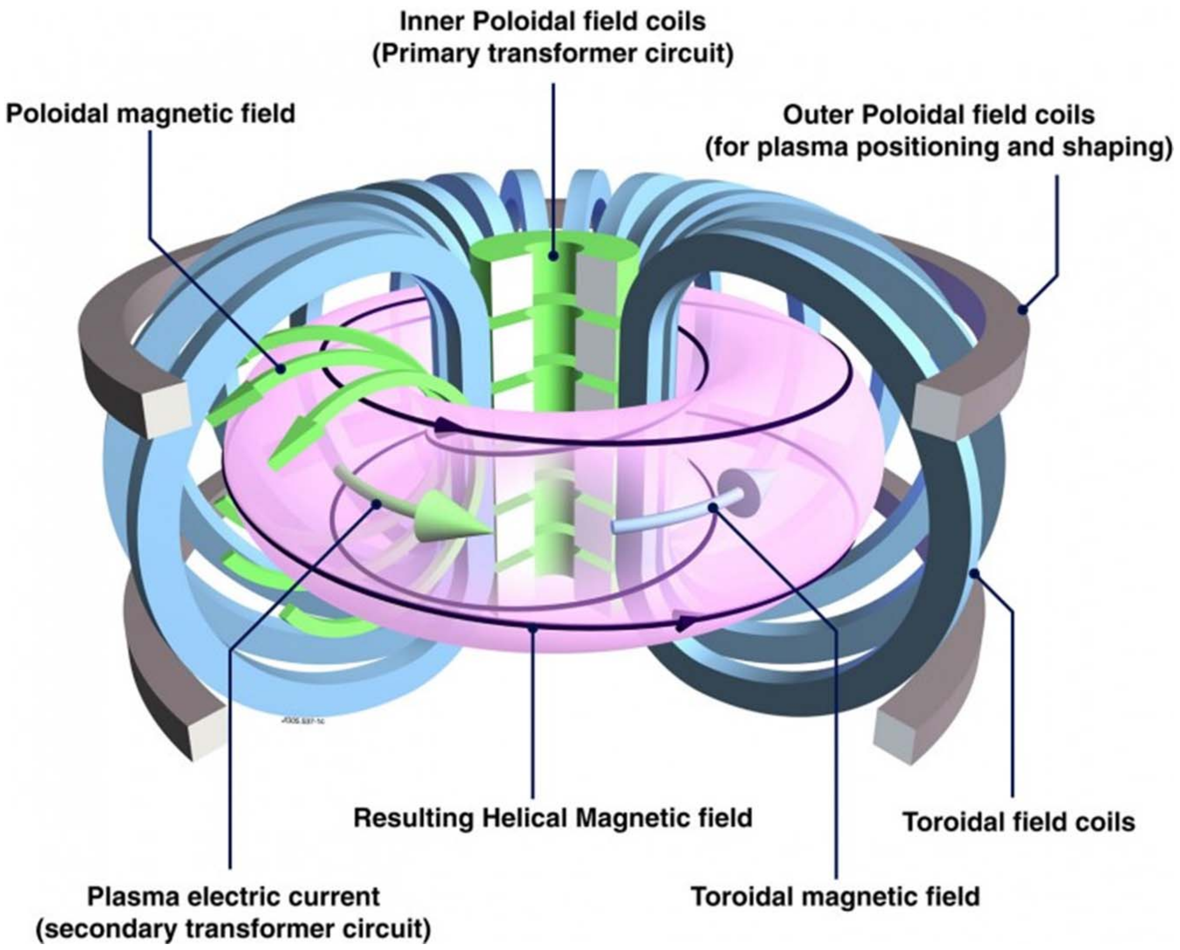
**But particles easily lost from ends…**

# Bend the field into a donut-shaped torus

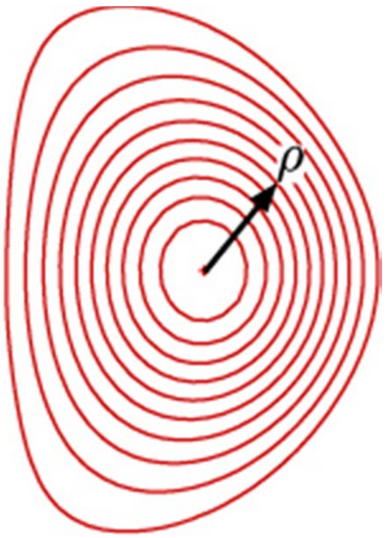


# The Tokamak (Russion acronym for “toroidal chamber with magnetic coils”)

- External coils create toroidal field
- Toroidal plasma current creates poloidal field (usually driven inductively, like a transformer)
- Additional coils used for control, plasma shaping



- **Nested flux surfaces confine hot plasma**

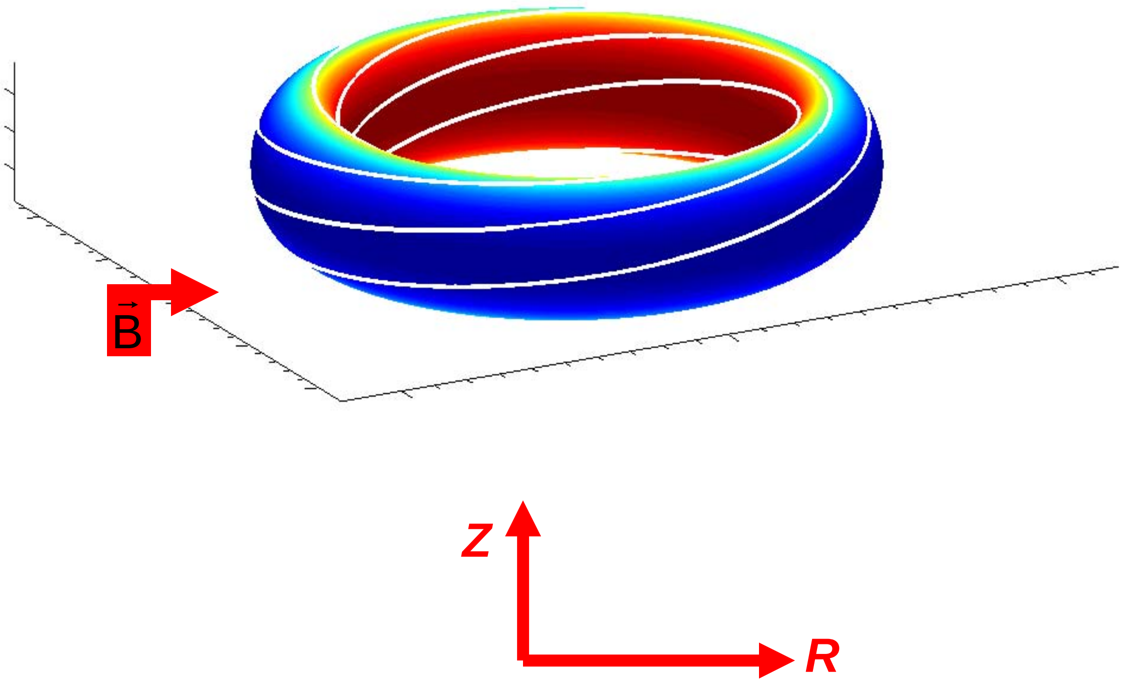


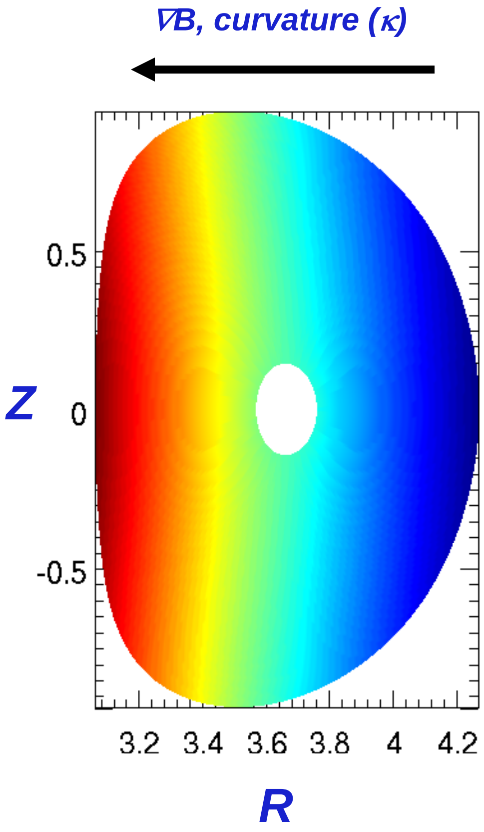
$$\text{safety factor} = q = \frac{\text{toroidal transits}}{\text{poloidal transits}}$$

# Why helical field lines?

# Toroidicity Leads To Inhomogeneity in |B|

- Magnetic field strength varies as B ~ 1/R, weaker on the outboard side
- ∇B and curvature (κ) point towards symmetry axis, leads to additional perpendicular drifts



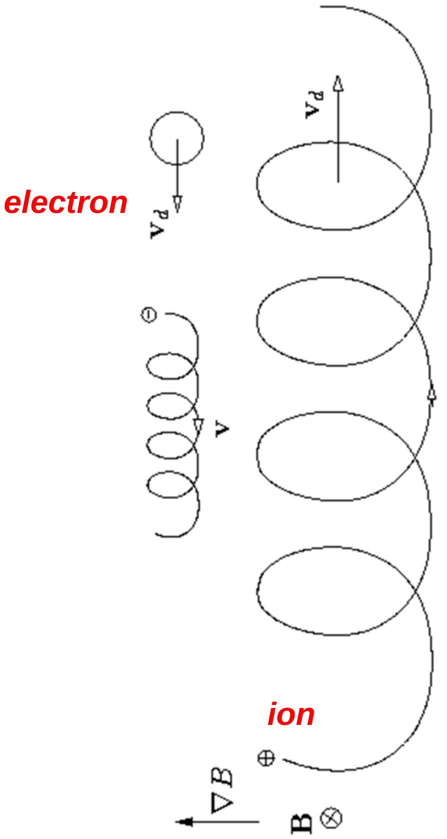


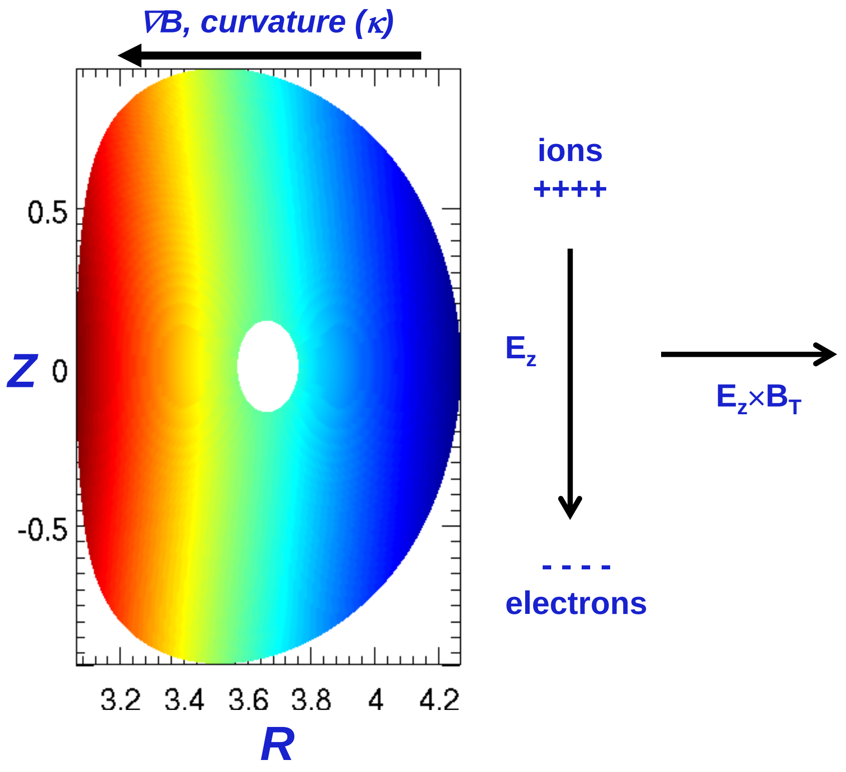
# $\nabla B$ & Curvature Lead To Perpendicular Drifts

$$\vec{v}_{\kappa} = m v_{\parallel}^{2}\,\frac{\hat{b}\times\vec{\kappa}}{qB}$$

$$\vec{v}_{\nabla B} = \frac{m v_{\perp}^{2}}{2}\,\frac{\hat{b}\times\nabla B/B}{qB}$$

- Drifts are mostly vertical (Z direction), electrons and ions separate
- Resulting E field leads to E×B drift, particles would leave too rapidly
- Vertical drifts on outboard side cancelled on inboard side *by using helical field lines*





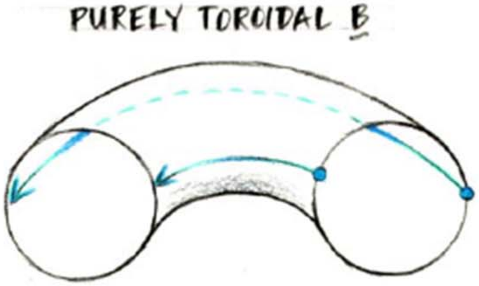
# Strong pressure gradient + current gradient in plasma can lead to all kinds of instabilities

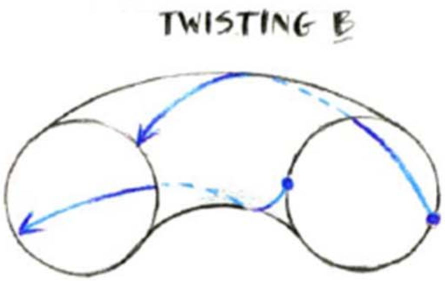
- Large scale <u>macroscopic</u> instabilities can seriously degrade plasma performance or even cause disruptions
  - Have to operate in a regime of parameter space to avoid/minimize such instabilities
  - Typically limits the maximum achievable normalized pressure, given by $\underline{\beta=p/(B^2/2\mu_0)}$ ~ few % for conventional tokamaks (much higher for NSTX)

- Small scale <u>microscopic</u> instabilities (turbulence) set the confinement level, i.e. how much power required to achieve a given pressure/temperature

# The Secret for Stabilizing Bad-Curvature Instabilities

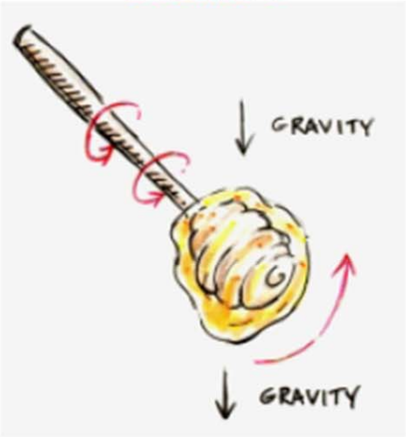
Twist in ***B*** carries plasma from bad curvature region
to good curvature region:





Unstable

Stable

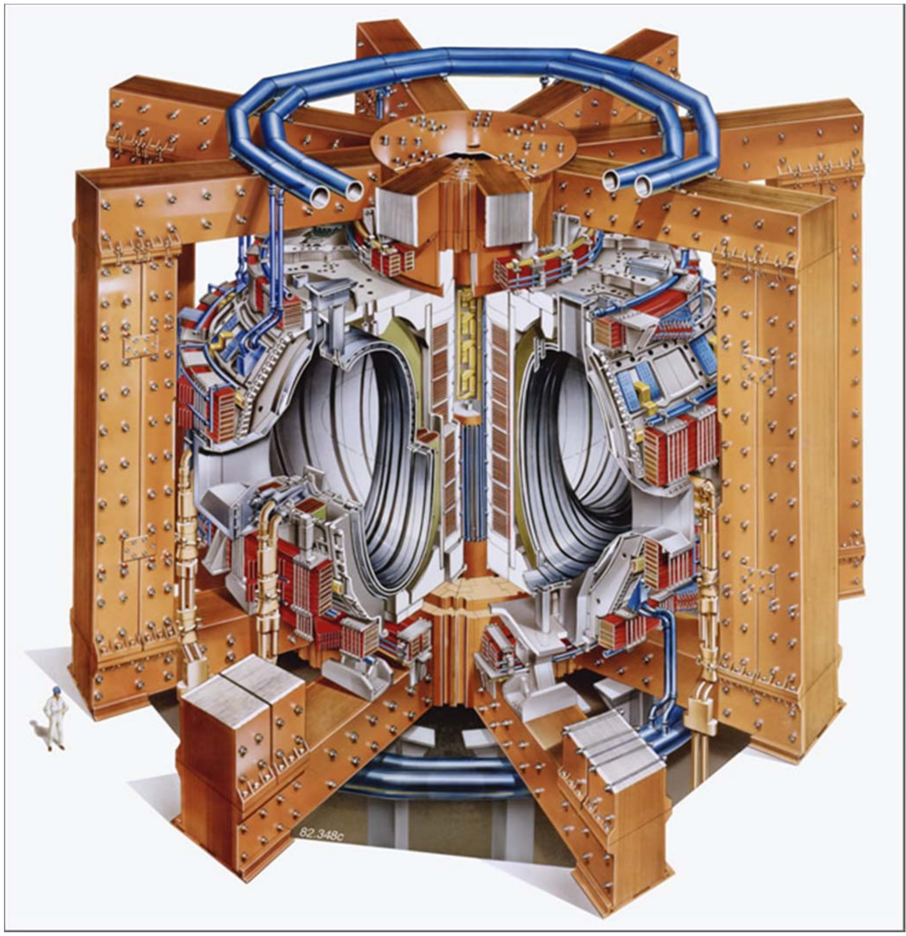


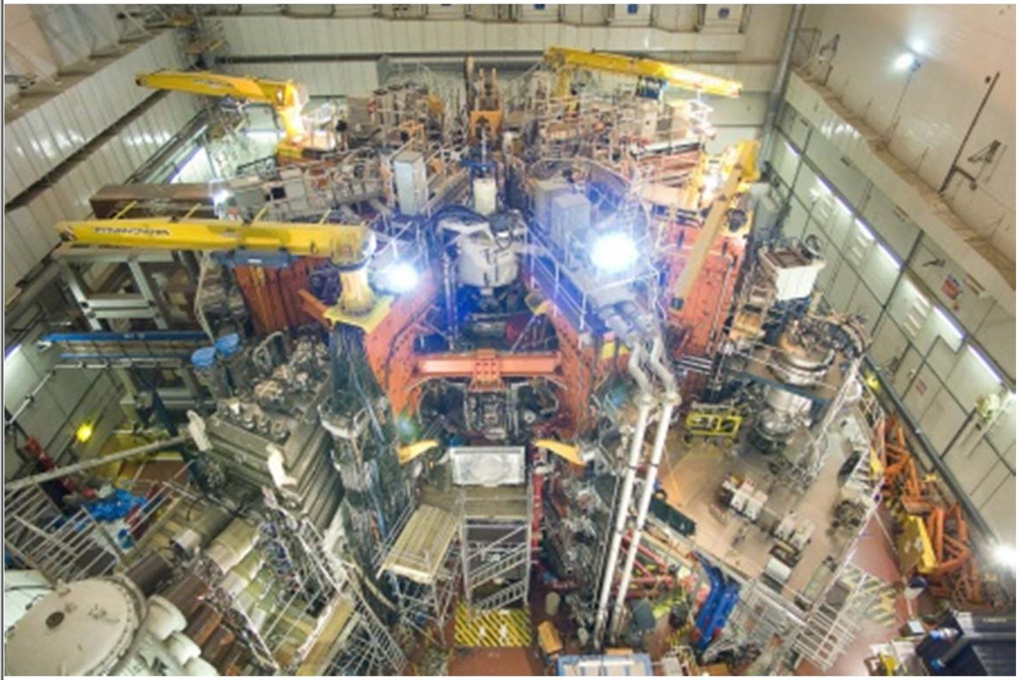
Similar to how twirling a honey dipper can prevent honey from dripping.

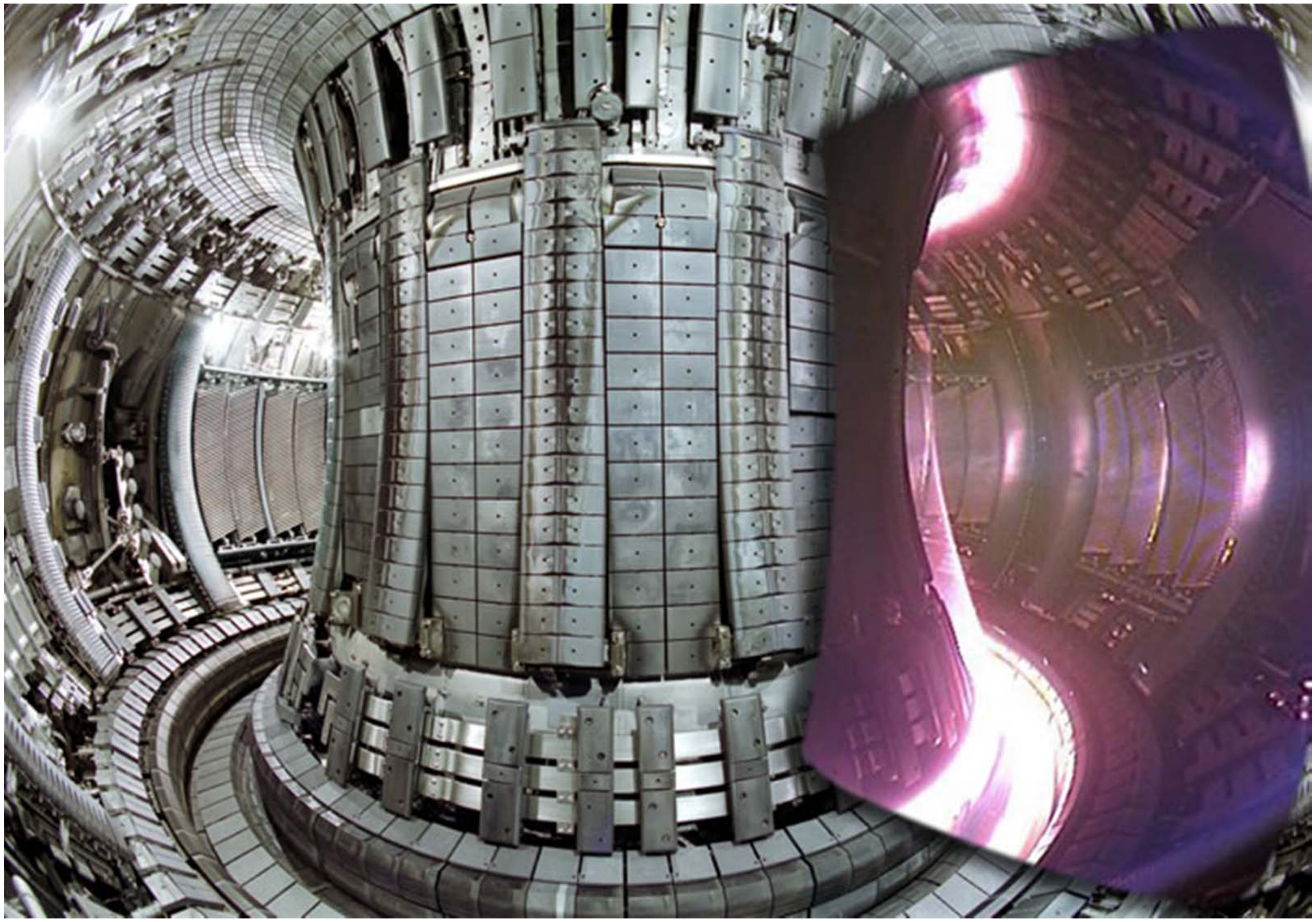
*Courtesy Greg Hammett, PPPL (w3.pppl.gov/~hammett)*

# Real world tokamaks

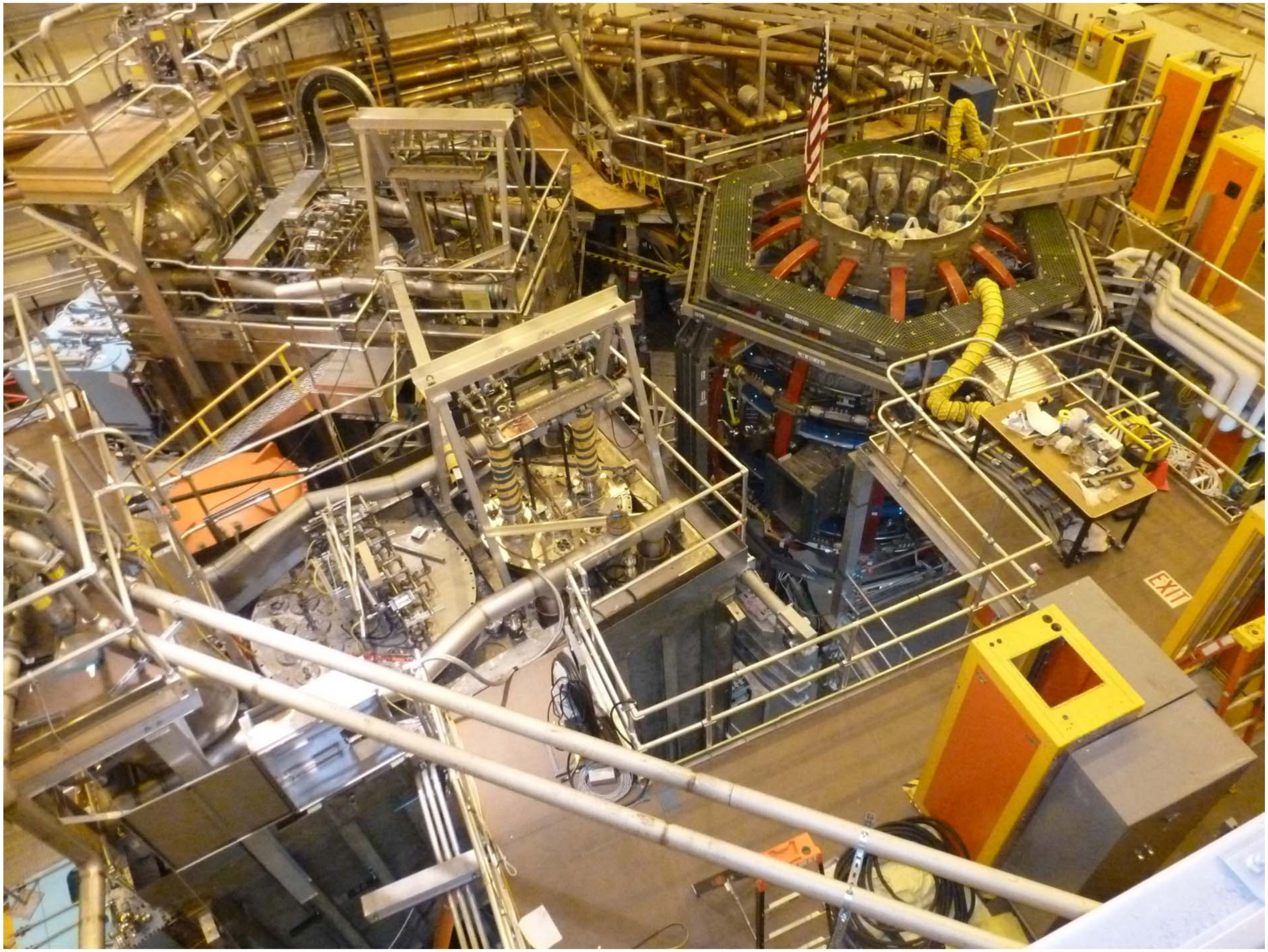
# European JET tokamak (located in UK)







# Here at PPPL:
# National Spherical Torus Experiment-Upgrade (NSTX-U)



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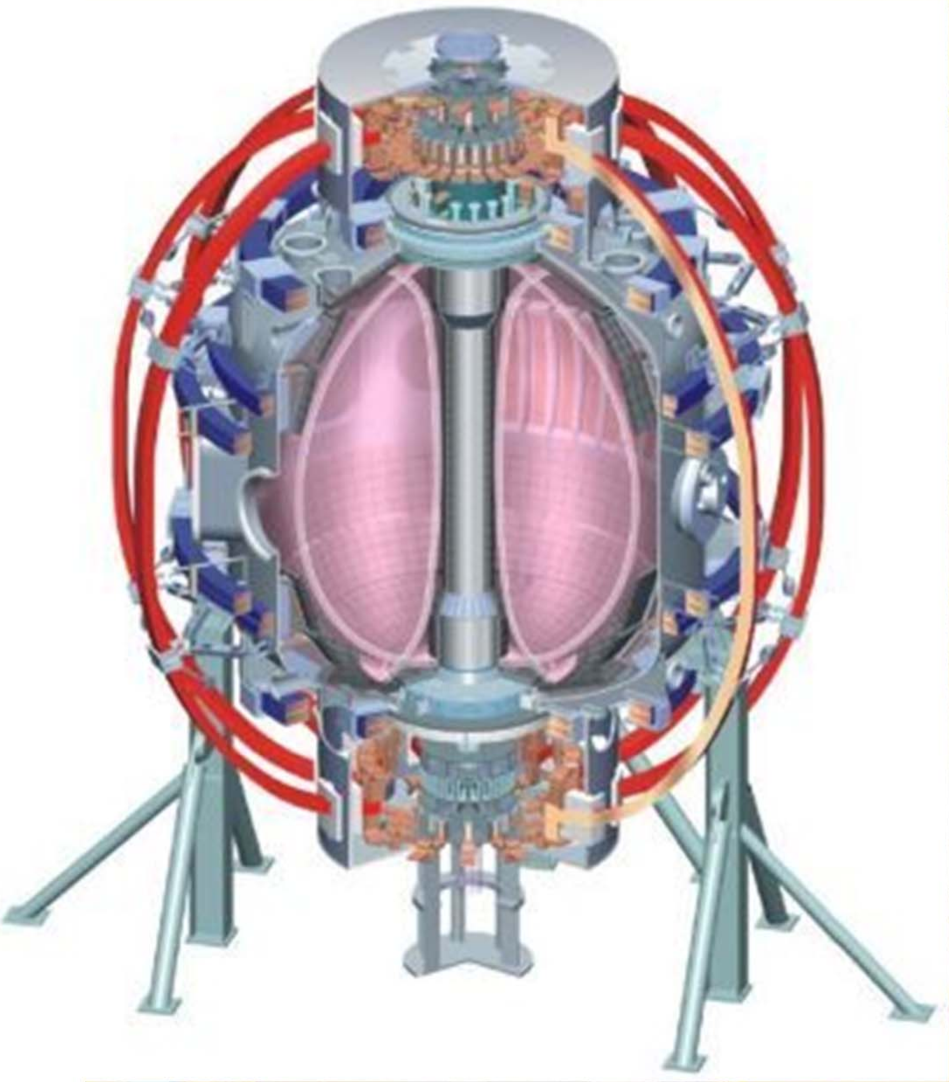
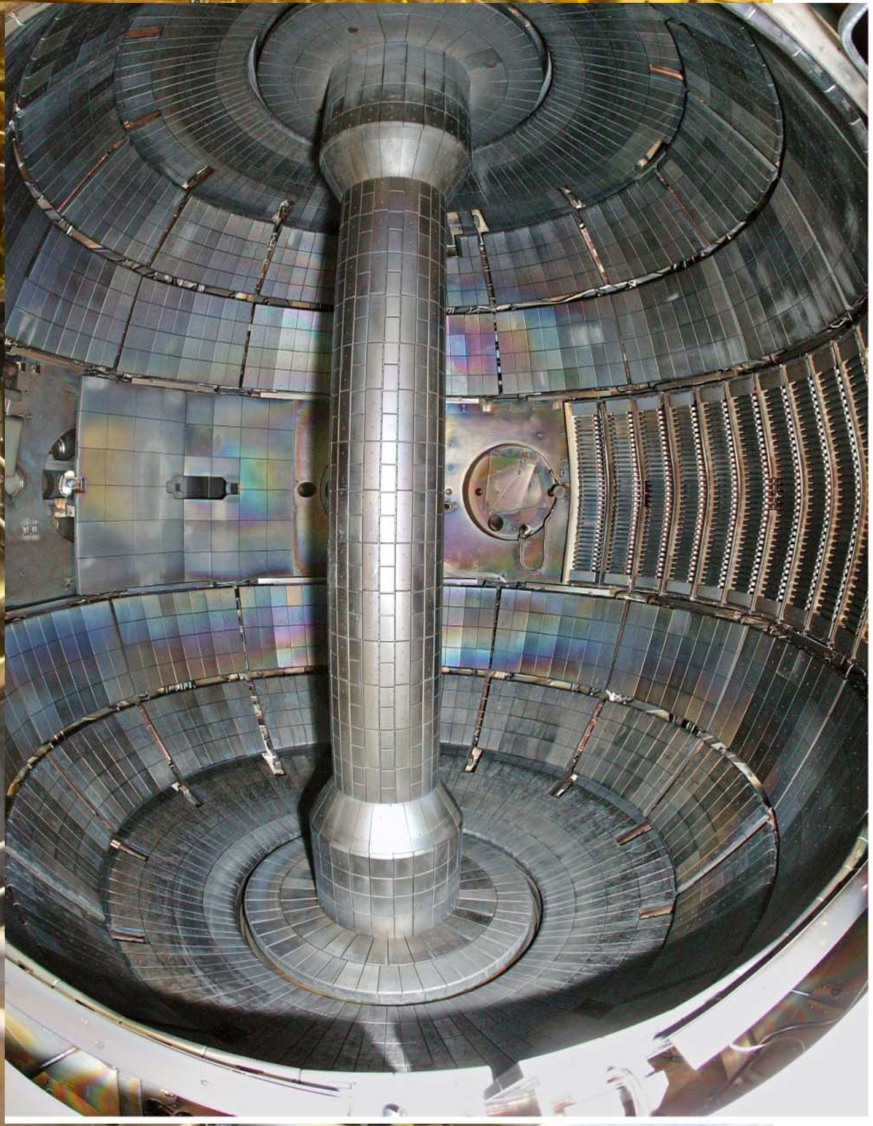
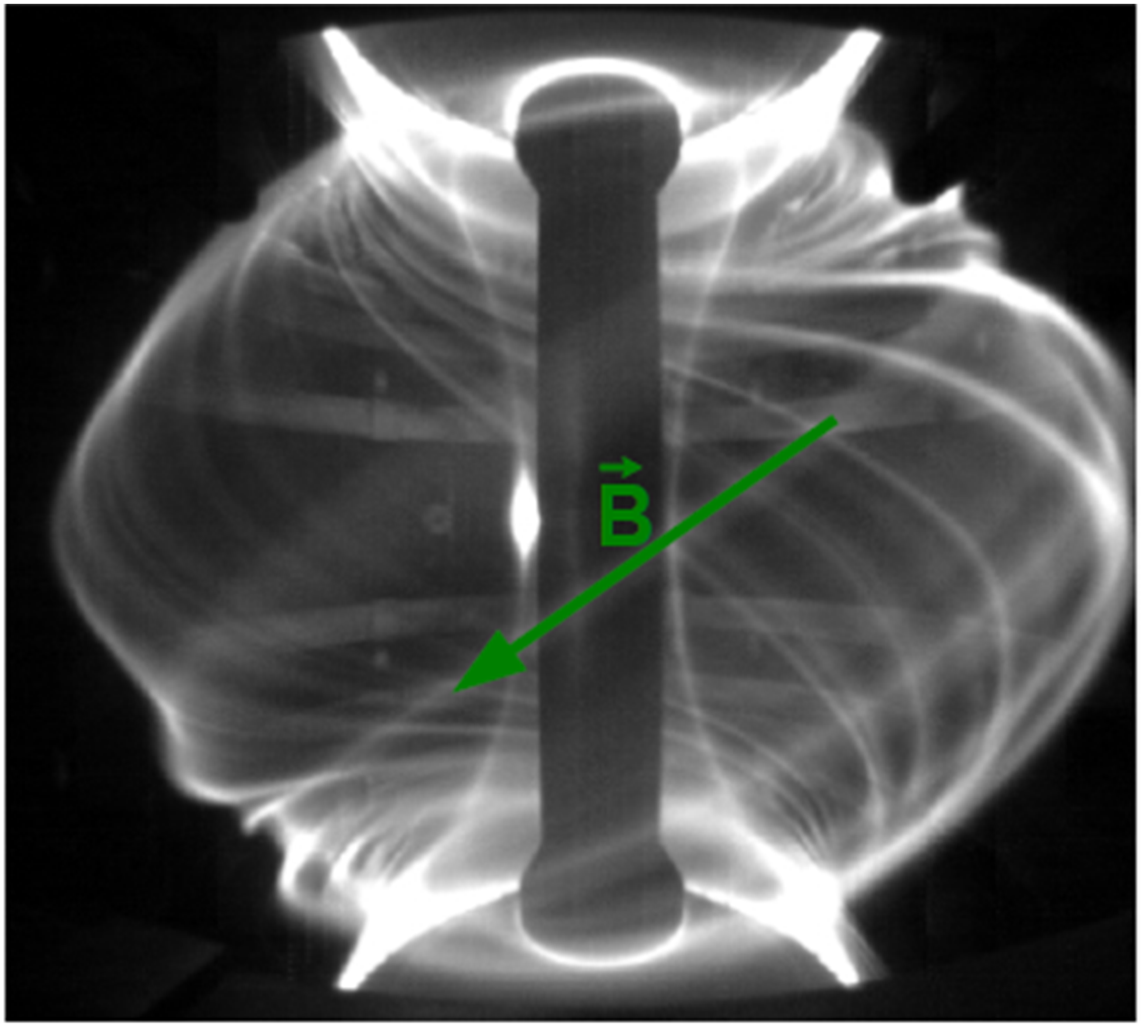


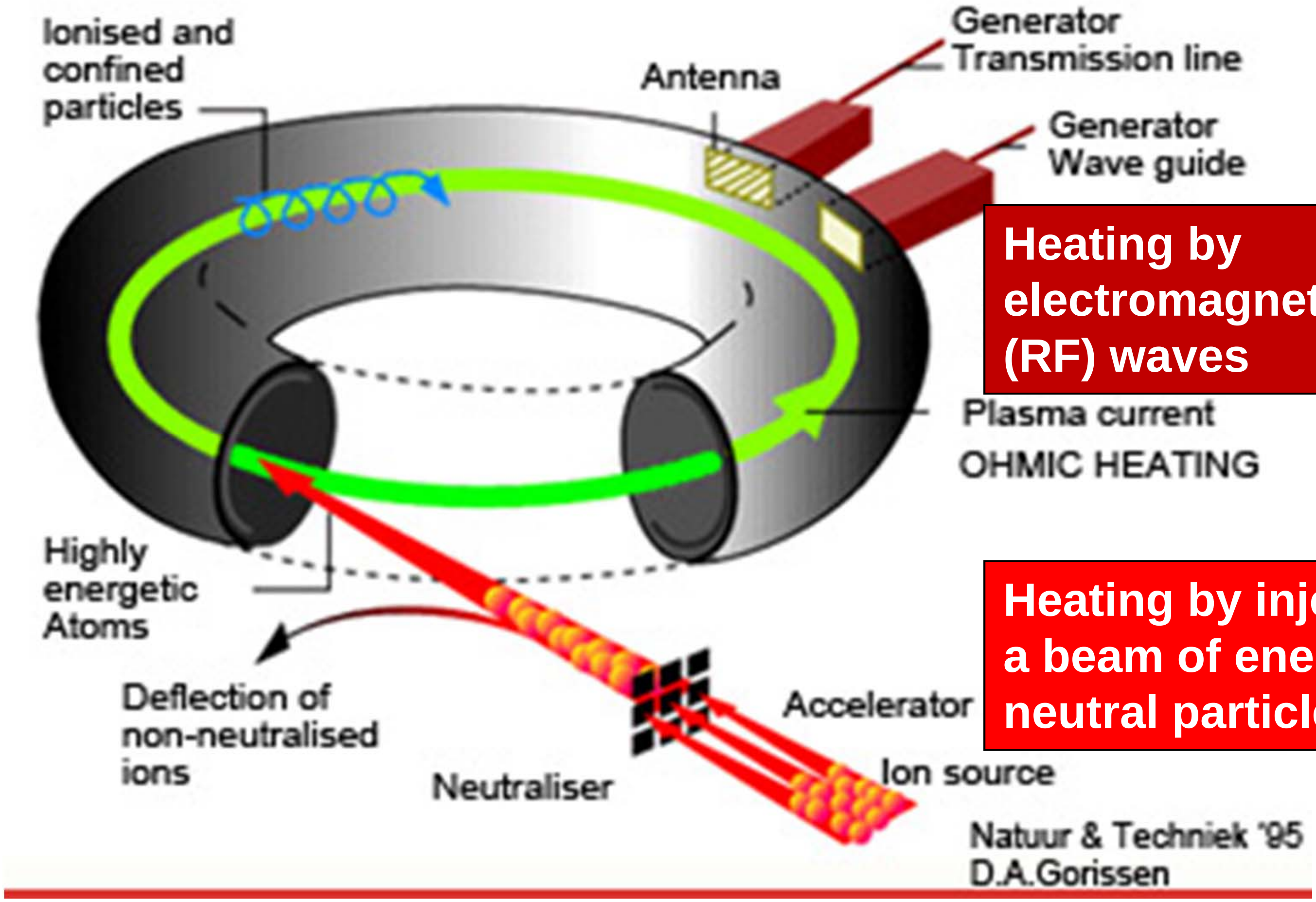


# MAST tokamak (UK)



# We’ve created a magnetically confined plasma – how do we heat it?

# Can heat plasma using neutral beam injection (NBI) or resonances with RF waves

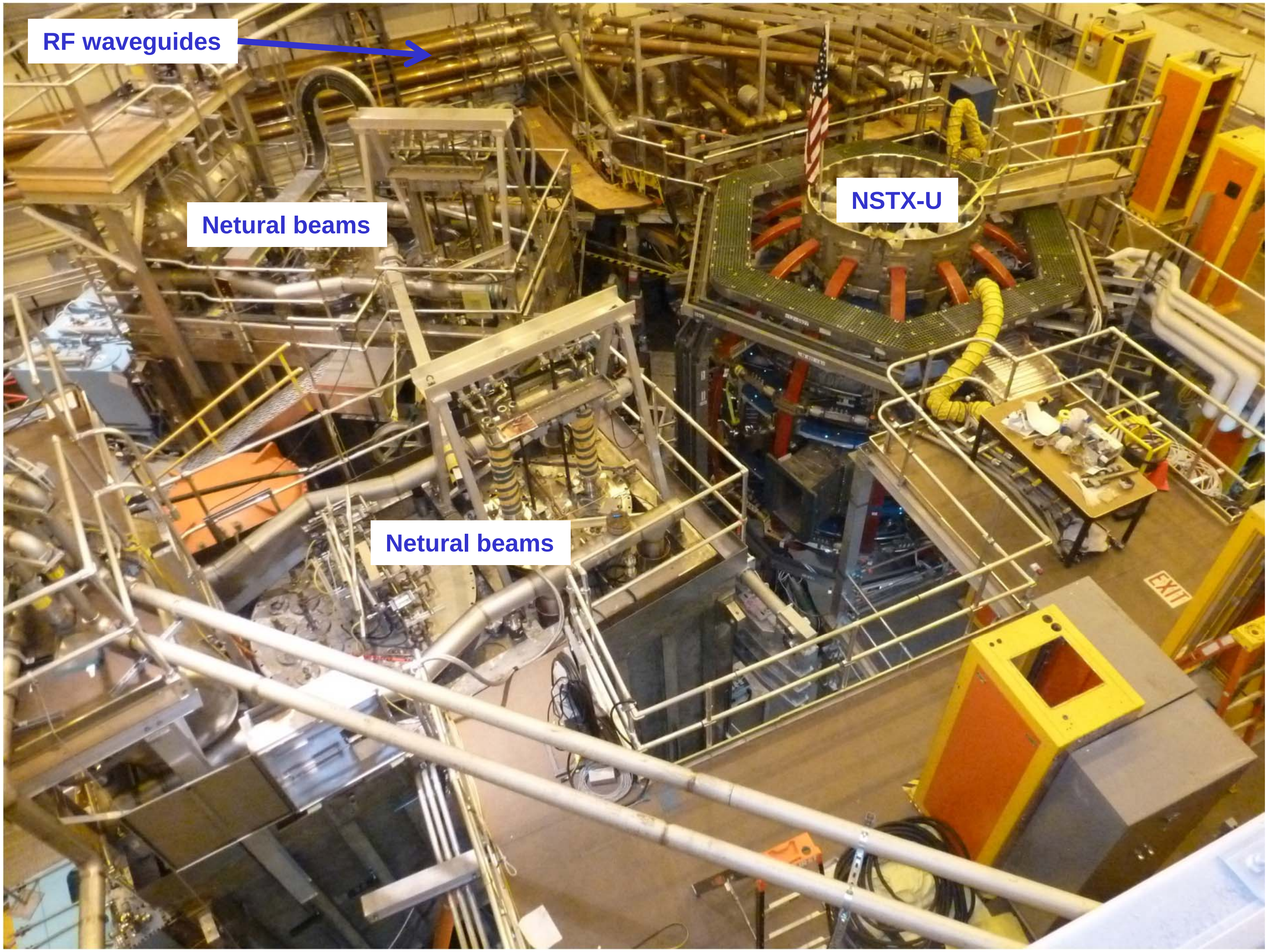


Natuur & Techniek '95
D.A.Gorissen

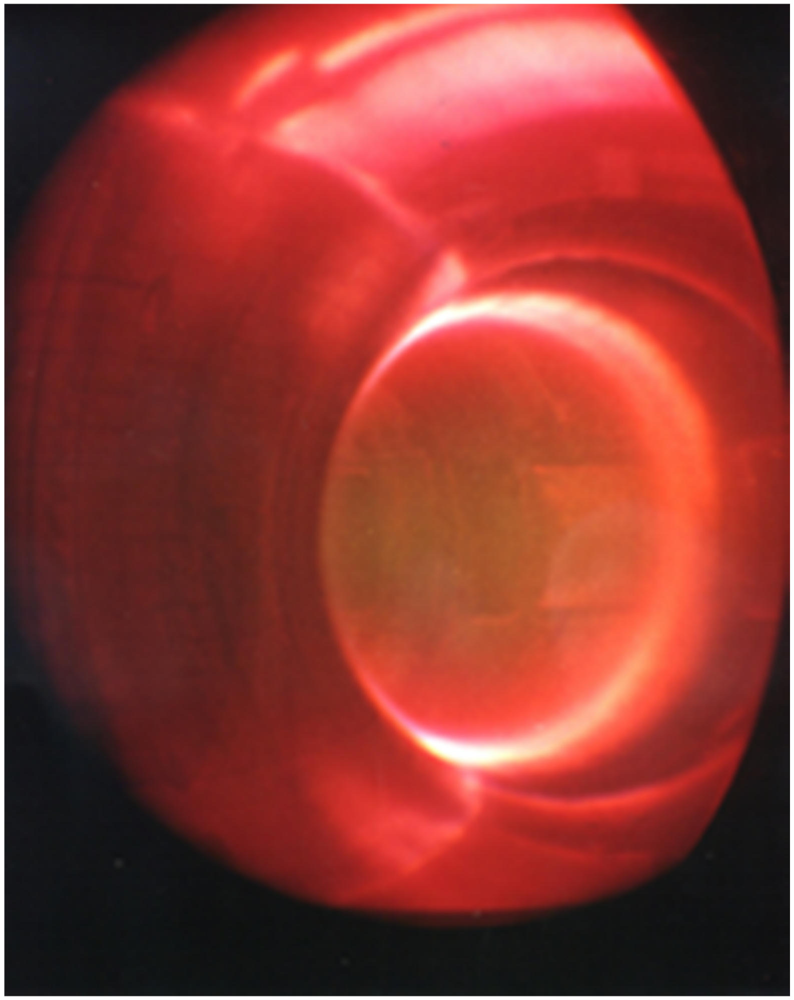
**Heating by electromagnetic (RF) waves**

**Heating by injecting a beam of energetic neutral particles**

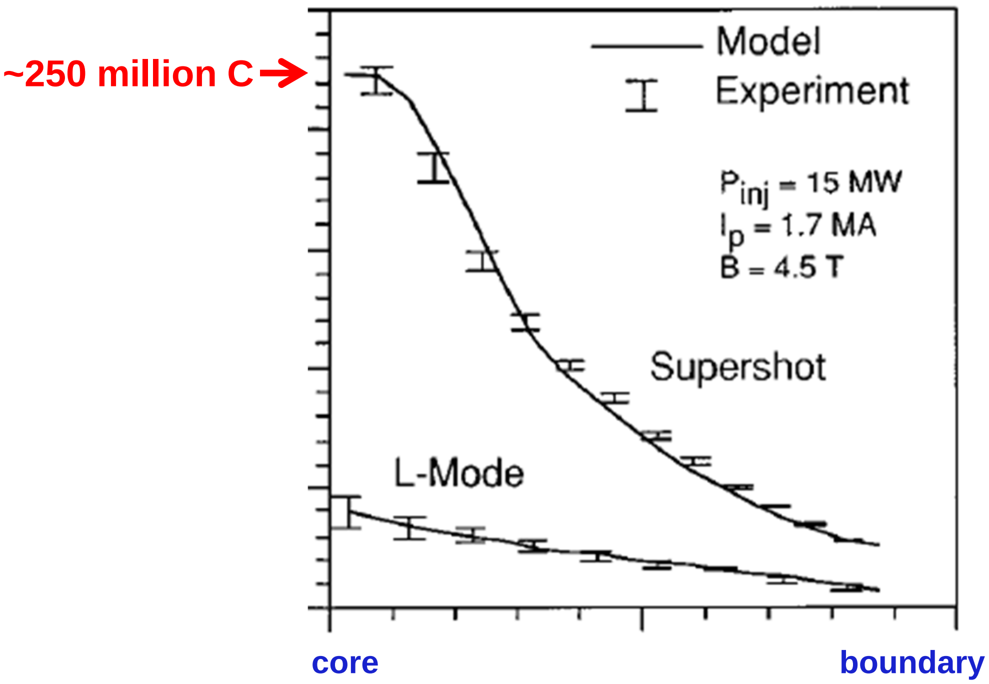
- Both methods can also drive plasma current
- NBI also imparts momentum


RF waveguides
Netural beams
NSTX-U
Netural beams
EXIT

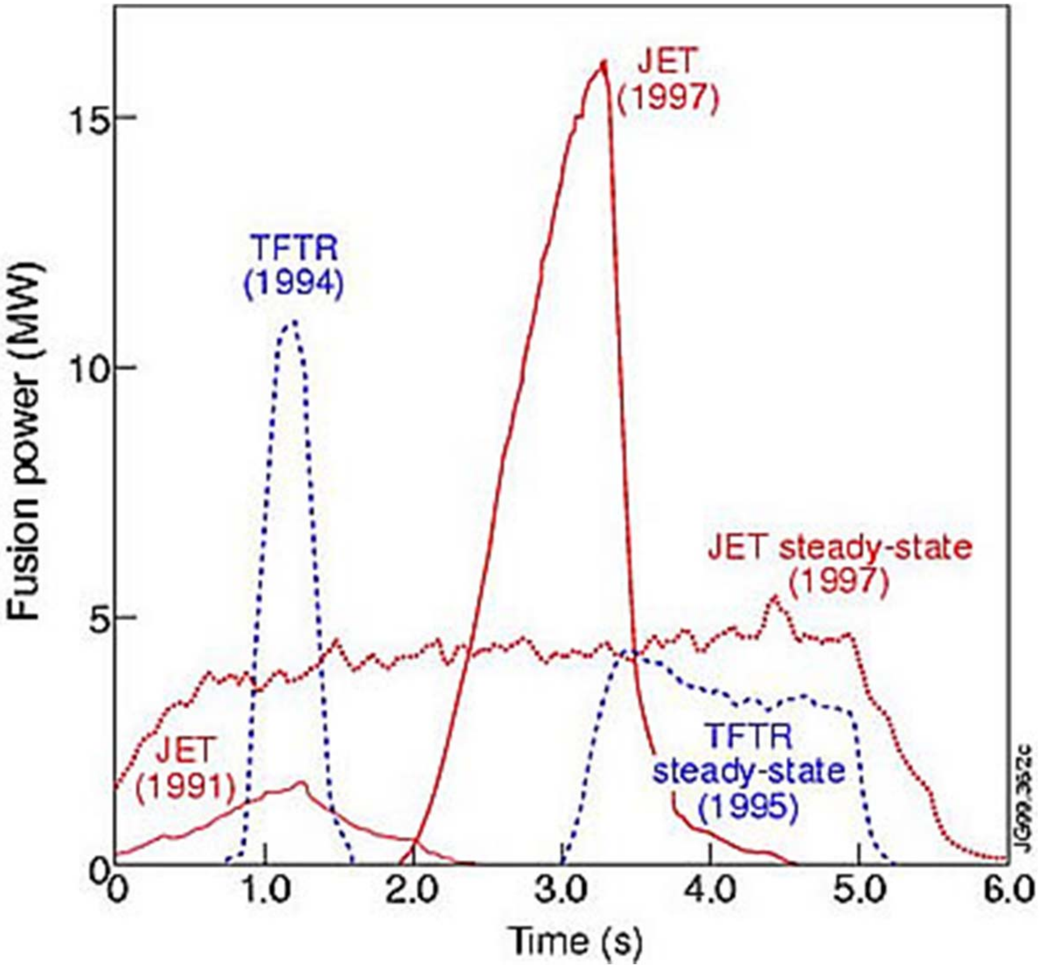
# Have achieved sufficient temperatures!



TFTR at PPPL (1990’s)



# Have achieved fusion power of many MW for seconds when fueling with D+T



- **JET tokamak to revisit D-T experiments (~2017-2019)**

# What do we need to make “sufficient” fusion <u>energy</u>?

# Require much more fusion power out than power to heat the plasma – “fusion gain”

**Fusion gain** $$\boxed{Q = \frac{\text{fusion power}}{\text{heating power}}}$$

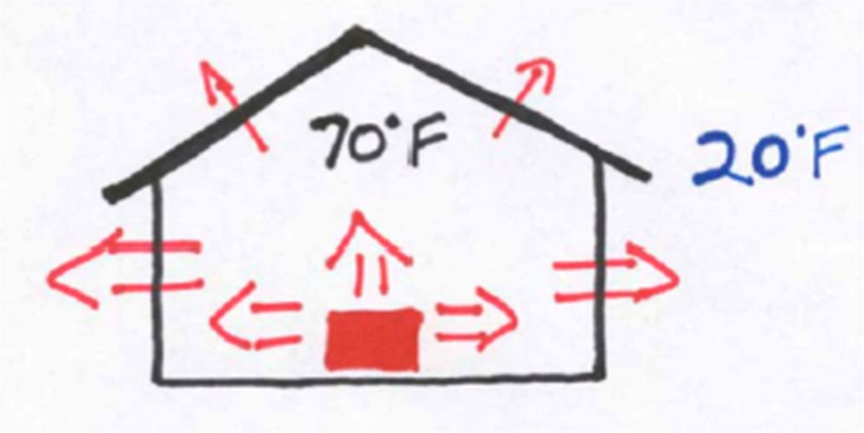
Fusion power ~ $(\text{pressure})^2 \times$ volume

Fusion triple product

$$\boxed{Q \sim (\text{pressure}) \times (\text{confinement time}) = nT\tau}$$

$$\boxed{\tau = \text{confinement time} \sim \frac{\text{pressure} \times \text{volume}}{\text{heating power}}}$$

# Confinement time is a measure of how well insulated the plasma is from the surrounding boundary



$$\text{confinement time} \sim \frac{\text{energy in plasma (Joules)}}{\text{heating power (Watts)}}$$

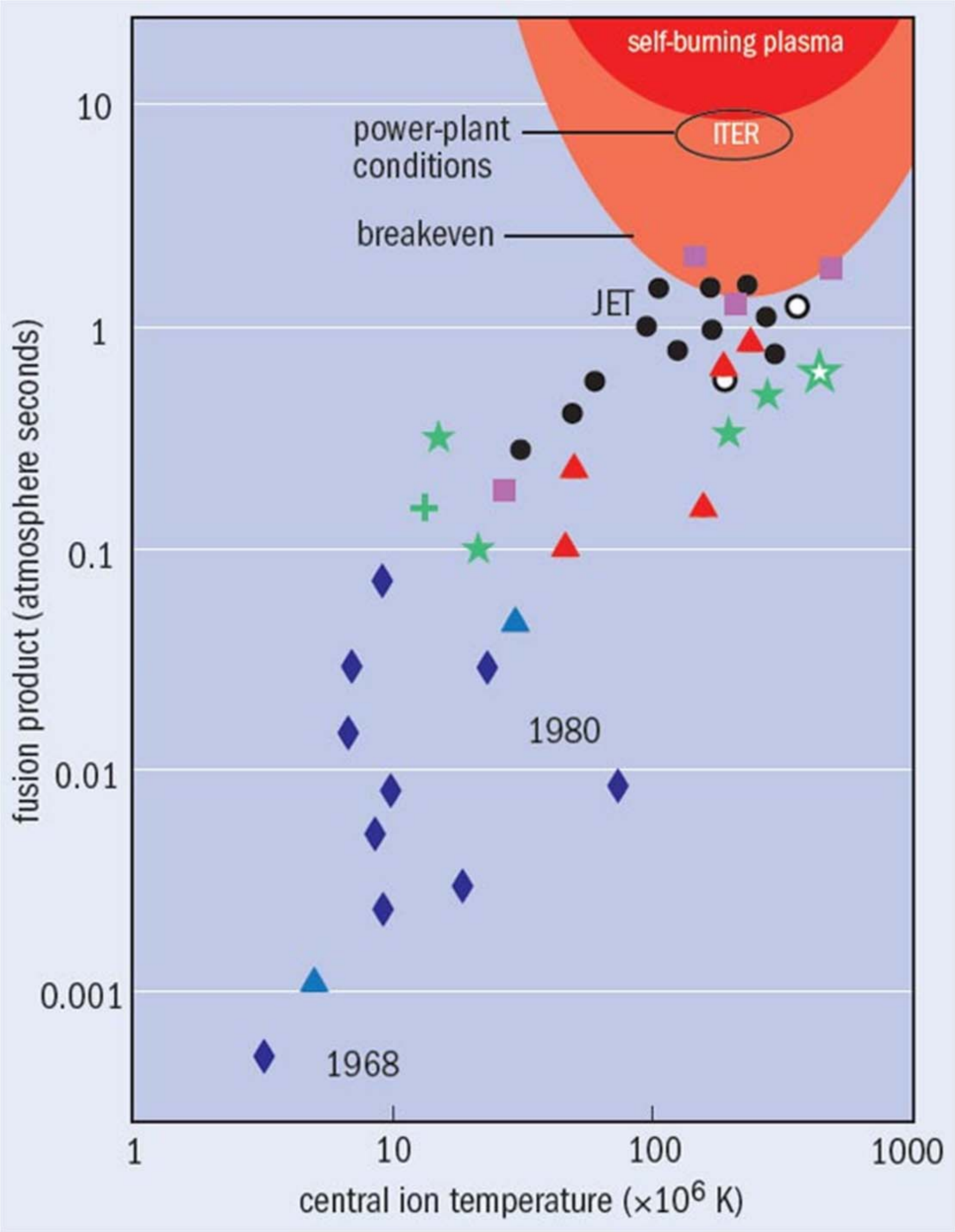
**<u>For ignition (a self-sustaining, “burning plasma”)</u>**

Q ~ pressure × confinement time > <u>8 atm·s</u> (at ~150 million C)

pressure ~ 2-4 × atmospheric pressure

confinement time ~ 2-4 seconds

# Have come very close to "break-even", or Q=1



TFTR (PPPL, 1994)

10.7 MW fusion power

46 MW heating power

**Q=0.23**

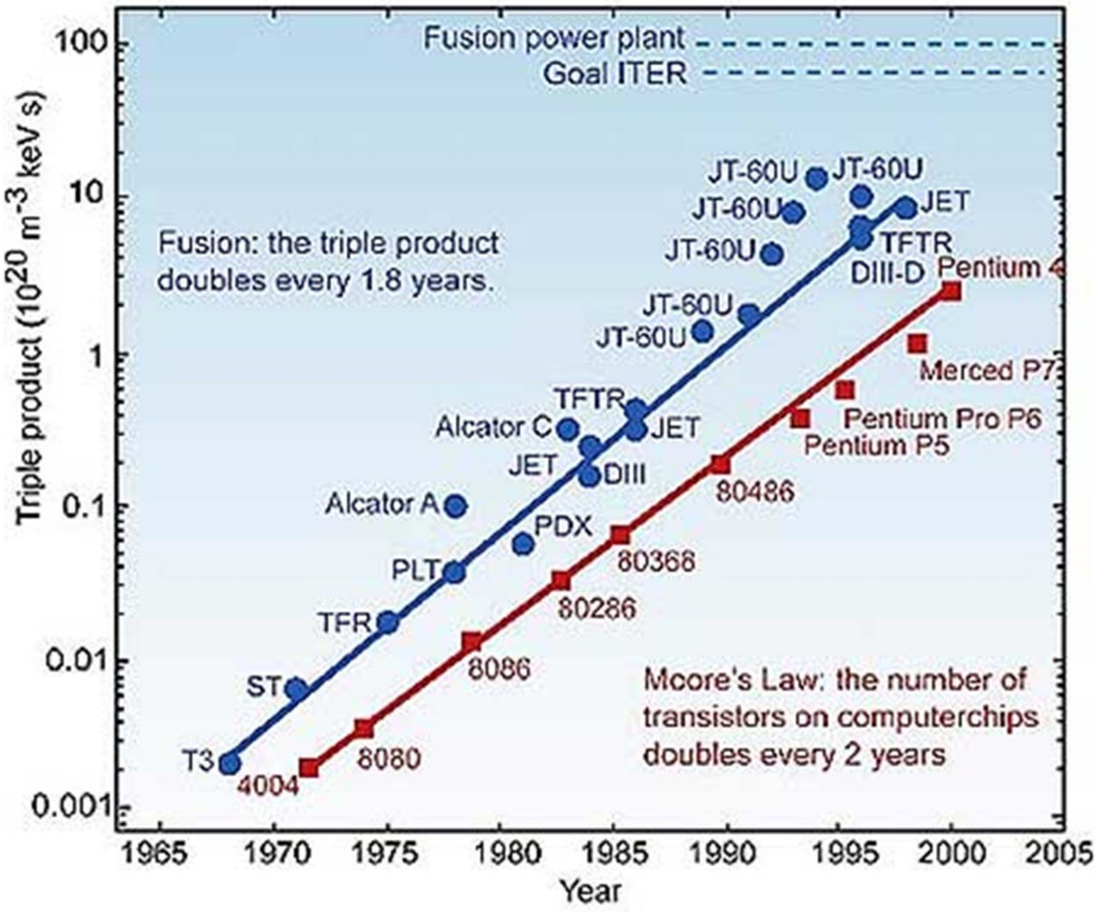
JET (UK, 1997)

16.1 MW fusion power

22 MW heating power

**Q=0.7**

# Pace of fusion gain has been very promising



# Next step: ITER is being built to study “burning plasmas”

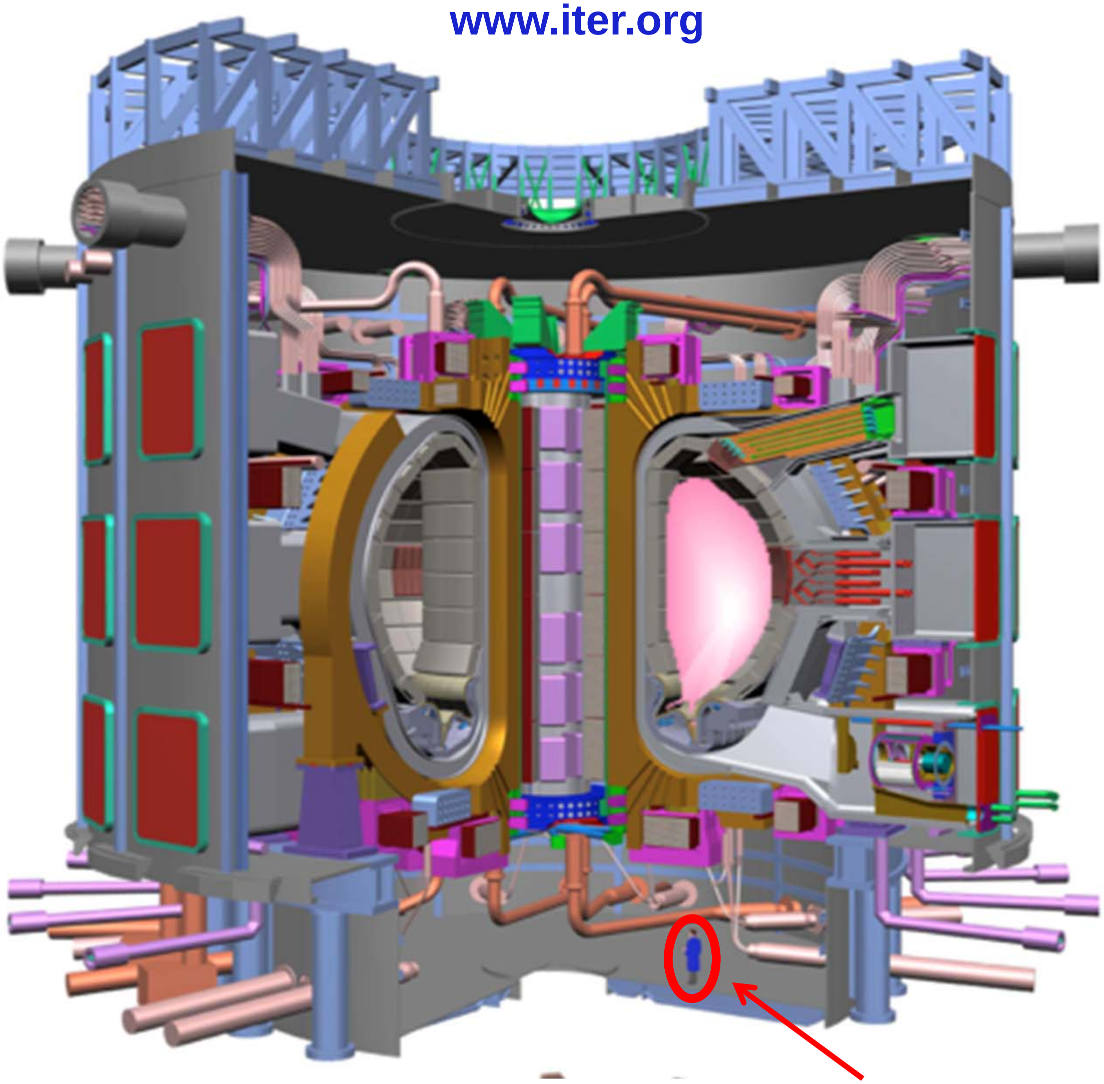
- **Goal:** deliver ten times the power (500 MW) it consumes (50 MW)

  →large fusion gain Q = 10

  Seven partners

  China, EU, India, Japan, Korea, Russia, US

www.iter.org



# ITER is being constructed in Cadarache, France

- First plasma – 2020 + ?
- D-T fusion – 2027 + ?

# So why is ITER so big (and expensive)?

# Need sufficient confinement to maximize fusion gain

Fusion gain

$$\boxed{Q = \frac{P_{\text{fusion}}}{P_{\text{heat}}} \sim \text{pressure} \times \text{confinement time}}$$

$\Rightarrow$ Maximize confinement time

$$\boxed{\text{confinement time} \sim \frac{\text{pressure} \times \text{volume}}{\text{heat loss}}}$$

Easiest (conservative) solution – make it big (confinement~V), but…

Increasing volume → larger device = $$$

Better to minimize power required (heat losses) to maintain pressure

# Diffusion by collisions will try to relax gradients

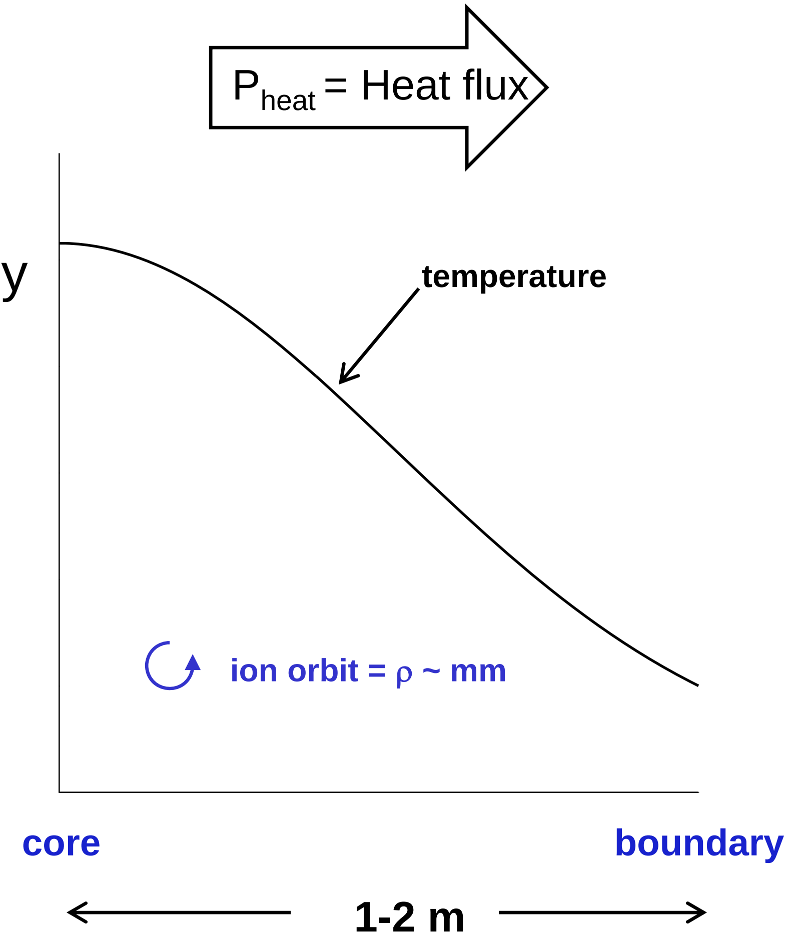
heat flux ~ $D_{\text{collisions}} \times (T_{\text{hot}} - T_{\text{cold}})$

$D_{\text{collisions}}$ ~ (step size)$^2$ × collision frequency

step size ~ particle orbits ~ mm

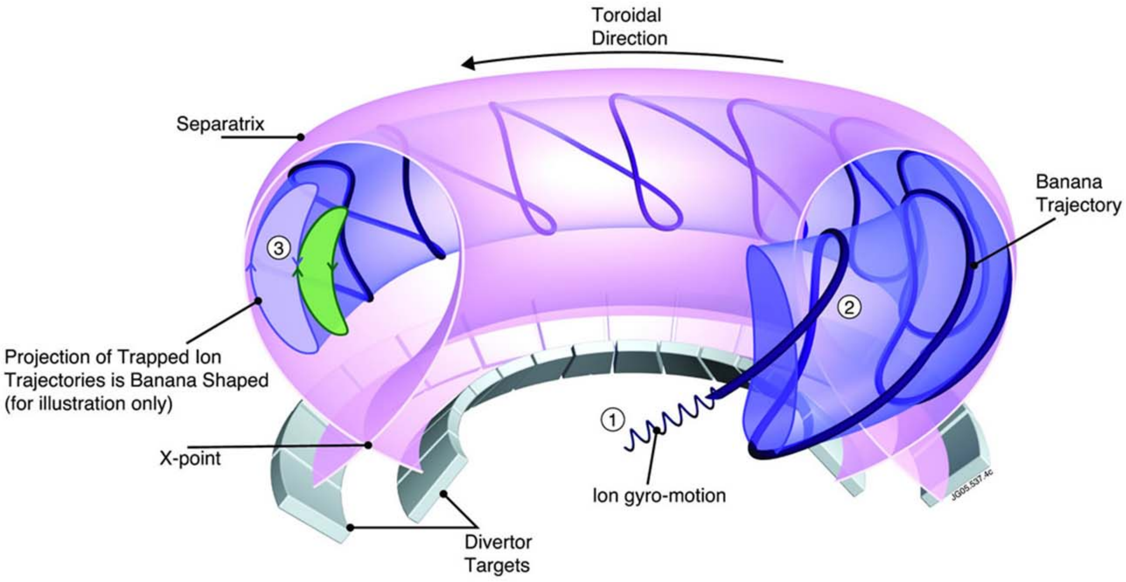
collision frequency ~ kHz

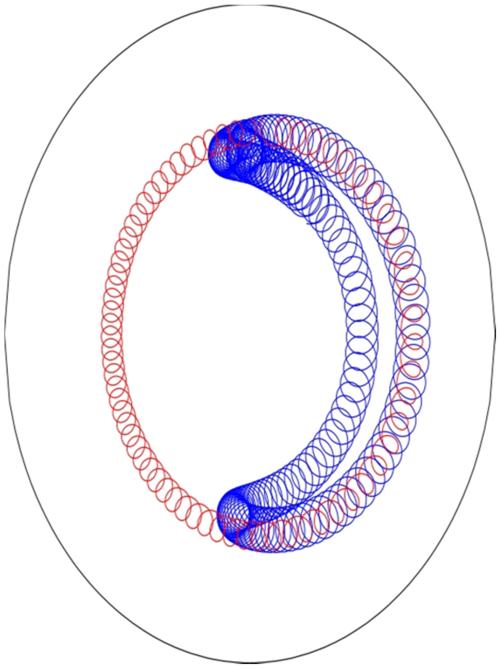
$$\boxed{\text{confinement time} \sim \frac{1}{D_{\text{collisions}}}}$$



Collisional confinement time estimate ~ 100 s

# Toroidicity ($\nabla B$ & $\kappa$) leads to particle drifts off flux surfaces, larger drift orbit widths

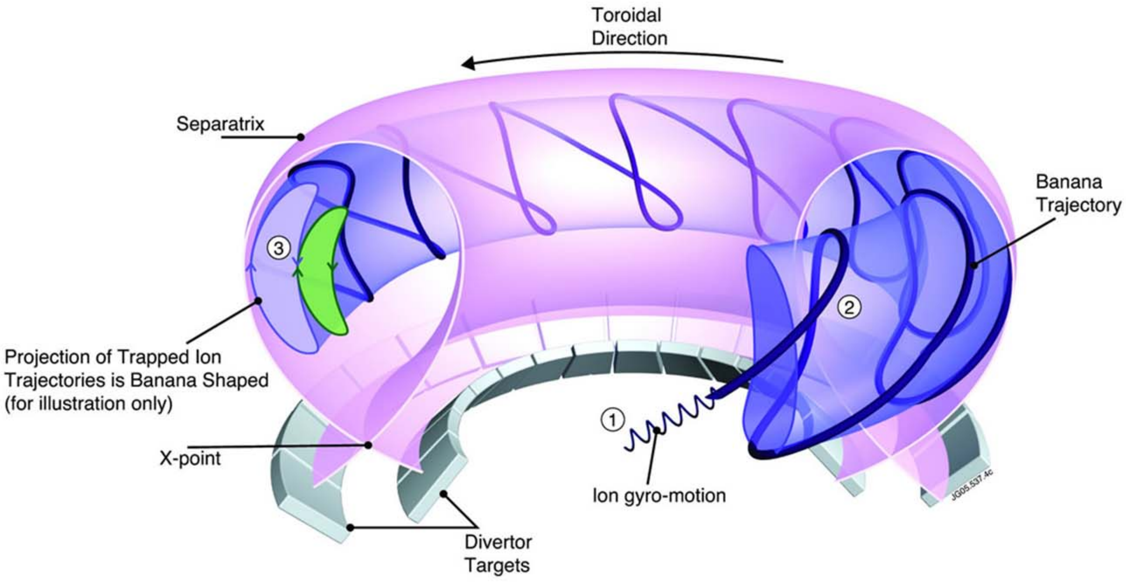


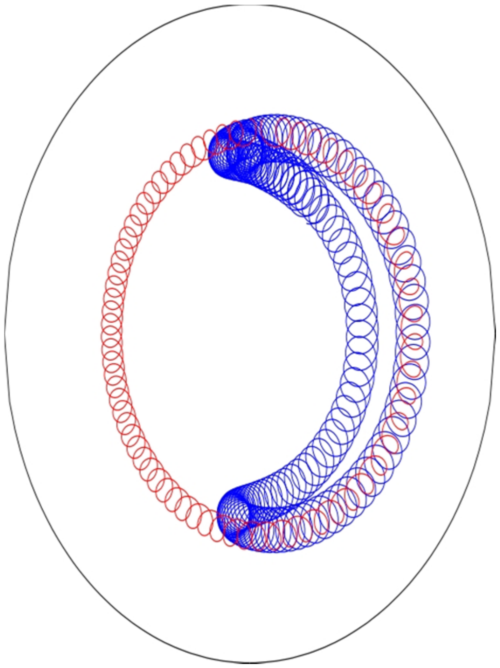


- Resulting “neoclassical” transport is ~10 times bigger than classical

Neoclassical confinement time estimate ~ 1-10 s

# Toroidicity ($\nabla B$ & $\kappa$) leads to particle drifts off flux surfaces, larger drift orbit widths

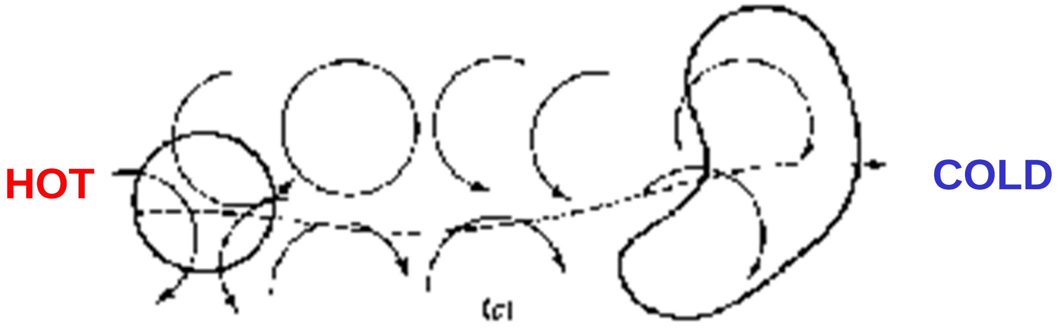




- Resulting “neoclassical” transport is ~10 times bigger than classical
  - Neoclassical theory doesn’t explain thermal confinement, but still generally important for understanding impurity transport

Neoclassical confinement time estimate ~ 1-10 s
Experimental confinement time ~ 0.1 s

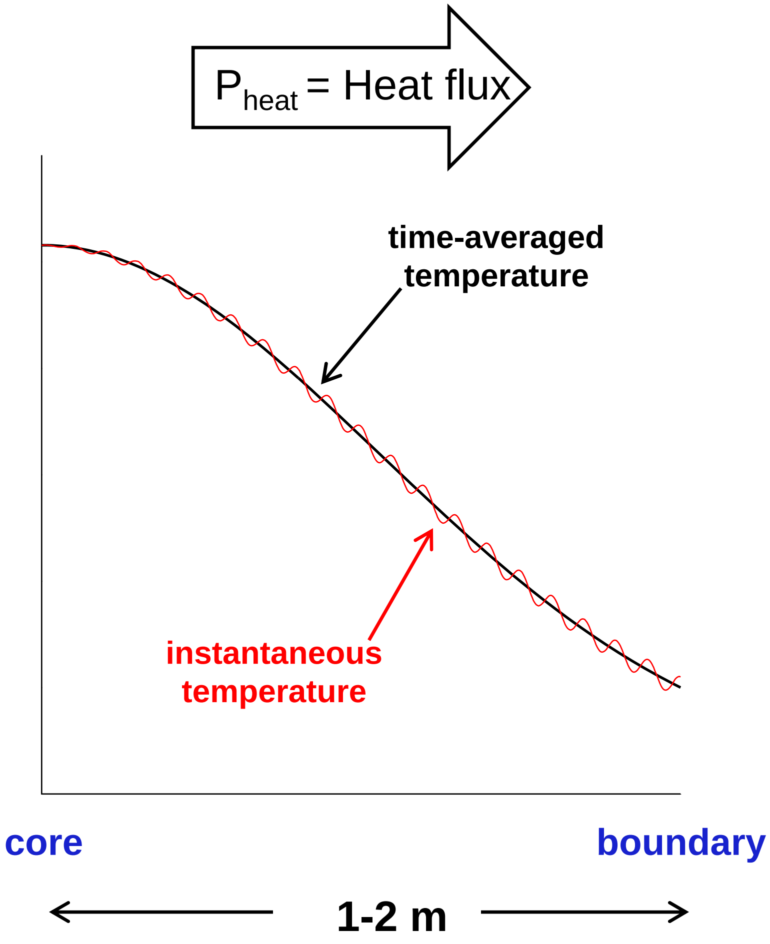
# Increasing gradients eventually cause small scale instability → turbulence



- Turbulent “eddies” → random velocity fluctuations mix hot and cold

- Can be small size, small amplitude (<1%)

**But still effective at transport**



$P_{heat}$ = Heat flux

time-averaged temperature

instantaneous temperature

core

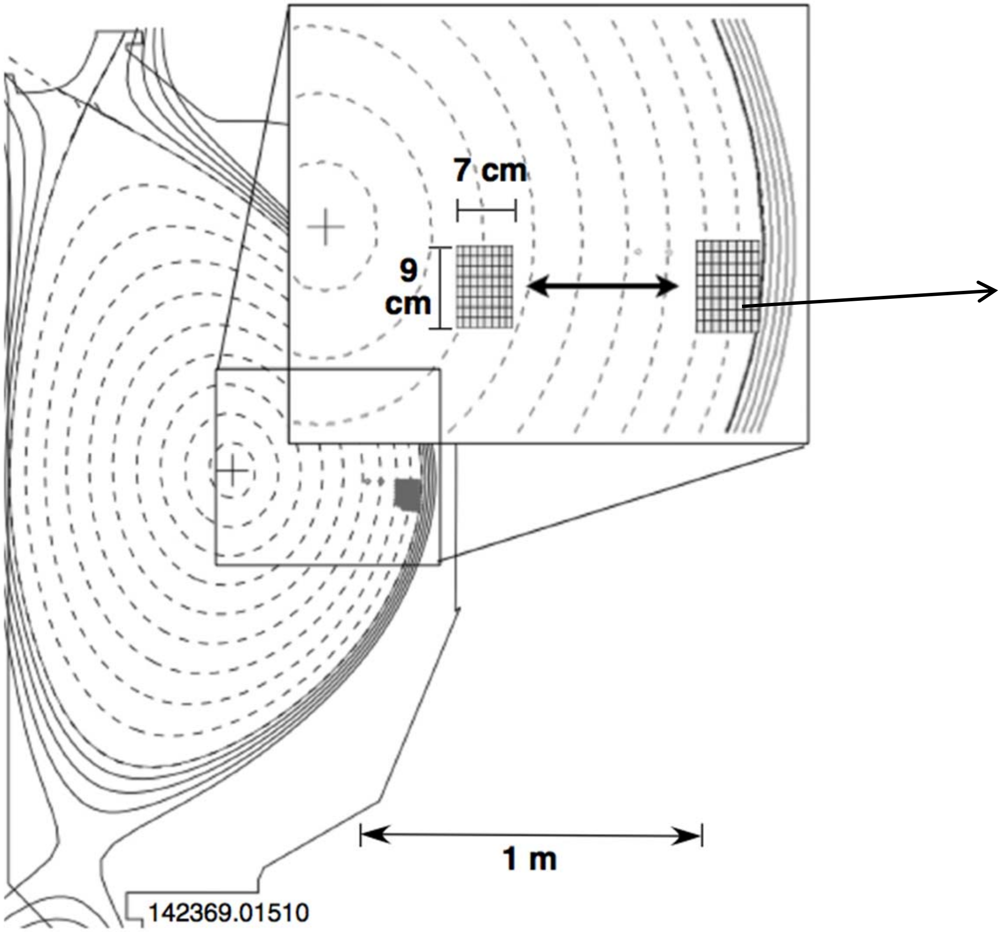
boundary

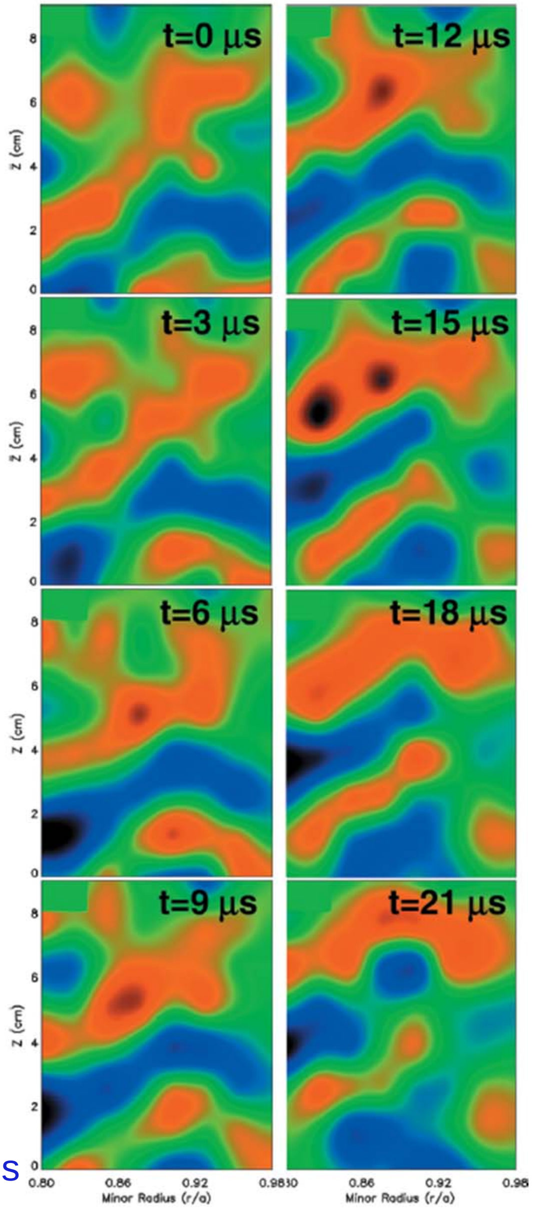
1-2 m

# Spectroscopic imaging provides a 2D picture of turbulence in tokamaks: cm spatial scales, μs time scales, <1% amplitude

- Utilize interaction of neutral atoms with charged particles to measure density

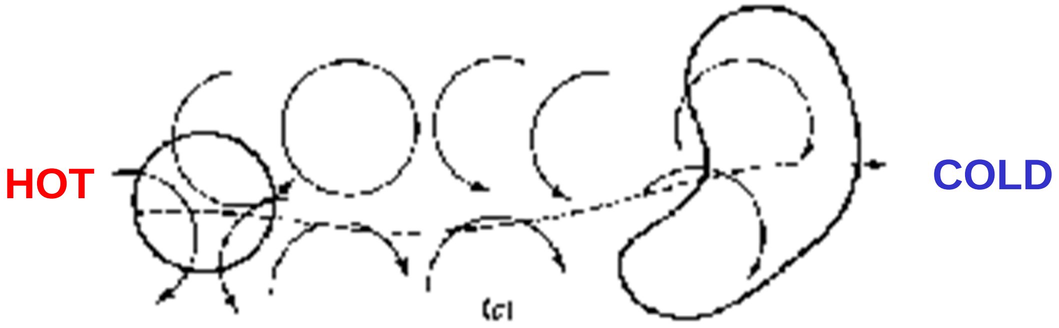
DIII-D tokamak (General Atomics)





Movies at: https://fusion.gat.com/global/BESMovies

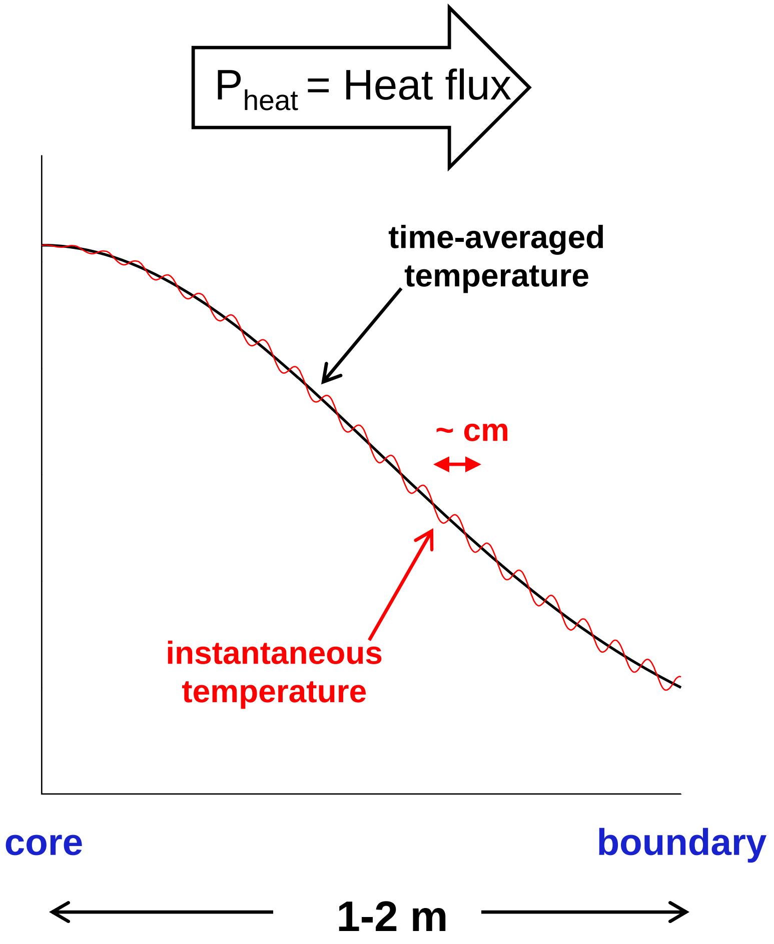
# Rough estimate of turbulent diffusivity indicates it’s a plausible explanation for confinement



- $D_{\text{turbulence}} \sim (\text{step size})^2 \times$ “collision frequency”

  step size ~ 5-7 particle orbits ~ cm’s
  “collision frequency” ~ 100 kHz

$$\boxed{\text{confinement time} \sim \frac{1}{D_{\text{turbulence}}}}$$



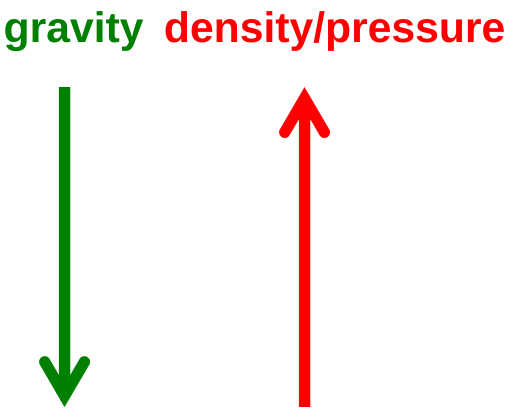
Turbulence confinement time estimate ~ 0.1 s
Experimental confinement time ~ 0.1 s

# Are there ways to reduce turbulence?

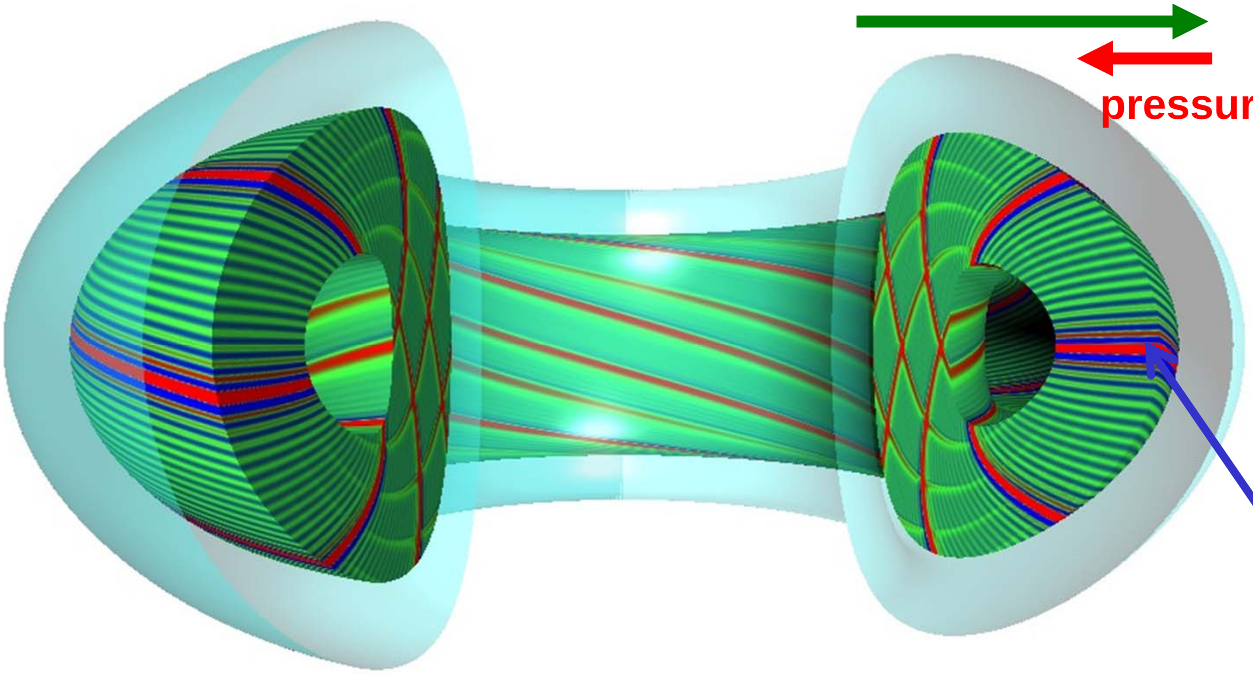
# Yes, but first we have to understand it

# Analogy for turbulence in tokamaks - density gradient in the presence of gravity

- Higher density on top of lower density, with gravity acting downwards (Rayleigh-Taylor instability)
- Any small perturbation becomes unstable
- Convection mixes regions of different density



# Centrifugal force in toroidal field acts like an effective gravity



centrifugal force

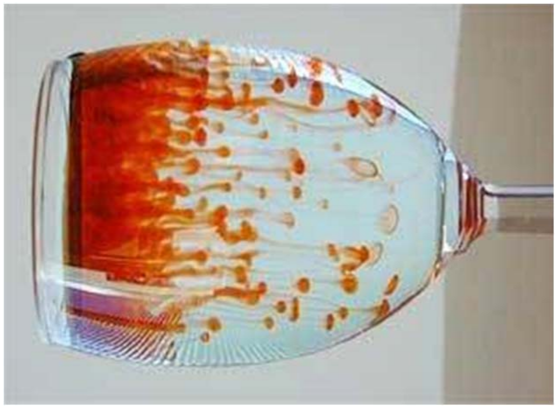
→effective gravity

pressure

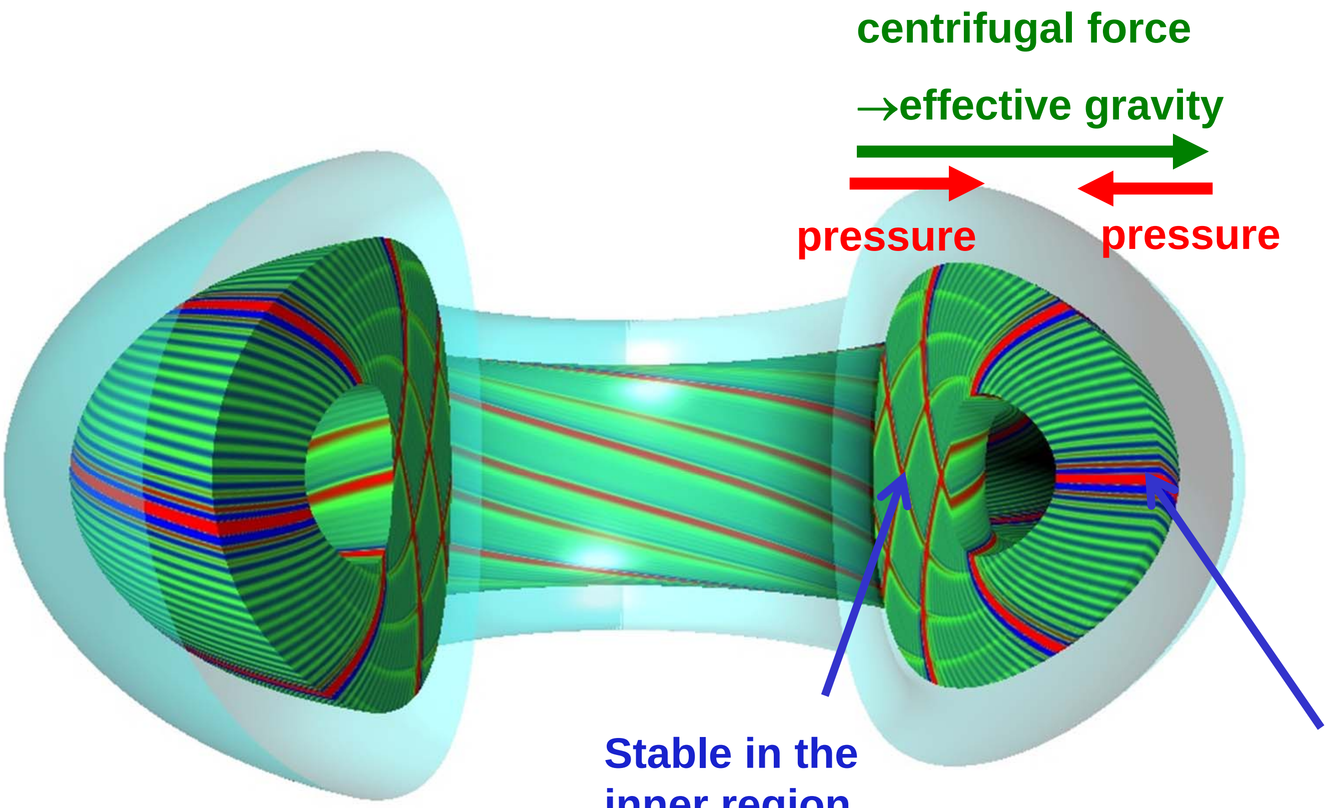
Unstable in the outer region

gravity

pressure



# Centrifugal force in toroidal field acts like an effective gravity



centrifugal force

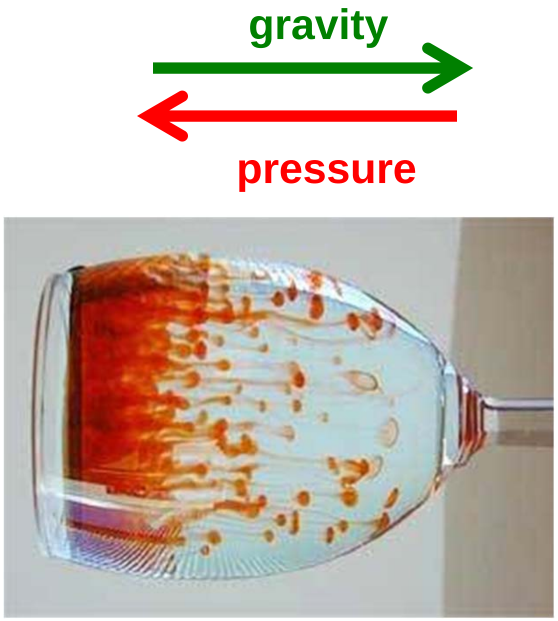
→effective gravity

pressure

pressure

**Stable in the inner region "good curvature"**

**Unstable in the outer region "bad curvature"**



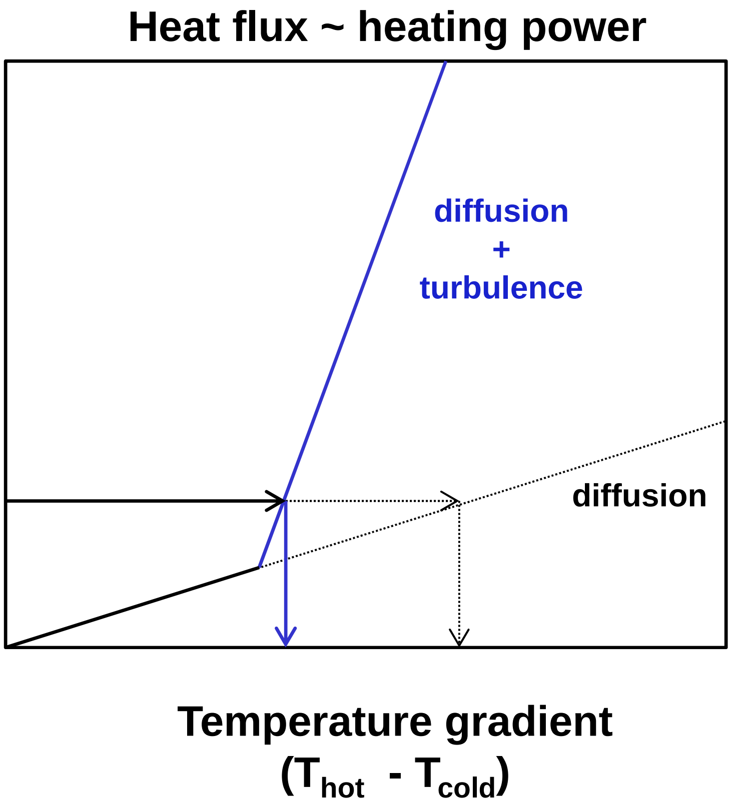
gravity

pressure

Fast parallel dynamics + helical field lines provides stability → gradient must surpass a threshold for instability

(remember honey dipper analogy)

# Onset of turbulence reduces the achieved temperature that would have been present due only to diffusion

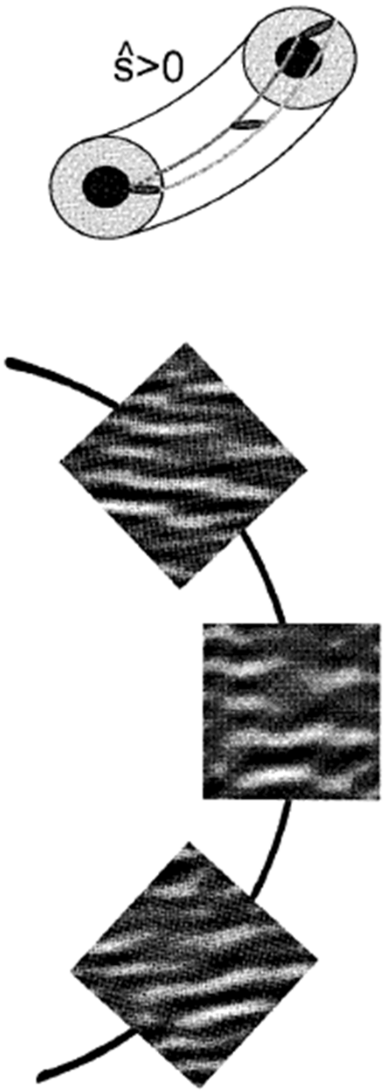


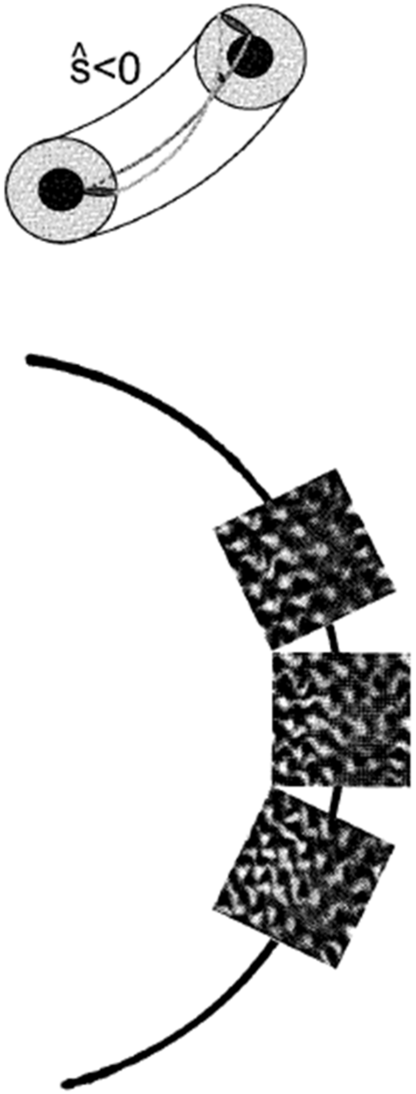
Analogous to convective transport when heating a fluid from below … boiling water (before the boiling)

Rayleigh, Benard, early 1900’s

# Magnetic field topology strongly impacts turbulence

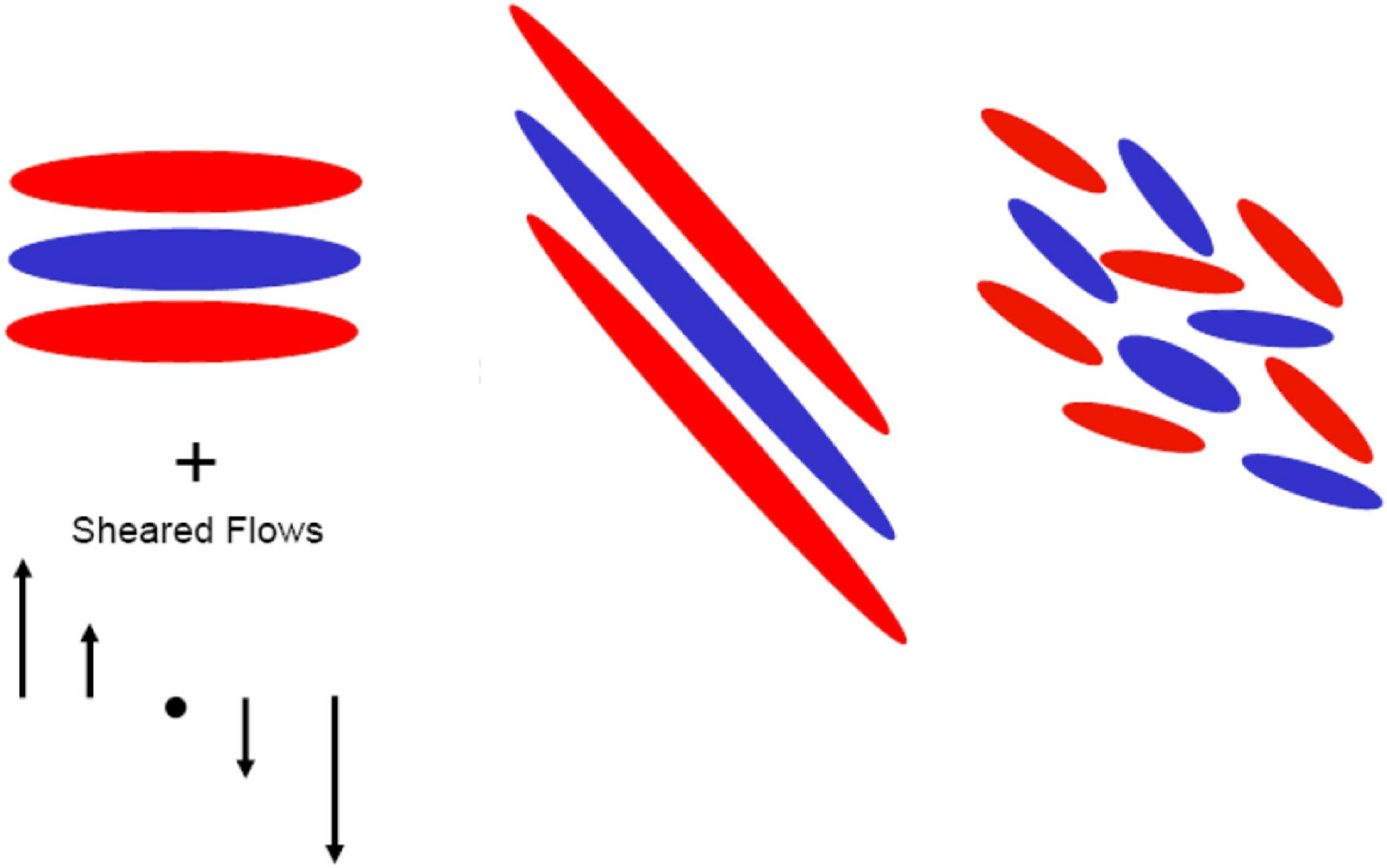
- Can optimize property of magnetic field to vary turbulence





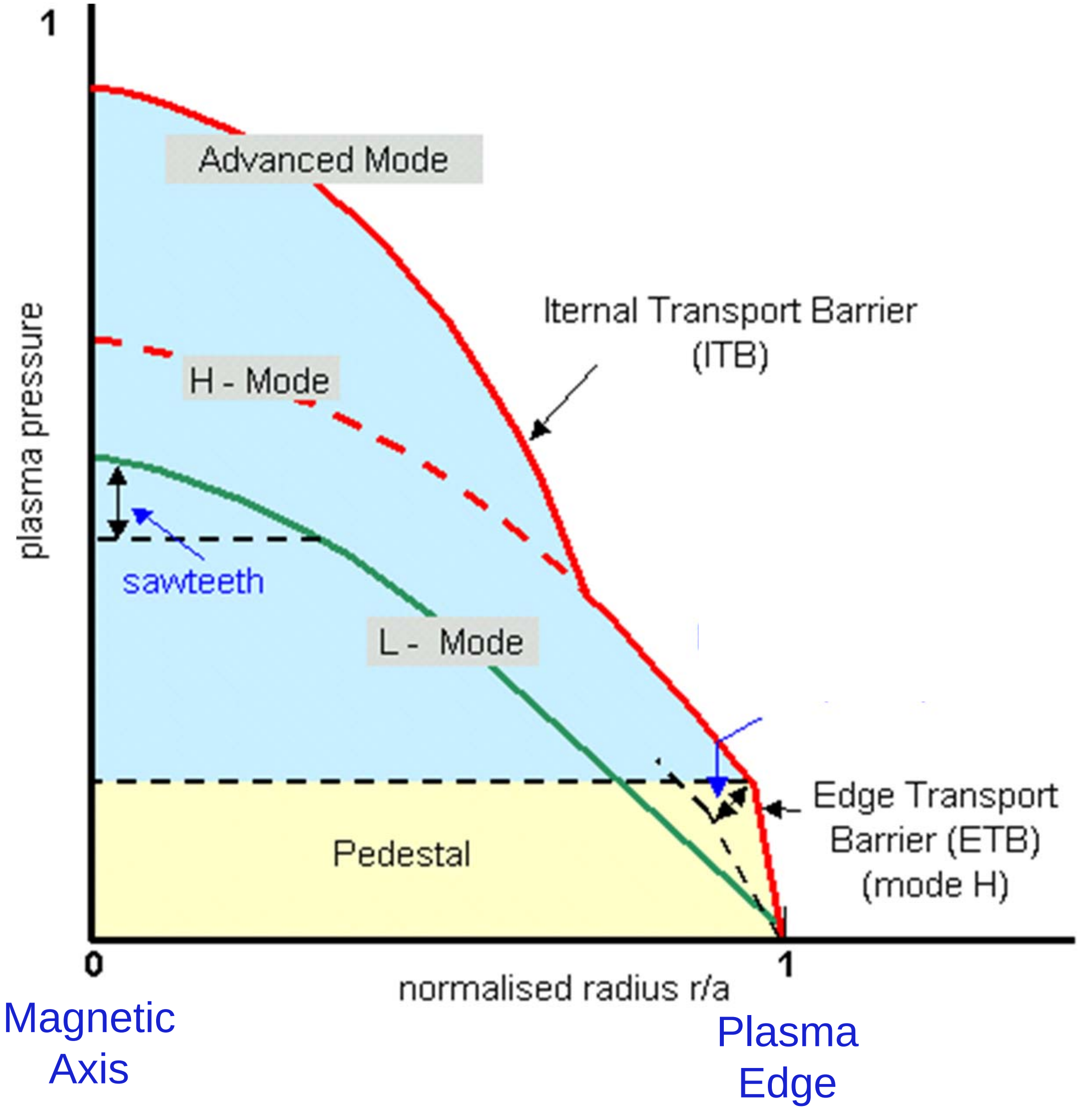
**Antoneson**

# Large scale sheared flows can tear apart turbulent eddies, reduce turbulence, mixing and transport

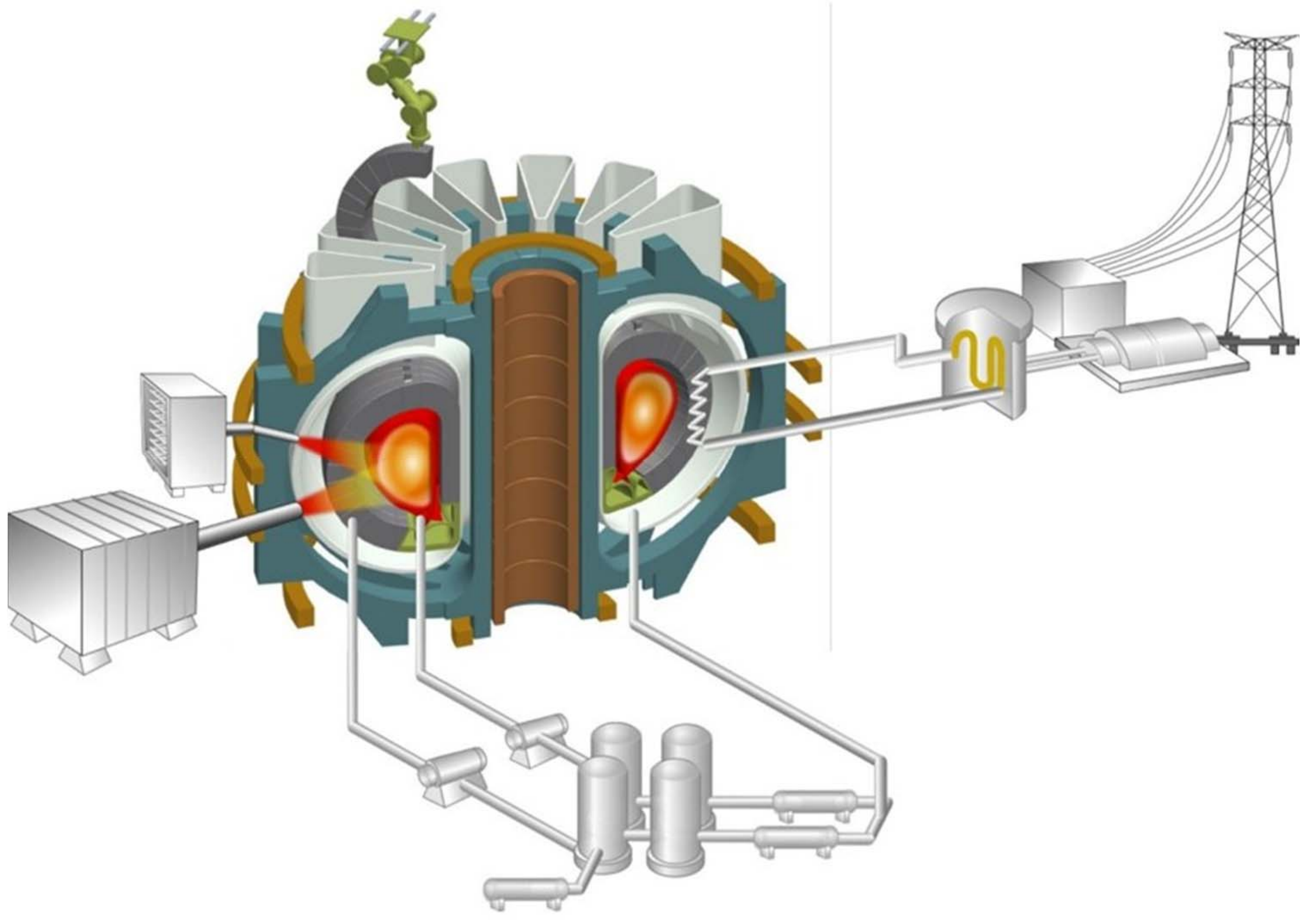


# Varying magnetic and flow profiles dramatically changes achievable pressure & profile shape

- L-mode
  - Smoothly increasing pressure from edge to core
- H-mode
  - Strong flow shear in the edge leads to “transport barrier”, higher total pressure
- H-mode with “Internal Transport Barrier”
  - Optimize shear in magnetic field and/or flow leads to additional transport barrier, more peaked pressure profile



# What else needed to make fusion reactors & electricity a reality?



# What else is needed to make fusion reactors & electricity a reality

- ✓ Hot enough, good confinement
- Steady-state, controllable
- Reliable, maintainable
- Means to handle exhaust heat, neutrons (materials, etc…)
- Tritium management (12 year half-life)
  - Need to breed tritium, likely from $Li+n \rightarrow He+T$
  - Need a Lithium “blanket” surrounding vacuum vessel

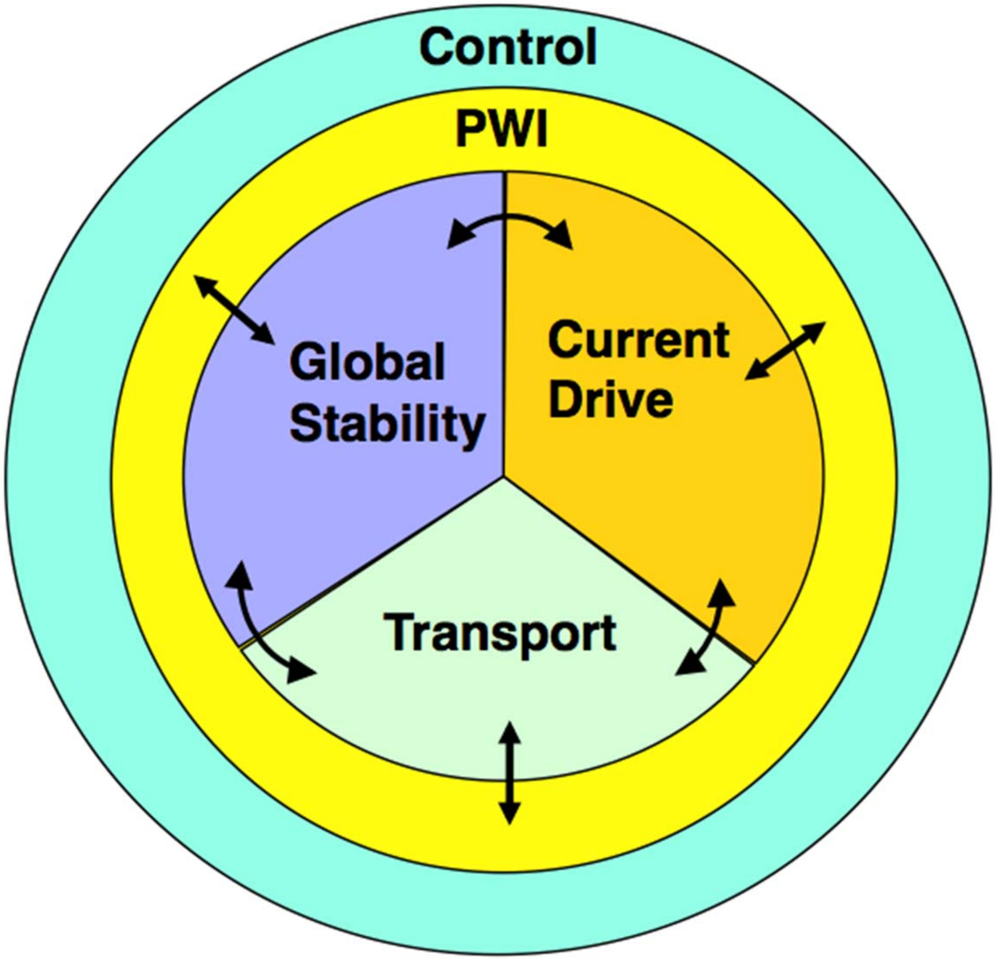
# What else is needed to make fusion reactors & electricity a reality

- ✓ Hot enough, good confinement
- **Steady-state, controllable**
- Reliable, maintainable
- Means to handle exhaust heat, neutrons (materials, etc…)
- Tritium management

# To achieve integrated steady-state operation must balance current drive, stability, and transport

- Complicated interconnection between three physics topics
  - Global stability: must avoid disruptions, macroscopic instabilities
  - Current drive: must supply 100% of the plasma current non-inductively
    - Through external current drive (NBI, RF) + self-generated “bootstrap current”
  - Transport: transport rate→plasma profiles must be compatible with current drive & stability requirements

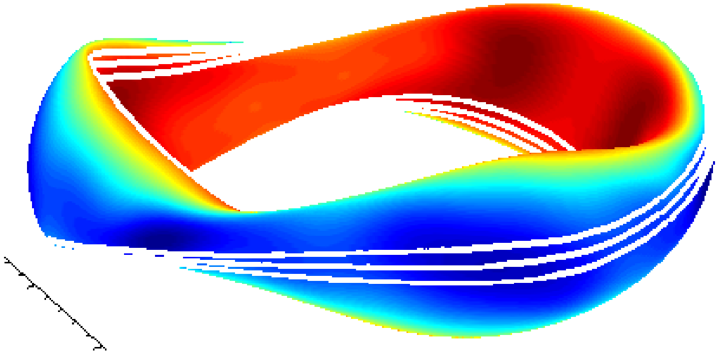
- Must also:
  - Integrate core plasma with the high heat flux region (PWI=Plasma Wall Interaction)
  - Be able to control plasma



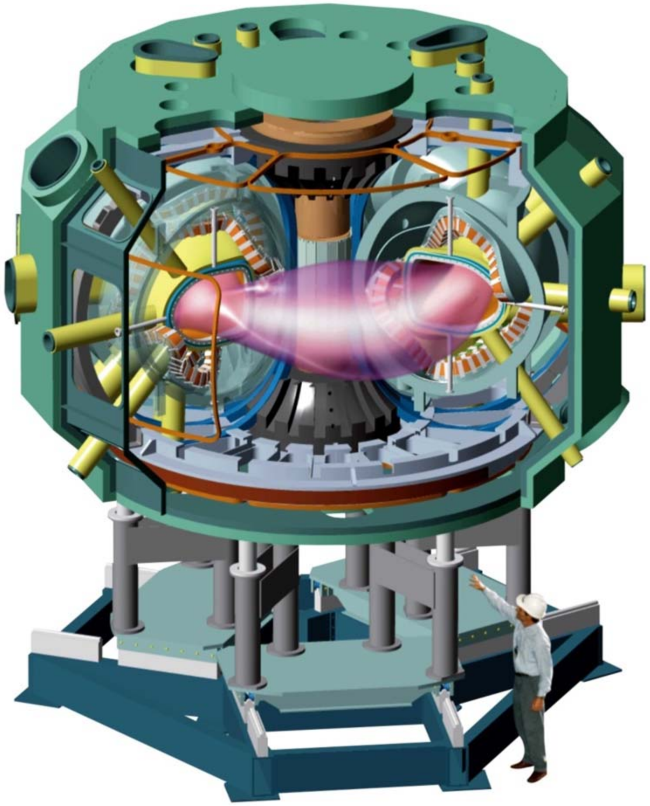
See T. Luce, Phys. Plasmas **18** For Discussion of Steady State Operations in Conventional Aspect Ratio Tokamaks

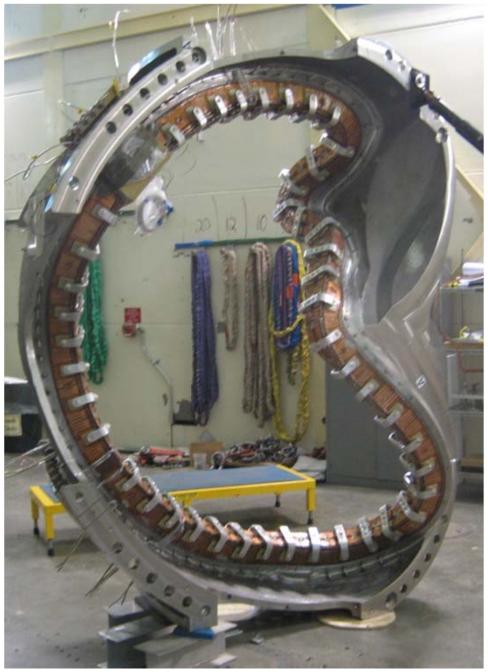
# Stellarators use complex external coils to create helical magnetic field lines, no need for internal current → <u>inherently steady-state</u>

- Much freedom to optimize magnetic field, <u>but</u> complex coils more challenging to engineer (and theory is generally more complex)



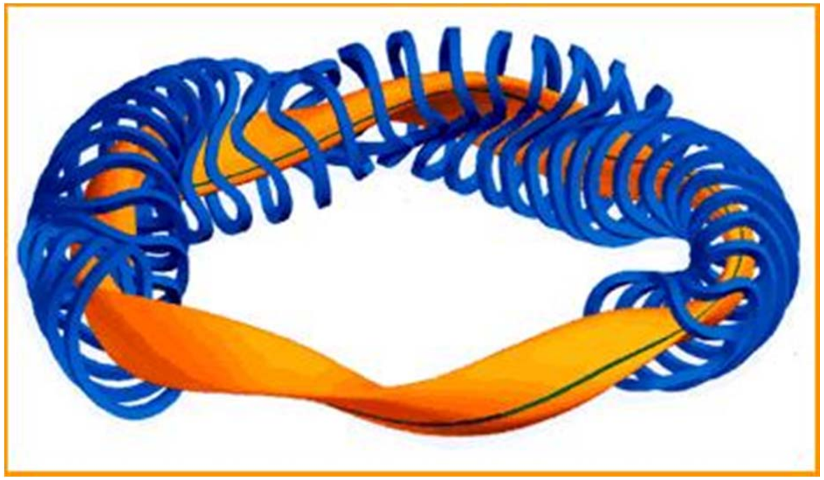
**National Compact Stellarator Experiment (NCSX, PPPL)**
**Now QUASAR**

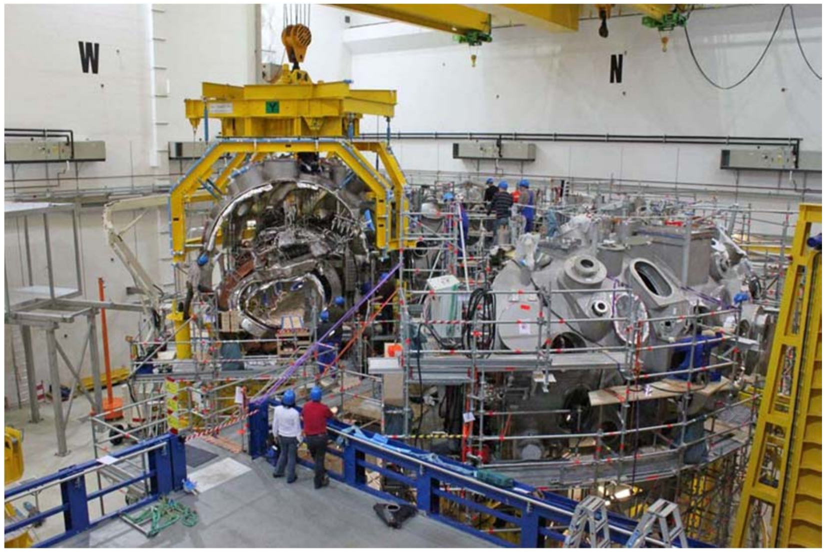




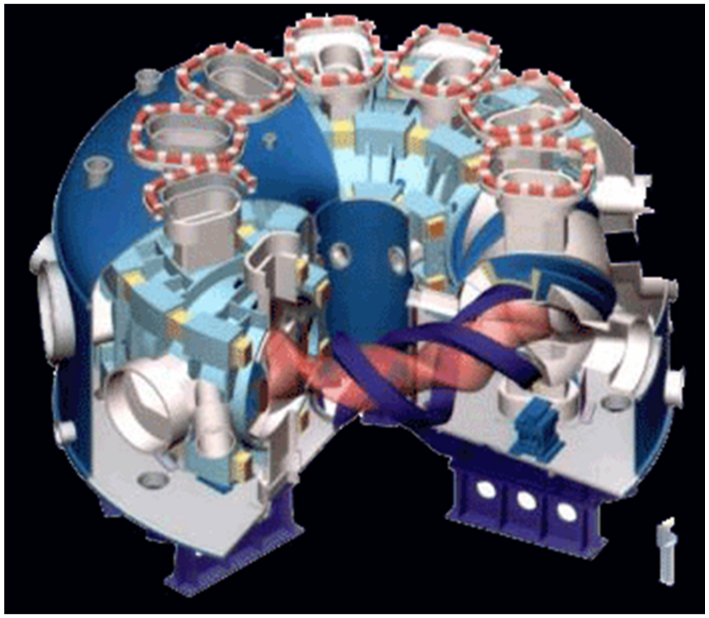
# Large stellarators around the world

**W7-X (EU/Germany)**
**Operational in 2015**





**LHD (Japan)**




(c)JOE NISHIZAWA

# What else is needed to make fusion reactors & electricity a reality

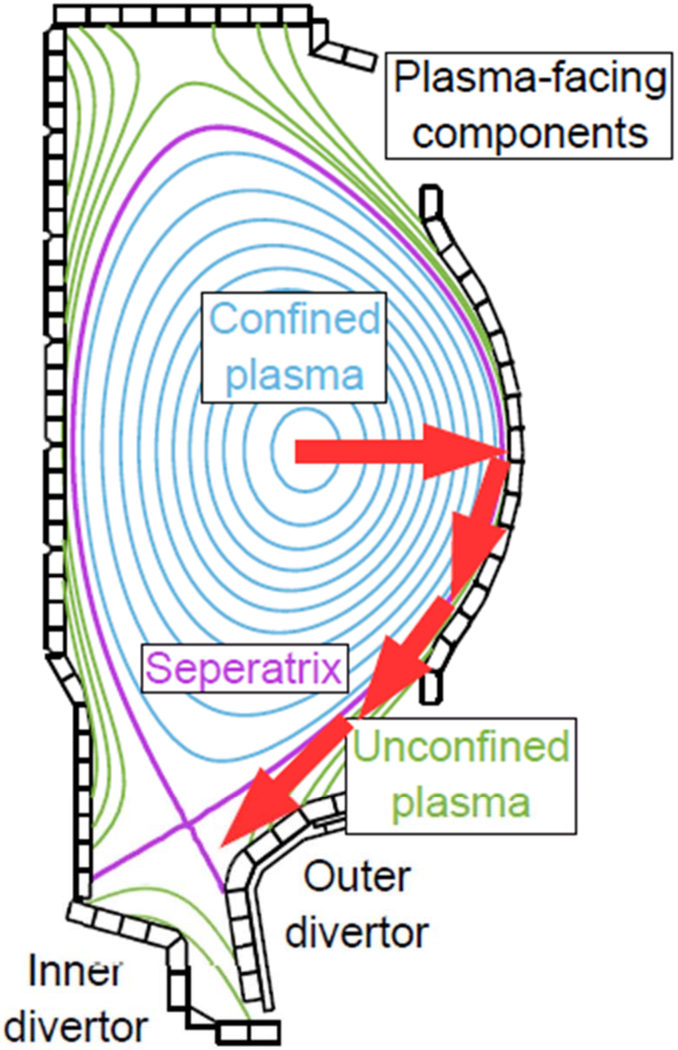
- ✓ Hot enough, good confinement
- Steady-state, controllable
- Reliable, maintainable
- **Means to handle exhaust heat, neutrons (materials, etc…)**
- Tritium management

# Removing power from the confined plasma sets extreme conditions on materials

**Fusion heat and particles** must be exhausted to the materials

This leads to heat fluxes on the materials of approximately

$$\boxed{Q_{\mathrm{materials}} \simeq 10\,\mathrm{MW\,m^{-2}}}$$



Courtesy Zach Hartwig, MIT (http://www.psfc.mit.edu/~hartwig/)

# Atmospheric reentry and arc welding require handling similar steady-state heat fluxes

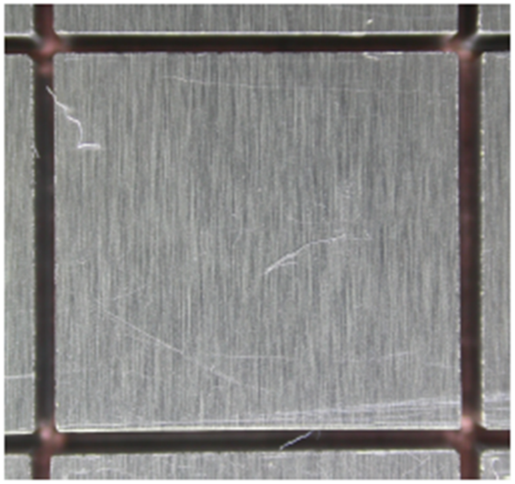
**Mars Curiosity Rover**
Q ~ 2.3 MW $m^{-2}$
T ~ 3800 K

**Arc Welding**
Q ~ 40-60 MW $m^{-2}$
T ~ 3900 K

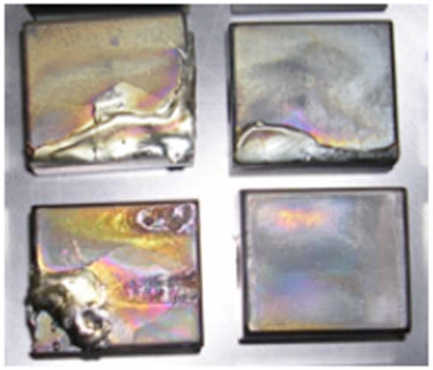
*Courtesy Zach Hartwig, MIT (http://www.psfc.mit.edu/~hartwig/)*

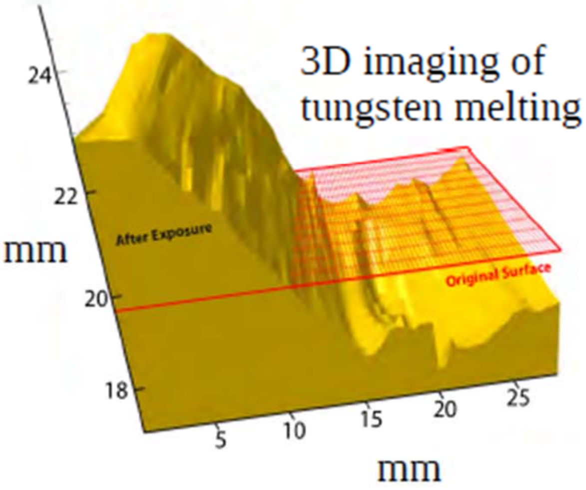
# Plasma substantially alters the ***macroscopic*** surface morphology of materials

Unexposed tungsten



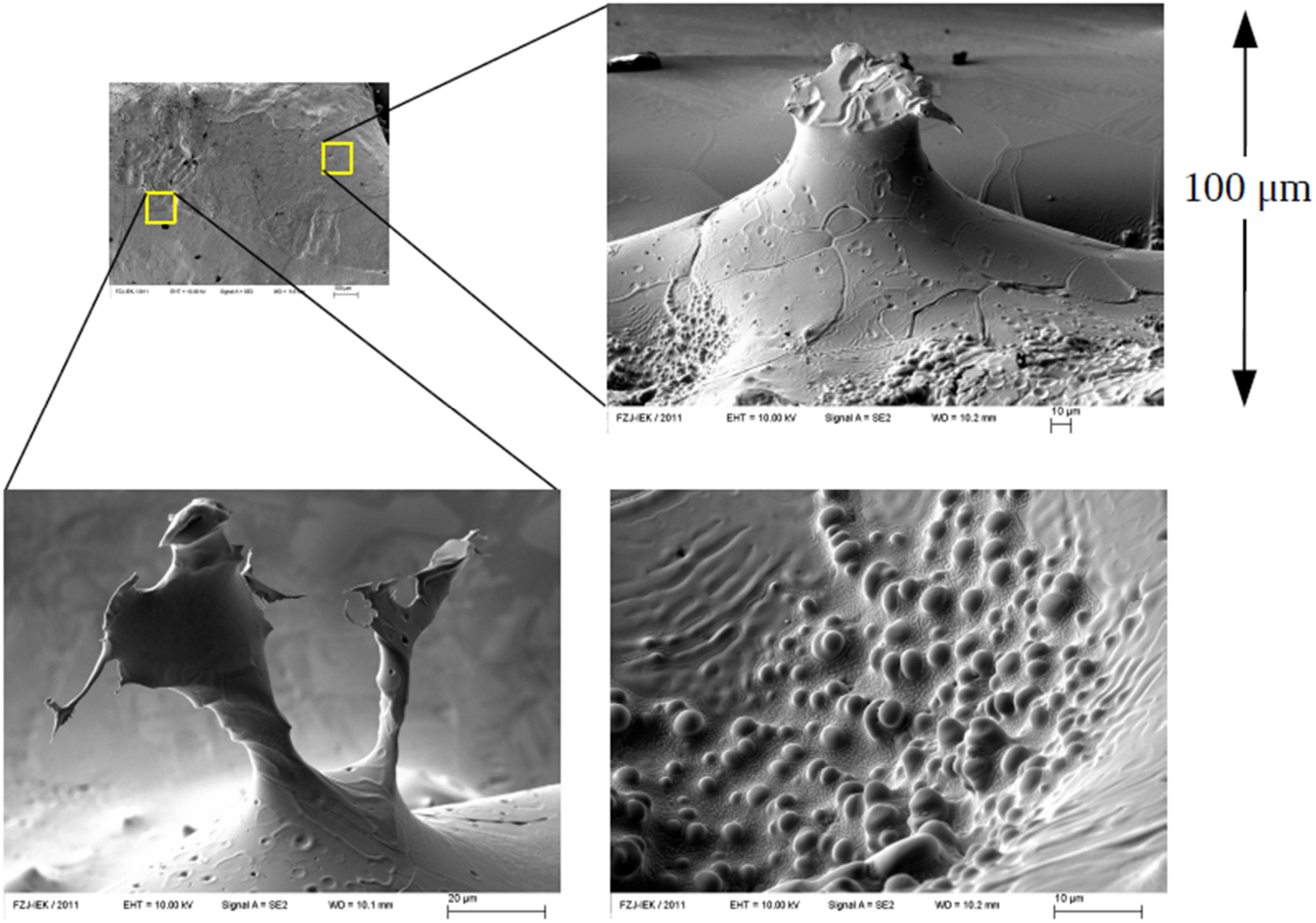
Exposed tungsten altered by PMI




3D imaging of tungsten melting

Courtesy Zach Hartwig, MIT (http://www.psfc.mit.edu/~hartwig/)

# Plasma substantially alters the ***microscopic*** surface morphology of materials

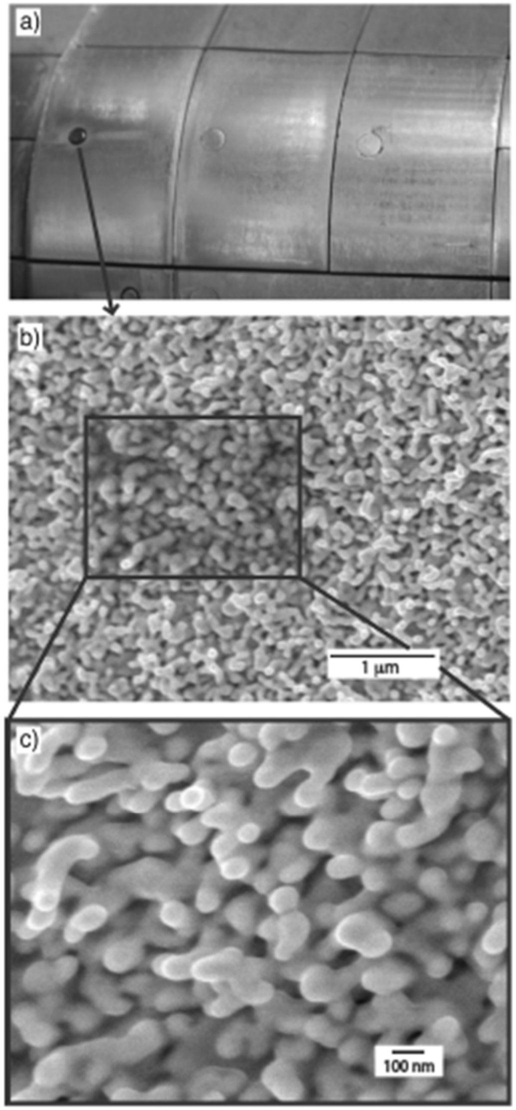


*Courtesy Zach Hartwig, MIT (http://www.psfc.mit.edu/~hartwig/)*

# Plasma substantially alters the ***microscopic*** surface morphology of materials

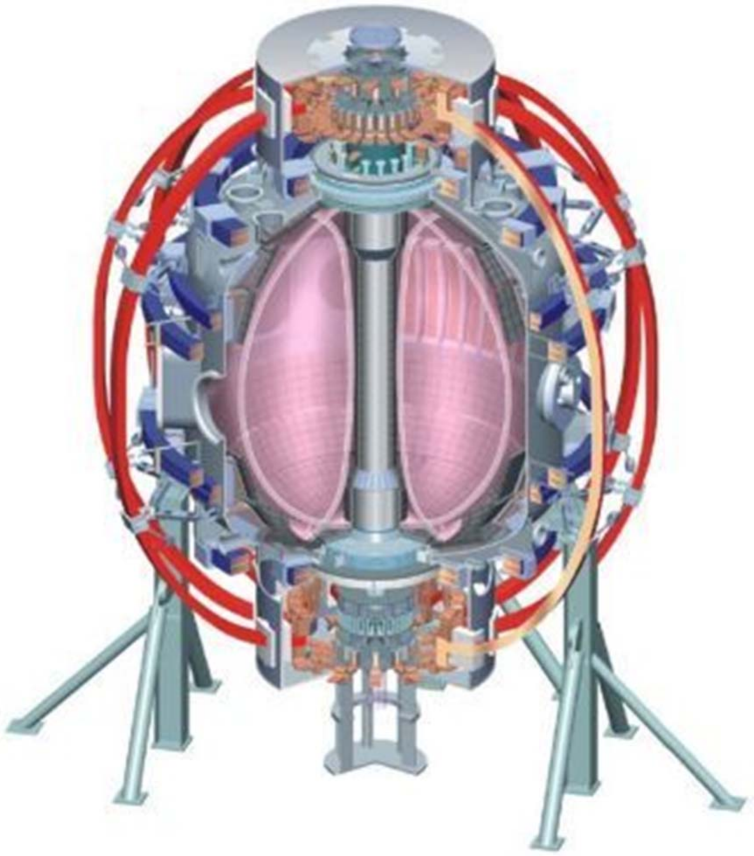
Recently, we have discovered that reactor-relevant plasma reforms tungsten surfaces into “fuzz”

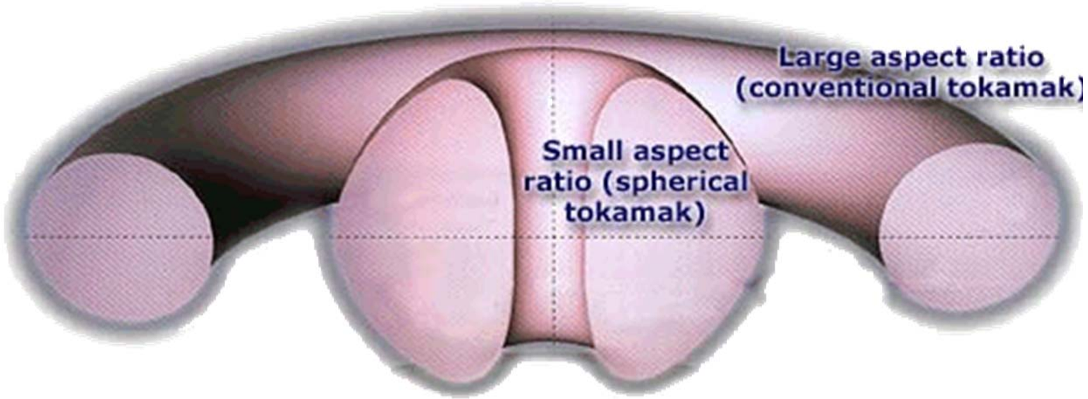
Unknowns:
- Physical formation mechanisms
- Effect of confined plasma
- Effect of material longevity
- (Avoidance strategies ?)



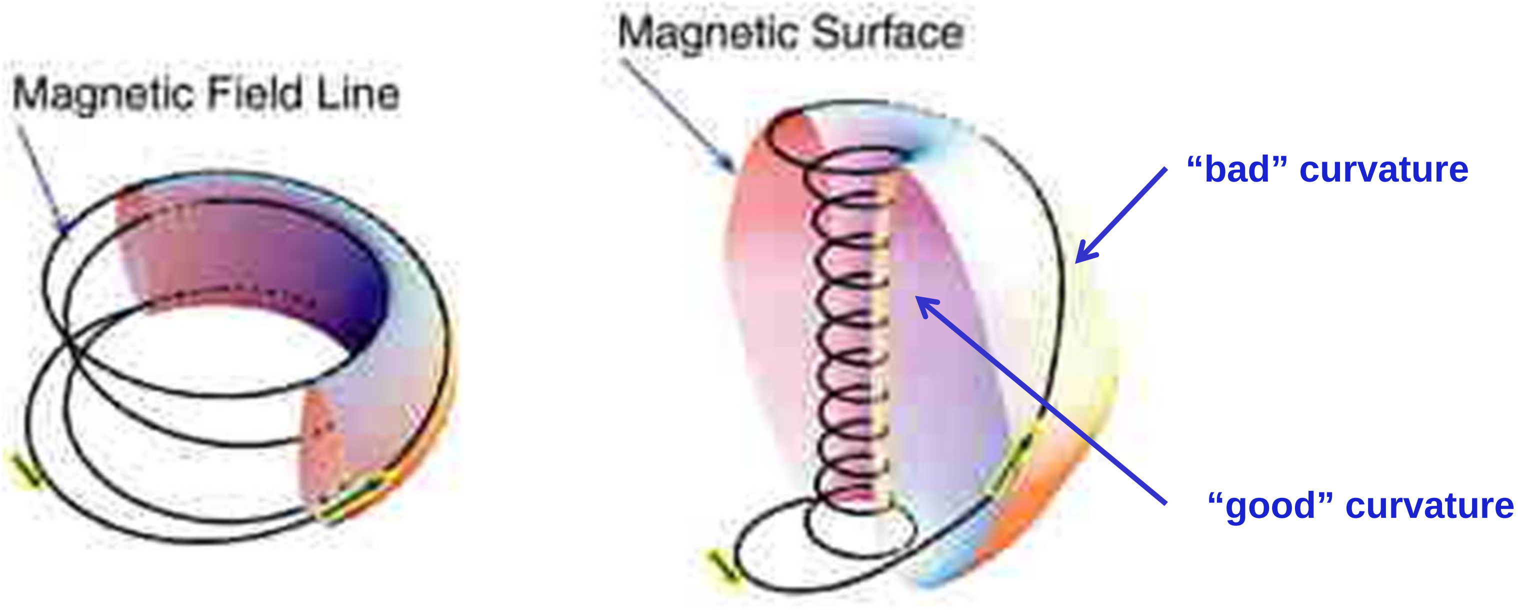
*Courtesy Zach Hartwig, MIT (http://www.psfc.mit.edu/~hartwig/)*

# NSTX-U: National Spherical Torus Experiment – Upgrade (PPPL)





# Spherical torus (ST) has improved confinement and pressure limits (but less room in center for coils)



*Tokamak Plasma*
*(safety factor q = 4)*

*Spherical Torus Plasma*
*(safety factor q = 12)*

- STs Inherently more stable to macroscopic instabilities, operate at much higher $\beta$=pressure/($B^2/2\mu_0$) compared to higher aspect ratio

→ Smaller device, weaker B required = **less $$$**

# Some goals of NSTX-U research

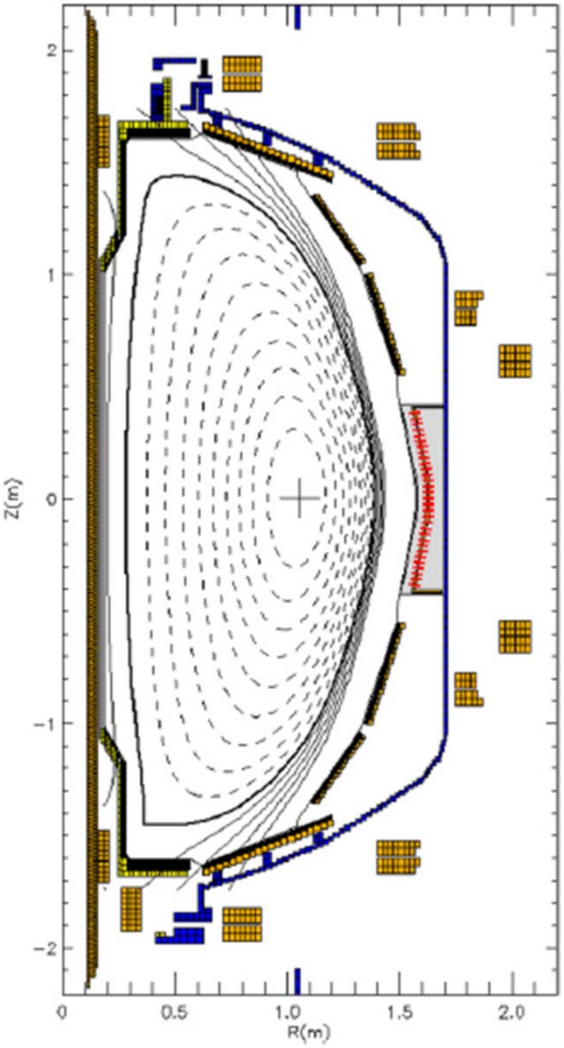
Study issues relevant for possible future ST devices, e.g.

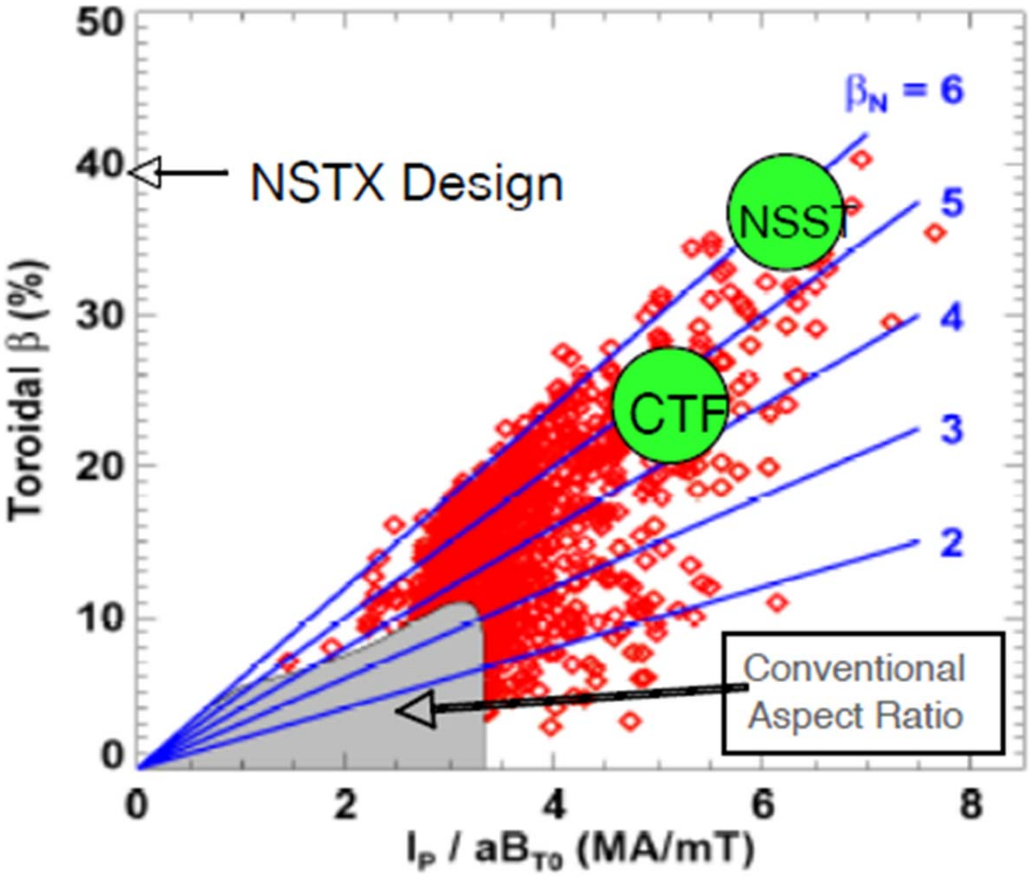
- Fusion Nuclear Science Facility (FNSF) ~ nuclear issues
- Component Test Facility (CTF) ~ materials issues
- Pilot Plant ~ electricity production

- Explore unique, high β plasma operation; both macroscopic and microscopic stability at high β
- Demonstrate steady-state (non-inductive) operation and control
- Study the plasma-material interface (PMI) & the influence of different plasma facing components (PFCs), e.g. liquid lithium

# High beta, disruption free discharges achieved with careful tailoring of magnetic geometry and flow profiles

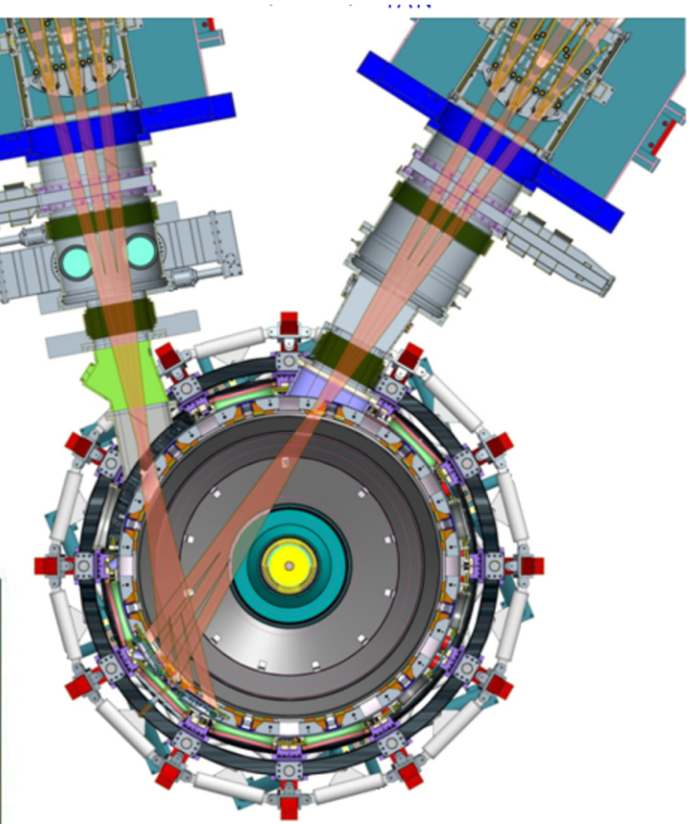
- Very strongly shaped magnetic geometry – far from circular!
- High β≤40% compared to conventional aspect ratio (β≤10%)



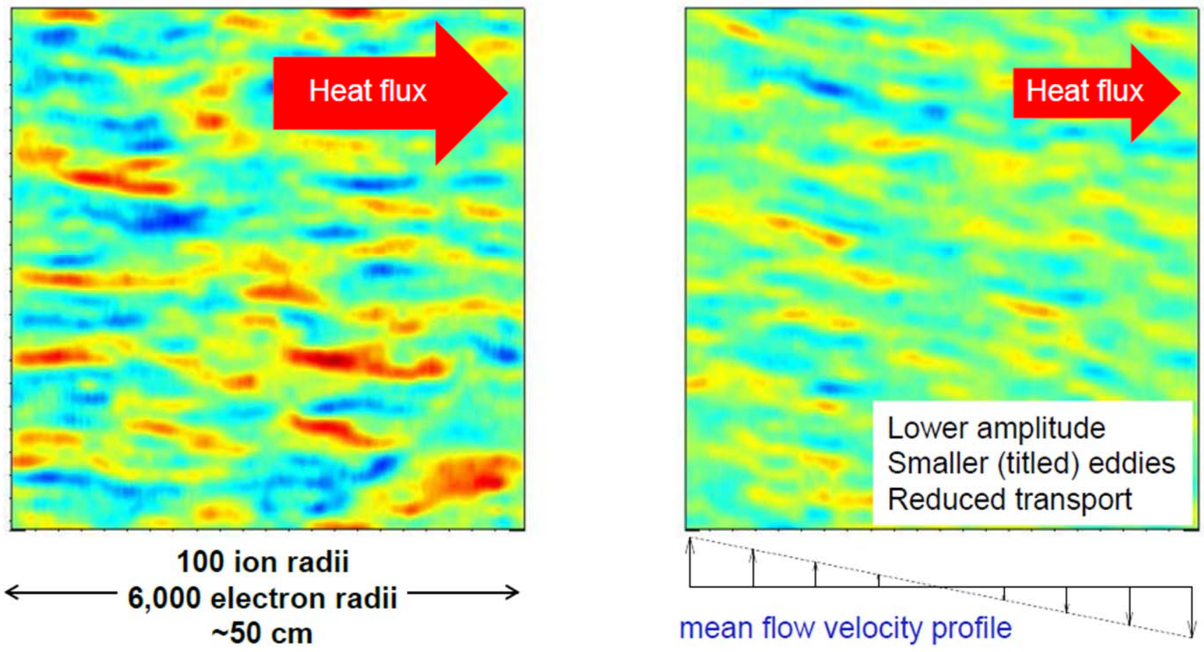


# Turbulence suppression due to flow shear in National Spherical Torus Experiment (NSTX)

- Plasma rotates rapidly (Mach number ~ 1) due to neutral beam injection
- Heat transported through ions reduced to level of collisional diffusion, turbulence fluctuations reduced (good!)



NSTX simulations



Snapshot of density without flow shear

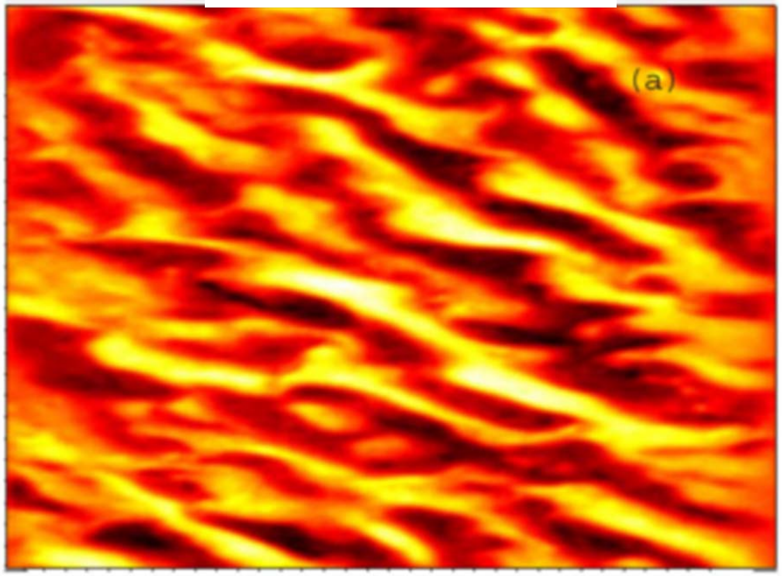
Snapshot of density with flow shear

Lower amplitude
Smaller (titled) eddies
Reduced transport

# Flow shear reduces turbulence at ion radii scales (cm), other “flavors” of turbulence important in NSTX

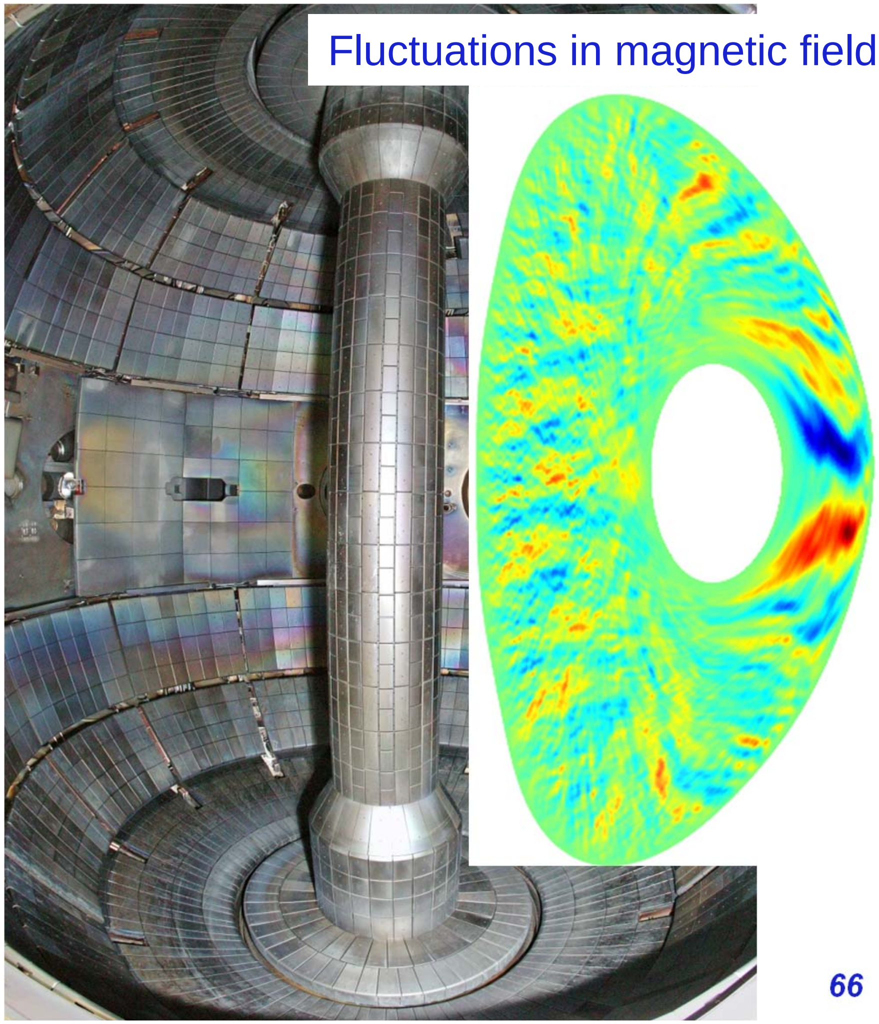
- Turbulence at electron radii scale (mm) can cause significant electron heat transport
- Too small to image → measure with microwave scattering

Density fluctuations



**6 ion radii**
**360 electron radii**
**~2 cm**

- At high $\beta$, magnetic turbulence important
- Magnetized plasma is birefringent → try to measure with polarimetry



Fluctuations in magnetic field

# Using lithium coating on plasma facing components (PFCs) leads to dramatic increase in energy confinement time

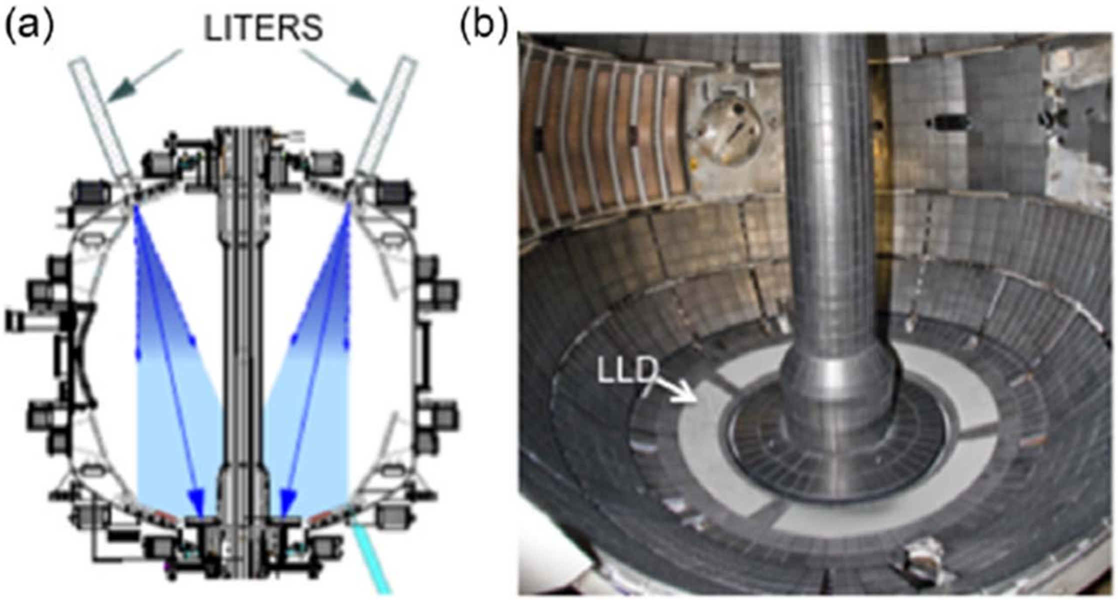
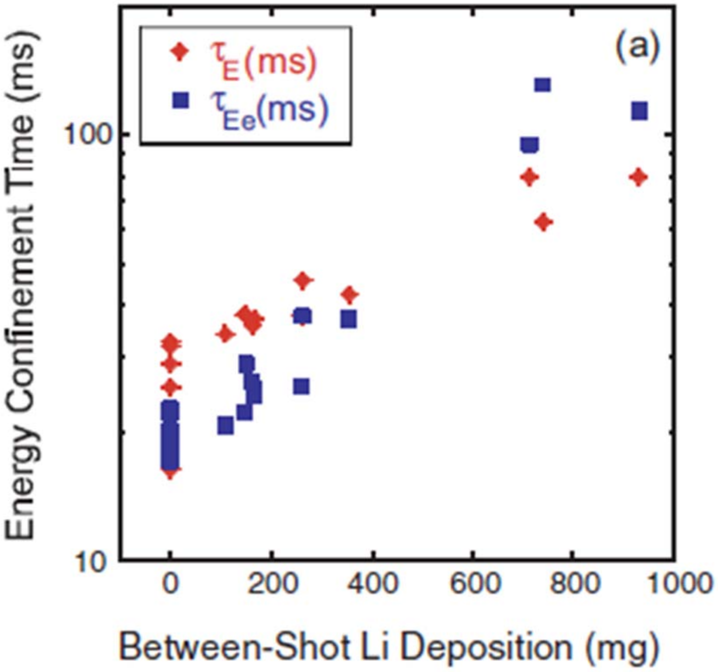


**Figure 1.** (*a*) Schematic of dual Li evaporator set-up. (*b*) Liquid Li divertor in NSTX.



# Using lithium coating on plasma facing components (PFCs) leads to elimination of detrimental edge instability

- Edge localized mode (ELM) found routinely in high performance tokamak plasmas
  - Leads to huge transient heat loads to PFCs
- Addition of lithium stabilizes edge– **ELMs are eliminated**

- Can be used as a tool to manipulate plasma boundary

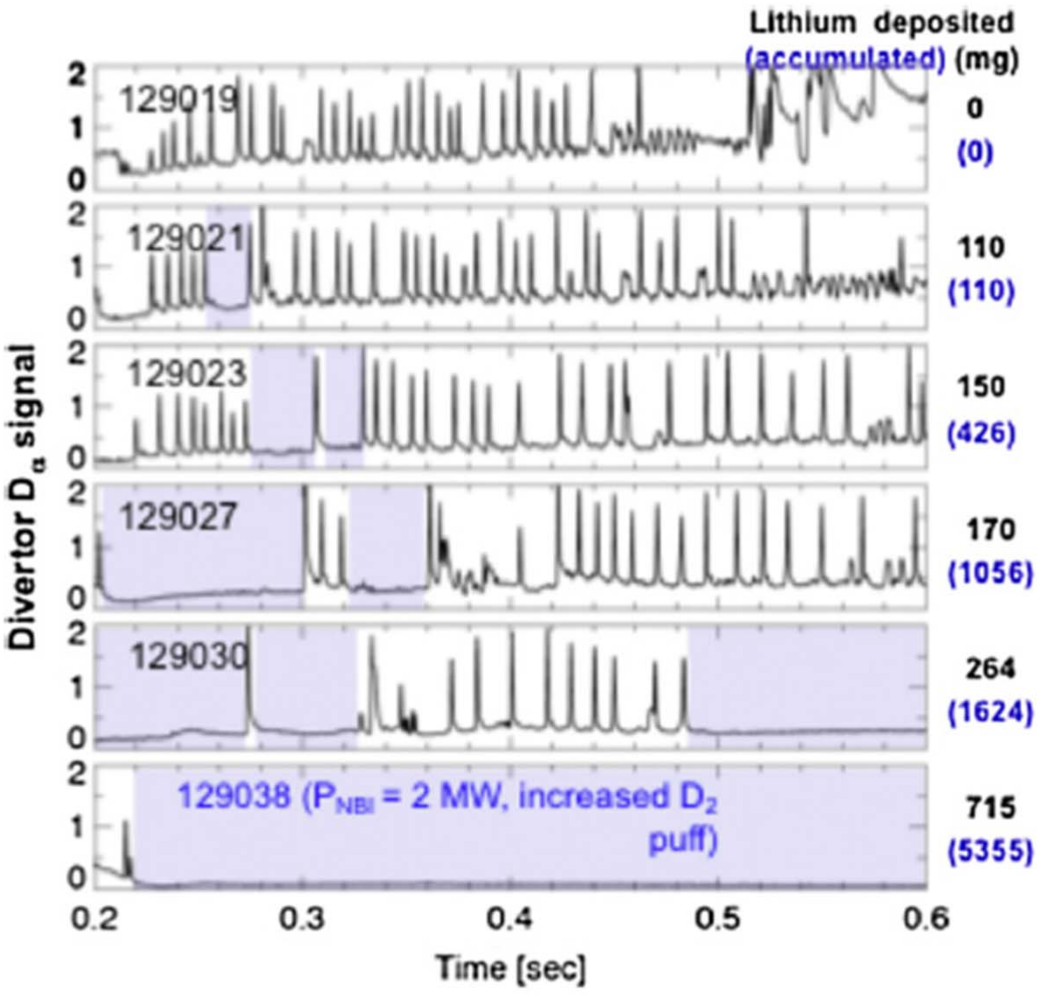
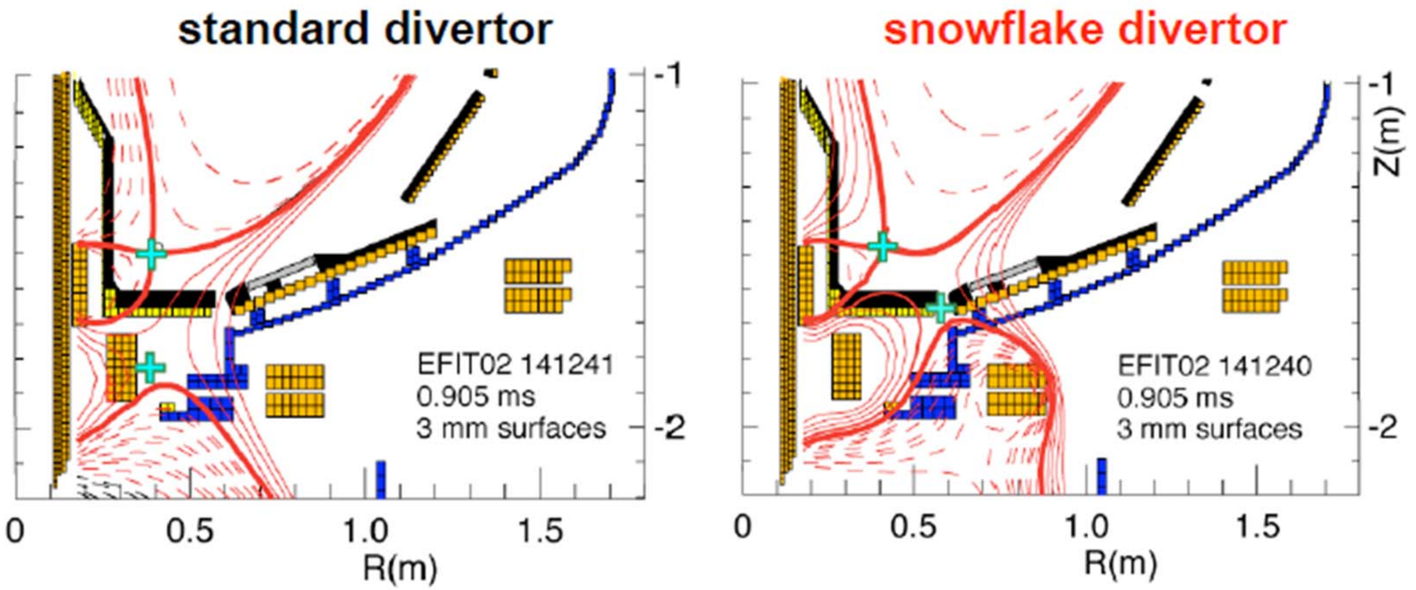
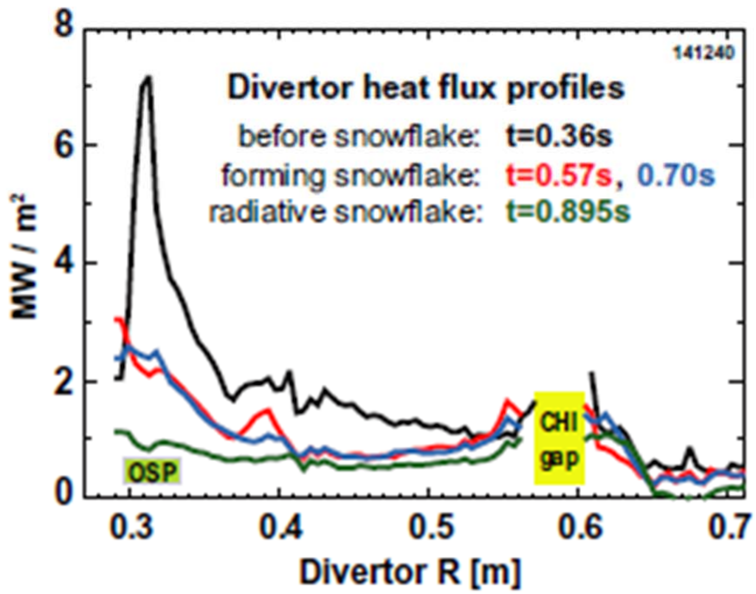


Fig. 5. Temporal edge D-alpha signal for various lithium deposition rate. The regularly occurring spikes represents the Edge Localized Modes (ELMs).

# Manipulating edge magnetic field line trajectories spreads exhaust heat on plasma facing components (PFCs)

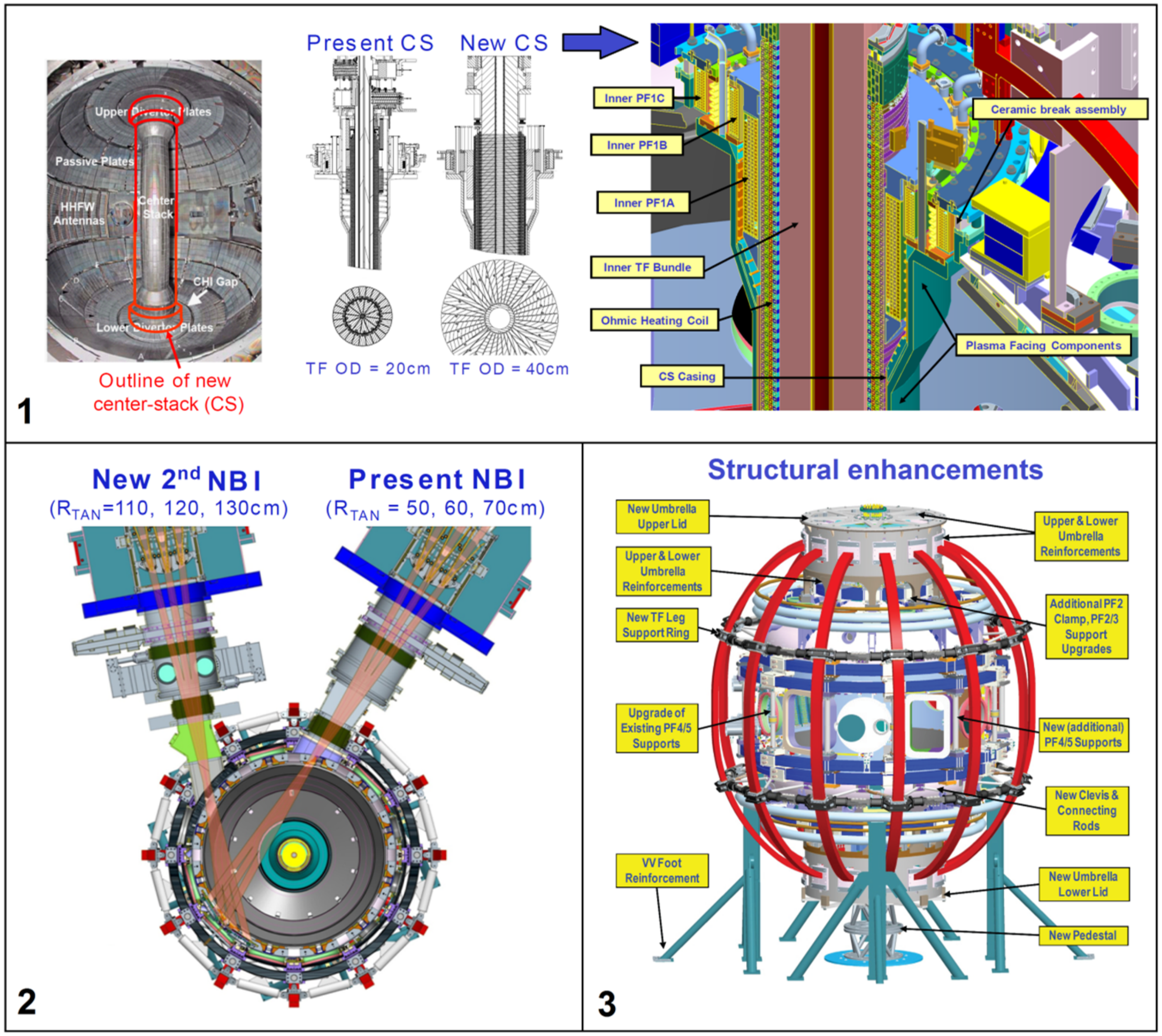


- Provides some control of peak heat flux on materials



# Can we optimize pressure & flow shear to reduce all "flavors" of turbulence, while simultaneously achieving high performance, non-inductive steady-state with a favorable boundary solution?

- NSTX presently undergoing an upgrade (stronger magnetic field, heating power, longer duration) to test these predictions (2015+)



nstx-u.pppl.gov

# Summary

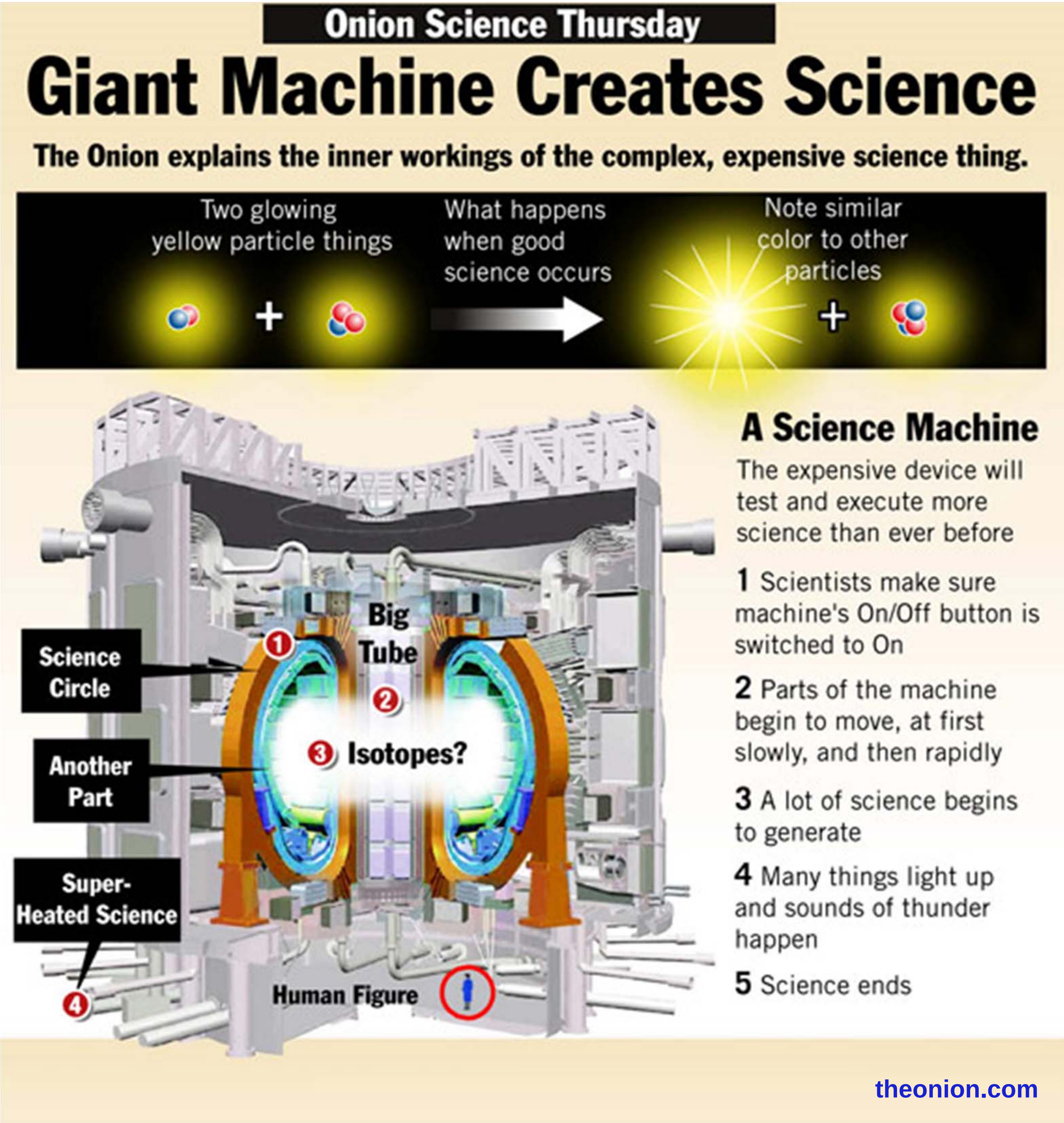
- Nuclear fusion offers a promising energy solution
  - Clean, safe, abundant energy, but challenging
  - ITER will demonstrate significant fusion gain, 500 MW, Q=10

- There are a number of scientific, technical and engineering issues that also need solving on the way to fusion energy & electricity
  - Steady state operation, handling & extracting intense heat flux at boundary, tritium management

- NSTX-U research is addressing many issues in fusion research
  - More economical confinement at low aspect ratio, high beta (reduced field) for reactors & general fusion nuclear science facilities
  - Steady-state & control solutions
  - Plasma-material interface questions

- Need the next generation of fusion scientists! (NSTX-U 2015+; ITER DT runs in ~2027+)

# Thank you!



Onion Science Thursday

# Giant Machine Creates Science

The Onion explains the inner workings of the complex, expensive science thing.

## A Science Machine

The expensive device will test and execute more science than ever before

1 Scientists make sure machine's On/Off button is switched to On

2 Parts of the machine begin to move, at first slowly, and then rapidly

3 A lot of science begins to generate

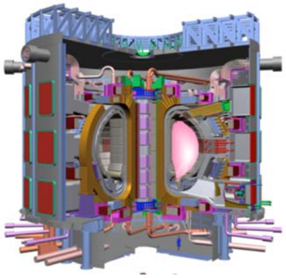
4 Many things light up and sounds of thunder happen

5 Science ends

theonion.com

# Yes, it's expensive, but for some perspective…

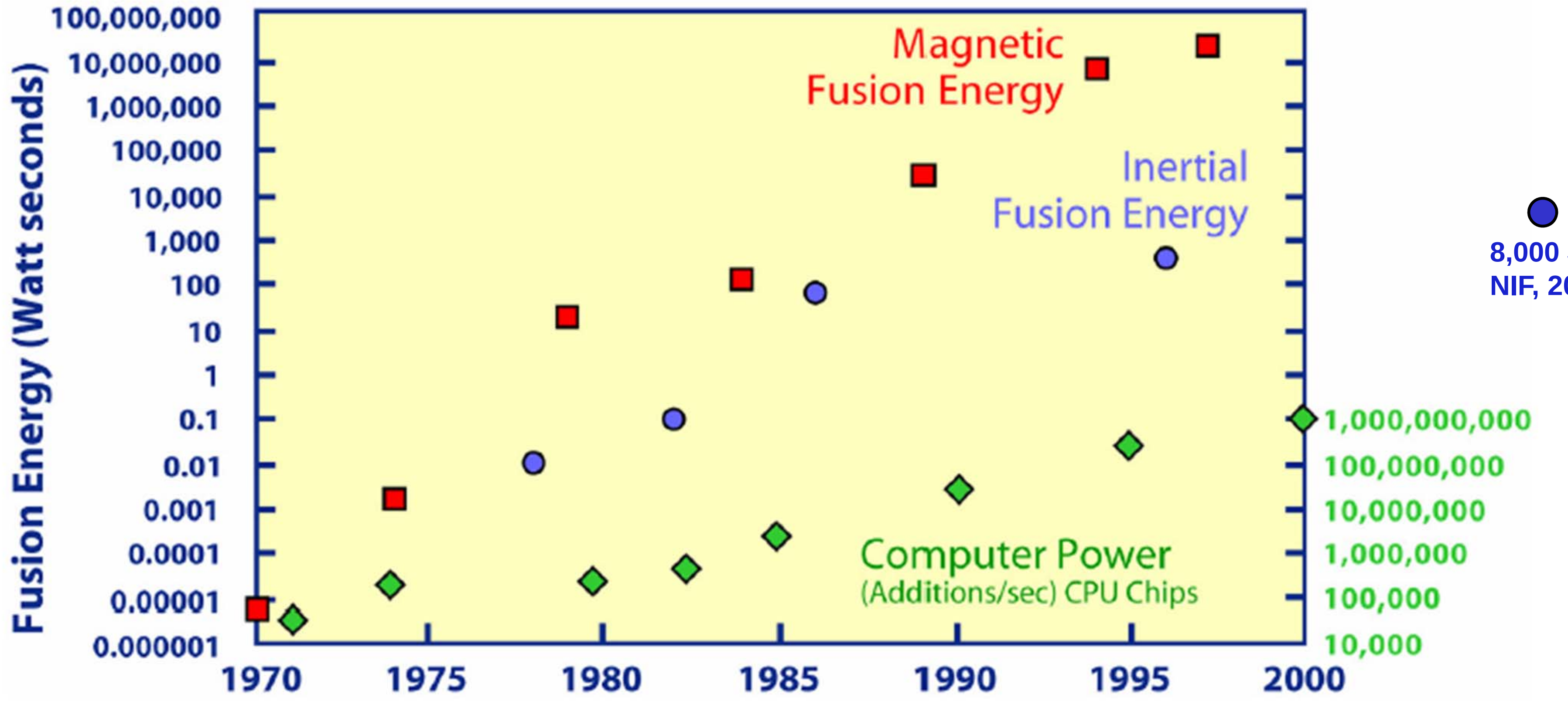
- ITER ~ <u>$20 B</u>



- International Space Station ~ <u>$150 B</u>

- Large Hadron Collider ~ <u>$9 B</u>
- New gigawatt (GW) coal/nuclear power plant ~ <u>$2-6 B</u>
- US consumes ~ 4,000 billion kW-h of electricity / year
  Average electricity prices ~ 0.10$/kW-h (US EIA)
  ~<u>$400 B</u> / year paid for electricity production

# Progress in fusion energy has outpaced computer speed



8,000 J
NIF, 2013

# Can we reduce the turbulence and improve confinement?

If we understand the turbulence, perhaps we can optimize performance

**(1) zonal flows**

(2) magnetic configuration

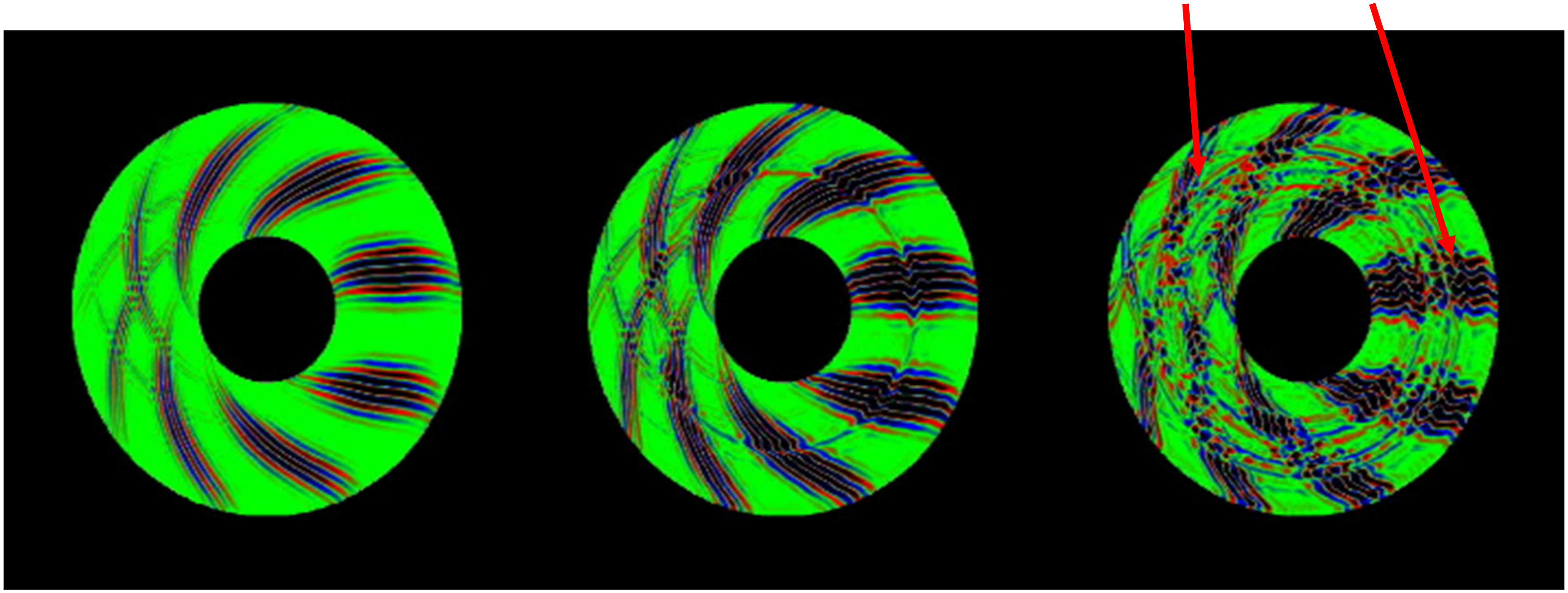
(3) flow shear

# Self-generated “zonal flows” impact saturation of turbulence and overall transport

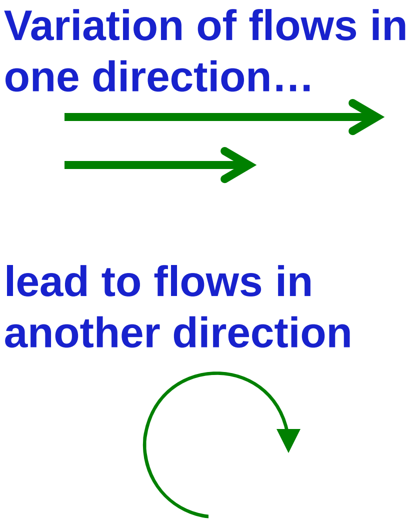
Linear instability stage demonstrates structure of fastest growing modes

Large flow shear from instability cause perpendicular “zonal flows”

Zonal flows help moderate the turbulence!!!



# Generation of zonal flows in tokamaks similar to “Kelvin-Helmotz” instability found throughout nature



Variation of flows in one direction…

lead to flows in another direction

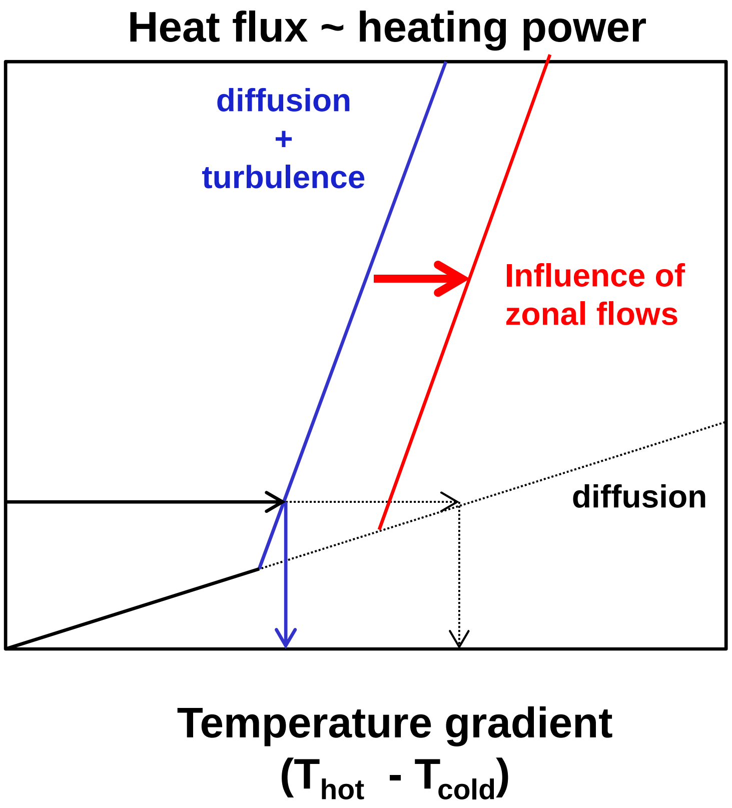
**Code:** **GYRO**

**Authors:** Jeff Candy and Ron Waltz

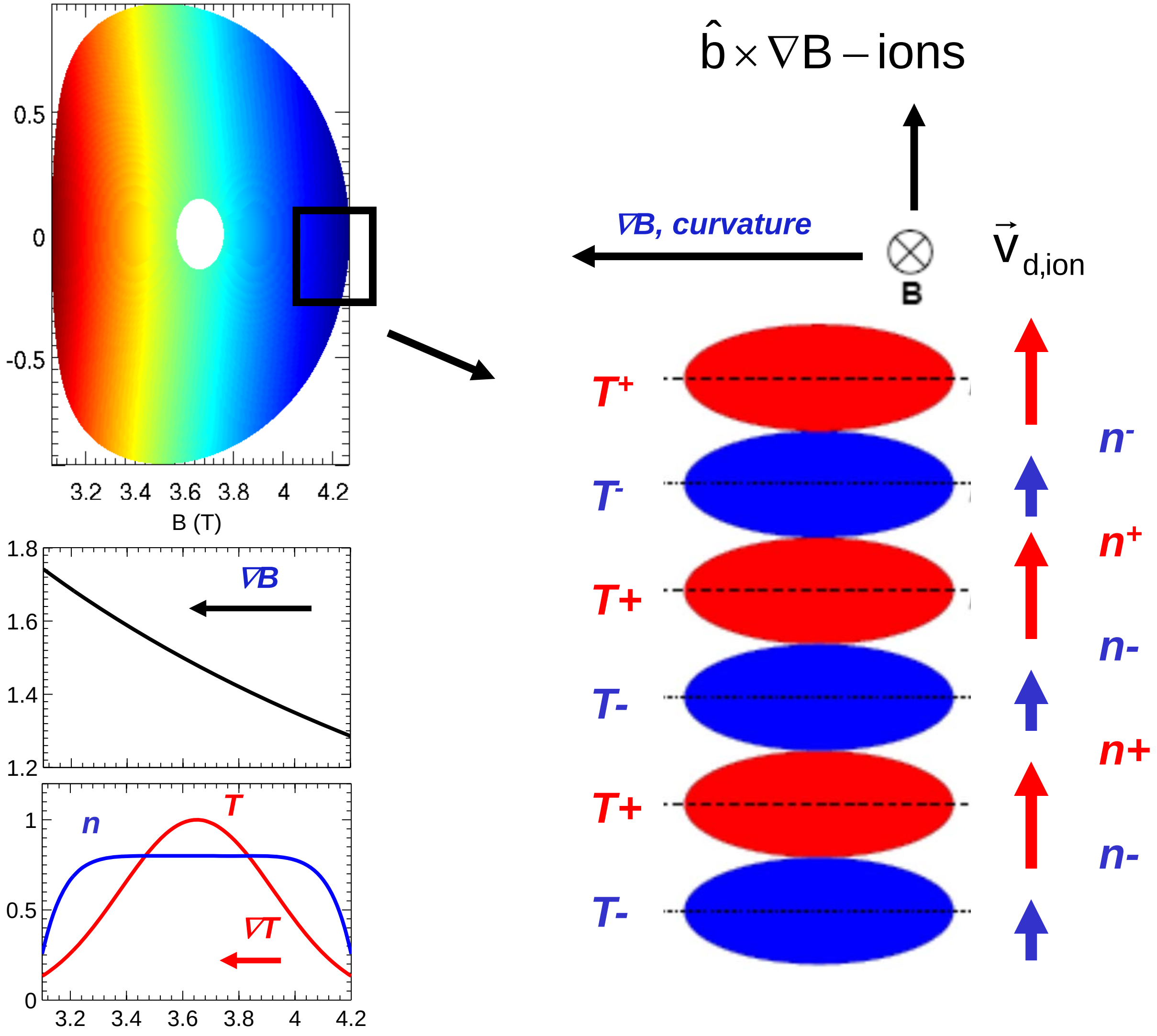
# The Jet Stream is a zonal flow (or really, vice-versa)

- NASA/Goddard Space Flight Center Scientific Visualization Studio

# Zonal flows reduce the heating power required to maintain a given temperature → improved confinement!



# Cartoon of Temperature Gradient Driven Instabilities



- Fourier decompose perturbations in space, assume small δT perturbation
- Spatial variation in T(θ) leads to variation in toroidal drifts
- Resulting compression ($\nabla \cdot v_{di}$) causes a density perturbation

# Dynamics Must Satisfy Quasi-neutrality

- Quasi-neutrality (Poisson equation, $k_\perp^2\lambda_D^2 \ll 1$) requires

$$-\nabla^2\tilde{\varphi} = \frac{1}{\varepsilon_0}\sum_s eZ_s\int d^3v f_s$$

$$\boxed{\tilde{n}_i = \tilde{n}_e}$$

$$\left(k_\perp^2\lambda_D^2\right)\frac{\tilde{\varphi}}{T} = \frac{\tilde{n}_i - \tilde{n}_e}{n_0}$$

- For this ion drift wave instability, parallel electron motion is very rapid

$$\omega < k_{||}v_{Te}$$

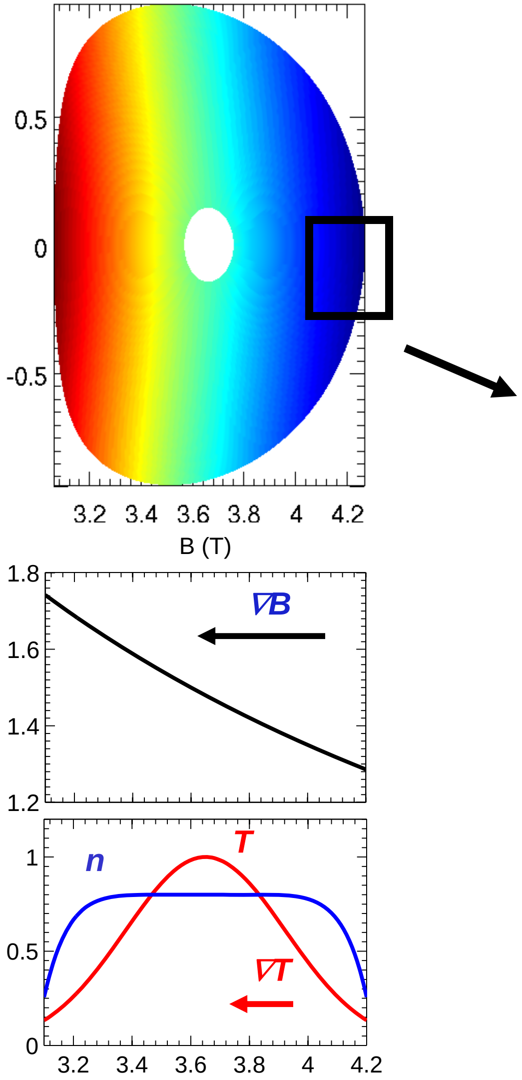
⇒ Electrons (approximately) maintain a Boltzmann distribution

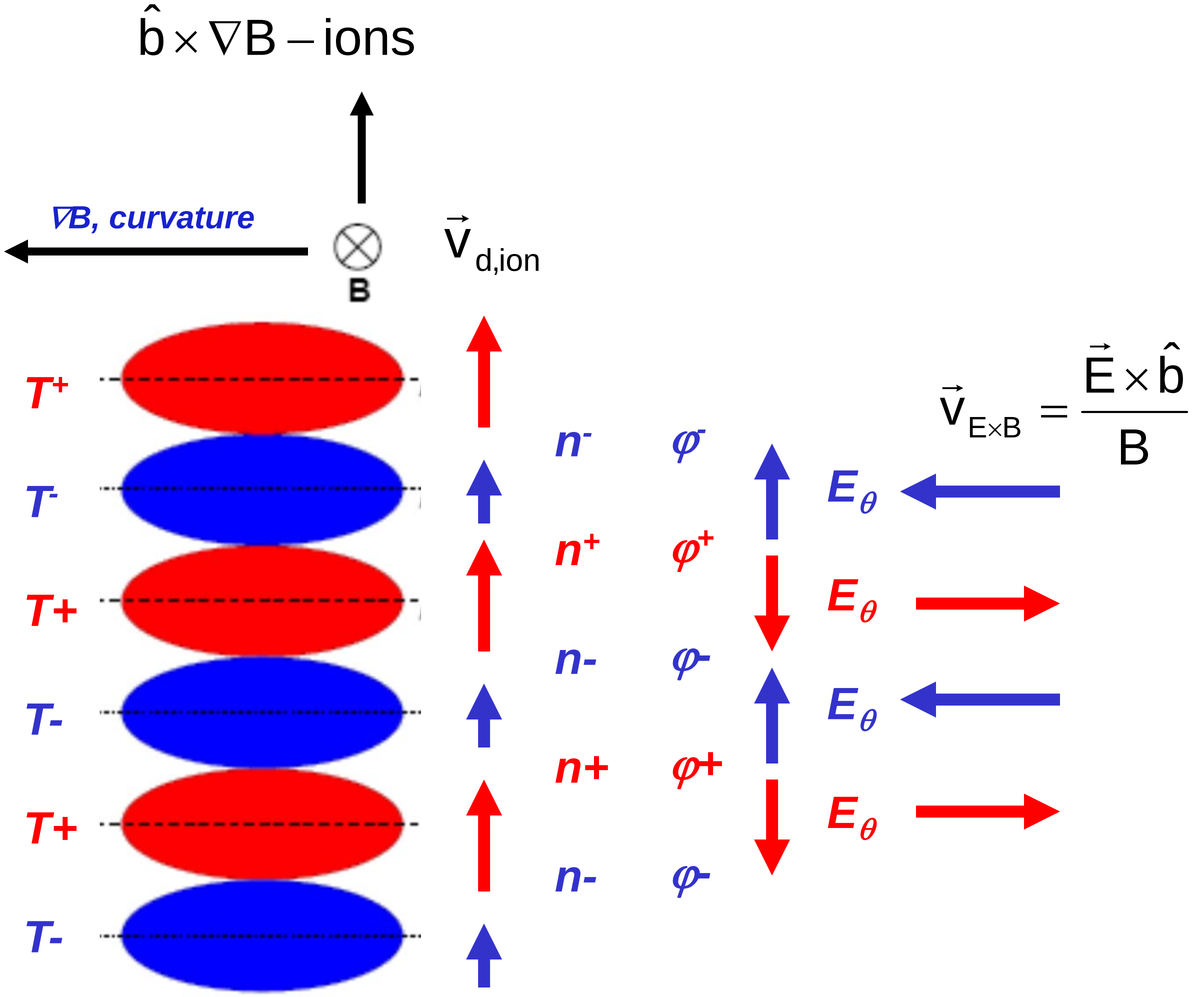
$$\left(n_0 + \tilde{n}_e\right) = n_0\exp\left(-e\tilde{\varphi}/T_e\right)$$

$$\tilde{n}_e \approx n_0 e\tilde{\varphi}/T_e \Rightarrow \underline{\tilde{n}_e \approx \tilde{\varphi}}$$

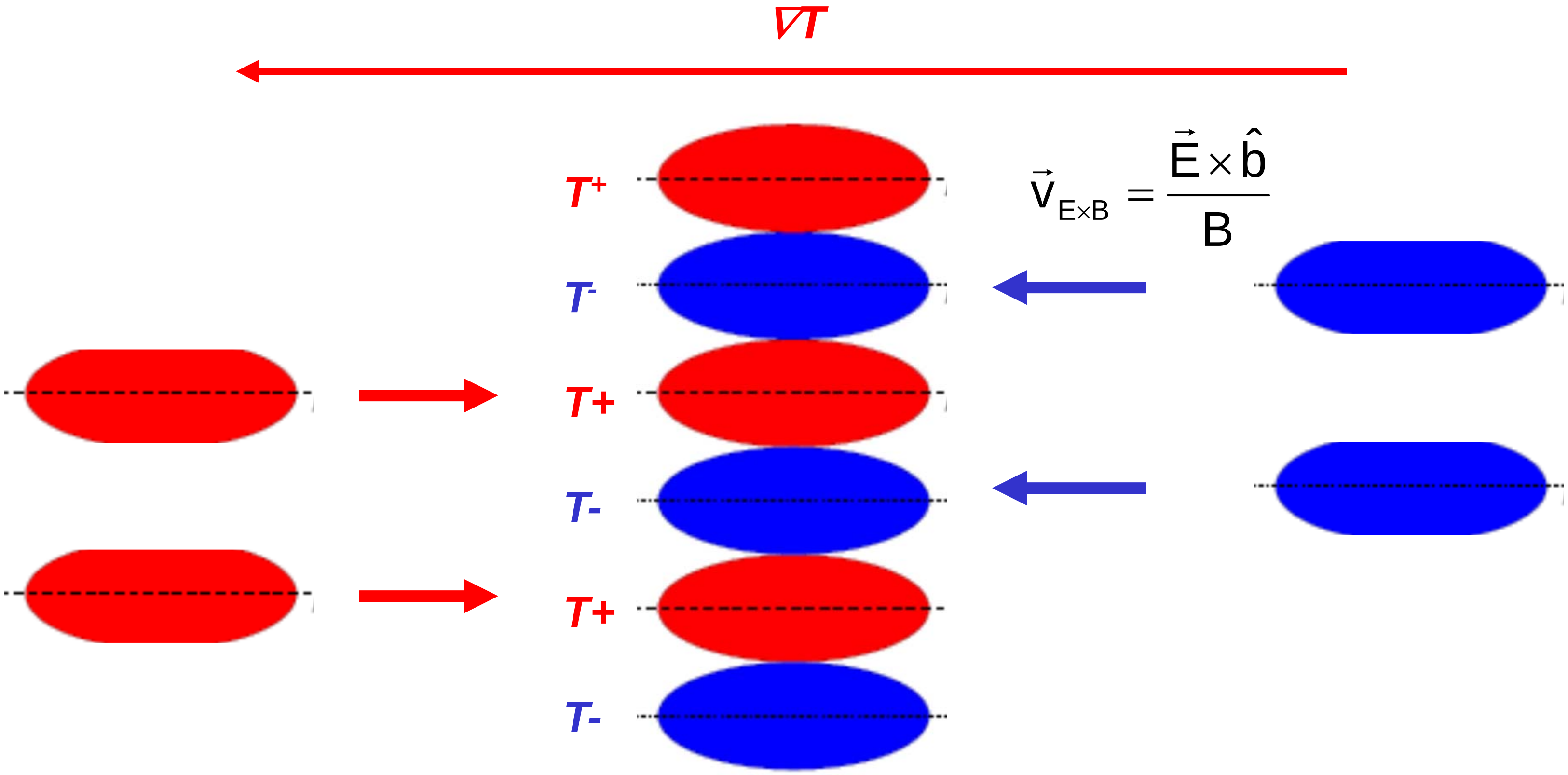
# Perturbed Potential Creates E×B Advection

- Advection occurs in the radial direction





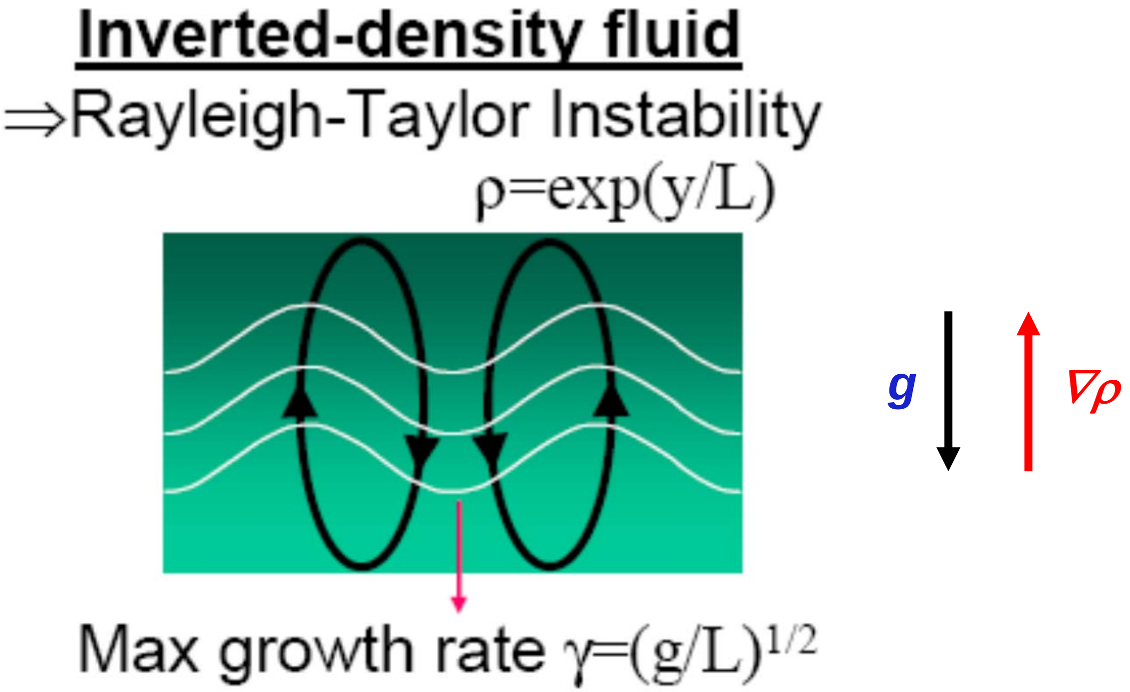
# Background Temperature Gradient Reinforces Perturbation ⇒ Instability



$$\vec{v}_{E\times B} = \frac{\vec{E}\times\hat{b}}{B}$$

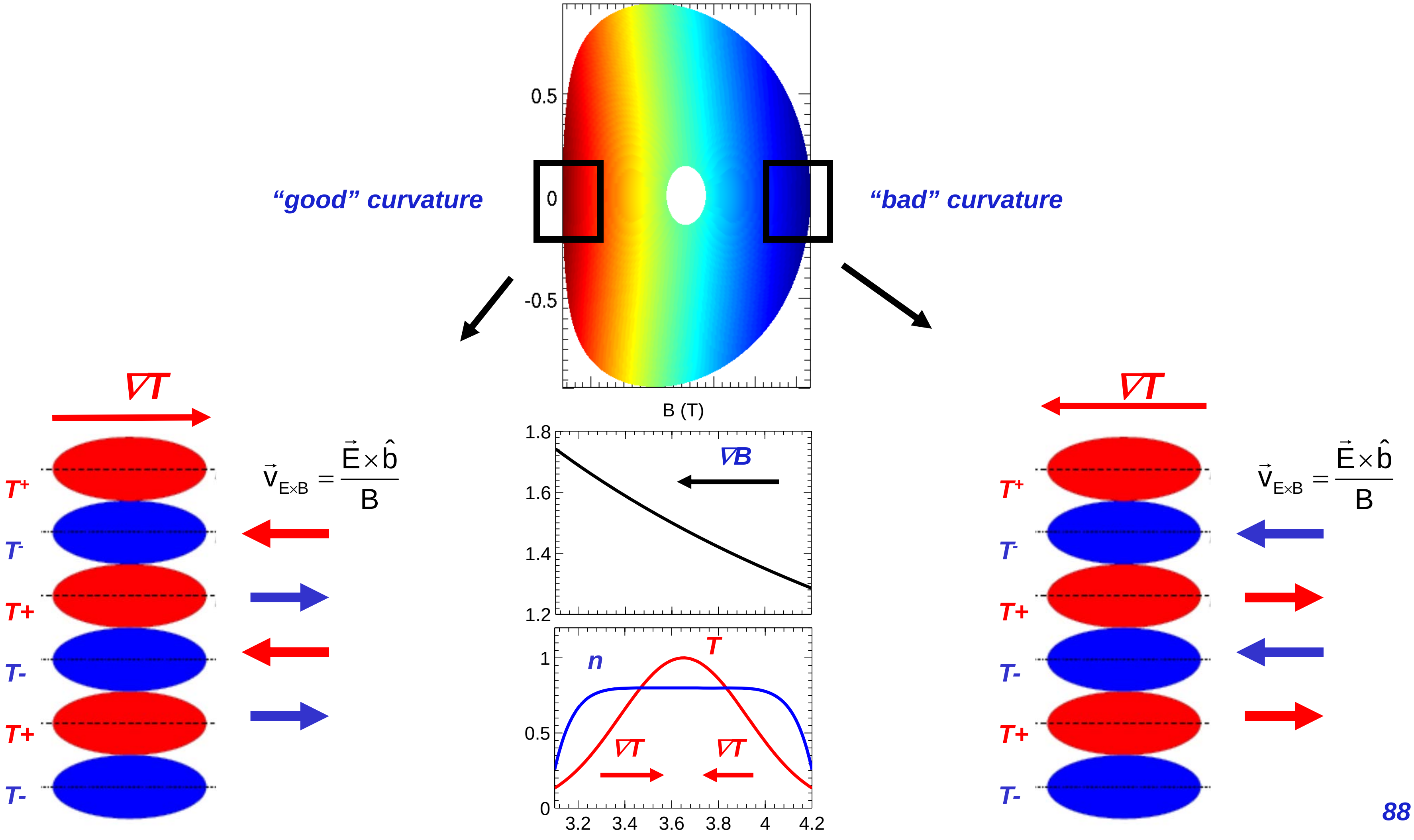
# Simple Analogy to Rayleigh-Taylor (Rayleigh-Benard) Instabilities

- Instability due to alignment of gravity force with density gradient force



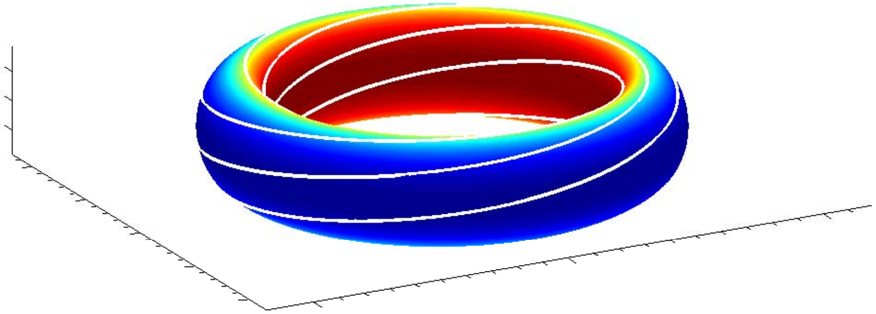
# Same Dynamics Occur On Inboard Side But Now Temperature Gradient Is Stabilizing

- Advection with ∇T counteracts perturbations on inboard side – "good" curvature region



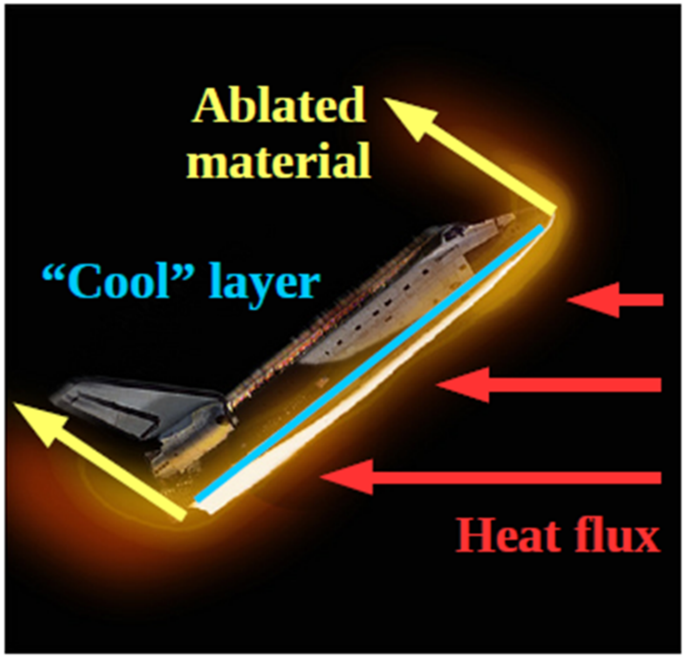
# Fast Parallel Motion Along Helical Field Line Connects Good & Bad Curvature Regions

- Approximate growth rate on outboard side $\gamma_{\text{instability}} \sim \dfrac{v_{th}}{\sqrt{RL_T}}$ $1/L_T = -1/T \cdot \nabla T$
- Parallel transit time $\gamma_{\text{parallel}} \sim \dfrac{v_{th}}{qR}$



- Expect instability if $\gamma_{\text{instability}} > \gamma_{\text{parallel}}$ , or $\left(\dfrac{R}{L_T}\right)_{\text{threshold}} \approx \dfrac{1}{q^2}$
- Threshold gradient for temperature gradient driven instabilities have been characterized over parameter space with more accurate calculations…

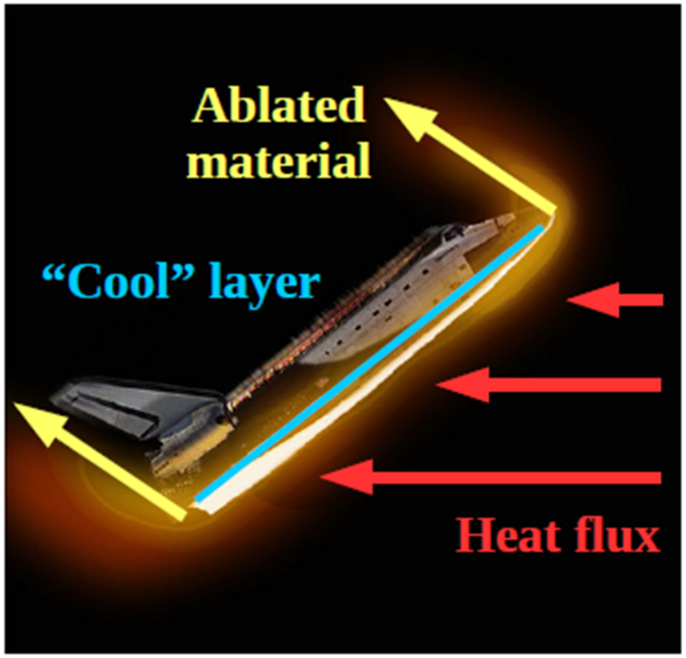
# Atmospheric reentry solves the problem by ablating material from a heat shield



$$\text{Ablation rate} \approx 30\times10^{-6}\,\frac{\text{m}}{\text{s}}$$

*Courtesy Zach Hartwig, MIT (http://www.psfc.mit.edu/~hartwig/)*

# Atmospheric reentry solves the problem by ablating material from a heat shield



Ablation cooling is not a solution for
24/7, 365 day/year fusion power plant!

$$\approx 30\times10^{-6}\,\frac{\text{m}}{\text{s}} \cdot 10^{7}\,\frac{\text{s}}{\text{year}} \approx 300\,\frac{\text{m}}{\text{year}}$$

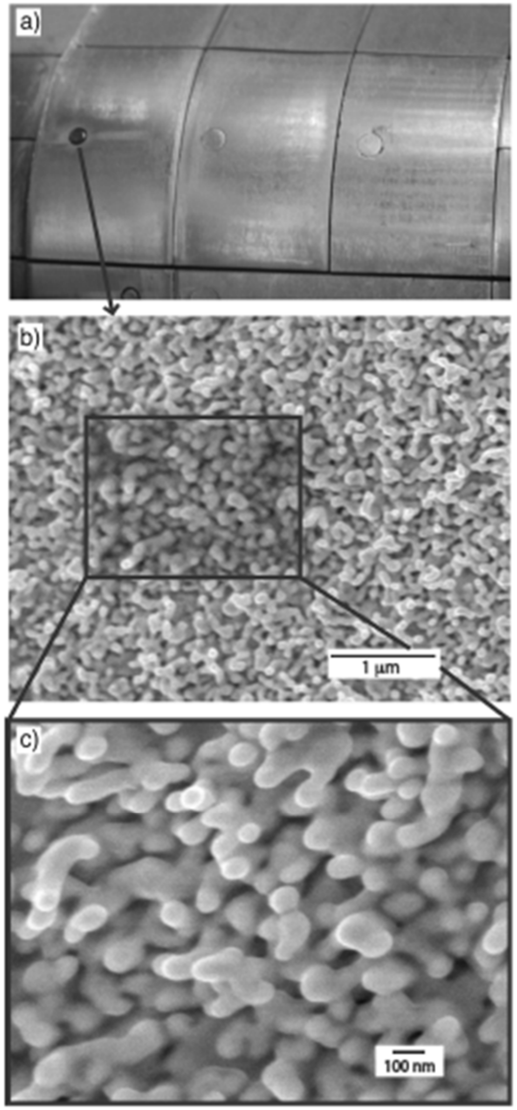
*Courtesy Zach Hartwig, MIT (http://www.psfc.mit.edu/~hartwig/)*

# Plasma substantially alters the *microscopic* surface morphology of materials

Recently, we have discovered that reactor-relevant plasma reforms tungsten surfaces into “fuzz”

Unknowns:

- Physical formation mechanisms
- Effect of confined plasma
- Effect of material longevity
- (Avoidance strategies ?)

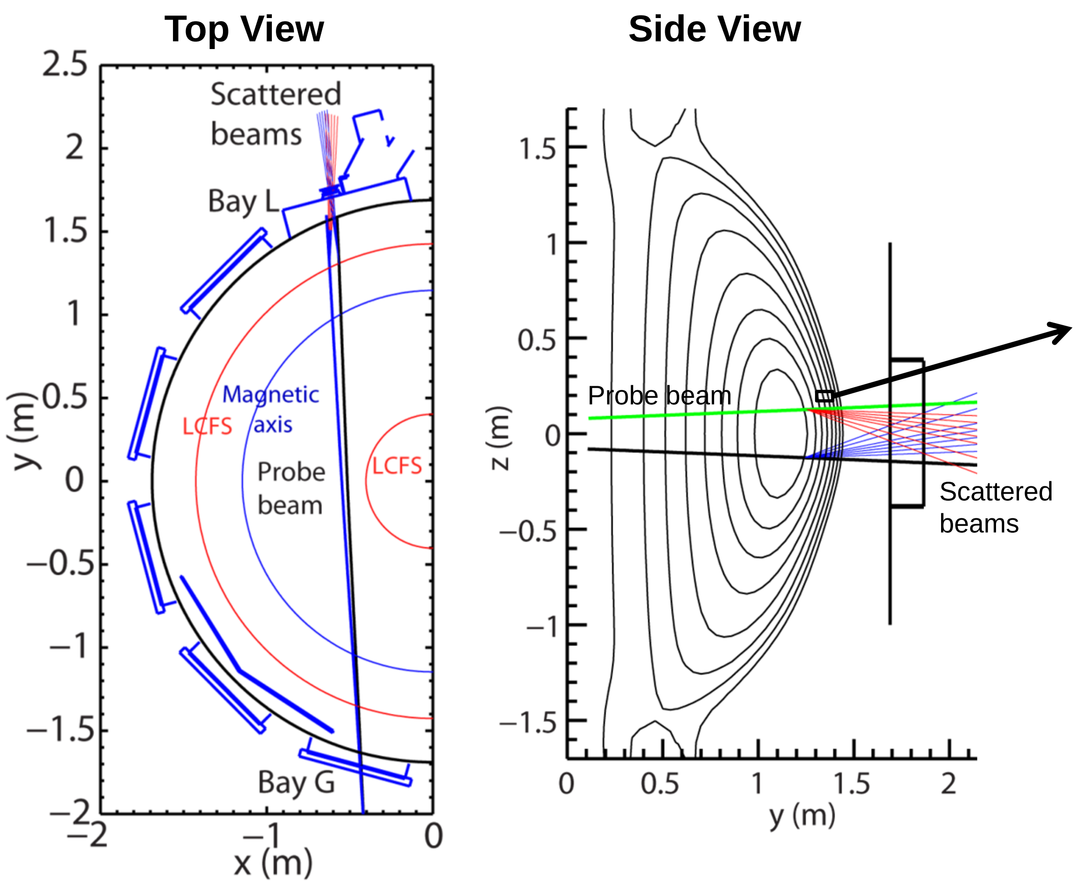


*Courtesy Zach Hartwig, MIT (http://www.psfc.mit.edu/~hartwig/)*

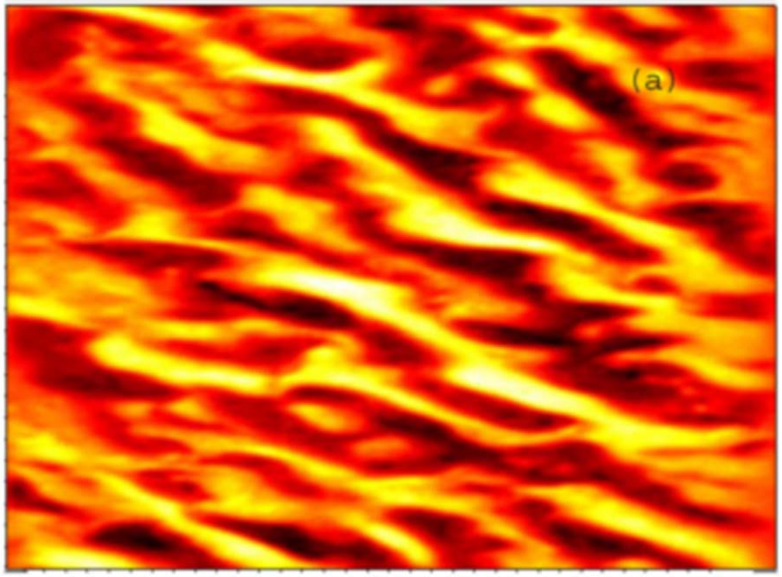
# While flow shear reduces turbulence at ion radii scales (cm), electron radii scale turbulence (mm) can become significant

- Challenge to diagnose such small fluctuations, can't image → use "microwave scattering"

NSTX tokamak (PPPL)



density fluctuations



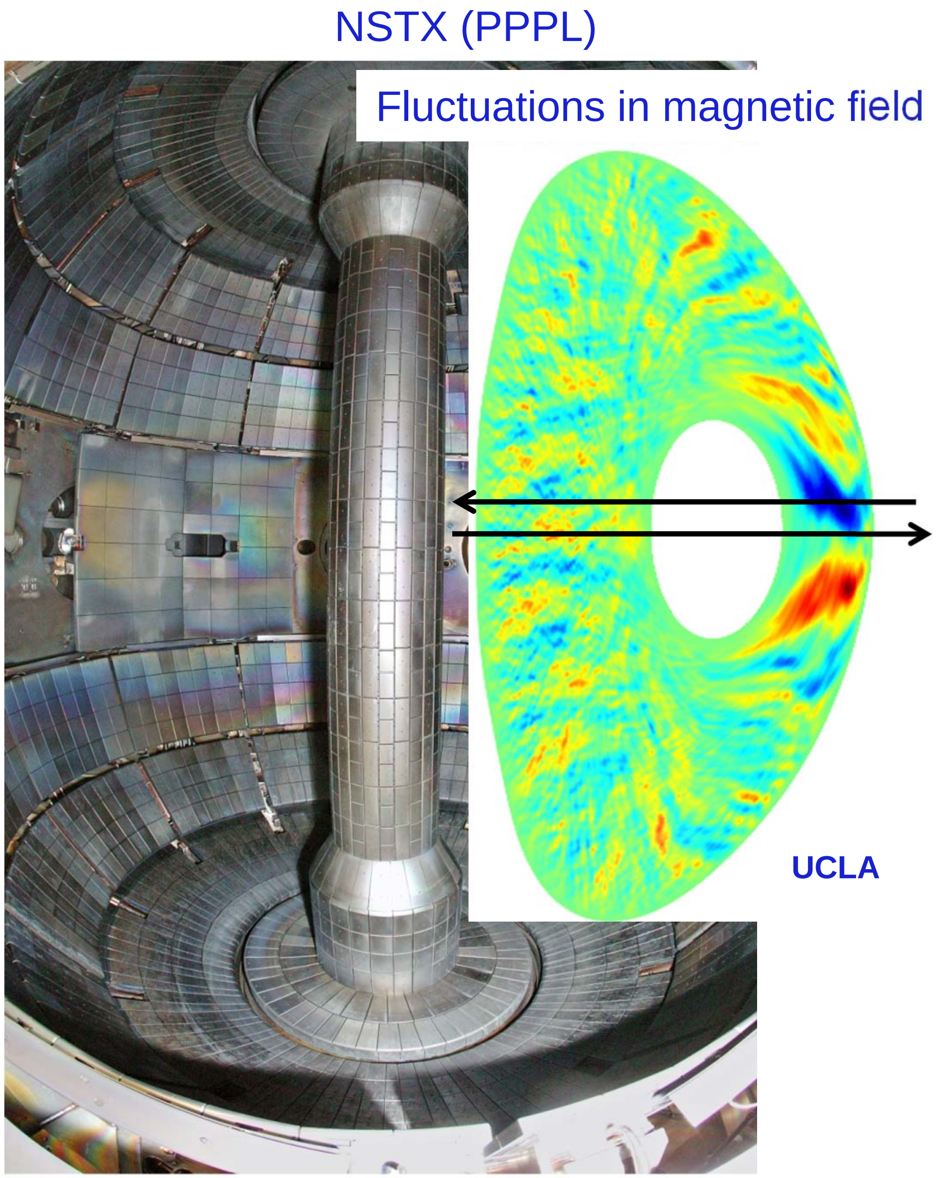
←— **6 ion radii** —→

**360 electron radii**

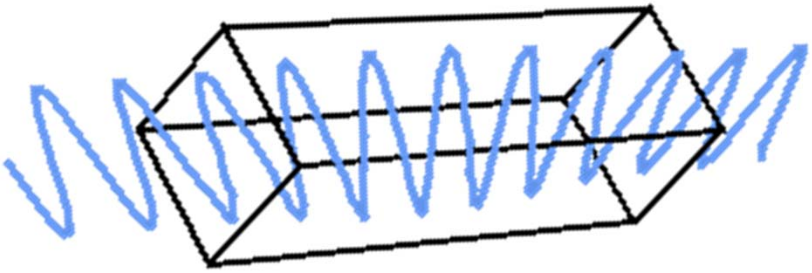
**~2 cm**

UC-Davis

# At high β, magnetic turbulence becomes important → another leaky hole to plug!



- Try to measure change in microwave polarization



- Injected microwaves experience shift in polarization, similar to birefringence in a crystal

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