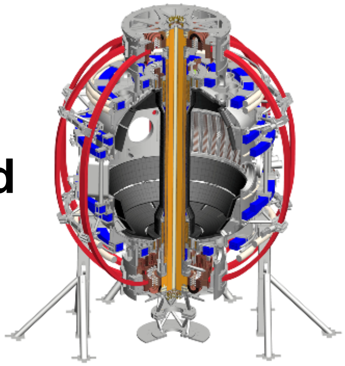
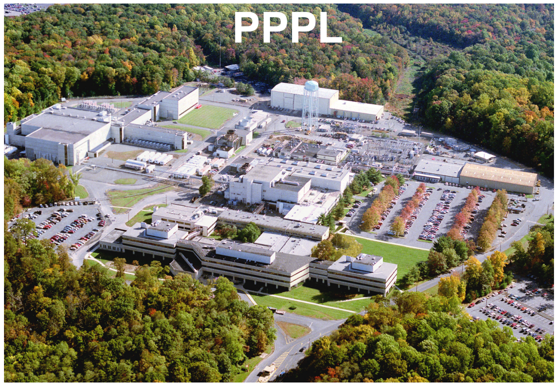
Spherical Tokamak for Economical Fusion Energy Development



Masayuki Ono

NSTX-U Department Head

PPPL, Princeton University



Innovation for Cool Earth Forum

October 5 - 6, 2016

Fusion for safe limitless energy source

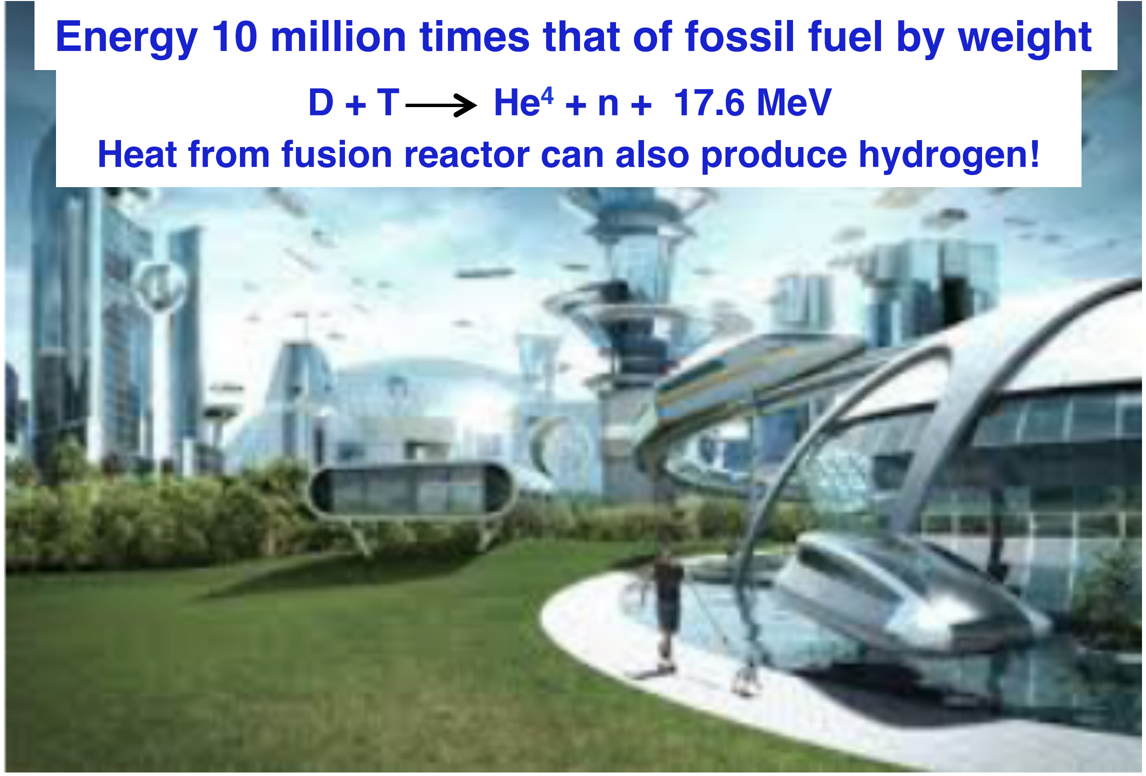
Fusion could provide energy for future mankind:

- Environmentally friendly
- Safe
- Globally abundant fuel
- High energy density
- Support hydrogen economy

Energy 10 million times that of fossil fuel by weight

$D + T \longrightarrow He^4 + n + 17.6$ MeV

Heat from fusion reactor can also produce hydrogen!



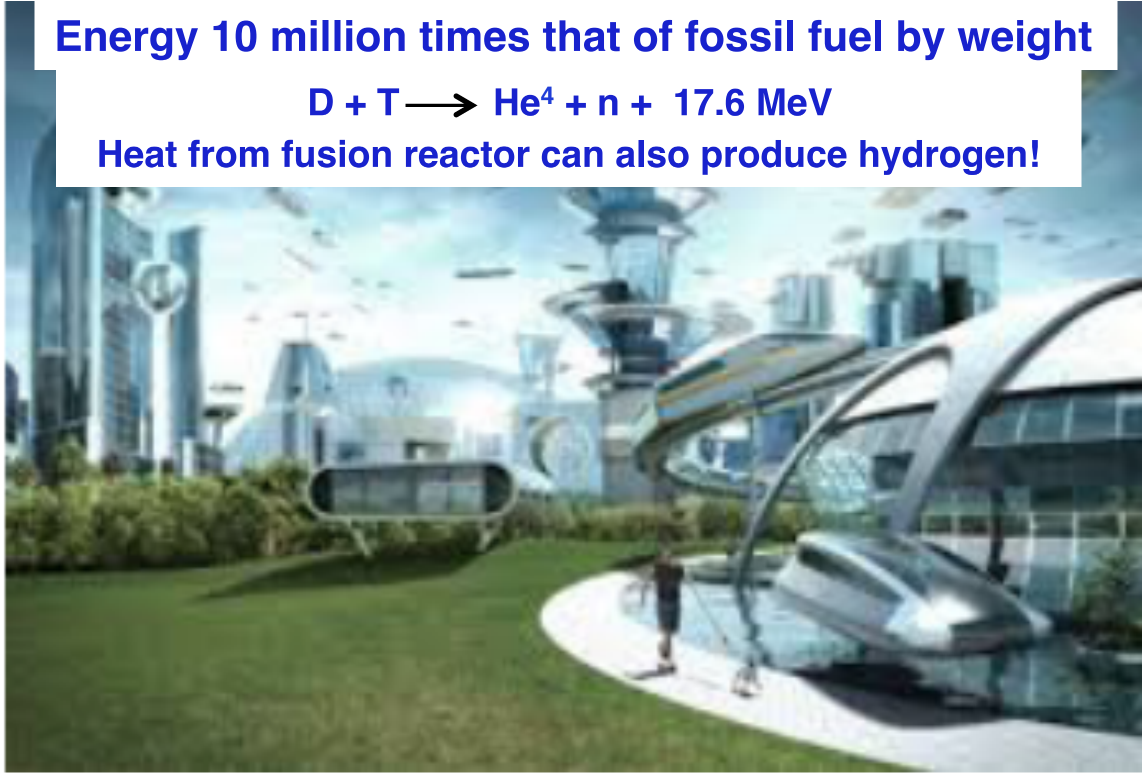
Fusion for safe limitless energy source
Fusion can also solve potential challenges for humanity

Fusion could provide energy for future mankind:

- Environmentally friendly
- Safe
- Globally abundant fuel
- High energy density
- Support hydrogen economy

Fusion could help solve future challenges facing mankind:

- Global warming
- Fission reactor spent fuel
- Space travel



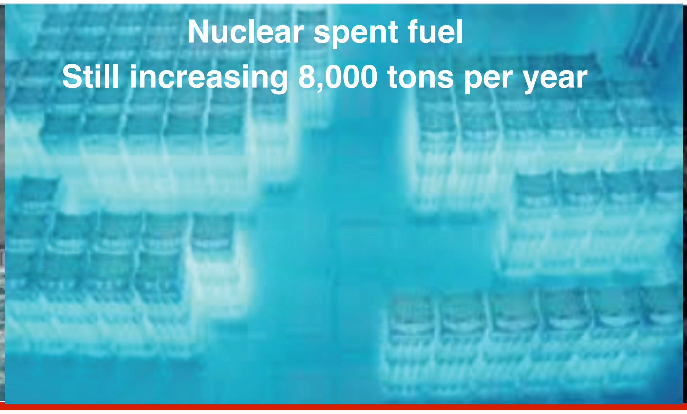
Energy 10 million times that of fossil fuel by weight

$$D + T \longrightarrow He^4 + n + 17.6\ \text{MeV}$$

Heat from fusion reactor can also produce hydrogen!

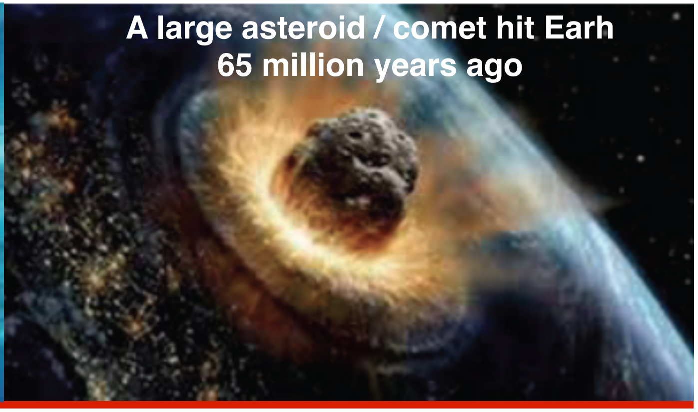
Global Warming

Annual CO_2 release – 40 billion tons



Nuclear spent fuel

Still increasing 8,000 tons per year



A large asteroid / comet hit Earh

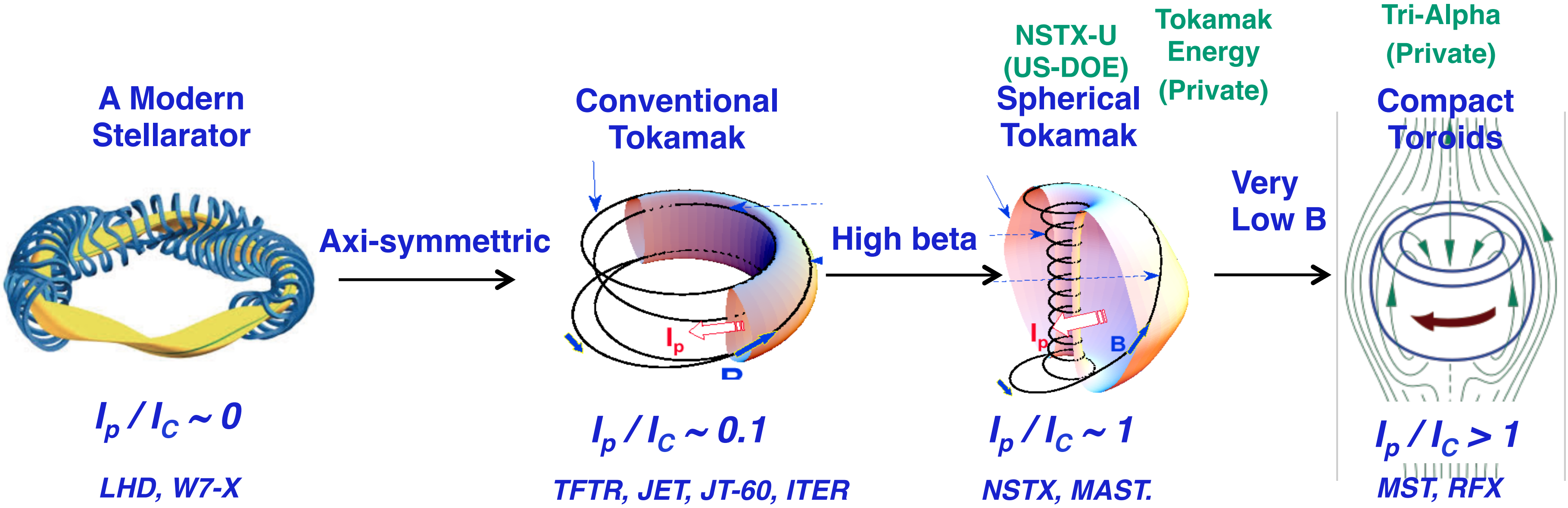
65 million years ago

Nuclear Fusion has many possible approaches Many Types of Magnetic Bottles!

Beta is a ratio of plasma pressure over magnetic pressure

- Plasma pressure produces fusion power

- Mangetic pressure provided by coils but cost $



A Modern Stellarator

$I_p / I_C \sim 0$

LHD, W7-X

Axi-symmettric

Conventional Tokamak

$I_p / I_C \sim 0.1$

TFTR, JET, JT-60, ITER

High beta

NSTX-U (US-DOE)

Spherical Tokamak

Tokamak Energy (Private)

$I_p / I_C \sim 1$

NSTX, MAST.

Very Low B

Tri-Alpha (Private)

Compact Toroids

$I_p / I_C > 1$

MST, RFX

I_p = plasma current helps plasma confinement and stability

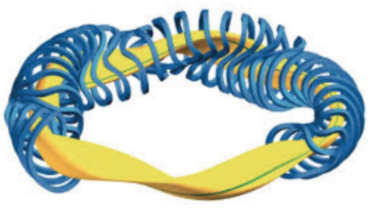
I_c = coil current also helps plasma confinement and stability but cost $

Nuclear Fusion has many possible approaches
Many Types of Magnetic Bottles!

What is the best fusion approach?

Higher beta*, smaller size, lower field, economical →

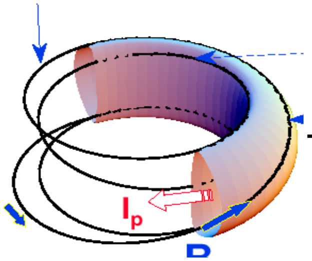
A Modern Stellarator



$I_p / I_C \sim 0$

Axi-symmettric →

Conventional Tokamak



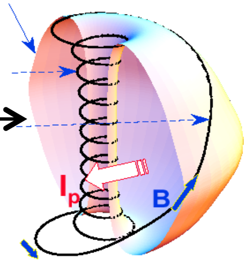
$I_p / I_C \sim 0.1$

High beta →

NSTX-U (US-DOE)

Spherical Tokamak

Tokamak Energy (Private)

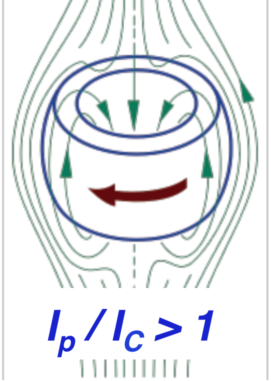


$I_p / I_C \sim 1$

Very Low B →

Tri-Alpha (Private)

Compact Toroids



$I_p / I_C > 1$

← **Enable more external control**

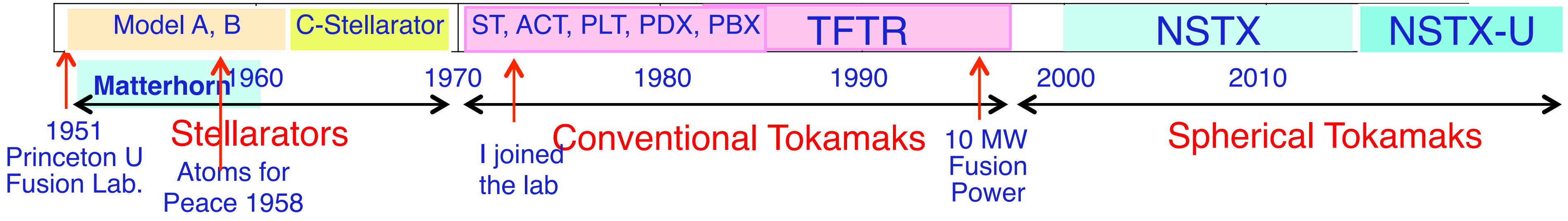
Beta is a ratio of plasma pressure over magnetic pressure

Princeton Plasma Physics Laboratory

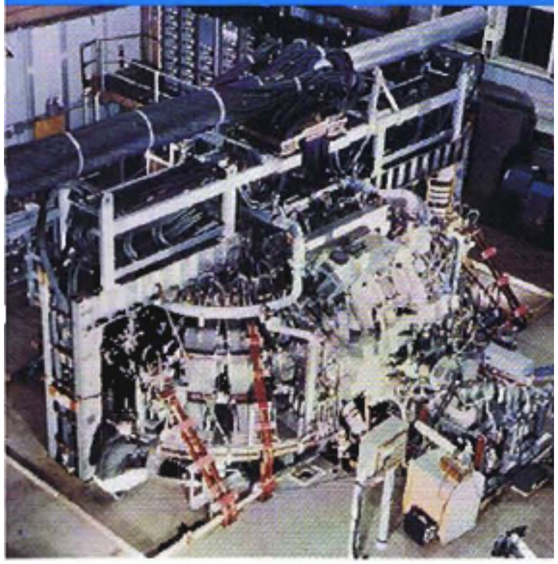
U.S. DEPARTMENT OF ENERGY

PRINCETON UNIVERSITY

PPPL investigates many type of magnetic bottles and plasma applications


Model A, B
C-Stellarator
ST, ACT, PLT, PDX, PBX
TFTR
NSTX
NSTX-U
Matterhorn
1960
1970
1980
1990
2000
2010
1951 Princeton U Fusion Lab.
Stellarators
Atoms for Peace 1958
I joined the lab
Conventional Tokamaks
10 MW Fusion Power
Spherical Tokamaks

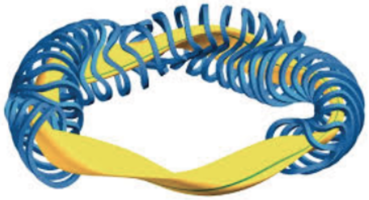
Model C Stellarator



TFTR Tokamak

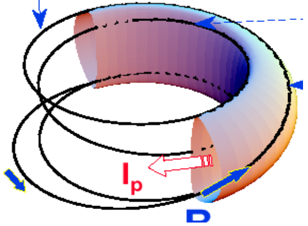
NSTX Spherical Tokamak

A Modern Stellarator



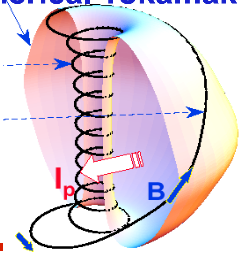
Axi-symmetric →

Conventional Tokamak



High beta →

Spherical Tokamak



A spherical tokamak (ST) is a high beta tokamak

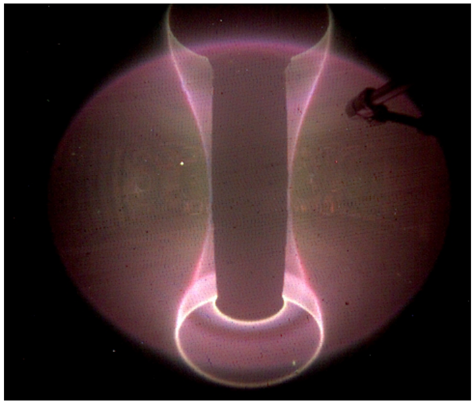
Favorable average curvature improves stability at high beta

Aspect Ratio $A = R/a$

Elongation $\kappa = b/a$

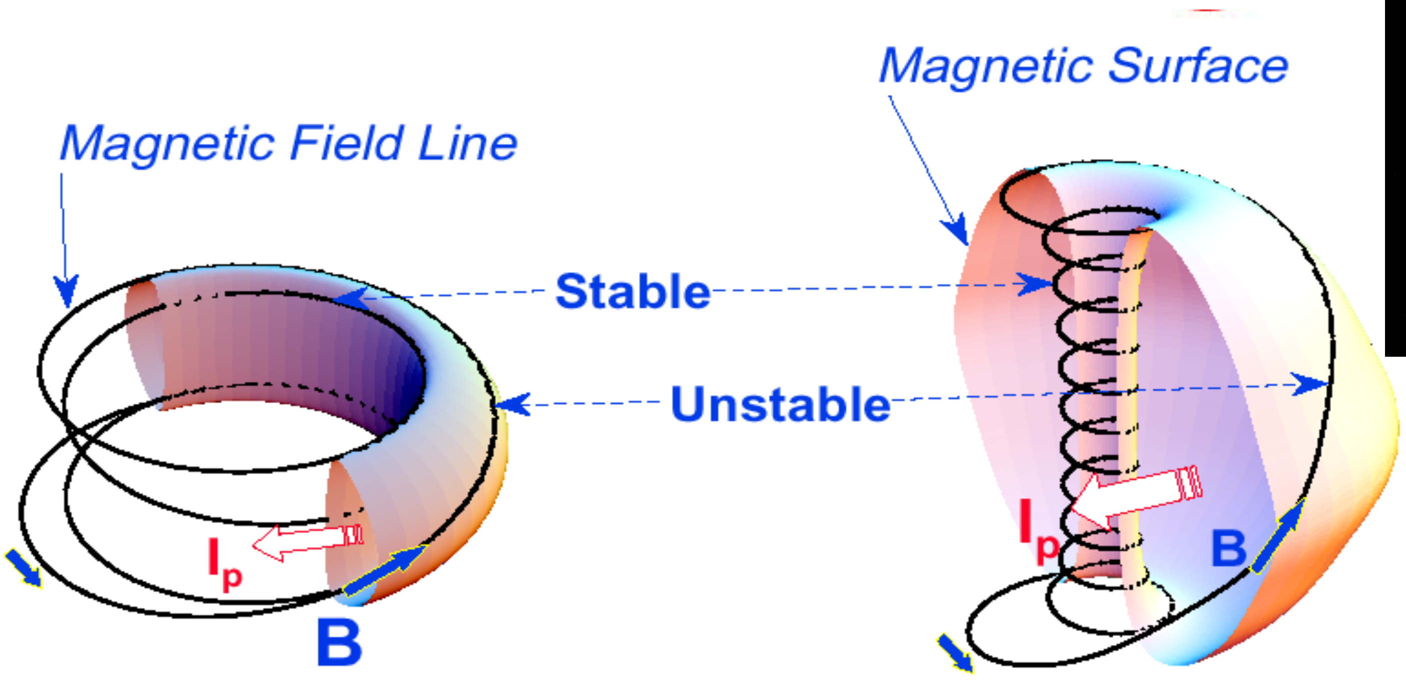
Toroidal Beta $\beta_T = \langle p \rangle / (B_{T0}^2 / 2\mu_0)$

Camera image from NSTX-U



Tokamak

ST



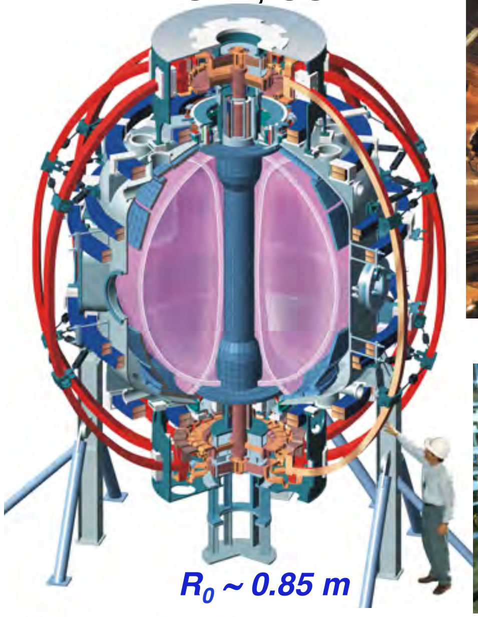
$A \sim 3$,
$\kappa = 1.5\text{-}2$,
$q_{95} = 3\text{-}4$,
$\beta_T = 3\text{-}10\%$

$A \sim 1.5$,
$\kappa = 2\text{-}3$,
$q_{95} = 8\text{-}12$,
$\beta_T = 10\text{-}40\%$

Operating ST Research Facilities Since 2000

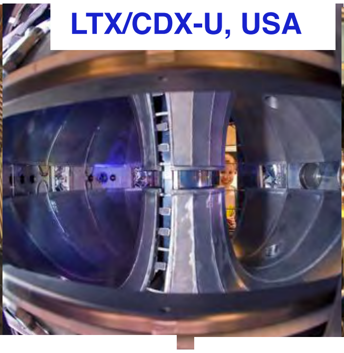
NSTX and MAST: MA-class STs, Smaller STs addressing topical issues

NSTX, USA

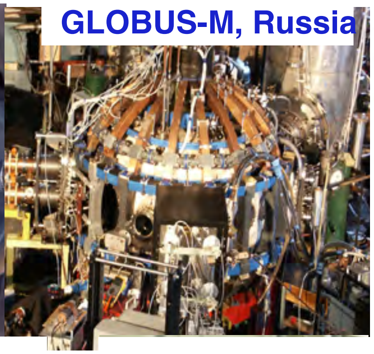


PEGASUS, USA

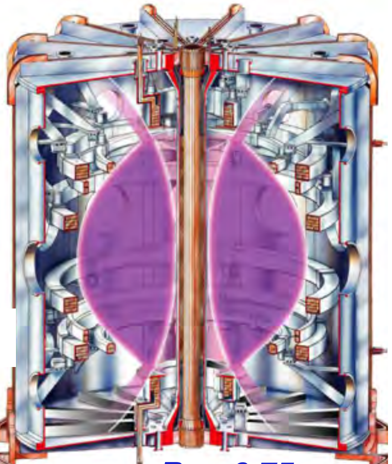
LTX/CDX-U, USA



GLOBUS-M, Russia

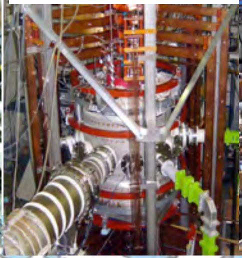


MAST, *UK*

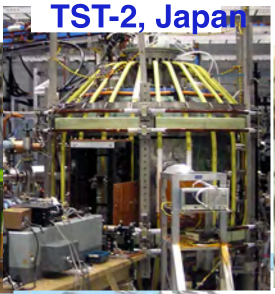


HIST, Japan

LATE, Japan

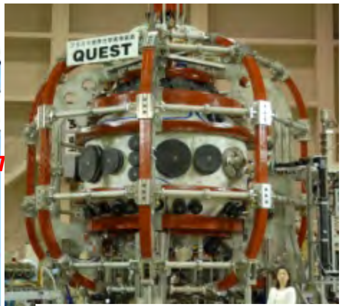


TST-2, Japan

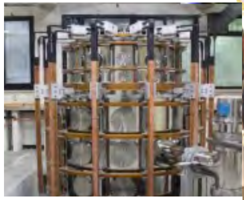


UTST, Japan

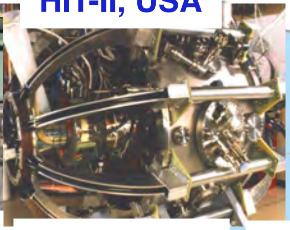
QUEST/CPD, Japan

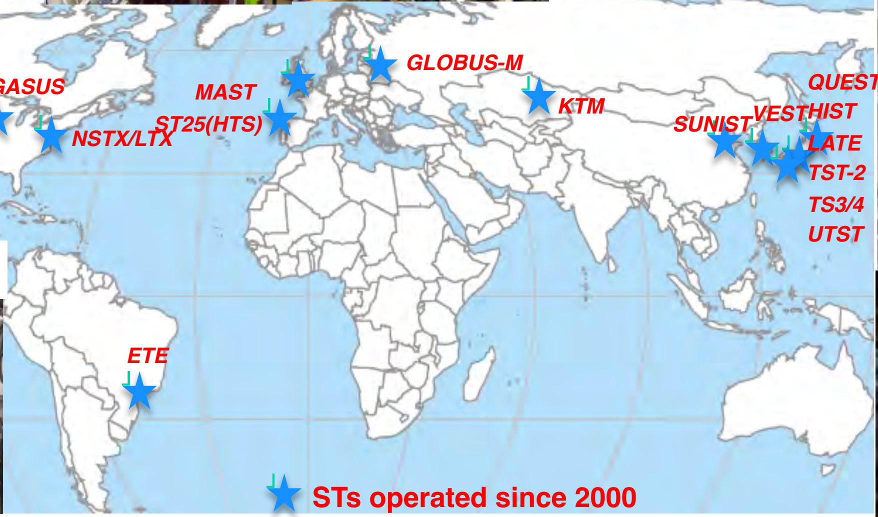


VEST, Korea



HIT-II, USA





★ STs operated since 2000

SUNIST, China

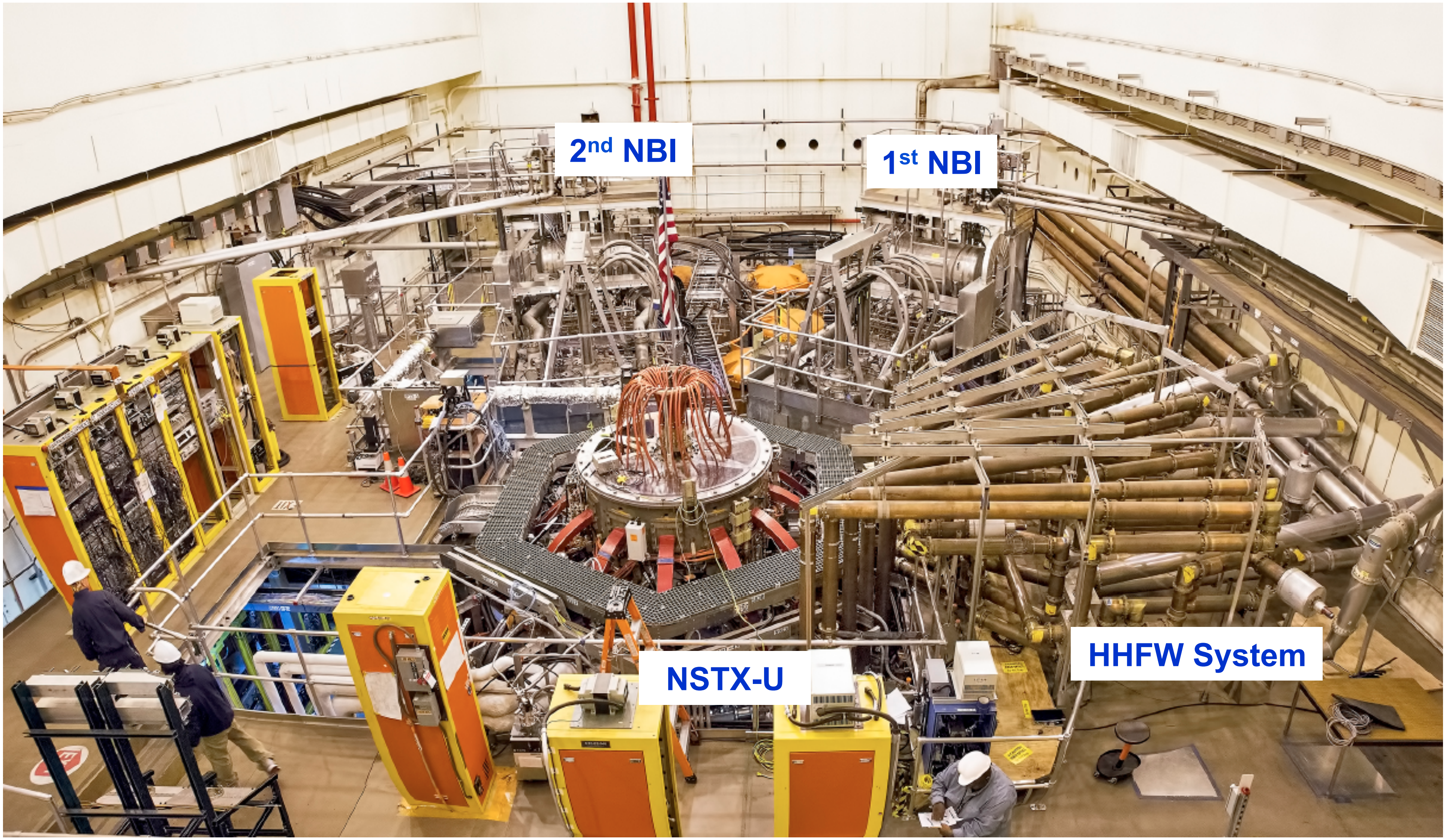
ETE, Brazil

ST25, UK

TS3/4, Japan

NSTX-U Facility Came On Line This year

To demonstrate fully sustained high beta plasmas



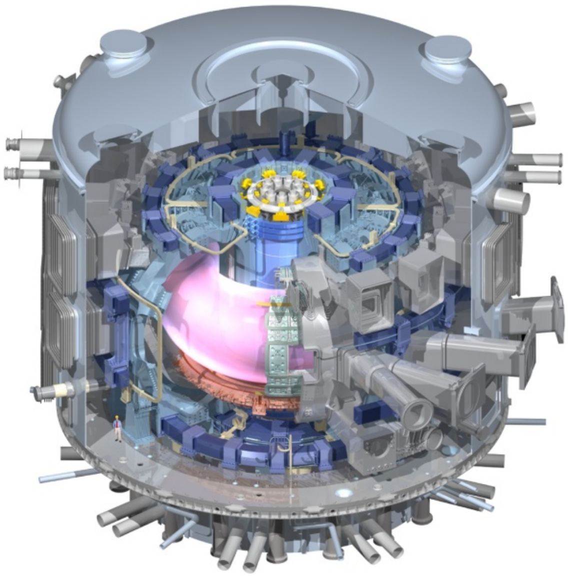
Unique ST properties support and accelerate a range of development paths toward fusion energy

Extend Predictive Capability for ITER and Toroidal Science

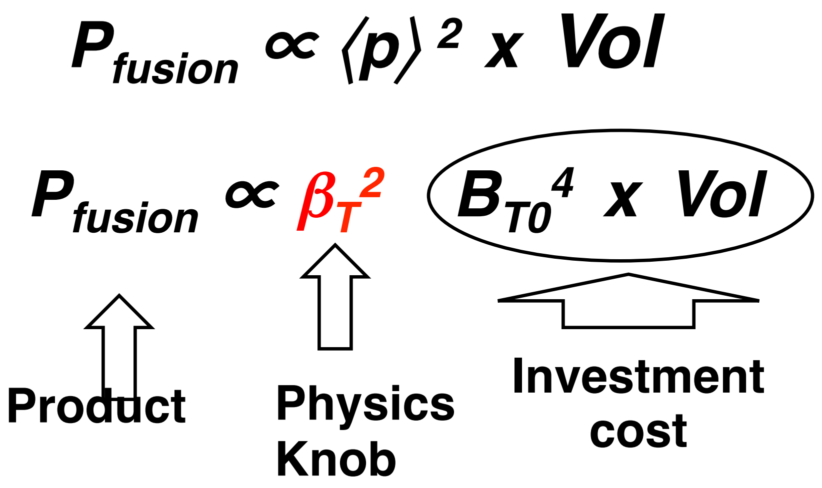
High β physics, rotation, shaping for MHD, transport

Non-linear Alfvén modes, fast-ion dynamics, Electron gyro-scale turbulence at low ν^*

Burning Plasma Physics -
ITER



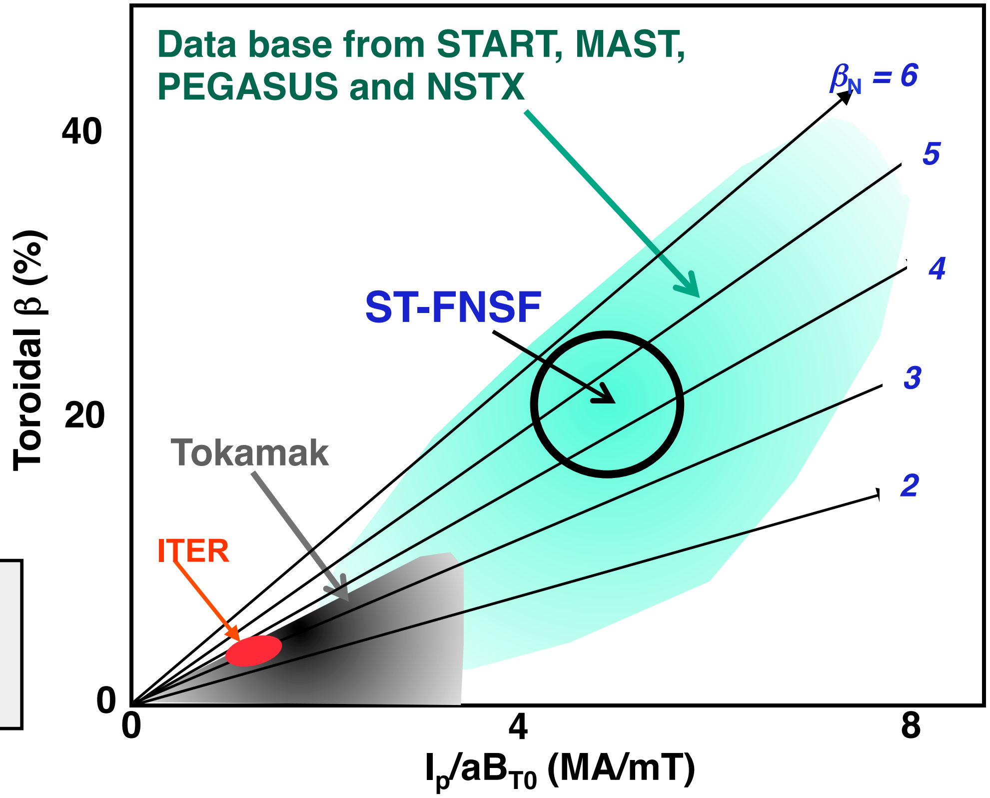
Higher β_T enables economical fusion power and compact neutron sources for near term and long term applications



$$P_{fusion} \propto \langle p \rangle^2 \times Vol$$

$$P_{fusion} \propto \beta_T^2 \; \boxed{B_{T0}^4 \times Vol}$$

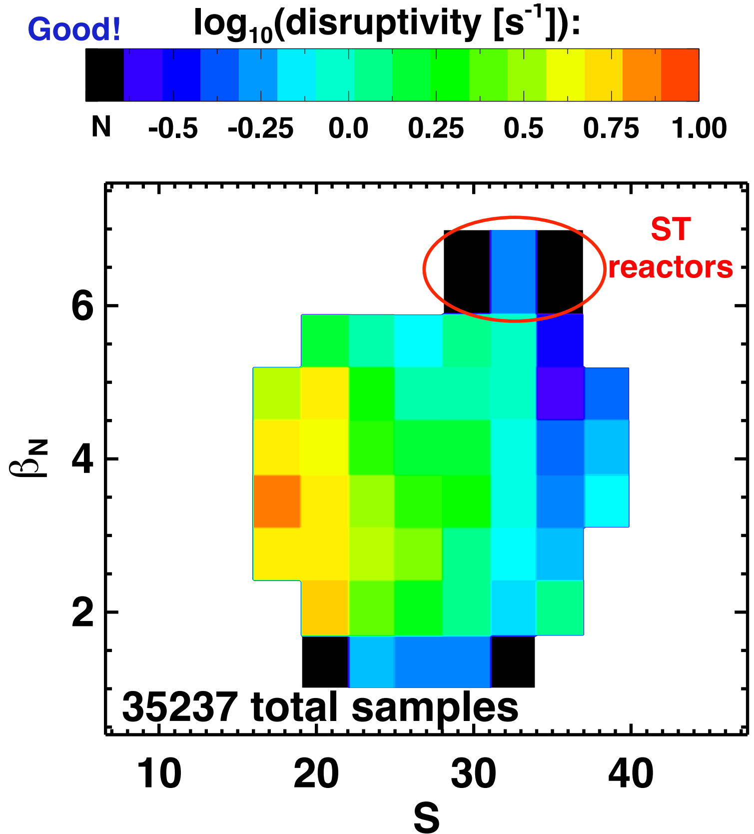
Higher β allows lower B_{T0} and/or smaller Vol both lower cost



Lower B_{T0} ⇨ Lower Cost, Greater Safety, and Reliability

Note: Ultra high β STs ~ 50% produced in TS-3 Device at Univ. Tokyo

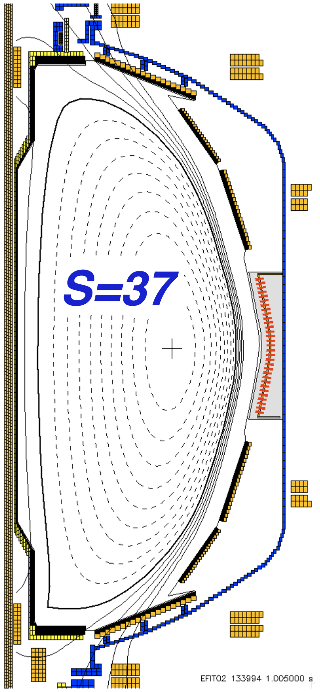
NSTX Data Demonstrates a Favorable Operations Window At High β For Reduced Disruptivity in an ST-FNSF

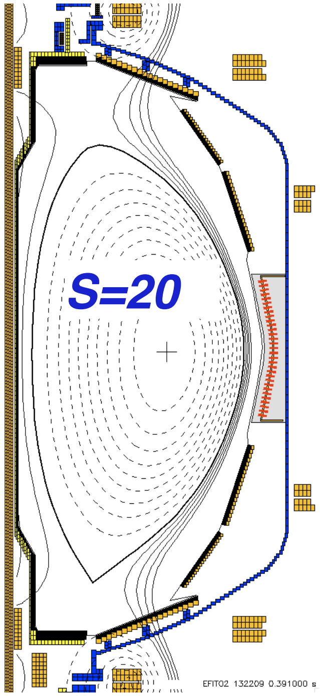


(S=$q_{95}I_P/aB_T$)

Example: Disruptivity is reduced with strong shaping of the plasma boundary.

S.P. Gerhardt et al., NF (2013)



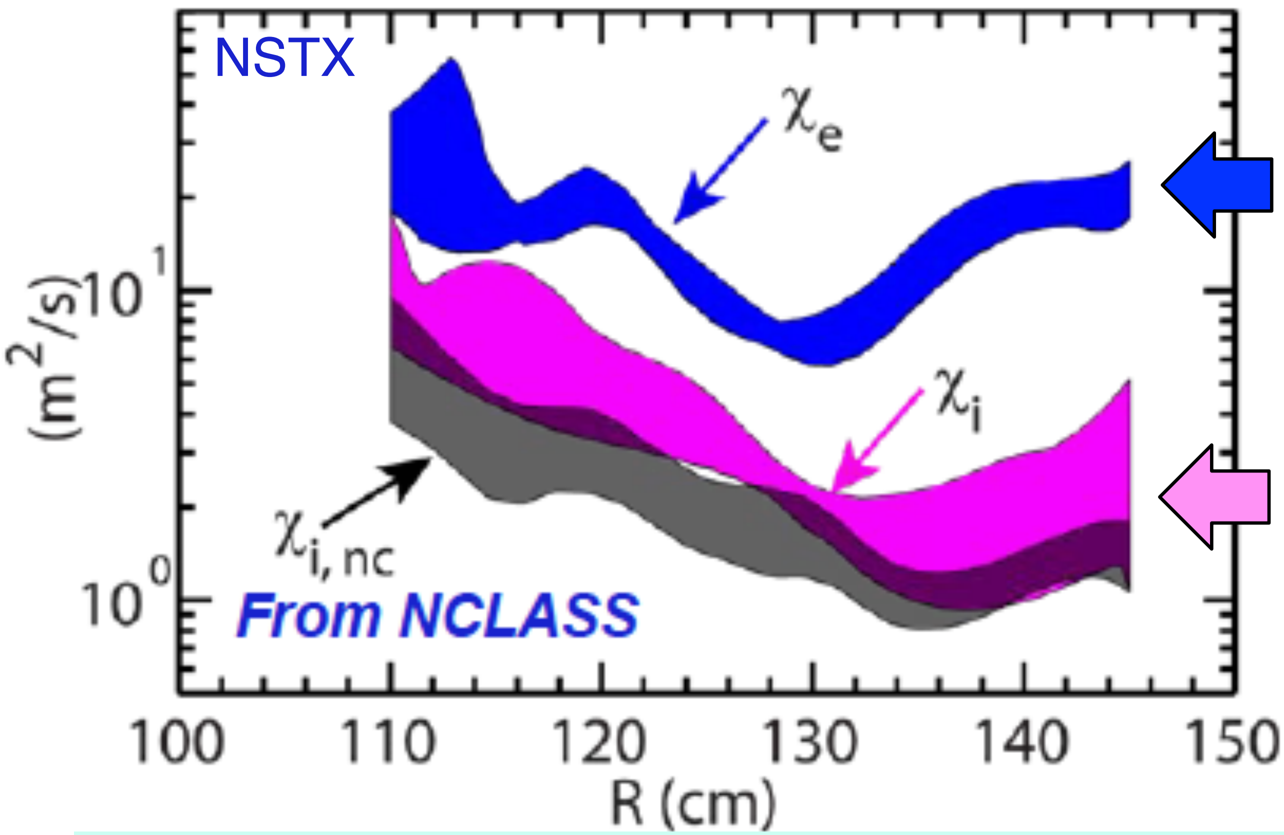


- No strong increase in disruptivity as β_N increases
- Reduction in disruptivity also with:
  - Decreasing l_i (broader current profile)
  - Decreasing pressure peaking

Upgrades will test and improve these favorable trends in a systematic way

Understanding Electron Energy Confinement is Critical for Reactor Design

Energy Diffusivity or Rate of Energy Loss



Electron energy is escaping from fusion plasma core much faster (much more than 10x) than neoclassical prediction – anomalous!

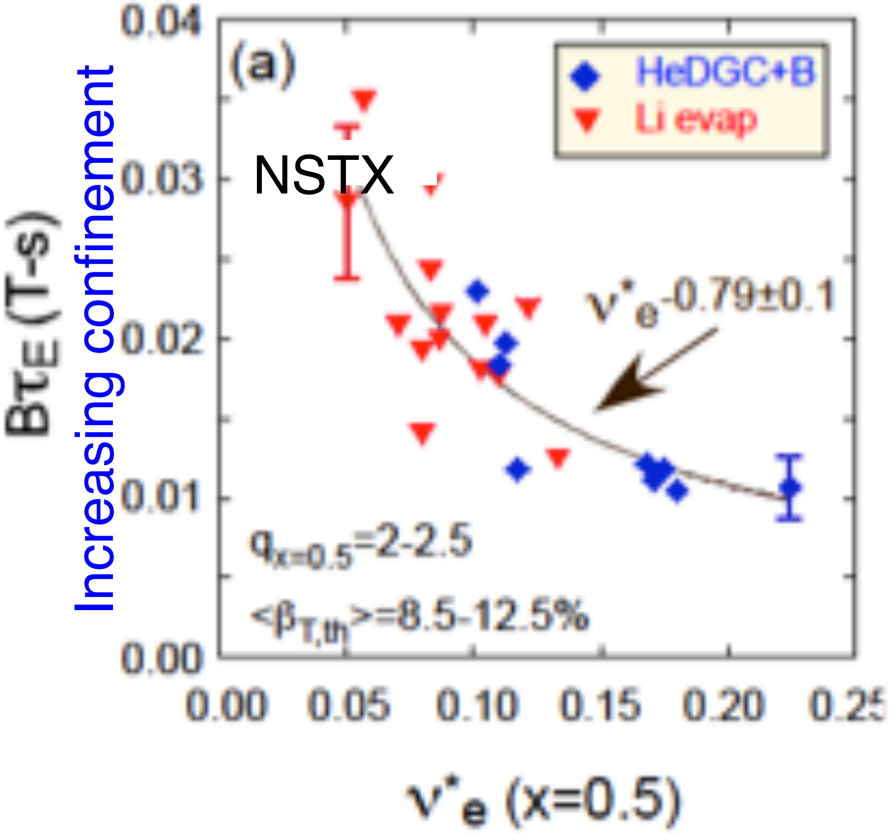
Ion energy is escaping from fusion plasma core not much faster than neoclassical prediction

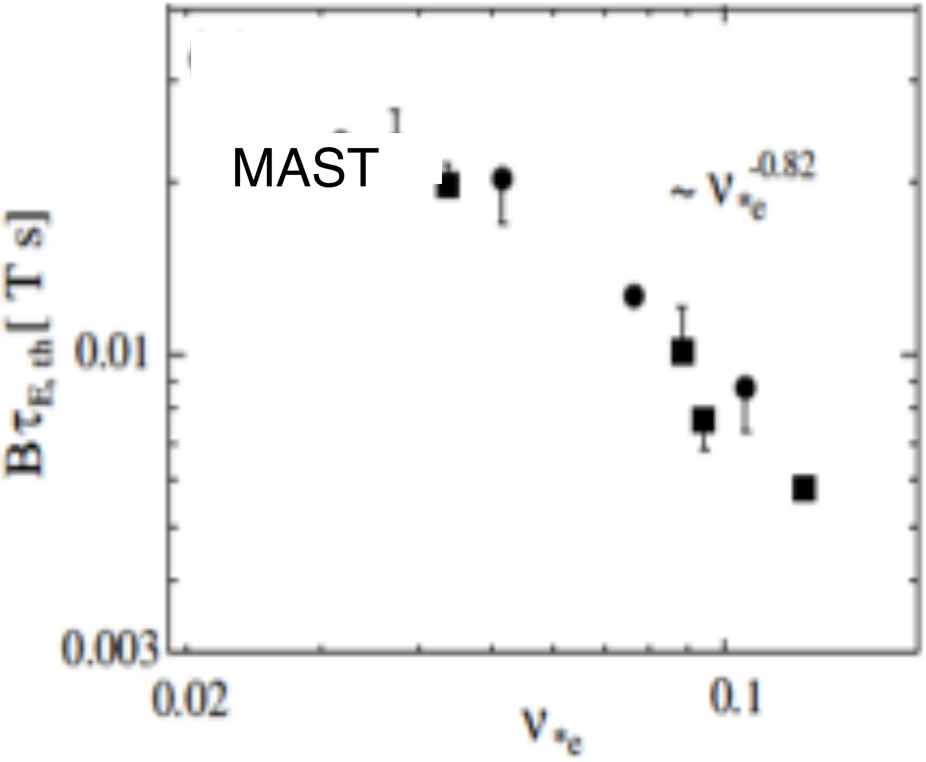
- Fusion Alpha-particle energy mainly heats electrons
- If electron energy loss is rapid, alpha-heating cannot keep fusion going

Y. Ren.

Encouraging Confinement Trend with Collisionality in STs

Important implications for future STs if trend continues





Increasing electron temperature

Increasing electron temperature

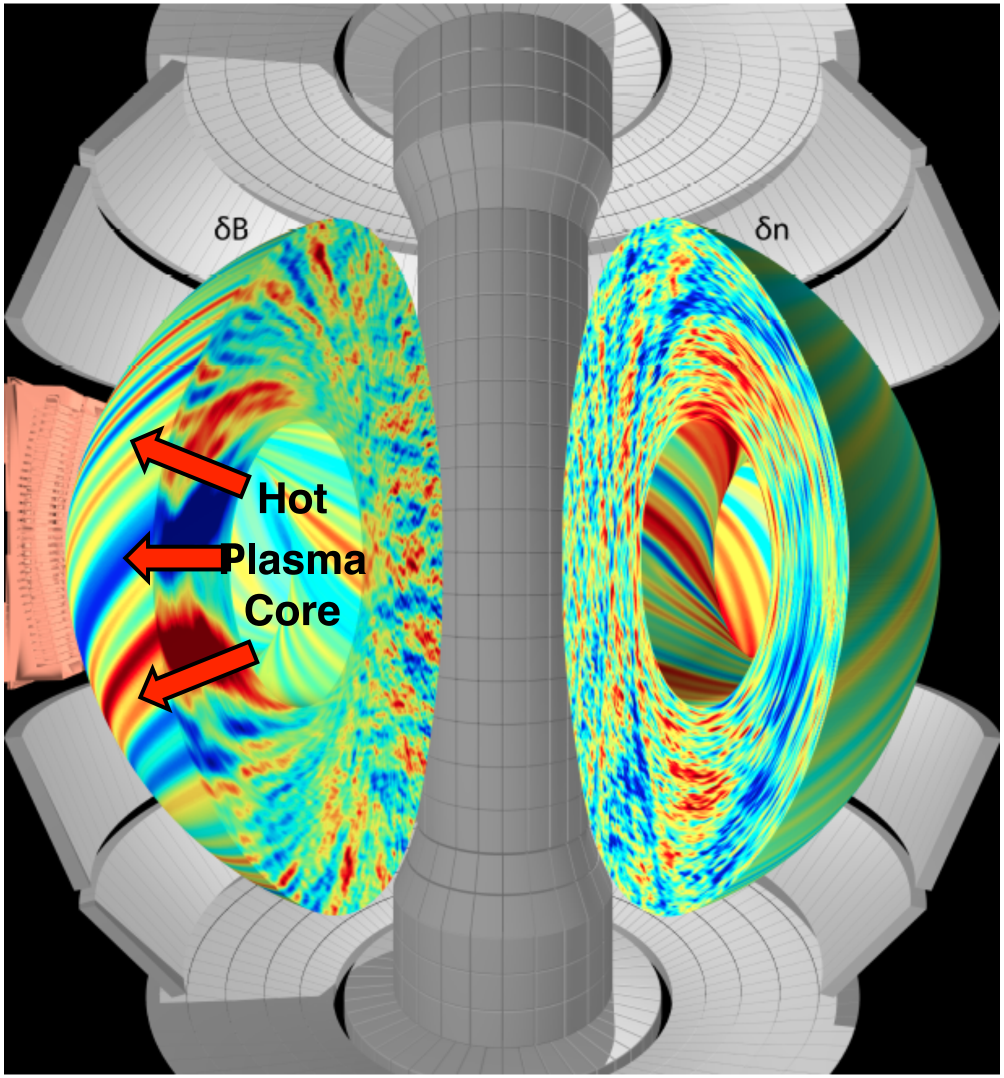
S.M. Kaye et al., NF(2013)

M. Valovic et al., NF (2011)

Favorable confinement trends with T_e and β help make economical compact fusion reactors

Fusion triple product = n τ T

- Conventional energy confinement time τ improves with device size (or volume) and magnetic field. But the cost increases with V and B.
- ST scaling suggests confinement improvement can be achieved with increased temperature which is achieved in reactor naturally for free.
- Improved confinement could lead to smaller volume more economical fusion reactor
- Better confinement could also enable small neutron sources which have many applications



NSTX-U Micro-tearing simulation by W. Guttenfelder and F. Scotti

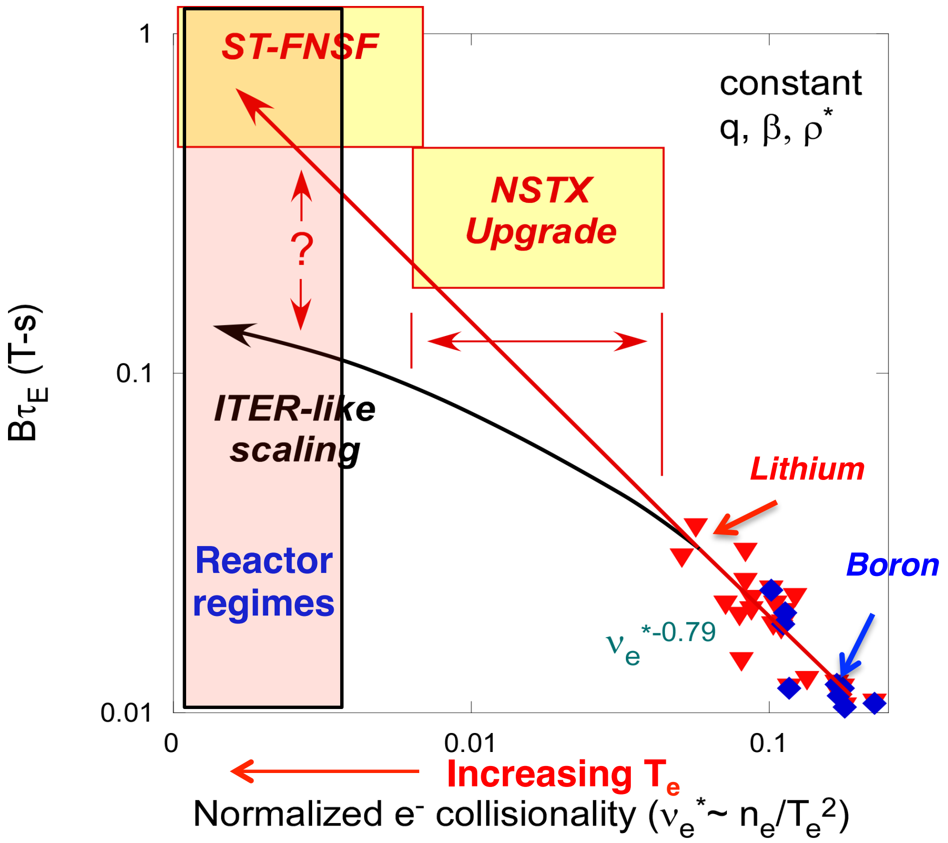
Favorable confinement trend with collisionality and β found in ST experiments

ST scaling observed in NSTX and MAST: $\tau_{E,\,th} \propto \nu_{*e}^{-0.8}\ \beta^{-0.0}$

Tokamak empirical scaling (ITER 98y,2): $\tau_{E,\,th} \propto \nu_{*e}^{-0.1}\ \beta^{-0.9}$

Surprising confinement scaling in STs!

Confinement time actually increased with temperature while previous scaling predicted just the opposite!

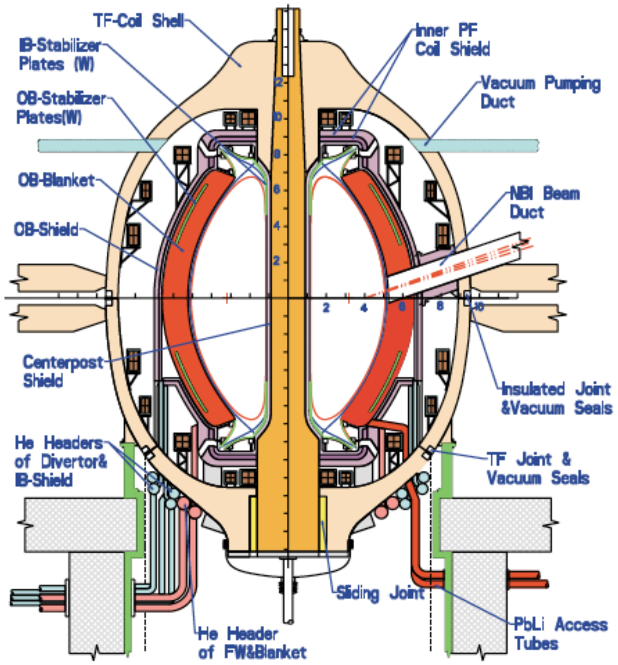


Also no confinement degradation observed in ST with plasma β

Several ST Fusion Power Plants Design Studied Low Toroidal Field and Magnetic Energy

ARIES-ST

Cu Power Plant



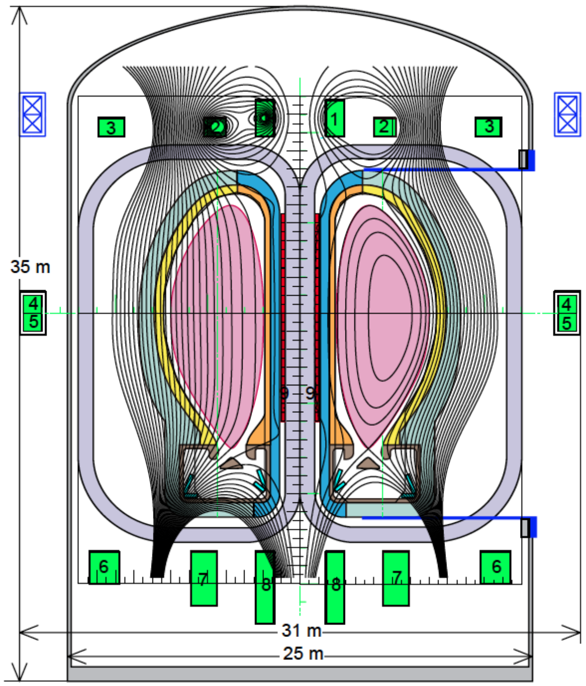
$R_0 \sim 3.2$ m

$B_{T0} \sim 2.1$T

F. Najmabadi et al., FED (2003)
H. R. Wilson, et al., NF (2004)

JUST

SC ST Power Plant

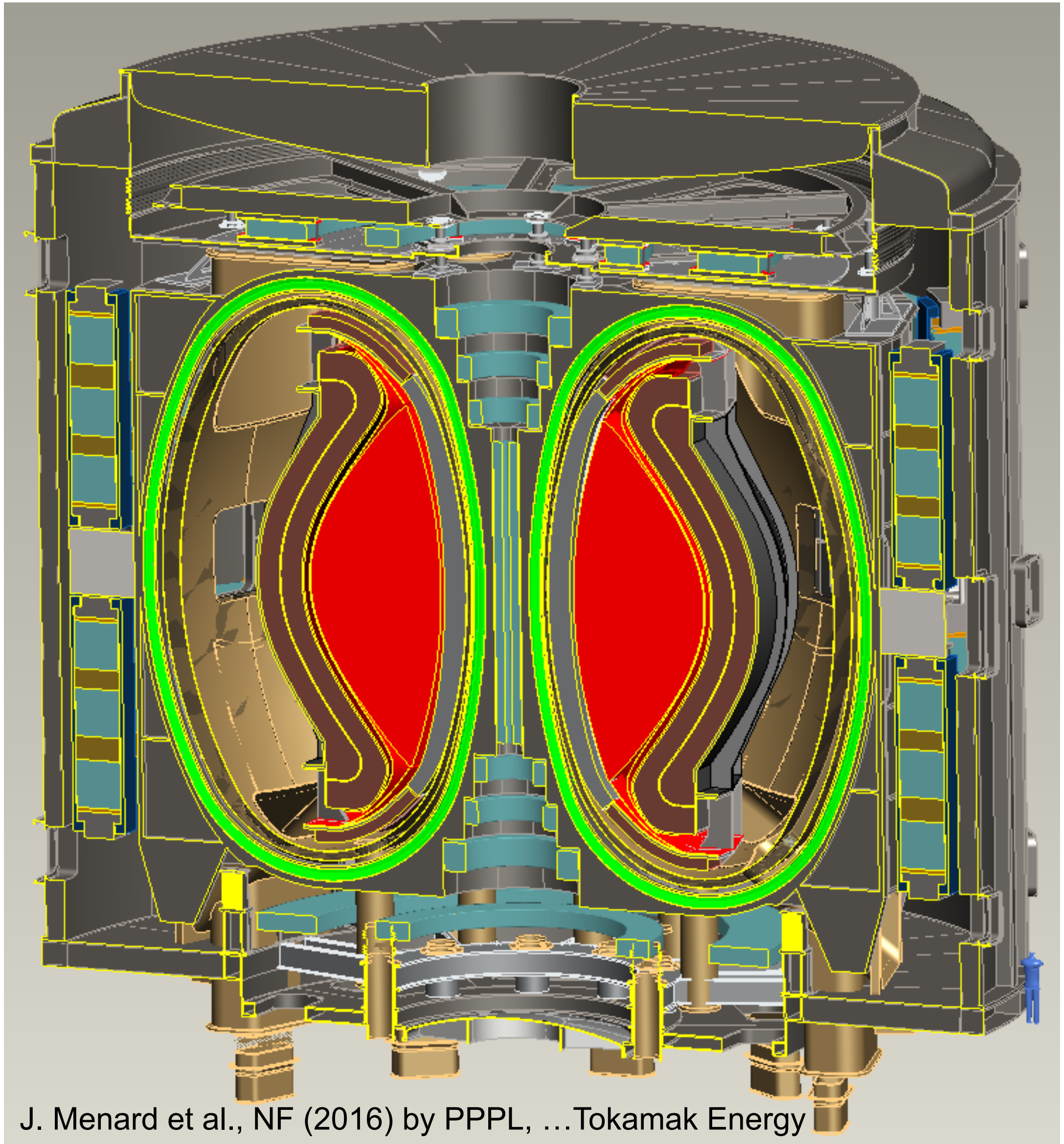


$R_0 \sim 4.5$m

$B_{T0} \sim 2.36$T

Y. Nagayama et al., IEEJ (2012)
B.G. Hong, Yet al.,NF (2011)
K. Gi NF (2015)

ST Fusion Plant Designed With High Temperature SC
A=2, R_0 = 3m HTS-TF FNSF / Pilot Plant



J. Menard et al., NF (2016) by PPPL, …Tokamak Energy

$B_T = 4T$, $I_P = 12.5MA$

$\kappa = 2.5$, $\delta = 0.55$

$\beta_N = 4.2$, $\beta_T = 9\%$

$H_{98} = 1.8$, $H_{Petty\text{-}08} = 1.3$

$f_{gw} = 0.80$, $f_{BS} = 0.76$

Startup I_P (OH) ~ 2MA

$J_{WP} = 70MA/m^2$

$B_{T\text{-}max} = 17.5T$

No joints in TF

Vertical maintenance

$P_{fusion} = 520$ MW

$P_{NBI} = 50$ MW, $E_{NBI} = 0.5MeV$

$Q_{DT} = 10.4$

$Q_{eng} = 1.35$

$P_{net} = 73$ MW

$\langle W_n \rangle = 1.3\ MW/m^2$

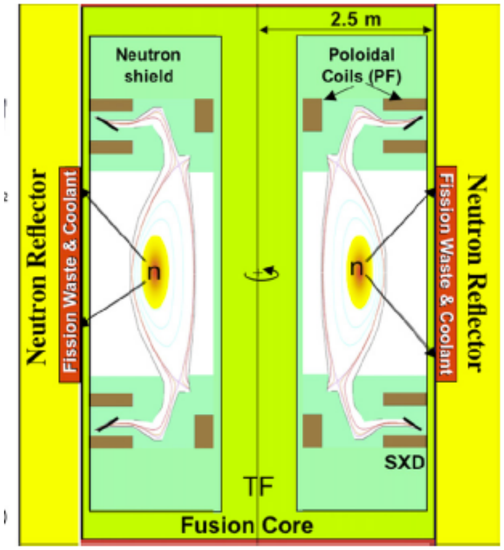
Peak n-flux = 2.4 MW/m^2

Peak n-fluence = 7 MWy/m^2

Fusion to Solve Fusion Waste Material Problem

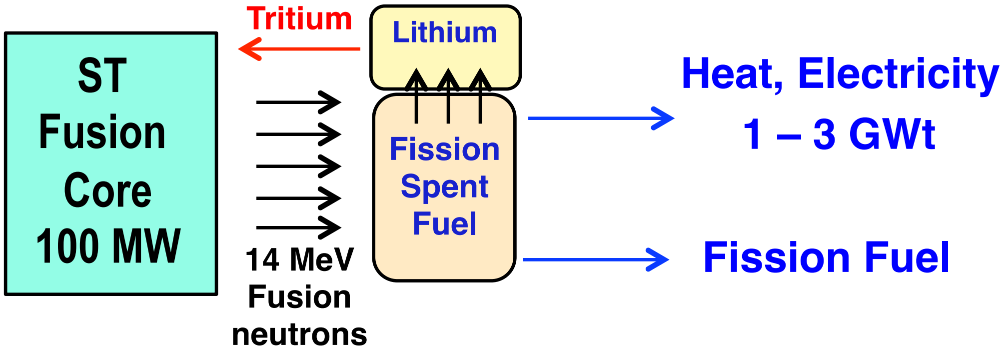
Only a Compact Fusion ST Cores Needed For Neutron Production

ST Fusion-Fission Hybrid
50 – 100 MW



ST-FNSF-like Q ~ 1 facility producing net energy / electricity by "burning" highly toxic long-lived nuclear waste

M. Kotschenreuther et al., FE&D (2009).



ST Fusion Core 100 MW

Tritium

Lithium

14 MeV Fusion neutrons

Fission Spent Fuel

Heat, Electricity 1 – 3 GWt

Fission Fuel

World is full of spent fuel from fission reactors – 20 t per year per reactor – 76,000 t just in the USA

- High energy fusion neutrons can break down the spent fuel further to reduce long live isotopes from fission spent fuel, e.g., Pu242, Am243, Cm244 and Cm246.
- This will also produce carbon-free energy to be used for electrical generation.
- Resulting thermal neutrons can be used to produce tritium to fuel the fusion core.
- This process can be also used to produce new fission fuel such as plutonium.

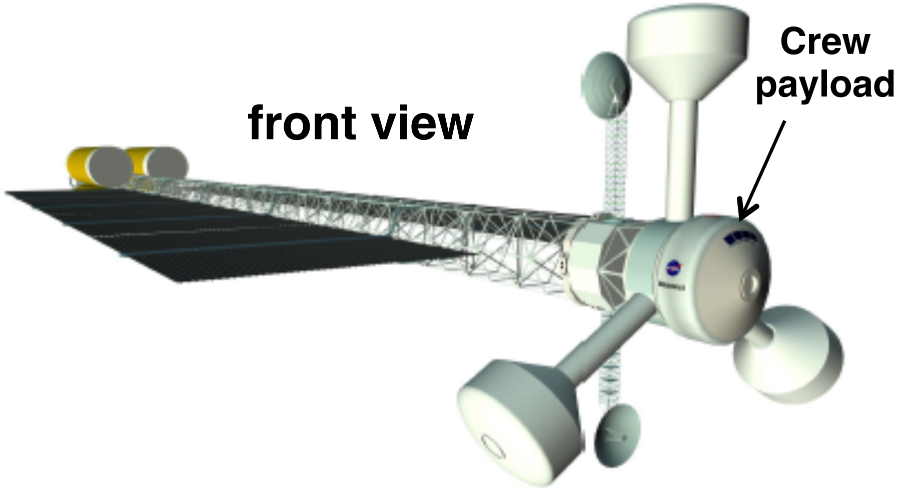
ST Fusion Power Reactor for Space Travel by NASA*
Taking advantage of high beta and light weight ST fusion core

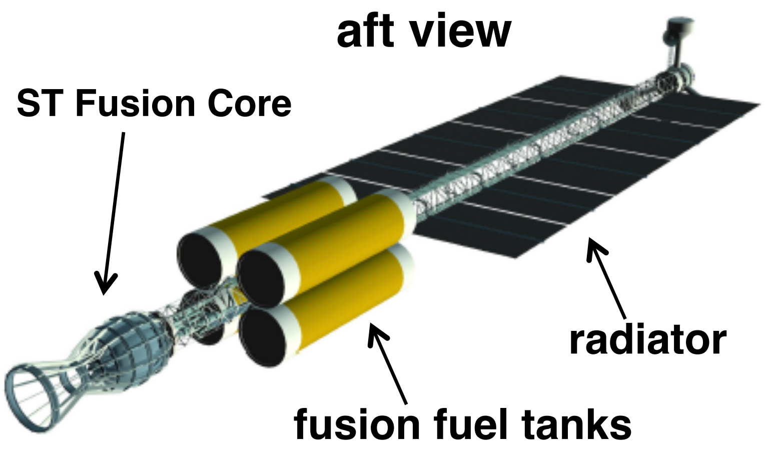
The Discovery II: Realizing "2001: A Space Odyssey"

Piloted Spherical Torus Nuclear Fusion Propulsion

Jupiter in 118 days and Saturn in 212 days!

C.H. Williams, et al., NASA/TM-2005-213559





In space, fusion provides the most efficient way to travel faster and furthe: vacuum is "free" and cryogenics are more efficient due low temperature space environment

- Most of fusion power goes into propulsion – ultra hot plasma simply exhausted into space - essentially eliminates fusion plasma-material issues!
- Only small fraction of fusion power (~ 15%) goes into electrical generation
- No toxic bi-products: $D + He^3 \longrightarrow He^4 + H + 18.3\ \text{MeV}$ (high energy release)

Spherical Tokamak for Economical Fusion System

Fusion can provide safe and green source of energy for mankind

- Fusion energy offers the prospect of safe and limitless energy source to sustain and enrich humanity.
- Spherical tokamak (ST) is being pursued due to its prospect of producing significant fusion power in an economical facility.
- More than sixteen ST research facilities operating worldwide have achieved remarkable advances in all areas of fusion research.
- These results suggest exciting future prospects for ST in both near term and longer term:
  - Compact fusion neutron sources for various applications including nuclear spent fuel remediation
  - Economical clean energy source to reduce green gas emission for global warming
  - Provide uniquely powerful clean propulsion and energy sources for space travel