Brief overview of PPPL, fusion, NSTX-U

J. Menard, R. Hawryluk, S. Kaye

Fermilab visit

September 16, 2015

U.S. DEPARTMENT OF ENERGY

PPPL PRINCETON PLASMA PHYSICS LABORATORY

PRINCETON UNIVERSITY

Princeton Plasma Physics Laboratory (PPPL)

88.5 acres, 33 buildings, ~750k GSF
~450 employees, > 300 guests and students per year
FY15 Funding ~$100M

PPPL Missions:

- Work with collaborators across the globe to develop fusion as an energy source for the world
- Conduct research along the broad frontier of plasma science and technology
- Nurture national research enterprise in above fields
- Educate next generation of plasma, fusion scientists

PPPL experimental activities: broad and diverse

Magnetic fusion

- Large tokamak facility: NSTX-U
- Collaboration with other domestic/international facilities, ITER
- Innovative tokamak: LTX (Lithium tokamak experiment)
- Non-tokamak fusion: field reversed configuration
- Plasma-material interface: surface science lab

Plasma physics (other than MFE) and applications

- Plasma astrophysics: reconnection experiments
  - magnetorotational instability expt
- Plasma nanotechnology
- High energy density plasmas: reconnection in laser fusion facilities
- X-ray spectroscopy: in laser and magnetic fusion facilities, worldwide

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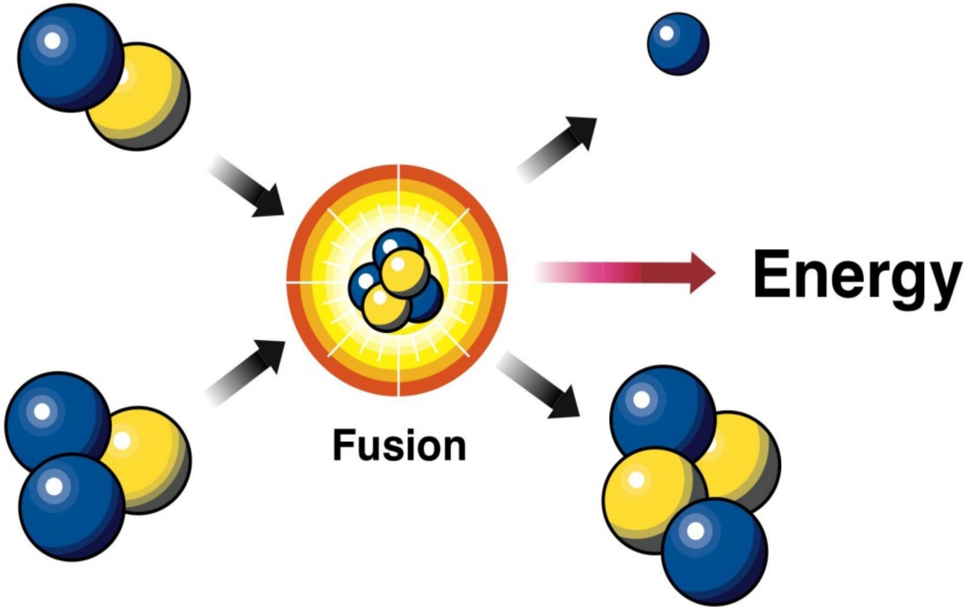
What is fusion?

“D-T” fusion reaction:



D: deuterium

n: neutron

T: tritium

α: helium

High energy gain
≈ 1000 ×

$$E = mc^2$$

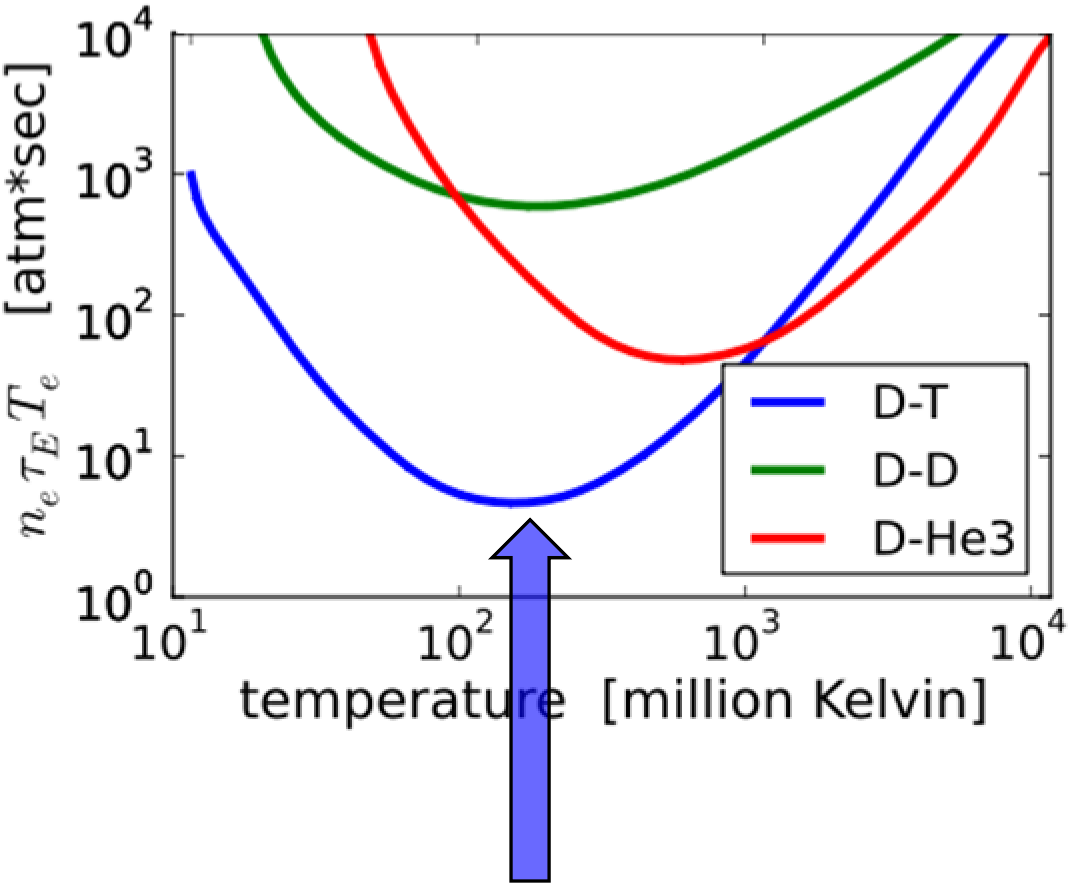
Advantages of fusion: safe, sustainable, high energy density, environmentally attractive

- Cannot have runaway reaction
  - Only small amount of fuel present
  - If particles cool, fusion stops
- Abundant fuel supply
  - D from seawater: HDO, D/H = 1/6400
  - T bred from lithium in earth's crust
- High energy density
  - 1 liter water = 500 liters gasoline
- Waste short-lived, low-level
- No CO_2 production

Fusion requires very high temperatures

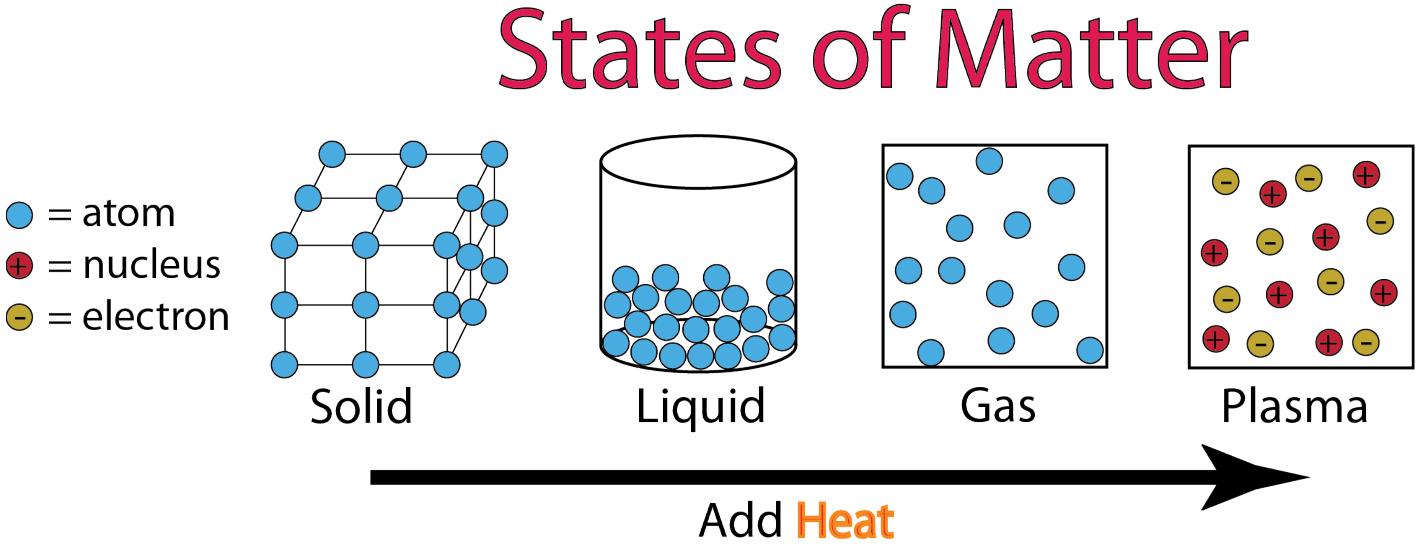
Fusion difficulty

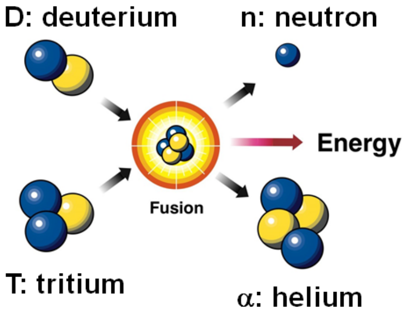
(pressure × confinement)



- Fusion is easiest here at 200 million °C (!!) (350 million °F)
  - Requires lowest pressure nT and energy confinement time τ_E
  - Minimum fusion “triple-product” value: 8 atmosphere-seconds ($T_i \approx$ 15keV)

Gas becomes plasma at fusion temperatures



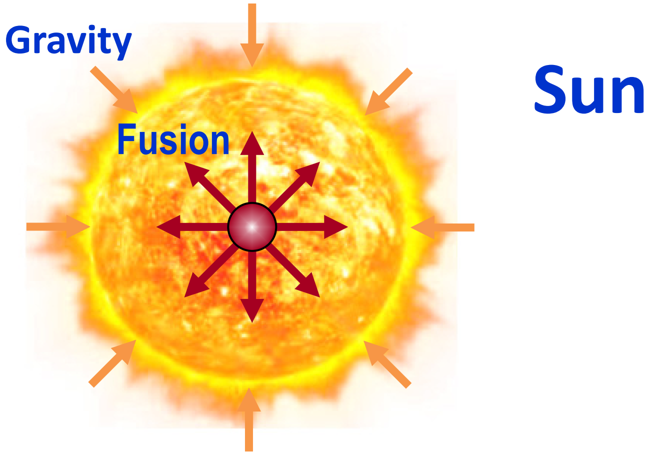


DT fusion:

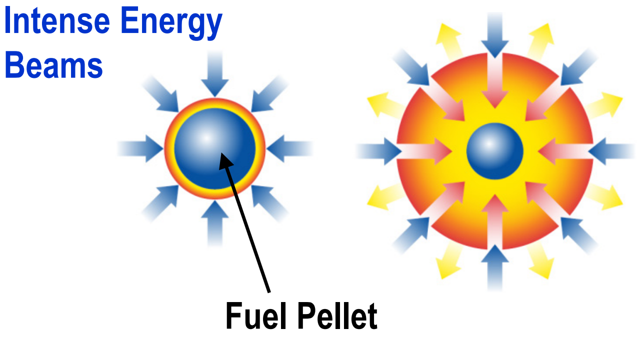
- Water: 0 °C 100 °C 160,000 °C 200,000,000 °C

Plasma confinement methods for fusion

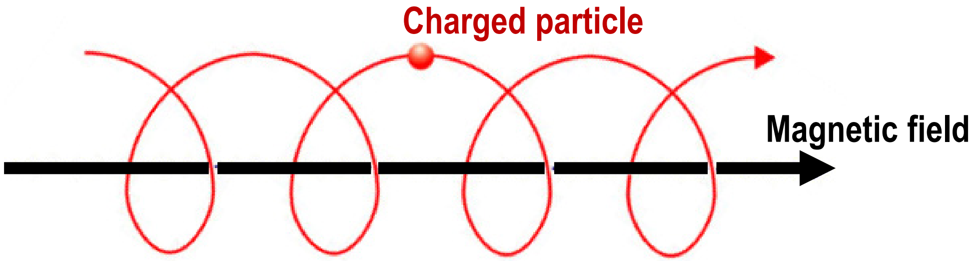
Gravitational Confinement



Inertial Confinement

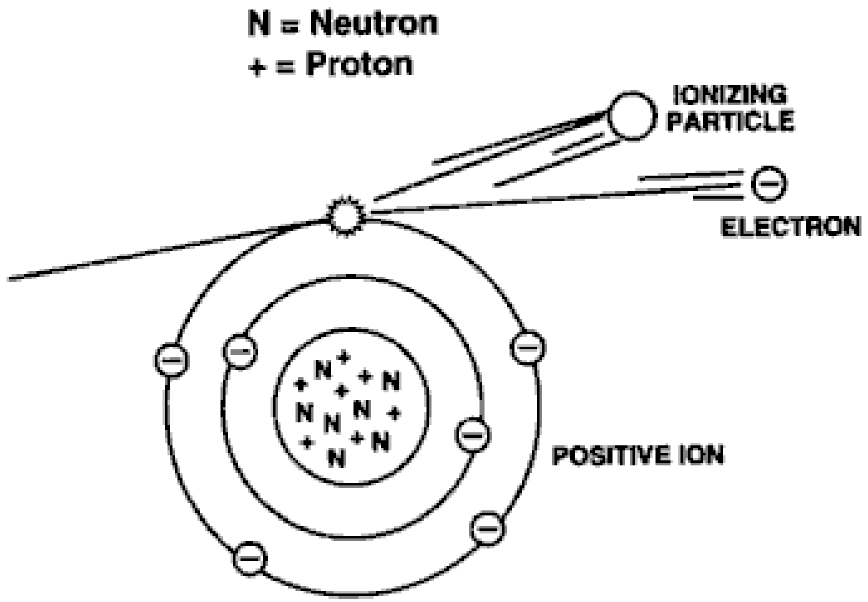


Magnetic Confinement



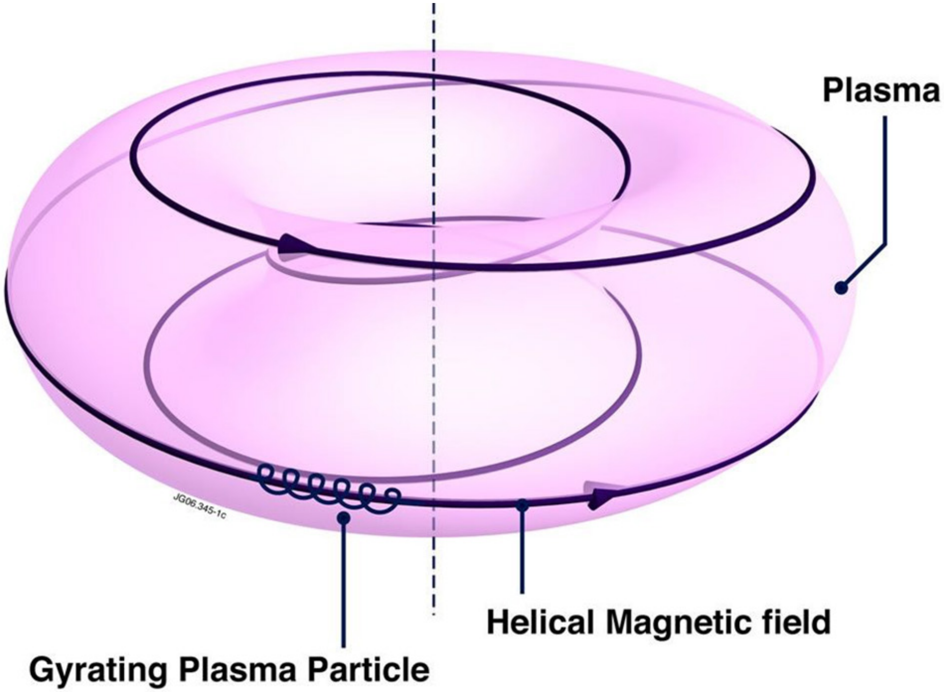
Plasma is a gas of charged particles:
"Soup" of negatively charged electrons, positive ions

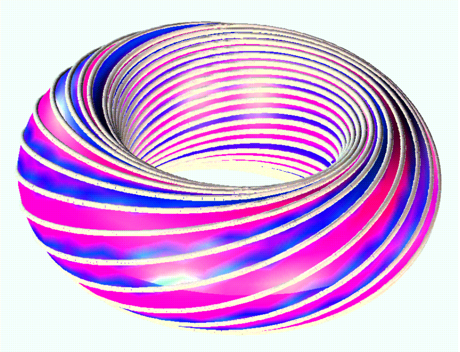
- At fusion temperatures, particles are so energetic that negatively charged (-) electrons are stripped from neutral atom leaving positively charged (+) ions

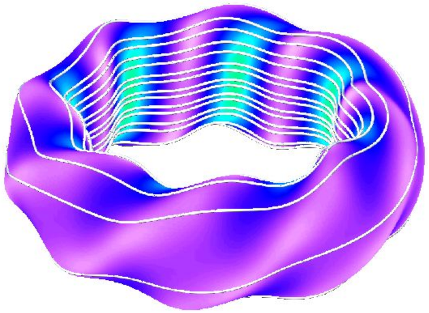


- One benefit of plasma state: charged particle motion can be manipulated by electric and magnetic fields

Helical magnetic field provides confinement




“Tokamak”

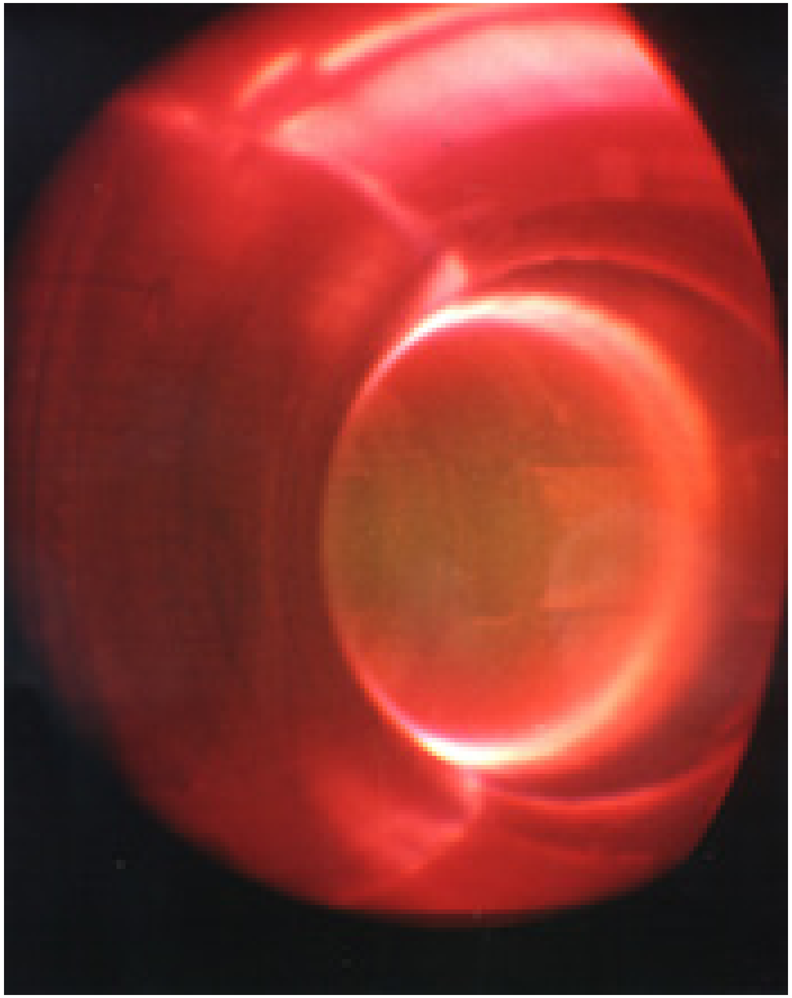

“Stellarator”

- “Helical” field = B-field covers toroidal surfaces
  - ➢ B arrows never puncture donut
- Allows currents to flow along magnetic field
- Short-circuits electric fields that would otherwise expel plasma

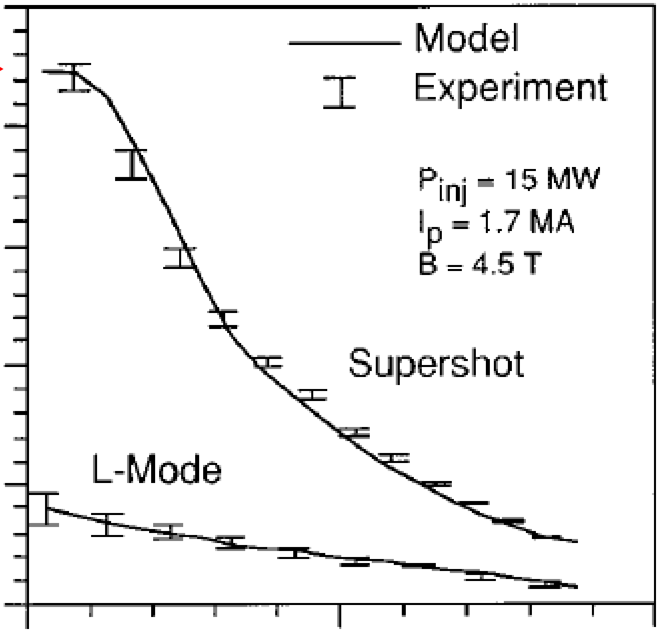
➢ Particles tied to surface

➢ Improved confinement

Magnetic fusion has already achieved the necessary very high temperatures



TFTR at PPPL (1990's)



~250 million C →

core

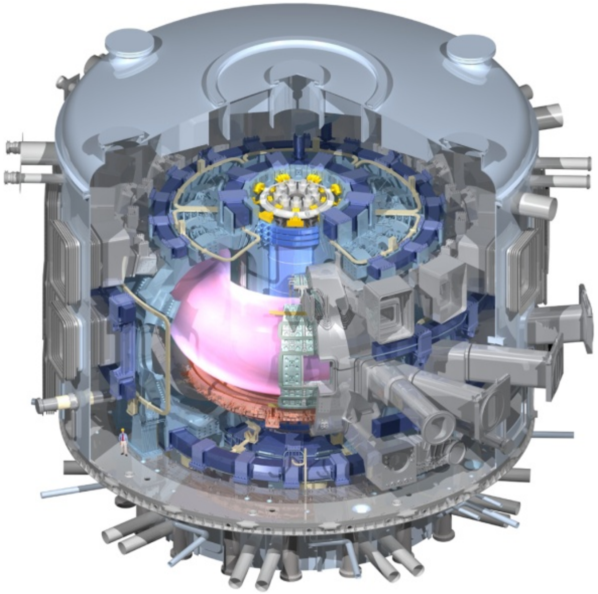
boundary

ITER will be first device to access “burning plasma”

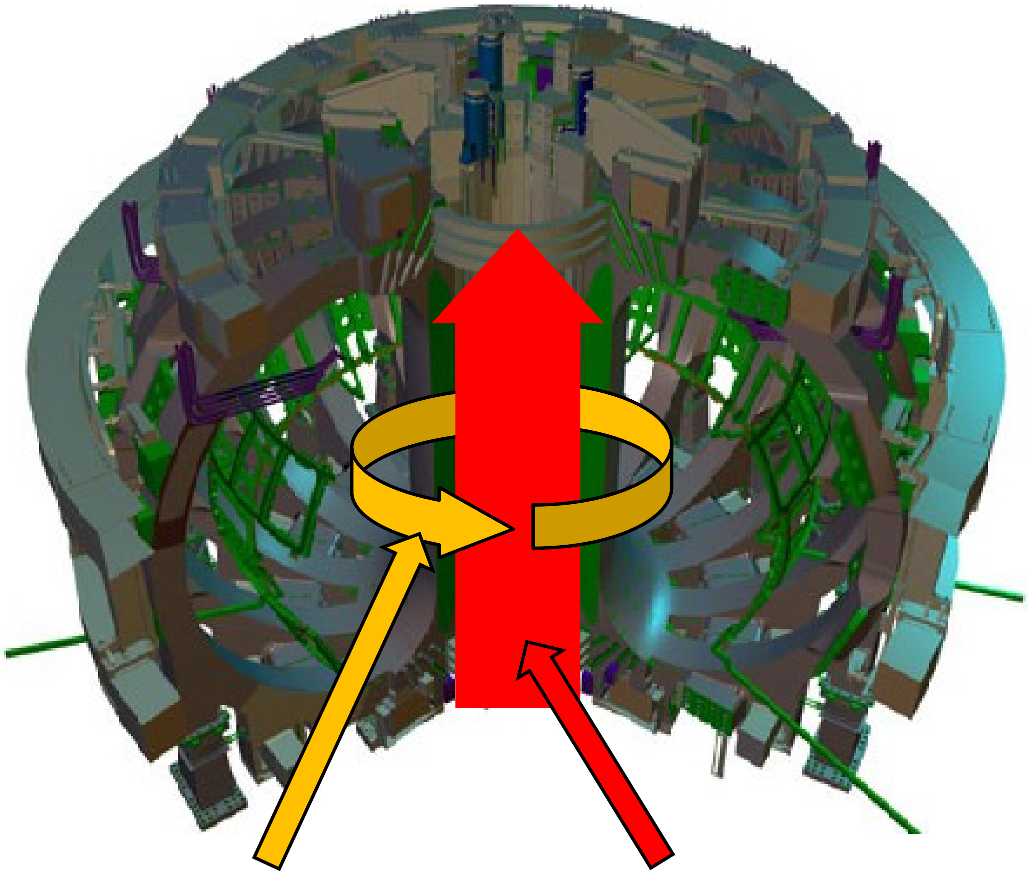
- Burning plasma: majority of plasma heating power comes from fusion alpha particles from DT reactions
  - ➢ DT reaction energy split: 1/5 in alphas, 4/5 in neutrons
- ITER goal $Q = P_{\text{fusion}} / P_{\text{external heating}} = 10$
- $Q = 10 \rightarrow P_{\text{alpha}} / P_{\text{external}} = 2$
- $P_{\text{alpha}} / P_{\text{alpha + external}} = 2 / 3 > 50\%$

ITER under construction in Cadarache, France

$A=3.1$, $R=6.2\text{m}$, $B_T=5.3\text{T}$, $I_P=15\text{MA}$



ITER magnets will be largest ever built



- 18 toroidal field magnets
- 12 Tesla at coil
- Weight: 6500 tons
- 80,000 km of Nb3Sn superconducting strand in total length

Plasma current:
15 million amps

Toroidal field current
165 million amps

15 amps
(1800W)

Size of ITER driven largely by plasma confinement

- Energy confinement scales with plasma current

- Large plasma current requires large toroidal field and/or plasma size for plasma to remain stable

- Current and confinement both scale with size

- **Can we make smaller devices with better confinement and smaller or cheaper magnets?**

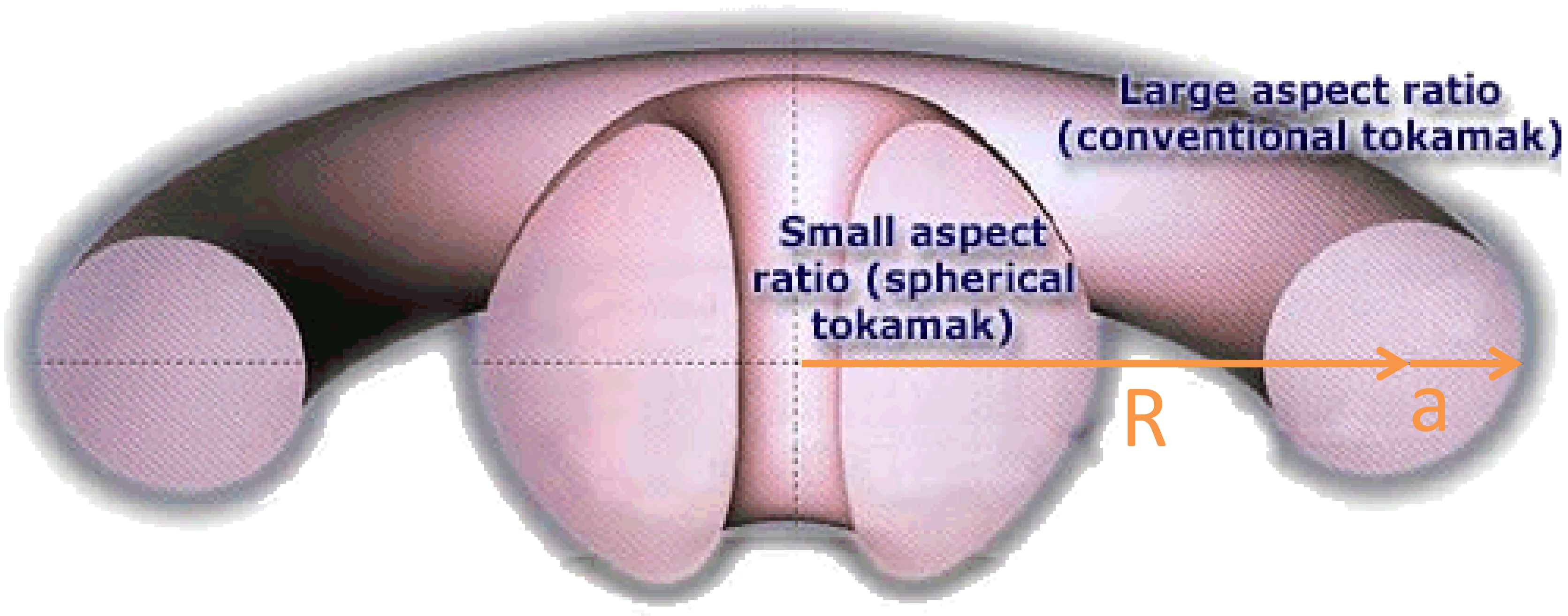
- **Such questions motivate exploring alternatives…**

  → For example "spherical" tokamaks

Aspect ratio is important free parameter

Aspect ratio A = R / a

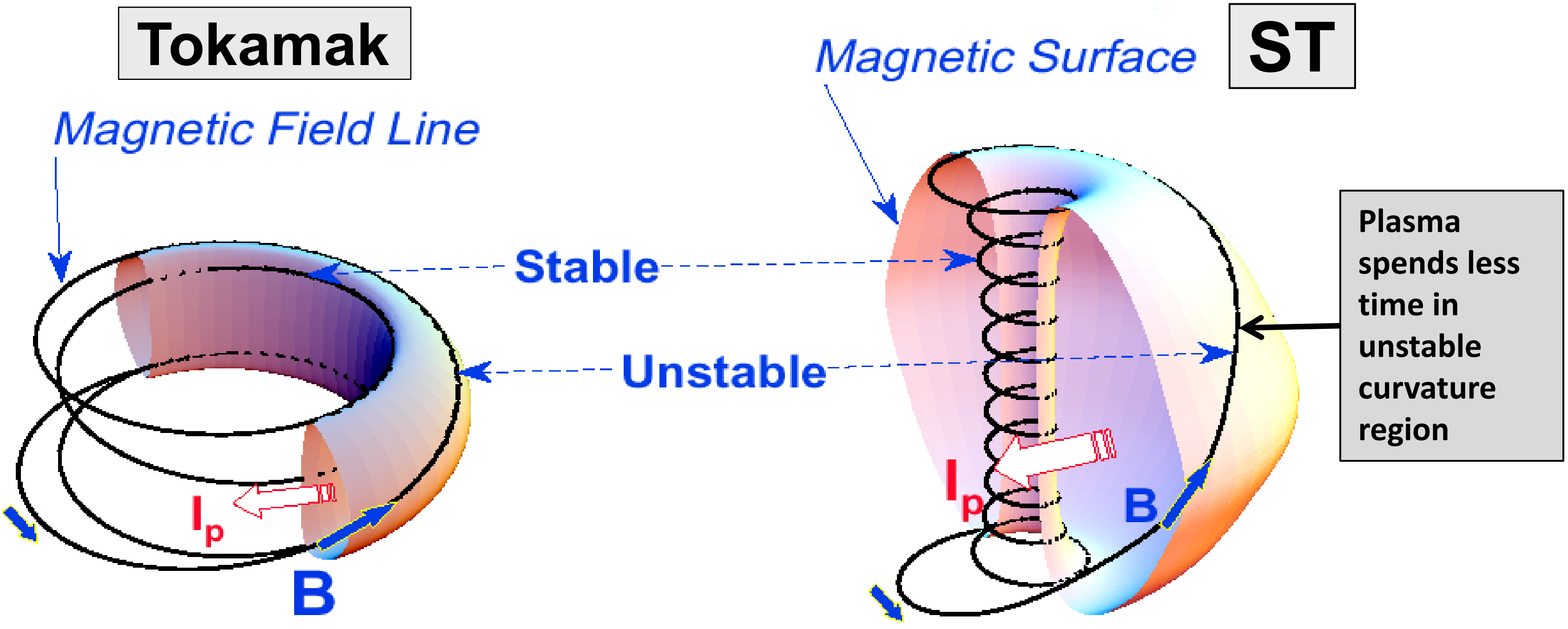
R = major radius   a = minor radius



Spherical torus/tokamak (ST) has A = 1.1-2

Conventional tokamak typically A = 3-4

Favorable average curvature improves stability



Plasma spends less time in unstable curvature region

Tokamak	ST
$A \sim 3$	$A \sim 1.5$
$\kappa = 1.5\text{-}2$	$\kappa = 2\text{-}3$
$\beta_T = 3\text{-}10\%$	$\beta_T = 10\text{-}40\%$

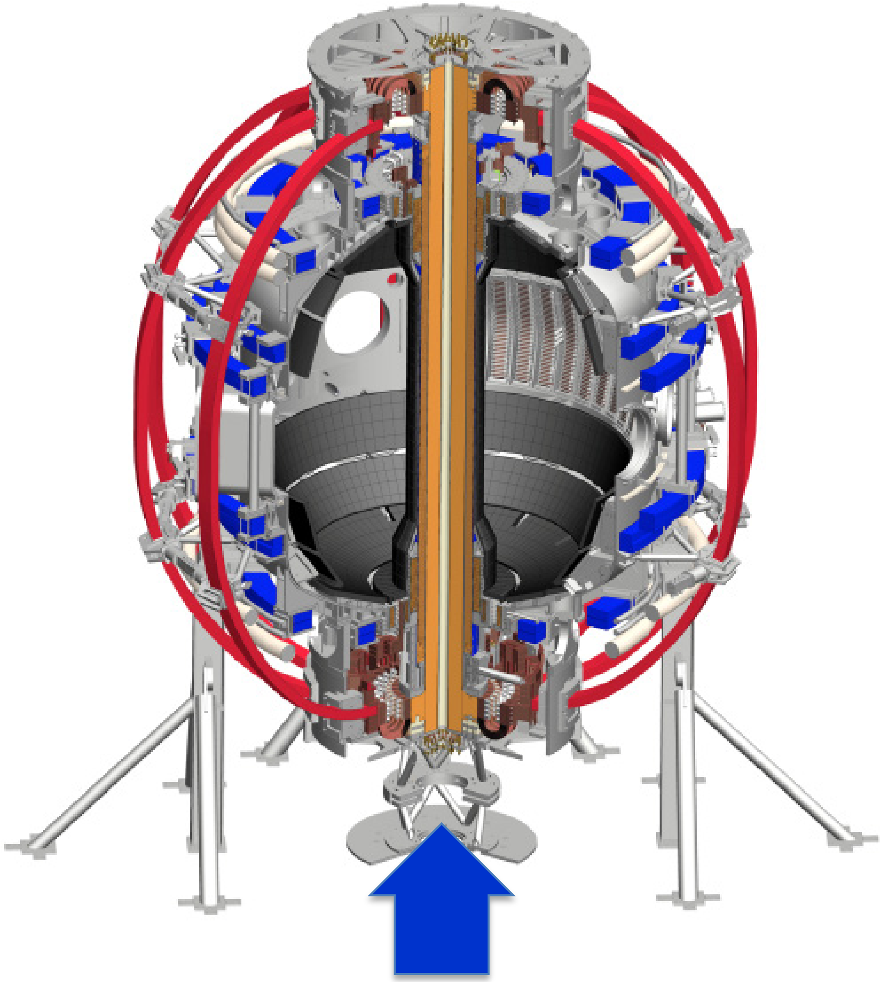
Aspect Ratio $A = R/a$

Elongation $\kappa = b/a$

Toroidal beta $\beta_T = \langle p \rangle / (B_{T0}^2/2\mu_0)$

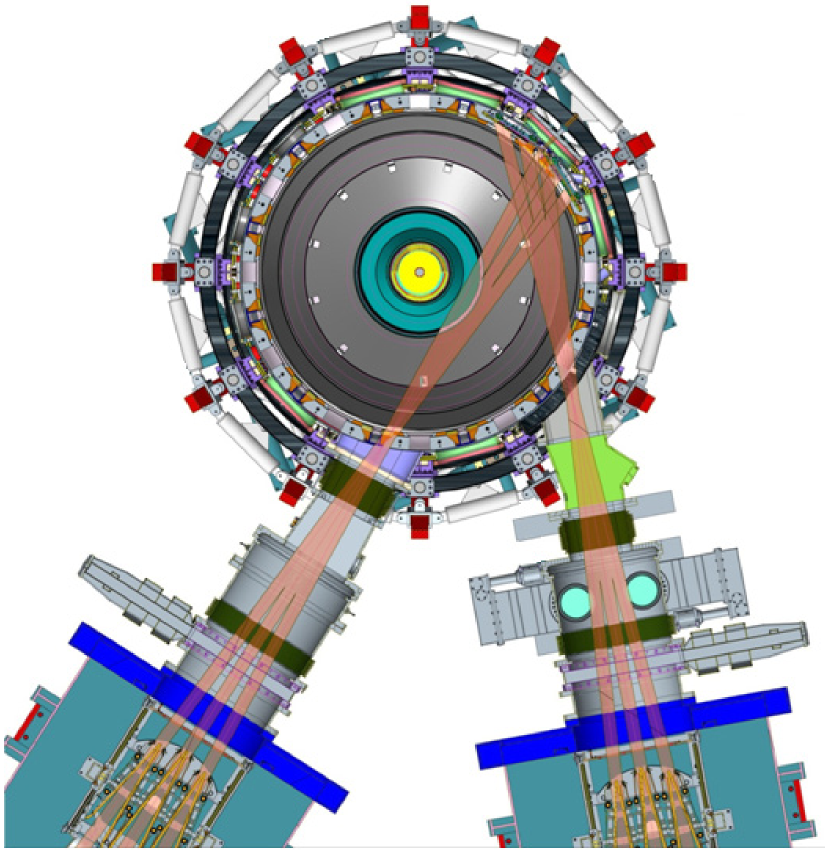
NSTX recently completed major upgrade

~2x higher B_T, I_p, P_{NBI} and ~5x pulse length vs. NSTX



New Central Magnet

1 Tesla at plasma center, I_p = 2MA, 5s



Original NBI

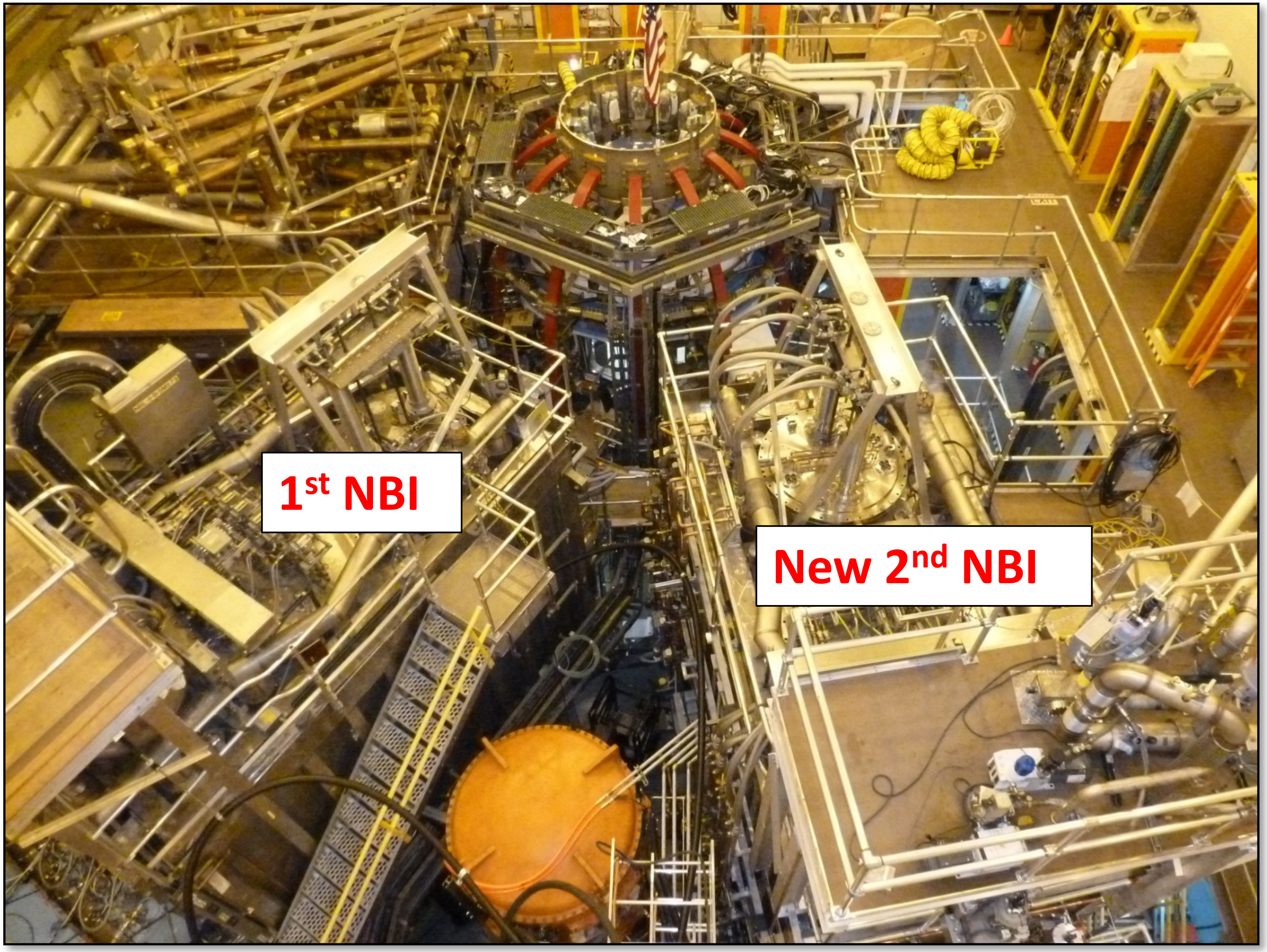
(R_{TAN} = 50, 60, 70cm)
5MW, 5s, 80keV

New 2nd NBI

(R_{TAN}=110, 120, 130cm)
5MW, 5s, 80keV

Project completed on-cost and schedule

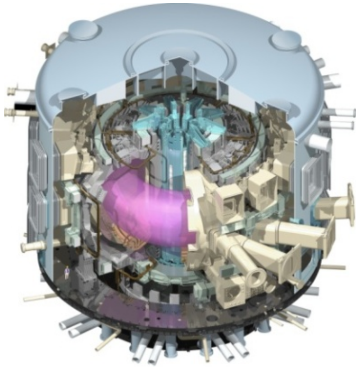
First test plasma ~100kA – Aug. 10, 2015



NSTX Upgrade mission elements

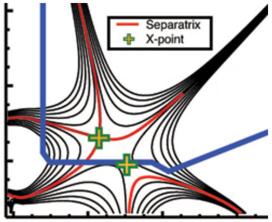
NSTX = National Spherical Torus Experiment

- Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond
- Develop solutions for the plasma-material interface (PMI) challenge
- Advance ST as candidate for Fusion Nuclear Science Facility (FNSF)
  - ➢ Sustain plasma current w/o transformer
- Develop ST as fusion energy system

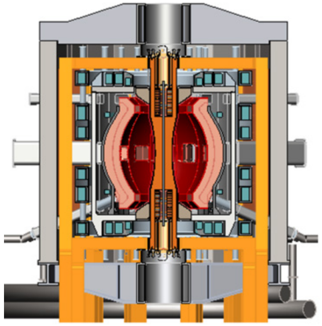


ITER

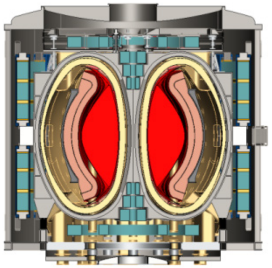
Lithium



“Snowflake”

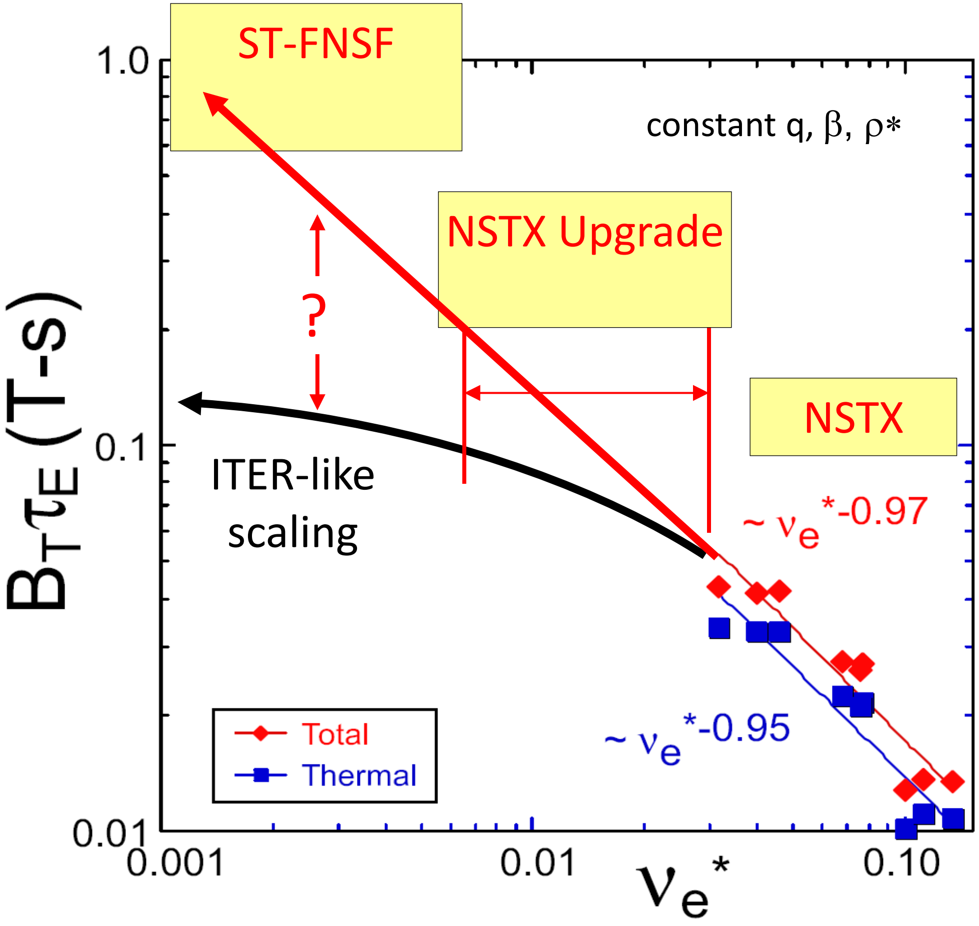


ST-FNSF / Pilot-Plant



STs have observed confinement increase at higher T_e (!)

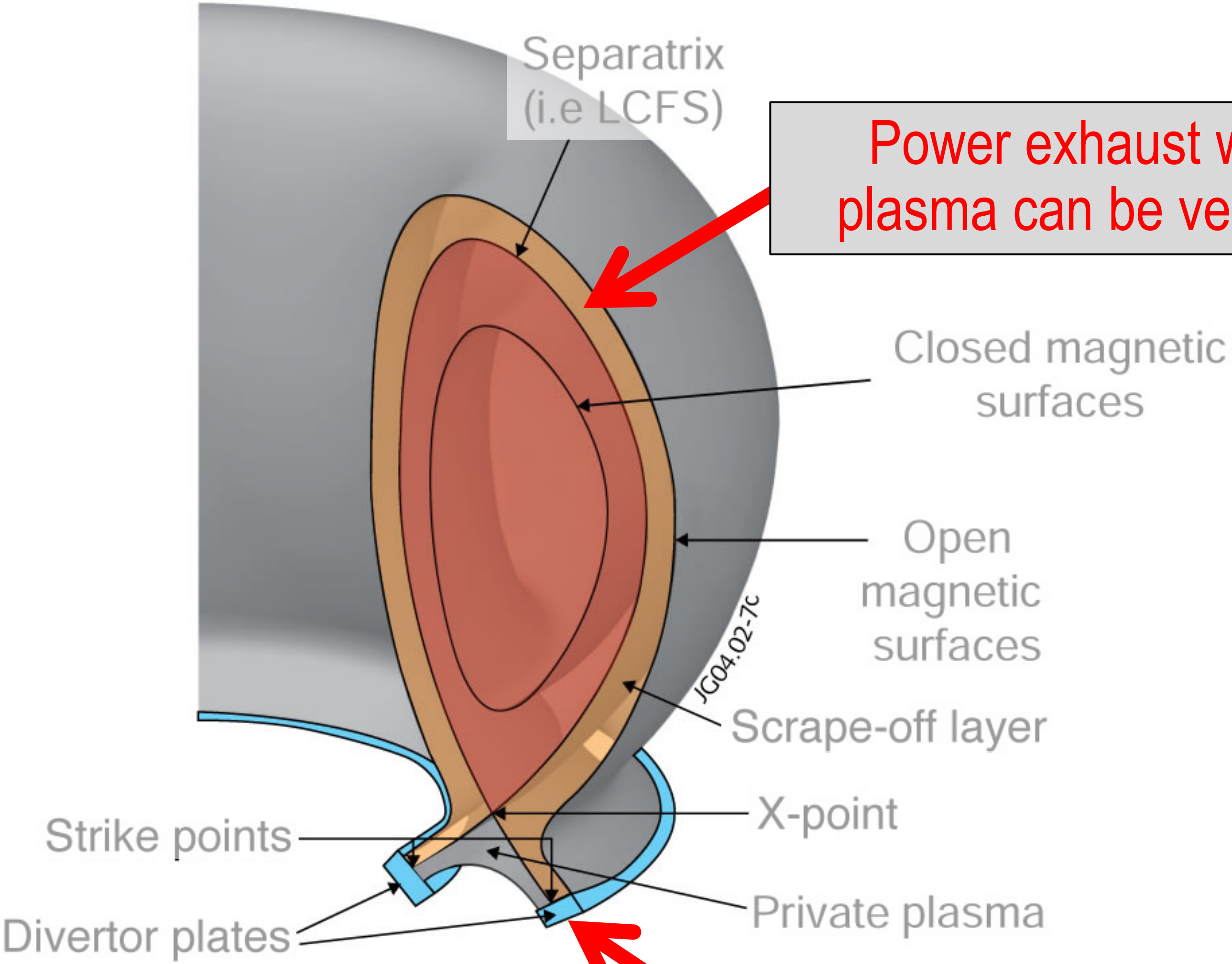
Will confinement trend continue, or look like conventional A?



Normalized electron collisionality $\nu_e^* \propto n_e / T_e^2$

Favorable confinement results could lead to more compact ST reactors

All modern tokamaks / STs use a “divertor” to control where power and particles are exhausted



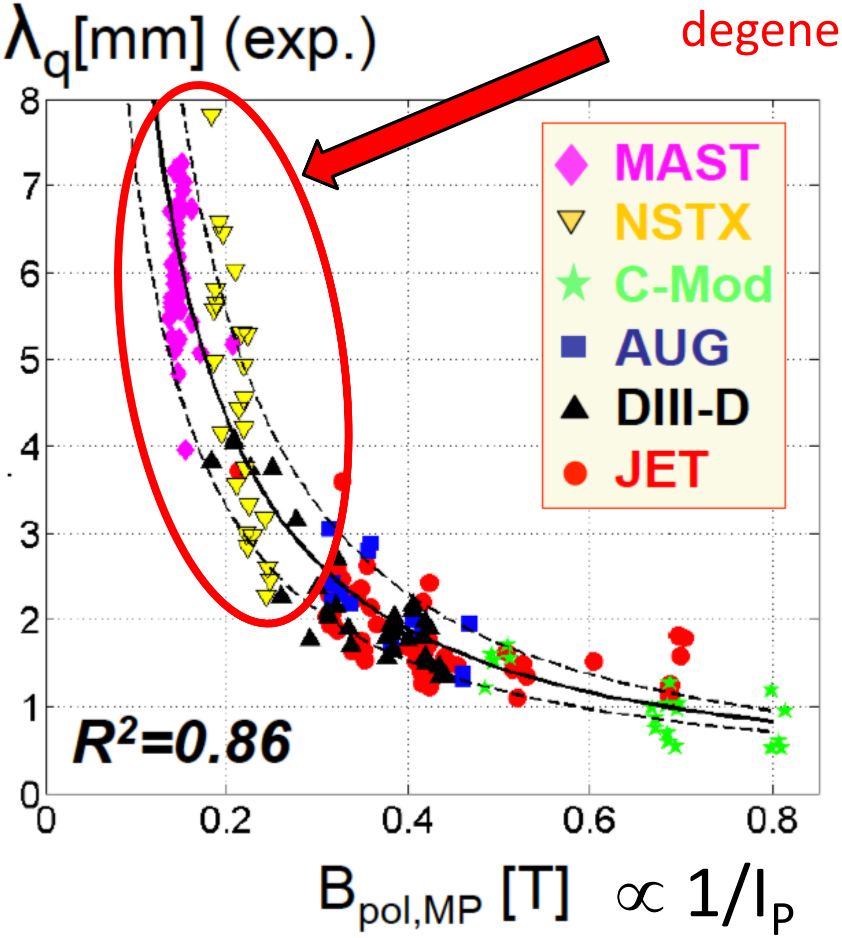
Power exhaust width outside main plasma can be very narrow (few mm)

Power / particles contact target plates here

Tokamak + ST data: power exhaust width varies as 1 / I_P

Will previous ST trend continue at 2× I_P , B_P , B_T, power?

ST data breaks aspect ratio degeneracy of data set



$\propto 1/I_P$

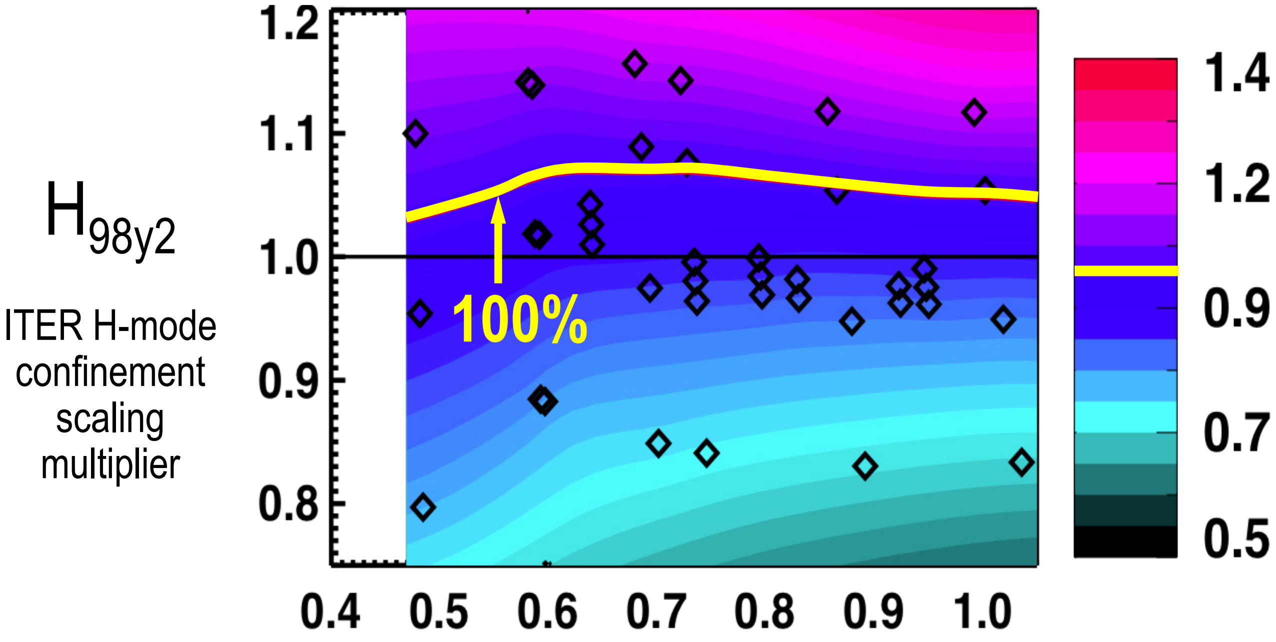
Issue: If peak heat flux in divertor region exceeds 10 MW/m^2 → material damage

Wider heat-flux width may offset smaller R → maybe better than tokamak

NSTX achieved 70% “transformer-less” current drive

Will NSTX-U achieve 100% as predicted by simulations?

TRANSP Contours of Non-Inductive Fraction

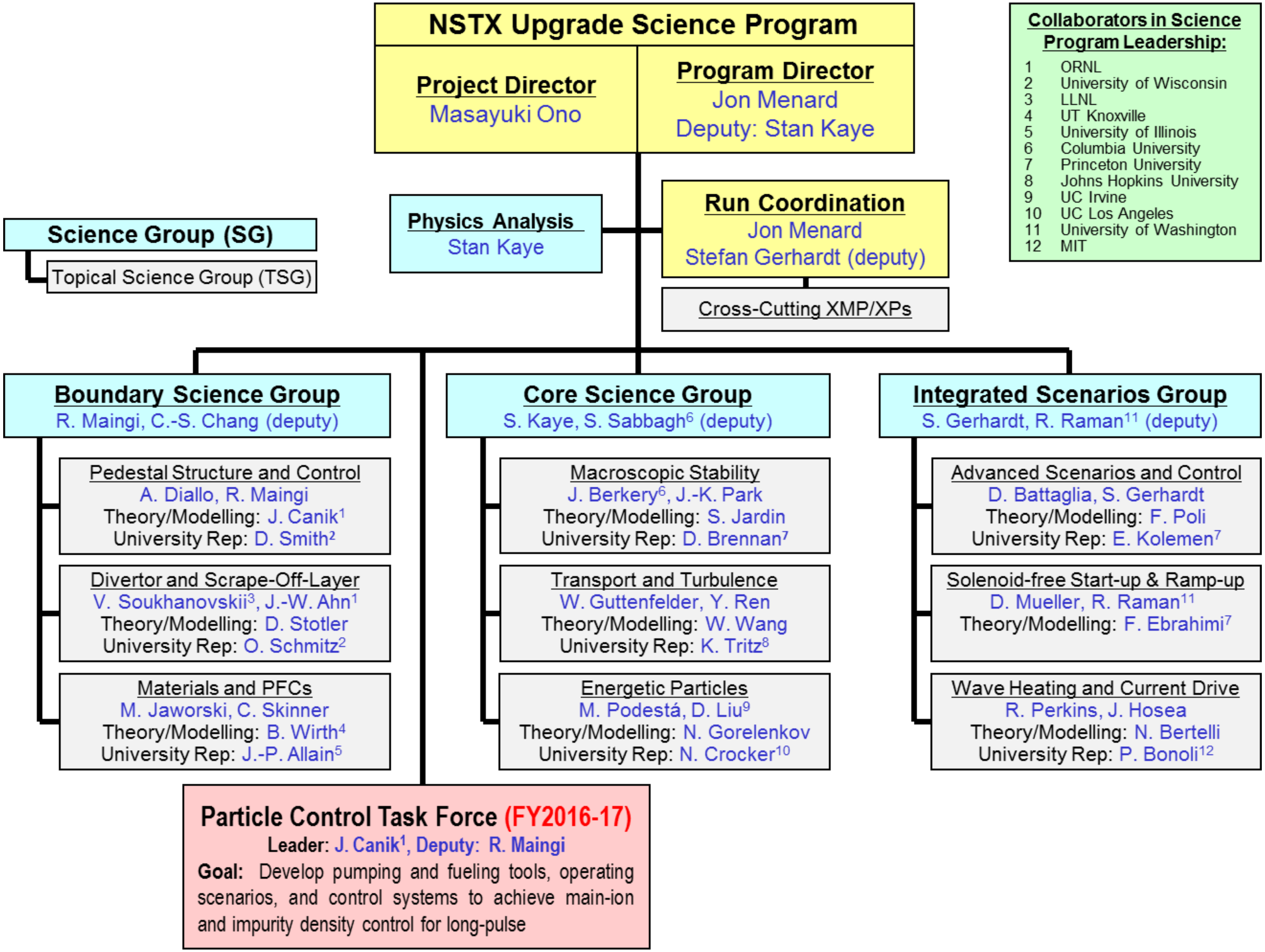


Normalized Density (Greenwald fraction)

I_P=1 MA, B_T=1.0 T, P_{NBI}=12.6 MW

Steady-state operation required for ST, tokamak, or stellarator FNSF

NSTX-U Scientific Organization



NSTX Upgrade Science Program

Project Director
Masayuki Ono

Program Director
Jon Menard
Deputy: Stan Kaye

Physics Analysis
Stan Kaye

Run Coordination
Jon Menard
Stefan Gerhardt (deputy)

Cross-Cutting XMP/XPs

Collaborators in Science Program Leadership:

1	ORNL
2	University of Wisconsin
3	LLNL
4	UT Knoxville
5	University of Illinois
6	Columbia University
7	Princeton University
8	Johns Hopkins University
9	UC Irvine
10	UC Los Angeles
11	University of Washington
12	MIT

Science Group (SG)
- Topical Science Group (TSG)

Boundary Science Group
R. Maingi, C.-S. Chang (deputy)

- Pedestal Structure and Control
  A. Diallo, R. Maingi
  Theory/Modelling: J. Canik[1]
  University Rep: D. Smith[2]
- Divertor and Scrape-Off-Layer
  V. Soukhanovskii[3], J.-W. Ahn[1]
  Theory/Modelling: D. Stotler
  University Rep: O. Schmitz[2]
- Materials and PFCs
  M. Jaworski, C. Skinner
  Theory/Modelling: B. Wirth[4]
  University Rep: J.-P. Allain[5]

Core Science Group
S. Kaye, S. Sabbagh[6] (deputy)

- Macroscopic Stability
  J. Berkery[6], J.-K. Park
  Theory/Modelling: S. Jardin
  University Rep: D. Brennan[7]
- Transport and Turbulence
  W. Guttenfelder, Y. Ren
  Theory/Modelling: W. Wang
  University Rep: K. Tritz[8]
- Energetic Particles
  M. Podestá, D. Liu[9]
  Theory/Modelling: N. Gorelenkov
  University Rep: N. Crocker[10]

Integrated Scenarios Group
S. Gerhardt, R. Raman[11] (deputy)

- Advanced Scenarios and Control
  D. Battaglia, S. Gerhardt
  Theory/Modelling: F. Poli
  University Rep: E. Kolemen[7]
- Solenoid-free Start-up & Ramp-up
  D. Mueller, R. Raman[11]
  Theory/Modelling: F. Ebrahimi[7]
- Wave Heating and Current Drive
  R. Perkins, J. Hosea
  Theory/Modelling: N. Bertelli
  University Rep: P. Bonoli[12]

Particle Control Task Force (FY2016-17)
Leader: J. Canik[1], **Deputy:** R. Maingi

Goal: Develop pumping and fueling tools, operating scenarios, and control systems to achieve main-ion and impurity density control for long-pulse

NSTX-U Scientific Organization – August 2015

Why are we visiting Fermilab?

- **To learn about your experience with remote collaboration, to help us improve collaboration:**

- **NSTX-U – 300+ researchers (400+ data users)**
  - 32 domestic institutions, 29 international
  - ~80% are domestic users
  - ➢ Want NSTX-U users to remotely monitor/ later lead experiments
- **PPPL also collaborates on other experiments:**
  - Tokamaks: US: DIII-D, C-Mod Asia: EAST, KSTAR
  - Stellarators: W7-X (Germany) – will operate soon
  - ➢ Want PPPL researchers to monitor / lead remote experiments
- **Longer-term:** PPPL is potential site / host for US researcher remote collaboration on ITER

Thank you!

Any questions?